

UNITED STATES PATENT AND TRADEMARK OFFICE

---

**BEFORE THE PATENT TRIAL AND APPEAL BOARD**

---

WESTERN DIGITAL TECHNOLOGIES, INC.,  
Petitioner,

v.

GODO KAISHA IP BRIDGE 1,  
Patent Owner.

---

Case No. IPR2025-00701  
U.S. Patent No. 10,367,138

---

**DECLARATION OF JEFFREY BOKOR, PH.D.**

## TABLE OF CONTENTS

|       |                                                        |    |
|-------|--------------------------------------------------------|----|
| I.    | INTRODUCTION .....                                     | 1  |
| II.   | BACKGROUND AND QUALIFICATIONS .....                    | 1  |
| III.  | MATERIALS CONSIDERED .....                             | 4  |
| IV.   | RELEVANT LAW .....                                     | 10 |
| V.    | PRIORITY DATE .....                                    | 14 |
| VI.   | LEVEL OF ORDINARY SKILL IN THE ART .....               | 15 |
| VII.  | TECHNOLOGY BACKGROUND.....                             | 16 |
| A.    | Conventional Magnetic Memory .....                     | 16 |
| B.    | Magnetic Tunnel Junctions (MTJs) And Spintronics ..... | 17 |
| C.    | Tunnel Magnetoresistance Ratio .....                   | 19 |
| D.    | Quantum Tunneling .....                                | 22 |
| E.    | MTJ Materials .....                                    | 25 |
| 1.    | Crystalline Structures.....                            | 25 |
| 2.    | Ferromagnetic Materials In MTJs.....                   | 28 |
| 3.    | Oxide Layer In MTJs .....                              | 33 |
| F.    | Oxygen Vacancy Defects In MgO Thin Films .....         | 37 |
| VIII. | OVERVIEW OF THE '138 PATENT .....                      | 42 |
| IX.   | CLAIM CONSTRUCTION .....                               | 44 |

|      |                                                                                                                                                                                                                                           |    |
|------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|----|
| X.   | PRIOR ART TO THE '138 PATENT.....                                                                                                                                                                                                         | 45 |
| A.   | Bowen <i>et al.</i> , <i>Large magnetoresistance in Fe/MgO/FeCo(001) epitaxial tunnel junctions on GaAs(001)</i> , 79 Appl. Phys. Letters 1655-1657 (2001) (EX1026, “Bowen”).....                                                         | 45 |
| B.   | Soukup <i>et al.</i> , <i>Voltage-Current Characteristics for Electrical Conduction Through Thin MgO Films</i> , 41 J. App. Phys. 3229-3236 (1970) (EX1028, “Soukup”).....                                                                | 47 |
| C.   | Wang <i>et al.</i> , <i>70% TMR at Room Temperature for SDT Sandwich Junctions with CoFeB as Free and Reference Layers</i> , 40 IEEE Trans. Magn. 2269-2271 (2004) (EX1055, “Wang”).....                                                  | 48 |
| D.   | U.S. Patent No. 7,270,896 to Parkin (EX1062, “Parkin”).....                                                                                                                                                                               | 49 |
| XI.  | SUMMARY OF OPINIONS OFFERED.....                                                                                                                                                                                                          | 51 |
| XII. | GROUND 1: CLAIMS 1-4, 7-10, AND 12-13 ARE OBVIOUS OVER PARKIN IN VIEW OF WANG AND SOUKUP .....                                                                                                                                            | 51 |
| A.   | Claim 1: Obviousness Over Parkin In View Of Wang And Optionally Soukup .....                                                                                                                                                              | 51 |
| 1.   | Claim 1[preamble]: “A magnetic tunnel junction (MTJ) device, comprising:” .....                                                                                                                                                           | 51 |
| 2.   | Claim 1[a]: “a first electrode comprising a first ferromagnetic material layer that includes Co, Fe, and B;” .....                                                                                                                        | 52 |
| 3.   | Claim 1[b]: “a barrier layer disposed over the first electrode, the barrier layer comprising a magnesium oxide (MgO) layer that is formed of a poly-crystalline MgO in which a (001) crystal plane is preferentially oriented; and” ..... | 58 |
| 4.   | Claim 1[c]: “a second electrode disposed over the barrier layer and comprising a second ferromagnetic material layer that includes Co, Fe, and B, and” .....                                                                              | 61 |

|    |                                                                                                                                                                                                                                          |    |
|----|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|----|
| 5. | Claim 1[d]: “wherein each of the first and second ferromagnetic material layers is entirely crystallized,[] and” .....                                                                                                                   | 63 |
| 6. | Claim 1[e]: “wherein a value of x in MgO <sub>x</sub> for the MgO layer is greater than 0 and less than 1.” .....                                                                                                                        | 69 |
| B. | Claim 2: Obviousness Over Parkin In View Of Wang And Optionally Soukup .....                                                                                                                                                             | 73 |
| 1. | Claim 2: “The MTJ device of claim 1, wherein the first ferromagnetic material layer is in direct contact with the barrier layer, and wherein the second ferromagnetic material layer is in direct contact with the barrier layer.” ..... | 73 |
| C. | Claim 3: Obviousness Over Parkin In View Of Wang And Optionally Soukup .....                                                                                                                                                             | 75 |
| 1. | Claim 3: “The MTJ device of claim 1, wherein the first ferromagnetic material layer is in direct contact with the MgO layer, and wherein the second ferromagnetic material layer is in direct contact with the MgO layer.” .....         | 75 |
| D. | Claim 4: Obviousness Over Parkin In View Of Wang And Soukup.....                                                                                                                                                                         | 75 |
| 1. | Claim 4: “The MTJ device of claim 1, wherein a barrier height $\phi$ of the barrier layer is in a range of 0.2 to 0.5 eV.” .....                                                                                                         | 75 |
| E. | Claim 7: Obviousness Over Parkin In View Of Wang And Optionally Soukup .....                                                                                                                                                             | 85 |
| 1. | Claim 7[preamble]: “A magnetic tunnel junction (MTJ) device, comprising:” .....                                                                                                                                                          | 85 |
| 2. | Claim 7[a]: “a first electrode made of a first CoFeB layer;” .....                                                                                                                                                                       | 85 |
| 3. | Claim 7[b]: “a barrier layer made of a magnesium oxide (MgO) layer that is a poly-crystalline layer in which a (001) crystal plane is preferentially oriented; and” .....                                                                | 86 |

|    |                                                                                                                                                                                                                         |    |
|----|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|----|
| 4. | Claim 7[c]: “a second electrode made of a second CoFeB layer, and” .....                                                                                                                                                | 86 |
| 5. | Claim 7[d]: “wherein the barrier layer is located between the first electrode and the second electrode, and” .....                                                                                                      | 86 |
| 6. | Claim 7[e]: “wherein both the first and second CoFeB layers are entirely crystallized, and” .....                                                                                                                       | 87 |
| 7. | Claim 7[f]: “wherein a value of x in MgO <sub>x</sub> for the MgO layer is greater than 0 and less than 1.” .....                                                                                                       | 87 |
| F. | Claim 8: Obviousness Over Parkin In View Of Wang And Optionally Soukup .....                                                                                                                                            | 88 |
| 1. | Claim 8: “The MTJ device of claim 7, wherein the first CoFeB layer is in direct contact with the MgO layer, and wherein the second CoFeB layer is in direct contact with the MgO layer.” .....                          | 88 |
| G. | Claim 9: Obviousness Over Parkin In View Of Wang And Optionally Soukup .....                                                                                                                                            | 88 |
| 1. | Claim 9: “The MTJ device of claim 7, wherein the MgO layer and the first CoFeB layer form a first interface of the MTJ, and wherein the MgO layer and the second CoFeB layer form a second interface of the MTJ.” ..... | 88 |
| H. | Claim 10: Obviousness Over Parkin In View Of Wang And Soukup.....                                                                                                                                                       | 90 |
| 1. | Claim 10: “The MTJ device of claim 7, wherein a barrier height $\phi$ of the MgO layer is in a range of 0.2 to 0.5 eV.” .....                                                                                           | 90 |
| I. | Claim 12: Obviousness Over Parkin In View Of Wang And Optionally Soukup .....                                                                                                                                           | 90 |
| 1. | Claim 12[preamble]: “A magnetic tunnel junction (MTJ) device, comprising:” .....                                                                                                                                        | 90 |
| 2. | Claim 12[a]: “a first ferromagnetic material layer that includes Co, Fe, and B;” .....                                                                                                                                  | 90 |

|       |                                                                                                                                                                                                                                                                                                                                                                                                              |    |
|-------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|----|
| 3.    | Claim 12[b]: “a barrier layer disposed on the first ferromagnetic material layer, the barrier layer comprising a magnesium oxide (MgO) layer that is a poly-crystalline MgO in which (001) crystal plane is preferentially oriented; and” .....                                                                                                                                                              | 91 |
| 4.    | Claim 12[c]: “a second ferromagnetic material layer that is disposed on the barrier layer and includes Co, Fe, and B, and” .....                                                                                                                                                                                                                                                                             | 91 |
| 5.    | Claim 12[d]: “wherein each of the first and second ferromagnetic material layers is entirely crystallized, and wherein a value of x in MgO <sub>x</sub> for the MgO layer is greater than 0 and less than 1.” .....                                                                                                                                                                                          | 91 |
| J.    | Claim 13: Obviousness Over Parkin In View Of Wang And Soukup.....                                                                                                                                                                                                                                                                                                                                            | 92 |
| 1.    | Claim 13: “The MTJ device of claim 12, wherein a barrier height $\phi$ of the barrier layer is in a range of 0.2 to 0.5 eV.” .....                                                                                                                                                                                                                                                                           | 92 |
| XIII. | GROUND 2: CLAIMS 5-6, 11, AND 14 ARE OBVIOUS OVER PARKIN IN VIEW OF WANG, SOUKUP, AND BOWEN.....                                                                                                                                                                                                                                                                                                             | 92 |
| A.    | Claim 5: Obviousness Over Parkin In View Of Wang, Soukup, And Bowen.....                                                                                                                                                                                                                                                                                                                                     | 92 |
| 1.    | Claim 5[preamble]: “The MTJ device of claim 4,” .....                                                                                                                                                                                                                                                                                                                                                        | 92 |
| 2.    | Claim 5[a]: “wherein the barrier height $\phi$ of the barrier layer is obtained by fitting J-V characteristics of the MTJ device to an equation (1): $J=[(2m\phi)^{1/2}/\Delta s](e/h)^2 \times \exp[-(4\pi\Delta s/h) \times (2m\phi)^{1/2}] \times V$ (1)” .....                                                                                                                                           | 92 |
| 3.    | Claim 5[b]: “where J is a tunnel current density flowing through the barrier layer, V is an applied bias voltage that is 100 mV or smaller, m is the free electron mass, e is the elementary electric charge, h is Planck's constant, $\Delta s$ is an effective thickness of the barrier layer that is equivalent to ( $t_{MgO}-0.5$ nm), and $t_{MgO}$ is an actual thickness of the barrier layer.” ..... | 98 |

|    |                                                                                                                                                                                                                                                                                                                                                                                                                                        |     |
|----|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-----|
| B. | Claim 6: Obviousness Over Parkin In View Of Wang, Soukup,<br>And Bowen.....                                                                                                                                                                                                                                                                                                                                                            | 103 |
| 1. | Claim 6: “The MTJ device of claim 1, wherein a value of<br>x in $\text{MgO}_x$ for the MgO layer is greater than 0.9 and less<br>than 1.” .....                                                                                                                                                                                                                                                                                        | 103 |
| C. | Claim 11: Obviousness Over Parkin In View Of Wang, Soukup,<br>And Bowen.....                                                                                                                                                                                                                                                                                                                                                           | 117 |
| 1. | Claim 11[preamble]: “The MTJ device of claim 10,” .....                                                                                                                                                                                                                                                                                                                                                                                | 117 |
| 2. | Claim 11[a]: “wherein the barrier height $\phi$ of the MgO<br>layer is obtained by fitting J-V characteristics of the MTJ<br>device to an equation (1): $J=[(2m\phi)^{1/2}/\Delta s](e/h)^2 \times \exp[-(4\pi\Delta s/h) \times (2m\phi)^{1/2}] \times V$ (1)” .....                                                                                                                                                                  | 117 |
| 3. | Claim 11[b]: “where J is a tunnel current density flowing<br>through the MgO layer, V is an applied bias voltage that is<br>100 mV or smaller, m is the free electron mass, e is the<br>elementary electric charge, h is Planck's constant, $\Delta s$ is an<br>effective thickness of the MgO layer that is equivalent to<br>( $t_{\text{MgO}}-0.5$ nm), and $t_{\text{MgO}}$ is an actual thickness of the MgO<br>layer.” .....      | 117 |
| D. | Claim 14: Obviousness Over Parkin In View Of Wang, Soukup,<br>And Bowen.....                                                                                                                                                                                                                                                                                                                                                           | 118 |
| 1. | Claim 14[preamble]: “The MTJ device of claim 13,” .....                                                                                                                                                                                                                                                                                                                                                                                | 118 |
| 2. | Claim 14[a]: “wherein the barrier height $\phi$ of the barrier<br>layer is obtained by fitting J-V characteristics of the MTJ<br>device to an equation (1): $J=[(2m\phi)^{1/2}/\Delta s](e/h)^2 \times \exp[-(4\pi\Delta s/h) \times (2m\phi)^{1/2}] \times V$ (1)” .....                                                                                                                                                              | 118 |
| 3. | Claim 14[b]: “where J is a tunnel current density flowing<br>through the barrier layer, V is an applied bias voltage that<br>is 100 mV or smaller, m is the free electron mass, e is the<br>elementary electric charge, h is Planck's constant, $\Delta s$ is an<br>effective thickness of the barrier layer that is equivalent to<br>( $t_{\text{MgO}}-0.5$ nm), and two [sic] is an actual thickness of the<br>barrier layer.” ..... | 118 |

|                                                                                                                                                                                                                                              |     |
|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-----|
| XIV. GROUND 3: CLAIMS 1-14 ARE OBVIOUS OVER BOWEN IN VIEW OF WANG AND SOUKUP .....                                                                                                                                                           | 119 |
| A. Claim 1: Obviousness Over Bowen In View Of Wang And Optionally Soukup .....                                                                                                                                                               | 119 |
| 1. Claim 1[preamble]: “A magnetic tunnel junction (MTJ) device, comprising:” .....                                                                                                                                                           | 119 |
| 2. Claim 1[a]: “a first electrode comprising a first ferromagnetic material layer that includes Co, Fe, and B;” .....                                                                                                                        | 120 |
| 3. Claim 1[b]: “a barrier layer disposed over the first electrode, the barrier layer comprising a magnesium oxide (MgO) layer that is formed of a poly-crystalline MgO in which a (001) crystal plane is preferentially oriented; and” ..... | 127 |
| 4. Claim 1[c]: “a second electrode disposed over the barrier layer and comprising a second ferromagnetic material layer that includes Co, Fe, and B, and” .....                                                                              | 132 |
| 5. Claim 1[d]: “wherein each of the first and second ferromagnetic material layers is entirely crystallized,[] and” .....                                                                                                                    | 136 |
| 6. Claim 1[e]: “wherein a value of x in MgO <sub>x</sub> for the MgO layer is greater than 0 and less than 1.” .....                                                                                                                         | 141 |
| B. Claim 2: Obviousness Over Bowen In View Of Wang And Optionally Soukup .....                                                                                                                                                               | 144 |
| 1. Claim 2: “The MTJ device of claim 1, wherein the first ferromagnetic material layer is in direct contact with the barrier layer, and wherein the second ferromagnetic material layer is in direct contact with the barrier layer.”.....   | 144 |
| C. Claim 3: Obviousness Over Bowen In View Of Wang And Optionally Soukup .....                                                                                                                                                               | 146 |

|    |                                                                                                                                                                                                                                                                                                                                                                                                                            |     |
|----|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-----|
| 1. | Claim 3: “The MTJ device of claim 1, wherein the first ferromagnetic material layer is in direct contact with the MgO layer, and wherein the second ferromagnetic material layer is in direct contact with the MgO layer.” .....                                                                                                                                                                                           | 146 |
| D. | Claim 4: Obviousness Over Bowen In View Of Wang And Soukup.....                                                                                                                                                                                                                                                                                                                                                            | 146 |
| 1. | Claim 4: “The MTJ device of claim 1, wherein a barrier height $\phi$ of the barrier layer is in a range of 0.2 to 0.5 eV.” .....                                                                                                                                                                                                                                                                                           | 146 |
| E. | Claim 5: Obviousness Over Bowen In View Of Wang And Soukup.....                                                                                                                                                                                                                                                                                                                                                            | 156 |
| 1. | Claim 5[preamble]: “The MTJ device of claim 4,” .....                                                                                                                                                                                                                                                                                                                                                                      | 156 |
| 2. | Claim 5[a]: “wherein the barrier height $\phi$ of the barrier layer is obtained by fitting J-V characteristics of the MTJ device to an equation (1): $J=[(2m\phi)^{1/2}/\Delta s](e/h)^2 \times \exp[-(4\pi\Delta s/h) \times (2m\phi)^{1/2}] \times V$ (1)” .....                                                                                                                                                         | 156 |
| 3. | Claim 5[b]: “where J is a tunnel current density flowing through the barrier layer, V is an applied bias voltage that is 100 mV or smaller, m is the free electron mass, e is the elementary electric charge, h is Planck's constant, $\Delta s$ is an effective thickness of the barrier layer that is equivalent to ( $t_{\text{MgO}}-0.5$ nm), and $t_{\text{MgO}}$ is an actual thickness of the barrier layer.” ..... | 156 |
| F. | Claim 6: Obviousness Over Bowen In View Of Wang And Soukup.....                                                                                                                                                                                                                                                                                                                                                            | 157 |
| 1. | Claim 6: “The MTJ device of claim 1, wherein a value of x in $\text{MgO}_x$ for the MgO layer is greater than 0.9 and less than 1.” .....                                                                                                                                                                                                                                                                                  | 157 |
| G. | Claim 7: Obviousness Over Bowen In View Of Wang And Optionally Soukup .....                                                                                                                                                                                                                                                                                                                                                | 170 |
| 1. | Claim 7[preamble]: “A magnetic tunnel junction (MTJ) device, comprising:” .....                                                                                                                                                                                                                                                                                                                                            | 170 |

|    |                                                                                                                                                                                                                         |     |
|----|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-----|
| 2. | Claim 7[a]: “a first electrode made of a first CoFeB layer;”<br>.....                                                                                                                                                   | 170 |
| 3. | Claim 7[b]: “a barrier layer made of a magnesium oxide (MgO) layer that is a poly-crystalline layer in which a (001) crystal plane is preferentially oriented; and” .....                                               | 170 |
| 4. | Claim 7[c]: “a second electrode made of a second CoFeB layer, and” .....                                                                                                                                                | 170 |
| 5. | Claim 7[d]: “wherein the barrier layer is located between the first electrode and the second electrode, and” .....                                                                                                      | 171 |
| 6. | Claim 7[e]: “wherein both the first and second CoFeB layers are entirely crystallized, and” .....                                                                                                                       | 171 |
| 7. | Claim 7[f]: “wherein a value of x in MgO <sub>x</sub> for the MgO layer is greater than 0 and less than 1.” .....                                                                                                       | 172 |
| H. | Claim 8: Obviousness Over Bowen In View Of Wang And Optionally Soukup .....                                                                                                                                             | 172 |
| 1. | Claim 8: “The MTJ device of claim 7, wherein the first CoFeB layer is in direct contact with the MgO layer, and wherein the second CoFeB layer is in direct contact with the MgO layer.” .....                          | 172 |
| I. | Claim 9: Obviousness Over Bowen In View Of Wang And Optionally Soukup .....                                                                                                                                             | 172 |
| 1. | Claim 9: “The MTJ device of claim 7, wherein the MgO layer and the first CoFeB layer form a first interface of the MTJ, and wherein the MgO layer and the second CoFeB layer form a second interface of the MTJ.” ..... | 172 |
| J. | Claim 10: Obviousness Over Bowen In View Of Wang And Soukup.....                                                                                                                                                        | 173 |
| 1. | Claim 10: “The MTJ device of claim 7, wherein a barrier height $\phi$ of the MgO layer is in a range of 0.2 to 0.5 eV.” ....                                                                                            | 173 |

|    |                                                                                                                                                                                                                                                                                                                                                                                                                           |     |
|----|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-----|
| K. | Claim 11: Obviousness Over Bowen In View Of Wang And Soukup.....                                                                                                                                                                                                                                                                                                                                                          | 173 |
| 1. | Claim 11[preamble]: “The MTJ device of claim 10,” .....                                                                                                                                                                                                                                                                                                                                                                   | 173 |
| 2. | Claim 11[a]: “wherein the barrier height $\phi$ of the MgO layer is obtained by fitting J-V characteristics of the MTJ device to an equation (1): $J=[(2m\phi)^{1/2}/\Delta s](e/h)^2 \times \exp[-(4\pi\Delta s/h) \times (2m\phi)^{1/2}] \times V$ (1)” .....                                                                                                                                                           | 174 |
| 3. | Claim 11[b]: “where J is a tunnel current density flowing through the MgO layer, V is an applied bias voltage that is 100 mV or smaller, m is the free electron mass, e is the elementary electric charge, h is Planck's constant, $\Delta s$ is an effective thickness of the MgO layer that is equivalent to $(t_{\text{MgO}} - 0.5 \text{ nm})$ , and $t_{\text{MgO}}$ is an actual thickness of the MgO layer.” ..... | 174 |
| L. | Claim 12: Obviousness Over Bowen In View Of Wang And Optionally Soukup .....                                                                                                                                                                                                                                                                                                                                              | 174 |
| 1. | Claim 12[preamble]: “A magnetic tunnel junction (MTJ) device, comprising:” .....                                                                                                                                                                                                                                                                                                                                          | 174 |
| 2. | Claim 12[a]: “a first ferromagnetic material layer that includes Co, Fe, and B;” .....                                                                                                                                                                                                                                                                                                                                    | 174 |
| 3. | Claim 12[b]: “a barrier layer disposed on the first ferromagnetic material layer, the barrier layer comprising a magnesium oxide (MgO) layer that is a poly-crystalline MgO in which (001) crystal plane is preferentially oriented; and” .....                                                                                                                                                                           | 175 |
| 4. | Claim 12[c]: “a second ferromagnetic material layer that is disposed on the barrier layer and includes Co, Fe, and B, and” .....                                                                                                                                                                                                                                                                                          | 175 |
| 5. | Claim 12[d]: “wherein each of the first and second ferromagnetic material layers is entirely crystallized, and wherein a value of x in $\text{MgO}_x$ for the MgO layer is greater than 0 and less than 1.” .....                                                                                                                                                                                                         | 175 |

|       |                                                                                                                                                                                                                                                                                                                                                                                                                      |     |
|-------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-----|
| M.    | Claim 13: Obviousness Over Bowen In View Of Wang And Soukup.....                                                                                                                                                                                                                                                                                                                                                     | 176 |
| 1.    | Claim 13: “The MTJ device of claim 12, wherein a barrier height $\phi$ of the barrier layer is in a range of 0.2 to 0.5 eV.” .....                                                                                                                                                                                                                                                                                   | 176 |
| N.    | Claim 14: Obviousness Over Bowen In View Of Wang And Soukup.....                                                                                                                                                                                                                                                                                                                                                     | 176 |
| 1.    | Claim 14[preamble]: “The MTJ device of claim 13,” .....                                                                                                                                                                                                                                                                                                                                                              | 176 |
| 2.    | Claim 14[a]: “wherein the barrier height $\phi$ of the barrier layer is obtained by fitting J-V characteristics of the MTJ device to an equation (1): $J=[(2m\phi)^{1/2}/\Delta s](e/h)^2 \times \exp[-(4\pi\Delta s/h) \times (2m\phi)^{1/2}] \times V$ (1)” .....                                                                                                                                                  | 176 |
| 3.    | Claim 14[b]: “where J is a tunnel current density flowing through the barrier layer, V is an applied bias voltage that is 100 mV or smaller, m is the free electron mass, e is the elementary electric charge, h is Planck's constant, $\Delta s$ is an effective thickness of the barrier layer that is equivalent to ( $t_{\text{MgO}}-0.5$ nm), and two [sic] is an actual thickness of the barrier layer.” ..... | 177 |
| XV.   | SECONDARY INDICIA OF NONOBVIOUSNESS .....                                                                                                                                                                                                                                                                                                                                                                            | 177 |
| XVI.  | CONCLUSION .....                                                                                                                                                                                                                                                                                                                                                                                                     | 177 |
| XVII. | APPENDIX: LIST OF PATENT CLAIMS .....                                                                                                                                                                                                                                                                                                                                                                                | 180 |

I, Jeffrey Bokor, hereby declare as follows:

## **I. INTRODUCTION**

1. I have prepared this Declaration in connection with Western Digital Technologies, Inc.’s Petition for *Inter Partes* Review of U.S. Patent No. 10,367,138 (“the ’138 Patent”) (EX1011).

2. In the course of preparing this Declaration, I reviewed the ’138 Patent and its prosecution file history as well as the other documents listed in Section III and/or discussed in this Declaration.

3. I have been retained by Western Digital Technologies, Inc. (“Western Digital” or “Petitioner”) as an expert in the field of integrated circuit device technologies, including magnetic devices, device physics, nanomagnetism, and spintronics. I am being compensated at my normal consulting rate for my time. My compensation is not dependent on, and in no way affects, the substance of my statements in this Declaration. I have no financial interest in Western Digital, the ’138 Patent, or the owner of the ’138 Patent.

## **II. BACKGROUND AND QUALIFICATIONS**

4. I have over 35 years of experience in the fields of integrated circuit device technologies, including magnetic devices, device physics, nanomagnetism, and spintronics. I received a Bachelor of Science degree in Electrical Engineering from the Massachusetts Institute of Technology in 1975, a Master of Science in

Electrical Engineering from Stanford University in 1976, and a Ph.D. in Electrical Engineering from Stanford University in 1980.

5. From 1980 until 1993, I was employed at AT&T Bell Laboratories, where I worked on semiconductor physics, laser physics, optoelectronics, and integrated circuit technology, among other topics. In particular, I worked on semiconductor surface and interface physics, CMOS device physics, advanced lithography for integrated circuit manufacturing, and integrated circuit process technology.

6. From 1993 until July 1, 2024, I was a Professor of Electrical Engineering and Computer Sciences (“EECS”) at the University of California (UC), Berkeley, with a joint appointment as a Faculty Scientist in the Materials Science Division at the Lawrence Berkeley National Laboratory (“LBNL”). At UC Berkeley, I held the National Semiconductor Distinguished Professorship in Engineering (an endowed Chair) from 2006-2015 and then the Paul Gray Distinguished Professorship in Engineering from 2015-2024. In 2008, I was appointed as a Senior Faculty Scientist at LBNL. On July 1, 2024, I retired from the University and LBNL with the title of Professor Emeritus. From 2012-2017, I served as Associate Dean for Research in the College of Engineering at UC Berkeley. In 2017, I was appointed as Chair of the Electrical Engineering Division in the EECS Department at UC Berkeley, and Associate Chair of the Department.

In July 2019, I was appointed as Chair of the EECS Department, and I served in that capacity until June 2021.

7. As Principal Investigator, I led the Nanoelectronics and Nanostructures research group at UC Berkeley, which focused on a wide range of topics, including magnetic tunnel junctions, voltage control of magnetism, spintronics, spin-based quantum computing, and ultrafast magnetism. Among my various major research accomplishments over the years, I demonstrated a nanoscale magnetic recording system using spin transfer torque switching from a scanned spin-polarized nanoprobe tip across a tunnel gap to a magnetic recording medium and magnetoresistive magnetic tunnel junction readout using the same probe. I also demonstrated spin transfer torque switching in sub-10 nm size magnetic tunnel junctions and ultrafast spin-orbit torque-based magnetic switching using current pulses of only 9 picosecond duration.

8. I have been elected Fellow of the Institute for Electrical and Electronic Engineers (“IEEE”), the American Physical Society (“APS”), and the Optical Society of America (“OSA”). During my career, I served on numerous program committees, scientific advisory committees, and technical advisory boards. I have also served as Chair or Co-Chair of numerous technical conferences, published over 330 articles in scientific and technical literature, including at least 90 papers relating to magnetic and/or spin-based devices dating back to 2002, and been awarded 12

patents in the areas of electronic devices, nanofabrication technologies, including 5 patents on magnetic memory and magnetic/spin-based devices.

9. For further details regarding my qualifications, including my employment and academic history, please refer to my curriculum vitae, which accompanies this declaration as Exhibit 1025 (EX1025).

### III. MATERIALS CONSIDERED

10. In addition to any other documents cited or referenced herein, I have reviewed the following materials in preparing this Declaration:

| Exhibit No. | Description                                 |
|-------------|---------------------------------------------|
| 1001        | U.S. Patent No. 7,884,403 (“403 Patent”)    |
| 1002        | File History for U.S. Patent No. 7,884,403  |
| 1003        | U.S. Patent No. 8,319,263 (“263 Patent”)    |
| 1004        | File History for U.S. Patent No. 8,319,263  |
| 1005        | U.S. Patent No. 8,405,134 (“134 Patent”)    |
| 1006        | File History for U.S. Patent No. 8,405,134  |
| 1007        | U.S. Patent No. 9,123,463 (“463 Patent”)    |
| 1008        | File History for U.S. Patent No. 9,123,463  |
| 1009        | U.S. Patent No. 9,608,198 (“198 Patent”)    |
| 1010        | File History for U.S. Patent No. 9,608,198  |
| 1011        | U.S. Patent No. 10,367,138 (“138 Patent”)   |
| 1012        | File History for U.S. Patent No. 10,367,138 |
| 1013        | U.S. Patent No. 10,680,167 (“167 Patent”)   |
| 1014        | File History for U.S. Patent No. 10,680,167 |
| 1015        | U.S. Patent No. 11,737,372 (“372 Patent”)   |
| 1016        | File History for U.S. Patent No. 11,737,372 |

| Exhibit No. | Description                                                                                                                                                            |
|-------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| 1017        | U.S. Patent No. 11,968,909 (“’909 Patent”)                                                                                                                             |
| 1018        | File History for U.S. Patent No. 11,968,909                                                                                                                            |
| 1019        | Patent Family Tree                                                                                                                                                     |
| 1020        | Japanese Patent No. JP2004071186                                                                                                                                       |
| 1021        | English Translation of Japanese Patent No. JP2004071186, from ’372 Patent File History (EX1016)                                                                        |
| 1022        | Japanese Patent Application No. JP2004313350                                                                                                                           |
| 1023        | Certified English Translation (with Translator Declaration) of Japanese Patent Application No. JP2004313350                                                            |
| 1026        | Bowen et al., <i>Large magnetoresistance in Fe/MgO/FeCo(001) epitaxial tunnel junctions on GaAs(001)</i> , 79 Appl. Phys. Letters 1655-1657 (2001) (“Bowen”)           |
| 1027        | European Patent Application No. EP1391942A1 to Nagahama et al. (“Nagahama”)                                                                                            |
| 1028        | Soukup et al., <i>Voltage-Current Characteristics for Electrical Conduction Through Thin MgO Films</i> , 41 J. Appl. Phys. 3229-3236 (1970) (“Soukup”)                 |
| 1029        | Japanese Patent Application Publication No. JP2002204004A to Sunai et al. (“Sunai”)                                                                                    |
| 1030        | Certified English Translation (with Translator Declaration) of Japanese Patent Application Publication No. JP2002204004A to Sunai et al. (“Sunai”)                     |
| 1031        | Simmons, <i>Generalized Formula for the Electric Tunnel Effect between Similar Electrodes Separated by a Thin Insulating Film</i> , 34 J. Appl. Phys. 1793-1803 (1963) |
| 1032        | Trasatti, <i>Electronegativity, Work Function, and Heat of Adsorption of Hydrogen on Metals</i> , 67 J. Chem. Soc. 229-236 (1972)                                      |
| 1033        | Jullière, <i>Tunneling between ferromagnetic films</i> , 54A Phys. Letters 225-226 (1975)                                                                              |

| Exhibit No. | Description                                                                                                                                                                                                                  |
|-------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| 1034        | Miyazaki et al., <i>Giant magnetic tunneling effect in Fe / Al<sub>2</sub>O<sub>3</sub> / Fe junction</i> , 139 J. Magnetism & Magnetic Materials L231-L234 (1995)                                                           |
| 1035        | Moodera et al., <i>Large Magnetoresistance at Room Temperature in Ferromagnetic Thin Film Tunnel Junctions</i> , 74 Phys. Rev. Lett. 3273–3276 (1995)                                                                        |
| 1036        | Wulff et al., <i>Characterization of MgO Layers on Different Alumina and Glass Substrates by Grazing Incidence Diffractometry and Grazing Incidence X-ray Reflectometry</i> , 23 Surface & Interface Analysis 148-154 (1995) |
| 1037        | Castanier et al., <i>Oxygen vacancies on MgO(100)</i> , 364 Surf. Sci. 1-16 (1996)                                                                                                                                           |
| 1038        | Moodera et al., <i>Ferromagnetic–insulator–ferromagnetic tunneling: Spin-dependent tunneling and large magnetoresistance in trilayer junctions (invited)</i> , 79 J. Appl. Phys. 4724-4729 (1996)                            |
| 1039        | Tehrani et al., <i>Progress and Outlook for MRAM Technology</i> , 35 IEEE Trans. Magn. 2814-2819 (1999)                                                                                                                      |
| 1040        | Yoon et al., <i>Growth characteristics and surface roughening of vapor-deposited MgO thin films</i> , 60 Phys. Rev. 2839-2843 (1999)                                                                                         |
| 1041        | Wollschläger et al., <i>Stoichiometry and morphology of MgO films grown reactively on Ag(100)</i> , 142 Appl. Surface Science 129-134 (1999)                                                                                 |
| 1042        | Pacchioni, <i>Ab initio theory of point defects in oxide materials: structure, properties, chemical reactivity</i> , 2 Solid State Scis. 161-179 (2000)                                                                      |
| 1043        | Heinrich et al., <i>Single Crystal Tunnel Junctions</i> , IEEE (2000)                                                                                                                                                        |
| 1044        | Butler et al., <i>Spin-dependent tunneling conductance of Fe MgO Fe sandwiches</i> , 63 Phys. Rev. B 054416 (2001)                                                                                                           |
| 1045        | Klaui et al., <i>Growth, structure, electronic, and magnetic properties of MgO/Fe(001) bilayers and Fe/MgO/Fe(001) trilayers</i> , 64 Phys. Rev. B. 134411 (2001)                                                            |
| 1046        | Mathon et al., <i>Theory of tunneling magnetoresistance of an epitaxial Fe/MgO/Fe(001) junction</i> , 63 Phys. Rev. 220403 (2001)                                                                                            |

| Exhibit No. | Description                                                                                                                                                                            |
|-------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| 1047        | Wulfhekel et al., <i>Single-crystal magnetotunnel junctions</i> , 78 Appl. Phys. Letters 509-511 (2001)                                                                                |
| 1048        | Bogicevic et al., <i>Effect of oxide vacancies on metal island nucleation</i> , 515 Surf. Sci. L481-486 (2002)                                                                         |
| 1049        | Kim et al., <i>MRAM Technology for High Density Memory Application</i> , 2 J. Semicond. Tech. Sci. 185-196 (2002)                                                                      |
| 1050        | Yuasa et al., <i>A large quantum-well oscillation of the TMR effect</i> , 35 J. Phys. D. 2427-2431 (2002)                                                                              |
| 1051        | Meyerheim, et al., <i>Geometrical and Compositional Structure at Metal-Oxide Interfaces: MgO on Fe(001)</i> , 87 Phys. Rev. Letters 076102 (2001)                                      |
| 1052        | Faure-Vincent et al., <i>High tunnel magnetoresistance in epitaxial Fe/MgO/Fe tunnel junctions</i> , 82 App. Phys. Letters 4507-4509 (2003)                                            |
| 1053        | Mitani et al., <i>Fe/MgO/FeCo(100) epitaxial magnetic tunnel junctions prepared by using in situ plasma oxidation</i> , 93 J. Appl. Phys. 8041-8043 (2003)                             |
| 1054        | Goniakowski et al., <i>Electronic States and Schottky Barrier Height at Metal/MgO(100) Interfaces</i> , 12 Interface Science 93–103 (2004).                                            |
| 1055        | Wang et al., <i>70% TMR at Room Temperature for SDT Sandwich Junctions With CoFeB as Free and Reference Layers</i> , 40 IEEE Trans. Magn. 2269-2271 (2004)                             |
| 1056        | U.S. Patent Publication No. 2004/0136232A1 (“Hosomi”)                                                                                                                                  |
| 1057        | Dieny et al., <i>Introduction to Magnetic Random-Access Memory</i> (IEEE Press 2017) (excerpts)                                                                                        |
| 1058        | Amodeo et al., <i>Dislocations and Plastic Deformation in MgO Crystals: A Review</i> , 8 Crystals 240 (2018)                                                                           |
| 1059        | Matthews et al., <i>Comment: “Generalized formula for the electric tunnel effect between similar electrodes separated by a thin insulating film,”</i> 123 J. Appl. Phys. 136101 (2018) |

| Exhibit No. | Description                                                                                                                                                                                 |
|-------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| 1060        | Jimbo et al., <i>Thermal stability of spin valves using amorphous CoFeB</i> , 165 J. Magnetism & Magnetic Materials 308-311 (1997)                                                          |
| 1061        | Cardoso et al., <i>Ferromagnetic Coupling Field Reduction in CoFeB Tunnel Junctions Deposited by Ion Beam</i> , 40 IEEE Trans. Magn. 2272-2274 (2004)                                       |
| 1062        | U.S. Patent No. 7,270,896 (“Parkin”)                                                                                                                                                        |
| 1063        | Complaint, <i>Godo Kaisha IP Bridge 1 v. Western Digital Corporation</i> , Case No. 24-cv-00342-RGA (D. Del. Mar. 15, 2024) (without exhibits)                                              |
| 1064        | Claim Chart for ’403 Patent, Exhibit D to Complaint, <i>Godo Kaisha IP Bridge 1 v. Western Digital Corporation</i> , Case No. 24-cv-00342-RGA (D. Del. Mar. 15, 2024)                       |
| 1065        | Claim Chart for ’263 Patent, Exhibit E to Complaint, <i>Godo Kaisha IP Bridge 1 v. Western Digital Corporation</i> , Case No. 24-cv-00342-RGA (D. Del. Mar. 15, 2024)                       |
| 1066        | Claim Chart for ’372 Patent, Exhibit F to Complaint, <i>Godo Kaisha IP Bridge 1 v. Western Digital Corporation</i> , Case No. 24-cv-00342-RGA (D. Del. Mar. 15, 2024)                       |
| 1067        | First Amended Complaint, <i>Godo Kaisha IP Bridge 1 v. Western Digital Corporation</i> , Case No. 24-cv-00342-RGA (D. Del. July 8, 2024)                                                    |
| 1068        | Amended Claim Chart for ’403 Patent, Exhibit AA to First Amended Complaint, <i>Godo Kaisha IP Bridge 1 v. Western Digital Corporation</i> , Case No. 24-cv-00342-RGA (D. Del. July 8, 2024) |
| 1069        | Amended Claim Chart for ’263 Patent, Exhibit BB to First Amended Complaint, <i>Godo Kaisha IP Bridge 1 v. Western Digital Corporation</i> , Case No. 24-cv-00342-RGA (D. Del. July 8, 2024) |
| 1070        | Amended Claim Chart for ’372 Patent, Exhibit CC to First Amended Complaint, <i>Godo Kaisha IP Bridge 1 v. Western Digital Corporation</i> , Case No. 24-cv-00342-RGA (D. Del. July 8, 2024) |

| Exhibit No. | Description                                                                                                                                                                                                                                                                                                                  |
|-------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| 1071        | Claim Chart for '909 Patent, Exhibit DD to First Amended Complaint, <i>Godo Kaisha IP Bridge 1 v. Western Digital Corporation</i> , Case No. 24-cv-00342-RGA (D. Del. July 8, 2024)                                                                                                                                          |
| 1072        | Claim Chart for '138 Patent, Exhibit EE to First Amended Complaint, <i>Godo Kaisha IP Bridge 1 v. Western Digital Corporation</i> , Case No. 24-cv-00342-RGA (D. Del. July 8, 2024)                                                                                                                                          |
| 1073        | Claim Chart for '198 Patent, Exhibit FF to First Amended Complaint, <i>Godo Kaisha IP Bridge 1 v. Western Digital Corporation</i> , Case No. 24-cv-00342-RGA (D. Del. July 8, 2024)                                                                                                                                          |
| 1074        | Claim Chart for '463 Patent, Exhibit GG to First Amended Complaint, <i>Godo Kaisha IP Bridge 1 v. Western Digital Corporation</i> , Case No. 24-cv-00342-RGA (D. Del. July 8, 2024)                                                                                                                                          |
| 1075        | Claim Chart for '167 Patent, Exhibit HH to First Amended Complaint, <i>Godo Kaisha IP Bridge 1 v. Western Digital Corporation</i> , Case No. 24-cv-00342-RGA (D. Del. July 8, 2024)                                                                                                                                          |
| 1076        | Claim Chart for '134 Patent, Exhibit II to First Amended Complaint, <i>Godo Kaisha IP Bridge 1 v. Western Digital Corporation</i> , Case No. 24-cv-00342-RGA (D. Del. July 8, 2024)                                                                                                                                          |
| 1077        | Docket, <i>Godo Kaisha IP Bridge 1 v. Western Digital Corporation</i> , Case No. 24-cv-00342-RGA (D. Del. Mar. 15, 2024)                                                                                                                                                                                                     |
| 1078        | U.S. District Courts – Combined Civil and Criminal Federal Court Management Statistics (Dec. 31, 2023), <a href="https://www.uscourts.gov/statistics-reports/federal-court-management-statistics-december-2023">https://www.uscourts.gov/statistics-reports/federal-court-management-statistics-december-2023</a> (excerpts) |
| 1079        | Microsoft Computer Dictionary (5th ed. 2002) (excerpts)                                                                                                                                                                                                                                                                      |
| 1081        | U.S. Patent No. 7,751,156 ('156 Patent)                                                                                                                                                                                                                                                                                      |
| 1082        | U.S. Patent No. 8,427,791 ('791 Patent)                                                                                                                                                                                                                                                                                      |
| 1083        | U.S. Patent No. 8,914,970 ('970 Patent)                                                                                                                                                                                                                                                                                      |
| 1092        | File History for U.S. Patent Application No. 10/824,835 to Parkin ("Parkin '835")                                                                                                                                                                                                                                            |

#### IV. RELEVANT LAW

11. I am not an attorney. For the purposes of this Declaration, I have been informed about certain aspects of the law that are relevant to my opinions. My understanding of the relevant law is summarized below.

12. I have been informed and understand that determining whether a patent claim is valid requires a two-step analysis. First, the claim must be construed. Second, the properly construed claim must be compared to the prior art.

13. I have been informed and understand that claim construction is a matter of law and that the final claim constructions for this proceeding will be determined by the Patent Trial and Appeal Board.

14. I have been informed and understand that in the context of an *inter partes* review, claims are construed from the perspective of a person of ordinary skill in the art at the time of the purported invention (which is approximated based on the earliest priority date of the patent). I understand that absent disclaimer or express definition, claim terms are given their plain and ordinary meaning to a person of ordinary skill in the art in view of the specification, file history, and knowledge of a person of skill in the art.

15. I have been informed and understand that a patent claim is invalid if it is anticipated by the prior art (*i.e.*, lacks novelty). I understand that anticipation

requires the disclosure in a single prior art reference of every limitation of the claim, expressly or inherently, with the limitations arranged as specified in the claim.

16. I have been informed and understand that, although not expressly disclosed, subject matter may be inherently disclosed in a prior art reference where that subject matter is necessarily present in the expressly disclosed subject matter and would be understood to be so by those of ordinary skill in the art. I understand that the fact that a certain result or characteristic may occur or be present in the prior art is not sufficient to establish the inherency of that result or characteristic.

17. I have been informed and understand that a patent claim is obvious and therefore invalid if the claimed subject matter as a whole would have been obvious to a person of ordinary skill in the art as of the priority date of the patent based on one or more prior art references and/or the knowledge of one of ordinary skill in the art.

18. I understand that an obviousness analysis must consider (1) the scope and content of the prior art, (2) the differences between the claims and the prior art, (3) the level of ordinary skill in the pertinent art, and (4) secondary considerations, if any, of non-obviousness (such as unexpected results, industry praise, commercial success, long-felt but unmet need, failure of others, copying by others, and skepticism of experts).

19. I understand that a prior art reference may be combined with other references to disclose each element of the invention under 35 U.S.C. § 103. I understand that a reference may also be combined with the knowledge of a person of ordinary skill in the art, and that this knowledge may be used to combine multiple references. I further understand that a person of ordinary skill in the art is presumed to know the relevant prior art. I understand that the obviousness analysis may take into account the inferences and creative steps that a person of ordinary skill in the art would employ.

20. In determining whether a prior art reference would have been combined with other prior art or other information known to a person having ordinary skill in the art, I understand that the following principles may be considered:

- a. A combination of familiar elements according to known methods is likely to be obvious if it yields predictable results;
- b. The substitution of one known element for another is likely to be obvious if it yields predictable results;
- c. The use of a known technique to improve similar items or methods in the same way is likely to be obvious if it yields predictable results;
- d. The application of a known technique to a prior art reference that is ready for improvement to yield predictable results;

- e. Any need or problem known in the field and addressed by the reference can provide a reason for combining the elements in the manner claimed; and
- f. The proper analysis of obviousness requires a determination of whether a person of ordinary skill in the art would have a “reasonable expectation of success”—not an “absolute predictability” of success—in achieving the claimed invention by combining prior art references.

21. I am informed that whether a prior art reference invalidates a patent claim as obvious is determined from the perspective of a person of ordinary skill in the art. While there is no requirement that the prior art contain an express suggestion to combine known elements to achieve the claimed invention, a suggestion to combine known elements to achieve the claimed invention may come from the prior art as a whole or individually, as filtered through the knowledge of one skilled in the art. In addition, the inferences and creative steps a person of ordinary skill in the art would employ are also relevant to the determination of obviousness.

22. When a work is available in one field, design alternatives and other market forces can prompt variations of it, either in the same field or in another. If a person of ordinary skill in the art can implement a predictable variation and would see the benefit of doing so, that variation is likely to be obvious. In many fields, there may be little discussion of obvious combinations, and in these fields market

demand – not scientific literature – may drive design trends. When there is a design need or market pressure and there are a finite number of predictable solutions, a person of ordinary skill in the art has good reason to pursue those known options.

23. It is my understanding that there is no rigid rule that a reference or combination of references must contain a “teaching, suggestion, or motivation” to combine references. But, I understand that the “teaching, suggestion, or motivation” test can be a useful guide in establishing a rationale for combining elements of the prior art. This test poses the question as to whether there is an express or implied teaching, suggestion, or motivation to combine prior art elements in a way that realizes the claimed invention, and it seeks to counter impermissible hindsight analysis.

## **V. PRIORITY DATE**

24. I have been asked to assume that 2004 is the priority date for the '138 Patent and thus the relevant date for determining the level of ordinary skill in the art. Throughout this declaration, when I refer to one of ordinary skill, I am referring to one of ordinary skill in the art as of 2004 unless otherwise specified. My opinions would be the same if the '138 Patent priority date were around the March 12, 2004 date of the first Japanese priority application to the '138 Patent, the October 28, 2004 date of the second Japanese priority application to the '138 Patent, or the March 10, 2005 PCT filing date of the '403 Patent from which the '138 Patent claims priority.

## **VI. LEVEL OF ORDINARY SKILL IN THE ART**

25. Based on my review of the '138 Patent and my background and experience in the field of electrical engineering and magnetic/spintronic device physics, it is my opinion that one of ordinary skill in the art as of the 2004 priority date (see paragraph 24) would be someone with:

- a Ph.D. in electrical engineering, physics, materials science, or a related field, and at least one year of experience in the research, design, and/or development of magnetic/spintronic devices, or the equivalent, or
- a Master's degree in electrical engineering, physics, materials science, or a related field, and four years of experience in the research, design, and/or development of magnetic/spintronic devices, or the equivalent.

Less work experience may be compensated by a higher level of relevant education, and vice versa. My opinion would be the same for a different date in the 2004-2005 timeframe than the 2004 priority date, as explained in paragraph 24 of this Declaration.

26. The '138 Patent generally relates to “a magnetic tunnel junction device and a method of manufacturing the same.” EX1011 ('138 Patent) at col. 1:32-33.

27. Based on my education and experience, I am familiar with the level of knowledge that one of ordinary skill would have possessed during the relevant period of time.

28. In reaching this opinion as to the qualifications of the hypothetical person of ordinary skill in the art, I have considered the types of problems encountered in the art, the prior art solutions to those problems, the rapidity with which innovations are made, the sophistication of the technology, and the educational level of active workers in the field.

29. By the 2004 priority date of the '138 Patent (see paragraph 24 of this Declaration), I was a person who had more than ordinary skill in the art. Nevertheless, the opinions I express in this Declaration are from the perspective of a person of ordinary skill in the art as I have defined it above.

## **VII. TECHNOLOGY BACKGROUND**

### **A. Conventional Magnetic Memory**

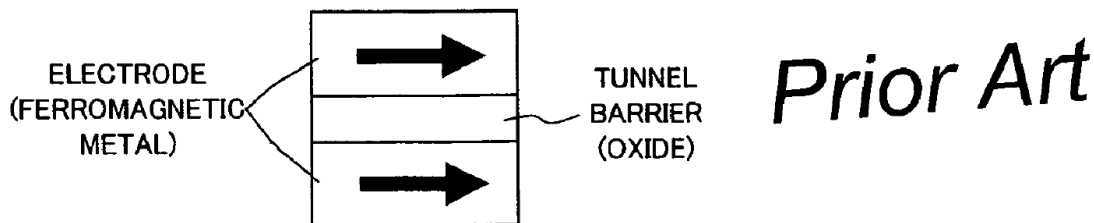
30. This IPR is related to magnetic memory technology. Magnetic memory operates differently than semiconductor-based memories like DRAM and EEPROM that store data as electrical charges. EX1057 (Dieny textbook) at page 1. Magnetic memory, including magnetoresistive random access memory (MRAM), uses magnetic tunnel junctions (MTJs) and is based on spintronics. EX1057 (Dieny textbook) at pages 1-2, 9.

**B. Magnetic Tunnel Junctions (MTJs) And Spintronics**

31. MTJs are “of high interest in the research field of magnetic nanostructures” because they “play a significant role in the development of non-volatile magnetic random access memories (MRAM’s).” EX1045 (Klaauw) at page 1.

32. Each electron has an elementary magnetic moment, or spin, which is explained by quantum mechanics. EX1057 (Dieny textbook) at pages 1-3. In a ferromagnetic metal (such as Fe or Co), quantum mechanics assigns different densities for “spin-up” and “spin-down” state electrons. The state (spin-up or spin-down) that has the greater density in the metal is known as the majority spin and the state with the smaller density is known as the minority spin. EX1057 (Dieny textbook) at pages 11-13.

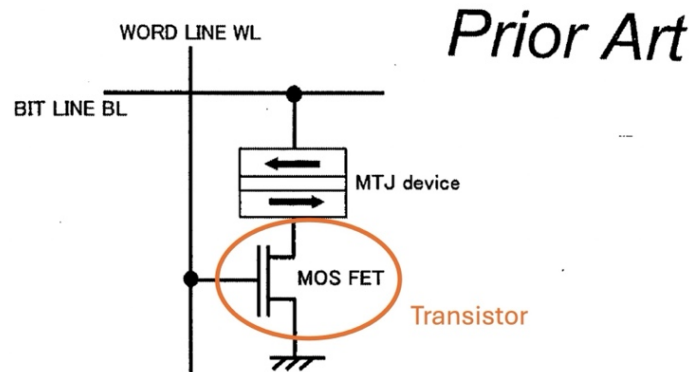
33. As illustrated in the “Prior Art” Figure 8 from the ’138 Patent below, showing the prior art, a magnetic tunnel junction (MTJ) consists of a tunnel junction with ferromagnetic metal layers (electrodes) on either side of an insulating layer (tunnel barrier layer).



EX1011 (’138 Patent) at Fig. 8(A); *see also id.* at Fig. 8(B), cols. 1:44-2:2; EX1057

(Dieny textbook) at page 9. MRAM stores bits in MTJs with a transistor typically controlling access to individual MTJs, as shown below.

FIG. 9 (B)

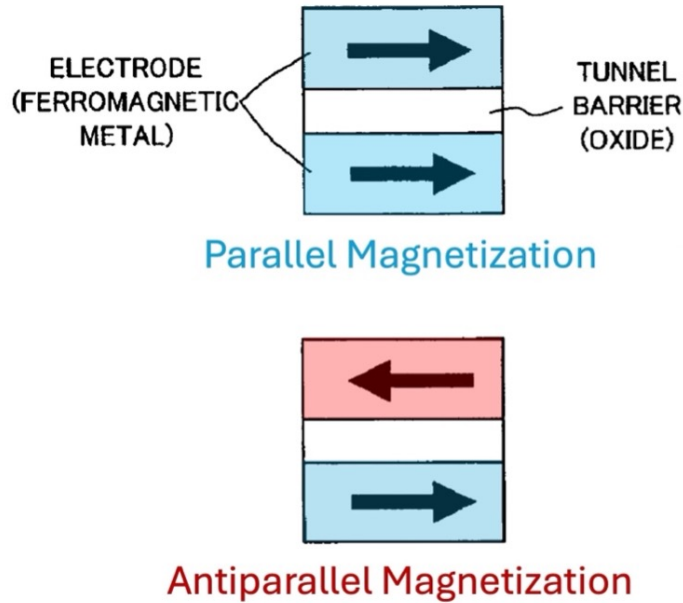


EX1011 ('138 Patent) at Fig. 9(B) (annotated); EX1030 (Sunai) ¶¶37-40, Figs. 4-5; EX1039 (Tehrani) at pages 2816, 2818; EX1049 (Kim) at Abstract, Fig. 2.

34. In MRAM, one of the MTJ's electrodes is set to a particular polarity and is often called the "fixed layer." The other electrode's magnetization can be changed by an external electric field. It is called the "free layer," and its state is used to store binary information, e.g., a "0" or "1." EX1057 (Dieny textbook) at page 29; EX1030 (Sunai) ¶19.

35. "Parallel" aligned electrodes have the same majority spin direction for their electrodes, while in the case of "antiparallel" alignment the majority spin directions of the two electrodes are opposite. EX1057 (Dieny textbook) at pages 11-13; EX1011 ('138 Patent) at col. 1:53-64. The parallel magnetization has a lower electrical resistance than antiparallel, allowing the magnetization state

(parallel or antiparallel) to be sensed with an electrical circuit. EX1057 (Dieny textbook) at pages 11-13; EX1011 ('138 Patent) at cols. 1:53-2:2.



EX1011 ('138 Patent) at Figs. 8(A)-8(B) (excerpted, annotated).

### C. Tunnel Magnetoresistance Ratio

36. The tunnel magnetoresistance ratio ("TMR") has been called "the most important parameter" for magnetic tunnel junction devices. EX1055 (Wang) at page 2269.

37. The TMR is equal to the difference in the resistance between the antiparallel ( $R_{ap}$ ) and parallel states ( $R_p$ ), divided by the parallel state resistance:

$$\text{TMR} = \frac{\Delta R}{R_p} = \frac{R_{ap} - R_p}{R_p}$$

EX1035 (Moodera 1995) at page 3273; EX1027 (Nagahama) ¶2; EX1011 ('138 Patent) at cols. 4:62-5:3 (TMR equation); EX1057 (Dieny textbook) at page 13. A high anti-parallel resistance  $R_{ap}$  compared to lower parallel resistance  $R_p$  results in high TMRs. Put another way, the TMR characterizes the effectiveness of the junction at passing parallel electrons while inhibiting antiparallel electron tunneling.

38. In 1995, Miyazaki and Moodera demonstrated the tunneling effect at room temperature, each by separately measuring TMR over 10%. EX1034 (Miyazaki) at Abstract (18% TMR at 300K); EX1035 (Moodera 1995) at Abstract (11.8% TMR at 295K).

39. Kim explained in 2002 that for conventional MRAM, “low MR ratio is a big issue for [a] high density device, and this makes the device slow.” EX1049 (Kim) at page 185. As a result, the price of (low MR ratio) MRAM “is quite higher than other competing [memory] devices, and the application has been limited.” EX1049 (Kim) at page 185.

40. Higher TMRs were necessary to improve MTJ performance and thereby achieve commercially viable MRAM.

41. The higher the TMR, the larger the resistance difference between the parallel and antiparallel electrode configurations, which increases the signal to noise ratio for electrical detection of the magnetization state. EX1055 (Wang) at page 2269 (“A high TMR value is desirable because it leads to greater signal level...”);

EX1055 (Wang) at page 2271 (“[A] functioning junction with high TMR value means high signal level, high sensitivity, high speed, and lower power consumption for devices based on tunnel junctions.”); EX1056 (Hosomi) ¶26 (When “the TMR ratio is higher, a memory device having a... low error rate can be realized.”).

42. Tunneling MRAM devices “promise[d] huge enhancement of the density, speed, reliability and power consumption of solid-state memory.” EX1049 (Kim) at page 185. Wang explained many benefits stemming from a high TMR value: “A high TMR value is desirable because it leads to greater signal level, lower power consumption, higher speed, and larger design margin for devices such as MRAM....” EX1055 (Wang) at page 2269; *see also* EX1049 (Kim) at page 186 (“[L]arger MR ratio is the [sic] another important issue for the high speed MRAM operations.”).

43. Higher TMR allowed lower voltages (and smaller currents) to determine the MTJ’s resistance and thus lowered power consumption. EX1055 (Wang) at page 2271; *see also* EX1055 (Wang) at page 2269 (“A high TMR value is desirable because it leads to... lower power consumption” for MRAM.).

44. Higher TMRs paved the way for higher speed and smaller, denser MRAMs. EX1049 (Kim) at pages 194-95 (“[W]e may require new MR device with over 100% MR ratio in the future.... The key issues of MRAM technology as a future memory candidate are resistance control and low current operation for small

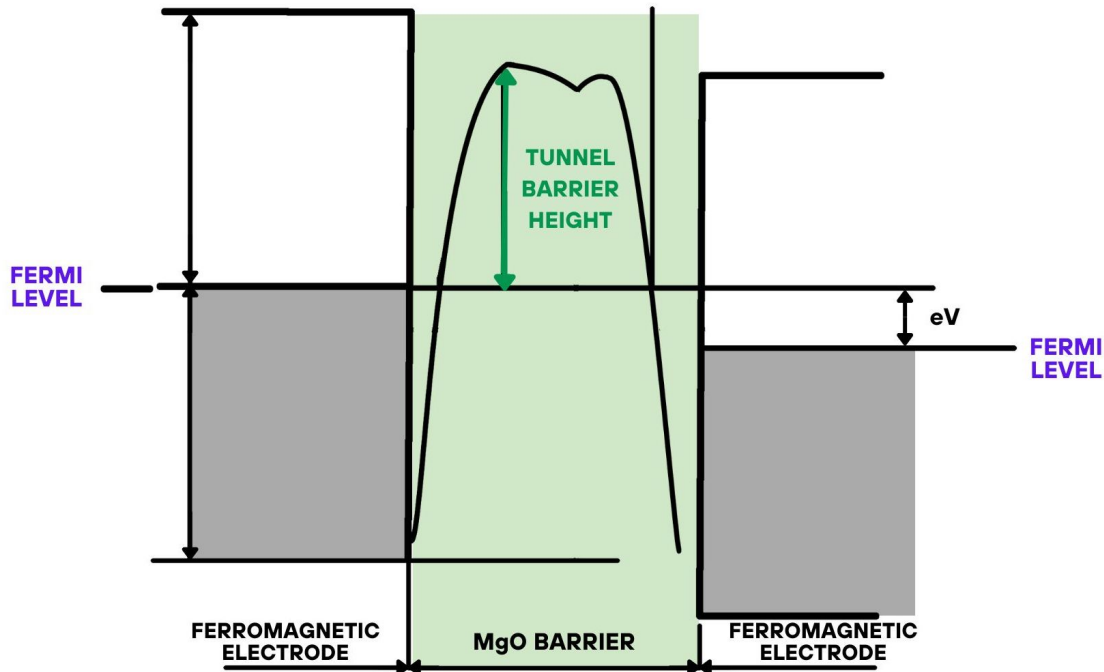
enough device size.”); EX1057 (Dieny textbook) at page 9 (“[L]arger TMR ratios... enabled new types of MRAM that could be scaled down in size and ramped up in density.”); EX1055 (Wang) at page 2269 (“A high TMR value is desirable because it leads to... higher speed....”). Hosomi explained that when “the TMR ratio is higher, a memory device having a high speed and a high degree of integration... can be realized.” EX1056 (Hosomi) ¶26. Hosomi contrasted MRAMs with high TMRs with existing MRAM designs where it was “difficult to downsize the MRAM, namely, increase the degree of integration of the MRAM.” EX1056 (Hosomi) ¶23.

#### **D. Quantum Tunneling**

45. MTJs operate based on tunneling. The “tunnel effect” is a quantum mechanical phenomenon where current (electrons) flows between two electrodes separated by a very thin insulating layer or barrier. EX1057 (Dieny textbook) at page 10.

46. Electrons that participate in tunneling from the injector to the collector lie at or near the **Fermi level**,  $E_F$ , of the injector, which corresponds to the highest energy level in the injector occupied by electrons at 0 K. EX1052 (Faure-Vincent) at page 4508 (tunneling “electrons [are] injected from the Fermi level in one side of the barrier”); EX1057 (Dieny textbook) at page 4. At zero bias voltage, also known as equilibrium, the Fermi levels of the two electrodes (**gray**) align so that the same number of electrons are tunneling in both directions across the barrier (**green**), such

that there is no net flow of electrons or current across the barrier. EX1057 (Dieny textbook) at page 11; EX1031 (Simmons) at page 1794, Fig. 3. When a bias voltage,  $V$ , is applied, the collector electrode's (right) Fermi level lowers by an energy given by  $eV$  (where  $e$  is the charge of a single electron), compared to the injector electrode (left), allowing the electrons to tunnel across the barrier from the injector to empty states above the **Fermi level** in the collector. EX1057 (Dieny textbook) at page 11; EX1031 (Simmons) at Fig. 3.



EX1031 (Simmons) at page 1794, Fig. 1 (modified and annotated).

47. This “tunnel effect” of electrons across the barrier is described and illustrated in Simmons’ seminal 1963 paper. EX1031 (Simmons) at pages 1793-94, Fig. 1; *see also* EX1057 (Dieny textbook) at pages 10-11, Fig. 1.4. Shown above is

an adapted version of Figure 1 from Simmons' paper illustrating a tunnel barrier between two ferromagnetic electrodes.

48. The **tunnel barrier height** represents the difference between the bottom of the conduction band of the tunnel barrier layer and the **Fermi level** of electrons in the metal conductor. EX1031 (Simmons) at Fig. 1; EX1047 (Wulfhekel) at page 509 (tunnel barrier height estimated by difference between bottom of the conduction band of the MgO layer and Fermi level of Fe in an Fe/MgO/Fe(100) junction). The patent agrees, explaining that "the height of the tunnel barrier" measures the value "between the bottom of the conduction band of the MgO(001) layer and the Fermi energy of the first or the second ferromagnetic material layer." EX1011 ('138 Patent) at col. 3:56-60.

49. In his 1963 paper, Simmons provided a mathematical formula, commonly known as Simmons' formula, for calculating the tunnel barrier height at a low-voltage range:

$$J = [3(2m\varphi)^{\frac{1}{2}}/2s](e/h)^2 V \times \exp[-(4\pi s/h)(2m\varphi_0)^{\frac{1}{2}}].$$

EX1031 (Simmons) at page 1797; *see also id.* at pages 1793-1803. Simmons had a typo (an extra factor of 3/2) in his published formula, and the corrected version is below:

$$J_c = \frac{(2m\phi_0)^{\frac{1}{2}}}{s} \left(\frac{e}{h}\right)^2 V \exp \left[ -\frac{4\pi s}{h} (2m\phi_0)^{\frac{1}{2}} \right].$$

EX1059 (Matthews) at page 1.

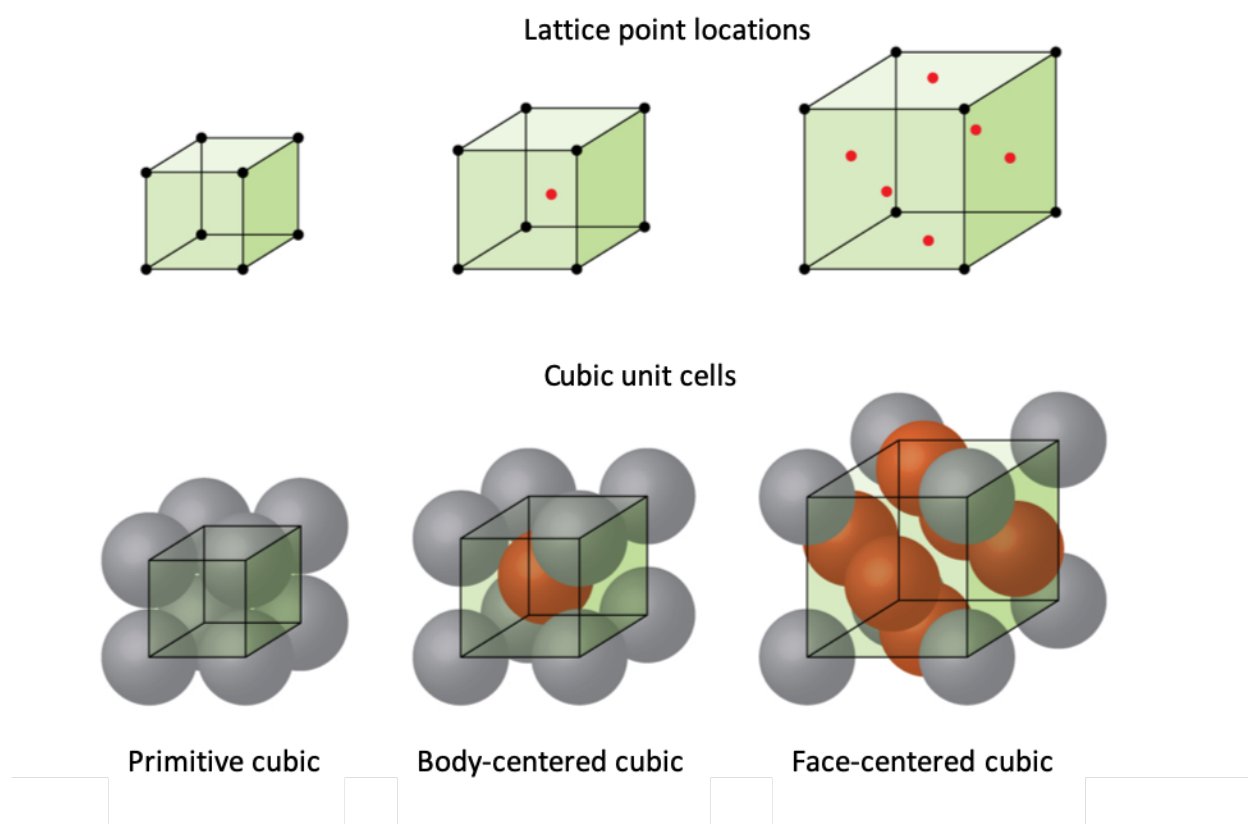
### **E. MTJ Materials**

50. Considerable research has been undertaken to study and improve the materials used in the MTJ barrier layer and electrodes in order to increase TMR. As explained by Wang: “New junction materials have been explored in dozens of laboratories around the world and ever increasing TMR values have been observed.”

EX1055 (Wang) at page 2269.

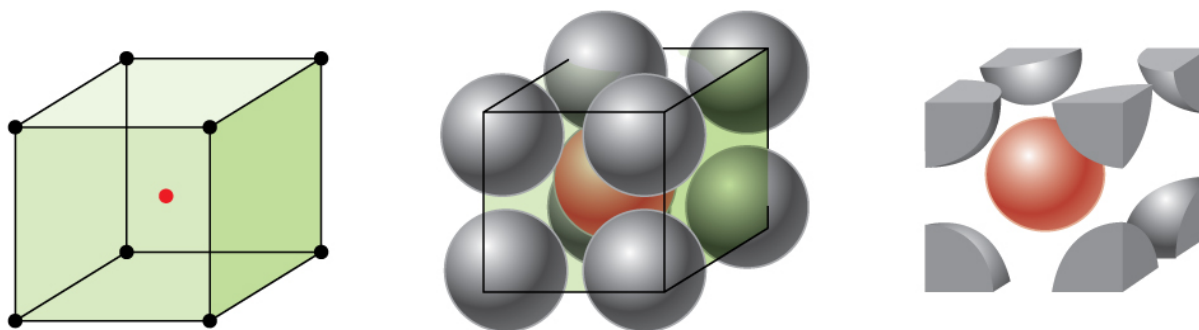
### **1. Crystalline Structures**

51. There are three basic types of cubic crystalline structures for metals, as shown in the below graphic:

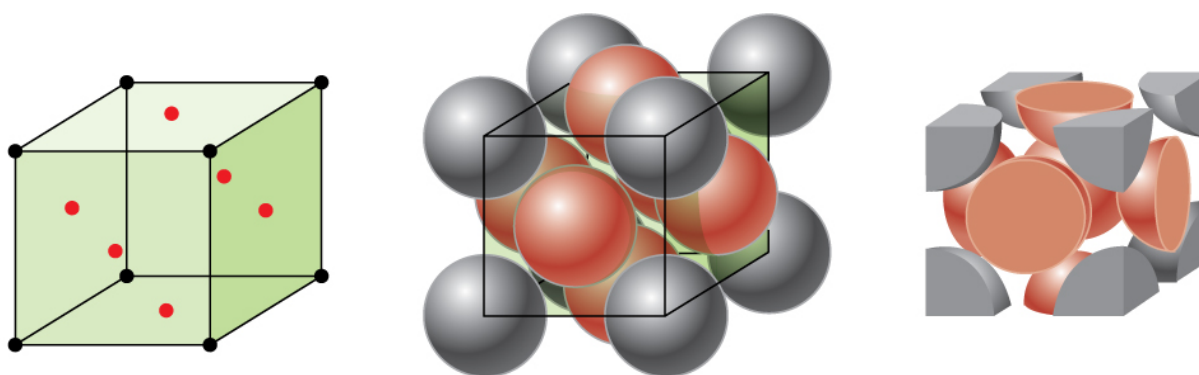


UW Madison Chemistry 103/104 Resource Book (“UW Chemistry Book”), Topic 61, Fig. 1, available at <https://wisc.pb.unizin.org/minimisgenchem/chapter/types-of-unit-cells-body-centered-cubic-and-face-centered-cubic-m11q5/>.

52. The simplest unit is the primitive cubic, with metal atoms on each corner. Body-centered cubic cells (BCC), shown in the above middle, have metal ions at all of the corners and in the center. Face-centered cubic cells (FCC), at the above right, crystallize with the metal atoms at all corners and the centers of each face. More detailed cross sections of BCC and FCC crystalline cells are reproduced below:



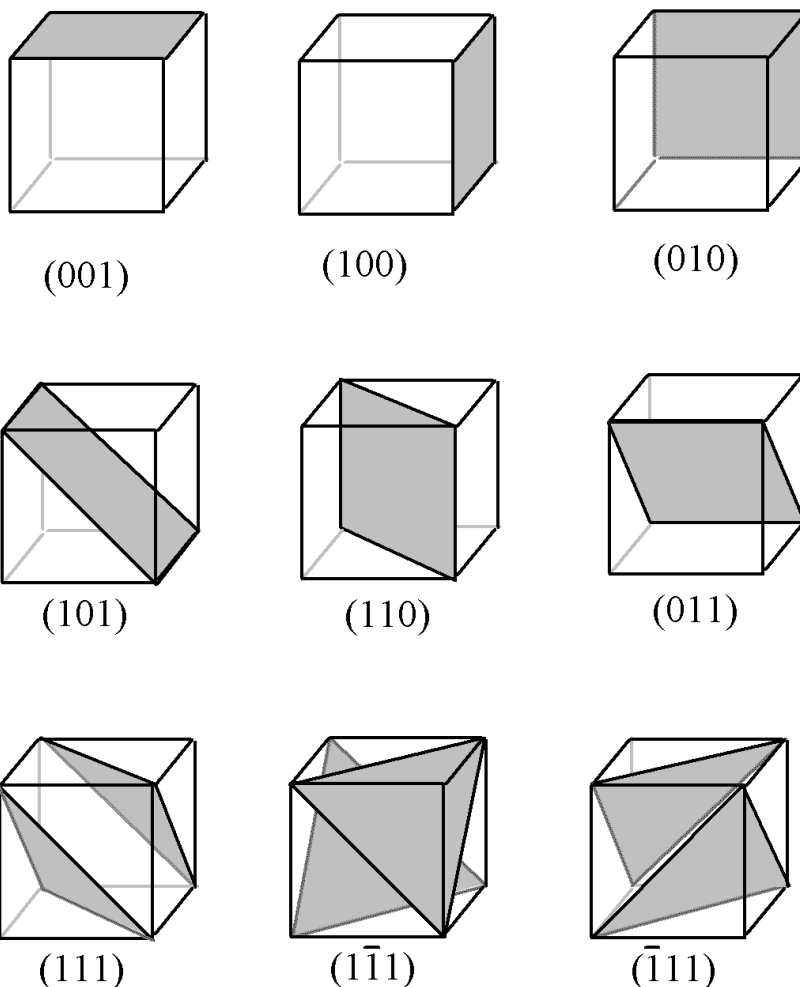
Body-centered cubic structure



Face-centered cubic structure

UW Chemistry Book at topic 61, Figs. 2-3.

53. Cubic crystals can be described by specific planes in three dimensions. As shown below, for a cubic crystalline structure, the (001), (010), and (100) planes are all the same:



WikiMedia Commons graphic, available at:  
[https://commons.wikimedia.org/wiki/File:Indices\\_miller\\_plan\\_exemple\\_cube.png](https://commons.wikimedia.org/wiki/File:Indices_miller_plan_exemple_cube.png).

The '138 Patent agrees. EX1011 ('138 Patent) at col. 4:39-41 (explaining that “because MgO has a cubic crystal structure (NaCl structure), the (001) plane, the (100) plane, and the (010) plane are all equivalent”).

## 2. Ferromagnetic Materials In MTJs

54. The ferromagnetic layers are comprised of ferromagnetic materials, such as iron (Fe), nickel (Ni), cobalt (Co), or their alloys, which typically have

crystalline structures. EX1030 (Sunai) ¶33 (“[F]erromagnetic materials” include “Fe, Co, Ni, and alloys containing them.”); EX1057 (Dieny textbook) at page 16.

55. Iron is a metal known to have a cubic crystalline structure. Iron typically has a body-centered cubic (BCC) structure at room temperature. UW Chemistry Book, Topic 61 (“Isomorphous metals with a BCC structure include K, Ba, Cr, Mo, W, and Fe at room temperature.”); EX1046 (Mathon) at page 1 (analyzing tunneling between “bcc Fe” and MgO barrier); EX1044 (Butler) at page 2 (calculating tunneling for “bcc Fe” and MgO layers). Iron can also have a face-centered cubic (FCC) crystalline structure at higher temperatures.

56. The alignment between the crystal of the ferromagnetic electrodes and the MgO barrier layer facilitates electron tunneling, increasing TMR. EX1044 (Butler) at page 1 (Butler observing that the tunneling across an MgO barrier was facilitated by the “symmetry” between the electrodes and barrier material which “are crucial to determining the tunneling conductance.”); *see also* EX1046 (Mathon) at page 1 (“only a small lattice mismatch of about 3.5%” shows close symmetry between the crystal structures of a thin MgO barrier and Fe electrodes in an MTJ).

57. Electron wave functions in crystalline structures are described by Bloch states, which are wave function solutions of the Schrödinger equation for a perfect, infinite crystalline structure. EX1057 (Dieny textbook) at page 16. The Bloch states

for these ferromagnetic crystals have specific symmetries, particularly for “delta-1” band electrons that allow for higher TMRs. EX1057 (Dieny textbook) at page 16.

58. Researchers found that using alloys of Fe and Co as ferromagnetic electrodes in MTJs improved electron spin polarization (difference between the majority and minority spin densities). Higher spin polarization in the electrodes increases the TMR. EX1057 (Dieny textbook) at pages 1, 18; EX1050 (Yuasa) at page 2428 (study on FeCo electrodes); EX1026 (Bowen) at page 1655 (Fe<sub>50</sub>Co<sub>50</sub> electrode layers); EX1052 (Faure-Vincent) at page 4507 (Fe and Co layers used to achieve the predicted high TMRs).

59. CoFeB ferromagnetic alloys were also known and studied. “Amorphous or nanocrystalline CoFeB films have been previously used in spin valves and tunnel junctions for their soft properties.” EX1061 (Cardoso) at page 2272. Adding boron (B) to FeCo resulted in an amorphous alloy. EX1055 (Wang) at Abstract; EX1030 (Sunai) ¶¶25, 30 (noting “crystallization is inhibited” in CoFeB). Jimbo *et al.* studied amorphous CoFeB electrodes in spin valves and found an improved MR ratio. EX1060 (Jimbo) at Abstract, page 310. Others found a similar result for MTJs: CoFeB electrodes increased TMRs and improved MTJ performance. Unlike FeCo films, which had to be deposited as thicker or discontinuous films, lowering the TMR, EX1030 (Sunai) ¶27, using CoFeB, which can result in a thinner 0.5 nm film, improved TMR. EX1030 (Sunai) ¶28. Cardoso

*et al.* fabricated CoFeB electrodes and found higher TMRs, particularly after annealing. EX1061 (Cardoso) at pages 2273-74.

60. Because of CoFeB's amorphous properties, a "CoFeB/MgO/CoFeB MTJ can theoretically be grown on all kinds of underlayers." EX1057 (Dieny textbook) at page 47. CoFeB's thinner, smoother interface ultimately produced an improved structure matched to the crystalline structure of the MgO barrier. EX1030 (Sunai) ¶¶24-28; EX1055 (Wang) at Abstract ("CoFeB has an amorphous structure and a smooth interface" with the tunnel barrier.). Without the addition of Boron, CoFe films typically had lower TMRs because they were often deposited as thicker or discontinuous films. EX1030 (Sunai) ¶27.

61. Annealing the amorphous CoFeB electrodes induced formation of a crystalline structure matching an adjoining crystalline layer. One of skill would have been aware that CoFeB would adopt the crystalline structure of an adjoining layer. Jimbo deposited CoFeB by sputtering, and then "[t]he annealing was performed for 1 hour." EX1060 (Jimbo) at page 308. Jimbo observed that CoFeB started to form a crystalline structure "first after annealing at 250°C and becomes still higher at 300°C." EX1060 (Jimbo) at page 308. The CoFeB adopted the fcc(111) structure of the adjoining Au fcc(111) top layer. EX1060 (Jimbo) at page 308. Jimbo found the MR ratio was "enhanced by the annealing." EX1060 (Jimbo) at page 311. Cardoso also found that CoFeB began to crystallize with annealing, measuring the

lattice and finding “CoFeB films are not amorphous.” EX1061 (Cardoso) at page 2273. A “Co<sub>60</sub>Fe<sub>20</sub>B<sub>20</sub> layer adjacent to an MgO(001) layer crystallizes in a bcc(001) structure.” EX1057 (Dieny textbook) at page 48. Parkin taught that “[c]ross-section transmission electron microscopy reveals that a portion of the [CoFeB] storage layer 175 adjacent to the MgO tunnel barrier 120’ has crystallized and is, moreover, textured in the same orientation as the crystalline MgO tunnel barrier. The simple cubic crystalline MgO layer thus provides a template for the formation of a thin crystalline ferromagnetic layer which has the bcc structure of CoFe and is oriented in the same (100) direction as the MgO layer.” EX1062 (Parkin) at col. 18:51-59.

62. Researchers extensively studied using CoFeB alloys to improve TMR. EX1030 (Sunai) ¶¶25-29. Wang taught the “benefit of using CoFeB is multifold” including “a higher TMR value.” EX1055 (Wang) at pages 2269-70. Hosomi found a similar result. EX1056 (Hosomi) ¶39 (A ferromagnetic layer “exhibits a larger TMR ratio” when “comprised of a CoFeB alloy.”). Jimbo found the MR ratios increased after annealing the CoFeB layers. EX1060 (Jimbo) at page 310. He noted that “the CoFeB layer is confirmed to be amorphous in the as-deposited state and begin[s] to crystallize after annealing at 250°C. The GMR effect itself is not only stable up to above 300°C but also enhanced by the annealing.” EX1060 (Jimbo) at page 311. Cardoso also found higher TMR values for its CoFeB electrodes after annealing. EX1061 (Cardoso) at pages 2273-74. Parkin similarly observed of his

CoFeB-MgO MTJ that “[t]he TMR of the device of FIG. 3A is nearly two times higher than the highest TMR ever reported in prior art devices using conventional alumina tunnel barriers.” EX1062 (Parkin) at col. 18:63-65.

### 3. Oxide Layer In MTJs

63. In this section I will discuss two types of oxide layers, aluminum oxide ( $\text{Al}_2\text{O}_3$ ) and magnesium oxide ( $\text{MgO}$ ), depicted below:

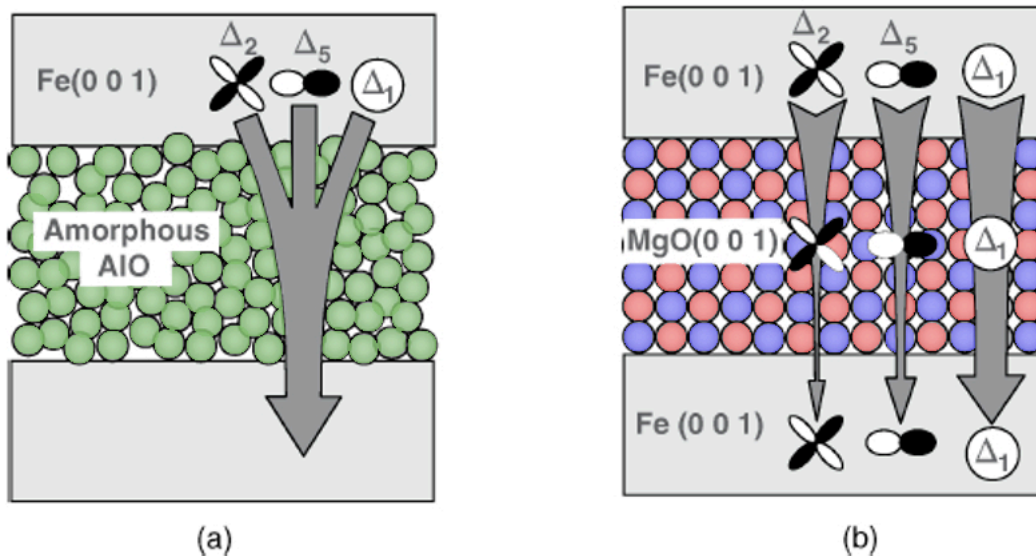


Figure 2.19 Schematic of electron tunneling through (a) an amorphous AlO barrier and (b) a crystalline  $\text{MgO}(0\ 0\ 1)$  barrier.

EX1057 (Dieny textbook) at page 44, Fig. 2.19 (annotated).

64. Researchers initially focused their efforts on studying aluminum oxide ( $\text{Al}_2\text{O}_3$ ) MTJs. EX1052 (Faure-Vincent) at page 4507. Butler noted this in his research paper, explaining: “There is presently great scientific and commercial interest in spin-dependent tunneling between ferromagnetic electrodes separated by

insulating oxide barriers. Most of the interest for applications currently centers on systems with amorphous aluminum oxide tunneling barriers because of the relative ease of growing adherent aluminum oxide without pinholes.” EX1044 (Butler) at page 1.

65. Aluminum oxide ( $\text{Al}_2\text{O}_3$ ) barriers are amorphous. Butler explained they “are difficult to characterize and model because of the noncrystalline nature of the oxide and the lack of any known epitaxial relationship between the oxide and the ferromagnetic electrodes.” EX1044 (Butler) at page 1. As a result, tunneling is incoherent and “complex; it consists of random hopping between oxide resonant states which are created by a number of poorly understood defects.” EX1045 (Klaauw) at page 1. Both parallel and antiparallel spin electrons are randomly scattered. EX1045 (Klaauw) at page 1.

66. Magnesium oxide ( $\text{MgO}$ ) later became commonly used as the insulating or barrier layer.  $\text{MgO}$  crystals are known for their cubic structure, similar to rock salt ( $\text{NaCl}$ ). EX1040 (Yoon) at page 2839 (“ $\text{MgO}$ ... has  $\text{NaCl}$  structure”); EX1041 (Wollschläger) at page 130 (“ $\text{MgO}$  crystallizes in the rocksalt structure”); EX1011 (’138 Patent) at col. 4:39-40 (“ $\text{MgO}$  has a cubic crystal structure ( $\text{NaCl}$  structure)”).

67. As I explained in Section VII.E.1 of this Declaration,  $\text{MgO}$ ’s cubic crystal structure means the (001), (100), and (010) crystalline planes are the same.

EX1011 ('138 Patent) at col. 4:39-41. The crystal structure of MgO enables well-defined tunneling wave function symmetry for electrons from the ferromagnetic electrodes. EX1057 (Dieny textbook) at page 17.

68. MgO has the special property that tunneling is governed by the majority (parallel) spin electrons. EX1045 (Klauda) at page 1. Research groups led by Butler (EX1044) and Mathon (EX1046) in 2001 “calculated optimistic TMR ratio is in excess of 1000% for an MgO barrier.” EX1046 (Mathon) at Abstract; *see also* EX1044 (Butler) at page 1, Fig. 16; EX1057 (Dieny textbook) at page 16. Their research established that a thin MgO barrier passed delta-1 electrons while largely blocking other electrons having opposite spin—leading the way to high TMRs. EX1044 (Butler) at page 1; EX1046 (Mathon) at page 1. As a 2001 paper by Klauda explained, unlike amorphous  $\text{Al}_2\text{O}_3$  barriers, for crystalline MgO barriers: “The tunneling resistance for the parallel orientation of the magnetic moments is estimated to be **100 times smaller** than that for the antiparallel orientation of the magnetic moments due to the absence of scattering in the barrier.” EX1045 (Klauda) at page 1 (emphasis added).

69. Mathon observed the symmetry between a thin MgO barrier and Fe electrode, with “only a small lattice mismatch of about 3.5%,” opened the door to high TMRs. EX1046 (Mathon) at page 1. This symmetry between MgO’s body-centered cubic (bcc) structure and Fe’s resulted in a “tunneling resistance for the

parallel” electrons “estimated to be 100 times smaller than that for the antiparallel” electrons, “due to the absence of scattering in the barrier” for Fe/MgO/Fe(001) MTJs. EX1045 (Klaua) at page 1. This resistance differential resulted in high TMRs.

70. In addition to single-crystal MgO, MgO barrier layers were also fabricated from polycrystalline MgO. Polycrystalline MgO layers are formed from numerous MgO crystals, reminiscent of grains of table salt. Because polycrystalline MgO is formed of many MgO crystals that may have varied planar orientations, the layer is characterized by its predominant planar direction, sometimes referred to as its preferential orientation. The structure of polycrystalline MgO made it well suited to deposition on a variety of surfaces, including amorphous layers. EX1036 (Wulff) at page 148 (studying MgO deposition on both crystalline substrates as well as on amorphous float glass and reporting that “[a]part from epitaxy, MgO grows with strong preferential <100> orientation regardless of the substrate selection”); EX1040 (Yoon) at page 2840 (similar: studying the deposition of highly (100)-oriented MgO crystalline thin films on Si, GaAs, and fused quartz substrates). It was commonly used with other amorphous materials, including CoFeB.

71. Polycrystalline MgO had other advantages. In 1996, Moodera *et al.* used a “polycrystalline MgO” barrier to obtain a lower barrier height. EX1026 (Bowen) at page 1656 (describing Moodera’s study at EX1038); EX1038 (Moodera

1996) at pages 4725-26. Nagahama also used polycrystalline MgO layers. EX1027 (Nagahama) ¶73 (describing “a (001)-highly-oriented MgO barrier layer”). Likewise, Yoon also grew a polycrystalline MgO barrier. EX1040 (Yoon) at page 2842.

72. After Butler and Mathon, “considerable interest has evolved in both the theoretical and experimental studies of the tunneling magnetoresistance (TMR) effect” because of “its importance [to] the development of” MRAM. EX1051 (Meyerheim) at page 1.

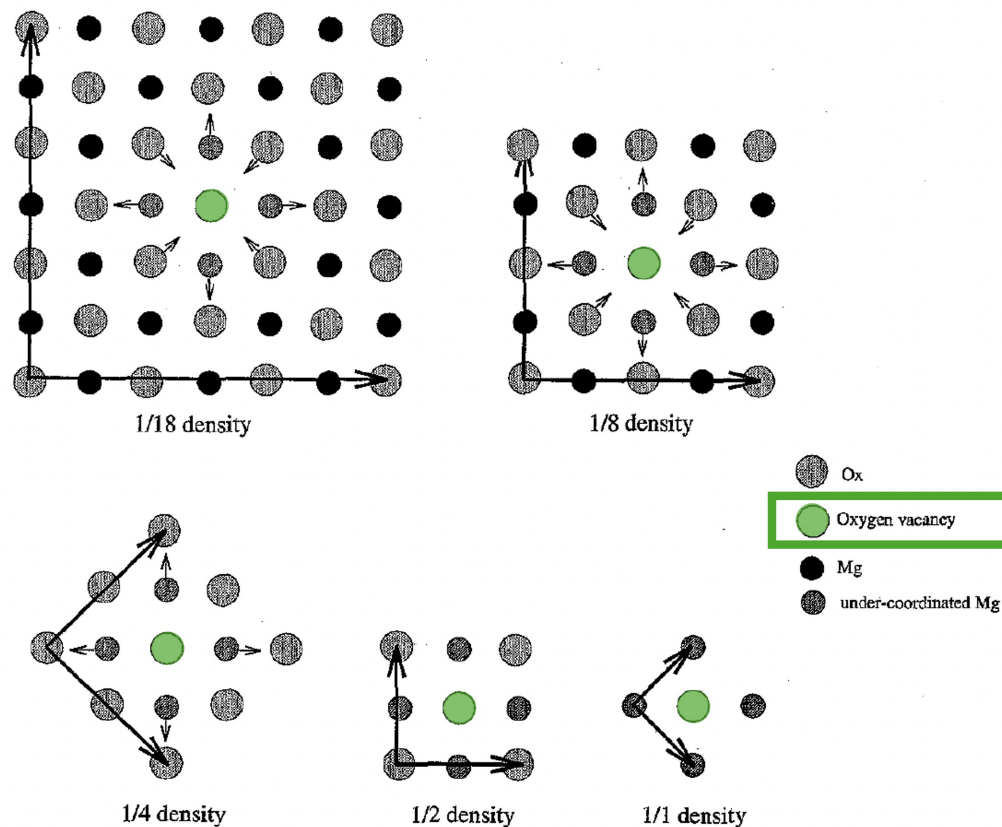
#### **F. Oxygen Vacancy Defects In MgO Thin Films**

73. Oxygen vacancies are one of the most important defects that are naturally present in every oxide. EX1042 (Pacchioni) at page 162. In the literature, oxygen vacancy defects in MgO are sometimes referred to as “color centers” or “F centers.” EX1042 (Pacchioni) at page 162; *see also* EX1048 (Bogicevic) at page 482 (studying “the propensity of oxygen vacancies ( $F_s$  centers)” in MgO(100) thin films).

74. MgO is a metal oxide with a 1:1 stoichiometric ratio of Mg and O atoms in a perfect crystalline structure. In other words, the MgO crystalline lattice has 1 magnesium atom for every 1 oxygen atom. However, perfect MgO crystal structures don’t exist in nature. In reality, there is always at least some concentration of oxygen vacancies, at least at finite temperature. EX1042 (Pacchioni) at page 162.

75. One way to characterize the level of oxygen vacancies in an MgO crystal is  $\text{MgO}_x$ , where  $x < 1$ , describing a sub-stoichiometric composition (e.g.,  $\text{MgO}_x$ ). *E.g.*, EX1041 (Wollschlager) at page 132 (“understoichiometric  $\text{MgO}_x$  ( $x < 1$ )”). In a perfect, stoichiometric MgO crystal,  $x$  would equal 1. This is described in the '138 Patent. EX1011 ('138 Patent) at cols. 7:6-7 (“[T]here is the possibility that there are oxygen vacancy defects such as  $\text{MgO}_x$  ( $0.9 < x < 1$ ).”), 7:22-24. The '138 Patent applicant provided this explanation about oxygen vacancy defects: “ $\text{MgO}_x$  ( $0 < x < 1$ )” and “ $x$  is  $0 < x < 1$ . (Namely, if this is represented as ‘MgO crystals,’ the crystals have oxygen vacancy defects.)” EX1002 ('403 Patent File History) at page 168.

76. Castanier *et al.* described and studied oxygen vacancy defects, providing the following images of different levels of oxygen vacancy defects in **green**:



EX1037 (Castanier) at page 3, Fig. 1 (annotated).

77. Oxygen vacancy defects lowered the barrier height of MgO thin films. Soukup experimentally observed a 0.33 eV barrier height for an MgO thin film, noting that increased oxygen vacancy defects lowered the barrier height of MgO. EX1028 (Soukup) at Abstract, page 3232.

78. Other researchers observed similar behavior. Klaua grew “nearly perfect crystalline MgO(001) films on high-quality single crystals of Fe,” and found they had high purity and “the correct stoichiometry.” EX1045 (Klaua) at pages 1-2. Yet they still had “a low density of local defects.” EX1045 (Klaua) at page 8. Klaua

noticed bright spots of current which they said “may be related to inhomogeneities in the substrate-oxide interface.” EX1045 (Klaaua) at page 4. Due to “defect states exist[ing] within the band gap of [the] MgO,... the tunneling probability via these defect states is largely enhanced.” EX1045 (Klaaua) at page 4. Yet the defect states were not due to surface errors or irregularities. EX1045 (Klaaua) at pages 4-5 (finding “[t]he local defects have dimensions of a few nm. They are not correlated with the surface topography....”). His assessment was that the observed defects in the MgO barrier “are most likely caused by structural defects, which create localized resonant tunneling states in the MgO bandgap.” EX1045 (Klaaua) at page 5. He “assume[d] that the observed defects are intrinsic to the MgO layer due to the agglomeration of atomic defects.” EX1045 (Klaaua) at page 5. In other words, the tunneling appeared related to oxygen vacancy defects intrinsic in the MgO barrier. Yet when Klaaua studied the properties of the MgO barrier, the IV characteristics “give no hint of the presence of any defects in the MgO layer.” EX1045 (Klaaua) at page 4. This strongly suggested that the concentration of vacancy defects is very small, perhaps on the order of less than a few percent.

79. Klaaua’s collaborators Wulfhekel and Meyerheim confirmed his results. Wulfhekel fabricated a high-quality MTJ where “the concentration of defects in the MTJ structure is low. The structures grown are not only of high crystalline quality but also of high electrical quality.” EX1047 (Wulfhekel) at page 511. Despite

attempting to “minimize the effect of lattice defects on tunneling,” EX1047 (Wulfhekel) at page 509, Wulfhekel found high tunneling currents that “are not correlated with the topography” of the MgO film, EX1047 (Wulfhekel) at page 510, finding “small variations of the local barrier height lead to strong variations of the tunneling current,” EX1047 (Wulfhekel) at page 511. “From this we conclude that the spikes are not caused by a thinner oxide film but by a lower tunneling barrier most likely due to localized states in the band gap of the barrier material.” EX1047 (Wulfhekel) at page 510. Wulfhekel noted that a “low tunneling barrier... point[s] [to] a high density of defects in the barrier.” EX1047 (Wulfhekel) at page 509. In other words, despite building a high-quality crystalline MgO MTJ, defects in the MgO resulted in a low tunneling barrier.

80. Meyerheim also observed that “[s]tructural defects strongly influence the electron tunneling in both the majority and the minority channels.” EX1051 (Meyerheim) at page 2.

81. Mitani also observed “the resistance decreases dramatically” for “tunneling transport through the MgO barrier” above 150 K, attributing it to “defects in the MgO barrier.” EX1053 (Mitani) at page 8042.

82. Similarly, Bowen observed a lower barrier height for an MgO thin film and hypothesized that it may have resulted from “the presence of stoichiometric and/or thickness inhomogeneities in the insulating film.” EX1026 (Bowen) at

page 1656. As Parkin observed, “[t]he exact composition of the MgO layer may differ from the stoichiometric [sic] composition.” EX1062 (Parkin) at col. 17:37-39. A skilled artisan would have understood from this extensive collection of research, and particularly Soukup’s, Bowen’s, and Parkin’s conclusions, that the “defects” causing MgO’s increased tunneling current were oxygen vacancies in the MgO structure.

### VIII. OVERVIEW OF THE ’138 PATENT

83. The ’138 Patent is titled “Magnetic Tunnel Junction Device.” EX1011 (’138 Patent) at [54]. It discloses an MTJ having a structure where “an oxide is sandwiched between a first and a second electrode made of a ferromagnetic metal.” EX1011 (’138 Patent) at col. 1:44-51; *see also id.* at cols. 1:51-2:2. As shown in Figure 1(B) below, the ’138 Patent discloses two Fe electrodes surrounding a single-crystalline or polycrystalline MgO barrier layer:

FIG. 1 (B)



EX1011 (’138 Patent) at Fig. 1(B) (modified), col. 5:39-45.

84. I provide a brief overview of some of the '138 Patent's claims. EX1011 ('138 Patent) at cols. 9:56-11:20.

- a. Independent Claim 1 requires, *inter alia*, “a first electrode comprising a first ferromagnetic material layer that includes Co, Fe, and B,” “a second electrode... comprising a second ferromagnetic material layer that includes Co, Fe, and B,” and “wherein each of the first and second ferromagnetic material layers is entirely crystallized.” EX1011 ('138 Patent) at cols. 9:56-10:2.
- b. Independent Claims 7 and 12 have similar requirements. EX1011 ('138 Patent) at cols. 10:27-38, 10:61-11:6.
- c. Claims 4, 10, and 13 further require that the barrier or MgO layer has a “barrier height  $\phi$ ” that is “in a range of 0.2 to 0.5 eV.” EX1011 ('138 Patent) at cols. 10:11-12, 10:47-48, 11:7-8.
- d. Claims 5, 11, and 14 require obtaining the “barrier height  $\phi$ ” by “fitting J-V characteristics of the MTJ device” to Simmons’ formula where the bias voltage is set to “100 mV or smaller,” the “effective thickness of the [barrier/MgO] layer” is “equivalent to  $(t_{\text{MgO}} - 0.5\text{nm})$ , and  $t_{\text{MgO}}$  is an actual thickness of the barrier layer.” EX1011 ('138 Patent) at cols. 10:13-24, 10:49-60, 11:9-20.

85. According to the '138 Patent, when fabricating the MgO layer, “separation of oxygen from MgO during the deposition of MgO” means “there is the possibility that there are oxygen vacancy defects such as  $\text{MgO}_x$  ( $0.9 < x < 1$ ).” EX1011 ('138 Patent) at cols. 6:67-7:7. The '138 Patent further explains that “[w]hen there are oxygen vacancy defects, the potential barrier height of the MgO tunnel barrier is thought to decrease (such as in the range of 0.10 to 0.85 eV; more specifically, 0.2 to 0.5 eV), which is thought to result in an increase in the tunneling current.” EX1011 ('138 Patent) at col. 7:7-11.

86. The '138 Patent also explains that the “basic structure of the MRAM,” as shown in Figure 9, is “Prior Art.” EX1011 ('138 Patent) at col. 2:3-4, Fig. 9. It explains, for example, that in an MRAM device, “the MRAM cell [is] disposed at the intersection of a word line and a bit line” and “comprises a MTJ device and a MOSFET directly connected to the MTJ device.” EX1011 ('138 Patent) at col. 2:10-13; *see also id.* at col. 2:3-29.

## **IX. CLAIM CONSTRUCTION**

87. I have been informed and understand that claim construction is viewed from the perspective of a person of ordinary skill in the art in question at the time of the invention.

88. In my opinion, the claims are obvious in view of the grounds discussed below based on the plain and ordinary meaning of the claim terms in view of the

'138 Patent's specification. Where relevant, I have identified teachings in the '138 Patent that inform the plain and ordinary meaning of the claim limitations.

## **X. PRIOR ART TO THE '138 PATENT**

89. I have been asked to assume that each of the references relied upon in my analysis, including those covered in detail in this section and those cited throughout my analysis below, are prior art to the '138 Patent except for the textbook, *Introduction to Magnetic Random-Access Memory* by Bernard Dieny *et al.* (EX1057), which I reference periodically for definitions and various concepts without regard to whether that reference itself is prior art. I am familiar with Dieny's textbook, published by Wiley, and understand that it is an authority relied upon in the field.

### **A. Bowen *et al.*, *Large magnetoresistance in Fe/MgO/FeCo(001) epitaxial tunnel junctions on GaAs(001)*, 79 Appl. Phys. Letters 1655-1657 (2001) (EX1026, "Bowen")**

90. In 2001, the journal Applied Physics Letters published experimental results from a group of European researchers on "Fe(001)/MgO(20 Å)/FeCo(001) single-crystal" MTJs. EX1026 (Bowen) at Abstract, page 1655. Guided by calculations from Butler and Mathon, Bowen *et al.* grew "FeCo/MgO/Fe epitaxial structures" (shown below) with "increasingly thin MgO layers" to study their TMR. EX1026 (Bowen) at pages 1655, 1657 nn.5-6, Fig. 1(a). Bowen used "good crystal

quality MgO films with sharp interfaces” in its tunneling experiments, resulting in an experimental TMR of 60%. EX1026 (Bowen) at Abstract, pages 1655-56.

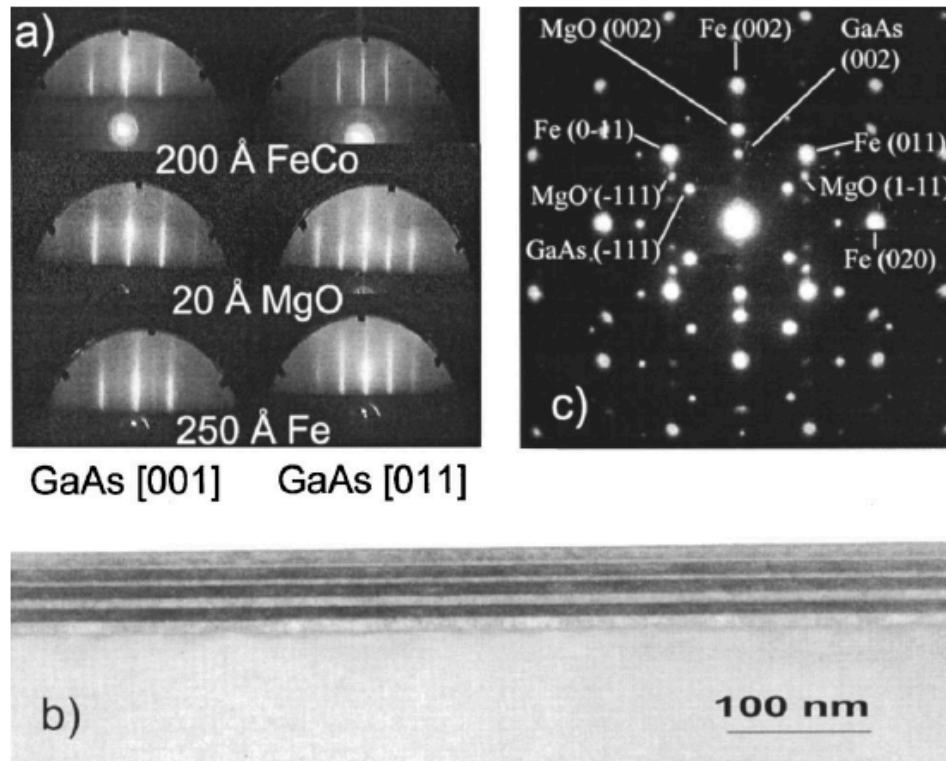


FIG. 1. (a) RHEED patterns along the GaAs [100] and [110] substrate azimuths of a typical FeCo/MgO/Fe epitaxial structure; (b) cross section TEM image of a Fe/MgO(001) multilayer with gradually decreasing MgO layer thickness; (c) TEM electron diffraction pattern.

EX1026 (Bowen) at Fig. 1.

91. Bowen noted the TMR values calculated by Butler were higher (2000% for 20 Å MgO) than its experimental value of 60%. EX1026 (Bowen) at page 1657. Bowen stated a goal “to confirm the predicted relative increase of the TMR” in “future experiments.” EX1026 (Bowen) at page 1657. Although Bowen used high-quality MgO films and obtained a 60% TMR, Bowen did not “rule out the presence

of stoichiometric and/or thickness inhomogeneities” in its MgO barrier. EX1026 (Bowen) at page 1656.

**B. Soukup *et al.*, Voltage-Current Characteristics for Electrical Conduction Through Thin MgO Films, 41 J. App. Phys. 3229-3236 (1970) (EX1028, “Soukup”)**

92. Published in 1970 and citing Simmons’ seminal 1963 paper on electron tunneling, Soukup was a Journal of Applied Physics article that studied voltage-current characteristics of MgO thin films. Soukup applied a high voltage to create a strong electric field across the barrier. EX1028 (Soukup) at pages 3235-36; *id.* at Abstract, pages 3229, 3236 n.1. Soukup observed at the outset that a “number of possible current flow mechanisms from metal to metal have been proposed for metal-insulator-metal sandwich devices” and that “[t]he simple band picture was used by Simmons to analyze the electron injection process in terms of tunneling, where the insulator presents a potential barrier to conduction electrons in the metals.” EX1028 (Soukup) at page 3229.

93. Soukup studied “Au-MgO-Au thin-film” devices by making “60 thin-film sample sets.” EX1028 (Soukup) at Abstract, page 3230. Soukup reported a barrier height of 0.33 eV for its thin MgO film. EX1028 (Soukup) at Abstract, page 3232.

94. Soukup also sought “to determine the effect of nonstoichiometry” of MgO “on the device characteristics” like barrier height. EX1028 (Soukup) at page

3232. It varied the oxygen level “during deposition of the MgO film” to “determine the dependence of the results on the insulating film composition.” EX1028 (Soukup) at pages 3229, 3232. Soukup conducted experiments with “devices fabricated with more oxygen present during MgO deposition, which could mean more stoichiometric oxide films,” hypothesizing “that admitting oxygen gas during deposition of the MgO film increases the stoichiometry of the film as seen by an increased barrier height.” EX1028 (Soukup) at page 3232. Soukup ultimately documented that “the barrier height was a function of the amount of oxygen present... with a higher barrier for larger amounts of oxygen present.” EX1028 (Soukup) at page 3236. Because a more stoichiometric MgO film means fewer oxygen vacancy defects, Soukup demonstrated that increasing stoichiometry (reducing oxygen vacancy defects) results in higher barrier height and, conversely, that increasing the amount of oxygen vacancy defects lowers the barrier height.

**C. Wang *et al.*, 70% TMR at Room Temperature for SDT Sandwich Junctions with CoFeB as Free and Reference Layers, 40 IEEE Trans. Magn. 2269-2271 (2004) (EX1055, “Wang”)**

95. Wang was an article published in the IEEE Transactions on Magnetism journal that reported improved TMR values from using CoFeB as free and reference layers. To achieve high TMR, Wang experimented with using CoFeB for the ferromagnetic layers in its MTJ. “By changing the free layer from NiFeCo to CoFeB,” Wang “increased the TMR value from 42.7% to 60.8%.” EX1055 (Wang)

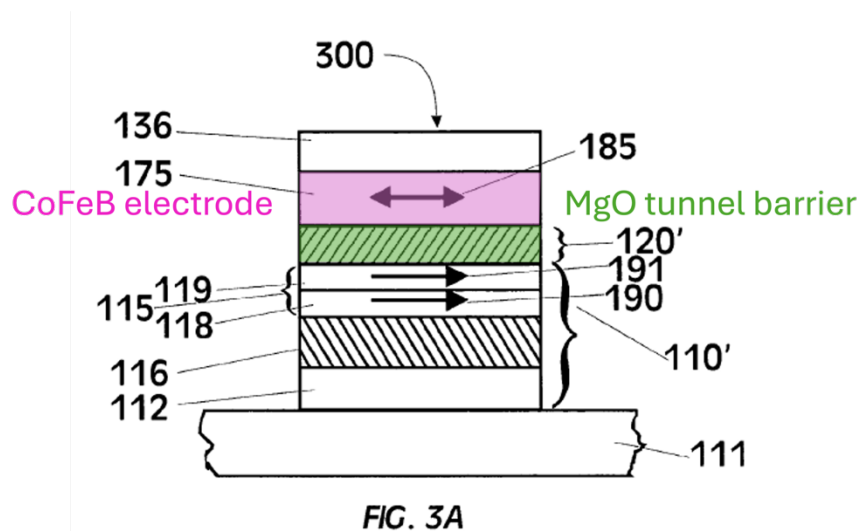
at page 2269. Wang documented high TMR values for its MTJs, explaining that “[t]he combination of a high TMR, a low  $H_c$ , and a low  $H_{\text{coupl}}$  is ideal for magnetic field sensor applications.” EX1055 (Wang) at Abstract, page 2269. Wang further observed that “[t]he benefit of using CoFeB is multifold: a higher TMR value, a lower coercivity ( $H_c$ ), and a lower coupling field ( $H_{\text{coupl}}$ ) for the free layer, which are all desirable for sensor applications.” EX1055 (Wang) at pages 2269-70.

96. Wang explained the many benefits of having high TMR: “A high TMR value is desirable because it leads to greater signal level, lower power consumption, higher speed, and larger design margin for devices such as MRAM, read heads, and a variety of magnetic field sensors.” EX1055 (Wang) at page 2269; *see id.* at page 2271 (same). According to Wang, “a high TMR value is a strong indication that a high quality of the tunnel barrier and its two interfaces is obtained.” EX1055 (Wang) at page 2271. Wang concluded that “[w]ith such a large increase of TMR value by changing the free layer from NiFeCo to CoFeB, it is natural to replace both the free and pinned layers to CoFeB to further increase the TMR value.” EX1055 (Wang) at page 2270.

**D. U.S. Patent No. 7,270,896 to Parkin (EX1062, “Parkin”)**

97. Parkin disclosed MgO-based MTJs with CoFeB electrodes. EX1062 (Parkin) at col. 19:10-19. As shown in Figure 3A below, Parkin’s “MgO crystalline layer 120” [green] is sandwiched between ferromagnetic electrodes. EX1062

(Parkin) at col. 19:16-17. Adjoining the MgO layer is a ferromagnetic “layer 175” [pink] which “may be comprised of 75 Å thick  $(\text{Co}_{73}\text{Fe}_{27})_{74}\text{B}_{26}$ .” EX1062 (Parkin) at col. 17:43-44. Parkin explained that the “highly (100) textured MgO layer is likely to form an excellent template layer for the formation of a thin crystalline layer of CoFeB.” EX1062 (Parkin) at col. 19:17-19. Parkin disclosed that the “MTJ device of FIG. 3A may also be inverted, such that the reference ferromagnetic electrode is formed above the tunnel barrier layer and the storage layer is formed beneath the tunnel barrier.” EX1062 (Parkin) at col. 17:7-10.



EX1062 (Parkin) at Fig. 3A (annotated).

98. According to Parkin, its MTJs were capable of obtaining “very high TMR values,” EX1062 (Parkin) at col. 18:49-51, and “[t]he TMR of the device of FIG. 3A is nearly two times higher than the highest TMR ever reported in prior art devices,” *id.* at cols. 18:63-19:10.

## **XI. SUMMARY OF OPINIONS OFFERED**

99. In my opinion, Claims 1-14 are obvious over the three grounds presented in this Declaration.

## **XII. GROUND 1: CLAIMS 1-4, 7-10, AND 12-13 ARE OBVIOUS OVER PARKIN IN VIEW OF WANG AND SOUKUP**

100. In my opinion, Claims 1-4, 7-10, and 12-13 are obvious over Parkin in view of Wang and Soukup. Soukup is optional in the combinations for Claims 1-3, 7-9, and 12.

### **A. Claim 1: Obviousness Over Parkin In View Of Wang And Optionally Soukup**

#### **1. Claim 1[preamble]: “A magnetic tunnel junction (MTJ) device, comprising:”**

101. I am informed and understand that claim preambles may or may not limit the claim. I have been asked to assume the preambles of the '138 Patent claims are limiting for purposes of this analysis. Assuming that the preamble of Claim 1 is limiting, it is disclosed or suggested by Parkin.

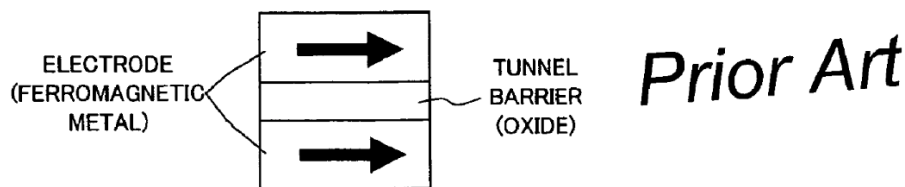
102. Parkin disclosed or suggested a magnetic tunnel junction (MTJ) device. Parkin taught an MTJ with a tunnel barrier layer and two ferromagnetic layers, as I explain for limitations 1[a] through 1[e]. *See* Sections XII.A.2-XII.A.6 of this Declaration.

103. Parkin's Figure 3A showed an “MTJ device” that “has an exchange biased reference electrode 110' formed beneath the MgO tunnel barrier” and a “top

ferromagnetic electrode which is” “the storage layer 175, located above the tunnel barrier 120’.” EX1062 at cols. 16:47-53, 17:3-4, 17:40-43; *see also id.* at Fig. 3A, cols. 16:47-17:59 (discussing the “structures and the method of forming” Parkin’s Figure 3A MTJ device).

104. In addition, MTJs were well known in the art. This is evident from the ’138 Patent itself. EX1011 (’138 Patent) at Figs. 8(A)-8(B), cols. 1:44-2:2. For example, Figure 8(A) of the ’138 Patent below shows an “MTJ device compris[ing] a tunnelling junction structure in which a tunnel barrier... made of an oxide is sandwiched between a first and a second electrode made of a ferromagnetic metal.” EX1011 (’138 Patent) at col. 1:47-51. The patent correctly identifies and labels this conventional MTJ design as “Prior Art”:

FIG. 8 (A)



EX1011 (’138 Patent) at Fig. 8(A) (“Prior Art” legend in original).

**2. Claim 1[a]: “a first electrode comprising a first ferromagnetic material layer that includes Co, Fe, and B;”**

105. This claim limitation is disclosed or suggested by Parkin in view of Wang.

106. The '138 Patent teaches that the “ferromagnetic material layer” is a layer made of a “ferromagnetic metal.” EX1011 ('138 Patent) at col. 1:47-51, Fig. 8(A). As specified in Claim 1[b] below, “first” indicates the “lower” ferromagnetic layer or ferromagnetic material layer beneath the barrier layer. EX1011 ('138 Patent) at col. 9:59-62.

107. MTJs containing metallic ferromagnetic material layers were conventional by 2004, as the '138 Patent acknowledges. EX1011 ('138 Patent) at col. 1:47-51 (Description of Related Art: “As shown in FIG. 8(A), a MTJ device comprises a tunnelling junction structure in which a tunnel barrier (to be hereafter also referred to as a ‘barrier layer’) made of an oxide is sandwiched between a first and a second electrode made of a ferromagnetic metal.”); *id.* at Figs. 8(A)-8(B) (labeled “Prior Art”); EX1045 (Klaauw) at page 1 (discussing “the extensive study of the growth of MgO on Fe(001) and of Fe/MgO/Fe(001) trilayers”).

108. Claim 1[a] does not specify the specific molecular composition or stoichiometry of the claimed “ferromagnetic material layer that includes Co, Fe, and B,” or CoFeB ferromagnetic material layer. EX1011 ('138 Patent) at col. 9:57-58. Thus, I was asked to assume that any CoFeB alloy satisfies Claim 1[a]. One of skill would have understood that alloys including Co, Fe, and B are referred to in the art as CoFeB or sometimes FeCoB. *E.g.*, EX1057 (Dieny) at page 45 (“many other bcc ferromagnetic metals and alloys that are based on Fe and Co (e.g.,

bcc Fe-Co, bcc CoFeB....)"). Further, a skilled artisan would have understood that CoFeB and FeCoB refer to the same alloy.

109. As shown in Figure 3A below, Parkin taught a **lower ferromagnetic layer**. In particular, Parkin disclosed "a ferromagnetic layer 115 of 35 Å  $\text{Co}_{70}\text{Fe}_{30}$ ." EX1062 (Parkin) at col. 17:18-19; *see also id.* at cols. 16:57 ("ferromagnetic layer 115"), 16:64-65 ("reference electrode 115"). Parkin's lower ferromagnetic CoFe layer 115 is deposited on top of an antiferromagnetic layer 116 and located immediately below an MgO tunnel barrier 120' which is subsequently "formed on top of the lower ferromagnetic electrode 110'." EX1062 (Parkin) at col. 17:14-22; *see also id.* at col. 17:3-10 (explaining that "layer 115" is "on the other side of the tunnel barrier").

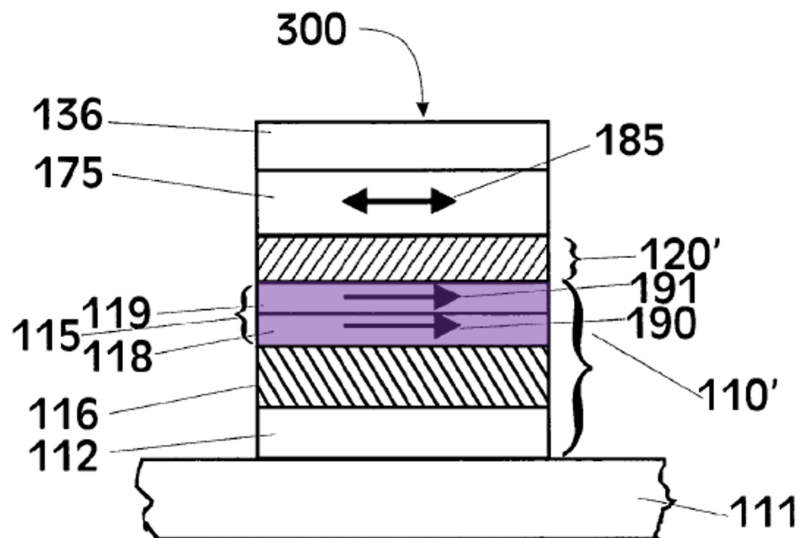


FIG. 3A

EX1062 (Parkin) at Fig. 3A (annotated).

110. One of skill would have found it obvious to replace Parkin's lower ferromagnetic CoFe layer 115 with a CoFeB layer.

111. To improve Parkin's MTJ, one of skill would have looked to Wang's teachings. Both Parkin and Wang sought to improve the TMR of magnetoresistive devices, a problem the '138 Patent claimed to address. EX1011 ('138 Patent) at Abstract, cols. 1:32-2:29. Parkin stated: "[T]his invention relates to an improved MTJ exhibiting high tunneling magnetoresistance...." EX1062 (Parkin) at col. 1:18-21. Similarly, Wang explained: "A high TMR value is desirable because it leads to greater signal level, lower power consumption, higher speed, and larger design margin for devices such as MRAM, read heads, and a variety of magnetic field sensors." EX1055 (Wang) at page 2269; *id.* at page 2269-71 (discussing the benefits of "high TMR").

112. Like the '138 Patent, Parkin and Wang also both discussed improving MRAM memory performance. EX1062 (Parkin) at cols. 2:65-3:1 ("[F]or non-volatile magnetic memory storage cells, high TMR values are needed for improving the performance of these devices."); EX1055 (Wang) at page 2269 ("A high TMR value is desirable because it leads to greater signal level, lower power consumption, higher speed, and larger design margin for devices such as MRAM...."); EX1011 ('138 Patent) at col. 2:57-60. Additionally, they both used ferromagnetic alloy electrodes, including CoFeB layers. EX1062 (Parkin) at Abstract, cols. 1:18-21

(“[T]his invention relates to an improved MTJ... with one or more electrodes formed from amorphous ferromagnetic materials.”), 19:16 (“CoFeB layer”); EX1055 (Wang) at pages 2270 (discussing using “CoFeB” for “both the free and pinned layers”), 2271 (“two ferromagnetic interfaces with the tunnel barrier”).

113. Because CoFeB electrodes had already been used with MTJs, one of skill would have found it to be straightforward and predictable to replace Parkin’s lower CoFe layer with CoFeB. MTJs, including Parkin’s own MTJ, had already used CoFeB alloy electrodes successfully to increase the TMR ratio, as well as lower  $H_f$  and  $H_c$ . EX1030 (Sunai) ¶¶24-28; EX1062 (Parkin) at cols. 18:49-51, 18:63-19:10; EX1055 (Wang) at pages 2269-70; EX1056 (Hosomi) ¶¶39, 78; EX1061 (Cardoso) at Abstract. Sunai taught that “when B is added to Co<sub>9</sub>Fe” alloy, it would improve TMR, EX1030 (Sunai) ¶28, and Parkin touted its “very high TMR values... for MTJs... with nominally amorphous [CoFeB] storage layers,” EX1062 (Parkin) at col. 18:49-51. Replacing Parkin’s lower CoFe layer with a CoFeB alloy was a straightforward and desirable improvement that would have predictably succeeded.

114. One of skill seeking to improve TMR would have been motivated to replace Parkin’s CoFe reference (or “pinned”) ferromagnetic layer with a CoFeB ferromagnetic layer based on Wang’s teaching that doing so would increase TMR. Indeed, increasing TMR was a key objective for researchers in the field. EX1062 (Parkin) at col. 6:14-16 (“What is needed is a method of forming MTJs with high

tunneling magnetoresistance with improved magnetic switching characteristics.”); EX1055 (Wang) at page 2271 (“[A] functioning junction with high TMR value means high signal level, high sensitivity, high speed, and lower power consumption for devices based on tunnel junctions.”). After comparing an MTJ device that used a CoFeB free electrode and a CoFe reference electrode to an MTJ device using both CoFeB free and reference electrodes, Wang reported that “[t]he TMR value is indeed improved to be 65.4%, comparing to 60.8% with CoFeB on only one side of the tunnel barrier.” EX1055 (Wang) at page 2270. Wang further observed that, “[w]ith such a large increase of TMR value by changing the free layer from NiFeCo to CoFeB, it is natural to replace both the free and pinned layers to CoFeB to further increase the TMR value.” EX1055 (Wang) at page 2270.

115. A skilled artisan would have understood that CoFeB was a superior material compared to CoFe electrodes. For example, Cardoso explained that “CoFe-based junctions ( $R \times A \sim 500 \Omega \cdot \mu m^2$ ) have lower TMR ( $\sim 35\%$ ) and larger  $H_f$  ( $\sim 5-6$  Oe) and  $H_c$  ( $\sim 12-14$  Oe)” compared to CoFeB-based junctions. EX1061 (Cardoso) at Abstract. As explained, Wang extolled the “benefit of using CoFeB is multifold,” including “a higher TMR value.” EX1055 (Wang) at pages 2269-70. Further, Hosomi taught that when an MTJ “ferromagnetic layer” is “comprised of a CoFeB alloy,” it “exhibits a larger TMR ratio.” EX1056 (Hosomi) ¶39; *id.* ¶¶ 67-68 (“both the ferromagnetic layers 5, 7 are made of an FeCoB” to achieve “improvement of

the TMR ratio”), 78 (discussing “improvement of the TMR ratio” by “adding B” to Fe-Co), 103-04 (explaining that “[c]urves 61 and 62 in FIG. 7 show TMR ratios (%) against the change of the external magnetic field with respect to, respectively, a TMR element having an information recording layer comprised of  $\text{Co}_{72}\text{Fe}_8\text{B}_{20}$ ”), Fig. 7. Hosomi found “remarkabl[e] increases in the TMR ratio” for certain CoFeB alloys. EX1056 (Hosomi) ¶76.

116. In sum, Claim 1[a] was disclosed or suggested by Parkin in view of Wang.

**3. Claim 1[b]: “a barrier layer disposed over the first electrode, the barrier layer comprising a magnesium oxide (MgO) layer that is formed of a poly-crystalline MgO in which a (001) crystal plane is preferentially oriented; and”**

117. This claim limitation is disclosed or suggested by Parkin.

118. Parkin taught an **MgO barrier layer** disposed over its first electrode: “An MgO tunnel barrier 120’ is then formed on top of the lower ferromagnetic electrode 110’....” EX1062 (Parkin) at col. 17:21-28. As shown in Parkin’s Figure 3A below, electrode 110’ includes a **lower ferromagnetic layer** “115 of 35 Å  $\text{Co}_{70}\text{Fe}_{30}$ ,” EX1062 (Parkin) at col. 17:18-19, which one of skill would have been motivated to replace with a CoFeB layer as explained for Claim 1[a] in Section XII.A.2 of this Declaration.

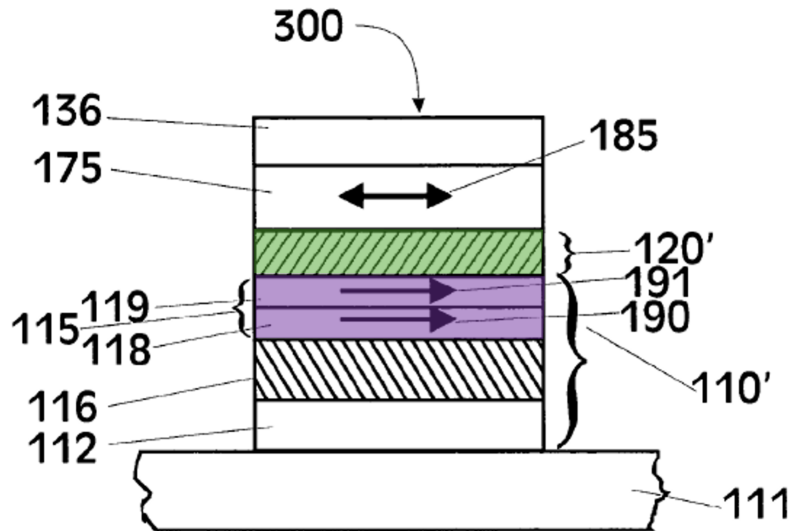


FIG. 3A

EX1062 (Parkin) at Fig. 3A (annotated).

119. Parkin taught forming a single MgO tunnel barrier layer in two steps. According to Parkin, to form its MgO barrier layer, first “a thin layer of Mg” is deposited followed by a “second layer, which is comprised of MgO.” EX1062 (Parkin) at col. 17:21-35. Parkin explained that “[d]uring the deposition of the MgO layer, the Mg underlayer becomes oxidized so that the two layers form a single MgO tunnel barrier.” EX1062 (Parkin) at col. 17:35-37. Parkin further noted that its MgO barrier layer may have oxygen vacancy defects, for example, due to the first Mg layer being deposited without the presence of oxygen. EX1062 (Parkin) at cols. 17:25-35, 17:37-39 (“The exact composition of the MgO layer may differ from the stoichiometric [sic] composition.”). As I explain in greater detail for Claim 1[e], non-stoichiometric MgO and oxygen vacancy defects in an MgO layer both refer to

missing oxygen atoms in the MgO crystal. *Supra* Section XII.A.6 of this Declaration.

120. Parkin also taught using polycrystalline MgO tunnel barrier layers with the (001) crystal plane preferentially oriented. Parkin stated that “[t]he preferred embodiments and implementations of the invention are directed to MgO or Mg-ZnO tunnel barrier layers which are substantially (100) oriented or textured.” EX1062 (Parkin) at col. 9:16-18; *see also id.* at col. 9:58-60 (“Notwithstanding the polycrystalline nature of the film structures described herein, which are in any case preferable for ease of manufacturing....”). Parkin noted, and a skilled artisan would have understood, that polycrystalline tunnel barrier layers are “what is commonly referred to as textured.” EX1062 (Parkin) at col. 9:19-24. For example, Yoon studied the formation of MgO polycrystalline thin films on various substrates and described the deposited films as “highly textured”: “The growth behaviors of MgO films on GaAs and fused quartz substrates were further investigated. All the films show highly (100)-textured structure regardless of the substrate materials, as shown in Fig. 1(b).” EX1040 (Yoon) at page 2840. In addition, as I explained above in Section VII.E.1 of this Declaration, the (100) and (001) planes for an MgO crystal are the same. EX1011 (’138 Patent) at col. 4:39-41 (“[B]ecause MgO has a cubic crystal structure (NaCl structure), the (001) plane, the (100) plane, and the (010) plane are all equivalent.”).

121. Parkin taught that its MgO barrier layer in Figure 3A was a polycrystalline MgO tunnel barrier layer with the (001) crystal plane preferentially oriented. Describing Figure 3A, Parkin observed that “very high TMR values are unexpectedly found for MTJs with *highly textured (100) MgO tunnel barriers....*” EX1062 (Parkin) at col. 18:49-51 (emphasis added); *see also id.* at cols. 18:56 (“cubic crystalline MgO layer”), 19:17 (“highly (100) textured MgO layer”). As I explained in Paragraph 120 above, one of skill would have understood that “textured” or “highly textured” tunnel barriers referred to polycrystalline tunnel barriers.

122. MTJs containing barrier layers, including barrier layers disposed over an electrode or ferromagnetic layer, were conventional by 2004, as the ’138 Patent acknowledges. EX1011 (’138 Patent) at col. 1:47-51 (Description of Related Art: “As shown in FIG. 8(A), a MTJ device comprises a tunnelling junction structure in which a tunnel barrier (to be hereafter also referred to as a ‘barrier layer’) made of an oxide is sandwiched between a first and a second electrode made of a ferromagnetic metal.”); *id.* at Figs. 8(A)-8(B) (labeled “Prior Art”).

**4. Claim 1[c]: “a second electrode disposed over the barrier layer and comprising a second ferromagnetic material layer that includes Co, Fe, and B, and”**

123. This claim limitation is disclosed or suggested by Parkin.

124. As explained for Claim 1[a], the '138 Patent teaches that the “ferromagnetic material layer” is a layer made of a “ferromagnetic metal.” EX1011 ('138 Patent) at col. 1:47-51, Fig. 8(A). As specified in Claim 1[c], “second” indicates the “upper” ferromagnetic layer or ferromagnetic material layer above the barrier layer. EX1011 ('138 Patent) at col. 9:63-65.

125. As shown in Figure 3A below, Parkin taught a “**top ferromagnetic electrode**” comprising CoFeB that is disposed over, or on top of, the **MgO tunnel barrier layer**. EX1062 (Parkin) at col. 17:40-44.

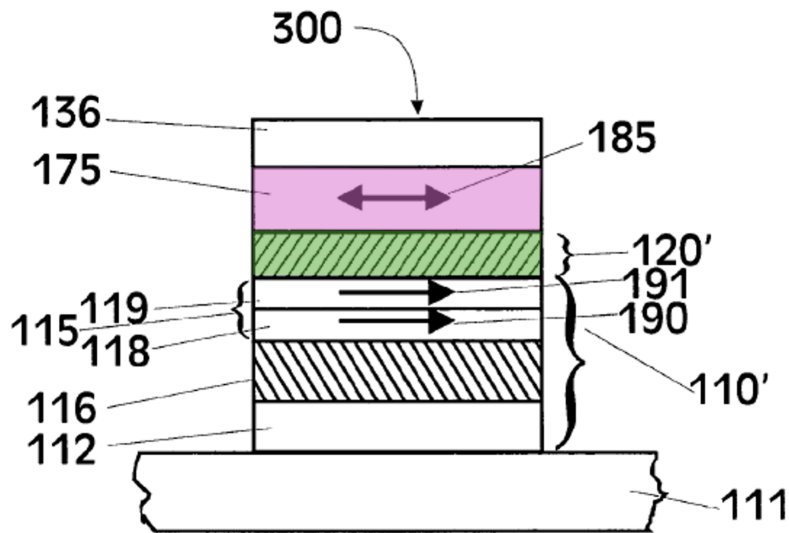


FIG. 3A

EX1062 (Parkin) at Fig. 3A (annotated).

126. According to Parkin, after forming the MgO tunnel barrier layer, “the MTJ device shown in FIG. 3A is completed by forming the top ferromagnetic electrode which is the storage layer.” EX1062 (Parkin) at col. 17:40-42. Parkin

taught that “[t]he storage layer is comprised of an amorphous ferromagnetic layer 175,” “[f]or example, the layer 175 may be comprised of 75 Å thick (Co<sub>73</sub>Fe<sub>27</sub>)<sub>74</sub>B<sub>26</sub>.” EX1062 (Parkin) at col. 17:42-44. Further, as I explained above for Claim 1[a], I was asked to assume that any CoFeB alloy satisfies the claimed “ferromagnetic material layer that includes Co, Fe, and B,” or CoFeB ferromagnetic material layer. *Supra* Section XII.A.2 of this Declaration.

127. As I explained above for Claim 1[a] in Section XII.A.2 of this Declaration, MTJs containing metallic ferromagnetic material layers were conventional by 2004, as the ’138 Patent acknowledges. EX1011 (’138 Patent) at col. 1:47-51, Figs. 8(A)-8(B).

**5. Claim 1[d]: “wherein each of the first and second ferromagnetic material layers is entirely crystallized,[] and”**

128. Claim 1[d] is disclosed or suggested by Parkin.

129. As I explained for Claim 1[c] in Section XII.A.4 of this Declaration, Parkin taught forming a “top ferromagnetic electrode... comprised of an amorphous ferromagnetic layer 175... of 75 Å thick (Co<sub>73</sub>Fe<sub>27</sub>)<sub>74</sub>B<sub>26</sub>.” EX1062 (Parkin) at col. 17:40-44; *see also id.* at col. 16:47-50 (“FIG. 3A shows a device of the current invention, which uses a free layer formed from an amorphous alloy of CoFeB....”).

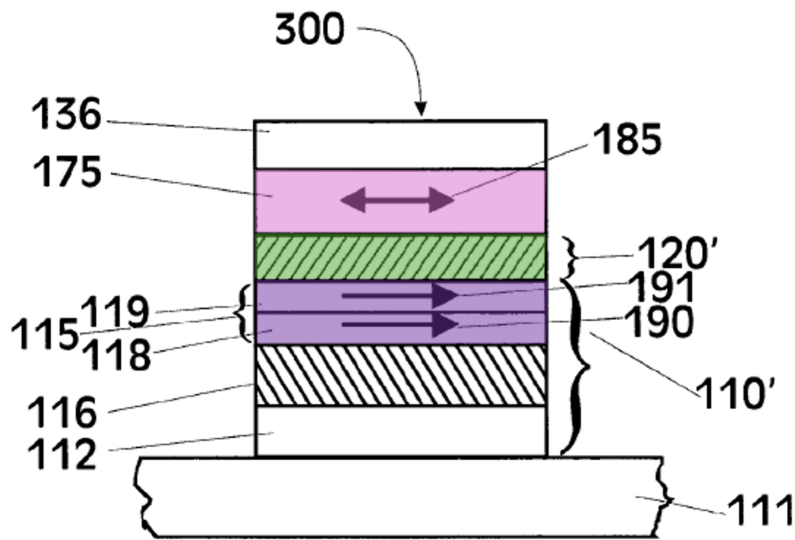


FIG. 3A

EX1062 (Parkin) at Fig. 3A (annotated).

130. Parkin further taught that annealing increased the TMR for its Figure 3A MTJ. Parkin explained that “[t]he magnitude of the tunneling magnetoresistance increases with anneal temperature, as shown in more detail in FIG. 5, and reaches a value of nearly 140% after an anneal at 380° C.” EX1062 (Parkin) at col. 18:13-16; *see also id.* at col. 18:45-48 (“TMR values of more than 220% were found after an anneal treatment at 350° C. The TMR of these devices was found to increase substantially on annealing as shown in FIG. 5.”).

131. Using “[c]ross-section transmission electron microscopy,” Parkin observed that “a portion of the storage layer 175 adjacent to the MgO tunnel barrier 120’ has crystallized and is, moreover, textured in the same orientation as the crystalline MgO tunnel barrier.” EX1062 (Parkin) at col. 18:51-55. Parkin credited

this as explaining the “very high TMR values... unexpectedly found for MTJs with highly textured (100) MgO tunnel barriers but with nominally amorphous storage layers.” EX1062 (Parkin) at col. 18:49-55. In particular, Parkin reported that “[t]he simple cubic crystalline MgO layer thus provides a template for the formation of a *thin crystalline ferromagnetic layer* which has the bcc structure of CoFe and is oriented in the same (100) direction as the MgO layer.” *Id.* at col. 18:55-59 (emphasis added).

132. In my opinion, Parkin’s “thin crystalline ferromagnetic layer” of CoFeB, EX1062 (Parkin) at col. 18:57, is “entirely crystallized” as required by Claim 1[d]. Parkin refers to the “thin crystalline ferromagnetic layer” as having “the bcc structure of CoFe,” EX1062 (Parkin) at col. 18:57-58, but a skilled artisan would understand from Parkin that the layer is CoFeB. Indeed, Parkin explained that “[t]he highly (100) textured MgO layer is likely to form an excellent template layer for the formation of a thin crystalline layer of CoFeB.” EX1062 (Parkin) at col. 19:17-19; *see also* EX1057 (Dieny) at page 48 (explaining that “a  $\text{Co}_{60}\text{Fe}_{20}\text{B}_{20}$  layer adjacent to an MgO(001) layer crystallizes in a bcc(001) structure, although the stable structure of  $\text{Co}_{60}\text{Fe}_{20}\text{B}_{20}$  is not bcc....”). Parkin further stated that “the B diffuses away from the interface with the MgO layer, during the thermal anneal treatments, to leave a thin interface layer at this interface which is much lower in B content.” EX1062 (Parkin) at col. 19:19-22. One of skill would have understood that Parkin’s

reference to “B content” that is “lower,” or even “much lower,” does not equate to no boron. In other words, some boron remains such that the “thin crystallized layer” includes CoFeB, as Parkin expressly taught. EX1062 (Parkin) at col. 19:17-19 (“formation of a thin crystalline layer of CoFeB”).

133. Parkin’s reference to the “thin crystalline ferromagnetic layer which has the bcc structure of CoFe and is oriented in the same (100) direction as the MgO layer” is not intended to indicate that there is no boron remaining in the layer or that the structure excludes boron. EX1062 (Parkin) at col. 18:57-59. Instead, a skilled artisan would understand Parkin to be referring to the fact that the crystallized CoFeB layer has a body-centered cubic (bcc) structure in the same manner that crystallized CoFe would. Similarly, Parkin’s observation that “[a] lowered boron content is likely to aid the formation of a thin crystalline CoFe interface layer,” EX1062 (Parkin) at col. 19:25-27, is explaining that the crystal structure will be largely CoFe due to the “lowered boron content.” But a “lowered boron content” means that the boron content will be “lowered,” not zero. Thus, one of skill in the art would understand Parkin’s discussion of a crystallized CoFeB layer to disclose that the layer, even after crystallization, includes Co, Fe, and B.

134. Other researchers in the field observed results similar to Parkin, including that annealing resulted in CoFeB films that are crystallized and not amorphous. EX1061 (Cardoso) at page 2273 (“X-ray measurements of bulk CoFe

and CoFeB 200 Å thick films (Fig. 3) confirmed that the CoFeB films *are not amorphous*. In fact, the spectra show clearly the existence of a peak around 45.3 ° corresponding to a *strong texture enhancement upon annealing*.” (emphases added)). Cardoso also observed that “CoFe-based junctions ( $R \times A \sim 500 \Omega \cdot \mu\text{m}^2$ ) have lower TMR (~35%) and larger  $H_f$  (~5-6 Oe) and  $H_c$  (~12-14 Oe)” compared to CoFeB-based junctions. EX1061 (Cardoso) at Abstract; *see also id.* (“The CoFeB layer has a strong (111) texture that can be the origin of lower  $H_f$  and coercivity when compared with CoFe.”).

135. Notably, the '138 Patent itself discloses far less than Parkin on this subject. For example, the totality of the '138 Patent's disclosure of “entirely crystallized” layers of CoFeB is as follows:

As the amorphous magnetic alloy, FeCoB, FeCoBSi, FeCoBP, FeZr, and CoZr may be used, for example. Although an anneal process after the preparation of the MTJ device might cause the amorphous magnetic alloy in the electrode layers to be partially or entirely crystallized, this would not lead to a significant deterioration of the MR ratio. Thus, such a crystallized amorphous magnetic alloy may be used in the electrode layers.

EX1011 ('138 Patent) at col. 9:20-27. The '138 Patent simply refers to annealing a FeCoB amorphous magnetic alloy, which might cause partial or entire crystallization. The '138 Patent's description of this process provides far less detail

than Parkin even though Parkin's process of annealing its CoFeB free layer 175 resulting in partial crystallization in the embodiment of Figure 3A falls within the description provided here in the '138 Patent. Moreover, as evident from the infringement allegations in Patent Owner's complaint, the prior art captures what Patent Owner accuses of infringement with at least the same level of detail. I understand that Patent Owner contends that the "entirely crystallized" requirement of Claim 1[d] is met so long as the CoFeB immediately adjacent to the MgO barrier layer is crystallized:

[E]ach of the first and second ferromagnetic material layers in the WD Accused Products is entirely crystallized after anneal.

...

Another WD patent (U.S. Patent No. 8,427,791...) describes that ... "In order to obtain a high MR ratio in amorphous CoFeB/crystalline MgO/amorphous CoFeB MTJs, an annealing step is necessary in order to produce *crystallized bcc CoFeB* (100)/MgO(100)/*crystallized bcc CoFeB* (100)." ...

As another example, in another WD patent (U.S. Patent No. 7,751,156...), it is described that ... "During anneal, *the CoFeB immediately contacting the MgO barrier layer 717* crystallizes thus forming the desired CoFeX/MgO/CoFeX structure...."

EX1072 (First Amended Complaint, Exhibit EE claim chart for '138 Patent) at pages 6-7 (quoting U.S. Patent Nos. 8,427,791 (EX1082), 7,751,156 (EX1081) (emphases in original)); *see also id.* (citing U.S. Patent No. 8,914,970 (EX1083)); EX1012 ('138 Patent File History) at page 200 (Examiner: “[T]he annealing process of [the prior art] to one of skilled in the art would allow the first and second ferromagnetic layers to be entirely crystallized based on the annealing process....”).

136. Like Parkin’s top ferromagnetic layer 175, if Parkin’s lower “ferromagnetic layer 115 of 35 Å  $\text{Co}_{70}\text{Fe}_{30}$ ” were replaced with CoFeB as explained for Claim 1[a] in Section XII.A.2 of this Declaration, the lower ferromagnetic layer 115 would also initially be an amorphous alloy. EX1062 (Parkin) at col. 17:18-19. After annealing the MTJ to increase the TMR, one of skill would have understood that a thin crystalline layer including CoFeB would be formed, as explained in paragraphs 131-135 above, which would also satisfy the “entirely crystallized” requirement of Claim 1[d].

**6. Claim 1[e]: “wherein a value of x in  $\text{MgO}_x$  for the MgO layer is greater than 0 and less than 1.”**

137. Claim 1[e] is disclosed or suggested by Parkin alone or in view of Soukup.

138. Parkin. Parkin disclosed or suggested  $\text{MgO}_x$  where the x is a value greater than 0 and less than 1, e.g.,  $0 < x < 1$ . As I explained in Section VII.F of this

Declaration,  $\text{MgO}_x$  where  $0 < x < 1$  refers to a non-stoichiometric MgO crystal where the ratio of oxygen to magnesium atoms is less than 1:1. In other words, there is less than 1 oxygen atom for every 1 magnesium atom. This is due to the presence of oxygen vacancy defects in the MgO crystal, indicating that an oxygen atom is missing at certain places in the crystalline structure.  $\text{MgO}_x$ , non-stoichiometric MgO, and oxygen vacancy defects in an MgO layer are interchangeable terminology and all refer to the same phenomenon: missing oxygen atoms in the MgO crystal. *E.g.*, EX1041 (Wollschläger) at page 132 (“understoichiometric  $\text{MgO}_x$  ( $x < 1$ )”); EX1037 (Castanier) at page 3, Fig. 1 (showing “sub-stoichiometric  $\text{MgO}\{100\}$  surfaces with various densities of oxygen vacancies”).

139. The '138 Patent uses this terminology in the same way. For example, the patent contrasts using barrier layers of “MgO of the stoichiometric composition (the ratio of Mg to O is 1:1)” compared to MgO “with oxygen vacancy defects.” EX1011 ('138 Patent) at col. 6:27-34. It explains that when fabricating the MTJ, “there is the possibility that there are oxygen vacancy defects such as  $\text{MgO}_x$  ( $0.9 < x < 1$ ).” EX1011 ('138 Patent) at col. 7:6-7. The '138 Patent applicant said the same thing to the Patent Office, explaining that “ $\text{MgO}_x$  ( $0 < x < 1$ )” means the MgO “crystals have oxygen vacancy defects.” EX1002 ('403 Patent File History) at page 168.

140. Any oxygen vacancy defects in MgO produce  $\text{MgO}_x$  ( $0 < x < 1$ ). Said another way,  $\text{MgO}_x$  where ( $0 < x < 1$ ) is inherent in any MgO substance that has oxygen vacancy defects. That is because the ratio of oxygen to magnesium has to be greater than zero for the substance to constitute MgO. In other words, there must be some oxygen present to have MgO. Otherwise, it would simply be Mg. Similarly, to have oxygen vacancy defects, the ratio of oxygen to magnesium must be less than 1, which simply means less than the stoichiometric ratio of oxygen to magnesium. *See* Section VII.F of this Declaration.

141. Parkin taught or suggested oxygen vacancy defects in its MgO barrier layer. As I explained above for Claim 1[b] in Section XII.A.3 of this Declaration, Parkin formed its “MgO tunnel barrier 120” in Figure 3A in two steps—first depositing Mg alone followed by depositing MgO—and noted that the “exact composition” of the resulting “MgO layer may differ from the stoichiometric [sic] composition.” EX1062 (Parkin) at col. 17:21-39. Thus, Parkin itself explained that its MgO barrier layer may have oxygen vacancy defects.

142. Parkin, through Parkin ’835, also taught oxygen vacancies in the MgO barrier layer. In particular, Parkin explained that its “MgO tunnel barrier layer 120” was formed “using the method described in U.S. patent application Ser. No. 10/824,835 to Parkin titled ‘MgO tunnel barriers and method of formation’” (“Parkin ’835,” EX1092). EX1062 (Parkin) at col. 17:21-25. Parkin ’835 was incorporated

by reference into Parkin. EX1062 (Parkin) at cols. 3:24-26 (noting that Parkin '835 "is hereby incorporated by reference"), 17:21-28 (describing formation of MgO barrier layer disclosed in Parkin '835). Parkin '835 taught that "[d]uring the deposition of the layer 124, the Mg layer 122 is exposed to oxygen and will become partially or completely oxidized, depending on the oxidation conditions and the thickness of the Mg layer 122." EX1092 (Parkin '835) at page 34. A partially oxidized Mg layer will result in understoichiometric MgO due to the presence of oxygen vacancies.

143. In sum, Parkin taught or suggested an MgO layer wherein the value of  $x$  in  $MgO_x$  for the MgO layer is greater than 0 and less than 1.

144. Obviousness over Parkin and Soukup. This limitation was also disclosed or suggested by Parkin in view of Soukup. As discussed in the preceding Paragraph 141, Parkin stated that "[t]he exact composition of the MgO layer may differ from the stoichiometric [sic] composition." EX1062 (Parkin) at col. 17:37-39. Soukup also studied the "effect of nonstoichiometry on the device characteristics" of his MgO thin film. EX1028 (Soukup) at page 3232. Soukup here is referring to oxygen vacancy defects in his MgO barrier. EX1028 (Soukup) at page 3232. He fabricated devices with different levels of nonstoichiometry in the MgO layer and assessed their barrier heights. EX1028 (Soukup) at Abstract, pages 3232-33, Table I.

145. For the reasons I provided for Claim 4 in Section XII.D of this Declaration, a skilled artisan would have been motivated to apply Soukup's teachings about oxygen vacancy defects in the MgO barrier to Parkin's non-stoichiometric MgO barrier. Parkin sought to improve the TMR of its MTJ using an MgO barrier layer. EX1062 (Parkin) at col. 6:14-16 ("What is needed is a method of forming MTJs with high tunneling magnetoresistance with improved magnetic switching characteristics."). One of skill in the art looking to improve the tunneling and TMR of Parkin's MTJ would have been motivated to experiment with different levels of oxygen vacancy defects to study their impact on the MgO barrier properties and therefore improve tunneling and TMR. EX1028 (Soukup) at page 3232.

**B. Claim 2: Obviousness Over Parkin In View Of Wang And Optionally Soukup**

- 1. Claim 2: "The MTJ device of claim 1, wherein the first ferromagnetic material layer is in direct contact with the barrier layer, and wherein the second ferromagnetic material layer is in direct contact with the barrier layer."**

146. As I explained in Section XII.A of this Declaration, Claim 1 is obvious over Parkin in view of Wang and optionally Soukup. Claim 2 depends from Claim 1 and thus incorporates all of Claim 1's requirements. Claim 2 is obvious over Parkin in view of Wang and optionally Soukup as explained in the following paragraphs.

147. Parkin in view of Wang disclosed or suggested first and second CoFeB ferromagnetic material layers sandwiching the "single MgO tunnel barrier" layer

and in direct contact with the MgO barrier layer, as I explained for Claims 1[a]-1[c] in Sections XII.A.2-XII.A.4 of this Declaration. EX1062 (Parkin) at col. 17:35-37. In addition, as I explained for Claim 1[d] in Section XII.A.5 of this Declaration, the first and second CoFeB layers are annealed, which would result in entirely crystallized CoFeB layers in direct contact with the MgO barrier layer. EX1062 (Parkin) at cols. 18:51-55 (“Cross-section transmission electron microscopy reveals that a portion of the storage layer 175 adjacent to the MgO tunnel barrier 120’ has crystallized and is, moreover, textured in the same orientation as the crystalline MgO tunnel barrier.”), 19:17-19 (“The highly (100) textured MgO layer is likely to form an excellent template layer for the formation of a thin crystalline layer of CoFeB.”).

148. Further, as I explained above for Claim 1[a] in Section XII.A.2 of this Declaration, MTJs containing ferromagnetic material layers sandwiching and in direct contact with a barrier layer were conventional by 2004, as the ’138 Patent acknowledges. EX1011 (’138 Patent) at col. 1:47-51, Figs. 8(A)-8(B).

**C. Claim 3: Obviousness Over Parkin In View Of Wang And Optionally Soukup**

- 1. Claim 3: “The MTJ device of claim 1, wherein the first ferromagnetic material layer is in direct contact with the MgO layer, and wherein the second ferromagnetic material layer is in direct contact with the MgO layer.”**

149. Claim 3 is disclosed or suggested for the same reasons explained above for Claim 2. *Supra* Section XII.B of this Declaration; *see also supra* Section XII.A (Claim 1) of this Declaration.

150. The only difference between Claims 2 and 3 is that Claim 2 refers to “barrier layer” whereas Claim 3 recites an “MgO layer.” As I explained for Claim 1[b] in Section XII.A.3 of this Declaration, Parkin’s barrier layer is an MgO layer.

**D. Claim 4: Obviousness Over Parkin In View Of Wang And Soukup**

- 1. Claim 4: “The MTJ device of claim 1, wherein a barrier height  $\phi$  of the barrier layer is in a range of 0.2 to 0.5 eV.”**

151. As I explained in Section XII.A of this Declaration, Claim 1 is obvious over Parkin in view of Wang and optionally Soukup. Claim 4 depends from Claim 1 and thus incorporates all of Claim 1’s requirements. Claim 4 is obvious over Parkin in view of Wang and Soukup as explained in the following paragraphs.

152. Parkin in view of Soukup taught or suggested a barrier height  $\phi$  that is in a range of 0.2 to 0.5 eV. As I explained previously in Section VII.D of this Declaration, the barrier height measures the difference between the Fermi level of the electrode and the bottom of the conduction band of the barrier layer.

153. One of skill reading Parkin would have understood it to teach or suggest that lowering the barrier height for electrons would facilitate tunneling. As I explain in Paragraph 157 below, skilled artisans would have understood, including from Butler and Mathon, that MgO barriers would achieve higher TMRs due to improved symmetry matching between the MgO barrier and ferromagnetic electrodes, facilitating tunneling of parallel electrons across the barrier compared to antiparallel tunneling. Parkin similarly described a polycrystalline MgO tunnel barrier layer where “the arrangement of atoms in a bcc structure oriented in the (100) direction with respect to the direction of tunneling of electrons.” EX1062 (Parkin) at col. 14:35-41, Fig. 2; *see also id.* at col. 15:26-34 (discussing “Fe/MgO/Fe” MTJs and explaining that “the high TMR values are related to the spin-dependent tunneling of wave-functions of a particular symmetry from the Fe layer through the MgO tunnel barrier”).

154. Soukup measured a “barrier height” of “about 0.33 eV” for its MgO thin film that is within the ’138 Patent’s disclosed range of 0.2 to 0.5 eV. EX1028 (Soukup) at Abstract, pages 3231-32, Fig. 5, Table I; EX1011 (’138 Patent) at col. 7:7-11 (“When there are oxygen vacancy defects, the potential barrier height of the MgO tunnel barrier is thought to decrease (such as in the range of... 0.2 to 0.5 eV), which is thought to result in an increase in the tunneling current.”).

155. Indeed, oxygen vacancy defects in an MgO barrier impact the barrier height. Soukup investigated the “effect of nonstoichiometry on the device characteristics.” EX1028 (Soukup) at page 3232. Soukup suggested there was a “higher barrier?[] present for the devices fabricated with more oxygen present during MgO deposition, which could mean more stoichiometric oxide films.” EX1028 (Soukup) at page 3232. Said another way, Soukup found that a lower level of oxygen vacancy defects may result in a higher barrier height. This suggested a higher level of oxygen vacancy defects lowered the barrier height. EX1028 (Soukup) at page 3232. In sum, Soukup taught there was an inverse correlation between oxygen vacancy defects and the barrier height of the MgO layer.

156. A skilled artisan would have had a motivation to take Soukup’s teachings about an MgO thin-film barrier with a “barrier height” of “about 0.33 eV” and apply them to Parkin’s MgO barrier as modified to have first and second ferromagnetic CoFeB layers. EX1028 (Soukup) at Abstract, pages 3232, 3236. As is evident from the TMR equation (reproduced below), lowering the resistance for parallel spin electrons ( $R_p$ ) compared to antiparallel electrons ( $R_{ap}$ ) improved TMRs:

$$\text{TMR} = \frac{\Delta R}{R_p} = \frac{R_{ap} - R_p}{R_p}$$

EX1035 (Moodera 1995) at page 3273; EX1027 (Nagahama) ¶2; EX1011 (’138 Patent) at cols. 4:62-5:3 (TMR equation); EX1057 (Dieny textbook) at page 13;

EX1044 (Butler) at pages 1-9. Lowering the barrier height was understood to increase tunneling current based on Simmons' equation. EX1026 (Bowen) at page 1656 (referencing "good agreement" in calculating barrier height using Simmons' equations); EX1031 (Simmons) at page 1797 (showing Equation 25 for low voltage range in which tunneling current density is proportional to  $\frac{\sqrt{\phi}}{e^{\sqrt{\phi}}}$  where  $\phi$  is barrier height and in Simmons' equation tunneling current density (J) increases with decreasing barrier height). Despite theoretically increased tunneling current due to lower barrier height, electrons cannot tunnel from one electrode to another if there are no available states to receive them in the opposite electrode as explained in detail by Butler. *E.g.*, EX1044 (Butler) at page 9 ("On the right-hand side of the barrier however these states cannot propagate because there are no minority  $\Delta_1$  propagating states at the Fermi energy. Therefore, they continue to decay within the minority Fe leading to total reflection of the  $\Delta_1$  Bloch state."). Where the theoretical tunneling current is increased by lowering barrier height, the parallel resistance ( $R_p$ ) decreases with matching electron states in both electrodes and minimal decay in the barrier. As Butler explains, the dominant current contributor is the  $\Delta_1$  state. EX1044 (Butler) at page 1 (Abstract) ("One particular state with  $\Delta_1$  symmetry is able to effectively couple from the Fe into the MgO."). However, the anti-parallel resistance ( $R_{ap}$ ) continues to be controlled by rapid decay and lack of available corresponding Bloch states in the receptor electrode, and in the case of the dominant  $\Delta_1$  state, it is

essentially unable to convey electrons. *E.g.*, EX1044 (Butler) at page 9 (“[The  $\Delta_1$  propagating states] continue to decay within the minority Fe leading to total reflection of the  $\Delta_1$  Bloch state.”). Thus, in the parallel magnetization, the electrons take advantage of the decreased barrier height leading to reduced  $R_p$ , while Butler teaches that the electrons in the anti-parallel magnetization are essentially blocked, leading to largely unaffected  $R_{ap}$ .

157. The TMR was and is a key parameter for improving MRAM performance. EX1062 (Parkin) at cols. 2:65-3:1 (“For applications of magnetic tunnel junctions for either magnetic recording heads or for non-volatile magnetic memory storage cells, high TMR values are needed for improving the performance of these devices.”), 6:14-16; EX1055 (Wang) at page 2269; EX1049 (Kim) at pages 185-88, 194. As explained in Section VII.E.3 of this Declaration, Butler and Mathon taught that MgO barriers would achieve higher TMRs due to improved symmetry matching between the MgO barrier and ferromagnetic electrodes, facilitating tunneling of parallel electrons across the barrier compared to antiparallel tunneling. EX1044 (Butler) at page 1-9; EX1046 (Mathon) at page 1; *see also* EX1045 (Klaauw) at page 1 (“The tunneling resistance for the parallel orientation of the magnetic moments is estimated to be 100 times smaller than that for the antiparallel orientation of the magnetic moments due to the absence of scattering in the barrier.”). Parkin acknowledged Butler’s teachings, citing to Butler and discussing these “[t]heoretical

predictions of high TMR in MTJs.” EX1062 (Parkin) at page 2, col. 15:26-34. Mathon explained that tunneling was enhanced due to “only a small lattice mismatch of about 3.5%” between electrodes and barrier. EX1046 (Mathon) at page 1. Following this research, Parkin and others were quite interested in increasing TMRs to enable better-performing MRAM. *E.g.*, EX1062 (Parkin) at cols. 2:25-3:1; EX1055 (Wang) at page 2271. Parkin provided an overview of the research that led to improvements in TMR in MTJs, *see* EX1062 (Parkin) at col. 2:25-64, and explained that, “[f]or applications of magnetic tunnel junctions for either magnetic recording heads or for non-volatile magnetic memory storage cells, high TMR values are needed for improving the performance of these devices,” EX1062 (Parkin) at cols. 2:65-3:1. MgO had been extensively studied for decades. One of skill would have been motivated to consult the literature on MgO, including Soukup.

158. To increase TMR of an MgO barrier, skilled artisans would have been motivated to explore lower barrier heights to facilitate tunneling of parallel electrons. One of skill in the art that was interested in improving Parkin’s MgO MTJ would have looked to Soukup’s teachings about MgO barriers and how defects lowered the barrier height. Parkin’s and Soukup’s research dovetailed together. Both Parkin and Soukup focused on improving MgO tunnel barriers, including discussing the properties of MgO barriers and tunneling, EX1062 (Parkin) at cols. 6:14-16, 17:21-39; EX1028 (Soukup) at pages 3229-30, which is a problem also addressed

by the '138 Patent. EX1011 ('138 Patent) at Abstract, cols. 1:32-2:29. Soukup also discussed Simmons' seminal 1963 paper and well-known formula for determining barrier height. EX1028 (Soukup) at page 3229.

159. A skilled artisan also would have had a reasonable expectation of success in applying Soukup's teachings to Parkin to achieve a tunnel barrier height in the range of 0.2 to 0.5 eV. Soukup had already fabricated an MgO barrier with a tunnel barrier height of 0.33 eV, EX1028 (Soukup) at Abstract, and one of skill in the art would have been motivated to use a barrier with the same or similar height in an MgO MTJ to improve tunneling and hence TMR in Parkin.

160. The claimed tunnel barrier height range of 0.2 to 0.5 eV was obvious. As I explained above in Paragraphs 155-156 of this Declaration, a skilled artisan would have looked to Soukup's teachings. One of skill would have been motivated to use Soukup's teachings to deposit an MgO barrier with a lower barrier height than the "0.9 eV" barrier height disclosed by Bowen and others. EX1026 (Bowen) at page 1656 (citing EX1038); EX1038 (Moodera 1996) at pages 4725-26. One of skill applying Soukup's teachings to Parkin would have readily achieved lowering tunnel barrier height to within the claimed range.

161. As I mentioned in Paragraph 155 of this Declaration, oxygen vacancy defects impacted the barrier height. Soukup observed a relationship between barrier height and MgO stoichiometry (oxygen vacancy defects). EX1028 (Soukup) at

pages 3232, 3236 (“[B]arrier height was a function of the amount of oxygen present... with a higher barrier for larger amounts of oxygen present” and “more stoichiometric” MgO film.). Bowen hypothesized that the low barrier height he observed, which was “lower than half” of the calculated value for “an ultrathin layer” of MgO, may be due to the “presence of stoichiometric... inhomogeneities in the insulating film.” EX1026 (Bowen) at page 1656. Others in the field also observed a lower tunneling barrier for MgO barriers with defects. *See, e.g.*, EX1043 (Heinrich) at page 1 (noting that the “sharp increases in tunneling current were caused by localized defects in the MgO layer” and “the tunneling barrier is significantly decreased”); EX1045 (Klaauw) at page 7 (“[S]mall variations in the electronic structure of the MgO lead to strong variations in the local tunneling current.”); EX1053 (Mitani) at page 8042 (reporting “the resistance decreases dramatically” for “tunneling transport through the MgO barrier,” attributing it to “defects in the MgO barrier”); EX1047 (Wulfhekel) at page 510 (observing “defects in the MgO barrier” and concluding that spikes in current are likely caused by “a lower tunneling barrier”).

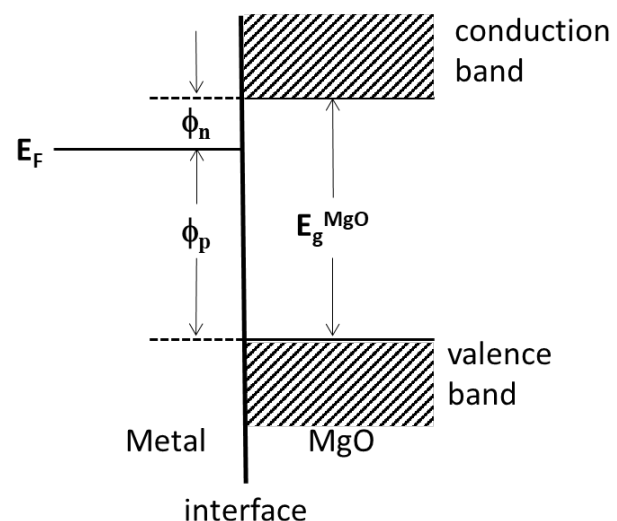
162. According to the '138 Patent, “[w]hen there are oxygen vacancy defects, the potential barrier height of the MgO tunnel barrier is thought to decrease (such as in the range of... 0.2 to 0.5 eV), which is thought to result in an increase in the tunneling current.” EX1011 ('138 Patent) at col. 7:7-11. Thus, the '138 Patent

itself recognized that the tunnel barrier height is lowered when there are oxygen vacancy defects as taught by Soukup and Bowen. EX1028 (Soukup) at pages 3232, 3236; EX1026 (Bowen) at page 1656.

163. One of skill would have been motivated to adjust oxygen vacancy defects to improve TMR by lowering the barrier height.

164. Soukup reported a barrier height of 0.33 eV for his MgO barrier with an Au/MgO interface. EX1028 (Soukup) at pages 3229, 3232. The barrier height is principally driven by the barrier itself, in this case MgO. *E.g.*, EX1054 (Goniakowski) at Fig. 1; *id.* at page 96, Table 2. One of skill would have expected a barrier height for a ferromagnetic/MgO interface to be about the same or even lower than Soukup's Au/MgO interface.

165. Goniakowski studied barrier heights for a large number of metal/MgO interfaces. In Figure 1, Goniakowski showed experimental data exhibiting a strong trend for p-type Schottky barrier heights,  $\phi_p$ , for many metals on MgO in which the barrier height decreases linearly with the increase of the Pauling electronegativity of the metal. EX1054 (Goniakowski) at Fig. 1; *see also id.* at page 96, Table 2. One of skill would



have understood the tunnel barrier height for electrons,  $\phi_n$ , is related to  $\phi_p$  by the relation:  $\phi_p + \phi_n = E_g^{\text{MgO}}$ , where  $E_g^{\text{MgO}}$  is the band gap of MgO. This is depicted schematically in the figure above, where  $E_F$  represents the Fermi level of the metal. Thus, Goniakowski showed a strong trend for tunnel barrier heights in which the barrier height increases linearly with the increase of the Pauling electronegativity of the metal, or correspondingly decreases with the decrease of the Pauling electronegativity of the metal.

166. Trasatti reported experimental data for the Pauling electronegativity for many metals. EX1032 (Trasatti) at Table 1; *see also id.* at pages 229-31. In Table 1, Trasatti showed two values for the Pauling electronegativity for Au. 2.37 is given as the value by “a number of authors,” but 2.10 is the value given as the “operative” value “corresponding to the state of the metal as used in electrochemistry or catalysis.” EX1032 (Trasatti) at page 231, Table 1. Trasatti’s Table 1 also showed a value for the Pauling electronegativity of 1.8 for Co and 1.77 for Fe. EX1032 (Trasatti) at Table 1. One of skill would have understood that a thin film of metal deposited on MgO using the techniques disclosed in Parkin (“reactive magnetron sputtering using an argon-oxygen plasma containing 3 atomic percent oxygen”) is not consistent with the state of the metal as used in electrochemistry or catalysis. EX1062 (Parkin) at col. 17:32-37. Nevertheless, for either value of Pauling electronegativity cited for Au, the values of the Pauling electronegativity of Co and

Fe are each lower. EX1032 (Trasatti) at Table 1. Thus, one of skill reading Goniakowski in light of Trasatti would have concluded that a tunnel barrier height for Fe or Co (or an alloy of Fe or Co) on MgO would be lower than the value found by Soukup for Au on MgO. At a minimum, one of skill would have been aware of the trend for tunnel barrier heights disclosed in Goniakowski and would have understood that there would be a reasonable expectation of success in achieving a low barrier height using Fe or Co, or an alloy of Fe or Co such as CoFeB.

167. In sum, Claim 4 was disclosed or suggested by Parkin in view of Wang and Soukup.

**E. Claim 7: Obviousness Over Parkin In View Of Wang And Optionally Soukup**

**1. Claim 7[preamble]: “A magnetic tunnel junction (MTJ) device, comprising:”**

168. This claim limitation is disclosed or suggested for the same reasons explained above for Claim 1[preamble]. *Supra* Section XII.A.1 of this Declaration; *see also infra* Sections XII.E.2-XII.E.7 of this Declaration.

**2. Claim 7[a]: “a first electrode made of a first CoFeB layer;”**

169. This claim limitation is disclosed or suggested for the same reasons explained above for Claim 1[a]. *Supra* Section XII.A.2 of this Declaration. As I explained for Claim 1[a], a skilled artisan would have understood that an electrode

made of a CoFeB layer referred to the same alloy as a ferromagnetic layer including Co, Fe, and B.

- 3. Claim 7[b]: “a barrier layer made of a magnesium oxide (MgO) layer that is a poly-crystalline layer in which a (001) crystal plane is preferentially oriented; and”**

170. This claim limitation is disclosed or suggested for the same reasons explained above for Claim 1[b]. *Supra* Section XII.A.3 of this Declaration.

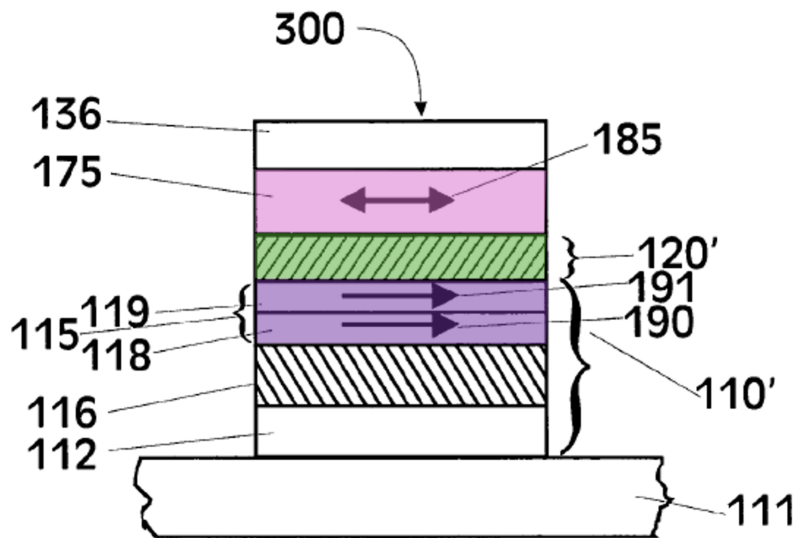
- 4. Claim 7[c]: “a second electrode made of a second CoFeB layer, and”**

171. This claim limitation is disclosed or suggested for the same reasons explained above for Claims 1[c] and 7[a]. *Supra* Sections XII.A.4 and XII.E.2 of this Declaration.

- 5. Claim 7[d]: “wherein the barrier layer is located between the first electrode and the second electrode, and”**

172. This claim limitation is disclosed or suggested for the same reasons explained above for Claims 1[a]-1[c], 2 and 3. *Supra* Sections XII.A.2-XII.A.4, XII.B, and XII.C of this Declaration.

173. As explained and shown below, Parkin taught an MgO barrier layer 120' that is located between the lower electrode 115 and upper electrode 175:



EX1062 (Parkin) at Fig. 3A (annotated).

6. **Claim 7[e]: “wherein both the first and second CoFeB layers are entirely crystallized, and”**

174. This claim limitation is disclosed or suggested for the same reasons explained above for Claim 1[d]. *Supra* Section XII.A.5 of this Declaration.

7. **Claim 7[f]: “wherein a value of  $x$  in  $\text{MgO}_x$  for the MgO layer is greater than 0 and less than 1.”**

175. This claim limitation is disclosed or suggested for the same reasons explained above for Claim 1[e]. *Supra* Section XII.A.6 of this Declaration.

**F. Claim 8: Obviousness Over Parkin In View Of Wang And Optionally Soukup**

- 1. Claim 8: “The MTJ device of claim 7, wherein the first CoFeB layer is in direct contact with the MgO layer, and wherein the second CoFeB layer is in direct contact with the MgO layer.”**

176. Claim 8 is disclosed or suggested for the same reasons explained above for Claims 2 and 3. *Supra* Sections XII.B-XII.C of this Declaration; *see also supra* Section XII.E (Claim 7) of this Declaration.

**G. Claim 9: Obviousness Over Parkin In View Of Wang And Optionally Soukup**

- 1. Claim 9: “The MTJ device of claim 7, wherein the MgO layer and the first CoFeB layer form a first interface of the MTJ, and wherein the MgO layer and the second CoFeB layer form a second interface of the MTJ.”**

177. Claim 9 is disclosed or suggested for the same reasons explained above for Claims 2 and 3. *Supra* Sections XII.B-XII.C of this Declaration; *see also supra* Section XII.E (Claim 7) of this Declaration.

178. As used in Claim 9, “interface” means the boundary between two materials. In Claim 9, the “first interface” refers to the boundary between the MgO layer and the first CoFeB layer, and the “second interface” refers to the boundary between the MgO layer and the second CoFeB layer. EX1011 (’138 Patent) at cols. 1:53-64 (Description of Related Art: discussing “the interfaces of the tunneling junction structure”), 5:47-51; *id.* at Figs. 8(A)-8(B).

179. As explained above in Sections XII.B-XII.C of this Declaration and shown below, Parkin in view of Wang and optionally Soukup disclosed or suggested a first CoFeB layer in direct contact with the MgO layer, forming a **first interface** of the MTJ, and a second CoFeB layer in direct contact with the MgO layer, forming a **second interface** of the MTJ:

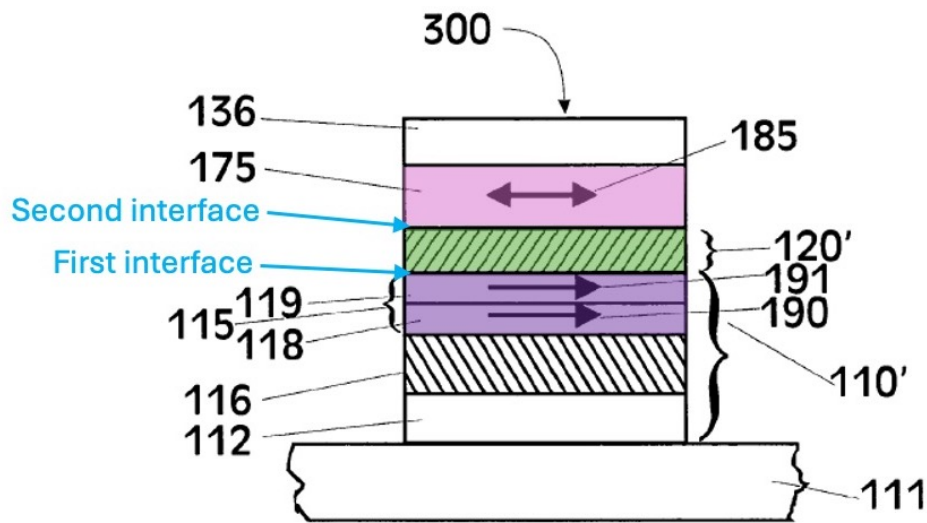


FIG. 3A

EX1062 (Parkin) at Fig. 3A (annotated). Parkin described an “interface” as the boundary between two layers. EX1062 (Parkin) at cols. 2:41-43 (referring to “the interface between the  $\text{Al}_2\text{O}_3$  tunnel barrier and the ferromagnetic electrodes”), 11:21-67, 15:26-29 (discussing “Fe/MgO interface” of “Fe and MgO layers”), 19:6-27. Parkin further described the significance of the “interface between the ferromagnetic electrode and the tunnel barrier,” explaining, for example, that “the magnitude of the TMR is extremely sensitive to the nature of the interface between

the tunneling barrier and the ferromagnetic electrode.” EX1062 (Parkin) at cols. 11:49-52, 11:64-67.

**H. Claim 10: Obviousness Over Parkin In View Of Wang And Soukup**

**1. Claim 10: “The MTJ device of claim 7, wherein a barrier height  $\phi$  of the MgO layer is in a range of 0.2 to 0.5 eV.”**

180. Claim 10 is disclosed or suggested for the same reasons explained above for Claim 4. *Supra* Section XII.D of this Declaration; *see also supra* Section XII.E (Claim 7) of this Declaration.

**I. Claim 12: Obviousness Over Parkin In View Of Wang And Optionally Soukup**

**1. Claim 12[preamble]: “A magnetic tunnel junction (MTJ) device, comprising:”**

181. This claim limitation is disclosed or suggested for the same reasons explained above for Claim 1[preamble]. *Supra* Section XII.A.1 of this Declaration; *see also infra* Sections XII.I.2-XII.I.5 of this Declaration.

**2. Claim 12[a]: “a first ferromagnetic material layer that includes Co, Fe, and B;”**

182. This claim limitation is disclosed or suggested for the same reasons explained above for Claim 1[a]. *Supra* Section XII.A.2 of this Declaration.

- 3. Claim 12[b]: “a barrier layer disposed on the first ferromagnetic material layer, the barrier layer comprising a magnesium oxide (MgO) layer that is a poly-crystalline MgO in which (001) crystal plane is preferentially oriented; and”**

183. This claim limitation is disclosed or suggested for the same reasons explained above for Claim 1[b]. *Supra* Section XII.A.3 of this Declaration. As I explained for Claim 1[b], Parkin’s MgO barrier layer was formed over, or disposed on, the lower ferromagnetic layer. EX1062 (Parkin) at col. 17:21-37.

- 4. Claim 12[c]: “a second ferromagnetic material layer that is disposed on the barrier layer and includes Co, Fe, and B, and”**

184. This claim limitation is disclosed or suggested for the same reasons explained above for Claim 1[c]. *Supra* Section XII.A.4 of this Declaration. As I explained for Claim 1[c], Parkin’s CoFeB top ferromagnetic layer was formed over, or disposed on, the MgO barrier layer. EX1062 (Parkin) at col. 17:40-44.

- 5. Claim 12[d]: “wherein each of the first and second ferromagnetic material layers is entirely crystallized, and wherein a value of x in MgO<sub>x</sub> for the MgO layer is greater than 0 and less than 1.”**

185. This claim limitation is disclosed or suggested for the same reasons explained above for Claims 1[d] and 1[e]. *Supra* Sections XII.A.5 and XII.A.6 of this Declaration.

**J. Claim 13: Obviousness Over Parkin In View Of Wang And Soukup**

**1. Claim 13: “The MTJ device of claim 12, wherein a barrier height  $\phi$  of the barrier layer is in a range of 0.2 to 0.5 eV.”**

186. Claim 13 is disclosed or suggested for the same reasons explained above for Claim 4. *Supra* Section XII.D of this Declaration; *see also supra* Section XII.I (Claim 12) of this Declaration.

**XIII. GROUND 2: CLAIMS 5-6, 11, AND 14 ARE OBVIOUS OVER PARKIN IN VIEW OF WANG, SOUKUP, AND BOWEN**

187. In my opinion, Claims 5-6, 11, and 14 are obvious over Parkin in view of Wang, Soukup, and Bowen.

**A. Claim 5: Obviousness Over Parkin In View Of Wang, Soukup, And Bowen**

**1. Claim 5[preamble]: “The MTJ device of claim 4,”**

188. As I explained above in Section XII.D of this Declaration, Parkin in view of Wang and Soukup disclosed or suggested an MTJ device satisfying Claim 4. *See also supra* Section XII.A.1 (Claim 1[preamble]) of this Declaration.

**2. Claim 5[a]: “wherein the barrier height  $\phi$  of the barrier layer is obtained by fitting J-V characteristics of the MTJ device to an equation (1):  $J = [(2m\phi)^{1/2} / \Delta s] (e/h)^2 \times \exp[-(4\pi\Delta s/h) \times (2m\phi)^{1/2}] \times V$  (1)”**

189. Soukup and Bowen disclosed or suggested Claim 5[a].

190. Claim 5[a] recites “equation (1),” which is merely a recitation of the Simmons formula, which was widely known to be used to calculate the tunnel barrier

height at a low-voltage range. EX1031 (Simmons) at pages 1796-97 (showing Simmons' formula for "Low-Voltage Range" as Equation (25)); *supra* Section VII.D of this Declaration.

191. In his 1963 paper, Simmons detailed his derivation of an equation that can be used to calculate the tunnel barrier height. EX1031 (Simmons) at Abstract ("A formula is derived for the electric tunnel effect through a potential barrier of arbitrary shape existing in a thin insulating film."). Simmons quantified the "tunnel effect" and provided a formula for quantifying the barrier height, or the energy required for electrons to tunnel across an insulating barrier between two similar electrodes. EX1031 (Simmons) at Abstract, pages 1793-94. Simmons started by deriving an equation for "any shape of potential barrier" and then simplified the equation to apply it to "rectangular potential barrier[s]" at "low voltages" and "high voltages." EX1031 (Simmons) at pages 1796-98.

192. It was known to one of skill that the formula in Simmons' 1963 paper contained an error, and researchers later corrected Simmons' formula to remove an erroneous factor of  $3/2$ . EX1059 (Matthews) at page 1. This corrected formula is identical to Simmons' formula, except for the erroneous factor of  $3/2$ , and is the formula used in Claim 5[a]. *Compare* EX1011 ('138 Patent) at col. 10:16-17 (equation (1) in Claim 5[a]), *with* EX1031 (Simmons) at page 1797 (Equation (25)).

193. The '138 Patent acknowledged that “equation (1)” recited in Claim 5[a] is Simmons’ formula for calculating tunnel barrier height. EX1011 ('138 Patent) at cols. 7:28-34 (citing EX1031 (Simmons)), 7:59-8:3; *see also* EX1074 (First Amended Complaint, Exhibit GG) at pages 5, 14-15 (acknowledging that, in Claim 1, “equation (1)” is the “Simmons formula”). The '138 Patent explains that it applies a low bias voltage  $V$  across the MTJ to allow for electron tunneling, “100 mV or smaller,” EX1011 ('138 Patent) at col. 7:56-59, and thus relies on the “low-voltage” Simmons formula to calculate tunnel barrier height, *compare* EX1011 ('138 Patent) at cols. 7:58-8:3, *with* EX1031 (Simmons) at pages 1796-97 (explaining that Equation (25) is a “more convenient” formula derived from Equation (20) for “low voltages”).

194. One of skill would have understood that a bias voltage of “100 mV or smaller” is considered to be a “low voltage.” The '138 Patent explains that bias voltages that are typically applied to MTJs are “on the order of 500 mV to 1000 mV.” EX1011 ('138 Patent) at col. 7:35-37. Similarly, Moodera also explained that “higher bias” voltages were larger than “0.1 V” or 100 mV. EX1035 (Moodera 1995) at page 3273; *see also* EX1038 (Moodera 1996) at page 4729 (“low bias (below ~100 mV)”).

195. Simmons’ formula was well known, and one of skill in the art would have understood that it was used to approximate the barrier height of an MTJ. *See*,

*e.g.*, EX1026 (Bowen) at pages 1656, 1657 n.13 (calculating “barrier height” with “Simmons’ equations”); EX1028 (Soukup) at pages 3229, 3236 n.1 (citing Simmons); EX1035 (Moodera) at pages 3274, 3276 n.16 (using “Simmons’ theory of tunneling to obtain values of tunnel barrier height” (internal citation omitted)); EX1038 (Moodera) at pages 4725, 4729 n.16 (“Simmon’s [sic] theory of tunneling was used to derive the barrier height...”); EX1043 (Heinrich) at page 1 (using “Simmons rule” to calculate the “tunneling barrier”); EX1047 (Wulfhchel) at page 511 & n.18 (discussing “Simmons’ rule” for “the barrier height”); EX1050 (Yuasa) at pages 2429, 2431 n.22 (“using Simmons’ I—V formula”); EX1053 (Mitani) at pages 8042, 8043 n.14 (“The barrier width and height [were] estimated from the numerical fitting of Simmons’ formula....”). The tunnel barrier height is conventionally determined by fitting the barrier’s J-V curves to Simmons’ formula. EX1031 (Simmons) at page 1796 (“[I]f the current-voltage characteristic of a tunnel junction is known, the mean barrier height can be determined.”). Both Bowen and Soukup disclosed that Simmons’ formula was used to approximate tunnel barrier height.

196. Bowen used “I(V) curves [to] place[] the barrier height at  $\phi=0.9$  eV” at 10 mV for its Fe/MgO/FeCo MTJ. EX1026 (Bowen) at page 1656. Citing to Simmons’ 1963 paper, Bowen compared its measurements to the results of

“Simmons’ equations,” finding them to be “in good agreement.” EX1026 (Bowen) at pages 1656, 1657 n.13 (citing EX1031 (Simmons)).

197. Soukup also acknowledged that “Simmons’ model” was used to evaluate the “height and the bias dependence of the insulator potential-energy barrier.” EX1028 (Soukup) at pages 3229, 3236 n.1 (citing EX1031 (Simmons)). One of skill would have understood the “height and the bias dependence of the insulator potential-energy barrier” included the tunnel barrier height. *See* Section VII.D of this Declaration.

198. It would have been obvious to a skilled artisan to use Simmons’ formula, as taught by Bowen, to calculate the claimed “barrier height  $\phi$ ” in Parkin’s MgO MTJ as modified by Wang and Soukup. Not only was Simmons’ formula long known to one of skill in the art, but it was also long known that Simmons’ formula was an accepted method for calculating the tunnel barrier height of an MTJ, as evidenced by Bowen, Soukup, and others. *Supra* ¶195 of this Declaration. Indeed, as discussed above, Bowen taught using Simmons’ formula to calculate barrier height. EX1026 (Bowen) at page 1656.

199. A skilled artisan would have additionally looked to apply Bowen’s teachings about Simmons’ formula to Parkin’s MTJ because both Bowen and Parkin sought to improve the TMR of magnetoresistive devices, a problem the ’138 Patent claimed to address. EX1011 (’138 Patent) at Abstract, cols. 1:32-2:29. Bowen

presented “experimental results showing large TMR values in Fe(001)/MgO(001)/FeCo(001) epitaxial tunnel junctions.” EX1026 (Bowen) at Abstract, page 1655. Parkin stated: “[T]his invention relates to an improved MTJ exhibiting high tunneling magnetoresistance....” EX1062 (Parkin) at col. 1:18-21. Wang also sought to improve TMR and explained its benefits: “A high TMR value is desirable because it leads to greater signal level, lower power consumption, higher speed, and larger design margin for devices such as MRAM, read heads, and a variety of magnetic field sensors.” EX1055 (Wang) at page 2269; *id.* at page 2271 (discussing the benefits of “high TMR”).

200. Like the '138 Patent, Bowen and Parkin also both discussed improving MRAM memory performance. EX1011 ('138 Patent) at cols. 1:32-35, 2:35-39 (“[T]he characteristics of the MTJ device, which is the heart of MRAM, needs to be improved if higher levels of integration are to be achieved”), 2:57-60 (“It is an object of the invention to increase the output voltage of a MTJ device. It is another object of the invention to provide a memory device with a high magnetoresistance for stable operation.”). For example, Bowen stated: “The magnetoresistance of magnetic tunnel junctions (MTJs) is of uncontested interest for important applications with, in particular, promising perspectives for the fabrication of nonvolatile memories (Magnetic RAM).” EX1026 (Bowen) at page 1655. Similarly, Parkin explained that “for non-volatile magnetic memory storage cells, high TMR values are needed

for improving the performance of these devices.” EX1062 (Parkin) at cols. 2:65-3:1. Additionally, both Bowen and Parkin used MgO barriers and ferromagnetic alloy electrodes. EX1026 (Bowen) at Abstract, page 1655; EX1062 (Parkin) at Abstract, cols. 1:18-21 (“[T]his invention relates to an improved MTJ... with one or more electrodes formed from amorphous ferromagnetic materials.”), 17:21-35 (discussing manufacture of “MgO tunnel barrier 120”).

201. Given the known relationship between barrier height and TMR as I explained for Claim 4 in Ground 1, one of skill would have considered it both useful and desirable to quantify and otherwise evaluate the performance of an MTJ using barrier height. *Supra* Section XII.D of this Declaration. It also would have been straightforward and routine to use Simmons’ formula to calculate the barrier height given that Simmons’ formula was well known and understood to be used for that purpose.

3. **Claim 5[b]: “where J is a tunnel current density flowing through the barrier layer, V is an applied bias voltage that is 100 mV or smaller, m is the free electron mass, e is the elementary electric charge, h is Planck's constant,  $\Delta s$  is an effective thickness of the barrier layer that is equivalent to  $(t_{\text{MgO}} - 0.5 \text{ nm})$ , and  $t_{\text{MgO}}$  is an actual thickness of the barrier layer.”**

202. Claim 5[b] was disclosed or suggested by Soukup and Bowen. As I explained above in Section XIII.A.2 of this Declaration, Claim 5[a] recites Simmons’ formula for calculating the tunnel barrier height. Claim 5[b] simply

identifies certain variables, and certain values for some of those variables, for use in Simmons' formula. EX1011 ('138 Patent) at col. 10:18-24. One of skill would have found these variables, and the recited values, obvious.

203. Calculating the tunnel barrier height using Simmons' formula, as set forth in Claim 5[a] with the variables and values identified in Claim 5[b], would have been routine and obvious to a skilled artisan. Simmons' well-known 1963 paper explained how to calculate the barrier height using the same formula. EX1031 (Simmons) at pages 1794-97. Further, as I explained above in Section XIII.A.2 of this Declaration, both Bowen and Soukup disclosed that Simmons' formula was used to approximate tunnel barrier height.

204. As set forth in the table below, the '138 Patent uses and describes the same variables from Simmons' 1963 publication.

| <b>Claim 5[b] limitations<br/>[EX1011 ('138 Patent) at<br/>col. 10:18-24]</b> | <b>Simmons' formula (1963)<br/>[EX1031 (Simmons) at page 1794]</b>                                                     |
|-------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------------------|
| "J is a tunnel current density"                                               | "J=tunnel current density"                                                                                             |
| "V is an applied bias voltage"                                                | "V=voltage across film"                                                                                                |
| "m is the free electron mass"                                                 | "m=mass of electron"                                                                                                   |
| "e is the elementary electric charge"                                         | "e=charge of electron"                                                                                                 |
| "h is Planck's constant"                                                      | "h=Planck's constant"                                                                                                  |
| " $\Delta s$ is an effective thickness of the barrier layer"                  | " $\Delta s = s_2 - s_1$ ," where "s=thickness of insulating film" and " $s_1, s_2$ =limits of barrier at Fermi level" |

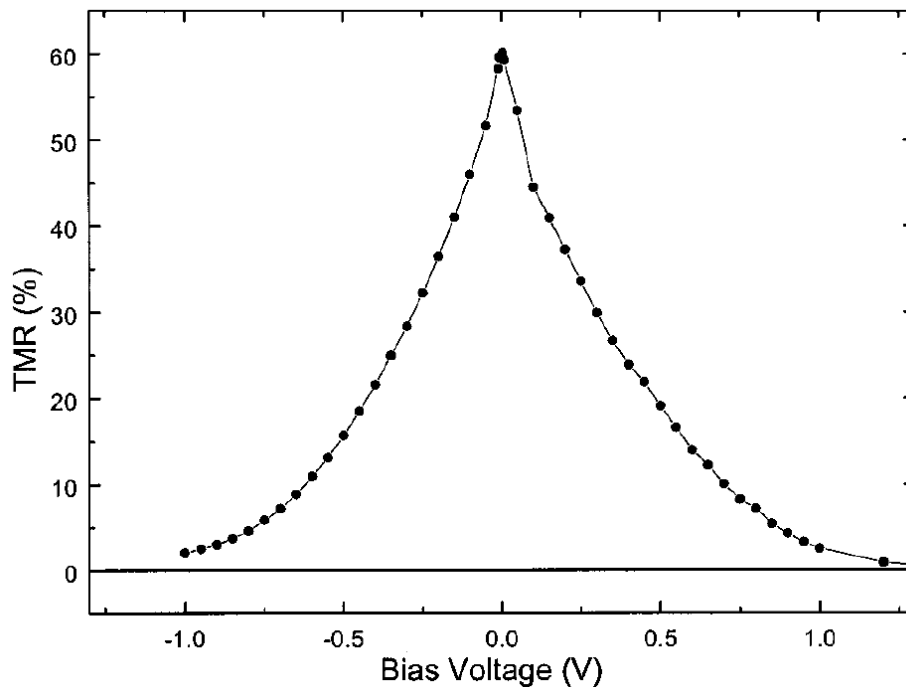
Compare EX1011 ('138 Patent) at col. 10:18-24, with EX1031 (Simmons) at page 1794 (defining variables).

205. Each of the requirements of Claim 5[b] would have been obvious to one of skill.

206. First, the requirement that “J is a tunnel current density flowing through the barrier layer” was obvious. EX1011 ('138 Patent) at col. 10:18-19. As set forth in the table in Paragraph 204, the '138 Patent is merely restating a well-known variable in Simmons' formula, that is, “J=tunnel current density.” EX1031 (Simmons) at page 1794. According to Simmons, “[t]he purpose of this paper is to derive a single theory for the *current flow through a generalized barrier.*” EX1031 (Simmons) at page 1794 (emphasis added).

207. Second, the requirement that “V is an applied bias voltage that is 100 mV or smaller” was also well known. EX1011 ('138 Patent) at col. 10:19-20. It was obvious to apply a low voltage of less than or equal to 100 mV. As I explained above for Claim 5[a] in Section XIII.A.2 of this Declaration, Bowen measured the barrier height “at 10 mV,” satisfying Claim 5[b]. EX1026 (Bowen) at page 1656. Bowen applied various bias voltages to its MTJ, finding the highest TMR “value of 60% at 10 mV.” EX1026 (Bowen) at page 1657. As shown in Figure 3 below, Bowen's applied voltages spanned between about -1 V to 1 V, including spanning 0 to 100 mV. Bowen paid special attention to the 0 to 100 mV range and found the

peak TMR in that range. As Bowen explained, the “TMR decreases almost symmetrically from a value of 60% at 10 mV to nearly 0 around 1.4 V.” EX1026 (Bowen) at page 1657.



EX1026 (Bowen) at Fig. 3.

208. One of skill would have understood that the requirement of an “applied bias voltage that is 100 mV or smaller” was encompassed by Simmons’ equation (25) for the “Low-Voltage Range:  $V \approx 0$ .” EX1031 (Simmons) at page 1797. As I explained above for Claim 5[a] in Section XIII.A.2 of this Declaration, “100 mV or smaller” is a low voltage, and a skilled artisan would have understood Simmons’ “Low-Voltage Range” equation was applicable to cases where the applied bias voltage was “100 mV or smaller.”

209. Claim 5[b]'s requirement that " $\Delta s$  is an effective thickness of the barrier layer that is equivalent to  $(t_{\text{MgO}} - 0.5 \text{ nm})$ " was obvious as well. EX1011 ('138 Patent) at col. 10:21-23. As set forth in the table in Paragraph 204, the Claim 5[b] recitation of  $\Delta s$  is equivalent to  $\Delta s$  in Simmons' formula. Simmons explained that  $\Delta s = s_2 - s_1$ , where " $s$ =thickness of insulating film" and " $s_1, s_2$ =limits of barrier at Fermi level." EX1031 (Simmons) at page 1794. Simmons'  $\Delta s$  variable thus refers to an "effective thickness" of the barrier layer. For example, the '138 Patent explained that the "effective thickness  $\Delta s$  of the tunnel barrier was determined to be smaller than the thickness of the actual MgO(001) tunnel barrier layer ( $t_{\text{MgO}}$ )" and that "[t]his is the result of the effective thickness  $\Delta s$  of the tunnel barrier having been reduced from the actual MgO(001) layer thickness by the effect of the image potential produced at the interface between the MgO(001) layer and the alloy layer consisting mainly of Fe and Co." EX1011 ('138 Patent) at col. 7:42-51.

210. Bowen also rendered obvious a tunnel barrier layer having an effective thickness "that is equivalent to  $(t_{\text{MgO}} - 0.5 \text{ nm})$ ." EX1011 ('138 Patent) at col. 10:22-23. Claim 5[b] recites that " $t_{\text{MgO}}$  is an actual thickness of the barrier layer." EX1011 ('138 Patent) at col. 10:23-24. Thus, Claim 5[b] requires that the effective thickness of the tunnel barrier be equal to 0.5 nm less than its actual thickness. Bowen taught this. Bowen fabricated an Fe/MgO/FeCo MTJ with an MgO barrier of "20 Å" or 2 nm. EX1026 (Bowen) at Abstract, page 1656. Using Simmons'

equations, Bowen calculated “a barrier thickness  $d \sim 15 \text{ \AA}$ ,” or 1.5 nm, for its Fe/MgO/FeCo MTJ. EX1026 (Bowen) at page 1656. Thus, Bowen taught an effective thickness (1.5 nm) that was 0.5 nm less than the actual thickness (2 nm). EX1026 (Bowen) at page 1656.

211. In sum, Claim 5[b] would have been obvious to one of skill as shown by Soukup and Bowen.

**B. Claim 6: Obviousness Over Parkin In View Of Wang, Soukup, And Bowen**

**1. Claim 6: “The MTJ device of claim 1, wherein a value of  $x$  in  $\text{MgO}_x$  for the MgO layer is greater than 0.9 and less than 1.”**

212. As I explained in Section XII.A of this Declaration, Claim 1 is obvious over Parkin in view of Wang and optionally Soukup. Claim 6 depends from Claim 1 and thus incorporates all of Claim 1’s requirements. Claim 6 is obvious over Parkin in view of Wang, Soukup, and Bowen as explained in the following paragraphs. As explained for Claim 5 in Section XIII.A of this Declaration, a skilled artisan would have found it obvious to look to Bowen in order to improve Parkin, Wang, and Soukup.

213. The claimed  $\text{MgO}_x$  oxygen vacancy defect range of “greater than 0.9 and less than 1” was inherent to Parkin’s and Soukup’s MgO barrier layers for the same reasons that I explained for Claim 1[e] in Section XII.A.6 of this Declaration. Indeed, as I explained above in Paragraphs 74-75 and 140 of this Declaration,

oxygen vacancy defects were understood to be inherent to  $\text{MgO}_x$  layers where  $0 < x < 1$ . One of skill would understand that the claimed range of  $0.9 < x < 1$  is a subrange of the oxygen vacancy defects inherent to Parkin's and Soukup's MgO barrier layers. Because  $0.9 < x < 1$  is a subrange of  $0 < x < 1$ , it necessarily overlaps with  $0 < x < 1$ .

214. Claim 6 is also obvious because the general conditions for fabricating an MTJ with the claimed MgO barrier layer oxygen vacancy range of  $0.9 < x < 1$  were already disclosed in the prior art. For example, Castanier studied oxygen vacancies for “non-stoichiometric  $\text{MgO}\{100\}$  surfaces, with several densities of neutral oxygen vacancies” studied. EX1037 (Castanier) at Abstract. They modeled oxygen vacancies down to a  $1/18$  density as shown in the image below, which would correspond to  $\text{MgO}_x$  with  $x$  approximately equal to 0.944, within the claimed range. EX1037 (Castanier) at page 3, Fig. 1. Others in the field at the time of the 2004 priority date would have been both motivated and able to obtain MgO barrier layer oxygen vacancy defects in this range through routine optimization.

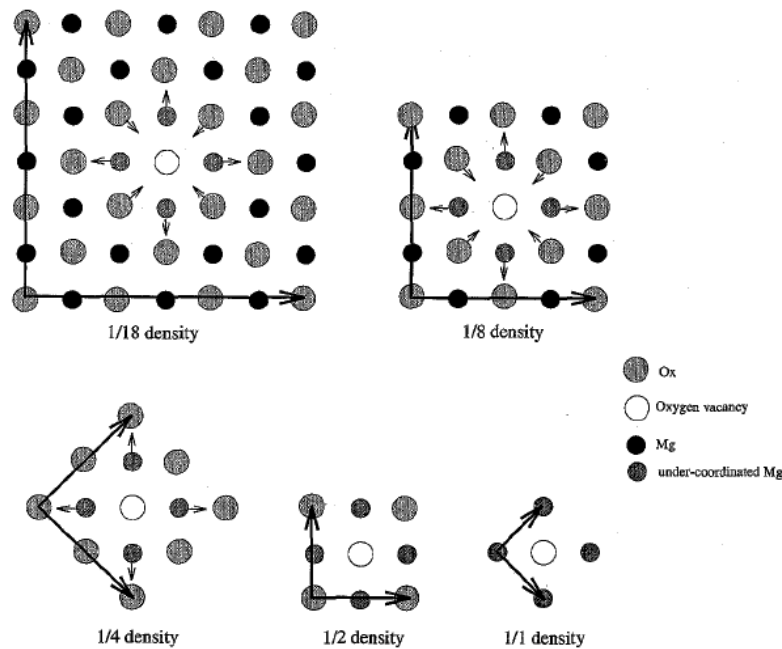


Fig. 1. Surface cells for sub-stoichiometric MgO{100} surfaces with various densities of oxygen vacancies. The magnesiums located close to a vacancy are specified and an arrow indicates their displacement in the surface plane.

EX1037 (Castanier) at Fig. 1.

215. The claimed invention of the '138 Patent is directed to an MTJ device that produced a high TMR. EX1011 ('138 Patent) at cols. 1:32-35, 2:57-60, 4:64-5:3 (setting forth the equation for determining the "magnetoresistance (MR) ratio of a MTJ device"). Others in the field at the time of the 2004 priority date of the '138 Patent were also interested in increasing the TMR. Increasing the TMR was an obvious improvement to MgO MTJs. As I explained in Sections VII.C, XII.A.6 (Ground 1, Claim 1[e]), and XII.D (Ground 1, Claim 4) of this Declaration, increasing TMR was a prerequisite to improving MRAM performance to obtain smaller, denser devices. As Parkin explained:

For applications of magnetic tunnel junctions for either magnetic recording heads or for non-volatile magnetic memory storage cells, high TMR values are needed for improving the performance of these devices....

...

What is needed is a method of forming MTJs with high tunneling magnetoresistance with improved magnetic switching characteristics.

EX1062 (Parkin) at cols. 2:65-3:1, 6:14-16; *see also* EX1055 (Wang) at pages 2269 (“A high TMR value is desirable because it leads to greater signal level, lower power consumption, higher speed, and larger design margin for devices such as MRAM, read heads, and a variety of magnetic field sensors.”), 2271.

216. In 2001, both Butler and another group led by Mathon each calculated very high TMRs for MgO MTJs due to symmetry matching between the MgO and Fe layers. EX1044 (Butler) at Fig. 16; EX1046 (Mathon) at Abstract, page 1 (optimistic TMR “in excess of 1000%” for an MgO barrier). The close match of the crystalline symmetry between MgO and Fe facilitated tunneling of parallel electrons compared to antiparallel electrons, opening the door to these very high TMRs. EX1044 (Butler) at page 1; EX1046 (Mathon) at page 1.

217. After Butler and Mathon announced their findings of four-figure TMRs for MgO MTJs, many researchers sought to experimentally validate their results. The '138 Patent itself acknowledged that existing MTJ devices with aluminum oxide

barriers had already achieved an “MR ratio of approximately 70%.” EX1011 (’138 Patent) at col. 5:19-25; *see also id.* at col. 2:50-52. Indeed, before the ’138 Patent in 2004, other researchers had observed TMRs exceeding 70% in MTJs with MgO barriers. EX1027 (Nagahama) ¶74 (disclosing “a larger tunnel magnetoresistive effect of more than 90%”); EX1052 (Faure-Vincent) at Abstract (reporting TMR of 100% in an Fe/MgO/Fe/Co tunnel junction).

218. Bowen cited research by Butler calculating a high TMR for MgO MTJs like Bowen’s. Bowen stated: “TMR values calculated by Butler *et al.* are much higher (2000% for 20 Å MgO) than our experimental value of 60%....” EX1026 (Bowen) at page 1657. Bowen reported a TMR of 60% for an MgO MTJ and expressed his intent to “aim to confirm the predicted relative increase of the TMR” in “future experiments.” EX1026 (Bowen) at page 1657. Thus, Bowen expressly provided a motivation for one of skill in the art to increase the TMR of an MgO MTJ. EX1026 (Bowen) at page 1657. As I also explain for Claims 1[e] and 4 in Sections XII.A.6 and XII.D of this Declaration, one of skill in the art would have found it obvious to do exactly that.

219. Others in the field before 2004 were already aware of the general MTJ conditions for fabricating MgO barrier layers that could result in the claimed  $\text{MgO}_x$  wherein  $0.9 < x < 1$ . For example, Parkin taught oxygen vacancy defects in forming its MgO barrier. EX1062 (Parkin) at col. 17:35-39; EX1092 (Parkin ’835) at

page 34; *supra* Section XII.A.6 (Ground 1, Claim 1[e]) of this Declaration. Soukup examined the “effect of nonstoichiometry on the device characteristics,” EX1028 (Soukup) at page 3232, and experimented with devices fabricated with different levels of nonstoichiometry, EX1028 (Soukup) at Abstract, pages 3232-33, Table I. Parkin’s, Bowen’s, and Soukup’s MgO barrier layer fabrication methodologies were consistent with the fabrication methods disclosed for the ’138 Patent’s two MTJ device embodiments.

220. The ’138 Patent’s first embodiment is identified as the “Fe(001)/MgO(001)/Fe(001) MTJ device.” EX1011 (’138 Patent) at col. 6:7-14. The disclosure explains that the fabrication schematics are illustrated in Figures 2(A) through 2(D). EX1011 (’138 Patent) at col. 6:10-14. The first step of the fabrication method includes growing an “MgO(001) seed layer 15” onto the “single-crystal MgO(001) substrate 11” using “molecular beam epitaxy (MBE).” EX1011 (’138 Patent) at col. 6:15-19, Fig. 2(A). Then the “epitaxial Fe(001) lower electrode (first electrode) 17” is grown on top of the “MgO(001) seed layer 15.” EX1011 (’138 Patent) at col. 6:19-22, Fig. 2(B). The “MgO(001) barrier layer 21” was then “epitaxially grown on the Fe(001) lower electrode (first electrode) at room temperature” using “the MgO electron-beam evaporation method.” EX1011 (’138 Patent) at col. 6:38-42, Fig. 2(C). Finally, the “Fe(001) upper electrode (a second electrode) 23” was then “formed on the MgO(001) barrier layer 21” followed by

deposition of the “Co layer 25” on top of the “Fe(001) upper electrode (second electrode) 23.” EX1011 (’138 Patent) at col. 6:45-50.

221. Focusing specifically on the fabrication of the MgO barrier layer of this first embodiment, the ’138 Patent discloses the following:

The source material of the electron-beam evaporation was MgO of the stoichiometric composition (the ratio of Mg to O being 1:1), the distance between the source and the substrate was 40 cm, the base vacuum pressure was  $1 \times 10^{-8}$  Pa, and the O<sub>2</sub> partial pressure was  $1 \times 10^{-6}$  Pa. Alternatively, a source with oxygen vacancy defects may be used instead of the MgO of the stoichiometric composition (the ratio of Mg to O is 1:1).

EX1011 (’138 Patent) at col. 6:27-34. One of skill would understand that “vacuum pressure” refers to pressure that is less than atmospheric pressure. It would also be understood that “O<sub>2</sub> partial pressure” refers to the pressure attributable to O<sub>2</sub> gas in the deposition chamber in relation to the total pressure attributable from all the gas in the deposition chamber. The ’138 Patent goes on to disclose that “MgO evaporation using an electron beam involved the formation of a film under ultrahigh vacuum of  $10^{-9}$  Torr.” EX1011 (’138 Patent) at col. 6:56-58. One of skill would understand that  $10^{-9}$  Torr converts to  $1.3 \times 10^{-7}$  Pa (1 Torr equals 133.3 Pascals).

222. The '138 Patent discloses that this first MTJ device embodiment produced a TMR value of 88% at room temperature, as illustrated in Figure 6. EX1011 ('138 Patent) at col. 8:4-8, Fig. 6.

223. Regarding oxygen vacancy defects in the MgO barrier layer of the first MTJ device embodiment, the '138 Patent discloses the following related to data provided in its Figure 5:

These results indicate the separation of oxygen from MgO during the deposition of MgO. Since the separated oxygen is pumped out of the deposition chamber using vacuum pumps, there is the possibility that there are oxygen vacancy defects such as  $\text{MgO}_x$  ( $0.9 < x < 1$ ).

EX1011 ('138 Patent) at col. 7:2-7. These purported results are consistent with the understanding at the time that MgO layers inherently had oxygen vacancy defects. Specifically, despite depositing the “MgO(001) barrier layer 21” using “stoichiometric MgO,” oxygen vacancy defects were still expected to exist in this layer.

224. The '138 Patent also discloses a second MTJ device embodiment, which is also referred to as an “Fe(001)/MgO(001)/Fe(001) MTJ device.” EX1011 ('138 Patent) at col. 8:43-47. There are no disclosures of any TMR values or quantification of any oxygen vacancy defects of the MgO barrier layer for this second embodiment. *See generally* EX1011 ('138 Patent). Additionally, the '138 Patent only provides fabrication details for the MgO layer, presumably the barrier

layer, disclosing that “MgO(001) is initially deposited in a poly-crystalline or amorphous state by sputtering or the like, and then an annealing process is performed such that a poly-crystal in which the (001) crystal plane is preferentially oriented or a single-crystal is obtained.” EX1011 (’138 Patent) at col. 8:47-51. The ’138 Patent goes on to explain that “sputtering was conducted in an Ar atmosphere” at “room temperature,” and the temperature was increased to “300° C” to “crystalize[]” the “amorphous” MgO. EX1011 (’138 Patent) at col. 8:51-60.

225. One of skill would appreciate that “Ar atmosphere” referred to argon gas, and that this disclosure implied that deposition occurred in the absence of oxygen. According to this disclosure, one of skill would also understand that the vacuum pressure is “on the order of no more than  $10^{-6}$  Pa” because “oxygen is not introduced.” EX1011 (’138 Patent) at col. 9:38-42. “[O]n the order of” is understood to mean an order of magnitude. For example, within an order of magnitude of  $10^{-6}$  Pa (also written as  $1 \times 10^{-6}$  Pa or 0.000001 Pa), would include a pressure of  $9 \times 10^{-6}$  Pa (also written as 0.000009 Pa). Likewise, the ’138 Patent discloses that the vacuum pressures “where oxygen is introduced” are on the “order of  $10^{-4}$  Pa” (also written  $1 \times 10^{-4}$  Pa or 0.0001 Pa), indicating that other pressure values within the ten-thousandths place or smaller, would be acceptable. EX1011 (’138 Patent) at col. 9:38-42.

226. Parkin's, Bowen's and Soukup's general fabrication methods were comparable to those disclosed in the '138 Patent. According to the '138 Patent's disclosure, "while the MgO layer has been described to be deposited by electron-beam evaporation or sputtering, it should be obvious that other deposition methods are also possible." EX1011 ('138 Patent) at col. 9:35-38. Indeed, the '138 Patent does not attribute or highlight anything about its disclosed fabrication methods that are inventive or unexpectedly lead to higher-than-expected performance.

227. Parkin described forming its "MgO tunnel barrier 120" as follows:

For the device of FIG. 3A, a Mg layer 6 Å thick was used, followed by an MgO layer 22 Å thick formed by reactive magnetron *sputtering* using an argon-oxygen plasma containing 3 atomic percent oxygen. During the deposition of the MgO layer, the Mg underlayer becomes oxidized so that the two layers form a single MgO tunnel barrier.

EX1062 (Parkin) at col. 17:21-37 (emphasis added). Parkin discussed forming its MgO barriers "using standard deposition techniques," which a skilled artisan would have understood to include sputtering. EX1062 (Parkin) at col. 8:21-27. Parkin '835, which was incorporated by reference into Parkin, further disclosed that "depending on the oxidation conditions and the thickness of the Mg layer 122," the "Mg layer 122 is exposed to oxygen and will become partially or completely oxidized." EX1092 (Parkin '835) at page 34; *see also* EX1062 (Parkin) at col. 3:24-26 (noting that Parkin '835 "is hereby incorporated by reference").

228. Bowen's MgO barrier layer was also fabricated using sputtering, which is the same methodology used to fabricate the '138 Patent's MTJ device of the second embodiment. Bowen describes fabricating its "FeCo/MgO/Fe epitaxial structures... in a combined sputtering/laser ablation system with a base pressure of  $2 \times 10^{-9}$  mbar," wherein the MgO layer is deposited at "400 °C." EX1026 (Bowen) at page 1655. One of skill would understand that  $2 \times 10^{-9}$  mbar converts to  $2 \times 10^{-7}$  Pa (1 mbar equals 100 Pa). One of skill would also understand that  $2 \times 10^{-7}$  is the same number as  $0.2 \times 10^{-6}$ . While Bowen does not disclose the gas composition used during deposition, the vacuum pressure is acceptable according to the '138 Patent's disclosure whether or not oxygen is present. EX1011 ('138 Patent) at col. 9:38-42 ("on the order of no more than  $10^{-6}$  Pa" when oxygen was not introduced and "on the order of  $10^{-4}$  Pa" when oxygen was introduced).

229. Soukup's fabrication method is the same method the '138 Patent discloses using for its first MTJ device embodiment. Soukup discloses fabricating the MgO barrier layer using an "evaporation source" at a vacuum pressure of " $10^{-8}$  Torr," wherein the substrates were heated to "400°C." EX1028 (Soukup) at page 3230.  $10^{-8}$  Torr converts to  $1.33 \times 10^{-6}$  Pa, which is also within the acceptable "ultrahigh" vacuum pressures the '138 Patent discloses, whether or not oxygen is present. EX1011 ('138 Patent) at col. 9:38-42. In particular, Soukup describes using an electron beam as indicated by his explanation that the "thickness of the films were

determined by precalibrating deposition rate vs electron beam power using a quartz crystal monitor.” EX1028 (Soukup) at page 3230.

230. As the disclosed general MgO barrier layer fabrication conditions were understood by others in the field by 2004, a skilled artisan would readily optimize oxygen vacancy defects through experimentation to determine the level of oxygen vacancy defects that produced the best result. And a skilled artisan would have known that the claimed  $0.9 < x < 1$  range, overlapping with  $0 < x < 1$ , was within the zone of potential oxygen vacancy defects to be considered. As I explained previously, both Bowen and Soukup indicated that oxygen vacancy defects in their respective MgO barrier layers likely impacted their calculated barrier heights. EX1026 (Bowen) at page 1656; EX1028 (Soukup) at Abstract, page 3232. Despite not quantifying these defects, as I explained for Claim 1[e] in Section XII.A.6, one of skill would understand that Parkin’s, Bowen’s, and Soukup’s MgO barrier layers inherently had oxygen vacancy defects in their  $\text{MgO}_x$  layers wherein  $0 < x < 1$ . Skilled artisans understood that reducing the height of the barrier layer would achieve higher TMR values. EX1044 (Butler) at page 1-9; EX1046 (Mathon) at page 1; EX1045 (Klaau) at page 1; EX1031 (Simmons) at page 1797; *supra* Section XII.D of this Declaration. One of skill would have been motivated to optimize MgO barrier layers during MTJ fabrication by optimizing oxygen vacancy defects through experimentation because it was understood that these defects impacted barrier height

and thus also affected TMR values. Oxygen vacancy defects in the MgO barrier layer had an understood relationship to TMR within the grasp of one of skill by the time of the '138 Patent's priority date.

231. In addition, the '138 Patent did not disclose that the oxygen vacancy defects in the claimed range of "greater than 0.9 and less than 1" had an unexpected or novel impact on its MTJ devices of the claimed invention. The '138 Patent explains that oxygen vacancy defects could be introduced using several methods and did not indicate any were particular or critical to the object of the invention:

Oxygen vacancy defects may be introduced by a method whereby oxygen vacancy defects is [sic] produced during growth, a method whereby oxygen vacancy defects is introduced subsequently, or a method whereby a state with oxygen vacancy defects is subjected to an oxygen plasma process or natural oxidation so as to achieve a certain oxygen deficit level.

EX1011 ('138 Patent) at col. 8:61-67.

232. Additional disclosure in the '138 Patent further supports the conclusion that the  $0.9 < x < 1$  claimed range is not critical. When referring to the purported oxygen vacancy defects measured for its first MTJ device embodiment, the patent appears to speculate:

Since the separated oxygen is pumped out of the deposition chamber using vacuum pumps, there is the *possibility* that there are oxygen vacancy defects *such as*  $\text{MgO}_x$  ( $0.9 < x < 1$ ). When there are oxygen

vacancy defects, the potential barrier height of the MgO tunnel barrier is thought to decrease (such as in the range of 0.10 to 0.85 eV; more specifically, 0.2 to 0.5 eV), which is thought to result in an increase in the tunneling current.

EX1011 ('138 Patent) at col. 7:4-11 (emphases added). One of skill would understand from this disclosure that this oxygen vacancy defect range was more of an estimate, not an accurate quantification.

233. Soukup's barrier height of 0.33 eV was within the range disclosed by the '138 Patent as indicative of "oxygen vacancy defects." EX1028 (Soukup) at Abstract; EX1011 ('138 Patent) at col. 7:7-11. One of skill would understand from the '138 Patent that Soukup's barrier height of 0.33 eV indicated that Soukup's MgO barrier layer had the preferred oxygen vacancy defect ranges disclosed by the '138 Patent, according to the '138 Patent's own teachings.

234. The '138 Patent's specification also explains that there are ways to impact barrier height other than introducing oxygen vacancy defects in the MgO barrier layer. Specifically, that "the height of the tunnel barrier may be adjusted by doping Ca or Sr, *instead* of introducing an [sic] oxygen vacancy defects to the MgO layer." EX1011 ('138 Patent) at col. 9:32-35 (emphasis added). By disclosing other approaches to manipulating the barrier height, one of skill would also understand that introducing MgO barrier layer oxygen vacancy defects was not the only way to achieve the object of the invention.

**C. Claim 11: Obviousness Over Parkin In View Of Wang, Soukup, And Bowen**

**1. Claim 11[preamble]: “The MTJ device of claim 10,”**

235. As I explained above in Section XII.H of this Declaration, Parkin in view of Wang and Soukup disclosed or suggested an MTJ device satisfying Claim 10. *See also supra* Section XII.A.1 (Claim 1[preamble]) of this Declaration.

**2. Claim 11[a]: “wherein the barrier height  $\phi$  of the MgO layer is obtained by fitting J-V characteristics of the MTJ device to an equation (1):  $J=[(2m\phi)^{1/2}/\Delta s](e/h)^2 \times \exp[-(4\pi\Delta s/h) \times (2m\phi)^{1/2}] \times V$  (1)”**

236. This claim limitation is disclosed or suggested for the same reasons explained above for Claim 5[a]. *Supra* Section XIII.A.2 of this Declaration.

**3. Claim 11[b]: “where J is a tunnel current density flowing through the MgO layer, V is an applied bias voltage that is 100 mV or smaller, m is the free electron mass, e is the elementary electric charge, h is Planck's constant,  $\Delta s$  is an effective thickness of the MgO layer that is equivalent to  $(t_{\text{MgO}} - 0.5 \text{ nm})$ , and  $t_{\text{MgO}}$  is an actual thickness of the MgO layer.”**

237. This claim limitation is disclosed or suggested for the same reasons explained above for Claim 5[b]. *Supra* Section XIII.A.3 of this Declaration.

**D. Claim 14: Obviousness Over Parkin In View Of Wang, Soukup, And Bowen**

**1. Claim 14[preamble]: “The MTJ device of claim 13,”**

238. As I explained above in Section XII.J of this Declaration, Parkin in view of Wang and Soukup disclosed or suggested an MTJ device satisfying Claim 13. *See also supra* Section XII.A.1 (Claim 1[preamble]) of this Declaration.

**2. Claim 14[a]: “wherein the barrier height  $\phi$  of the barrier layer is obtained by fitting J-V characteristics of the MTJ device to an equation (1):  $J=[(2m\phi)^{1/2}/\Delta s](e/h)^2 \times \exp[-(4\pi\Delta s/h) \times (2m\phi)^{1/2}] \times V$  (1)”**

239. This claim limitation is disclosed or suggested for the same reasons explained above for Claim 5[a]. *Supra* Section XIII.A.2 of this Declaration.

**3. Claim 14[b]: “where J is a tunnel current density flowing through the barrier layer, V is an applied bias voltage that is 100 mV or smaller, m is the free electron mass, e is the elementary electric charge, h is Planck's constant,  $\Delta s$  is an effective thickness of the barrier layer that is equivalent to ( $t_{\text{MgO}} - 0.5$  nm), and two [sic] is an actual thickness of the barrier layer.”**

240. This claim limitation is disclosed or suggested for the same reasons explained above for Claim 5[b]. *Supra* Section XIII.A.3 of this Declaration.

241. I understand that the applicant indicated during prosecution that “ $t_{\text{MgO}}$ ,”—not “two” as recited in Claim 14[b]—represented “an actual thickness of the barrier layer” in “ $J=[(2m\phi)^{1/2}/\Delta s](e/h)^2 \times \exp[-(4\pi\Delta s/h) \times (2m\phi)^{1/2}] \times V$ .” EX1012 (’138 Patent File History) at pages 356-57, 360.

**XIV. GROUND 3: CLAIMS 1-14 ARE OBVIOUS OVER BOWEN IN VIEW OF WANG AND SOUKUP**

242. In my opinion, Claims 1-14 are obvious over Bowen in view of Wang and Soukup. Soukup is optional in the combinations for Claims 1-3, 7-9, and 12.

**A. Claim 1: Obviousness Over Bowen In View Of Wang And Optionally Soukup**

**1. Claim 1[preamble]: “A magnetic tunnel junction (MTJ) device, comprising:”**

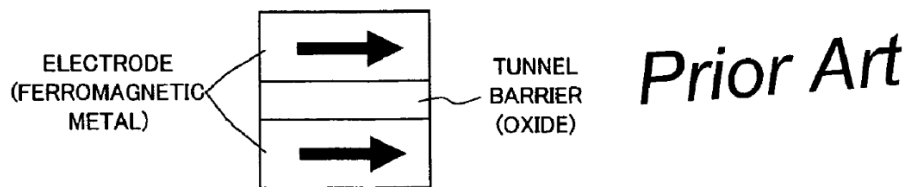
243. I am informed and understand that claim preambles may or may not limit the claim. I have been asked to assume the preambles of the '138 Patent claims are limiting for purposes of this analysis. Assuming that the preamble of Claim 1 is limiting, it is disclosed or suggested by Bowen.

244. Bowen disclosed or suggested a magnetic tunnel junction (MTJ) device. Bowen taught an MTJ with a tunnel barrier layer and two ferromagnetic material layers, as I explain for limitations 1[a] through 1[e]. *See* Sections XIV.A.2-XIV.A.6 of this Declaration.

245. Bowen explained that: “The magnetoresistance of magnetic tunnel junctions (MTJs) is of uncontested interest for important applications with, in particular, promising perspectives for the fabrication on nonvolatile memories (Magnetic RAM).” EX1026 (Bowen) at page 1655; *id.* at Abstract, page 1655 (discussing FeCo/MgO/Fe epitaxial structure), Fig. 1.

246. In addition, MTJs were well known in the art. This is evident from the '138 Patent itself. EX1011 ('138 Patent) at Figs. 8(A)-8(B), cols. 1:44-2:2. For example, Figure 8(A) of the '138 Patent below shows an “MTJ device compris[ing] a tunnelling junction structure in which a tunnel barrier... made of an oxide is sandwiched between a first and a second electrode made of a ferromagnetic metal.” EX1011 ('138 Patent) at col. 1:47-51. The patent correctly identifies and labels this conventional MTJ design as “Prior Art”:

FIG. 8 (A)



EX1011 ('138 Patent) at Fig. 8(A) (“Prior Art” legend in original).

**2. Claim 1[a]: “a first electrode comprising a first ferromagnetic material layer that includes Co, Fe, and B;”**

247. This claim limitation is disclosed or suggested by Bowen in view of Wang.

248. The '138 Patent teaches that the “ferromagnetic material layer” is a layer made of a “ferromagnetic metal.” EX1011 ('138 Patent) at col. 1:47-51, Fig. 8(A).

249. As specified in Claim 1[b] below, “first” indicates the “lower” ferromagnetic layer or ferromagnetic material layer beneath the barrier layer. EX1011 (’138 Patent) at col. 9:59-62.

250. Bowen’s first ferromagnetic material layer consists of an “Fe” layer. EX1026 (Bowen) at pages 1655 (describing an MTJ comprised of a “Fe bottom electrode”), 1656 (“Fe(200 Å)/MgO(20 Å)/FeCo(250 Å) trilayer”). Iron (Fe) is a ferromagnetic material. EX1030 (Sunai) ¶33 (“[F]erromagnetic materials” include “Fe, Co, Ni, and alloys containing them.”); EX1057 (Dieny textbook) at page 3 (“The ferromagnetic transition metals, such as Fe, Co, Ni, and their alloys... are the key compounds in today’s spintronic devices....”); *id.* at page 2 (Fe and Co are “magnetic materials.”); EX1011 (’138 Patent) at col. 6:14-15 (“Fe(001) refers to a ferromagnetic material....”).

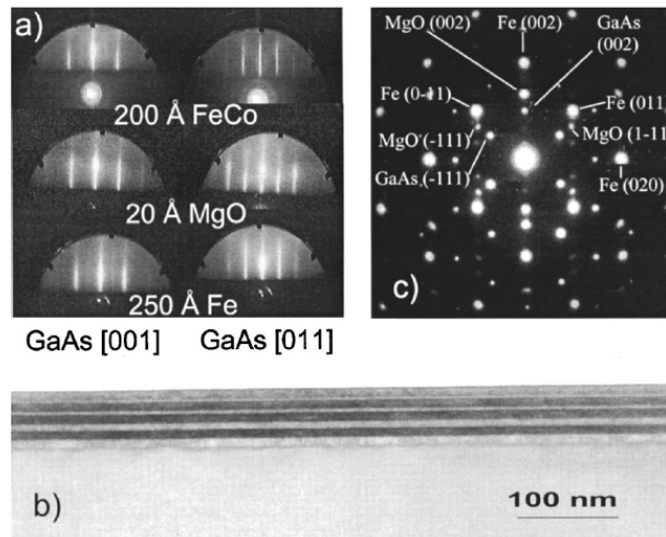


FIG. 1. (a) RHEED patterns along the GaAs [100] and [110] substrate azimuths of a typical FeCo/MgO/Fe epitaxial structure; (b) cross section TEM image of a Fe/MgO(001) multilayer with gradually decreasing MgO layer thickness; (c) TEM electron diffraction pattern.

EX1026 (Bowen) at Fig. 1 (annotated).

251. MTJs containing metallic ferromagnetic material layers were conventional by 2004, as the '138 Patent acknowledges. EX1011 ('138 Patent) at col. 1:47-51 (Description of Related Art: “As shown in FIG. 8(A), a MTJ device comprises a tunnelling junction structure in which a tunnel barrier (to be hereafter also referred to as a ‘barrier layer’) made of an oxide is sandwiched between a first and a second electrode made of a ferromagnetic metal.”); *id.* at Figs. 8(A)-8(B) (labeled “Prior Art”); EX1045 (Klaau) at page 1 (discussing “the extensive study of the growth of MgO on Fe(001) and of Fe/MgO/Fe(001) trilayers”).

252. Claim 1[a] does not specify the specific molecular composition or stoichiometry of the claimed “ferromagnetic material layer that includes Co, Fe,

and B,” or CoFeB ferromagnetic material layer. EX1011 (’138 Patent) at col. 9:57-58. Thus, I was asked to assume that any CoFeB alloy satisfies Claim 1[a]. One of skill would have understood that alloys including Co, Fe, and B are referred to in the art as CoFeB or sometimes FeCoB. *E.g.*, EX1057 (Dieny) at page 45 (“many other bcc ferromagnetic metals and alloys that are based on Fe and Co (e.g., bcc Fe-Co, bcc CoFeB....)”). Further, a skilled artisan would have understood that CoFeB and FeCoB refer to the same alloy.

253. It would have been obvious to replace Bowen’s lower Fe electrode with a CoFeB ferromagnetic layer, as taught by Wang, including to improve TMR. EX1055 (Wang) at page 2270 (teaching to “replace both the free and pinned layers to CoFeB to further increase the TMR value”). Iron (Fe) and cobalt (Co) were known ferromagnetic materials, and CoFeB was a known ferromagnetic alloy based on Fe and Co. EX1030 (Sunai) ¶33 (“[F]erromagnetic materials” include “Fe, Co, Ni, and alloys containing them.”); EX1057 (Dieny textbook) at pages 2-3, 18 (“ferromagnetic metals, such as cobalt (Co) and alloys based on Fe and Co”); EX1026 (Bowen) at page 1655.

254. To improve Bowen’s MTJ, one of skill would have looked to Wang’s teachings. Bowen and Wang both sought to improve the TMR of magnetoresistive devices, one of the problems the ’138 Patent claimed to address. EX1026 (Bowen) at Abstract, page 1655; EX1055 (Wang) at pages 2269-71 (discussing benefits of

“high TMR”); EX1011 (’138 Patent) at Abstract, cols. 1:32-2:29. Like the ’138 Patent, Bowen and Wang also both discussed improving MRAM memory performance. EX1026 (Bowen) at page 1655; EX1055 (Wang) at page 2269 (“A high TMR value is desirable because it leads to greater signal level, lower power consumption, higher speed, and larger design margin for devices such as MRAM....”); EX1011 (’138 Patent) at col. 2:57-60. Further, they both used ferromagnetic alloy electrodes. EX1026 (Bowen) at Abstract, page 1655; EX1055 (Wang) at pages 2270 (discussing using “CoFeB” for “both the free and pinned layers”), 2271 (“two ferromagnetic interfaces with the tunnel barrier”).

255. Wang touted CoFeB’s many benefits: “The benefit of using CoFeB is multifold: a higher TMR value, a lower coercivity ( $H_c$ ), and a lower coupling field ( $H_{\text{coupl}}$ ) for the free layer, which are all desirable for sensor applications.” EX1055 (Wang) at pages 2269-70. After studying the effect of using CoFeB for its ferromagnetic layers in an MTJ using a  $\text{Al}_2\text{O}_3$  tunnel barrier, Wang reported high TMR values for its MTJs, explaining that “[t]he combination of a high TMR, a low  $H_c$ , and a low  $H_{\text{coupl}}$  is ideal for magnetic field sensor applications.” EX1055 (Wang) at Abstract, page 2269. According to Wang, “[b]y changing the free layer from NiFeCo to CoFeB, we have increased the TMR value from 42.7% to 60.8%....” EX1055 (Wang) at page 2269. A skilled artisan would have understood from Wang that changing both the free and pinned layers to CoFeB would result in even higher

TMRs. Indeed, Wang noted that “[w]ith such a large increase of TMR value by changing the free layer from NiFeCo to CoFeB, it is natural to replace both the free and pinned layers to CoFeB to further increase the TMR value.” EX1055 (Wang) at page 2270.

256. Others also observed that CoFeB was a superior material compared to Fe or CoFe electrodes. For example, Sunai taught that CoFeB electrodes improved the TMR of an MTJ compared to CoFe. EX1030 (Sunai) ¶¶24-25, 27-28 (discussing improved TMR resulting from adding B to CoFe); *see also* EX1061 (Cardoso) at Abstract (“CoFe-based junctions ( $R \times A \sim 500 \Omega \cdot \mu m^2$ ) have lower TMR ( $\sim 35\%$ ) and larger  $H_f$  ( $\sim 5-6$  Oe) and  $H_c$  ( $\sim 12-14$  Oe) [compared to CoFeB-based junctions].”). Hosomi taught that when an MTJ “ferromagnetic layer” is “comprised of a CoFeB alloy,” it “exhibits a larger TMR ratio.” EX1056 (Hosomi) ¶39; *id.* ¶¶78 (discussing “improvement of the TMR ratio” by “adding B” to Fe-Co), 103-04 (explaining that “[c]urves 61 and 62 in FIG. 7 show TMR ratios (%) against the change of the external magnetic field with respect to, respectively, a TMR element having an information recording layer comprised of  $Co_{72}Fe_8B_{20}$ ”), Fig. 7. Hosomi found “remarkabl[e] increases in the TMR ratio” for certain CoFeB alloys. EX1056 (Hosomi) ¶76. Further, Parkin observed “very high TMR values are unexpectedly found for MTJs with highly textured (100) MgO tunnel barriers but with nominally amorphous [CoFeB] storage layers.” EX1062 (Parkin) at cols. 18:49-62, 19:17-19.

257. Bowen aimed to increase the TMR in its MgO MTJ, EX1026 (Bowen) at pages 1655, 1657, and understood that the properties of the MTJ's electrodes contributed to improving the tunneling and hence TMR of its device:

As corroborating evidence, Butler *et al.* point out in recently published first principles conductance calculations for Fe(100)/MgO(100)/Fe(100) trilayers that, despite a strongly negative spin polarization on the interfacial Fe layer, the spin polarization of tunneling electrons should be positive due to wave function *symmetry matching in the Fe electrodes and in the MgO barrier*.

EX1026 (Bowen) at page 1657 (emphasis added). Because TMR was so important to optimizing MTJ design for commercial applications like MRAM, as I explained in detail in Section VII.C of this Declaration, Wang's and other researchers' teachings about CoFeB would have provided a strong motivation to modify Bowen's MTJ to include a CoFeB electrode to increase the TMR.

258. One of skill would have been motivated to replace Bowen's MTJ electrodes with CoFeB electrodes. Changing up the ferromagnetic materials of the electrodes had long been an area of research to find improvements in TMR. Almost a decade before the '138 Patent, a 1995 paper by Moodera taught trying different Co, Fe, and CoFe alloys for the top and bottom electrodes and obtained better results with CoFe than Fe:

Co, Fe, and NiFe and CoFe alloys were tried in this study as both bottom and top electrodes. The best results were obtained with a CoFe bottom electrode and a Co or NiFe top electrode. With Fe films as one of the electrodes, for the thickness range of Al used, the junctions were too low in resistance.

EX1035 (Moodera 1995) at page 3274. Others in the literature had already suggested using CoFeB in both the top and bottom electrodes. As I mentioned, Wang found that “[w]ith such a large increase of TMR value by changing the free layer... to CoFeB, it is natural to replace both the free and pinned layers to CoFeB to further increase the TMR value.” EX1055 (Wang) at page 2270. Similarly, Hosomi explained that “both the ferromagnetic layers 5, 7 are made of an FeCoB” to achieve “improvement of the TMR ratio.” EX1056 (Hosomi) ¶¶67-68. Experimenting with different ferromagnetic layers including CoFeB to improve TMR and tunneling was widely known, desirable, and an obvious modification that would have had a reasonable expectation of success as demonstrated by Wang and others.

**3. Claim 1[b]: “a barrier layer disposed over the first electrode, the barrier layer comprising a magnesium oxide (MgO) layer that is formed of a poly-crystalline MgO in which a (001) crystal plane is preferentially oriented; and”**

259. This claim limitation is disclosed or suggested by Bowen. Bowen taught that its barrier layer was MgO(001). Bowen explained: “We present

tunneling experiments on Fe(001)/MgO (20 Å)/FeCo(001) single-crystal epitaxial junctions of high quality grown by sputtering and laser ablation.” EX1026 (Bowen) at Abstract. Bowen’s “MgO barrier is grown at 400 °C in order to obtain good crystallinity.” EX1026 (Bowen) at page 1655, Fig. 1. His reference to “MgO(001)” refers to the (001) crystalline plane. EX1026 (Bowen) at page 1655 (“In this letter, we present experimental results showing large TMR values in Fe(001)/**MgO(001)**/FeCo(001) epitaxial tunnel junctions.” (emphasis added)).

260. Bowen taught that its MgO barrier layer was disposed over, or on top of, its Fe layer. Bowen explained that its MTJ was an “Fe(001)/MgO (20 Å)/FeCo(001) single-crystal epitaxial junction[.]” EX1026 (Bowen) at Abstract; *id.* at page 1656 (describing “Fe(200 Å)/MgO(20 Å)/FeCo(250 Å) trilayer”). Bowen further described its Fe layer as an “Fe bottom electrode.” EX1026 (Bowen) at page 1655, Abstract, Fig. 1. Thus, Bowen’s MgO barrier layer was disposed over its Fe bottom layer as shown in Figure 1 below.

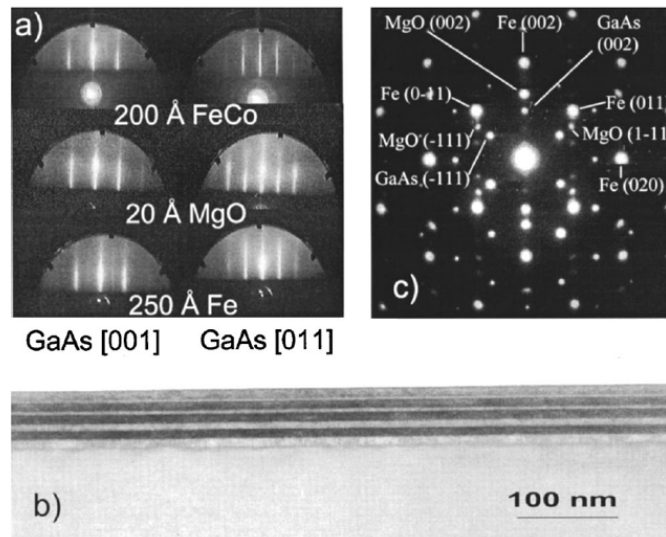


FIG. 1. (a) RHEED patterns along the GaAs [100] and [110] substrate azimuths of a typical FeCo/MgO/Fe epitaxial structure; (b) cross section TEM image of a Fe/MgO(001) multilayer with gradually decreasing MgO layer thickness; (c) TEM electron diffraction pattern.

EX1026 (Bowen) at Fig. 1 (annotated).

261. MTJs containing barrier layers, including barrier layers disposed over an electrode or ferromagnetic layer, were conventional by 2004, as the '138 Patent acknowledges. EX1011 ('138 Patent) at col. 1:47-51 (Description of Related Art: “As shown in FIG. 8(A), a MTJ device comprises a tunnelling junction structure in which a tunnel barrier (to be hereafter also referred to as a ‘barrier layer’) made of an oxide is sandwiched between a first and a second electrode made of a ferromagnetic metal.”); *id.* at Figs. 8(A)-8(B) (labeled “Prior Art”).

262. One of skill would have found it obvious to substitute Bowen’s single-crystal MgO(001) barrier with a polycrystalline MgO barrier with the (001) crystal plane preferentially oriented. Bowen itself discussed Moodera’s 1996 study,

acknowledging that Moodera reported the same 0.9 eV barrier height obtained by Bowen but for a “polycrystalline MgO.” EX1026 (Bowen) at page 1656 (citing EX1038); EX1038 (Moodera 1996) at pages 4725-26 (For “studies done with MgO barriers, values of  $\phi \cong 0.9$  eV... were obtained.”); EX1047 (Wulfhekel) at pages 509 & 511 nn. 5-7 (recognizing that Moodera 1996 and other “[s]tudies using polycrystalline MgO indicated a low tunneling barrier of  $\approx 0.9$  eV”). Moodera’s 1996 study taught depositing the base electrode and MgO layer on “[g]lass substrates cooled to 77K” and “then warmed to room temperature and subjected to oxygen glow discharge to create an insulating layer of Al<sub>2</sub>O<sub>3</sub> or MgO.” EX1038 (Moodera 1996) at page 4725. One of skill would understand that Moodera’s technique would *not* result in a single-crystalline MgO barrier layer, *see id.*, and Bowen explained that Moodera’s MgO barrier was polycrystalline, EX1026 (Bowen) at page 1656 (citing EX1038). A skilled artisan would have understood that using a polycrystalline MgO barrier in place of a single-crystal MgO barrier was routine, predictable, and would yield the same desirable results. EX1026 (Bowen) at page 1656.

263. Polycrystalline MgO barrier layers were well known. Bowen himself noted Moodera’s 1996 study used a “polycrystalline MgO” barrier to achieve a 0.9 eV barrier height. EX1026 (Bowen) at page 1656 (citing EX1038); EX1038 (Moodera 1996) at pages 4725-26. Further, one of skill would have known

polycrystalline MgO was an available and useful barrier layer, capable of achieving low barrier heights and thus high TMRs. EX1026 (Bowen) at page 1656; EX1047 (Wulfhekel) at page 509 (explaining that “[s]tudies using polycrystalline MgO indicated a low tunneling barrier of  $\approx 0.9$  eV”). One of skill would have been motivated to use polycrystalline MgO with a reasonable expectation of success. EX1026 (Bowen) at page 1656 (citing EX1038); EX1038 (Moodera 1996) at pages 4725-26.

264. Polycrystalline MgO provided its own advantages. It was easily formed on a variety of substrates and other materials, including ones that were not single-crystalline. EX1062 (Parkin) at col. 9:58-60 (describing the “polycrystalline nature of the film structures” as “preferable for ease of manufacturing”). For example, Wulff studied MgO deposition on both crystalline substrates as well as on amorphous float glass, reporting that “[a]part from epitaxy, MgO grows with strong preferential  $\langle 100 \rangle$  orientation regardless of the substrate selection.” EX1036 (Wulff) at page 148. Yoon also studied the deposition of polycrystalline highly (100)-oriented MgO crystalline thin films on Si, GaAs, and fused quartz substrates, reporting: “The growth behaviors of MgO films on GaAs and fused quartz substrates were further investigated. All the films show highly (100)-textured structure regardless of the substrate materials, as shown in Fig. 1(b).” EX1040 (Yoon) at page

2840. As I explained above in Section VII.E.1 of this Declaration, the (100) and (001) planes for an MgO crystal are the same.

265. Because polycrystalline MgO was a known and available material for the barrier layer and provided its own advantages, one of skill would have found it obvious to form a barrier layer with polycrystalline MgO having the (001) crystal plane preferentially oriented, in place of Bowen's single-crystal MgO barrier, to realize its benefits.

266. In addition, if CoFeB ferromagnetic material layers are used as I explain for Claims 1[a] and 1[c] in Sections XIV.A.2 and XIV.A.4 of this Declaration, a skilled artisan would have understood that Bowen's MgO(001) barrier could be either polycrystalline or single-crystal but would still have the same (001) orientation. EX1026 (Bowen) at page 1655; EX1062 (Parkin) at cols. 9:58-10:2 (describing use of polycrystalline or single-crystal MgO), 18:49-51 ("highly textured (100) MgO tunnel barriers"); EX1011 ('138 Patent) at col. 4:39-41 ("[B]ecause MgO has a cubic crystal structure (NaCl structure), the (001) plane, the (100) plane, and the (010) plane are all equivalent.").

**4. Claim 1[c]: "a second electrode disposed over the barrier layer and comprising a second ferromagnetic material layer that includes Co, Fe, and B, and"**

267. Bowen in view of Wang disclosed or suggested Claim 1[c].

268. As explained for Claim 1[a], the '138 Patent teaches that the “ferromagnetic material layer” is a layer made of a “ferromagnetic metal.” EX1011 ('138 Patent) at col. 1:47-51, Fig. 8(A).

269. As specified in Claim 1[c], “second” indicates the “upper” ferromagnetic layer or ferromagnetic material layer above the barrier layer. EX1011 ('138 Patent) at col. 9:63-65.

270. Bowen disclosed a second, upper FeCo ferromagnetic layer that met this claim limitation. EX1026 (Bowen) at page 1655. Bowen acknowledges that MTJs use “ferromagnetic electrodes.” EX1026 (Bowen) at page 1655. He says: “FeCo/MgO/Fe epitaxial structures were grown on GaAs(001) in a combined sputtering/laser ablation system....” EX1026 (Bowen) at page 1655; *id.* at Abstract, page 1656, Fig. 1. Bowen further described its FeCo layer as an “FeCo top electrode” in its “trilayer” structure. EX1026 (Bowen) at pages 1655-56, Fig. 1. Thus, Bowen’s FeCo layer was disposed over, or on top of, its MgO barrier layer as shown in Figure 1 below.

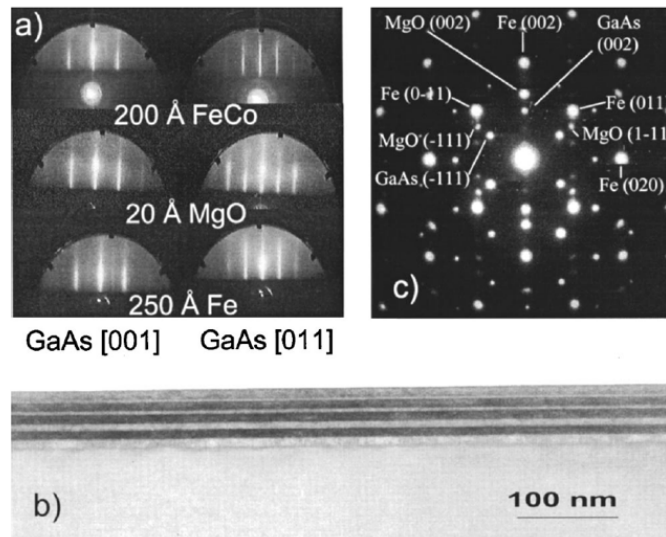


FIG. 1. (a) RHEED patterns along the GaAs [100] and [110] substrate azimuths of a typical FeCo/MgO/Fe epitaxial structure; (b) cross section TEM image of a Fe/MgO(001) multilayer with gradually decreasing MgO layer thickness; (c) TEM electron diffraction pattern.

EX1026 (Bowen) at Fig. 1 (annotated).

271. Iron cobalt (FeCo) was a well-known ferromagnetic material. EX1030 (Sunai) ¶33 (“[F]erromagnetic materials” include “Fe, Co, Ni, and alloys containing them.”); EX1057 (Dieny textbook) at page 3 (“The ferromagnetic transition metals, such as Fe, Co, Ni, and their alloys... are the key compounds in today’s spintronic devices....”); *id.* at page 2 (Fe and Co are “magnetic materials.”).

272. As I explained above for Claim 1[a] in Section XIV.A.2 of this Declaration, MTJs containing metallic ferromagnetic material layers were conventional by 2004, as the ’138 Patent acknowledges. EX1011 (’138 Patent) at col. 1:47-51, Figs. 8(A)-8(B).

273. One of skill would have been motivated to replace Bowen's upper FeCo ferromagnetic layer with a CoFeB layer, as taught by Wang, for the same reasons a skilled artisan would have been motivated to replace Bowen's lower Fe ferromagnetic layer with a CoFeB layer as I explained above for Claim 1[a]. *Supra* Section XIV.A.2 of this Declaration. For the reasons I provided with respect to Bowen's lower Fe layer, replacing Bowen's upper FeCo layer with a CoFeB ferromagnetic layer would have further improved Bowen's device, including improved tunneling and higher TMR, as well as lower  $H_f$  and  $H_c$ , and a skilled artisan would have had a reasonable expectation of success with this obvious modification. *Supra* Section XIV.A.2 of this Declaration. Indeed, researchers recognized that using CoFeB improved TMR compared with using CoFe. *Supra* Section XIV.A.2 of this Declaration.

274. As explained in more detail for Claim 1[a], Wang explained that CoFeB had many benefits: "The benefit of using CoFeB is multifold: a higher TMR value, a lower coercivity ( $H_c$ ), and a lower coupling field ( $H_{\text{coupl}}$ ) for the free layer, which are all desirable for sensor applications." EX1055 (Wang) at pages 2269-70; *supra* Section XIV.A.2 of this Declaration. Wang taught that "[w]ith such a large increase of TMR value by changing the free layer from NiFeCo to CoFeB, it is natural to replace both the free and pinned layers to CoFeB to further increase the TMR value." EX1055 (Wang) at page 2270. Thus, one of skill would have understood from Wang

that changing both the free and pinned layers to CoFeB would result in even higher TMRs, and a skilled artisan would have predictably done so with Bowen's free and pinned ferromagnetic layers.

**5. Claim 1[d]: "wherein each of the first and second ferromagnetic material layers is entirely crystallized,[] and"**

275. Claim 1[d] is disclosed or suggested by Bowen in view of Wang.

276. As I explained for Claims 1[a] and 1[c] in Sections XIV.A.2 and XIV.A.4 of this Declaration, Bowen in view of Wang disclosed or suggested substituting Bowen's bottom Fe and top FeCo layers with first and second CoFeB ferromagnetic material layers.

277. One of skill would have been motivated to anneal the CoFeB ferromagnetic layers to improve TMR and obtain entirely crystallized CoFeB layers.

278. The benefits of annealing were understood and known. Bowen and Wang both observed improved electrodes and performance with annealing. Bowen explained that "low-temperature deposition and subsequent annealing process leads to an optimal Fe electrode in terms of crystallinity, continuity, and interface sharpness." EX1026 (Bowen) at page 1655. Wang reported record TMR values after annealing: "The tunnel junctions were annealed at 250 °C for 1 h and tested for magneto-transport properties with tunnel magnetoresistive (TMR) values as high as

70.4% at room temperature, which is the highest value ever reported for such a sandwich structure.” EX1055 (Wang) at Abstract, page 2269.

279. A skilled artisan also would have understood and known that annealing resulted in crystallized CoFeB layers. For example, Cardoso observed that “[x]-ray measurements of bulk CoFe and CoFeB 200 Å thick films (Fig. 3) confirmed that the CoFeB films are not amorphous” and “the spectra show clearly the existence of a peak around 45.3 ° corresponding to a strong texture enhancement upon annealing” with the “intensity of the peak... much larger for CoFeB films than for the CoFe.” EX1061 (Cardoso) at page 2273; *id.* at Abstract (observing that “CoFe-based junctions ( $R \times A \sim 500 \Omega \cdot \mu m^2$ ) have lower TMR (~35%) and larger  $H_f$  (~5-6 Oe) and  $H_c$  (~12-14 Oe)” compared to CoFeB-based junctions, and that “[t]he CoFeB layer has a strong (111) texture that can be the origin of lower  $H_f$  and coercivity when compared with CoFe.”). Jimbo observed that “the CoFeB layer is confirmed to be amorphous in the as-deposited state and begin to crystallize after annealing at 250°C.” EX1060 (Jimbo) at page 311. Similarly, after annealing, Parkin, using “[c]ross-section transmission electron microscopy,” observed that “a portion of the storage layer 175 *adjacent to the MgO tunnel barrier* 120’ has crystallized and is, moreover, textured in the same orientation as the crystalline MgO tunnel barrier.” EX1062 (Parkin) at col. 18:51-55 (emphasis added); *see also id.* at col. 18:45-48 (“TMR values of more than 220% were found after an anneal treatment at 350° C.

The TMR of these devices was found to increase substantially on annealing as shown in FIG. 5.”). Parkin further reported that “[t]he simple cubic crystalline MgO layer thus provides a template for the formation of a thin crystalline ferromagnetic layer which has the bcc structure of CoFe and is oriented in the same (100) direction as the MgO layer.” EX1062 (Parkin) at col. 18:55-59.

280. Thus, it was known that if an MgO MTJ with CoFeB layers is annealed, at least a portion of those CoFeB layers adjacent to the MgO barrier layer would crystallize. EX1062 (Parkin) at col. 19:17-27 (“The highly (100) textured MgO layer is likely to form an excellent template layer for the formation of a thin crystalline layer of CoFeB. It could also be that the B diffuses away from the interface with the MgO layer, during the thermal anneal treatments, to leave a thin interface layer at this interface which is much lower in B content.”). It is evident from Parkin, Cardoso, and others that crystallization was inherent in annealing CoFeB layers. In my opinion, after annealing, the portion of the CoFeB layers adjacent to the MgO barrier would be “entirely crystallized” as required by Claim 1[d]. As I explained for Claim 1[d] in Ground 1, this is true even if some boron diffuses away from the interface with the MgO layer. *Supra* Section XII.A.5 of this Declaration.

281. Patent Owner agrees. I understand that Patent Owner contends that the “entirely crystallized” requirement of Claim 1[d] is met so long as the CoFeB

immediately adjacent to the MgO barrier layer is crystallized. In Patent Owner's claim chart for the '138 Patent, Patent Owner alleges:

[E]ach of the first and second ferromagnetic material layers in the WD Accused Products is entirely crystallized after anneal.

...

Another WD patent (U.S. Patent No. 8,427,791...) describes that ... "In order to obtain a high MR ratio in amorphous CoFeB/crystalline MgO/amorphous CoFeB MTJs, an annealing step is necessary in order to produce *crystallized bcc CoFeB* (100)/MgO(100)/*crystallized bcc CoFeB* (100)." ...

As another example, in another WD patent (U.S. Patent No. 7,751,156...), it is described that ... "During anneal, *the CoFeB immediately contacting the MgO barrier layer 717 crystallizes* thus forming the desired CoFeX/MgO/CoFeX structure...."

EX1072 (First Amended Complaint, Exhibit EE) at pages 6-7 (quoting U.S. Patent Nos. 8,427,791 (EX1082), 7,751,156 (EX1081) (emphases in original)); *see also id.* (citing U.S. Patent No. 8,914,970 (EX1083)); EX1012 ('138 Patent File History) at page 200 (Examiner: "[T]he annealing process of [the prior art] to one of skilled in the art would allow the first and second ferromagnetic layers to be entirely crystallized based on the annealing process...."). As evident from the infringement

allegations in Patent Owner's complaint, the prior art captures what Patent Owner accuses of infringement with at least the same level of detail.

282. Annealing MTJs with CoFeB layers was routine and not new, and a skilled artisan annealing CoFeB layers would have achieved high TMRs with a reasonable expectation of success. *E.g.*, EX1056 (Hosomi) ¶74 (“In the alloy composition of FeCoB or FeCoNiB constituting the ferromagnetic layer.... [t]he ferromagnetic layer is subjected to treatment of annealing within a magnetic field to completely impart magnetic anisotropy into the ferromagnetic layer.”); EX1061 (Cardoso) at page 2272 (explaining that after deposition of CoFeB layers, “the structures were annealed 10 min at 280 °C”).

283. Parkin taught that annealing increased the TMR for its Figure 3A MTJ. Parkin explained that “[t]he magnitude of the tunneling magnetoresistance increases with anneal temperature, as shown in more detail in FIG. 5 [shown at right], and reaches a value of nearly 140% after an anneal at 380° C.” EX1062 (Parkin) at col. 18:13-16; *see also id.* at col. 18:45-48 (“TMR values of more than 220% were found after an anneal treatment at 350° C. The TMR of these devices was found to increase substantially on annealing as shown in FIG. 5.”).

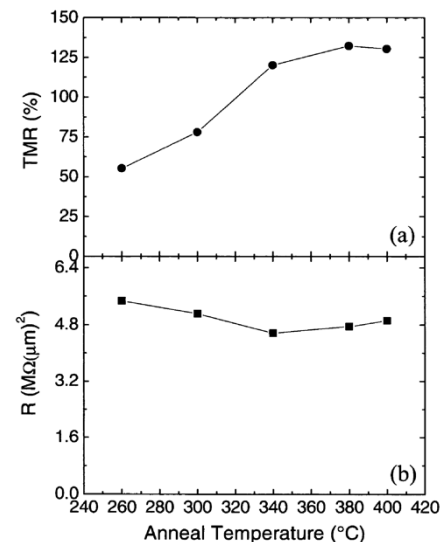


FIG. 5

284. In sum, it would have been obvious to one of skill to anneal CoFeB electrodes to crystallize them and increase TMR. A skilled artisan would have been motivated to anneal Bowen's MTJs after its Fe and FeCo layers were replaced with CoFeB layers and would have done so with a reasonable expectation of success.

**6. Claim 1[e]: “wherein a value of  $x$  in  $MgO_x$  for the MgO layer is greater than 0 and less than 1.”**

285. Claim 1[e] is disclosed or suggested by Bowen alone or in view of Soukup.

286. Obviousness over Bowen. Bowen disclosed or suggested  $MgO_x$  where the  $x$  is a value greater than 0 and less than 1, e.g.  $0 < x < 1$ . As I explained in Section VII.F of this Declaration,  $MgO_x$  where  $0 < x < 1$  refers to a non-stoichiometric MgO crystal where the ratio of oxygen to magnesium atoms is less than 1:1. In other words, there is less than 1 oxygen atom for every 1 magnesium atom. This is due to the presence of oxygen vacancy defects in the MgO crystal, indicating that an oxygen atom is missing at certain places in the crystalline structure.  $MgO_x$ , non-stoichiometric MgO, and oxygen vacancy defects in an MgO layer are interchangeable terminology and all refer to the same phenomenon: missing oxygen atoms in the MgO crystal. *E.g.*, EX1041 (Wollschläger) at page 132 (“understoichiometric  $MgO_x$  ( $x < 1$ )”); EX1037 (Castanier) at page 3, Fig. 1

(showing “sub-stoichiometric  $\text{MgO}\{100\}$  surfaces with various densities of oxygen vacancies”).

287. The '138 Patent uses this terminology in the same way. For example, the patent contrasts using barrier layers of “ $\text{MgO}$  of the stoichiometric composition (the ratio of Mg to O is 1:1)” compared to  $\text{MgO}$  “with oxygen vacancy defects.” EX1011 ('138 Patent) at col. 6:27-34. It explains that when fabricating the MTJ, “there is the possibility that there are oxygen vacancy defects such as  $\text{MgO}_x$  ( $0.9 < x < 1$ ).” EX1011 ('138 Patent) at col. 7:6-7. The '138 Patent applicant said the same thing to the Patent Office, explaining that “ $\text{MgO}_x$  ( $0 < x < 1$ )” means the  $\text{MgO}$  “crystals have oxygen vacancy defects.” EX1002 ('403 Patent File History) at page 168.

288. Any oxygen vacancy defects in  $\text{MgO}$  produce  $\text{MgO}_x$  ( $0 < x < 1$ ). Said another way,  $\text{MgO}_x$  where ( $0 < x < 1$ ) is inherent in any  $\text{MgO}$  substance that has oxygen vacancy defects. That is because the ratio of oxygen to magnesium has to be greater than zero for the substance to constitute  $\text{MgO}$ . In other words, there must be some oxygen present to have  $\text{MgO}$ . Otherwise, it would simply be Mg. Similarly, to have oxygen vacancy defects, the ratio of oxygen to magnesium must be less than 1, which simply means less than the stoichiometric ratio of oxygen to magnesium. *See* Section VII.F of this Declaration.

289. Bowen taught or suggested oxygen vacancy defects in its MgO barrier layer. Bowen posited that the 0.9 eV MgO tunnel barrier height he observed may be attributed to a non-stoichiometric MgO barrier, explaining:

This value is lower than half of the 5.5 eV MgO band gap calculated for an ultrathin layer. This difference may be due to metal-induced gap states in the MgO barrier although we cannot completely rule out the *presence of stoichiometric and/or thickness inhomogeneities in the insulating film.*

EX1026 (Bowen) at page 1656 (emphasis added). A skilled artisan would have understood the use of less than stoichiometric amounts of oxygen in MgO in tunnel barrier layers.

290. Obviousness over Bowen and Soukup. This limitation was also disclosed or suggested by Bowen in view of Soukup. As discussed in the preceding Paragraph 289, Bowen stated that the properties of his MgO barrier may be explained by “the presence of stoichiometric and/or thickness inhomogeneities in the insulating film.” EX1026 (Bowen) at page 1656. Soukup also studied the “effect of nonstoichiometry on the device characteristics” of his MgO thin film. EX1028 (Soukup) at page 3232. Soukup here is referring to oxygen vacancy defects in his MgO barrier. EX1028 (Soukup) at page 3232. He fabricated devices with different levels of nonstoichiometry in the MgO layer and assessed their barrier heights. EX1028 (Soukup) at Abstract, pages 3232-33, Table I.

291. For the reasons I provided for Claim 4 in Section XIV.D of this Declaration, a skilled artisan would have been motivated to apply Soukup's teachings about oxygen vacancy defects in the MgO barrier to Bowen's non-stoichiometric MgO barrier. Bowen sought to improve the TMR of its MTJ using an MgO barrier layer. EX1026 (Bowen) at page 1655. One of skill in the art looking to improve the tunneling and TMR of Bowen's MTJ would have been motivated to experiment with different levels of oxygen vacancy defects to study their impact on the MgO barrier properties and therefore improve tunneling and TMR. EX1028 (Soukup) at page 3232.

**B. Claim 2: Obviousness Over Bowen In View Of Wang And Optionally Soukup**

**1. Claim 2: "The MTJ device of claim 1, wherein the first ferromagnetic material layer is in direct contact with the barrier layer, and wherein the second ferromagnetic material layer is in direct contact with the barrier layer."**

292. As I explained in Section XIV.A of this Declaration, Claim 1 is obvious over Bowen in view of Wang and optionally Soukup. Claim 2 depends from Claim 1 and thus incorporates all of Claim 1's requirements. Claim 2 is obvious over Bowen in view of Wang and optionally Soukup as explained in the following paragraphs.

293. Bowen taught fabricating "FeCo/MgO/Fe epitaxial structures" and forming an MgO barrier layer in direct contact with the first or lower ferromagnetic layer, as I explained for Claim 1[b] in Section XIV.A.3 of this Declaration. EX1026

(Bowen) at page 1655. In particular, Bowen taught that “the MgO barrier is grown at 400 °C in order to obtain good crystallinity” on top of the “Fe bottom electrode.”

EX1026 (Bowen) at pages 1655-56, Fig. 1.

294. In forming “FeCo/MgO/Fe epitaxial structures,” Bowen also taught forming a second or upper ferromagnetic layer in direct contact with the MgO barrier layer, as I explained for Claim 1[c] in Section XIV.A.4 of this Declaration. Specifically, Bowen described forming its “trilayer” structure with an “FeCo top electrode” such that the FeCo layer is on top of the MgO barrier layer. EX1026 (Bowen) at pages 1655-56, Fig. 1.

295. In addition, as I explained for Claims 1[a] and 1[c] in Sections XIV.A.2 and XIV.A.4 of this Declaration, Bowen in view of Wang disclosed or suggested substituting Bowen’s bottom Fe and top FeCo layers with first and second CoFeB ferromagnetic material layers sandwiching the MgO tunnel barrier layer and in direct contact with the MgO barrier layer. Annealing those first and second CoFeB layers would result in entirely crystallized CoFeB layers in direct contact with the MgO barrier layer, as I explained for Claim 1[d] in Section XIV.A.5 of this Declaration.

296. Further, as I explained above for Claim 1[a] in Section XIV.A.2 of this Declaration, MTJs containing ferromagnetic material layers sandwiching and directly contacting a barrier layer were conventional by 2004, as the ’138 Patent acknowledges. EX1011 (’138 Patent) at col. 1:47-51, Figs. 8(A)-8(B).

**C. Claim 3: Obviousness Over Bowen In View Of Wang And Optionally Soukup**

- 1. Claim 3: “The MTJ device of claim 1, wherein the first ferromagnetic material layer is in direct contact with the MgO layer, and wherein the second ferromagnetic material layer is in direct contact with the MgO layer.”**

297. Claim 3 is disclosed or suggested for the same reasons explained above for Claim 2. *Supra* Section XIV.B of this Declaration; *see also supra* Section XIV.A (Claim 1) of this Declaration.

298. The only difference between Claims 2 and 3 is that Claim 2 refers to “barrier layer” whereas Claim 3 recites an “MgO layer.” As I explained for Claim 1[b] in Section XIV.A.3 of this Declaration, Bowen’s barrier layer is an MgO layer.

**D. Claim 4: Obviousness Over Bowen In View Of Wang And Soukup**

- 1. Claim 4: “The MTJ device of claim 1, wherein a barrier height  $\phi$  of the barrier layer is in a range of 0.2 to 0.5 eV.”**

299. As I explained in Section XIV.A of this Declaration, Claim 1 is obvious over Bowen in view of Wang and optionally Soukup. Claim 4 depends from Claim 1 and thus incorporates all of Claim 1’s requirements. Claim 4 is obvious over Bowen in view of Wang and Soukup as explained in the following paragraphs.

300. Bowen in view of Soukup taught or suggested a barrier height  $\phi$  that is in a range of 0.2 to 0.5 eV. As I explained previously in Section VII.D of this Declaration, the barrier height measures the difference between the Fermi level of the electrode and the bottom of the conduction band of the barrier layer.

301. Bowen disclosed an MTJ with a “barrier height at  $\phi = 0.9$  eV” for his MgO barrier. EX1026 (Bowen) at page 1656. Soukup measured a “barrier height” of “about 0.33 eV” for its MgO thin film that is within the ’138 Patent’s disclosed range of 0.2 to 0.5 eV. EX1028 (Soukup) at Abstract, pages 3231-32, Fig. 5, Table I; EX1011 (’138 Patent) at col. 7:7-11 (“When there are oxygen vacancy defects, the potential barrier height of the MgO tunnel barrier is thought to decrease (such as in the range of... 0.2 to 0.5 eV), which is thought to result in an increase in the tunneling current.”).

302. Indeed, oxygen vacancy defects in an MgO barrier impact the barrier height. Soukup investigated the “effect of nonstoichiometry on the device characteristics.” EX1028 (Soukup) at page 3232. Soukup suggested there was a “higher barrier?[] present for the devices fabricated with more oxygen present during MgO deposition, which could mean more stoichiometric oxide films.” EX1028 (Soukup) at page 3232. Said another way, Soukup found that a lower level of oxygen vacancy defects may result in a higher barrier height. This suggested a higher level of oxygen vacancy defects lowered the barrier height. EX1028 (Soukup) at page 3232. In sum, Soukup taught there was an inverse correlation between oxygen vacancy defects and the barrier height of the MgO layer.

303. A skilled artisan would have had a motivation to take Soukup’s teachings about an MgO thin-film barrier with a “barrier height” of “about 0.33 eV”

and apply them to Bowen's MgO barrier. EX1028 (Soukup) at Abstract, pages 3232, 3236. As is evident from the TMR equation (reproduced below), lowering the resistance for parallel spin electrons ( $R_p$ ) compared to antiparallel electrons ( $R_{ap}$ ) improved TMRs:

$$\text{TMR} = \frac{\Delta R}{R_p} = \frac{R_{ap} - R_p}{R_p}$$

EX1035 (Moodera 1995) at page 3273; EX1027 (Nagahama) ¶2; EX1011 ('138 Patent) at cols. 4:62-5:3 (TMR equation); EX1057 (Dieny textbook) at page 13; EX1044 (Butler) at pages 1-9. Lowering the barrier height was understood to increase tunneling current based on Simmons' equation. EX1026 (Bowen) at page 1656 (referencing "good agreement" in calculating barrier height using Simmons' equations); EX1031 (Simmons) at page 1797 (showing Equation 25 for low voltage range in which tunneling current density is proportional to  $\frac{\sqrt{\phi}}{e^{\sqrt{\phi}}}$  where  $\phi$  is barrier height and in Simmons' equation tunneling current density ( $J$ ) increases with decreasing barrier height). Despite theoretically increased tunneling current due to lower barrier height, electrons cannot tunnel from one electrode to another if there are no available states to receive them in the opposite electrode as explained in detail by Butler. *E.g.*, EX1044 (Butler) at page 9 ("On the right-hand side of the barrier however these states cannot propagate because there are no minority  $\Delta_1$  propagating

states at the Fermi energy. Therefore, they continue to decay within the minority Fe leading to total reflection of the  $\Delta_1$  Bloch state.”). Where the theoretical tunneling current is increased by lowering barrier height, the parallel resistance ( $R_p$ ) decreases with matching electron states in both electrodes and minimal decay in the barrier. As Butler explains, the dominant current contributor is the  $\Delta_1$  state. EX1044 (Butler) at page 1 (Abstract) (“One particular state with  $\Delta_1$  symmetry is able to effectively couple from the Fe into the MgO.”). However, the anti-parallel resistance ( $R_{ap}$ ) continues to be controlled by rapid decay and lack of available corresponding Bloch states in the receptor electrode, and in the case of the dominant  $\Delta_1$  state, it is essentially unable to convey electrons. *E.g.*, EX1044 (Butler) at page 9 (“[The  $\Delta_1$  propagating states] continue to decay within the minority Fe leading to total reflection of the  $\Delta_1$  Bloch state.”). Thus, in the parallel magnetization, the electrons take advantage of the decreased barrier height leading to reduced  $R_p$ , while Butler teaches that the electrons in the anti-parallel magnetization are essentially blocked, leading to largely unaffected  $R_{ap}$ .

304. The TMR was and is a key parameter for improving MRAM performance. EX1062 (Parkin) at cols. 2:65-3:1 (“For applications of magnetic tunnel junctions for either magnetic recording heads or for non-volatile magnetic memory storage cells, high TMR values are needed for improving the performance of these devices.”), 6:14-16; EX1055 (Wang) at page 2269; EX1049 (Kim) at pages

185-88, 194. As explained in Section VII.E.3 of this Declaration, Butler and Mathon taught that MgO barriers would achieve higher TMRs due to improved symmetry matching between the MgO barrier and ferromagnetic electrodes, facilitating tunneling of parallel electrons across the barrier compared to antiparallel tunneling. EX1044 (Butler) at page 1-9; EX1046 (Mathon) at page 1; *see also* EX1045 (Klaauw) at page 1 (“The tunneling resistance for the parallel orientation of the magnetic moments is estimated to be 100 times smaller than that for the antiparallel orientation of the magnetic moments due to the absence of scattering in the barrier.”). Mathon explained that tunneling was enhanced due to “only a small lattice mismatch of about 3.5%” between electrodes and barrier. EX1046 (Mathon) at page 1. Following this research, Bowen and others were quite interested in increasing TMRs to enable better performing MRAM. *E.g.*, EX1026 (Bowen) at Abstract (showing “[t]unnel magnetoresistance measurements” of 60%), page 1655 (“present[ing] experimental results showing large TMR values in Fe(001)/MgO(001)/FeCo(001) epitaxial tunnel junctions”); EX1055 (Wang) at page 2271. MgO had been extensively studied for decades. One of skill would have been motivated to consult the literature on MgO, including Soukup.

305. To increase TMR of an MgO barrier, skilled artisans would have been motivated to explore lower barrier heights to facilitate tunneling of parallel electrons. One of skill in the art interested in improving Bowen’s MgO MTJ would have looked

to Soukup's teachings about MgO barriers and how defects lowered the barrier height. Bowen's and Soukup's research dovetailed together. Both Bowen and Soukup studied properties of MgO barriers, including the barrier height, and discussed tunneling, EX1026 (Bowen) at Abstract, pages 1655-57; EX1028 (Soukup) at pages 3229-30, which is a problem also addressed by the '138 Patent. EX1011 ('138 Patent) at Abstract, cols. 1:32-2:29. Bowen and Soukup discussed Simmons' seminal 1963 paper and well-known formula for determining barrier height. EX1026 (Bowen) at page 1656; EX1028 (Soukup) at page 3229.

306. A skilled artisan also would have had a reasonable expectation of success in applying Soukup's teachings to Bowen to achieve a tunnel barrier height in the range of 0.2 to 0.5 eV. Soukup had already fabricated an MgO barrier with a tunnel barrier height of 0.33 eV, EX1028 (Soukup) at Abstract, and one of skill in the art would have been motivated to use a barrier height with the same or similar height in an MgO MTJ to improve tunneling and hence TMR in Bowen.

307. The claimed tunnel barrier height range of 0.2 to 0.5 eV was obvious. As I explained above in Paragraphs 302-303 of this Declaration, a skilled artisan would have looked to Soukup's teachings to lower Bowen's calculated barrier height. One of skill would have been motivated using Soukup to try to deposit an MgO barrier with a lower barrier height than the "0.9 eV" barrier height disclosed by Bowen and others. EX1026 (Bowen) at page 1656 (citing EX1038); EX1038

(Moodera 1996) at pages 4725-26. One of skill applying Soukup's teachings to Bowen would have readily achieved lowering tunnel barrier height to be within the claimed range.

308. As I mentioned in Paragraph 302 of this Declaration, oxygen vacancy defects impacted the barrier height. Bowen itself hypothesized that the low barrier height he observed, which was "lower than half" of the calculated value for "an ultrathin layer" of MgO, may be due to the "presence of stoichiometric... inhomogeneities in the insulating film." EX1026 (Bowen) at page 1656. Soukup observed a relationship between barrier height and MgO stoichiometry (oxygen vacancy defects). EX1028 (Soukup) at pages 3232, 3236 ("[B]arrier height was a function of the amount of oxygen present... with a higher barrier for larger amounts of oxygen present" and "more stoichiometric" MgO film.). Others in the field also observed a lower tunneling barrier for MgO barriers with defects. *See, e.g.*, EX1043 (Heinrich) at page 1 (noting that the "sharp increases in tunneling current were caused by localized defects in the MgO layer" and "the tunneling barrier is significantly decreased"); EX1045 (Klaauw) at page 7 ("[S]mall variations in the electronic structure of the MgO lead to strong variations in the local tunneling current."); EX1053 (Mitani) at page 8042 (reporting "the resistance decreases dramatically" for "tunneling transport through the MgO barrier," attributing it to "defects in the MgO barrier"); EX1047 (Wulfskel) at page 510 (observing "defects

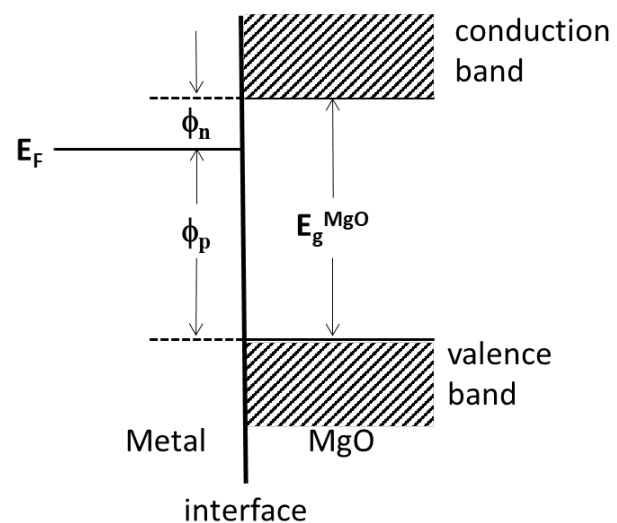
in the MgO barrier” and concluding that spikes in current are likely caused by “a lower tunneling barrier”).

309. According to the '138 Patent, “[w]hen there are oxygen vacancy defects, the potential barrier height of the MgO tunnel barrier is thought to decrease (such as in the range of... 0.2 to 0.5 eV), which is thought to result in an increase in the tunneling current.” EX1011 ('138 Patent) at col. 7:7-11. Thus, the '138 Patent itself recognized that the tunnel barrier height is lowered when there are oxygen vacancy defects as taught by Bowen and Soukup. EX1026 (Bowen) at page 1656; EX1028 (Soukup) at pages 3232, 3236.

310. One of skill would have been motivated to adjust oxygen vacancy defects to improve TMR by lowering the barrier height.

311. Soukup reported a barrier height of 0.33 eV for his MgO barrier with an Au/MgO interface. EX1028 (Soukup) at pages 3229, 3232. The barrier height is principally driven by the barrier itself, in this case, MgO. *E.g.*, EX1054 (Goniakowski) at Fig. 1; *id.* at page 96, Table 2. One of skill would have expected a barrier height for a ferromagnetic/MgO interface to be about the same or even lower than Soukup’s Au/MgO interface.

312. Goniakowski studied barrier heights for a large number of metal/MgO interfaces. In Figure 1, Goniakowski showed experimental data exhibiting a strong trend for p-type Schottky barrier heights,  $\phi_p$ , for many metals on MgO in which the barrier height decreases linearly with the increase of the Pauling electronegativity of the metal. EX1054 (Goniakowski) at Fig. 1; *see also id.* at page 96, Table 2. One of skill would have understood the tunnel barrier height for electrons,  $\phi_n$ , is related to  $\phi_p$  by the relation:  $\phi_p + \phi_n = E_g^{\text{MgO}}$ , where  $E_g^{\text{MgO}}$  is the band gap of MgO. This is depicted schematically in the figure on the right, where  $E_F$  represents the Fermi level of the metal.



Thus, Goniakowski showed a strong trend for tunnel barrier heights in which the barrier height increases linearly with the increase of the Pauling electronegativity of the metal, or correspondingly decreases with the decrease of the Pauling electronegativity of the metal.

313. Trasatti reported experimental data for the Pauling electronegativity for many metals. EX1032 (Trasatti) at Table 1; *see also id.* at pages 229-31. In Table 1, Trasatti showed two values for the Pauling electronegativity for Au. 2.37 is given as the value by “a number of authors,” but 2.10 is the value given as the “operative”

value “corresponding to the state of the metal as used in electrochemistry or catalysis.” EX1032 (Trasatti) at page 231, Table 1. Trasatti’s Table 1 also showed a value for the Pauling electronegativity of 1.8 for Co and 1.77 for Fe. EX1032 (Trasatti) at Table 1. One of skill would have understood that a thin film of metal deposited on MgO using the techniques disclosed in Bowen (“triode sputtering with an Ar pressure of  $4 \times 10^{-4}$  mbar”) is not consistent with the state of the metal as used in electrochemistry or catalysis. EX1026 (Bowen) at page 1655. Nevertheless, for either value of Pauling electronegativity cited for Au, the values of the Pauling electronegativity of Co and Fe are each lower. EX1032 (Trasatti) at Table 1. Thus, one of skill reading Goniakowski in light of Trasatti would have concluded that a tunnel barrier height for Fe or Co (or an alloy of Fe or Co) on MgO would be lower than the value found by Soukup for Au on MgO. At a minimum, one of skill would have been aware of the trend for tunnel barrier heights disclosed in Goniakowski and would have understood that there would be a reasonable expectation of success in achieving a low barrier height using Fe or Co, or an alloy of Fe or Co such as CoFeB.

314. In sum, Claim 4 was disclosed or suggested by Bowen in view of Wang and Soukup.

**E. Claim 5: Obviousness Over Bowen In View Of Wang And Soukup**

**1. Claim 5[preamble]: “The MTJ device of claim 4,”**

315. As I explained above in Section XIV.D of this Declaration, Bowen in view of Wang and Soukup disclosed or suggested an MTJ device satisfying Claim 4.

*See also supra* Section XIV.A.1 (Claim 1[preamble]) of this Declaration.

**2. Claim 5[a]: “wherein the barrier height  $\phi$  of the barrier layer is obtained by fitting J-V characteristics of the MTJ device to an equation (1):  $J = [(2m\phi)^{1/2} / \Delta s](e/h)^2 \times \exp[-(4\pi\Delta s/h) \times (2m\phi)^{1/2}] \times V$  (1)”**

316. Bowen and Soukup disclosed or suggested Claim 5[a].

317. As I explained for Claim 5[a] in Ground 2, Claim 5[a] merely recites Simmons’ formula, which was widely known to be used for calculating the tunnel barrier height. *Supra* Section XIII.A.2 of this Declaration. For the reasons I provided for Claim 5[a] in Ground 2, Bowen in view of Soukup disclosed or suggested the use of Simmons’ formula to obtain the claimed “barrier height  $\phi$ .” *Supra* Section XIII.A.2 of this Declaration.

**3. Claim 5[b]: “where J is a tunnel current density flowing through the barrier layer, V is an applied bias voltage that is 100 mV or smaller, m is the free electron mass, e is the elementary electric charge, h is Planck's constant,  $\Delta s$  is an effective thickness of the barrier layer that is equivalent to  $(t_{\text{MgO}} - 0.5 \text{ nm})$ , and  $t_{\text{MgO}}$  is an actual thickness of the barrier layer.”**

318. Claim 5[b] was disclosed or suggested by Bowen and Soukup.

319. As I explained for Claim 5[b] in Ground 2, Claim 5[b] simply identifies certain variables, and certain values for some of those variables, for use in Simmons' formula. *Supra* Section XIII.A.3 of this Declaration. For the reasons I provided for Claim 5[b] in Ground 2, a skilled artisan would have found these variables, and the recited values, obvious over Bowen in view of Soukup. *Supra* Section XIII.A.3 of this Declaration. Indeed, the variables and values in Claim 5[b] were known and understood based on Simmons' 1963 paper, and calculating the tunnel barrier height using Simmons' formula, as set forth in Claim 5[a] with the variables and values identified in Claim 5[b], would have been routine and obvious to a skilled artisan.

**F. Claim 6: Obviousness Over Bowen In View Of Wang And Soukup**

**1. Claim 6: "The MTJ device of claim 1, wherein a value of  $x$  in  $MgO_x$  for the  $MgO$  layer is greater than 0.9 and less than 1."**

320. As I explained in Section XIV.A of this Declaration, Claim 1 is obvious over Bowen in view of Wang and optionally Soukup. Claim 6 depends from Claim 1 and thus incorporates all of Claim 1's requirements. Claim 6 is obvious over Bowen in view of Wang and Soukup.

321. The claimed  $MgO_x$  oxygen vacancy defect range of "greater than 0.9 and less than 1" was inherent to Bowen's and Soukup's  $MgO$  barrier layers for the same reasons that I explained for Claim 1[e] in Section XIV.A.6 of this Declaration. Indeed, as I explained above in Paragraphs 74-75 and 288 of this Declaration, oxygen vacancy defects were understood to be inherent to  $MgO_x$  layers where

$0 < x < 1$ . One of skill would understand that the claimed range of  $0.9 < x < 1$  is a subrange of the oxygen vacancy defects inherent to Bowen's and Soukup's MgO barrier layers. Because  $0.9 < x < 1$  is a subrange of  $0 < x < 1$ , it necessarily overlaps with  $0 < x < 1$ .

322. Claim 6 is also obvious because the general conditions for fabricating an MTJ with the claimed MgO barrier layer oxygen vacancy range of  $0.9 < x < 1$  were already disclosed in the prior art. For example, Castanier studied oxygen vacancies for “non-stoichiometric MgO{100} surfaces, with several densities of neutral oxygen vacancies” studied. EX1037 (Castanier) at Abstract. They modeled oxygen vacancies down to a 1/18 density as shown in the image below, which would correspond to  $\text{MgO}_x$  with  $x$  approximately equal to 0.944, within the claimed range. EX1037 (Castanier) at page 3, Fig. 1. Others in the field at the time of the 2004 priority date would have been both motivated and able to obtain MgO barrier layer oxygen vacancy defects in this range through routine optimization.

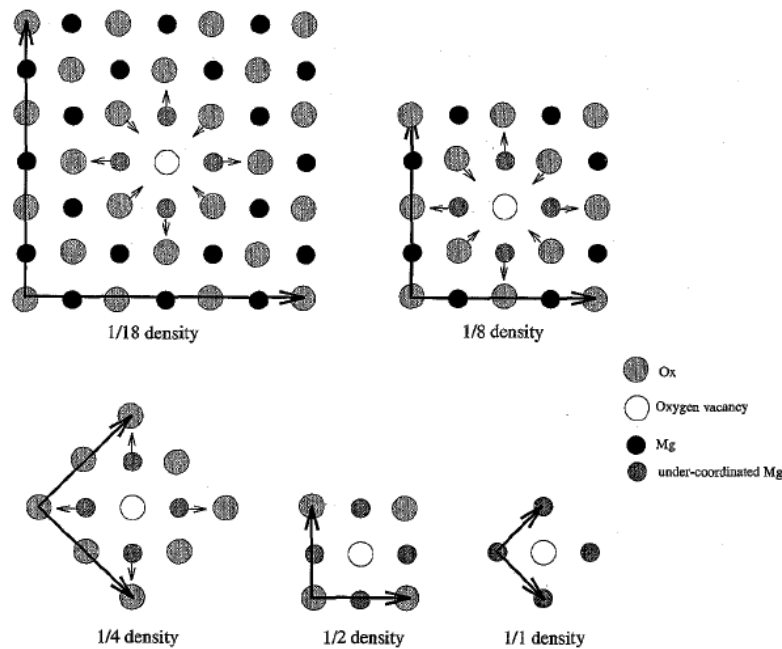


Fig. 1. Surface cells for sub-stoichiometric MgO{100} surfaces with various densities of oxygen vacancies. The magnesiums located close to a vacancy are specified and an arrow indicates their displacement in the surface plane.

EX1037 (Castanier) at Fig. 1.

323. The claimed invention of the '138 Patent is directed to an MTJ device that produced a high TMR. EX1011 ('138 Patent) at cols. 1:32-35, 2:58-60, 4:64-5:3 (setting forth the equation for determining the “magnetoresistance (MR) ratio of a MTJ device”). Others in the field at the time of the 2004 priority date of the '138 Patent were also interested in increasing the TMR. Increasing the TMR was an obvious improvement to MgO MTJs. As I explain in Sections VII.C, XIV.A.6 (Claim 1[e]), and XIV.D (Claim 4) of this Declaration, increasing TMR was a prerequisite to improving MRAM performance to obtain smaller, denser devices. As Bowen explained, researchers long sought to optimize TMRs to improve MRAM:

magnetoresistance of magnetic tunnel junctions (MTJs) is of uncontested interest for important applications with, in particular, promising perspectives for the fabrication of nonvolatile memories (Magnetic RAM).

EX1026 (Bowen) at page 1655.

324. In 2001, both Butler and another group led by Mathon each calculated very high TMRs for MgO MTJs due to symmetry matching between the MgO and Fe layers. EX1044 (Butler) at Fig. 16; EX1046 (Mathon) at Abstract, page 1 (optimistic TMR “in excess of 1000%” for an MgO barrier). The close match of the crystalline symmetry between MgO and Fe facilitated tunneling of parallel electrons compared to antiparallel electrons, opening the door to these very high TMRs. EX1044 (Butler) at page 1; EX1046 (Mathon) at page 1.

325. After Butler and Mathon announced their findings of four-figure TMRs for MgO MTJs, many researchers sought to experimentally validate their results. The '138 Patent itself acknowledged that existing MTJ devices with aluminum oxide barriers had already achieved an “MR ratio of approximately 70%.” EX1011 ('138 Patent) at col. 5:19-25; *see also id.* at col. 2:50-52. Indeed, before the '138 Patent in 2004, other researchers had observed TMRs exceeding 70% in MTJs with MgO barriers. EX1027 (Nagahama) ¶74 (disclosing “a larger tunnel magnetoresistive effect of more than 90%”); EX1052 (Faure-Vincent) at Abstract (reporting TMR of 100% in an Fe/MgO/Fe/Co tunnel junction).

326. Bowen cited research by Butler calculating a high TMR for MgO MTJs like Bowen's. Bowen stated: "TMR values calculated by Butler *et al.* are much higher (2000% for 20 Å MgO) than our experimental value of 60%...." EX1026 (Bowen) at page 1657. Bowen reported a TMR of 60% for an MgO MTJ and expressed his intent to "aim to confirm the predicted relative increase of the TMR" in "future experiments." EX1026 (Bowen) at page 1657. Thus, Bowen itself expressly provided a motivation for one of skill in the art to increase the TMR of his MTJ. EX1026 (Bowen) at page 1657. As I also explained for Claims 1[e] and 4 in Sections XIV.A.6 and XIV.D of this Declaration, one of skill in the art would have found it obvious to do exactly that.

327. Others in the field before 2004 were already aware of the general MTJ conditions for fabricating MgO barrier layers that could result in the claimed  $\text{MgO}_x$  wherein  $0.9 < x < 1$ . For example, Bowen hypothesized that his observed decrease in MgO barrier height was due to oxygen vacancy defects. EX1026 (Bowen) at page 1656. Soukup examined the "effect of nonstoichiometry on the device characteristics," EX1028 (Soukup) at page 3232, and experimented with devices fabricated with different levels of nonstoichiometry, EX1028 (Soukup) at Abstract, pages 3232-33, Table I. Bowen's and Soukup's MgO barrier layer fabrication methodologies were consistent with the fabrication methods disclosed for the '138 Patent's two MTJ device embodiments.

328. The '138 Patent's first embodiment is identified as the "Fe(001)/MgO(001)/Fe(001) MTJ device." EX1011 ('138 Patent) at col. 6:7-14. The disclosure explains that the fabrication schematics are illustrated in Figures 2(A) through 2(D). EX1011 ('138 Patent) at col. 6:10-14. The first step of the fabrication method includes growing an "MgO(001) seed layer 15" onto the "single-crystal MgO(001) substrate 11" using "molecular beam epitaxy (MBE)." EX1011 ('138 Patent) at col. 6:15-19, Fig. 2(A). Then the "epitaxial Fe(001) lower electrode (first electrode) 17" is grown on top of the "MgO(001) seed layer 15." EX1011 ('138 Patent) at col. 6:19-22, Fig. 2(B). The "MgO(001) barrier layer 21" was then "epitaxially grown on the Fe(001) lower electrode (first electrode) at room temperature" using "the MgO electron-beam evaporation method." EX1011 ('138 Patent) at col. 6:38-42, Fig. 2(C). Finally, the "Fe(001) upper electrode (a second electrode) 23" was then "formed on the MgO(001) barrier layer 21" followed by deposition of the "Co layer 25" on top of the "Fe(001) upper electrode (second electrode) 23." EX1011 ('138 Patent) at col. 6:45-50.

329. Focusing specifically on the fabrication of the MgO barrier layer of this first embodiment, the '138 Patent discloses the following:

The source material of the electron-beam evaporation was MgO of the stoichiometric composition (the ratio of Mg to O being 1:1), the distance between the source and the substrate was 40 cm, the base vacuum pressure was  $1 \times 10^{-8}$  Pa, and the O<sub>2</sub> partial pressure was  $1 \times 10^{-6}$

Pa. Alternatively, a source with oxygen vacancy defects may be used instead of the MgO of the stoichiometric composition (the ratio of Mg to O is 1:1).

EX1011 ('138 Patent) at col. 6:27-34. One of skill would understand that “vacuum pressure” refers to pressure that is less than atmospheric pressure. It would also be understood that “O<sub>2</sub> partial pressure” refers to the pressure attributable to O<sub>2</sub> gas in the deposition chamber in relation to the total pressure attributable from all the gas in the deposition chamber. The '138 Patent goes on to disclose that “MgO evaporation using an electron beam involved the formation of a film under ultrahigh vacuum of 10<sup>-9</sup> Torr.” EX1011 ('138 Patent) at col. 6:56-58. One of skill would understand that 10<sup>-9</sup> Torr converts to 1.3×10<sup>-7</sup> Pa (1 Torr equals 133.3 Pascals).

330. The '138 Patent discloses that this first MTJ device embodiment produced a TMR value of 88% at room temperature, as illustrated in Figure 6. EX1011 ('138 Patent) at col. 8:4-8, Fig. 6.

331. Regarding oxygen vacancy defects in the MgO barrier layer of the first MTJ device embodiment, the '138 Patent discloses the following related to data provided in its Figure 5:

These results indicate the separation of oxygen from MgO during the deposition of MgO. Since the separated oxygen is pumped out of the deposition chamber using vacuum pumps, there is the possibility that there are oxygen vacancy defects such as MgO<sub>x</sub> (0.9<x<1).

EX1011 ('138 Patent) at col. 7:2-7. These purported results are consistent with the understanding at the time that MgO layers inherently had oxygen vacancy defects. Specifically, despite depositing the “MgO(001) barrier layer 21” using “stoichiometric MgO,” oxygen vacancy defects were still expected to exist in this layer.

332. The '138 Patent also discloses a second MTJ device embodiment, which is also referred to as an “Fe(001)/MgO(001)/Fe(001) MTJ device.” EX1011 ('138 Patent) at col. 8:43-47. There are no disclosures of any TMR values or quantification of any oxygen vacancy defects of the MgO barrier layer for this second embodiment. *See generally* EX1011 ('138 Patent). Additionally, the '138 Patent only provides fabrication details for the MgO layer, presumably the barrier layer, disclosing that “MgO(001) is initially deposited in a poly-crystalline or amorphous state by sputtering or the like, and then an annealing process is performed such that a poly-crystal in which the (001) crystal plane is preferentially oriented or a single-crystal is obtained.” EX1011 ('138 Patent) at col. 8:47-51. The '138 Patent goes on to explain that “sputtering was conducted in an Ar atmosphere” at “room temperature,” and the temperature was increased to “300° C” to “crystalize[]” the “amorphous” MgO. EX1011 ('138 Patent) at col. 8:51-60.

333. One of skill would appreciate that “Ar atmosphere” referred to argon gas, and that this disclosure implied that deposition occurred in the absence of

oxygen. According to this disclosure, one of skill would also understand that the vacuum pressure is “on the order of no more than  $10^{-6}$  Pa” because “oxygen is not introduced.” EX1011 (’138 Patent) at col. 9:38-42. “[O]n the order of” is understood to mean an order of magnitude. For example, within an order of magnitude of  $10^{-6}$  Pa (also written as  $1 \times 10^{-6}$  Pa or 0.000001 Pa), would include a pressure of  $9 \times 10^{-6}$  Pa (also written as 0.000009 Pa). Likewise, the ’138 Patent discloses that the vacuum pressures “where oxygen is introduced” are on the “order of  $10^{-4}$  Pa” (also written  $1 \times 10^{-4}$  Pa or 0.0001 Pa), indicating that other pressure values within the ten-thousandths place or smaller would be acceptable. EX1011 (’138 Patent) at col. 9:38-42.

334. Bowen’s and Soukup’s general fabrication methods were comparable to those disclosed in the ’138 Patent. According to the ’138 Patent’s disclosure, “while the MgO layer has been described to be deposited by electron-beam evaporation or sputtering, it should be obvious that other deposition methods are also possible.” EX1011 (’138 Patent) at col. 9:35-38. Indeed, the ’138 Patent does not attribute or highlight anything about its disclosed fabrication methods that are inventive or unexpectedly lead to higher-than-expected performance.

335. Bowen’s MgO barrier layer was fabricated using sputtering, which is the same methodology used to fabricate the ’138 Patent’s MTJ device of the second embodiment. Bowen describes fabricating its “FeCo/MgO/Fe epitaxial structures...

in a combined sputtering/laser ablation system with a base pressure of  $2 \times 10^{-9}$  mbar,” wherein the MgO layer is deposited at “400 °C.” EX1026 (Bowen) at page 1655. One of skill would understand that  $2 \times 10^{-9}$  mbar converts to  $2 \times 10^{-7}$  Pa (1 mbar equals 100 Pa). One of skill would also understand that  $2 \times 10^{-7}$  is the same number as  $0.2 \times 10^{-6}$ . While Bowen does not disclose the gas composition used during deposition, the vacuum pressure is acceptable according to the ’138 Patent’s disclosure whether or not oxygen is present. EX1011 (’138 Patent) at col. 9:38-42 (“on the order of no more than  $10^{-6}$  Pa” when oxygen was not introduced and “on the order of  $10^{-4}$  Pa” when oxygen was introduced).

336. Soukup’s fabrication method is the same method the ’138 Patent discloses using for its first MTJ device embodiment. Soukup discloses fabricating the MgO barrier layer using evaporation at a vacuum pressure of “ $10^{-8}$  Torr,” wherein the substrates were heated to “400°C.” EX1028 (Soukup) at page 3230.  $10^{-8}$  Torr converts to  $1.33 \times 10^{-6}$  Pa, which is also within the acceptable “ultrahigh” vacuum pressures the ’138 Patent discloses whether or not oxygen is present. EX1011 (’138 Patent) at col. 9:38-42. Specifically, Soukup describes using an electron beam as indicated by his explanation that the “thickness of the films were determined by precalibrating deposition rate vs electron beam power using a quartz crystal monitor.” EX1028 (Soukup) at page 3230.

337. As the disclosed general MgO barrier layer fabrication conditions were understood by others in the field by 2004, a skilled artisan would readily optimize oxygen vacancy defects through experimentation to determine the level of oxygen vacancy defects that produced the best result. And a skilled artisan would have known that the claimed  $0.9 < x < 1$  range, overlapping with  $0 < x < 1$ , was within the zone of potential oxygen vacancy defects to be considered. As I explained previously, both Bowen and Soukup indicated that oxygen vacancy defects in their respective MgO barrier layers likely impacted their calculated barrier heights. EX1026 (Bowen) at page 1656; EX1028 (Soukup) at Abstract, page 3232. Despite not quantifying these defects, as I explained for Claim 1[e] in Section XIV.A.6, one of skill would understand that Bowen's and Soukup's MgO barrier layers inherently had oxygen vacancy defects in their  $\text{MgO}_x$  layers wherein  $0 < x < 1$ . Skilled artisans understood that reducing the height of the barrier layer would achieve higher TMR values. EX1044 (Butler) at page 1-9; EX1046 (Mathon) at page 1; EX1045 (Klaau) at page 1; EX1031 (Simmons) at page 1797; *supra* Section XIV.D of this Declaration. One of skill would have been motivated to optimize MgO barrier layers during MTJ fabrication by optimizing oxygen vacancy defects through experimentation because it was understood that these defects impacted barrier height and thus also affected TMR values. Oxygen vacancy defects in the MgO barrier

layer had an understood relationship to TMR within the grasp of one of skill by the time of the '138 Patent's priority date.

338. In addition, the '138 Patent also did not disclose that the oxygen vacancy defects in the claimed range of  $0.9 < x < 1$  had an unexpected or novel impact on its MTJ devices of the claimed invention. The '138 Patent explains that oxygen vacancy defects could be introduced using several methods and did not indicate any were particular or critical to the object of the invention:

Oxygen vacancy defects may be introduced by a method whereby oxygen vacancy defects is [sic] produced during growth, a method whereby oxygen vacancy defects is introduced subsequently, or a method whereby a state with oxygen vacancy defects is subjected to an oxygen plasma process or natural oxidation so as to achieve a certain oxygen deficit level.

EX1011 ('138 Patent) at col. 8:61-67.

339. Additional disclosure in the '138 Patent further supports the conclusion that the  $0.9 < x < 1$  claimed range is not critical. When referring to the purported oxygen vacancy defects measured for its first MTJ device embodiment, the patent appears to speculate:

Since the separated oxygen is pumped out of the deposition chamber using vacuum pumps, there is the *possibility* that there are oxygen vacancy defects *such as*  $\text{MgO}_x$  ( $0.9 < x < 1$ ). When there are oxygen vacancy defects, the potential barrier height of the MgO tunnel barrier

is thought to decrease (such as in the range of 0.10 to 0.85 eV; more specifically, 0.2 to 0.5 eV), which is thought to result in an increase in the tunneling current.

EX1011 ('138 Patent) at col. 7:4-11 (emphases added). One of skill would understand from this disclosure that this oxygen vacancy defect range was more of an estimate, not an accurate quantification.

340. Soukup's barrier height of 0.33 eV was within the range disclosed by the '138 Patent as indicative of "oxygen vacancy defects." EX1028 (Soukup) at Abstract; EX1011 ('138 Patent) at col. 7:7-11. One of skill would understand from the '138 Patent that Soukup's barrier height of 0.33 eV indicated that Soukup's MgO barrier layer had the preferred oxygen vacancy defect ranges disclosed by the '138 Patent, according to the '138 Patent's own teachings.

341. The '138 Patent's specification also explains that there are ways to impact barrier height other than introducing oxygen vacancy defects in the MgO barrier layer. Specifically, that "the height of the tunnel barrier may be adjusted by doping Ca or Sr, *instead* of introducing an [sic] oxygen vacancy defects to the MgO layer." EX1011 ('138 Patent) at col. 9:32-35 (emphasis added). By disclosing other approaches to manipulating the barrier height, one of skill would also understand that introducing MgO barrier layer oxygen vacancy defects was not the only way to achieve the object of the invention.

**G. Claim 7: Obviousness Over Bowen In View Of Wang And Optionally Soukup**

**1. Claim 7[preamble]: “A magnetic tunnel junction (MTJ) device, comprising:”**

342. This claim limitation is disclosed or suggested for the same reasons explained above for Claim 1[preamble]. *Supra* Section XIV.A.1 of this Declaration; *see also infra* Sections XIV.G.2-XIV.G.7 of this Declaration.

**2. Claim 7[a]: “a first electrode made of a first CoFeB layer;”**

343. This claim limitation is disclosed or suggested for the same reasons explained above for Claim 1[a]. *Supra* Section XIV.A.2 of this Declaration. As I explained for Claim 1[a], a skilled artisan would have understood that an electrode made of a CoFeB layer referred to the same alloy as a ferromagnetic layer including Co, Fe, and B.

**3. Claim 7[b]: “a barrier layer made of a magnesium oxide (MgO) layer that is a poly-crystalline layer in which a (001) crystal plane is preferentially oriented; and”**

344. This claim limitation is disclosed or suggested for the same reasons explained above for Claim 1[b]. *Supra* Section XIV.A.3 of this Declaration.

**4. Claim 7[c]: “a second electrode made of a second CoFeB layer, and”**

345. This claim limitation is disclosed or suggested for the same reasons explained above for Claims 1[c] and 7[a]. *Supra* Sections XIV.A.4 and XIV.G.2 of this Declaration.

**5. Claim 7[d]: “wherein the barrier layer is located between the first electrode and the second electrode, and”**

346. This claim limitation is disclosed or suggested for the same reasons explained above for Claims 1[a]-1[c], 2, and 3. *Supra* Sections XIV.A.2-XIV.A.4, XIV.B, and XIV.C of this Declaration.

347. As explained and shown below, Bowen taught an MgO barrier layer that is located between its lower and upper electrodes:

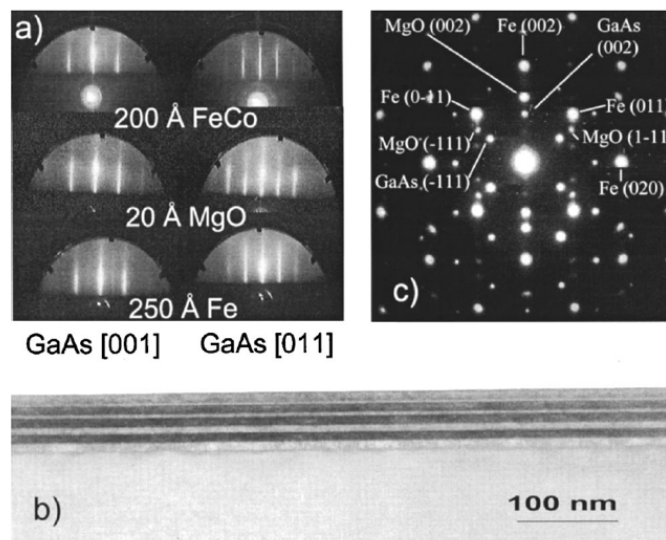


FIG. 1. (a) RHEED patterns along the GaAs [100] and [110] substrate azimuths of a typical FeCo/MgO/Fe epitaxial structure; (b) cross section TEM image of a Fe/MgO(001) multilayer with gradually decreasing MgO layer thickness; (c) TEM electron diffraction pattern.

EX1026 (Bowen) at Fig. 1 (annotated).

**6. Claim 7[e]: “wherein both the first and second CoFeB layers are entirely crystallized, and”**

348. This claim limitation is disclosed or suggested for the same reasons explained above for Claim 1[d]. *Supra* Section XIV.A.5 of this Declaration.

- 7. Claim 7[f]: “wherein a value of  $x$  in  $MgO_x$  for the MgO layer is greater than 0 and less than 1.”**

349. This claim limitation is disclosed or suggested for the same reasons explained above for Claim 1[e]. *Supra* Section XIV.A.6 of this Declaration.

**H. Claim 8: Obviousness Over Bowen In View Of Wang And Optionally Soukup**

- 1. Claim 8: “The MTJ device of claim 7, wherein the first CoFeB layer is in direct contact with the MgO layer, and wherein the second CoFeB layer is in direct contact with the MgO layer.”**

350. Claim 8 is disclosed or suggested for the same reasons explained above for Claims 2 and 3. *Supra* Sections XIV.B-XIV.C of this Declaration; *see also supra* Section XIV.G (Claim 7) of this Declaration.

**I. Claim 9: Obviousness Over Bowen In View Of Wang And Optionally Soukup**

- 1. Claim 9: “The MTJ device of claim 7, wherein the MgO layer and the first CoFeB layer form a first interface of the MTJ, and wherein the MgO layer and the second CoFeB layer form a second interface of the MTJ.”**

351. Claim 9 is disclosed or suggested for the same reasons explained above for Claims 2 and 3. *Supra* Sections XIV.B-XIV.C of this Declaration; *see also supra* Section XIV.G (Claim 7) of this Declaration.

352. As used in Claim 9, “interface” means the boundary between two materials. In Claim 9, the “first interface” refers to the boundary between the MgO layer and the first CoFeB layer, and the “second interface” refers to the boundary

between the MgO layer and the second CoFeB layer. EX1011 ('138 Patent) at cols. 1:53-64 (Description of Related Art: discussing “the interfaces of the tunneling junction structure”), 5:47-51; *id.* at Figs. 8(A)-8(B).

353. As explained above in Sections XIV.B-XIV.C of this Declaration, Bowen in view of Wang and optionally Soukup disclosed or suggested a first CoFeB layer in direct contact with the MgO layer, forming a first interface of the MTJ, and a second CoFeB layer in direct contact with the MgO layer, forming a second interface of the MTJ.

**J. Claim 10: Obviousness Over Bowen In View Of Wang And Soukup**

**1. Claim 10: “The MTJ device of claim 7, wherein a barrier height  $\phi$  of the MgO layer is in a range of 0.2 to 0.5 eV.”**

354. Claim 10 is disclosed or suggested for the same reasons explained above for Claim 4. *Supra* Section XIV.D of this Declaration; *see also supra* Section XIV.G (Claim 7) of this Declaration.

**K. Claim 11: Obviousness Over Bowen In View Of Wang And Soukup**

**1. Claim 11[preamble]: “The MTJ device of claim 10,”**

355. As I explained above in Section XIV.J of this Declaration, Bowen in view of Wang and Soukup disclosed or suggested an MTJ device satisfying Claim 10. *See also supra* Section XIV.A.1 (Claim 1[preamble]) of this Declaration.

2. **Claim 11[a]: “wherein the barrier height  $\phi$  of the MgO layer is obtained by fitting J-V characteristics of the MTJ device to an equation (1):  $J = [(2m\phi)^{1/2} / \Delta s](e/h)^2 \times \exp[-(4\pi\Delta s/h) \times (2m\phi)^{1/2}] \times V$  (1)”**

356. This claim limitation is disclosed or suggested for the same reasons explained above for Claim 5[a]. *Supra* Section XIV.E.2 of this Declaration.

3. **Claim 11[b]: “where J is a tunnel current density flowing through the MgO layer, V is an applied bias voltage that is 100 mV or smaller, m is the free electron mass, e is the elementary electric charge, h is Planck's constant,  $\Delta s$  is an effective thickness of the MgO layer that is equivalent to  $(t_{\text{MgO}} - 0.5 \text{ nm})$ , and  $t_{\text{MgO}}$  is an actual thickness of the MgO layer.”**

357. This claim limitation is disclosed or suggested for the same reasons explained above for Claim 5[b]. *Supra* Section XIV.E.3 of this Declaration.

**L. Claim 12: Obviousness Over Bowen In View Of Wang And Optionally Soukup**

1. **Claim 12[preamble]: “A magnetic tunnel junction (MTJ) device, comprising:”**

358. This claim limitation is disclosed or suggested for the same reasons explained above for Claim 1[preamble]. *Supra* Section XIV.A.1 of this Declaration; *see also infra* Sections XIV.L.2-XIV.L.5 of this Declaration.

2. **Claim 12[a]: “a first ferromagnetic material layer that includes Co, Fe, and B;”**

359. This claim limitation is disclosed or suggested for the same reasons explained above for Claim 1[a]. *Supra* Section XIV.A.2 of this Declaration.

- 3. Claim 12[b]: “a barrier layer disposed on the first ferromagnetic material layer, the barrier layer comprising a magnesium oxide (MgO) layer that is a poly-crystalline MgO in which (001) crystal plane is preferentially oriented; and”**

360. This claim limitation is disclosed or suggested for the same reasons explained above for Claim 1[b]. *Supra* Section XIV.A.3 of this Declaration. As I explained for Claim 1[b], Bowen’s MgO barrier layer was formed over, or disposed on, the lower ferromagnetic layer. EX1026 (Bowen) at Abstract, pages 1655-56, Fig. 1.

- 4. Claim 12[c]: “a second ferromagnetic material layer that is disposed on the barrier layer and includes Co, Fe, and B, and”**

361. This claim limitation is disclosed or suggested for the same reasons explained above for Claim 1[c]. *Supra* Section XIV.A.4 of this Declaration. As I explained for Claim 1[c], Bowen in view of Wang taught a CoFeB upper ferromagnetic layer that was formed over, or disposed on, the MgO barrier layer.

- 5. Claim 12[d]: “wherein each of the first and second ferromagnetic material layers is entirely crystallized, and wherein a value of x in MgO<sub>x</sub> for the MgO layer is greater than 0 and less than 1.”**

362. This claim limitation is disclosed or suggested for the same reasons explained above for Claims 1[d] and 1[e]. *Supra* Sections XIV.A.5 and XIV.A.6 of this Declaration.

**M. Claim 13: Obviousness Over Bowen In View Of Wang And Soukup**

- 1. Claim 13: “The MTJ device of claim 12, wherein a barrier height  $\phi$  of the barrier layer is in a range of 0.2 to 0.5 eV.”**

363. Claim 13 is disclosed or suggested for the same reasons explained above for Claim 4. *Supra* Section XIV.D of this Declaration; *see also supra* Section XIV.L (Claim 12) of this Declaration.

**N. Claim 14: Obviousness Over Bowen In View Of Wang And Soukup**

- 1. Claim 14[preamble]: “The MTJ device of claim 13,”**

364. As I explained above in Section XIV.M of this Declaration, Bowen in view of Wang and Soukup disclosed or suggested an MTJ device satisfying Claim 13. *See also supra* Section XIV.A.1 (Claim 1[preamble]) of this Declaration.

- 2. Claim 14[a]: “wherein the barrier height  $\phi$  of the barrier layer is obtained by fitting J-V characteristics of the MTJ device to an equation (1):  $J = [(2m\phi)^{1/2} / \Delta s] (e/h)^2 \times \exp[-(4\pi\Delta s/h) \times (2m\phi)^{1/2}] \times V$  (1)”**

365. This claim limitation is disclosed or suggested for the same reasons explained above for Claim 5[a]. *Supra* Section XIV.E.2 of this Declaration.

3. **Claim 14[b]: “where J is a tunnel current density flowing through the barrier layer, V is an applied bias voltage that is 100 mV or smaller, m is the free electron mass, e is the elementary electric charge, h is Planck’s constant,  $\Delta s$  is an effective thickness of the barrier layer that is equivalent to  $(t_{\text{MgO}} - 0.5 \text{ nm})$ , and two [sic] is an actual thickness of the barrier layer.”**

366. This claim limitation is disclosed or suggested for the same reasons explained above for Claim 5[b]. *Supra* Section XIV.E.3 of this Declaration.

367. I understand that the applicant indicated during prosecution that “ $t_{\text{MgO}}$ ,”—not “two” as recited in Claim 14[b]—represented “an actual thickness of the barrier layer” in “ $J = [(2m\phi)^{1/2}/\Delta s](e/h)^2 \times \exp[-(4\pi\Delta s/h) \times (2m\phi)^{1/2}] \times V$ .” EX1012 (’138 Patent File History) at page 357.

## **XV. SECONDARY INDICIA OF NONOBVIOUSNESS**

368. Pertinent to Grounds 1-3 above, I am not aware of any evidence of secondary considerations of nonobviousness for which there is any nexus to any claim of the ’138 Patent. Should I become aware of such evidence, I may offer opinions on it at that time.

## **XVI. CONCLUSION**

369. Based on the foregoing, it is my opinion that Claims 1-14 of the ’138 Patent are obvious as discussed above.

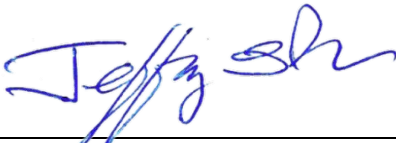
370. In signing this Declaration, I recognize that the Declaration will be filed as evidence in a contested case before the Patent Trial and Appeal Board of the

United States Patent and Trademark Office. I also recognize that I may be called upon to testify in deposition or before the Patent Trial and Appeal Board. If called upon to testify, I would testify truthfully and competently to all matters stated in this Declaration.

371. I reserve the right to supplement my opinions in the future to respond to any arguments that Patent Owner raises and to take into account new information as it becomes available to me.

372. I hereby declare that all statements made herein of my own knowledge are true, and that all statements made on information and belief are believed to be true and that such statements are made with the knowledge that willful false statements and the like are punishable by fine or imprisonment, or both, under Section 1001 of Title 18 of the United States Code.

Dated: March 5, 2025

  
\_\_\_\_\_  
Jeffrey Bokor

## **XVII.APPENDIX: LIST OF PATENT CLAIMS**

1[pre] A magnetic tunnel junction (MTJ) device, comprising:

1[a] a first electrode comprising a first ferromagnetic material layer that includes Co, Fe, and B;

1[b] a barrier layer disposed over the first electrode, the barrier layer comprising a magnesium oxide (MgO) layer that is formed of a polycrystalline MgO in which a (001) crystal plane is preferentially oriented; and

1[c] a second electrode disposed over the barrier layer and comprising a second ferromagnetic material layer that includes Co, Fe, and B, and

1[d] wherein each of the first and second ferromagnetic material layers is entirely crystallized,[] and

1[e] wherein a value of x in MgO<sub>x</sub> for the MgO layer is greater than 0 and less than 1.

2. The MTJ device of claim 1, wherein the first ferromagnetic material layer is in direct contact with the barrier layer, and wherein the second ferromagnetic material layer is in direct contact with the barrier layer.

3. The MTJ device of claim 1, wherein the first ferromagnetic material layer is in direct contact with the MgO layer, and wherein the second ferromagnetic material layer is in direct contact with the MgO layer.

4. The MTJ device of claim 1, wherein a barrier height  $\phi$  of the barrier layer is in a range of 0.2 to 0.5 eV.

5[pre] The MTJ device of claim 4,

5[a] wherein the barrier height  $\phi$  of the barrier layer is obtained by fitting J-V characteristics of the MTJ device to an equation (1):

$$J=[(2m\phi)^{1/2} / \Delta s](e/h)^2 \times \exp[-(4\pi\Delta s/h) \times (2m\phi)^{1/2}] \times V \quad (1)$$

5[b] where J is a tunnel current density flowing through the barrier layer, V is an applied bias voltage that is 100 mV or smaller, m is the free electron mass, e is the elementary electric charge, h is Planck's constant,  $\Delta s$  is an

effective thickness of the barrier layer that is equivalent to  $(t_{\text{MgO}} - 0.5 \text{ nm})$ , and  $t_{\text{MgO}}$  is an actual thickness of the barrier layer.

6. The MTJ device of claim 1, wherein a value of  $x$  in  $\text{MgO}_x$  for the MgO layer is greater than 0.9 and less than 1.

7[pre] A magnetic tunnel junction (MTJ) device, comprising:

7[a] a first electrode made of a first CoFeB layer;

7[b] a barrier layer made of a magnesium oxide (MgO) layer that is a polycrystalline layer in which a (001) crystal plane is preferentially oriented; and

7[c] a second electrode made of a second CoFeB layer, and

7[d] wherein the barrier layer is located between the first electrode and the second electrode, and

7[e] wherein both the first and second CoFeB layers are entirely crystallized, and

7[f] wherein a value of  $x$  in  $\text{MgO}_x$  for the MgO layer is greater than 0 and less than 1.

8. The MTJ device of claim 7, wherein the first CoFeB layer is in direct contact with the MgO layer, and wherein the second CoFeB layer is in direct contact with the MgO layer.

9. The MTJ device of claim 7, wherein the MgO layer and the first CoFeB layer form a first interface of the MTJ, and wherein the MgO layer and the second CoFeB layer form a second interface of the MTJ.

10. The MTJ device of claim 7, wherein a barrier height  $\phi$  of the MgO layer is in a range of 0.2 to 0.5 eV.

11[pre] The MTJ device of claim 10,

11[a] wherein the barrier height  $\phi$  of the MgO layer is obtained by fitting J-V characteristics of the MTJ device to an equation (1):

$$J = [(2m\phi)^{1/2} / \Delta s] (e/h)^2 \times \exp[-(4\pi\Delta s/h) \times (2m\phi)^{1/2}] \times V \quad (1)$$

11[b] where  $J$  is a tunnel current density flowing through the MgO layer,  $V$  is an applied bias voltage that is 100 mV or smaller,  $m$  is the free electron mass,  $e$  is the elementary electric charge,  $h$  is Planck's constant,  $\Delta s$  is an effective thickness of the MgO layer that is equivalent to  $(t_{\text{MgO}} - 0.5 \text{ nm})$ , and  $t_{\text{MgO}}$  is an actual thickness of the MgO layer.

12[pre] A magnetic tunnel junction (MTJ) device, comprising:

12[a] a first ferromagnetic material layer that includes Co, Fe, and B;

12[b] a barrier layer disposed on the first ferromagnetic material layer, the barrier layer comprising a magnesium oxide (MgO) layer that is a polycrystalline MgO in which (001) crystal plane is preferentially oriented; and

12[c] a second ferromagnetic material layer that is disposed on the barrier layer and includes Co, Fe, and B, and

12[d] wherein each of the first and second ferromagnetic material layers is entirely crystallized, and wherein a value of  $x$  in  $\text{MgO}_x$  for the MgO layer is greater than 0 and less than 1.

13. The MTJ device of claim 12, wherein a barrier height  $\phi$  of the barrier layer is in a range of 0.2 to 0.5 eV.

14[pre] The MTJ device of claim 13,

14[a] wherein the barrier height  $\phi$  of the barrier layer is obtained by fitting J-V characteristics of the MTJ device to an equation (1):

$$J = [(2m\phi)^{1/2} / \Delta s] (e/h)^2 \times \exp[-(4\pi\Delta s/h) \times (2m\phi)^{1/2}] \times V \quad (1)$$

14[b] where  $J$  is a tunnel current density flowing through the barrier layer,  $V$  is an applied bias voltage that is 100 mV or smaller,  $m$  is the free electron mass,  $e$  is the elementary electric charge,  $h$  is Planck's constant,  $\Delta s$  is an effective thickness of the barrier layer that is equivalent to  $(t_{\text{MgO}} - 0.5 \text{ nm})$ , and two *[sic]* is an actual thickness of the barrier layer.