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. IPR2024-01386
U.S. Patent No. 9,608,198

DECLARATION OF JEFFREY BOKOR, PH.D.

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2. Claim 1[a]: "wherein the tunnel barrier layer comprises a poly-crystalline magnesium oxide layer in which a (001) crystal plane is preferentially oriented," 90

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1. Claim 3[preamble]: "The tunnel barrier layer according to claim 2," 105

2. Claim 3[a]: "wherein the barrier height p of the tunnel barrier layer is obtained by fitting J-V characteristics of a tunnel barrier junction structure to an equation (1):

J=[(2mφ)1/2 /Δs](e/h)2×exp[−(4πΔs/h)×(2m#)1/2]×V (1)” 105

3. Claim 3[b]: “where J is a tunnel current density flowing through the tunnel 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 the Planck's constant, Δs is an effetive thickness of the tunnel barrier layer that is approximately equivalent to (tMgO−0.5 nm), and tMgO is an actual thickness of the tunnel barrier layer determined using a cross-sectional transmission electron microscope image.” 108

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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. 9,608,198 ("the '198 Patent") (EX1009).

2. In the course of preparing this Declaration, I reviewed the '198 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, nanomagnetics, 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 '198 Patent, or the owner of the '198 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, nanomagnetics, 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

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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")
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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 (EX1015)
1022	Japanese Patent Application No. JP2004313350
1023	Certified English Translation (with Translator Declaration) of Japanese Patent Application No. JP2004313350
1026	Bowen et al., *Large magnetoresistance in Fe/MgO/FeCo(001) epitaxial tunnel junctions on GaAs(001)*, 79 Appl. Phys. Letters 1655-1657 (2001) ("Bowen")
1027	European Patent Application No. EP1391942A1 to Nagahama et al. ("Nagahama")
1028	Soukup et al., *Voltage-Current Characteristics for Electrical Conduction Through Thin MgO Films*, 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, *Generalized Formula for the Electric Tunnel Effect between Similar Electrodes Separated by a Thin Insulating Film*, 34 J. Appl. Phys. 1793-1803 (1963)
1032	Trasatti, *Electronegativity, Work Function, and Heat of Adsorption of Hydrogen on Metals*, 67 J. Chem. Soc. 229-236 (1972)
1033	Jullière, *Tunneling between ferromagnetic* films, 54A Phys. Letters 225-226 (1975)

Exhibit No.	Description
1034	Miyazaki et al., *Giant magnetic tunneling effect in Fe / $A1_2O_3$ / Fe junction*, 139 J. Magnetism & Magnetic Materials L231-L234 (1995)
1035	Moodera et al., *Large Magnetoresistance at Room Temperature in Ferromagnetic Thin Film Tunnel Junctions*, 74 Phys. Rev. Lett. 3273–3276 (1995)
1036	Wulff et al., *Characterization of MgO Layers on Different Alumina and Glass Substrates by Grazing Incidence Diffractometry and Grazing Incidence X-ray Reflectometry*, 23 Surface & Interface Analysis 148-154 (1995)
1037	Castanier et al., *Oxygen vacancies on MgO(100)*, 364 Surf. Sci. 1-16 (1996)
1038	Moodera et al., *Ferromagnetic–insulator–ferromagnetic tunneling: Spin-dependent tunneling and large magnetoresistance in trilayer junctions (invited)*, 79 J. Appl. Phys. 4724-4729 (1996)
1039	Tehrani et al., *Progress and Outlook for MRAM Technology*, 35 IEEE Trans. Magn. 2814-2819 (1999)
1040	Yoon et al., *Growth characteristics and surface roughening of vapor-deposited MgO thin films*, 60 Phys. Rev. 2839-2843 (1999)
1041	Wollschläger et al., *Stoichiometry and morphology of MgO films grown reactively on Ag(100)*, 142 Appl. Surface Science 129-134 (1999)
1042	Pacchioni, *Ab initio theory of point defects in oxide materials: structure, properties, chemical reactivity*, 2 Solid State Scis. 161-179 (2000)
1043	Heinrich et al., *Single Crystal Tunnel Junctions*, IEEE (2000)
1044	Butler et al., *Spin-dependent tunneling conductance of Fe|MgO|Fe sandwiches*, 63 Phys. Rev. B 054416 (2001)
1045	Klaua et al., *Growth, structure, electronic, and magnetic properties of MgO/Fe(001) bilayers and Fe/MgO/Fe(001) trilayers*, 64 Phys. Rev. B. 134411 (2001)
1046	Mathon et al., *Theory of tunneling magnetoresistance of an epitaxial Fe/MgO/Fe(001) junction*, 63 Phys. Rev. 220403 (2001)

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

Exhibit No.	Description
1060	Jimbo et al., *Thermal stability of spin valves using amorphous CoFeB*, 165 J. Magnetism & Magnetic Materials 308-311 (1997)
1061	Cardoso et al., *Ferromagnetic Coupling Field Reduction in CoFeB Tunnel Junctions Deposited by Ion Beam*, 40 IEEE Trans. Magn. 2272-2274 (2004)
1062	U.S. Patent No. 7,270,896 ("Parkin")
1063	Complaint, *Godo Kaisha IP Bridge 1 v. Western Digital Corporation*, Case No. 24-cv-00342-RGA (D. Del. Mar. 15, 2024) (without exhibits)
1064	Claim Chart for '403 Patent, Exhibit D to Complaint, *Godo Kaisha IP Bridge 1 v. Western Digital Corporation*, Case No. 24-cv-00342-RGA (D. Del. Mar. 15, 2024)
1065	Claim Chart for '263 Patent, Exhibit E to Complaint, *Godo Kaisha IP Bridge 1 v. Western Digital Corporation*, Case No. 24-cv-00342-RGA (D. Del. Mar. 15, 2024)
1066	Claim Chart for '372 Patent, Exhibit F to Complaint, *Godo Kaisha IP Bridge 1 v. Western Digital Corporation*, Case No. 24-cv-00342-RGA (D. Del. Mar. 15, 2024)
1067	First Amended Complaint, *Godo Kaisha IP Bridge 1 v. Western Digital Corporation*, Case No. 24-cv-00342-RGA (D. Del. July 8, 2024)
1068	Amended Claim Chart for '403 Patent, Exhibit AA to First Amended Complaint, *Godo Kaisha IP Bridge 1 v. Western Digital Corporation*, Case No. 24-cv-00342-RGA (D. Del. July 8, 2024)
1069	Amended Claim Chart for '263 Patent, Exhibit BB to First Amended Complaint, *Godo Kaisha IP Bridge 1 v. Western Digital Corporation*, Case No. 24-cv-00342-RGA (D. Del. July 8, 2024)
1070	Amended Claim Chart for '372 Patent, Exhibit CC to First Amended Complaint, *Godo Kaisha IP Bridge 1 v. Western Digital Corporation*, 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, *Godo Kaisha IP Bridge 1 v. Western Digital Corporation*, Case No. 24-cv-00342-RGA (D. Del. July 8, 2024)
1072	Claim Chart for '138 Patent, Exhibit EE to First Amended Complaint, *Godo Kaisha IP Bridge 1 v. Western Digital Corporation*, Case No. 24-cv-00342-RGA (D. Del. July 8, 2024)
1073	Claim Chart for '198 Patent, Exhibit FF to First Amended Complaint, *Godo Kaisha IP Bridge 1 v. Western Digital Corporation*, Case No. 24-cv-00342-RGA (D. Del. July 8, 2024)
1074	Claim Chart for '463 Patent, Exhibit GG to First Amended Complaint, *Godo Kaisha IP Bridge 1 v. Western Digital Corporation*, Case No. 24-cv-00342-RGA (D. Del. July 8, 2024)
1075	Claim Chart for '167 Patent, Exhibit HH to First Amended Complaint, *Godo Kaisha IP Bridge 1 v. Western Digital Corporation*, Case No. 24-cv-00342-RGA (D. Del. July 8, 2024)
1076	Claim Chart for '134 Patent, Exhibit II to First Amended Complaint, *Godo Kaisha IP Bridge 1 v. Western Digital Corporation*, Case No. 24-cv-00342-RGA (D. Del. July 8, 2024)
1077	Docket *Godo Kaisha IP Bridge 1 v. Western Digital Corporation*, 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), https://www.uscourts.gov/statistics-reports/federal-court-management-statistics-december-2023 (excerpts)
1079	Microsoft Computer Dictionary (5th ed. 2002) (excerpts)

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 '198 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 '198 Patent priority date were around the March 12, 2004 date of the first Japanese priority application to the '198 Patent, the October 28, 2004 date of the second Japanese priority application to the '198 Patent, or the March 10, 2005 PCT filing date of the '198 Patent.

VI. LEVEL OF ORDINARY SKILL IN THE ART

25. Based on my review of the '198 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 '198 Patent generally relates to "a magnetic tunnel junction device and a method of manufacturing the same." EX1009 ('198 Patent) at col. 1:30-31.

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 '198 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.

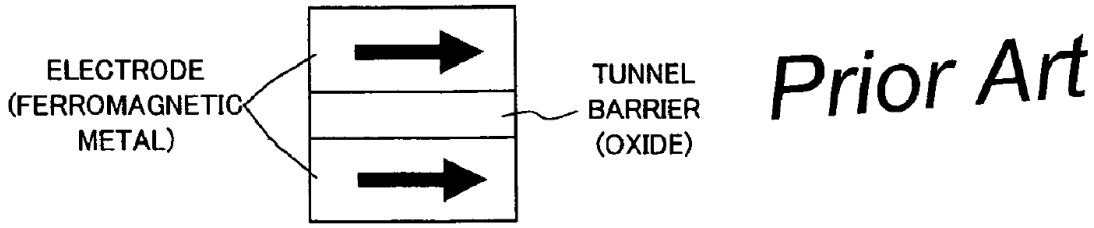
B. Magnetic Tunnel Junctions (MTJs) And Spintronics

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 (Klaua) 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 '198 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).

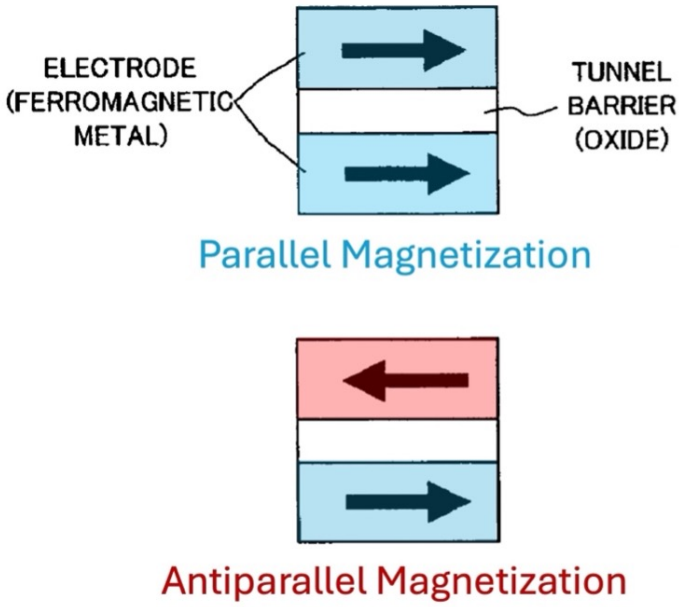


EX1009 ('198 Patent) at Fig. 8(A); *see also id.* at Fig. 8(B), col. 1:42-67; EX1057 (Dieny textbook) at page 9.

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; EX1009 ('198 Patent) at col. 1:51-62. 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; EX1009 ('198 Patent) at col. 1:51-67.



EX1009 ('198 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:

$$\mathrm{TMR} = \frac{\Delta R}{R_{\mathrm{p}}} = \frac{R_{\mathrm{ap}} - R_{\mathrm{p}}}{R_{\mathrm{p}}}$$

EX1035 (Moodera 1995) at page 3273; EX1027 (Nagahama) ¶2; EX1009 ('198 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

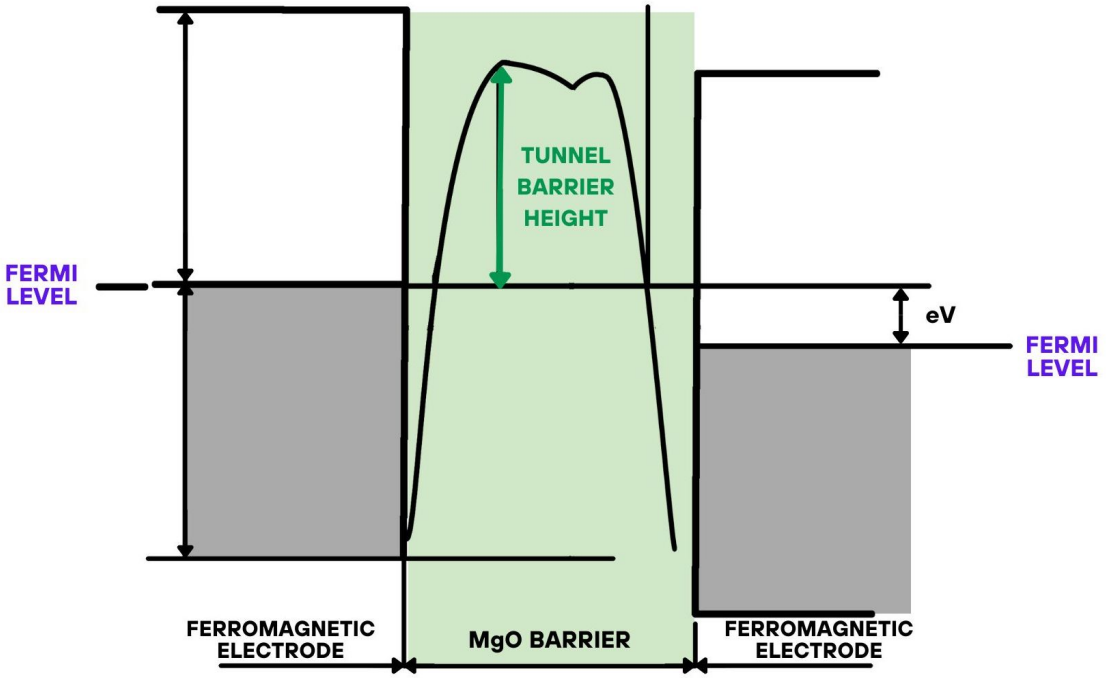
over 100% MR ratio in the future…. The key issues of MRAM technology as a future memory candidate are resistance control and low current operation for small enough device size."); EX1057 (Dieny textbook) at page 9 ("[L]arger TMR ratios… enabled new types of MRAM that could be scaled down in size and 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 on 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." EX1009 ('198 Patent) at col. 3:57-60.

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:

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

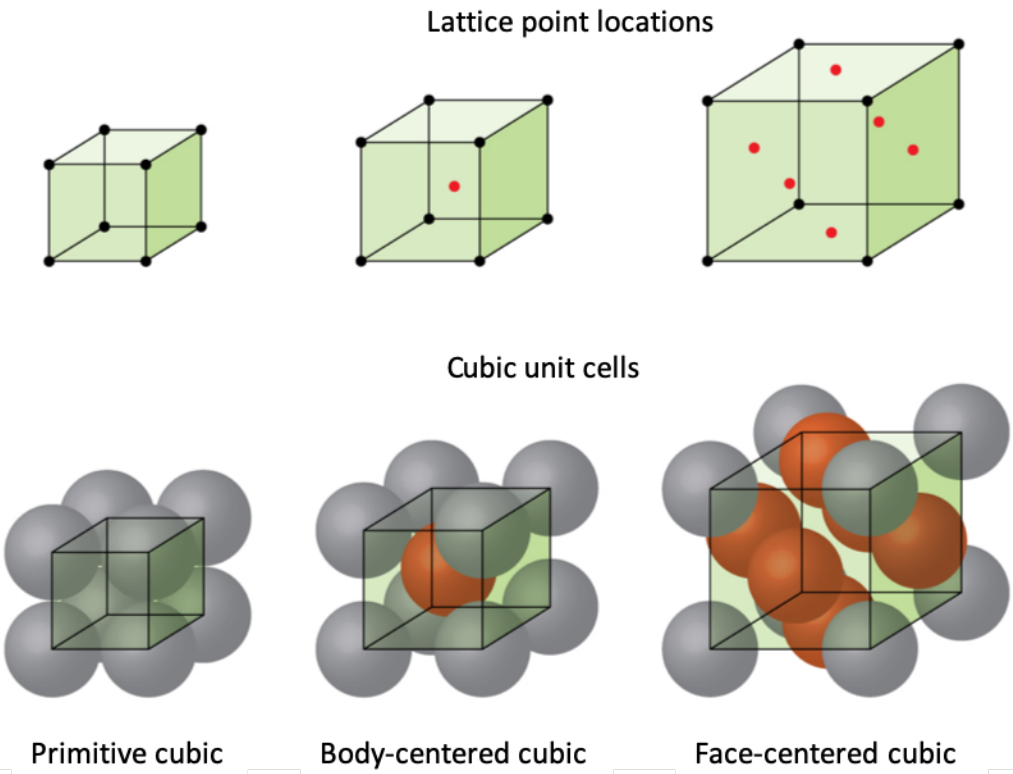
EX1059 (Matthews) at page 1.

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.

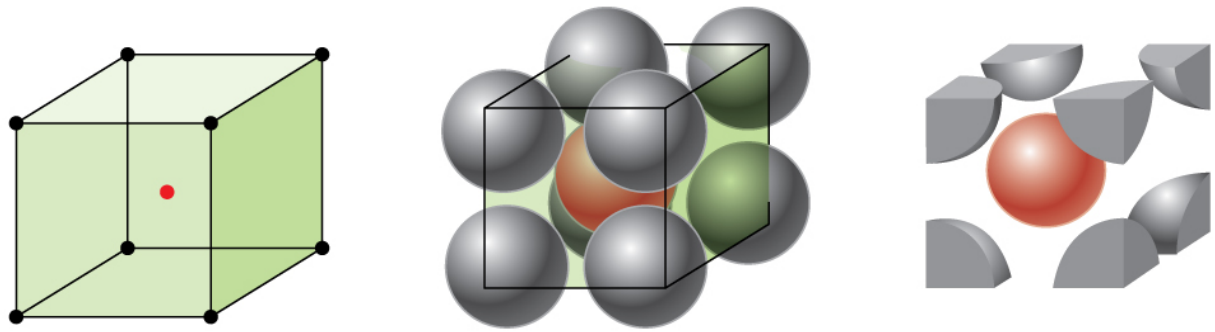
1. Crystalline Structures

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

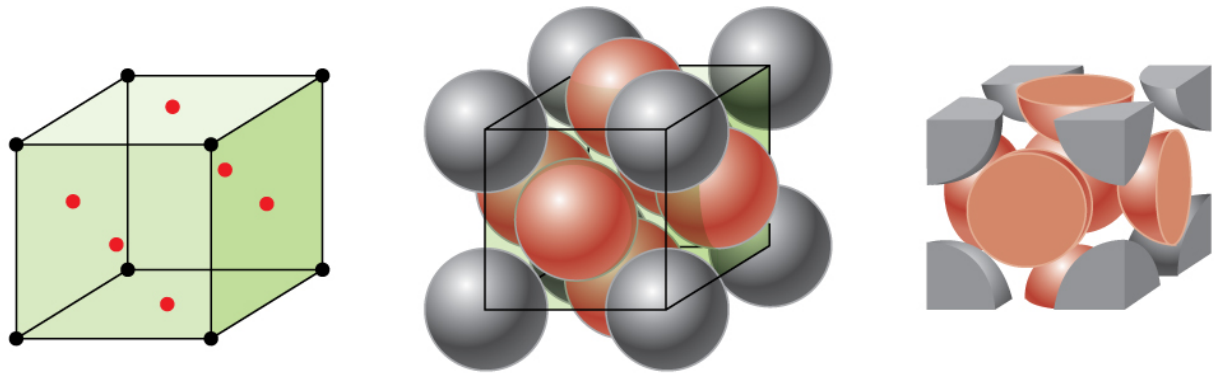


UW Madison Chemistry 103/104 Resource Book ("UW Chemistry Book"), Topic 61, Fig. 1, *available at* https://wisc.pb.unizin.org/minimisgenchem/chapter/types-of-unit-cells-body-centered-cubic-and-face-centered-cubic-m11q5/.

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:



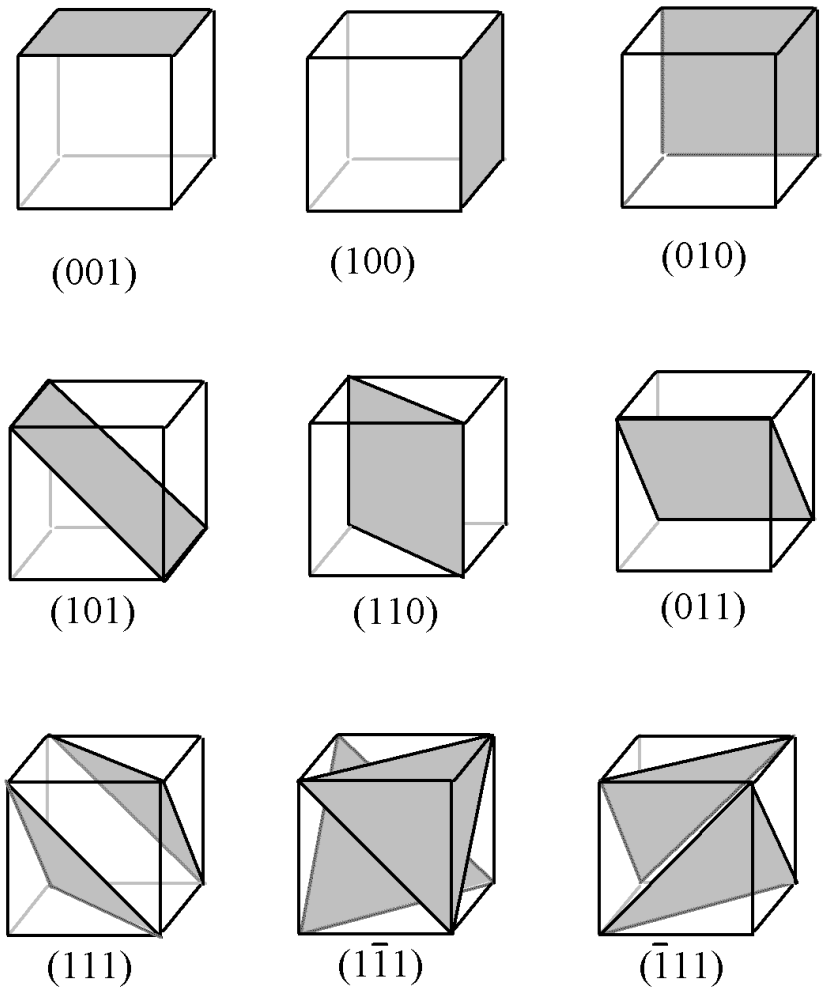
Body-centered cubic structure



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. The '198 Patent agrees. EX1009 ('198 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 ($Fe_{50}Co_{50}$ 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 was 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 "$Co_{60}Fe_{20}B_{20}$ 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 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 (Al_2O_3) and magnesium oxide (Mg), depicted below:

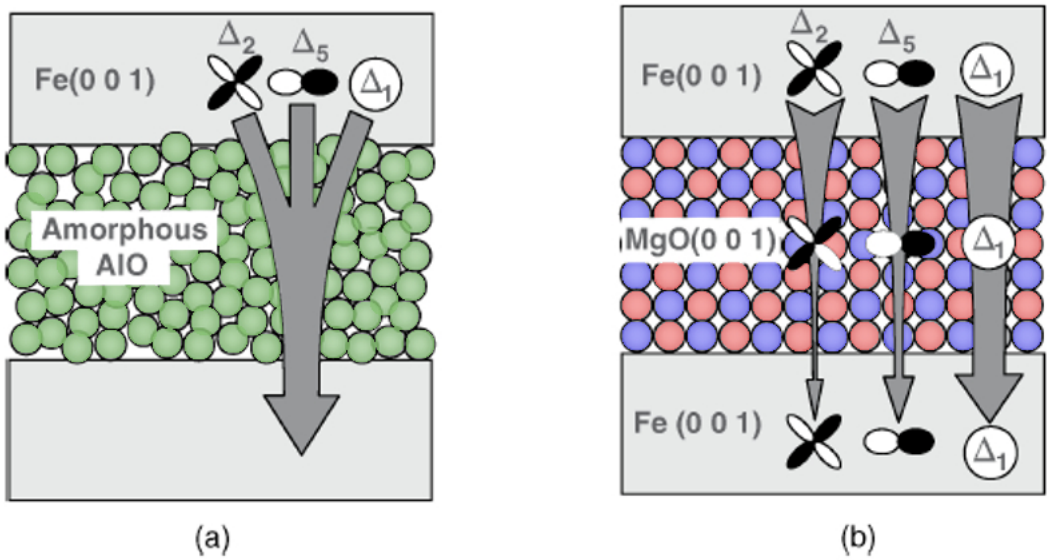


Figure 2.19 Schematic of electron tunneling through (a) an amorphous AlO barrier and (b) a crystalline MgO(0 0 1) barrier.

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

64. Researchers initially focused their efforts on studying aluminum oxide (Al_2O_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 (Al_2O_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 (Klaua) at page 1. Both parallel and antiparallel spin electrons are randomly scattered. EX1045 (Klaua) at page 1.

66. Magnesium oxide (MgO) later became commonly used as the insulating or barrier layer. MgO crystals are known for their cubic structure, similar to rock salt (NaCl). EX1040 (Yoon) at page 2839 ("MgO… has NaCl structure"); EX1041 (Wollschläger) at page 130 ("MgO crystallizes in the rocksalt structure"); EX1009 ('198 Patent) at col. 4:39-40 ("MgO has a cubic crystal structure (NaCl structure)").

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

EX1009 ('198 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 (Klaua) 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 Klaua explained, unlike amorphous Al_2O_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 (Klaua) 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 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

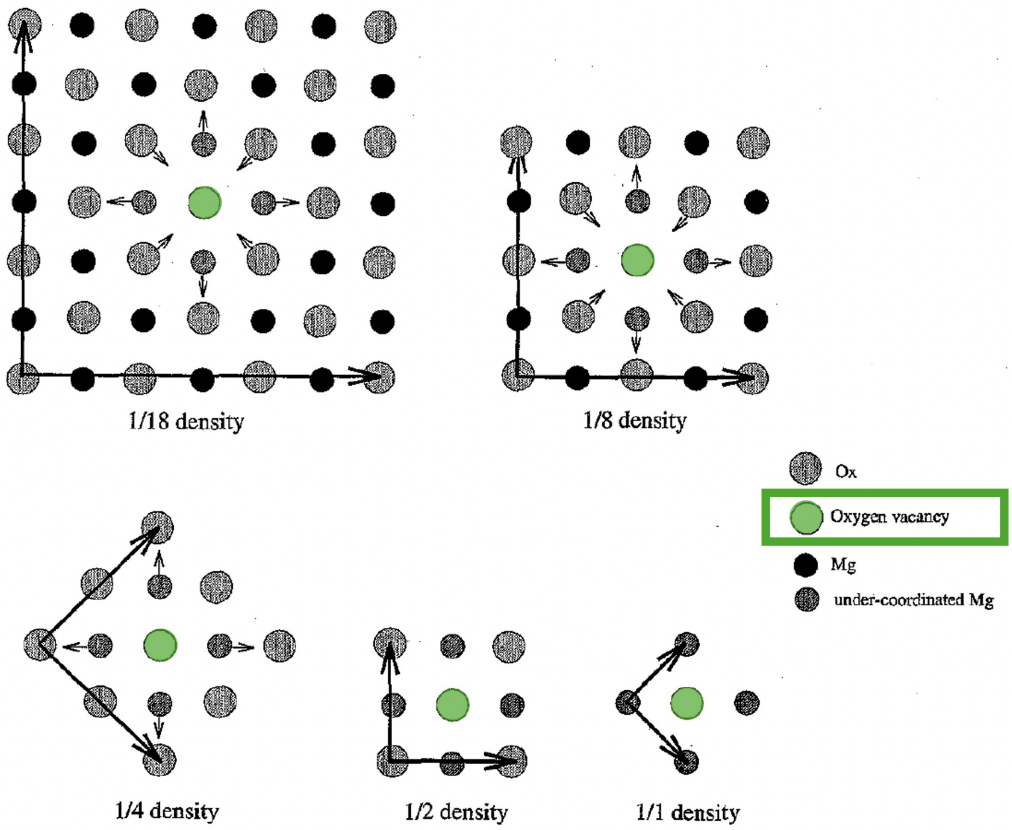
73. Oxygen vacancies are one of the most important defects that are naturally present in every oxide. EX1042 (Pacchioni) at page 162. In the literature, oxygen vacancy defects in MgO are sometimes referred to as "color centers" or "F centers." EX1042 (Pacchioni) at page 162; *see also* EX1048 (Bogicevic) 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, as shown above. 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 MgO_x, where x<1, describing a sub-stoichiometric composition (e.g. MgO_x). *E.g.*, EX1041 (Wollschlager) at page 132 ("understoichiometric MgO_x (x < 1)"). In a perfect, stoichiometric MgO crystal, x would equal 1. This is described in the '198 Patent. EX1009 ('198 Patent) at cols. 7:6-7 ("[T]here is the possibility that there are oxygen vacancy defects such as MgO_x (0.9<x<1)."), 7:22-24. The '198 Patent applicant provided this explanation about oxygen vacancy defects: "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 (Klaua) 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 (Klaua) at page 4. Yet the defect states were not due to surface errors or irregularities. EX1045 (Klaua) 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 (Klaua) at page 5. He " assume[d] that the observed defects are intrinsic to the MgO layer due to the agglomeration of atomic defects." EX1045 (Klaua) at page 5. In other words, the tunneling appeared related to oxygen vacancy defects intrinsic in the MgO barrier. Yet when Klaua studied the properties of the MgO barrier, the IV characteristics "give no hint of the presence of any defects in the MgO layer." EX1045 (Klaua) 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. Klaua'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 effects of lattice defects on tunneling," EX1047 (Wulfhekel) at page 509, Wulfhekel found high tunneling current 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.

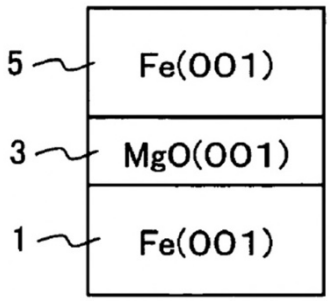
82. Similarly, Bowen observed a lower barrier height for an MgO thin film and hypothesized that it may have resulted from "the presence of stoichiometric and/or thickness inhomogeneities in the insulating film." EX1026 (Bowen) at

page 1656. As Parkin observed, "the exact composition of the MgO layer may differ from the stochiometric [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 '198 PATENT

83. The '198 Patent is titled "Magnetic Tunnel Junction Device." EX1009 ('198 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." EX1009 ('198 Patent) at col. 1:42-49; *see also id.* at col. 1:49-67. As shown in Figure 1(B) below, the '198 Patent discloses two Fe electrodes surrounding a single-crystalline or polycrystalline MgO barrier layer:

FIG. 1 (B)



EX1009 ('198 Patent) at Fig. 1(B), col. 5:39-45.

84. Each of the '198 Patent's six claims, Claims 1-6, are directed to an MTJ device with a tunnel barrier layer. EX1009 ('198 Patent) at col. 10:6-48. Claim 1

purports to claim an MTJ device that is disposed over a substrate, wherein the lower, or first, electrode comprises "an Fe-Co alloy of BCC which alloy comprises Fe, Co, and B." EX1009 ('198 Patent) at col. 10:6-17 (Claim 1); *see also id.* at cols 10:35-48 (Claims 4-6). Dependent Claims 2 and 3 further require a tunnel barrier height "in a range of 0.2 to 0.5 eV." EX1009 ('198 Patent) at col. 10:18-21. Claim 3 further requires that the barrier height be "obtained by fitting J-V characteristics of a tunnel barrier junction structure to" Simmons' formula where the bias voltage is set to "100 mV or smaller," the "effective thickness of the tunnel barrier layer" is "approximately equivalent to (t_{MgO}–0.5nm), and t_{MgO} is an actual thickness of the tunnel barrier layer." EX1009 ('198 Patent) at col. 10:21-35.

85. According to the '198 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 MgO_x ($0.9<x<1$)." EX1009 ('198 Patent) at cols. 6:61-7:7. The '198 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." EX1009 ('198 Patent) at col. 7:7-12.

86. The '198 Patent also explains that the "basic structure of the MRAM," as shown in Figure 9, is "Prior Art." EX1009 ('198 Patent) at col. 2:1-2, 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." EX1009 ('198 Patent) at col. 2:8-11; *see also id.* at cols. 2:1-28.

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 '198 Patent's specification. Where relevant, I have identified teachings in the '198 Patent that inform the plain and ordinary meaning of the claim limitations.

X. PRIOR ART TO THE '198 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 '198 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.

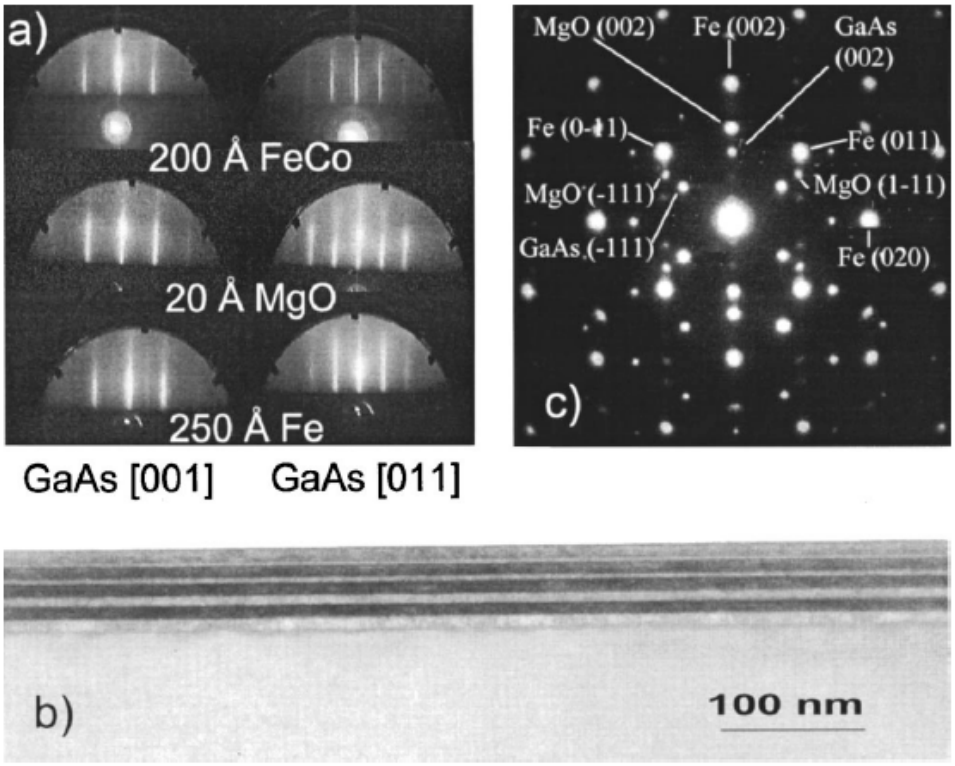


FIG. 1. (a) RHEED patterns along the GaAs [100] and [110] substrate azimuths of a typical FeCo/MgO/Fe epitaxial structure; (b) cross section TEM image of a Fe/MgO(001) multilayer with gradually decreasing MgO layer thickness; (c) TEM electron diffraction pattern.

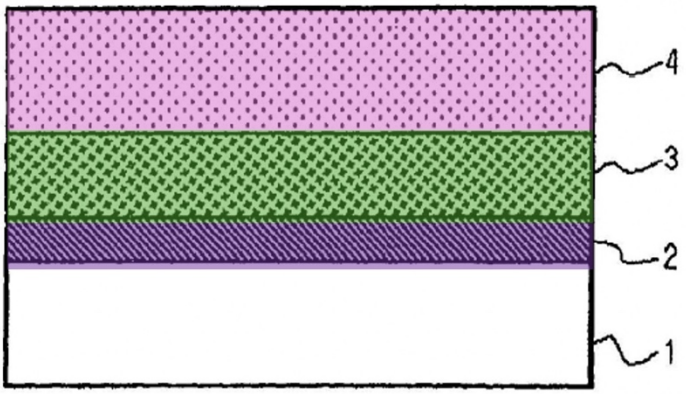
EX1026 (Bowen) at Fig. 1.

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. European Patent Application Publication No. EP1391942A1 to Nagahama *et al*. (EX1027, "Nagahama")

92. Nagahama was a collaboration between the named inventor of the '198 Patent and two other researchers, then at the National Institute of Advanced Industrial Science and Technology in Japan. EX1027 (Nagahama) at page 1. Nagahama disclosed an MTJ having an MgO barrier disposed between two ferromagnetic layers. EX1027 (Nagahama) at page 1, ¶73.

FIG. 3

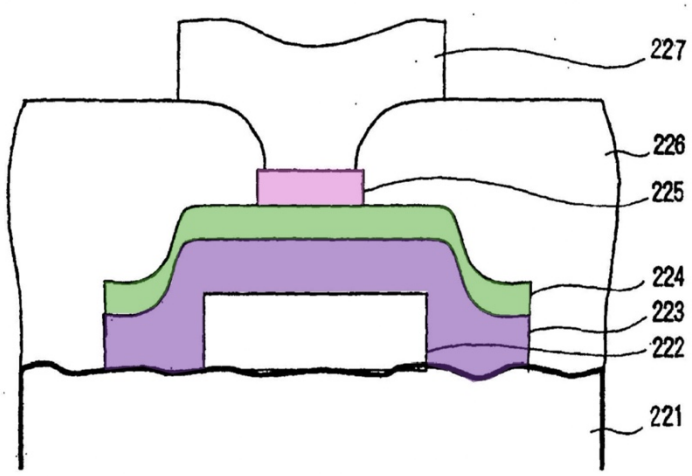


EX1027 (Nagahama) at Fig. 3 (excerpted, annotated).

93. As shown in the excerpted and shaded Figure 3 (reproduced above), Nagahama generally disclosed an MTJ structure with a ferromagnetic electrode 4 [**pink**], an insulating layer 3 [**green**], and an ultrathin ferromagnetic layer 2 [**purple**] on a substrate underlayer 1 [white]. EX1027 (Nagahama) at Abstract.

94. Nagahama further disclosed a polycrystalline MgO thin-film MTJ shown, for example, in Figure 17 reproduced below with a lower ferromagnetic electrode (223) [**purple**], a barrier layer (224) [**green**], and an upper ferromagnetic electrode (225) [**pink**]. EX1027 (Nagahama) ¶76. In another example, Nagahama taught "a (001)-highly-oriented lower ferromagnetic electrode layer, a (001)-highly-oriented MgO barrier layer, and a (001)-highly-oriented upper ferromagnetic electrode layer." EX1027 (Nagahama) ¶73. Nagahama taught that its invention could be implemented using a "body-centered cubic lattice." *E.g.*, EX1027 (Nagahama) ¶¶1, 18 (item [20]). Observing that Bowen *et al.* experimentally obtained a TMR of "more than 60%," EX1027 (Nagahama) ¶14, Nagahama disclosed that its MgO-based MTJ obtained superior results: "a larger tunnel magnetoresistive effect of more than 90%," *id.* ¶74.

FIG. 17



EX1027 (Nagahama) at Fig. 17 (annotated).

95. Under the heading "Industrial Applicability," Nagahama taught that its MTJ is "suitably used in a magnetic sensor of a pickup head of a hard disk drive or a ferromagnetic random access memory." EX1027 (Nagahama) ¶82.

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

96. 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.

97. 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.

98. 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.

D. Japanese Patent Application Publication No. JP2002204004A to Sunai *et al.* (EX1029/EX1030, "Sunai")

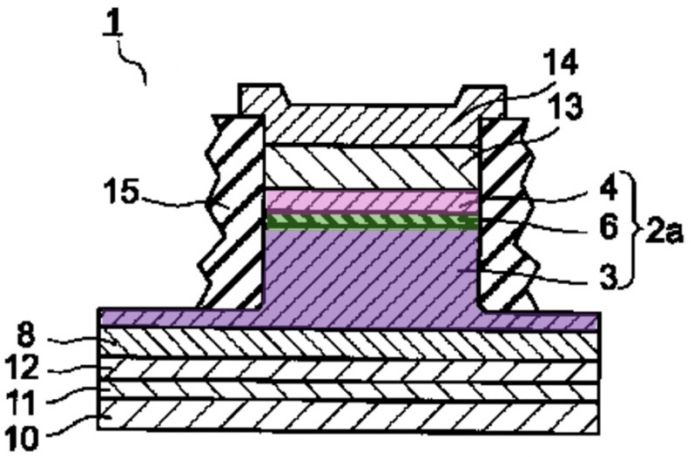
99. Published in 2002, Sunai is a Japanese patent application titled "Magnetoresistance effect element, magnetic memory, magnetic head, and magnetic reproducing device." EX1030 (Sunai) at page 1.

100. I am informed that EX1029 is a copy of Sunai and EX1030 is a copy of a certified English translation of Sunai. I will reference the English translation in this declaration unless otherwise indicated.

101. Sunai described providing an MTJ for "magnetic memory" that "can maintain a sufficiently high magnetoresistance ratio." EX1030 (Sunai) at Abstract. Sunai specifically disclosed using its MTJ in a "magnetic random access memory: MRAM." EX1030 (Sunai) ¶4.

102. As shown in Figure 1 below, Sunai disclosed a conventional 3-layer MTJ with "a first ferromagnetic layer 3" [**purple**], "a second ferromagnetic layer 4" [**pink**], and "a first tunnel barrier layer 6 [**green**] interposed between the first ferromagnetic layer 3 and the second ferromagnetic layer 4." EX1030 (Sunai) at Abstract, ¶1.

[Figure 1]

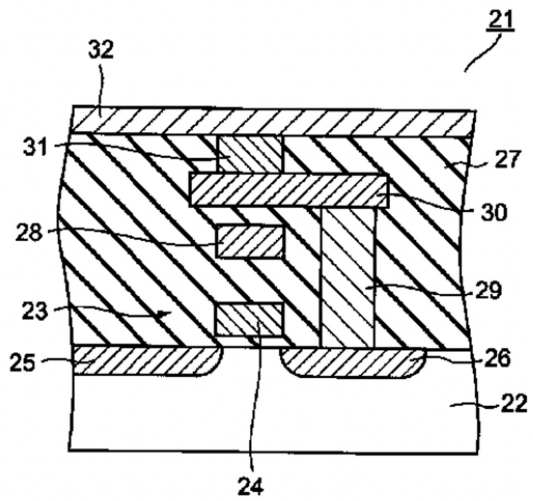


EX1030 (Sunai) at Fig. 1 (annotated).

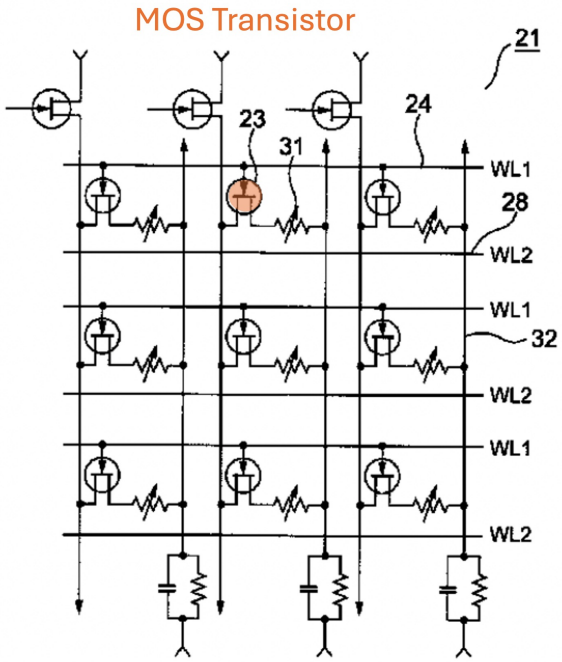
103. Sunai further disclosed that the ferromagnetic layer 4 in its MTJ included a CoFeB alloy. EX1030 (Sunai) ¶24 ("[T]he composition of the ferromagnetic layer 4 is represented by the general formula $(CoFe)_{100-x}Y_x$ … [where] Y is at least one element selected from the group consisting of B" or other elements.); *id.* at Abstract, ¶11.

104. As shown in Figures 4-5 below, Sunai taught and depicted how to use its MTJ in an MRAM:

[Figure 4]



[Figure 5]



EX1030 (Sunai) ¶¶38-40, Figs. 4-5 (Fig. 5 annotated). Figure 4 provides a "cross-sectional view that shows a schematic of a magnetic memory (MRAM) using" Sunai's MTJ (called "TMR 31" in Sunai), while Figure 5 depicts the "equivalent circuit diagram of the MRAM shown in Figure 4." EX1030 (Sunai) ¶38. A

transistor (MOS transistor 23) and an MTJ (TMR 31) together form the memory cell in Sunai's MRAM 21. EX1030 (Sunai) ¶¶39, 42.

XI. SUMMARY OF OPINIONS OFFERED

105. In my opinion, the claims are obvious over the two grounds presented in this Declaration.

XII. GROUND 1: CLAIMS 1-6 ARE OBVIOUS OVER BOWEN IN VIEW OF SUNAI (AND SOUKUP)

106. In my opinion, Claims 1-6 are obvious over the prior art. Specifically:

a. Claims 1 and 4-6 are obvious over Bowen in view of Sunai.

b. Claims 2 and 3 are obvious over Bowen in view of Sunai and Soukup.

A. Claim 1: Obviousness Over Bowen In View Of Sunai

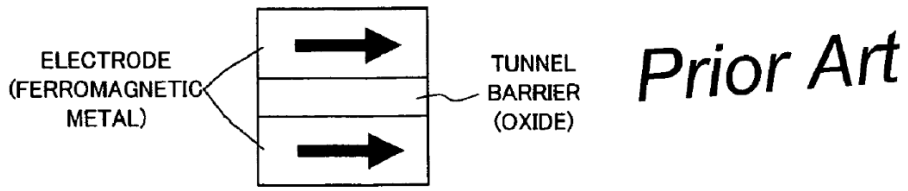
1. Claim 1[preamble]: "A tunnel barrier layer disposed between a first ferromagnetic material layer and a second ferromagnetic material layer that are disposed over a substrate,"

107. 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 '198 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.

108. Magnetic tunnel junctions (MTJs), including those with a three-layer MTJ structure, were well known in the art. This is evident from the '198 Patent itself. EX1009 ('198 Patent) at Figs. 8(A)-8(B), col. 1:42-67. For example,

Figure 8(A) of the '198 Patent below shows a "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 material." EX1009 ('198 Patent) at col. 1:45-49. The patent correctly identifies and labels this conventional MTJ design as "Prior Art":

FIG. 8 (A)



EX1009 ('198 Patent) at Fig. 8(A) ("Prior Art" legend in original).

109. Bowen disclosed a magnetoresistive device having a tunnel barrier layer arrangement as recited in this claim.

110. Claim 1[preamble]'s "ferromagnetic material layer" refers to an electrode made of a "ferromagnetic metal." EX1009 ('198 Patent) at col. 1:45-49, Fig. 8(a). The "tunnel barrier" layer refers to "an oxide [that] is sandwiched between a first and a second electrode made of a "ferromagnetic metal." EX1009 ('198 Patent) at col. 1:45-49. According to the '198 Patent, "first ferromagnetic material layer" refers to the "lower" ferromagnetic electrode that is closest to the substrate and below the tunnel barrier layer, and the "second ferromagnetic material layer"

refers to the "upper" ferromagnetic electrode located above the tunnel barrier layer. EX1009 ('198 Patent) at Abstract.

111. Bowen's first ferromagnetic material layer consists of an "Fe" layer, while its second ferromagnetic material layer consists of a "FeCo" layer. EX1026 (Bowen) at 1655 (describing an MTJ comprised of a "Fe bottom electrode" and a "FeCo top electrode"). Iron (Fe) and cobalt (Co) are ferromagnetic materials. EX1030 (Sunai) ¶33 ("ferromagnetic 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."); EX1009 ('198 Patent) at col. 6:14-15 ("Fe(001) refers to a ferromagnetic material….").

112. Bowen disclosed a MgO tunnel barrier layer. Bowen explained: "We present tunneling experiments on Fe(001)/***MgO*** (20 Å)/FeCo(001) single-crystal epitaxial junctions of high quality…." EX1026 (Bowen) at Abstract (emphasis added). Bowen's "MgO barrier is grown at 400 °C in order to obtain good crystallinity." EX1026 (Bowen) at page 1655, Fig. 1.

113. Bowen explains that its "Fe bottom electrode" is formed on a first side of its MgO barrier layer and its FeCo layer is the "top electrode," and is thus formed on a second side of the MgO barrier layer. EX1026 (Bowen) at page 1655, Abstract,

Fig. 1. Thus, one of skill would understand that Bowen's MgO tunnel barrier layer was sandwiched or located between its first and second ferromagnetic layers.

114. Bowen also disclosed a "GaAs(001)" substrate that included an MgO interdiffusion barrier. Bowen explains that its "FeCo/MgO/Fe epitaxial structures" were grown on top of the "GaAs(001)" substrate. EX1026 (Bowen) at page 1655; *id.* at Fig. 1. Under Bowen's configuration, the first ferromagnetic layer, or "Fe bottom electrode," was deposited on top of the substrate. To prevent "the incorporation of As from the substrate into the Fe bottom electrode," Bowen added "a MgO buffer layer as an interdiffusion barrier" as part of its substrate and below the first ferromagnetic layer. EX1026 (Bowen) at page 1655. One of skill would have understood that Bowen's configuration disclosed that the GaAs/MgO substrate sits beneath the MTJ layers, meaning that Bowen's MTJ layers were deposited on top of, or "disposed over," the GaAs/MgO substrate.

115. It was also obvious for MTJ layers to be positioned on top of a substrate with or without the presence of an "MgO buffer layer." Depositing MTJs on top of a substrate was well known. Miyazaki disclosed depositing $Fe/Al_2O_3/Fe$ MTJs "onto a glass substrate." EX1034 (Miyazaki) at page 232. Both Miyzaki and Bowen relied on MTJs with Fe ferromagnetic material layers to improve TMR. EX1034 (Miyazaki) at page 232 (attempting to obtain "a large magnetoresistance ratio"); EX1026 (Bowen) at page 1655 ("[W] e present experimental results showing large

TMR values….”). Thus, one of skill would have known that Bowen’s MTJ layers would be placed on top of a substrate. EX1034 (Miyazaki) at page 232; EX1026 (Bowen) at page 1655.

2. Claim 1[a]: “wherein the tunnel barrier layer comprises a poly-crystalline magnesium oxide layer in which a (001) crystal plane is preferentially oriented,”

116. This claim limitation was taught or suggested by Bowen.

117. As I explained for Claim 1[preamble] in Section XII.A.1 of this Declaration, Bowen disclosed a single-crystal MgO(001) tunnel barrier layer. EX1026 (Bowen) at Abstract, page 1655. Bowen’s reference to MgO(001) refers to the (001) crystalline plane. EX1026 (Bowen) at Abstract, page 1655. One of skill would have found it obvious to use a polycrystalline MgO barrier with the (001) crystal plane preferentially oriented in place of Bowen’s single-crystal MgO barrier.

118. 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. One of skill knew polycrystalline 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 ≈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.

119. Polycrystalline MgO provided its own advantages. It was easily be 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 <100> orientation regardless of the substrate selection." EX1036 (Wulff) at page 148. Yoon also studied the deposition of 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.

120. Because using 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 tunnel 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.

3. Claim 1[b]: "wherein the first ferromagnetic material layer is composed of an Fe—Co alloy of BCC which alloy comprises Fe, Co, and B,"

121. Claim 1[b] is disclosed or suggested by Bowen in view of Sunai. As I explained for Claim 1[preamble] in Section XII.A.1, Bowen disclosed a first or lower Fe ferromagnetic layer.

122. Claim 1[b] does not specify the specific molecular composition of the claimed "CoFeB alloy." EX1009 ('198 Patent) at col. 10:13-15 (Claim 1[b]). Thus, I was asked to assume that any CoFeB alloy satisfies Claim 1[b].

123. Bowen's Fe ferromagnetic layer is bcc structured: "$Fe_{50}Co_{50}$ and ***Fe layers are bcc structured*** with sharp diffraction lines for both azimuths." EX1026 (Bowen) at page 1655 (emphasis added). BCC structured refers to a crystalline body-centered cubic lattice structure. EX1057 (Dieny textbook) at page 16 ("bcc stands for body-centered cubic, relative to the arrangement of the atoms in the crystal"); *supra* §VII.E.1 of this Declaration. The '198 Patent agrees. EX1009 ('198 Patent) at cols. 4:44-47 ("BCC structure" means "body-centered cubic lattice structure."), 6:14-15 ("Fe(001) refers to a ferromagnetic material with the BCC structure.").

124. It would have been obvious to replace Bowen's lower Fe electrode with a CoFeB ferromagnetic layer, as taught by Sunai, including to improve TMR. EX1030 (Sunai) ¶¶28 (teaching CoFeB electrode by adding B to Co_9Fe), 24 (teaching "ferromagnetic layer 4 is represented by the general formula $(CoFe)_{100-x}Y_x$" and specifying Y is an "element selected from the group consisting of B" or other elements); *id.* ¶¶25-29. Fe and cobalt (Co) were known ferromagnetic materials, and CoFeB was a known ferromagnetic alloy based on Fe and Co. EX1030 (Sunai) ¶33 ("ferromagnetic 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.

125. To improve Bowen's MTJ, one of skill would have looked to Sunai's teachings. Bowen and Sunai both sought to improve the TMR of magnetoresistive devices, one of the problems the '198 Patent claimed to address. EX1026 (Bowen) at Abstract, page 1655; EX1030 (Sunai) at Abstract, ¶¶1, 10; EX1009 ('198 Patent) at Abstract, cols. 1:30-2:28. Like the '198 Patent, Bowen and Sunai also both discussed improving MRAM memory performance. EX1026 (Bowen) at page 1655; EX1030 (Sunai) at Figs. 4-5, ¶¶1, 4, 38-40; EX1009 ('198 Patent) at cols. 1:35-41, 2:34-38. Further, they both used an MgO barrier layer and ferromagnetic alloy electrodes. EX1026 (Bowen) at Abstract, page 1655; EX1030 (Sunai) ¶¶24, 35.

126. Sunai explained 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. EX1030 (Sunai) ¶¶27-28 (discussing improved TMR resulting from adding B to CoFe). Other researchers agreed. Wang extolled the "benefit of using CoFeB is multifold," including "a higher TMR value." EX1055 (Wang) at pages 2269-70. Hosomi taught that when an MTJ "ferromagnetic layer" is "comprised of a CoFeB alloy," it "exhibits a larger TMR ratio." EX1056 (Hosomi) ¶39. Hosomi found "remarkabl[e] increases in the TMR ratio" for certain CoFeB alloys. EX1056 (Hosomi) ¶76.

127. 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, Sunai's and other researchers'

teachings about CoFeB would have provided a strong motivation to modify Bowen's MTJ to include a CoFeB electrode to attempt to increase the TMR.

128. One of skill would have been motivated to replace either or both of Bowen's MTJ electrodes with a CoFeB electrode. 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 '198 Patent, a 1995 paper by Moodera taught trying different Co, Fe, and CoFe alloys for the top and bottom electrodes:

> 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. Wang found "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 to improve TMR and tunneling was widely known and an obvious modification.

129. Further, a skilled artisan knew that using CoFeB adjacent to MgO crystalline layers produced bcc crystalline structures of CoFeB. This is because of the template effect of the MgO barrier on the CoFeB electrodes. One of skill was 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. Jimbo's 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. One of skill was aware that MgO would crystallize in a cubic structure with the (001), (100), and (010) crystalline planes being the same. *See* Section VII.E.1 of this Declaration. One of skill would have been aware that CoFeB would adopt the (001) crystalline structure of an adjoining MgO (001) layer. *E.g.*, EX1060 (Jimbo) at page 308. This was true in Jimbo despite a lattice mismatch between the Au and CoFeB. EX1060 (Jimbo) at page 309, Figure 1. One of skill in the art would expect CoFeB to crystallize in the same crystalline plane of an adjoining MgO layer because of the closer lattice match between CoFeB and MgO. *E.g.*, EX1046 (Mathon) at page 1 ("only a small lattice mismatch of about 3.5%" between in-plane distances of Fe and O). Indeed, Parkin, for example, described the effect of using

CoFeB adjacent to the MgO crystal structure, explaining that the MgO layer "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; *see also id.* at col. 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."). Thus, when substituting a CoFeB electrode in place of an Fe electrode in an MgO MTJ, one of skill understood that doing so would result in a bcc CoFeB structure.

130. Because CoFeB electrodes had already been used with MTJs, one of skill would have found it to be straightforward and predictable to replace Bowen's lower Fe electrode with CoFeB. Certainly MTJs already used CoFeB alloy electrodes successfully to increase the TMR ratio. EX1030 (Sunai) ¶¶27-28; EX1055 (Wang) at pages 2269-70; EX1056 (Hosomi) ¶¶39, 78. Sunai itself taught that "when B is added to Co_9Fe" alloy, it would improve TMR. EX1030 (Sunai) ¶28. Replacing Bowen's electrode with a CoFeB alloy was a straightforward and desirable improvement.

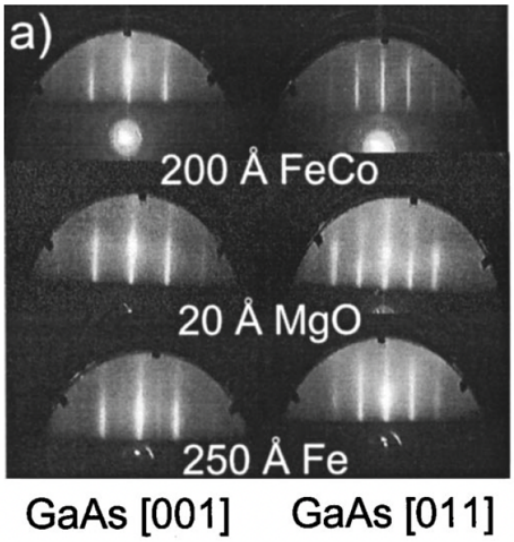
4. Claim 1[c]: "wherein the first ferromagnetic material layer is located between the tunnel barrier layer and the substrate."

131. Bowen taught or suggested this limitation. As I explained for Claim 1[preamble] in Section XII.A.1 of this Declaration, Bowen disclosed a first or lower

Fe ferromagnetic layer located between the MgO tunnel barrier layer and a GaAs(001) substrate.

132. Bowen taught growing "FeCo/MgO/Fe epitaxial structures" on a substrate. EX1026 (Bowen) at page 1655. Bowen's "Fe bottom electrode" was located on a first or bottom side of the MgO barrier layer and deposited on top of a GaAs(001) substrate. EX1026 (Bowen) at pages 1655-56, Fig. 1. Bowen taught growing a 20 Å thick MgO(001) tunnel barrier layer on top of its "Fe bottom electrode." EX1026 (Bowen) at page 1655; *id.* at Abstract, Fig. 1.

133. Bowen examined the quality of its MTJ using reflection high energy electron diffraction. EX1026 (Bowen) at page 1655. Figure 1 on the right depicts the RHEED patterns obtained for Bowen's MTJ. EX1026 (Bowen) at Fig. 1 (excerpted). As shown in the figure, Bowen's first ferromagnetic layer (Fe) was located between the MgO tunnel barrier layer and the GaAs substrate.



134. As I explained for Claim 1[preamble] in Section XII.A.1 of this Declaration, to prevent "the incorporation of As from the substrate into the Fe bottom electrode," Bowen added an "MgO buffer layer as an interdiffusion barrier" between its substrate and first ferromagnetic layer. EX1026 (Bowen) at page 1655.

One of skill would have understood that Bowen's lower Fe electrode was nonetheless located between the tunnel barrier layer and the substrate, as shown in Figure 1 in the preceding Paragraph 133. As I explained, it was also obvious for MTJ layers to be positioned on top of a substrate without the presence of an "MgO buffer layer." *Supra* § XII.A.1.

B. Claim 2: Obviousness Over Bowen In View Of Sunai And Soukup

1. Claim 2: "The tunnel barrier layer according to claim 1, wherein a barrier height of the tunnel barrier layer is in a range of 0.2 to 0.5 eV."

135. As I explained previously in Section XII.A of this Declaration, Claim 1 is obvious over Bowen in view of Sunai. Claim 2 depends from Claim 1 and thus incorporates all of Claim 1's requirements. Claim 2 is obvious over Bowen in view of Sunai and Soukup.

136. Bowen in view of Sunai and Soukup taught or suggested Claim 2. Claim 2 adds a single requirement: a tunnel barrier height in a range of 0.2 to 0.5 eV. As I explained previously in Section VII.D of this Declaration, the tunnel barrier height measures the difference between the Fermi level of the electrode and the bottom of the conduction band of the barrier layer.

137. The '198 Patent acknowledges this is the definition of a tunnel barrier height. It explains that "the height of the tunnel barrier" is "the band discontinuity value… between the bottom of the conduction band of the MgO(00l) layer and the

Fermi energy of the Fe(00l) layer." EX1009 ('198 Patent) at col. 3:12-16. And: "the discontinuous value (the height of the tunnel barrier) between the bottom of the conduction band of the MgO(00l) layer and the Fermi energy of the first or the second ferromagnetic material layer." EX1009 ('198 Patent) at col. 3:56-62.

138. In sum, Claim 2 requires a tunnel barrier height in a claimed range of 0.2 to 0.5 eV.

139. Bowen in view of Sunai and Soukup taught or suggested a tunnel barrier height between 0.2 to 0.5 eV.

140. 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 claimed range of 0.2 to 0.5 eV. EX1028 (Soukup) at Abstract, pages 3231-32, Fig. 5, Table I.

141. 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.

142. 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 (barrier height) for parallel spin electrons compared to antiparallel improved TMRs:

$$\mathrm{TMR} = \frac{\Delta R}{R_{\mathrm{p}}} = \frac{R_{\mathrm{ap}} - R_{\mathrm{p}}}{R_{\mathrm{p}}}$$

EX1035 (Moodera 1995) at page 3273; EX1027 (Nagahama) ¶2; EX1009 ('198 Patent) at cols. 4:62-5:3 (TMR equation); EX1057 (Dieny textbook) at page 13.

143. The TMR ratio was and is a key parameter for improving MRAM performance. 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; 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.

144. 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 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 '198 Patent. EX1009 ('198 Patent) at Abstract, cols. 1:30-2:28. 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.

145. 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.

146. The claimed tunnel barrier height range of 0.2 to 0.5 eV was obvious. As I mentioned in Paragraph 141 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 (Klaua) 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

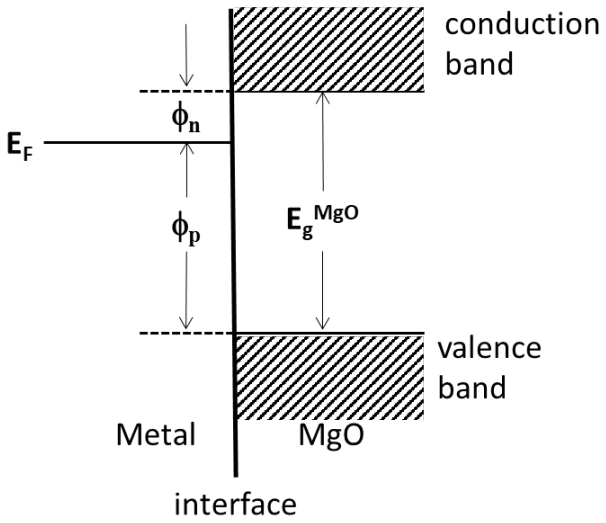
"defects in the MgO barrier"); EX1047 (Wulfhekel) at page 510 (observing "defects in the MgO barrier" and concluding that spikes in current are likely caused by "a lower tunneling barrier").

147. According to the '198 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." EX1009 ('198 Patent) at col. 7:7-11. Thus, the '198 Patent itself recognized that the tunnel barrier height limitation is inherent when there are oxygen vacancy defects as taught by Bowen and Soukup. EX1026 (Bowen) at page 1656; EX1028 (Soukup) at pages 3232, 3236.

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

149. 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.

150. 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, ϕ_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, ϕ_n, is related to ϕ_p by the relation: $\phi_p + \phi_n = E_g^{MgO}$, where E_g^{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.

151. 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 Co as 1.8 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 X 10^{-4} mbar") is not consistent with the state of the metal as used in electrochemistry or catalysis, nevertheless for either value of Pauling electronegativity cited for Au, the values of the Pauling electronegativity of Co and Fe are each lower. EX1026 (Bowen) at page 1655; 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 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.

152. In sum, Claim 2 is obvious over Bowen in view of Sunai and Soukup.

C. Claim 3: Obviousness Over Bowen In View Of Sunai And Soukup

1. Claim 3[preamble]: "The tunnel barrier layer according to claim 2,"

153. As I explained above in Sections XII.A-XII.B of this Declaration, Bowen in view of Sunai and Soukup disclosed or suggested a tunnel barrier layer satisfying Claim 2, which depends from Claim 1.

2. Claim 3[a]: "wherein the barrier height p of the tunnel barrier layer is obtained by fitting J-V characteristics of a tunnel barrier junction structure to an equation (1): $J=[(2m\varphi)^{1/2}/\Delta s](e/h)^2\times\exp[-(4\pi\Delta s/h)\times(2m\#)^{1/2}]\times V$ (1)"

154. This limitation was taught or suggested by Bowen in view of Sunai and Soukup.

155. Claim 3[a] and its recited "equation (1)" is merely a recitation of the Simmons formula, which can 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* §VII.D. I understand that the applicant indicated during prosecution that "ϕ,"—not "p" or "#" as recited in Claim 3[a]—represented tunnel "barrier height" in "$J=[(2m\phi)^{1/2}/\Delta s](e/h)^2\times\exp[-(4\pi\Delta s/h)\times(2m\phi)^{1/2}]\times V$." EX1010 ('198 Patent File History) at page 252.

156. 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.

157. 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 3. *Compare* EX1009 ('198 Patent) at col. 10:25 (equation (1) in Claim 3[a]), *with* EX1031 (Simmons) at page 1797 (Equation (25)).

158. The '198 Patent acknowledged that "equation (1)" recited in Claim 3[a] is Simmons' formula for calculating tunnel barrier height. EX1009 ('198 Patent) at cols. 7:27-33 (citing EX1031 (Simmons)), 7:59-8:3; *see also* EX1074 (First Amended Complaint, Exhibit GG) at 5, 14-15 (acknowledging "equation (1)" is the "Simmons formula" for an equivalent limitation in the '463 Patent). The '198 Patent explains that it applies a low bias voltage V across the MTJ to allow for electron tunneling, "100 mV or smaller," EX1009 ('198 Patent) at col. 7:55-58, and thus

relies on the "low-voltage" Simmons formula to calculate tunnel barrier height, *compare* EX1009 ('198 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").

159. One of skill would have understood that a bias voltage of "100 mV or smaller" is considered to be a "low voltage." The '198 Patent explains that bias voltages that are typically applied to MTJs are "on the order of 500 mV to 1000 mV." EX1009 ('198 Patent) at col. 7:35-36. 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)").

160. 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 theory of tunneling was used to derive the barrier height…"); EX1043 (Heinrich) at page 1 (using "Simmons rule" to calculate the "tunneling barrier"); EX1047 (Wulfhekel) 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.

161. Bowen used "I(V) curves [to] place[] the barrier height at ϕ=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)).

162. 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.

163. In sum, Claim 3[a] was obvious over Bowen in view of Sunai and Soukup. Simmons' formula was long-known, and it was long-known that Simmons' formula was used to calculate the tunnel barrier height of an MTJ.

3. Claim 3[b]: "where J is a tunnel current density flowing through the tunnel 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 the Planck's constant, Δs is an effective thickness of the tunnel barrier layer that is approximately equivalent to (tMgO−0.5 nm), and tMgO is an actual thickness of the tunnel barrier layer determined using a cross-sectional transmission electron microscope image."

164. Claim 3[b] was taught or suggested by Bowen in view of Sunai and Soukup. As I explained above in Section XII.C.2 of this Declaration, Claim 3[a] merely recites Simmons' formula for calculating the tunnel barrier height. Claim 3[b] simply identifies certain variables, and certain values for some of those variables, for use in Simmons' formula. EX1009 ('198 Patent) at col. 10:27-35. One of skill would have found these variables, and the recited values, obvious.

165. Calculating the tunnel barrier height using Simmons' formula, as set forth in Claim 3[a], with the variables and values identified in Claim 3[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 XII.C.2 of

this Declaration, both Bowen and Soukup disclosed that Simmons' formula was used to approximate tunnel barrier height.

166. As set forth in the table below, the '198 Patent uses and describes the same variables from Simmons' 1963 publication.

Claim 3[b] limitations [EX1009 ('198 Patent) at col. 10:27-35]	**Simmons' formula (1963) [EX1031 (Simmons) at page 1794]**
"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 the Planck's constant"	"h=Planck's constant"
"Δs is an effective thickness of the tunnel 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"

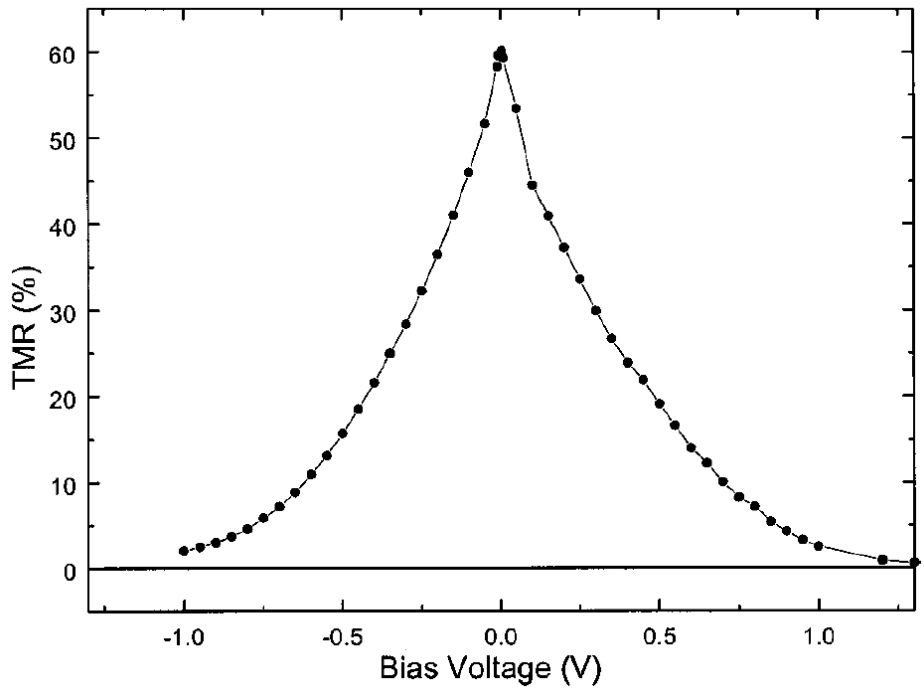
Compare EX1009 ('198 Patent) at col. 10:27-35, *with* EX1031 (Simmons) at page 1794 (defining variables).

167. Each of the requirements of Claim 3[b] would have been obvious to one of skill.

168. First, the requirement that "J is a tunnel current density flowing through the tunnel barrier layer" was obvious. EX1009 ('198 Patent) at col. 10:27-28. As set forth in the table in Paragraph 166, the '198 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).

169. Second, the requirement that "V is an applied bias voltage that is 100 mV or smaller" was also well known. EX1009 ('198 Patent) at col. 10:28-29. It was obvious to apply a low voltage of less than 100 mV. As I explained above for Claim 3[a] in Section XII.C.2 of this Declaration, Bowen measured the barrier height "at 10 mV," satisfying Claim 3[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 1V, including spanning 0 to 100 mV. 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.

170. 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≃0." EX1031 (Simmons) at page 1797. As I explained above for Claim 3[a] in Section XII.C.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."

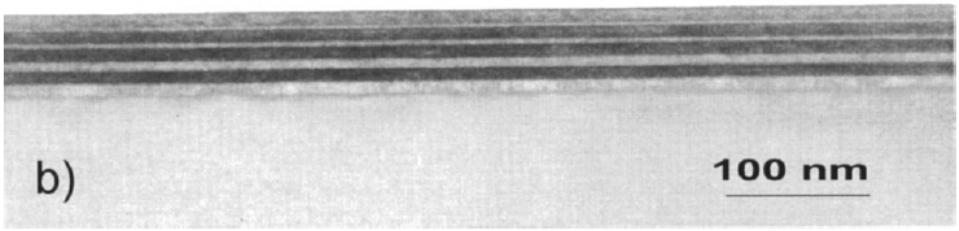
171. Claim 3[b]'s requirement that "Δs is an effective thickness of the tunnel barrier layer that is approximately equivalent to (T_{MgO}−0.5 nm)" was obvious as well. EX1009 ('198 Patent) at col. 10:30-32. As set forth in the table in

Paragraph 166, the Claim 3[b] recitation of Δs is equivalent to Δs 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' Δs variable thus refers to an "effective thickness" of the barrier layer. For example, the '198 Patent explained that the "effective thickness Δs of the tunnel barrier was determined to be smaller than the thickness of the actual MgO(001) tunnel barrier layer (t_{MgO})" and that "[t]his is the result of the effective thickness Δs 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." EX1009 ('198 Patent) at col. 7:41-50.

172. Bowen also rendered obvious a tunnel barrier layer having an effective thickness "that is approximately equivalent to (T_{MgO}−0.5 nm)." Claim 3[b] recites that "t_{MgO} is an actual thickness of the tunnel barrier layer." EX1009 ('198 Patent) at col. 10:31-33. Thus, Claim 3[b] requires that the effective thickness of the tunnel barrier to be approximately 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 $d \sim 15$ Å," 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 approximately 0.5 nm less than the actual thickness (2 nm). EX1026 (Bowen) at page 1656.

173. Further, Bowen taught Claim 3[b]'s requirement that "t_{MgO} is an actual thickness of the tunnel barrier layer determined using a cross-sectional transmission electron microscope image." EX1009 ('198 Patent) at col. 10:33-35. It would have been obvious to use a cross-sectional transmission electron microscope (TEM) image to measure layer thickness, including the thickness of an MgO barrier layer. Bowen taught using "cross section transmission electron microscopy (TEM)" to measure the thickness of MgO layers, EX1026 (Bowen) at page 1655, as shown in Figure 1 below.



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

174. In sum, Claim 3[b] was obvious to one of skill including over Bowen in view of Sunai and Soukup.

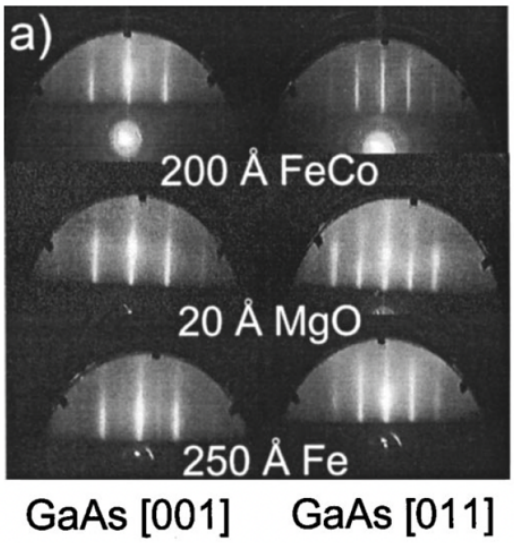
D. Claim 4: Obviousness Over Bowen In View Of Sunai

1. Claim 4: "The tunnel barrier layer according to claim 1, wherein the second ferromagnetic material layer is composed of an alloy comprising Fe and Co, and wherein the second ferromagnetic material layer is located above the tunnel barrier layer."

175. As discussed below and as I also explained above for Claims 1[preamble], 1[b], and 1[c] in Sections XII.A.1 and XII.A.3-XII.A.4 of this Declaration, Bowen in view of Sunai disclosed or suggested this limitation.

176. Bowen's upper FeCo electrode satisfied this claim limitation. FeCo is an alloy comprising Fe and Co. Claim 4 does not specify the specific molecular composition or stoichiometry of the claimed "alloy comprising Fe and Co." EX1009 ('198 Patent) at col. 10:35-40 (Claim 4). Thus, I was asked to assume that any bcc CoFe alloy satisfies Claim 4.

177. Bowen taught growing "***FeCo***/MgO/Fe epitaxial structures" by first depositing the "Fe bottom electrode" onto a substrate, then depositing the MgO tunnel barrier layer on top of the "Fe bottom electrode," followed by an "FeCo top electrode" deposited on top of the MgO barrier. EX1026 (Bowen) at pages 1655-56 (emphasis added); *id.* at Abstract, Fig. 1. As shown in Figure 1 below, Bowen's "FeCo top electrode" is located above the MgO tunnel barrier layer.



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

E. Claim 5: Obviousness Over Bowen In View Of Sunai

1. Claim 5: "The tunnel barrier layer according to claim 1, wherein the second ferromagnetic material layer is composed of an alloy comprising Fe, Co, and B, and wherein the second ferromagnetic material layer is located above the tunnel barrier layer."

178. Claim 5 does not specify the specific molecular composition or stoichiometry of the claimed "alloy comprising Fe, Co, and B." EX1009 ('198 Patent) at col. 10:40-45 (Claim 5). Thus, I was asked to assume that any CoFeB alloy satisfies Claim 5. As I explained above for Claims 1[preamble], 1[b], 1[c], and 4 in Sections XII.A.1, XII.A.3-XII.A.4, and XII.D.1 of this Declaration, Bowen in view of Sunai disclosed or suggested this limitation.

F. Claim 6: Obviousness Over Bowen In View Of Sunai

1. Claim 6: "The tunnel barrier layer according to claim 1, wherein the tunnel barrier layer is disposed on the first ferromagnetic material layer."

179. Bowen in view of Sunai disclosed or suggested this limitation for the same reasons I explained above for Claim 1[c] in Section XII.A.4 of this Declaration.

XIII. GROUND 2: CLAIMS 1-6 ARE OBVIOUS OVER NAGAHAMA IN VIEW OF SUNAI (AND SOUKUP)

180. In my opinion, Claims 1-6 are obvious over the prior art. Specifically:

a. Claims 1 and 4-6 are obvious over Nagahama in view of Sunai.

b. Claims 2 and 3 are obvious over Nagahama in view of Sunai and Soukup.

A. Claim 1: Obviousness Over Nagahama In View Of Sunai

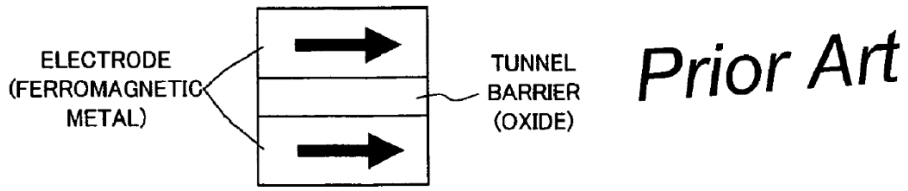
1. Claim 1[preamble]: "A tunnel barrier layer disposed between a first ferromagnetic material layer and a second ferromagnetic material layer that are disposed over a substrate,"

181. 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 '198 Patent claims are limiting for purposes of this analysis. Assuming that the preamble of Claim 1 is limiting, Nagahama taught or suggested it.

182. Magnetic tunnel junctions (MTJs), including those with a three-layer MTJ structure, were well known in the art. This is evident from the '198 Patent

itself. EX1009 ('198 Patent) at Figs. 8(A)-8(B), col. 1:42-67. For example, Figure 8(A) of the '198 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 material." EX1009 ('198 Patent) at col. 1:45-49. The patent correctly identifies and labels this conventional MTJ design as "Prior Art":

FIG. 8 (A)



EX1009 ('198 Patent) at Fig. 8(A) ("Prior Art" legend in original).

183. Nagahama disclosed a magnetoresistive device having a tunnel barrier layer arrangement as recited in this claim.

184. Nagahama taught various MTJ embodiments having a conventional structure of a ferromagnetic electrode on top of an insulating layer on top of an ultrathin ferromagnetic electrode that is above an underlayer. EX1027 (Nagahama) at 10 (claim 1), ¶¶73-74 (describing same arrangement with MgO barrier layer); *see also id.* at Abstract, ¶¶21-21, Fig. 3. One of skill would have found it obvious to use

Nagahama's teachings regarding MTJs to form a single structure meeting the requirements of Claim 1.

185. Nagahama disclosed a "magnetoresistive element," EX1027 (Nagahama) ¶73, having a structure satisfying the Claim 1 preamble:

> another magnetoresistive element was prepared which includes a (001)-highly-oriented lower ferromagnetic electrode layer, a (001)-highly-oriented MgO barrier layer, and a (001)-highly-oriented upper ferromagnetic electrode layer on the MgO double underlayer of the present invention.

EX1027 (Nagahama) ¶73; *id.* at Abstract, ¶¶21-22, 74-76, Figs. 3, 17. Nagahama's magnetoresistive devices took the conventional form, as depicted in Figures 3 and 17 below.

FIG. 3

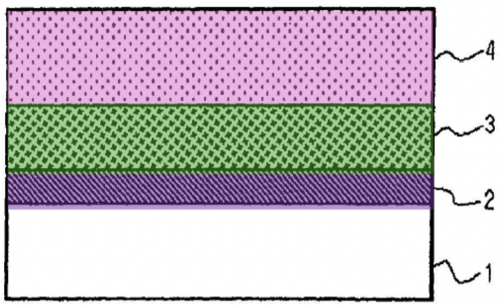
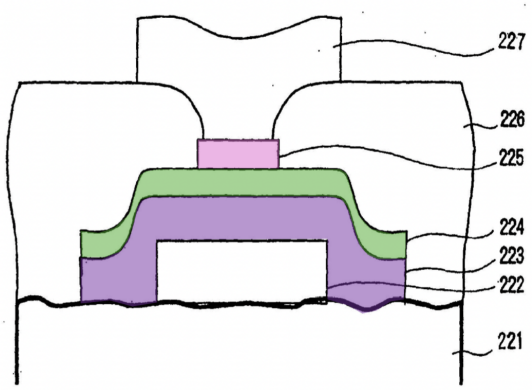


FIG. 17



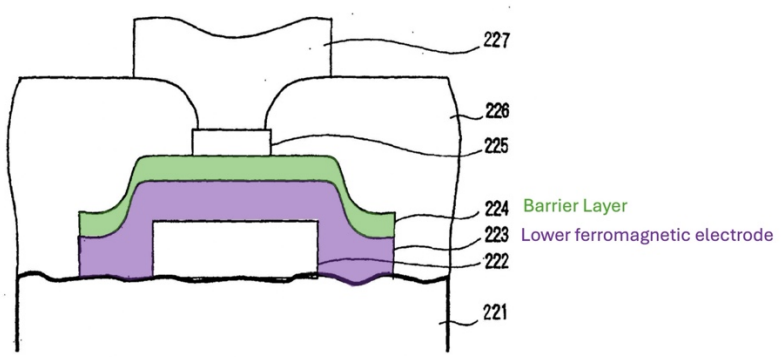
EX1027 (Nagahama) at Figs. 3, 17 (Fig. 3 excerpted, both annotated).

186. Claim 1[preamble]'s "ferromagnetic material layer" refers to an electrode made of a "ferromagnetic metal." EX1009 ('198 Patent) at col. 1:45-49, Fig. 8(a). The "tunnel barrier layer" refers to "an oxide [that] is sandwiched between a first and a second electrode made of a "ferromagnetic metal." EX1009 ('198 Patent) at col. 1:45-49. According to the '198 Patent, "first ferromagnetic material layer" refers to the "lower" ferromagnetic electrode that is closest to the substrate and below the tunnel barrier layer, and the "second ferromagnetic material layer" refers to the "upper" ferromagnetic electrode located above the tunnel barrier layer. EX1009 ('198 Patent) at Abstract.

187. Figures 3 and 17 of Nagahama show this conventional arrangement of an MTJ structure. EX1027 (Nagahama) ¶¶21-22, 75-76; *id.* at Figs. 3, 17. In Figures 3 and 17, 1 and 222 represent a substrate (or underlayer); 2 and 223 represent a **lower ferromagnetic electrode**; 3 and 224 represent a **barrier layer**; and 4 and 225 represent an **upper ferromagnetic layer**. EX1027 (Nagahama) ¶¶21-22, 75-76.

188. Nagahama's "**lower ferromagnetic electrode**" was a first ferromagnetic material layer, as shown below.

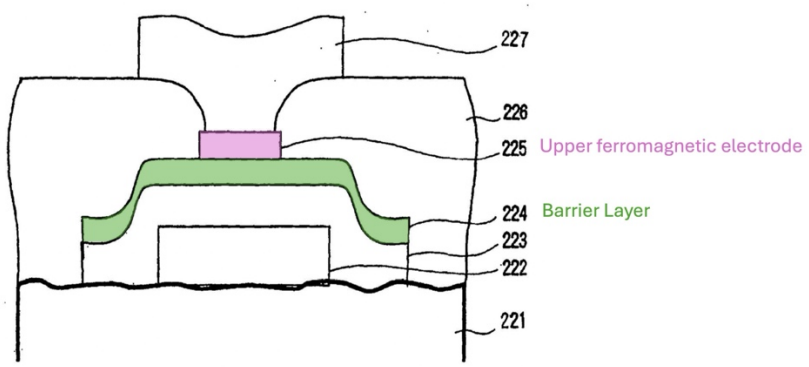
FIG. 17



EX1027 (Nagahama) at Fig. 17 (annotated); *id.* ¶¶75-76.

189. Nagahama's **"upper ferromagnetic electrode"** was a second ferromagnetic layer, as shown below.

FIG. 17



EX1027 (Nagahama) at Fig. 17 (annotated); *id.* ¶¶75-76.

190. As shown in the preceding Paragraphs 188-189, Nagahama taught that its lower ferromagnetic electrode is located below the tunnel barrier layer and that its upper ferromagnetic electrode is located above the tunnel barrier layer, such that the tunnel barrier layer is sandwiched or located between the lower and upper

ferromagnetic electrodes. Nagahama's various MTJ embodiments, including the paragraphs 73-74 embodiment, describe this same basic structure, rendering this arrangement obvious to one of skill. Each of these layers is collectively disposed over a substrate (or underlayer) 222, as shown above in Nagahama's Figure 17, such as the MgO double underlayer in the paragraphs 73-74 embodiment.

191. Thus, Nagahama disclosed or suggested the conventional structure of a tunnel barrier layer disposed between a first ferromagnetic material layer and a second ferromagnetic material layer that are disposed over a substrate.

2. Claim 1[a]: "wherein the tunnel barrier layer comprises a poly-crystalline magnesium oxide layer in which a (001) crystal plane is preferentially oriented,"

192. This limitation is disclosed or suggested by Nagahama. As I explained for Claim 1[preamble] in Section XIII.A.1 of this Declaration, Nagahama disclosed a tunnel barrier layer. Nagahama disclosed using a polycrystalline MgO tunnel barrier layer that is preferentially oriented in the (001) plane in its MTJ: "a (001)-highly-oriented MgO barrier layer." EX1027 (Nagahama) ¶73.

193. Given its reference to "highly-oriented," one of skill would have understood Nagahama's "(001)-highly-oriented MgO barrier layer" to refer to a polycrystalline MgO barrier. *See, e.g.*, EX1027 (Nagahama) ¶¶40, 43 (referring to "single-crystal ***or*** highly-oriented-polycrystalline" (emphasis added)); *id.* ¶54 (referring to "single crystal ***or*** a highly oriented polycrystal"); *see also* EX1040

(Yoon) at page 2842 (MgO "polycrystalline structures" have "preferred orientation"); EX1057 (Dieny) at page 46 ("highly oriented polycrystalline"). Indeed, because single-crystal layers have equivalent orientations throughout the crystalline lattice, the term "highly-oriented" is used to describe the predominant orientation of a polycrystalline layer containing many crystals. Although Nagahama disclosed the claimed (001) orientation, the '198 Patent also explained that "because MgO has a cubic crystal structure (NaCl structure), the (001) plane, the (100) plane, and the (010) plane are all equivalent." EX1009 ('198 Patent) at col. 4:39-41.

3. Claim 1[b]: "wherein the first ferromagnetic material layer is composed of an Fe—Co alloy of BCC which alloy comprises Fe, Co, and B,"

194. Claim 1[b] is taught or suggested by either (1) Nagahama alone, or alternatively, (2) Nagahama in view of Sunai. As I explained for Claim 1[preamble] in Section XIII.A.1 of this Declaration, Nagahama disclosed or suggested a first or lower ferromagnetic layer.

195. It would have been obvious to replace Nagahama's lower ferromagnetic layer with a CoFeB ferromagnetic layer, as taught by Sunai, including to improve TMR. EX1030 (Sunai) ¶¶28 (teaching CoFeB electrode by adding B to Co_9Fe), 24 (teaching "ferromagnetic layer 4 is represented by the general formula $(CoFe)_{100-x}Y_x$" and specifying Y is an "element selected from the group consisting of B" or other elements); *id.* ¶¶25-29.

196. 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"). Nagahama taught using a "Fe-Co Alloy" for the ferromagnetic layers to "increase the spin polarization." EX1027 (Nagahama) ¶6. It would have been obvious to use CoFeB as taught by Sunai in Nagahama's "(001)-highly-oriented lower ferromagnetic electrode layer" of the paragraphs 73-74 embodiment.

197. As I explained above in Ground 1, one of skill would have been motivated to use Sunai's CoFeB electrode in an MTJ. *Supra* Claim 1[b], §XII.A.3 of this Declaration. One of skill would have been motivated to replace either or both of Nagahama's lower and upper electrodes with CoFeB to improve TMR. EX1055 (Wang) at page 2270 ("[I]t is natural to replace both the free and pinned layers to CoFeB to further increase the TMR value."); EX1056 (Hosomi) ¶¶67-68; EX1035 (Moodera 1995) at page 3274. Nagahama sought to "obtain a high magnetoresistive effect" in its MgO MTJ, EX1027 (Nagahama) ¶6, and understood that the properties of the ferromagnetic electrodes impacted TMR, EX1027 (Nagahama) ¶23. It was understood by one of skill that using a CoFeB alloy for the electrodes improved TMR in an MTJ. EX1055 (Wang) at pages 2269-70 ("The benefit of using CoFeB

is multifold: a higher TMR value….”); EX1056 (Hosomi) ¶39 (“larger TMR ratio” when “CoFeB alloy” is used); EX1030 (Sunai) ¶¶27-28 (discussing improved TMR resulting from adding B to CoFe).

198. To improve Nagahama’s MTJ, one of skill would have looked to Sunai’s teachings. Nagahama and Sunai sought to improve the TMR of magnetoresistive devices, a problem to which the ’198 Patent was directed. EX1027 (Nagahama) ¶¶6, 15; EX1030 (Sunai) at Abstract, ¶¶1, 10; EX1009 (’198 Patent) at Abstract, cols. 1:30-2:28. Both Nagahama and Sunai also discussed improving MRAM memory performance. EX1027 (Nagahama) ¶¶3, 49; EX1030 (Sunai) at Figs. 4-5, ¶¶1, 4, 38-40. Further, they both used an MgO barrier layer and similar ferromagnetic alloy electrodes. EX1027 (Nagahama) ¶¶6, 73; EX1030 (Sunai) ¶¶24, 35.

199. It would have been predictable and routine to replace Nagahama’s lower electrode with a CoFeB electrode. CoFeB alloys had long been used in MTJ electrodes. EX1030 (Sunai) ¶¶24, 28; EX1055 (Wang) at pages 2269-70; EX1056 (Hosomi) ¶39. One of skill was aware that using CoFeB would increase the TMR of an MTJ. *Id*. It would have been obvious and straightforward to improve Nagahama’s MTJ by using CoFeB in Nagahama’s lower electrode because CoFeB was already proven successful in increasing TMR in MTJs. EX1030 (Sunai) ¶¶27-28.

200. According to Nagahama, the MTJ of its "present invention" utilized "a tunnel magnetoresistive element whose crystal orientation is set to the (001) direction of a ***body-centered cubic lattice***, a face-centered cubic lattice, or a tetragonal lattice." EX1027 (Nagahama) ¶1 (emphasis added); *see also id.* ¶23 ("Fe atoms enter a crystal to form a body-centered cubic lattice…."). A body-centered cubic lattice structure is also referred to as bcc, as I explained in Section VII.E.1 of this Declaration. One of skill in the art would have found Nagahama's teachings of a bcc ferromagnetic electrode in paragraphs 1, 18, and 23 to be applicable to Nagahama's disclosure of the MTJ in paragraphs 73-74. This is because one of skill would have understood that using a bcc structure for the ferromagnetic electrodes would have been a desirable and obvious option. Nagahama itself explained that using a bcc structure was desirable to achieve "a large magnetoresistive effect." EX1027 (Nagahama) ¶¶18 (item [20]), 81 (item [F]); *id.* at page 11 (claim 20).

201. Even if one of skill changed the material of Nagahama's ferromagnetic electrode layer(s), the skilled artisan would have retained the matching crystalline structures of the ferromagnetic layers and tunnel barrier because that was key to lowering barrier height and increasing TMR. That is why Nagahama taught that each of its ferromagnetic layers and tunnel barrier in the paragraphs 73-74 embodiment were set to the (001)-highly-oriented direction, such that they were

polycrystalline, and that its ferromagnetic layers be body-centered cubic. EX1027 (Nagahama) ¶¶1, 11 (claim 20: "by using the underlayer so that a ferromagnetic electrode layer is oriented in the (001) direction of a ***body-centered cubic lattice***, … and using a (001)-highly-oriented MgO layer as a barrier layer, a large magnetoresistive effect is produced."), 73 (describing its ferromagnetic layers as "(001)-highly-oriented").

202. Replacing either or both of Nagahama's lower and upper electrodes with CoFeB, as taught by Sunai, would still produce a CoFeB layer that is bcc structured. This is because of the template effect of the MgO barrier on the CoFeB electrodes. One of skill was 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. Jimbo's 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. One of skill was aware that MgO would crystallize in a cubic structure with the (001), (100), and (010) crystalline planes being the same. *See* Section VII.E.1 of this Declaration. One of skill would have been aware that CoFeB would adopt the (001) crystalline structure of an adjoining MgO (001) layer.

E.g., EX1060 (Jimbo) at page 308. This was true in Jimbo despite a lattice mismatch between the Au and CoFeB. EX1060 (Jimbo) at page 309, Figure 1. One of skill in the art would expect CoFeB to crystallize in the same crystalline plane of an adjoining MgO layer because of the closer lattice match between CoFeB and MgO. *E.g.*, EX1046 (Mathon) at page 1 ("only a small lattice mismatch of about 3.5%" between in-plane distances of Fe and O). Indeed, Parkin, for example, described the effect of using CoFeB adjacent to the MgO crystal structure, explaining that the MgO layer "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; *see also id.* at col. 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."). Thus, in using a CoFeB electrode in an MgO MTJ, one of skill understood that doing so would result in a bcc CoFeB structure.

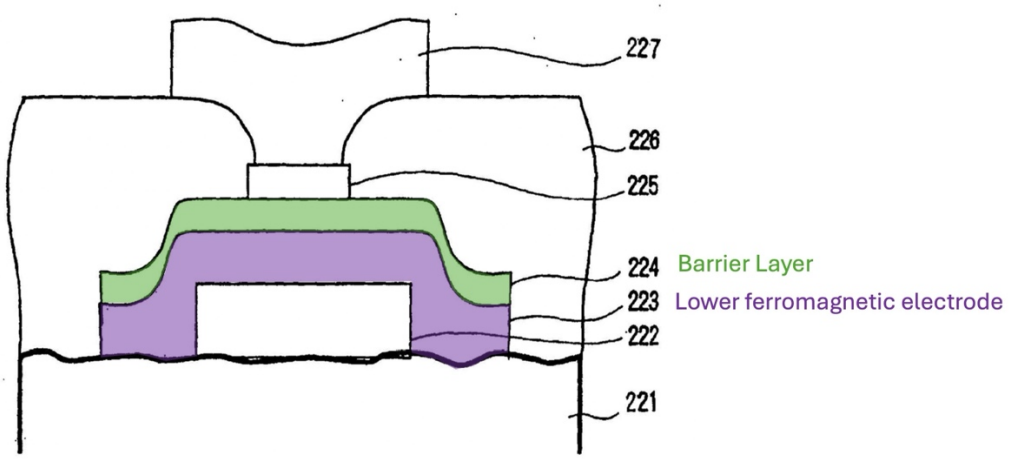
4. Claim 1[c]: "wherein the first ferromagnetic material layer is located between the tunnel barrier layer and the substrate."

203. Nagahama disclosed or suggested this limitation. As I explained for Claim 1[preamble] in Section XIII.A.1, Nagahama disclosed or suggested a first ferromagnetic layer located between the tunnel barrier layer and the substrate.

204. Nagahama described a "(001)-highly-oriented lower ferromagnetic electrode layer" sandwiched or located between a "(001)-highly-oriented MgO barrier layer" and an "MgO double underlayer" substrate. EX1027 (Nagahama) ¶73.

205. Additionally, as shown in another example reflecting the same arrangement in Figure 17 below, Nagahama's lower ferromagnetic electrode 223 is located between the barrier layer 224 and MgO double underlayer substrate 222, with the barrier layer 224 disposed on the lower ferromagnetic electrode 223. EX1027 (Nagahama) ¶76, Fig. 17.

FIG. 17



EX1027 (Nagahama) at Fig. 17 (annotated).

B. Claim 2: Obviousness Over Nagahama In View of Sunai And Soukup

1. Claim 2: "The tunnel barrier layer according to claim 1, wherein a barrier height of the tunnel barrier layer is in a range of 0.2 to 0.5 eV."

206. As I explained previously in Section XIII.A of this Declaration, Claim 1 is obvious over Nagahama in view of Sunai. Claim 2 depends from Claim 1 and thus incorporates all of Claim 1's requirements. Claim 2 is obvious over Nagahama in view of Sunai and Soukup

207. Nagahama in view of Sunai and Soukup taught or suggested Claim 2. Claim 2 adds a single requirement: a tunnel barrier height in a range of 0.2 to 0.5 eV. As I explained previously in Section VII.D of this Declaration, the tunnel barrier height measures the difference between the Fermi level of the electrode and the bottom of the conduction band of the barrier layer.

208. Nagahama in view of Sunai and Soukup taught or suggested an MgO tunnel barrier height for an MgO barrier layer in the claimed range of 0.2 to 0.5 eV. Nagahama disclosed using an MgO barrier for its MTJ. EX1027 (Nagahama) ¶¶73-76, Abstract, Figs. 3, 17. Soukup observed a "barrier height" of "about 0.33 eV" for its MgO thin film. EX1028 (Soukup) at Abstract; *id.* at pages 3231-32, Fig. 5, Table I.

209. Soukup studied the "effect of nonstoichiometry on the device characteristics," EX1028 (Soukup) at page 3232, documenting that higher oxygen

vacancy defects in the MgO barrier resulted in lowering the barrier height. According to Soukup, "the barrier height was a function of the amount of oxygen present… during deposition of the MgO film with a higher barrier for larger amounts of oxygen present" and "[r]aising the oxygen pressure during deposition of the MgO film probably leads to a more stoichiometric film." EX1028 (Soukup) at page 3236. One of skill would have understood Soukup as teaching a lower barrier height with less stoichiometric oxide films, or equivalently, a higher level of oxygen vacancy defects, by using a relatively low oxygen pressure during deposition of the MgO film. EX1028 (Soukup) at pages 3232, 3236.

210. In my opinion, one of skill would have been motivated to apply Soukup's teachings about an MgO thin film barrier with a "barrier height" of "about 0.33 eV" to Nagahama's MgO barrier. Soukup fabricated an MgO thin-film barrier with a low tunnel barrier height in the range of 0.2 to 0.5 eV, and that higher levels of oxygen vacancy defects in the MgO barrier resulted in lowering the barrier height. EX1028 (Soukup) at Abstract, pages 3232, 3236. One of skill would have understood and would have been motivated to fabricate Nagahama's MTJ with an MgO tunnel barrier with a tunnel barrier height having a value in the range of 0.2 to 0.5 eV by introducing oxygen vacancy defects as taught by Soukup.

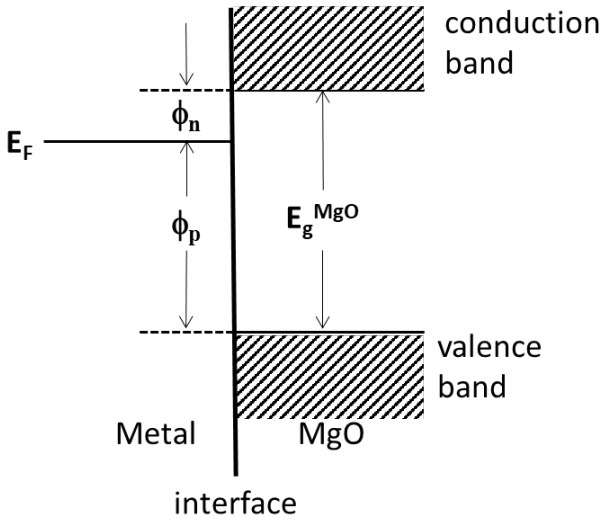
211. As I explained previously in Section VII.C of this Declaration, the TMR was and is a key parameter for improving MRAM performance, and skilled artisans

have long been interested in increasing TMRs to enable better performing MRAM. Additionally, lowering the resistance (barrier height) for parallel spin electrons compared to antiparallel would improve TMRs. *Supra* §XII.B.1; EX1035 (Moodera 1995) at page 3273; EX1027 (Nagahama) ¶2; EX1009 ('198 Patent) at cols. 4:64-5:3 (TMR equation); EX1057 (Dieny textbook) at page 13.

212. Nagahama aimed to improve the TMR in its MTJ. EX1027 (Nagahama) ¶15 (stating that "a first object of the present invention is to provide a tunnel magnetoresistive element capable of producing a larger magnetoresistive effect"); EX1027 (Nagahama) ¶6 ("obtain[ing] a high magnetoresistive effect"); EX1027 (Nagahama) ¶¶3-8. Nagahama sought to increase TMR by modifying properties of the MgO barrier layer. EX1027 (Nagahama) ¶¶15-17. It was understood to one of skill that lowering the barrier height to increase tunneling would have increased the TMR. Soukup documented how to fabricate an MgO thin-film barrier with a low tunnel barrier height between 0.2 and 0.5 eV, explaining how higher levels of oxygen vacancy defects in the MgO barrier resulted in lowering the barrier height. EX1028 (Soukup) at Abstract, pages 3232, 3236. One of skill would have been motivated to modify Nagahama's MgO barrier layer to increase TMR by increasing oxygen vacancy defects and thus lowering the barrier height as taught by Soukup.

213. Soukup's report of a barrier height as low as 0.33 eV pertained to Au-MgO barriers. However, one of skill would have expected a barrier height for ferromagnetic layers such as Fe or Co adjacent to an MgO barrier layer to be about the same or even lower.

214. 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, ϕ_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, ϕ_n, is related to ϕ_p by the relation: $\phi_p + \phi_n = E_g^{MgO}$, where E_g^{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.

215. 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 Co as 1.8 and 1.77 for Fe. EX1032 (Trasatti) at Table 1. 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 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.

216. In my opinion, one of skill looking to improve tunneling and TMR in Nagahama's MgO barrier would have been motivated to read the literature on MgO thin films, including Soukup's study of an MgO barrier. EX1028 (Soukup) at Abstract, page 3229. Nagahama acknowledged and discussed prior research on

increasing TMR in MgO barriers by Mathon, Bowen, and others. EX1027 (Nagahama) ¶¶2-14. Nagahama and Soukup both studied tunneling and other properties of MgO barriers and were focused on improving tunneling devices, the problem to which the '198 Patent was apparently directed. EX1027 (Nagahama) ¶¶2-4, 13-15; EX1028 (Soukup) at pages 3229-30. One of skill would have been aware of Soukup's teachings about the low barrier height of Au on MgO thin films, would have been aware of Goniakowski's and Trasatti's teaching about the low barrier height of Fe or Co on MgO films, and would have been motivated to apply Soukup's teachings to Nagahama to achieve a tunnel barrier height in the range of 0.2 to 0.5 eV.

217. A skilled artisan also would have had a reasonable expectation of success in applying Soukup's teachings to Nagahama 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 Nagahama.

218. A tunnel barrier height in the range of 0.2 to 0.5 eV would have been obvious to one of skill. One of skill would have known that the presence of oxygen vacancy defects affected barrier height. Soukup documented the relationship between barrier height and the stoichiometry of the MgO film. EX1028 (Soukup) at

pages 3232 (observing "higher barrier" for "more stochiometric oxide films"), 3236 (noting that "barrier height was a function of the amount of oxygen present… with a higher barrier for larger amounts of oxygen present" or "more stoichiometric" MgO film).

219. Others in the field also found a lower tunneling barrier for defects in the MgO film. For example, Heinrich observed that "sharp increases in tunneling current were caused by localized defects in the MgO layer" and "the tunneling barrier is significantly decreased." EX1043 (Heinrich) at page 1. Klaua and others also observed a similar relationship. *See, e.g.*, EX1045 (Klaua) at Abstract ("Tunneling I-V curves at the defects showed a lower tunneling barrier than that in the majority of the MgO film."); *id.* at page 4 ("But if defect states exist within the band gap of MgO, as in Fig. 6(c), then the tunneling probability via these defect states is largely enhanced."); *id.* at page 7 ("[S]mall variations in the electronic structure of the MgO lead to strong variations in the local tunneling current."); 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"); EX1053 (Mitani) at page 8042 (observing "the resistance decreases dramatically" for "tunneling transport through the MgO barrier," attributing it to "defects in the MgO barrier").

220. As I explained above for Ground 1, Claim 2 in Section XII.B.1 of this Declaration, the '198 Patent itself recognized that the tunnel barrier height limitation is inherent when there are oxygen vacancy defects. EX1009 ('198 Patent) at col. 7:7-11.

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

222. In sum, Claim 2 is taught or suggested by Nagahama in view of Sunai and Soukup.

C. Claim 3: Obviousness Over Nagahama In View of Sunai And Soukup

1. Claim 3[preamble]: "The tunnel barrier layer according to claim 2,"

223. As I explained above in Sections XIII.A-XIII.B of this Declaration, Nagahama in view of Sunai and Soukup disclosed or suggested a tunnel barrier layer satisfying Claim 2, which depends from Claim 1.

2. Claim 3[a]: "wherein the barrier height p of the tunnel barrier layer is obtained by fitting J-V characteristics of a tunnel barrier junction structure to an equation (1): $J=[(2m\varphi)^{1/2}/\Delta s](e/h)^2\times\exp[-(4\pi\Delta s/h)\times(2m\#)^{1/2}]\times V$ (1)"

224. This limitation was taught or suggested by Nagahama in view of Sunai and Soukup.

225. As I explained for Ground 1, Claim 3[a] in Section XII.C.2 of this Declaration, "equation (1)" in Claim 3[a] merely recites Simmons' formula, which can be used to calculate the tunnel barrier height at a low-voltage-range.

226. As I previously explained for Claim 1[preamble], Nagahama taught or suggested an MgO tunnel barrier layer. EX1027 (Nagahama) ¶¶73-74; *supra* §XIII.A.1.

227. Nagahama sought to "obtain a high magnetoresistive effect" in its MgO MTJ. EX1027 (Nagahama) ¶6; *id.* ¶15 ("[A] first object of the present invention is to provide a tunnel magnetoresistive element capable of producing a larger magnetoresistive effect…."). Nagahama taught that the properties of the ferromagnetic electrodes impacted TMR, EX1027 (Nagahama) ¶23, and aimed to increase TMR by modifying properties of the MgO barrier layer, EX1027 (Nagahama) ¶¶15-17.

228. One of skill would have understood that there was a relationship between the barrier height and TMR, and would be particularly interested in determining the tunnel barrier height. For example, Klaua explained that "tunneling from the valence band of MgO is suppressed due to the large active barrier height of over 7 eV" but that "if defect states exist within the band gap of MgO… then the tunneling probability via these defect states is largely enhanced" due to the lower barrier height. EX1045 (Klaua) at page 4. Similarly, Wulfhekel observed that

"small variations of the local barrier height lead to strong variations of the tunneling current" and concluded that spikes in current were likely caused by "a lower tunneling barrier." EX1047 (Wulfhekel) at pages 510-11. And Heinrich noted that "sharp increases in tunneling current were caused by localized defects in the MgO layer" and "the tunneling barrier is significantly decreased." EX1043 (Heinrich) at page 1.

229. As I explained for Ground 1, Claim 3[a] in Section XII.C.2 of this Declaration, it was also understood and well known that Simmons' formula was used to approximate the barrier height of an MTJ. Soukup recognized "Simmons' model" was used to evaluate the "height and the bias dependence of the insulator potential-energy barrier." EX1028 (Soukup) at page 3229 (citing EX1031 (Simmons), 3236 n.1 (citing EX1031)). Soukup also acknowledged that "Simmons' model" was used to calculate the tunnel barrier height of an MTJ. *Supra* §XII.C.2; EX1028 (Soukup) at pages 3229 (referencing "Simmons' model" to evaluate the "height and the bias dependence of the insulator potential-energy barrier"), 3236 n.1 (citing EX1031 (Simmons)).

230. Claim 3[a] was taught or suggested by Nagahama in view of Sunai and Soukup. Simmons' formula was long known, and it was long known that Simmons' formula was used to calculate the tunnel barrier height of an MTJ.

3. Claim 3[b]: "where J is a tunnel current density flowing through the tunnel 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 the Planck's constant, Δs is an effective thickness of the tunnel barrier layer that is approximately equivalent to (tMgO−0.5 nm), and tMgO is an actual thickness of the tunnel barrier layer determined using a cross-sectional transmission electron microscope image."

231. Claim 3[b] was taught or suggested by Nagahama in view of Sunai and Soukup. As I explained for Ground 1, Claim 3[b] in Section XII.C.3 of this Declaration, Claim 3[b] simply identifies certain variables, and certain values for some of those variables, for use in Simmons' formula. EX1009 ('198 Patent) at col. 10:27-35. One of skill would have found these variables, and the recited values, obvious.

232. As I explained for Ground 1, Claim 3[a] in Section XII.C.2 of this Declaration, Simmons' formula was well known and one of skill understood how to apply it 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 theory of tunneling was used to derive the barrier height…"); EX1043 (Heinrich) at page 1 (using "Simmons rule" to calculate the "tunneling

barrier"); EX1047 (Wulfhekel) 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 variables recited in Claim 3[b] were the same ones recited in Simmons' formula and a skilled artisan was well aware of those variables and understood how to apply them. EX1031 (Simmons) at pages 1794 (defining variables), 1797 (Simmons' formula for "Low-Voltage Range"); *supra* §XII.C.3.

233. Further, Bowen and its discussion of Simmons' formula, as I described above in Section XII.C.3 of this Declaration, was well within the knowledge of one of skill. Indeed, Bowen was expressly referenced in Nagahama, confirming that one of skill was aware of it. EX1027 (Nagahama) ¶14 ("[A] giant tunnel magnetoresistive effect of more than 60% has been experimentally obtained (M. Bowen et al., Applied Physics Letters, volume 79, number 11 (2001), pages 1655-1657).").

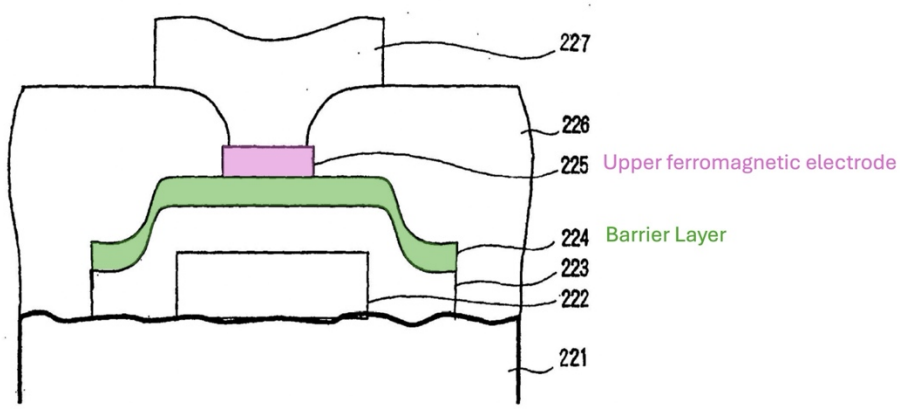
D. Claim 4: Obviousness Over Nagahama In View Of Sunai

1. Claim 4: "The tunnel barrier layer according to claim 1, wherein the second ferromagnetic material layer is composed of an alloy comprising Fe and Co, and wherein the second ferromagnetic material layer is located above the tunnel barrier layer."

234. As discussed below and as I also explained above for Claims 1[preamble], 1[b], and 1[c] in Sections XIII.A.1 and XIII.A.3-XIII.A.4 of this Declaration, Nagahama, or alternatively Nagahama in view of Sunai.

235. Nagahama described a "(001)-highly-oriented upper ferromagnetic electrode layer" located above a "(001)-highly-oriented MgO barrier layer." EX1027 (Nagahama) ¶73. Additionally, as shown in the similarly configured Figure 17 example below, Nagahama's upper ferromagnetic electrode 225 is located above the barrier layer 224. EX1027 (Nagahama) ¶76, Fig. 17.

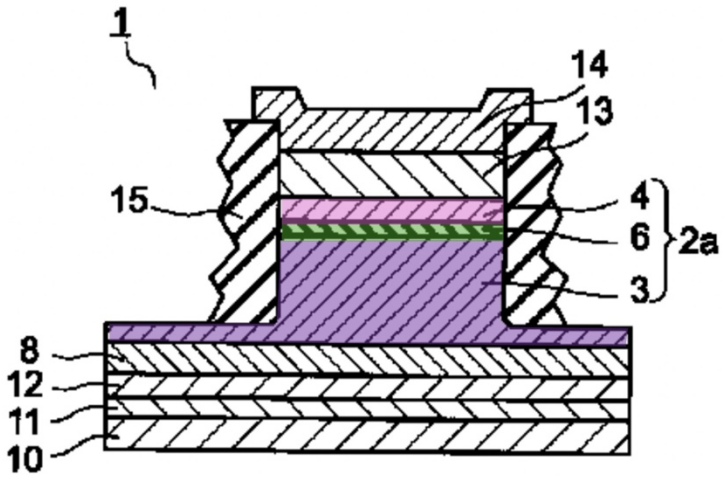
FIG. 17



EX1027 (Nagahama) at Fig. 17 (annotated).

236. As shown in Figure 1 below, Sunai also taught and illustrated a ferromagnetic layer 4 (**pink**) that was disposed on top of a tunnel barrier layer 6 (**green**).

[Figure 1]



EX1030 (Sunai) at Fig. 1 (annotated); *id.* at Abstract, ¶1.

237. It was conventional and obvious to fabricate an MTJ by starting with a substrate at the bottom and adding the following layers in succession: a first Fe-based electrode, an MgO tunnel barrier layer, and a second Fe-based electrode. EX1009 ('198 Patent) at col. 1:45-49 (Description of Related Art); *id.* at Figs. 8(A)-8(B) (labeled "Prior Art").

238. Nagahama taught using a "Fe-Co Alloy" for the ferromagnetic layers to "increase the spin polarization," EX1027 (Nagahama) ¶6, and disclosed using FeCo as an upper electrode, EX1027 (Nagahama) ¶¶68 ("FeCo polycrystalline alloy

serving as an upper electrode"), 70 ("FeCo upper ferromagnetic electrode"). Using FeCo, an alloy comprising Fe and Co, as an upper electrode was routine and acceptable, which is confirmed by Nagahama's own recommendation of a FeCo alloy.

239. As I explained above for Claim 1[b] in Section XIII.A.3 of this Declaration, it also would have been obvious to replace either or both of Nagahama's electrodes—including Nagahama's upper electrode—with a CoFeB ferromagnetic layer, as taught by Sunai, including to improve TMR. CoFeB is an alloy comprising Fe and Co.

E. Claim 5: Obviousness Over Nagahama In View Of Sunai

1. Claim 5: "The tunnel barrier layer according to claim 1, wherein the second ferromagnetic material layer is composed of an alloy comprising Fe, Co, and B, and wherein the second ferromagnetic material layer is located above the tunnel barrier layer."

240. As I explained above for Claims 1[preamble], 1[b], 1[c], and 4 in Sections XIII.A.1, XIII.A.3-XIII.A.4, and XIII.D.1 of this Declaration, Nagahama in view of Sunai disclosed or suggested this limitation.

F. Claim 6: Obviousness Over Nagahama In View Of Sunai

1. Claim 6: "The tunnel barrier layer according to claim 1, wherein the tunnel barrier layer is disposed on the first ferromagnetic material layer."

241. Nagahama in view of Sunai disclosed or suggested this limitation for the same reasons I explained above for Claim 1[c] in Section XIII.A.4 of this Declaration.

XIV. SECONDARY INDICIA OF NONOBVIOUSNESS

242. Pertinent to both Grounds 1 and 2 above, I am not aware of any evidence of secondary considerations of nonobviousness for which there is any nexus to any claim of the '198 Patent. Should I become aware of such evidence, I may offer opinions on it at that time.

XV. CONCLUSION

243. Based on the foregoing, it is my opinion that Claims 1-6 of the '198 Patent are rendered obvious as discussed above.

244. 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.

245. 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.

246. 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: August 30, 2024

Jeffrey Bokor

XVI. APPENDIX: LIST OF CHALLENGED PATENT CLAIMS

1[pre] A tunnel barrier layer disposed between a first ferromagnetic material layer and a second ferromagnetic material layer that are disposed over a substrate,

> 1[a] wherein the tunnel barrier layer comprises a poly-crystalline magnesium oxide layer in which a (001) crystal plane is preferentially oriented,
>
> 1[b] wherein the first ferromagnetic material layer is composed of an Fe—Co alloy of BCC which alloy comprises Fe, Co, and B,
>
> 1[c] wherein the first ferromagnetic material layer is located between the tunnel barrier layer and the substrate.

2. The tunnel barrier layer according to claim 1, wherein a barrier height of the tunnel barrier layer is in a range of 0.2 to 0.5 eV.

3[pre] The tunnel barrier layer according to claim 2,

> 3[a] wherein the barrier height p of the tunnel barrier layer is obtained by fitting J-V characteristics of a tunnel barrier junction structure to an equation (1):
>
> $$J=[(2m\varphi)1/2\ /\Delta s](e/h)2\times\exp[-(4\pi\Delta s/h)\times(2m\#)1/2\ ]\times V \qquad (1)$$
>
> 3[b] where J is a tunnel current density flowing through the tunnel 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 the Planck's constant, Δs is an effective thickness of the tunnel barrier layer that is approximately equivalent to (tMgO−0.5 nm), and tMgO is an actual thickness of the tunnel barrier layer determined using a cross-sectional transmission electron microscope image.

4. The tunnel barrier layer according to claim 1, wherein the second ferromagnetic material layer is composed of an alloy comprising Fe and Co, and wherein the second ferromagnetic material layer is located above the tunnel barrier layer.

5. The tunnel barrier layer according to claim 1, wherein the second ferromagnetic material layer is composed of an alloy comprising Fe, Co, and B, and wherein the second ferromagnetic material layer is located above the tunnel barrier layer.

6. The tunnel barrier layer according to claim 1, wherein the tunnel barrier layer is disposed on the first ferromagnetic material layer.

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