

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. IPR2024-01494
Patent No. 11,968,909

**DECLARATION OF CAROLINE A. ROSS, Ph.D.
IN SUPPORT OF PATENT OWNER'S RESPONSE**

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I, Caroline A. Ross, Ph.D., declare as follows:

I. INTRODUCTION

1. I have been retained by Wolf, Greenfield & Sacks, P.C., counsel for Patent Owner GODO KAISHA IP BRIDGE 1, to provide my opinions concerning a Petition filed by Petitioner Western Digital Corp challenging claims of U.S. Patent No. 11,968,909 (“the ‘909 patent”). I am being compensated for my time at my standard rate of \$500.00 per hour, plus actual expenses. My compensation is not dependent in any way upon the outcome of the inter partes review of the ‘909 patent.

II. PERSONAL AND PROFESSIONAL BACKGROUND

2. I have over 30 years of experience in the fields of magnetic materials, magnetic nanostructures, ferroelectricity, magnetoresistance, thin film deposition, fabrication of spin-valve structures, including magnetic and spintronic devices. In my research, I have investigated the structure, crystallographic and magnetic properties of thin films, giant magnetoresistance metal layered structures, micromagnetic structures and the fabrication of such structures. A copy of my curriculum vitae is provided as EX2054.

3. I have extensive experience with magnetic recording media including magnetoresistive read/write heads; magnetic multilayer stacks including magnetoresistive and exchange bias layers; thin film oxide deposition; electrical

measurements of magnetoresistance; and characterization of microstructure, epitaxy and composition of thin film stacks.

4. I hold a B.A. and a Ph.D. in the field of Materials Science and Metallurgy, which I received from Cambridge University in 1985 and 1988, respectively. From 1989-1990, I was a Post-doctoral Fellow at Harvard University.

5. From 1991 to 1997, I was employed as an Engineer at Komag Inc., a manufacturer of hard disks, that was acquired by Western Digital in 2007. As part of my employment, I conducted research into hard disks and recording heads, including studies of thin film growth, magnetic and mechanical properties, patterning of thin films, and microstructural characterization.

6. Since 1997, I have been a Professor in the Department of Materials Science and Engineering at the Massachusetts Institute of Technology (MIT), appointed as assistant professor in 1997, associate professor in 2000 and full professor in 2004. I was the Associate Head of MIT's Department of Materials Science and Engineering for over 10 years before becoming Interim Department Head in 2023-2024. MIT's Department of Materials Science and Engineering is ranked as #1 by both US News and World Report 2024-25 and the QS World University Rankings 2025-6 for its undergraduate and graduate programs.

7. Throughout the course of my career, I have been invited to give over 170 lectures at conferences, laboratories, and universities. I have authored over 475 peer-reviewed articles, edited two books, and I have been awarded 22 U.S. patents. My publications include studies on magnetic tunnel junctions. In 2011, I was selected as one of the “Top 100 Materials Scientists of the Past Decade.”

8. Six of my papers that specifically address magnetic tunnel junctions are: Conductive Atomic Force Microscopy of Small Magnetic Tunnel Junctions with Interface Anisotropy, Stephan K. Piotrowski, Mukund Bapna, Hamid Almasi, Wei-Gang Wang, Larysa Tryputen, Caroline A. Ross, Mingen Li, Chia-Ling Chien, and Sara A. Majetich, IEEE Trans. Magn. 51(11) 4400504 (2015) 10.1109/TMAG.2015.2434798; Logic circuit prototypes for three-terminal magnetic tunnel junctions with mobile domain walls, J. A. Currivan-Incorvia, S. Siddiqui, S. Dutta, E. R. Evarts, J. Zhang, D. Bono, C. A. Ross, and M. A. Baldo, Nat. Commun. 7 10275 pp1-7 (2016) <DOI: 10.1038/ncomms10275>; Patterning of sub-50 nm Perpendicular CoFeB/MgO-based Magnetic Tunnel Junctions, Larysa Tryputen, Kun-Hua Tu, Stephan K. Piotrowski, Mukund Bapna, Sara A. Majetich, Congli Sun, Paul Voyles, Hamid Almasi, Weigang Wang, Patricio Vargas, Jason S. Tresback, Caroline A. Ross, Nanotechnol. 27 185302 (2016) (7pp) doi:10.1088/0957-4484/27/18/185302; Magnetic reversal and thermal stability of CoFeB perpendicular magnetic tunnel junction arrays patterned by

block copolymer lithography, Kun-Hua Tu, Eduardo Fernandez, Hamid Almasi, Weigang Wang, David Navas Otero, Konstantinos Ntetsikas, Dimitrios Moschovas, Apostolos Avgeropoulos and Caroline A Ross, *Nanotechnology* 29 (2018) 275302 (12pp), <https://doi.org/10.1088/1361-6528/aabce8>; Spintronic logic circuit and device prototypes utilizing domain walls in ferromagnetic wires with tunnel junction readout, J. A. Currivan-Incorvia; S. Siddiqui; S. Dutta; E. R. Evarts; C. A. Ross; M. A. Baldo, 2015 IEEE International Electron Devices Meeting (IEDM) Pages: 32.6.1 - 32.6.4, DOI: 10.1109/IEDM.2015.7409817 IEEE Conference Publications; and A Logic-in-Memory Design with 3-Terminal Magnetic Tunnel Junction Function Evaluators for Convolutional Neural Networks, Sumit Dutta, Saima A. Siddiqui, Felix Büttner, Luqiao Liu, Caroline A. Ross, and Marc A. Baldo, *2017 IEEE/ACM International Symposium on Nanoscale Architectures (NANOARCH)*. p83-88 doi.ieeecomputersociety.org/10.1109/NANOARCH.2017.8053724

9. Some of my other papers that are particularly relevant to the Yuasa patents are those that address growth and structure of ultra-thin layers of oxides and metals such as: Ross, C.A., “Electrodeposited multilayer thin films,” *Annual Review of Materials Science*, 24 159-188 (1994); C.A. Ross, S. Haratani, F.J. Castaño, B. Vogeli, S. Sumita, “Fabrication of MRAM structure and their magnetic properties”, *J. of the Society of Materials Engineering for Resources of*

Japan 14 p43-51 (2001); F.J. Castaño, Y. Hao, C.A. Ross, B. Vogeli, Henry I. Smith, S. Haratani, “Switching field trends in sub-100 nm pseudo spin valve arrays”, J. Appl. Phys. 91 7317-9 (2002); M. Shima, T. Tepper, C.A. Ross, “Magnetic properties of chromium oxide and iron oxide films produced by pulsed laser deposition J. Appl. Phys. 91 7920-22 (2002); C.A. Ross, F.J. Castaño, E. Rodriguez, S. Haratani, B. Vögeli and Henry I. Smith, “Size-dependent switching of multilayer magnetic elements”, J. Applied Physics 97, 053902 (2005); Magnetic structure and anisotropy of [Co/Pd]₅/NiFe multilayers, Larysa Tryputen, Feng Guo, Frank Liu, T. N. Anh Nguyen, Majid S. Mohseni, Sunjae Chung, Yeyu Fang, Johan Akerman, R. D. McMichael, and Caroline A. Ross, Phys. Rev. B 91, 014407 p1-6 (2015); Rare-Earth Iron Garnet Superlattices with Sub-unit Cell Composition Modulation, B Khurana, A.C. Kaczmarek, C.T. Chou, T. Su, K. Lasinger, T. Grossmark, D.C. Bono, L. Liu, C.A. Ross, **ACS Nano** 18 (52), 35269–35275 (2024); those that describe magnetoresistive measurements such as: Walsh M., Y. Hao, C.A. Ross, H.I. Smith, “Optimization of a lithographic and ion beam etching process for nanostructuring magnetoresistive thin film stacks”, J. Vac. Sci. Technol. B 18 3539-3543 (2000); F.J. Castaño, S. Haratani, Y. Hao, C.A. Ross, H.I. Smith, “Giant Magnetoresistance in 60 – 150 nm wide pseudo spin-valve nanowires”, Appl. Phys. Letts. 81 2809-11 (2002); F. J. Castaño, D. Morecroft, W. Jung and C. A. Ross “Spin-dependent scattering in multilayered

magnetic rings”, Phys. Rev. Letts. 95 137201 1-4 (2005); D. Morecroft, F. J. Castaño, W. Jung, C. A. Ross, Angular dependence of the giant magnetoresistance in multilayer rings with different contact configurations, J Appl. Phys. 99 08T104 1-3 (2006); Jeong Dae Suh, C. A. Ross, Dependence of the giant magnetoresistance ratio on the nano-oxide layer position in NiFe/Cu/Co pseudo-spin valve films, Phys. Stat. Sol. (b) 244 4474-7 (2007); F.J. Castaño, B.G. Ng, I.A. Colin, D. Morecroft, W. Jung, C.A. Ross, Magnetoresistance of submicron multilayer Wheatstone bridges as a probe of magnetic reversal mechanism, J. Phys. D 41 132005 (2008) and those that address structural and compositional characterization such as: T J Bromwich, A. Kohn, A K Petford-Long, T Kasama, R Dunin-Borkowski, S Newcomb, C A Ross, “Remanent magnetization states and interactions in square arrays of 100 nm cobalt dots measured using transmission electron microscopy”, J. Appl. Physics 98 053909 1-8 (2005) These examples are not a complete list of my relevant publications.

10. At Komag, my work included development of thin film media consisting of sputtered thin films of magnetic materials, underlayers, and overlayers; studies of epitaxial, polycrystalline and amorphous layers in thin films and multilayers; and the analysis of materials for read/write heads including magnetic pole piece materials, magnetoresistive elements and overcoat materials.

III. MATERIALS REVIEWED AND CONSIDERED

11. In addition to the Petition (Paper 1), the Board's Institution Decision (Paper 9), and any other documents cited or reference herein, Appendix A provides a list of material that I have considered in forming the opinions set forth in this Declaration.

IV. LEGAL PRINCIPLES

12. In developing my opinions, I discussed various relevant legal principles with Petitioners' attorneys. I understood these principles when they were explained to me and have relied upon such legal principles, as explained to me, in the course of forming the opinions set forth in this declaration. My understanding in this respect is as follows:

13. I understand that "inter partes review" (IPR) is a proceeding before the United States Patent & Trademark Office for evaluating the patentability of an issued patent's claims based on prior-art patents and printed publications.

14. I understand that, in this proceeding, Petitioner has the burden of proving that the challenged claims of the '167 patent are unpatentable by a preponderance of the evidence. I understand that "preponderance of the evidence" means that a fact or conclusion is more likely true than not true.

15. I understand that, in IPR proceedings, claim terms in a patent are given their ordinary and customary meaning as understood by a person of ordinary

skill in the art (“POSA”) in the context of the entire patent and its prosecution history. If the specification or prosecution history provides a special definition for a claim term that differs from the meaning the term would otherwise possess, that special definition applies. I have applied these standards in preparing the opinions in this declaration.

16. I understand that for an invention claimed in a patent to be patentable, it must be, among other things, not obvious from the prior art. My understanding of that standards is set forth below.

A. Obviousness

17. I understand that a patent claim may be unpatentable if it would have been obvious in view of a single prior-art reference or a combination of prior-art references.

18. I understand that a patent claim is obvious if the differences between the subject matter of the claim and the prior art are such that the subject matter as a whole would have been obvious to a person of ordinary skill in the relevant field at the time the invention was made. Specifically, I understand that the obviousness question involves a consideration of:

- the scope and content of the prior art;
- the differences between the prior art and the claims at issue;
- the knowledge of a person of ordinary skill in the pertinent art; and

- objective factors indicative of non-obviousness, sometimes referred to as “secondary considerations.”

19. I understand that in order for a claimed invention to be considered obvious, a POSA must have had a reason for combining teachings from multiple prior-art references (or for altering a single prior-art reference) in the fashion proposed.

20. I understand that obviousness is determined in light of all the facts and that in evaluating alleged reasons to combine references the references must be considered for all their teachings. Furthermore, I understand that the teachings of references or the knowledge of a person having ordinary skill in the art (as discussed below) is understood to teach away from forming a combination achieving a claimed invention if it would have discouraged a person of ordinary skill in the art from forming a combination or would have caused a person having ordinary skill in the art to follow a path that diverged from path taken by the inventor.

21. I understand that obviousness requires that a person of ordinary skill in the art would have had a reasonable expectation of success that a purported combination would have achieved an intended result that meets the claim limitations.

22. I understand that for a single reference or a combination of references to render the claimed invention obvious, a POSA must have been able to arrive at the claimed invention by modifying, implementing, or combining the teachings of the applied references.

B. Claim Interpretation

23. I understand that determining whether a claimed invention is novel and non-obvious requires comparing the prior art to the claims. In this section, I discuss the interpretations I have applied to certain claim terms in my analysis.

24. I have been informed that patent claims are construed from the viewpoint of a person of ordinary skill in the art at the time of the alleged invention. I have been informed that patent claims generally should be interpreted consistent with their plain and ordinary meaning as understood by a person of ordinary skill in the art in the relevant time period (at the time of the purported invention, or the so called “effective filing date” of the patent application), after reviewing the patent claim language, the specification, and the prosecution history (the intrinsic record).

25. I have further been informed that a person of ordinary skill in the art must read the claim terms in the context of the claim itself, as well as in the context of the entire patent specification. I understand that in the specification and prosecution history, the patentee may specifically define a claim term in a way that

differs from the plain and ordinary meaning. I understand that the prosecution history of the patent is a record of the proceedings before the U.S. Patent and Trademark Office and may contain explicit representations or definitions made during prosecution that affect the scope of the patent claims. I understand that an applicant may, during the course of prosecuting the patent application, limit the scope of the claims to overcome prior art or to overcome an examiner's rejection, by clearly and unambiguously arguing to overcome or distinguish a prior art reference, or to clearly and unambiguously disavow claim coverage.

26. In interpreting the meaning of the claim language, I understand that a person of ordinary skill in the art may also consider "extrinsic" evidence, including expert testimony, inventor testimony, dictionaries, technical treatises, other patents, and scholarly publications. I understand this evidence is considered to ensure that a claim is construed in a way that is consistent with the understanding of those of skill in the art at the time of the alleged invention. This can be useful for technical terms whose meaning may differ from its ordinary English meaning. I understand that extrinsic evidence may not be relied on if it contradicts or varies the meaning of claim language provided by the intrinsic evidence, particularly if the applicant has explicitly defined a term in the intrinsic record.

27. I understand that determining whether a claimed invention is novel and non-obvious requires comparing the prior art to the challenged claim. In this

Declaration, I apply the above standards to the terms in the challenged claims. The meanings of specific terms are discussed below in connection with evaluating the disclosure in the priority documents.

V. PERSON OF ORDINARY SKILL IN THE ART (“POSA”)

28. I have been informed and understand a patent and prior-art references must be assessed from the perspective of a person having ordinary skill in the art (“POSA”) to which the patent is related, based on the understanding of that person at the time of the patent claim’s priority date. I have been asked to provide my opinions as to the state of the art in the 2004 timeframe. I use this timeframe because the face of the ‘909 patent indicates an earliest claimed priority date to a Japanese application filed on March 12, 2004. I understand that the ‘909 Patent also claims priority to a second Japanese application filed October 28, 2004 and a PCT application filed on March 10, 2005. When I refer to a POSA, I am referring to one of ordinary skill in 2004 unless specified otherwise, even if I do not say so specifically in each case. My opinions would not change for a POSA as of any of the above-mentioned dates. I have applied this standard throughout my declaration.

29. I understand that Petitioner and Petitioner’s expert Dr. Bokor have proposed that a POSA as of 2004 would be someone that would have had 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

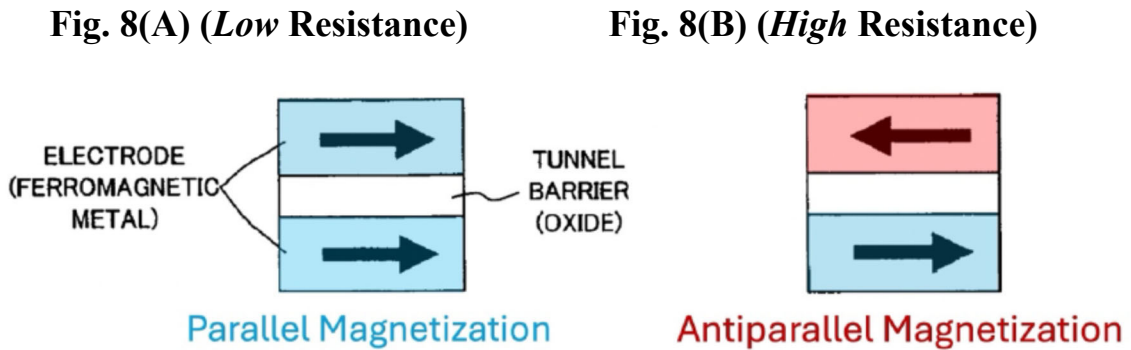
magnetic/spintronic devices, or the equivalent, or a Master's degree in electrical engineering, physics, materials science, or a related field, and four years of experience in the research, design, and/or development of magnetic/spintronic devices, or the equivalent. Less work experience may be compensated by a higher level of relevant education, and vice versa. EX1024 ¶25.

30. My opinions set forth in this declaration are from the perspective of that POSA. By 2004, I held a Ph.D. in Materials Science and Metallurgy from Cambridge University, held a Postdoctoral Fellowship in the Engineering and Applied Sciences department at Harvard University, held a Professorship at Massachusetts Institute of Technology, had 6 years of experience as an engineer at Komag Inc. (later acquired by Western Digital) and had more than a decade of experience in magnetic materials and devices, including spintronics. Therefore, I was a person of more than ordinary skill in the art during the relevant timeframe. However, I worked with many people who fit the characteristics of the POSA, and I am familiar with their level of skill. When developing the opinions set forth in this declaration, I assumed the perspective of a person having ordinary skill in the art, as set forth above. My opinions are from that perspective even when I do not specifically say so.

VI. MAGNETIC TUNNEL JUNCTION DEVICES

A. Tunneling Magnetoresistance Ratio (TMR)

31. An MTJ device has parallel and antiparallel configurations or states corresponding to different relative magnetizations between its magnetic electrodes. The resistance of the MTJ in the antiparallel configuration, referred to as the antiparallel resistance R_{ap} is higher than the resistance of the MTJ in the parallel configuration, referred to as the parallel resistance R_p . MTJs are referred to as “magnetoresistive” because the magnetic state impacts the device’s resistance.



32. The “tunnel magnetoresistance ratio” (“TMR”) is the difference between R_{ap} and R_p normalized by R_p , most commonly expressed by the TMR equation below. Some authors normalize instead by R_{ap} . A higher TMR desirably makes it easier to determine which state the MTJ device is in because it reflects a larger difference between the antiparallel and parallel resistances. EX1017, 5:10-16.

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

33. The reciprocal of resistance is conductance G (i.e., $R = 1/G$). By this reciprocal relationship, the conductance of a MTJ in the antiparallel state (G_{ap}) is lower (higher resistance) than the conductance of the MTJ in the parallel state (G_p) (lower resistance). Thus, TMR can also be expressed in terms of the MTJ's conductance as the difference between G_p and G_{ap} normalized by G_{ap} , as shown by the TMR equation below expressed in terms of both conductance G and resistance R .

$$TMR = \frac{\Delta G}{G} = \frac{G_p - G_{ap}}{G_{ap}} = \frac{R_{ap} - R_p}{R_p}$$

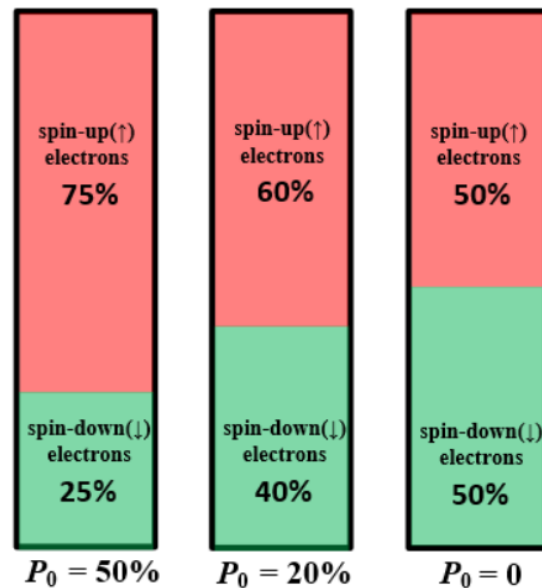
EX1057, 13 (Eq. 1.9); EX2005, 37 (Eq. 3); EX1033, 225-226. (Some authors normalize by R_{ap} instead of R_p .)

34. This TMR effect was observed at low temperature through a Fe-Ge-Co junction by Julliere (EX1033). EX1034, 231; EX2010, 172; EX1057, 42. Julliere modeled this effect in terms of the “spin polarization” of the magnetic electrodes discussed in further detail below. EX1033, 225-226.

B. Spin-Dependent Tunneling

35. Though the actual band structure is more complicated, magnetic materials have an asymmetry in the number of electrons whose spins are aligned with the local magnetization of the material (referred to as “spin-up” ($\uparrow$) or “majority spin” electrons) and the number of electrons whose spins are anti-aligned

with the local magnetization (referred to as “spin-down” ($\downarrow$) or “minority spin” electrons). EX1033, 225-226; EX1057, 4. The fractional difference between the spin-up ($\uparrow$) and spin-down ($\downarrow$) electrons in a magnetic electrode is the electrode’s spin polarization P_0 , often multiplied by 100 to express the material’s polarization as a percentage, i.e. $P_0 = 100(n_{\uparrow} - n_{\downarrow}) / (n_{\uparrow} + n_{\downarrow})$ where n represents the number of electrons. Several examples of hypothetical materials with different polarizations are illustrated schematically below. The examples are not intended to represent any particular material or how electrons of different spins are distributed in the material, but merely to demonstrate the principle of spin polarization (including a non-magnetic electrode with $P_0 = 0$). EX1033, 225-226; EX1057, 12; EX2010, 172-173.

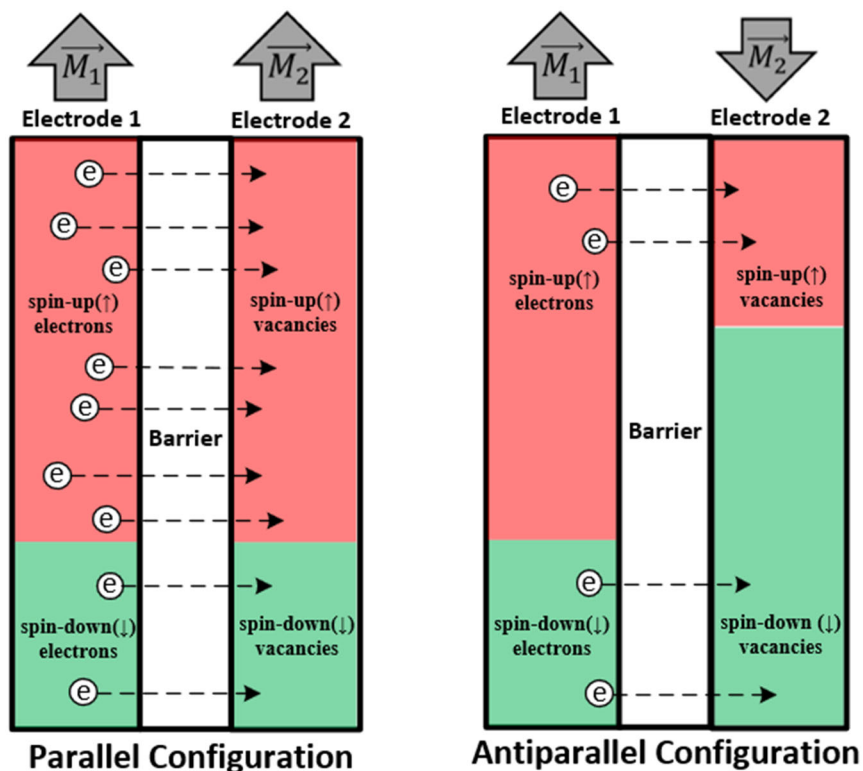


36. Spin-dependent tunneling means that an electron’s spin is preserved when tunneling from one electrode to another. Tunneling is a quantum mechanical

effect in which an electron is described as a cloud of possible states described by the electron's wave function. The electron wave function gives the probability of an electron being in a particular quantum state at a given point in time, including a probability that an electron will tunnel from one electrode to the other through the barrier. The number of electrons available for tunneling is described in quantum mechanics by the density of states (DOS) that describes the number of electron states per interval of energy around each energy level available to be occupied by electrons. For purposes of providing a simple illustration, spin-dependent tunneling can be thought of in terms of the number of electrons of a given spin-state in one electrode and the number of electron vacancies (i.e. unoccupied states) with the same energy in the other electrode. An electron can only tunnel from one electrode to fill an electron vacancy of the same spin state and energy in the other electrode.

37. When a magnetic electrode's magnetization is flipped, its spin states invert so the majority of electrons are spin-down ($\downarrow$) and the minority are spin-up ($\uparrow$). The mismatch in the number of electrons/vacancies aligned in the same spin

state when the electrodes' magnetizations are antiparallel reduces tunneling conductance, as illustrated schematically below.¹



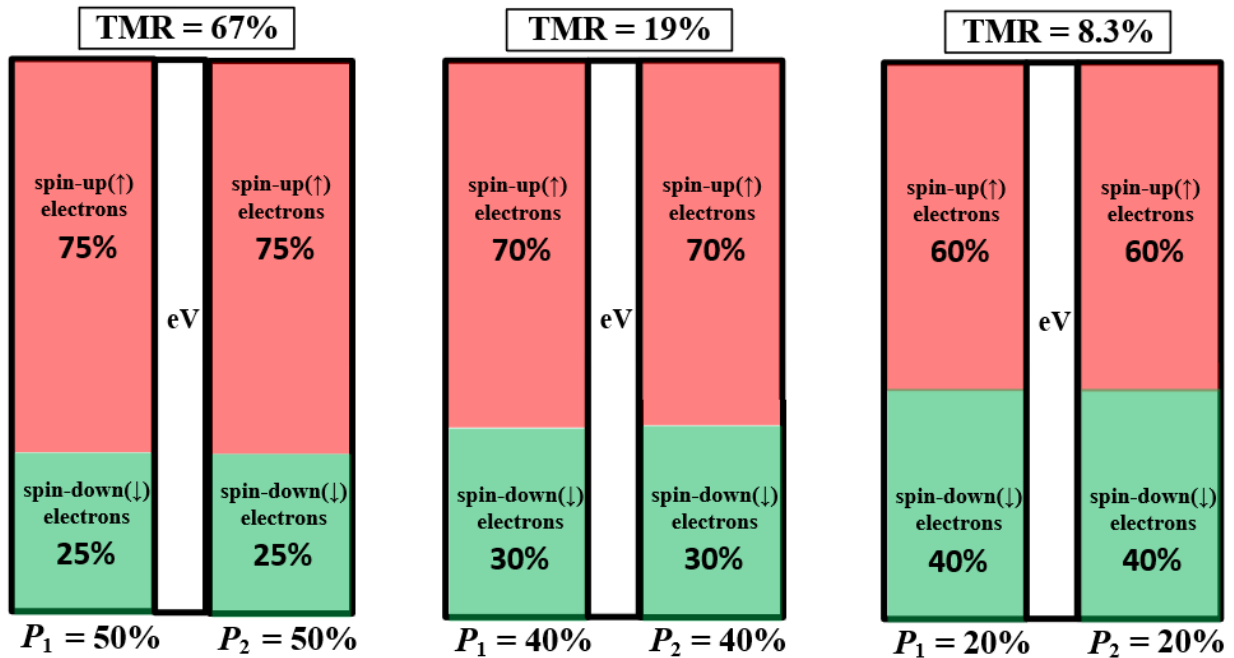
38. Thus, TMR results from this quantum mechanical effect of spin-dependent tunneling (i.e., the preservation of spin states during tunneling) so that spin state polarization in magnetic electrodes will produce different amounts of tunneling conduction depending on the magnetic state of the electrodes. EX1033, 225-226; EX1050, 2427 (“The TMR effect is known to originate from the spin

¹ At zero voltage bias, electrons tunnel in both directions equally, producing no net current. Applying a voltage across the electrodes lowers the Fermi energy of one electrode and biases electron flow in one direction—producing a net current.

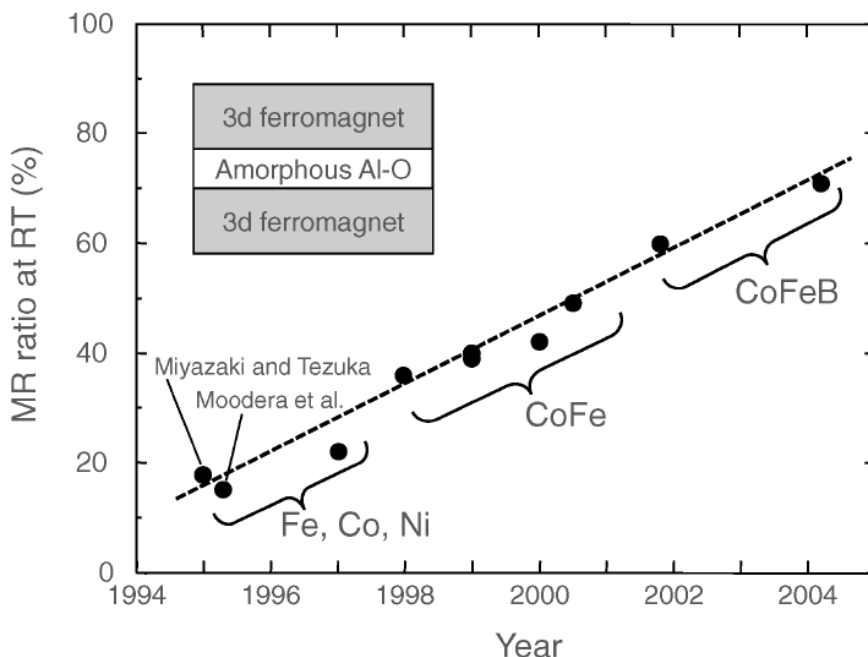
polarization of the electrodes, i.e. the difference between the densities of states (DOSs) of the up- and down-spin subbands in the two electrodes”); EX1057, 11-13, 42 (“The origin of the TMR effect is tunneling of spin-polarized electrons”); EX1024, ¶58 (“Higher spin polarization in the electrodes increases the TMR”).

39. Julliere thus expressed TMR purely in terms of the spin polarization of the electrodes, finding that TMR could be predicted from the spin polarizations P_1 and P_2 of the MTJ’s magnetic electrodes as follows, with examples shown conceptually below. Julliere’s equation was frequently used as a best case prediction of TMR and was a useful tool for comparison to experimental values of TMR obtained from fabricated MTJs.

$$\text{TMR} = \frac{G_P - G_{AP}}{G_{AP}} = \frac{R_{AP} - R_P}{R_P} = \frac{2P_1P_2}{1 - P_1P_2}$$



40. Work on MTJs in the 1990s was performed predominantly using Al_2O_3 barriers with significant research into electrode materials with high spin polarization that could take advantage of spin-dependent tunnelling. EX1057, 43 (Figure 2.18 reproduced below); EX1034, 231; EX1035, 3274;



C. Coherent Tunneling

41. Theoretical models of crystalline Fe-MgO-Fe junctions predicted higher TMRs than with Al_2O_3 barriers due to symmetry-coupling between the crystalline MgO barrier and crystalline Fe electrodes. EX1044, 1; EX1046, 1. Electron wave functions in crystalline materials are described by Bloch states. The Bloch states of crystalline magnetic transition metals such as Fe, Ni, Co have specific symmetries referred to as $\Delta 1$ symmetry, $\Delta 2$ symmetry, and $\Delta 5$ symmetry (often referred to simply as $\Delta 1$ state, $\Delta 2$ state, etc.). EX1057, 16; EX1044, 5-6.

Crystalline MgO has associated Δ_1 , Δ_2' and Δ_5 state symmetry that can couple with Δ_1 , Δ_2 and Δ_5 states in a Fe electrode, respectively, as shown in Figure 2.19(b) of Dieny (EX1057, 45) reproduced below. EX1057, 16; EX1044, 5-6.

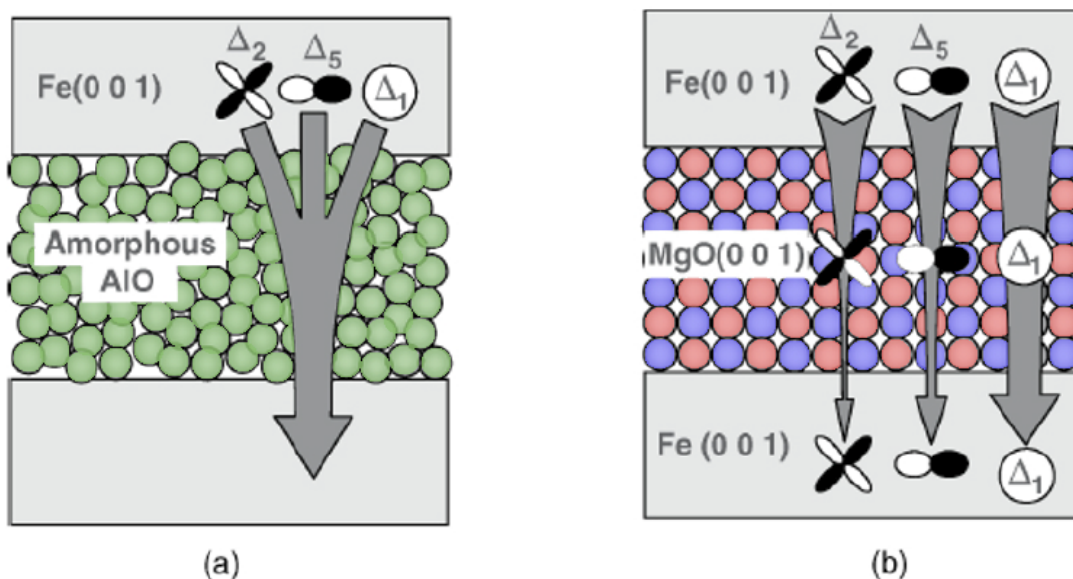


Figure 2.19 Schematic of electron tunneling through (a) an amorphous AlO barrier and (b) a crystalline MgO(0 0 1) barrier.

42. Symmetry coupling (above-right) increases the likelihood that an electron will tunnel from one electrode, through the barrier, to fill a vacancy of the same symmetry-state in the other electrode and is referred to as coherent tunneling enhancement. EX1057, 16-17, 44-45. Amorphous Al_2O_3 barriers (above-left) lack crystallographic symmetry and have no coherent tunneling enhancement (the barrier attenuates the probability of electron tunneling the same way for all electrons). EX1057, 16.

43. Ferromagnetic Fe electrodes have a relatively large number of majority spin electrons in the Δ_1 state ($\Delta_{1\uparrow}$) and none in the minority spin Δ_1 state

($\Delta_1\downarrow$), corresponding to 100% spin polarization of the Δ_1 electrons. EX1057, 45; EX1017, 6:1-8, FIG. 1A. Crystalline Fe/MgO/Fe devices were thus predicted by theoretical models (e.g., Butler (EX1044) and Mathon (EX1046) to exhibit relatively large Δ_1 -state coherent tunneling enhancement in the parallel configuration, but none in the antiparallel configuration, yielding higher TMR under the above-discussed spin polarization mechanism (spin polarization of Bloch states). EX1057, 17, 44-45; EX1017, 6:7-14 (“Because of such half-metallic characteristics of the Fe Δ_1 band, there is the possibility of a very high MR ratio can be obtained in a coherent spin polarized tunneling.”); EX1046, (“the calculated large TMR ratio R_{TMR} in the asymptotic regime is due, entirely, to a very low spectral density of minority-spin electrons at the Γ point.”); EX1044, 1, 9

D. Resistance-Area Product (RA)

44. The resistance-area product (RA) of an MTJ device is the resistance R per unit area of the device in ohms (Ω) per μm^2 . EX2017, 869; EX2012, 866-867. An MTJ’s RA is an important consideration for an MTJ device used in a circuit because it impacts the output voltage across an MTJ at a given current under Ohm’s law ($V=IR$). A too-high or too-low RA value would make it difficult for sensing circuitry to distinguish between an MTJ’s parallel and antiparallel configurations.

E. Tunnel Barrier Height

45. An MTJ's "tunnel barrier height" refers to the energy difference in electron volts (eV) between the Fermi energy (E_F) of the electrode material and the bottom of the conduction band of the barrier material (also referred to as the conduction band minimum (CBM)). The tunnel barrier height thus depends on the electrode and the barrier material. EX1031, 1794-1796, FIGS. 1-2; '909 Patent, 4:2-8. The upper limit of the tunnel barrier height for an electrode/barrier pairing, what the '909 Patent calls its "ideal" value, can be determined from analysis of the band structure of the electrode and barrier materials. The '909 patent uses the 3.6 eV calculated by Wulfhekel (EX1047) as the ideal tunnel barrier height for iron (Fe) paired with magnesium oxide (MgO) and this value has been widely used by others. EX1017, 4:66-57 (citing EX1047), 7:26-31; EX1047, 509; EX1045, 2; EX1043, 1. This ideal tunnel barrier height is an intrinsic property of the electrode and barrier materials that are chosen for a given MTJ.

46. A fabricated MTJ will have a lower barrier height because perfect uniform, planar and defect-free material layers are not realizable by thin-film deposition processes. This deviation from the ideal barrier height can be seen in the table below comparing the "ideal" and estimated barrier heights (ϕ) for a number of MTJs manufactured with MgO barrier layers. The barrier height of a fabricated MTJ device can be estimated from the I - V curves measured from the device. For

example, as explained in the '909 Patent, if the thickness of the barrier layer can be determined (e.g., via electron microscopy), the barrier height can be estimated by fitting I - V measurements to a tunneling model such as the Simmons (EX1031) formula. EX1017, 7:63-8:14.

Reference	Stack	Ideal ϕ	Estimated ϕ
EX1045	Fe/MgO/Fe	3.6 eV	2.5 to 3.6 eV
EX1043	Fe/MgO/Fe-Ni-Au	3.7 eV	3.7 eV (Simmons)
EX1026	Fe/MgO/Fe	Cites EX1047	0.9 eV, 1.1 eV ($I(V)$ temp curves, Simmons)
EX1053	Fe/MgO/FeCo	Not Specified	0.9 eV (Simmons)
EX1047	Fe/MgO/Fe	3.6 eV	1.8 eV (Simmons)
EX2012	CoFe/MgO/CoFe	3.6 eV	1.1 to 1.7 eV (Simmons)

47. I understand that Petitioner to have alleged that a POSA, with the aim of increasing the TMR, would have been motivated to lower the barrier heights in Bowen's (EX1026) and Nagahama's (EX1027) MTJs to 0.33 eV reported in Soukup (EX1028) by introducing oxygen vacancy defects into the MgO barrier layer. Petition, 33-36 and 57-59. But as Bowen, Nagahama and the evidence Petitioner submitted, POSAs sought to fabricate MgO-based MTJs as defect-free

as possible to achieve the high TMR values predicted by theoretical models of coherent tunneling in ideal perfect crystal multilayer structures.

48. Attempts to manufacture MTJs using MgO layers to take advantage of high TMR values predicted by theoretical models (e.g., Butler (EX1044) and Mathon (EX1046)) were met with limited success due to the difficulty in fabricating defect-free MgO layers. EX1047, 509 (“A magnetoresistance of several hundred percent has been predicted for perfect Fe/MgO/Fe junctions due to band structure effects [citing Butler (EX1044)]....MTJs using MgO have enjoyed only limited success. Studies using polycrystalline MgO indicated a low tunneling barrier of ≈ 0.9 eV [] pointing at a high density of defects in the barrier.”).

49. It was widely recognized that depositing high quality crystalline MgO that was as defect-free as possible would be needed to realize the high TMR values predicted by models on ideal perfect crystals. EX1047, 509 (“The LEED spots for MgO and Fe surfaces are equally sharp, with a low background intensity, indicating that the MgO film is crystalline, flat and of high quality...All MgO thicknesses used in this study were below the onset of misfit dislocations to minimize the effect of lattice defects on tunneling.”), 511 (“In conclusion, we have produced single crystalline and flat tunneling junctions and have presented a method by which to study the buried oxide film with tunneling spectroscopy”); EX1051 (“Structural defects strongly influence the electron tunneling in both the

majority and the minority channels. For example, the modification of interface states can result in a less peaked conductance around $k_{\parallel} = 0$, and reduce considerably the magnetoresistance $\Delta R/R$.”); EX1045, 1 (“In this paper we show that one is able to grow nearly perfect crystalline MgO(001) films on high-quality single crystals of Fe. The I - V characteristics of these structures are dominated by the intrinsic properties of the Fe/MgO/Fe(001) structure, allowing one, in principle, to test the wealth of predictions based on first-principles calculations.”); EX1046, 4 (“It is clear from Figs. 3 and 4 that the calculated large TMR ratio R_{TMR} in the asymptotic regime is due, entirely, to a very low spectral density of minority-spin electrons at the Γ point. To observe such a large R_{TMR} it is, therefore, essential that the Fe/MgO interface is perfect so that the theoretical minority-spin spectral density is well reproduced.”)

VII. THE ‘909 PATENT

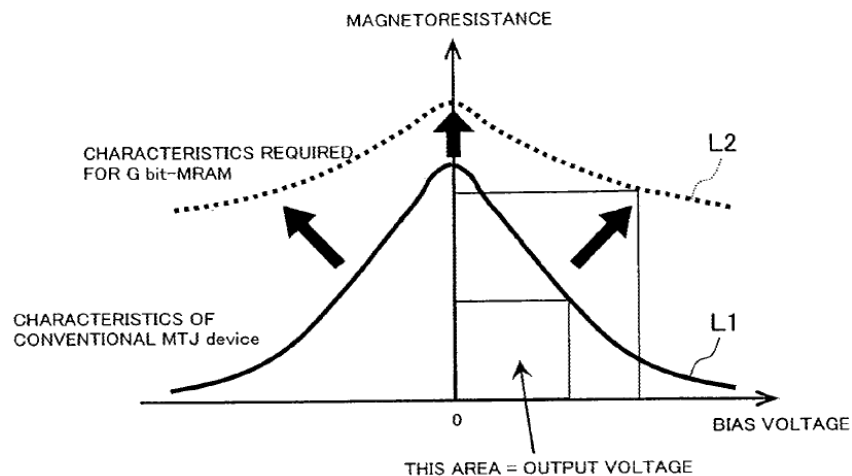
A. Overview

50. The ’909 Patent is directed to an MTJ device with improved characteristics suitable for use in applications such as MRAM. The ’909 Patent recognized that while “MRAMs with capacities on the order of 64 Mbits” could be achieved using then-current technologies, “the characteristics of the MTJ device [] needs to be improved if higher levels of integration are to be achieved.” EX1017, 2:45-67. This required smaller MRAM cell sizes which would make it more

challenging to accurately detect the signal indicating whether the MTJ was in its parallel or antiparallel state given the circuit's noise. EX1017, 2:45-67.

51. FIG. 10 illustrates TMR characteristics of conventional MTJ devices. As shown by line L1, conventional MTJs had a “small” TMR that “drastically decrease[s] upon application of bias voltage” which rendered those MTJ devices unsuitable for MRAM devices. *Id.*, 2:52-61. As shown by the line dotted line L2, an MTJ with a higher peak TMR and slower decay with increasing bias voltage would be needed to support a Gigabit MRAM.

FIG. 10



52. As a result of the low peak TMR and its rapid decay, conventional MTJs had small output voltages (a voltage signal representative of the MTJs magnetic state) of 200 mV that would not be able to support higher-capacity MRAMs. EX1017, 2:59-65, 8:31-46 (discussing output voltages). The inventor sought to increase TMR and decrease its bias voltage dependency to address the

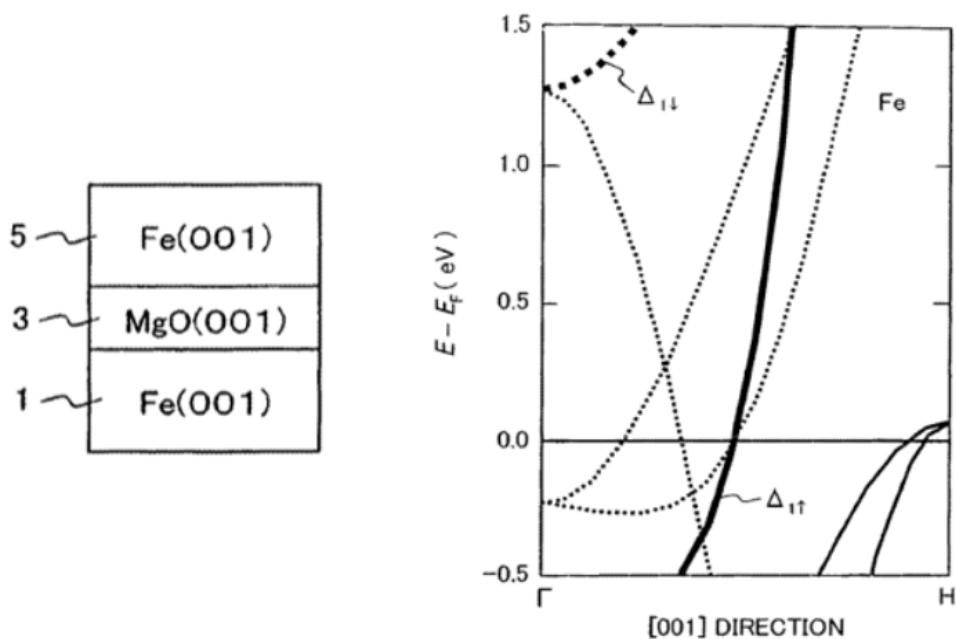
problem of conventional MTJs that, as the level of integration in MRAM increases, “signals are increasingly lost in noise and cannot be read.” EX1017, 2:49-67. The inventor explained that “Julliere’s formula predicts a highest estimated MR ratio of about 70%.” *Id.*, 5:8-38. The inventor noted that although this approximately 70% TMR had been obtained with “an amorphous Al-O tunnel barrier and polycrystalline electrodes, it has been difficult to obtain the output voltage of 200 mV ... thereby preventing the realization of MRAM.” *Id.*, 5:8-38; *see also* 2:62-68.

B. Invention

53. As explained above, the '909 Patent recognized that conventional Al₂O₃-based MTJs would not exhibit the TMR characteristics needed for use in practical applications such as large capacity MRAM where the increased density of the circuits would make it difficult to distinguish the TMR signal from the noise. EX1017, 2:45-67. The '909 Patent also explained that Julliere’s equation predicted limits on the TMR achievable from electrode spin polarization alone and that, even with “the highest estimated MR ratio of about 70%” for ferromagnetic transition metals and alloys, conventional MTJs “using an amorphous Al—O tunnel barrier and polycrystalline electrodes,” the low achievable output voltages would prevent realization of high-capacity MRAM. EX1017, 5:25-38.

54. The '909 Patent recognized the benefit of using “a single-crystal (001) of magnesium oxide (MgO) or a polycrystalline MgO in which the (001) plane is preferentially oriented” as the tunnel barrier in an MTJ device because, unlike amorphous aluminum oxide, “the electrons are not scattered and the coherent states of the electrons are con[s]erved during the tunneling process. EX1017, 5:39-47.

FIG. 1(B) (below left) illustrates one embodiment of an MgO-based MTJ device structure and FIG. 1(A) (below right) shows the energy band structure of the ferromagnetic Fe(001) in that structure. EX1017, 5:47-57.



55. As shown in FIG. 1(A), the “majority spin $\Delta 1$ band (solid line) has states at the Fermi energy E_F , whereas the minority spin $\Delta 1$ band (broken line) does not have state at the Fermi energy E_F .” EX1017, 6:8-11. Because of this characteristic in the Fe(001) electrode, “there is the possibility that a very high MR

ratio can be obtained in a coherent spin polarized tunneling.” EX1017, 6:11-14.

The '909 Patent explains that since in a “single-crystal” or “(001) oriented polycrystal” MTJ device (such as FIG. (1A)’s MTJ above) the scattering of electrons is suppressed during the tunneling process, it provides an ideal MTJ structure for “realizing the aforementioned coherent tunneling.” EX1017, 6:14-18.

56. The inventor of the '909 Patent, Dr. Shinji Yuasa, recognized that the tunnel barrier height for defect-free crystalline MgO (what the '909 Patent refers to as the “ideal value”) was too high for MRAM applications because the *RA* of the MTJ would be too high. EX1017, 6:12-18, 4:66-5:7, 7:26-27; EX2017, 869 (“the barrier height of an ideal MgO tunnel barrier height (3.7 eV) is too high for the device [MRAM] applications.”). Dr. Yuasa’s solution to that problem was to lower the tunnel barrier height by introducing oxygen vacancy defects into the MgO crystal to lower the bottom of the conduction band of the MgO barrier layer. EX1017, 3:59-61, 7:19-37, 9:4-10 (describing techniques for introducing oxygen vacancy defects); EX2017, 869.

57. The expectation at the time was that lowering the barrier height would decrease TMR as it was known to do for Al₂O₃-based MTJs. EX2017, 869; EX2037, L1036. Yet, Dr. Yuasa surprisingly achieved “the highest MR ratios that [had] so far been obtained at room temperature” with small bias voltage dependency and a “resistance-area (RA) product” that was “suitable for MRAM.”

EX1017, 8:19-30, 31-46; FIG. 6 (below showing TMR and RA values), FIG. 7(A) (below showing TMR and slow decay); EX2017, 869 (“It should also be noted that for an Al–O tunnel barrier, a lower barrier height yields a lower MR ratio [citing EX2037]. It is surprising that in Fe/MgO/Fe MTJs, there is an enormous TMR effect despite the low barrier height. This is very favourable in applications because both a low RA and a high MR ratio can be achieved”).

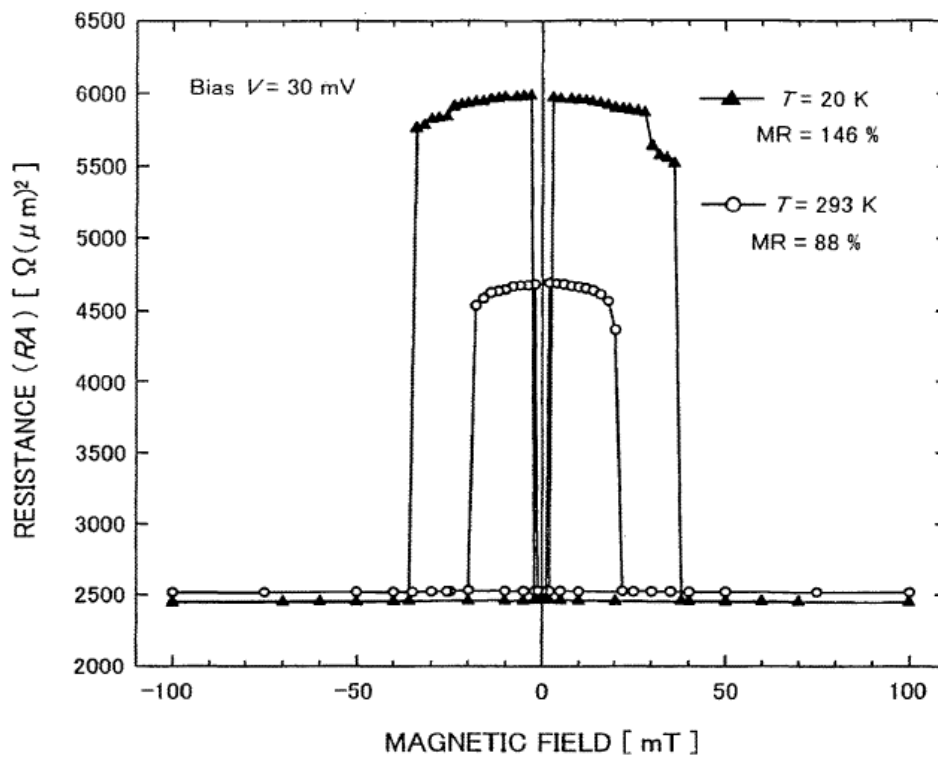
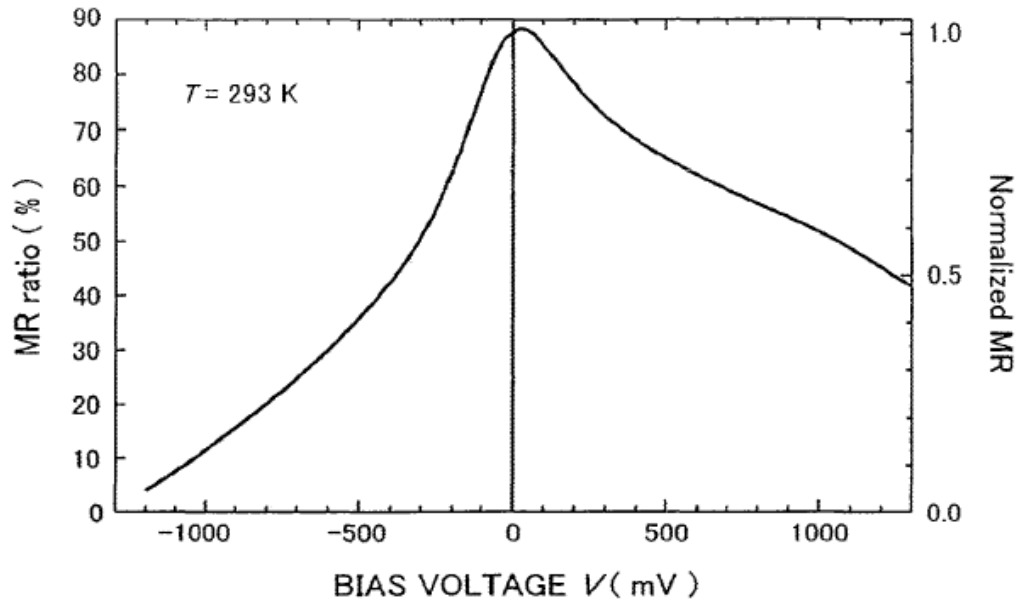


FIG. 7 (A)



58. As I explained in Section VI.E above, prior to Dr. Yuasa's invention, MTJs manufactured with MgO were unable to achieve high TMR values predicted by theoretical models, or even to achieve TMR values that exceeded those achieved with aluminum oxide barriers. EX1026; EX1053, 8043. The conventional understanding of those seeking to achieve the theoretically high TMRs with MgO barriers that were predicted (an understanding that would have been shared by a POSA) was that MgO barriers that were as defect-free as possible would need to be manufactured to mimic the perfect crystalline MgO layers on which the theoretical models were based.

59. Dr. Yuasa recognized that to make an MTJ suitable for use in high capacity MRAM, its RA should be within a certain range to allow the MTJ device's

state (parallel or antiparallel) to be accurately detected by sensing circuitry. EX1017, 8:28-30, FIG. 6; EX2017, 869-870. If the MTJ's RA is too high, current through the MTJ will be small in both the parallel and antiparallel states. Even if the TMR were high, the sensing circuitry would have difficulty distinguishing between those two small current values given signal variation from other circuit components in the MRAM. Increasing density of such circuits exacerbate the problem. If RA is too low, resistance of other circuit components (*e.g.*, metallization) can become comparable to the MTJ's resistance, making the difference between the parallel and antiparallel resistances small relative to the rest of the MRAM circuit and thus making it difficult to accurately detect the MTJ's state. Low RA values may also favor non-tunneling current through the MTJ which is independent of its magnetic state and that would decrease TMR.

60. To achieve a suitable RA , Dr. Yuasa recognized that he would need to lower the barrier height of the MTJ because the tunnel barrier height of MgO in a perfect Fe/MgO/Fe junction was too high despite the expectation that this would lower the TMR. EX2017, 869 (citing EX2037).

61. Dr. Yuasa's discovery that an MTJ device with ferromagnetic electrodes and an MgO barrier layer could be realized in a device with RA characteristics and TMR suitable for commercial applications by lowering the tunnel barrier height via targeted introduction of oxygen vacancy defects was a

departure from expectations and provided a surprising result that was recognized as a break-through advance in MTJs, as explained in detail in Section IX below.

62. EX2017 (“Yuasa NM paper”) cited in the above discussion is Dr. Yuasa’s October 2004 paper describing his work on Fe/MgO/Fe MTJs described in the ’909 Patent, which was published in Nature Materials journal shortly after filing the two Japanese patent applications to which the ’909 Patent claims priority. EX1017, Patent Face at (30). He also published his work on Fe/MgO/Fe MTJs in the Japanese Journal of Applied Physics (“Yuasa JJAP paper”) in April of 2004 (EX2016) and published his work on CoFeB/MgO/CoFeB MTJs described in the ’909 Patent in the Applied Physics Letters (“Yuasa APL paper”) on February 23, 2005 (EX2021). These are prominent peer-reviewed journals.

VIII. CHALLENGE TO CLAIMS

63. Each of the ’909 Patent’s claims 5-6 and 9-20 requires a tunnel barrier layer comprising magnesium oxide (MgO) and recites a barrier height of either 0.1-0.85 eV (claims 5, 9-11 and 13-14) or 0.2-0.5 eV (claims 6, 12 and 15-20). I understand that claims 1-4 and 7-8 are not at issue in this proceeding.

64. I understand that Petitioner to have alleged that a POSA would have been motivated to lower the barrier heights in Bowen’s (EX1026) and Nagahama’s (EX1027) MTJs to 0.33 eV reported in Soukup (EX1028) by introducing oxygen vacancy defects into the MgO barrier layer in order to increase TMR. Petition, 33-

36 and 57-59. The Petition alleges that “[a]ccording to the equation for TMR, lowering the resistance (barrier height) for parallel electrons (R_p) would improve TMR.” Petition, 34 (referring to the TMR equation reproduced on page 6, reproduced below).

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

65. First, barrier height and R_p are different. The barrier height refers to the energy difference in electron volts (eV) between the Fermi energy (E_F) of the electrode material and the bottom of the conduction band of the barrier—i.e., it is an energy barrier in electron volt units. The resistance R_p is the reciprocal of the conductance of an MTJ in the parallel configuration (i.e., when the magnetic state of the MTJ’s electrodes are aligned in the same direction) and is measured in Ohms (Ω). The two quantities of barrier height and parallel resistance R_p are in no sense equivalent.

66. Second, lowering the barrier height would not increase TMR unless it lowered R_p by a proportionately greater amount than R_{ap} . For completeness, lowering the parallel resistance R_p would increase TMR if: (1) R_{ap} remained unchanged; (2) R_{ap} increased; or (3) R_{ap} decreased, but by proportionally less than the amount by which R_p decreased. All three scenarios fall under the umbrella of the parallel resistance R_p needing to be lowered by a proportionally greater amount

than the antiparallel resistance R_{ap} . Dr. Bokor agrees. EX2013, 118:1-119:14. Dr. Bokor in his Declaration testified that “[a]s is evident from the TMR equation [same TMR equation above], lowering the resistance (barrier height) for parallel spin electrons compared to antiparallel improved TMRs.” EX1024, ¶169. I understand that the Board interpreted Dr. Bokor’s testimony to have alleged that lowering the barrier height would have lowered the parallel resistance R_p compared to the antiparallel resistance R_{ap} . Institution Decision (Paper 9), 17-18. That is not what Dr. Bokor said in the above-quoted testimony and Dr. Bokor confirmed at his deposition that he was not testifying that lowering the barrier height in an MTJ would reduce parallel resistance by more than it reduces the antiparallel resistance, but only that “if you reduce the resistance for parallel compared to antiparallel, that would increase the TMR.” EX2013, 133:1-134:17.

67. Dr. Bokor further stated his opinion during his deposition that a POSA would not have known whether lowering the barrier height in Bowen’s or Nagahama’s MTJ device would have increased TMR or decreased TMR. EX2013, 47:18-49:11, 50:7-51:22, 52:6-20, 52:21-54:3, 54:4-57:6, 57:7-58:16, 79:15-80:24, 126:7-127:19, 129:18-130:3 (Q: “[I]t is also your testimony that the person of ordinary skill in the art would not have known how TMR would have changed if barrier height were reduced in the MgO barrier layer of Bowen; right? A: “It would not have known quantitatively how much the – how much the TMR would change

or the sign.” Q: “And by sign, you mean they wouldn’t have known if it would have increased or decreased? A: Increased or decreased.”); 154:1-19 (Q: “it is your opinion that a POSA did not actually know that reducing the barrier height would increase TMR? A: I do not have evidence for that. Q: . . . You do not have evidence that a POSA would have known that reducing barrier height would increase TMR; right? A: That’s what I’ve been testifying.”).

A. A POSA Would Not Have Understood That Lowering Barrier Height Would Have Increased TMR and Would Have Understood the Opposite

68. I understand that the Board found that Moodera (EX1035) appears to support Dr. Bokor’s testimony that by lowering the barrier height “ R_p would be lowered disproportionately” compared to R_{ap} because Moodera “not[ed] the strong influence of tunnel barrier height on $\Delta R/R$.” Institution Decision, 17-18 (citing Moodera at page 3273). As noted above, Dr. Bokor confirmed during his deposition that that is not what he testified in his declaration. The first page of Moodera (pg. 3273) that the Board cites reads as follows:

Another theory of FM-FM tunneling has been proposed by Slonczewski [13]. This model analyzes the transmission of charge and spin currents through a rectangular barrier separating free electron-like FM metals. It predicts strong influence of tunnel barrier height on the orientation of the spins tunneling across the FM-I interface, thereby affecting the spin polarization and also the exchange coupling between the ferromagnets, and was consistent with the low values of $\Delta R/R$ seen previously.

69. Moodera is not saying that lowering barrier height would increase TMR. I note that Dr. Bokor agreed during his deposition that Moodera does not say that either. 2013, 146:7-148:9; see also 140:12-142:25 (confirming that he cited Moodera because it provides a TMR equation), 143:1-5 (“Q: Do you agree that nothing in Exhibit 1035 (Moodera) states that lowering the barrier height of a barrier layer will increase TMR? A: I – nothing in here discloses that. I agree with that.”). As discussed below, Moodera in fact teaches the opposite. EX1035, 3276.

70. The theory that Moodera discusses in this passage is described in a 1989 paper (EX2041) by Slonczewski to describe tunneling through a uniform rectangular barrier (i.e., the model did not account for “barrier, nonuniformity, crystal potential, electron-electron correlations, spin waves, and inelastic tunneling,” pg. 7000). EX2041, 6995. Moodera discusses Julliere’s model first, then presents Slonczewski as “[a]nother theory of FM-FM tunneling.” EX1035, 3273. Moodera initially explains that according to Julliere’s model, TMR can be estimated by the spin polarization of the two ferromagnetic electrodes. Moodera explains that Julliere’s formulation predicts the ideal TMR “in the absence of limiting factors like domain walls in the junction area, interfacial and barrier spin scattering, direct coupling between the two FM films, and degradation of FM films, which could diminish the expected effect” and that “[s]uch factors certainly contributed to the low values of $\Delta R/R$ previously measured.” EX1035, 3273.

Moodera discusses those previously measured values in the opening paragraph. Moodera made the observation that previously measured values of $\Delta R/R$ were lower than predicted by Julliere due to other contributing factors not taken into account by Julliere's model.

71. Moodera then introduces Slonczewski's theory and states that it is "consistent with the low values of $\Delta R/R$ seen previously" because in Slonczewski, the barrier height impacts the spin polarization of the electrodes that produce the TMR effect, and this can in some cases lead to a predicted low TMR. To understand this we need to further discuss Slonczewski's model. In simple terms, Slonczewski's theory predicts the TMR of a metal/insulator/metal MTJ based on the assumption of a rectangular barrier separating two metal electrodes with 'free electron' behavior. EX2041, It goes beyond Julliere's model in determining that the characteristics of both the metallic magnetic electrodes as well as the barrier affect the TMR. It derives an "effective spin polarization" of the metal/barrier/metal stack which depends not only on the spin polarization of the metals but on the characteristics of the barrier (its height and thickness). In other words, Slonczewski predicts how the barrier height would affect the TMR, which is not considered in Julliere's model. Slonczewski found that the effective spin polarization of the metal/barrier/metal stack can pass through zero and change sign with decreasing barrier height, with the result that the TMR is predicted to vary in

a complex manner with barrier height. EX2041, 6995-6998. The Dieny reference (EX1057) that Dr. Bokor cited in his declaration and explained at his deposition was a “well-known textbook” (EX2013, 139:2-3) and “a very good comprehensive text” (EX2013, 140:6-7) provides a simple discussion of Slonczewski’s theory. EX1057, 14-16. Dieny expresses Slonczewski’s equation for the “effective spin polarization of the ferromagnetic-barrier couple” (EX2041, 6997, Eq), P , which serves an equivalent role as that of the spin polarization, P_0 , in Julliere’s model, as follows:

$$P = \frac{(k_{F,\uparrow} - k_{F,\downarrow})(\kappa^2 - k_{F,\uparrow}k_{F,\downarrow})}{(k_{F,\uparrow} + k_{F,\downarrow})(\kappa^2 + k_{F,\uparrow}k_{F,\downarrow})} = P_0 \frac{(\kappa^2 - k_{F,\uparrow}k_{F,\downarrow})}{(\kappa^2 + k_{F,\uparrow}k_{F,\downarrow})}$$

EX1057, 15 (Eq. 1.10).

72. In the above expression, $k_{F,\uparrow}$ and $k_{F,\downarrow}$ are the wave vectors for majority and minority electrons at the Fermi level, respectively, κ corresponds to the decay coefficient of the electrons’ tunneling probability through the insulating barrier, and P_0 is the electrode spin polarization using Julliere’s equation. EX1057, 15, 10-14; EX2041, 6997; EX1033, 225-226. As Dieny describes, in “the limit of large barrier height Φ , and hence large decay coefficient, the resulting polarization is equivalent to the one defined in the Julliere’s model” (i.e., the model approaches Julliere at high barrier heights). EX1057, 15, 12 (Eq. 1.6). Lowering the barrier height scales down the effective spin polarization and thus decreases TMR until a

theoretical point at a low barrier height where the effective spin polarization and the TMR go to zero. Further decreasing the barrier height starts to increase TMR again. The cross-over occurs at very low barrier heights, as discussed in further detail below. EX1057, 15; EX2041, 7000.

73. As Moodera explains, Slonczewski's theory "predicts a decrease in the spin polarization with barrier height, but for the characteristics of the present junctions it seems to predict a value of $\Delta R/R < 1\%$." EX1035, 3276. "The present junctions" are those studied by Moodera consisting of CoFe/Al₂O₃/Co or Ni. Thus, Moodera's comment interpreted by PTAB—"Another theory of FM-FM tunneling has been proposed by Slonczewski [13]. This model analyzes the transmission of charge and spin currents through a rectangular barrier separating free electron-like FM metals. It predicts strong influence of tunnel barrier height on the orientation of the spins tunneling across the FM-I interface, thereby affecting the spin polarization and also the exchange coupling between the ferromagnets, and was consistent with the low values of $\Delta R/R$ seen previously"—reflects Moodera's understanding that the low $\Delta R/R$ seen previously is consistent with predictions of Slonczewski's model.

74. Moodera's understanding of the "strong influence of tunnel barrier height on the orientation of the spins tunneling across the FM-I interface, thereby affecting the spin polarization and also the exchange coupling between the

ferromagnets” was that barrier heights affected TMR. Moodera’s later statement “The Slonczewski theory [13] predicts a decrease in the spin polarization with barrier height... ” on p3276 clarifies Moodera’s understanding of lower barrier height yielding lower TMR. Moodera confirmed that understanding in a subsequent paper (EX1038) for MgO barriers. EX1038, 4728 (“MgO, with its smaller barrier height, is affected more than the Al₂O₃ barrier. This can increase the tunneling probability for the minority spins. The spin polarization of the tunneling current can then be expected to decrease, as discussed in Slonczewski’s theory.”). In other words, a lower barrier leads to lower spin polarization and hence lower TMR.

75. This is understanding in the art is consistent with Slonczewski’s theory and reinforced by Saito’s (EX2037) experiments. Saito (EX2037) published a paper in 2000 in which he measured TMRs for MTJ devices manufactured with different barrier heights and plotted them on the graph shown in Fig. 1 of Saito reproduced below with annotations in color. EX2037, L1036 (Fig. 1). The solid line in the graph represents calculated TMR values based on a free electron model for Fe electrodes and using tunneling currents “calculated on the basis of a Tsu-Esaki-type equation.” EX2037, L1036. Saito explained that his model results are roughly consistent with values predicted by Slonczewski’s theory—i.e., that “transmission coefficients of up and down spin depend on the barrier height.”

EX2037, L1036. In the discussion below, I am assuming that Saito was correct that his theoretical model was consistent with Slonczewski's theory and I have no reason to doubt it. I note that Dr. Bokor also had no reason to doubt it. EX2013, 195:4-197:21, 204:7-12. The squares and circles in Saito's Fig. 1 represent actual measured values at 3.7 K and 250 K for the devices that Saito fabricated, respectively, showing the well-known property that TMR increases as temperature decreases. EX2012, 865. The 250 K data is more relevant to Bowen and Nagahama who sought to make devices that would function around room temperature (approximately 293-298 K).

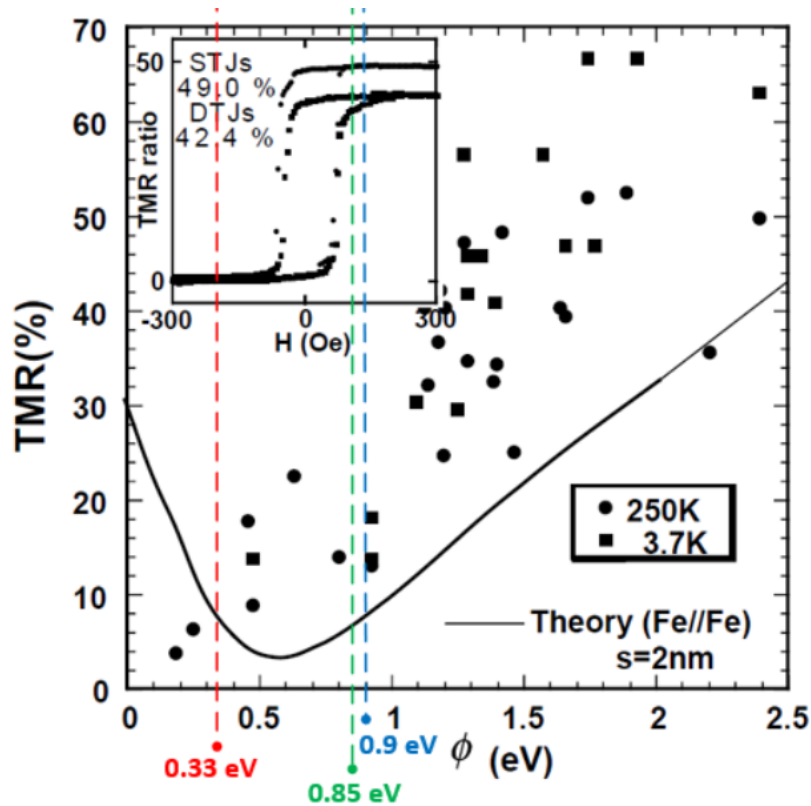


Fig. 1. Barrier height dependence on *TMR* ratio, measured at 3.7 K and 250 K, in STJs. The solid line represents the calculation result using the free electron model, assuming Fe electrodes. Inset shows minor hysteresis loops of magnetoresistance curves in the STJs and DTJs.

76. Saito's assessment of the results obtained from the experiment was that the "TMR ratio increased with increasing barrier height." EX2037, L1036. This is shown by the downward trend in the TMR for lower barrier heights of the devices that Saito fabricated and measured. However, Saito's data did not show a change in direction of measured TMRs at very low barrier heights as the theory predicted but instead the TMR continued to trend downward. Saito explained that devices with the low barrier heights would have many defects and that the TMR of those devices with low barrier heights would have the potential to be higher if they could be made without defects in the tunnel barrier. EX2037, L1036; EX2041, 7000.

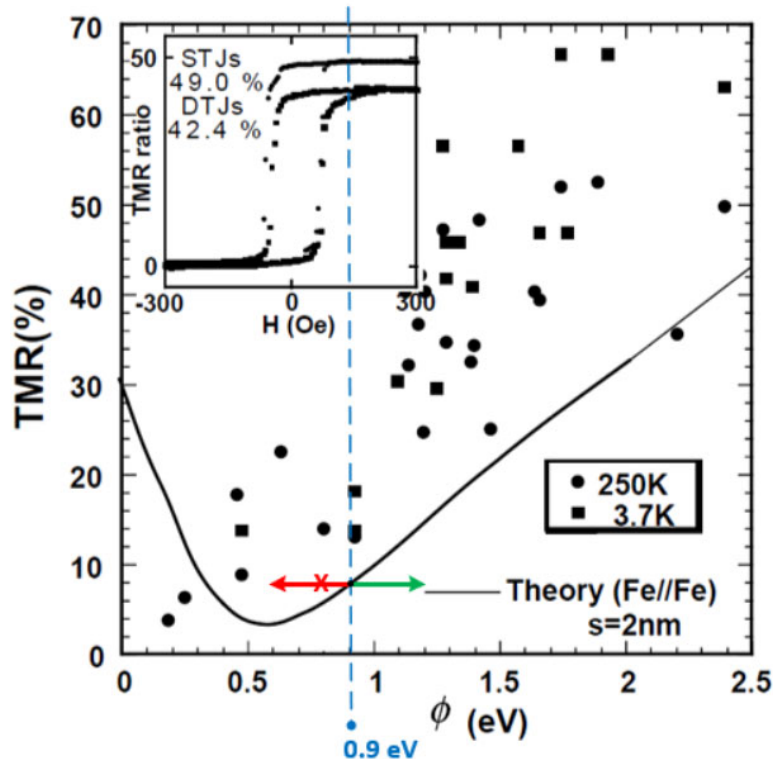
77. Saito's experiment demonstrates the limitations of theoretical models in predicting the behavior of actual fabricated devices. As Saito's data demonstrates, the model increasingly diverges from the results of real devices as the barrier height is deviated further from its "ideal" value via changing the fabrication conditions to lower the barrier height. This introduces defects into the barrier, as well as changing other properties of the MTJ, that theoretical models cannot account for. Saito, L1037 explains that defects in the barrier allows for hopping conductance through the defects—i.e., spin-independent two-step tunneling via defect states—which is an important mechanism for the loss of TMR that is not considered in Saito's or Slonczewski's models. Saito's theoretical model

tends to predict lower TMR values than were measured, consistent with what Moodera found for Slonczewski's model. EX1035, 3276 ("The Slonczewski theory [] predicts a decrease in the spin polarization with barrier height, but for the characteristics of the present junctions it seems to predict a value of $\Delta R/R < 1\%$ ").

78. Both the predicted values of TMR calculated from the theoretical model and Saito's measured data demonstrate that a POSA would not have expected Bowen's TMR to increase if its barrier height were lowered from 0.9 eV to 0.33 eV. According to Saito's model (which appears to be consistent with Slonczewski's theory as Saito said it was), whether the TMR of an aluminum oxide MTJ would increase or decrease in response to lowering barrier height depends where on the curve one begins, i.e., what is the starting barrier height value. The above annotations to Saito's Fig. 1 graph show where a 0.33 eV barrier height (red dotted line) and Bowen's reported 0.9 eV (blue dotted line) intersect the theoretical TMR curve. As shown, the predicted values are about the same.

79. According to Saito's data, and Saito's assessment that "[t]he TMR ratio increased with increasing barrier height," a POSA would have expected that lowering Bowen's barrier height from 0.9 eV to 0.33 eV would have thus decreased the barrier height rather than increased it. EX2037, L1036. Dr. Yuasa's 2004 paper in Nature Materials reinforces that a POSA's expectation was that lowering the barrier height would decrease TMR. EX2017, 869 (citing Saito as

teaching that “for an Al-O tunnel barrier height, a lower barrier height yields a lower MR ratio” and explaining that “[i]t is surprising in Fe/MgO/Fe MTJs, there is an enormous TMR effect despite the low barrier height.”). The annotation to Saito’s Fig. 1 above also shows where the 0.85 eV barrier height of the larger claimed range intersects the predicted TMR curve. Both predicted values and Saito’s data demonstrate that reducing Bowens’ barrier height from 0.9 eV to 0.85 eV would have undesirably decreased TMR.



80. My understanding from Dr. Bokor’s testimony in his declaration (EX1024), is that he has alleged that a POSA would have been motivated to lower Bowen’s barrier height of 0.9 eV to 0.33 eV (EX1024, ¶¶169-171) and would have applied a barrier height of 0.33 eV in Nagahama (EX1024, ¶¶275-277) to increase

TMR. In my opinion, the theoretical models used by Saito and Slonczewski and Saito's actual data measured from devices that were fabricated would have motivated a POSA to do the opposite. According to both the theoretical models and Saito's data, a POSA seeking to increase Bowen's TMR would have increased (not decreased) Bowen's barrier height. A POSA seeking to improve TMR for Nagahama would not have chosen a barrier height of 0.33 eV for the same reasons. Both Slonczewski's and Saito's models predict, and Saito's data show, higher TMRs with larger barrier heights. The models show an uptick in TMR at the lowest barrier heights, but the experimental data of Saito does not follow this prediction and a POSA would be well aware that a low barrier height would incur mechanisms such as hopping conductance or thermionic emission not included in the models that degrade TMR and would have expected Saito's actual measured values to more accurately reflect TMR at a barrier height of 0.33 eV. This is particularly true for the way the Petition proposes lowering barrier height by injecting oxygen defects into the MgO barrier layer.

81. As discussed above, Dr. Yuasa also expressed that the expectation was that lowering the barrier height in MgO devices would have decreased TMR. EX2017, 869. Mitani (EX1053) expressed the same expectation. Mitani explained for the Fe/MgO/FeCo devices that were fabricated that the "estimated barrier height [0.9 eV] is high enough to observe the TMR effect but is much smaller than

the value expected from half of the band gap of bulk MgO.” EX1053, 8042.

Mitani also explained that the “TMR of 23%” that was observed at 4.2 K was “smaller than that reported for the Fe/MgO/FeCo MTJ prepared by using laser ablation, suggesting that TMR in the MgO based epitaxial MTJs depends on the barrier and interface structures as well as alumina-based MTJs.” That is, Mitani noted a lower-than-expected barrier height that was “high enough” to observe the TMR effect but that the TMR was also lower than expected. This suggested to Mitani that TMR in MgO based MTJs depend on the barrier like it does for alumina-based MTJs.

82. For these reasons, it is my opinion that a POSA had the expectation that lowering the barrier height in MgO-based MTJs would decrease TMR as was the expectation for amorphous barriers such as aluminum oxide. Thus, it is my opinion that a POSA would not have been motivated to lower Bowen’s or Nagahama’s barrier height to increase TMR. A POSA’s understanding was that doing so would have decreased TMR.

83. In his declaration, Dr. Bokor testified that “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.” EX1024, ¶170 (citing EX1044 (Butler) at page 1 and EX1046

(Mathon) at page 1). Dr. Bokor also testified that “Mathon explained that tunneling was enhanced due to ‘only a small lattice mismatch of about 3.5%’ between electrodes and barrier.” EX1024, ¶170 (citing EX1046 (Mathon) at page 1). According to Dr. Bokor, “[f]ollowing this research, Bowen and other were quite interested in increasing TMRs to enable better performing MRAM.” EX1024, ¶170 (citing EX1026 (Bowen) at Abstract, 1655 and EX1055 (Wang) at page 2271). Dr. Bokor next states that “MgO had been extensively studied for decades” and that “[o]ne of skill would have been motivated to consult the literature on MgO, including Soukup.” EX1024, ¶170. I understand Dr. Bokor to be citing Butler and Mathon (citing only to page 1 of both references) as supporting the assertion that “Bowen and other were quite interested in increasing TMRs to enable better performing MRAM” because that is all that Dr. Bokor says about these references.

84. Nowhere does Dr. Bokor allege that any of Butler, Mathon, Bowen, Wang or Soukup taught that lowering the barrier height of Bowen’s or Nagahama’s MTJs would have increased TMR. None do. In fact, Dr. Bokor testified during his deposition that none of the references that he cited in his declaration teach that lowering the barrier height would increase TMR and he is not aware of any evidence that teaches that. EX2013, 114:2-115:6, 126:10-127:19, 132:10-134:18; 136:12-143:5; 149:8-23; 150:12-153:4; 154:1-19; 186:22-190:5.

Bowen (EX1026) notes that the barrier heights estimated for the fabricated MTJs were in agreement with some, lower than others and much lower than half the MgO bandgap of 5.5 eV, which Bowen attributes to manufacturing defects—suggesting that Bowen perceived the low barrier height as undesirable. EX1026, 1655. Wang (EX1055) discloses a multi-layer stack using an Al₂O₃ barrier. EX1055, 2270. Wang does not report on barrier height, but notes that “[f]or a practical junction, a high TMR value is a strong indication that a high quality of the tunnel barrier and its two interfaces is obtained” and discloses that optimizing the barrier by ensuring a smooth interface and slightly increasing barrier thickness provided the highest TMR. EX1055, 2271.

85. I understand that during his deposition that Dr. Bokor alleged that a POSA would have understood Butler to teach that changing the barrier would impact TMR, but that a POSA would not have known whether TMR would have gone up or gone down and that a POSA would not have known how to determine that from Butler. EX2013, 61:12-64:24, 66:24-67:15, 70:2-72:25, 104:8-17, 115:14-124:11, 128:4-130:3; EX2014, 36:1-40:15.² I do not see Dr. Bokor’s

² EX2014 is Dr. Bokor’s deposition testimony regarding his declarations in connection with U.S. Patent Nos. 8,405,134 (“the ’134 patent”) and 10,680,167 (“the ’167 patent”).

deposition arguments anywhere in Dr. Bokor's declaration testimony, nor do I understand Dr. Bokor as having made that argument in his declaration. Instead, Dr. Bokor's testimony regarding Butler is that it was known that high TMRs were predicted by Butler using an MgO barrier layer (Dr. Bokor also cites to page 2 of Butler as "calculating tunneling for 'bcc Fe' and MgO layers in ¶55 of his declaration). EX1024, ¶¶55-56, 64, 68, 72, 90, 91, 141-142, 143, 170, 188, 257. Butler quite clearly does not say anything about the impact of changing the barrier height and I disagree that a POSA would have drawn any conclusions from Butler about the impact of lowering the barrier on TMR.

1. Butler (EX1044)

a. Overview

86. Butler used "first principles electronic structure techniques to calculate the tunneling between Fe(100) electrodes separated by MgO tunneling barriers." EX1044, 1. Butler formulated a physical model for the interface between the Fe(100) and MgO and the electronic structure of a system consisting of bulk iron plus 12 embedded layers (four MgO monolayers and four atomic layers of Fe on each side of the MgO) was calculated. EX1044, 2. The "Fermi energy was maintained equal to that of the bulk iron as the self-consistent electronic structure was calculated for the entire system," which allowed for

rearrangement of charge between layers to “correctly offset the bands of the MgO relative to those of Fe.” EX1044, 1, FIG. 2.

87. The electronic density of states (DOS) was then calculated for each layer and for the majority and minority spin channels. EX1044, 2, FIGS. 3 and 4. Butler calculated the tunneling through the Fe(100)|MgO(100)|Fe(100) sandwich using the Landauer conductance formula that relates the conductance to the probability of a Bloch electron in one of the Fe electrodes being transmitted through the MgO barrier layer to the opposite electrode. EX1044, 4. This is illustrated conceptually in FIG. 5 of Butler (reproduced below) as two reservoirs of electrons (μ_1 and μ_2) separated by a ‘sample’.

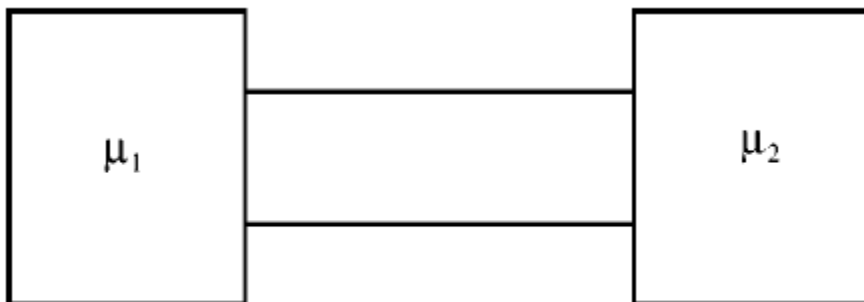
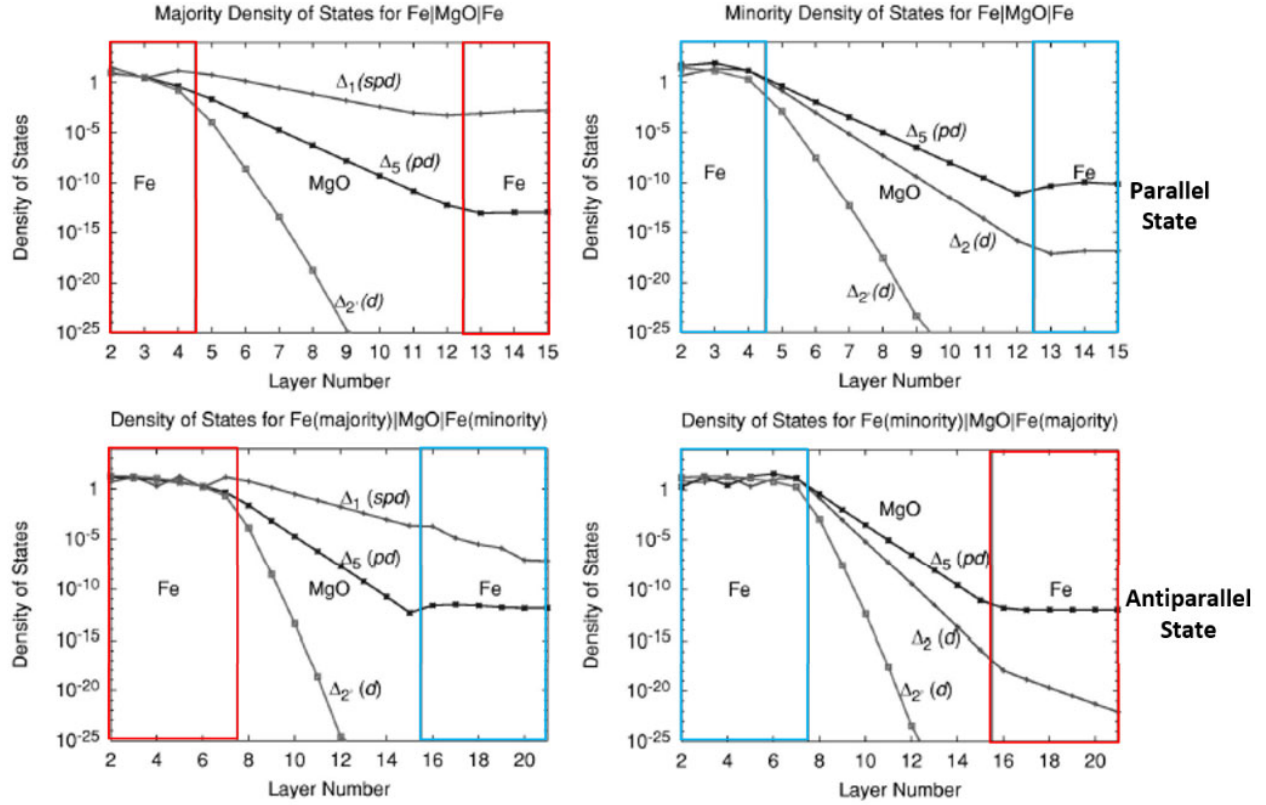


FIG. 5. Two electron reservoirs connected by a sample.

88. In Butler’s model, the ‘sample’ consists of the MgO tunneling barrier between left and right Fe electrodes whose chemical potentials are represented by μ_1 and μ_2 , respectively. Butler thus expresses the current density for electrons that leave the left Fe electrode and enter the right Fe electrode and vice versa (EX1044,

4, Eqs. (1)-(5)), the net current of which (Eq. (6)) yields the Landauer conductance formula (Eq. (7)). EX1044, 4.

89. FIG. 7 of Butler (annotated below) shows the tunneling DOS (TDOS) for each of the Fe(100) Bloch states with wave-vectors that are normal to the plane of the MgO layer ($k_{\parallel}=0$). EX1044, 5. The TDOS is defined to be the density of electronic states subject to the following boundary conditions: “on the left-hand side of the interface there is an incoming Bloch state with unit flux and the corresponding reflected Bloch states; on the right-hand side are the corresponding transmitted Bloch states.” EX1044, 5. Thus, the TDOS plots in FIG. 7 show only the tunneling probability for Bloch states having $k_{\parallel}=0$. EX1044, 5-6. The top two plots show the TDOS of Fe-MgO-Fe sandwich in the parallel configuration and bottom two plots show the TDOS in the antiparallel configuration.



90. As shown by the top left plot (parallel state), the largest conductance in the majority ($\uparrow$) channel (**red** to **red**) is predicted to be via Δ_1 state tunneling (i.e., majority $\Delta_1^\uparrow$ electrons tunneling to majority vacant $\Delta_1^\uparrow$ states) due to the large DOS of majority Δ_1 states in Fe(100) and effective coupling to and slow decay of evanescent Δ_1 states in the MgO barrier. EX1044, 5-7. As the top right plot shows (parallel state), no Δ_1 state tunneling is predicted for the minority channel (**blue** to **blue**) because there are no $\Delta_1^\downarrow$ states in the Fe(100) at the Fermi energy. EX1044, 9-10.

91. Thus, no Δ_1 state tunneling is predicted for either channel in the antiparallel state because $\Delta_1^\uparrow$ states in the first electrode propagate through the

MgO barrier but are reflected because of the lack of $\Delta 1^\downarrow$ states in the second electrode and there are no $\Delta 1^\downarrow$ states in the first electrode as discussed above. EX1044, 9 (“The $\Delta 1$ electrons readily enter the MgO where they decay slowly with distance as discussed in Sec. IV.B. On the right-hand side of the barrier however there are no minority $\Delta 1$ propagating states at the Fermi energy. Therefore, they continue to decay within the minority Fe leading to total reflection of the $\Delta 1$ Bloch state.”), 10.

92. As shown in the TDOS plots of FIG. 7, Butler’s model predicts large TMR values for Fe/MgO/Fe devices due to the loss of $\Delta 1$ symmetry tunneling conductance in the antiparallel state and that TMR is expected to increase with barrier thickness due to the slower decay of $\Delta 1$ symmetry coupling in the barrier. EX1044, 1, 10. Butler’s model predicts nothing about the effect of lowering the barrier height on TMR—nor could it. Butler modeled a Fe/MgO/Fe structure based on the band structure of crystalline MgO and then calculated the density of states for $\Delta 1$, $\Delta 2$, and $\Delta 5$ symmetries in the MgO barrier as a function of barrier thickness. EX1044, 2-10.

b. Butler Says Nothing About Barrier Height Impacting TMR Nor Would a POSA Have Drawn Any Conclusions About the Impact of Barrier Height on TMR from Butler

93. Butler’s Abstract enumerates four general results that were obtained from the “first-principles based calculations of the tunneling conductance and

magnetoconductance of epitaxial Fe(100)|MgO(100)|Fe(100) sandwiches.” None of these results says anything about the impact of barrier height on TMR. EX1044, 1. Butler also makes two predictions based on those calculations: (1) Fe(100)-MgO(100)-Fe(100) sandwiches were predicted to have a high TMR because of the effective coupling of the $\Delta 1$ symmetry from the Fe into the MgO in the majority channel and the loss of that conductance path in the minority channel; and (2) TMR was predicted to increase with barrier thickness due to the slower decay of the $\Delta 1$ symmetry in the MgO barrier. EX1044, 1. Nowhere in the analysis of the calculations does Butler say anything about barrier height impacting TMR.

94. Dr. Bokor agreed during his deposition that Butler does not describe the effect of changing barrier height on TMR. EX2013, 71:22-72:7. I have reviewed Dr. Bokor’s deposition testimony and I disagree that a POSA would have drawn any new or different conclusions from Butler about whether changing barrier height would impact TMR in an MgO barrier. I agree with Dr. Bokor that a POSA would not have been able to draw any conclusions about how a change in barrier height would impact TMR and would not have been able to determine that. EX2013, 61:12-64:24, 66:24-67:15, 70:2-72:25, 104:8-17, 115:14-124:11, 128:4-130:3; 2014, 37:2-24.

95. Butler obtained model data for a single structure: a single-crystal Fe(100)-MgO(100)-Fe(100). Neither Butler’s physical model, calculation of the

electronic structure of the layers, nor the Landauer conductance formula have an explicit barrier height parameter that can be modified. Butler calculated the electronic structure of the Fe and MgO layers from first-principles techniques of the materials themselves. The Fermi level of bulk Fe was used and the bands of the MgO relative to those of Fe were determined from the calculations of the electronic structure of the Fe(100)|MgO(100)|Fe(100).

96. An electrode/barrier/electrode sandwich that would result in a different “barrier height” using Butler’s model would not be a Fe(100)|MgO(100)|Fe(100) structure but would by definition have a different electronic structure and different electronic density of states. Butler does not provide any data for any structure other than the one the authors modeled and a POSA would not have drawn any conclusions beyond those reached by Butler, let alone any conclusion that would have motivated a POSA to lower the barrier height in Bowen’s or Nagahama’s MTJs.

c. Butler’s Contemporaries Did Not Understand Butler to Have Suggested that Barrier Height Would Impact TMR

97. I agree with Dr. Bokor that Butler is a frequently cited foundational theoretical paper that sparked considerable interest in experimentation into MgO devices. EX1024, ¶¶72, 141-142. Contrary to Dr. Bokor’s testimony that a POSA would have understood Butler to disclose that changing the barrier height would

meaningfully impact TMR in one direction or the other and then experimented with lowering the barrier height of an MgO barrier layer to increase TMR, I have seen no evidence that anyone seeking to realize the high TMR predicted by Butler understood Butler to disclose that, posited that lowering the barrier height would increase TMR, nor endeavored to do so. Dr. Bokor confirmed that he has seen no evidence of that either. EX2014, 41:16-25 (“Q: Dr. Bokor, is there a single publication that you can identify that articulates this theory or this understanding of Butler that based on this paragraph you identify in Exhibit 1044, page 1, 20 bottom paragraph on the right-hand column, TMR would be expected -- TMR in a magnesium oxide crystalline barrier layer would be expected to vary with barrier height? A: I haven’t found a publication that explicitly discusses that.”), 42:5-15 (stating same). As explained in Section VI.E above, as demonstrated by the evidence that Petitioner submitted, POSAs sought to manufacture as near-perfect crystalline MgO and as near-perfect Fe/Mgo/Fe junctions as possible. See e.g., EX1047, EX1051, EX1045, EX1046. In my opinion the lack of evidence that a POSA understood Butler to have suggested that lowering the barrier height of an MgO layer would have increased TMR, nor any evidence showing that anyone tried to do so demonstrates that is not how a POSA would have understood Butler either.

2. Mathon (EX1046)

98. I also understand that during his deposition (EX2014) in connection with his declarations concerning the '134 and '167 patents, which was taken on the day after his deposition for the '909 patent (EX2013, 2; EX2014, 2), Dr. Bokor pointed to page 4 of Mathon to support his deposition theory that a POSA would have understood from Butler that changing the barrier height would have impacted TMR, but admitted he did not cite this page in his declaration (for the '167 patent). EX2014, 53:15-54:14. Dr. Bokor also did not cite page 4 of Mathon in his declaration for the '909 patent. Dr. Bokor cites only to page 1 of Mathon (EX1024, ¶¶55-56, 68-69, 72, 90, 141-142, 154, 170, 257, 281, 326) and to page 3 (EX1024, ¶324 (“Mathon described its MgO barrier layers as ranging from 7 to 20 atomic layers.”)).

99. Dr. Bokor also admitted that he came up with the opinion that Mathon (page 4) was evidence that a POSA would have had reason to believe that changing the barrier height of an MgO layer would alter MgO was at his deposition for the '134 and '167 patents. EX2014, 55:17-56:1 (“Q: So, Dr. Bokor, you've been working on this case since winter of last year. And this is the first time that you've come up with this opinion that this passage in Mathon, Exhibit 1046, page 4, bottom left column, is evidence that a person of ordinary skill in the art in

2004 would have had reason to believe that changing the barrier height of a magnesium oxide barrier layer would alter TMR. Is that right? A: Correct.”).

100. The evidence in Mathon that Dr. Bokor says he “hadn’t noticed before just now” is the statement in Mathon on page 4 that “the on-site potentials of one of the iron electrodes are shifted slightly away from their nominal values, the TMR ratio can be altered very significantly in the preasymptotic regime.” EX2014, 54:16-55:16. Dr. Bokor could not say which direction TMR would be altered by shifting “on-site potentials.” In the sentence following the passage Dr. Bokor cites, Mathon states: “However, the calculated values of R_{TMR} remain very stable for MgO thickness greater than seven or eight atomic planes. We therefore conclude that the optimum MgO thickness for observation of a large TMR ratio in an Fe/MgO/Fe(001) junction is around ten atomic planes of MgO.” EX1046, 4. Mathon’s model considers the band structure of Fe and MgO and uses a barrier height of 3.5 eV (corresponding to the Fermi level being aligned with the mid-gap of the MgO) to align the bands of the Fe and MgO this asymptotic regime. EX1046, 1.

101. Mathon does not draw any relation to “shifting the on-site potentials of one of the Fe electrodes” to changing the barrier height, but rather, as Mathon makes clear, Mathon is attempting to model a perfect Fe/MgO interface which Mathon says is essential to obtaining a large TMR. EX1046, 4 (“It is clear from

Figs. 3 and 4 that the calculated large TMR ratio R_{TMR} in the asymptotic regime is due, entirely, to a very low spectral density of minority-spin electrons at the Γ point. To observe such a large R_{TMR} it is, therefore, essential that the Fe/MgO interface is perfect so that the theoretical minority-spin spectral density is well reproduced.”). Mathon says nothing about any relationship between barrier height and TMR, as Dr. Bokor acknowledged (EX2014, 56:10-25), nor would a POSA have understood Mathon to be teaching anything about the impact of changing the barrier height’s on TMR. Like Butler, Mathon models and reports on a single structure, a perfect Fe/MgO/Fe junction, and Mathon stresses the importance of the structure being perfect to obtain a high TMR, which is antithetical to the use of defects to lower the barrier height.

102. POSAs understood Butler and Mathon both to teach (1) that high TMRs were predicted to be achieved by making perfect crystalline MgO layers and perfect Fe/MgO/structures, and (2) that increasing the thickness of the MgO layer was also predicted to increase TMR. EX1026, 1657; EX1027, ¶¶14-15, 17. Dr. Bokor testified in his declaration that Bowen was “[g]uided by calculations from Butler and Mathon” and so grew ‘FeCo/MgO/Fe epitaxial structures’ of ‘good crystal quality MgO films with sharp interfaces’ in its tunneling experiments.” EX1024, ¶90 (citing EX1026, 1657). At his deposition, Dr. Bokor testifies for the first time that a POSA would have understood Butler and Mathon to teach that

changing the barrier height would impact TMR (but would not have known what that impact would be) and that would have motivated a POSA to try lowering the barrier height, despite the fact that Dr. Bokor acknowledged that he could not point to any evidence that a POSA understood Butler or Mathon to say that, and despite that his declaration testimony was that Bowen was guided by Butler and Mathon to attempt to grow as perfect crystalline layers as possible, which in addition to the prediction that increasing barrier thickness would increase TMR (see e.g., EX1026, 1657), are the only things the evidence shows a POSA would have understood Butler and Mathon to have taught.

B. Overview of Soukup

1. Soukup's Emission Diodes

103. Soukup fabricated thin-film Au-MgO-Au devices by evaporating Au and MgO films onto glass substrates heated to 400°C. EX1028, 3230. During deposition of the MgO layer, the pressure in the vacuum chamber rose to 10^{-8} Torr. Soukup fabricated 60 devices, 13 devices of which were “studied in detail.” EX1028, 3230. The devices that were studied were fabricated with MgO thicknesses between 60-680 Å (6-68 nm). EX1028, 3231. To “determine the effect of nonstoichiometry on the device characteristics a number of devices were fabricated by depositing the oxide film with oxygen gas present in the vacuum system.” EX1028, 3232. Device PY-G-22(2) was fabricated by admitting oxygen

gas to a pressure of 1×10^{-8} Torr and device PY-G-25(3) was fabricated by admitting oxygen gas to a pressure of 1×10^{-7} Torr. Device PY-G-38(1) was fabricated by admitting oxygen gas to a pressure of 1×10^{-5} Torr. EX1028, 3232. The device data for devices that Soukup studied are shown in Table I of Soukup reproduced below. EX1028, 3233.

TABLE I. Summary of device data.

Device No.	S^a	S_0^b	φ_1^c	φ_2^d	$P_{O_2}^e$
PY-G-11(1)	80	200	0.714	0.33	
PY-G-16(3)	105	...	0.721	...	...
PY-G-17(1)	200	194	0.721	0.33	...
PY-G-18(1)	105	...	0.694	0.34	...
PY-G-18(2)	105	222	0.700	0.35	...
PY-G-19(2)	70	133	0.710	0.33	...
PY-G-20(1)	680	...	0.695	...	...
PY-G-20(3)	680	...	0.695	...	...
PY-G-21(3)	90	...	0.732	0.34	...
PY-G-22(2)	90	209	0.780	0.21	10^{-8}
PY-G-25(3)	60	200	0.823	0.11	10^{-7}
PY-G-38(1)	120	...	1.9, 1.74 ^f	...	10^{-5} , ...

^a S = oxide thickness, in Å.

^b S_0 = overlayer thickness, in Å.

^c φ_1 = barrier obtained by zero intercept method, in eV.

^d φ_2 = barrier obtained from slope of Arrhenius plot, in eV.

^e P_{O_2} = pressure of admitted O_2 during MgO deposition, in Torr.

^f The barrier was obtained from the slope of the Fowler-Nordheim plot.

2. Soukup's Study of Au-MgO-Au Emission Diodes

104. The purpose of Soukup's experiment was to determine the current-flow mechanism in "metal-insulator-metal sandwich devices" because in 1970 "the electron processes of importance in these devices [were] in some doubt and must surely depend on the materials used and the method of fabrication." EX1028, 3229.

Soukup assessed 13 of the fabricated Au-MgO-Au devices by measuring their electron emissions into a vacuum at different voltages and temperatures to obtain I - V (current-voltage) characteristics. EX1028, 3230. Soukup compared the measured I - V data against expected characteristics described by models for different known current-flow mechanisms and ruled out those current mechanism for which the measured I - V characteristics did not fit the model. EX1028, 3230-3233.

105. Soukup first “ruled out” tunneling as the electron process of importance for 12 of his 13 devices (3230, 3235) because the I - V characteristics “did not plot as a straight line on a $\ln(I/V^2)$ vs I/V plot” as would have been expected if tunneling was of significance (3230). The only device (PY-G-38(1)) for which Soukup found “the injection mechanism could now be tunneling,” Soukup calculated barrier heights of 1.9 eV and 1.74 eV. EX1028, 3232-3233; Table I (annotated below).

TABLE I. Summary of device data.

Device No.	S^a	S_0^b	φ_1^c	φ_2^d	$P_{O_2}^e$
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PY-G-19(2)	70	133	0.710	0.33	...
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PY-G-20(3)	680	...	0.695	...	...
PY-G-21(3)	90	...	0.732	0.34	...
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PY-G-25(3)	60	200	0.823	0.11	10^{-7}
PY-G-38(1)	120	...	1.9, 1.74 ^f	...	10^{-5} , ...

^a S = oxide thickness, in Å.^b S_0 = overlayer thickness, in Å.^c φ_1 = barrier obtained by zero intercept method, in eV.^d φ_2 = barrier obtained from slope of Arrhenius plot, in eV.^e P_{O_2} = pressure of admitted O_2 during MgO deposition, in Torr.^f The barrier was obtained from the slope of the Fowler-Nordheim plot.

106. For the 12 devices for which tunneling was “ruled out,” Soukup found the measured I - V characteristics consistent with Schottky field emission because the I vs $V^{1/2}$ plots were linear as predicted by van der Ziel’s equation. EX1028, 3230, 3232, 3235-3256. After ruling out a final current-flow mechanism (“Poole-Frenkel effect”), Soukup computed barrier heights by fitting the I - V curves to the Richardson-Schottky equation (referred to as “Schottky plots”) and using the zero-field intercept method which yielded values from 0.694-0.823 eV. EX1028, 3231-3232, Table I (highlighted in green below). Soukup also calculated barrier heights from the slope of an Arrhenius plot—which measures temperature-dependence of the I - V curves (shown in FIG. 5)—and obtained different barrier height values ranging from 0.11-0.35 eV. EX1028, 3232, Table I (highlighted in yellow below).

TABLE I. Summary of device data.

Device No.	S^a	S_0^b	φ_1^c	φ_2^d	$P_{O_2}^e$
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PY-G-20(1)	680	...	0.695	...	...
PY-G-20(3)	680	...	0.695	...	...
PY-G-21(3)	90	...	0.732	0.34	...
PY-G-22(2)	90	209	0.780	0.21	10^{-8}
PY-G-25(3)	60	200	0.823	0.11	10^{-7}
PY-G-38(1)	120	...	1.9, 1.74 ^f	...	10^{-5} , ...

^a S = oxide thickness, in Å.^b S_0 = overlayer thickness, in Å.^c φ_1 = barrier obtained by zero intercept method, in eV.^d φ_2 = barrier obtained from slope of Arrhenius plot, in eV.^e P_{O_2} = pressure of admitted O_2 during MgO deposition, in Torr.^f The barrier was obtained from the slope of the Fowler-Nordheim plot.

107. Soukup's Arrhenius plots were obtained by first plotting " $\ln I$ vs. $V^{1/2}$ over a temperature range of about 100°C," as shown in Fig. 4 of Soukup. EX1028, 3232, 3231 (Fig. 4). Soukup note the I-V characteristics plotted in Fig. 4 were temperature dependent as expected since the Schottky mechanism is "very temperature dependent." EX1028, 3232. Soukup then plotted the zero-field intercept current I_0 obtained from Fig. 4 on a $\ln(I_0/T^2)$ vs. $1/T$ plot. EX1028, 3232. Soukup explained that these plots (Soukup's Arrhenius plots) should be a straight line, and the slope of the line would then again give the barrier height. EX1028, 3232. Soukup noted that most of the Arrhenius plots were not straight lines. Soukup explains that an Arrhenius plot of "this type" is made in Fig. 5 and notes

that the plot is a straight line. Soukup found that the “slope of the straight drawn in the figure gives a barrier of ϕ_R^* of .33 eV.” EX1028, 3232. The caption to Fig. 5 notes that this plot corresponds to plotting the zero-field intercept current I_0 obtained from Fig. 4 for device PY-G-11 on a $\ln(I_0/T^2)$ vs. $10^3/T$ plot. As discussed below, Soukup’s PhD dissertation shows that the Arrhenius plot for device PY-G-11(1) was also not a straight line. It yields a barrier height consistent with Soukup’s barrier heights computed for the other devices via the Arrhenius plot method highlighted in yellow above, with the exception of the two devices (PY-G-22(2) and PY-G-22(2)) for which oxygen was introduced (discussed below). EX1028, 3232-3233 (Table I).

108. The Soukup article is based on the investigation Soukup performed for his doctoral dissertation (EX2039) that describes this study in greater detail. In the more detailed discussion of the discrepancy Soukup noted regarding the Arrhenius plots, Soukup explained that because the slopes of the Arrhenius plots were not straight lines, the “slope of these plots will not be proportional to the barrier height, which may explain the difference seen between the barriers found by the two methods.” EX2039, 88. Because the barrier heights were computed from the best straight line fit to the Arrhenius plots, “the slope of the Arrhenius plot will give a value for the barrier height which is actually less than the real barrier height.” EX2039, 89. Figure 33 of the Soukup dissertation (PDF page 193)

shows that the Arrhenius plot for device PY-G-11(1) is also not a straight line. Figure 39 (PDF page 199) reproduces the Arrhenius plot for device PY-G-11(1) along with devices PY-G-22(2) and PY-G-22(2) and Soukup confirms that “none of these curves plot as straight lines.” As Soukup explained, the Arrhenius plots obtained from the measured I - V characteristics should have been straight lines, but none were. This raises some doubt concerning the accuracy of the barrier heights computed from the zero-field intercept of the Schottky plots, which were obtained from the same I - V characteristics that should have produced straight-line Arrhenius plots but did not. Neither Soukup’s reported barrier heights calculated from the zero-field intercept of the Schottky plots, nor from the slope of the Arrhenius plots are tunnel barrier heights as claimed because Soukup used the Schottky model to calculate all his barrier heights and not Simmons’s model. POSAs understood from the ’909 Patent that the claimed tunnel barrier heights are determined using Simmons’s formula. EX1017, 7:39-8:14. A POSA would understand that the two models, Schottky and Simmons, predict I - V curves with very different functional forms and therefore the barrier heights derived from each are not comparable.

109. Dr. Bokor attempted to rescue Soukup’s data by arguing that the Arrhenius plot calculations were not straight lines for only two devices (PY-G-22(2) and PY-G-25(3)) where oxygen was introduced during deposition (discussed below), which two devices Dr. Bokor acknowledged have “some serious

discrepancies.” EX2013, 179:18-180:5, see also 169:13-176:1, 176:6-181:13, 184:8-185:17. But Dr. Bokor ignored the other five devices (PY-G-17(1), PY-G-18(1)-(2), PY-G-19(2) and PY-G-21-22(2)) having similar barrier heights to PY-G-11(1) calculated from Arrhenius plots that were not straight lines. This make sense because as Soukup’s dissertation made clear, device PY-G-11(1) also did not produce a straight-line Arrhenius plot. All of Soukup’s devices share this discrepancy. Thus, the reason Dr. Bokor gave for finding any of the barrier heights reported in Soukup reliable is based on the incorrect assumption that device PY-G-11(1) had a straight-line Arrhenius plot that it did not in fact have and that only two devices had non-linear Arrhenius plots. Thus, in addition to a POSA’s understanding that Soukup’s barrier heights calculated from straight-line approximations of non-linear Arrhenius plots were incorrect, a POSA would have had reason to doubt the reliability of the barrier heights calculated from the zero intercept of the Schottky plots that came from the same I - V measurements. EX2013, 174:12-176:5, 176:6-177:21 (acknowledging that the barrier heights computed by the two different methods are “not independent” but “connected” and acknowledging that reading Soukup’s data as having a problem for both methods was “one way to look at it.”).

110. In the summary of the investigation, Soukup explained that he ruled out all of the current flow mechanisms that were examined against the measured I -

I-V curves except for Schottky emission. EX1028, 3235. Soukup noted that the “only evidence that the current flow mechanism in these device is not Schottky emission is found in the temperature dependence of the *I-V* curves” (i.e., the non-linearity of the Arrhenius plots discussed above). EX1028, 3236. Though this still would not rule out Schottky emission if the barrier were a function of temperature, because no evidence of that was obtained, Soukup could make “no definite conclusions as to the type of current flow mechanism” in these devices. EX1028, 3236. But Soukup did not propose that the alternative was tunneling, which Soukup ruled out because it did not fit the data at all, except for the sole device (PY-G-38(1)) for which Soukup found “the injection mechanism could now be tunneling.” EX1028, 3232-3233. Soukup instead pointed to the evidence showing that the “emission current must be due to the electrons in the tail of the Fermi distribution above the energy level of the oxide conduction band.” Soukup, 3235-3236.

111. For the three devices that Soukup studied to determine nonstoichiometric effects (PY-G-11(1) for no oxygen and PY-G-22(2) and PY-G-25(3) for oxygen gas admitted at 1×10^{-8} and 1×10^{-7} Torr, respectively), Soukup’s two measurement techniques yielded contradictory results in terms of whether added oxygen increased or decreased barrier height. EX1028, 3229 (“The apparent barrier height determined from the zero-field intercept went up for increasing

oxygen pressure and the barrier height determined from the Arrhenius plot went down.”), 3232, Table I (annotated below).

TABLE I. Summary of device data.

Device No.	S^a	S_0^b	φ_1^c	φ_2^d	$P_{O_2}^e$
PY-G-11(1)	80	200	0.714	0.33	
PY-G-16(3)	105	...	0.721	...	...
PY-G-17(1)	200	194	0.721	0.33	...
PY-G-18(1)	105	...	0.694	0.34	...
PY-G-18(2)	105	222	0.700	0.35	...
PY-G-19(2)	70	133	0.710	0.33	...
PY-G-20(1)	680	...	0.695	...	...
PY-G-20(3)	680	...	0.695	...	...
PY-G-21(3)	90	...	0.732	0.34	...
PY-G-22(2)	90	209	0.780	0.21	10^{-8}
PY-G-25(3)	60	200	0.823	0.11	10^{-7}
PY-G-38(1)	120	...	1.9, 1.74 ^f	...	10^{-5} , ...

^a S = oxide thickness, in Å.

^b S_0 = overlayer thickness, in Å.

^c φ_1 = barrier obtained by zero intercept method, in eV.

^d φ_2 = barrier obtained from slope of Arrhenius plot, in eV.

^e P_{O_2} = pressure of admitted O_2 during MgO deposition, in Torr.

^f The barrier was obtained from the slope of the Fowler-Nordheim plot.

C. A POSA Would Not Have Understood Soukup to be Analogous to the '909 Patent

112. I understand that each of claims 5-6 and 9-20 of the '909 Patent at issue in this proceeding are challenged as being obvious in view of a combination of Bowen and Soukup (Ground 1) or a combination of Nagahama and Soukup (Ground 2). I have been informed that for a reference to be eligible prior art for the purpose of establishing obviousness of a claim, the reference must be analogous to the patent at issue because non-analogous art would not have been

considered by a POSA. I have been asked to give my opinion as to whether Soukup is analogous to the '909 Patent. I have been informed that for a prior art reference to be analogous it must either be (1) in the same field of endeavor as the patent at issue, or (2) reasonably pertinent to the particular problem with which the inventor is involved.

1. Soukup Is Not In the Same Field of Endeavor as the '909 Patent

113. I have also been informed that way the field of endeavor of a patent is ascertained is to look at the patent's title, the Abstract, the Field of the Invention, the Background of the Invention, the preamble of the patent's claims, and the function and structure of the claimed invention.

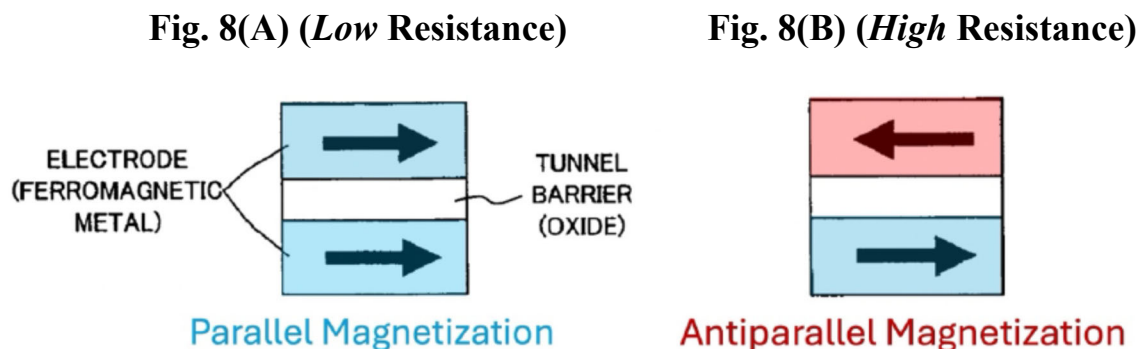
a. The '909 Patent's Field of Endeavor is MTJ Devices

114. The '909 Patent's Title recites a "magnetoresistive" device. The '909 Patent's "Background of the Invention" includes a "Field of the Invention" section and a "Description of Related Art." EX1017, 1:33-2:41. The '909 Patent's field of the invention states:

The present invention relates to *a magnetic tunnel junction device* and a method of manufacturing the same, particularly to *a magnetic tunnel junction device with a high magnetoresistance* and a method of manufacturing the same.

115. Likewise, the '909 Patent's description of the related art discusses the operation of a "magnetic tunnel junction device" (i.e., an "MTJ device") in

connection with FIGS. 8(A) and 8(B) (annotated below) to explain the different resistances an MTJ device exhibits in the parallel and antiparallel states. EX1017, 1:51-2:4.



116. As the '909 patent's description of the related art also discusses the use of the difference between resistances in the parallel and antiparallel magnetic states to encode/decode binary data with one state corresponding to a "0" and the other corresponding to a "1" thereby allowing an MTJ device to operate as a non-volatile storage element in "[m]agnetoresistive random access memories (MRAMs)." EX1017, 2:4-40.

117. The '909 patent's abstract describes increasing the output voltage of an "Fe(001)/MgO(001)/Fe(001) MTJ device." EX1017, Abstract (57). Each of the '909 patent's claims recite a "magnetoresistive device comprising a magnetic tunnel junction structure" in the preamble. EX1017, 9:65-11:5 (claims). I note that Dr. Bokor also characterized the claims in the same way: "The '909 Patent's claims are directed to an MTJ device." EX1024, ¶84. Thus, all of the sources that I

have been told are used to identify a patent's field of endeavor convey that the '909 Patent's field is MTJ devices.

b. Soukup's Field of Endeavor is Electrical Conductance Through MgO Films

118. Soukup is titled "Voltage-Current Characteristics for Electrical Conductance Through Thin MgO Films." Soukup, 3229. Soukup fabricated 60 thin-film "Au-MgO-Au emission diodes" and measured I - V characteristics of 13 of them in order to determine what the current flow mechanism was for these devices. Soukup concluded that "The voltage-current characteristics of Au-MgO-Au thin-film emission diodes formed by electron beam evaporation of Au and MgO are consistent with an expression derived for Schottky field emission into the conduction band of the oxide." Soukup, 3229 (Abstract), 3230-3230.

119. First, Soukup's studied "Au-MgO-Au emission diodes." Gold is not magnetic. EX1027, [0011]-[0012] ("nonmagnetic" gold), [0043]. Soukup's devices are not magnetoresistive devices, nor are they MTJs. Soukup was published in 1970 before Julliere discovered the TMR effect in 1975. EX1033 (Julliere); EX2010, 172; EX1057 (Dieny 2017), 42.

120. Second, the current-flow mechanism of importance in an MTJ is tunneling and Soukup determined that the electron process of importance in the devices that Soukup studied was *not* tunnelling, but instead the dominant current flow mechanism was Schottky field emission. Soukup concluded that the "voltage-

current characteristics of *Au-MgO-Au thin-film emission diodes* ... are consistent with an expression derived for *Schottky field emission*.” Soukup, 3229 (Abstract). As I explained in Section VIII.B.2 above, the only current mechanism that Soukup did not rule out was Schottky emission. Soukup stopped short of drawing a definite conclusion because many of the fabricated devices did not exhibit the temperature-dependency expected and no evidence was found for a temperature-dependent barrier height that would explain this discrepancy. EX1028, 3236. But Soukup did not offer an alternative theory and definitively “ruled out” tunneling as being inconsistent with the I - V characteristics of the devices that he studied. EX1028, 3235 (“A number of current flow mechanisms were ruled out since the functional dependence of I upon V was wrong for these mechanisms”), 3230 (ruling out tunneling), except for one device (PY-G-38(1)) for which Soukup found “the injection mechanism could now be tunneling,” EX1028, 3232-3233. I note that Dr. Bokor agreed that the dominant current mechanism in Soukup’s devices were Schottky emission and not tunneling. EX2013, 185:11-17 (responding to the question that “if the data is consistent with the Schottky model, doesn't that mean that the current transport mechanism in [Soukup’s] devices was Schottky emission, Dr. Bokor answered that “it means that the dominant current mechanism in these devices was Schottky emission.”); EX2014, 222:17-24, 224:22-225:5.

121. Soukup’s study of *non-magnetic* devices in which the dominant current-flow mechanism was found not to be tunneling is not in the same field (*magnetic tunnel* junction devices) as the ‘909 Patent. A POSA would have recognized that Soukup, published in 1970, could not have been directed to the field of MTJ devices because the TMR effect would not be observed for approximately five years until the publication of M. Julliere’s seminal 1975 paper. EX1033 (Julliere); EX2010, 172 (“It was Julliere who first discovered the effect,” citing EX1033); EX1057 (Dieny 2017), 42 (“The TMR effect was first discovered in 1975 by Julliere,” citing EX1033), Petition, 5 (“In 1973, the ‘pioneering work of Julliere’ (EX1033), EX1057 at 9, discovered tunneling magnetoresistance in an MTJ at a low temperature (4.2 K, -452°F)”).

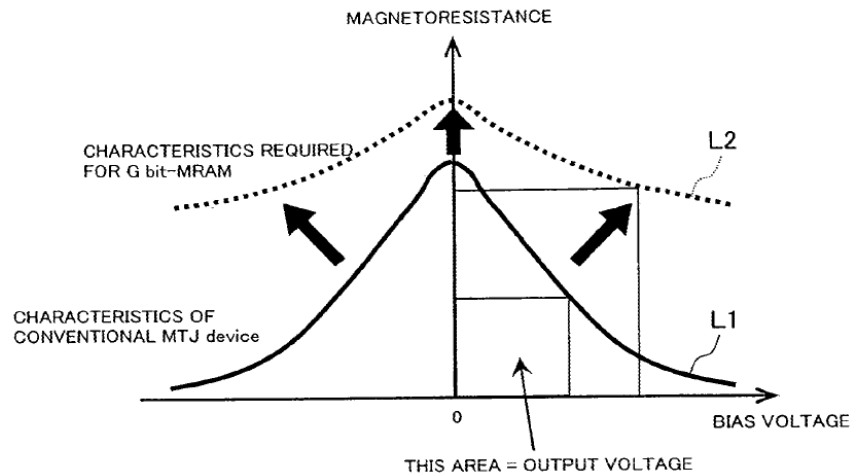
2. Soukup Is Not Reasonably Pertinent to the Particular Problem with Which the ‘909 Patent is Involved

122. The problem the inventor sought to solve was improving “the characteristics of the MTJ device” to support MRAMs with greater capacities than the 64 Mbits achievable with then-current technologies. EX1017, 2:45-49. the inventor recognized that “the magnetoresistance [TMR] must be increased and the bias voltage characteristics must be improved” for an MTJ device to be viable for higher capacity MRAMs. EX1017, 2:49-52.

123. The ‘909 Patent illustrates problems of a conventional MTJ device that need to be addressed in FIG. 10 reproduced below. As shown by solid-line L1,

conventional MTJs had a “small” peak TMR (labelled “magnetoresistance”) of approximately 70% that “drastically decrease[d] upon application of bias voltage.” *Id.*, 2:52-58. As a result of the low peak TMR and its rapid decay, conventional MTJs had small output voltages (a voltage signal representative of the MTJs magnetic state) of 200 mV that would not be able to support higher-capacity MRAMs. EX1017, 2:59-65, 8:31-46 (discussing output voltages).

FIG. 10

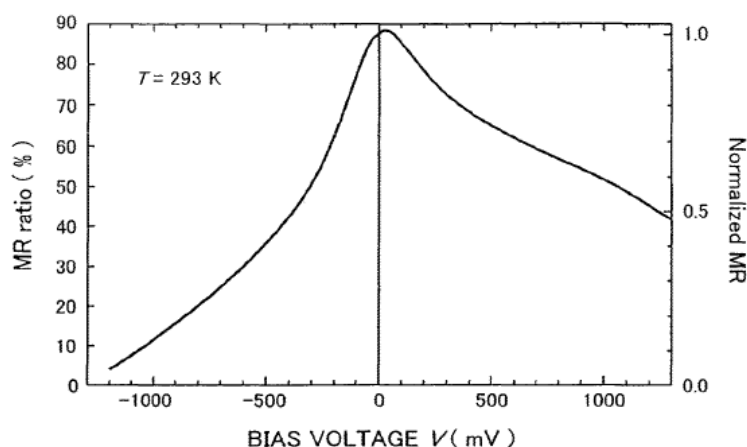


124. The inventor sought to increase TMR and decrease its bias voltage dependency to address the problem of conventional MTJs that, as the level of integration in MRAM increases, “signals are increasingly lost in noise and cannot be read.” EX1017, 2:49-67. The inventor explained that “Julliere’s formula predicts a highest estimated MR ratio of about 70%.” *Id.*, 5:8-38. He noted that although this approximately 70% TMR had been obtained with “an amorphous Al-O tunnel barrier and polycrystalline electrodes, it has been difficult to obtain the

output voltage of 200 mV ... thereby preventing the realization of MRAM.” *Id.*, 5:8-38; *see also* 2:62-68.

125. Thus, the problem the '909 Patent sought to solve was achieving an MTJ device with a high TMR with less bias voltage decay and a high enough output voltage suitable for use in larger MRAMs. EX1017, 2:45-4:8. The inventor solved this problem. For example, an Fe(001)/MgO(001)/Fe(001) MTJ embodiment achieved a TMR of 88% at room temperature (293 K) which was the highest TMR “ratios so far obtained at room temperature,” as shown in FIG. 7(A) of the '909 Patent reproduced below. EX1017, 8:15-21. The room temperature TMR is important for commercial applications that typically do not operate at cryogenic temperatures but instead operate in room temperature conditions.

FIG. 7 (A)

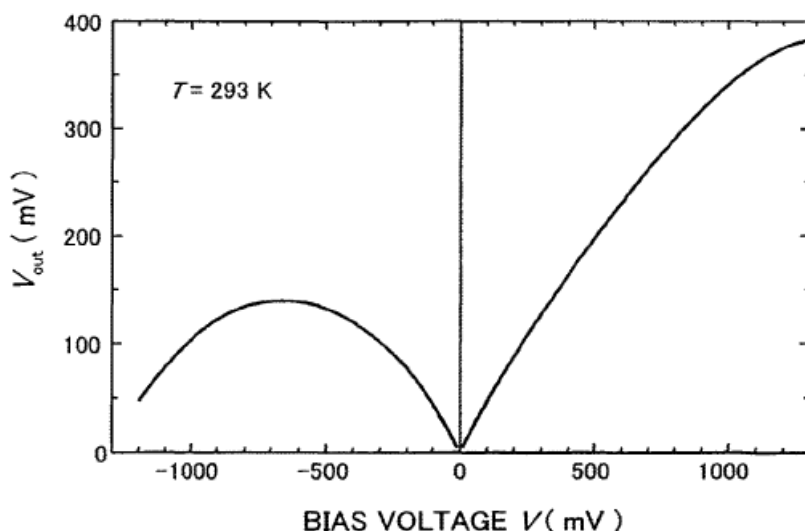


126. As I explained in Section VII.B above, this high TMR was thought to be achieved because of “coherent spin-polarized tunneling” (EX1017, 8:21-24) between the Fe electrodes and the MgO layer. In particular, the inventor explained

in the Fe(001), the “majority spin $\Delta 1$ band (solid line [FIG. 1(A)]) has states at the Fermi energy E_F , whereas the minority spin $\Delta 1$ band (broken line) does not have state at the Fermi energy E_F .” EX1017, 6:8-11. Because a “single-crystal” or “(001) oriented polycrystal” MgO barrier suppresses scattering of electrons, the majority spin $\Delta 1$ states (and lack of minority spin $\Delta 1$ states) will enhance the difference in tunneling conductance between the MTJs two magnetic states and hence the TMR. EX1017, 6:11-18. See also Section VI.C above discussing coherent tunneling.

127. The TMR of the '909 Patent's MTJs also desirably had fairly small “bias voltage dependency” at room temperature. EX1017, 8:15-21. As a result of the high TMR and small bias voltage dependency, an output voltage of 380 mV was achieved, which was “about twice as large” as that from conventional Al-O barriers, as illustrated in FIG. 7(B) of the '909 Patent reproduced below. EX1017, 8:41-45. “These high values in terms of both [T]MR ratio and output voltage suggest the effectiveness of the technique according to the present embodiment.” EX1017, 8:44-46.

FIG. 7 (B)



3. Soukup's Study of Emission Diodes Was Not Reasonably Pertinent to the Problem the '909 Patent Solved

128. Soukup's fabricated and studied Au-MgO-Au devices. These devices did not have magnetic electrodes, so they did not have different magnetic state behavior and thus these devices had no TMR. Soukup, 3229. A POSA would not have understood Soukup to be reasonably pertinent to the problem of increasing the TMR and reducing TMR dependency on bias voltage in an MTJ device.

129. Soukup also determined that the Schottky emissions were the dominant current flow mechanism in Soukup's devices, not tunneling. Given that Soukup's oxide thicknesses were from 3 to 34 times as thick as the MgO layer in the '909 Patent, Soukup's conclusion would have been unsurprising to practitioners in the 2004 timeframe. EX1028, 3232, 3233 (Table I). Thus, a POSA would not have found Soukup's study of Au-MgO-Au device reasonably pertinent

even to tunneling behavior through an MgO barrier layer, let alone coherent tunneling through MgO barrier layers that the '909 Patent employed to solve the problem of low TMR in conventional MTJs. EX1017, 6:1-18.

130. As explained in Section VII.B above, the inventor identified the desirable property that in Fe/MgO/Fe(001), Fe electrodes have $\Delta 1^\uparrow$ states but no $\Delta 1^\downarrow$ states at the Fermi energy and made use of that property to preserve $\Delta 1$ states during tunneling through MgO rather than scattering them. EX1017, 6:1-18. Soukup did not use ferromagnetic electrodes and the only thing that Soukup says about the character of the MgO layers was the range of thicknesses that they were deposited. Soukup does not say anything about the crystallinity or the orientation of the device's MgO layers of the fabricated devices.

131. A POSA thus would not have found anything about Soukup's study of the electron transport mechanisms through an MgO layer in Au-MgO-Au devices reasonably pertinent to any problem the '909 Patent was involved with, nor to ways in which the inventor solved them.

D. Soukup Would Not Have Been Motivated a POSA to Modify the Barrier Height of Bowen's or Nagahama's MTJ Device to be 0.33 eV

132. I understand that each of claims 5-6 and 9-20 of the '909 Patent at issue in this proceeding are alleged to be obvious in view of the combination of Bowen or Nagahama with Soukup because a POSA would allegedly have been

motivated to apply the barrier height of 0.33eV reported by Soukup (EX1028) to Bowen's or Nagahama's MTJ device. Petition, 33-36 and 57-59. I have been asked to give my opinion on whether a POSA would have been motivated to modify the barrier height of Bowen's or Nagahama's MTJ device in that way based on Soukup. I understand that for a POSA to have been motivated to modify a reference based on the teachings of another reference, a POSA must have had a reason to do so and that a POSA would not have made a modification that teachings in the prior art references would have discouraged.

1. A POSA Would Not Have Been Motivated by Soukup's Non-Magnetic Emission Diodes With Dominant Schottky Emissions To Lower the Barrier Height in Bowen's or Nagahama's MTJ Devices to Increase TMR

133. Both Bowen and Nagahama disclose MTJ devices. For reasons discussed in Section VIII.A above, a POSA would not have been motivated to lower the barrier of an MTJ device to increase TMR. Soukup's Au-MgO-Au do not have a TMR and so would have taught a POSA nothing about ways to increase TMR. EX2014, 219:24-223:8. I understand that Petitioner alleged that a POSA would have found Soukup's teachings relevant because "Bowen and Soukup studied properties of MgO barriers and were focused on improving tunneling devices." Petition, 35, 58 (Nagahama). But Soukup was not directed to fabricating any particular type of device, let alone focused on improving them. Rather, Soukup sought to identify what current mechanism was at work in the devices that Soukup

fabricated. As discussed in Section VIII.B.2 above, Soukup ruled out tunneling as an important transport process because the measured I - V characteristics were wrong for that mechanism. EX1028, 3230, 3225. In my opinion, Soukup would not have motivated a POSA to lower the barrier heights of Bowen's or Nagahama's MTJs for any reason. Soukup introduced oxygen into the vacuum chamber to investigate the effects of non-stoichiometry of the MgO barrier layer (see Section VIII.B.2 above). Soukup hypothesized that introducing oxygen into the vacuum chamber would increase barrier height (and got conflicting results), but provided no view on whether a higher or lower barrier height was preferred for any reason. Thus, a POSA would not have understood Soukup's lower barrier heights to have offered any advantage in the MTJ devices disclosed in Bowen or Nagahama.

2. A POSA Would Have Understood that Soukup's Lower Barrier Heights Would Have Decreased TMR in Bowen and Nagahama's MTJs

134. Neither Bowen nor Nagahama were seeking to lower the barrier height of their MTJ devices. Bowen pointed to various potential defects introduced during fabrication to explain why the barrier height was lower than half the band gap calculated for ultrathin layers of MgO because Bowen was seeking to manufacture MTJs with as near-to-perfect crystalline MgO as could be achieved. EX1026, 1656. Nagahama does not discuss barrier height at all. The prevailing

view in the art was that reducing the barrier height of Bowen or Nagahama would have decreased, not increased TMR. Even if a POSA would have considered Soukup to be relevant, Soukup's finding that the dominant current mechanism was Schottky emissions for devices at any barrier heights within the claimed range would not have wanted to adopt those barrier heights because a POSA understood that increasing forms of current flow other than tunneling would *decrease* TMR. A POSA would have found nothing beneficial about the I - V characteristics of Soukup's device, but instead would have understood such characteristics to be detrimental.

135. TMR results from the quantum mechanical effect of spin-dependent tunneling (i.e., the preservation of spin states during tunneling through the barrier of electrons having energy below the energy barrier—EX1028, 3229 and EX1031, 1794) so that spin state polarization in magnetic electrodes will produce different amounts of tunneling conduction depending on the magnetic state of the electrodes. EX1033, 225-226; EX1050, 2427 (“The TMR effect is known to originate from the spin polarization of the electrodes, i.e. the difference between the densities of states (DOSs) of the up- and down-spin subbands in the two electrodes”); EX1057, 11-13, 42 (“The origin of the TMR effect is tunneling of spin-polarized electrons”); EX1024, ¶58 (“Higher spin polarization in the electrodes increases the TMR”); EX1017, 6:7-14 (“Because of such half-metallic

characteristics of the Fe $\Delta 1$ band, there is the possibility of a very high MR ratio can be obtained in a coherent spin polarized tunneling.”); EX1046, (“the calculated large TMR ratio R_{TMR} in the asymptotic regime is due, entirely, to a very low spectral density of minority-spin electrons at the Γ point.”); EX1044, 1, 9.

136. A POSA understood that lowering the barrier height to where the dominant current-flow mechanism is Schottky emission, or any mechanism other than spin-dependent tunneling, would disadvantageously decrease TMR because of the increased percentage of the MTJ’s conductance being contributed by current-flow mechanisms that do not depend on the magnetic state of the MTJ—i.e., an increase in the conductance in both parallel and antiparallel states. This result comes straight from the TMR equation, which can be most easily shown using the equivalent conductance ratio.

$$TMR = \frac{\Delta G}{G} = \frac{G_p - G_{ap}}{G_{ap}} = \frac{R_{ap} - R_p}{R_p}$$

EX1057, 13 (Eq. 1.9); EX2005, 37 (Eq. 3); EX1033, 225-226

137. Any additional thermionic current flow such as Schottky current (where, unlike tunneling, electrons have sufficient energy to surmount the energy barrier—EX1028, 3229 and EX1031, 1794) or any other spin-independent current flow (i.e., a current flow mechanism that does not depend on the magnetic state) would add an additional conductance component to the conductance of the MTJ in

both states. Thus, an MTJ that is modified so that it has an additional magnetic-state-independent conductance G_I would have a lower TMR than it had before the modification, as shown by the TMR equation below.

$$\frac{(G_p + G_I) - (G_{ap} + G_I)}{(G_{ap} + G_I)} = \frac{G_p - G_{ap}}{(G_{ap} + G_I)} < \frac{G_p - G_{ap}}{G_{ap}}$$

138. Independent of the size of the additional conductance component G_I , TMR will decrease. Lowering the barrier heights of Bowen's or Nagahama's device to those reported in Soukup such that Schottky emissions dominate would be expected to dramatically decrease TMR because, as shown above, any additional current contribution that does not contribute to spin-dependent tunneling would decrease TMR. The principle is similar in principle to decreases in TMR at higher temperatures and bias voltages—reduced amounts of conductance contributed by spin-dependent tunneling. EX1057, 19; EX2037, L1037. Thermionic emissions like Schottky emissions are not intrinsically spin-conservative. Thus, lowering the barrier height to where thermionic emission becomes the dominant current-flow mechanism would reduce the percentage of current flow that is magnetic-state-dependent and thus decrease TMR. The only one of Soukup's devices that suppressed Schottky emission at low voltages where tunneling behavior could be seen, had significantly larger barrier heights (1.94 and 1.74 eV). EX1028, 3232, 3233 (Table I). Furthermore, the manner of lowering the

barrier height by introducing oxygen vacancy defects would be expected to increase the amount of spin-independent tunneling through defect states, as was found by Saito. EX2037, L1037.

139. I agree with Dr. Bokor that a POSA would have been concerned that lowering an MTJ's barrier height so that a significant percentage of the current flowing through the MTJ was from non-tunnelling thermionic emission (like Schottky emission) would decrease TMR and that this would have been a reason to avoid low barrier heights in an MTJ. EX2013, 86:21-87:19, 88:1-15 (acknowledging that reducing the barrier height from 0.9 eV to .33 eV would have resulted in increased thermionic emissions). A POSA would have understood from Soukup's findings in the devices that were investigated that the lower barrier heights reported present those conditions. Indeed, a POSA would have understood Soukup's finding that the only device for which "the injection mechanism could now be tunneling, i.e., a higher barrier [1.9 eV, 1.74 eV]" as reinforcing the understanding that higher barrier heights increase the percentage of current flow contributed by tunneling. EX1028, 3232, 3233 (Table I).

140. Thus, if a POSA would have looked to Soukup for any reason, a POSA would not have lowered the barrier height in either Bowen's or Nagahama's MTJ to be within either claimed range because Soukup teaches that at those barrier

heights current flow is dominated by Schottky emissions which would have *decreased* TMR, rather than increased it.

3. A POSA Would Not Have Understood Soukup's Barrier Heights Computed From Arrhenius Plots to be Accurate

141. For the reasons I discussed in Section VIII.B.2 above, a POSA would have understood that the barrier heights computed using the Arrhenius plots were not correct and Soukup himself acknowledged that they were not. EX1028, 3232; EX2039, 88-89, Figure 33, Figure 39. A POSA would not have been motivated to “apply Soukup’s teaching about an MgO thin-film barrier with a ‘barrier height’ of ‘about 0.33 eV’ (Petition, 34) to Bowen’s or Nagahama’s MgO barrier because a POSA would have understood those values to be wrong as Soukup said they were. As also discussed above in Section VIII.B.2, Soukup obtained conflicting results as to whether introducing oxygen into the vacuum chamber during fabrication increased or decreased the barrier height. If a POSA would have credited Soukup’s barrier height values calculated using the Arrhenius plot method, then the POSA would have believed that adding oxygen vacancy defects would have increased barrier height and would not have added oxygen vacancy defects in an attempt to lower the barrier height of Bowen or Nagahama as Petitioner alleges. Petition, 33-35, 57-59.

142. Conversely, if a POSA would have believed that the zero-field intercept method accurately measures barrier height and its relationship to oxygen

vacancy defects, a POSA would have considered the correct barrier height values to be those reported using that method. The values calculated using the zero-field intercept method (0.694-0.823 eV per Table I of Soukup) fail to meet the ranges recited in claims 6, 12 and 15-20.

4. A POSA Would Not Have Been Motivated to Inject Oxygen Vacancies Into the MgO Layer in Bowen and Nagahama to Increase TMR

143. As discussed in Section VI.E above, POSAs attempting to achieve the high TMR values predicted by the theoretical models of Butler and Mathon sought to fabricate crystalline MgO layers that were as defect-free as possible. A POSA would not have injected oxygen vacancy defects in an attempt to increase TMR, but would have attempted to do the opposite and would have tried to eliminate oxygen vacancy defects. A POSA reading Soukup would not have found any teachings to the contrary. Soukup does not in fact teach introducing oxygen vacancy defects, but rather Soukup introduced oxygen into the vacuum chamber to reduce oxygen vacancy defects.

5. Reasonable Expectation of Success

144. Petitioner alleges that a POSA would have had a reasonable expectation of success in “achieving a tunnel barrier height in the claimed range in Bowen’s MTJ” because “Soukup fabricated an MgO barrier that achieved a height of 0.33 eV” and a POSA was motivated “to achieve Soukup’s barrier height in an

MgO MTJ.” Petition, 35, 58 (same argument for Nagahama). For the reason explained above, a POSA understood that that the Arrhenius plot method produced values below the “actual barrier heights” and would not have understood Soukup to have “achieved” a barrier height of 0.33 eV. EX2039, 89. Soukup was not attempting to achieve any particular barrier height but instead measured the barrier heights of the devices that were fabricated and explained that the barrier heights calculated using the Arrhenius plot method were not correct but were in fact too low. None of Soukup’s barrier heights, moreover, were achieved by injecting oxygen vacancies. Neither Soukup nor any other prior art reference cited by Petitioner supports the assertion that the tunnel barrier height of Bowen or Nagahama could be lowered to 0.33 eV simply by introducing oxygen vacancy defects. If a POSA believed that Soukup’s zero-field intercept method was the method that accurately measures barrier height and its relationship to oxygen vacancy defects, a POSA would have considered the correct barrier height values to be those reported using the zero-field intercept method which are well above the 0.33 eV. EX1028, 3233 (Table I).

145. Additionally, the tunnel barrier height of an MTJ device is impacted by characteristics beyond the amount of oxygen vacancy defects in the MgO layer including the material of each ferromagnetic layer, the crystalline structure (or not) of the ferromagnetic layers, the crystalline structure (or not) of the MgO layer and

how it relates to the crystalline structure of each ferromagnetic layer, the fabrication techniques. These characteristics in the devices in Bowen and Nagahama are different than in Soukup's devices. In my opinion, the assertion that a POSA would have reasonably expected to achieve a barrier height of 0.33 eV in Bowen or Nagahama simply by introducing oxygen vacancy defects without undue experimentation is not unsupported by any evidence. The Petitioner does not explain how, when or how much oxygen vacancies would be injected into either of Nagahama's or Bowen's different fabrication processes.

146. During his deposition (see EX2013, 90:3-99:20, 100:15-104:11), Dr. Bokor alleged that a POSA would have explored modifying Bowen's fabrication techniques to use Soukup's evaporation process to deposit the magnesium oxide layer and would have experimented with other different techniques not disclosed in Soukup to achieve a barrier height of 0.33 eV. EX2013, 92:16-99:20, 100:15-104:3. Dr. Bokor admitted that he did not describe applying Soukup's fabrication technique of evaporating MgO to achieve 0.33 eV in his declaration (EX2013, 96:3-22) and that he did not cite any evidence beyond what Soukup disclosed that would have taught a POSA how to modify Bowen to increase the oxygen vacancies to achieve a barrier height of .33 eV (EX2013, 103:3-104:3). First, I disagree with Dr. Bokor's assertion that Soukup attributed the reported barrier height of .33 eV to a high concentration of oxygen vacancies. EX2013, 102:3-14.

As discussed in Section VIII.B.2, Soukup introduced oxygen into the vacuum chamber to see what the effects would be and found that adding oxygen—reducing oxygen vacancies—decreased the barrier heights calculated from the Arrhenius plots that a POSA would allegedly be trying to achieve. Second, other researchers manufacturing MTJs deposited MgO layers used evaporation to deposit MgO layers and that did not result in any barrier height lower than Bowen’s 0.9 eV barrier height, as shown by the table from Section VI.E above reproduced below with the technique used to deposit the MgO barrier layer added. Soukup, 3229 (reporting that “emission diodes formed by electron beam evaporation of Au and Mgo”).

Reference	Stack	MgO Deposition	Ideal ϕ	Estimated ϕ
EX1045	Fe/MgO/Fe	Electron beam evaporation (room temperature)	3.6 eV	2.5 to 3.6 eV
EX1043	Fe/MgO/Fe-Ni-Au	Electron beam evaporation	3.7 eV	3.7 eV (Simmons)
EX1026	Fe/MgO/Fe	Sputtering/Laser ablation	Cites EX1047	0.9 eV, 1.1 eV (I(V) temp curves, Simmons)
EX1053	Fe/MgO/FeCo	Electron beam evaporation (room temperature)	Not Specified	0.9 eV (Simmons)
EX1047	Fe/MgO/Fe	MBE Epitaxy, Laser Deposition	3.6 eV	1.8 eV (Simmons)

EX2012	CoFe/MgO/CoFe	Electron beam evaporation, thermal evaporation, reactive magneton sputtering	3.6 eV	1.1 to 1.7 eV (Simmons)
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147. As demonstrated by the table above, numerous different techniques were used to deposit MgO barrier layers and none resulted in barrier heights anywhere near 0.33 eV. Every MgO-based MTJ cited by Dr. Bokor had a barrier height at or above 0.9 eV. A POSA would not have had a reasonable expectation of success in achieving a 0.33 eV barrier layer simply by injecting oxygen vacancies into the MgO layer and, for the reasons discussed in Section VIII.A, would not have even attempted to do so because of the expectation that it would decrease TMR. Thus, I disagree with Dr. Bokor's suggestion that it would have been routine experimentation (EX2013, 100:15-103:20) to try to achieve Soukup's reported barrier height of 0.33 eV because it might have increased TMR for multiple reasons: (1) POSAs would not have understood Soukup's devices to have had a barrier height of 0.33 eV (Sections VIII.B.2 and VIII.D.3), (2) POSAs would not have been experimenting with any lower barrier height reported in Soukup because of the expectation that doing so would decrease TMR (Sections VIII.A and VIII.D.2), and (3) POSAs understood that depositing MgO layers via evaporation had not resulted in lower barrier heights than those reported by

Bowen, and (4) there is no evidence of that a barrier height of 0.33 eV could have been achieved simply by injecting oxygen vacancies into the MgO layer.

E. A POSA Would Not Have Found Lowering Bowen's or Nagahama's Barrier Height to 0.85 eV to Have Been Obvious

148. The Petition alleges that “the claimed tunnel barrier height range of 0.1 to 0.85 eV also would have been obvious” because the “claimed range is only slightly below the barrier height at ‘0.9 eV’ taught by Bowen and others.” I disagree for several reasons. First, the Petition does not point to any evidence that a POSA would have been seeking to lower Bowen's or Nagahama's barrier height in the first place. To the contrary, Bowen noted that the reported barrier heights were in agreement with some, lower than others and much lower than half the MgO bandgap of 5.5 eV and attributed the differences to unwanted manufacturing defects. EX1026, 1655. Nagahama did not report barrier heights at all. Second, the barrier height of an MTJ is the result of the choice of material for each of the layers in an MTJ and the fabrication processes used to deposit them, not a parameter that a designer of an MTJ merely chooses to employ. Absent the inventor's insight, the Petition provides no reason that a POSA would have tried to lower Bowen's barrier height and, for the reasons discussed above, would not have wanted to do so because of the expected increase in TMR. Third, the Petition's allegation that 0.85 eV is only “slightly below” 0.9 eV ignores that this difference is not slight in the

context of an MTJ. The difference between a 0.85 eV and an 0.9 eV barrier height results in a substantial change in RA because barrier height because an MTJ's resistance increases as an exponential function of barrier height and barrier thickness. At a 2nm barrier thickness like Bowen's (EX1026, 1656), a change from 0.9 eV to 0.85 eV results in a change in RA by a factor of 68%—that device would not have the same properties as Bowen's. This can be seen from a simple calculation using the Simmons formula that describes the RA of a tunnel barrier: $RA = p(t/\sqrt{\phi})\exp(q(t/\sqrt{\phi}))$ where p and q are constants involving only physical parameters (Planck's constant, electron charge, electron mass), t is the thickness of the barrier and ϕ is the barrier height. For a barrier thickness of 2 nm, the ratio $RA(\phi = 0.9 \text{ eV})/RA(\phi = 0.85 \text{ eV}) = 1.68$.

IX. SECONDARY CONSIDERATIONS

149. In this section I evaluate secondary considerations of non-obviousness including industry praise, the recognition of contemporaries, failure of others, and solving a long-felt but unmet need. Even if the combinations in the Petition did not have the problems I discussed above, these secondary considerations would still compel a conclusion that the claims are non-obvious.

150. I understand that certain secondary considerations can include evidence of how others reacted to Dr. Yuasa's invention and, therefore, such evidence is sometimes dated after the date of invention for the Challenged Claims.

I understand that this evidence is highly relevant to evaluating the nonobviousness of the invention in the Challenged Claims because it objectively demonstrates the reactions of those in the field who were most familiar with Dr. Yuasa's work and how it impacted the art.

151. The objective indicia discussed below are reasonably commensurate with the scope of the claims for aspects that were not in the prior art, and taken individually or as a whole plainly show the invention in the Challenged Claims was non-obvious over the alleged combinations of Bowen in view of Soukup (Ground 1) and Nagahama in view of Soukup (Ground 2).

A. The Claimed Technology Received Widespread Praise from Industry and Academia

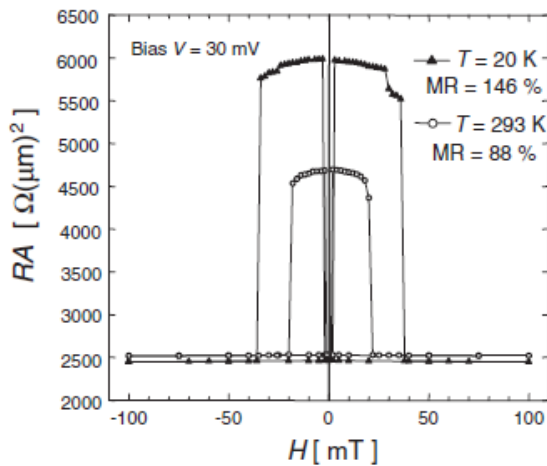
152. Shortly after filing the two Japanese patent applications to which the '909 Patent claims priority, Dr. Yuasa publicly disclosed the '909 Patent's embodiments through articles in the in the Japanese Journal of Applied Physics ("Yuasa JJAP paper") in April of 2004 (EX2016) and in Nature Materials ("Yuasa NM paper") in October 2004 (EX2017), then published his work on CoFeB/MgO/CoFeB MTJs in Applied Physics Letters ("Yuasa APL paper") on February 23, 2005 (EX2015). These are prominent peer-reviewed journals (referred to hereinafter as the "Yuasa Papers"). The Nature Materials article (EX2017) has been cited more than 4,200 times and the APL paper has been cited more than 1,200 times. EX2008, 2009.

153. Dr. Yuasa disclosed the '909 Patent's claimed device in the Yuasa NM Paper follows:

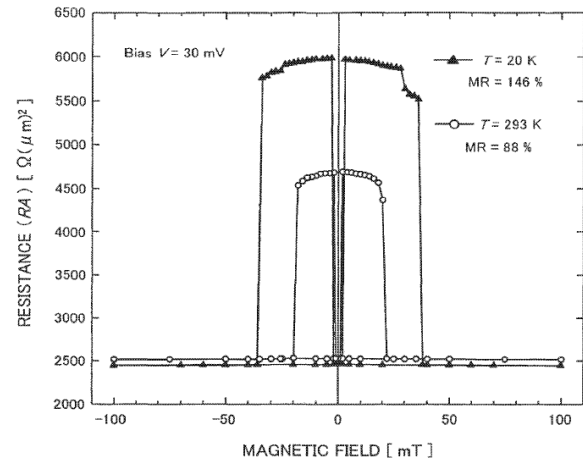
- The Yuasa NM paper discloses limitations 1[pre], 9[pre], 15[pre] by disclosing “magnetic tunnel junctions (MTJs)” comprising a multi-layer stack—“Fe(001)/MgO(001)/Fe(001) MTJs” (EX2017, 868-869);
- The Yuasa NM paper discloses limitations 1[a], 9[a] and 15[a], 15[c] (“ferromagnetic material layer” limitations) by disclosing MTJs with “**Fe(001)**/MgO(001)/**Fe(001)** junctions” (EX2017, 868-869);
- The Yuasa NM paper discloses limitations 1[b], 9[b] and 15[b] (“a tunnel barrier comprising magnesium oxide” limitations) by disclosing “Fe(001)/**MgO(001)**/Fe(001) junctions” (EX2017, 869);
- The Yuasa NM paper discloses limitation 1[c] (“wherein said tunnel barrier layer comprises crystalline MgO_x (001) with oxygen vacancy defects and (0<x<1)”) by disclosing that the “barrier height of our MTJs is considerably lower than the values in the literature^{9,10}, which should be due to the oxygen vacancy defects in MgO” (EX2017, 869); and
- The Yuasa NM Paper discloses limitations 9[c], 15[b], claims 5 and 6 (“barrier height” limitations) by disclosing that “a barrier height ϕ of 0.39 eV” and “ $\phi = 0.37\text{--}0.40$ eV” (EX2017, 869).

154. Versions of the '909 Patent's figures showing the RA and TMR characteristics of Dr. Yuasa's ground-breaking MTJs appear in Yuasa JJAP and Yuasa NM papers as shown below.

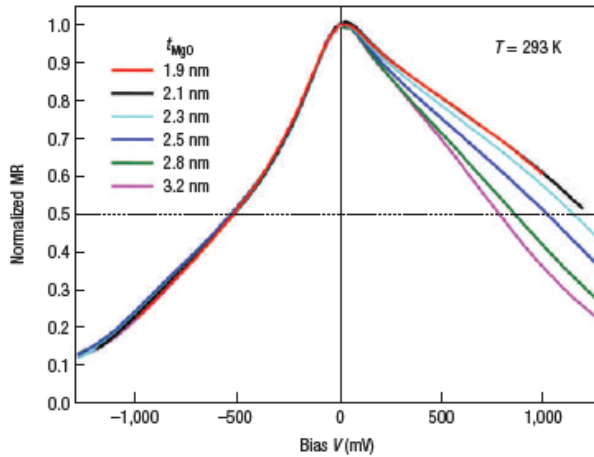
JJAP Fig. 3



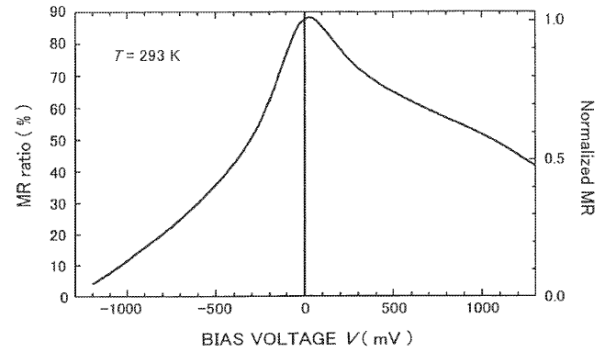
'909 Patent Fig. 6



Nature Fig. 3a



'909 Patent Fig. 7(A)



155. A 2005 *Advances in Physics* journal article characterized Dr. Yuasa's devices as having “unprecedentedly large TMR ratios” using “MgO barriers” and “pure Fe electrodes.” EX2019, 591-592 (citing EX2017 (Yuasa NM paper)).

Albert Fert—a Nobel laureate in physics for his work in spintronics, and notably a co-author on Petitioner's primary reference Bowen—when providing a historical overview of spintronics in a 2012 textbook, specifically referred to Dr. Yuasa's work in his famous 2004 *Nature Materials* paper (EX2017) as an “important breakthrough” in “the most important step [of] the transition from MTJ with amorphous tunnel barrier (alumina) to single-crystal MTJ and especially MTJ with MgO barrier.” EX2020, 8 (citing 2017 (Yuasa NM paper)); EX1057, 7. This “breakthrough” is seen in the figure below from a textbook by Dieny (EX1057) Petitioner submitted showing a greater than 250% increase in TMR.

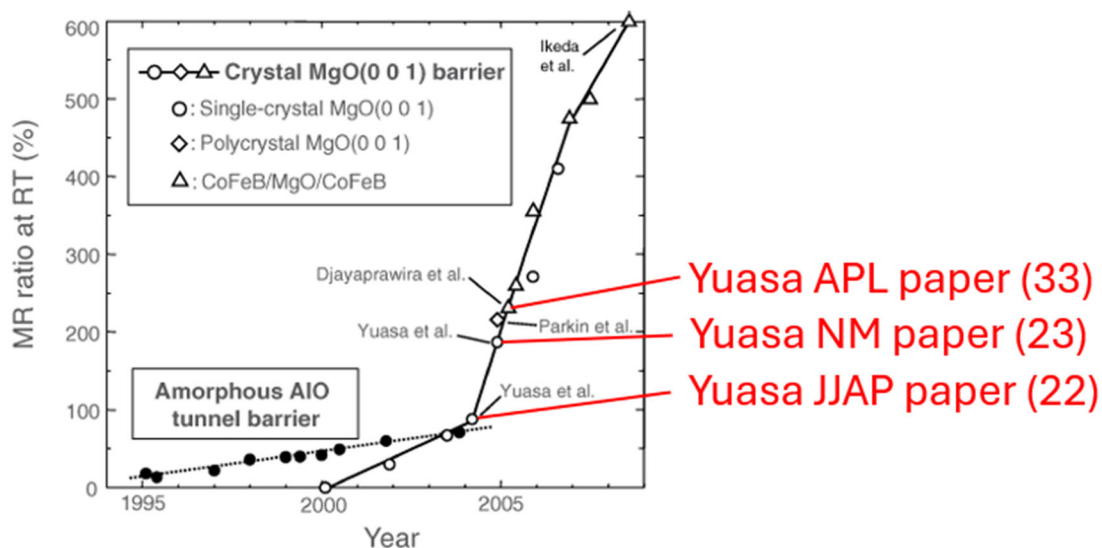


Figure 2.21 History of improvement in MR ratio at RT for MTJs with amorphous AlO barrier (solid circles) or crystalline MgO(0 0 1) barrier (open symbols). Data are shown for work by Yuasa et al. (22,23), Parkin et al. (24) Djayaprawira et al. (33), and Ikeda et al. (36).

EX1057, Figure 2.21 (annotated)

156. I note that the Dieny chapter in which Figure 2.21 was authored by Dr. Yuasa, but what the data shows is undisputed: Dr. Yuasa's MgO-based MTJ devices described in his papers were the first to achieve high TMR values predicted by theoretical models, marking the inflection point for MgO-based MTJs shown in the above figure. EX2017 (Yuasa NM paper), 868-869; EX2016, 588-590 (Yuasa JJAP paper), EX2015, 1-2 (Yuasa APL paper). Because Dr. Yuasa's NM paper disclosed the claimed MTJs that resulted in "unprecedentedly large TMRs" and the "important breakthrough" in "the most important step [of] the transition from MTJ with amorphous tunnel barrier (alumina) to single-crystal MTJ," there is a direct nexus between the praise and the claimed invention.

157. Zheng Gao, "Recording Head Development Group, Western Digital Corporation" credited Dr. Yuasa as the first to demonstrate in 2004 that with coherent tunneling, the "effective barrier height can also be smaller [], which makes a TMR sensor with *low resistance and high TMR possible*." EX2022, 107 citing EX2017 (Yuasa NM Paper). Dr. Yuasa's development of the first low-resistance high-TMR MTJ sparked further research, including his own (EX2021), into developing MTJs with further reductions in MTJ resistances down to the "*RA* range [] desired for [the hard disk drive] read head application." EX2022, 107 (citing EX2021); *see also* EX2005, 38 (Petitioner's employee Chando Park hailed

Dr. Yuasa's NM paper as one of "two independent experimental investigations show[ing] greater than 180% and 220% TMR ratios at room temperature" spawning a "surge in research [that] quickly followed"); EX1063, ¶22. Because the Yuasa NM paper disclosed the claimed method that demonstrated that with coherent tunneling the effective barrier could be smaller, which made "a TMR sensor with low resistance and high TMR possible," there is a direct nexus between the praise and the claimed invention. EX2017 (Yuasa NM paper), 868-869.

158. In recognition of his groundbreaking work related to the invention of the '909 patent, Dr. Yuasa has been awarded or co-awarded many prizes. In 2022, Dr. Yuasa was awarded the "Japan Society of Applied Physics Achievement Award," for his "pioneering work on magnetic tunnel junctions (MTJs) with magnesium oxide (MgO) tunnel barriers" including his development of "technologies to reduce the resistivity of elements, which is indispensable when increasing the density of HDDs and MRAMs." EX2024, 2-3. In 2021, he was made an "IEEE Fellow" for his "contributions to MgO-based magnetic tunnel junctions." EX2026, 1.

159. In 2016, Dr. Yuasa won the "Science and Technology Prize" for his "new type of tunnel magnetoresistance element ... using crystalline magnesium oxide (MgO) as the tunnel insulating film," for which "*a giant tunnel*

magnetoresistance effect of approximately 200% at room temperature was realized for the first time in the world,” and for his research that resulted in “magnetic sensor elements using MgO tunnel magnetoresistance elements hav[ing] been put to practical use and are now used in all hard disk storage devices (HDDs) currently being manufactured, resulting in a dramatic increase in HDD capacity, lower prices, and reduced power consumption.” EX2029, 2.

160. Dr. Yuasa was awarded the Tsukuba Prize in 2009, which included a monetary award of 5 million yen for his development of the “first successful creation of a three-layer ‘magnetic tunnel junction element (MTJ element) in the world, composed of iron and MgO (magnesium oxide), paving the way for mass production.” EX2033, 2; *see also* EX2032, 1.

161. Dr. Yuasa has received numerous other awards for his work on MTJs, including the JSPS Prize in 2010 for the “Development of High Performance Magnetic Tunnel Junction Devices,” the Asahi Award in 2008 for his “Studies on development and application of tunnel magnetoresistive effect,” the IBM Japan Science Prize in 2007 for “Studies on tunnel magnetoresistive effects and their application,” the Tokyo Techno Forum 21 Gold Medal Prize in 2006 for “Study on spintronics technology for MRAM,” the Marubun Science Prize in 2006 for the “Study on tunnel magnetoresistance effect,” and the Ichimura Science Prize in 2005. EX2028, 4.

162. In sum, Dr. Yuasa has been repeatedly praised for his development of the method for making MTJs disclosed and claimed in the '909 Patent. These awards were directly linked to the inventive MTJs claimed in the '909 Patent.

B. The Claimed Technology Solved a Long-Felt but Unmet Need

163. MTJ devices fall into a larger field—called spin-based electronics or spintronics—spawned by discovery of the giant magnetoresistance (GMR) effect in metallic structures in 1988. EX2020, vii, 3; EX1057, 1-2. GMR had been used in magnetoresistive heads in hard disk drives from 1998-2004. EX1057, 8-9. Another commercial application for spintronics was MRAM, which promised a non-volatile storage alternative to volatile memories such SRAM and DRAM. EX1039, 2814; EX1017, 1:44-50. MRAM began to be considered seriously in 1995 after an MTJ with a 10% TMR was achieved. EX1057, 1-2 (citing EX1035, EX1034). In 1999, MTJ devices were considered one of the “most viable” MRAM technology, providing key advantages over GMR. EX1039, 2819. But commercialization was not feasible in 1999 because TMRs were too low and manufacturing techniques were incompatible with large scale manufacturing. EX2038, 6-7; EX2055, 8-9 (higher TMRs were needed).

164. Before Dr. Yuasa’s invention, researchers tried but failed to solve the problem of obtaining a high TMR. From 1995-2000, extensive experimental effort was made on MTJs with amorphous AlO (alumina) tunnel barriers, but the

resulting TMRs were only 10-70 %, “lower than those needed for many applications of spintronic devices.” EX1057, 9; EX2055, 5-9.

165. In 2001, theorists Butler (EX1044) and Mathon (EX1046) speculated that higher TMRs could be obtained using crystalline MgO tunnel barriers with Fe electrodes. EX1057, 16. These theoretical predictions “led to numerous experimental studies to explore the possibility of high TMR in epitaxial (100) oriented Fe/MgO/Fe tunnel junctions.” EX2055, 10-11. But early attempts using MgO tunnel barriers failed to produce large TMR values. EX2055, 10-16 (citing EX1047, EX1052, EX1053, EX1026 (Bowen) as failed attempts to achieve high predicted TMR values); EX1047, 509. Ground 1’s Bowen reference was one such failure. Bowen produced TMR values of only 27% — much lower than had been achieved with conventional amorphous AlO tunnel barriers. EX2055, 12 (citing EX1026); EX1057, 45 (citing EX1026); EX2020, 8 (Nobel laureate and co-author of Bowen citing EX1026 as an early failed attempt).

166. As noted by Petitioner’s employee Zheng Gao, Dr. Yuasa led the way to an MTJ usable for the hard disk drive “read head application” when he discovered that the barrier height could “be smaller” and made “a TMR sensor with *low resistance and high TMR possible*.” EX2022, 107 (citing EX2017 (Yuasa NM Paper) and EX2021). Dr. Yuasa solved the long-felt need for an MTJ device with the low resistance and high TMR needed for commercial applications

with his work described in the '909 Patent. He achieved an MgO-based MTJ with a TMR of 88% at a room temperature—"the highest MR ratios that have so far been obtained at room temperature." EX1017, 8:15-21.

167. Dr. Yuasa also recognized that by introducing oxygen vacancy defects into the MgO barrier the tunnel barrier height could be lowered from 3.6 eV (for an ideal MgO crystal) to a range of 0.10-0.85 eV, and more specifically 0.2-0.5 eV, thus providing a "resistance-area (RA) product of the MTJ device [] suitable for MRAM." EX1017, 8:15-30, 7:19-38, 9:4-10. Despite the expected loss of TMR due to lowering the barrier height, Dr. Yuasa surprisingly and unexpectedly achieved the highest MR ratio MTJs seen at that time and created the first "TMR sensor with low resistance and high TMR" needed for commercial applications, such as HDD and MRAM. EX2022, 107 (citing EX2017 (Yuasa NM paper)); EX2017, 867-869.

X. CONCLUSION

168. I declare that all statements made herein of my own knowledge are true, that all statements made on information and belief are believed to be true, and that these statements were 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.

169. I declare under penalty of perjury that the foregoing is true and correct.

Dated: 7/12/2025 By: 
Caroline A. Ross, Ph.D.

APPENDIX A: MATERIALS CONSIDERED

Exhibit	Description
Paper 1	Petition for Inter Partes Review of U.S. Patent No.
Paper 7	Institution Decision
1017	U.S. Patent No. 11,968,909 (“’909 Patent”)
1024	Declaration of Jeffrey Bokor, Ph.D.
1026	Bowen et al., <i>Large magnetoresistance in Fe/MgO/FeCo(001) epitaxial tunnel junctions on GaAs(001)</i> , 79 Appl. Phys. Letters 1655-1657 (2001) (“Bowen”)
1027	European Patent Application No. EP1391942A1 to Nagahama et al. (“Nagahama”)
1028	Soukup et al., <i>Voltage-Current Characteristics for Electrical Conduction Through Thin MgO Films</i> , 41 J. Appl. Phys. 3229-3236 (1970) (“Soukup”)
1031	Simmons, <i>Generalized Formula for the Electric Tunnel Effect between Similar Electrodes Separated by a Thin Insulating Film</i> , 34 J. Appl. Phys. 1793-1803 (1963)
1033	Julliere, <i>Tunneling between ferromagnetic films</i> , 54A Phys. Letters 225-226 (1975)
1034	Miyazaki et al., <i>Giant magnetic tunneling effect in Fe / Al₂O₃ / Fe junction</i> , 139 J. Magnetism & Magnetic Materials L231-L234 (1995)
1035	Moodera et al., <i>Large Magnetoresistance at Room Temperature in Ferromagnetic Thin Film Tunnel Junctions</i> , 74 Phys. Rev. Lett. 3273–3276 (1995)
1038	Moodera et al., <i>Ferromagnetic–insulator–ferromagnetic tunneling: Spin-dependent tunneling and large magnetoresistance in trilayer junctions (invited)</i> , 79 J. Appl. Phys. 4724-4729 (1996)
1039	Tehrani et al., <i>Progress and Outlook for MRAM Technology</i> , 35 IEEE Trans. Magn. 2814-2819 (1999)
1043	Heinrich et al., <i>Single Crystal Tunnel Junctions</i> , IEEE (2000)
1044	Butler et al., <i>Spin-dependent tunneling conductance of Fe MgO Fe sandwiches</i> , 63 Phys. Rev. B 054416 (2001)
1045	Klaui et al., <i>Growth, structure, electronic, and magnetic</i>

Exhibit	Description
	<i>properties of MgO/Fe(001) bilayers and Fe/MgO/Fe(001) trilayers</i> , 64 Phys. Rev. B. 134411 (2001)
1046	Mathon et al., <i>Theory of tunneling magnetoresistance of an epitaxial Fe/MgO/Fe(001) junction</i> , 63 Phys. Rev. 220403 (2001)
1047	Wulfhekel et al., <i>Single-crystal magnetotunnel junctions</i> , 78 Appl. Phys. Letters 509-511 (2001)
1050	Yuasa et al., <i>A large quantum-well oscillation of the TMR effect</i> , 35 J. Phys. D. 2427-2431 (2002)
1051	Meyerheim, et al., <i>Geometrical and Compositional Structure at Metal-Oxide Interfaces: MgO on Fe(001)</i> , 87 Phys. Rev. Letters 076102 (2001)
1052	Faure-Vincent et al., <i>High tunnel magnetoresistance in epitaxial Fe/MgO/Fe tunnel junctions</i> , 82 App. Phys. Letters 4507-4509 (2003)
1053	Mitani et al., <i>Fe/MgO/FeCo(100) epitaxial magnetic tunnel junctions prepared by using in situ plasma oxidation</i> , 93 J. Appl. Phys. 8041-8043 (2003)
1055	Wang et al., <i>70% TMR at Room Temperature for SDT Sandwich Junctions With CoFeB as Free and Reference Layers</i> , 40 IEEE Trans. Magn. 2269-2271 (2004)
1057	Dieny et al., <i>Introduction to Magnetic Random-Access Memory</i> (IEEE Press 2017) (excerpts)
1063	Complaint, <i>Godo Kaisha IP Bridge 1 v. Western Digital Corporation</i> , Case No. 24-cv-00342-RGA (D. Del. Mar. 15, 2024) (without exhibits)
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APPENDIX B: U.S. PATENT NO. 11,968,909 CLAIM LIST

This claim list uses Petitioner's taxonomy for marking limitations as provided in the Petition's List of Challenged Claims. Petition, xvii-xix.

Ref	Limitation
1[pre]	A magnetoresistive device comprising a magnetic tunnel junction structure comprising a multi-layer material stack including
1[a]	first and second ferromagnetic material layer; and
1[b]	a tunnel barrier layer between the first and second ferromagnetic material layers such that the tunnel barrier layer is above the first ferromagnetic material layer and below the second ferromagnetic material layer,
1[c]	wherein said tunnel barrier layer comprises crystalline MgO_x (001) with oxygen vacancy defects and ($0 < x < 1$).
5	The magnetoresistive device of claim 1, wherein a barrier height of the tunnel barrier layer is in a range of 0.1 eV to 0.85 eV.
6	The magnetoresistive device of claim 5, wherein the barrier height of the tunnel barrier layer is in a range of 0.2 eV to 0.5 eV.
7	The magnetoresistive device of claim 1, wherein the first ferromagnetic material layer and/or the second ferromagnetic material layer comprises Boron.
8	The magnetoresistive device of claim 1, wherein the first ferromagnetic material layer and/or the second ferromagnetic material layer is partially or entirely crystallized.
9[pre]	A magnetoresistive device comprising a magnetic tunnel junction structure comprising:
9[a]	first and second ferromagnetic material layer; and

9[b]	a tunnel barrier layer between the first and second ferromagnetic material layers,
9[c]	wherein said tunnel barrier layer comprises magnesium oxide and has a barrier height in a range of 0.1 eV to 0.85 eV.
10	The magnetoresistive device of claim 9, wherein the tunnel barrier layer comprises partially or fully crystalline magnesium oxide.
11	The magnetoresistive device of claim 10, wherein the first ferromagnetic material layer and/or the second ferromagnetic material layer is partially or entirely crystallized.
12	The magnetoresistive device of claim 11, wherein the barrier height is in a range of 0.2 eV to 0.5 eV.
13	The magnetoresistive device of claim 11, wherein the first ferromagnetic material layer and/or the second ferromagnetic material layer exhibits a body-centered cubic (BCC) structure.
14	The magnetoresistive device of claim 11, wherein the first ferromagnetic material layer and/or the second ferromagnetic material layer comprises Cobalt and Iron.
15[pre]	A magnetoresistive device comprising:
15[a]	a first ferromagnetic material layer;
15[b]	a tunnel barrier comprising magnesium oxide and having a barrier height in a range of 0.2 eV to 0.5 eV; and
15[c]	a second ferromagnetic material layer disposed on the tunnel barrier layer and separated from the first ferromagnetic material layer by the tunnel barrier layer.
16	The magnetoresistive device of claim 15, wherein the tunnel barrier layer comprises partially or fully crystalline magnesium oxide.

17	The magnetoresistive device of claim 16, wherein the first ferromagnetic material layer and/or the second ferromagnetic material layer is partially or entirely crystallized.
18	The magnetoresistive device of claim 17, wherein the first ferromagnetic material layer and/or the second ferromagnetic material layer exhibits a body-centered cubic (BCC) structure.
19	The magnetoresistive device of claim 17, wherein the first ferromagnetic material layer and/or the second ferromagnetic material layer comprises Cobalt and Iron.
20	The magnetoresistive device of claim 15, wherein the tunnel barrier layer has a thickness less than 10 nm.