MAGNETORESISTIVE (MR) HEADS AND THE EARLIEST MR HEAD-BASED DISK DRIVES: SAWMILL AND CORSAIR

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Why it is Important

Hard disk drives (HDDs) have survived as the information storage device of choice because of the sustained and steep advances achieved in **storage density**.

Density advances required downward **scaling** of the key components. The resulting smaller head-disk spacing and reduced magnetic fields from the disk were the key technology challenges.

The reduction in the size of stored bits caused signal amplitude reductions which necessitated the invention of more powerful detectors. **Magnetoresistive (MR) heads** were the successful answer.

These **new film heads**, together with **new film disks**, provided successful components for future HDDs up to the present time. They solved the joint challenge of ultra small signals and ever-reduced spacing of the heads and disks. Since 1990, this combination improved data density, with concomitant cost per bit reductions, by approximately **20,000 times.**

Two companies led the industry in independently developing MR heads, IBM and HP. IBM was first to market in 1990. HP was second in 1994. Seagate also benefited from the HP heads since 1995. The rest of the industry started using MR heads in 1996.

Magnetoresistive (MR) Heads

Prior to 1990, all hard disk drives used the same inductive head for reading and writing. The readback signal amplitude from an inductive head is proportional to the magnetic flux captured from a stored bit, to the number of turns of wire wrapped on the head, and to the velocity at which the head flies on the disk. There are engineering limits to the number of turns and the disk velocity, so as bits on the disk became smaller, with correspondingly smaller magnetic flux to couple to the head, the readback signal from an inductive head became so small that the signal-to-noise ratio became inadequate.

Magnetoresistive heads use an entirely different method of readback. A tiny electrical resistor inside the head changes resistance in the presence of changing magnetic flux from the disk. This is independent of the disk velocity, so the signal is the same at any speed. The size of the signal is proportional to the percentage change in resistance, and to the amount of energy that the magnetoresistive element can dissipate without damage. As it turns out, the resultant signal can be much larger than that from an inductive head.

HDDs have used three classes of MR heads. Each new class provided a larger percentage change in resistance with magnetic field. Anisotropic magnetoresistive (AMR) heads were first introduced in 1990[1], giant magnetoresistive (GMR) heads were introduced in 1997[2], and tunneling magnetoresistive (TMR) heads were introduced in 2004.[3]

> AMR heads are based on the phenomenon of anisotropic magnetoresistance, first discovered by Lord Kelvin in 1856. The effect involves a resistance change in an electrical conductor produced by application of an external magnetic field. Lord Kelvin found in experiments with iron and nickel conductors that electrical resistance increases when the applied magnetic field is parallel to the conductor, but resistance decreases when the magnetic field is perpendicular to the conductor. The changes were about 5% in these experiments.
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> GMR heads are based on the phenomenon of giant magnetoresistance, discovered by Albert Fert and Peter Grunberg in 1988 (recognized by the Nobel Prize in Physics in 2007). GMR relies on alternating layers of magnetic and non-magnetic conductive materials. When nearby magnetic layers are magnetized in parallel, electrical resistance is lower than when layers are magnetized in opposite directions, which increases the observed resistance change effect to about 10%.
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> TMR heads are based on the phenomenon of tunneling magnetoresistance. John Slonczewski was first to propose in 1974 that magnetic tunnel junctions could be used as a "Magnetic Gate" to detect magnetic fields such as the fields from a magnetic bubble or magnetic recording transition.[4] TMR involves electrons moving through an insulating barrier between magnetic layers (a quantum mechanical tunneling effect), resulting in an even larger resistance change effect, well in excess of 100% today, between the parallel and anti parallel orientations of the magnetizations of the films. It is this latter technology that is currently used in most disk drives.

A key characteristic of MR heads is that such heads enabled dual element magnetic recording heads, with one inductive (non-MR) element optimized for writing data and a second magnetoresistive element optimized for reading data. The ability to separately optimize these two head functions allowed the attainment of much higher magnetic write fields as well as much sharper read head resolutions than would have been possible with the previously used, single element inductive heads used for both writing and reading. The sequential use of the AMR, GMR and TMR phenomena enabled a systematic increase of the sensitivity of the read element over time.

The first MR heads were used in the longitudinal magnetic recording (LMR) configuration. The separate write head allowed capitalizing on the full potential of LMR

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[1] IBM 9345 HDD.
[2] IBM DTTA-351680 (Deskstar 16GP) HDD.
[3] Seagate 100 GB Backup Plus circa 3Q 2004.
[4] John Slonczewski, Presented at IBM technical meeting on January 22, 1974, personal communication.

film disks by supporting about a 10-fold increase in the magnetic field used to write the disk. This high intensity write field allowed use of magnetic disks with higher resistance to demagnetization (higher coercivity), resulting in a corresponding increase in stored energy seen by the read head. This, in turn, allowed the use of smaller bits. The most recent MR heads, the TMR versions introduced in 2004, have been used in the perpendicular magnetic recording (PMR) configuration. A PMR configuration superior to LMR would not have been possible without dual element MR heads. Diagrams depicting the GMR heads used for LMR and PMR can be found in Figure 1 of a recent white paper published by scientists at Hitachi.[5] This figure is reproduced below. The diagrams in this figure would also apply to depicting AMR and TMR heads by substituting these terms for the read element labeled "GMR Sensor".

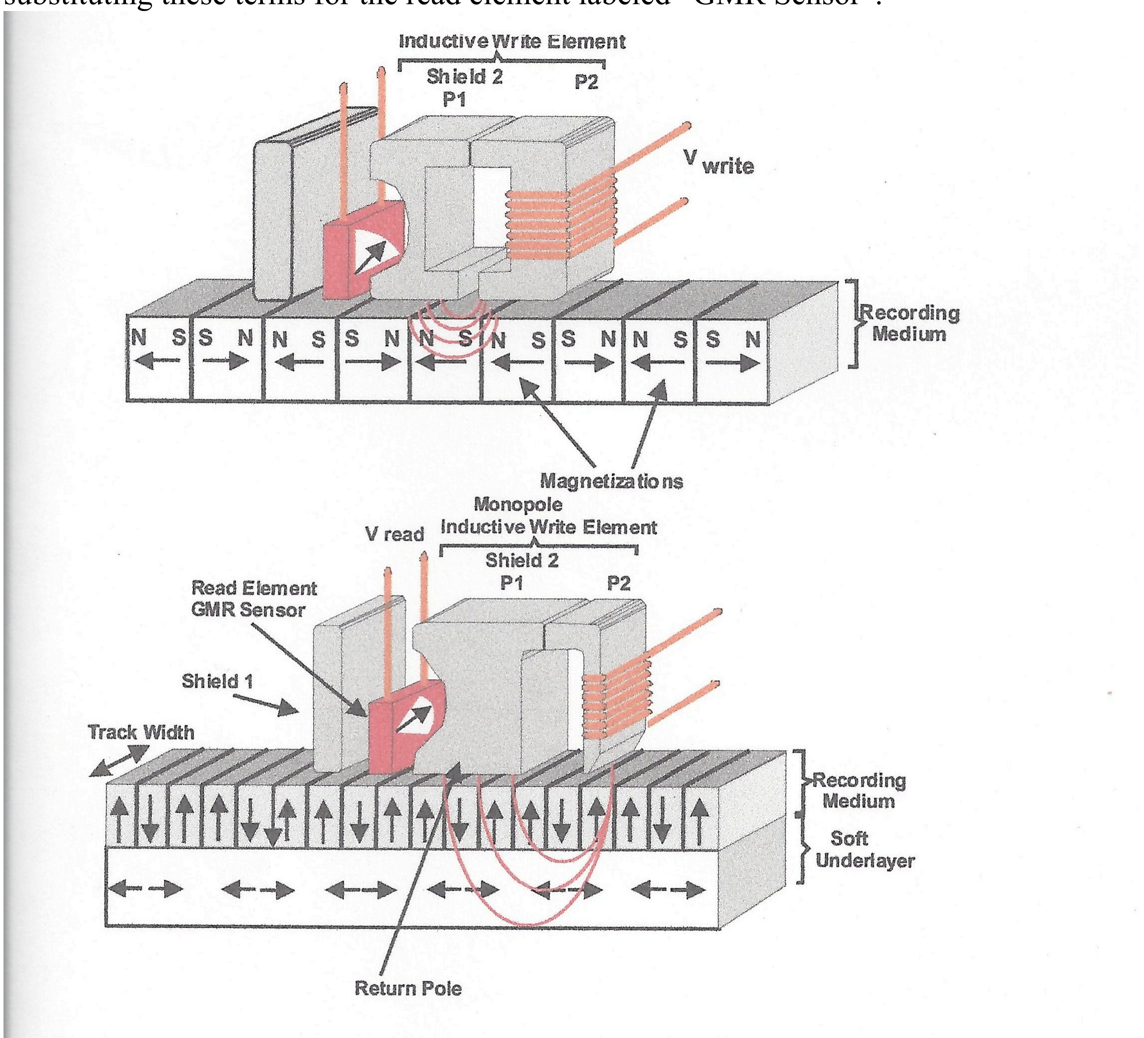

Figure 1: Longitudinal recording diagram (top) and perpendicular recording diagram (bottom)

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[5] R. Wood, Y. Hsu and M. Schultz, "Perpendicular Magnetic Recording Technology", white paper: http://www.hgst.com/tech/techlib.nsf/techdocs/F47BF010A4D29DFD8625716C005B7F34/$file/PMR_white_paper_final.pdf

The aforementioned progress also enabled dramatic miniaturization of HDDs, from 5 ¼ in., to 3 ½ in., to 2 ½ in., to 1.8 in. and to 1.0 in. devices, while delivering extraordinary data capacity to end users in the smaller form factors. HDDs capable of storing several terabytes of data are the norm today.

R. P. Hunt of Ampex was the first to propose the use of unshielded, Permalloy-based MR read elements for sensing of magnetically recorded data in 1966.[6] But, the unshielded option had linear data density limitations because the minimum bit spacing was comparable to the read element's height.[7] This limitation notwithstanding, Hunt-type MR heads, packaged in hand-held wands, were commercialized by IBM in 1975, for use as readers of magnetically pre recorded price tags in consumer transaction applications.[8] Macy's is an example of a department store that used such point of sales (POS) systems with MR device readers between 1975 and the early 1980s.

The potential of MR read elements for use in higher density applications was enhanced significantly with the invention of an element placed in the gap of a magnetic head, called a "shielded MR head".[9] The use of closely spaced shields, made of a high magnetic permeability material like ferrite or Permalloy, to sandwich Hunt's MR stripe, significantly decreased inter symbol interference, i.e. increased the linear bit density that could be resolved with MR heads. Ferrite-shielded MR heads were first commercialized by IBM in 1984, for storing and reading data in the IBM 3480 magnetic tape storage system.[10] However, it took another 6 years, until 1990, to successfully commercialize shielded MR heads for use in HDDs.

Challenges of MR heads for HDDs

There are two key requirements for the read element of AMR, GMR and TMR heads in HDDs: **1.** Biasing the device to operate in a quasi-linear response mode, in order to distinguish the polarity of the sensed fields from data, and **2.** Operating the device in a single domain mode to avoid magnetic switching noise, also known as "Barkhausen" noise, in order to achieve a high signal-to-noise ratio (SNR).

Achieving these characteristics turned out to be much more difficult for the very narrow read elements required by HDDs. HDDs have consistently had track widths about 100 times narrower than tape recorders.

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[6] R.P. Hunt, "A Magnetoresistive Readout Transducer", IEEE Trans. Mag. **7**, 150 (1971); patent 3,493,694 (1970).
[7] R. L. Anderson, C. H. Bajorek and D. A. Thompson, "Numerical Analysis of a Magnetoresistive Transducer", IEEE Trans. Mag. **10**, 1445 (1973).
[8] C. H. Bajorek, C, Coker, L. T. Romankiw and D. A. Thompson, "Hand-held Magnetoresistive Transducer", IBM J. Res. Dev. **18**, No. 6, 541 (1974); IBM 3660/3663 POS System.
[9] D. A. Thompson, "Three-Legged Magnetic Recording Head Using a Magnetoresistive Element", patent 3,921,217 (1975).
[10] D. M. Cannon, W. R. Dempwolf, J. M. Schmalhorst, F. B. Shelledy and R. D. Silkensen, "Design and Performance of a Magnetic Head for a High Density Tape Drive", IBM J. Res. Dev. **30**, No. 3, 270 (1986).

The first requirement is attained via two closely coupled (closely spaced) ferromagnetic films, one of the films being free to respond to the magnetic field from data, i.e. the “free layer”, and a second permanent magnet film which does not respond to the data field, the “pinned layer”, also called the “reference layer”. The second requirement is attained by applying a “longitudinal magnetic field” to the free layer, via permanent magnet films in close proximity (co planar) to the ends of the free layer.

IBM’s MR head work started in 1969, under the leadership of David Thompson, in the Thomas J. Watson Laboratory of the Research Division, in Yorktown Heights, NY. Lubomyr Romankiw led the group that processed the early devices. The author joined this project in 1971.

The hand-held MR head for the POS application was developed via joint work between the Yorktown Heights group and a group in IBM Boulder, CO. This Boulder group also started the development of the ferrite - shielded MR head for tape use. The latter MR head program was then transferred to IBM Tucson, AZ and was commercialized in the IBM 3480 tape drive in 1984.

The Yorktown Heights MR head effort was transferred to the San Jose, CA Laboratory of the Research Division in the late 1970s. This phase of research succeeded in prototyping the first fully functioning HDD MR heads in 1983. This success was the basis for initiating a full blown HDD MR head product development program in 1984, in IBM’s General Products Division (GPD) in San Jose, CA. The program was initially staffed by engineers and scientists from both divisions working in a newly established interdivisional laboratory, the IBM Magnetic Recording Institute, under the direction of Denis Mee.

In the end, it took the work of hundreds of individuals to overcome all of the challenges to take HDD MR heads from proof of principle[11] to volume production. The author was fortunate to participate in or manage most of this work. These teams also had to deal with the very serious surprises that were discovered late in the head commercialization cycle. It took approximately 20 years to complete the first cycle to market.

Three important innovations that encouraged IBM to commit to use MR heads in its HDDs were:

- Magnetic shields for high resolution[12],
- Soft Adjacent Layer (SAL) bias field for linearizing the head signal[13] [14] [15] [16], and

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[11] C. H. Bajorek, S. Krongelb, L. T. Romankiw and D. A. Thompson, “An Integrated Magnetoresistive Read, Inductive Write High Density Recording Head”, AIP Conf. Proc. **24**, 548 (1975).
[12] D. A. Thompson, “Three-Legged Magnetic Recording Head Using a Magnetoresistive Element”, patent 3,921,217 (1975).
[13] T. J. Beaulieu and D. A. Nepela, “Induced Bias Magnetoresistive Read Transducer”, patent 3,864,751 (1975).
[14] C. H. Bajorek, S. Krongelb, L. Romankiw and D. Thompson, “A Permalloy Current Sensor”, IEEE Trans. Mag. **12**, No. 6, 813 (1976).

- Antiferromagnet (AFM) - based bias field for minimizing magnetic noise[17] [18].

IBM had also decided to commercialize the MR heads in combination with a new slider that had a negative pressure air bearing.[19] [20] This type of bearing was expected to provide superior control of head fly height and a more uniform fly height over the entire disk surface.

It was always recognized that a change to separate read and write heads would require significant changes to the signal electronics and track-following mechanisms of the drive. The signal waveshape was different. The response to large transients that occur while switching from write mode to read mode was different. Optimum positioning of the head element on track might be slightly different between read and write modes. A different preamplifier design incorporating a current source to excite the magnetoresistive element had to be used. Although expected, these changes required substantial engineering effort.

Fortunately, these problems had to be solved only once. MR, GMR, and TMR heads look very similar, as far as the rest of the system is concerned.

These innovations were subsequently refined and used to achieve the same or equivalent characteristics in all GMR and TMR heads.

The Surprises

IBM first committed to use the MR heads for the 3390 family of HDDs. But, early integration work ran into several unexpected problems:

- Thermal asperities in flying heads,
- Shield-to-sensor smearing/shorting on particulate disks,
- Excessive failure from corrosion, and
- Electrical discharge–induced melting between the heads and the disks.

The preamp had to be redesigned to be able to rapidly recover from the large noise spikes caused by thermal asperities. The preamp redesign also had to insure a near zero volt potential of the MR sensor to avoid electrical discharges to a grounded disk. Data header information had to be beefed up with redundant bits to defend against thermal asperities in this portion of the information. Ensuring data integrity also required application of superior error correction codes. Eliminating shield smearing required changing the

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[15] C. H. Bajorek, R. D. Hempstead, S. Krongelb and A. F. Mayadas, "Magnetoresistive Sandwich Including Sensor Electrically Parallel With Electrical Shunt and Magnetic Biasing Layers", patent 4,024,489 (1977).
[16] C. H. Bajorek, L. T. Romankiw and D. A. Thompson, "Self Biased Magnetoreistive Sensor", patent 3,840,898 (1974).
[17] Ibid.
[18] C. H. Bajorek and D. A. Thompson, "Method for Eliminating Part of Magnetic Crosstalk in Magnetortesistive Sensors", patent 3,887.944 (1975).
[19] M. Garnier, T. Tang and J. White, "Magnetic Head Slider Assembly", patent 3,855,625 (1974).
[20] D. S. Chabra, S. A. Bolasna, L. K. Dorius and L. S. Samuelson, "Air Bearing Design Considerations for Constant Fly Height Applications", IEEE Trans. Mag. **30**, No. 2, 417 (1994).

material of the leading edge shield from Permalloy to Sendust.[21] The Sendust magnetic alloy was much less malleable than Permalloy, thereby inhibiting the formation of conductive filaments on the air bearing surface by asperities on the disk. The leading edge shield of later MR heads, the ones used on film disks, was switched back to Permalloy because film disks were much smoother than particulate disks. And achieving adequate corrosion resistance required passivating the air bearing surface of the head with a thin layer of diamond-like carbon. Diagnosing the root causes of these surprises and implementing the solutions took another 3-4 years.

Such delay required de-committing the MR head from the IBM 3390 program. Later, with a positive outlook to solve these problems, the head was re-committed for the drive program code named "Corsair". And positive progress of integrating the improved heads in Corsair led another HDD program, code named "Sawmill" to also adopt MR heads. Sawmill completed its development and qualification cycle first and shipped in 1990 as the IBM 9345. Corsair followed in 1991 as the IBM 0663. All other IBM HDD programs adopted MR heads shortly thereafter.

The length of the time cycle to commercialize the first MR head was in part influenced by the need to also develop the manufacturing processes and tools to produce such heads and the corresponding HDDs. Key tools for making and testing the heads were not available from suppliers and had to be designed and built internally. Mounting the heads on to suspensions and actuators, and merging the actuators into HDDs required revolutionary upgrades to clean rooms and assembly procedures to protect the heads from electrostatic discharge (ESD) damage. To accelerate progress IBM drafted about 20 engineers and scientists from the Semiconductor Technology Division in East Fishkill, NY. The challenges went substantially beyond the practices and tools used in the most advanced semiconductor device factories of that era.

Sawmill and Corsair

Sawmill was a special 1.5 GB HDD designed to use 5 ¼ in. disks.[22] This program was sponsored by Jack Harker's IBM Fellow program and managed by Jim Makiyama in IBM San Jose, CA. Jim Makiyama started this program while reporting to the author. Special attention was paid to all design details of the device to achieve a highly reliable HDD. For example, it did not conform to the standard 5 ¼ in. HDD form factor in order to accommodate a linear actuator, with a very robust base casting to minimize vibrations and thereby reliably achieve very fast access times.[23] It was used on several IBM low end mainframe and specialized systems, and was sold to NEC on an OEM basis. Sawmill had modest unit sales over its life but it turned out to be one of the most reliable HDDs in the history of the industry. Even though Sawmill demonstrated extraordinarily high reliability, several of its applications were in RAID environments where redundant

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[21] C. H. Bajorek, C. T. Cheng and E. T. Yen, "Process for Making a Shielded Magnetoresistive Sensor", patent 4,918,554 (1990).

[22] Computer History Museum article: http://www.computerhistory.org/collections/accession/102649194

[23] D.P. Fazzio et al, "Head actuator dynamics of an IBM 51/4-inch disk drive", IBM JRD **37**, No. 4, 479 (1993).

drives provided significant additional reliability.[24] [25] Today's mission-critical data servers all utilize one of several RAID configurations.

Corsair was the industry's first 3 ½ in. HDD with a capacity of 1 GB. This program was initiated and managed by Tom Porter in IBM Rochester, MN. Tom Porter reported to the author throughout Corsair's development. This HDD was used in IBM's AS 400 systems, high end PCs and work stations. The Corsair program exceeded sales of one million units over its life, much higher than Sawmill. As such, Corsair is generally recognized as the first significant user of MR heads in the HDD industry, but not as urban legend would have it, the first HDD to use MR heads.[26]

The Rest of the Story

HP also invested in developing its own MR head technology. HP has not yet published a description of this program. HP chose to focus on a different read element design, the dual element option.[27] But, HP chose not to manufacture this design. It licensed it to Dastek which later became Headway. Headway was populated by alumni from IBM's MR program. Headway supplied the HP-based heads to HP and to Seagate starting in 1995. Seagate also produced part of its needs for the HP-based heads internally. Headway was purchased by TDK. Headway-TDK and Seagate later also adopted the IBM, single element MR head design. The IBM design became the industry's de facto standard.

It took until 1998, for the rest of the HDD industry to fully master the single element AMR heads.

IBM also commercialized the industry's first GMR head, also known as a "spin valve" head, in 1997.[28] [29] [30] [31] The rest of the industry adopted GMR heads in 1999. The commercialization cycle for GMR heads was half as long as the cycle for AMR heads. This was largely because, even though it was not known at the time, the single stripe AMR heads were actually inefficient GMR heads, with half the maximum spin valve

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[24] B. E. Clark, F. D. Lawlor, W. E. Schmidt-Stumpf, T. J. Stewart, G. D. Timms, "Parity Spreading to Enhance Storage Access", patent 4,761,785 (1988).
[25] For example, the AdStar (IBM) 9570 subsystem used Sawmill drives in a RAID-3 configuration.
[26] For example, see PC World's Timeline: 50 Years of Hard Drives, http://www.pcworld.com/article/127105/article.html
[27] T.C. Anthony, S. L. Naberhuis, J. A. Brug, M. K. Bhattacharyya, L. T. Tran, V. W. Hesterman and G. G. Lopatin, "Dual-Stripe Magnetoresistive Heads for High Density Recording", IEEE Tans. Mag. **30**, No. 2, 303 (1974).
[28] R. Scranton, "IBM Deskstar 16 GP (14GXP); First Use of Giant Magnetoresistance (GMR) Heads in a Commercial Product", Computer History Museum article (2012).
[29] B. Dieny, B. A. Gurney, S. E. Lambert, D. Mauri, S. S. P. Parkin, V. S. Speriousu and D. Wilholt, "Magnetoresisitive Sensor Based on the Spin Valve Effect", patent 5,206,590 (1993).
[30] D. E. Heim, R. E. Fontana, V. S. Speriousu, B. A. Gurney and M. L. Williams, "Design and Operation of Spin Valve Sensors", IEEE Tarns. Mag **30**, No. 2, 316 (1994).
[31] B. A. Gurney and V. S. Speriousu, "For key technical contributions to the development of spin valve giant magnetoresistance recording heads for computer data storage devices", IEEE Reynold B. Johnson Information Storage Systems Award (2004).

signal amplitude. Specifically, the AMR heads had a sensor stack of two Permalloy films separated by a thin spacer of titanium or tantalum. Such heads would have exhibited the GMR effect if this spacer had been copper. In the author's judgment, based on the benefit of hindsight, it was this similarity between AMR and GMR heads that in part sped up the commercialization of the phenomenon of GMR discovered by Fert and Grunberg in 1988.

Led by IBM, in 1998, the stability of the pinned layer of GMR heads was improved via incorporation of a synthetic antiferromagnet (SAF) coupled to the AFM-based pinning layer. The application of the SAF effect to GMR heads was first described by Grunberg.[32] This effect, also known as "negative exchange coupling", involves two ferromagnetic films such as Permalloy, separated by a thin non magnetic layer that causes the magnetization of the two magnetic films to polarize in opposite directions. The preferred spacer film is a thin layer of ruthenium.

TMR heads were attractive because of the promise of resistance changes even larger than those attainable with AMR and GMR heads. Electron tunneling phenomena in semiconductors and superconductors were first investigated by Leo Esaki[33] and Ivar Giaever[34] respectively, circa 1960. Their pioneering work, as well as the prediction by Brian David Josephson, of a super current through a tunnel barrier, known as the Josephson Effect, were recognized by the Nobel Prize in Physics in 1973.

Circa 1974 M. Julliere was first to propose tunneling between ferromagnetic films and present supporting experimental data at very low temperatures.[35] As mentioned above, at approximately the same time John Slonczewski independently proposed using such a magnetic tunnel junction to detect magnetic fields at room temperature.

John Slonczewski submitted his ideas as an invention disclosure to IBM in 1974.[36] IBM published the ideas in its Technical Disclosure Bulletin in 1976.[37] John Slonczewski persevered throughout the rest of his career in developing his ideas centered on interactions of polarized electrons, including being first to propose the mechanism of **switching by** spin - transfer torque, which is used to switch the state of the storage cells in the latest MRAM devices.[38] His achievements were recently recognized by a prestigious Award from the IEEE.[39]

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[32] P. Grunberg, "Magnetic Field Sensor with Ferromagnetic Thin Layers Having Magnetically Antiparallel Polarized Components", patent 4,949,039 (1990).
[33] Leo Esaki, Biographical, Nobel Lectures, Physics 1971-1980, Editor Stig Lundqvist, World Scientific Publishing Co., Singapore (1992).
[34] Ivar Giaever, Biographical, Nobel Lectures, Physics 1971-1980, Editor Stig Lundqvist, World Scientific Publishing Co., Singapore (1992).
[35] M. Julliere, "Tunneling Between Ferromagnetic Films", Phys. Let. **54A**, No. 3, 225 (1975).
[36] John Slonczewski, personal communication.
[37] John Slonczewski, "Magnetic Bubble Tunnel Detector", IBM TDB **11-76**, 2328 (1976)
[38] J.C. Slonczewski:"Current-driven excitation of magnetic multilayers (1996)", Journal of Magnetism and Magnetic Materials **159**, Issues 1-2, L1 (1996).
[39] IEEE Magnetics Society Achievement Award (2012).

In 2001 two groups of theoreticians, independently predicted that use of magnesium oxide barriers could result in very large magnetoresistance changes, much larger than the ones exhibited by the early TMR heads.[40] [41] Beginning in mid – 2001, these predictions were confirmed experimentally via highly oriented MgO - based junctions by a group at IBM. [42] [43] [44] Approximately 2 years later, a team at Anelva also demonstrated large magnetoresistance changes in single crystal MgO – based junctions.[45] Significantly, the Anelva team was also first to achieve very large magnetoresistance, about 230%, in practical polycrystalline CoFeB/MgO/CoFeB junctions.[46] The latter breakthrough led the entire industry to adopt MgO as the tunnel barrier of choice for all TMR heads since then.

Seagate was first to commercialize TMR heads with a titanium oxide barrier in 2004.[47] The product TMR heads were based on the heads exemplified in a 2006 publication from Seagate.[48] Figure 1 of this publication also shows an image of the Seagate drive that first used its TMR heads. Headway – TDK, an independent supplier of heads to the HDD industry, was a close second with TMR heads using an aluminum oxide barrier in early 2005.[49] The rest of the HDD industry adopted TMR heads shortly thereafter.

The commercialization cycle of TMR heads took 30 years following Julliere's and Slonczewski's pioneering results and inventions. The length of the TMR cycle was in part affected by the need for TMR heads to adopt the technologies that had to be first mastered for the success of AMR and GMR heads, technologies such as magnetic shields, AFM - based pinning, hard bias to suppress Barkhausen noise, and SAF – based stability enhancement. The length of the TMR cycle was also affected by the extraordinary challenges that had to be overcome in making reliable and reproducible tunnel oxide barriers.

Summary

MR heads on sliders with negative pressure air bearings have been very important in facilitating data density advances in HDDs, 20,000 times since 1990. All HDDs have

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[40] W.H. Butler et al, "Spin-dependent tunneling conductance of Fe/MgO/Fe sandwiches", Phus. Rev. B **63**, 054416 (2001).

[41] J. Mahon and A. Umerski, "Theory of tunneling magnetoresistance of an epitaxial Fe/MgO/FeO (001) junction", Pys. Rev. B **63**, 220403 (2001).

[42] William J. Gallagher, personal communication.

[43] S. S. P.Parkin et al, results which were later published in "Giant tunneling magnetoresistance at room temperature with MgO (100) tunnel barriers", Nature Mater. **3**, 862 (2004).

[44] Also see corrected Figure 5 of publication by W. J. Gallagher and S. S. P. Parkin, "Development of the magnetic tunnel junction MRAM at IBM: From first junctions to a 16 – Mb MRAM demonstrator chip", IBM J. Res. & Dev. **50,** No. 1, 5 (2006).

[45] S. Yuasa et al, Giant room-temperature magnetoresistance in single crystal Fe/MgO/Fe magnetic tunnel junctions", Nature Mat. **3**, 868 (2004).

[46] K. Tsunekawa et al, "CoFeB/MgO/CoFeB magnetic tunnel junctions with high TMR ratio and low junction resistance", Digest of the IEEE Magnetics Conf., 2005/Intermag Asia 2005, 1223 (2005).

[47] Seagate 100 GB Backup Plus circa 3Q 2004.

[48] Sining Mao et al, "Commercial TMR Heads for Hard Disk Drives: Characterization and Extendibility at 300 Gbit/in2" IEE Trans Mag. **42**, No. 2, 97 (2006).

[49] The first Headway TMR head was used in a 60 GB/disk 2 ½ in. HDD by Toshiba (shipped in April, 2005). Mao-Min Chen, Headway, and Yoichiro Tanaka, Toshiba, private communication.

used MR heads for about 20 years. Today, all HDDs use the latest version of such heads, the TMR heads. In 2014 he industry is expected to produce approximately 800 million TMR head-based HDDs. These HDDs will consume approximately 2 billion TMR heads.

Acknowledgments

I dedicate this write-up to the many colleagues who contributed to the commercialization of the various types of MR heads. I also thank Denis Mee, David Thompson, John Slonczewski and Tom Gardner for useful discussions and suggestions pertaining to the write-up.

Glossary

AFM Anitferromagnet
AMR Anisotropic magnetoresistance
ESD Electro discharge
GMR Giant magnetoresistance
HDD Hard disk drive
LMR Longitudinal magnetic recordin/ g
MR Magnetoresistance
OEM Original equipment manufacturer
PMR Perpendicular magnetic recording
POS Point of sales
RAID Redundant array of inexpensive drives
SAF Synthetic antiferromagnet
SAL Soft adjacent layer
SNR Signal to noise ratio
TMR Tunneling magnetoresistance