Institution: City University London

Unit of Assessment: 10 Mathematical Sciences

Title of case study: Tunneling Magnetoresistance: from theoretical proposal to practical application

1. Summary of the impact

The significant increase in hard disk storage capacity in the last few years can be in part attributed to theoretical research in Mathematics undertaken at City University London. A material or device is said to exhibit the property of magnetoresistance if its electrical resistance changes when the direction of an external magnetic field is varied. The work undertaken at City concluded that devices based on magnesium oxide (MgO) would exhibit magnetoresistances very much larger than previously observed. In 2004 these conclusions were confirmed experimentally. By 2008 a new type of disk read head (the device that senses data on a magnetic disk) based on this structure was being manufactured commercially, enabling a significant increase in hard disk storage capacity. Today all computer hard disks use read heads based on this technology in an industry with 2012 sales exceeding $28 billion. The increase in hard disk storage capacity achieved (from gigabytes to terabytes: 1 terabyte = 1,000 gigabytes) and the consequent improvement in disk performance for users can be partly attributed to the City research.

2. Underpinning research

The modern day hard disk reading head is the first commercial device to use the spin of an electron rather than its charge to control the resistance. It exploits the phenomenon of magnetoresistance which is an important part of a new multidisciplinary field of study called spintronics, which attempts to exploit electron spin in solid state devices. The Mathematics Department at City University London has been involved in the spintronics field from an early stage. The work was led by Professor J Mathon (at City since 1970) with Dr A Umerski (Research Assistant at City 1996-2000). The initial research addressed interlayer exchange coupling and magnetoresistance effects in metallic and model tunneling systems. This work set the foundation for the 2001 publication on tunneling magnetoresistance in magnesium oxide (MgO) [1], which is regarded as a very significant achievement in the field of spintronics with over 800 citations. It should be noted that the calculation of this effect posed significant technical problems because it required a highly accurate calculation of the tiny tunneling current. This demanded significant expertise in spintronics.

In 1989 a magnetoresistance (MR) of quantum mechanical origin, which utilises the spin of an electron, was discovered by Albert Fert and Peter Grunberg who later received the 2007 Nobel Prize for their work. This discovery was quickly developed commercially. In 1997 IBM brought out a hard disk drive (HDD) in which the read head used this effect to sense the magnetic 'bits' of the disk. By the late 1990s, all hard disk reading heads were based on this form of MR. This development is primarily responsible for the increase in disk storage density from 0.1 to 100 $Gbit/in^2$ between 1991 and 2003.

The efficiency of the modern-day reading head depends on a quantity called the magnetoresistance ratio (MR ratio). This can be thought of as the maximum percentage change in resistance as the direction of applied magnetic field is varied. A reading head with a large MR ratio implies a more sensitive device which can read smaller magnetic bits on the hard disk, enabling a higher storage density.

Early metallic-based read heads, used commercially from 1997 until 2005, had MR ratios limited to less than 50%. Developments using an amorphous insulating barrier produced MR ratios of up to 70% and; this was briefly used in Seagate read heads in 2005.

In 2001 Mathon and Umerski at City [1], simultaneously with a group in the US [2], proposed an entirely new system based on a crystalline insulator, magnesium oxide (MgO). The underlying physics, based on coherent, spin-dependent, quantum electron tunneling through the crystalline MgO barrier, is entirely different to the earlier systems. It was predicted that the MR ratio of this novel tunneling device could exceed 1000%, some 15 times higher than previously achieved. This MR effect is called tunneling magnetoresistance (TMR) and the magnetoresistive MgO system is referred to as an MgO tunnel junction.

Nanostructure devices were successfully produced three years later when two world-leading experimental groups, one from Tsukuba in Japan and one from IBM Almaden in the US, published separate confirmation of large MR ratio in MgO-based systems in the same issue of Nature Materials [3, 4]. The first such TMR read head reached the market in 2007 and since 2009 all manufactured hard disks have been based on this technology (see corroborating source B).

Our theoretical research into coherent tunneling in MgO based tunneling junctions continues. Our latest proposal to enhance significantly the MR ratio is based on the so-called collimation effect achieved by attaching the standard MgO junction to a semiconductor lead. This work is described in [5] and [6]. The theoretical expectation is that the MR ratio in collimated junctions could be enhanced by a factor of 100.

3. References to the research

[1] Mathon J. & Umerski A. (2001) Theory of tunneling magnetoresistance of an epitaxial Fe/MgO/Fe(001) junction *Phys. Rev. B,* **63**, 220403(R) 10.1103/PhysRevB.63.220403
[2] Butler W. H. *et al.* (2001) Spin-dependent tunneling conductance of Fe|MgO|Fe sandwiches *Phys. Rev. B,* **63**, 054416 10.1103/PhysRevB.63.054416
[3] Yuasa S., Nagahama T., Fukushima A., Suzuki Y., & Ando K. (2004) Giant room-temperature magnetoresistance in single-crystal Fe/MgO/Fe magnetic tunnel junctions *Nature Mat.,* **3**, 868 10.1038/nmat1257
[4] Parkin S. S. P. *et al. (*2004) Giant tunnelling magnetoresistance at room temperature with MgO (100) tunnel barriers *Nature Mat.,* **3**, 862 10.1038/nmat1256
[5] Autes G., Mathon J. & Umerski A. (2010) Strong Enhancement of the Tunneling Magnetoresistance by Electron Filtering in an Fe/MgO/Fe/GaAs(001) Junction *Phys. Rev. Lett.,* **104**, 217202 10.1103/PhysRevLett.104.217202
[6] Autes G., Mathon J. & Umerski A. (2011) Theory of ultrahigh magnetoresistance achieved by k-space filtering without a tunnel barrier *Phys. Rev. B,* **83**, 052403 10.1103/PhysRevB.83.052403

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4. Details of the impact

The impact of the 2001 Mathon and Umerski paper predicting that MgO-based systems would exhibit very high MR ratios was immediate. Preliminary results were presented at the ICM 2000 Conference in Recife, Brazil, with a number of world leading experimentalists in the audience. In addition the group were in close communication with experimental groups in Japan and the US where high-quality magnetic layer systems were being developed. Nevertheless it took three years to manufacture successfully MgO tunnel junctions of sufficient quality that a large MR ratio was observed. The difficulty arises because the phenomenon is of quantum mechanical origin and consequently requires very high quality interfaces. Several experimental papers were published during the period 2002-2004, with observed MR ratios gradually increasing. In December 2004, the Japanese Tsukuba group simultaneously with the US IBM group reported values of 180%-220% at room temperature, in Nature Materials [3,4]. Both these experimental papers cite the predictions of Mathon and Umerski and of Butler *et al.* as motivation and there can be little doubt that the results of these theoretical papers both laid the groundwork for success and gave experimentalists the impetus required to keep trying until that success was achieved.

Following the experimental success, focus shifted to the creation of a commercial product. This required the mass production of MgO-based tunnel devices, previously only produced in two world-leading laboratories drawing on great experimental expertise. Significant technological developments were required in order to do this, principally pioneered by the Japanese Tsukuba group and the US IBM group (reviewed in [G] and [H]). The first TMR read head reached the market in 2007. Since 2009 all manufactured hard disks have been based on this technology. This is confirmed by S.S.P. Parkin (head of the research group at IBM and the author of reference 4) who states: *"The work of Mathon and Umerski clearly played an important role in the development of these materials and their subsequent widespread application to recording read heads in ~2007. All disk drives manufactured since about 2008-2009 use recording read heads based on magnetic tunnel junctions."* [B]

Today there are only three major manufacturers of hard disk drives: Western Digital, Seagate and Toshiba [A]. In 2008 Western Digital reported that *"the industry has made the transition to tunnel-junction magneto resistive ("TMR") technology for the head reader function. We have completed the transition to PMR [Perpendicular Magnetic Recording] and TMR in our 2.5-inch products and in the majority of our 3.5-inch products"* [C]. In 2009 they reported *"We have completed the transition to PMR and TMR across all product platforms"* [D]. An example of the use of TMR technology by Toshiba is given in their product information for internal notebook hard drives which *"use proven state of the art….TMR Head Recording technology for increased capacity, reliability and performance"* [E].

High-tech companies are naturally somewhat reluctant to disclose the detailed operation of their products so it is difficult to trace the development of MgO tunnel junctions once they left the confines of university laboratories. However, the technological benefit of MgO-based read heads to the companies which manufacture hard disks is perhaps most clearly demonstrated in the following claim of industrial espionage. The American Arbitration Association reported on a 5-year dispute between Seagate and Western Digital regarding an employee (Dr Mao) who moved from Seagate to Western Digital in September 2006 at a critical time when hard disk manufacturers were developing the new MgO-based read heads [F]. The report provides the following summary of the background to the case (Section A5 on page 4): "*Seagate claims that Dr Mao stole Seagate trade secrets and confidential information regarding TMR technology and provided it to Western Digital, which used trade secrets and confidential information to design and manufacture an MgO TMR read head. As a result Seagate claims that Western Digital was able to introduce products, incorporating an MgO TMR read head, into the market many months ahead of when it would have been able to do so without Seagate trade secrets and confidential information. Seagate asserts that as a result of using stolen Seagate trade secrets and confidential information, Western Digital avoided substantial research and development costs and made substantial profits.*" The alleged move of Dr Mao is likely to have saved Western Digital many months of research and development. In 2011 the American Arbitration Association ruled that for this infringement Seagate was entitled to recover $525,000,000 plus pre-award interest at 10% per annum. This demonstrates the enormous financial importance of the new MgO-based technology.

It is difficult to say precisely what the increase in hard disk capacity is as a result of the MgO-based read head. Firstly, because other factors like write density are also important. Secondly. because MgO-based read heads are still being developed, with improvements in growth morphology leading to greater MR ratios. We can say that in 2005, just before the new read heads were introduced, Toshiba introduced a hard drive with a record-breaking storage density of 179 Gbit/in^2. In 2012 the highest density commercially available was about 620Gb/in^2 although work continues towards a 1Tb/in^2 drive, demonstrated by Seagate with great fanfare in March 2012 [J]. An increase by a factor of five to date can certainly be claimed. The difficulty at present appears to be with stable recording rather than reading, and for the near future the MgO based read head looks likely to remain.

The role of Mathon and Umerski's work in the emergence of MgO-barrier magnetic tunnel junctions is emphasised in the reviews cited at [G] and [H]. The 20th Tsukuba Prize was awarded to Drs Yuasa and Suzuki (authors of reference 3) for "Giant tunnel magnetoresistance in MgO-based magnetic tunnel junctions and its industrial applications". The prize citation traces a direct path from the theoretical prediction to the industrial application. It emphasises the significance of the industrial application and impact on society of TMR technology, stating: *"The giant TMR effect in MgO MTJs (magnetic-tunnel-junctions) is expected to contribute to our society by significantly* *reducing the power consumption of electronics devices and improving the performance and security of computers"* [I].

The MR ratio observed in MgO-based systems is now very close to the original theoretical prediction of 1000%. The conclusions of the Mathon and Umerski theoretical paper, later confirmed experimentally, have directly influenced the design of the hard disk reading head commercially manufactured since 2008. This has led to increase in hard disk storage capacity by more than a factor of five. The original 2001 publication has attracted more than 500 citations and, along with that of Butler *et al.*, is regarded as a seminal paper in spintronics, one source of the explosion of interest in MgO-based systems. Such systems are also the basis of magnetic random access memory (MRAM), a new type of non-volatile memory, which is being actively developed and may someday replace both hard disks and existing random access memory [G, H].

5. Sources to corroborate the impact

[A] Bizmology article: 'Consolidation in the hard disk drive market: then there were three' http://bizmology.hoovers.com/2012/03/19/consolidation-in-the-hdd-hard-disk-drive-market-then-there-were-three/ (Archived by WebCite® at http://www.webcitation.org/6BhSl9Ylg)

[B] Letter from S.S.P. Parkin FRS, Magnetoelectronics Manager, IBM Almaden Research Center, confirming the important role of Umerski and Mathon in the development of Fe/MgO/Fe TMR junctions (Sept 2012).

[C] Western Digital 2008 Annual Report and Form 10-K https://materials.proxyvote.com/Approved/958102/20080917/AR_27910/images/Western_Digital-AR2008.pdf. (Archived by WebCite® at http://www.webcitation.org/6BX5o4wht)

[D] Western Digital 2009 Annual Report and Form 10-K https://materials.proxyvote.com/Approved/958102/20090916/AR_46224/HTML2/default.htm. (Archived by WebCite® at http://www.webcitation.org/6BX5xyQ8a).

[E] Toshiba Storage Products 'Internal Notebook Hard Drives' product details webpage http://storage.toshiba.com/storagesolutions/archived-models/internal-notebook-hard-drives. (Archived by WebCite® at http://www.webcitation.org/6BX6Eic0N)

[F] http://amlawdaily.typepad.com/01302012western_interim.pdf *(Archived by WebCite® at* http://www.webcitation.org/6DwPHDu1U*).*

[G] *S Yuasa and D D Djayaprawira, J. Phys. D: Appl. Phys. 40 (2007) R337–R354. Particularly the conclusion Section 7 which contains a brief summary.*

[H] IEEE Transactions on Electron Devices **54** 991 (2007) section 3A.

[I] *Citation for the 20th Tsukuba prize*
http://www.suzukiylab.mp.es.osaka-u.ac.jp/Top/tsukuba_english.pdf *(Archived by WebCite® at* http://www.webcitation.org/6BX6MlwDd).
http://storageeffect.media.seagate.com/2012/03/storage-effect/paving-the-way-for-big-hard-drive-capacity-gains/ *(Archived by WebCite® at* http://www.webcitation.org/6DzIQc2I7*)*