Institution: The Open University

Unit of Assessment: B10 Mathematical Sciences

Title of case study: Hard disks based on tunneling magnetoresistance

1. Summary of the impact

Since 2009 the read heads of all hard disks have used a technology based on magnesium oxide (MgO). The development of this technology can be partly attributed to a 2001 publication [3.1] co-authored by Dr Andrey Umerski of The Open University, which concluded that a system based on MgO would lead to a huge increase in magnetoresistance, a physical property that determines the efficiency of hard disk read heads.

In 2004 these theoretical predictions were confirmed experimentally; by 2008 the new type of read head based on MgO was manufactured commercially, leading to significant increases in storage capacity, from GBs to TBs.

2. Underpinning research

Key publication: The modern-day hard disk read head is the first commercial device to use the spin of an electron rather than its charge. It exploits a phenomenon called magnetoresistance, which is an important part of a new multidisciplinary field of study called spintronics. Dr Umerski was involved in the spintronics field from an early stage. From 1994 to 2000 he was a PDRA to Professor J. Mathon and Professor D.M. Edwards (City University and Imperial College, respectively) before taking up a lectureship at The Open University in January 2001.

Umerski and Mathon's 2001 publication on tunneling magnetoresistance in MgO [1], which is the subject of the present case study, is regarded as a milestone in the field of spintronics, gaining more than 500 citations. Since 2001, Umerski and Mathon have continued to build on the work pioneered in [3.1] with ten further publications exploring different aspects of MgO tunneling junctions – these include: oscillatory and resonance effects (2003, 2004, 2005 and 2009), the effect of disorder (2003, 2004 and 2006), and more recent work on strong enhancement of magnetoresistance discussed below.

Magnetoresistance: A material is said to exhibit magnetoresistance (MR) if its electrical resistance changes when the direction of an external magnetic field is varied. MR is characterised by a quantity called the magnetoresistance ratio (MR ratio) – the maximum percentage change in resistance as the direction of applied magnetic field is varied. A read head with a large MR ratio can read smaller magnetic 'bits' on the hard disk, and hence a higher storage density.

Earlier research: In 1989 an MR of quantum mechanical origin, which utilises the spin of the electron, was discovered by Albert Fert and Peter Grünberg, who later received the 2007 Nobel Prize for their finding. This discovery was quickly developed commercially and, 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 HDD read heads were based on this form of MR, and this development is the main cause of the huge increase in disk storage density from 0.1 to 100Gbit/in^2 between 1991 and 2003.

This early form of MR, called giant magnetoresistance (GMR), was based on entirely metallic systems. The GMR based read head had MR ratios limited to less than 50%. Another system, using an alumina insulating barrier, produced a modest increase in MR ratios (70%) and was briefly developed into a read head by Seagate in 2005. The physical mechanism behind both these systems involves non-coherent scattering of the electrons.

The MgO idea: In 2001 Mathon and Umerski [3.1], simultaneously with a group in the US [3.2], proposed an entirely new system using a crystalline insulator, magnesium oxide (MgO). The underlying physics relies on coherent, spin-dependent, quantum electron tunneling through the crystalline MgO barrier and so is entirely different to the GMR and the alumina systems. The theoretical calculations in [3.1] predicted that the MR ratio of this novel tunneling device can 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.

Recent theoretical work: Recently Umerski and Mathon, together with their EPSRC-funded PDRA Autès, showed how MR ratios could be massively enhanced (to more than 100,000%), both in MgO tunnel junctions and in metallic GMR junctions [3.5, 3.6]. Experimentalists are currently trying to confirm these predictions, which have the potential to lead to the next generation of spintronic based devices.

3. References to the research

3.1. Mathon, J. and Umerski, A. (2001) 'Theory of tunneling magnetoresistance of an epitaxial Fe/MgO/Fe(001) junction', *Physical Review B*, vol. 63, 220403(R).

3.2. Butler, W.H., Zhang, X.G., Schulthess, T.C. and MacLaren, J.M. (2001) 'Spin-dependent tunneling conductance of Fe|MgO|Fe sandwiches' *Physical Review B*, vol. 63, 054416.

3.3. Yuasa, S., Nagahama, T., Fukushima, A., Suzuki, Y. and Ando, K. (2004) 'Giant room-temperature magnetoresistance Fe/MgO/Fe magnetic tunnel junctions', *Nature Materials*, vol. 3, pp. 868–71.

3.4. Parkin, S.S.P., Kaiser, C., Panchula, A., Rice, P.M., Hughes, B., Samant, M. and Yang, S.H. (2004) 'Giant tunneling magnetoresistance at room temperature with MgO (100) tunnel barriers', *Nature Materials*, vol. 3, pp. 862–7.

3.5. Autès, G., Mathon, J. and Umerski, A. (2010) 'Strong enhancement of the tunneling magnetoresistance by electron filtering in an Fe/MgO/Fe/GaAs(001) junction', *Physical Review Letters*, vol. 104, no. 21, p. 217202.

3.6. Autès, G., Mathon, J. and Umerski, A. (2011) 'Theory of ultrahigh magnetoresistance achieved by k-space filtering without a tunnel barrier', *Physical Review B*, vol. 83, no. 5, p. 052403.

Papers [3.5] and [3.6] were supported by EPSRC grants EP/F023472/1 and EP/F022808/1:

dates: 01/01/08 – 31/12/10, project titles: 'Solving the fundamental limitations for RT spintronics - the role of interfaces in electron spin detection and injection', total value £338,268, principal investigators Dr. A. Umerski of The Open University and Prof. J. Mathon of City University London, respectively.

4. Details of the impact

Experimental impact: The impact of the Mathon and Umerski 2001 paper [3.1], predicting that MgO-based systems would exhibit very high MR ratios, was immediate. The race to observe this effect experimentally, with its obvious commercial application, ended in a dead heat in December 2004 when the Tsukuba group in Japan and the IBM group in the US simultaneously reported MR ratios of 180–220% at room temperature in Nature Materials [3.3, 3.4] [5.12]. Both these papers cite the predictions of [3.1] and [3.2] as motivation. Moreover, the emphasis in [3.1] on the importance of interface quality must have helped the experimentalists achieve their goals.

Commercial developments: The motivation then moved to creating a commercial product, principally by the Tsukuba group in Japan and the IBM group in the US (see [5.7] and [5.8] for a review). The first TMR read head reached the market in 2007. By 2009 all new hard disks were based on this technology and this remains the case. This is confirmed by S.S.P. Parkin (head of the IBM research group responsible for [3.4]), 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.' [5.2]

Today, there are only three major manufacturers of HDDs: Western Digital, Seagate and Toshiba [5.1]. In 2008 Western Digital reported that 'the industry has made the transition to tunnel-junction magneto resistive ("TMR") technology for the head reader function' [5.3]. By 2009 it reported that '[we] have completed the transition to PMR [Perpendicular Magnetic Recording] and TMR across all product platforms' [5.4]. An example of the use of TMR technology by Toshiba is given in its product information for internal notebook hard drives, which 'use proven state of the art … TMR Head Recording technology for increased capacity, reliability and performance' [5.5].

To date, the increase in hard disk capacity as a result of the MgO-based read head is about a factor of five [5.10] and for the near future the MgO-based read head looks likely to remain. The paper [5.11] contains a 2010 report on the expected design and operation of a future 2TB/in2 read head, by researchers at Seagate, which they say 'will likely use a higher quality MgO tunneling giant magnetoresistance (TGMR) stack'. They conclude by saying '[we] expect the MgO barrier technology to be continuously improved to fulfil the industry's mid-term needs'.

Commercial impact: The hard disk industry has annual sales exceeding $28 billion [5.1]. The huge commercial benefit of MgO-based read heads to the industry is clearly demonstrated in the following claim of industrial espionage. [5.6] is a link to the findings of the American Arbitration Association in a five-year dispute between Seagate and Western Digital regarding an employee (Dr Mao) who moved from Seagate to Western Digital in September 2006, when HDD manufacturers were developing the new MgO-based read heads. Page 4 of [5.6] states:

'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.'

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 [5.6, page 28].

Impact on society: The role of [3.1] is highlighted in reviews [5.7, 5.8], and in the original experimental papers [3.3, 3.4]. The significance of the industrial application of TMR technology and its impact on society is emphasised in the citation [5.9] for the 20th Tsukuba Prize, awarded to Drs Yuasa and Suzuki (of [3.3]) for 'Giant tunnel magnetoresistance in MgO-based magnetic tunnel junctions and its industrial applications'. This citation acknowledges the role of the earlier theoretical predictions about MgO and states:

'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.'

Summary: The predictions of Mathon and Umerski's 2001 publication [3.1] have directly influenced the design of all hard disk read heads commercially manufactured since 2009. This has led to more than a five-fold increase in hard disk storage capacity in an industry with annual sales exceeding $28 billion [5.1]. The publication has attracted more than 500 citations and is regarded as a seminal paper in spintronics, giving birth to the explosion of interest in MgO-based systems. Moreover, such systems are also the basis of magnetic random access memory (MRAM), a new type of non-volatile memory that is being actively developed and may someday replace both hard disks and existing random access memory [5.7, 5.8].

5. Sources to corroborate the impact

The Wikipedia article http://en.wikipedia.org/wiki/Tunnel_magnetoresistance contains a brief overview of MgO-based tunnel magnetoresistance and its applications. Reference [3.1] is cited.

5.1. 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)

5.2. Letter from 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).

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

5.4. 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).

5.5. 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)

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

5.7. Yuasa, S. and Djayaprawira, D.D. (2007) 'Giant tunnel magnetoresistance in magnetic tunnel junctions with a crystalline MgO(001) barrier', *Journal of Physics D-Applied Physics*, vol. 40, no. 21, p. R337–54. Particularly the conclusion in Section 7, which contains a brief summary.

5.8. Ikeda, S., Hayakawa, J., Lee, Y.M., Matsukura, F., Ohno, Y., Hanyu, T. and Ohno, H. (2007) 'Magnetic tunnel junctions for spintronic memories and beyond', *IEEE Transactions on Electron Devices*, vol. 54, no. 5, pp. 991–1002. See section 3A.

5.9. 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).

5.10. Ignoring other factors like write density, this estimate is based on the fact that, in 2005, just before the new read heads were manufactured, Toshiba introduced a hard drive with a storage density of 179 Gbit/in^2. Whereas in March of 2012 Seagate demonstrated a 1TB/in^2 drive: 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*).*

5.11 Chen, Y., Song, D., Qiu, J., Kolbo, P., Wang, L., He, Q., Covington, M., Stokes, S., Sapozhnikov, V., Dimitrov, D., Gao, K. and Miller, B. (2010) '2 Tbit/in^2 reader design outlook', *IEEE Transactions on Magnetics*, vol. 46, no. 3, pp. 697–701.

5.12 Recent experiments with improved growth techniques have measured magnetoresistances of about 1100% at low temperature, in agreement with the original prediction of Mathon and Umerski: Ikeda, S., Hayakawa, J., Ashizawa, Y., Lee, Y.M., Miura, K., Hasegawa, H., Tsunoda, M., Matsukura, F. and Ohno, H. (2008) 'Tunnel magnetoresistance of 604% at 300*K* by suppression of Ta diffusion in CoFeB/MgO/CoFeB pseudo-spin-valves annealed at high temperature', *Applied Physics Letters*, vol. 93, no. 8, 082508.