Institution: Imperial College London

Unit of Assessment: 10 Mathematical Sciences

Title of case study: C8 - A theoretical prediction leading to a redesigned read head used in all hard-disk drives (HDDs) manufactured today

1. Summary of the impact (indicative maximum 100 words)

We demonstrate a strong influence on the design of the read head used in the present state-of-the-art hard-disk drive (HDD) first produced commercially in 2008. This much improved read head, enabling disk storage density to increase by a factor of 5 to around 1 Tbit/in^2, relies crucially on a magnetic tunnel junction with a MgO barrier whose huge tunneling magnetoresistance was predicted theoretically in a 2001 paper co-authored by Dr A. Umerski [1], the RA on one of our EPSRC-funded research grants. This prediction relied on techniques developed by us over many years, specifically in refs [2] and [3]. Such magnetic tunnel junctions are used in all computer HDDs manufactured today with predicted sales in 2012 amounting to more than $28 billion [section 5, source A].

2. Underpinning research (indicative maximum 500 words)

In 1989 Professors D.M. Edwards (Imperial) and J. Mathon (City University) set up a collaboration on the theory of magnetic multilayers which lasted for 20 years with almost continuous SERC and EPSRC funding [G1-G5]. This followed the 1988 discovery of the giant magnetoresistance (GMR) effect for which Fert and Gruenberg were awarded a Nobel Prize in 2007. In a metallic system consisting of two ferromagnetic layers, separated by a non-magnetic spacer layer, the GMR effect is observed as a change in electrical resistance when the angle between the magnetizations of the two magnets is varied due to a magnetic field. In 1997 IBM brought out a GMR hard-disk drive (HDD) in which the read head used this effect to sense the magnetic ‘bits’ of the disk. An increase in storage density from 0.1 to 100 Gbit/in^2 between 1991 and 2003 was largely enabled by GMR.

In practice GMR in metallic systems was necessarily observed with the electric current parallel to the layers and depended on defect scattering of the electrons so that precise calculation of the effect was impossible. Consequently theoreticians concentrated on another effect which was observed in parallel with GMR by a group at IBM led by Stuart S.P. Parkin: oscillations in interlayer exchange coupling (IEC) as a function of spacer thickness. In 1990, the same year as its discovery, Edwards and Mathon presented the first theory of this effect at the E-MRS Spring Meeting in Strasbourg. Green’s function techniques for multilayers were developed to make the theory completely quantitative for real materials; this was done for a Co/Cu/Co trilayer in 1995 [1, 2].

The techniques of [1, 2] were an essential underpinning for the subsequent research which had a direct impact on tunnelling magnetoresistance (TMR) read head technology. This subsequent research was largely carried out by Dr A. Umerski, the RA employed at Imperial on the grant [G3], in collaboration with Professor J. Mathon of City University. A TMR read head is very similar to a GMR read head but with the metallic spacer replaced by an insulating barrier through which the current tunnels perpendicular to the layers. A TMR read head with an amorphous alumina barrier was commercialised by Seagate (a manufacturer of HDDs) in 2005. Meanwhile, in 2001 Mathon and Umerski [3] had published a paper, simultaneously with one by a US group, showing with precise calculations that a much larger TMR effect could be obtained from a crystalline (001)-

oriented Fe/MgO/Fe system. This paper has more than 400 citations. The calculation combines the Kubo formula for conductance with the Green's function techniques we had built up for our interlayer exchange coupling work [1, 2]. It posed considerable technical problems and the high accuracy required to calculate the very small tunnelling current could not have been achieved without the prior work on surface Green's functions of [2]. The large TMR predicted was verified experimentally in 2004 by S.S.P. Parkin's IBM group and a Japanese group. MgO TMR HDDs have swept the market since 2008.

Key Researchers:

- Dr. A. Umerski, RA, Department of Mathematics 1995-31st Oct 2000 (joint appointment with City University, 50% salary from Imperial, 50% from City).
- Prof. D. M. Edwards, Senior Research Investigator, Department of Mathematics, 1999-present, formerly Head of Mathematical Physics Section.
- Prof. J. Mathon, Professor of Mathematical Physics, City University.

3. References to the research (* References that best indicate quality of underpinning research)

[1] *J.Mathon, M.A.Villeret, R.B.Muniz, J.d'Albuquerque e Castro and D.M.Edwards, "*Quantum well theory of the exchange coupling in Co/Cu/Co(001)*", Phys. Rev. Lett., **74,** 3696 (1995). DOI

[2] *A. Umerski, "Closed-form solutions to surface Green's functions", Phys. Rev. B, **55,** 5266 (1997). DOI

[3] *J.Mathon and A.Umerski, "*Theory of tunneling magnetoresistance of an epitaxial Fe/MgO/Fe(001) junction*", Phys. Rev B, **63,** 220403(R) (2001). DOI [N.B. Umerski's Imperial affiliation and grant GR/L92594 were inadvertently omitted on the paper but the bulk of the work reported was done while employed 50% by Imperial (a statement by Umerski to this effect is available upon request).]

Relevant Research Grants:

[G1] EPSRC GR/J37263, 'Exchange coupling in magnetic multilayers; trends across the periodic table and biquadratic exchange', £36,313, 18/04/94 - 17/05/96 (PI: DM Edwards, Imperial)

[G2] EPSRC GR/L13292 ,'Quantum well theory of exchange, giant magnetoresistance and anisotropy in magnetic multilayers', £46,373, 06/05/96 - 05/05/98 (PI: DM Edwards, Imperial)

[G3] EPSRC GR/L92594, 'Theory of tunneling magnetoresistance and interface anisotropy', £66,191, 06/05/98 - 05/05/2001 (RA Dr A Umerski, 50% Imperial, 50% City University, PI: DM Edwards, Imperial College)

[G4] EPSRC GR/N09039, 'Real space theory of magnetotransport and anisotropy in magnetic nanostructures far from equilibrium', £65,032, 01/11/2000 - 31/10/2003 (PI: DM Edwards, Imperial)

[G5] EPSRC EP/D505798/1, 'Spin@rt: Room temperature spintronics', £87,504, 02/05/2006 - 01/08/2009 (PI: DM Edwards, Imperial). This was part of a £2.3M grant for a consortium of seven universities with Imperial and City responsible for theory.

4. Details of the impact (indicative maximum 750 words)

The performance index for a magnetoresistive device, frequently called the MR ratio, is conventionally cited as $(R_{AP} – R_P)/R_P \cdot 100\%$ where R_P and R_{AP} are the resistances of the device when the magnetizations of the two magnetic layers are parallel and antiparallel respectively. In a read head, the larger the MR ratio the smaller the magnetic bits on the disk which can be sensed and the higher the disk storage density. Higher storage density means smaller portable devices. The GMR sensor was used in HDD read heads from 1997 until 2005 but its MR ratio levelled out at

15-20%. It was gradually replaced by a TMR read head from 2005 onwards when Seagate produced such a device with an amorphous alumina barrier and an MR ratio of up to 70%. It seemed possible that a larger MR ratio might be obtained with coherent tunnelling through a crystalline barrier but no-one had any idea how large it would be. Consequently we proposed to do an accurate calculation of the MR ratio for a crystalline Fe/MgO/Fe junction, a good candidate due to a favourable lattice match [G3]. The detailed calculation was carried out by Andrey Umerski in collaboration with George Mathon and the remarkable result was an MR ratio of over 1000% [3]. A calculation for the same system by a different method was made at the same time independently by Prof William Butler's group at Oak Ridge National Laboratory with a similar result. Both of these calculations were published in 2001 and the huge predicted MR ratio immediately presented a challenge to experimentalists. Umerski and Mathon stressed the importance of a rather perfect Fe/MgO interface which was difficult to achieve in practice. The race to observe the effect, with its obvious commercial application, ended in a dead heat in 2004 (S.S.P. Parkin et al, Nat. Mater. **3** 862 (2004), S. Yuasa et al, Nat. Mater. **3** 868 (2004)), both of the successful groups citing the theoretical work. This 3-year world-wide effort might not have been sustained without the startling theoretical prediction of such a large MR ratio.

There was still a long path to the market-place for the MgO-TMR read head. Parkin had already taken an important step by preparing Fe/MgO/Fe junctions of sufficient quality by sputter deposition which is suitable for mass production, unlike the molecular beam epitaxy (MBE) method used by Yuasa et al. The latter group subsequently collaborated with Canon-Anelva to use their sputtering system. The MgO-TMR read head began to reach the market in 2007 but its main impact occurred in 2008-9 since when all manufactured HDDs are based on this technology. This is confirmed by S.S.P. Parkin (IBM) 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]

IBM subsequently sold its hard disk business to Hitachi Global Storage Technologies who have recently (2012) been bought by Western Digital. There are now only three major manufacturers of HDDs: Western Digital, Seagate and Toshiba [A]. In 2008 Western Digital reported *"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"* (Western Digital 2008 Annual Report and Form 10-K, [C]). By 2009 they reported *"We have completed the transition to PMR and TMR across all product platforms"* (Western Digital 2009 Annual Report and Form 10-K, [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].

The role of Mathon and Umerski's paper [3] in the emergence of MgO-barrier magnetic tunnel junctions is emphasised in a review by S. Ikeda for IEEE Transactions on Electron Devices [F]. The 20th Tsukuba Prize was awarded to Drs Yuasa and Suzuki for "Giant tunnel magnetoresistance in MgO-based magnetic tunnel junctions and its industrial applications". The significance of the industrial application and impact on society of TMR technology is clearly stated in the prize citation: in addition to tracing a direct path from the theoretical prediction to the industrial application the prize citation states *"The giant TMR effect in MgO MTJs is expected to contribute to our society by significantly reducing the power consumption of electronics devices and improving the performance and security of computers"* [G]. Umerski's theoretical prediction of 2001 has definitely had an impact on the huge global HDD market, which was estimated to be $28 billion in 2012 [A].

5. Sources to corroborate the impact (indicative maximum of 10 references)

[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 at https://www.imperial.ac.uk/ref/webarchive/phf on 22/04/13)

[B] 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, available from Imperial on request).

[C] Western Digital 2008 Annual Report and Form 10-K, page 10, https://materials.proxyvote.com/Approved/958102/20080917/AR_27910/images/Western_Digital-AR2008.pdf (Archived here)

[D] Western Digital 2009 Annual Report and Form 10-K, page 11, https://materials.proxyvote.com/Approved/958102/20090916/AR_46224/HTML2/default.htm. (Archived here)

[E] Toshiba Storage Products 'Internal Notebook Hard Drives' product details webpage, http://storage.toshiba.com/storagesolutions/archived-models/internal-notebook-hard-drives. (Archived at https://www.imperial.ac.uk/ref/webarchive/rhf on 22/04/13)

[F] IEEE Transactions on Electron Devices 54 991 (2007) section 3A, DOI: 10.1109/TED.2007.894617

[G] Citation for the 20th Tsukuba Prize: http://www.suzukiylab.mp.es.osaka-u.ac.jp/Top/tsukuba_english.pdf (Archived here)