Funding Breakthrough Technology

Case summary : Giant Magnetoresistance

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This case summary is part of the 'Funding Breakthrough Technology' project. This project is in the commercialisation stream of activities of the EPSRC funded Cambridge Integrated Knowledge Centre (CIKC) in photonics and macro molecular material. Historical case studies of eight breakthrough technologies of the last 60 years are being investigated with the specific focus of how these technologies were supported and finance in their journey from the lab to market. The other case studies are Light emitting diodes (LEDs), Liquid Crystal Displays (LCD), Inkjet printing, Fibre optic communications, Photovoltaics and Microelectronic mechanical systems (MEMS).

All of the case study documents are works in progress. If you would like to comment on any of the case study summaries please contact Dr. Samantha Sharpe at the Centre for Business Research on email (s.sharpe@cbr.cam.ac.uk) or telephone (+44 (0) 1223 765 333. As these documents are works in progress we would request that the case studies not be cited without the author's permission.

Introduction[1]

The Giant Magnetoresistance (GMR) effect is one of the earliest examples of a new field of microelectronic research and device applications - spintronics. Until the discovery of GMR, electronic devices have used charge-based methods for information processing, but as such devices have miniaturized to the scale of nanometres, researchers are facing the presence of quantum mechanics[2] affecting the operation of electrons (Awschalom, Flatte et al. 2002). Quantum mechanics, limits the current progress of microelectronics to smaller and smaller scales for charge-based devices, but it offers the opportunity to exploit the quantum properties of an electron, such as electron spin.

Devices that rely on an electron's spin for their activities fall into a field of research called spintronics (spin-based electronics) and are also known as magnetoelectronics (Awschalom, Flatte et al. 2002). GMR provided the first wave of scientific advance and then related application development in spintronics. The GMR effect sees very large resistance changes in materials consisting of thin layers of metal in response to relatively small changes in external magnetic fields (Tregar and Wolf 2008).

As far back as 1959, Richard Feynman, in his now famous, *'There is plenty of room at the bottom'* talk at the American Physical Society conference in 1959 predicted "computers with wires no wider than 100 atoms, a microscope that can imagine individual atoms, a machine that can manipulate atoms one by one and circuits that utilize quantised energy level or the interaction of quantized spins" (Wolf and Tregar 2000 p.2748). This speech is largely credited as the beginning of the nanotechnology age, despite the fact that the transistors, at this time, were only one year old (McCray 2009).

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[1] This paper draws extensively from McCray, W. P. (2009). "From Lab to iPod: A story of discovery and commercialisation in the Post-Cold War Era." Technology and Culture **50**: 58-81.

[2] Quantum mechanics refers to a set of principles which describe physical reality at the atomic level of matter (molecules and atoms) and the subatomic (electrons, protons, and even smaller particles).

Progress in all the areas that Feynman mentioned has been impressive, although on the last point using energy from the quantized spin of atoms has probably been the most recent. As evidenced in the following quote, "Until very recently the spin of an electron was ignored by mainstream electronics. Adding the spin degree of freedom to electronics will provide significantly more capability and performance to future electronic products and we have only seen the tip of the iceberg with the recent introduction of very high performance disk drives using GMR read heads. Indeed there are many ways that the spin of the electron can be utilised to add new capabilities and new functionality. These range from near term products like non-volatile, very high density, very high speed, very low power random access memories to longer term very esoteric realm of quantum computing" (Wolf and Tregar 2000, p.2748).

The discovery of Giant Magnetoresistance

The magnetoresistance effect was first noted by William Thomson (Lord Kelvin) in 1857. The change in resistance of an electrical conductor when placed in a magnetic field formed the basis for applications of computer hard drive information storage and sensors that could detect other magnetic fields (Awschalom, Flatte et al. 2002; McCray 2009).

Giant Magnetoresistance was discovered in 1988, by two groups of researchers, one group led by Peter Grunberg of Forschungszentrum in Julich Germany, and the other led by Albert Fert of Universite Paris-Sud in France[3]. The two groups were working independently of each other and made the discovery of a fall in electrical resistance when a magnetic field was applied to thin, multilayered metal structures.

The two groups of researchers also came to the discovery of GMR from different scientific perspectives. Grunberg in Germany was researching the behaviour of semiconducting materials and metals, at the time specifically iron and chromium layered metals (using MBE). Fert, on the

[3] Peter Grunberg, born in 1939 in Plzen, Czech Republic earned his PhD at the Technical University of Darmstadt in 1969. He moved to the Forschungszentrum in Julich in 1972 and remained there until his retirement in 2004. Albert Fert was born in 1938 in Carcassonne, France. He was awarded his PhD in 1970 at the University de Paris-Sud, remaining at the University until 1995, when he left and became the director of a joint-venture between CNRS and Thales. Both Grunberg and Fert received the 2007 Nobel Prize for Physics (Day 2007).

other hand was working on magnetic metals, particularly fabricating multilayer (30 layer plus) of iron and chromium at the nano level. Both researchers noticed unexpectedly large changes in their materials electrical resistance in response to a small magnetic field (6-50% changes). Fert coined the term ‘giant magnetoresistance’ to describe the new phenomenon, whilst Grunberg recognised the potential applications in detecting magnetic field, and applied for a patent (Day 2007). Both research teams wrote up their results and submitted them to the same conference and the *Physical Review Journal* in 1988. When they became aware of each other’s work and the essential similarities of their research, Fert and Grunberg agreed to share credit for the discovery (McCray 2009).

The discovery of GMR was surprising, because although the magnetoresistance effect was well known in physics, scientists had observed very little improvement in the performance of the effect over some 150 years of research. The discovery of GMR led to the creation of a new range of electrical devices and a new research community; *spintronics*, where electron spin (as opposed to electron charge) was the focus of research. GMR was also acknowledged to be one of the first successful applications of nanotechnology (with GMR relying on multiple layers of metals deposited at the nano scale (McCray 2009).

Fert and Grunberg received the Nobel Prize in Physics in 2007 for their discovery. The Nobel Committee described the importance of the discovery, “…the discovery of giant magnetoresistance immediately opened the door to a wealth of new scientific and technological possibilities, including a tremendous influence on the technique of data storage and magnetic sensors. Thousands of scientists all around the world are today working on magnetoelectronic phenomena and their exploitation. The story of the GMR effect is a very good demonstration of how a totally unexpected scientific discovery can give rise to completely new technologies and commercial products,” (RSAS 2007 p.2).

The progress from theoretical discussions about the use of electron spin in microelectronics along the lines of Feynman’s prediction, to actual applications depended on other complementary scientific and technological developments. As this was a new phenomenon, new techniques for measurement and tools for making materials needed to be developed to move the research from beyond abstract (McCray 2009). One such new tool was 'Molecular Beam Epitaxy' or MBE. MBE allows 'researchers to make new materials and nanostructures by, "spray painting…with atoms" (McCray 2007 p.259). Pure sources of material were vaporised in separate ovens, and then the atoms or molecules released and transported as a 'beam' to a substrate, where they were deposited. By varying the source materials and controlling the release of atoms and molecules, scientists could build, one atomic layer at a time, nanostructures with precisely controlled compositions.

MBE and early work by RCA, Bell Labs and IBM

The development of MBE as a technique for the production of molecular materials can be traced back to a number of research teams in the 1950s and 1960s. Herbert Kroemer[4] working in the Central Telecommunications Laboratory of the German Postal Service and then later at the USA RCA labs theorised about the energy potential of heterostructures[5] of mixtures of semiconducting materials (McCray 2007). Such theory was difficult to operationalise without a technique for building such mixtures of semiconducting materials. The ability to test this theory would take a further ten years and work from IBM and Bell Labs.

The majority of the early work on developing MBE was completed in 1968-1973 at IBM's Thomas J. Watson Research Centre in Yorktown Heights, NY and Bell Labs Murray Hill facility, New Jersey. Bell researcher John R. Arthur Jr. applied for a patent on the construction of epitaxial gallium arsenide layers using molecular beams of these elements in 1968. With fellow

[4] Herbert Kroemer received his PhD in 1954 from the University of Gottingen, Germany. He then went to work with the Central Telecommunications Laboratory, German Post Office before moving to the USA and working at RCA and then Varian. For his work on heterostructures of semiconducting materials he was one of four recipients of the 2000 Nobel Prize in Physics, with Russian scientist, Zhores Alferov who was instrumental in the discovery of semiconductor diode lasers and Bell Labs researcher Jack Kilby, who invented the Integrated Circuit (IC) (McCray 2007, Hecht 2004).

[5] A heterostructure is the combination of a number of heterojunctions (the junction between layers of different semiconducting materials) into a device.

scientist Alfred Y. Cho, Arthur developed a fabrication technique and built the necessary equipment to create the first MBE.

At IBM, two researchers Leo Esaki and Ray Tsu developed the concept of 'super lattice', semiconductor mixtures made up of more than two layers, to build materials that had higher energy potential. Esaki and Tsu's super-lattice work was supported by an Army Research Office grant for several years. As in the case with Bell Labs, IBM researchers also had to build their own MBE equipment from scratch, nowadays there are thousands of MBE machines in labs and universities around the world, each machine costing around $1m (US) (McCray 2007). MBE made it possible for researchers to engineer nanoscale materials (McCray 2009). Both Fert[6] and Grunberg used MBE to create the multilayered metal materials they were using when they discovered GMR.

MBE was relatively slow in comparison to other deposition techniques and required much more stringent control on impurities and higher vacuum (McCray 2009). For the research teams that discovered GMR these were advantages; A slow crystal growth rate meant that crystals grew in an ordered manner, but for other researchers (after the GMR discovery) the MBE method was simply too complicated, time consuming and expensive for real applications to emerge from it. It was only when simpler and less expensive fabrication methods were developed that GMR applications emerged (ScienceWatch 1992). IBM was to be the main firm involved in developing these new fabrication techniques, their role in the commercialisation of GMR applications will be discussed below.

Commercialising GMR

The commercial potential of GMR was quickly recognised. On one hand this was a new field of physics, spintronics was, and still is, very much in its early days and largely focused on basic

[6] Fert actually did not have access to a MBE machine in his lab but one of his former students, Alain Friederich had recently taken up a position as research manager at the French electronics company, Thomson. After Fert met up with his former student at a conference in the US, Friederich offered Fert the use of an MBE machine at Thomson for his work (Day 2007).

science discovery. Currently researchers are investigating spintronics in semiconductors and even further ‘blue sky’ research on manipulating the quantum spin states of individual electrons which could speculatively led to step changes in how computers and other electronic devices operate, the so-called quantum computing (Awschalom, Flatte et al. 2002).

On the other hand, GMR gave spintronics more near-future applications as well; including the detection of magnetic fields (such as landmine detectors), the increased magnetic effect in computer disk drives[7], magnetic random access memory (MRAM)[8] and GMR based galvanic isolators[9]. All of these applications have ready funding sources; military funders in the case of magnetic sensors and computing companies for the computer disk drives.

The US Navy had a long running research interest in magnetic detectors and sensors for submarine detection. Other companies began seeking out more commercially oriented applications for the newly discovered GMR and many of these activities are still underway. In fact most of the firms’ currently researching and commercialising GMR applications are reluctant to comment on their research direction because of competitive reasons (Daughton 2004). Two firms that have commercialised GMR applications are IBM and NVE Corporation. One is a major corporate (IBM) and the other a start-up (Non Volatile Electronics (NVE)). The progress of the two firms is outlined in further detail next.

[7] IBM’s ‘spin valve’ read heads introduced in 1997.

[8] MRAM (Magnetic random access memory) is a new form of electronic memory made using nanotechnology and using electron spin to encode data. It has been in development since 1995 with a research programs at Motorola (later spun out into Freescale in 2004) and then later at IBM in 2000. MRAM has been called the ‘holy grail’ or ‘universal memory’ because it has the potential to combine the speed of Static RAM, the density of Dynamic RAM and the non-volatility of flash memory (Businesswire 2004).

[9]GMR based galvanic isolators are a combination of an integrated coil and a GMR sensor on a chip, they can eliminate ground noise in communications between electronic blocks, acting in a similar manner to opto-isolators but at speeds of 10 to 100 times faster than current opto-isolators (Daughton 2004).

IBM and the spin-valve

Although IBM New York played a role in the development of the MBE method, which allowed researchers to fabricate nanoscale metal layered materials, it was another IBM research lab, the Almaden lab in San Jose that was to make the breakthrough application using the GMR effect; the spin valve. Thomas J Watson research Centre in Yorktown Heights, where MBE was developed, had a research focus on semiconductor logic devices. The Almaden lab in San Jose however was focused on magnetic information storage (McCray 2009).

One of the researchers at IBM's Almaden Lab was Stuart Parkin[10]. He was interested in the results that Fert and Grunberg had achieved in discovering the GMR effect and wanted to replicate them, but he did not have access to the enormously expensive and complicated MBE equipment to create the metal layered materials (Day 2007). Instead he used the more widely available sputter-deposition method[11]. This method is widely used in the fabrication of thin film semiconductor materials (integrated circuits) as well as glass, optical and photovoltaic applications. The sputtering method produced more defects that the more precise MBE but as the method was much cheaper and less complicated Parkin and his team could explore the GMR effect on a range of different materials[12]. This work on fabrication and characterisation was essential in better understanding the GMR effect. As GMR was relatively new there were still many unanswered questions about how the effect operated. One question particularly relating to magnetic data storage in hard disks was how GMR related to the transport of data in a magnetic field.

[10] Stuart Parkin received his BA degree in physics and theoretical physics in 1977 received his PhD from the Cavendish Laboratory at the University of Cambridge, UK in 1980. In 1980-1981 he completed an exchange fellowship with the Laboratoire de Physique des Solides, Universite Paris-Sud in Orsay (the same University as Fert). In 1982 he joined the IBM Almaden lab working initially on high-temperature superconductivity, before switching to GMR after Fert and Grunberg made their discovery. After his discovery of the 'spin value' Parkin was awarded an IBM fellowship (highest honour for IBM employee) and now co-directs the IBM/ Stanford University 'spintronics' research lab, SpinAps (ScienceWatch 1992, McCray 2009, IBM 2004).

[11] Sputter deposition is a physical vapor deposition method that deposits a thin film of vaporized material by sputtering (ejecting) material from a source and then depositing onto a substrate such as a silicon wafer.

[12] Parkin and the team at IBM made and characterized over 30,000 different multilayer combinations (McCray 2009).

Traditional magnetic disk drives use AMR (anisotropic magnetoresistance) read heads which are operated by using small changes in magnetic resistance when the direction of an applied magnetic field is changed (parallel to perpendicular) (Day 2007). Using GMR was the obvious next step in read head evolution, but as the GMR was much stronger than its predecessors and could therefore detect much weaker changes in magnetic fields, the read heads needed to be much more sensitive to operate at these lower magnetic fields, and therefore take advantage of the resultant increased memory capacity that increased sensitivity would provide. This is what Stuart Parkin and IBM achieved[13]. IBM created new, highly sensitive magnetic read head called the 'spin valve'[14].

IBM filed a patent for the technology in 1991 and the patent was awarded in October 1992. The GMR based read-heads went into production in 1997, just nine years after the discovery of GMR. IBM rapidly licensed the technology to other firms (Western Digital, NEC, Honeywell) in addition to producing the own read-head drives for IBM computers[15]. It is estimated that currently the GMR effect is used in 5 billion hard drives and has accounted for billions of dollars in annual sales since 1997 (Day 2007).

Non-volatile Electronics Corp. (NVE)

NVE represents another side of GMR commercialisation, whilst IBM is a major corporate, NVE was a start-up and now currently only has 50-60 employees. Non-volatile Electronics was founded by former IBM and Honeywell researcher James M Daugton[16] in 1989. The company

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[13] US Patent no. 5,159,513 "Magnetoresistive Sensor Based on the Spin Valve Effect", assigned to IBM based on invention by Bernard Dieny, Bruce Gurney, Serhat Metin, Stuart Parkin and Virgil Speriosu.

[14] The spin valve was two magnetic layers separated by a non-magnetic layer of ruthenium. When the magnetic moment of the layers is aligned, electrons move between the layers easily and there is low resistance, when the layers are not aligned, the spin-dependent movement of the electrons is impeded and resistance goes up. This is why it is called a valve, as it affects the transport of electrons depending whether the resistance is on or off (McCray 2009).

[15] After steep competition from other hard drive manufacturers and declining profit margins IBM sold 70% of its hard drive division to Hitachi in July 2002 (McCray 2009).

[16] James Daughton received his PhD from Iowa State University. He worked for IBM at both their Yorktown heights and Burlington research facilities on magnetic and semiconductor devices, before moving to Honeywell as Vice President, and managing their solid state R&D programs. He founded Non-volatile Electronics in 1989 (which

was founded one year after the initial GMR discovery with the aim of exploiting the GMR effect to create smaller and more sensitive magnetic sensors for a broad range of applications and also with the more long-term goal of developing magnetic random access memory (MRAM). Magnetic sensors have many applications across a number of industries including landmine sensors, sensors in pacemakers and other medical equipment, anti-lock breaking systems and engine controls in automobiles.

When Daughton left Honeywell to start NVE he licensed magnetoresistance[17] technology from Honeywell relating to MRAM when he made the move. It was fortunate timing given the close proximity of the new discovery of giant magnetoresistance however the struggle to develop and commercialise MRAM would prove difficult for this successful but small technology company.

In the firm's early years development was funded primarily by R&D contracts from the US government. By 1994 NVE had received over $5.5m in US government research contracts through both the SBIR (Small Business Innovative Research[18]), ATP (Advanced Technology Program[19]), Defence Advanced Research Projects Agency (DARPA))[20] and the US Navy as well as

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eventually became NVE Corporation when it merged with Canadian electronics firm Premis Corporation in 2000). Up until the Premis merger Daughton had been President, CEO and Board Chairman of NVE Corporation. He relinquished his job as President the year after the merger remained CEO and Board Chairman until 2001 and CTO from 2001 to 2006 when he retired. Daughton has published over 80 papers and has approximately 40 US patents to his name.

[17] Related to MRAM but not using GMR.

[18] The Small Business Innovation Research (SBIR) programme offers contracts with a US federal government agency for the development of technology. The contract provides 100 per cent of the costs involved in the project and is part of the government procurement process. This contracting activity provides an important source of external finance for US NTBFs with the programme annually awarding approximately 4,000 contracts with total funding in the order of US $2 billion (£2.7 billion) (Connell 2006).

[19] ATP was launched in 1998 under the Clinton administration with an annual budget of approx $430 m (US). The program was administered through the Department of Commerce National Institute of Standards and Technology and was aimed at supporting industrial research in enabling technologies. The ATP was a public-private partnership with the program making competitive awards of funding on a cost-share basis to individual companies and larger awards to joint ventures (Wessner 2001). The program was suspended under the Bush administration in 2005 and disbanded in August 2007.

$2.5m from Norwest venture capital partners (Youngblood 1994). Their first research contract was through the ATP and was $1.7m over three years to develop a one-megabit chip (Carey 1994) and others followed relating to the development of MRAM (from the National Science Foundation (NSF)) and biosensors (also NSF). Although this research did not yield any immediate MRAM products[21], NVE continued to receive government funding throughout the 1990s and 2000s. Whilst the development of MRAM became the focus of the majority of government contracts during this time, NVE leveraged its expertise in GMR materials to develop GMR sensors and isolators which they manufactured and sold to customers[22] as an ongoing revenue source to support firm development and continued exploitation of their R&D program. NVE's products and services included magnetic field sensors[23], gradiometers, arrays, and assemblies; magnetic-based isolators; MRAM research and development; magnetic modelling/simulation; custom design services; back-end IC processing; and custom thin-film sputtering (NVE 2009). In 2000 NVE's product revenues were $300,000 and the firm had approximately 65 employees (Lux 2006).

In November 2000, NVE completed a merger with Premis Corporation, a publicly traded Canadian corporation, which sold off all its assets and ceased operations in September 2000. The new firm was called NVE Corporation. This reverse merger was described as a 'dubious

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[20] Particularly the DARPA GMR consortium program ($5m in 1995) and the later SPINTRONICS program (2000-2006) worth $100m over the six years and in which four companies; Honeywell, Motorola, IBM and NVE participated in. The project was aimed at developing MRAM applications for satellite memory but more widespread industrial applications were also envisaged (McCray 2009). In addition to these two engineering focused programs DARPA also ran a $30m basic research program called SPINS. Started in Jan 2000, the aim of the program was to encourage a spintronics community between scientists (both university and industry based) and government R&D labs. The program funded an annual conference and various workshops as well as grant funding for basic research into spintronics (McCray 2009).

[21] In 2003 Cypress Semiconductors announced a prototype MRAM 128 kb chip in a partnership with NVE (Cypress Semiconductors invested $6m in NVE in 2002 for a 24% equity stake)(Businesswire 2002). In 2005 Cypress announced another batch of MRAM samples 256kb chips but as of yet there is still not product on the market. Freescale (Motorola's MRAM spin out) made available the first commercial MRAM product in 2006.

[22] Customers include St Jude Medical purchasing spintronics components and Agilent Technologies.

[23] The largest market for NVE sensors is in industrial robots and implanted medical devices (such as pacemakers) and weapons sensors (Nanotechwire.com, 2006).

financial instrument' used to take the company public easily (Lux 2006) also gave NVE a US$1 million cash injection. NVE began trading on the NASDAQ in 2003.

Work on MRAM continues at NVE although the firm could now be described as a contract R&D supplier. NVE is the smallest firm operating in the MRAM space; competitors include Motorola, IBM, Micron, Honeywell and Cypress Semiconductors.

All of NVE's revenue comes from either R&D contracts (in excess of US $50m since start-up (Lux 2006)) or the sale of sensors and isolators mentioned above, both of these markets have potential for multi-million dollar growth. For the 2009 financial year, total revenue increased 14% to $23.4 million from $20.5 million in 2008. The increase was due to a 7% increase in product sales and an 81% increase in contract research and development revenue. Net income for fiscal 2009 increased 36% to $9.78 million (NVE 2009). No revenue currently comes from IP licence fees, despite NVE's strong IP position in regards to MRAM[24]. They have in the past licensed out their MRAM IP to Motorola (since 2002), Honeywell (since early 1990s), Agilent (since 2001) and Cypress Semiconductors (since 2002). Although currently Motorola pays no fees on their licenses and Cypress Semiconductors has since ended their agreement.

The future direction and application of MRAM is unknown. The market potential of such technology is well recognised but the path to achieving a commercially viable product is not. MRAM could progress in such a way that NVE's patents become vital to all the large corporates integrating MRAM into their products, in which case NVE could profit massively from their early participation in MRAM. On the other hand, a key breakthrough could emerge from else where[25] and make the NVE IP portfolio less valuable. The NVE case shows that small firms can participate in breakthrough technology, but from a position where the majority of their breakthrough R&D programs are externally funded (either through government or client R&D contracts) and a profitable product revenue stream.

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[24] The firm has over 50 US and 100 International patents the majority relating to MRAM. The patents are also described as expansive (Jutiagroup.com 2009).

[25] An advance by MIT researchers called 'MRAM tunnelling' in 2006 is such an example.

Conclusions

The discovery of giant magnetoresistance was not just a discovery of a new phenomenon but also the beginning of a new field of research, spintronics. The commercialisation of GMR, the first wave of spintronics occurred quickly, in comparison to some other breakthrough technologies. Spintronics is an emerging field, it is the focus many research programs around the world but applications thus far have been restricted to magnetic read heads in computer hard drives, magnetic sensors and isolators. MRAM looks to be the source for the new wave of spintronics applications. Research on MRAM has been underway since the early 1990s and we are years away from viable commercial products which integrate MRAM functionality.

GMR and spintronics have emerged in a later era than the majority of the other case study technologies, a post cold-war era. Other technologies examined in this project including LCD, fibre optics, LEDs and photovoltaics benefited from the massive R&D programs by major corporations in the1960s and 1970s funded by large US government military contracts. It is clear that despite the decline of corporate R&D activity, particularly in the US, and globally the reduction in military R&D spending that both corporate labs and government funding still play a critical role in the establishment of breakthrough technologies.

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