How spintronics went from the lab to the iPod

W. Patrick McCray

The commercial success of products based on giant magnetoresistance is often cited as a reason for supporting basic physics research. The reality is more complex, given the range of bodies, including IBM and the US military, involved in developing new technologies based on this Nobel-prize-winning discovery.

In 1988, Albert Fert and Peter Grünberg independently discovered that the electrical resistance of structures made of alternating layers of magnetic and non-magnetic metals can change by an unexpectedly large amount in the presence of an applied magnetic field. Within a decade, this seemingly esoteric observation had revolutionized the electronics industry by allowing hard drives to store ever-increasing amounts of data. And when Fert and Grünberg shared the Nobel Prize in Physics in 2007 for the discovery of giant magnetoresistance (GMR), the Royal Swedish Academy of Sciences announced that "GMR technology may also be regarded as one of the first major applications of the nanotechnology that is now so popular in a very diverse range of fields." (ref. 1).

However, the discovery of GMR is interesting for reasons beyond its 'nano-ness'. The story of GMR raises a number of questions about the nature of contemporary knowledge production[2]. Does the venerable linear model[3,4] — with basic research leading to applications — apply to nanoscience and technology? Or, as some have argued, is nanotechnology an example of 'post-academic' science, funded by governments and corporations to solve specific problems rather than advancing knowledge for the sake of knowledge?[5,6]

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Peter Grünberg (left) and Albert Fert discuss their Nobel-Prize-winning discovery of giant magnetoresistance with the press in 2007.

Discovery and commercialization

Magnetoresistance, a change in the electrical resistance of a conductor caused by an applied magnetic field, was first observed by the physicist William Thomson (Lord Kelvin) in 1857, wheras the physics underlying electron spin — which is the ultimate source of magnetism in most materials — dates back to the work of Paul Dirac, Wolfgang Pauli and others in the golden era of quantum mechanics. The effect was quite small, typically a few percent, but it was still large enough to be exploited in read heads for magnetic disks and sensors for detecting magnetic fields. However, that all changed with the discovery of GMR in 1988.

Grünberg and his team at the Jülich Research Center in Germany made their discovery — a change of about 10% in electrical resistance in the presence of a magnetic field — in a structure containing a 1-nm thick layer of chromium (which is not magnetic) sandwiched between two thicker layers of iron (which is magnetic)[7]. Meanwhile Fert and co-workers at the University of Paris-Sud and Thomson CSF observed an even larger effect (a change of about 50%) in more complex structures containing about 60 alternating layers of chromium and iron[8]. Both teams used molecular beam epitaxy (MBE), a central if often-overlooked research tool in the history of nanotechnology[9], to make their multilayer samples.

Although the French team coined the term 'giant magnetoresistance', it was Grünberg who recognized that this effect could be used to detect faint magnetic fields, so he filed for a patent as his group wrote up its results. However, the two group leaders agreed to share the credit for the discovery (see Box 1). GMR also represented the first example of a new kind of technology called 'spintronics', so-called because it exploits the spin of the electron, as well as its electric charge, to store and process information.

Engineers first used GMR in niche applications, such as sensors to detect very weak magnetic fields, but other companies were eager to apply it in bigger and more lucrative markets. In particular, Stuart Parkin and colleagues at IBM's Almaden laboratory near San Jose exploited GMR to make read heads that allowed magnetic disc drives to become smaller while holding eight times more data than before, an achievement that was reported on the front page of *The Wall Street Journal* in November 1997 (ref. 10). A central part of Parkin's work was to show that GMR devices could be produced by 'sputtering', which was much faster than MBE, and some observers wondered why he did not share the Nobel Prize with Fert and Grünberg[11–13].

These developments helped set the stage for the subsequent explosion in computer memory that, in turn, helped make it possible to store gigabytes of music, photos, videos and so forth on iPods and other portable gadgets. These innovations prompted a member of the Nobel physics committee to comment that "you would not have an iPod without this [GMR] effect." (ref. 14). IBM's GMR-based innovation brought the broader field of spintronics to a market worth billions of dollars per year (although the first iPods — introduced by Apple in 2001 — actually used GMR-based hard drives made by Toshiba.)

Seizing an opportunity

As actual products exploiting the GMR effect appeared on the market and more scientists began to do research in spintronics[15], science managers from military laboratories and funding agencies began to take notice. The Defense Advanced Research Projects Agency (DARPA) was one of GMR's first champions. Founded in the wake of Sputnik, DARPA had a reputation among scientists as lean, agile and able to direct considerable resources to high-risk, high-payoff technologies. During the 1990s, DARPA invested millions of dollars into university-based spintronics research, funding fundamental and applied projects.

Stuart A. Wolf, a physicist at the Naval Research Laboratory in Washington, DC, was the main champion for spintronics and other GMR-based research programmes at DARPA. One technology he was especially interested in was magnetic random-access memory (MRAM). Like GMR-enabled disk drives, MRAM is based on metallic materials, not semiconductors. And because they store data using magnetic storage elements instead of electrical charge, MRAM devices have the potential advantage of retaining information even after a computer is switched off, unlike regular random-access memory. MRAM devices would also be less vulnerable to radiation damage, which appealed to DARPA for space-based applications.

Wolf sold his programme by lugging in a memory component pulled from a satellite system into the DARPA offices in 1995. "I plopped it on the director's desk," Wolf told me in an interview in 2006. "It weighed forty pounds and cost a quarter of a million dollars. I said, I'm going to replace this with a fifty-cent chip."

Over the next decade, DARPA provided tens of millions of dollars to support a modestly sized international research community made up of university-based researchers, scientists from government laboratories and representatives from the electronics industry, most of whom attended an annual DARPA meeting on spintronics. This community included physicists (both theoretical and experimental), materials scientists, chemists and engineers.

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The interest and support that DARPA and companies like IBM gave to researchers interested in spintronics coincided with a larger movement underway in the United States and other countries to generate political support for a broader research-and-development effort in nanotechnology. Advocates of national policies to support nanotechnology used the economic importance of nanoelectronics, and the commercial success of spintronics in particular, to support this broader agenda (see, for example, ref. 16).

In the US, for instance, nanoelectronics figured prominently in the discussions between scientists and funding agencies that led to the establishment of the National Nanotechnology Initiative (NNI). In 1997 and 1998, the National Science Foundation (NSF) organized studies to evaluate possible opportunities in nanotechnology, and a standard case for supporting nanotechnology started to emerge: some time in the next ten-to-fifteen years the semiconductor industry will encounter serious technical problems in its effort to improve the performance of devices by reducing their size. The path to a replacement technology was unknown, and without investment in new technologies for the computer and semiconductor industries, economic competitiveness could suffer.

Scientists, engineers and policy makers in the United States all interpreted the commercialization of GMR as a sign that investment in nanotechnology was both sensible and prescient. Consequently, nanoelectronics — along with novel materials and new technologies for health, energy and biological applications — became a "priority research area" in the initial formulation of the NNI (see, for example, ref. 17).

Research initiatives in Europe and Asia took similar paths. The resulting flood of money for research transformed nanotechnology into one of the most robustly funded, aggressively pursued and widely promoted research areas in modern science and engineering.

Reflections

Debates about the nature of nanoscience, with its emphasis on applications rather than discovery, have suggested that it is one of the first fully realized examples of post-academic science[6]. However, others cite GMR-based hard drives as an example of the commercial benefits that follow from support for basic research and of the importance of funding the best science and scientists rather than research that is expected to deliver economic returns[4]. In the most basic form of this so-called 'linear model' of research (presented most famously in a report called *Science, The Endless Frontier*[3] that was prepared for the US president by Vannevar Bush in 1945) there is a direct path from scientific discovery to application.

Historians, of course, recognize that 'pure science' is very much a social construction and one that often, after closer scrutiny, may not be quite so unfettered as it seems at first. However, as recent sociological and historical studies of the nano-enterprise continue to

Box 1 | Sharing the credit for GMR

Grünberg and co-workers submitted their paper to *Physical Review B* on 31 May 1988, followed by a revised version on 12 December, and it was published in the 1 March 1989 issue. Fert and co-workers submitted their results to *Physical Review Letters* several months later — on 24 August — but their paper was published in the 21 November 1988 issue, which was several months before the Grünberg paper appeared in print. Both teams also presented their results at the 12th International Colloquium on Magnetic Films and Surfaces (ICMFS-1988) in Le Creusot, France, in August 1988. In a press release[21] issued by the French Centre National de la Recherche Scientifique (CNRS) in 2003, Fert explained that "Grünberg and I agreed from the beginning to consider that our experiments had taken place almost simultaneously and that we thus shared the discovery of GMR."

IBM; RESEARCH CENTRE JÜLICH

The read–write head in this IBM TS1130 tape drive (left), which can store one terabyte of data, is based on GMR. Inside a GMR-based hard-disk drive (right).

show, new ways of producing knowledge are emerging that may represent breaks from traditional modes of discovery-driven academic research[18,19]. It is often argued, for example, that the rise of nanoscience and technology will lead to more multidisciplinary research, even to the point of involving researchers from the social sciences and the humanities[20].

The history of spintronics reflects this realignment. During the Cold War, for example, the military nurtured research in materials science and solid-state physics, areas that would later be central to the development of spintronics. After the collapse of the Soviet Union, military agencies continued to foster new scientific fields, albeit sometimes through new alliances with industry or hybrid government–university–industry programmes. Government-based grants officers at DARPA and other agencies acted as ‘institutional entrepreneurs’ and built programmes that melded military funding with corporate investment and goals.

To a first approximation, the case of spintronics appears to lend credence to the traditional linear model that posits science as a prime mover for technological applications. The real story, of course, was much more complex, revealing the interplay between basic science, instrumentation, federal policy, industrial research and perceived commercial goals. One cannot help but conclude that the ‘basic’ linear model, even if applicable, is anything but simple when examined closely enough.

Fert and Grünberg originally discovered GMR in the tradition of small-scale basic physics research. Businesses, large and small, swiftly patented and integrated it into products worth billions of dollars in annual sales and a new scientific community emerged around it. And by studying the history of GMR, we can discern connections between contemporary scientific research and engineering applications, and also gain some insight into the boundaries and shifting relations between science and technology. ❒

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References

1. <http://nobelprize.org/nobel_prizes/physics/laureates/2007/info.html>.
2. Jones, R. *Nature Nanotech.* **3**, 60–62 (2008).
3. Bush, V. *Science, The Endless Frontier* (1945); available at <http://www.nsf.gov/od/lpa/nsf50/vbush1945.htm>.
4. Moriarty, P. *Nature Nanotech.* **3**, 60–62 (2008).
5. Ziman, J. *Real Science* (Cambridge Univ Press, Cambridge, 2000).
6. Vogt, T., Baird, D. & Robinson, C. *Nature Nanotech.* **2**, 329–333 (2007).
7. Binasch, G., Grunberg, P., Saurenbach, F. & Zinn, W. *Phys. Rev. B* **39**, 4828–4830 (1989).
8. Baibach, M. N. *et al. Phys. Rev. Lett.* **61**, 2472–2475 (1988).
9. McCray, W. P. *Nature Nanotech.* **2**, 2–4 (2007).
10. Narisetti, R. *The Wall Street Journal* 1 (10 November 1997).
11. Vedantam, S. *The Washington Post* A3 (10 October 2007).
12. Cho, A. *Science* **318**, 179 (2007).
13. Brumfiel, G. *Nature* **449**, 643 (2007).
14. Overbye, D. *The New York Times* A13 (10 October 2007).
15. Wolf, S. A. *et al. Science* **294**, 1488–1495 (2001).
16. *Nanotechnology Research Directions: IWGN Workshop Report* (eds Roco, M. C., Williams, S. & Alivisatos, P.) Ch. 6 (World Technology Evaluation Center, Baltimore, Maryland, 1999); available at: <http://www.wtec.org/loyola/nano/IWGN.Research.Directions/>.
17. Subcommittee on Nanoscale Science, Engineering and Technology *National Nanotechnology Initiative: the Initiative and its Implementation Plan* 28–30 (National Science and Technology Council, Washington, DC, 2000); available at <http://www.nano.gov/html/res/nni2.pdf>.
18. Johnson, A. *Sci. Stud.* **19**, 35–51 (2006).
19. Mody, C. C. M. *Technol. Culture* **47**, 56–80 (2006).
20. Mody, C. C. M *Phys. Today* **61**, 38–44 (2008).
21. <http://www.cnrs.fr/cw/en/pres/compress/Albert_Fert.htm>.

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