

# The 2007 Nobel Prize in Physics

## Albert Fert and Peter Grünberg



**Albert Fert** and **Peter Grünberg** are well-known for having opened a new route in science and technology by their **discovery of the Giant MagnetoResistance (GMR)** in 1988. Soon after this discovery, the exploitation of the GMR had a considerable impact in **data storage technologies**. The GMR-based read heads developed by several major companies have led to a considerable increase of the density of information stored on computer's hard discs drives (HDD) of today and are the most important of the multiple applications of the GMR. The discovery of GMR kicked off the development of a new field in science and technology called **spintronics** in considerable expansion today. Not only Albert Fert and Peter Grünberg are regarded as the "fathers" of spintronics but they have also made outstanding contributions to its development until today. Their recent work on magnetic tunnel junctions, current-induced magnetization switching, microwave generation by spin transfer, or applications of carbon nanotubes in spintronics will certainly have an important impact on the technology of the near future.

### The roots of spintronics and the discovery of GMR

GMR and spintronics take their roots in the pioneering work of Albert Fert around 1970 on the influence of the spin on the mobility of electrons in ferromagnetic materials (Fert and Campbell, Phys. Rev. Lett. 21, 1190, 1968; J. Phys. F 6, 849, 1976, for a review). After having experimentally demonstrated that, in a ferromagnetic metal, the electrons of opposite spin directions (spin up and spin down along the magnetization axis) carry different currents (as originally suggested by Mott), Fert worked out the well known "two current model" of the electrical conduction in ferromagnetic metals. He also showed that very large spin asymmetries of the conduction can be obtained by doping the ferromagnetic metal with impurities selected to scatter very differently the spin up and spin down electrons (iron or cobalt impurities in nickel, for example, scatter the spin down electrons 20 times more strongly than the spin up electrons). Moreover, some experiments of Fert on ternary alloys were already introducing the idea that he will exploit later to produce the GMR effects. He showed that the resistivity of a ternary alloy, for example  $N_{1-x}(A_x, B_y)$ , is strongly enhanced if the scattering by the impurities A and B have inverse spin asymmetries. Replacing the impurities A and B by magnetic layers A and B, one equally expects a large enhancement of the resistivity when their magnetizations are in opposite directions, which is the basic concept of the GMR. However, this concept can work only if the thickness of the layers is in the nanometer range. The fabrication of multilayers with thicknesses in this range became technologically possible in the mid-eighties and, in particular, the growth of magnetic multilayers by Molecular Beam Epitaxy (MBE) was developed in the groups of Albert Fert and Peter Grünberg.

Another important step, two years before the discovery of the GMR, came from the demonstration by Brillouin scattering experiments in the group of Peter Grünberg that the magnetizations of two layers of iron separated by an ultra-thin layer of chromium were spontaneously oriented in opposite directions by an antiferromagnetic "exchange interaction" (Grünberg et al, Phys. Rev. Lett. 57,

2442, 1986). This was opening the way to the design of Fe/Cr multilayered structures in which the magnetizations of the adjacent magnetic layers can be switched from their spontaneous opposite orientations to parallel by applying a magnetic field.

The GMR was discovered almost simultaneously in 1988 on Fe/Cr multilayers by Albert Fert (Baibich et al, Phys. Rev. Lett. 61, 2412, 1988) and on Fe/Cr/Fe trilayers by Peter Grünberg (Binash et al, Phys. Rev. B 39, 4828, 1989). Fert's paper presented both the experimental results and their interpretation on the basis of his previous work on the spin dependent conduction in ferromagnetic materials. As the change of resistance between the parallel and antiparallel magnetic configurations of the Fe/Cr multilayer was as large as 80%, Fert also coined the expression "Giant Magnetoresistance" to describe such huge effects. The paper of Grünberg reporting the results on the Fe/Cr/Fe trilayers in 1989 was preceded by an outstanding patent filed in 1988, introducing the concept of Spin Valve (SV), and anticipating most of the present applications of the GMR (US patent 4949039, 1990). The discovery of the GMR created a considerable stir, first because it immediately turned out that it was opening a new field of research (called today spintronics), and secondly because the potential of applications became rapidly very clear as detailed in the final section. In 2003, with 2455 citations (more than 3500 in 2007), Fert's article of 1988 was ranked 6 in the "Top Ten" of the most cited Physical Review Letters since the creation of the review in 1953.

### **From GMR to spintronics**

The goal of this section is not to review the entire field of spintronics but rather highlight some major steps and the contributions of Fert and Grünberg. The discovery of GMR triggered immediately an extensive research on magnetic multilayers and GMR attracting researchers worldwide in the new field of spintronics. On the experimental side, it was rapidly shown that GMR effects could be obtained not only with samples grown by molecular beam epitaxy but also with the faster and cheaper method of sputtering. In 1991, the GMR of the Co/Cu system was simultaneously discovered on samples grown by sputtering in Fert's group (Mosca et al, J. Magn. Mater. 94, L1, 1991) and S. Parkin's group (PRL 66, 2152, 1991). Co/Cu became the archetypal structure for GMR and inspired the advanced materials used today in the sensors of HDD's read heads. On the theory side, the first semi-classical model of the GMR was published in 1989 Phys. Rev. Lett. by Camley and Barnas in the laboratory of Peter Grünberg. Together with Levy and Zhang, Fert equally worked out the first quantum mechanical theory of the GMR in 1990 (Phys. Rev. Lett. 65, 1643, 1990). Initially studied in the CIP configuration (Current In the Plane), experiments soon followed exploring the Current Perpendicular to the Plane (CPP) geometry. CPP-GMR is not only interesting for applications but also because it has revealed spin accumulations effects which were analyzed in a seminal paper (T. Valet and A. Fert, Phys. Rev. B 48, 7099, 1993). These effects play a major role in the most recent developments of spintronics such as spintronics with semiconductors (A. Fert et al, IEEE Transactions on Electron Devices, 54(5), 921, 2007), or molecular spintronics (L. Hueso, A. Fert et al, Nature 445, 410, 2007) which will not be detailed here.

The second important step in the history of spintronics is related to the introduction of the Magnetic Tunnel Junctions (MTJ). A MTJ is another type of SV in which the two magnetic layers are separated by an ultra-thin insulating layer (around 1 nm) instead of a metallic layer. Its electrical resistance is different for the parallel and antiparallel magnetic configurations of the electrodes, what is called the Tunneling MagnetoResistance effect (TMR). Some early observations of TMR effects, small and at low temperature, were already reported in 1975, but they had been hardly reproducible during 20 years. It is only in 1995 that large ( $\approx 20\%$  for the ratio of the resistance change to the resistance of the parallel state) and reproducible effects were obtained by Moodera (MIT) and Miyazaki (Sendai) groups on MTJ with a tunnel barrier of amorphous alumina. Among others, Fert and Grünberg have actively contributed to the research on TMR. Grünberg studied the potential of semiconducting tunnel barriers (Europhys. Lett. 66, 736, 2004). On the fundamental side, a better understanding of the physics of MTJ came from the classical paper in

which Fert demonstrated the active role of the electronic properties of the barrier on the TMR (Science 286, 507, 1999). Also new directions were explored to obtain much higher TMR than with the alumina-based MTJ. Very high TMR ratios (1800% at low temperature) were obtained in the group of Fert with MTJ based on the magnetic oxide  $\text{La}_{2/3}\text{Sr}_{1/3}\text{MnO}_3$  (Appl. Phys. Lett. 82, 233, 2003). The exploration of these new directions was of high fundamental interest, but, for applications, the  $\text{La}_{2/3}\text{Sr}_{1/3}\text{MnO}_3$ -based MTJ had a too low TMR at room temperature. The real breakthrough for the TMR came from the development of MgO-based single crystal MTJ. The first publication reporting TMR effects on MgO-based MTJ was published by the group of Fert in collaboration with a Spanish group and showed that, with similar electrodes, the TMR could be slightly larger with MgO than with alumina (Appl. Phys. Lett. 79, 1655, 2001). This triggered the research on similar junctions in several groups, and, in 2004, the major breakthrough was the demonstration by an IBM group and by a Japanese group that the TMR ratio of MgO-based MTJ could reach 200% at room temperature. It was the kick off of an intense research on MgO-based MTJ which has led to TMR ratios as high as 500% together with relatively small resistances needed for many applications. These remarkable MTJ will have multiple applications (see last section). From a technological point of view, the interest of the MTJ with respect to the metallic spin valves comes from the vertical direction of the current and from the resulting possibility of a reduction of the lateral size to a submicronic scale by lithographic techniques.

The third important step is related to the spin transfer phenomenon. In a spin transfer phenomenon, one manipulates the magnetic moment of a ferromagnetic body without applying any magnetic field but only by a transfer of spin angular momentum from a spin-polarized electrical current. The result of this transfer of spin can be described as a torque acting on the magnetization (Spin Transfer Torque or STT). This torque can be used either to rotate and switch the magnetization, or to displace a domain wall separating two magnetic domains, or to generate oscillations in the microwave frequency range. Originally predicted by John Slonczewski from IBM, a group in Cornell in 2000 and the group of Fert in 2001 (Grollier et al., Appl. Phys. Lett. 78, 3663, 2001) were the first to observe the reversal of a magnetization by spin transfer-induced precessions. These results triggered an intense activity of research and, today, the precessional magnetic switching by spin transfer torque is mastered in several types of magnetic devices, metallic multilayers, spin valves or tunnel junctions. Grünberg has explored spin transfer effects in epitaxial magnetic nanostructures (Acta Materiala 55, 1182 2007).

As discussed in the next section, magnetic switching by STT, that is by an electronically induced precession without any need of magnetic field, will replace the switching by an applied field used in today's MRAM.

### **Present and future technological impact of GMR and spintronics**

Most applications of the GMR are based on trilayer structures of spin valve (SV) type, in which the switching between magnetic states (antiparallel and parallel magnetizations) is obtained at very low field by the rotation of the magnetization of a "free" magnetic layer. The concept was initially described in Grünberg's 1988 patent and, with some additional aspects, in an IBM patent of 1993 (US patent 52065590r). GMR read heads for hard discs drives (HDD) were introduced onto the market by IBM in 1997 only 8 years after the discovery of GMR. In terms of economical impact, about 5 billion GMR read-heads have been produced in total as for 2007 with a worldwide annual revenue larger than 31 billion \$. The sensitivity of the GMR to detect small fields has led to a huge increase of the density of magnetic information stored in a disc. The compound growth rate of storage areal density has increased up to 100% per year (doubling every in the period 1997-2002), and the areal density is now around 200 Gbit/in<sup>2</sup>, which corresponds to an increase by more two orders of magnitude with respect to the pre-GMR HDD. This opened the way to both smaller HDD forms factors (down to 0.85" disc diameter !) for mobile appliances such as ultra laptops or portable multimedia players, and to record HDD capacities (up to 1 Tbyte !). More generally, the availability of cheap HDD with high capacity (> 100 GB) has triggered today's pervasiveness of hard disk drives in consumer's electronics such as portable MP3 players, hard-disk-video recorders, automotive HDDs, and digital cameras to list a few. HDD are also now replacing tape in at least the

first tiers of data archival strategies, for which they provide faster “random” access and higher data rates. A transition to TMR heads began in 2004 (Seagate) with volumes now at about 300 million vs GMR heads of 500 million (2007 projected). The TMR provides a higher sensitivity than the conventional GMR but sensors have a large resistance and the increase of this resistance at smaller size is a disadvantage for a further downscaling of the heads. Going forward to reach an areal density above the Tbit/in<sup>2</sup>, a transition back to all metallic GMR multilayer devices is likely due to favourable sheet resistance scaling with smaller size. These heads will exploit the CPP-GMR effect.

Actually GMR/TMR has many other applications than the HDD. A very important application relates to non volatile memories called MRAM (Magnetic Random Access Memory). The MRAMs, with their combination of the non volatility (they retain data after the power is turned off), a fast random access similar to that of the semiconductor-based RAM (5 ns read/write has been demonstrated for MRAM) and an infinite endurance (against 10<sup>5</sup> cycles for a Flash), are likely candidates for becoming the “universal memory”, one of the “Holy Grails” of nanoelectronics. The first generation of MRAM was developed with alumina-based MTJ. The first product, a 4 Mbit standalone memory, was commercialized by Freescale in 2006 and soon voted “Product of the Year” by Electronics Products Magazine. Moreover Freescale introduced in June 2007 a new version able to work in the enhanced -40°C to 105°C temperature range, i.e. qualifying for military and space applications where the MRAM will also benefit from the intrinsic radiation hardness of magnetic storage. However, a major limitation to ultrahigh density in this first generation of MRAM comes from the relatively low TMR of the alumina-based MTJ and from the resulting requirement of one transistor per MTJ. Another limitation comes from the writing by magnetic fields generated by current lines. With this type of writing, the needed very large current densities and the unavoidable distribution of the writing parameters also limits the downscaling of the device. These limitations will be turned away in the next generation of MRAM using the very high TMR of MgO-based MTJ and a new concept of writing based on the STT mechanism (both described above). Several companies have already presented very promising demonstrators of this new type of MRAM which has been called “STT-RAM”.

GMR/TMR has also a significant impact on magnetic field sensing devices, used in a number of very competitive markets. GMR-based magnetic field sensors for the automotive industry have been on the market since 1993. GMR/TMR sensors are also used now for biomedical applications, for example in the analysis of biomolecules (ultra-sensitive detection of molecules once they have been labeled with magnetic particles, see, for example, D.K. Wood et al., *Sensors and Actuators A* 120, 1, 2005), and show promises for biomedical imaging such as magnetocardiography and magnetoencephalography (Chaves et al. *Appl. Phys. Lett.* 91, 102504, 2007).

Last but not least, spin transfer devices will certainly have also important applications in the technology of telecommunications for the generation of oscillations in the microwave frequency range. The so-called Spin Transfer Oscillators (STO) have interesting advantages, in particular the easy and fast control (agility) of the frequency by tuning a DC current. Up to recently, they had the disadvantage of needing an applied field but the group of Fert has now conceived and operated a special type of STO working at zero field (*Nature Physics*, doi:10.1038, 2007). As, at the moment, the microwave power of the STOs is still too small for applications, synchronizing an array of STOs to increase this power is now the crucial challenge before developing practical devices. Fert’s team is one of the three groups in the world having already obtained successful theoretical (*Phys. Rev. B* 73, 060409, 2006) and experimental results (unpublished) on this problem of synchronization of STOs.

In summary, the pioneering research of Albert Fert and Peter Grünberg on spin dependent transport and magnetic multilayers led them to the discovery of the GMR in 1988. Following this discovery, the new field of spintronics has undergone outstanding progress in twenty years, under the

convergence of a chain of scientific breakthroughs and technology advances. Traditional hard disk recording has gained orders of magnitude in storage capacity, thus entering the consumer electronics market. New applications have or will appear, yet only for niche markets, but expected to progress and impact rapidly. On a more long term, the use of spin injection and spin currents may lead to spin logic devices, a promising route for nanoelectronics.

