2. The GMR effect

The magnetoresistance is the change of electrical resistance of a conductor when subjected to an external magnetic field. In bulk ferromagnetic conductors, the leading contribution to the magnetoresistance is due to the anisotropic magnetoresistance (AMR) discovered in 1857 by W. Thomson (Lord Kelvin) (Proc. R. Soc. London **A8**, 546 (1857)). This originates from the spin-orbit interaction, which leads to a different electrical resistivity for a current direction parallel or perpendicular to the magnetization direction. As a magnetic field is applied, misoriented magnetic domains tend to align their magnetization along the field direction, giving rise to a resistance change of the order of a few percent. Magnetoresistive effects are of great interest for industrial applications, and the AMR has been applied for making magnetic sensors and read-out heads for magnetic disks. Until 1988, the 130 years old AMR remained the most important contribution to the magnetoresistance of ferromagnets. The situation at that time is best summarized by the following pessimistic quotation, taken from an authorative treatise on magnetic sensor technology written in 1988: *"More than two decades of research and development have established the principle of magnetoresistive sensors. (...). It is doubtful, however, whether magnetoresistive layers themselves will be improved considerably in the coming years."* (From *"Sensors, A Comprehensive Survey, Vol. 5: Magnetic Sensors"*, VCH (1989)).

It was therefore a great sensation when, in 1988, Albert Fert and Peter Grünberg independently discovered that a much greater magnetoresistive effect (hence dubbed "giant magnetoresistance" or GMR) can be obtained in magnetic multilayers. These systems essentially consist of an alternate stack of ferromagnetic (e.g., Fe, Co, Ni, and their alloys) and non-ferromagnetic (e.g., Cr, Cu, Ru, etc.) metallic layers. Each individual layer in these multilayers is only a few atomic layers thick. Fert and Grünberg discovered that when the relative orientation of the magnetization of the successive ferromagnetic layers is changed from antiparallel to parallel by applying an external magnetic field, the electrical resistance of the multilayers is reduced by as much as 50% as shown schematically in Figure 1.

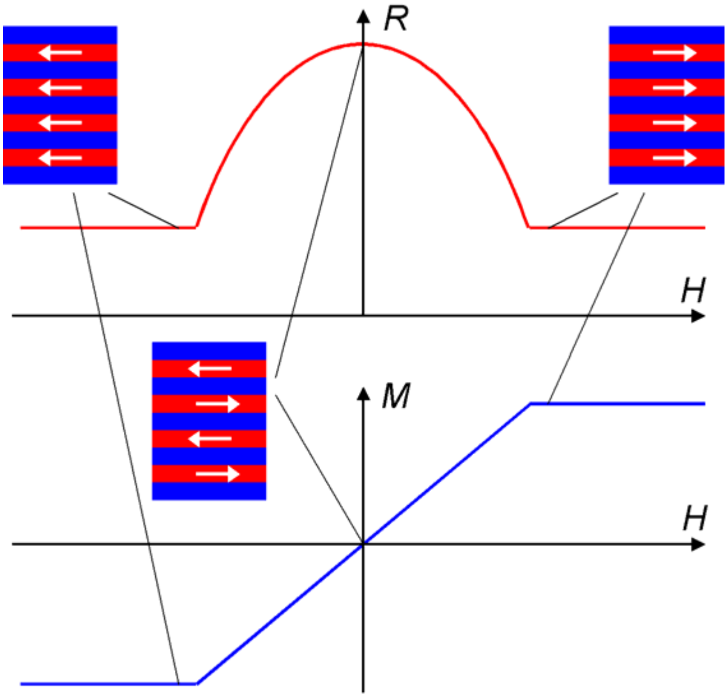

Fig. 1. Schematic description of the giant magnetoresistance effect. Blue curve: magnetization of the multilayer versus applied magnetic field. Red curve: electrical resistance of the multilayer. The insets indicate the magnetic configuration of the multilayer in zero field and at positive and negative saturation fields.

The phenomenon of GMR results from a combination of two physically distinct new effects. The first one is the very fact that the electrical resistance of the multilayer varies considerably as the configuration is switched from parallel (P) to antiparallel (AP). This effect arises as a consequence of the **spin-dependent scattering of electrons in ferromagnetic layers**, which in the 70's has been intensively studied by Albert Fert in bulk ferromagnets and ferromagnetic alloys. This effect is shown schematically in Figure 2.

The second important new effect is the **antiferromagnetic interlayer exchange coupling** (discovered by Peter Grünberg in 1986), which leads to an antiparallel orientation of the magnetizations of successive ferromagnetic layers in absence of an external field; this effect allows one (by applying an external magnetic field) to effectively switch from the AP configuration to the P configuration, and thus to reveal the GMR phenomenon.

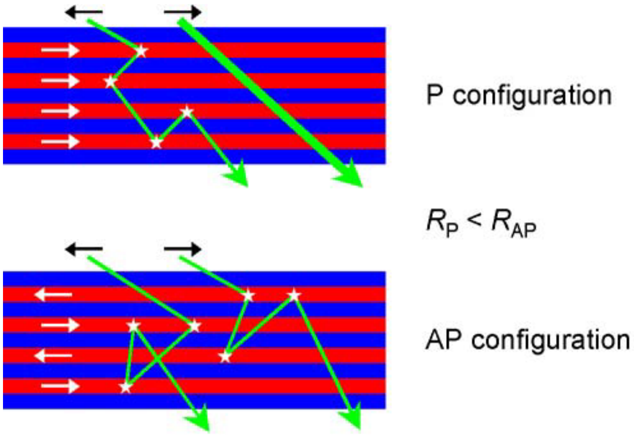

Fig. 2. Schematic description of the spin-dependent scattering mechanism for the giant magnetoresistance. Electrons are strongly scattered in magnetic layers with magnetizations (white arrows) antiparallel to their spin (black arrows), and weakly scattered in magnetic layers with magnetizations parallel to their spin. This results in a short-circuit effect in the P configuration, where half of the electrons are seldom scattered, yielding a lower net resistance.

The GMR has originally been discovered in the “current-in-plane” (CIP) configuration, which is the easiest to study experimentally. Later, it was shown that an even larger effect takes place in the “current-perpendicular-to-plane” (CPP) configuration.

3. Scientific contributions of Albert Fert

Long before the discovery of giant magnetoresistance, the study of spin-polarized electronic transport in magnetic materials has been a major research topic of Albert Fert. In the 70’s, together with I.A. Campbell, he performed pioneering studies on the resistivity of ferromagnetic alloys (Phys. Rev. Lett. **21**, 1190 (1968)[*]; J. de Physique **C1-32**, 1 (1971); J. Phys. F **6**, 849 (1976)). In these studies, he developed the concepts of spin-dependent currents (originally suggested by Mott), of spin-dependent resistivity and spin-dependent scattering, which later became the key conceptual ingredients of the GMR effect.

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[*] The references marked in blue are linked via internet to the corresponding paper. Depending on the online subscription of your institution, you may either have access to the full text or only to the abstract.

In the mid-80's, Albert Fert started working on magnetic multilayers, and his experience with spin-polarized transport in magnetic alloys prompted him to focus on their electronic transport properties. He soon realized that the effect of spin-dependent scattering would give rise to magnetoresistance effects of unprecedented magnitude, provided one finds a mean to switch the relative orientation of the magnetization of successive magnetic layers in a multilayer from parallel to antiparallel. That this idea was indeed correct was further suggested by observations of J.-P. Renard's group who reported small but striking anomalies in the resistivity of uncoupled Co/Au magnetic multilayers at the coercive field (Physica Scripta T**19**, 405 (1987); Phys. Rev. B **37**, 668 (1988)). The missing link for obtaining a strong magnetoresistance was provided by exploiting Grünberg's discovery of antiferromagnetic exchange coupling in magnetic multilayers (Phys. Rev. Lett. **57**, 2442 (1986)). **In 1988, Albert Fert and his coworkers discovered a giant magnetoresistance effect (about 50% change in resistance) in Fe/Cr multilayers** (see Figure 3) (Phys. Rev. Lett. **61**, 2472 (1988)). Fert's article reporting the discovery of the giant magnetoresistance has been cited about 2500 times in the literature. The same effect was also discovered independently and simultaneously by Peter Grünberg (Phys. Rev. B **39**, 4828 (1989)) (see next Section). Later on, by using more complex multilayers comprising materials of suitable spin-asymmetric scattering, Fert and his coworkers were able to produce an *inverse* GMR effect (Phys. Rev. Lett. **72**, 408 (1994)).

Besides the experimental discovery of the GMR, Albert Fert was also very active in developing theoretical concepts to explain the GMR effect. Together with P.M. Levy and S.F. Zhang, he worked out the first quantum mechanical theory of the GMR (Phys. Rev. Lett. **65**, 1643 (1990)). He also proposed a theory of the CPP-GMR (Phys. Rev. B **48**, 7099 (1993)) (now a classic known as the Valet-Fert model), in which he pointed out the importance of spin-flip processes and of the concept of spin accumulation. Those ideas were confirmed experimentally by investigating the magnetoresistance of multilayered nanowires in collaboration with L. Piraux (Appl. Phys. Lett. **65**, 2484 (1994)).

Albert Fert and his coworkers also made important contributions on the topic of tunneling magnetoresistance: they were the first to show that the tunneling magnetoresistance can reach huge values when the electrodes consist of half-metallic materials (J. Magn. Magn. Mater. **199**,1 (1999)) and that the sign and amplitude of the tunneling magnetoresistance ratio do not only depend on the electrodes, but also on the barrier material (Science **286**, 507 (1999)).

From the theoretical point of view, Albert Fert (together with J. Barnas) considered the interplay between tunneling magnetoresistance and the Coulomb blockade in magnetic nanostructures and predicted striking new effects (Phys. Rev. Lett. **80**, 1058 (1998)), thereby opening a new direction of development for single electron transistors (SET).

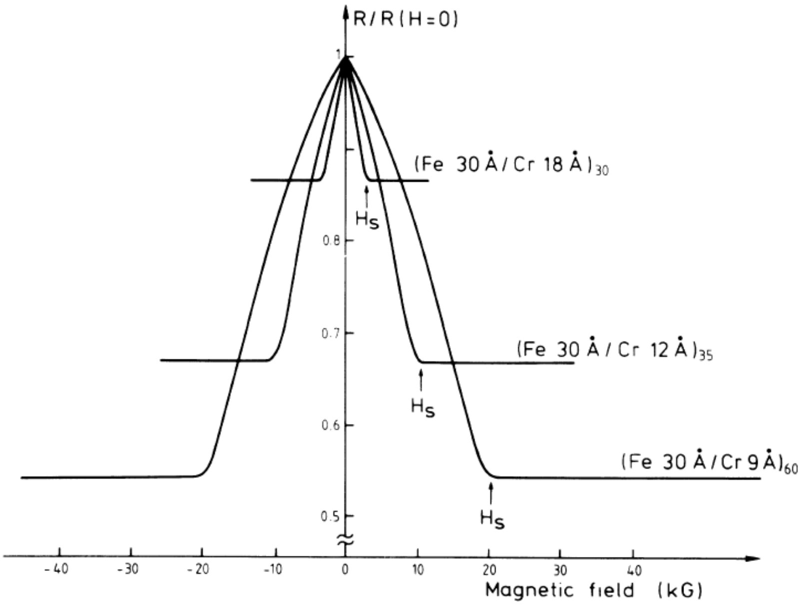

Fig. 3. Giant magnetoresistance of Fe/Cr multilayers, reported by Albert Fert's group (Phys. Rev. Lett. **61**, 2472 (1988)).

Most recently, Albert Fert's group addressed the problem spin-current-induced magnetic switching (Appl. Phys. Lett. **78**, 3663 (2001)), one of the new hot topics in spin-electronics.

4. Scientific Contributions of Peter Grünberg

Prior to 1986 Peter Grünberg had a long-standing record of improving the growth and of characterizing the properties of magnetic layers. In particular he developed the Brillouin scattering technique to such a precision, that he could detect surface magnons and standing spinwaves down to monolayer thicknesses. Based on this experience, he started studying the exchange coupling of two ferromagnetic iron layers separated by non-magnetic metallic interlayers. This culminated 1986 in the pioneering letter (Phys. Rev. Lett. **57**, 2442 (1986)) reporting the discovery of interlayer exchange coupling in transition metal systems. Using Brillouin scattering he could unambiguously show that two Fe layers separated by a Cr interlayer couple for certain Cr thicknesses antiparallel to each other and can be aligned parallel to each other by applying an external magnetic field. All previous experiments had obtained only ferromagnetic coupling due to Fe "pinholes" penetrating the Cr layers.

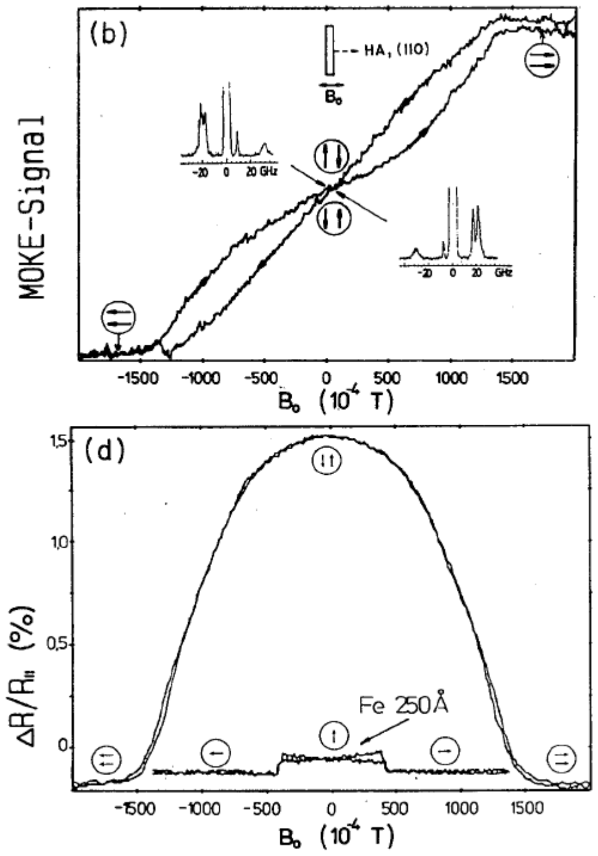

Fig. 4. Giant magnetoresistance of Fe/Cr/Fe bilayers, reported by Peter Grünberg's group (Phys. Rev. B **39**, 4828 (1989)). Upper panel: Magnetization curve (the Brillouin spectra in inset show the AP configuration of Fe layers in zero field). Lower panel: Electrical resistance (the lower curve shows the much smaller AMR of a single Fe layer).

This discovery initiated substantial experimental and theoretical studies. **Two years later, Peter Grünberg and his co-workers discovered, independently and simultaneously with the Fert group, the Giant Magnetoresistance (GMR) effect in Fe/Cr layers** (Phys. Rev. B **39**, 4828 (1 March 1989), received there already 31 May, 1988). Contrary to Fert, who studied an Fe/Cr multilayer, Grünberg investigated an Fe/Cr/Fe trilayer and obtained therefore a smaller GMR value of 1.5 % at room temperature (see Figure 4). Grünberg's papers reporting the discoveries of the antiferromagnetic interlayer coupling (1986) and of the giant magnetoresistance (1989) have received more than 800 and 650 citations, respectively.

While Albert Fert directly offered in his publication the correct explanation of the GMR effect in terms of spin-dependent scattering, Peter Grünberg immediately realized the prospect of interesting technological applications and applied for a patent, firstly (1988) in Germany (DE 3820475), then in Europe (0346817) and the USA (4,949,039). It turned out to be a very comprehensive patent, which has been acknowledged worldwide by all major companies, and which is now seen as the key patent for Magnetoelectronics. How farsighted Grünberg's ideas were, shows up by the long time span of seven years, before first license fees came in. How important the patent is, shows up in the strong increase of license fees, which up to 2001 amounted to a total of 10.5 million $. At present there exist worldwide about thousand patents in the field of Magnetoelectronics/Spin-electronics. This best characterizes the rich technological harvest expected in this field, all originating from the discovery of the GMR effect.

The antiparallel arrangement of the two ferromagnetic layers, which is essential for the GMR effect, can also be realized in the non-coupling case, as was demonstrated by Grünberg and co-workers (Phys. Rev. B **42**, 8110 (1990)) as well as C. Dupas *et al.* (J. Appl. Phys. **67**, 5680 (1990)) and T. Shinjo *et al.* (J. Phys. Soc. Japan **59**, 3061 (1990)) by using hard and soft magnetic layers. Another realization consists in using an antiferromagnet in direct contact, known as "exchange biasing". In the literature these systems are referred to as "spin valve systems", although there is no difference with respect to the GMR effect.

Another important contribution of Grünberg, this time achieved in collaboration with the group of A. Hubert, was the discovery of the bi-quadratic coupling (phys. stat. sol. (a) **125**, 635 (1991)). This is an anharmonic exchange interaction being quadratic in the scalar product $M_1 \cdot M_2$ of the two moments and is particularly important for layered systems. It can favor a 90° alignment of the magnetic layers and shows up in a region of spacer thicknesses between the ferro- and antiferromagnetic coupling. There are several other important contributions by Peter Grünberg. For instance, he was one of the firsts to observe the short period of interlayer coupling in Fe/Cr and first reported multiperiodic oscillatory coupling in Fe/Au/Fe systems.

Present work of Grünberg includes silicon and silicide interlayers (Phys. Rev. Lett., **87**, 157202 (2001)) which can mediate surprisingly strong antiferromagnetic interlayer coupling.

5. Emergence of a new field: Spin Electronics

In the aftermath of the discovery of the giant magnetoresistance, a tremendous research activity has been initiated, both in academic and industry institutes, involving several thousands of researchers worldwide, in order to exploit the potential revealed by Fert and Grünberg. A number of important discoveries, which will be briefly reviewed below, followed rapidly. This new field of research has been named **spin electronics** (also *magnetoelectronics*, or *spintronics*). In its most precise definition, spin electronics refers to new phenomena of electronic transport, in which the spin of the electron plays a central active role (in contrast to conventional electronics, for which the electron spin is essentially irrelevant). In practice, a somehow looser definition is frequently accepted (including new phenomena not directly related to transport). While it is fair to mention that some of the topics listed below already started before 1988, the discovery of the GMR undoubtedly contributed in a decisive manner to reveal their great potential and to reach their full impact.

Oscillatory interlayer exchange coupling

The most spectacular development in the field of interlayer exchange coupling is due to S.S.P. Parkin who discovered that the interlayer coupling exhibits a remarkable oscillatory behavior as a function of the interlayer thickness (Phys. Rev. Lett. **64**, 2304 (1990); Phys. Rev. Lett. **67**, 3598 (1991)). This discovery stimulated an important experimental and theoretical activity. It culminated with impressive experiments by J. Unguris *et al.* (Phys. Rev. Lett. **67**, 140 (1991); Phys. Rev. Lett. **79**, 2734 (1997)). Theoretically, this effect, which is related to the Ruderman-Kittel-Kasuya-Yosida (RKKY) interaction between magnetic impurities in a non-magnetic metal, could be successfully interpreted as a quantum size effect due to spin-dependent electron confinement, and excellent quantitative agreement between theoretical predictions and experimental observations was obtained. From the practical point of view, the oscillatory interlayer coupling provides an outstanding tool for the *quantum engineering* of the magnetic properties of multilayers.

Tunneling magnetoresistance

Giant magnetoresistance effects have also been found in systems comprising an insulating tunneling junction sandwiched between two ferromagnetic metallic electrodes. Early pioneering investigations on the problem of spin-dependent tunneling were performed in the 70's by P.M. Tedrow and R. Meservey (Phys. Rev. B **7**, 318 (1973)), by M. Jullière (Phys. Lett. **54A**, 225(1975)), and by S. Maekawa and U. Gäfvert (IEEE Trans. Magn. **18**, 707 (1982)). However, they attracted little attention for more almost 20 years. Renewed interest was triggered recently, on one hand by the progress in technology (allowing to fabricate reliable and reproducible tunnel junctions without pinholes), and on the other hand by the discovery of GMR in metallic multilayers. Large magnetoresistance in magnetic tunnel junctions were observed at room temperature by J.S. Moodera (Phys. Rev. Lett. **74**, 3273 (1995)) and T. Miyazaki (J. Magn. Magn. Mater. **139**, L231 (1995)), followed by many other groups. On the theoretical point of view, the mechanism was explained on the basis of a simple model originally proposed by Jullière, and later developed by other authors. Modern theoretical approaches, based upon sophisticated *ab initio* methods now allow accurate quantitative predictions. The industrial potential of the tunneling magnetoresistance will be presented in the next Section below.

Colossal magnetoresistance

In 1994, S. Jin *et al.* discovered an even larger magnetoresistive effect in mixed valence manganese perovskites (Science **264**, 413 (1994)). The change of resistance under magnetic field reaches several orders of magnitudes in this class of materials, so that the effect was dubbed *colossal magnetoresistance* (CMR). Although the materials were known since the 50's, and in spite of important pioneering contributions by Zener and de Gennes, their extraordinary magnetoresistive property remained elusive for almost half a century. The discovery of the CMR attracted a considerable attention, and a large part of the scientific community working on high-temperature superconductivity moved to this new field. This class of materials reveals an exceptionally rich variety of physical properties, in which electronic correlations, spin and orbital ordering play an essential role.

Half-metallic materials

The efficiency of spin electronic effects depend strongly on the degree of spin-polarization of the density of states of the magnetic materials at the Fermi energy: the higher the spin-polarization, the stronger the magneto-electronic effects. It is therefore of great interest to find materials with a high spin-polarization. In 1983, de Groot *et al.* theoretically predicted the existence of a new class of materials, called *half-metallic ferromagnets*, in which one spin-subband is metallic and the other spin-subband is insulating (Phys. Rev. Lett. **50**, 2024 (1983)). Those materials therefore have 100% spin-polarization at Fermi energy. Soon after the discovery of the GMR, the interest of half-metallic ferromagnets for spin-electronics became obvious. Half-metallic character was first confirmed experimentally for CrO_2 (Phys. Rev. Lett. **59**, 2788 (1987); Phys. Rev. Lett. **86**, 5585 (2001)). Enhanced magnetoresistance was indeed reported for half-metallic CrO_2 (Science **278**, 1607 (1997)).

Magnetic semiconductors

In order to fully exploit the potential of spin electronics, it is desirable to have some materials that are simultaneously semiconducting and magnetic. As soon as this was realized, people started to search actively for magnetic semiconductors with high Curie temperature (ideally, the latter should be well above 300 K). Major progress in this field was achieved by the group of H. Ohno, who reached a Curie temperature of 110 K in (Ga,Mn)As (Science **281**, 951 (1998)) and proved the possibility of an electric control of the Curie temperature by means of a gate voltage (Nature **408**, 944 (2000)). Intense research (both experimental and theoretical) on this problem, which is considered to be of major importance, is currently going on.

Spin injection

When electrons are injected from a ferromagnet into a non-magnetic material they can retain their spin polarization over a certain distance. This effect is called spin-injection and can be used to create new electronic devices. This was first demonstrated by M. Johnson who, after some pioneering work in the mid-80's (Phys. Rev. Lett. **55**, 1790 (1985)), succeeded in operating an all-metal *bipolar spin transistor* (Science **260**, 320 (1993)). Later on, a great effort was devoted to performing spin injection from a metallic ferromagnet into a *semiconductor*. This turned out to be extremely difficult, and an important obstacle was indicated; nevertheless, very recently, H.J. Zhu *et al.* (Phys. Rev. Lett. **87**, 016601 (2001)) and A.T. Hanbicki *et al.* (Appl. Phys. Lett. **80**, 1240 (2002)) could overcome this problem and demonstrated successful spin-injection from Fe into GaAs. Spin injection into a semiconductor from a *magnetic semiconductor* was also demonstrated by R. Fiederling *et al*. (Nature **402**, 787 (1999)) and by Y. Ohno *et al.* (Nature **402**, 790 (1999)), but this requires very low temperatures and/or an external magnetic field.

Spin transport in semiconductors

A further aspect of great importance is whether spin-polarized electrons can be transported through semiconductors without losing their spin polarization. Major progress on this problem was achieved in particular by the group of D.D. Awshalom who demonstrated that electrons can retain their spin polarization over unexpectedly long times and distances (Science **277**, 1284 (1997); Nature **411**, 770 (2001); Science **292**, 2458 (2001)).

Magnetic switching induced by spin-current

In 1996, J.C. Slonczewski (J. Magn. Magn. Mater. **159**, L1 (1996)) and L. Berger (Phys. Rev. B **54**, 9353 (1996)) theoretically pointed out that a spin-polarized current driven through a magnetic multilayer creates a torque on the magnetic layers, which can lead to a magnetization reversal. This provides a completely new method for writing information in a magnetic memory. The prediction was first confirmed experimentally by E.B. Myers *et al.* (Science **285**, 867 (1999)), J.A. Katine *et al*. (Phys. Rev. Lett. **84**, 3149 (2000)), and F.J. Albert *et al.* (Appl. Phys. Lett. **77**, 3809 (2000)).

6. Industrial Applications

It is unusual that a basic effect like GMR leads in less than a decade after discovery to commercial applications. A decisive step for applications was Parkin's discovery that GMR with a large magnetoresistance ratio at room temperature can be obtained in multilayers prepared by sputtering (Phys. Rev. Lett. **66**, 2152 (1991); Appl. Phys. Lett. **58**, 2710 (1991)). Magnetic field sensors based on GMR were already introduced as soon as 1996 by Non-Volatile Electronics and in 1997 by Siemens, aiming at applications in mechanical and automotive industries for monitoring machinery operations. For instance, if a GMR-sensor is placed close to a rotating ferrous gear, the moment direction of the soft magnetic sensor layer can switch every time a gear tooth passes the sensor, if the field induced by the gear exceeds a critical value. Such sensors can be used as a contactless potentiometer or to measure angles or distances. There are many other interesting applications of GMR sensors, e.g. in connection with a highly magnetostrictive layer as strain sensor or as actuator, or as magnetocouplers for the galvanic separation of signals, presently the domain of optocouplers. A particular interesting application is the use in biochips. Here magnetic particles are coated with a suitable antibody that will only bind to a specific analyte (virus, bacteria, etc.). By using an array of GMR sensors individually coated with the specific antibody of interest, the analyte will bind to the sensor, carrying with it the magnetic particle, the magnetic fringing field of which will rotate the magnetization of the sensor layer and thus change the resistance.

The most important application of GMR sensors is the use as read-out heads in computer hard-disk drives (see Figure 5), being introduced in 1997 by IBM. These sensors have now replaced the AMR (Anisotropic Magnetoresistance) - based heads, because the GMR effect is larger and moreover scales better. At present they have a storage density of more than 50 Gbit/in^2 (see Figure 6) and a total market volume of around $ 1 billion per year. Another fascinating invention of IBM is the Microdrive. The latest model packs 1 Gbyte of storage capacity on a disk the size of an U.S. quarter (see Fig. 7). These miniature devices aim at another mass market, i.e. handheld electronic products like digital cameras, video cameras, personal digital assistants (PDAs), etc.

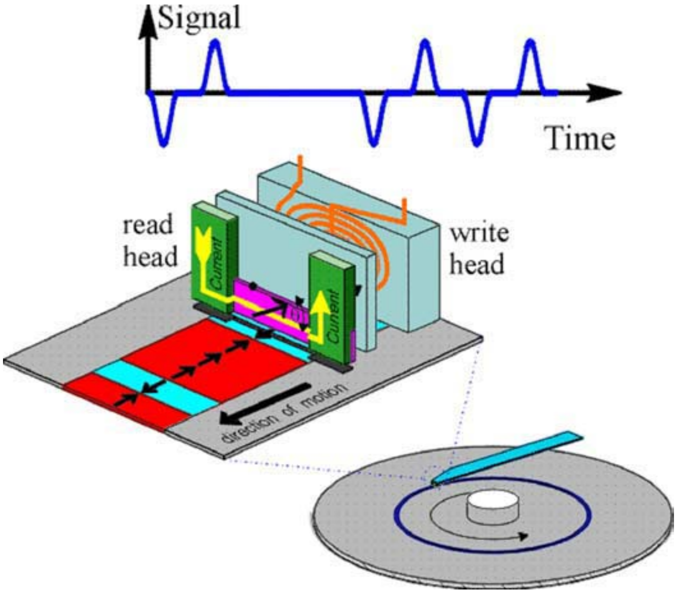

Fig. 5. Schematic description of a GMR read head for magnetic disks.

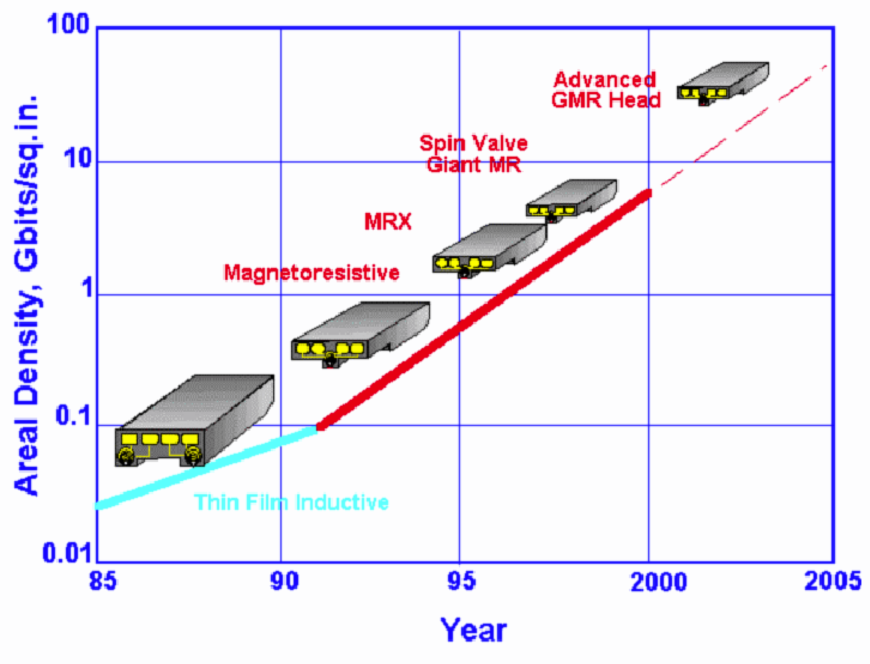

Fig. 6. Recent evolution of the storage density of magnetic disks.

Fig. 7. IBM’s ``quarter dollar´´ 1 GB Microdrive.

At present the most ambitious project with potentially large economic impact is the use of magnetic tunnel junctions as non-volatile magnetic random access memories (MRAM). The present semiconductor-based memories (DRAM, SRAM, ...) are nonpermanent (volatile) and the information is lost, when the computer is switched off. An MRAM consists of two perpendicular arrays of conducting wires being connected by a tunnel junction at the crossing points (see Figure 8). The wires allow both to read the information stored in the junctions by the TMR effect as well as to switch the magnetization by the magnetic field induced by the currents. In addition to being non-volatile, MRAMs have some further advantages with respect to DRAMS, such as lower energy consumption and higher scalability, which make them particularly well suited for computers and mobile phones. The total market, at which the MRAM development aims, is huge; alone the volume of DRAM was $ 29 billion in 2000. Industrial MRAM projects exist in the USA, in Europe (Infineon in collaboration with IBM) and Japan (Hitachi, Toshiba and NEC).

The two leading companies, IBM/Infineon and Motorola, plan to introduce first commercial MRAM products in 2004. In parallel to these projects also GMR-based MRAMs have been developed for aerospace applications, primarily because of their radiation hardness. Also high-density GMR-MRAM for computer applications are in development, but the TMR-based MRAMs seem to be more promising.

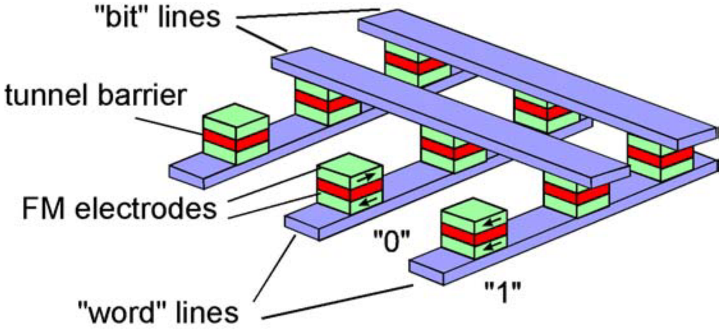

Fig. 8. Schematic description of a magnetic random access memory (MRAM).

With GMR read-out heads in widespread use and MRAM devices soon to reach the market, there are many more visionary projects, which could have a strong impact on our future electronics. The TMR or GMR sensor is already a simple logic gate, where the two magnetizations can be used to define its function as an AND, OR, NAND or NOR gate. For a set of such magnetoresistive elements, these functions can then be altered, ``on the fly´´, by merely resetting the magnetization on the appropriate elements, which could form the basis of a reprogrammable logic technology. This would basically result in a universal processor, which can be optimized for any calculational step. There are even more visionary ideas, e.g. for quantum computing. Only time can show how these visions can be transformed into real products, leading to a true spin electronics industry.

Summary

The Giant Magnetoresistance effect found independently by Albert Fert and Peter Grünberg represents the most important achievement in the field of magnetism during the last decades. It has led to a whole series of important discoveries and opened the door for a new field: spin electronics. Within the unusually short time of seven years, the fundamental discovery turned into commercially available products with huge market share. Without doubt spin electronics will be a major topic in the physics of the 21st century and will have a strong impact on information technology.