Magnetic memory cells

Giant Magnetoresistance

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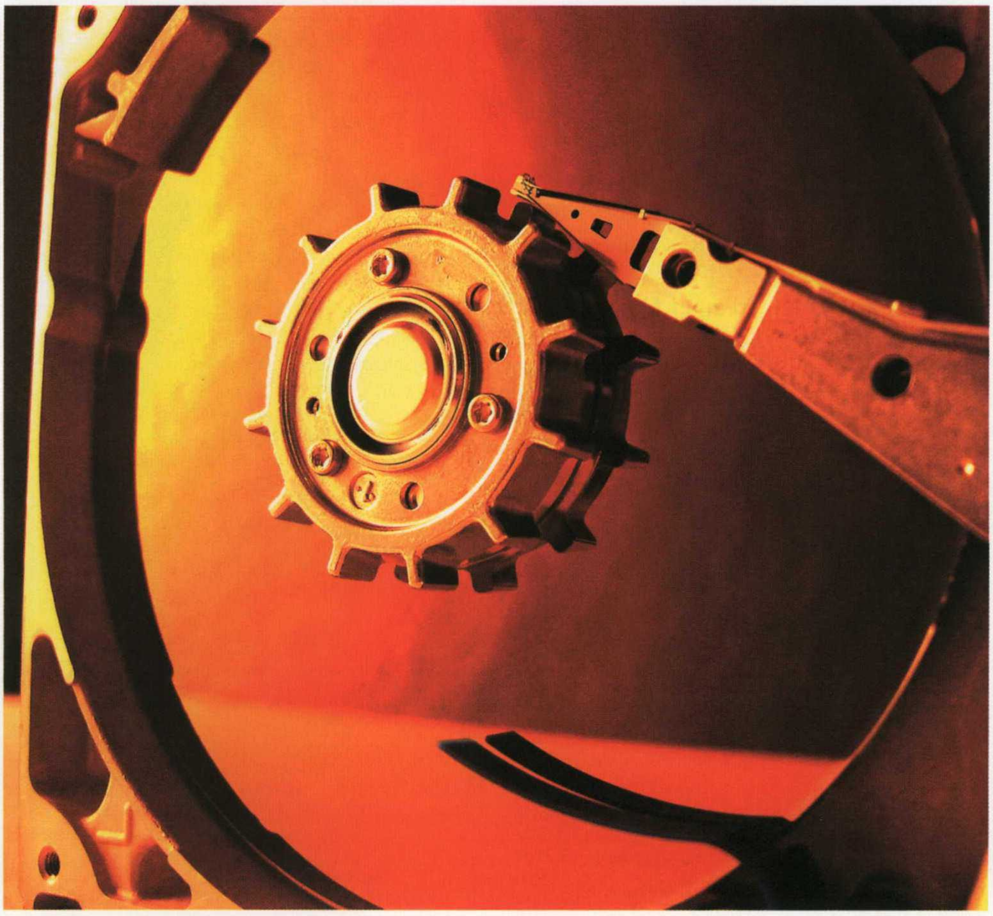
Prof. Józef Barnaś, a laureate of the Maria Skłodowska-Curie Research Award and deputy dean of the Faculty of Physics at Adam Mickiewicz University, spent a year and a half working at the laboratory of Prof. Albert Fert and nearly two years in the team of Prof. Peter Grünberg

The density of information stored on computer hard drives has been rising exponentially in the past few decades, doubling on average every year and a half

This empirical regularity is known as Moore's law. The density at which data can be written is mainly dictated by two factors: our ability to produce disks with ever-smaller memory cells, and the technology used in recording and reading back the information stored in such cells. It is the reading of recorded information, however, that poses the greatest challenges. The read heads used in the 1990s utilized a phenomenon called anisotropic magnetoresistance, based on how the electrical resistance of ferromagnetic metals depends upon the mutual orientation of current flow and magnetization. Information is thus read by detecting changes in the electric resistance of the head's magnoresistant element, caused by the magnetic field from the magnetic memory cells. Although many physical phenomena causing magnetoresistance are known, not many of them are suitable for detecting the kind of weak magnetic fields that are generated by memory cells. Those

50 Gb, or perhaps 100 Gb, or even 500 Gb? When buying a new computer we face an incredible choice of hard drive sizes, and great advances have been made in this field in recent years. Today's disks contain tens more times the amount of data as was carried on similar devices back in 1997, for instance



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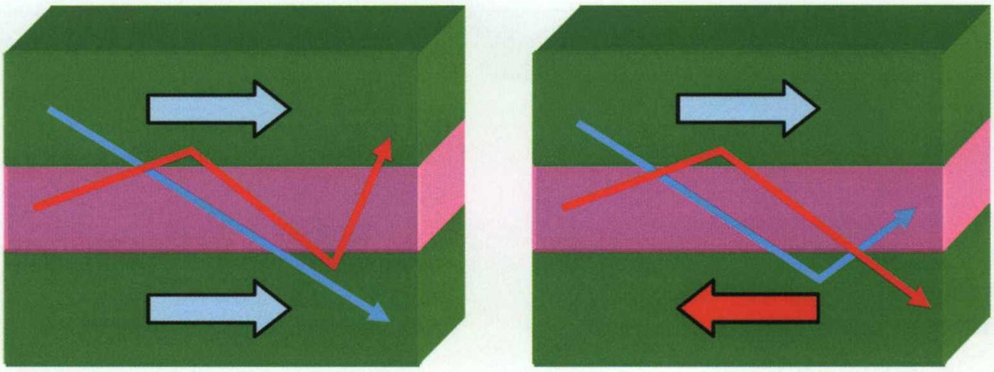

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The physical mechanism of giant magnetoresistance (GMR): electrical resistance is significantly lower in the parallel configuration (left) than in the antiparallel one (right)

conditions were indeed met by anisotropic magnetoresistance, yet it is a relatively weak effect and the limited capabilities of such read heads hampered further increases in recording density.

Breakthrough discovery

New possibilities emerged with the discovery of the phenomenon of giant magnetoresistance (GMR) in multilayer magnetic structures, by Albert Fert's team at Paris-Sud University (France) and Peter Grünberg's team at the Jülich Research Center (Germany). This discovery earned Fert and Grünberg the 2007 Nobel Prize in physics. In the 1980s, the two prizewinners were studying the technology of ultrathin multilayer structures, comprised of magnetic layers of transition metals (e.g. iron, Fe) separated by nonmagnetic layers (e.g. chrome, Cr). At that stage the main priority was to improve the structural quality of such systems and to identify the optimal conditions for creating them. An important step forward in multilayer magnetic structure research came with Peter Grünberg's 1986 discovery of antiferromagnetic interlayer coupling in Fe/Cr/Fe structures: with chrome layer thicknesses on the order of several atomic planes, the iron layers become antiferromagnetically coupled and in the absence of an applied magnetic field their direction of magnetization is antiparallel (i.e. oriented in opposite directions).

In systems exhibiting the antiferromagnetic exchange interaction between Fe layers studied by Fert and Grünberg, the magnetization directions of neighboring layers (without an external magnetic field) are opposite yet remain within the plane of the layers. The presence of an applied magnetic field, in turn, forces the magnetization to orient in the direction of that field. The essence of the giant magnetoresistance discovery was to demonstrate that electric current flowing within the plane of the layers, at a constant voltage, increases (i.e. the electrical resistance decreases) when the magnetic configuration shifts from antiparallel in the absence of a magnetic field to parallel in the presence a magnetic field, regardless of whether the applied magnetic field is perpendicular to the plane of the layers, or is within the plane and oriented either in the direction of the current or perpendicular to it. In other words, the resistance of these structures alters significantly (even up to 50%) under the influence of an outside magnetic field. The structures studied by Peter Grünberg's team consisted of two Fe layers separated by one Cr layer (Fe/Cr/Fe), while the systems studied by Albert Fert's team consisted of a much greater number of Fe and Cr layers, more precisely (Fe/Cr)40. The drop in resistance seen in Fe/Cr/Fe structures was on the order of several percent in a field of ca. 0.1 tesla, but considerably larger in (Fe/Cr)40 systems, reaching 50 percent in a magnetic field of several tesla. This change in electrical resistance is what is known as the GMR effect.

Spin governs resistance

The physical mechanism underlying the GMR effect was correctly explained in subsequent work. Flowing current is a stream of moving electrons, which exhibit spin in addition to electric charge. They may be imagined as elementary magnets which in ferromagnetic metals are oriented either in the direction of magnetization or in the opposite direction. The resistance of a metal essentially represents the degree to which flowing electrons get scattered by

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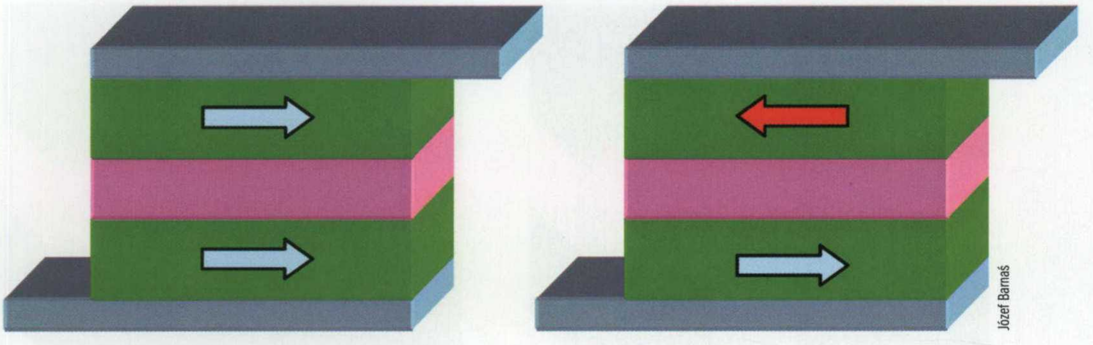

Two states of an MRAM magnetic memory cell, recording the information '0' (left) or '1' (right)

structural imperfections. In ferromagnetic metals, the resistance which electrons encounter depends on their spin orientation with respect to the direction of magnetization. A change in the magnetic configuration from antiparallel to parallel involves a change in that mutual orientation, which as a consequence entails greater resistance in the antiparallel configuration than in the parallel one. Thus the GMR effect is closely related to electron spin. Successful exploitation of the GMR effect is based on the construction of structures known as spin valves, in which the change in magnetic configuration, and thereby the jump in electric resistance, occurs in very small magnetic fields. In the structures exhibiting antiferromagnetic exchange interaction initially studied, the magnetic field necessary to alter the configuration was much larger due to the need to "overcome" the exchange field. Such structures are not very useful from the practical perspective. More promising are structures without interlayer exchange interaction.

The essence of a spin valve is that the magnetic moment of one of the layers is coupled to the antiferromagnetic base by exchange anisotropy, while the moment of the other layer can freely rotate in the weak magnetic field. Because the magnetic field needed to change the magnetic configuration in such spin valves is comparable to the magnetic field generated by memory cells, spin valves have proven to be excellently suited for use in the heads that read back the information recorded on hard discs, thus replacing such heads based on ansiotropic magnetoresistance. Information on a hard disc is represented in the form of encoded zeros and ones, implemented as regions magnetized with opposing orientations. The more accurately a hard drive head is able to distinguish regions magnetized in differing orientations, the smaller the surface of those regions may be and the more data may be stored on a disk. Harnessing the GMR phenomenon in such read heads has enabled the density of information to be significantly increased, and contemporary hard drives now contain tens more times the amount of data as was carried on similar devices back in 1997, for instance.

Further experimental work has shown that the GMR effect also occurs when electric current flows perpendicularly to the plane of the layers. Moreover, the effect in this configuration is generally greater than with current flowing in the plane of the layers. That has enabled the dimensions of spin valves to be further reduced. Certain structures have also been shown to exhibit the reverse effect, i.e. structures whose resistance is greater in the parallel configuration than in the antiparallel one. The success of the GMR effect has also initiated intensive work on ferromagnetic tunnel junctions, where current flows as a consequence of the quantum tunnel effect. The corresponding effect is known as tunnel magnetoresistance (TMR), and it was first observed back in 1975.

Magnetic memories

A spin valve comprised of two magnetic layers separated by a nonmagnetic layer can also be used as an element of memory itself. The parallel configuration then corresponds to the recorded information '0' while the antiparallel configuration corresponds to the information '1.' Writing information then involves using a magnetic field to set the proper magnetic configuration, and the GMR effect can be harnessed to read it. Memory cells based on such layered structures with a metallic interlayer have been proposed for developing magnetic memory of the RAM type (called MRAM). Importantly, such memory is non-volatile, which means that unlike semiconductor-based RAMs the recorded information is stable and does not disappear when power is switched off. Nevertheless, the parameters of such memories did not meet the necessary conditions and have not come into significant use. Significantly better parameters are exhibited by MRAM memories based on magnetic tunnel junctions.

Magnetic spin valves open up still more possibilities. Spin-polarized current turns out to be able to affect the magnetic configuration of such a structure and if such current is great enough, it can generate switching between the parallel and antiparallel configuration states. If the electric current flowing in one direction switches the system into the parallel configuration, then current in the opposite direction will switch it into the antiparallel configuration. This effect is in a certain sense the reverse of the GMR effect and the two are correlated. Interest in this effect stems from the possibility of recording information in MRAM memory cells using an electrical impulse rather than a magnetic field generated by current flowing in additional lines. However, the current necessary for such switching is relatively great, especially in metallic structures. It is somewhat smaller in tunnel junctions, which raises hopes of their finding practical application. Another possibility of the practical use of such systems, particularly in telecommunications, may lie in the fact that in certain structures electric power may be utilized to generate microwaves without the need to employ an external magnetic field. ■

Further reading:

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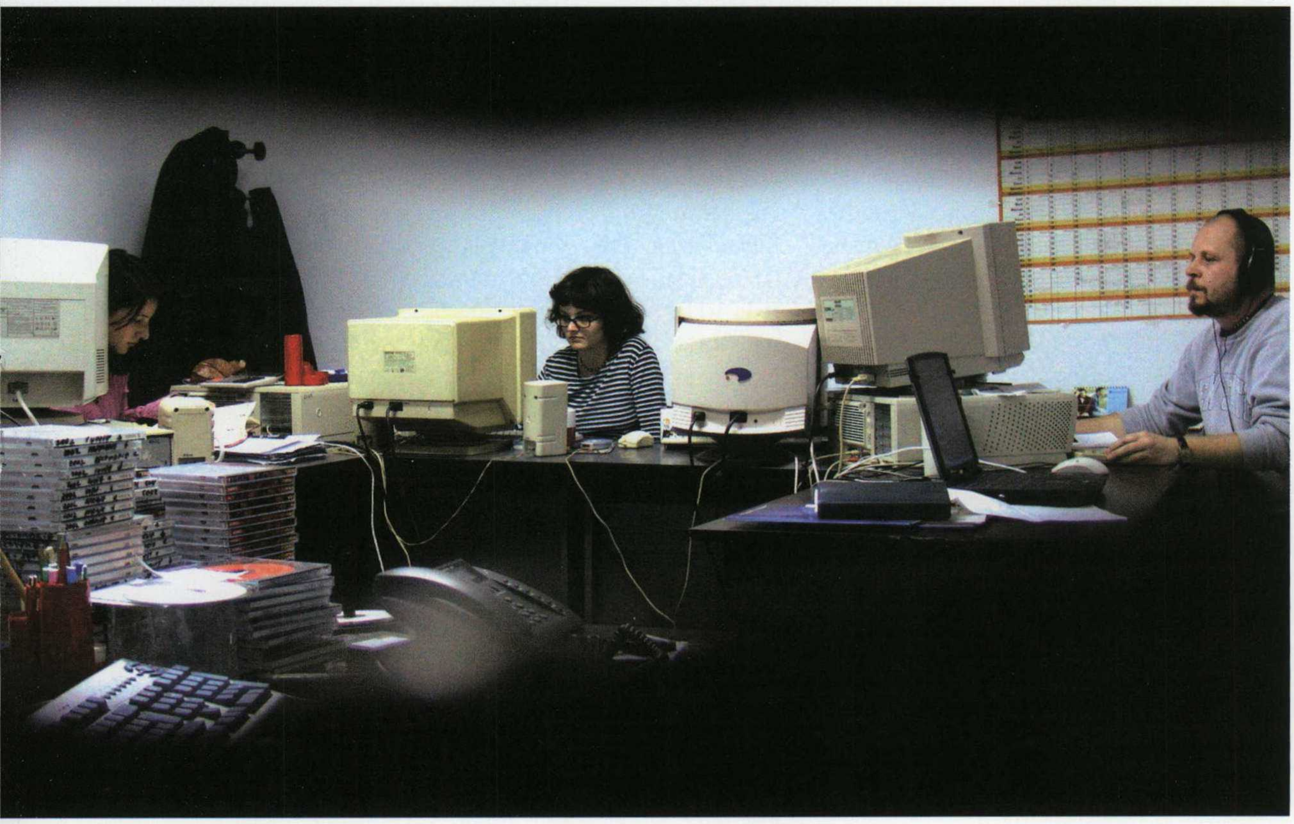

Lehel Mor

Stacks of DVDs or just a large hard drive? The latter choice is just one of the many benefits brought to us by the discovery of giant magnetoresistance. It is also being considered for use in telecommunications, and even for creating non-volatile magnetic memory of the RAM type