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Scientific Background on the Nobel Prize in Physics 2007

The Discovery of Giant Magnetoresistance

compiled by the Class for Physics of the Royal Swedish Academy of Sciences

1. Introduction

The phenomenon called **magnetoresistance** (MR) is the change of resistance of a conductor when it is placed in an external magnetic field. For ferromagnets like iron, cobalt and nickel this property will also depend on the direction of the external field relative to the direction of the current through the magnet. Exactly 150 years ago W. Thomson (1) (Lord Kelvin) measured the behaviour of the resistance of iron and nickel in the presence of a magnetic field. He wrote “*I found that iron, when subjected to a magnetic force, acquires an increase of resistance to the conduction of electricity along, and a diminution of resistance to the conduction of electricity across, the lines of magnetization*”. This difference in resistance between the parallel and perpendicular case is called **anisotropic magnetoresistance** (AMR) (2). It is now known that this property originates from the electron spin-orbit coupling. In general magnetoresistance effects are very small, at most of the order of a few per cent.

The MR effect has been of substantial importance technologically, especially in connection with read-out heads for magnetic disks and as sensors of magnetic fields. The most useful material has been an alloy between iron and nickel, $\text{Fe}_{20}\text{Ni}_{80}$ (permalloy). In general, however, there was hardly any improvement of the performance of magnetoresistive materials since the work of Kelvin. The general consensus in the 1980s was that it was not possible to significantly improve on the performance of magnetic sensors based on magnetoresistance.

Therefore it was a great surprise when in 1988 two research groups independently discovered materials showing a very large magnetoresistance, now known as **giant magnetoresistance** (GMR). These materials are so called magnetic multilayers, where layers of ferromagnetic and non-magnetic metals are stacked on each other (figure 1). The widths of the individual layers are of nanometre size – i.e. only a few atomic layers thick. In the original experiments leading to the discovery of GMR one group, led by Peter Grünberg (3), used a trilayer system $\text{Fe}/\text{Cr}/\text{Fe}$, while the other group, led by Albert Fert (4), used multilayers of the form $(\text{Fe}/\text{Cr})_n$ where n could be as high as 60.

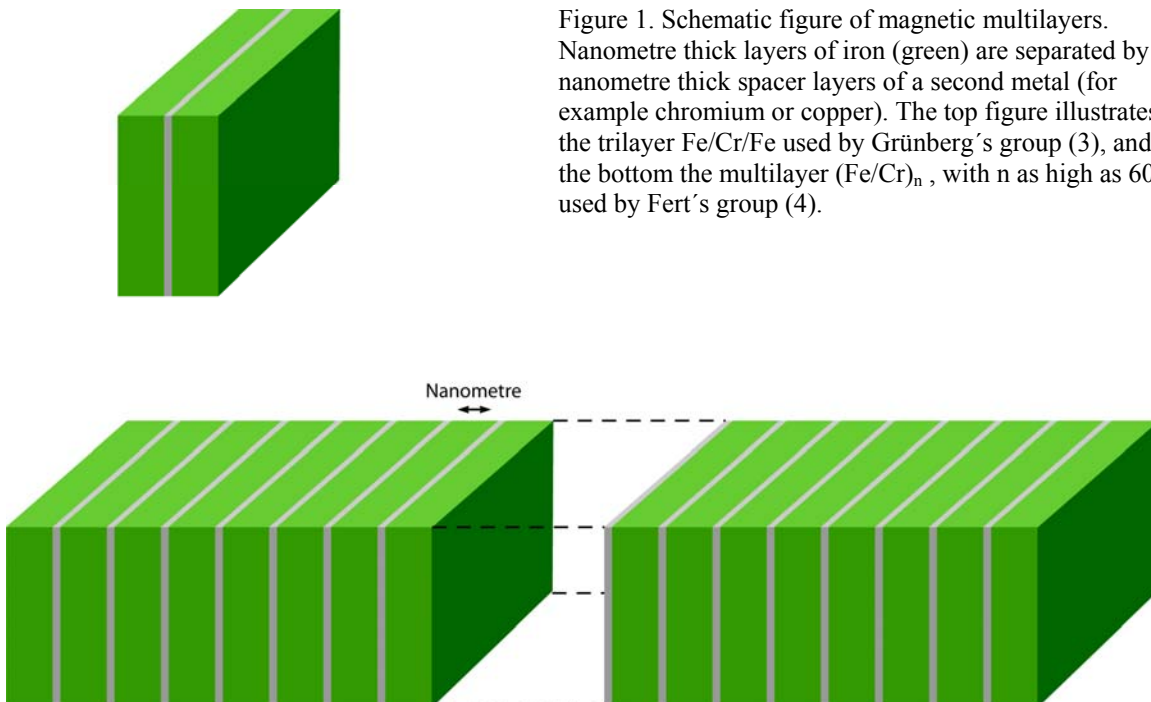


Figure 1. Schematic figure of magnetic multilayers. Nanometre thick layers of iron (green) are separated by nanometre thick spacer layers of a second metal (for example chromium or copper). The top figure illustrates the trilayer $\text{Fe}/\text{Cr}/\text{Fe}$ used by Grünberg’s group (3), and the bottom the multilayer $(\text{Fe}/\text{Cr})_n$, with n as high as 60, used by Fert’s group (4).

In figure 2 the measurements of Grünberg's group are displayed (left) together with those of Fert's group (right). The y-axis and x-axis represent the resistance change and external magnetic field, respectively. The experiments show a most significant negative magnetoresistance for the trilayer as well as the multilayers. The systems to the right, involving large stacks of layers, show a decrease of resistance by almost 50% when subjected to a magnetic field. The effect is much smaller for the system to the left, not only because the system is merely a trilayer but also because the experiments led by Grünberg were made at room temperature, while the experiments reported by Fert and co-workers were performed at very low temperature (4.2K).

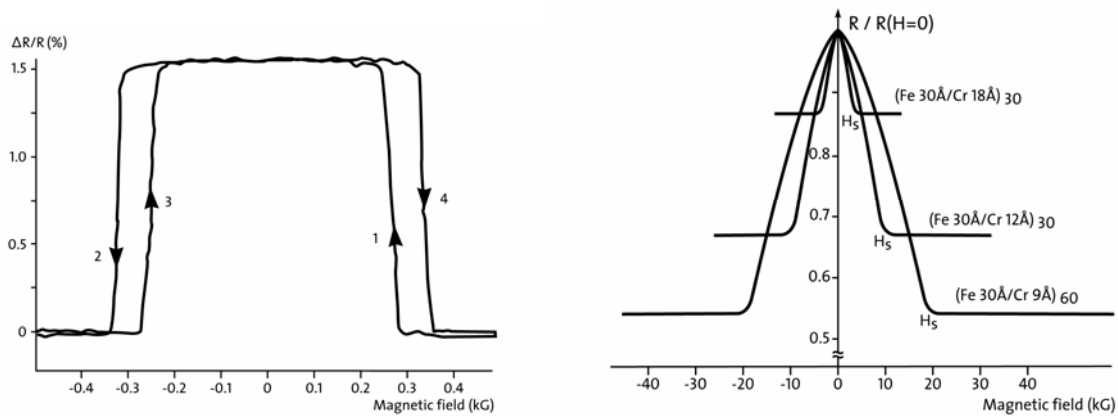


Figure 2. After refs. (3) and (4).

Left: Magnetoresistance measurements (3) (room temperature) for the trilayer system Fe/Cr/Fe. To the far right as well as to the far left the magnetizations of the two iron layers are both parallel to the external magnetic field. In the intermediate region the magnetizations of the two iron layers are antiparallel. The experiments also show a hysteresis behaviour (difference 1 and 4 (2 and 3)) typical for magnetization measurements.

Right: Magnetoresistance measurements (4) (4.2K) for the multilayer system $(\text{Fe/Cr})_n$. To the far right ($>H_S$, where H_S is the saturation field) as well as to the far left ($< -H_S$) the magnetizations of all iron layers are parallel to the external magnetic field. In the low field region every second iron layer is magnetized antiparallel to the external magnetic field. 10 kG = 1 Tesla.

Grünberg (3) also reported low temperature magnetoresistance measurements for a system with three iron layers separated by two chromium layers and found a resistance decrease of 10%.

Not only did Fert and Grünberg measure strongly enhanced magnetoresistivities, but they also identified these observations as a new phenomenon, where the origin of the magnetoresistance was of a totally new type. The title of the original paper from Fert's group already referred to the observed effect as "Giant Magnetoresistance". Grünberg also realized at once the new possibilities for technical applications and patented the discovery. From this very moment the area of thin film magnetism research completely changed direction into magnetoelectronics.

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 exploration. 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.

2. Background

A. Ferromagnetic metals

Among the d transition metals (Sc...Cu, Y...Ag, Lu...Au, i.e. 3d, 4d, and 5d transition elements), the 3d metals iron, cobalt and nickel are well-known to be ferromagnets. Among the lanthanides (the 4f elements, La-Lu) gadolinium is also a ferromagnet. The origin of magnetism in these metals lies in the behaviour of the 3d and 4f electrons, respectively. In the following it is mainly the magnetism in the 3d elements that will be discussed.

In the free atoms, the 3d and 4s atomic energy levels of the 3d transition elements are hosts for the valence electrons. In the metallic state these 3d and 4s levels are broadened into energy bands. Since the 4s orbitals are rather extended in space there will be a considerable overlap between 4s orbitals belonging to neighbouring atoms, and therefore the corresponding 4s band is spread out over a wide energy range (15–20 eV). In contrast to this, the 3d orbitals are much less extended in space. Therefore the energy width of the associated 3d energy band is comparatively narrow (4–7 eV). In practice one cannot make a clear distinction between the 3d and 4s orbitals since they will hybridize strongly with each other in the solid. Nevertheless for simplicity this two band picture will be used here and the 3d electrons will be considered as metallic – i.e. they are itinerant electrons and can carry current through the system, although they are still much less mobile than the 4s electrons.

A useful concept in the theory of solids is the electron density of states (DOS), $n(E)$, which represents the number of electrons in the system having energy within the interval $(E, E+dE)$. According to the exclusion principle for fermions (in this case electrons), only one electron can occupy a particular state. However each state is degenerate with respect to spin and can therefore host both an electron with spin up and an electron with spin down. In the ground state all the lowest energy levels are filled by electrons and the highest occupied energy level is called the Fermi energy, E_F . In figure 3 (left) the density of states is illustrated schematically for a non-magnetic 3d metal, sometimes referred to as a paramagnet, where there are equally many electrons with spin up as with spin down, i.e. there is no net magnetization. The so called spin polarization, P , [$P = (N_{\uparrow} - N_{\downarrow}) / (N_{\uparrow} + N_{\downarrow})$, where N_{\uparrow} (N_{\downarrow}) = number of electrons with spin up (down)], is here equal to zero.

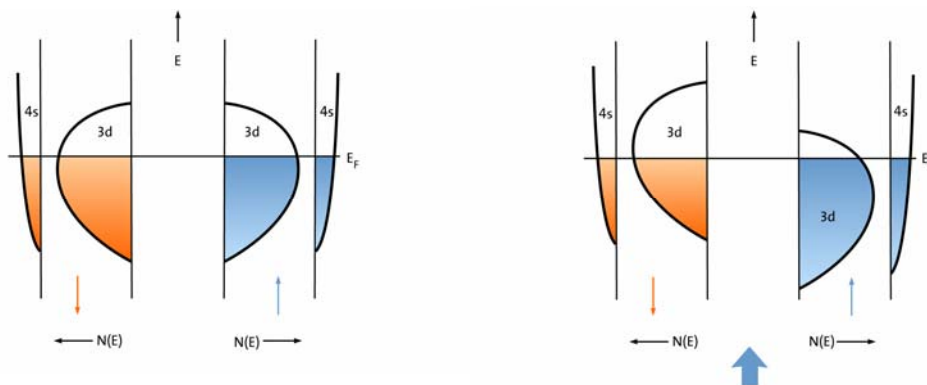


Figure 3. **To the left** a schematic plot is shown for the energy band structure of a d transition metal. The density of states $N(E)$ is shown separately for the spin up and down electrons and where a simplified separation has been made between the 4s and 3d band energies. For the non-magnetic state these are identical for the two spins. All energy levels below the Fermi energy are occupied states (orange and blue). The coloured area (orange + blue) corresponds to the total number of valence electrons in the metal. **To the right** the corresponding picture is illustrated for a ferromagnetic state, with a spin-polarization chosen to be in the up direction ($N_{\uparrow} > N_{\downarrow}$; blue area > orange area). This polarization is indicated by the thick blue arrow at the bottom figure to the right.

For a ferromagnet N_{\uparrow} is larger than N_{\downarrow} , so that there is a net spin polarization, $P > 0$. In order to compare the energy for the ferromagnetic state with the energy for the paramagnetic state one can start from the paramagnetic state and allow for a small imbalance in the number of spin up and spin down electrons. A transfer of spin down electrons from the spin down band into the spin up band leads to more exchange energy in the system, which means a **lowering** of the total energy (a gain) On the other hand such a process requires a transfer of electrons from spin down levels below the initial Fermi energy, into spin up levels situated just above the initial Fermi energy. This will necessarily lead to a loss of band energy, “kinetic energy” and thus to an **increase** of the total energy (a loss). Thus there is a competition between two opposite effects. This can be formulated as the so called Stoner criterion (5) for magnetism, namely that when

$$I N(E_F) > 1,$$

the system will be a ferromagnet. Here I is called the Stoner exchange parameter and $N(E_F)$ is the density of states at the Fermi energy. The Stoner parameter has a specific value for the individual element, while $N(E_F)$ depends much more on the particular spatial arrangements of the atoms relative to each other (like crystal structure). Furthermore, and most important, $N(E_F)$ tends to be high for systems with narrow energy bands as is the case for the heavier 3d transition elements (Fe, Co and Ni). This is the explanation for the ferromagnetism among the d transition metals.

The situation for a ferromagnetic spin polarization is illustrated to the right in figure 3 (with a direction chosen to be upwards). The vertical displacement between the spin up and spin down densities of states exemplifies the exchange energy splitting between the spin up and spin down energy bands, which is relevant for the metals Fe, Co and Ni. In particular the density of states at the Fermi energy $N(E_F)$ can now be very different for the two spin bands. This also means that for a ferromagnet the character of the state at the Fermi energy is quite different for spin up and spin down electrons. This is an important observation in connection with the GMR effect. This picture of 3d energy bands (figure 3 to the right) for the ferromagnetic metals is often referred to as the itinerant model (6), also known as the Stoner-Wohlfarth model (5).

One important property of ferromagnets is that at high temperature their magnetism is lost. This happens at a well defined temperature, the so called Curie temperature, T_C . For the present systems (Fe, Co and Ni) these critical temperatures are far above room temperature and can be neglected.

B. Resistance

An electrical current of electrons sent through a metallic system will always experience a resistance R . (Exceptions are the so called superconductors where below a certain temperature the current can flow without resistance). There are a number of reasons for this. In a crystal the atoms will always vibrate (phonons) around their equilibrium positions, thereby deviating from the perfect lattice positions, and the conduction electrons may be scattered by these deviations (electron – phonon interaction). Other important contributions to the resistance of a metal are scattering of electrons against impurities and defects. The only electrons that participate in the electrical conduction process are those at (or very close to) the Fermi level. For paramagnetic metals there is no difference between the spin up and spin down electrons, and they contribute equally to the resistance.

Already in 1936 Sir Nevil Mott (7) considered the electrical conductivity of d transition elements. He suggested that the conductivity was mainly determined by the 4s electrons which are easily mobile due to the wide energy range of the bands derived from the 4s-states. However in a scattering process the s electrons can scatter into the many d states which are available at the Fermi level. Therefore they

experience a strong scattering giving rise to a considerable resistance. On the other hand for Cu, the element following Ni in the Periodic Table, all the 3d states are situated below the Fermi level and therefore not available for scattering processes. This explains the particularly high conductivity of Cu.

In the 1960s and 1970s Fert together with Campbell studied in great detail the conductivity of 3d ferromagnetic materials (3,8). They carried out extensive investigations of resistivity changes which occur when low concentrations of alloying elements, like Cr and other transition metals, are put as scattering centres into for example Fe and Ni. From these studies they could confirm that in a ferromagnet like iron there are two types of carriers, one made up from spin up electrons and one from spin down electrons. Since the density of states at the Fermi surface is quite different for the two spin states it follows that there is a significant difference in resistance for the spin up electrons and the spin down electrons. There could also be contributions to the resistance from scattering processes where the spins are flipped. This could for example be due to scattering against spin waves or from the spin orbit coupling. However these effects are small and will be neglected here. Thus the picture which is emerging is that the electrical current in a ferromagnet like iron, cobalt and nickel consists of spin up and spin down carriers, which experience rather different resistances.

C. Growth of superlattices

From the beginning of the 1970s the development in physics, chemistry and materials science had led to new experimental techniques allowing scientists to manufacture completely novel materials. Using what was called epitaxial growth one could start to produce artificial materials building one atomic layer after the next. Techniques that were introduced at this time involved for example sputtering, laser ablation, molecular beam epitaxy and chemical vapour deposition. Molecular beam epitaxy was already being used in the late 1960s to make thin semiconducting materials and at the end of the 1970s nanometre thick metallic layers could be produced. This was first applied to non-magnetic metals, but later also to metallic ferromagnets. At the same time, a number of characterization techniques had been largely improved, utilizing for example the magneto-optic Kerr effect (MOKE) and light scattering from spin waves. Using these methods it was possible to grow metallic multilayers involving for example iron and study their magnetic properties.

In order to produce well-defined materials the choice of substrate on which to grow the material is of great importance. Commonly used materials are silicon, silicon dioxide, magnesium oxide and aluminium oxide. To obtain well-behaved metallic multilayers it is important that the lattice parameters for the different metallic layers match each other (figure 4) and it is also an advantage if the two metals forming the multilayer have the same crystal structure. This is the case for chromium and iron, where both metals adapt the bcc (body-centred cubic) crystal structure and where in addition they have very similar lattice spacings. This was important for the studies for which this Nobel Prize is awarded undertaken by the groups of Fert and Grünberg. In addition it was also extremely important that it was now possible to grow multilayers where the spatial separation between the magnetic layers is of the order of nanometres. In order to exhibit the GMR effect the mean free path length for the conduction electrons has to greatly exceed the interlayer separations so that the electrons can travel through magnetic layers and pick up the GMR effect. Without the new experimental growth techniques this requirement could not have been fulfilled and the GMR effect would have remained unknown. In this connection it should be mentioned that, in several publications prior to the work of Fert and Grünberg, there were reports of observations of substantial (of the order of a few per cent) magnetoresistance effects (9,10,11,12). In none of them were the observations recognized as a new effect.

