Giant Magnetoresistance

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The discovery of giant magnetoresistance (GMR) has been a huge impact on our life, especially for mass data storage devices. Initial experiments conducted by Gruberg and Fert are explained. Basic physics of the GMR effect can be explained by the two-current model, which the conduction of a current is consist of two different spin electrons. Details of GMR applications, such as hard-disk read-heads and magnetic memory chips are presented.

Introduction

In our every day life, it's inseparable to live without digital data. The discovery of giant magnetoresistance (GMR) in 1988 by two french and german scientists, Albert Fert[1] and Peter Grunberg[3] has been dramatically improving our way to live. GMR's application to the read head of hard discs greatly contributed to the fast rise in the density of stored information and led to the extension of the hard disk technology to consumer's electronics. For instance, since the introduction of GMR-type sensors as reading elements, in around 1997, storage capacities have increased approximately 100 times. [7] Besides in terms of further technological advances, the development of spintronics revealed many other phenomena related to the control and manipulation of spin currents. Thus basically GMR of the magnetic multilayers opened the way to an efficient control of the motion of the electrons by acting on their spin through the orientation of a magnetization.

Family of magnetoresistance

Generally, GMR should be distinguished from other magnetoresistance effects, such as regular bulk magnetoresistance (MR) and anisotropic magnetoresistance (AMR) which are also exhibited in layered systems. Lorentz force on the electrons due to the external magnetic field changes the electrons path, and this is an origin of ordinary magnetoresistance. Ordinary magnetoresistance exhibits only small changes in the resistance compared to GMR (less than 1% in fields of the order of 1 Tesla)[12] and does not saturate at the saturation magnetic field. AMR originates from the spin-orbit interaction and causes the resistance to depend on the relative orientations of the magnetization and the electric current.

In addition to ordinary, anisotropic and giant magnetoresistance, there also exists "colossal" magnetoresistance (CMR) which was found in doped manganite perovskites such as La3-xCaxMnO3[5, 11]. The CMR effect can be extremely large resulting in a resistance change of a few orders in magnitude. CMR originates from a metal-insulator transition in the low temperature near the Curie temperature the vicinity of the Curie temperature and requires magnetic fields of the order of several Tesla. The latter property makes the applicability of CMR materials fairly limited. On the other hand, tunneling magnetoresistance aroused considerable interest recently due to possible applications in the magnetic sensor and storage industry. Tunneling magnetoresistance (TMR) is observed in magnetic tunnel junctions[9][8], in which ferromagnetic metallic layers are separated by a thin insulating spacer layer. Similar to GMR, TMR is determined by the relative orientation of the magnetic moments of the ferromagnetic layers. Although both these phenomena may have similar applications, they are very distinct from the point of view of the physics involved. GMR is observed in magnetic metallic multilayer structures and therefore the physics of GMR is related to spin-dependent electronic transport in complex metal systems. On the other hand, TMR is observed in layered systems where magnetic metallic layers are separated by an insulating spacer layer and is a consequence of spin-polarized tunneling[12].

Experiment & Discovery

Giant magnetoresistance was discovered in 1988 by the group of Albert Fert on Fe/Cr magnetic multilayer[1, 6] and the group of Peter Grünberg on Fe/Cr/Fe trilayers[3, 7]. In both cases the samples were grown using MBE and had [001] orientation of the layers. Specifically, in order to have more experimental possibilities available, Grunberg et al. used samples grown epitaxially on (110) oriented GaAs. The film plane was parallel to a (110) atomic plane and had an easy (EA) and a hard (HA) axis. For the thickness d of the individual Fe films, they chose d =12 nm. The Cr thickness was d_0 =1 nm, so that the Fe layers were coupled antiferromagnetically providing an antiparallel alignment of their magnetizations at zero applied magnetic field. As a reference sample, they also made a single Fe film with thickness d=25 nm in 100 order to measure the anisotropic magnetoresistance (AMR) effect for comparison. Laterally, the samples had the shape of a long strip with contacts at both ends. From Fig. 2, they have an MR effect both due to the anisotropic effect (negative values) and antiparallel alignment (positive values).

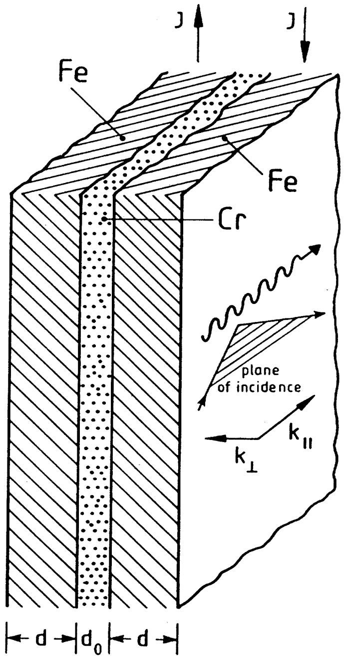

Figure 1: The multilayer of ferrogmagnetic (Iron) and non-magnetic (Chromium) metals with antiparallel alignment of the magnetizations. [3]

As the applied field is increased, the magnetic moments of the ferromagnetic layers progressively rotate towards the field, leading to a decrease in the resistance of the multilayer. At saturation the magnetizations end up in a configuration of parallel alignment with the lowest value of the resistance. Fig. 3 shows the variation in the resistance of the Fe/Cr multilayer. The highest magnitude of GMR in these experiments was found of 79% at T = 4.2 K. The GMR effect was ascribed to the spin-dependent transmission of the conduction electrons between the Fe and Cr layers.

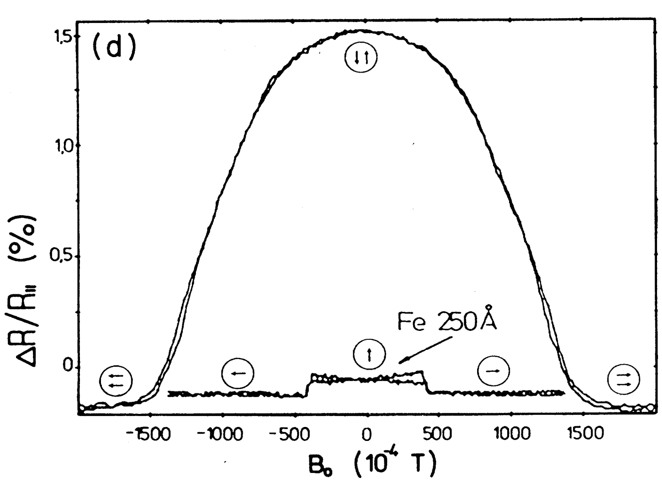

Figure 2: Magnetoresistance from Fe double layers with antiferromagnetic coupling, and also the anisotropic MR effect of a only Fe film. [3, 7]

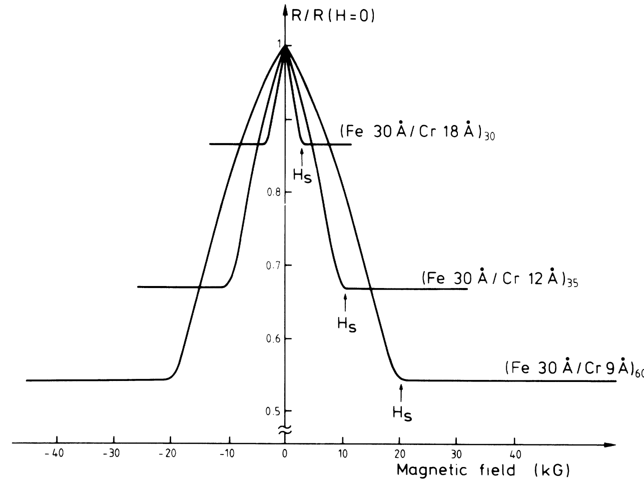

Figure 3: Magnetoresistance of three Fe/Cr superlattices at 4.2 K. [1]

Theory

Sir Nevil Mott proposed a two-current model for the description of the electrical resistivity of magnetic alloys[10]. This model is based on the fact that the resistivity is due to electron scattering. In magnetic materials, this is dependent on spin orientation. Due to the quantum mechanical spatial quantization, this orientation is only parallel or antiparallel with respect to the local magnetization. As spin flip processes occur seldom, each of the two orientations defines a current. With this picture, one expects that there would be a strong resistivity change if one could manage to change the direction of the local magnetization within the mean free path of the electrons or on an even shorter scale. In a case where the scattering rates are different, there is a better chance that the total scattering rate is increased. As mean free paths are of the order of 10 nm, the 1 nm thickness by which the magnetic layers are separated in the coupled structures perfectly fulfills this condition.

Let's consider the magnetic multilayer, which is made of cobalt and copper (Fig. 4). The cobalt ferromagnetic layers (FM) are separated by copper nonmagnetic (NM) spacer layers. Due to antiferromagnetic interlayer exchange coupling they are aligned antiparallel at zero magnetic field as is indicated by the blue and red arrows. Under the external magnetic field, at the saturation field the magnetic moments are aligned parallel (the blue arrows).

Using Mott's arguments it is straightforward to explain GMR in magnetic multilayers. We consider the two-current model that a current is consist of each spin-up (blue arrow) and spin-down (red arrow) electrons movement, and a sample is made of combinations of ferromagnetic and non-magnetic metals layers simultaneously as is shown in Fig. 4, and assume that the scattering is strong for electrons with spin antiparallel to the magnetization direction, and is weak for electrons with spin parallel to the magnetization direction. This is supposed to reflect the asymmetry in the density of states at the Fermi level, in accordance with Mott's second argu-

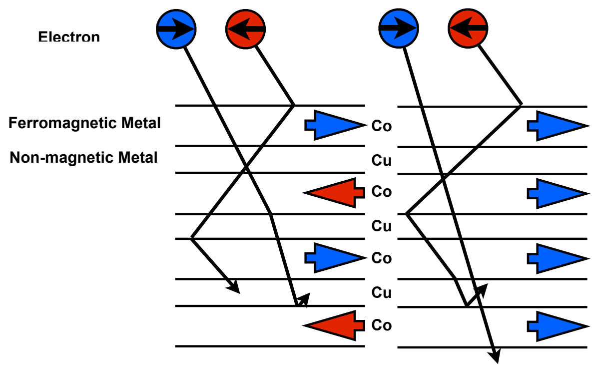

Figure 4: Left: antiferromagnetic alignment, Right: parallel alignment

ment. For the antiparallel-aligned multilayer, left figure in Fig. 4, both the up-spin and down-spin electrons are scattered strongly within one of the ferromagnetic layers, because within the one of the layers the spin is antiparallel to the magnetization direction. Thus, in this case the total resistivity of the multilayer is high. For the parallelaligned magnetic layers, right one in Fig. 4, the up-spin electrons pass through the structure almost without scattering, because their spin is parallel to the magnetization of the layers. On the other hand, the down-spin electrons are scattered strongly within both ferromagnetic layers, because their spin is antiparallel to the magnetization of the layers. Since conduction occurs in parallel for the two spin channels, the total resistivity of the multilayer is determined mainly by the highly-conductive up-spin electrons and appears to be low.

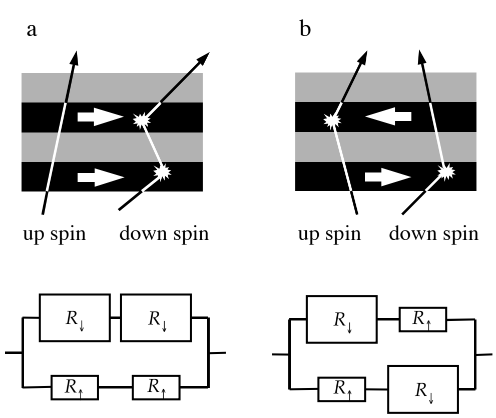

Figure 5: Schematic illustration of electron transport in a multilayer for parallel (a) and antiparallel (b) magnetizations of the successive ferromagnetic layers. The magnetization directions are indicated by the arrows. The solid lines are individual electron pathes with the two spin channels. Bottom panels show the resistor network within the two-current series resistor model[12].

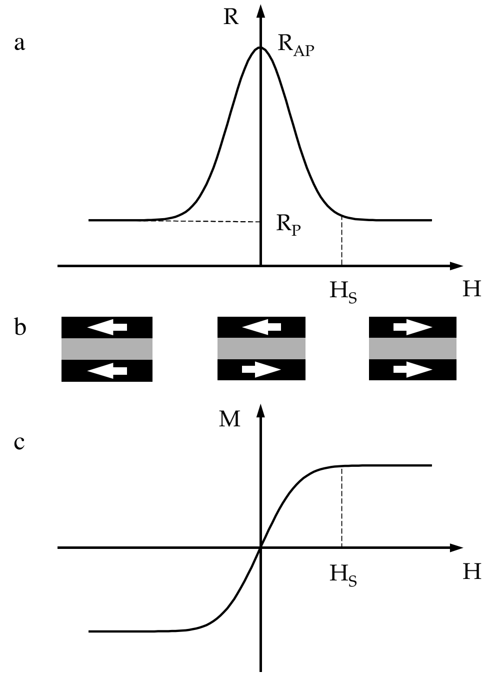

Figure 6: Schematic of the GMR effect. (a): Change in the resistance of the magnetic multilayer as a function of applied magnetic field. (b): The magnetization configurations of the multilayer: the magnetizations are aligned antiparallel at zero field; the magnetizations are aligned parallel when the external magnetic field H is larger than the saturation field HS. (c): The magnetization curve for the multilayer. [12]

There are generally two different geometry of GMR, i.e. current perpendicular to plane (CPP)-MR[2] and the more usual current in plane (CIP)-MR.[1, 3] CIP geometry is currently used for the industrial applications of GMR. CPP geometry is much more difficult. This is due to the very small thickness of the multilayer and consequently the very low CPP resistance, which is not easy to detect. [12]

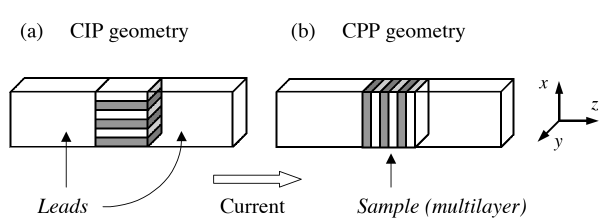

Figure 7: Geometry for the CIP (a) and CPP (b) GMR. A sample (a magnetic multilayer) is placed between semiinfinite perfect leads. The electric current flows in the z direction. [12]

Current and Futher Applications

The discovery of GMR has heavily contributed in HDD's read heads technology. Anisotropic magnetoresistance (AMR) read heads had been used for a long time, however the amplitude of magnetoresistance is weak (up to a few percent variation on changing the relative orientation of magnetization and current). AMR read heads was approaching its sensitivity limit with the reduction of the head and the bits dimension. Nevertheless, the introduction of the spin-valve based (GMR) read head by IBM in 1997 immediately increased growth rate for storage areal density up to 100 percent per year (Fig. 8)[4]. In more details, the spin-valve sensor is just a trilayer film in which one layer has its magnetization pinned along on orientation. The rotation of the free layer magnetization then control the flow of electrons by giant magnetoresistance effect. The standard spin valve shows about 5~6 % magnetoresistance. Therefore, the sequential introduction of the magnetoresistance and spin-valve head, by providing a sensitive and scalable read technique, contributed to increase the raw HDD areal recording density by three order of magnitude around 10 years.

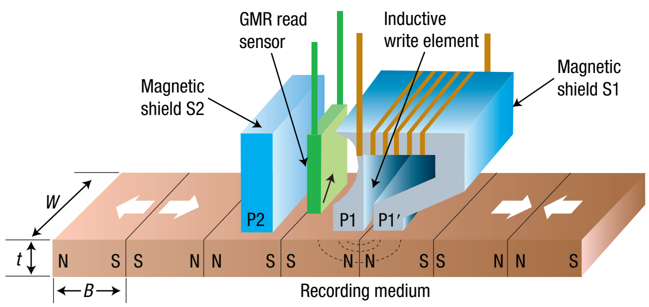

Figure 8: Magnetoresistance head for hard-disk recording. Schematic structure of the magnetoresistive head introduced by IBM in 1991. [4]

GMR has motivated people to develop solid state magnetic storage. The free layer magnetization of the spin valve is constrained to take only the two opposite orientation of an easy magnetization axis, arrays of patterned spin-valve elements can be sued to store binary information with resistive readout. By replacing the non-magnetic metallic spacer layer of the pin valve by a thin non-magnetic insulating layer, so creating a magnetic tunnel junction (MTJ). In this structure, the electrons travel from one ferromagnetic layer to the other by a tunnel effect, which conserves the spin. Since the discovery of TMJ in 1994, a research of developing magnetic random access memories (MRAM) has started. The principle of MRAM is shown in Fig. 9. The binary information 0 and 1 is recorded on the two opposite orientations of the magnetization of the free layer along its easy magnetization axis. The MTJs are connected to the crossing points of two perpendicular arrays of parallel conducting lines. For writing, current pulses are sent through one line of each array, and only at the crossing point of these lines is the resulting magnetic field high enough to orient the magnetization of the free layer. For reading the resistance between the two lines connecting the addressed cell is measured.

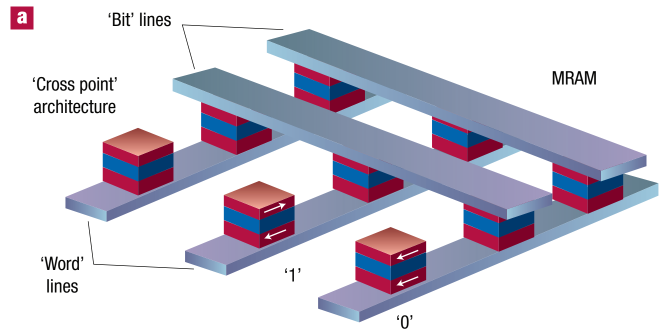

Figure 9: Magnetic random access memory. Principle of MRAM, in the basic cross-point architecture. The binary information 0 and 1 is recorded on the two opposite orientations of the magnetization of the free layer of magnetic tunnel junctions (MTJ). [4]

Conclusion

Since the discovery of giant magnetoresistance (GMR), people has been studied a fundamental physics behinds the phenomenon and applications of using the effect. The GMR has been a huge impact on our life, especially for mass data storage devices. GMR's application to the read head of hard discs greatly contributed to the fast rise in the density of stored information and led to the extension of the hard disk technology to consumer's electronics. Besides in terms of further technological advances, the development of spintronics revealed many other phenomena related to the control and manipulation of spin currents. Thus basically GMR of the magnetic multilayers opened the way to an efficient control of the motion of the electrons by acting on their spin through the orientation of a magnetization.

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