Giant Magnetoresistance

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This paper briefly introduces anisotropic magnetoresistance, the forerunner of giant magnetoresistance, and then presents a topical discussion of the science of GMR as well as the history of the discovery of GMR. The practical use of GMR within computer hard drive technology is outlined, as well as GMR's impact on the storage media industry over the past ten years.

I. INTRODUCTION

In today's world of portable, high capacity music players and consumer hard drives with storage sizes of up to a terabyte, the ubiquitousness of information and the space to store it seems to be almost taken for granted in our society. However, the emergence of such vast and economical storage of data has only occurred within the past 10 years. The most prominent driving force of this technological revolution can be traced back to the discovery of the phenomenon known as giant magnetoresistance (GMR). Giant magnetoresistance is an outstanding example of the many ways in which research in fundamental science can produce surprisingly large advancements in industrial and consumer technology.

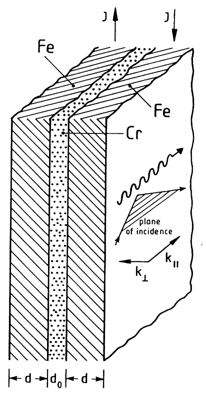

FIG. 1: A trilayer Fe-Cr-Fe sample used in Grünberg's original paper on GMR.[3]

II. SCIENCE OF GMR

A. Anisotropic Magnetoresistance

Before delving into the science of giant magnetoresistance, it is beneficial to briefly look at the anisotropic magnetoresistance effect. In 1857, long before the first papers on GMR were published in 1988, the British physicist Lord Kelvin had already reported "that iron, when subjected to a magnetic force, acquires an increase in resistance to the conduction of electricity along, and a diminution of resistance to the conduction of electricity across, the lines of magnetization."[1] This effect was known as Anisotropic Magnetoresistance (AMR), and its cause is electron spin-orbit coupling. As will be described later, AMR can be used to detect changes in magnetization, and it was the basis of hard drive read sensors before the discovery of GMR. However, the magnitude of the AMR effect is usually small, with a resistance change on the order of a few percent[1]. This limits its sensitivity to weak magnetic fields. giant magnetoresistance produces a far larger change in resistance, and therefore can be used to detect much weaker fields.

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B. Giant Magnetoresistance

GMR can be understood using the Mott model, introduced in 1936.[2]. The key observations of this model are as follows:

- The electrical conductivity in metals can be described in terms of two largely independent conducting channels, corresponding to the up-spin and down-spin electrons, and electrical conduction occurs in parallel for the two channels.
- In ferromagnetic metals the scattering rates of the up-spin and down-spin electrons are different.

In the subsequent discussion, we will assume that the scattering is strong for electrons with spin antiparallel to the magnetization direction and weak for electrons with spin parallel to the magnetization direction.

The simplest system in which to examine GMR consists of a thin layer of nonmagnetic material sandwiched between two layers of magnetic material, as shown in figure 1. Consider a current passing through such a structure. If the magnetizations of both magnetic layers are aligned, then those electrons with parallel spin will pass through the structure with little scattering, resulting in low resistance. This situation is shown in figure 2, with the corresponding circuit diagram representation in figure 3.

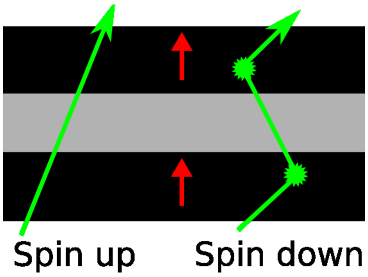

FIG. 2: A trilayer structure with parallel magnetization. The black regions are the magnetized layers, the gray region is the nonmagnetic spacer layer, the red arrows represent the direction of magnetization (aligned with spin up) within the magnetic layers, and the green arrows represent electron paths.

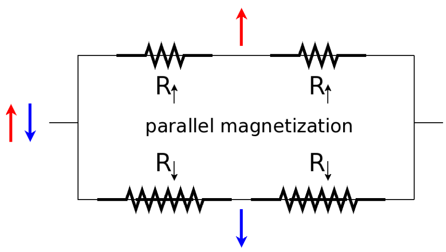

FIG. 3: Circuit diagram representation of figure 2. The red and blue arrows indicate the up spin and down spin electron conduction channels, respectively. Therefore the top path is the spin up channel, and the bottom path is the spin down channel.

However, if the magnetizations of the magnetic layers are antiparallel, then all electrons passing through the structure will experience strong scattering in one layer or the other, resulting in increased resistance, as shown in figures 4 and 5.

To see this explicitly, refer to the parallel case in figure 3 and let the resistance of the spin up electrons through the ferromagnetic layers be $R_\uparrow$ and the resistance of the spin down electrons through the ferromagnetic layers be $R_\downarrow$. By addition of resistances, the total resistance for the parallel case is $R_{\text{para}} = \frac{2R_\uparrow R_\downarrow}{R_\uparrow + R_\downarrow}$. Now, in the antiparallel case in figure 5, the spin up and spin down electrons will still experience a resistance of $R_\uparrow$ and $R_\downarrow$, respectively, in the magnetic layers aligned with them, but they will experience the opposite resistance in the layers antialigned with them. Therefore the total resistance for the antiparallel case is $R_{\text{antipara}} = \frac{1}{2}(R_\uparrow + R_\downarrow)$, and the difference in resistance is given by

$$\Delta R = R_{\text{para}} - R_{\text{antipara}} = -\frac{1}{2}\frac{(R_\uparrow - R_\downarrow)^2}{(R_\uparrow + R_\downarrow)}$$

III. DISCOVERY OF GMR

The giant magnetoresistance effect was first observed independently by Professor Albert Fert of Université

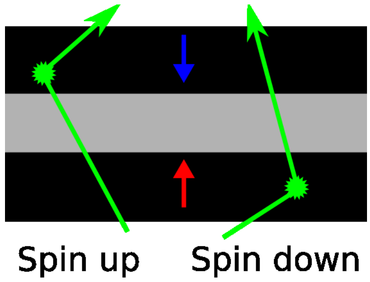

FIG. 4: A trilayer structure with antiparallel magnetization. The black regions are the magnetized layers, the gray region is the nonmagnetic spacer layer, the red and blue arrows represent the direction of magnetization (aligned with spin up and spin down, respectively) within the magnetic layers, and the green arrows represent electron paths.

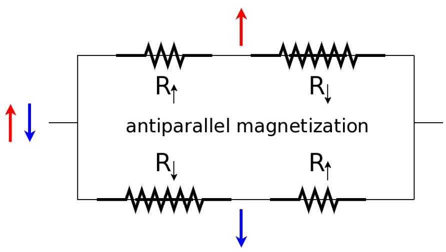

FIG. 5: Circuit diagram representation of figure 4. The red and blue arrows indicate the up spin and down spin electron conduction channels, respectively. Therefore the top path is the spin up channel, and the bottom path is the spin down channel.

Paris-Sud in France and Professor Peter Grünberg of Forschungszentrum in Jülich, Germany.[4] Both research groups observed that, when a magnetic field was applied to a structure consisting of thin iron and chromium layers, a significant decrease in electrical resistance resulted. In Fert's case, using a 60-bilayered structure at 4.2 K, a nearly 50% drop in resistance was observed, as shown in figure 6, while Grünberg reported a 1.5% drop in a Fe-Cr-Fe trilayer (Fig. 1) at room temperature as shown in figure 7 as well as a 10% drop in a trilayer at 5 K. The results of both groups' experiments were submitted to *Physical Review* in the summer of 1988.[4] Realizing the potential applications of this phenomenon for developing improved magnetic sensor devices, Stuart Parkin of I.B.M.'s Almaden Research Center attempted to reproduce the effect[6]. However, whereas Grünberg's and Fert's samples had been prepared by molecular beam epitaxy, Parkin used sputtering, a faster and cheaper, though less exact, method to prepare his samples. Parkin's group succeeded in reproducing the earlier results, observing the giant magnetoresistance effect in the first multilayer samples produced.[6] With this success and the ability to produce multilayer samples quickly and economically through the sputtering method, the Almaden labs, lead by Bruce Gurney, began to experiment with variations of sample composi-

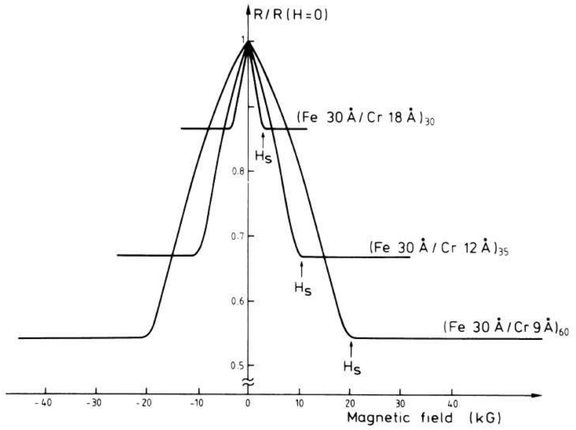

FIG. 6: The results from Fert's original paper. T = 4.2 K. The current and the applied magnetic field are along the same axis in the plane of the layers.[5]

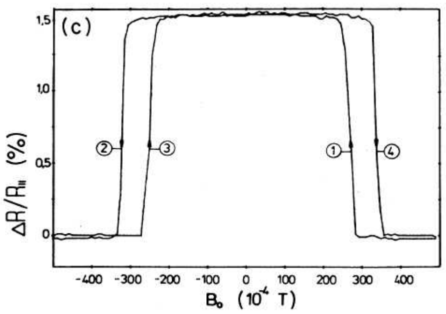

FIG. 7: The results from Grünberg's original paper. T = room temperature. The current and the applied magnetic field are along the same axis in the plane of the layers. [3]

tions and layer thicknesses to learn how giant magnetoresistance worked and how to achieve GMR effects under room-temperature, low-field conditions with the goal of using GMR to improve hard drive sensor technology.

IV. APPLICATION OF GMR

A. Hard Drive Technology

The basic method by which computer hard drives store and recall information works by magnetizing discrete areas of the disk and then scanning those areas, reading a certain direction of magnetization as a binary one, and the opposite direction as a binary zero. These magnetized regions encode the "bits" of information within the drive. Before the discovery of GMR, a common method of reading this information relied on anisotropic magnetoresistance (AMR). A current would pass through the magnetic conducting AMR read sensor as it travelled over the hard drive disk. As the magnetic regions passed under the AMR sensor, they would alter the magnetization

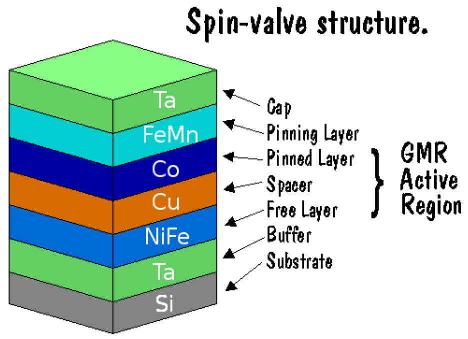

FIG. 8: A spin valve structure. The Si substrate is 1 mm thick, the entire spin valve structure is 300 Å thick, and the active GMR region is roughly 100 Å thick.[7]

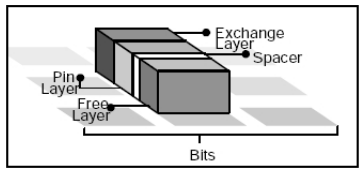

FIG. 9: A GMR spin valve reading data bits[8]

of the AMR device. Since resistance in the AMR device is based on the relative angle of the current and the device's magnetization, this would produce a change in the resistance of the AMR device, and therefore a change in the magnitude of the current passing though it, which could then be interpreted as a binary one or a binary zero.

In order to store more information on a hard disk without increasing its size, the size of the discrete magnetized areas must shrink. However, this also means that the magnetic field in each area becomes weaker and harder to detect. Therefore, increasing hard drive information storage density requires developing a more sensitive method of reading magnetic fields. The giant magnetoresistance effect, far more sensitive to magnetic fields than anisotropic magnetoresistance, provides just such a method.

In practice, GMR is utilized in hard drive read heads through the integration of a spin valve. A typical spin valve structure is shown in figure 8. The Si layer is the substrate, the Ta layers serve as end caps to provide a good surface to grow on and to prevent oxidation, and the antiferromagnetic FeMn layer pins the magnetization of the first active GMR layer (in this case, the Co layer) The Cu layer is the nonmagnetic separation layer, and the NiFe layer is the second magnetic layer, in this case free to change its magnetization. The Co and NiFe layers correspond to the two black layers in figures 2 and 4, and the Cu layer corresponds to the gray layer in figures 2 and 4. The process of using a spin valve to read information from a hard disk, illustrated in figure 9, is similar to that employed by AMR sensors. Current runs through the spin valve located on the drive read head. As

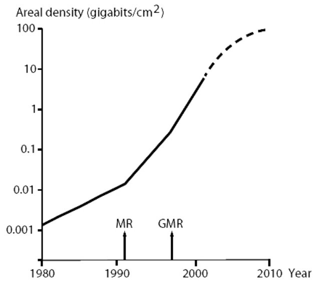

FIG. 10: Areal density of information storage versus year. Note that the density axis is plotted on a logarithmic scale. [11]

the spin valve passes over the magnetized regions of the hard drive, the magnetization of the free layer changes in response to the magnetic field of the bit. As the relative alignment between the magnetization of the free layer and the magnetization of the fixed layer changes, this in turn produces a significant change in the electrical resistance of the spin valve, much stronger than the change produced by AMR, which again registers as a change in the current passing through the spin valve and is interpreted as a binary one or zero. While the resistance changes in AMR devices are approximately 2 percent, they are typically at least 7 to 8 percent in GMR devices.[9]

B. Impact of GMR on the Storage Media Industry

Application of the greater magnetic sensitivity of GMR-based spin valves to hard drive technology provided a breakthrough in increasing information storage density. By the late 1990s, GMR was understood well enough to begin mass producing hard drives incorporating spin valve technology. I.B.M. deployed the first such hard drive in 1997 with its Deskstar 16 GP, capable of storing 16.8 gigabytes of data [10]. It set a new world record in disk drive information density of about 2.7 billion bits per square inch [10], and the maximum achievable areal information density continued to increase at a much faster rate than was possible in earlier decades, as shown in figure 10.

In addition, figure 11 shows that the commercial introduction of GMR-based hard drives also dramatically lowered the cost per gigabyte of hard drives, placing large amounts of economical data storage within the hands of everyone, from scientists to multimedia artists. In 2007, nearly 20 years after the initial discovery of giant magnetoresistance, Albert Fert and Peter Grünberg were honored with the Nobel Prize in physics for their contribution to the advancement of digital storage technology.[13] In the same year, those advances made possible by GMR produced the first one terabyte consumer hard drive. [14].

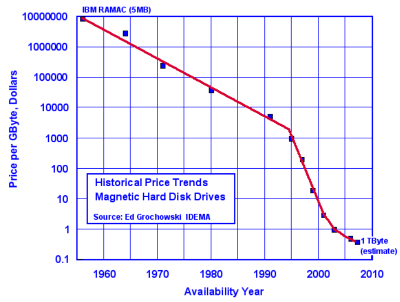

FIG. 11: Price per GB of storage (in US dollars) verses year. Notice the sharp drop occurring around 1997, the year I.B.M. introduced the first GMR-based consumer hard drives. [12]

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