A Review of Anisotropic Magnetoresistance Effects in Ferromagnetic Semiconductors

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I. ABSTRACT

Anisotropic magnetoresistance (AMR) is a property of magnetic materials that has many applications in the field of spintronics. This review firstly describes the basic physics of the phenomenon, then provides an insight on the useful applications of this effect in the field of spintronics. Finally, a few summaries of recent research being carried out to understand the effect of AMR in semiconductors, in particular, the ferromagnetic(FM) semiconductor GaMgAs (gallium manganese arsenide), are given. The summaries focus on two widely studied advancements of AMR research: enhancing the Curie temperature and observing TAMR effects in GaMgAs. A conclusion and speculations about future research direction are included at the end.

II. INTRODUCTION

Electric resistance is a measure of how much opposition an electric current encounters when flowing through a material. In certain materials, this resistance is also dependent on the magnitude and direction of the magnetization applied to the material. This phenomenon is known as anisotropic magnetoresistance (AMR). Scottish physicist Lord Kelvin first observed this phenomenon in 1856 by experimenting with pieces of ferromagnetic metals — iron and nickel[1]. He discovered that the resistance decreased when the direction of magnetic force was perpendicular to the current and increased when their directions were aligned. The applications of AMR can be found in spintronics, a solid-state technology where the spins of electrons are manipulated to create useful properties. Spintronics is used in a variety of technologies, e.g. navigation systems in vehicles and hard disks for data storage[2].

Most modern-day electronic devices use charge to store information. Moore's Law states that the number of transistors in an integrated circuit doubles every two years, which enables a higher capacity of data storage and a smaller size of device. However, as components reach a nanoscopic scale, the issue of charge leakage (loss of information) arises. Spintronics can solve this issue by encoding information based on the spin configurations of electrons. Spin configurations can be changed by applying a magnetic field to them, and this is a consistent and reliable way to store information. Having non-volatile memory can also significantly lower the power consumption in integrated circuits.

There are two types of spintronics: metal-based and semiconductor-based. Semiconductor-based spintronics devices may have more flexible designs than metal-based spintronics because semiconductors can be adjusted to give different properties[3]. Semiconductors have a resistivity somewhere between that of conductors and insulators. They are used in all kinds of electronic devices and are important to economic growth. In recent years, there's been a greater emphasis on research focusing on how to combine the fields of semiconductors and spintronics together, as this could potentially transform contemporary information storage technology.

III. AMR AND CURIE TEMPERATURE

AMR arises from the combined effects of spin-orbit interaction and the asymmetry in the arrangement of a ferromagnetically ordered state of the system[4]. Semiconductors change their conductivity by doping with impurities to increase the number of charge carriers. Semiconductors doped with transition metals are known as Dilute Magnetic Semiconductors (DMS), and their ferromagnetism can be manipulated by the amount of doping. A lot of semiconductor-based spintronics research uses GaMnAs, which is considered as a prototype of ferromagnetic semiconductor to be studied and to have theories tested on. The low Curie temperature of ferromagnetic semiconductors is an obstacle to their being used in devices that operate at room temperature. Vašek et al. [5] conducted an experimental study on two sets of GaMnAs samples to understand the behaviour of the AMR effect on the materials. Theoretically speaking, the density of free holes provided by impurities should be a main contributing factor to the ferromagnetic properties, such as the Curie temperature, of a material. The concentration of holes was controlled by annealing and hydrogenation. The results showed that the concentration of free holes is not the only determining parameter and suggested that anisotropy of the scattering rate could be the other important control parameter that influences the ferromagnetism. This study gives an insight into the dependence of the Curie temperature on the change of strain from doping and the scattering rate. Future studies of Curie-temperature could use this as a reference to test if strain engineering and accelerating the scattering rate could be a method to increase the Curie temperature.

In 2011, Chen et al. [6] explored the technique of enhancing the Curie temperature of GaMnAs films via nanostructure engineering. They increased Curie temperature from the previous limit of 193K up to 200K. This is not a significant increase, but the research also suggested that higher temperatures could be achieved by enhancing the nanodevices' efficiency of annealing and using FM films with a high priorly annealed Curie temperature. This method can be used as a reference to future research into operating FM semiconductors at standard ambient temperature. In 2002, Jungwirth et al. [7] carried out a theoretical study that has led them to conclude that the sign and magnitude of the AMR effect in a sample supposedly can be changed by tuning its chemical composition. Howells et al. [8] conducted a physical experiment to investigate the parameters that affect the AMR effect present in a quaternary FM semiconductor, GaMnAsSb. The electromagnetic properties of this material can be manipulated through changing the alloy composition. The cross cubic term is a factor that contributes to the total AMR effect. The researchers have noticed that the GaMnAsSb sample has a cross cubic term that is 5 times bigger than what's been observed for a GaMnAs sample. This increase could originate from GaMnAsSb having a bigger compressive strain from incorporating Sb ions or having a stronger spin-orbit interaction than GaMnAs. The results they obtained suggested that by arranging the chemical composition of the semiconductor, accurate control of the AMR effect could be achieved. A similar study on GaMnAsP by Lee et al. [9] further proved the incorporation of the relatively small P ions into the host lattice changes the tensile strain on the film, hence alternating the magnetic behaviour of the sample.

IV. THE POTENTIAL OF AFM SEMICONDUCTORS

In recent years, the interests of the AMR effect in antiferromagnetic (AFM) semiconductors as opposed to ferromagnetic semiconductors have risen. Theoretically speaking, the AMR effect is equally present in both AFM and FM semiconductors. A study published by Nature in 2014 suggested a new direction for semiconductor based spintronics [10]. The team observed the AMR effect in an AFM semiconductor, Sr2IrO. Their results show that non-negligible AMR signals can be easily found in this AFM semiconductor, and that in SIO materials with low impurity concentrations AMR signal could potentially be siginificantly increased. Instead of focusing on FM semiconductors, which have a low Curie temperature, many AFM semiconductors can work at room temperature. Both TMR and TAMR effects have been observed in AFM semiconductors.

V. THE TUNNELING ANISOTROPIC MAGNETORESISTANCE (TAMR)

In 1975, Michel Jullière discovered the Tunnelling magnetoresistance (TMR) effect in magnetic tunnel conjunction (MTJ), which is a barrier between two films of conductive materials. Particles can pass through the tunnel conjunction by quantum tunnelling. In TMR, electric conductivity depends on the relative direction of magnetizations of the two films[11].

In 2006, a team of scientists investigated an effect known as Tunneling Anisotropic Magnetoresistance (TAMR) present in GaMnAs, where conductivity also depends on the absolute direction of magnetizations[12]. They found the TAMR effect is present from 1.6K to 20K and it involves just a single layer of ferromagnetic film as opposed to the two layers required by TMR. They also discovered that the signal disappears before the temperature reaches 30K. Their study suggested that the magnitude of the TAMR effect depends on the Mn spin density and various other parameters of the film. TAMR is a recently discovered effect that could give alternative spintronics applications. It is too early to conclude how much of an impact it will have on the advancement of the field of spintronics, however, the elimination of the need for a second FM layer in the TAMR phenomenon provides an insight to explore the potential of using this structure at room temperature. This could be useful for widely marketed and more accessible quantum computing.

VI. RESULTS

Spintronics associated AMR effects, such as TAMR, have been observed in GaMnAs, which may serve as an important prototype in spintronics application studies. The understanding of the AMR effect in semiconductors is crucial for merging the field of semiconductors with the field of spintronics to create new nanotechnology devices. This promising field of research is still at a preliminary stage of development. The applications of semiconductor-based spintronics include non-volatile memory devices, spin-transistors, and magnetic sensing, with many more exciting possibilities that are waiting to be explored.

One research aim is to use semiconductor-based spintronics devices at room temperature. To achieve this, more extensive research needs to be done to arrive at a fundamental breakthrough in enhancing the Curie temperature of FM semiconductors through nanotechnology engineering. Alternatively, AFM semiconductors instead of FM semiconductors could be used as a prototype for future study as they operate at room temperature. The realisation of semiconductors at room temperature will introduce a new class of spintronic devices and transform the microelectronics industry.

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