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Study of various Spintronics devices and their effects and mechanism in magnetic field

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ABSTRACT

This work is devoted to the study of various Spintronic devices and their effects in magnetic field and devices. Currently, there is much interest in the development of Spin-torque devices, in which harnessing the spins of electrons (rather than just their charges) is anticipated to provide new functionalities that go beyond those possible with conventional electronic devices. One widely studied example of an effect that has its roots in the electron's spin degree of freedom is the torque exerted by a spin-polarized electric current on the spin moment of a nano- metre-scale magnet. The discovery of the spin torque effect has made magnetic nano devices realistic candidates for active elements of memory devices and applications.

Keywords: Spintronics, spin torque devices, magnetic, applications.

INTRODUCTION

Spintronics is also known as spinelectronics or fluxtronics. It is the study of the intrinsic spin of the electron and its associated magnetic moment, in addition to its fundamental electronic charge, in solid-state devices.

Spintronics differs from the older magnetoelectronics in that spins are manipulated by both magnetic and electrical fields. The electrons that carry charge current in electronic circuits also have spins. In non-ferromagnetic samples, the spins are usually randomly oriented and do not play a role in the behavior of the device. However, when ferromagnetic components are incorporated into a device, the flowing electrons can become partially spin polarized and these spins can play an important role in device function. Due to spin-based interactions between the ferromagnets and electrons, the orientations of the magnetization for ferromagnetic elements can determine the amount of current flow. By means of these same interactions, the electron spins can also influence the orientations of the magnetizations. This last effect, the so-called spin transfer torque, is the topic of the following series of articles.

Spintronics emerged from discoveries in the 1980s concerning spin-dependent electron transport phenomena in solid-state devices. This includes the observation of spin-polarized electron injection from a ferromagnetic metal to a normal metal by Johnson and Silsbee and the discovery of giant magnetoresistance independently by Albert Fert et al. and Peter Grünberg et al. The origins of spintronics can be traced to the ferromagnet/superconductor tunneling experiments pioneered by Meservey and Tedrow and initial experiments on magnetic tunnel junctions by Julliere in the 1970s. The use of semiconductors for spintronics began with the theoretical proposal of a spin field-effect-transistor by Datta and Das in 1990 and of the electric dipole spin resonance by Rashba in 1960.

The torque causes the magnetic moment to rotate 1–19 at potentially useful frequencies. Here we report a very different phenomenon that is also based on the interplay between spin dynamics and spin-dependent transport, and which arises from unusual diode behaviour. We show that the application of a small radio-frequency alternating current to a nanometre-scale magnetic tunnel junction 20–22 can generate a measurable direct-current (d.c.) voltage across the device when the frequency is resonant with the spin oscillations that arise from the spin-torque effect: at resonance (which can be tuned by an external magnetic field), the structure exhibits different resistance states depending on the direction of the current. This behaviour is markedly different from that of a conventional semiconductor diode23, and could form the basis of a nano- metre-scale radio-frequency detector in telecommunication circuits.

We have discussed and make analysis on a magnetic tunnel junction (MTJ) in the structure Si (substrate)/PtMn (15 nm)/CoFe (2.5 nm)/Ru (0.85 nm)/CoFeB (3 nm)/MgO (0.85 nm)/CoFeB (3 nm); see Fig. 1a. This multi-layered film was further patterned into oval-shaped pillars of dimension 200 nm £ 100 nm, using electron-beam lithography and ion milling techniques. The bottom anti-ferromagnetically coupled CoFe and CoFeB layers (the synthetic antiferromagnetic layer) act as a pinned layer, while the top CoFeB layer acts as a free layer, whose magnetization can be changed. The resistance of the MTJ depends on the relative orientations of the pinned and free layers. The present MTJ shows a giant tunnelling magnetoresistance (TMR) due to the crystalline MgO (001) tunnelling barrier. A current passing through the MTJ gets spin-polarized by the pinned layer, and exerts a torque on the free layer.

The experimental arrangement to measure the diode effect is shown in Fig. 1a. A bias T is used to pass high-frequency current (200 MHz to 15 GHz) through the MTJ and to measure the d.c. voltage simultaneously. For all the experiments described here, the external magnetic field was applied at an angle of 308 from the pinned-layer magnetization axis within the film plane (see inset of Fig. 1b). In this geometry the sample showed a giant TMR of 100%, as shown in Fig. 1b. We also measured microwave power from the MTJ arising from the thermal fluctuations of the free-layer magnetization 24,25. The power was measured by a spectrum analyser, by passing a d.c. current of 1 mA using a bias T.

The radio frequency (r.f.) response of the MTJ was first tested using a network analyser. The results obtained showed evidence of magnetic resonance excited by r.f. current.

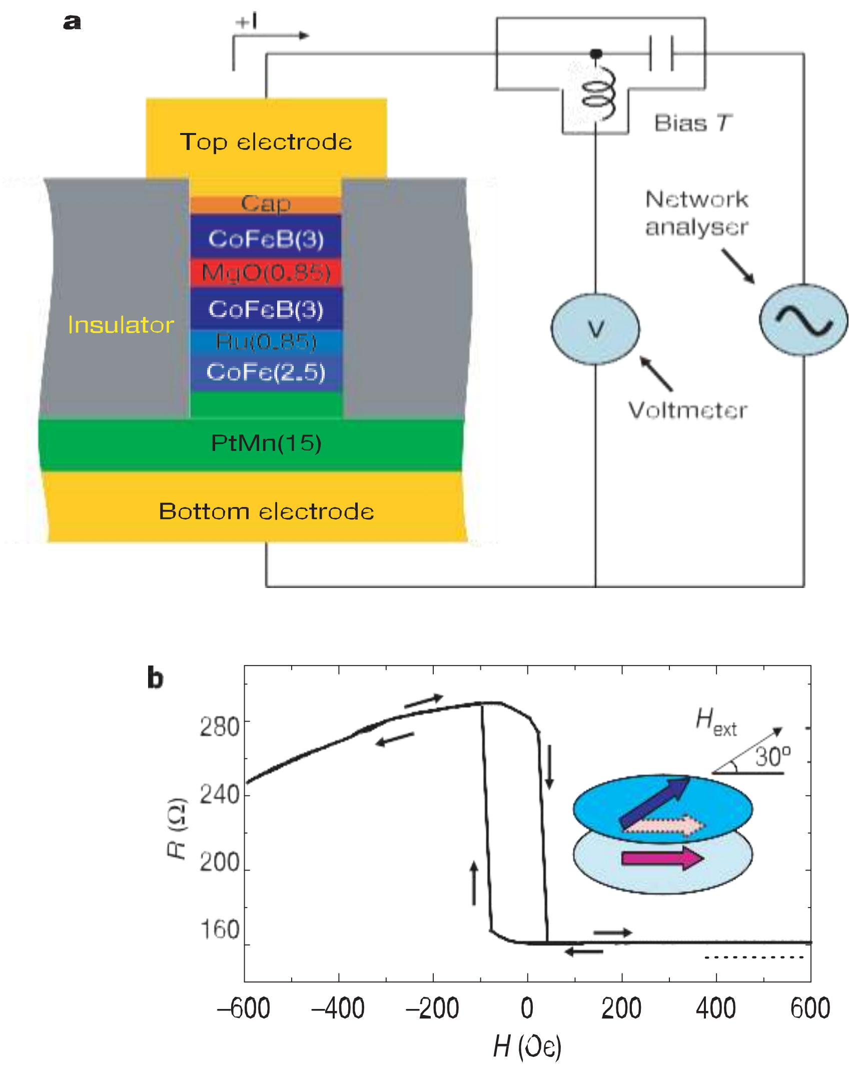


Figure 1: Schematic diagram of the experimental set-up and cross-sectional view of the magnetic tunnel junction (MTJ) device.

The thicknesses of various layers of the device in nanometres are given in brackets. The bottom CoFeB and CoFe layers, coupled anti-ferromagnetically through the Ru layer, act as a pinned layer. The top CoFeB layer acts as a free layer, the magnetization of which can be changed. The pinned and free layers are separated by a tunnelling MgO barrier. The experimental set-up measures the d.c. voltage produced across the device on applying the r.f. current. b, The magnetoresistance of the device, by applying magnetic field at 308 from the pinned-layer magnetization. The arrows indicate the sweeping direction of the magnetic field. Current-induced resonance has recently been observed also in a magnetic domain wall in the megahertz frequency range 26. The signal is, however, small, and its phase determination is prone to errors in the calibration of the network analyser. In contrast, we found that the MTJ produces d.c. voltage because of its nonlinear behaviour and this diode-effect measurement offers phase-problem-free results. The effect of alternating current (a.c.) on the precession of magnetization induced by large d.c. current has recently19 been studied.

However, in the present experiment, we excite the magnetization only with alternating current, without applying a d.c. bias. The d.c. voltage response measured by passing 0.55 mA of r.f. current is plotted in Figure 2. The response shows a large resonance structure, whose position depends on the magnetic field. Figure 3a shows the noise power spectra having a large peak, along with a small side peak, the positions of which also depend on the magnetic field.

BASIC PRINCIPLES & MECHANISM OF SPINTRONICS

The working principles of the spin-torque diode and the semi- conductor p–n junction diode are compared. When current flows from the n side to the p side, the space charge region around the p–n junction is enlarged, and so the resistance of the p–n junction is higher in this case. For the opposite direction of current, the space charge region is shrunk, which gives lower resistance. In the case of the spin-torque diode, the alternating current passing through it exerts a torque on the free-layer spin moment. When the frequency of the alternating current nears the precession frequency of the free-layer spin-moment, the spin is tilted towards the pinned-layer magnetization during the negative (or positive) half of the alternating current. This configuration has low resistance. During the next half of the alternating current, spin is tilted in the opposite direction, which is a high-resistance state. The difference in resistance during positive and negative currents produces d.c. voltage, in the case of both the diodes. In contrast to the semiconductor diode, the spin-torque diode is resistant to the noise because it produces d.c. voltage only in a narrow frequency range around the resonance frequency, which can be tuned by applying a magnetic field.

To begin with, let's understand how computation is done in conventional CMOS circuits. The computations in CMOS integrated circuits (ICs) use the movement of charges under the influence of electric fields: device operation mechanisms are based on how to block or unblock these charge movements. Consequently, device performance depends on the effectiveness of the barrier faced by the carriers and the propagation time of charges through the device. Although, device material and specific methods of controlling the barrier can vary, charge based devices will have similar basic device operation mechanisms. In other words, as long as charge movement is used to represent information, any new device idea can only make incremental improvements over CMOS. Fundamental change in the device architecture can be realized by identifying a new computational state variable other than the electronic charge. One of the most promising candidates for this alternative state variable is the spin or magnetic moment. Spin angular momentum, or simply spin is another intrinsic property of the electron in addition to its mass and charge. There are peculiar attributes of spin that make it an attractive candidate to supplant charge-based devices. First, spin angular momentum can be transferred between particles. It allows a spin signal to be transferred from a point A to B without transporting the particle. This opens up the possibility of building a logic device without movement of charge, which possibly can save energy, given that the energy to generate the spin signal does not offset the energy saving. Second, neighboring spins are coupled either positively or negatively. Depending on the material property, there is a tendency to align the neighboring spins in the same direction or the opposite direction. This is called exchange coupling, whose property extends to the macroscopic level and bi-layer ferromagnetic devices manifest two stable resistance states called magneto-resistance (MR) when two magnetic layers are positively coupled or negatively coupled as shown in figure 3.

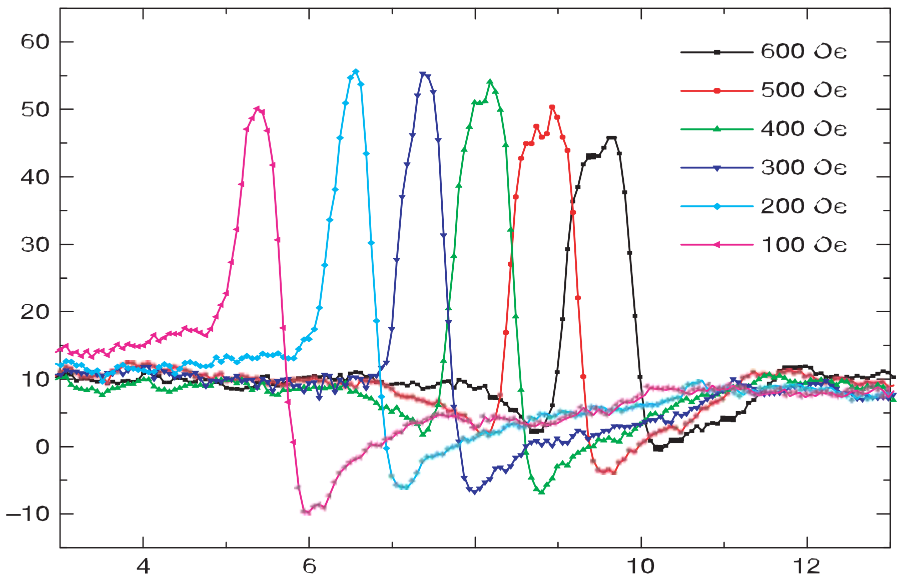
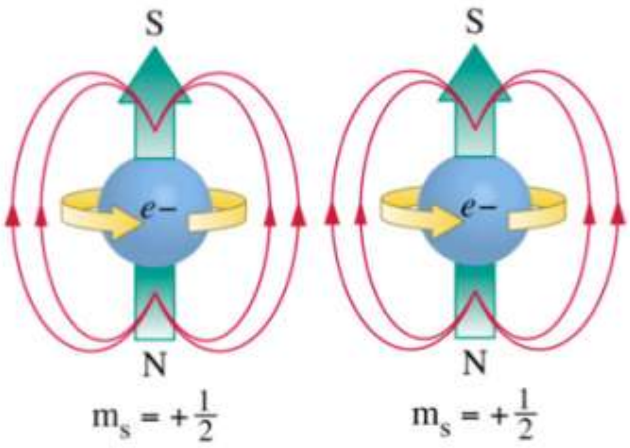
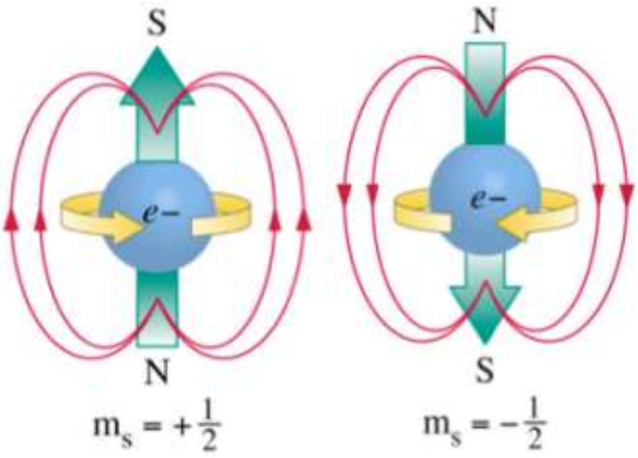


Figure 2: Direct-current voltage generated by the device in response to the alternating current. The d.c. voltage is plotted as a function of the frequency of the a.c. current (0.55 mA).



(a) Positive Coupling



(b) Negative Coupling

Figure 3: Exchange coupling of electron spins (a) positive coupling (b) negative coupling

Furthermore, magnetic devices can be electrically controlled with a phenomenon called spin-torque transfer, which will be discussed in detail in later sections. As a result, scalable nanomagnetic logic devices including those termed "Spintronic" devices are finally achievable by exploiting the extensive CMOS fabrication processes that are available today. For example, Figure 4 shows one of the most successful spintronic devices called a Magnetic Tunnel Junction (MTJ). It is a two terminal device with a sandwich structure of two ferromagnetic metals like Co, Fe, Ni that are separated by a tunneling oxide in the middle. It has many layers, perhaps as many as the burger on the left.

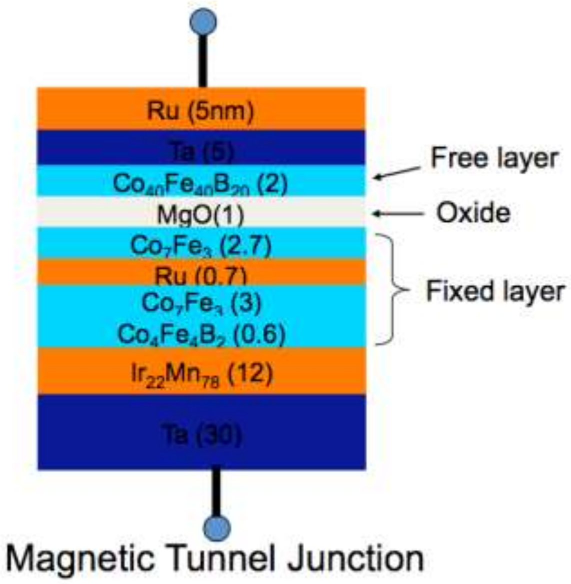


Figure 4: Magnetic Tunnel Junction.

This device is interesting because,

1. It has hysteresis between two resistance states

2. It is a magnetic device, whose magnetization can be controlled electrically

Two-terminal spintronics device is widely adopted for MRAM and hard disk drive readhead applications. It consists of two ferromagnetic layers (free, fixed layers), tunneling oxide layer and many others.

SPIN-TORQUE TRANSFER EFFECT AND MAGNETIC REVERSAL

The spins of neighboring electrons are "exchange" coupled: they have a tendency to align the neighboring spins in the same direction or the opposite direction. Now let's extend our discussion to the case when spin-polarized electrons are injected into non-polarized electrons. As the electrons from two groups encounter, non-polarized electrons increasingly become spin-polarized into the same spin directions as the injected electrons due to exchange coupling. This phenomenon can be macroscopically understood that there is a "transfer" of spin angular momentum and this time change in the spin is called spin-torque. Spin-torque transfer effect has a huge theoretical and practical significance, because it opens up a way to electrically control magnetic devices.

Spin-valves and MTJs are the most successful spin-torque devices. They are all in nano-pillar shape. Nano-pillars (cross-section of 100x100nm2) are suitable structure to observe spin-torque effect because,

i. it has a single magnetic domain, which is less random and has controllable magnetization
ii. it increases current density.
iii. spin-torque transfer phenomenon will be more effective at smaller dimension

Magnetic devices with an elliptical shape have an associated energy called *magnetic shape anisotropy*. Magnetizations in all the sub-domains tend to align to the longer axis. This can be explained by considering surface magnetic charges – imaginary magnetic charges always positioned at the surface or boundaries of the device as shown in figure 5. If the magnetization is aligned along the short axis, (i.e., the hard-axis) 1) the distance between the magnetization and the surface charge is short and 2) surface area also larger – more "magnetic" charges. These result in high magnetic potential energy. If the magnetization is aligned along the longer axis, (i.e., the easy axis), distance to the surface charges is large and the magnetic energy becomes smaller and magnetizations aligned along the easy-axis becomes more stable than in the hard-axis case.

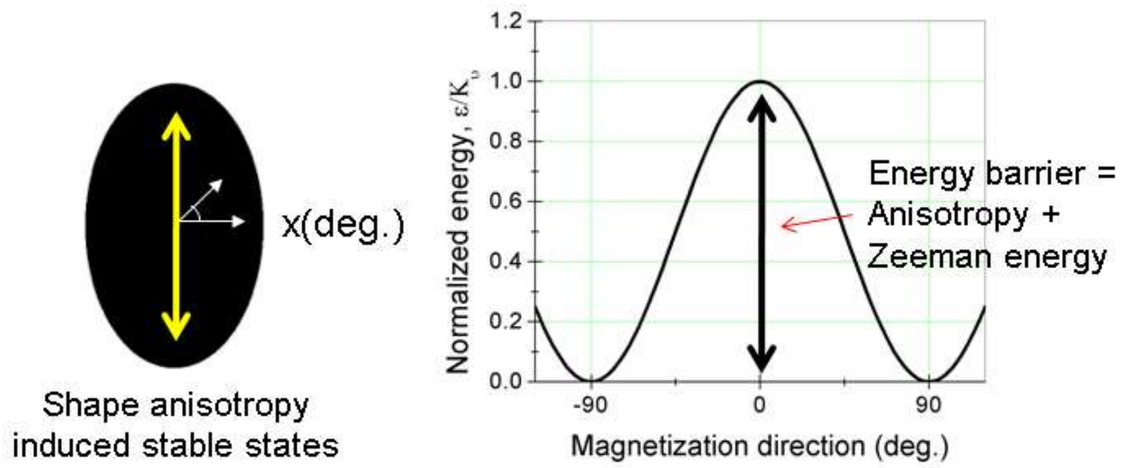


Figure 5: Energy barrier of nano-pillar shaped spin-torque device. The elliptical shape induces two stable states at +90◦ and -90◦ magnetizations

CONCLUSION

Despite the discovery of a number of fundamentally new spintronic phenomena and major progress in our understanding of the basic physics, we are still far from demonstrating useful logic devices which take advantage of spintronics. For example, for field effect transistors, which utilize spin currents, there are significant challenges in spininjection, spin transport and spin detection and, furthermore, in devising schemes that would enable them to compete in performance with conventional charge based devices. The magnetic coupled spintronic devices have power gain and fan-out, and can implement the entire Boolean logic family of devices. Magnetoresistive effects allow the read-out of increasingly small magnetic bits, and the spin torque provides an efficient tool to manipulate - precisely, rapidly and at low energy cost - the magnetic state, which is in turn the central information medium of spintronic devices.

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