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Spin Valve Transistors

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***Abstract*— In our conventional electronic devices we use semi conducting materials for logical operation and magnetic materials for storage, but spintronics uses magnetic materials for both purposes. These spintronic devices are more versatile and faster than the present one. One such device is spin valve transistor. Spin valve transistor is different from conventional transistor. In this for conduction we use spin polarization of electrons. Only electrons with correct spin polarization can travel successfully through the device. These transistors are used in data storage, signal processing, automation and robotics with less power consumption and results in less heat. This also finds its application in Quantum computing, in which we use Qubits instead of bits. In this paper, the physics underlying the operation of Spin Valve Transistors is explained, a brief details of its construction and working are presented, and issues of current interest are discussed.**

***Keywords*— Spintronics, spin, schottky barrier, magneto resistance**

I. Introduction

Two experiments in 1920's suggested spin as an additional property of the electron. One was the closely spaced splitting of Hydrogen spectralines, called fine structure. The other was Stern –Gerlach experiment, which in 1922 that a beam of silver atoms directed through an inhomogeneous magnetic field would be forced in to two beams. These pointed towards magnetism associated with the electrons.

Spin is the root cause of magnetism that makes an electron tiny magnet. Magnetism is already been exploited in recording devices. Where data is recorded and stored as tiny areas of magnetized iron or chromium oxide. To access that information the head detects the minute changes in magnetic field. This induces corresponding changes in the head's electrical resistance – a phenomenon called Magneto Resistance.

II. Evolution of Spintronics

Spintronics came into light by the advent of Giant Magneto Resistance (GMR) in 1988. GMR is 200 times stronger than ordinary Magneto Resistance. It results from subtle electron – spin effects in ultra-multilayers of magnetic materials that cause a huge change in electrical resistance. The discovery of Spin Valve Transistor (GMR in magnetic multilayers) has led to a large number of studies on GMR systems. Usually resistance of multilayer is measured with the Current in Plane (CIP). For instance, Read back magnetic heads uses this property. But this suffers from several drawbacks such as; shunting and channeling, particularly for uncoupled multilayers and for thick spaced layers diminish the CIP magneto resistance. Diffusive surface scattering reduces the magneto resistance for sandwiches and thin multilayers.

To erase these problems we measure with Current Perpendicular to the Plane (CPP), mainly because electrons cross all magnetic layers, but a practical difficulty is encountered; the perpendicular resistance of ultra-thin multilayers is too small to be measured by ordinary techniques. The use of Micro fabrication techniques for CPP measurements, from 4.2 K to 300 K was first shown for Fe/Cr multilayers, where the multilayers were etched into micropillars to obtain a relatively large resistance (a few milli ohms). These types of measurements have confirmed the larger MR for the CPP configuration, but they suffer from general complexity of realization and measurement techniques. Experiments using electro deposited nanowires showed CPP MR up to 15% at room temperature, such multilayers find an application in Spin Valve Transistors.

A spin valve multilayer serves as a base region of an n silicon metal base transistor structure. Metal base transistors have been proposed for ultrahigh frequency operations because of

1. Negligible base transport time.
2. Low base resistance, but low gain prospects have limited their emergence.

The first evidence of a spin valve effect for hot electrons in Co/Cu multilayers is the spin valve transistor. In this we see a very large change in collector current (215% at 77K) under application of magnetic field of 500 Oe. In spin valve transistor (SVT) electrons are injected in to metallic base across a Schottky barrier (Emitter side) pass through the spin valve and reach the opposite side (Collector side) of transistor. When these injected electrons traverse the metallic base electrons are above Fermi level, hence hot electron magneto transport should be considered in Spin Valve Transistor (SVT). The transport properties of hot electrons are different from Fermi electrons. For example spin polarization of Fermi electrons mainly depends on Density of States (DOS) at Fermi level, while the spin polarization of hot electron is related to the density of unoccupied states above the Fermi level. For the preparations of transistor we apply direct bonding, both to obtain device quality semiconductor material for the emitter and to allow room temperature processes.

III. Construction

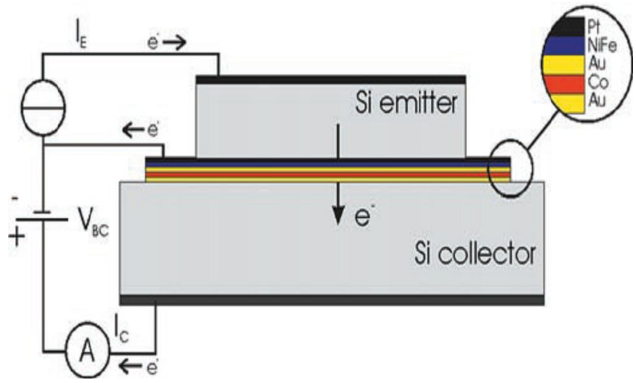

Fig. 1 Spinvalve Transistor

The starting material for both emitter and collector is a 380um, 5-10Ocm, n-si (100) wafer. After back side n++ implantation, wafer is dry oxidized to anneal the implant and to form a SIO2 layer .After depositing a Pt ohmic contact on to the back side, wafer is sawn in to 10X10mm collector and 1.6X1.6mm emitters. Collector is subsequently dipped in HNO3, 2% HF to remove the native oxide on silicon fragments, 5% Tetra methyl Ammonium Hydroxide at 90°, and buffered HF to remove thermal oxide .following each step the collector is rinsed in demineralized water. After this procedure base multilayer (Cu 2nm/Co 1.5nm), is RF sputtered through a laser cut metal shadow mask on to the collector substrate defining square base regions slightly larger than the emitter surface. Directly after cleaning the emitter in a similar manner its hydrophobic surface is contacted to the multilayer surface, forming a bond through spontaneous adhesion.

Here metal parts were laid down directly on to the doped Silicon base layer, which resulted in the information of metal silicides at the interface. These degrade device performance due to the large depolarizing effect they have on the flow of spin polarized charge carriers through the interface which severely reduces the magnetic sensitivity of devices.

IV. Working

The energy band diagram of the bonded Co/Cu of spin valve transistor is shown below.

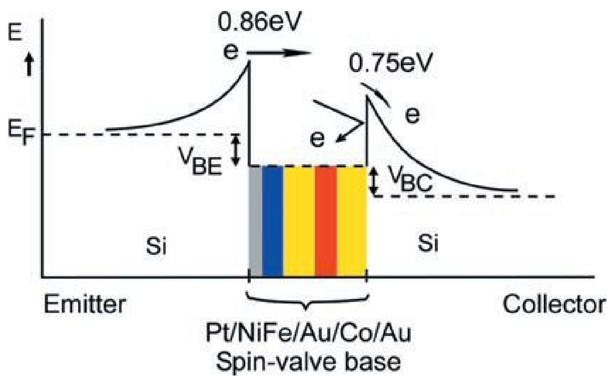

Fig. 2 Energy Band Diagram

The collector barrier height about 0.7eV while the emitter barrier height is 0.6eV.The emitter and collector Schottky barrier are in forward and reverse bias respectively as illustrated by the CB configuration in Fig. 1. The emitter bias accelerates the electrons towards the emitter barrier, after which they constitute the hot "Ballistic" electrons in the base. The probability of passing the collector barrier is limited by the collisions in the base which effect their energy and trajectory by optical phonon scattering in the semiconductor and by quantum mechanical reflections at the base collector interface. For a base transistor with a single metal base film, this can be expressed by the CB current transfer ratio or current gain.

$$\alpha_o = (J_c - J_{leak}) / Je = \alpha_c\, \alpha_e\, \alpha_{qm}\, e^{-W/\lambda}$$

where
α_e = emitter efficiency
α_c = collector efficiency
α_{qm} = quantum mechanical transmission
W = base width

And λ is the hot electron mean free path (MFP), in the base. The factor $e^{-W/\lambda}$ represents the probability of transmission of the hot electrons through the base. J_c is the total collector current, J_{leak} is the collector leakage current, determined by the reverse biased collector Schottky barrier and J_e is the injected emitter current. The α_c and α_e depend among others, on the type and quality of the semiconductors. In the SVT under consideration, the thickness of the individual layers (Co/Cu) are much smaller than the spin-slip diffusion length (a few nm ascompared to several tens of nm). Neglecting, therefore, spin flip scattering, we consider the spin up and spin down electrons to carry the current in parallel (two current model). Furthermore it has been shown that in this limit no spin relaxation occurs in the CPP-MR and that consequently the perpendicular transport properties can be very simply described by considering a network of serial resistance for each channel of electrons corresponding to the resistances of successive layers and interfaces. Following this idea as a first approach, the collector current of Co/Cu SVT can be expressed as

$$J_c = J_{c+} + J_{c-} = J_c\, \alpha_c\, \alpha_e\, \alpha_{qm}\, [\Pi\, P_{i+} + \Pi\, P_{i-}] + J_{leak} \quad (1)$$

where $\Pi\, P_{i+(-)}$ denotes the product of transmission probabilities of spin up (+) and down (-) electrons through each layer and interface. In first approximation we take αe αc and αqm similar for two species of electrons since these quantities reflect the properties of the semiconductor and Schottky barriers. At saturation all Co layers have their magnetization parallel. The sum of the transmission probability factors for the two spin channels can be written as

$$= [\,\Pi\, P_{i+} + \Pi\, P_{i-}\,]$$
$$= e^{-Wcu\,/\,\lambda cu}\,[e^{-Wco\,/\,\lambda co\uparrow}\, e^{-WF/N\,/\,\lambda F/N\uparrow} + e^{-Wco\,/\,\lambda co\downarrow}\, e^{-WF/N\,/\,\lambda F/N\downarrow}] \quad (2)$$

At the coercive field, this quantity becomes.

$$= [\,\Pi\, P_{i+} + \Pi\, P_{i-}\,]_{AP}$$
$$= e^{-WCu\,/\,\lambda Cu}\,[2e^{-WCo\,/2\lambda Co\uparrow}\, e^{-WF/N\,/\,2\lambda F/N\uparrow}\, e^{-WCo\,/\,2\lambda Co\downarrow}\, e^{-WF/N\,/\,2\lambda F/N\downarrow}] \quad (3)$$

where W_{Co} expresses the sum of all Co layer widths (total Co thickness), W_{Cu} the total Cu thickness. $\lambda_{Co\,(Cu)\,\uparrow\,(\downarrow)}$. The majority (minority) MFP's in Co layers (copper layers) and exp. $(-W_{F/N}\,/\lambda_{F/N\uparrow(\downarrow)})$, a spin dependent factor which takes into account the spin dependent scattering at the interfaces. The values of the collector current in the parallel and antiparallel magnetic configurations are then obtained by inserting expression 2 and 3 into 1. The first part of RHS of equation 1 wills be denoted by JMC, the magneto current.

V. MAGNETIC SENSITIVITY

The barrier height of collector and emitter as determined at room temperature by the current voltage method are 0.7 and 0.6 eV. Because of the low barrier heights and large area of the collector the leakage current is quiet large (30μA) and exceeds the magneto current for an injection current of 100mA. Magneto current measurements have been performed at 77 K reducing the leakage current to acceptable values, magneto current measurements have been performed with the CB setup of fig.1, I_e = 100 mA and V_{BC} = 0V. The collector current V_S the applied magnetic field is plotted in fig. 3 as large current change with field is observed, with typical GMR characteristics of a second peak Co/Cu multilayer, such as saturation field and hysteresis. The corresponding CIP-MR value of implemented multilayer was only 3% in 10K Oe. The large values of MC (%) and J_e/J_c indicate a short $\lambda_{\uparrow(\downarrow)}$ (Of order Of 0.5 to 1 nm): however bulk MFP will require further measurements

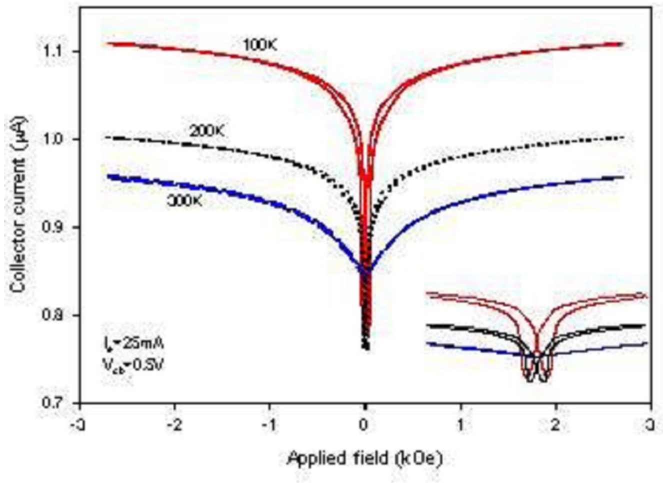

Fig.3 Magnetic sensitivity of collector current at different temperatures

VI. Temperature Effects

Transport property of hot electron is not fully understood at very low energy regime at finite temperatures. So, it is necessary to probe the temperature dependence of the hot electron transport property in relation to the SVT. The collector current across the spin valve changes its relative orientation of magnetic movements at finite temperature. Surprisingly the collector current showed different behaviors depending on the relative spin orientation in Ferro Magnetic layers. The parallel collector current is increasing up to 200 K and decreasing after that, while anti-parallel collector current is increasing up to room temperature. Actually in ordinary metals, the scattering strength increases with temperature T. This implies that any thermally induced scattering process enhances the total scattering. As a result measured current should be decreased, but it is happening so, increasing of collector current with temperature T may not be related to the ordinary scattering events in the metallic base. Two different mechanisms are suggested. One of them is spatial distribution of Schottky barrier diode. This may explain the behaviors of both parallel and antiparallel collector current upto 200K because thermal energy contributes to overcome the Schottky barrier height at Collector side with the increasing temperature T. This mechanism not related to any dependent property but only for the absolute magnitude of both parallel and antiparallel collector current. Therefore, physicist attributes the measured temperature dependence of magneto current to this spin mixing effect.

Basically spin mixing is spin flip process by thermal spin wave emission or absorption at finite temperatures. For example majority (minority) electrons can flip its spin by absorbing (emitting) thermal spin wave and then goes into spin down (up) channel.

VII. Advantages

Spin transistors have huge potential for incorporation in stable, high sensitivity magnetic field sensors for automotive, robotic, mechanical engineering & data storage applications. This may also be used as Magnetically Controlled Parametric Amplifiers & Mixers, as magnetic signal processors, for control of brush less DC motors & as Magnetic Logic elements. In log applications they have the advantage over conventional semiconductor chips that they do not require power to maintain their memory slate. It finds its application towards Quantum Computer, a new trend in computing. Here we use Qubits instead of bits. Qubit also represents only 1& 0 but here they show superposition these classical states. But it is in pioneering stage.

There are major efforts ongoing at Honeywell, IBM, Motorola in developing RAM based on spin valves and metal tunnel junctions such devices called MRAM have demonstrated faster speed, high density low power consumption, non-volatility and radiation harness they are promising replacements for the Semi Conducting RAM currently used.

VIII. Applications

- Traditional transistors use on & off charge currents to create bits – the binary 0&1 of Computer information. Quantum spin field effect transistor will use up & down spin states to generate the same binary data.
- A currently logic is usually carried out using conventional electrons, while spin is used for memory. Spintronics will combine both.
- In most Semi Conducting transistors the relative proportion of the up & down carries types are equal. If Ferro Magnetic material is used as the carrier source then the ratio can be deliberately skewed in one direction.
- Amplification and / or switching properties of the Device can be controlled by the external magnetic field applied to the device.
- One of the problems of charge current electrons is that we pack more devices together, the chip heats up. Spin current releases heat but it is rather less.

IX. Conclusions

Now it is clear that, Spin valve transistor is more versatile and more robust but it needs further fabrication methods to improve magnetic sensitivity of collector current. The greatest hurdle for spintronic engineers may be controlling all that spin. To do it on a single transistor is already feasible while to do it on a whole circuit will require some clever ideas. Transistors are the building blocks of the electronic devices that power the digital world, and much of the growth in computing power over the past many decades has been made possible by increases in the number of transistors that can be packed onto silicon chips. But that growth, if left to current technology, may soon be coming to an end. Many in the semiconductor field think that the industry is fast approaching the physical limits of transistor miniaturization. The major problem in modern transistors is power leakage leading to the generation of excessive heat from billions of transistors in close proximity. Only one thing is certain: if the pace of miniaturization continues unabated, the quantum properties of electrons will become crucial in determining the design of electronic devices before the end of the next decade.It is also one of the key building blocks needed to make quantum computers which promise exponential increases in processing speed over today's computers through their use of the "spin", or magnetic orientation, of individual electrons to represent data in their calculations. However the key question will be whether any potential benefit of such technology will be worth the production cost. Spin valve transistors and other spin devices will become affordable by using common metals. The future of research on Spin valve transistors looks very bright. It now seems that electronics based on individual molecules and electron spin effects will replace conventional circuits based on scaled-down versions of field-effect transistors.

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