Magnetoresistive Characteristics of Schottky - Tunnel Hot Electron Spin Transistors

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Abstract-**Spin transistors were fabricated by combining spin dependent tunneling (STD) junctions with a Schottky barrier. The basic structure of these three terminal device is [nSi collector] / [NiFeCo base] / [Al_2O_3 emitter barrier] / [CoFe / IrMn spin polarized emitter]. The magnetoresistive properties of the devices were observed while operating them in a constant emitter current mode while the changing the relative orientation of the emitter and base layers from parallel to antiparallel. An arbitrarily large percentage change in collector current can be observed with proper voltage biasing of the Schottky barrier. However, the utility of the present device is limited by the low fraction of emitter current which is collected.**

Index Terms—**Spin dependent tunneling, Hot electron transistor, GMR, Spin transistor, Al_2O_3.**

I. Introduction

The persistent trend in electronics toward higher circuit density and faster circuit operation drives a need for ways to more closely integrate magnetoresistive devices with their underlying silicon circuitry. This, in turn, creates interest in new devices in which the magnetic and amplification functions are combined. Motivated by these trends, measurements of the magnetotransport properties of a three-terminal, two-barrier "spin transistor" structure have been performed at room temperature to evaluate them for use in commercial magnetoelectronics devices. These devices were fabricated using common semiconductor industry techniques and are fully integrable with other silicon devices. The Schottky - Tunnel type of structure described here was first suggested by Monsma, Lodder, Popma, and Dieny [1,2]; and first constructed and measured by Mizushima, Kinno, Yamauchi, and Tanaka [3,4]. The devices described here have similar barriers to Mizushima's, but the details of the magnetic construction differ. The data in [1]-[4] were all collected at 77K or below. Data presented here were all collected at room temperature.

The device in [1] was a Schottky-Schottky type structure, which requires a difficult vacuum bonding technique for fabrication and were rather large. An integrable version of this technique has been developed which permitted μm sized device construction [5]. The double Schottky structure has the limitation that the injected electrons are not polarized because they come from a non-magnetic semiconductor. One of the Mizushima structures did use a ferromagnetic / tunnel emitter, although the base material on the other side of the tunnel barrier was non magnetic.

The device described here is the first to use a ferromagnetic film on both sides of the emitter tunnel barrier. The objective is to have a population of emitted electrons with a high degree of spin polarization. In principle, their conduction through the base will be strongly dependent on the magnetic state of the base: when the emitter and base are parallel, a much larger number of electrons should be able to traverse the base and be collected; but when the emitter and base are antiparallel, the mean free path for the majority of emitted electrons is drastically shorter, and very few electrons will be collected. This spin dependent Hot Electron Transistor (HET) concept is illustrated in Figure 1.
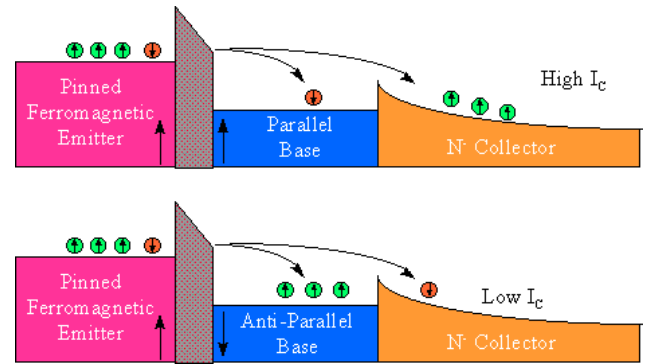

Fig. 1. Schematic operating mode of the spin dependent hot electron transistor. The spin orientation of electrons is indicated by the arrows, as are the magnetic states of the emitter and base.

II. Experiment

There were three phases in the fabrication of the spin transistors: Si wafer preparation, SDT material deposition, and device patterning and interconnection. The starting material was 4" prime grade p-Si wafers. Electrically isolated device regions were created in the wafers using a standard "LOCOS" thick oxide formation. n wells in the device regions were implanted with As^+ to an ion density of 10^{17} ions/cm^3 and a depth of 200 nm. High conductivity contact regions in the n wells were made with an additional P^+ implant to a density of 10^{19} ions/cm^3 and a depth of 200 nm. The wafers were annealed at 900 ^{0}C for 30 minutes to activate the implants. The "LOCOS" growth and implanting were performed at Honeywell HTC in , Minnesota.

Following the preparation of device regions in the starting silicon wafers, SDT material was deposited using rf diode sputtering in a PE2400 system with a base pressure below 1.5x10^{-7} Torr. The wafer surface was prepared with a dilute HF dip just before deposition. The layer structure was NiFeCo (7.5 or 12.5) / Al_2O_3 (1.5 or 2.0) / CoFe 5.0 / IrMn 10.0 (in nm). The Al_2O_3 barrier layers were formed by

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oxidizing Al layers in a plasma. A magnetic field of 20 Oe was applied during magnetic layer depositions [6].

The SDT junctions were then patterned using standard photolithography, Si_3N_4 hard masks formed by Reactive Ion Etching (RIE), and a Commonwealth ion mill to etch the layers. After formation of the SDT structure on the nSi well, the entire device was passivated with Si_3N_4, and Al interconnects were formed [6]. A schematic view of the device is shown below in Figure 2.
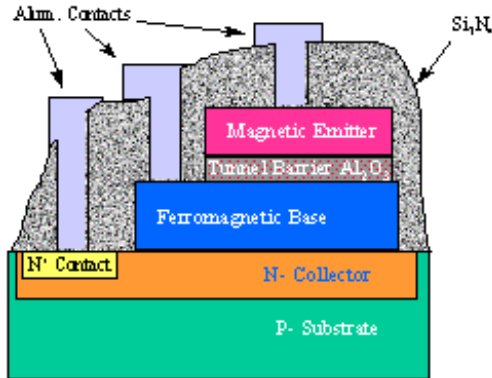

Fig. 2. Cross section view of the Hot Electron Spin Transistor.

The smallest device design had lateral dimensions of 5x5, 10x20, and 20x40 μm for the emitter, base, and collector, respectively. The largest device design had dimensions of 100x200, 104x204, and 150x250 μm. Magnetotransport data were collected using a computer controlled test station and an HP 4145A Parameter Analyzer. Wafers were then scanned for high quality devices, defined as having high magnetoresistance (> 10%) and properly rectifying Schottky barriers. Good devices were measured using the electrical setup shown in figure 3 below.
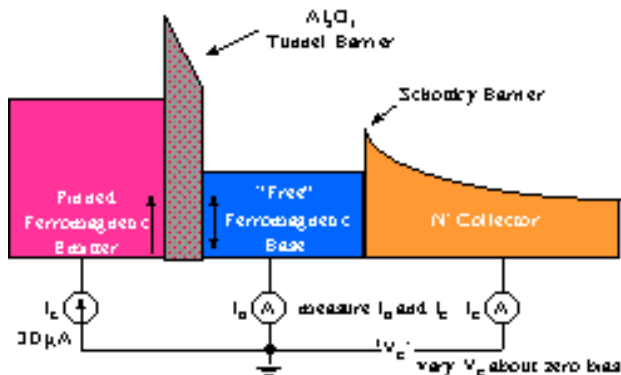

Fig. 3. Electrical connections to the parameter analyzer. Fixed current was driven through the emitter tunnel barrier into the base. Collector current was measured while the Schottky barrier voltage bias was swept about zero Volts. This set of measurements was taken for cases when the magnetization of the base was both parallel and antiparallel to the emitter.

III. RESULTS AND DISCUSSION

The Resistance Area Product (RAP) of the SDT junctions was 3.5 MΩ-μm^2 for the 1.5 nm Al_2O_3 barriers and 175 MΩ-μm^2 for the 2.0 nm tunnel barriers. The SDT Junction Magnetoresistance (JMR) exhibited the expected asymmetrical "spin valve" shape with soft layer switching thresholds at +/- 10 Oe and pinning strength of 200 Oe. The JMR value was between 10 and 20% for the devices measured. While the single step breakdown voltage for the junctions was above 1 V, the junctions were short lived for voltage biases above 0.5V. This severely hampered our ability to measure phenomena of interest.

Nonetheless, when the magnetic state of the base was reoriented from parallel to antiparallel with the emitter, the collected current changed measurably. This effect is shown below for several emitter currents in Figure 4 and for a single emitter current in Figure 5.
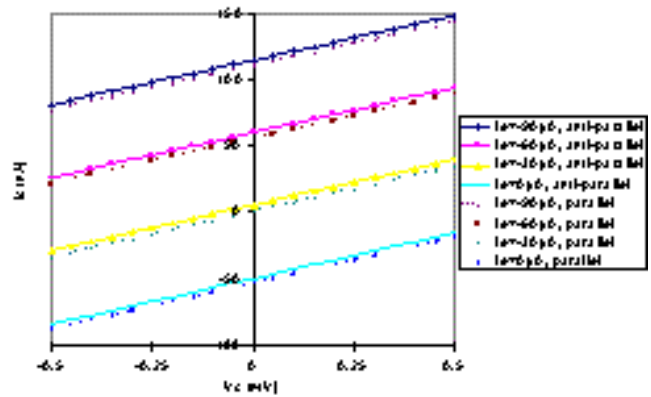

Fig. 4, Collector current for a range of emitter currents on a 50 x 100 μm device with emitter bias ranging from 0 to about 300 mV.

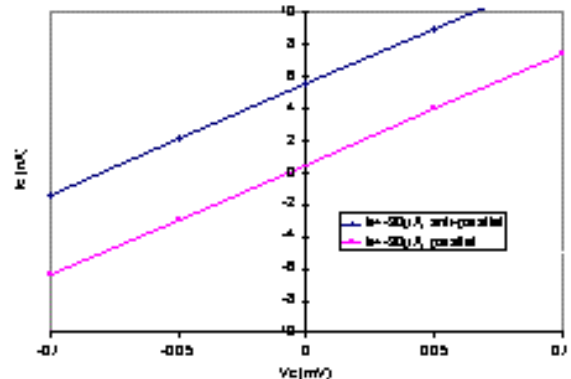
Fig. 5. Collector current vs. base-collector voltage bias for a constant emitter current of 30 μA . There is some calibration offset in the HP parameter analyzer which results in a translation in the vertical axis of Fig. 4 and Fig. 5 on the order of 50 nA. Note that a 100 μV change in the base-collector bias results in as much change in collector current as is due to the magnetic orientation change.

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The collected current represents about 0.2% of the total emitted current, a very small value. The change in collected current is about 5 nA for an emitter current of 30 μA. The cause of this shift is not completely clear. Interpretation is difficult partly because the absolute current is so small.

The magnetic design of the device results in two effects when the magnetization states change: the effective resistance changes (JMR), and the mean free path in the base changes for spin polarized currents (HET). When a constant current is being used, the increased resistance of the junction for the antiparallel configuration results in a higher required voltage bias which presumably enhances the probability of traversing the base. These two phenomena would appear to have competing effects on the collected current.

Another limitation with using a SDT junction to provide spin polarized electrons is that the tunneling spin polarization as indicated by the measured JMR, decreases with increasing voltage bias. This has been observed by other workers in the field [8] and is shown below in Figure 6 for our own junctions. Due to the height of the collector Schottky barrier, optimal operating biases for the spin HET structure are likely to be on the order of 1 V.
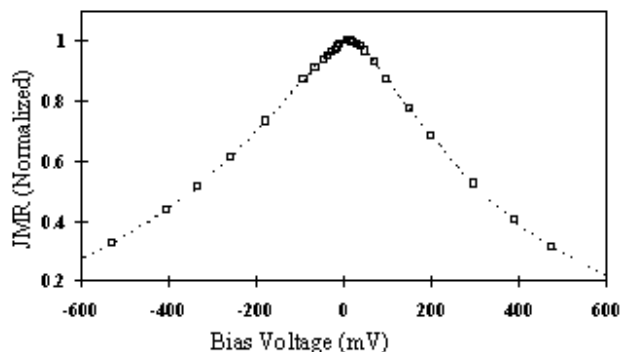

Fig. 6. Bias voltage dependence of normalized JMR values for a typical SDT junction. The bias voltage at half maximum JMR ($V_{1/2}$), is ~340 mV.

Because of this bias dependence, there is little observable spin polarization at emitter biases high enough to result in significant transmission probability.

Another difficulty with the spin transistor HET concept is that the energy of the emitted electrons is not limited to a narrow band about the emitter Fermi energy ($E_{f\ emitter}$). Rather, there is net electron flow from electrons tunneling into the base from bands in the emitter ranging from the $E_{f\ base}$ up to $E_{f\ emitter}$. A significant improvement would come from some structure which would narrow the energy range of the emitted electrons.

IV. SUMMARY

The device described here is the first spin transistor to have a pinned emitter, and to use the SDT effect in the emitter. As mentioned above, the SDT effect is not optimal as implemented here because the JMR effect works against the HET effect. The structure should work better with a second separate magnetic layer in the base to act as an "analyzer," or instead with non-magnetic metal at the emitter-barrier base interface. It is interesting to note that, while percentage change of the collected current is what is most often cited in the literature, this value is not very indicative of the true utility of the device. In fact, it is practically an arbitrary value because the collector current is also very sensitive to the base-emitter bias, as shown in Figure 6. A better measure is the change in collector current vs. emitter current, which for the data shown here is about 0.03%.

There is a great deal of room for improvement in the emitter barrier, the base structure, and the Schottky barrier. Should the improvements result in a transmission probability approaching 50%, the device will be enormously useful for a wide range of magnetoresistive devices including magnetoresistive random access memory (MRAM), galvanic isolators, read heads for hard drives, and magnetic field sensors.

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