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Ahmad, E., Valavanis, A., Claydon, J.S. et al. (2 more authors) (2005) Vertical spinal electronic device with large room temperature magnetoresistance. IEEE Transactions on Magnetics, 41 (10). pp. 2592-2594. ISSN 0018-9464

https://doi.org/10.1109/TMAG.2005.854797

Vertical Spinal Electronic Device With Large Room Temperature Magnetoresistance

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We report experimental transport measurements of a vertical hybrid ferromagnetic (FM)/III-V semiconductor (SC)/ferromagnetic(FM) type structure, i.e., Cr(20ML)/Co(15ML)/GaAs(50 nm, n-type)/$Al_{0.3}Ga_{0.7}As$(200 nm, n-type)/FeNi(30 nm). The current-voltage (I–V) characteristics reveal Schottky/tunneling type behavior in the direction of FeNi/Semiconductor/Co and observed to be dependent on external magnetic field. The magnetoresistance (MR) behavior shows a strong dependence on the measured current and field. At low fields no significant change in MR has been observed with increasing current. However, at high fields the MR initially increases with increasing current and becomes stable beyond a critical current of 10 μA. A maximum of 12% change in the MR has been observed at room temperature, which is far larger than that of the conventional AMR effect. This property of the device could be utilized as field sensors or magnetic logic devices.

***Index Terms*—CPP geometry, magnetoresistance, spintronics.**

I. Introduction

SPIN injection from ferromagnetic metals (FM) into semiconductors (SC) has attracted much interest [1] and is an issue of fundamental relevance in spintronics. Consequently, hybrid ferromagnet-semiconductor spintronics devices where ferromagnetic materials are used in conjugated with semiconductor materials emerges as a significant area of research [2]. The hybrid structures offer easy integration of ferromagnetic materials with digital semiconducting processing and are inspired by the long spin lifetimes and long spin coherence length in semiconductors [3], [4]. Although, it has been pointed out that the basic obstacle for spin injection from a ferromagnetic metal into semiconductor originates from the conductivity mismatch between these materials [5], a high spin injection is predicted to be achieved by fabricating ferromagnet/semiconductor interfaces with suitable energy barriers [6], [7]. In the process, successful spin injection from FM to SC [8], and spin detection from SC to FM [9] have been reported.

Recently, we have studied FM/SC/FM vertical devices with the aim to probe directly the spin injection and detection through magnetotransport measurements. In this paper we present the I–V characteristics and MR measurements of a two-terminal spinal vertical device with following structural specification Cr(20ML)/Co(15ML)/GaAs(50 nm, n-type)/$Al_{0.3}Ga_{0.7}As$ (200 nm, n-type)/FeNi(30 nm).

II. Experimental Procedure

A 15 ML of Co layer was deposited on a 10 $\times$ 10 mm As-adsorbed GaAs(100) substrate. The GaAs(100) substrate contains epilayers of $Al_{0.3}Ga_{0.3}$ As and GaAs with the following structure As-capping/GaAs(50 nm, n-type, 10^{18}/cm)/$Al_{0.3}Ga_{0.3}As$ (200 nm, n-type, 10^{18}/cm)/GaAs(100). The As was desorbed at a temperature of 300° C. The Co was then grown epitaxially in a UHV chamber with base pressure of 1×10^{-10} mbar. Then, the Co layer was capped with 20 ML of Cr. The sample was then covered by 350 nm of Al deposited by thermal evaporation. This layer is used for bonding at later stage. The sample was then mounted upside down on a piece of glass of low melting point wax and thinned down to 100 μm using H_2SO_4:H_2O_2:H_2 O (1:8:8) mixture. Optical lithography was performed on the thinned sample from the back side to open a 200 $\times$200 μm window. Selective chemical etching was done through the backside window with H_2O_2:NH_2OH (40:1) solution which selectively etches GaAs and stops on AlGaAs. The surface of the AlGaAs appears to be very flat when observes under optical microscope. When the AlGaAs layer is reached the etch pit starts broadening etching the GaAs sidewise. This way one could be sure of reaching the AlGaAs layer. Once the AlGaAs layer is reached the sample was put into a thermal evaporator and a 30 nm of NiFe layer followed by 10 nm of Cr layer was evaporated and lift-off was performed. After the lift-off a 350 nm of Al layer was deposited by thermal evaporation on the backside of the sample to ensure that the NiFe in the etched pit is electrically connected. The sample was then attached upside down on a chip holder and electrical connections on the back surface were made by Al-wire bonding. The top surface which was attached to the chip holder is the other conducting path. The transport measurements were done in a current-perpendicular to plan (CPP) geometry from NiFe to Co layer through the AlGaAs/GaAs layer. Electrical measurements were done by a Keithly 2400 source meter. All measurements were done at room temperature. Fig. 1 shows the cross sectional view of the sample schematically.

III. Results and Discussion

The field dependent I–V characteristic of the device is shown in Fig. 2. The I–V characteristics are highly rectifying and depend on the applied field. Although the device conducts about 0.5 V (as shown in the insert of Fig. 2 for a particular case) the actual field dependency becomes apparent above 5 V. The current is observed to be decreasing with increasing field values. The effect is identical for both polarities of applied field. The break down is occurred at a reversed bias voltage of about 30 V

Digital Object Identifier 10.1109/TMAG.2005.854797

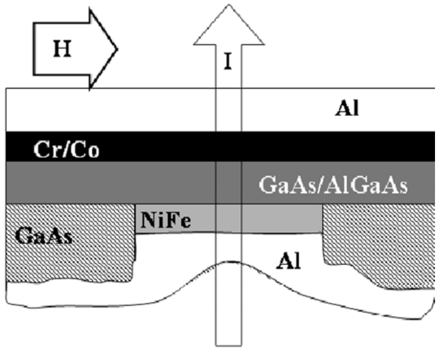

Fig. 1. Cross-sectional view of the device structure is shown schematically. The directions of current flow and the magnetic field are shown with arrows.

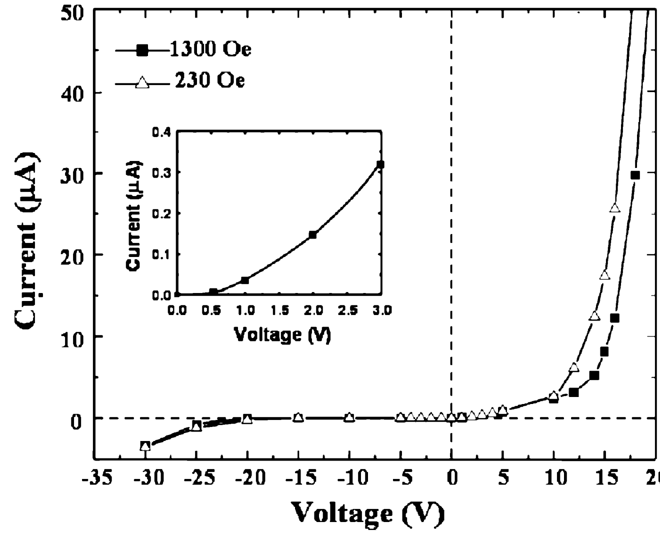

Fig. 2. I–V characteristics of the vertical device at different field strengths. Insert shows that the device conducts about 0.5 V.

and the leakage current begins to build up at a voltage of 20 V. In this device the current is established between the NiFe and Co layers such that electrons are injected into the GaAs/AlGaAs layer through Co side by applying certain bias voltage between the NiFe (positive) and Co (negative). Ideally we expect that Schottky barriers would be formed at the NiFe/AlGaAs and GaAs/Co interfaces. In a simplistic equivalence we could then imagine two head-on Schottky diodes, only now the electrons which are entering the semiconductors could be spin polarized as it passes through the magnetic material here the NiFe layer. It is also reasonable to consider that the Schottky barriers at two interfaces are not identical. When we apply a bias voltage from NiFe to Co layer, the Schottky diode at the NiFe end gets forward bias and the Co end gets reverse biased. Ideally, in the absence of any magnetic materials we would expect to see that with increasing bias voltage the current flowing through the NiFe side would overcome the reverse biased barrier of the Schottky diode at the Co end and would start conducting beyond the barrier voltage which is typically less than a volt. This analogue is not very far from the actual case as we could see that the conduction in the forward bias region starts around 0.5 V. However, no field dependence is observed at this range. The current stats building up once the bias voltage reaches 5 V and a rapid increase is observed beyond 10 V. In addition the influence of applied magnetic field becomes apparent. Here the field is applied normal to the plane of current and along the easy direction of the Co film. The rapid increase at and beyond 10 V could be an indication that one of the interfaces is putting up a usually high resistance to the current than a Schottky barrier could. It is apparent from the fabrication procedure that the barrier at the NiFe side is the one producing the high resistance to the current. This because of the fact that the AlGaAs side of the sample was exposed to ambient atmosphere before it is placed into the thermal evaporation and the NiFe was deposited by thermal evaporation Therefore, the NiFe/AlGaAs interface is not perfectly clean and the probability of incorporating an insulating/oxide layer giving rise to the unusually high barrier is very likely. This high barrier could possibly be responsible for hot electron injection affecting the I–V characteristics at high voltages. Fig. 2 depicted the nature of the magnetoresistance (MR) produced by the device for a single field cycle when the field is applied along the easy axis of the Co layer. Here a certain current is passed through the device and voltage is measured at different fields. Here we define MR as $\Delta\mathrm{R}/\mathrm{R}$, where $\Delta\mathrm{R} = \mathrm{R(H)} - \mathrm{R_{min}}$, and $\mathrm{R} = \mathrm{R_{min}}$. A reversed sense of MR curve with minimum at 200 Oe is observed. The reason for the decrease of the current at high fields in Fig. 2 thus becomes apparent as the MR is observed to be increasing with high fields.

The magnetic behavior of the device could not be measured as the membrane is fragile and incompatible with standard magnetic measurement techniques. It is possible that the magnetic property of the individual ferromagnetic layers of the sandwich structure could be influenced by the fact that it is of the form of a membrane. The membrane usually forms convex surface that could influence the magnetic properties of the sandwich structure through straining the individual FM layers. The occurrence of the minimum of the MR curve at the field value of 200 Oe could be related to this possible change in the magnetic property of the sandwich structure.

The effect of biasing current on the magnetoresistance is also observed in Fig. 3. In general the MR increases with increasing field at a biasing current higher than 2 μA. A maximum of >12% increase is observed at the highest applied field at room temperature for a current of 15 μA. The increase in the MR could be related to Lorentz force that has been exerted on the electron during the traverse in a direction normal to the applied field and/or to spin polarized current (if present) which would expect to increase with high biasing current.

A very unique behavior has been depicted in Fig. 4 where the current dependency of the MR is presented. At low field the MR did not show significant variation, whereas, at high fields the MR increases sharply with increasing basing current and become somewhat stable or saturated beyond the current of 10 μA. A maximum change of greater than 10% has been observed for biasing higher than a critical current at the highest applied field. This is a large change compared to ordinary AMR effect measured at room temperature. The change in the MR

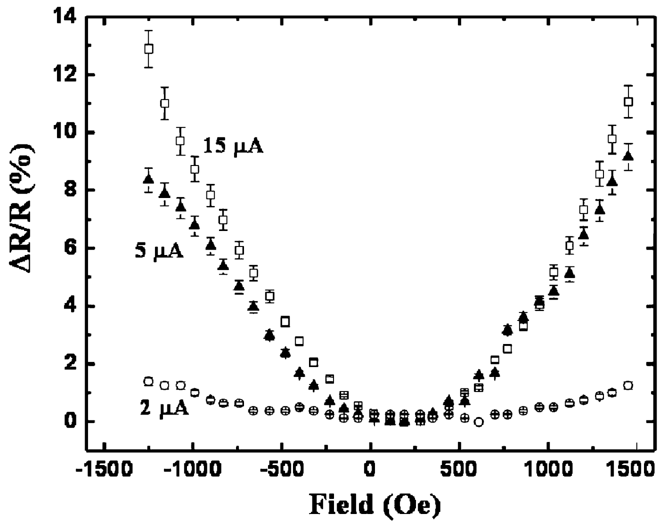

Fig. 3. MR behavior of the device at different biasing currents.

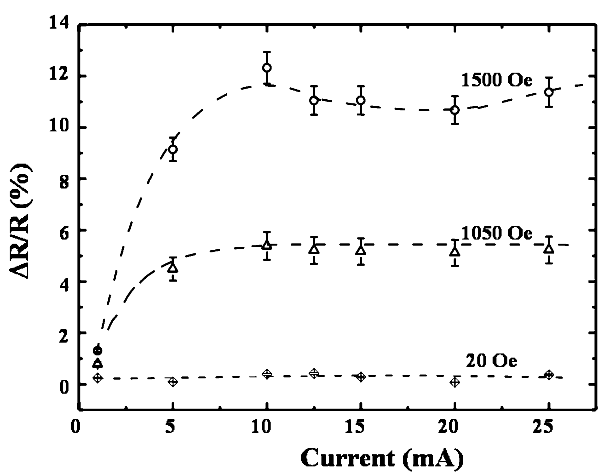

Fig. 4. Field dependent MR behavior of the device. The characteristics resemblances the characteristics of a semiconductor field effect transistor.

becomes stable beyond the critical current at high fields. It provides the indication that the MR could not be of Lorentz-MR type as that would be increasing with increasing current in a fixed field. However, the Lorentz MR could contribute to the region up to 10 μA where we observed a increase of MR for a fixed field. But beyond this current the MR became stable or saturated indicating that there could be phenomenon other than the Lorentz force responsible for this. As we have a sandwich structure with a SM layer between two FM layers, we could not rule out the possibility that a contribution to the MR could come from spin injection and detection through the FM layers. However, the overall behavior is still an open question to us and might be dependent on more details scenario involving band structures of individual materials.

It is worth mentioning here that the curves in Fig. 4 have interesting resemblance with field effect transistor characteristics. This similarity evokes the possibility that a two terminal vertical device like ours could serve the purpose of a three terminal device like a field effect transistor. A transistor could be turned "on" and "off" states by controlling the Gate voltage. Like wise, our two terminal vertical device could be turned "on" (high MR) or "off" (low MR) just by varying applied magnetic field for a critical current of greater than 5 μA. Thus, a device like this could be of immense interest in spintronic logics or field sensors.

IV. Summary

We have reported experimental transport properties of a vertical hybrid ferromagnetic/III-V semiconductor/ferromagnetic structure of the type Cr (20 ML)/Co (15 ML)/GaAs (50 nm, n-type)/$Al_{0.3}Ga_{0.3}$ As (200 nm, n-type)/FeNi (30 nm).

The I–V characteristics revealed Schottky/tunneling type behavior and are dependent on external fields beyond a bias voltage of 5 V indicating that a high barrier related to interface oxide layer has been introduced in the device. The MR shows a strong dependence both on biasing current and applied field. A 12% change in MR has been observed at room temperature, which is far larger than that of conventional AMR effect. It could be argued that ordinary AMR or Lorentz-AMR could not be the sole contributing factor to this high AMR, indicating strong spin injection and detection occurred in this device. The device also exhibited interesting field dependent MR behavior, which could be compared to field effect transistor characteristics, and could be of interest in spintronic logics. We are in the process of understanding the spin transport mechanism of this device, which remains a challenging issue.

Acknowledgment

The authors would like to thank the EPSER for funding the project.

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Manuscript received February 6, 2005.