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Spin-valve effect in an FM/Si/FM junction

K. I. LEE[1,2], H. J. LEE[2,3], J. Y. CHANG[2], S. H. HAN[2], Y. K. KIM[3], W. Y. LEE[1,*]
[1]Department of Materials Science and Engineering, Yonsei University, 134 Shinchon-Dong, Seoul 120-749, Korea
E-mail: wooyoung@yonsei.ac.kr
[2]Nano Device Research Center, Korea Institute of Science and Technology, POB 131, Seoul 136-792, Korea
[3]Department of Materials Science and Engineering, Korea University, Anam-Dong, Seoul 136-701, Korea

The spin transport in a lateral spin-injection device with an FeCo/Si/FeCo junction has been investigated. Magnetoresistance (MR) signals were found to appear at low magnetic fields in the range 4–300 K. This is attributable to the switching of the magnetisation of the two ferromagnetic contacts in the device for certain magnetic fields over which the magnetisation in one contact is aligned antiparallel to that in the other. The spin-valve effect was found to be independent of temperature. Data from the device suggest that the spin-polarised electrons are injected from the first contact and, after propagating through the bulk Si, are collected by the second contact.

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1. Introduction

Semiconductor spintronics has been extensively investigated because of their importance in device applications such as spin-based light emitting diodes (spin LEDs), field effect transistors (spin FETs), and resonant tunnelling diodes (spin RTDs), offering novel functionalities to carry signals and process information [1]. In particular, intensive work [2–6] has focused on spin-polarised electron transport in semiconductors, since Datta and Das [2] proposed the idea of a spin-polarised FET. It is an electronic analogue to the electron-optic modulator in which the current modulation results from the spin precession due to the spin-orbit coupling in narrow gap semiconductors, while an imbalance of spin-polarised electrons is injected from a ferromagnetic contact into a two-dimensional electron gas (2DEG) and detected by another ferromagnetic contact. Such a hybrid ferromagnetic metal/semiconductor spin transistor has been expected to open an opportunity towards a novel class of spintronic devices due to the potential advantage of being integrated with complementary metal oxide semiconductor (CMOS) technology.

However, spin injection at a ferromagnetic metal/semiconductor interface still remains elusive to prove due to a basic obstacle to spin injection from a ferromagnetic metal emitter into a semiconductor originating from the conductivity mismatch between these materials [7, 8]. Recently, electrical spin injection from a ferromagnetic metal into a semiconductor in spin LEDs has been demonstrated, persisting to room temperature [9, 10]. Nevertheless, direct spin injection and detection efficiency in a hybrid ferromagnetic metal/semiconductor structure by electrical measurements has not been observed yet for realisation of a spin transistor, providing new routes for non-volatile memory and spin-based logic elements.

In the present work, we report on spin-valve effect in a lateral spin-injection device, consisting of n-type bulk Si and two ferromagnetic (FM) contacts. We found magnetoresistance (MR) signals at low magnetic fields in the range 4–300 K, whose magnitude is independent of temperature. The detailed mechanism of the spin-valve effect in the device with an FM/Si/FM junction structure will be discussed.

2. Experiment

The device consists of n-type bulk Si ($n \approx 7\times 10^{16}$/cm^3, $\mu_H \approx 10^3$cm^2/Vs, $\rho \approx 10\Omega\cdot$cm) and two ferromagnetic contacts: a spin injector (FM1) and a detector (FM2) as schematically shown in Fig. 1. A 20 nm thick SiO$_2$ top layer was grown on the Si wafer by thermal oxidation to make the contacts FM1 and FM2 only in contact with the Si. The contacts were defined by electron beam lithography and contacted to the external circuitry with a network of extended Ti/Au contacts patterned by optical lithography. Prior to deposition of the ferromagnetic contacts, the SiO$_2$ layer was removed with a buffered oxide etchant and then the Si was etched by reactive ion etch (RIE) to a depth of 300 nm. The ferromagnetic contacts ($Fe_{16}Co_{84}$) with spin polarisation of 52% were deposited in a dc magnetron sputtering system with a base pressure of 4×10^{-9} Torr and then the surface of the contacts was passivated by a 5 nm thick layer of Ta so as

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[*] Author to whom all correspondence should be addressed.

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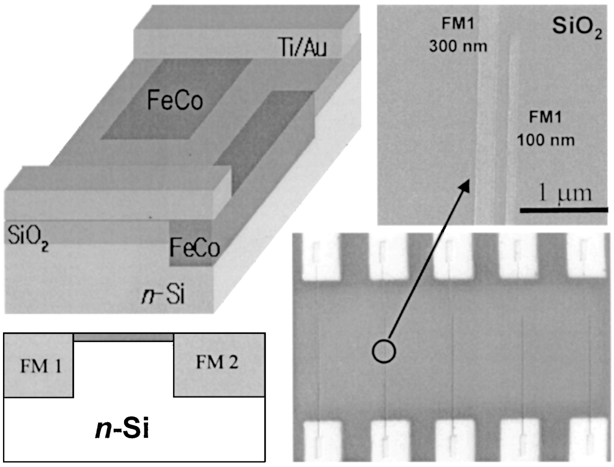

Figure 1 Schematic diagrams of the device with ferromagnetic nanocontacts and cross-sectional and top view of the junctions.

to protect them from oxidation. The contact FM1 was 100 nm wide and the contact FM2 300 nm wide. The different width of the electrodes is expected to give rise to two distinct switching fields due to magnetic shape anisotropy so that their relative magnetisation configuration (parallel and antiparallel) can be controlled by sweeping a magnetic field, applied parallel to their long axes. Both electrodes are 300 nm thick and 30 μm long. The distance between two parallel contacts, spin channel length (L) through Si, is 100 nm.

3. Result and discussion

The spin FET proposed by Datta and Das [2] is based on ferromagnetic source/drain electrodes and a two-dimensional electron gas (2DEG), which are electrically connected by Ohmic contacts. The two-terminal device with Ohmic contacts is believed to be advantageous for device applications, since it prevents possible problems occurring in high impedance devices, e.g., limited fan-out, slow dynamic response, and large power dissipation at steady bias [11]. In the present work, we intend for ferromagnetic contacts to be Ohmic by making the embedded electrodes in the bulk Si, although tunnel contacts [5, 8] and Schottky contacts [9, 10] have proven effective in spin injection across a ferromagnetic metal/semiconductor junction. Fig. 2 presents I-V curve for the device with the FeCo/Si/FeCo junction, indicating Ohmic-like behavior below ±1 V. The resistance was found to be a few hundred Ω. This is in contrast to that in a Ni/Si/Ni junction [3] with the nano-scale Ni contacts deposited on the surface of the Si, giving rise to very high contact resistance (10 MΩ) due to Schottky barrier (0.59 eV).

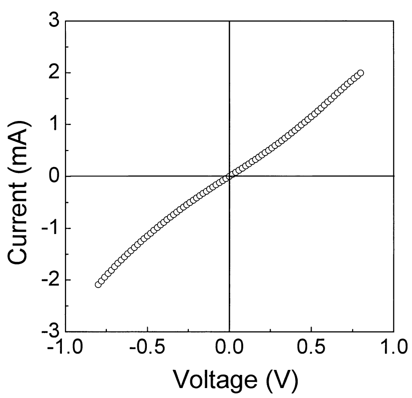

Figure 2 I-V curve for the junction across FeCo/Si/FeCo. The contact FM1 was 100 nm wide and the contact FM2 300 nm wide, and both 300 nm thick. The distance between two parallel contacts are 100 nm.

In Fig. 3, shown is the variation of the resistance in the device as a function of magnetic field applied along the long axis of the FeCo contacts, measured in the range 4–300 K. First of all, the resistance in the device was found to increase with a magnetic field above 20 kOe and below −20 kOe, indicating ordinary MR due to the classical Lorentz force on the charge carriers in Si [see Fig. 3(a)]. On the other hand, striking peaks were also found to appear at 4 and 300 K, respectively, in the field range $-400 < H < +400$ Oe [see Fig. 3(b)]. This is believed to be due to the switching of the magnetisation of the two ferromagnetic contacts in the device for certain magnetic fields (100–200 Oe and −100–−200 Oe) over which the magnetisation in one contact is aligned antiparallel to that in the other [see the inset of Fig. 3(b)].

This spin-valve effect reflects that the spin-polarised electrons are injected from the first contact and, after propagating through the Si, are collected by the second contact. The MR ratio is ∼0.1%, defined as $\Delta R/R_{H=0} = R_H - R_{H=0}$, where R_H is the resistance at a given magnetic field. The antiparallel configuration of the magnetisations in the two electrodes shows the minimum resistance, indicating inverse MR. Our results differ from that in the Ni/Si/Ni junctions [3], showing maximum resistance in the antiparallel configuration. Such inverse MR has been observed in previous work [6, 12], which might be related to momentum scattering effects according to spin channel length [12].

Fig. 4 displays temperature dependence of the MR ratio for the device, indicating that the MR ratio is hardly dependent upon temperature in the range 4–300 K. In previous work [6, 12], MR signal in the spin-injection devices with FM/2DEG/FM junction has been reported to disappear above 10 K. Recently, Hammar and Johnson [5] demonstrated spin injection across FM/InAs 2DEG junction by non-local geometry measurements, persisting to 150 K, as the consequence of a spin dependent resistance. The spin-injection mechanism still remains controversial, since it may be associated with anisotropic magnetoresistance (AMR) [8, 11–13], the fringe-field induced local Hall effect, particularly, on a low-density 2DEG [11], and weak localisation [12]. In the present work, the observed MR signal could be in conjunction with AMR effect, dominating the overall change of the resistance in the device [13]. The detailed mechanism for the spin-valve effect in our device is not clear yet. However, it should be noted that AMR shows temperature dependence that it decreases with increasing temperature. It is required to investigate spin-valve effect by non-local geometry measurements in order to demonstrate spin injection and discriminate AMR contribution in the FM/Si/FM junction [4, 5, 7].

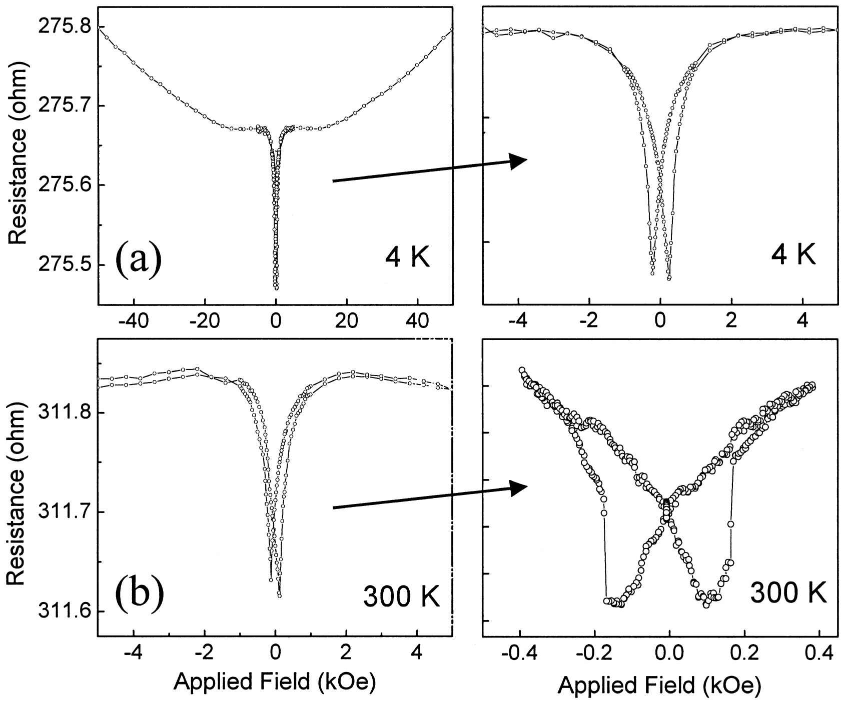

Figure 3 The variation of the resistance against magnetic fields at 4 K and 300 K in the spin-injection device.

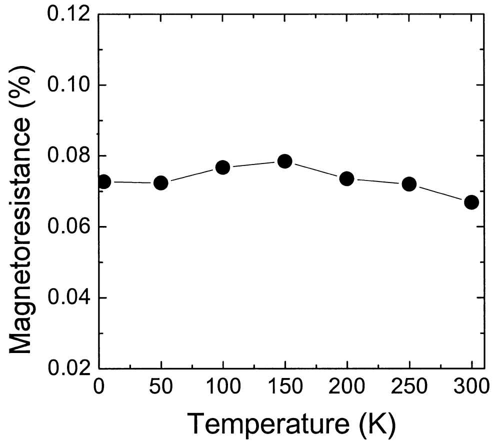

Figure 4 The variation of MR in the spin-injection device as a function of temperature.

4. Summary

We have investigated spin transport in a lateral spin-injection device with an FM/Si/FM junction. Magnetoresistance (MR) signals were found to appear at low magnetic fields in the range 4–300 K. This is believed to be due to the switching of the magnetisation of the two ferromagnetic contacts in the device for certain magnetic fields (100–200 Oe and −100–−200 Oe), corresponding to antiparallel magnetisation configuration. The spin-valve effect hardly varies with increasing temperature in the range 4–300 K. Our results demonstrate spin-valve effect in the FM/Si/FM structure at room temperature.

Acknowledgment

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