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A vertical transport geometry for electrical spin injection and extraction in Si

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ABSTRACT

Schottky barriers formed between ferromagnetic metal and Semiconductor are of particular interest for spin injection and detection experiments. Here, we investigate electrical spin polarized carrier injection and extraction in Si using a Co/Si/Ni vertical structure built on a 250 nm thick Si membrane. Current–voltage measurements performed on the devices at low temperatures showed evidence of the conduction being dominated by thermionic field emission, which is believed to be the key to spin injection using Schottky junctions. This, however, proved inconclusive as our devices did not show any magnetoresistance signal even at low temperatures. We attribute this partially to the high resistance-area product in our Schottky contacts at spin injection biases. We show the potential of this vertical spin-device for future experiments by numerical simulation. The results reveal that by growing a thin highly doped Ge layer at the Schottky junctions the resistance-area products could be tuned to obtain high magnetoresistance.

1. Introduction

The conductivity mismatch of a ferromagnet (FM) and a semiconductor (SC) to spin polarized electrons prevent ohmic contacts from being used for spin injection [1,2]. As an alternative, Schottky barriers (SB) and FM/insulator/SC contacts have been used [3,4] that introduce a spin dependent resistance at the FM/SC interface. Accordingly, an all-electrical spin injection and extraction device has been investigated in lateral [5] and vertical [6] geometry. A FM/SC/FM back-to-back Schottky-barrier-based spin injection and extraction device has been proposed [7].

The current conduction of a FM/SC Schottky junction in a lowly n-doped semiconductor is usually dominated by thermionic emission (TE) [8] which is believed to be unsuitable for spin injection and extraction as the electron transmission occurs well above the Fermi level. An image force lowering effect pushes the barrier-peak away from the interface at a point in the semiconductor where the density of states is not spin-dependent. On the other hand, the current conduction of a reverse-biased FM/SC Schottky junction in a highly n-doped semiconductor is dominated by thermionic field emission (TFE) [9], where the electron tunneling takes place at a lower energy at a point where spin-dependent density of states exists resulting in spin polarized transmission.

The motivation towards a Si based device is due to its technology dominance in the device industry. Si also offers long spin lifetimes and diffusion lengths due to its weak spin orbit interactions. Lateral spin transport structures based on Si have recently been reported [10], where a nonlocal detection technique has been adopted, which benefits from excluding any spurious contributions from anisotropic magnetoresistance or local Hall effects on spin currents. For practical applications, however, electrical spin injection and detection in semiconductor needs to take place locally requiring additional stringent conditions e.g., large tunnel spin polarization (for a tunnel contact) and a proper resistance-area (RA) product [11].

In this article we investigate a vertical spin transport structure of Co/Si/Ni junctions fabricated on a Si membrane that uses Co/Si and Ni/Si Schottky contacts as the spin injection and extraction electrodes. The structure benefits from increased control over the vertical scalability of Si enhancing the potential spin transfer between the two electrodes. We observed a thermionic field emission mechanism to be dominant in the current (I)–voltage (V) characteristics of the devices which is confirmed by fitting numerical simulation results. No magnetoresistance (MR) signal was observed in any of the devices even at low temperatures which is partly attributed due to a high RA product at the interfaces. However, our experiments show that an electrically well functioning back-to-back diode can be fabricated using the membrane technique and further experiments can build upon these results. As an example, we show by numerical simulation that by using a highly doped thin Ge layer at the Schottky interface the RA products could be tuned to obtain high MR.

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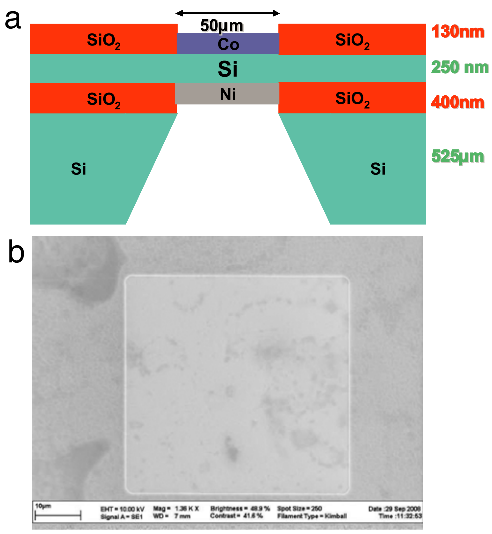

Fig. 1. (a) A schematic representation (not to scale) of the vertical Co/Si/Ni back-to-back Schottky barrier based spin injection–extraction device. (b) A scanning electron micrograph of the fabricated device showing the top Co contact.

2. Experimental procedure

The Co/Si/Ni devices have been fabricated on Si membranes using SOI wafers as starting material. The top and back square windows of 50 μm^2 area have been created by using a combination of standard lithography, oxidation and KOH anisotropic etching. The nominal thickness of the membrane is 250 nm and the active Si membrane is separated from the Si handle layer by 400 nm of SiO_2. A range of dopant concentrations of 4×10^{23} m^{-3} to 4×10^{25} m^{-3} in the Si membranes were obtained by P-implant. Metallization of 250 nm Ni and 50 nm Co was performed by evaporation. Deposition on both sides of the sample required breaking the vacuum to flip the sample over. However, prior to each deposition process a 20:1 buffered HF dip for 20 s followed by deionized water dip was performed to remove any native oxides from the Si membrane area. A schematic diagram of the fabricated device is presented in Fig. 1a. A scanning electron micrograph of the device is presented in Fig. 1b. I–V characteristics measurements were performed using a Hewlett Packard 4155C semiconductor parameter analyzer. For MR measurements, a dc sense current was passed through the current leads and the resistance was recorded automatically using a two terminal method as the in-plane magnetic field was swept. The measurements were performed at temperatures ranging from 50 to 300 K. The low temperature measurements were performed using a Bio-Rad DL 4960 cryostat temperature controller that enables a temperature variation from 1.5 K to room temperature.

3. Experimental results

Typical I–V characteristics of the Co/Si/Ni device measured at various temperature for various Si membrane doping density (N_d) are presented in Fig. 2. During measurements the anode and the cathode were connected to the Ni and the Co pad, respectively. Therefore, at positive biases, the current is dominated by the reverse bias current of the Co/Si junction, whereas, at negative biases, this is limited by the reverse current of the Ni/Si junction. For the doping densities considered in the Si membranes of our devices, the current conduction mechanism is usually dominated by TFE at the temperature ranges concerned. Therefore, the increase of current with increasing bias voltage, observed in Fig. 2, is due to the tunneling of electrons at the respective Schottky interfaces. The slight difference in the rate of current increase with

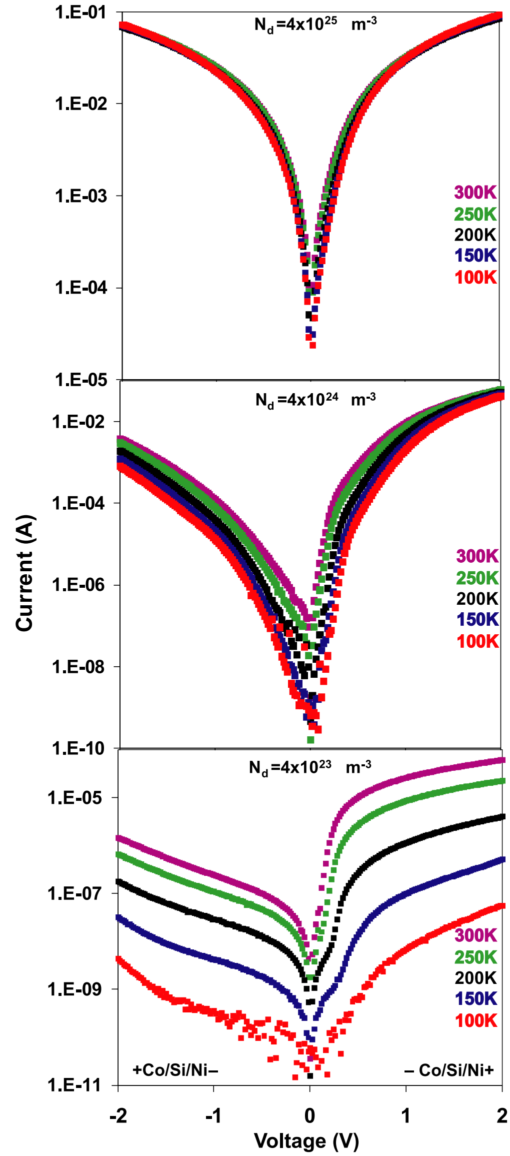

Fig. 2. I–V characteristics of the Co/Si/Ni devices as a function of temperature measured for various Si membrane doping densities (N_d).

increasing positive and negative biases is attributed to the different barrier heights of the Co/Si (0.65 eV [12]) and Ni/Si (0.70 eV [9]) junctions, respectively. Fig. 2 also reveals that the current density becomes less temperature dependent with increasing N_d, which again can be explained by a standard TFE model [9]. From these curves the currents were extracted for the corresponding spin injection bias voltage ranges of +0.1–0.3 V (taking the Co/Si contact as the injector and the Ni/Si contact as the detector) and −0.1–0.3 V (taking the Ni/Si contact as the injector and the Co/Si contact as the detector) at various temperatures.

We performed MR measurements of the fabricated Co/Si/Ni spin devices using the corresponding dc sense currents for bias voltages of ±0.1 V, ±0.2 V and ±0.3 V while sweeping an in-plane magnetic field in the range of −5000 Oe to +5000 Oe at a temperature range from 100–300 K. However, no MR signal corresponding to electrical spin injection was observed for any of the devices. An increase of MR of 0.04% due to Lorentz deflection was, however, observed only for the lowly doped Si membrane at an applied magnetic field of 5000 Oe when a sense current of 1 μA was passed. The noise level of the obtained signal was very low (∼0.0001%) confirming our measurement setup to be insensitive to

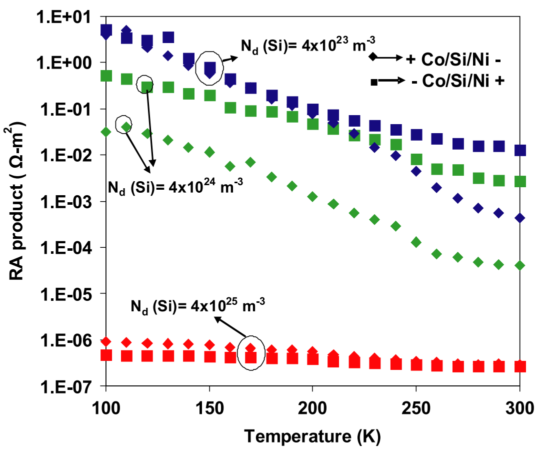

Fig. 3. Resistance-area (RA) product measured at ± 0.2 V bias of the Co/Si/Ni spin injection–extraction device for various Si membrane doping densities (N_d).

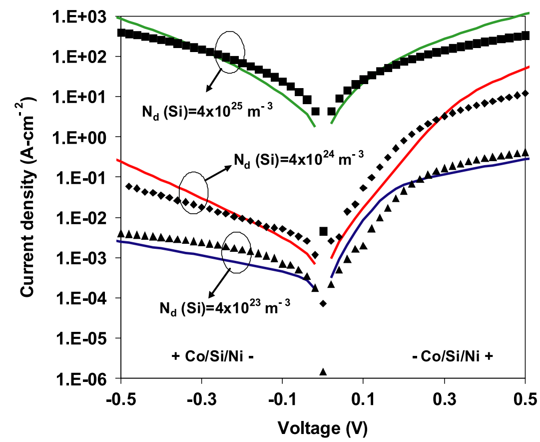

Fig. 4. J–V characteristics (symbols) of the fabricated Co/Si/Ni spin injection–extraction device for various Si membrane doping density. The solid lines refer to the J–V curves modeled by the Sentaurus Device simulator tool.

the anisotripic magnetoresistance of the vertical FMs. The reason behind the absence of a spin sensitive MR could be the indiffusion of magnetic contaminants into semiconductor by the high energy deposition technique, severely decreasing the spin polarization as mentioned by Roy et al. [13]. The high energy Ni deposition could have produced an interfacial silicide layer hampering spin transport across the FM–SC interface. This could be avoided by electrochemical deposition of Ni on Si [8], which is immune to silicide formation. Alternatively, a thin oxide tunnel barrier at the interface would be beneficial. Another important factor for the lack of spin injection could be an improper RA product of the injection electrodes as investigated experimentally by Min et al. [11]. The RA product of a contact is defined as the voltage (V) divided by the current density (I/A) at a particular value of V. The calculated RA products from the I–V measurements on our devices for spin injection condition (0.2 V) are plotted as a function of temperature in Fig. 3. The minimum RA products obtained in these samples, for example, when $N_d = 4 \times 10^{25}$ m^{-3}, are in the region of 10^{-6} Ωm^2. This is too high for a measurable MR, according to the calculation done by Min et al.

4. Simulation results

As an attempt to reduce the RA products of the Co/Si/Ni devices we investigate by numerical simulation the effect of growing a thin highly doped Ge layer at the Co/Si and Ni/Si interfaces. Recently [14], we have successfully used the commercial TCAD simulator Sentaurus Device from Synopsys for estimating the leakage currents in a Ge-based SB-MOSFET by calibrating the simulator to experimental Schottky diode results. This simulator provides a self-consistent and fully coupled implementation of nonlocal tunneling models of electrons for calculating the SB currents. The devices are generated using the Sentaurus Structure Editor and its Meshing engine. Here, at first the simulator is calibrated by using the Schottky barrier heights (0.70 eV for Ni/Si contact and 0.64 eV for Co/Si contact) and the various experimental doping densities (N_d) of the Si membranes. During this calculation various physical models, for example, effect of image force barrier lowering, bandgap narrowing and electron barrier tunneling have been used. The corresponding calculated current density (J) versus applied voltage curves for the various substrate doping densities are presented in Fig. 4 along with the experimental curves measured at 300 K. The concordance of the experimental and simulated current density curves confirms near full calibration of the simulator tool.

We now simulate the effect of incorporating a 2 nm n-type Ge layer of 1×10^{20} cm^{-3} doping density at both of the Schottky interfaces, which has the effect of thinning the Schottky tunnel barrier [7]. The resulting RA products of the contacts for a ± 0.2 V bias are plotted in Fig. 5 as a function of various Si membrane doping density along with the experimental results obtained at 300 K. It is observed that the RA products have been reduced to the high MR region for all devices. Therefore, a further experiment can be built on our Si-membrane-based vertical spin injection device by growing a δ-doped Ge layer at the Schottky interfaces.

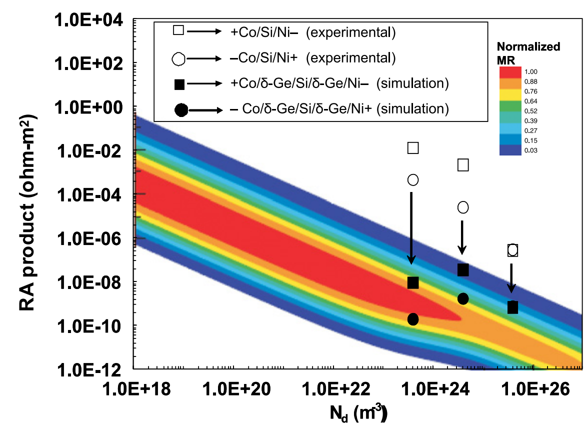

Fig. 5. RA products of the fabricated Co/Si/Ni device and the simulated Co/δ-Ge/Si/δ-Ge/Ni device as a function of Si doping density for applied biases of ± 0.2 V. The calculated MR of a Si spin transistor as a function of the contact RA product and Si doping density is adopted from Ref. [11], where the color legend shows the value of normalized MR.

5. Conclusions

We investigate the electrical spin injection and extraction in a vertical geometry of Co/Si/Ni Schottky junction built on Si membranes with doping densities of 4×10^{23} m^{-3} to 4×10^{25} m^{-3}. The devices show increased TFE effect with increasing doping at low temperatures. However, no MR was observed in the devices indicating the absence of spin polarized carriers in the semiconductor even at low temperatures. We show by numerical simulation that by growing a δ-doped Ge layer at the Schottky interfaces the RA products of the contacts could be tuned to achieve a high MR.

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