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Spin-valve effect in nanoscale Si-based devices with ferromagnetic electrodes

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Abstract

We report on the spin transport in nano-scale silicon (Si)-based spin-valve devices with Fe electrodes, MgO/Ge tunnel barriers, and a 20 nm-long Si channel. We observed clear spin-valve effect when a magnetic field was applied in the film plane along the Si channel transport direction. The magnetoresistance (MR) ΔR strongly depends on the applied bias voltage and temperature, indicating that the observed signal is not due to the anisotropy magnetoresistance (AMR) effect from the Fe ferromagnetic electrodes. Moreover, when the magnetic field was applied in the film plane normal to the channel transport direction, we observed a similar spin-valve effect, which indicates that the tunneling anisotropy magnetoresistance (TAMR) effect is also not the origin of this signal. These results indicate that the observed MR is governed by spin transport through the nano-scale Si channel. A large spin-dependent output voltage of 8 mV was observed at a bias voltage of 1 V at 50 K, which is among the highest value reported so far. The spin-valve effect remains observable up to 200 K.

1. Introduction

Conventional computing relies on the manipulation of the electron charges in solid-state electronic devices. However, nano-scale electronic devices are facing serious problems such as leaky off-currents and high idling power consumption. Hence, there is a strong demand to find alternative low-power solutions to overcome these issues. Spin transistors, which utilize the spin degree of freedom in semiconductors, are promising devices in the Beyond CMOS era [1]. The silicon (Si) based spin-MOSFET [1] is considered to be one of the most promising candidates because of its high compatibility with CMOS technology [1] and long spin lifetime in Si [2]. Recently, spin injection into microns of Si channels by using the three terminal Hanle [3] or four-terminal spin-valve effect [4] have been demonstrated up to 150 K with the spin output signal voltage around 1 mV. However, there is no report on transport in nano-scale Si channels, which is important for realization of nano-scale spin-MOSFETs. It is expected that the ballistic transport of electron in nano-scale Si channel would overcome the conductivity mismatch problem between the ferromagnetic (FM) electrodes and Si channel, resulting in a higher spin-dependent output in the nano-scale Si channel [5]. In this work, we fabricated nano-scale Si-based spin-valve devices and systematically investigated their spin transport characteristics.

2. Experiments

Device fabrication

In this study, we use the highly doped n-type Si (100) substrate with electron density $n = 1\times10^{18}$ cm^{-3}. Firstly, we cleaned the Si substrates by an H_2SO_4/H_2O_2 solution. Then, we removed the native oxide layer of the substrates by diluted hydrofluoric acid, and rinsed them in the de-ionized water. After that, we transferred the Si substrates to an electron beam (EB) evaporation chamber to deposit a 10 nm-thick Fe ferromagnetic (FM) electrodes at room temperature. An MgO / Ge double layer was inserted between the Fe electrodes and Si substrates to enhance the spin injection efficiency to the Si channel. To investigate the role of this double layer tunnel barrier, we fabricated two spin-valve devices; device 1 with Fe electrodes deposited directly on a 20 nm-long Si channel, and device 2 with a 2 nm-thick MgO / 1 nm-thick Ge double layer inserted between the Fe electrodes and the 20 nm-long Si channel as shown in Figure 1.

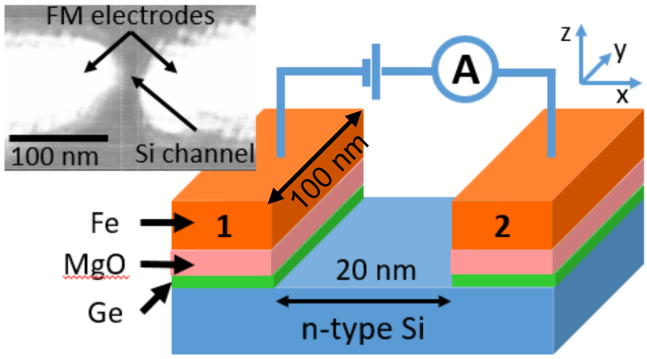

Fig. 1 Schematic structure of device 2 with MgO / Ge tunnel barriers and the set-up of local spin-valve measurement. Inset shows a scanning electron microscope image of a device 2.

After depositing the tunnel barrier and the FM layer, we used the e-beam lithography (EBL) and ion-milling technique to fabricate the nano-scale Si spin-valve devices. First, we used the EBL and EB evaporation to pattern a 30 nm Au hard-mask layer on these samples. Then, we used Ar ion milling to define the 20 nm Si channels. Finally, we fabricated pad electrodes of Au (40 nm) / Cr (5 nm) by e-beam evaporation and standard photolithography.

Results and discussions

Because the Hanle effect cannot be measured in nano-scale Si channels, we employed the two-terminal (local) spin-valve effect to detect spin transport. Figure 2(a) shows a representative MR of device 2 (with MgO / Ge double layers as a tunnel barrier) measured at 4.3 K with a magnetic field applied along the Si channel (along the *x*-direction in Fig. 1) and a bias voltage of 100 mV. We observed a high change of resistance ΔR up to 12 Ω, corresponding to $\Delta R/R = 0.8\%$.

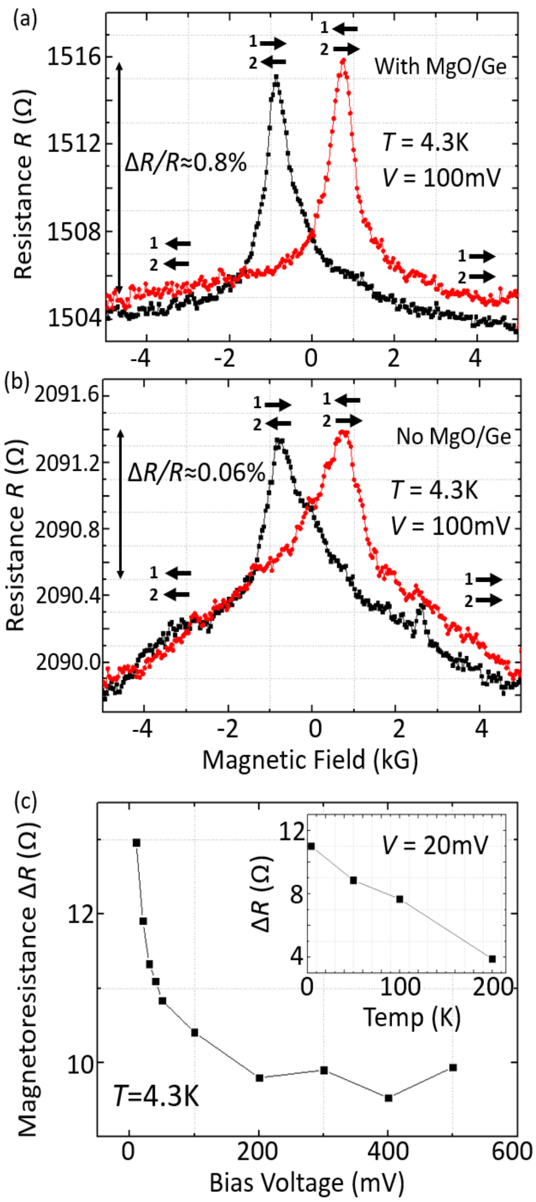

Fig. 2 (a) Spin-valve effect of device 2 (with MgO / Ge tunnel barrier) measured at 4.3 K with a bias voltage of 100 mV. (b) Device 1 (without MgO / Ge tunnel barrier) measured at 4.3 K with a bias voltage of 100 mV. (c) Bias voltage dependence of ΔR of device 2 with MgO / Ge at 4.3 K. Inset shows temperature dependence of ΔR.

Figure 2(c) shows the ΔR values at different bias voltages. We found that ΔR strongly depends on the applied bias voltage V, indicating that the observed MR was not the consequence of the AMR effect of the Fe electrodes. The inset in Fig. 2(c) shows the evolution of ΔR with increasing temperature. ΔR remains observable up to 200 K, which is in good agreement with previous reports on spin injection into a Si substrate [4,6].

Furthermore, we measured the magnetoresistance when the magnetic field was applied normal to the Si channel (along the *y*-direction in Fig. 1). The same MR curves was observed, indicating that the observed MR is not caused by the TAMR effect. These results indicate that the observed MR is governed by the spin transport through the nano-scale Si channel. In device 2, we achieved the spin-dependent output voltage $(\Delta R/R)V$ of 8 mV at the bias voltage of 1 V at 50 K, which is among the highest values reported so far.

In contrast, the device 1 (without the tunnel barrier layer) shows a much smaller $\Delta R/R$ of 0.06% as shown in Fig. 2(b), which demonstrates the important role of the double-layer tunnel barrier.

3. Conclusions

We have fabricated and investigated the spin transport in nano-scale Si spin-valve devices. Systematic investigations of the bias voltage dependence, temperature dependence, and magnetic field direction dependence of the magnetoresistance indicate that the observed spin-valve effect is governed by spin transport through the nano-scale Si channel. The highest spin-dependent output voltage is 8 mV for the device with an MgO / Ge tunnel layer at 50 K. The spin-valve effect remains observable up to 200 K. Our result is an important step toward realization of nano-scale spin-MOSFETs.

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