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Spin Injection and Transport in a Si Channel at Room Temperature

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1. Introduction

Si-based spintronics has been an emerging research area, as listed in the International Technology Roadmap for Semiconductors [1]. Much effort has been, so far, paid for realizing spin injection and transport in Si, and long spin coherence (> 350 μm) at 150 K [2] and large spin accumulation at room temperature (RT) [3] were realized. An indispensable milestone, which has not been and should be achieved for the practical application of Si spintronics, is realization of spin transport in Si at RT.

Here, we show the first demonstration of the simultaneous spin injection and transport in a highly doped Si channel at RT. Spin current was generated using a nonlocal technique, and nonlocal magnetoresistance effect and Hanle-type spin precession were successfully detected at 300 K in lateral spin valve devices with a spin injector and detector consisting of an Fe/MgO tunnel barrier. The spin diffusion length and its lifetime at 300 K were estimated to be 0.6 μm and 1.3 ns, respectively.

2. Experiments

Four-terminal lateral spin valve devices were prepared on a silicon-on-insulator (SOI) substrate with a (100) plane consisting of P-doped Si (100 nm)/silicon oxide (200 nm)/undoped Si wafer. The electron concentration in the Si top layer was determined to be 5×10^{19} cm^{-3} by Hall effect measurement. An Fe (13 nm)/MgO (0.8 nm) layer was grown on the Si top layer by molecular beam epitaxy after the native oxide layer on the surface of the Si layer was removed using dilute hydrofluoric acid (HF) solution. Before the growth of the MgO layer, 2 × 1 and 1 × 2 patterns of the Si surface were observed by reflection high-energy electron diffraction in this study, which was not done in our previous studies [4-6].

Figure 1 shows a schematic cross-sectional view of the lateral device fabricated by electron beam lithography for patterning. The Si channel was fabricated by a mesa-etching technique and two ferromagnetic (FM) electrodes–contact 2 of 0.5 × 21 μm^2 and contact 3 of 2 × 21 μm^2–formed by ion milling. Contacts 1 and 4 were formed with Al.

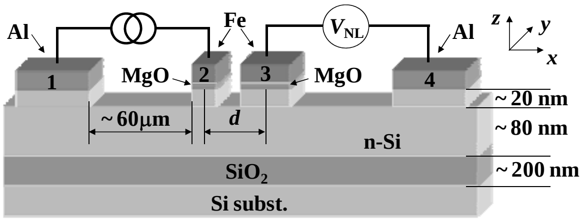

Fig. 1 Schematic cross-sectional view of a four-terminal lateral device. A current was injected between contacts 1 and 2, and the output voltage was detected between contacts 3 and 4 by the nonlocal detection technique.

3. Results and Discussion

Figure 2 shows the results obtained by the nonlocal detection technique (NL) [7]. The spin accumulation voltages ΔV were obtained with subtracting the constant background voltages produced by an electric coupling between the electric pads from the raw data, and converted into the NL magnetoresistance ΔR by using an injection current of 1 mA. Steep changes in ΔR with clear plateaus were successfully obtained at a temperature of not only 8 K but also 300 K. With the increase in temperature, the field for the transition in ΔR shifted slightly to the lower field. As previously reported [4], anisotropic magnetoresistance (AMR) hysteresis was also observed in dummy samples. Thus, the changes in ΔR can be explained by the magnetization reversal of each FM electrode. Therefore, we can assert that the changes in ΔR resulted from the amount of spin accumulations detected as the spin valve effect. This is evidence of the spin current through the Si channel at 300 K.

The spin diffusion length λ_N can be accurately estimated from the gap length dependence of ΔR, because the clear plateaus on the ΔR curves result from successful anti-parallel magnetization alignment. The inset of Fig. 2 shows that the ΔR curve decays exponentially with increasing gap length between contacts 2 and 3. Using the tunnel barrier, ΔR decreases as a function of the gap length [7, 8]. As previously reported method [4-6], λ_N was estimated to be 1.98 and 0.987 μm at 8 and 300 K, respectively. These values are consistent with those obtained using the Hanle method, as shown later.

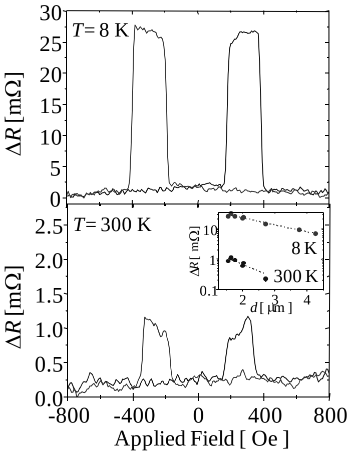

Fig. 2 Nonlocal magnetoresistance ΔR curves at 8 (upper panel) and 300 (lower panel) K, observed in a sample with a gap length d of 1.75μm. The insert shows the gap length dependence of ΔR.

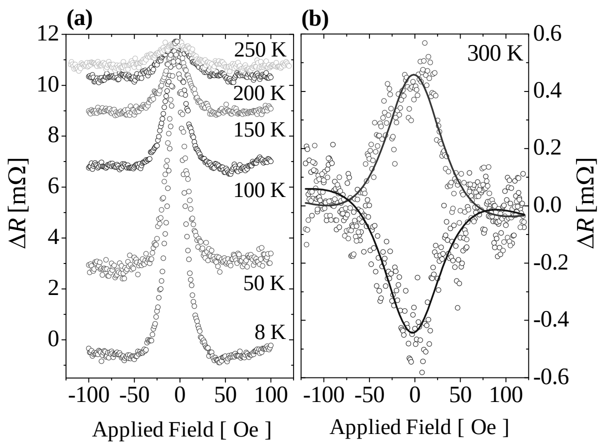

Fig. 3 Hanle curves observed at different temperature of the sample with a gap length d of 1.75μm. The curves at (a) 8, 50, 100, 150, 200, 250, and (b) 300 K.

Figure 3 shows the Hanle-type spin precession signals in the same geometry as that in the NL method, as a function of the measurement temperature. Each point of the curve is shown by the average of the signals obtained by several measurements. As the temperature increases, the signal becomes smaller and the full width at half maximum intensity widens gradually. However, a reverse of the Hanle signals is clearly observed by applying the reverse field, even at 300 K. This is strong evidence for the spin current through the Si channel up to 300 K.

λ_N and other spin transport parameters were estimated by fitting with the analytical solution [7, 9]. The fitting lines are in good agreement with the data, as shown by the example in Fig. 3(b). λ_N at 8 and 300 K were estimated to be 1.99 and 0.58 μm, respectively. These values are almost the same as those obtained by the NL, as mentioned above. This indicates that our measurements are highly reliable in the temperature range of 8 to 300 K.

The spin lifetime τ_{sp} were estimated to be 10.0 and 6.3 ns at 8 and 100 K, respectively. These value are roughly the same as those obtained in our previous study in the temperature range of 8 to 125 K [6]. This is because both τ_{sp} and λ_N are related to the nature of the Si channel. Furthermore, τ_{sp} at 300 K was estimated to be 1.32 ns in this study.

On the other hand, the spin polarization P of 3.6 % was estimated at 8 K. This value is twofold higher than that in our previous study [6], resulting in an enhancement of ΔV. In this study, the surface purification of Si was improved over that in the previous study. Therefore, we infer that the spin polarization must depend on the MgO/Si interface quality. Although the value is not yet sufficiently high in this study, higher spin polarization and higher spin accumulation voltage can be expected with the realization of a higher-quality MgO/Si interface.

4. Conclusions

The simultaneous spin injection and transport were demonstrated in a highly doped Si channel for the first time at room temperature and spin transport parameters were successfully estimated up to room temperature. The results obtained by two measurement method–the NL and the Hanle effect measurement methods–were sufficiently consistent. This demonstration will stimulate the research in the Si spintronics for practical devices.

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