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Temperature Dependence of Nonlocal Spin Transport in Si<100> Lateral Spin-Valve Devices

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Abstract

In our previous report on the spin transport in silicon (Si) lateral spin-valve (LSV) devices, nonlocal spin signals at room temperature were reproducibly enhanced when the crystal orientation of the spin-transport channel was changed from <110> to <100>. Here we find that this feature can be observed in the wide temperature range from 50 to 303 K at a bias current of -0.5 mA. From the analyses based on the one-dimensional spin diffusion model, the spin diffusion length of the Si<100> channel is nearly equivalent to that of the Si<110> one from 50 to 303 K. Thus, the observed difference in the magnitude of the nonlocal spin signals is not related to the spin relaxation mechanism depending on the crystal orientation.

1. Introduction

Spin-based logic devices using semiconductors have been proposed theoretically [1-3]. To realize these kinds of spintronic devices, efficient spin injection, transport, and detection in group-IV semiconductors such as Si and Ge are important. Up to now, we have explored the enhancement in the nonlocal spin signals in Si- and Ge-based lateral spin-valve (LSV) devices [4-7]. Recently, we found that the magnitude of the nonlocal spin signals for Si<100> LSV device is twice as large as that for Si<110> LSV ones at room temperature [8]. We inferred that these differences are attributed to the enhancement in the spin injection/detection efficiency at the ferromagnet/MgO/Si interfaces [8]. However, there is no information on the influence of the external temperature on the crystal orientation effect.

In this paper, we examine the temperature dependence of the nonlocal spin transport in both Si<100> and Si<110> LSV devices from 50 to 303 K. Since the spin diffusion length of Si<100> is nearly equivalent to that of Si<110> in the wide temperature range from 50 to 303 K, the difference in the magnitude of spin signals is not related to the spin relaxation mechanism depending on the crystal orientation of the Si spin-transport channel but attributed to the difference in the spin injection/detection efficiency at the ferromagnet/MgO/Si interfaces.

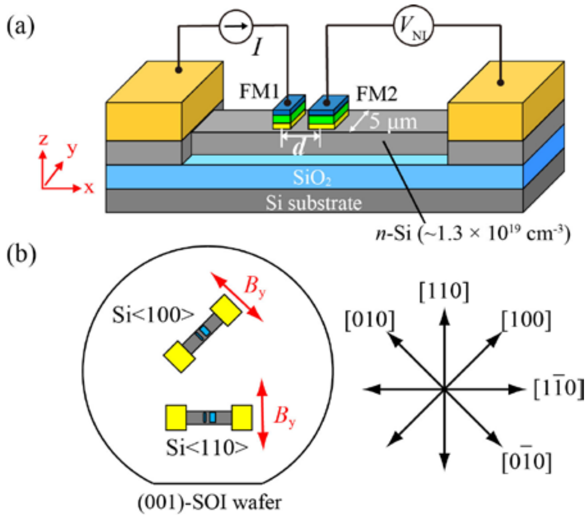

Fig. 1 Schematic diagrams of (a) the lateral four-terminal device with the Si spin-transport layer and (b) the relationship between the crystal orientations, <100> or <110>, and the fabricated Si spin-transport channels.

2. Fabrication of Si LSV devices.

We fabricated two kinds of LSV devices along <100> and <110>, as shown in Fig. 1(b), on a phosphorous-doped (n ~ 1.3×10^{19} cm^{-3}) (001)-Si on insulator (SOI) (~ 61 nm) layer. As a tunnel barrier, an MgO (1.1 nm) layer was deposited by electron-beam evaporation at 200 ºC on the SOI layer [4]. Then, a CoFe (10 nm) and Ru cap (7 nm) layers were sputtered on top of it. The MgO and CoFe layers were epitaxially grown on (001)-SOI, where the (001)-textured MgO layer was grown on Si(001) owing to an insertion of a thin Mg layer into MgO/Si interface. From the detailed characterizations, the CoFe(001)<100> / MgO(001)<110> / Si(001)<110> heterostructures were confirmed [9].

Conventional processes with electron beam lithography and Ar ion milling were used to fabricate LSV devices. A schematic of the fabricated LSV device is shown in Fig. 1(a). The Ru/CoFe/MgO contacts, FM1 and FM2, were patterned into 2.0 x 5.0 µm^2 and 0.5 x 5.0 µm^2 in sizes, respectively, and the width of the Si spin-transport channel was 7.0 µm. Here the center-to-center distance (d) in the LSV device was varied from 1.75 µm to 3.25 µm.

3. Results and Discussion

Conventional nonlocal magnetoresistance measurements, shown in Fig. 1(a), were performed at a bias of -0.5 mA to demonstrate reliable spin transport in Si [4-8]. Clear nonlocal magnetoresistance and Hanle-effect curves were observed for lots of Si<100> and Si<110> LSV devices at various temperatures. At 50 K, we found that the magnitude of nonlocal spin signals ($|\Delta R_{NL}|$) for Si<100> LSV devices is evidently larger than that for Si<110> LSV ones. This feature is consistent with our previous report at room temperature [8]. Here we examine the temperature dependence of $|\Delta R_{NL}|$ for both Si<100> and Si<110> LSV devices with d = 1.75 μm and 3.25 μm, as shown in Fig. 2(a). For d = 1.75 μm, although $|\Delta R_{NL}|$ decreases with increasing external temperatures, the value of $|\Delta R_{NL}|$ for Si<100> LSV devices is always greater than that for Si<110> LSV devices.

From the one-dimensional spin diffusion analysis [10,11] of the d dependence of $|\Delta R_{NL}|$, we calculated the average spin diffusion length (λ_{Si}) for both Si<100> and Si<110> LSV devices. Figure 2(b) shows the summary of the temperature dependence of λ_{Si} for Si<100> and Si<110>. Interestingly, although there are large differences in the value of $|\Delta R_{NL}|$ between Si<100> and Si<110> LSV devices, the value of λ_{Si} for Si<100> is almost equivalent to that for Si<110>. Here we also estimated electron Hall mobility from the Hall-effect measurements of Hall-bar devices fabricated along Si<100> and Si<110>, as shown in the inset of Fig. 2(b). This means that the diffusion constant is almost the same. From these results, the difference in $|\Delta R_{NL}|$ between Si<100> and Si<110> LSV devices is not related to the spin relaxation mechanism depending on the crystal orientation of the Si spin-transport channel but attributed to the difference in the spin injection/detection efficiency at the ferromagnet/MgO/Si interfaces.

4. Conclusions

We clarified that the spin diffusion length of the Si<100> channel is nearly equivalent to that of the Si<110> one in the wide temperature range from 50 to 303 K. The difference in the nonlocal spin signals between Si<100> and Si<110> LSV devices is not related to the spin relaxation mechanism depending on the crystal orientation but attributed to the spin injection/detection efficiency at the ferromagnet/MgO/Si interfaces.

Acknowledgements

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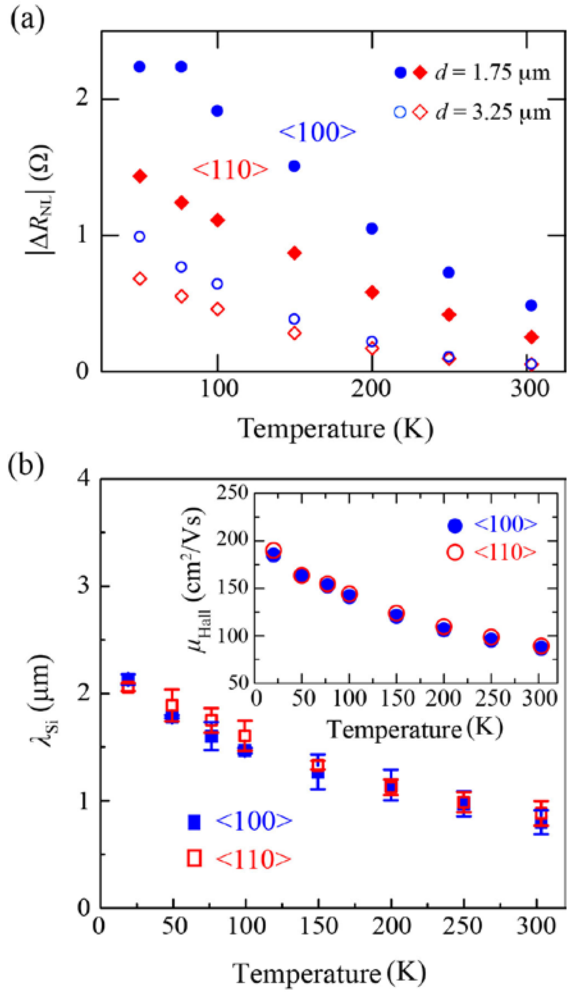

Fig. 2 Temperature dependence of (a) $|\Delta R_{NL}|$ and (b) λ_{Si}, estimated by d dependences of $|\Delta R_{NL}|$ at various temperatures, for Si<100> and Si<110> LSV devices. The inset of (b) shows the temperature-dependent electron Hall mobility.

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