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Correlation between the intensities of differential conductance curves and the spin accumulation signals in Si for CoFe/MgO/SOI devices

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Abstract

We have investigated the spin accumulation signals and the bias current (I_{bias}) dependence on differential conductance (dI/dV) for CoFe/crystalline MgO/Si on insulator (SOI) devices with three different impurity concentrations in the Si channels. The intensities of dI/dV vs. I_{bias} for the spin-extraction condition are sensitive to the carrier density in the range of around 10^{19} cm^{-3}. We find that there is a strong correlation between the intensity of dI/dV vs. I_{bias} curves and the intensity of spin accumulation signals in Si in the spin extraction bias condition. Considering the conventional spin diffusion theory, we regard the correlation between the intensities of dI/dV curves and the spin accumulation signals as a consequence of the density of state of bcc-structured CoFe. These results indicate that the designs of the ferromagnet DOS and the shape of *dI/dV* curves are two of keys for observing large spin accumulation signals in Si.

1. Introduction

Since the successful detection of spin accumulation signals in Si at room temperature, [1] electrical spin injection and detection in semiconductors have been actively studied [1-4] for realizing spin field effect transistors (spin-FETs). [5-7] Spin-FETs, whose source and drain electrodes have ferromagnetic materials, are expected to lead to new architecture involving the spin degree of freedom. To realize the spin-FETs, it is necessary to improve injection and detection efficiencies of electrical spin in semiconductors more than ever.

We pay attention to the tunnel barrier which is one of key elements to control the efficiencies of spin injection and detection, and have observed the increase of spin accumulation signals in Si with increasing MgO tunnel barrier thickness [3] or with increasing bias voltage (V_{bias}) [4] only in the spin-extraction condition of V_{bias}. Considering the conventional spin diffusion theory, we have proposed the models [3, 4] in which the spin accumulation signals are influenced by both the spin absorption effect and the density of states (DOS) of a bcc structured CoFe. [8] Although precise mechanism is now open question, understanding and investigation of the mechanisms of the spin signal intensities are very important for CoFe/MgO/SOI devices.

In this study, we further investigated the spin accumulation signals observed by three-terminal Hanle measurements and the bias current (I_{bias}) dependence on differential conductance (dI/dV) for CoFe/crystalline MgO/Si on insulator (SOI) devices with three different impurity concentrations in the Si channels. As a result, we found that the results of different impurity concentration dependence on ΔV indicate that intensity of ΔV is much influenced by the shape of bias current dependence on differential conductance (dI/dV).

2. Experimental

We prepared three CoFe/MgO/SOI devices (devices A-1, B-1 and C-1) with three different impurity concentrations in the Si channels and with the comparable resistance area product (RA~15 kΩμm^2). All the devices were fabricated on phosphorus-doped (100)-textured SOI substrates. The carrier densities of the SOI layer confirmed by measuring Hall effect at 77 K are 2.0×10^{19} cm^{-3}, 2.2×10^{19} cm^{-3} and 2.6×10^{19} cm^{-3} for the devices A-1, B-1 and C-1, respectively. These SOI layers have degenerate low-resistive metallic characteristics. After a natural oxidation layer on a surface of the SOI layer was removed by hydrofluoric acid, an MgO tunnel barrier was deposited by electron beam evaporation with a base pressure better than 2.0×10^{-9} Torr. Then, a $Co_{50}Fe_{50}$ (CoFe) and a Ru capping layers were sputtered in the same ultra-high vacuum deposition system. We observed a crystalline CoFe/MgO layers on (100)-textured SOI by measuring the reflective high-energy electron diffraction and the cross-sectional transmission electron microscopy methods. The CoFe/MgO contact was patterned into 2×100 μm^2 by using photolithography and Ar ion milling techniques. Finally, ohmic pads consisting of Au/Ti were formed for all the contacts. Using three-terminal devices, [3] we can electrically detect spin accumulation signals in SOI as ΔV via Hanle-type spin precessions. The perpendicular magnetic field (H_Z) was applied after the magnetization of the CoFe contact was aligned parallel to the plane along the long axis of the contact. The detailed ΔV signals and the I_{bias} dependence on dI/dV for these devices were measured at 77 K.

3. Results and discussions

Figure 1 shows the spin accumulation signals (ΔV) detected by three-terminal Hanle measurements under I_{bias} = +10 mA (spin extraction condition) at 77 K for devices A-1, B-1 and C-1, which have the comparable resistance area product (RA~15 k$\Omega\mu m^2$). A quadratic background voltage depending on B_Z is subtracted from the raw data for the each Hanle curves. All the devices show spin accumulation signals, however, the intensities of Hanle curves are quite different from each other. This result indicates that the intensities of the spin accumulation signals are not related only by the RA value of CoFe/MgO/n$^+$-Si junction. Considering the conventional spin diffusion theory, absolute values of spin accumulation signals ($|\Delta V|$) are given by $|\Delta V| \propto P_{Si}^2 \rho_{Si} \lambda_{Si} I / 2A$, where P_{Si} is spin polarization in Si, ρ_{Si}, I and A are the resistivity of the Si and measured current and the contact area of CoFe/MgO electrode. In our case, the values of I, A, ρ_{Si} and λ_{Si} are constant for each devices,[9] therefore, $|\Delta V| \propto P_{Si}^2$.

Figure 2 shows the dI/dV properties as a function of bias current measured at 77 K for the devices A-1, B-1 and C-1 shown in Fig. 1. The intensities of dI/dV vs. I_{bias} for the spin-extraction condition are sensitive to the carrier density in the range of around 10^{19} cm^{-3}. Since Fig. 1 was measured by constant current mode, therefore, we plotted (dI/dV) as a function of bias current (I_{bias}). As shown in Figs. 1 and 2, in the spin extraction condition, we find strong correlation between the intensity of dI/dV curves and the $|\Delta V|$ signal intensity. The results in Fig. 2 indicate that device A-1 tends to flow the current in the high current (that is, high voltage) bias regime compared to the device B-1 and C-1 in the spin-extraction condition. In the high voltage bias regime, the DOS of up and down spins for bcc-CoFe[8] has large difference compared to that in the low voltage bias regime for the extraction bias condition. Therefore, flowing more current in the high current (voltage) bias regime would induce enlarge the intensity of spin accumulation signals in Si. On the other hand, in the injection condition (I_{bias} < 0), as shown in Fig. 2, the values of tunnel conductance are smaller than those in extraction condition for all the devices. These properties are consistent with the properties of bias voltage dependence of $|\Delta V|$.[9] Considering the conventional spin diffusion theory, we believe these correlations would be due to the consequence of the density of state of bcc-structured CoFe in the spin extraction conditions.

4. Conclusions

We first observed the correlation between the intensities of dI/dV curves and the $|\Delta V|$ signals in Si. Considering the conventional spin diffusion theory, we regard this correlation between the intensities of dI/dV curves and the spin accumulation signals as a consequence of the density of state of bcc-structured CoFe in the spin extraction conditions. These results indicate that the designs of the ferromagnet DOS and the shape of dI/dV curves are two of keys for observing large spin accumulation signals in a Si.

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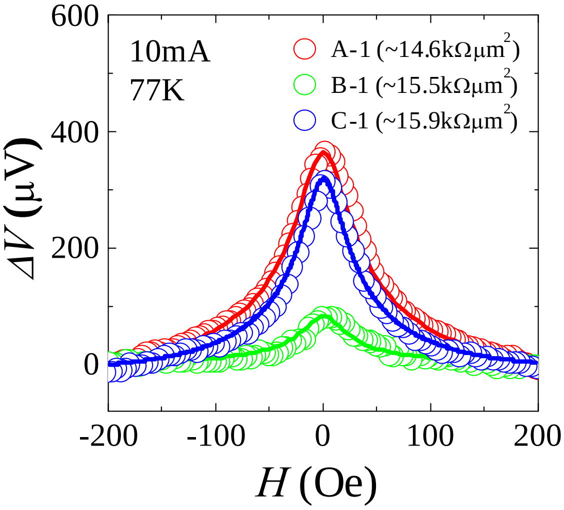

Fig. 1 Spin accumulation signals detected by three-terminal Hanle measurements at 10 mA and 77 K for the devices A-1, B-1 and C-1, which have the comparable resistance area product (RA~15 k$\Omega\mu m^2$).

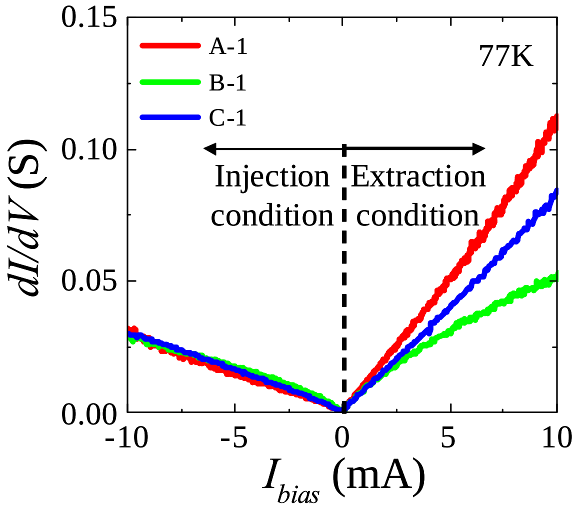

Fig. 2 dI/dV properties depending on the bias current at 77 K for the devices A-1, B-1 and C-1.

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