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Asymmetric bias voltage dependence in spin accumulation signals observed by the three-terminal Hanle measurements for CoFe/crystalline MgO/SOI devices

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1. Introduction

Spin-metal-oxide-semiconductor field effect transistors (spin-MOSFETs), [1, 2] whose source and drain electrodes have ferromagnetic materials, are expected to lead to new architecture involving the spin degree of freedom. The most promising application as the first target for the spin-MOSFETs is a reconfigurable logic chip. [3, 4] Since the spin-MOSFET directly couples the logic element with the nonvolatile memory, one can open up a way to a new kind of an ultimate logic-in-memory architecture.

To realize the spin-MOSFETs, electrical spin injection and detection in semiconductors are two of the important subjects. Among various semiconductors, silicon (Si) can be expected as a promising host material for introducing spin functionality because its weak spin-orbit and hyperfine interaction lead to long spin coherence.[5, 6] The first experimental demonstration of the electrical spin injection and detection in Si at low temperatures was reported by using vertical devices with insulating tunnel barriers (Al_2O_3).[7] Recently, several groups have reported room-temperature detection of spin accumulation in Si-based devices.[8-11] In particular, clear room-temperature spin transport and its manipulation by applying transverse magnetic fields were achieved in lateral devices with an n^+-Si channel.[9] We have also observed room-temperature detection of spin accumulation in CoFe/MgO/Si on insulator (SOI) [12] and CoFe/AlO_x/SOI [13] devices. For the CoFe/MgO/SOI devices, the relatively long spin lifetime of 1.4 nsec and large spin polarization of 0.47 were observed at room temperature (RT) by fitting the simple spin diffusion model, reported in Ref. [12]. Additionally, we have observed the enhancement of the absolute value of three-terminal voltage changes ($|\Delta V|$) via Hanle-type spin precessions as a function of interface resistance [8, 10, 11, 16]. Here we have considered evident effect of the interface resistance on spin accumulation by the influence of the spin absorption from Si into CoFe. In the three-terminal Hanle measurements, we have observed spin accumulation in Si only under the forward bias (extraction condition) where the electrons are extracted from the conduction band of Si into the spin polarized states of ferromagnet CoFe, indicating the asymmetric bias voltage dependence. In terms of bias voltage dependence on spin accumulation, we could not explain only by the mechanism of spin absorption from Si into CoFe electrode.

In this study, we show the detailed bias voltage dependence on spin accumulation in Si as voltage change (ΔV) by the three-terminal Hanle measurements for the CoFe/MgO/SOI devices with various MgO thicknesses. To discuss the possible origins of the bias voltage dependence on the spin accumulation signals, we should take into account two additional possible origins. One is the difference in electrical detectability between spin injection and extraction as described in Refs. [14] and [15], and the other is the effect depending on the density of states (DOS) of bcc-structured CoFe electrode.

2. Experimental

We designed a wedge-shaped MgO tunnel barrier layer on 3 inch wafer and fabricated three-terminal devices for Hanle-effect measurements, as shown in Fig. 1. The devices were fabricated on phosphorus-doped (100) textured SOI substrates. The carrier density of the SOI layer was ~ 3.0×10^{19} cm^{-3} at 20 K and ~ 2.0×10^{19} cm^{-3} at RT, respectively, indicating that the SOI layer has 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 with a thickness ranging from 1.54 to 2.04 nm 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 successfully observed a crystalline MgO tunnel barrier on (100)-textured SOI by measuring the cross-sectional transmission electron microscope. 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 shown in Fig. 1, one can electrically detect spin accumulation in Si as voltage changes via Hanle-type spin precessions. In this study, a small perpendicular magnetic field (between -200 and +200 Oe), B_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 bias voltage dependence on $|\Delta V|$ for the CoFe/MgO/SOI devices with various MgO thicknesses was measured at 77K.

2. Results and discussions

Figure 2 shows a typical bias voltage dependence of $|\Delta V|$ for the device with the largest interface resistance (~ 20.0 kΩ μm^2 for 10mA) defined as $A(V/I)$, where A is the contact area, V and I are voltage and current, respectively. We can find an exponential increase in $|\Delta V|$ with a rise of bias voltage for extraction condition ($I > 0$). As discussed in Ref. [12], we should consider the spin absorption from Si into CoFe as one of the mechanism for explaining bias voltage dependence on $|\Delta V|$. It is expected that $|\Delta V|$ decreases because the interface resistance decreases with increasing bias voltage. On the other hand, the increase of a current should increase the $|\Delta V|$. When the $|\Delta V|$ is multiplied by the current normalized factor ($|\Delta V|_{\mathrm{Nor}} = |\Delta V| \times$ factor of $[10(\mathrm{mA})/I_{\mathrm{measured}}]$), $|\Delta V|_{\mathrm{Nor}}$ still slightly increases with increasing bias voltage when increasing bias voltage. Therefore, we should take into account other additional mechanism for explaining the exponential increase in bias voltage dependence.

We propose here the model including the effect of the DOS of the bcc-structured CoFe for explaining the slight increase of $|\Delta V|_{\mathrm{Nor}}$ as a function of bias voltage. Here we focus on the spin polarization (P). In Fig. 2, the P values estimated by fitting the existing spin diffusion model [16] are plotted as a function of bias voltage. The observed increase in the P values as a function of bias voltage is consistent with the formation close to the Fermi level in the DOS of the bcc-structured CoFe. On the other hand, when electrons are injected from CoFe into the conduction band of n^+-Si ($I < 0$), we can see no Hanle-like signal up to I = -10 mA. The same features with asymmetric bias dependence have already been observed and discussed in Fe/GaAs [14] and CoFe/Si devices [15]. The asymmetric bias dependence was explained by the difference in the electrical detectability between spin injection and spin detection.[14, 15] The small difference between majority and minority DOS of the bcc-structured CoFe in the injection condition should decrease the spin accumulation in the conduction band of Si compared with spin extraction conditions. This would also make difficult in electrical detectability for spin injection condition.

Thus, we believe that, at least, we should take into account three mechanisms ((1) spin absorption into the ferromagnet, (2) the difference in electrical detectability between spin injection and extraction, and (3) the DOS of bcc-structured CoFe electrode) to explain the observed bias voltage dependence of $|\Delta V|$.

3. Conclusions

We measured detailed bias voltage dependence on spin accumulation for the CoFe/MgO/SOI devices with various MgO thicknesses. Asymmetric bias voltage dependence on ΔV was observed for the CoFe/MgO/SOI devices. We discussed possible explanations for the exponential enhancement of the three-terminal Hanle signal $|\Delta V|$ as a function of interface resistance and the asymmetric bias dependence of ΔV. In terms of the reason of exponential enhancement of $|\Delta V|$ as a function of interface resistance, the spin absorption into the ferromagnet would be most effective. In terms of the asymmetric bias dependence, we should take into account two additional possible origins. One is the difference in electrical detectability between spin injection and extraction as described in Refs. [14] and [15], and another is the effect depending on the DOS of bcc-structured CoFe electrode.

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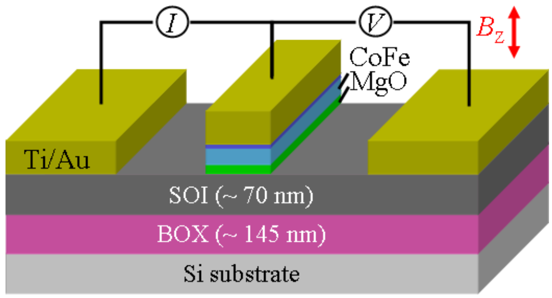

Fig. 1 Fabricated three-terminal devices for Hanle-effect measurements.

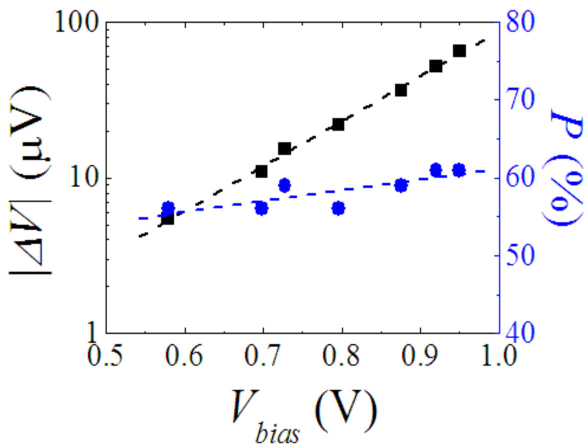

Fig. 2 A typical bias voltage dependence of $|\Delta V|$ for the device with the largest resistance area product (RA) of ~ 20.0 kΩ μm^2 for 10mA.