Generation of highly spin-polarized electrons in Si at room temperature using low-resistance CoFe/Fe/Mg/MgO/n^+-Si junctions

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Si-based spin metal-oxide-semiconductor field-effect transistors (spin MOSFETs), which use ferromagnetic metals as the source/drain electrodes, are promising for low-power electronics applications, such as reconfigurable logic circuits and high-density nonvolatile random-access memory, since their transistor characteristics can be programmed in a nonvolatile manner by the relative magnetization configuration between the source and drain ferromagnets [1]. The most crucial parameter is the magnetoresistance (MR) ratio that is proportional to P_S^2/R_T, where P_S is the spin polarization of tunneling electrons through a Si-based ferromagnetic tunnel junction and R_T is the total series resistance including the source and drain junction resistances R_J and the Si two-dimensional channel resistance [2]. Thus, Si-based ferromagnetic tunnel junctions with both high P_S and low R_J are essential for realizing high-performance spin MOSFETs toward practical use. However, such junctions have yet to be realized because of the trend in the relationship between P_S and R_J: higher P_S is mostly obtained with increasing resistance-area product (RA) [3]. This is the main reason why the MR ratio currently stands at only ~0.04% at room temperature [4].

It is known that P_S through a ferromagnetic tunnel junction is fundamentally limited by the spin polarization at the Fermi level of the ferromagnetic metal when the spin-filter effect of the tunneling barrier is absent. Hence, ferromagnetic materials with a high spin polarization are effective to enhance P_S. In this respect, CoFe is promising because CoFe has a higher spin polarization (~50%) than Fe (~45%) [5] that is frequently used for Si-based spin injection experiments. On the other hand, RA is related to the tunnel barrier layer in a Si-based ferromagnetic tunnel junction. So far, our experimental studies at room temperature revealed that Fe/Mg/MgO/n^+-Si has P_S = 7.3% and RA = 4 – 6 kΩμm^2 [2]. whereas Fe/Mg/SiO_xN_y/n^+-Si has P_S = 7.5% and RA = 0.7 kΩμm^2 [6]. Hence, SiO_xN_y or SiN is very useful to obtain lower RA, which is partly because a thin insulator tunnel barrier can be formed by direct oxi-nitridation or nitridation of Si surface with RF plasma. Here, we study ferromagnetic tunnel junctions with both a high P_S and a low R_J using CoFe and SiN, in which P_S is estimated from Hale signals measured with a three-terminal device and R_J is estimated from the *I*-*V* curve at around zero bias. Furthermore, we discuss the junction capability through a simple estimation of MR ratio using the device parameters in our previous spin MOSFET [2].

Figure 1 shows our three-terminal device structure having CoFe(10 nm)/Fe(0.7 nm)/Mg(0.5 nm)/SiN(1 nm)/n^+-Si tunnel junctions with 25 μm^2 in area and the measurement setup for Hanle signals at room temperature. The junction contains two interface-control layers; an Fe layer between Mg and CoFe to suppress Co interdiffusion [7] and a Mg layer between Fe and SiN to prevent interfacial reaction as well as to control the band alignment [6]. Figure 2 shows current density J versus junction bias voltage V, suggesting direct-tunneling-dominated transport. Figure 3 shows a Hanle signal measured with a constant current I_B = –10 mA in the spin extraction geometry, where red squares show experimental signal data and a black solid line shows a theoretical fitting curve [2]. After the analysis of Hanle signals obtained for three devices, the averaged P_S and RA values are 15.8% and 2.5 kΩμm^2, respectively. Then, the MR ratio was estimated using formulas in ref. [2], under the assumption that this junction is replaced with the source and drain of the spin MOSFET, where the Si two-dimensional inversion channel length and width are 0.4 μm and 180 μm, respectively, the gate oxide thickness is 200 nm, the source-to-gate voltage V_{GS} is 40 V, and the experimental junction characteristics in Figs. 2 and 3 are used. Since the P_S is increased and the MR ratio up to 0.76% is predicted, this junction structure has high potential for Si-based spin MOSFETs.

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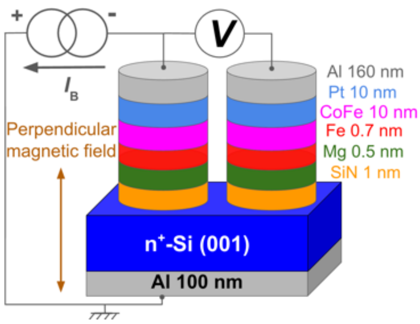

Fig.1 Schematic illustration of the device and three-terminal measurement setup.

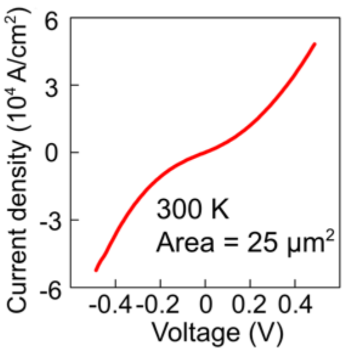

Fig.2 Current density J versus junction bias voltage V measured at 300 K.

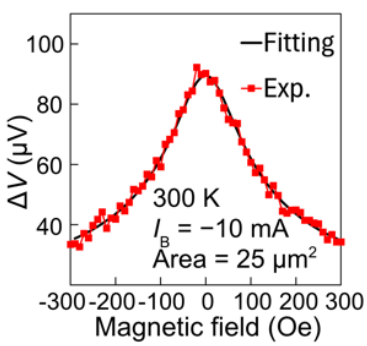

Fig. 3 Hanle signal measured at 300 K with a constant current I_B = -10 mA.