Enhancement of spin polarization in Si using a Fe/Mg/MgO/SiO_x/Si spin injector

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For the last decade, spin injection into Si through a ferromagnetic metal(FM)/MgO/Si tunnel junction has been intensively studied [1-3]. However, spin polarization of electrons in Si (P_S = 7.5 – 15%) was much smaller than that of FM (P_{FM} ~ 45 – 56%) used in the experiments. It has been pointed out that spin polarization of electrons passing through such ferromagnetic tunnel junction is reduced by a magnetically-dead layer formed at the FM/MgO interface and electron trap states near the MgO/Si interface [4]. Whereas the former is effectively suppressed by a Mg insertion layer between FM and MgO [3], the latter is possibly improved by a method used in the metal-oxide-semiconductor (MOS) technology. In this study, we show that P_S in Si-based spin devices with a Fe/Mg/MgO/Si junction is enhanced by decreasing the surface state density N_{SS} (cm^{-2}) with plasma oxidation of the MgO/Si structure during the junction formation, leading to the formation of MgO/SiO_2/Si structure.

The sample preparation was as follows: After thermal cleaning of a H-terminated Si(001) substrate in an ultra-high vacuum, a 0.8-nm-thick MgO layer was deposited at room temperature by EB evaporation. Subsequently, the MgO/Si structure was oxidized at room temperature by a RF plasma source for 1 min (a non-oxidized MgO/Si structure was also prepared for a reference sample.). On this surface, three types of structures were prepared at room temperature: (1)For three-terminal measurements, a Al (10 nm)/Mg (1 nm)/Fe (3 nm)/Mg (1 nm) (from top to bottom) was deposited by MBE, (2)For *C-V* measurements and the conductance method for MOS capacitors[5], a Al/MgO (=5, 10, and 15 nm) was deposited by EB evaporation and MBE, and (3)For X-ray photoelectron spectroscopy (XPS) measurements, Al was deposited by MBE. After exposure to air, the fabrication process of the top and bottom electrodes was the same as that in our previous report [3]. Phosphorus-doped Si(001) substrates with ~1 mΩcm and ~100 mΩcm were used for (1)(3) and (2), respectively. Figure 1 shows a three-terminal device with circular junctions with 17.8 μm in diameter and the three-terminal measurement setup, in which the voltage change ΔV was measured with a constant current I = 30 mA (spin extraction geometry) driven from the top to bottom electrodes while a perpendicular magnetic field was applied and swept from -3 to 3 kOe.

From XPS spectra of Si 2p (Fig. 2) and *I-V* measurements, the reference sample (without oxidation) does not have SiO_x and has a junction-area product (*RA*) of 5.5 kΩμm^2, whereas the oxidized sample has a ~0.26-nm-thick SiO_x layer (between MgO and Si) and has a *RA* of 24 kΩμm^2. Figure 3 shows Hanle signals measured at 4 K of the reference sample (green curve) and the oxidized sample (red curve), and the black curve is the fitting for each signal using Eq. (2) in Ref.[3]. Assuming that the diffusion constant D of electrons in Si is 3.5 cm^2/s [1], P_S and spin lifetime (τ_S) in the reference sample were estimated to be 8% and 2.5 ns, respectively, and those in the oxidized sample were estimated to be 19% and 2.8 ns, respectively. Thus, P_S was enhanced by a factor of 2.4 in the oxidized MgO/SiO_2/Si structure. From *C-V* and *G-frequency* measurements at room temperature, N_{SS} of the reference sample was estimated to be ~ 2.1×10^{13} cm^{-2} over the flat band energy level to the midgap energy level of Si bandgap. On the other hand, N_{SS} of the oxidized sample was lower than that of the reference sample (MgO/Si structure) at every energy level, and the maximum decreasing rate was 60%. Therefore, the enhancement of P_S by the oxidation process is caused by the decrease of N_{SS} in the MgO/SiO_2/Si structure.

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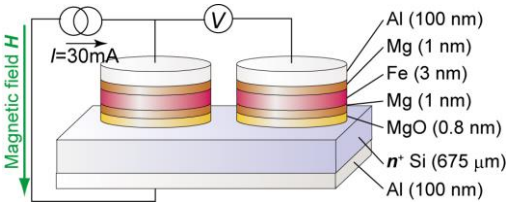

Fig. 1 Schematic structure of a three-terminal device with multi-layered magnetic junctions formed without the oxidation process. Junction formed with the oxidation process has an additional ~0.26-nm-thick SiO_x layer between MgO and the Si substrate. Our Hanle measurement setup is also illustrated.

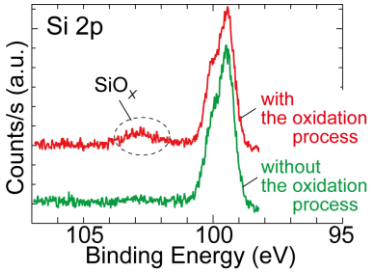

Fig. 2 XPS spectra of Si 2p in Al/MgO/Si samples formed with(red curve) and without (green curve) the oxidation process.

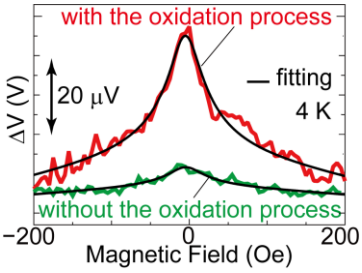

Fig. 3 Hanle signals measured at 4 K of three-terminal devices formed with (red curve) and without (green curve) the oxidation process. The black curve for each experimental curve is the fitting.