# Spin injection/extraction into/from a $n^+$-Si channel using a $Fe/Mg/Si_3N_4/Si(001)$ junction

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Towards the realization of Si-based spintronic transport devices, we have studied spin injection/extraction into/from a $n^+$-Si(001) substrate using Fe(3 nm)/Mg($t_{Mg}$ = 0–1 nm)/ $SiO_xN_y$(1 nm)/Si junctions ($x : y = 4 : 6$), and we have achieved a relatively high spin polarization of electrons $P_S$ = 16% and a relatively long spin lifetime $\tau_S$ = 5.6 ns in the Si channel when $t_{Mg}$ = 1 nm and the three-terminal measurement temperature $T_M$ was 4 K [1, 2]. This junction structure was found to be promising because of its fabrication method compatible with the Si complementary metal-oxide-semiconductor (CMOS) technology and its low junction resistance-area product $RA$ ~700 $\Omega\mu m^2$. To deeply understand spin-related transport concerning spin injection/extraction through the $Fe/Mg/SiO_xN_y$ junctions, further experiments with a different $x/y$ ratio are very helpful. In this study, we prepare spintronic devices having a Fe(3 nm)/Mg(1 nm)/$Si_3N_4$/Si junction, and estimate $P_S$ and $\tau_S$ using the three-terminal method. Our main finding is that the barrier material and its interface at the Si(001) surface have a crucial influence on $P_S$ and $\tau_S$, since these parameters are slightly decreased by changing from $SiO_xN_y$ ($x : y = 4 : 6$) to $Si_3N_4$.

The phosphorus doping concentration of the Si substrate ($8 \times 10^{19}$ $cm^{-3}$), device structure, and fabrication process were basically the same as those in our previous reports [1, 2]. There are two differences in the formation of a tunnel barrier; a boron nitride reactor tube instead of a quarts reactor tube was installed in a radio-frequency (RF) plasma gun to form a $Si_3N_4$ tunnel barrier, and the substrate temperature $T_S$ during the nitridation was set to 870°C which was higher than that (500°C) in the previous report. For efficient spin injection/extraction, $T_S$ was increased to reduce the defects in the barrier layer and the interface at the Si surface. To confirm the stoichiometry ratio Si/N, a X-ray photoelectron spectroscopy (XPS) was used for an unprocessed $Si_3N_4$/Si(001) structure prepared in the same manner. Figure 1 shows the junction structure and the three-terminal measurement setup with the definition of the constant bias current polarity. In three-terminal measurements, we applied a constant bias current $I$ between the top electrode of a circular junction with 25 $\mu m^2$ in area and the backside of the substrate, and measured the voltage between the junction and another junction located in a distant place (more than a few mm) while a sweeping magnetic field was applied along the normal to the substrate plane. The estimation procedure of $P_S$ and $\tau_S$ was the same as that in the previous reports [1, 2], and $T_M$ was ranging from 4 to 300 K.

The XPS spectrum of Si-2p was found to have a peak at the binding energy of 118.5 eV, which directly means the successful formation of the $Si_3N_4$ tunnel barrier layer. From the $I$-$V$ characteristics at room temperature measured for more than five junctions, the average $RA$ was found to be ~500 $\Omega\mu m^2$. Using the direct tunneling formula by Simmons [3], we estimated the thickness of the $Si_3N_4$ layer to be ~1.0 nm, assuming the barrier height of 1.72 eV which was estimated from the electron affinity of $Si_3N_4$ and the work function of Mg in ref. [4].

Figure 2 shows the three-terminal Hanle signal in the spin extraction geometry, which was measured with $I$ = –20 mA at 4 K. As seen, a clear narrow Hanle signal with a half-width at the half-maximum of 24 Oe directly indicates the successful spin extraction. From this signal, $P_S$ and $\tau_S$ were estimated to be 11% and 2.3 ns, respectively, which were slightly smaller than those ($P_S$ = 16% and $\tau_S$ = 5.6 ns) obtained for the $SiO_xN_y$ barrier. Since the junction structure except the barrier layer was the same and $RA$ was almost the same as those in the previous report, the above smaller values are attributed to the properties of the barrier layer. This consideration is consistent with a different $\tau_S$ value in our another previous report [5]; $P_S$ = 16% and $\tau_S$ = 1.7 ns for the same junction structure with a MgO barrier layer, even though the substrate was cut out from the same wafer in refs. [1, 2] and this study. Gathering all these results, we concluded that the barrier material and its interface at the Si(001) surface have a crucial influence on $P_S$ and $\tau_S$. This finding will greatly contribute to the understanding of the physics of spin injection/extraction in ferromagnet/semiconductor junctions. Other three-terminal measurement results, such as temperature and bias dependences, will be presented at the conference.

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**References** [1]T. Hada, *et al.*, JSAP Fall meeting 2016. [2]R. Nakane, *et al.*, PASPS-IV, 2017. [3] J. Simmons, J. Appl. Phys. **34**, 6 (1963). [4]CRC Handbook of Chemistry and Physics. [5]S. Sato, *et al.*, Phys. Rev. **B 96**, 235204 (2017).

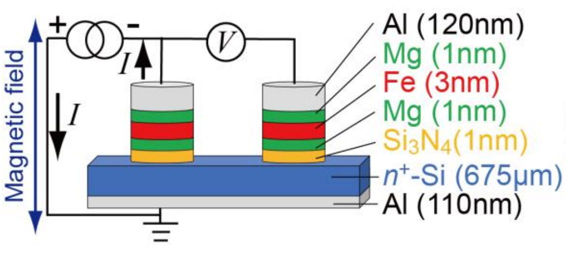


Fig. 1 Schematic illustration of our device and the three-terminal measurement setup.

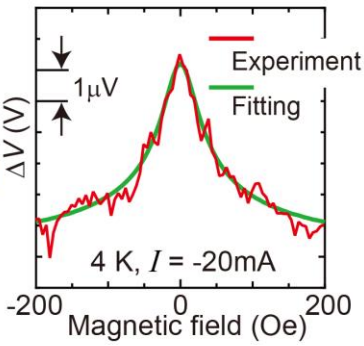


Fig. 2 Three-terminal Hanle signal measured with $I$ = –20 mA (the spin extraction geometry) at 4 K, where red and green curves represent experimental and fitting results, respectively.