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# Fe/$SiO_2$/Si 接合における三端子 Hanle 信号の磁場方向依存性

## 3T-Hanle signals of Fe/$SiO_2$/Si junctions measured with various magnetic field directions

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To investigate the spin injection/extraction-related physics in spintronic devices with various channel materials, the three terminal (3T) Hanle method[1,2] has been widely used. However, the spin lifetime and spin injection/extraction efficiency estimated from the Lorentzian signals obtained by the 3T Hanle method contradict theoretical predictions and those estimated from other experimental methods, such as the four terminal method.[3] Thus, the physics which leads to the 3T signals must be clarified. The main purposes of this study are to clarify temperature insensitivity of the 3T signals and to judge whether stray fields at the $SiO_2$/Si interface influence the 3T signals or not.

We observed clear Hanle-type signals in 3T devices with Fe/$SiO_2$/Si tunnel junctions and a Si channel, as shown in Fig.1, in the temperature range from 6 K to room temperature. The shape of the normalized signals does *not* change in the whole temperature range and the magnitude of the signal at 6 K is twice as large as that at room temperature. To analyze the signals in detail, we performed 3T Hanle measurements (see Fig.1) with various magnetic field angles between $\theta$ = 0° (in-plane direction) and $\theta$ = 90° (perpendicular direction), and plotted in Fig. 2(a). Using the magnetization curve of the Fe electrode at various $\theta$, we construct the universal fitting function valid for any $\theta$, as shown in Fig. 2(b). The half-width at half maximum (HWHM) of the 3T signal at $\theta$ = 90°, which can be well fitted by a Lorentzian, is found to be determined by both the magnetization of the Fe electrode and the external magnetic field. Therefore, the temperature insensitivity of the signals can be explained by the temperature-insensitive magnetic characteristics of the Fe electrode in the measurement temperature range. Moreover, the HWHM of the 3T signals in the devices with various $SiO_2$ thicknesses (1.3 – 2.0 nm) were completely identical, indicating that the present 3T signals are not induced by the stray field at the $SiO_2$/Si interface, but by the internal field at the Fe/$SiO_2$ interface.

From the analysis, we conclude that the 3T signals are determined by the magnetic field distribution in the non-ferromagnetic interlayer at the Fe/$SiO_2$ interface and the HWHM of the 3T signals gives no information about the spin lifetime in Si. In the next presentation, we will present a new model to explain the 3T signal and discuss the spin injection/extraction efficiency via the Fe/$SiO_2$/Si junction.

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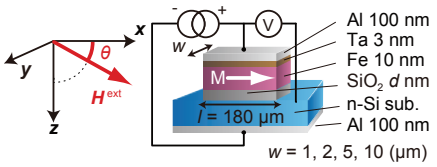


Fig. 1 Schematic illustration of our 3T device in this study. The $SiO_2$ thickness $d$ was controlled by the oxidation time. The 3T signals (voltage) were measured with a constant current (spin-polarized electron injection from Fe to Si) under a sweeping external magnetic field applied along the red arrow that is defined by the angle $\theta$ from the $x$ axis (easy axis of the Fe electrode) in the $x$-$z$ plane.

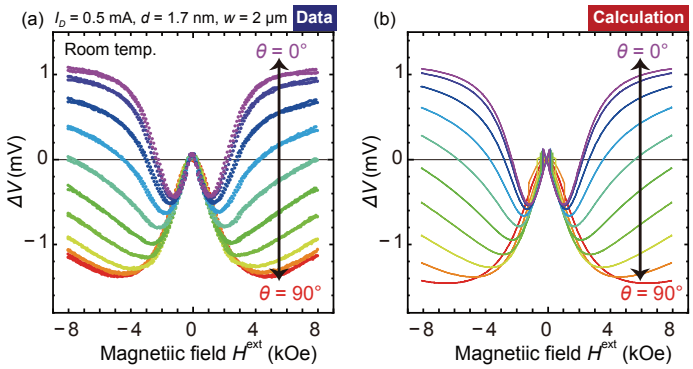


Fig. 2 (a) 3T signals measured with various magnetic field directions between $\theta$ = 0° and $\theta$ = 90° in the step of 10° at room temperature. (b) Calculated signals using the universal function we have proposed.