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三端子 Hanle 信号の理論的解析

Theoretical analysis of 3 terminal Hanle signals

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From the experimental analysis of Hanle signals in three terminal (3T) spintronic devices with Fe/SiO_2/Si junctions and a Si channel, we found that the amplitude of the signal is strongly related to the voltage drop of the tunnel barrier, and that the shape of the signal is determined by the internal magnetic field at the Fe/SiO_2 interface. From these results, the tunnel current is probably modulated by the internal magnetic field, and this consideration is the basis of our theoretical model for 3T-Hanle signal. In this study, we propose a new theoretical model for 3T-Hanle signals based on the Valet-Fert model[1] and the spin-dependent tunneling, and explain the experimental temperature-insensitive 3T-Hanle signals. Hereafter, we describe the case when electrons are injected from the Fe electrode to the Si channel.

To construct a new physical model, the following two conditions are taken into account: i) There is a paramagnetic interlayer at the Fe/SiO_2 interface, and ii) there are spin-dependent density of states in the emitting (interlayer) and receiving (Si) electrodes. The outline of our model is the following: Spin polarized electrons in the Fe bulk region (far from the Fe/SiO_2 interface) are partially depolarized by the non-uniform internal magnetic field in the interlayer, and then they are injected into Si. Owing to the accumulation of the spin-polarized electrons at the SiO_2/Si interface, the tunnel current through SiO_2 depends on the spin polarizations of electrons in both electrodes, the interlayer and Si.

As can be seen in Fig. 1, one notable finding is that the ratio $Q \equiv \Delta V_{\text{n-3TH}}/(\Delta V_{\text{n-3TH}} + \Delta V_{\text{i-3TH}})$ indicates the degree of ferromagnetism of the interlayer, where $\Delta V_{\text{n-3TH}}$ and $\Delta V_{\text{i-3TH}}$ are the amplitudes of the 3T-Hanle signals under normal ($\theta = 90°$) and in-plane ($\theta = 0°$) magnetic fields, respectively. When $Q = 1$, the interlayer is ferromagnetic, *i.e.* no interlayer is formed at the Fe/SiO_2 interface. In this case, the spin polarization in the interlayer equals to that in the Fe electrode (β~40%). On the other hand, when $Q = 1/3$, the interlayer is completely paramagnetic (this is well known as "magnetically-dead layer"[2]) and the spin polarization in the interlayer decreases to $\beta/\sqrt{3}$. Another notable finding is that there exists a parallel or anti-parallel magnetic interaction between the Fe bulk region and the interlayer. This interaction has a strong influence on the shape of the in-plane 3T-Hanle signal, as shown in Fig. 1(b) and (c). Our model can explain the experimental results reported so far including our data in a unified way.

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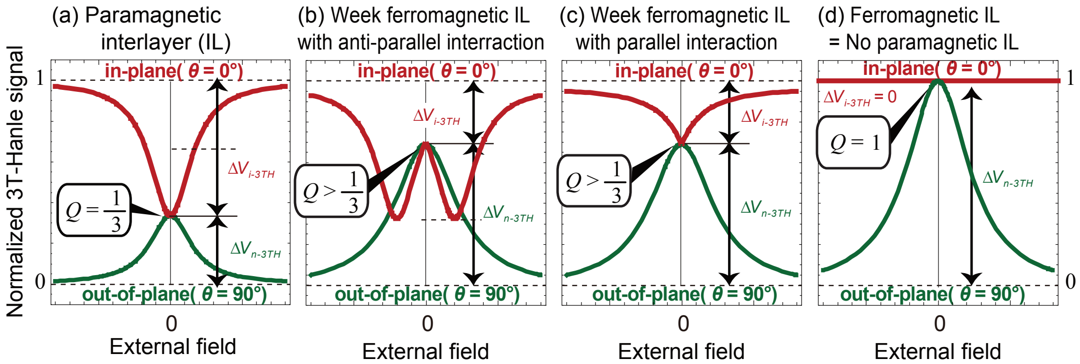

Fig. 1 Calculated 3T-Method signals with (a) paramagnetic, (b)(c) week ferromagnetic, (d) ferromagnetic interlayer (IL). IL have (b) anti-parallel or (c) parallel interaction with the Fe bulk region.