Analysis of 3-terminal and 4-terminal spin signals in Si-based vertical and lateral devices

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Recently, we have studied 3-terminal (3T) Hanle signals using a bulk Si substrate with Al/Mg/Fe/Mg/MgO/n^+-Si junctions (vertical device) and demonstrated that suppressing a magnetically-dead layer between Fe and MgO leads to the reduction of the broader 3T Hanle signal (B-3TH), which is not related with spin injection, and enhancement of the narrower 3T Hanle signal (N-3TH), which indicates spin injection into Si [1]. The striking point is that the simple 3T measurements with proper analyses allow us to accurately estimate the junction resistance, spin polarization P_i, and spin lifetime τ_S, since electrons vertically pass through the junction. On the other hand, studying spin-related phenomena with the four-terminal (4T) nonlocal method is also important, because both τ_S and spin diffusion length λ_S can be estimated from the 4T Hanle signal (4TH) that is the strong evidence of the spin current transport.[2] Previous analytical studies pointed out that N-3TH measured in a lateral device with a thin channel is different from that measured in a vertical device, ending up inaccurate P_i and τ_S estimation[3,4]; however, precise analytic function and experimental demonstration are missing. In this study, we introduce analytic functions, and analyze N-3TH and 4TH signals measured in 4T devices and N-3TH signals obtained in our previous study, leading to the accurate estimation of P_i and τ_S.

We fabricated a 4T device with Al (10 nm)/Mg (1 nm)/Fe (3 nm)/Mg (1.0 nm)/MgO (0.8 nm)/n^+-Si tunnel junctions on a (001)-oriented silicon-on-insulator (SOI) substrate, in which the doping concentration of phosphorus and the thickness d_{SOI} of the Si channel layer are ~ 10^{20} cm^{-3} and 50 nm, respectively, the width of injection and detection electrodes are w_i = 1 μm and w_d = 5 μm, respectively, and the channel length is L_{ch} = 2 μm. Figure 1 shows our measurement setup and the vertical view of the 4T device structure. We observed a clear nonlocal spin valve signal (Fig. 2(a)), a 4TH signal (Fig. 2(b)), and an N-3TH signal with a B-3TH (Fig. 2(c)) at 4 K. Considering that the amplitudes of B-3TH (dashed curve in Fig. 2(c)) were almost the same in the 4T and vertical devices (not shown), the N-3TH signal in the 4T device became about 20 times larger than that in the vertical device. This is caused by the enhancement of spin accumulation by the channel confinement. Taking this confinement into consideration, we constructed the following fitting functions for N-3TH and 4TH signals in the 4T device:

$$\Delta V^{N-3TH} = P_i^2 J \rho_{Si} \lambda_S \sum_{n=0}^{\infty} \mathrm{Re}\left[\frac{1}{\sqrt{1+i\gamma H\tau_S}} \exp\left(-\frac{2d_{SOI}\times n}{\lambda_S}\sqrt{1+i\gamma H\tau_S}\right)\right],$$

$$\Delta V^{4TH} = \frac{1}{2} P_i P_d J \rho_{Si} \lambda_S \sum_{n=0}^{\infty} \int_0^{w_d} \mathrm{Re}\left[\frac{1}{\sqrt{1+i\gamma H\tau_S}} \exp\left(-\frac{\sqrt{(L_{ch}+x)^2+(2d_{SOI}\times n)^2}}{\lambda_S}\sqrt{1+i\gamma H\tau_S}\right)\right]\frac{dx}{w_d},$$

where P_i and P_d are the spin polarization of injector/detector, respectively, ρ_{Si} = 1 mΩcm, and $J = I/180$ A/μm^2 is the current density in the injector junction. The fitting curves are plotted as black curves in Fig 2(b) and (c), in which P_i = 5.3% (assuming $P_i = P_d$), τ_S = 1.4 ns, and λ_S = 1.0 μm for the 4TH signal, and τ = 1.6 ns and P_i = 4.2% for the N-3TH signal. The comparable values of P_i and τ_S in both the 4TH and N-3TH signals indicate that the channel confinement should be taken into account for analyzing spin signals in lateral spintronic devices with a thin channel thickness.

This work was partially supported by Grants-in-Aid for Scientific Research (including (B)) and Spintronics Research Network of Japan (Spin-RNJ). References [1] S. Sato et al., JSAP Autumn meeting, 2016. [2] F. J. Jedema et al., Nature **410**, 2001. [3] A. Fert and H. Jaffrés, PRB **64**, 2001. [4] Y. Saito et al., JAP **117**, 2015.

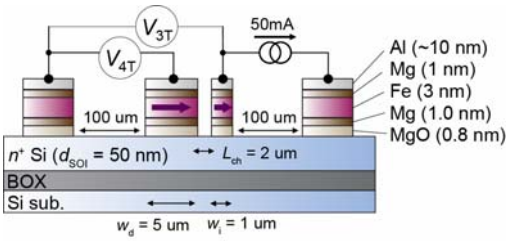

Fig. 1 Device structure and measurement setup for 4T method. 3T and 4T signals are measured simultaneously.

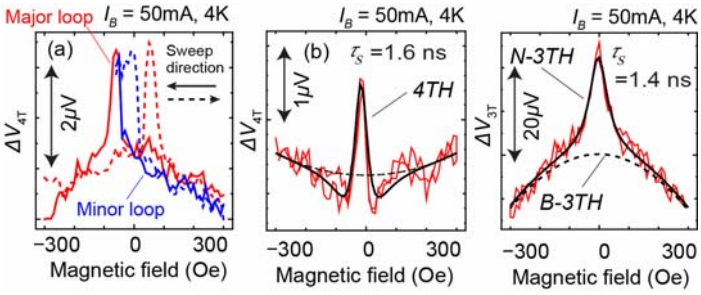

Fig. 2 (a) 4T spin valve signals. (b) 4T Hanle signal(red curves) and fitting (black curve). (c) 3T Hanle signal(red curves), fitting (black curve), and B-3TH (dashed curve).