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Spin transport in Si-based spin metal-oxide-semiconductor field-effect transistors: Spin drift effect in the inversion channel and spin relaxation in the n^+-Si source/drain regions

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Abstract

We have experimentally and theoretically investigated the electron spin transport and spin distribution at room temperature in a Si two-dimensional inversion channel of back-gate-type spin metal-oxide-semiconductor field-effect transistors (spin MOSFETs). To clarify the detailed spin transport physics in Si-based spin MOSFETs and to improve the magnetoresistance (MR) ratio, we construct analytical formulas that precisely take into account the n^+-Si regions at the source(S) and drain(D) electrodes as well as the spin drift effect in the inversion channel. The analytical formulas were obtained by solving the one demensional spin drift-diffusion equation. We found that the injected spins are substantially flipped in the n^+-Si regions even though their thickness (~5 nm) is far shorter than the spin diffusion length (~ 0.5 µm).

1. Introduction

In the past decade, Si-based spin metal-oxide-semiconductor field-effect transistors (spin MOSFETs) [1] have been extensively studied as potential key devices in next-generation electronics due to their spin-functional nonvolatile/reconfigurable characteristics. Although some previous experimental studies showed the basic operation, the magnetoresistance (MR) ratio was lower than 1% [2,3], which is too small for practical applications. To clarify the detailed spin transport physics in Si-based spin MOSFETs and to improve the MR ratio, we construct analytical formulas that precisely take into account the n^+-Si regions at the source(S) and drain(D) electrodes as well as the spin drift effect [4] in the inversion channel.

2. Experiment

Figure 1 shows our spin MOSFET device structure examined in this study, which has Fe/Mg/MgO/n^+-Si ferromagnetic tunnel junctions at S/D and a 8-nm-thick p-Si channel ($N_A \sim 1\times10^{15}$ cm^{-3}) with various channel lengths L_{ch} (= 0.4 – 10 µm). Transistor operation with a high on/off ratio of ~10^6 and spin-valve signals with an MR ratio of ~0.02 % were obtained at 295 K, as shown in Fig. 2.

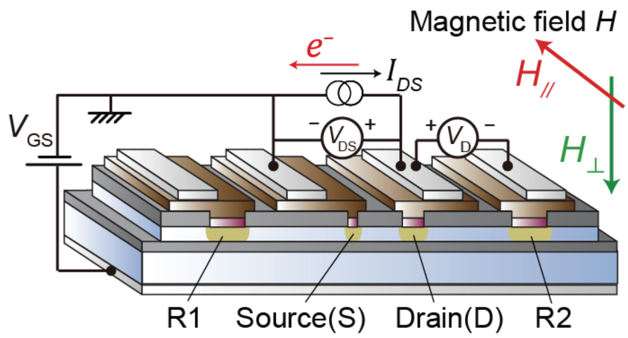

Figure 1 Schematic illustration of our spin MOSFET device structure and measurement setup, where the voltage between the S and D (the D and R2) electrodes are measured simultaneously by the voltage meters V_{DS} (V_D) while a constant current I_{DS} is driven from the D to S electrodes and a constant positive gate-source voltage V_{GS} is applied to the back side with respect to the grounded S electrode.

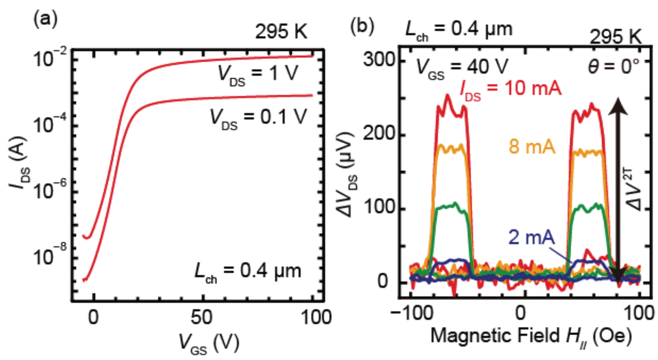

Figure 2 (a) $I_{DS} - V_{GS}$ characteristics measured at 295 K for the same device, where V_{DS} = 0.1 V and 1 V. (b) Spin-valve signals measured at 295 K with various I_{DS} and V_{GS} = 40 V. The blue, green, orange, and red solid curves are the major loops measured with I_{DS} = 2, 5, 8, and 10 mA, respectively.

3. Analysis of the Hanle signals using the one-dimensional (1D) spin drift-diffusion model

Clear Hanle precession signals were also obtained at V_{GS} = 40 V with various I_{DS} = 10, 8, and 5 mA, as shown in Fig. 3, which clearly indicates the spin transport through the 10-µm-long inversion channel. To analyze the spin distributions in our spin MOSFET, we construct analytical formulas that precisely take into account the device structure. Figure 4 shows the model of our spin MOSEFET, in which we assumed the spin injection (detection) point at $y = 0$ ($y = L_{ch}$), spin drift between $0 \leq y \leq L_{ch}$, and the frequent spin relaxation in the n^+-Si regions ($-L_S \leq y \leq 0$, $L_{ch} \leq y \leq L_{ch} + L_D$). Under these conditions, we solved the one dementional (1D) spin drift-diffusion equation and obtained analytical formulas [5].

Dashed curves in Fig .2 are fittings, which perfectly reproduce the data. Thus, we concluded that our model accurately expresses the spin transport phenomena in our spin MOSFETs. From the analysis, we found that the injected electron spins are substantially flipped in the n^+-Si regions even though their thickness (~5 nm) is far shorter than the spin diffusion length (~ 0.5 µm). To solve this problem, the lateral lengths of the both n^+-Si regions L_S and L_D should be reduced. It was found that the design guideline for spin MOSFETs utilizing electron spin transport is different from that for the ordinary MOSFETs utilizing electron charge transport.

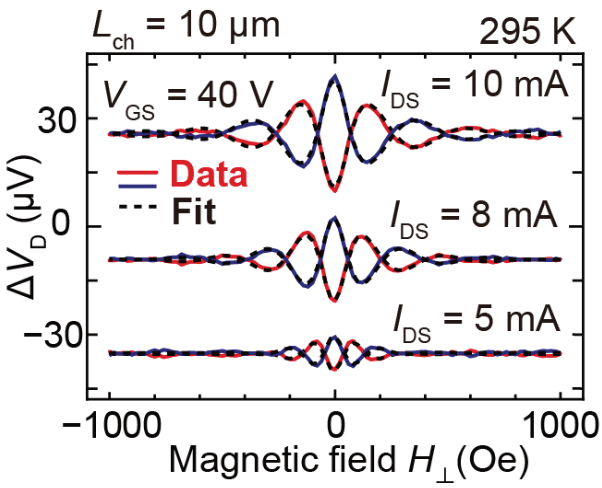

Figure 3 Hanle signals obtained at V_{GS} = 40 V with various I_{DS} = 10, 8, and 5 mA. Red and blue solid curves are obtained in parallel and anti-parallel magnetization configurations, respectively, and dashed curves are fittings.

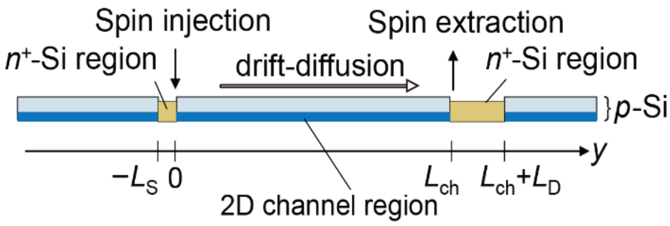

Figure 4 1D spin transport model used in this study in which spin injection and detection point at $y = 0$ and $y = L_{ch}$ are assumed, respectively.

Acknowledgements

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