Temperature Evolution of Spin-Polarized Electron Tunneling in Silicon Nanowire–Permalloy Lateral Spin Valve System

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A huge nonlocal spin valve signal over 700 Ω has been observed in silicon-nanowire-based lateral spin valve with permalloy electrodes. The magnitude of the observed huge spin signal was quantitatively explained using the conventional spin diffusion model in a one-dimensionally confined silicon channel. From the temperature dependence of the spin signal, the interface spin polarization was found to be strongly depolarized by raising the temperature. This special characteristic can be reasonably explained by considering an increase in the tunneling of thermally activated electrons through the Schottky barrier with an extremely thin depletion layer.

The combination of nanoelectronics and electron–spin degrees of freedom is a promising approach for overcoming the fundamental limit of downscaling in semiconductor devices. Numerous devices utilizing nonvolatile spin functionalities such as spin field-effect transistor (FET), spin metal–oxide–semiconductor (MOS) FET, and hot-electron spin transistors have been proposed. In order to realize such semiconductor spin devices, efficient electrical spin injection and detection are key ingredients. Significant developments in spin injection into semiconductors have been achieved by employing a highly resistive tunnel barrier at the ferromagnetic metal (FM)/semiconductor interface. In their experiments, creation of the spin accumulation in a semiconductor channel has been verified by nonlocal spin valve or Hanle spin precession measurements. However, the device structures reported so far consist of FM electrodes with large lateral dimensions over several μm on bulk or thin-film silicon (Si) channels, which are far from the realistic dimensions in the practical nanoelectronic devices. For the semiconductor channel, we focus on a silicon nanowire (SiNW), which enables easy access to the miniaturization of a MOSFET. Moreover, the enhancement of the spin accumulation is expected in a SiNW because of the weak spin–orbit interaction, the elastic scattering at the side edge, and the quasi-one-dimensional confinement in the SiNW. We previously reported on nonlocal spin injection into SiNWs using cobalt (Co) leads. However, the large grain size and poor oxidation resistance of the Co electrode make it difficult to study the spin transport in SiNWs systematically. In the present work, permalloy (Py: Ni80Fe20) was used for the ferromagnetic contact in view of its negligible magnetostriction and its relatively high stability against oxidation as compared with Co. We investigate the temperature dependence of the nonlocal spin signal in a SiNW-based lateral spin valve with secure Py/SiNW interfaces.

The n-type (111)-oriented SiNWs with plausible carrier concentration ~5–7 × 1019 cm−3 were grown by the gold-nanocatalyst-mediated chemical vapor deposition method, and transferred on a Si substrate with a 200-μm-thick SiO2 top layer. To make a multiterminal lateral spin valve structure based on SiNW, two-step electron-beam lithography and liftoff processes were carried out. Details of the device fabrication process have been described previously. Figure 1 shows a scanning electron micrograph of a representative lateral spin valve device consisting of nonmagnetic Ti/Au (5 nm/80 nm) electrodes (C1 and C4) and Py (80 nm) spin injector (C2) and detector (C3), which are connected via the 40-nm-diameter SiNW. The Py electrodes were covered by a 5-nm-thick MgO capping layer in order to prevent surface oxidation. The center-to-center separation (d) between the Py injector and detector was 1250 nm. Since the Py injector and detector have different edge shapes, their magnetization configuration can be controlled by simply adjusting the external magnetic field along the Py wires. Spin transport properties in the SiNW were evaluated by the nonlocal spin valve measurement, where the charge-current-induced spurious effects can be eliminated. Spin-polarized electrons were injected into the SiNW by biasing C2 and C1 with an ac excitation current of 3 nA, and the voltage difference between C3 and C4 was

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Fig. 1. Representative SEM image of the multiterminal SiNW lateral spin valve device. In the nonlocal measurement geometry (green labels), spin-polarized current injection uses C2 and C1 contacts, while the nonlocal voltage is measured across C3 and C4. The distance between C2 and C3 varies depending on the length of the SiNW. The additional artifacts (dust) seen on the SEM image are due to handling prior SEM, and not intrinsic to the device.
measured via the ac lock-in technique at a frequency of 17 Hz. The in-plane magnetic field was swept from −50 to +50 mT and vice versa.

Figure 2(a) shows the nonlocal spin signal as a function of the in-plane magnetic field in the temperature range from 2.5 to 20 K, wherein a clear spin valve effect is observed. The signals exhibit two levels corresponding to either parallel (low) or antiparallel (high) magnetization alignment states. The resistance change due to nonlocal spin injection is ∆R_S ≈ 170 Ω at 20 K and increases drastically below 15 K as seen in Fig. 2(b). Finally, it reaches ∼750 Ω at 2.5 K. These values are significantly larger than those reported in other spin valve devices utilizing bulk or thin-film Si channels, implying that the quasi-one-dimensional confinement in a SiNW enhances the spin accumulation voltage.

In order to understand the main mechanism of the relatively large spin signal and its strong temperature dependence more quantitatively, we investigate the resistances of the SiNW channel and the Py/SiNW interface. Figure 3(a) shows the two-terminal dc current–voltage (I–V) characteristics measured at 2.5 K between C2 and C3 exhibiting slight nonlinearity. The corresponding conductance–voltage (dI/dV–V) curve is asymmetrically parabolic, which suggests the presence of asymmetric Schottky tunnel barriers at the SiNW/Py interfaces. The temperature dependence of the zero-bias resistance (ZBR), which is estimated from a linear interpolation fit about V_{SD} = 0, is plotted in the inset. The parabolic nature of the conductance and the weak insulator-like temperature dependence of the ZBR reveal the tunneling nature at the Py/SiNW interface.

15,16 The tunnel barrier is a necessity to overcome the conductance mismatch, which is a serious obstacle for injecting spins into a semiconductor from a ferromagnetic metal. Moreover, since the resistance of the SiNW channel obtained by four-probe measurement is ∼10 kΩ, the large two-terminal resistance (800–900 kΩ) and its temperature dependence are primarily dominated by the resistances of the two Py/SiNW interfaces.

In the situation that the interface resistance is much larger than the resistance of the nonmagnetic channel, the nonlocal spin signal ∆R_S can be calculated as

\[ \Delta R_S \approx P_I^2 \frac{\rho_{SiNW} I_{SiNW}}{S_{SiNW}} \exp \left( -\frac{d}{\lambda_{SiNW}} \right), \]

where \( P_I \) is the interface spin polarization and \( \rho_{SiNW}, I_{SiNW}, \) and \( S_{SiNW} \) are the electrical resistivity, spin diffusion length, and cross-sectional area of the SiNW, respectively. Using the experimental values \( \rho_{SiNW} \sim 10 \mu\Omega \cdot \text{m}, S_{SiNW} \sim 1.26 \times 10^{-15} \text{m}^2, \) and assuming \( \lambda_{SiNW} = 2.5 \mu\text{m}, \) \( P_I \) can be estimated as 0.25 at 2.5 K, which is a reasonable value for the

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Py electrode. This implies that the SiNW has comparable spin diffusion length as that of thin Si films even in the nanometer-sized cross section. This could be attributed to the elastic scattering events, which do not flip spins, at the side edge of the SiNW.\textsuperscript{19} The SiNW therefore has the advantage over most nonmagnetic systems, which are known to exhibit reduction in spin diffusion length with decreasing cross-sectional area.\textsuperscript{20,21}

The nonlocal spin signal given by eq. (1) depends on three physical parameters, $\rho_{\text{SiNW}}$, $\lambda_{\text{SiNW}}$, and $P_i$. As mentioned above, the electrical resistivity of the SiNW, $\rho_{\text{SiNW}}$, is almost constant from 2.5 to 20 K. This is because the freeze out effect can be negligible in highly doped degenerated semiconductors. We also expected that the spin diffusion length of the SiNW, $\lambda_{\text{SiNW}}$, in this temperature range does not change significantly because phonon scattering events are suppressed. Therefore, the observed temperature change of the spin signal is mainly caused by the change of the interface spin polarization $P_i$.

To elucidate the temperature dependence of the interface spin polarization, we consider the influence of the thermal activation during the tunneling process through the Py/SiNW Schottky barrier. Figure 3(b) shows the conductance $G$ as a function of temperature $T$. The conductance becomes almost constant below 4 K, while it characteristically increases at higher temperatures. Assuming the activation behavior at the Py/SiNW interface, the two-terminal conductance can be expressed as

$$\frac{dI}{dV}\bigg|_{V_{SD}=+5\text{mV}} (T) = G_0 \exp\left(-\frac{E_a}{k_B T}\right),$$

where $k_B$ is the Boltzmann constant, $G_0$ is a preexponential factor, and $E_a$ is the activation energy. Fitting of the experimental results yielded approximate values of 2.6 mS and 0.5 meV for $G_0$ and $E_a$, respectively. The value of 0.5 meV is much smaller than the estimated Schottky barrier height of $\approx 0.9$ eV for the SiNW/Pt contact.\textsuperscript{22,23} This may be because the high donor concentration produces the extremely thin depletion layer width (5–10 nm). In such a Schottky barrier, the tunneling probability strongly depends on the energy level of the electron. That is, electrons at higher energy states have higher tunneling probability. This means that the thermally activated electrons have higher tunneling probability. Since the spin polarization of the thermally activated electrons is expected to be smaller than that of the nonactivated electrons, the reduction of the nonlocal spin signal at higher temperatures can be explained by the increase of the thermally activated electrons. Thus, the significant enhancement of the nonlocal spin signal below 10 K can be understood by the suppression of the thermally activated electron tunneling events. This implies that the Schottky barrier in a highly doped semiconductor/ferromagnetic metal interface is a crucial issue for the efficient spin injection at high temperatures.

In summary, nonlocal spin injection experiments were carried out using a silicon nanowire-based lateral spin valve with permalloy contacts. Because of the relatively small cross section of the SiNW, the obtained spin signal was much larger than the values previously reported in the devices composed of Si substrates and films. However, the spin signal was found strongly reduced by raising the temperature due to the depolarization of the tunneling electrons induced by the thermal activation. The suppression of the tunneling of the thermally activated electrons may be the key for the efficient spin injection at high temperatures.

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