Dynamical Spin Injection into p-Type Germanium at Room Temperature

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We demonstrate dynamical spin injection into p-type germanium (Ge) at room temperature (RT) using spin pumping. The generated pure spin current is converted to a charge current by the inverse spin-Hall effect (ISHE) arising in the p-type Ge sample. A clear electromotive force due to the ISHE is detected at RT. The spin-Hall angle for p-type Ge is roughly estimated to be $\theta_{\text{ISHE}} = 9.6 \times 10^{-4}$ at RT.

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Group-IV spintronics using carbon, silicon (Si), and germanium (Ge) has attracted considerable attention in recent years.\textsuperscript{1,2} Carbon and Si essentially exhibit a small spin–orbit interaction (SOI), which allows a long coherence of spins injected into these materials. Ge exhibits a comparatively large SOI and a high carrier mobility, enabling coherent spin transport in FETs with a short channel. Currently, Ge-based MOSFETs are a potential candidate for overcoming the scaling limit of Si-based MOSFETs.\textsuperscript{3} A great deal of effort has been undertaken to realize Ge-based MOS transistors, including attempts at fabricating high-quality Ge on insulators and investigations of metal/Ge contacts.\textsuperscript{4–6} In addition, Ge-based spintronics have been studied intensively.\textsuperscript{7,8} Although demonstrations of spin injection in Ge at room temperature (RT) have been reported by several groups,\textsuperscript{9–11} the measurement techniques were limited mainly to the electrical non-local three-terminal (NL3T) method. As reported previously, this method does not always allow precise investigations,\textsuperscript{12} and a new method for confirming successful spin injection into Ge is eagerly awaited. A promising example is the study by Jain et al.,\textsuperscript{13} in which a dynamical method was used; however, only spin injection into n-type Ge was realized. Since the carrier mobility in p-type Ge is much higher than those in other typical p-type semiconductors, such as p-Si and p-GaAs, which is significantly superior to any other semiconductors, p-type Ge is expected to be the most promising materials for realization of p-MOS FET. Therefore successful and reliable spin injection in p-type Ge at RT is also strongly desired. In this study, we demonstrate spin injection into p-type Ge at RT using a dynamical spin pumping method. The appearance of the inverse spin Hall effect (ISHE) in p-type Ge provides strong evidence of spin injection, and the spin Hall angle for p-type Ge is qualitatively investigated.

Figure 1(a) shows a schematic illustration of a sample used in this study. A p-type Ge layer, the dopant and doping concentration of which were boron (B) and $1 \times 10^{18}$ cm\textsuperscript{-3}, respectively, was formed by using ion implantation. A 25-nm-thick Ni$_{80}$Fe$_{20}$ (Py) layer was formed on the p-type Ge layer by electron beam evaporation at RT. A thin Al layer (~4 nm) was formed without breaking the vacuum after the Py deposition in order to prevent oxidation of the Py surface. It is worth noting that the Py/p-type Ge contact is ohmic because of Fermi level pinning\textsuperscript{14,15} and that dynamical spin injection is not impeded by the Schottky barrier. In order to inject spins dynamically, we employed a spin pumping method using an electron spin resonance (ESR) system. The details of the spin pumping method are described in the literature.\textsuperscript{16} During the measurements of ferromagnetic resonance (FMR) signals and output voltages, the samples were placed at the center of a TE$_{001}$ microwave cavity with a frequency of $f = 9.1$ GHz. In order to excite FMR in the Py layer, an external magnetic field, $H$, was applied to the...
sample at an angle of $\theta_\text{HT}$ as shown in Fig. 1(a). Under the FMR condition, the spin current density $j_s$ generated by the spin pumping method at the Py/p-type Ge interface is theoretically expressed as

$$j_s = g_i^\dagger \gamma^2 h^2 [h^2/4\pi M_{\text{SF}} + \sqrt{(4\pi M_{\text{SF}})^2 \gamma^2 + 4\alpha^2}]$$

where $h$, $\gamma$, and $\alpha$ are the microwave magnetic field, the Dirac constant and the Gilbert damping constant, respectively. $\omega = 2\pi f$, where $f$ is the microwave frequency is the angular frequency of the magnetization precession. $g_i^\dagger$ is the real part of the mixing conductance and is given by

$$g_i^\dagger = 2\sqrt{3} \pi M_{\text{SF}} d_F \gamma^2 h^2 \sin^2 \theta_\text{HT}$$

where $g$, $\mu_B$, $d_F$, $W_{F/N}$, and $W_F$ are the $g$-factor, the Bohr magneton, the thickness of the Py layer, the FMR spectral width for the Py/p-type Ge film, and the FMR spectral width for the Py film, respectively. The generated spin current diffuses from the Py/Ge interface into the Ge layer. The injected spins are converted to a charge current due to the ISHE, resulting in the generation of an electric voltage. The electromotive force due to the ISHE is expressed as

$$V_{\text{ISHE}} = \frac{W_{F/N} - W_F}{d_S \sigma_N + d_F \sigma_F} (W_{F/N} - W_F),$$

where $w$ is the length of the Py layer defined as in Fig. 1(a). $d_F$ and $\sigma_F$ are the thickness and electric conductivity of the Py layer, respectively. $d_S$ and $\sigma_N$ are the thickness and electric conductivity of the p-type Ge layer, respectively. Since p-type Ge layer and p-type Ge substrate are conductive, the contribution of Ge layer and Ge substrate to the total resistance should be taken into account. Here, the effective channel thickness of Ge layer and Ge substrate is regarded to be about 100 nm and 350 $\mu$m, respectively.

Figure 1(b) shows the FMR spectra, $dI(H)/dH$, for the Py/p-type Ge/Ge(111) sample (red curve) and the Py/SiO$_2$/Si(100) sample (black curve) under a microwave excitation power of $P_{\text{MW}} = 200$ mW for $\theta_\text{HT} = 0^\circ$. Here, $d$ denotes the microwave absorption intensity. For the Py/p-type Ge sample, $W_{F/N}$ was estimated to be 2.97 mT, which is clearly larger than that for the Py/SiO$_2$/Si(100) sample ($W_F = 2.56$ mT). The enhancement of the spectral width is reproducible for several samples. Since the spin angular momentum of the Py layer is reduced by the generation of the spin current for several samples. Since the spin angular momentum of the Py layer is reduced by the generation of the spin current, the in-plane HFFMR condition, the spin current density at the Py/p-type Ge interface are calculated to be $g_i^\dagger = 1.8 \times 10^{19}$ m$^{-2}$ and $j_s = 8.4 \times 10^9$ Jm$^{-2}$, respectively. Using these values and $h = 0.16$ mT, $\alpha_N = 27$ mT.
In summary, we demonstrated successful spin injection into p-type Ge using dynamical spin pumping at RT and experimentally corroborated this demonstration by observing the electromotive forces due to the ISHE of p-type Ge. The spin Hall angle $\theta_{\text{SHE}}$ for p-type Ge was roughly estimated to be $9.6 \times 10^{-4}$, which is larger than that of p-type Si.

Table 1. Physical parameters for estimating the spin Hall angle. Magnetic and electrical parameters for the Py/p-type Ge sample used for the theoretical estimation of the spin Hall angle. The $g$-factor and $\gamma$ are reported in Refs. 19 and 22, respectively.

| Parameter | Value |
|-----------|-------|
| $g$-factor | 1.6 |
| $4\pi M_s$ (T) | 0.918 |
| $\gamma$ (T^{-1} s^{-1}) | $1.86 \times 10^{11}$ |
| $\omega$ (s^{-1}) | $5.73 \times 10^{10}$ |
| $\alpha$ | 0.008 |
| $W_F$ (mT) | 2.56 |
| $W_{\text{FN}}$ (mT) | 2.97 |
| $d_0$ (\Omega^{-1}) | 0.063 |
| $d_0\xi$ (\Omega^{-1}) | 0.036 |
| $w$ (nm) | 2 |

nm, and $V_{\text{SHE}} = 13.5 \mu V$, the spin-Hall angle $\theta_{\text{SHE}}$ for p-type Ge film is roughly estimated to be $9.6 \times 10^{-4}$, which is larger than that of p-type Si.

Fig. 3. Angular dependence of ISHE signal. Magnetic field angle ($\theta_H$) dependence of (a) the FMR spectra, $dI(H)/dH$, and (b) the electromotive force $V_{\text{out}}$ for the Py/p-type Ge sample. Apparent reversal of the electromotive forces due to the ISHE of p-type Ge was observed.

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