Pure spin current transport in a SiGe alloy

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The binary semiconductor alloys Si1−xGex (0 ≤ x ≤ 1) have been studied for use in complementary metal–oxide–semiconductor (CMOS) technologies and optoelectronics for telecommunications, quantum Hall systems, and quantum information processing. In particular, SiGe alloys have been utilized to introduce strain to the channel layers in the source/drain area or in the substrate to enhance the electron and hole mobility in CMOS transistors. In addition, Si/SiGe and Ge/SiGe heterostructures enable band gap engineering, and one can control the conduction and valence band structures by adjusting the Ge content x. Accordingly, if spintronic technologies are integrated into Si-CMOS technologies, the compatibility between SiGe and spintronics should be explored.

By electrical means in spin-valve device structures, spin injection/detection and spin relaxation in SiGe alloys have been investigated in detail. In particular, recent progress in technological developments for detecting pure spin current transport at room temperature in SiGe and Ge/SiGe by four-terminal nonlocal magnetoresistance measurements is noteworthy. On the other hand, such technologies using SiGe alloys have not been developed yet, although generation of spin-polarized carriers induced by circularly polarized light has been reported. For bulk Si1−xGex (0 ≤ x ≤ 1), if the composition reaches x ~ 0.85, the bottom of the conduction band can vary from the L point to the Δ point, leading to marked changes in the electrical properties, including the g-factor. However, there is almost no information on the physics of pure spin current transport in SiGe alloys. As a first step toward developing SiGe spintronic technologies, one should concentrate on a simple composition of x ~ 0.85, which is known to maintain a Ge-like electronic band structure in which the bottom of the conduction band is around the L point in k-space.

In this letter, by using four-terminal nonlocal magnetoresistance measurements in Si0.5Ge0.5-based lateral spin-valve (LSV) devices, we show reliable pure spin current transport in an n-type Si0.5Ge0.5 (n-SiGe) layer at low temperatures. Clear nonlocal spin-valve signals and Hanle effect curves are observed at low temperatures, indicating generation, manipulation, and detection of pure spin currents in n-SiGe. From one-dimensional spin diffusion models, we can estimate the spin diffusion length (λSiGe) and spin lifetime (τSiGe) of the SiGe layer used here to be ~0.5 μm and ~0.2 ns, respectively.

In the following, the growth of the Si0.5Ge0.5 spin transport layer used in this study is explained. Using molecular beam epitaxy (MBE), we first formed an undoped Si(111) layer (~30 nm) grown at 350 °C (LT-Ge) on an undoped Si(111) substrate (~1000 Å), followed by an undoped Ge(111) layer (~70 nm) grown at 700 °C (HT-Ge). Next, we grew a 7-nm-thick phosphorus-doped n-Si0.1Ge0.9(111) layer by MBE at 350 °C on top of the HT-Ge layer. The Ge content x of the SiGe layer was adjusted by controlling the deposition rates of Si and Ge, determined by X-ray diffraction (XRD) measurements of the SiGe layer grown on the Ge(111) substrate. The carrier concentration (n) in the n-SiGe(111) layer was determined to be n ~ 5 × 10^18 cm^-3 from Hall effect measurements. Because the electrical properties of the HT-Ge layer were p-type conduction and relatively high resistivity compared to the spin transport (n-SiGe) layer, we can ignore spin diffusion into the HT-Ge layer. To promote tunneling conduction of electron spins through the Schottky barriers, a 7-nm-thick P-doped Ge layer with an ultrathin Si layer was grown on top of the spin transport layer. A schematic of the grown heterostructure is shown in Fig. 1(a).

Figure 1(b) shows Raman spectra of the grown SiGe layer and a pure Ge layer. Three main peaks corresponding to Si–Si (~450 cm^-1), Si–Ge (~390 cm^-1), and Ge–Ge (~290 cm^-1) bonds are observed, and their positions are consistent with previous reports on high-Ge-content SiGe layers. Here the weaker peak at ~300 cm^-1, which is almost equivalent to that of pure Ge, comes from the 7-nm-thick Ge capping layer shown in Fig. 1(a). From these Raman spectra, we can determine that a (111)-oriented SiGe layer was formed on the epitaxial Ge layer on Si(111). In addition, we characterized the grown SiGe layer by XRD, and the fringe patterns related to the SiGe peak were not observed (not shown here), indicating that the grown Ge/SiGe interface was not smooth and fully pseudomorphic. Thus, misfit dislocations were included in the grown SiGe layer. From longitudinal and transverse resistance measurements, we confirmed the n-type conduction and degenerate electrical properties of the grown SiGe layer.
SiGe layer in the range of 8 to 300 K, as shown in Figs. 1(c) and 1(d). An electron mobility ($\mu\sim325\ cm^2\ V^{-1}\ s^{-1}$) and an $n$ value of $\sim5\times10^{15}\ cm^{-3}$ were obtained at 8 K, which are not markedly lower than those of pure Ge obtained in our previous works. Therefore, we can understand that the influence of the misfit dislocations on the electrical properties of the SiGe layer is relatively limited.

To investigate spin transport in the grown SiGe layer, we grew a 10-nm-thick Co$_2$FeAl$_{0.5}$Si$_{0.5}$ (CFAS) film as a spin injector/detector on top of the SiGe layer by well-established low-temperature MBE techniques. Figure 2(a) shows a schematic of the fabricated LSVs with CFAS/SiGe Schottky tunnel contacts. The detailed fabrication processes were described elsewhere.37 The sizes of the spin injector and detector in the LSVs are 0.4 $\times$ 5.0 and 1.0 $\times$ 5.0 $\mu$m$^2$, respectively. To evaluate the spin diffusion length of the SiGe layer, we varied the edge-to-edge distance ($d$) between the spin injector and spin detector from 0.4 to 2.0 $\mu$m. Measurements of the current–voltage ($I$–$V$) characteristics revealed Schottky tunnel conduction through the CFAS/SiGe interfaces, as shown in our previous works, and these properties were reproduced from device to device.

Figure 2(b) shows a hysteresis curve of the nonlocal magnetoresistance ($\Delta R_{NL}=\Delta V_{NL}/I$) in an LSV with $d=0.5\ \mu$m under in-plane magnetic fields ($B_z$) measured at $I=-3.5\ mA$ at 50 K, where the negative sign of $I$ ($I<0$) means that electrons are injected from the CFAS into the SiGe channel, that is, under the spin injection condition, through the Schottky tunnel barrier. A nonlocal spin-valve signal with a magnitude ($\Delta R_{NL}$) of $\sim1.7\ m\Omega$ can be seen at 50 K, and the observed spin-valve behavior is attributed to the change in the magnetization configurations of the two different CFAS contacts used in the parallel and antiparallel magnetization states.

However, the value of $|\Delta R_{NL}|$ is markedly small compared to that for the CFAS/Ge LSVs. The difference in $|\Delta R_{NL}|$ might be due to the degraded quality of the CFAS/SiGe heterointerface. Using the nonlocal four-terminal geometry under an out-of-plane magnetic field ($B_z$), we also recorded Hanle-type spin precession curves for the parallel and antiparallel magnetization states of the CFAS contacts, as shown in Fig. 2(c). The recorded $\Delta R_{NL}$ curves are evidence of generation, manipulation, and detection of pure spin currents in the n-SiGe layer. The data shown in Fig. 2 represent the first experimental demonstration of pure spin current transport in an n-SiGe alloy.

Using the following one-dimensional spin drift diffusion model,56,57 we can tentatively obtain the spin lifetime ($\tau_{SiGe}$) and diffusion constant ($D$) of the SiGe layer used here.

$$\Delta R_{NL}(B_z) = \pm A \int_0^\infty \phi(t) \cos(\omega_{NL}t) \exp\left(-\frac{t}{\tau_{SiGe}}\right) dt,$$

where

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The electron mobility ($\lambda$) higher temperatures, there was almost no change in the spin diode measurements. The solid and dashed lines indicate the results of fitting to Eq. (2).

$A = \frac{P_{\text{inj}}P_{\text{det}}\rho_{\text{SiGe}}D}{S}$,

$\phi(t) = \frac{1}{\sqrt{4\pi Dt}} \exp\left(-\frac{L^2}{4Dt}\right)$.

$P_{\text{inj}}$ and $P_{\text{det}}$ are the electron spin polarizations in SiGe created by the spin injector and detector, respectively; $\rho_{\text{SiGe}}$ is the resistivity ($\rho_{\text{SiGe}} = 4.3$ mΩ cm); and $S$ is the cross section ($S = 0.49 \mu m^2$) of the n-SiGe layer used here. $L$ is the center–center distance between the spin injector and detector ($L = 1.2 \mu m$), $a_0 = \frac{g\mu_BB}{\hbar}$ is the Larmor frequency, $g$ is the electron g-factor ($g = 1.56$) of Si$_0.1$Ge$_{0.9}$; and $\mu_B$ is the Bohr magneton. As a result, a $\lambda_{\text{SiGe}}$ value of 0.2 ± 0.06 ns and a $D$ value of 11.2 ± 0.6 cm$^2$/s can be estimated by fitting to the Hanle data using Eq. (1). Using the relation $\lambda = \sqrt{D\tau}$, we can obtain a rough $\lambda_{\text{SiGe}}$ value of 0.47 ± 0.02 µm at 50 K.

We also measured $\Delta R_{NL}$ for SiGe LSVs with various $d$ values. The $d$ dependence of $|\Delta R_{NL}|$ at 30 and 50 K is shown in Fig. 3. The value of $|\Delta R_{NL}|$ decreases exponentially with increasing $d$. In general, the $d$ dependence can be represented by the following equation:  

$$|\Delta R_{NL}| = \frac{|P_{\text{inj}}|P_{\text{det}}^{\lambda_{\text{SiGe}}}D}{S} \exp\left(-\frac{d}{\lambda_{\text{SiGe}}}\right),$$

where $\rho_{\text{SiGe}} = 4.3$ mΩ cm, and $S = 0.49 \mu m^2$. From fitting the decay of $|\Delta R_{NL}|$ to Eq. (2), the values of $\lambda_{\text{SiGe}}$ can be estimated to be 0.51 and 0.48 µm at 30 and 50 K, respectively. These values are consistent with the value obtained from the fits to the Hanle data shown in the previous paragraph. We also note that a $\lambda_{\text{SiGe}}$ value of ~0.5 µm at low temperatures is consistent with the spin diffusion length of pure Ge layers with $n = (4–8) \times 10^{18}$ cm$^{-3}$ at low temperatures, which was reported previously in Refs. 35 and 36. Although we could not examine the $d$ dependence of the nonlocal spin signals at higher temperatures, there was almost no change in $\lambda_{\text{SiGe}}$ between 30 and 50 K, which is also consistent with the data for Ge in Ref. 35. We can also discuss $\tau_{\text{SiGe}}$ in terms of the $d$ dependence in Fig. 3 and the relation $\lambda = \sqrt{D\tau}$. Here the value of $D$ can be estimated from Eq. (4) in Ref. 59 and the electron mobility ($\mu \sim 330$ cm$^2$ V$^{-1}$ s$^{-1}$ at 30 K, $\mu \sim 307$ cm$^2$ V$^{-1}$ s$^{-1}$ at 50 K) of the used SiGe layer, which was experimentally obtained by Hall effect measurements. The calculated values of $D$ at 30 and 50 K are 13.8 and 13.5 cm$^2$/s, respectively. As a consequence, $\tau_{\text{SiGe}} \sim 0.18$ ns can be obtained at 30 and 50 K. The estimated $\tau_{\text{SiGe}}$ value is also consistent with that obtained from Hanle measurements. From these results, we can judge that, for n-Si$_0.1$Ge$_{0.9}$, reliable values of $\lambda_{\text{SiGe}}$ (~0.5 µm) and $\tau_{\text{SiGe}}$ (~0.2 ns) at low temperatures are found in this study.

Recently, Song et al. theoretically proposed that spin relaxation at low temperatures in multivalley semiconductors such as Si and Ge is dominated by the intervalley spin–flip scattering induced by the central-cell potential of impurities, which is called donor-driven spin relaxation. We have experimentally clarified that the spin relaxation mechanism at low temperatures in degenerate Si$^{39}$ and Ge$^{35,36}$ cannot be quantitatively interpreted in terms of the Elliott–Yafet mechanism but the mechanism due to the impurity- and phonon-induced intervalley spin–flip scattering. Using their theory, we can tentatively discuss the spin lifetime in the degenerate SiGe layers. When the Fermi energy ($e_F$) is larger than the thermal energy ($k_BT$) at low temperatures, the spin scattering rate (1/$\tau$) depends on the concentration of donor impurities ($N_D$) under degenerate conditions, where $\k_B$ is the Boltzmann constant. If $N_D$ is regarded as $n$ in the degenerate Si$_0.1$Ge$_{0.9}$ used here, the donor-driven spin relaxation in degenerate SiGe can be expressed as follows.

$$\frac{1}{\tau} \approx \frac{4\pi \mu_B m^*_h}{2\hbar^2} (3\pi^2 n)^{1/3} \Delta_{\text{av}},$$

where $a_H$ and $m_e$ are the Bohr radius and the electron effective mass in Si$_0.1$Ge$_{0.9}$, respectively. $\Delta_{\text{av}}$ is the spin–orbit–coupling-induced splitting of the triply degenerate 1s (T$_2$) donor state in Si$_0.1$Ge$_{0.9}$. Here we assigned a value of $e_F \approx \frac{2\pi}{\sqrt{m^*_e} (3\pi^2 n)^{1/3}}$ to the conduction electron energy ($e_F$) from Eq. (4) in Ref. 60. According to previous reports, we can assume that the parameters for Si$_0.1$Ge$_{0.9}$, such as $a_H$, $m_e$, and $\Delta_{\text{av}}$, are almost equal to those of pure Ge. Thus, we tentatively used $a_H = 6.45$ nm, $n = 5.0 \times 10^{18}$ cm$^{-3}$, $m_e = 0.16m_0$, and $\Delta_{\text{av}} = 0.11$ meV, which is consistent with that obtained from Si$_0.1$Ge$_{0.9}$ alloy. However, the growth of the Si$_{1−x}$Ge$_x$ alloys is limited to only the HT-Ge(111)/LT-Ge(111) structure on a Si(111) substrate, leading to strained Si$_{1−x}$Ge$_x$ alloys with $x \leq 0.85$. When strain is induced in Si$_{1−x}$Ge$_x$ alloys, its effect on the spin-related physics can be dominant. Therefore, at around $x \sim 0.85$, it may be difficult to observe the great change in the spin-related physics depending on $x$.

In summary, we studied pure spin current transport in Si$_0.1$Ge$_{0.9}$ alloy ($n \sim 5.0 \times 10^{18}$ cm$^{-3}$). The four-terminal nonlocal magnetoresistance signals and Hanle effect curves of SiGe-based LSVs were observed. The spin diffusion length and spin lifetime of a SiGe layer at low temperatures were experimentally estimated to be ~0.5 µm and ~0.2 ns, respectively. This study demonstrates the possibility of exploring...
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