Efficient gate control of spin–orbit interaction in InSb nanowire FET with a nearby back gate

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Electrical tuning of spin–orbit interaction (SOI) is important for spintronics. Here we report that InSb nanowire with a nearby back gate structure enables efficient tuning of the Rashba SOI with small gate voltage. Consequently, the Rashba coupling parameter is larger than those obtained for various previously reported III–V nanowire devices. Our findings demonstrate that InSb nanowire with this back gate structure will provide prominent and easy-to-use devices in the fields of spintronics and spin–orbitronics. © 2019 The Japan Society of Applied Physics

III–V semiconductors have been intensively studied as the host material for spin field-effect transistors (FETs), since III–V narrow gap semiconductors are known to possess a large Rashba spin–orbit interaction (SOI), which involves an electron spin precession that can be used as a transistor ON/OFF switch. Over the last few decades, III–V semiconductor quantum wells and bottom-up grown InAs nanowires have been studied experimentally to examine whether the Rashba SOI, which is defined to be proportional to the effective electric field for the electron channel, can be practically controlled with an external gate electric field. Recently, it has been reported that the Rashba SOI can be enhanced for InAs nanowires with an ion-gate structure or gate-all-around structure more effectively than for two-dimensional III–V quantum wells, owing to a strong electric field around an InAs electron channel. Obtaining a large Rashba SOI through an external gate is critically important for a future spin FET, since this indicates that transistor channels could be made shorter and thus be compatible with current standard Si devices.

As is the same for InAs trend, InSb nanowire has also attracted attention for the large SOI, and has been expected to host Majorana Fermions as well as to be used for the spin FET. Bottom-up grown InSb nanowires tend to show moderate mobility, and then the value of the SOI has been investigated with quantum dot structures fabricated from InSb nanowire. The Rashba parameter obtained from quantum dot has been reported to be about 0.16 eVÅ, reaching one of the highest values of the Rashba SOI previously reported. Our results indicate that our device prototype will be useful for future devices associated with spintronics or novel technologies such as Majorana electronics that need the help of a large SOI.

InSb nanowire was continuously grown on InAs nanowire by using a similar method to that described in Ref. 21. We used Au particles as catalyst which were dispersed on InP (111)B substrates by using a 40 nm Au colloidal solution. The samples were grown in a low-pressure metalorganic vapor phase epitaxy (MOVPE) reactor. Sources were trimethylindium (TMIn), tertiarybutylarsine (TBA), and triethylantimony (TESb). We also used tertiarybutylchloride (TBCI) in order to enhance the axial growth and reduce the radial growth for nanowires. The InSb nanowires were grown at 350 °C for 60 min.

Figure 1 summarizes the results of a TEM analysis that we undertook to examine a quality of our InSb nanowire. A typical TEM image of our InSb nanowire is shown in Fig. 1(a), which includes an image of a closely deposited InAs nanowire for comparison. The area between the InSb nanowire and the InAs nanowire (gold catalyst) is marked A and B, and an enlarged image is shown in Figs. 1(b) and 1(c). As in Ref. 23, well-ordered crystalline structures demonstrate that our InSb nanowire is properly grown between the gold catalyst and the InAs nanowire. Figure 1(d) shows a...
high-angle annular dark field image, and 1(e) and 1(f) show images obtained with energy dispersive X-ray spectrometry (EDS), which reveals the chemical composition. We find that, while indium elements are distributed throughout the entire nanowire, antimony, arsenide, and gold are well separated. This confirms that the presence of mixed crystals such as InAsSb is negligible. The transport measurements are performed with a standard DC technique at 1.7 K.

Figure 2(a) shows a SEM image of our typical device, which has a standard FET structure with a gate length of 400 nm. A cross-section of our device is shown schematically in Fig. 2(b). We first fabricate a pre-gate (back gate) structure on a silicon-dioxide substrate, and deposit InSb nanowire coated with an ALD-grown high-k gate insulator Al₂O₃ (6 nm). (The ALD growth is done after we clean the surface of the InSb nanowire that has been grown by MOVPE method in a different chamber.) Ti/Al is deposited on both ends of the nanowire to provide source-drain electrodes. This geometry enables us to apply a larger electric field with a smaller gate voltage when compared with previously reported standard back-gated nanowire FETs. The Rashba SOI, which is in principle proportional to the applied electric field, is then expected to be largely controlled using this device structure.

Figure 2(c) shows two-terminal conductance as a function of gate voltage for various source-drain voltages $V_{sd}$. When the gate voltage is positively applied, the source-drain current and electrical conductance are greatly increased. The sub-threshold swing that is obtained with a log-scale plot is about 20 meV dec$^{-1}$ at 1.7 K, which is as small as that obtained for the previously developed gate-all-around InAs nanowire FET.$^{17}$

We next measure magnetoconductance ($G$) to examine whether or not the SOI can be controlled by the gate voltage. Figure 3(a) shows magnetoconductance difference ($\Delta G$) as a function of magnetic field ($B$). Here we smooth the measured conductance for the magnetic field and gate voltage to exclude universal conductance fluctuation as reported in previous studies.$^{17}$ and average the data measured for positive and negative magnetic fields to obtain better fitting accuracy as described below. As clearly shown in Fig. 3(a), the $B$ dependence of $\Delta G$ changes from a dip to a peak when the gate voltage is increased. This feature is well known as a crossover from a WL to a WAL, which occurs due to the presence of an enhanced SOI. We then fitted our data using the following formula, which has been used for a disordered one-dimensional nanowire$^{24,10}$

$$\Delta G = -2e^2/h \left[ \frac{3}{2} \left( \frac{1}{l^2} + \frac{W^2}{3l_B^4} \right) \right]^{-1/2} - \frac{1}{2} \left( \frac{1}{l^2} + \frac{W^2}{3l_B^4} \right)^{-1/2},$$

where $e$ is the electron charge, $h$ is Planck constant, $l$ is the phase relaxation length, $l_B$ is the spin–orbit interaction length, $W$ is the nanowire diameter ($W = 182$ nm for our device), and $l_B$ is
the magnetic length given by $l_B = \sqrt{\hbar/(2\pi eB)}$. We should note that our device satisfies the condition $l_e < W < l_G$ ($l_e$: mean free path, $l_G$: gate length), with which a one-dimensional model can be employed.10 Here $l_e$ is typically smaller than 10 nm for our device. To meet the small field requirements for using Eq. (1), we examined our data in a $-0.12 < B < 0.12$ T field range, corresponding to $W < \sqrt{\hbar/(eB)}$.14 As is shown in Fig. 3(a), the fitting curves well reproduce our experimental data.

Figure 4(b) shows the $V_G$ dependences of $l_{so}$ and $l_{so}/R$. While $l_0 < l_{so}$ with a small $V_G$, it changes to $l_0 > l_{so}$ with a larger gate voltage. This behavior corresponds to a crossover from WAL to WL. We note that $l_0 < W$ in our device appears to be incompatible with observing quantum effects such as WL and WAL. However, a simulation of the potential profile in a single-side-gated nanowire device10 suggests that electrons can be practically confined in an area of approximately $1/4-1/3$ W ($< l_0$). This indicates that the quantum effect can be reasonably observed in our system.

We next compare the $V_G$ dependence of $l_{so}$ obtained for our device with previous reports. Figure 4(a) compares our InSb nanowire device with back-gated, top-gated, and dual side-gated InAs nanowire devices. [Fig. 4(a) does not include single-gated InSb nanowires, since the corresponding data have yet to be reported.] As clearly shown in Fig. 4(a), nanowire devices with standard gate geometries require more than 10 V to substantially tune the SOI length, whereas our device with a nearby back gate requires only a few volts.

We next compare the data we obtained for our InSb nanowire device with those obtained for an InSb nanowire FET that combines a standard back gate with an $\Omega$ shaped top gate,15 whose gate insulator is so thin relative to the nanowire width that the resultant gate shape resembles the letter $\Omega$.25

Figure 4(b) shows the conductance dependence of $l_{so}$ for both devices and the spin precession length $l_R$ for the $\Omega$ shaped device. Note that the spin precession length is recognized to be the same as $l_{so}$ in a diffusive one-dimensional system as in our case but is represented differently from $l_{so}$ in a quasi-ballistic one-dimensional system as in the $\Omega$ shaped device case.15 This difference occurs because our device is a diffusive system with $l_e < W$, in which $l_{so}$ is extracted with the commonly used WL theory based on a disordered one-dimensional model and consequently $l_{so}$ has been widely recognized as the spin precession length. In contrast, the $\Omega$ shape gated device is a quasi-ballistic system with $W < l_e$, in which the spin relaxation caused by the linear Rashba and Dresselhaus effects is suppressed and only the cubic Dresselhaus SOI acts effectively when $W < l_R$.15,26 Therefore, in a quasi-ballistic system with $W < l_R$, $l_{so}$ becomes longer than $l_R$ associated with the band structure of the material.15 This is clearly the case with the $\Omega$ shape gated device in Fig. 4(b), where $l_R$ is reduced from $l_{so}$ and becomes similar in size to $W$.

We also note that $l_{so}$ in our case and $l_R$ in Ref. 15 are deduced based on the different theoretical models, but in the diffusive limit, the results obtained by these models are nearly the same.15 The model that we used to deduce $l_{so}$ has been widely used for analysis of the diffusive transport of one-dimensional nanowires,10-14,16,17 and is originally deduced from the Kettlemann model.27 On the other hand, the model by van Weperen et al. was introduced to calculate ballistic transport for nanowire. However, when we consider the diffusive limit and the equation is simplified, the results of van Weperen’s model do not differ from those of Kettelman model by more than 5%.15 These models are thus reasonably compared and used for each case.
When we compare \( l_R \) for their device with \( l_{so} \) for our device, we find that the values and their conductance dependences are nearly the same, which shows consistency between the two InSb nanowire devices. We next compare the gate voltage dependence of \( l_{so} \) and \( l_R \) for the devices as shown in Fig. 4(c). For the dual \( \Omega \) and back-gated device, \( l_{so} \) and \( l_R \) are modulated only slightly by the back gate, but tuned significantly within a few volts by the \( \Omega \) gate. On the other hand, our device with a nearby back gate exhibits a sharp modulation in \( V_g \) dependence, with the slope being slightly smaller than that of the \( \Omega \) gated device.

The Rashba coupling constant \( \alpha_R \) obtained from \( l_{so} \) and \( l_R \) using the relations \( \alpha_R = h^2 / (2m^*l) \) \((l = l_{so} \, \text{or} \, l_R) \) is plotted as a function of gate voltage and conductance in Figs. 5(a) and 5(b). Here we use \( m^* = 0.023 \, m_e \) for InAs and \( m^* = 0.012 \, m_e \) for InSb. These figures indicate that our InSb nanowire device achieves a larger \( \alpha_R \) with a smaller \( V_g \) than the previously reported InAs nanowire devices shown in Fig. 4(a). Moreover, the value of the Rashba coupling constant reaches the nearly highest value (~0.8 eVÅ) among the previous reports, \(^{3-16}\) which is comparable to Ref. 15 (~0.5 eVÅ) obtained for quasi-ballistic InSb nanowire.

We also note that \( \alpha_R \) shows approximately linear dependence on \( V_g \), which is reasonable from the fact that \( \alpha_R \) is proportional to the effective electric field (discussed later). This guarantees that \( V_g \) dependence of \( l_{so} \), estimated from the model is reasonable, even though our data regarding WL to WAL crossover is slightly scattered at each \( V_g \).

The large Rashba coupling constant is achieved firstly because the choice of material is better, i.e. the effective mass of InSb is smaller than that of InAs, and secondly because the gate geometry is improved, i.e. \( V_g \) tunability of \( \alpha_R \) is greatly improved compared with those of previously reported back-gated InAs nanowire devices, and is comparable to that of the \( \Omega \) gated sample. This demonstrates that our easy-to-fabricate device structure can provide a large SOI as well as high gate efficiency, which will contribute greatly to an improvement in fabrication yields toward the realization of novel spintronics devices.

We also compare the peak electric field \( E_p \), which is estimated from the gate geometry and applied voltage, with the electric field that is associated with \( \alpha_R \) with the relation given by \( \alpha_R = \alpha_0 E_p R \). \(^{14,17}\) At gate voltage around 2.4 V, \( E_p \) is approximately estimated to be \( 4 \times 10^8 \) V m\(^{-1}\). (We assumed that the distance to the electron channel is about 6 nm, corresponding to the thickness of the gate insulator.) In contrast, using \( \alpha_0 = 523 \) Å\(^2\) (Rashba constant specific to material) for InSb, \(^{28}\) we can see that \( E_p/E_p \) ratio is about 4%. This decrease can be attributed to decay in \( E_p \) due to screening by the thickness of the electron channel itself, \(^{12}\) and/or charge traps by the interface states that often appear in gate insulator in devices. \(^{29-31}\)

Table I. Rashba coupling constant for InSb devices with different structures. WL to WAL indicates magnetotransport that are used to observe a crossover from weak localization (WL) to weak antilocalization (WAL).

| Paper          | Structure            | Model          | Method                        | \( \alpha_R \) (eVÅ) |
|---------------|----------------------|----------------|-------------------------------|---------------------|
| This work     | Nanowire(NW) FET     | 1 D diffusive  | WL to WAL                     | ~0.8                |
| Ref. 15       | NW \( \Omega \) type FET | 3 D quasi-ballistic | WL to WAL                     | ~0.6                |
| Ref. 18       | NW quantum dot (QD)  | 0 D            | QD spectroscopy                | 0.16                |
| Ref. 8        | 2D quantum well      | 2 D            | WL to WAL                     | 0.03                |

When we compare \( l_R \) for their device with \( l_{so} \) for our device, we find that the values and their conductance dependences are nearly the same, which shows consistency between the two InSb nanowire devices. We next compare the gate voltage dependence of \( l_{so} \) and \( l_R \) for the devices as shown in Fig. 4(c). For the dual \( \Omega \) and back-gated device, \( l_{so} \) and \( l_R \) are modulated only slightly by the back gate, but tuned significantly within a few volts by the \( \Omega \) gate. On the other hand, our device with a nearby back gate exhibits a sharp modulation in \( V_g \) dependence, with the slope being slightly smaller than that of the \( \Omega \) gated device.

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Lastly, we compare the maximum $\alpha_R$ that we reached for our device with values for various InSb samples with different dimensions (Table I). Despite the difference in the estimation method, we can see that our device has larger $\alpha_R$ even in InSb samples, indicating that the effective electric field is large owing to our nearby back gate structure.

In summary, we have reported on an InSb nanowire FET with a nearby back gate structure. Magneto-transport measurements revealed that a crossover from WL to WAL occurs within a gate bias of a few volts. The extracted SOI and its gate voltage efficiency are sufficiently large to allow a further exploration of novel spintronics devices.

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