Gate-controlled spin-orbit interaction in an InAs nanowire MOSFET

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Abstract
We report FET characteristics and magnetotransport of a gate-all-around InAs nanowire FET. The on/off ratio and the field-effect mobility are over 2500 and 600 cm²/Vs at room temperature. Magnetococonductance measured at low temperature shows transition from weak localization to weak antilocalization caused by strong Rashba spin-orbit interaction modified by gate voltage. The estimated gate modulation of the Rashba coupling parameter is 1.5 × 10⁻¹¹ eVm per volt. Such a large modulation rate would lead to an application to nanowire spin MOSFET.

1. Introduction
InAs is promising material to realize a practical spin FET because of high electron mobility due to small effective electron mass and large spin-orbit interaction. To control Rashba spin-orbit interaction proportional to electric field, nanowire FET has a preferable geometry, in which electrons are confined in a quasi-one-dimensional potential and thus gate can induce electric field more effectively. However, conventional back-gated InAs nanowire FETs [1-4] employed SiO₂ of the underneath substrate as a gate insulator, and thus the voltage required to substantially modify the spin-orbit interaction length in the InAs channel often exceeds 10 V, giving a challenge to industrial application favoring low-power consumption.

Here we report on a MOS-type InAs nanowire FET using a gate-all-around (GAA) structure with thin high-κ gate dielectrics. This enables typical gate electric field applied to the channel to be ~ 1× 10⁷ V/m, which is larger than that for dielectrics. This enables typical gate electric field applied to a GAA structure with thin high-κ gate dielectrics. It is found that lₙ₀ is changed by 100 nm in a sub-voltage via the gate, corresponding to the Rashba coupling parameter variation of ~1.0 × 10⁻¹¹ eVm. Our results demonstrating gate-control of Rashba coupling parameter can open up a route to development of practical MOS nanowire spin FET.

2. Experimental
The sample is fabricated from InAs nanowire which was grown by VLS method. As shown in Fig. 1(a), the area covered by the gate electrode is more than 90 % of the channel length between source (S) and drain (D), allowing us to neglect contributions of the ungated regions and the contacts. To fabricate GAA structure [Fig. 1(b)] to induce strong electric field on the channel, Al₂O₃ (2 nm) and HfO₂ (4 nm) were first grown by ALD around the nanowire. The coated wire was then transferred to SiO₂/Si substrate with prepat-tered metal gate, and was successively subject to additional deposition of metal gate. This two-stage deposition of metal enables formation of the gate-all-around structure shown in Fig. 1(b). The details of the fabrication method were reported in Refs. [5] and [6]. The electrical characterization of FET performance was conducted at room temperature, and magnetotransport measurement to investigate spin-orbit interaction was carried out at around 1.5 K.

3. Results and discussion
Figure 1(c) shows transfer characteristics of our GAA InAs nanowire FET taken at room temperature at source-drain voltage (Vₕ) of 300 mV. When the gate voltage (Vₙ) increases from -2 V, the source-drain current (Iₕ) rapidly increases around 0.6 V, showing transition from off to on state with on/off ratio of more than 2500. The peak mobility at Vₙ = 0.6 V is ~600 cm²/Vs. These values are comparable to those of previously reported various types of InAs nanowire FETs [7,8]. Figure 1(d) shows Iₕ as a function of Vₕ at Vₙ = 0.8 and 1.2 V at room temperature and 1.5 K. Linear Iₕ - Vₕ features are shown up to Vₕ ~ 0.1 V for both temperatures.

We next turn to magnetotransport measurements taken at ~1.5 K to investigate the effect of the spin-orbit interaction
on the nanowire channel. Figure 2 shows correction of magnetoconductance (ΔG) as a function of the magnetic field (B), where the magnetoconductance was deduced from two-terminal dc-transport at Vgs = 10 mV. The data shown in Fig. 2 have been smoothed over Vgs ± 15 mV and B ± 15 mT to exclude conductance fluctuations or other fluctuations due to impurities, as was done in Refs. [2] and [3]. In addition, our data are further averaged with respect to reversed magnetic field sweep direction to make the data fitting more reliable. At Vgs = 0.24 V, ΔG increases upon application of B, whereas at Vgs = 0.87 V, ΔG first decreases and turns to increase. This indicates a transition from weak localization to weak antilocalization, which was known to occur in the presence of strong spin-orbit interaction due to interplay between the spin-orbit interaction length and the phase coherence length (lφ) [9].

Such a transition from weak localization to weak antilocalization was previously observed for various types of InAs nanowire devices: back-gated FETs measured individually [2] or in parallel [1], a suspended nanowire [8], double gated one [10] and ion-gated nanowire [10]. For these devices, mean free path is smaller than nanowire diameter, and thus lso and lφ is deduced using the following equation describing correction of magnetoconductance in one-dimensional disordered metallic channel [7],

\[ \Delta G = \frac{2e^2}{\hbar L_g} \left[ \frac{3}{2} \left( \frac{1}{l_{so}^2} + \frac{4}{3l_{so}^2} + \frac{1}{D \tau_B} \right)^{3/2} - \frac{1}{2} \left( \frac{1}{l_{so}^2} + \frac{1}{D \tau_B} \right)^{3/2} \right] \]  

(1)

where e is electron charge, h is Plank constant, Lg is gate length, D is diffusion constant, and \( \tau_B \) is magnetic relaxation time. Here \( \tau_B \) is given by

\[ \tau_B = \frac{3l_{so}^4}{\hbar^2 D} \]  

(2)

with lφ being magnetic length given by \( l_{so} = \sqrt{\hbar/2neB} \). Note that this reduces the fitted parameters to be only lso and lφ.

Regarding our device, the mean free path is ~ 12 nm and is smaller than the nanowire diameter of 100 nm. Therefore, Eq. (1) is used to nicely fit our data as shown in Fig. 2(a). Estimated lso and lφ are ~140 and 270 nm at Vgs = 0.24 V, and ~190 and 130 nm at Vgs = 0.87 V. Note that the relative magnitude of lso and lφ directly correlates to the transition from weak localization to weak antilocalization, as pointed out in Ref. [3]. Vφ dependence of Rashba coupling parameter α, defined as \( \alpha = h^2/(2m_e l_{so}) \) with h being reduced Planck constant, is plotted in Fig. 2(b). As shown clearly, our device enables to change α much more efficiently than back-gated InAs nanowire FETs [1]. Such high tunability of the Rashba coupling parameter will contribute to open up a route to application of nanowire spin FETs.

3. Conclusions

We report electrical transport of a GAA InAs nanowire FET using high-κ gate insulator. It shows on/off ratio of more than 2500 and the field-effect mobility of 600 cm²/Vs. Our FET also demonstrates high gate tunability of the spin-orbit interaction length and the Rashba coupling parameter.

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References