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Spin orbit induced electronic spin polarization and its future application

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Abstract

We generated and detected spin polarization in a fully electrical way using a nano-sized InGaAs-based field effect transistor, so-called a Rashba spin-orbit coupling quantum point contact. We experimentally demonstrated 70% spin polarization without an external magnetic field and magnetic materials. Our new approach to polarizing electron spin in semiconductors represents a new direction for the seamless integration of electrical spin generation, manipulation, and detection in a single semiconductor device without the need for an external magnetic field or magnetic materials.

1. Introduction

The electron spin plays a central role for the information storage due to the non-volatility with magnetic materials, while the electron charge has been utilized in semiconductor electronics for the information processing. Rapid progress in spintronics leads to the strong interest to develop and integrate spin generation, manipulation, and detection in semiconductors for potential spintronic devices. Rashba spin-orbit interaction (SOI)[1] induces an effective magnetic field for an electron moving in a semiconductor, which plays a key role for electrical control of spin orientation[2]. Indeed, by using Rashba SOI, electric gate control of spin rotation[3,4], electron spin resonance[5,6] and persistent spin helix state[7] have been successfully demonstrated. In order to fully realize semiconductor-based spintronic devices, however, it is essential to create and detect high spin polarization without any external magnetic fields and magnetic materials. However, a feasible method to resolve this problem has long been lacking. Here, we demonstrate electrical spin generation and detection at zero magnetic field by controlling the Rashba SOI in an InGaAs/InGaAsP heterostructure[11]. The central idea of the electrical spin generation and detection in this study is schematically shown in Fig. 1. By making a quantum point contact (QPC)[9,10], the spatial modulation of the effective magnetic field is induced in the QPC channel[11]. This effective magnetic field gradient generates the spin dependent force as the same concept of Stern-Gerlach spin separation experiment in 1922. As a result, a spin split conductance plateau is observed as $0.5(2e^2/h)$ and spin polarization is found to reach as high as 70%. The spin orientation is electrically reversed by switching the source-drain bias direction due to the momentum-dependent effective magnetic field. The present achievement opens up the potential for fusion of electrical spin generation, manipulation, and detection in a single semiconductor device without any external magnetic field and magnetic materials.

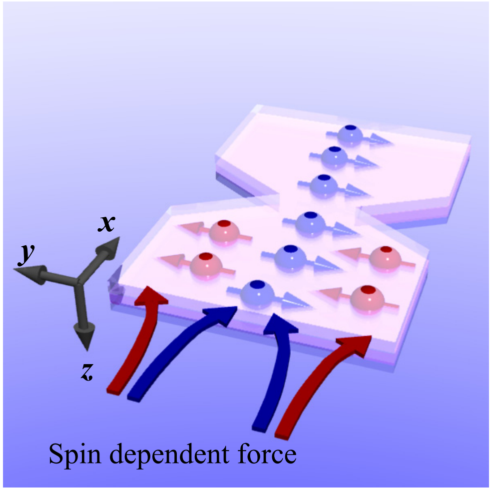

Fig. 1 Schematic picture of spin orbit induced spin polarization in a quantum point contact.

2. Sample structure and measurement setup

The InGaAs/InGaAsP heterostructure was epitaxially grown on a (001) InP substrate by metal organic chemical vapour deposition. The QPC was fabricated by electron beam lithography and reactive ion etching techniques. The width (W) of the QPC was designed as $300 \leq W \leq 500$ nm. Atomic layer deposition of 150 nm Al_2O_3 was performed for the top-gate insulator. To form a top-gate electrode, 5-nm Cr / 150-nm Au was evaporated and lifted off. AuGeNi (200 nm) was evaporated for voltage probes and source-drain electrodes. Four-terminal measurements were performed by applying the source-drain voltage (V_{sd}) to probe the quantized conductance as functions of top (V_{TG}) and side (V_{SG}) gate voltages and external magnetic fields. The external magnetic field was applied parallel to the effective magnetic field (y direction in Fig. 1) for differential conductance measurement.

3. Results

We first measured conductance plateaus at $B = 0$ T and $T = 3.6$ K. While V_{TG} was fixed, V_{SG} was swept to negative bias with identical voltages between the left and right side gates. As shown in Fig. 2, for $V_{TG} = +5.8$ V, clear conductance plateaus are observed from $G = 1(2e^2/h)$ to $3(2e^2/h)$ in steps of $2e^2/h$, showing the formation of one-dimensional channels by the side gates. When V_{TG} is reduced to +2.4 V, a half-integer plateau appears at $0.5(2e^2/h)$, indicating the

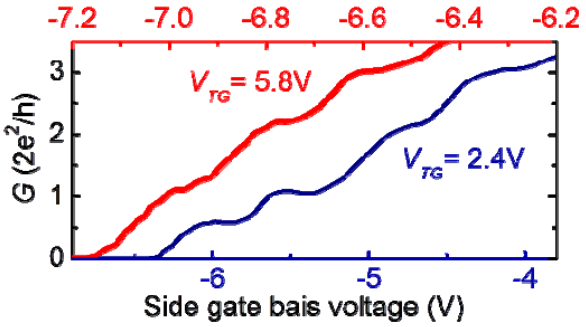

Fig. 2 Quantized conductance as a function of side gate bias voltage at T = 3.6 K. lateral axes for V_{TG} = 5.8Vand 2.4V are upper and lower sides, respectively.

formation of a spin polarized single channel. The decrease of V_{TG} causes an increase in the Rashba SOI, indicating that the effective magnetic field B_{eff} is responsible for the spin generation.

For exploring the mechanism of spin polarization owing to Rashba SOI, we consider the spatially-modulated effective magnetic field due to lateral confinement in the QPC. Such an effective magnetic field induces the spin dependent force. We calculate the spin polarization in the QPC by employing wave-packet dynamics. Figure 3 shows the time evolution of the wave packet and the y-direction spin density in the QPC channel calculated by the equation-of-motion method based on the exponential product formula[12]. Figure 3(a) shows the initial state of the electron wave packet moving in the +x direction without spin polarization. As the wave packet approaches the QPC potential, the down spin (blue/dark) wave packet moves to the center of the channel and the up spin (red/light) wave packets then move away from the channel and are accumulated in the channel sides (Fig. 3(b)). While the down spin (blue/dark) wave packet travels through the channel, the up spin (red/light) wave packet is reflected by the QPC potential (Fig. 3(c)), resulting in the spin polarization.

In order to evaluate the spin polarization at $0.5(2e^2/h)$ plateau, we measured shot noise[13] in the QPC at B_{ex} = 0 T and T = 4.2 K. At $0.5(2e^2/h)$ plateau large difference between spin-up and spin-down transmission probabilities is observed and the maximum value of spin polarization reaches P_s = 0.7.

3. Conclusions

We demonstrated the spin orbit induced spin polarization in the InGaAs QPC structure. By introducing the spin dependent force originated from the spatial modulation of the effective magnetic fields, up-spin and down-spin polarizations are spatially separated and only one spin polarization is transmitted through the QPC. This is the experimental manifestation of Stern-Gerlach spin separation in the semiconductors. Since highly polarized spin current is induced without any external magnetic fields and magnetic materials, present spin polarization technique paves the way towards the integration of electrical spin generation, manipulation, and detection in future semiconductor-based spintronic devices and quantum information technology.

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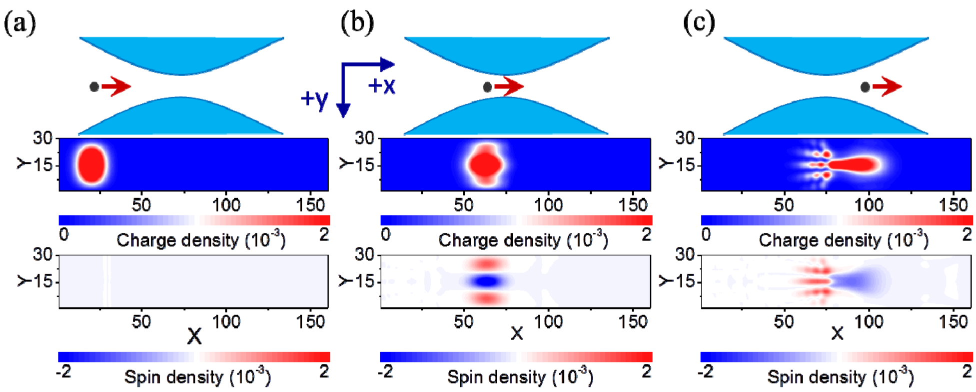

Fig. 3 Time evolution of electron wave packet for the charged density and the spin density in the QPC. (a) initial state of the wave packet moving +x direction (b) Just before the narrowest constriction (c) after transmission through the narrowest constriction.