Semiconductor Spintronics

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Abstract

In semiconductor spintronics, electron spin rather than charge is the key property. This paper describes several spin-related devices using spin-orbit interaction. We have experimentally confirmed that the spin-orbit interaction in a semiconductor two-dimensional electron gas channel can be controlled by a gate voltage. This is the first step towards the creation of functional spin devices. The operating principles of a spin field effect transistor, a spin filter, and a spin interference device are discussed.

1. Introduction

Semiconductor and ferromagnetic materials are indispensable for present electronics technologies. Semiconductor spintronics (or spin electronics) combines semiconductor microelectronics with spin-dependent effects that arise from the interaction between the spin of a charge carrier and the magnetic properties of the materials. Ferromagnetic metals show a magnetization hysteresis loop in which the cooperative motion of a large number of electron spins plays a role. This hysteresis loop has been used in the development of nonvolatile memory devices, such as hard disk drives. Recently, much attention has been focused on the development of magnetic random access memory (MRAM), whose nonvolatile memory function is expected to reduce power consumption because no current (refresh) is required to maintain it, unlike dynamic random access memory (DRAM). The MRAM is based on the tunneling magnetoresistance effect arising from the dependence of device resistance on the spin orientations between two ferromagnetic electrodes [1]. However, it is very difficult to make an active device, such as a logic circuit from only ferromagnetic metals.

Semiconductor materials enable logic functions to be made because channel properties can be very easily controlled by an electric field, which has been the main reason for the tremendous progress of semiconductor electronics. An example is three-terminal operation using gate electrodes in field effect transistors (FETs). This FET operation is the foundation of many functional devices. Downscaling of semiconductor devices has mainly been responsible for the progress of integrated circuits (ICs). Downscaling reduces the capacitance of components and allows us to increase the number of components. The lower capacitance increases the operating speed of ICs and decreases their power consumption. However, it is predicted that semiconductor fabrication technology will reach the downscaling limit in a few years.

Overcoming the downscaling limit requires a new paradigm in electronics. In semiconductor electronics, electron charge plays the key role while electron spin plays no role at all. Electronics based on the spin degrees of freedom of the electron represents a new paradigm, which will require a way of controlling electron spins in semiconductor channels by using the gate voltage.

In this paper, we describe several spin-related devices that use a semiconductor two-dimensional electron gas (2DEG) channel. We have experimentally confirmed that the spin-orbit interaction can be controlled by the gate voltage, which is the first step towards the development of functional spin devices. The operating principles of a spin-FET, a spin filter, and a spin interference device are discussed.

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2. Operating principle of spin-FET

The discovery of giant magnetoresistance (GMR) [2], [3] showed that there is an intimate connection between the charge and spin degrees of freedom of the electron. In a GMR device, the electrical resistance is small when the magnetization orientation of ferromagnetic thin layers is aligned, but very large when it is anti-parallel. This suggests that information can be encoded not only in the electron's charge but also in its spin state, i.e., through alignment of the spin (either "spin-up" or "spin-down") relative to the magnetization orientation of ferromagnetic film. In GMR devices, the magnetization orientation is controlled by an external magnetic field. The basic idea of the spin-FET, as proposed by Datta and Das [4], is to control the spin orientation by applying a gate voltage.

A spin-FET consists of ferromagnetic electrodes and a semiconductor 2DEG channel with a gate electrode, as shown in **Fig. 1**. It is basically similar in structure to a conventional FET. The source and drain electrodes are ferromagnetic metals, and the 2DEG channel should have a strong spin-orbit interaction. The spin-polarized electrons injected from the ferromagnetic source electrode (FM1) start to rotate because an effective magnetic field is created by the spin-orbit interaction in the 2DEG channel. The origin of the spin-orbit interaction is the relativistic effect, and an electron feels the effective magnetic field B_{eff} perpendicular to its motion in the electric field E and propagation velocity direction v, such that $B_{eff} \propto v \times E$. If the spin orientation in the 2DEG channel is aligned to the ferromagnetic drain electrode, the electrons can flow into the ferromagnetic drain electrode. However, when the spin orientation is flipped in the 2DEG as shown in Fig. 1, the electrons cannot enter the drain electrode (FM2) because there is no state for the flipped spin in FM2. The spin-orbit interaction is modified by the gate voltage (the effective magnetic field is changed). Therefore, the spin precession angle can be controlled by the gate voltage. In a spin-FET, current flow is modified by the spin precession angle.

A spin-FET would have several advantages over a conventional FET: It could be used not only as a logic gate, but also as a nonvolatile memory component. Less energy would be necessary to flip an electron's

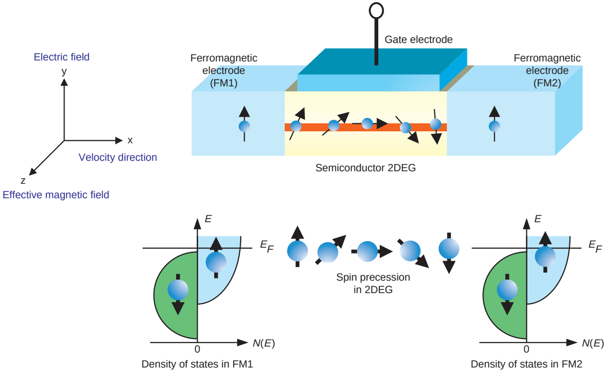

Fig. 1. Schematic of a spin-FET. Spin-polarized electrons are injected into the semiconductor 2DEG from the ferromagnetic source electrode (FM1). Injected electrons start to rotate because of an effective magnetic field created by a spin-orbit interaction. Spin-flipped electrons cannot enter the ferromagnetic drain electrode (FM2) because there is no state for the flipped spin at the Fermi energy in FM2. A gate voltage that can tune the spin-orbit interaction is used to control the spin precession angle.

spin, and the spin could be flipped much faster than electrons can be pushed away from their channel by a gate voltage. It may also be possible to change the magnetization direction of the electrodes by applying a magnetic field, which would allow us to change the function anytime by changing the magnetization orientation of the electrodes.

For spin-FETs, there are two ongoing issues: how much can the spin-orbit interaction be controlled by the gate voltage and how efficiently can spin-polarized electrons be injected into the 2DEG from the ferromagnetic electrode?

3. Gate control of spin-orbit interaction

It is well known that an external magnetic field lifts spin degeneracy. Even without an external magnetic field, an electric field perpendicular to the 2DEG yields an effective magnetic field for moving electrons. Two important alternative mechanisms for spin splitting are i) the host crystal electric field, the so-called Dresselhaus spin-orbit interaction [5] and ii) the interface electric field, the so-called Rashba spin-orbit interaction [6]. The possibility of gate control of the spin-orbit interaction was discussed in the early 1990s [4]. However, there has been no clear experimental evidence of such controllability until we experimentally verified gate-voltage control of spin-orbit interaction in InGaAs/InAlAs heterostructures [7]. The spin-orbit interaction parameter has since been obtained from the beating pattern in the Shubnikov-de Haas (SdH) oscillations [8]-[10]. The dominant mechanism governing the change in the spin-orbit interaction parameter is the Rashba spin-orbit interaction.

Figure 2(a) shows the gate voltage dependence of SdH oscillations at 0.4 K. The magnetic field was applied perpendicular to the 2DEG. Beating patterns are observed in the SdH oscillations because of the existence of two closely spaced SdH frequency components with similar amplitudes. These observed beating patterns are attributed to the spin splitting. When the negative gate voltage is increased, the node position shifts to a higher magnetic field. The spin-orbit interaction parameters were obtained from the analysis of the beating pattern observed in the SdH oscillations. In Fig. 2(a), a comparison between the measured SdH oscillations and numerical simulations shows good agreement. The dependence of carrier concentration Ns of the spin-orbit interaction α is plotted in **Fig. 2(b)**. The spin-orbit interaction parameter increases as Vg becomes more negative. A

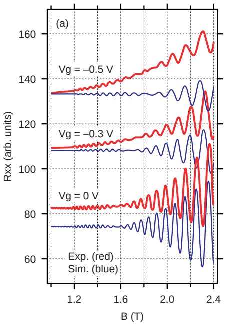

Fig. 2(a). Gate voltage dependence of SdH oscillations. Beating patterns in the SdH oscillations appear due to a spin-orbit interaction. By comparing the oscillations with the numerical simulation based on Rashba spin-orbit interaction, we can obtain spin-orbit interaction parameter α.

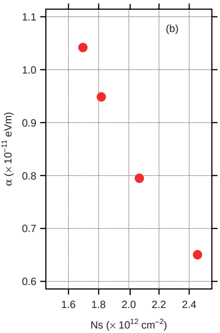

Fig. 2(b). Spin-orbit interaction parameter α is plotted as a function of carrier concentration Ns, which is related to gate voltage Vg. Spin-orbit interaction can be controlled by the gate voltage.

weak anti-localization analysis has also shown that the spin-orbit interaction can be controlled by the gate voltage [11].

In relating this result to the spin-FET, the spin precession angle θ is given by

$$\theta = \frac{2\alpha m^* L}{\hbar^2}, \tag{1}$$

where L is the distance between source and drain ferromagnetic electrodes. Equation (1) implies that the spin precession angle, which is proportional to the spin-orbit interaction, can be controlled by the gate voltage Vg. If we assume L = 0.5 µm, the spin precession angle can be controlled as $\theta = 1.2\pi$ at Vg = 0 V (Ns = 2.45×10^{12} cm^{-2}) to $\theta = 1.8\pi$ at Vg = –0.5 V (Ns = 1.82×10^{12} cm^{-2}). In this experiment, α did not saturate in the above gate voltage range, which suggests that it will be possible to obtain larger α modulation.

4. Spin injection from ferromagnetic electrode into 2DEG

To explore the roles of the spin degrees of freedom in a semiconductor, we must first create a spin-polarized current source. Much effort has been dedicated to demonstrating spin injection from a ferromagnetic contact (FM) into semiconductor (SM) because spin injection will allow us to exploit many new phenomena and applications in the field of spin-polarized transport. It has been pointed out that spin injection is very difficult due to the large conductivity mismatch between ferromagnetic contact and diffusive semiconductor [12]. In cases where we used FM/SM/FM structures, the resistance change due to the spin injection was less than 1% even at low temperature [13]. However, Rashba suggested that inserting a tunnel barrier (I) between the FM and SM can solve the conductivity mismatch problem [14]. We have shown, based on the free electron approximation model, that more than a 10% resistance change can be expected in FM/I/SM/I/FM junctions [15], [16].

A 2% spin injection efficiency at room temperature has been reported for epitaxially grown Fe on GaAs [17]. More recently, electron spin polarizations of 32% at 4.5 K have been obtained in a GaAs quantum well via electrical injection through an Fe/AlGaAs Schottky contact [18]. Despite the success of these approaches, it is also important to develop a spin-polarized current source or a spin filter that uses only nonmagnetic semiconductors from the viewpoints of both the attainability of high-quality heterostructures and the ability to eliminate the stray field that may have undesirable effects on the spin-filtered electrons.

We have proposed a spin filter that uses a triple barrier resonant tunneling diode and can generate a spin-polarized current without using magnetic materials [19]. We utilized the Rashba spin-orbit interaction to induce spin split resonant tunneling levels in the proposed device even in the absence of a magnetic field. The device combines spin splitting with level matching between the spin-dependent resonant tunneling levels. The level matching procedure is analogous to the proposed spin-blockade concept. Detailed calculations for the InAlAs/InGaAs material system predict that a splitting of a peak should be observed in the I-V curve of this device as a result of the spin-filtering effect. The filtering efficiency exceeds 99.9% at the peak position in the I-V curve.

5. Spin Interference device

We have also proposed a spin-interference device that works without any ferromagnetic electrodes and without any external magnetic field [20]. The phases acquired by the spin wave functions during a cyclic evolution are calculated in an Aharonov-Bohm (AB) ring in the presence of the Rashba spin-orbit interaction. The conductance modulation in a one-dimensional ring can be expressed by

$$G = \frac{e^2}{h}\left[1+\cos\left\{2\pi\sqrt{1+\left(R\frac{\alpha m^*}{\hbar^2}\right)^2}\right\}\right], \tag{2}$$

where R is the radius of the ring.

Figures 3(a) and **(b)** show the operating principle and an SEM image of a fabricated spin-interference device. The gate controls the spin-orbit interaction α and covers the whole AB ring area. The origin of the spin interference is the spin precession angle difference between the left and right branches. The phases acquired in the left and right branches are not the same: they have opposite signs because the precession orientation is opposite. It is interesting that the obtained spin dynamical phase is very similar to that of the spin-FET. In both cases, the origin of the phase difference is related to the spin precession.

In the case of the spin-FET, the spin-polarized electrons injected from the ferromagnetic electrode contribute to conductance modulation. The spin polarization in the conventional ferromagnetic metals is not 100%; values of 30 to 40% have been reported for

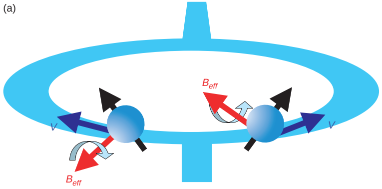

Fig. 3(a). Schematic of the spin-interference device. The electron spin feels an effective magnetic field perpendicular to its velocity direction; therefore, the precession angles of the left and right branches are different. A ring made of an InGaAs/InAlAs heterostructure is covered with a gate electrode, which controls the spin-orbit interaction.

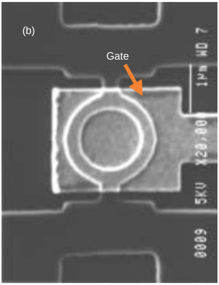

Fig. 3(b). SEM image of a fabricated spin-interference device.

superconductor(S)/I/FM tunneling experiments [21]. On the other hand, all carriers can contribute to spin interference in the proposed spin-interference device.

In the one-dimensional AB ring, the channel consists of a single mode. Here, we emphasize that this spin-interference device would also work with multiple modes because the phase difference of the spin waves is independent of the wave vector of the modes in the upper and lower branches. Generally, electron quantum interference devices must be single-mode in order to obtain sufficient modulation because the difference in the wave vector from one mode to another causes a difference in phase shift, which smears the interference effect. An important advantage of our spin-interference device is that the current modulation is not washed out even when multiple modes are involved. Experimental measurements are underway.

6. Concluding remarks

There are three important parameters related to electron spins in semiconductors: exchange interaction, spin-orbit interaction, and the electron g-factor. The feature of semiconductors is that the channel properties can be easily controlled by a gate voltage. This gate controllability is the basis of the transistor, and since its invention, many device applications have been established. However, the controllability is mainly limited to changing the number of carriers in the semiconductor channel. For future spin electronics, we must establish a way to control spin properties in semiconductors by a gate because the electrical manipulation of electron spins is a key technology. In this paper, we focused on gate control of spin-orbit interaction and its application in a spin-FET, spin filter, and a spin interference device. Recently, it has been experimentally confirmed that the electron g-factor can be controlled by the gate voltage [22]-[24], and gate control of ferromagnetism has been demonstrated in a diluted semiconductor (InMnAs) [25]. In addition, a ferromagnetic spin state has been predicted in a non-magnetic semiconductor quantum dot array [26], where ferromagnetism can be controlled by the gate voltage [27]. These electrical manipulations of the electron spin state will lead to a new paradigm of electronics based on spin degree of freedom.

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