Quantum transport analysis and narrow-gap heterojunction growth for Rashba-type spintronics devices

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Received 26 November 2004; revised 11 April 2005; accepted 12 April 2005
Available online 5 July 2005

Abstract

Research results of spintronics based on spin-orbit (SO) interaction in non-magnetic semiconductor hetero-junctions obtained recently have been described. Works are based on the two-dimensional electron gases (2DEGs) confined at compound semiconductor narrow band-gap hetero-interface. Due to the electric field originated from the confining potential asymmetry, the 2DEG often yields strong SO interaction which could reveal under no magnetic field. This type of SO interaction (Rashba interaction) can be controlled by the applied gate voltage and hence the field effect transistor (FET) utilizing this principle has so far been proposed and discussed extensively. We describe two recent results in this paper: First is molecular beam epitaxy (MBE) growth of novel narrow-gap modulation-doped heterojunction, InGaSb/InAlSb material system which possibly reveals high quality electronic properties as well as very strong Rashba SO coupling. Recently we indeed obtained the sample with a very large SO coupling constant of ~40 \times 10^{12} \text{ eVm} which is almost comparable to the best value obtained in the former InGaAs/InAlAs systems. Second is relating to the control of Rashba SO interaction in long wires with side gates. As a result of careful analysis about the dependencies of the SO coupling constant on the gate voltage, we confirmed the side-gate control of the Rashba effect for the first time, which could be a promising result to develop the spin-FET based quantum-bit devices.

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1. Introduction

In order to attain the fundamental operation of Rashba-type SO interaction-based spin-FET [1], we first need the 2DEG which has a large Rashba SO coupling constant controllable by an applied gate voltage [2–4]. For this purpose, a variety of heterojunction materials have already been grown and estimated. Among the III–V materials, InAs inverted structure [5] and high In-content (~75%) InGaAs/InAlAs heterojunction [6] were found to reveal highest SO coupling constants as 40–45 \times 10^{-12} \text{ eVm} with relatively high electron mobilities up to 3–4 \times 10^5 \text{ cm}^2/\text{Vs} at low temperatures. Second requirement is the electrode which can select or detect spin-polarization of electrons passing through the (ferromagnetic) electrode/semiconductor interface [7]. High efficient spin injection in the 2DEG samples has, however, not yet been realized so far. Third is the dimensional design of the device itself, since the Rashba interaction is a kind of traveling type effect and so the restriction of the initial velocity direction of the 2DEG would become important. In this sense, how the Rashba effect is modified or not modified in wires or narrow channels should be studied with a well-defined small structures fabricated carefully.

In this work, we first describe the recent progress in the growth of novel narrow gap heterojunction, high In-content (~90%) InGaSb/InAlSb system, containing the 2DEG with even stronger Rashba interaction, which is related to the first requirement. We also report the study of analyzing Rashba SO interaction in the channels with gate electrodes in the both sides. In the channels with gate electrode only in the one side, we recently observed the enhancement of Rashba SO coupling constant (\alpha) when the strong negative voltage bias is applied. The reason of the enhancement has, however, not been clarified completely yet. This problem is closely related to the third topic and suggests the interesting possibility of controlling the Rashba SO interaction not only by the top-gate in the former works [2–4] but also by the side-gate in an independent manner. In addition, since one prototype of qubit devices is a double-gate spin-FET [8], this result could be one of the important
basis of the spin-FET based quantum information processing devices [8].

2. Epitaxial growth of strain-free InGaSb/InAlSb heterojunctions

We so far developed and used modulation-doped high In-content (~75%) InGaAs/InAlAs heterojunctions grown on GaAs substrates as base materials for semiconductor Rashba effect spintronics. Typical SO coupling constant obtained under no gate bias in this system is \( \alpha \approx 10^{-12} \) eV m which corresponds to \( \Delta E_F \approx 10 \) meV spin-splitting at the Fermi level \( (\epsilon_F = \hbar^2 k^2/2m^* \) electron effective mass,). This value is, however, not enough to realize spin FETs operating at room temperatures (~25 meV). We thus proposed a new narrow-gap heterojunction consist of high In-content InGaSb and InAlSb. Rough estimation suggests four times and two times larger values of Rashba SO coupling constant, \( \alpha \), and electron mobility, \( \mu_e \), than those of InGaAs/InAlAs system, respectively, since \( \alpha \approx (1/m^*E_g) \) and \( \mu_e \approx (1/m^*) \) (\( E_g \): band gap). We have carried out MBE growth of the heterostructure confining 2DEG at InGaSb/InAlSb interface on GaAs substrates via thick undoped InAlSb buffer. The layer structure of the heterojunction is shown in Fig. 1 with some growth conditions. The thicknesses of 1, 2, 4 and 6 \( \mu m \) are examined for the InAlSb buffer. Fig. 2 displays temperature dependences of \( \mu_e \) (left panel) and \( N_s \) (right panel) for the four kind samples with different InAlSb buffer layer thicknesses. As seen in the figure, we have obtained electron mobility of \( \mu_e \approx 1.2 \times 10^5 \) cm\(^2\)/Vs for sheet electron density of \( N_s \approx 2.7 \times 10^{11} \) cm\(^2\) at ~4 K in the sample of 6 \( \mu m \) thick InAlSb buffer. Those values are almost comparable with the result reported [9] recently by Oklahoma University group.

We have then estimated Rashba-type SO interaction in this material system. Fig. 3 shows a typical magnetoresistance up to 4 Tesla (T) measured at 1.6 K in the directed Hall bar sample with 6 \( \mu m \) buffer. As is expected from the narrow-gap nature, the 2DEG effective mass is very light: the standard cyclotron resonance experiment has given 0.023 \( m_0 \) as the \( m^* \) value at \( \epsilon_F \) in this heterojunction 2DEG. As a result, Zeeman splitting of the \( R_{xx} \) peak is appearing from as low as 1 T. The assignments of Landau indices \( n \) for the \( R_{xx} \) peaks and of filling factors \( \nu \) for the \( R_{xy} \) steps have been done as shown in the figure. The clearness of the quantum Hall plateaus suggests the high structural qualities of the heterojunction samples. Although the fine structure in the low field range is not seen in this figure, some beating pattern should be observed, if

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**Fig. 1.** Layered structure of MBE grown InGaSb/InAlSb modulation-doped heterojunction. The substrate is GaAs and a thick InAlSb buffer is used.

**Fig. 2.** Temperature dependences of electron mobility and sheet electron density of the 2DEG formed at the heterojunction shown in Fig. 3. For the samples with InAlSb buffer thicker than 2 \( \mu m \), the 2D-like transport nature was confirmed.
the Rashba SO interaction is really enhanced in this heterojunction 2DEG. Fig. 4 shows an enlarged trace of $R_{xx}$ as a function of $1/B$ in the low field ($B$) region (left panel) and a corresponding fast Fourier transform (FFT) result (right panel). As is expected, the beating oscillation is indeed observed in $R_{xx}$ (vertical arrows are likely denoting the nodes of the beat) and the period of the nodes are found to be ~0.67 (1/T). The main peak in the FFT spectra was found to split into two peaks located at 5.5 and 7 (T). The difference between the magnetic fields almost corresponds to the inverse of 0.67 (1/T), which is obtained from the beat analysis. So that, those two peaks are likely concluded to be due to the Rashba splitting in this material system. If we use the value of $m^*_{Z0.023 m_0}$ mentioned above, we can estimate the $\alpha$ value of $\approx 40 \times 10^{-12}$ eV m, if the following equation is assumed:

$$\alpha = \frac{\hbar e}{4\pi m^*k_f}\left(\Delta l/\Delta(B^{-1})\right)$$

$i$: beat node number,

where 2DEG Fermi wavelength $k_f = (2\pi N_s)^{1/2}$. This value corresponds to the spin-splitting at $\epsilon_f$ of $\Delta \epsilon = 2\alpha k_f = 8$ meV. Those values are almost comparable to those in the former high-In-content InGaAs/InAlAs heterojunction 2DEG, although a large enhancement of $\alpha$ would be expected from the rough expectation. The optimization of the growth process is, however, not attained yet, so that the values of $\alpha$ as well as the electron mobility could be improved in the near future.

3. Study of spin-orbit interaction in long wires with side-gates

Control of Rashba-type SO interaction by the side-gate voltage is very much interesting, since that could be the basis to develop quantum bit devices based on the spin-FET described above. For example, in the dual-gate device [8], we are able to make two different axes of effective magnetic field, $B_{eff}$ = $B_{z}$ ($v$: electron velocity), each originating from the different directed electric field ($E$) due to the dual gates. In such a case, we can rotate electron spins in any spatial directions, which means the fundamental realization of quantum mechanical superimposed state by the traveling spins. By using self-align technique, we made long (initial structure width, $w \approx 2 \text{ mm}$ and length between the voltage probes, $l \approx 20 \mu m$) four-terminal wires having the side-gates with a very short air gap (400 nm) as shown in Fig. 5. We then estimated SO coupling constant $\alpha$ from the longitudinal magnetoresistance oscillation observed in low magnetic field [11]. Transport regime of the wire is thus diffusive, but the width of the wire even for the deepest applied side-gate voltage is still wide (estimated to be $\sim 1 \mu m$) and hence the transport regime is regarded to be still 2D. So that, the universal conductance fluctuations (UCFs) do not appear in those wires. The estimation of $\alpha$ is done by measuring low-field magneto-resistances with voltage pairs applied to the two side-gates as parameters. Fig. 6 shows the dependencies of four-terminal resistance, $R$, sheet electron density, $N_s$, estimated from the SdH oscillation and the value of $\alpha$ upon the pairs of the two gate voltages ($V_{SG1}$ and $V_{SG2}$) applied to the side-gates. $R$ and $N_s$ are found to increase...
monotonically with increasing $V_{SG1}$ and $V_{SG2}$ and reveals no
dependency on the asymmetry or the difference between
$V_{SG1}$ and $V_{SG2}$. However, in the low gate voltage pairs
(region a in right panel in Fig. 6), $\alpha$ is found to change
depending on the asymmetry between the gate-voltages,
$V_{SG1}$ and $V_{SG2}$, that is, $\alpha$ takes a minimum when
$V_{SG1} \sim V_{SG2}$. On the other hand, in the high gate voltages
(region b), $\alpha$ increases monotonically with increasing the gate-voltages
and shows no dependency on the asymmetry between $V_{SG1}$
and $V_{SG2}$.

We can understand the result as follows: When the side-
gate voltages are applied to the 2DEG channel, we need to
imagine two different electric fields acting on the 2DEG;
One is the horizontal electric fields acting over the air-gap,
$E_{HSG} = V_{HSG} d$ ($i = 1, 2$ and $d$ is the gap distance between
the 2DEG and the side-gate edge), and another is the vertical
electric field acting via the substrate,
$E_{VSG} = V_{VSG} d^0$ ($i = 1, 2$ and $d^0$ is the effective distance between the 2DEG and
the side-gate via the substrate). Since generally $d \ll d^0$,
$E_{HSG} \gg E_{VSG}$. So that, in the low gate voltage region
(the upper-right triangle in the right panel of Fig. 6),
horizontal electric fields likely play a relatively important
role to control the SO interaction in the channels and the
horizontal electric fields originated from $V_{SG1}$ and $V_{SG2}$,
$E_{SG1} = V_{SG1} d$ and $E_{SG2} = V_{SG2} d$ have the same strength
with opposite directions, when $V_{SG1} \sim V_{SG2}$. In such a case,
the vector summation of those two horizontal electric fields
becomes almost zero and the Rashba effect originated from
the horizontal electric field might reach a minimum value.
In contrast, in the high gate bias region (the lower-left
triangle), the situation of $E_{HSG} < E_{VSG}$ could be realized
due to the relatively high permittivity ($\varepsilon_r$) of the substrate
($\varepsilon_r \sim 12$ for GaAs, almost one order larger than that of air). In
this case, the effect of horizontal electric field might be
almost masked by the large effect of vertical electric field. In
other words, this situation is very much resemble to that in
the SO interaction in the back-gated 2DEGs. This picture
could be the origin of the monotonic increase of $\alpha$ in
the left-lower region (region b) in the $\alpha$ mapping in Fig. 6.
Those explanations are now examined further by the
calculation of electric field distribution around the channel
based on the finite element method (FEM).

The $\alpha$ dependencies on the pairs of side-gate voltages are
able to be compared and discussed with the recent work.
Rare but interesting result of $\alpha$ behavior in the narrow
channel has recently reported by Schaeppers et al. [12]. They
also observed the increase of $\alpha$ when the channel is
squeezed. But the reason seems not clear at present, since
they have adopted ‘lapped’ gate to the 2DEG channel. The
effects of the lapped gate are likely somewhat complicated,
if we consider the above discussion. Another interesting
work is proposed theoretically for the channels with
parabolic horizontal confinement [13]. They have defined
the SO coupling constant $\beta$ due to the lateral confinement
and obtained the rough estimation of $\beta \sim 0.1 \alpha$. This result
suggest that the magnitude of ‘horizontal’ spin-orbit
coupling is very much weak when compared to ‘vertical’
one. This seems to agree well qualitatively with the result
obtained here.

4. Summary

We have described two recent results which could have
important meanings in the progress of semiconductor
Rashba spintronics. First, we have succeeded to grow
the new kind narrow-gap heterojunction, high In-content
InGaSb/InAlSb system. The 2DEG accumulated at the
interface revealed a high electron mobility as well as large
SO coupling constant both comparable to the values in the
former materials. This means the creation of new materials
suitable for studying and developing Rashba spintronics.
Second, we have investigated the behaviors of spin-orbit
coupling constant in the diffusive long channel with

![Fig. 6. Typical result of four terminal resistance ($R$), sheet electron density ($N_s$) and SO coupling constant $\alpha$ as a function of pairs of side-gate voltages, $V_{SG1}$ and $V_{SG2}$. Note that the $\alpha$ dependency is different in between the region a and b.](image-url)
the side-gates. In the low gate bias conditions, the effect of horizontal electric field still dominates the SO interaction and the $\alpha$ minimum is confirmed when the two opposite side-gate voltages are balanced. In the high gate bias conditions, however, the effect of vertical electric field acting via the high permittivity substrate plays a dominant role and thus result in a monotonic increase of $\alpha$ against deeper side-gate voltages. This seems to coincide with the rough estimation of cross-sectional electric field distribution around the channel and/or the recent theory [13].

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