Spin splitting in InGaSb/InAlSb 2DEG having high indium content

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Abstract

We formed a novel metamorphic InGaSb/InAlSb two-dimensional electron gas (2DEG) having high indium contents around 0.9 by molecular beam epitaxy (MBE), and investigated its spin splitting through magneto-resistance (MR) characteristics by using Hall-bar samples. We observed clear Shubnikov-de Haas (SdH) type MR oscillations with some peak splitting induced by the Zeeman-like spin splitting over B=1 T at 1.5K. An Estimated splitting energy, ΔE, was 9 meV at B=4 T for the Landau index, n=1. Moreover, we also observed no peak splitting, i.e. spin split vanishing around B=1 T. Additionally, we confirmed some SdH beat patterns due to the zero-field spin splitting less than B=1 T, and the splitting energy at B=0, ΔE_0, was estimated to be 4~6 meV from the SdH fast Fourier transform (FFT) analysis. We successfully demonstrated well fitting curves for the Landau plots of SdH peaks across B=1 T, thus the Zeeman-like splitting, the spin split vanishing, and the beat patterns due to the zero-field splitting can be connected, smoothly. The fitting curves were obtained by assuming not the Rashba effect but the Dresselhaus effect on the (001) surface with the confinement. Therefore, it suggests that the zero-field spin splitting in the present InGaSb/InAlSb 2DEG originates from the Dresselhaus effect.

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1. Introduction

Narrow gap semiconductor (NGS) two-dimensional electron gases (2DEGs) are applicable to non-magnetic semiconductor spin devices, e.g. the spin field effect transistors (spin-FETs) proposed by Datta and Das [1], because such NGS-2DEGs are possible to show large zero-field spin splitting [2-5], which is necessary to control spin polarized electrons in the spin-FETs. Previously, we have formed metamorphic InGaAs/InAlAs 2DEGs with high indium contents over 75% [6], and have investigated their transport properties including some spin splitting [7-8]. Our 2DEGs have high mobility (μ~4×10^5cm^2/Vs) and large SO interaction (α~3×10^{-11}eVm) at low temperatures.

In this work, we have formed and investigated a novel metamorphic InGaSb/InAlSb 2DEG having indium contents around 0.9, which is another important candidate of NGS-2DEGs.

2. Experimental procedure

Figure 1 shows schematic illustrations of the InGaSb/InAlSb 2DEG structure. We grew the 2DEG on a semi-insulating GaAs (001) by a conventional molecular beam epitaxy (MBE) with a Sb cracker cell. The indium contents for the InGaSb and the InAlSb were fixed to 0.89 and 0.88, respectively. To reduce threading dislocations, a 6µm-thick InAlSb buffer layer was grown on the GaAs, directly. The thickness of the InGaSb channel layer was 30 nm, and the depth of the 2DEG interface was about 160 nm. The detail of the MBE growth and the influence of the threading dislocations will be discussed elsewhere [9].

After the growth, we fabricated some Hall-bar samples by using conventional photolithography techniques. The channel width was 50 µm, and the probe distance was 200µm. The channel directions were defined to [110], [-110] and [010] for the investigation of some transport anisotropy. By using the Hall-bar samples, we measured magneto-transports at 1.5K in a liquid He cryostat with a superconducting magnet. For the measurements, we used an AC lock-in setup. The typical current was 100 nA.

3. Experimental results and discussions

We summarized the sheet electron concentration N_S and the mobility μ for various channel directions in Table 1, which were estimated from Hall measurements at magnetic field B=0.3 T. Sometimes there is a large mobility anisotropy (almost twice) in such metamorphic 2DEGs [10], however, the mobility anisotropy in our present 2DEG was 13% i.e. not so large. Additionally, the sheet electron concentration was almost similar value around 2.7×10^{11}cm^{-2}. Therefore, the results indicate that our present 2DEG has high quality.

Figure 2 shows a magneto-resistivity (MR) ρ_{xx} curve and Hall-resistivity ρ_{xy} curve of the [110] channel sample as a function of magnetic fields. We observed the Zeeman-like splitting in ρ_{xx} and some quantum Hall plateaus in ρ_{xy} over B=1 T, which corresponded to the Landau index n<5. We note that the samples with other channel directions showed similar behavior, i.e. almost isotropic properties. The spin splitting energy ΔE at B=4 T was estimated to be about 9 meV from the Zeeman-like splitting for n=1. Such large value indicates that our present 2DEG has a large effective g factor. Moreover, we could not observe clear Zeeman-like splitting for n=5-7 around B=1 T. Thus the spin splitting seemed to be vanished around B=1 T.

In order to investigate the detail of the MR under low magnetic fields, we analyzed the second derivative of MR oscillations at B<1 T as shown in Fig. 3. We could observe a small splitting of peak for n=6, however, could not find such peak splitting for n=7-8. Under lower magnetic fields i.e. n>8, we could find some beating patterns of the MR amplitude. The amplitude modulation can be understood as the zero-field spin splitting. Through the fast Fourier transform (FFT) analysis [5, 7-8], we obtained that the zero-field spin splitting energy was estimated to be ΔE_0=4~6 meV.

In order to understand the connection of the spin splitting between the Zeeman dominant region and the zero-field dominant region, we plotted the Landau index with two kinds of fitting curves as a function of inverse magnetic fields B^{-1} as shown in Fig. 4. The fitting curves were calculated by assuming two kinds of inversion asymmetry effects as follows; one is the Rashba effect, and the other is the Dresselhaus effect. We neglected the contribution of k_F^3 term (k_F: the Fermi wave vector), which was not dominant at the present, therefore we considered the Dresselhaus effect only on the (001) surface with the 2DEG confinement. The Hamiltonian and the zero-field spin splitting energy for the Rashba effect [2-4] are written as

$$H_R=\alpha(\sigma_x k_y-\sigma_y k_x), \tag{1}$$

$$\Delta E_0=2\alpha k_F, \tag{2}$$

and those for the Dresselhaus effect [3] are written as

$$H_D=\beta(\sigma_y k_y-\sigma_x k_x), \tag{3}$$

$$\Delta E_0=2\beta k_F. \tag{4}$$

α and β are the SO coupling parameters. σ_x and σ_y are the Pauli spin matrices. k_x and k_y are the wave vector components in the 2DEG plane. By using the ΔE_0, the spin split Landau levels $E_{n\pm}$ including SO interaction can be described as

$$E_{n\pm}=\hbar\omega_c(n\pm\tfrac{1}{2}\,((1-v_0)^2+n\Delta E_0^2/E_F\hbar\omega_c)^{1/2}) \quad (5)$$

for the Rashba effect and

$$E_{n\pm}=\hbar\omega_c(n\pm\tfrac{1}{2}\,((1+v_0)^2+n\Delta E_0^2/E_F\hbar\omega_c)^{1/2}) \quad (6)$$

for the Dresselhaus effect, where

$$\omega_c=eB/m^*, \quad (7)$$

$$v_0= gm^*/2m_0. \quad (8)$$

E_F is the Fermi energy, which can be estimated from N_S and the effective mass m^*. g is the bulk g factor, and m_0 is the electron mass. For the calculation of the fitting curves, we used N_S and ΔE_0 values estimated from the FFT analysis of low magnetic field properties. m^* was assumed to be $0.023m_0$, which was estimated from the cyclotron resonance absorption experiment [11], and g was assumed to be -51 of bulk InSb value. The fitting curves assuming the Rashba effect (dash lines) have no crossing, and do not fit the experimental results. In contrast, the fitting curves assuming the Dresselhaus effect (solid lines) have a crossing point, and fit the experimental results very well from high magnetic fields to low magnetic fields. The fact indicates that the dominant zero-field spin splitting should be not the Rashba effect but the Dresselhaus effect in the present InGaSb/InAlSb 2DEG. However, underlying mechanism is not well understood. The present results also suggest that it is possible to obtain zero-field spin splitting energy ΔE_0 from high magnetic field properties, i.e. the transition of Zeeman-like spin splitting without beat pattern analysis, which is widely carried out [2-5, 7-8].

4. Summary

We formed a novel metamorphic InGaSb/InAlSb 2DEG having indium contents around 0.9, and characterized its spin splitting through a MR measurement. We observed clear SdH oscillations with some peak splitting induced by the Zeeman-like spin splitting over B=1 T, no peak splitting i.e. vanishing spin splitting around B=1 T, and some SdH beat patterns due to the zero-field spin splitting less than B=1 T. By assuming the Dresselhaus type zero-filed spin splitting, we successfully demonstrated the smooth transition between the Zeeman effect and the Dresselhaus effect.

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References

[1] S. Datta and B. Das, Appl. Phys. Lett. 56 (1990) 665.
[2] J. Luo, H. Munekata, F. F. Fang, P. J. Stiles, Phys. Rev. B 41 (1990) 7685.
[3] B. Das, S. Datta, R. Reifenberger, Phys. Rev. B 41 (1990) 8278.
[4] J. Nitta, T. Akazaki, H. Takayanagi, T. Enoki, Phys. Rev. Lett. 78 (1997) 1335.
[5] Th. Schäpers, G. Engels, J. Lange, Th. Klocke, M. Hollfelder, H. Lüth, J. Appl. Phys. 83 (1998) 4324.
[6] S. Gozu, C. Hong, S. Yamada, Jpn. J. Appl. Phys. 37 (1998) L1501.
[7] Y. Sato, T. Kita, S. Gozu, S. Yamada, J. Appl. Phys. 89 (2001) 8017.
[8] T. Kita, Y. Sato, S. Gozu, S. Yamada, Physica B 298 (2001) 65.
[9] T. Sato, T. Suzuki, S. Tomiya, S. Yamada, “Dislocation-limited electron transport in InSb and InGaSb/InAlSb grown on GaAs(001)”, The 23rd International Conference on Defects in Semiconductors, to appear (2005).
[10] T. D. Mishima, J. C. Keay, N. Goel, M. A. Ball, S. J. Chung, M. B. Johnson, M. B. Santos, J. Cryst. Growth 251 (2003) 551.
[11] K. Fujii, Y. Hachizawa, K. Ohnishi. T. Sato, T. Suzuki, S. Yamada, S. Gozu, “Investigation of electron spin states in InGaAs/InAlAs and InGaSb/InAlSb heterostructures”, Proceedings of 12th International Conference on Narrow Gap Semiconductors, to appear (2005).

Table 1. The sheet electron concentration and the mobility for various channel directions estimated from Hall measurement at 1.5K.

Channel direction	Sheet electron concentration N_S(cm^{-2})	Mobility μ(cm^2/Vs)
[110]	2.81×10^{11}	88200
[-110]	2.62×10^{11}	98600
[010]	2.71×10^{11}	97600

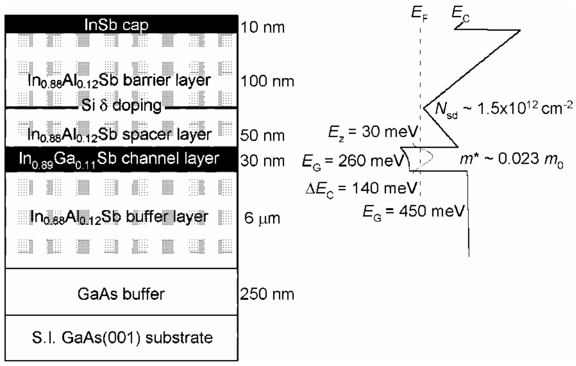

Fig.1. Layer and band structures of the InGaSb/InAlSb two-dimensional electron gas wafer.

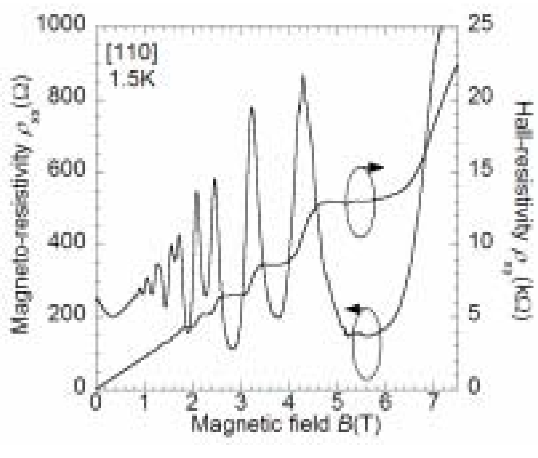

Fig. 2. Magneto-resistivity and Hall-resistivity curves of a [110] channel Hall-bar as a function of magnetic fields.

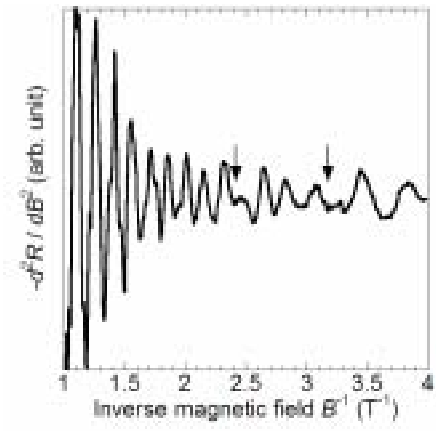

Fig. 3. Second derivative curve of magneto-resistivity as a function of inverse magnetic fields.

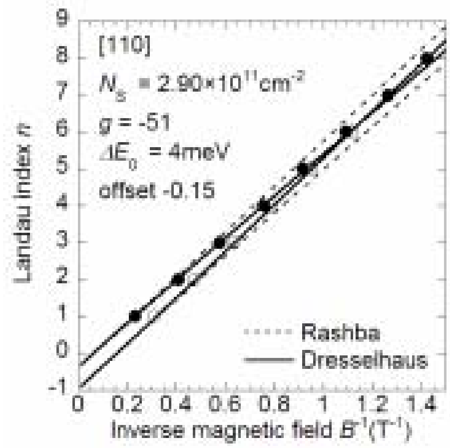

Fig. 4. Landau plots of magneto-resistivity peaks. Solid lines indicate the fitting curves assuming the Dresselhaus effect, and dashed lines indicate the fitting curves assuming the Rashba effect.