E-5-3
Extended Abstracts of the 2013 International Conference on Solid State Devices and Materials, Fukuoka, 2013, pp786-787

Landau Level Crossing and Anti-crossing of Bilayer Two-dimensional Hole Gas in Ge/SiGe Quantum Well

Rai Moriya[1], Yusuke Hoshi[2,3], K. Sawano[2], Y. Shiraki[2], N. Usami[3], S. Masubuchi[1,4], and T. Machida[1,4]

[1] Institute of Industrial Science, University of Tokyo
4-6-1 Komaba, Meguro, Tokyo 153-8505, Japan
Phone: +81-3-5452-6158 E-mail: moriyar@iis.u-tokyo.ac.jp
[2] Advanced Research Laboratories, Tokyo City University
8-15-1 Todoroki, Setagaya-ku, Tokyo 158-0082, Japan
[3] Graduate School of Engineering, Nagoya University
Furo-cho, Chikusa-ku, Nagoya, 464-8603, Japan
[4] Institute for Nano Quantum Information Electronics, University of Tokyo
4-6-1 Komaba, Meguro, Tokyo 153-8505, Japan

Abstract

A Hole gas in strained Ge has been received much attention for the transistor applications owing to its superior charge transport characteristics. However it is less known about its spin related properties such as *g*-factor and spin orbit interaction. To study these, we performed detailed angular dependent magneto transport measurement on single-layer (SL) and bi-layer (BL) two-dimensional hole gas (2DHG) in strained Ge/$Si_{0.35}Ge_{0.65}$ quantum well. We observed LL crossing in BL-2DHG, whereas no level crossing has been observed in SL-2DHG. The hole *g*-factor determined from the coincidence of LL suggest *g*~38 in BL-2DHG, which is more than an order of magnitude larger than SL-2DHG. We also observed LL anti-crossing at the third LL coincidence condition. We attribute this is due to the spin orbit coupling (SOC) of the 2DHG. From the low field magneto resistance measurement, a weak anti-localization (WAL) is observed. By analyzing the WAL data, we found cubic-Rashba term is dominant SOC contribution in Ge 2DHG system. These results reveal exotic spin related properties of 2DHG in Ge QW and the potential for the applications of spintronics.

1. Introduction

Recent development of crystal growth technology enable us to fabricate high mobility two-dimentional hole gas (2DHG). Particularly, the 2DHG in strained Ge is remarkable since it reveals large hole mobility and small effective mass almost comparable to that of electron. However, there have been only few studies on the quantum Hall effect (QHE) and its angular dependence of 2DHG in strained Ge/SiGe quantum well (QW). Since heavy hole of Ge does not couple with in-plane magnetic field, it was not possible to observe Landau level (LL) crossing of this material with a tilted magnetic field. Here we show, by using bilayer 2DHG in Ge/SiGe QW, clear LL level crossing and anti-crossing can be observed.

2. Experimental methods

A device structure used in this experiment is schematically shown in Fig. 1(a). A QW consist of 20 nm $Si_{0.35}Ge_{0.65}$/20 nm Ge/20 nm $Si_{0.35}Ge_{0.65}$ is grown on $Si_{0.35}Ge_{0.65}$/graded SiGe/Si(001) virtual substrate by using a combination of gas-source and solid-source molecular beam epitaxy (MBE)[1]. By introducing *p*-type doping on the top and bottom side of QW, BL-2DHG is created in the well. When we introduce *p*-type doping only one side of the QW, a SL-2DHG is obtained. A sheet hole density of the BL-2DHG is 6.0×10^{11} and 7.3×10^{11} cm^{-2}, respectively, determined by Shubnikov-de Haas oscillation (SdHO), and a mobility is 35,000 cm^2/Vs. A Hall resistance R_{xy} and longitudinal resistance R_{xx} is measured either in the dilution refrigerator at 50 mK or in the variable temperature crystat at 1.6 – 10 K. The external magnetic field is applied with superconducting magnet and by using a sample rotator, the direction of the field is changed.

3. Results and discussion

The R_{xy} and R_{xx} of bilayer 2DHG measured at 50 mK under the magnetic field $B_\perp$ perpendicular to the sample is shown in Fig. 1(b). It revealed clear signature of QHE. Resistance minima appeared at the LL filling factor ν =(4N+2) because of the bilayer QHE, whereas resistance minima appeared at ν =2N in SL-2DHG(not shown). Angular dependence of the R_{xx} is measured and results for BL-2DHG are shown in Fig. 2(a). The angular dependence reveal pronounced change of R_{xx}. A sequential change in between peak and dip structure of the R_{xx} can be seen. We plot the R_{xx} versus 1/cosθ at each filling ν as shown in Fig. 2(b). R_{xx} periodically changes with respect to 1/cosθ; this is a piece of evidence that the observed angular dependence is due to the LL crossing. At the peaks and dips in R_{xx} in the Fig. 2(b), LL crossing take place and coincident condition $\hbar\omega_c = ng\mu_B B_{total}$ (*n*: positive integer) is satisfied. Where, $\hbar\omega_c$ is cycron energy and $g\mu_B B_{total}$ is Zeeman energy. Up to three-times of the crossing was observed within our measurement range. This is very distinct from SL-DHG, where LL crossing was not observed within the same field range. From the coincident condition the *g*-factoer of the BL-2DHG is determined as *g*~40. Note that from the temperature and angular dependence of low field SdHO, we revealed that variation of hole effective mass and symmetric anti-symmetric splitting energy of the BL-2DHG is small during LL crossing; thus these factor only gives minor contribution on the determination of *g*-factor.

In Fig. 2(a), the R_{xx} does not show peak structure when $\nu = 16$ and 20, and $\theta = 58.4°$, although these satisfy LL crossing condition. After detailed examination of the angular dependence, we found this is due to the anti-crossing of the LLs[2]. LL anti-crossing can be observed when there is a large spin orbit coupling (SOC). To clarify this, we measured low field magneto resistance and results are shown in Fig. 3. A positive magneto resistance is observed around zero magnetic fields. We think this is due to the weak anti-localization (WAL) of the 2DHG. The WAL is analyzed with theory based on Rashba spin orbit coupling (SOC)[3]. We found WAL data is explained very well with cubic-Rashba SOC, consistent with the symmetry of heavy hole band structure of the Ge. The WAL provide more evidence of the LL anti-crossing due to the SOC.

4. Conclusions

We demonstrated LL crossing and SOC-driven LL anti-crossing of high mobility BL-2DHG in strained Ge/SiGe QW. We also demonstrated large enhancement of *g*-factor in BL-2DHG. These results indicate the potential of 2DHG in Ge for spintronics applications.

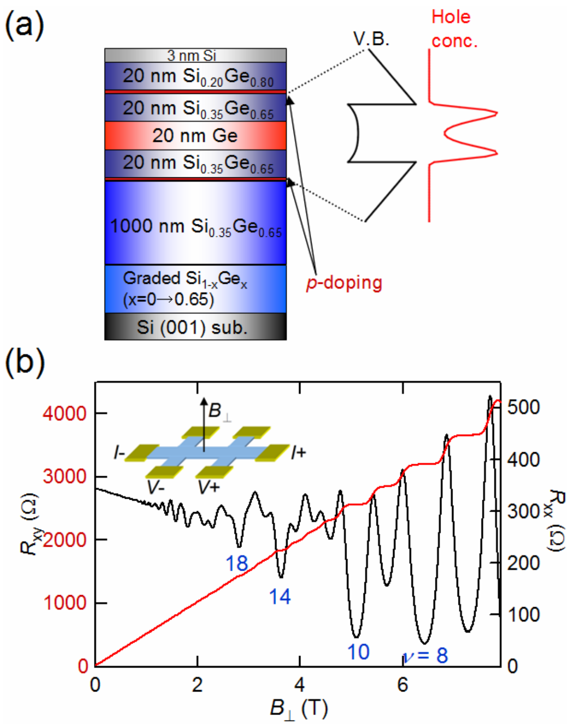

Fig. 1 (a) Device structure of Ge/SiGe quantum well. Valence band (V.B.) profile and hole carrier concentration in the QW is calculated by numerical calculation and shown together. (b) Perpendicular magnetic field dependence of longitudinal resistance (R_{xx}) and Hall resistance (R_{xy}).

Acknowledgements

This work is supported by the Special Coordination Fund for Promoting Science and Technology.

References

[1] K. Sawano, Y. Abe, H. Satoh, K. Nakagawa, and Y. Shiraki, Jpn. J. Appl. Phys. 44, L1320 (2005).

[2] W. Desrat, F. Giazotto, V. Pellegrini, M. Governale, F. Beltram, F. Capotondi, G. Biasiol, and L. Sorba, Phys. Rev. B 71, 153314 (2005).

[3] H. Nakamura, T. Koga, and T. Kimura, Phys. Rev. Lett. 108, 206601 (2012).

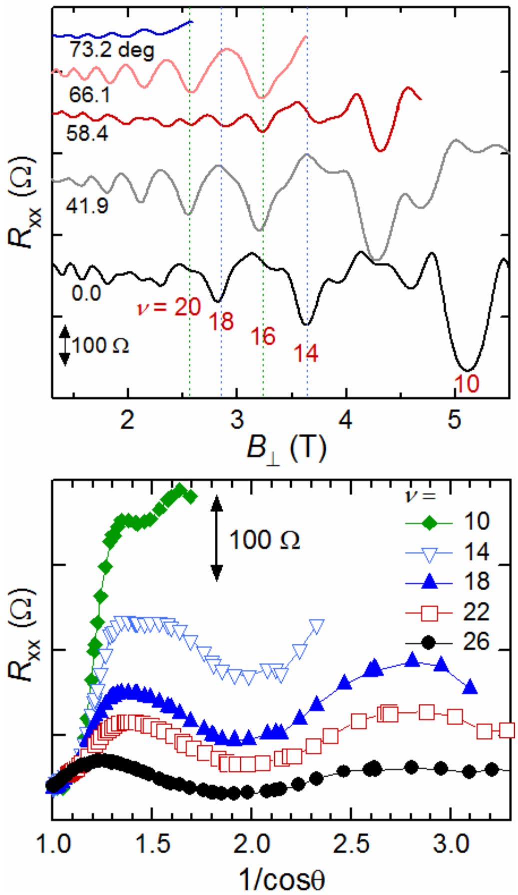

Fig. 2 (a)Angular dependence of R_{xx}. (b) R_{xx} vs. $1/\cos\theta$ of the angle of external magnetic field at various filling factor ν.

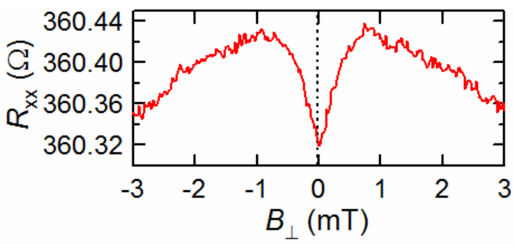

Fig. 3 Low field magneto resistance measured at 1.6 K.