Quantum Hall Effect in Semiconductor Superlattice in a Tilted Magnetic Field

Minoru Kawamura [a,*], Akira Endo [a], Shingo Katsumoto [a,b], Yasuhiro Iye [a,b], Chieko Terakura [c], Shinya Uji [c]

[a] *Institute for Solid State Physics, University of Tokyo, 5-1-5, Kashiwa-no-ha, Kashiwa, Chiba 277-8581, Japan*

[b] *CREST, Japan Science and Technology Corporation, 1-4-25, Mejiro, Toshima-ku, Tokyo 171-0031, Japan*

[c] *National Research Institute for Metals, 3-13 Sakura, Tsukuba, Ibaraki 305-0003, Japan*

Abstract

The vertical transport in multilayered quantum Hall systems has been studied under a tilted magnetic field. The out-of-plane resistance takes a peak value at integer filling, and the peak value increases with increasing in-plane field component. The effect is found to be similar in magnitude between the low temperature surface transport regime and the high temperature bulk transport regime, and can be accounted for by suppression of interlayer transfer by the in-plane field.

Key words: quantum Hall effect, vertical transport, tilted magnetic field, chiral surface state
PACS: 73.40.Hm, 73.20.Dx

Multilayered quantum Hall system has attracted much interest, following the theoretical prediction of chiral surface state [1,2]. A single layer two-dimensional electron gas (2DEG) exhibits the quantum Hall effect (QHE) when it is placed in a strong perpendicular magnetic field. The integer QHE in a single layer 2DEG is described in terms of the edge channel. In the quantum Hall state, all the bulk states at the Fermi energy are localized so that the Hall current is carried by the edge channels. These edge channels are free from backscattering because of their chirality. In a multilayered 2DEG system, weak interlayer transfer between the edge channels in adjacent layers leads to formation of a conducting surface sheath. The existence of such conducting sheath at the surface of a multilayered quantum Hall system has been experimentally demonstrated[3]. One of the most interesting aspects of this novel conducting state is that the localization (interference) effect is suppressed by its chiral nature. As the temperature is increased, interlayer hopping through the bulk states starts to contribute to the vertical conduction. The surface conductivity of the surface state depends on many parameters such as the interlayer transfer integral t, the edge velocity v and the elastic scattering length $l_{\rm el}$. It has been proposed[4] that one may be able to extract the value of the elastic scattering length from the transverse mag-

* Corresponding author.
E-mail address: minoru@issp.u-tokyo.ac.jp

netoresistance of the chiral surface state. According to their theory, the transverse magnetoresistance of the chiral surface state is given in the following Drude-like form,

$$\sigma(B_{\|}) = \frac{\sigma(B_{\|}=0)}{1+\left(B_{\|}/B_0\right)^2}. \qquad (1)$$

Here, $B_{\|}$is the field component parallel to the layer and perpendicular to the conducting surface, and $B_0 = \Phi_0/dl_{\mathrm{el}}$, where $\Phi_0 = h/e$ is the flux quantum and d is the interlayer spacing.

Another possible source of the transverse magnetoresistance is the reduction of the interlayer transfer integral by the in-plane magnetic field[6]. As for the latter mechanism, the in-plane magnetic field affects not only the interlayer transfer between the edge channels but also that between the bulk states. Therefore the effect of the reduction of the interlayer transfer is expected to appear not only in the low temperature limit but also in the higher temperature region where most of the vertical transport current flows through the bulk states.

In this work, we have studied the effect of the in-plane magnetic field on the vertical transport in the multilayered quantum Hall system.

GaAs/$Al_{0.15}Ga_{0.85}As$ semiconductor superlattice wafers were grown by molecular beam epitaxy. The superlattice part consisted of 100 units of a 10 nm wide GaAs well layer and a 15 nm wide AlGaAs barrier layer. The central 5 nm of each AlGaAs layer was doped with Si donors. The relatively low Al content was chosen for the barrier layer to achieve a sufficiently large interlayer transfer integral. For the vertical transport measurements, square columnar mesas were fabricated by photolithography and wet etching. Four mesas with different cross-sections of 50 × 50 μm^2, 100 × 100 μm^2, 200 × 200 μm^2 and 400 × 400 μm^2 were fabricated. The details of the sample

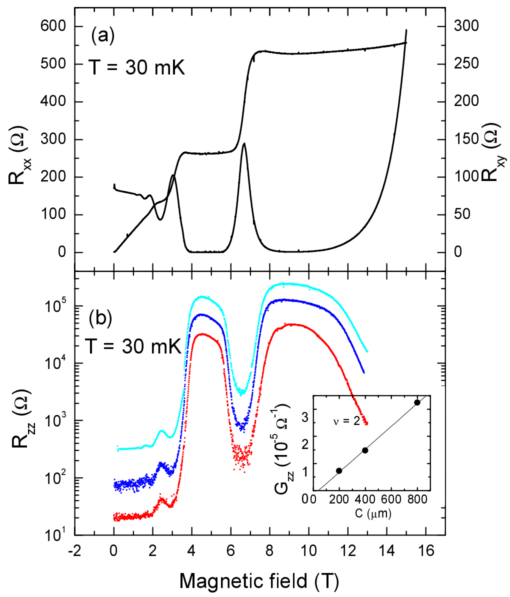

Fig. 1. (a) Magnetic field dependence of the in-plane resistance R_{xx} and the Hall resistance R_{xy}. (b) Magnetic field dependence of the out-of-plane resistance R_{zz} in three samples with cross-sections, 50 × 50, 100 × 100 and 200 × 200 μm^2 (from top to bottom). The inset shows G_{zz} at $\nu = 2$ versus sample perimeter.

preparation is given elsewhere[5]. Magnetotransport measurement were carried out using a dilution refrigerator at temperatures down to 30 mK. The in-plane magnetic field was applied by tilting the sample in a 18 T superconducting solenoid. A standard ac lock-in technique was employed for the resistance measurements.

Figure 1(a) shows the magnetic field dependence of the in-plane resistance R_{xx} and the Hall resistance R_{xy} at $T = 30$ mK. From the lateral transport measurement, the sheet carrier density per layer and the mobility are determined as $n_{2\mathrm{D}} = 2.3 \times 10^{11}$ cm^{-2}/layer and $\mu = 6300$ cm^2/Vsec. The QHE is observed at filling factors $\nu = 2$ and $\nu = 1$. In Fig. 1(b), the magnetic field dependence

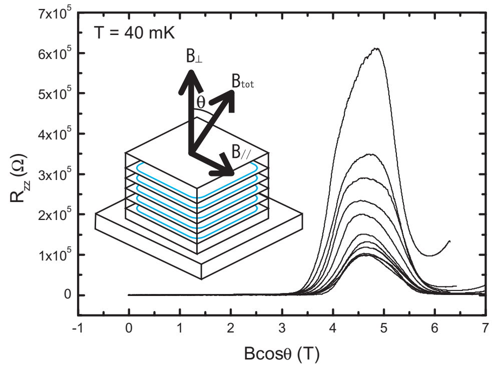

Fig. 2. Magnetic field dependence of R_{zz} for different tilt angles of the magnetic field at $T = 40$ mK. The tilt angle $\theta = 0$, 10, 15, 18, 25, 28, 33, 38, 44, 50, and 61 degree from bottom to top. The horizontal axis is the magnetic field component normal to the layer plane, $B_\perp = B\cos\theta$.

of the out-of-plane resistance R_{zz} is plotted for three mesas of different sizes, 50×50 μm^2, 100×100 μm^2 and 200×200 μm^2. At the magnetic field where the lateral transport shows QHE, R_{zz} becomes maximum. In the inset of Fig. 1(b), the size dependence of the out-of-plane conductance $G_{zz} = 1/R_{zz}$ at $\nu = 2$ is plotted. G_{zz} is proportional to the mesa perimeter C, suggesting that the vertical transport at $\nu = 2$ is dominated by the surface states at this low temperature.

Figure 2 shows the results of R_{zz} measurement under tilted magnetic fields. The tilt angle θ is defined with respect to the direction normal to the layer plane as shown in the inset of Fig. 2. The horizontal axis of Fig. 2 is the normal component of the magnetic field $B_\perp = B\cos\theta$. It is seen that the peak value of R_{zz} at $\nu = 2$ increases with increasing θ, or the in-plane field component $B_\parallel$.

Figure 3(a) shows the temperature dependence of R_{zz} at $\nu = 2$ for different tilt angles. Above 100 mK, R_{zz} shows an Arrhenius-type temperature dependence. R_{zz} in the high temperature regime is proportional to the sample cross-section, indicating that the dominant vertical transport is through the bulk states [3,5]. As temper-

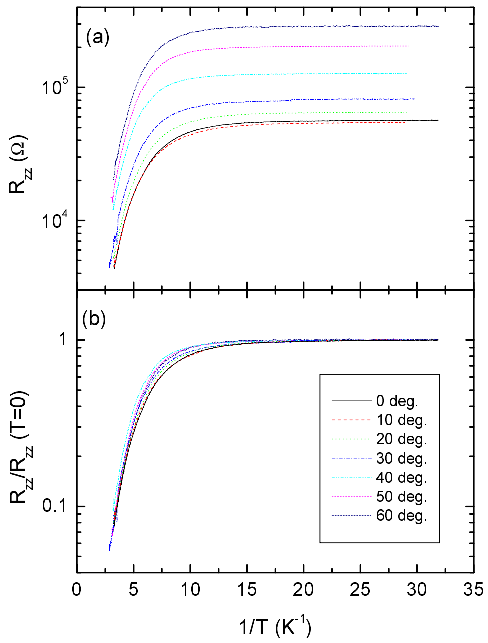

Fig. 3. (a) Temperature dependence of R_{zz} at $\nu = 2$ for several tilt angles. (b) The same set of data normalized by the value at the lowest temperature.

ature is decreased, R_{zz} tends to saturate. The size dependence of saturated value of R_{zz}below 100 mK, shown in the inset of Fig. 1(b), indicates that the current mainly flow at the surface state as stated earlier. With increasing tilt angle θ, R_{zz} increases both in high temperature bulk transport regime and in the low temperature surface transport regime. In Fig. 3(b), the same data normalized by the low temperature saturated value for each tilt angle are plotted. All the traces roughly collapse on a single curve. This means that the transverse magnetoresistance is similar in magnitude between the bulk transport and surface transport regimes. This fact suggests that the principal source of the magnetoresistance is the reduction of interlayer transfer by the in-plane magnetic field, and that semi-classical magnetoresistance of the chiral surface state as given by eq.(1) is of minor importance. This conclusion is further corroborated by the following comparison.

In Fig. 4, the transverse magnetoresistance normalized by $R_{zz}(\theta = 0)$ is plotted for two samples. Data for two representative temperatures, i.e. 250 mK (bulk transport regime) and 40 mK (surface transport regime) are shown. In the presence of the in-plane field component $B_{||}$, the interlayer transfer becomes

$$\tilde{t} = t \exp\left[-\frac{1}{4}\left(\frac{B_{||}}{B_{\perp}}\frac{d}{l_{B_{\perp}}}\right)^2\right] = t \exp\left(-\frac{d^2}{4l_{B_{\perp}}^2}\tan^2\theta\right), \qquad (2)$$

where $l_{B_{\perp}}$ is the magnetic length associated with the out-of-plane field component $B_{\perp}$. The vertical conductivity is expected to be proportional to $\tilde{t}^2$. The curve in Fig.4 shows $\exp\left(\frac{d^2}{2l_{B_{\perp}}^2}\tan^2\theta\right) - 1$ with the parameters $l_{B_{\perp}} = 12$ nm and $d = 25$ nm. It is seen that the experimentally observed angular dependence is reproduced by the theoretical curve with no adjustable parameters up to about $\theta = 30°$. The reason for the deviation at higher angles is not understood at the moment.

A similar experiment using a rectangular sample with a large aspect ratio was carried out by Druist *et al.*[7]. They found no significant dependence on the in-plane magnetic field direction, which is another piece of evidence that the semi-classical magnetoresistance is small.

In summary, we have studied the effect of in-plane magnetic field on the out-of-plane resistance of the multilayered quantum Hall systems. The magnetoresistance is same in the low temperature surface transport regime and the high temperature bulk transport regime. The major part of the measured transverse magnetoresistance can be attributed to the suppression of the interlayer transfer by the in-plane magnetic field, and the effect is similar in magnitude for the interlayer hopping through the bulk states and through the edge states.

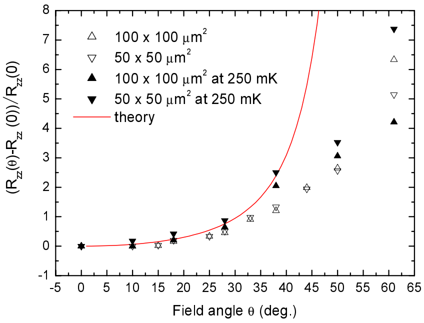

Fig. 4. The transverse magnetoresistance normalized by $R_{zz}(\theta = 0)$ is plotted for two samples. Data for two representative temperatures of 250 mK (bulk transport regime) and 40 mk (surface transport regime) are shown. The solid line shows $\exp\left(d^2/2l_{B_{\perp}}^2 \tan^2\theta\right) - 1$, with parameters $l_{B_{\perp}} = 12$ nm and $d = 25$ nm.

References

[1] J. T. Chalker and A. Dohmen, Phys. Rev. Lett. 75 (1995) 4496.

[2] L. Balents and M. P. A. Fisher, Phys. Rev. Lett 76 (1996) 2782.

[3] D. P. Druist *et al.*, Phys. Rev. Lett. 80 (1998) 365.

[4] J. T. Chalker and S. L. Sondhi, Phys. Rev. B 59 (1999)4999.

[5] M. Kawamura *et al.*, J. Phys. Soc. Jpn. 68 (1999) 2186.

[6] J. Hu and A. H. MacDonald, Phys. Rev. B 46 (1992) 12554, D. Yoshioka, J. Phys. Soc. Jpn. 64 (1995) 3168.

[7] D. P. Druist *et al.*, Physica E 6 (2000) 619.