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Magnetoresistance anomalies at level crossing in double layer quantum Hall systems

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Abstract

We have investigated magnetotransport behavior of a double quantum well system with weak interlayer tunneling. The scaling behavior of the localization property for the Landau levels associated with either layer is in agreement with earlier reports. For the case of Landau level coincidence between the two layers, an anomalous value of the exponent $\kappa \approx 0.50$ is observed. We have observed a peculiar resistance peak at $B \simeq 9$ T for which the corresponding Hall resistance remains unchanged on both sides of the resistance peak. Hysteretic transition has been found in the region of crossing of the LLs originating from different layers.
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1. Introduction

The quantum Hall effect in double layer two-dimensional electron gas (2DEG) systems has attracted much attention in recent years. The bilayer (pseudospin) degree of freedom introduces an extra complexity in the Landau level scheme in addition to the ordinary spin degree of freedom. Depending on the relevant parameter values, various situations of level scheme and crossing of the Landau levels can occur and they lead to novel electronic states dictated by interplay between the interlayer tunneling and the intra- and interlayer Coulomb interactions.

In the present work, we have investigated the magnetoresistance features of bilayer 2DEG systems in quantum Hall regime under asymmetric conditions where the electron densities of the two layers are off-balance.

2. Experimental

The sample used in this work is a gated GaAs/AlGaAs double quantum well structure consisting of two 20 nm thick GaAs quantum wells separated by a 5 nm thick $Al_{0.33}Ga_{0.67}As$ barrier. Carriers are supplied from the two Si delta-doping sheets, each of which is placed 10 nm away from the respective quantum well. The calculated symmetric-antisymmetric tunneling gap energy Δ_{SAS} is about 0.1 meV, but we could not resolve Δ_{SAS} experimentally because of the collision broadening. A front gate was used to control the carrier density.

Magnetotransport measurements were performed by a standard low-frequency lock-in technique at temperatures down to ∼30 mK and in magnetic fields

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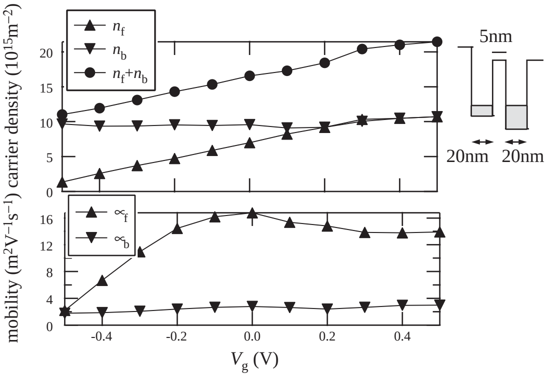

Fig. 1. The electron density and mobility in the front and back layers as a function of the front gate bias.

up to 15 T. Fig. 1 shows the characteristics of carriers in each of the two layers as a function of the front gate bias V_g, as determined from the Shubnikov–de Haas and Hall measurements. Here, n_f and μ_f (n_b and μ_b) represent the electron density and mobility in the front (back) layer. The relatively large barrier layer thickness and the asymmetric condition make the interlayer coupling unimportant except in the regions of level crossing.

The electron mobility in the back layer is rather low $\mu_b \approx 2$ m^2/Vs. The front layer mobility increases with n_f until it decreases in the region of $n_f \approx n_b$. This decrease in μ_f is attributed to formation of the resonant states [1]. The disparity of the mobility implies that the degree of disorder is substantially different for the two layers and the correlation between their potential landscape is minimal.

3. Results and discussion

Fig. 2 shows the magnetoresistance traces at various front gate biases ranging from −0.6 to 0.5 V. We can easily identify the Landau level (LL) peaks originating from the front layer 2DEG which shift with V_g and the peaks associated with the back layer which basically stay constant.

At a large negative bias ($V_g = -0.6$ V), the front layer is completely depleted and the system is reduced to a single layer. At a large positive bias ($V_g = 0.5$ V), the front and back layers are nearly equally populated. Although the LL peaks associated with the back layer do not shift much with V_g, there is a distinct S-shaped movement of the back layer peaks in the region between crossings with those of the front layer. This is attributed to interlayer charge redistribution which occurs so as to minimize the total energy [2].

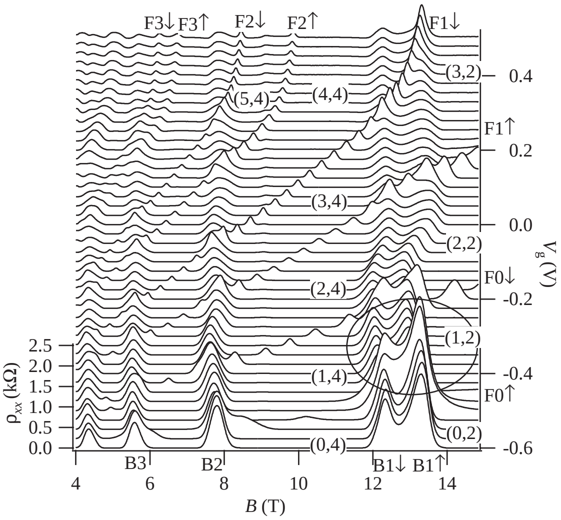

Fig. 2. Magnetoresistance data at various front gate biases. Quantum Hall states between the peaks are identified with a set of filling factors (ν_f, ν_b) of the front and back layers. The Landau level peaks are marked with the Landau level index and spin orientation as, for example, “F1 ↓” meaning the up-spin $N = 1$ LL in the front layer, and “B2” meaning the spin-degenerate $N = 2$ LL in the back layer.

Interesting features occur when the LLs of the two layers cross with each other. It is seen, for example, in the encircled region of Fig. 2 that when the F0 ↑ peak crosses with the B1 ↑ and B1 ↓, the width and height of the resistance peak becomes much larger than a simple superposition of the respective peaks. In regard to the localization phenomenon in bilayer quantum Hall system, Sørensen and MacDonald have proposed that even a weak interlayer tunneling can give rise to a dramatic increase in localization length when the disorder potentials of the two layers are uncorrelated [3]. The physical picture is that each time an electron tunnels into the other layer, it sees a different potential landscape so that it has a better chance of finding a different localized state when it tunnels back to the original layer.

In order to gain further insight on this point, we studied the temperature dependences of ρ_{xx} and ρ_{xy}. Localization properties and the divergence of the localization length have been studied extensively. Experiments on single layer systems have shown that the temperature dependence of the maximum slope of

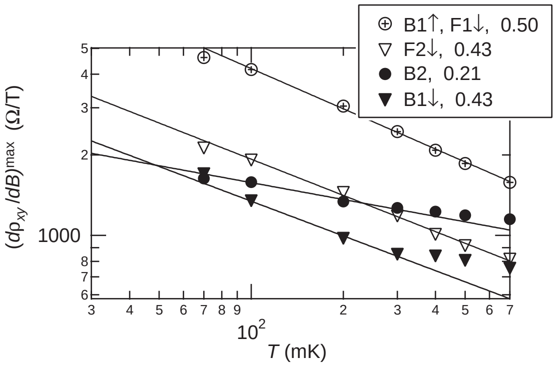

Fig. 3. The temperature dependence of the maximum $(\mathrm{d}\rho_{xy}/\mathrm{d}B)^{\max}$ for $V_g = 0.5$ V.

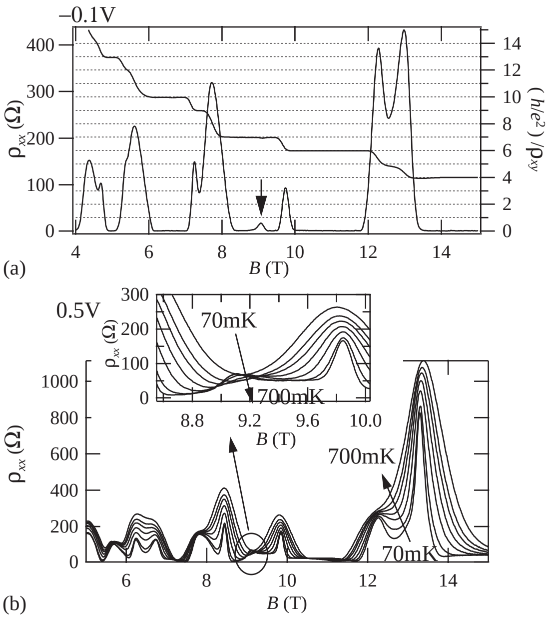

Fig. 4. (a) Magnetoresistance ρ_{xx} and the inverse Hall resistance $(h/e^2)/\rho_{xy}$ (the filling factor) at $V_g = -0.1$ V. The peak in $\rho_{xx}(B)$ at $B \simeq 9$ T (marked by the arrow) is peculiar in that the corresponding Hall resistance remains unchanged on both sides of the peak. (b) Similar data at $V_g = 0.5$ V.

$\rho_{xy}(B)$ curve and that of the inverse half width of ρ_{xx} peak both follow the $T^{-\kappa}$ [4]. The exponent has been found to be $\kappa \approx 0.42$ for spin split case and $\kappa \approx 0.21$ for spin degenerate case. Fig. 3 shows the temperature dependences of $(\mathrm{d}\rho_{xy}/\mathrm{d}B)^{\max}$ for the present bilayer system at $V_g = 0.5$ V. Data are shown for the following LL peaks; F2 $\downarrow$, B3, B1 $\downarrow$, and (B1 $\uparrow$ +F1 $\downarrow$). The power law behavior $(\mathrm{d}\rho_{xy}/\mathrm{d}B)^{\max} \propto T^{-\kappa}$ is observed at low temperatures. The temperature dependence of the half-width of the ρ_{xx} peaks was found to be consistent with this behavior, although the data was less clear on account of the difficulties in deconvoluting overlapping peaks.

The extracted values of the exponent are $\kappa = 0.43$ for spin polarized states (F2 $\downarrow$ and B1 $\downarrow$), and $\kappa = 0.21$ for spin degenerated state (B2) in good agreement with the previous reports on monolayer systems [5]. For the B1 $\uparrow$ +F1 $\downarrow$ peak, we obtained $\kappa = 0.50$. This is an anomalous result for the following reason. When the two spin-split LLs originating from the two layers become degenerate and there is a weak interlayer coupling, the resulting LL peak is expected to behave in a similar manner as the above-mentioned spin degenerate case, and the value of κ close to 0.2 is expected. Deviation from this expectation may occur in the following situations; (1) zero interlayer tunneling, (2) strong interlayer tunneling leading to a large symmetric/antisymmetric splitting, and (3) strongly correlation between the disorder potentials in the two layers. In regard to the first possibility, it might be argued that the interlayer tunneling between the LLs with opposite spins can be very small. However, there is not much difference between the behavior of the B1 $\uparrow$ +F1 $\downarrow$ peak and, for example, the B1 $\downarrow$ +F1 $\downarrow$ peak. The second possibility is not applicable to the present system. The third possibility cannot be ruled out but is unlikely in view of the large difference in the degree of disorder between the two layers. Possible cause may be sought to the large difference in degree of disorder between the two layers, which leads to a large difference in localization length. In such a case, the ability to tunnel to the other layer may not increase the localization length for the electrons in the less disordered layer.

Fig. 4(a) shows magnetotransport data for the gate bias $V_g = -0.1$ V. The resistance peak at $B \simeq 9$ T (marked by the arrow) is peculiar in that the corresponding Hall resistance remains unchanged on both sides of the peak. The position of this anomalous peak is insensitive to the front gate bias, which suggests that it should be attributed to the electron system in the back layer. However, there is no obvious candidate that gives rise to a finite conductivity in the middle of the quantized Hall plateau. Fig. 4(b) is a similar data at $V_g = 0.5$ V with the temperature dependence. Two features are worthy of note; (1) The $\rho_{xx}(B)$ curve shows a terrace-like structure on the

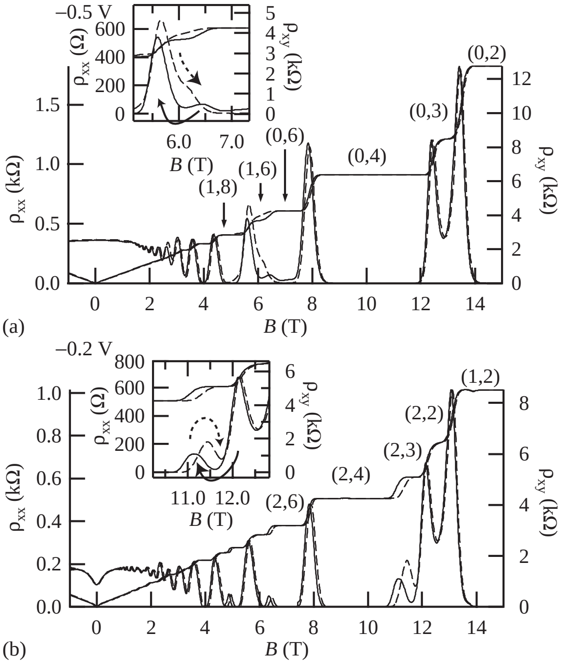

Fig. 5. Magneto- and Hall resistance traces that shows hysteretic behavior at a certain field range where LLs of two layers cross with each other. (a) $V_g = -0.5$ V, (b) $V_g = -0.2$ V.

higher field side of the 9 T peak. This feature is conspicuous in the positive V_g range. (2) The height of the peak at 9 T decreases with temperature, as shown in the inset of Fig. 4. The origin of this anomalous feature is not known at the moment.

Recently some interesting hysteretic behaviors were observed in 2DEGs with spin or pseudospin degree of freedom [6,7]. We have also observed a hysteretic behavior at a certain range of magnetic field. Fig. 5(a) shows magnetotransport data for an extremely asymmetric case, $n_f/n_b \simeq 0.1$ realized at $V_g = -0.5$ V. The solid (dashed) curves are the data taken on down-sweep (up-sweep) of the magnetic field. The filling factors of the front and back layers are given as the numbers in the parenthesis (ν_f, ν_b) in the figure. A distinct hysteresis is observed at $B \simeq 6$ T, where the $N = 0$ LL in the front layer and the $N = 2$ LL in the back layer come close to each other. The resistivity dip identified as the $\nu_{total} = 7$ ($\nu_f = 1$, $\nu_b = 6$) quantum Hall state is more distinct for the down-sweep trace. A similar phenomenon is observed for the $\nu_{total} = 5$ ($\nu_f = 2$, $\nu_b = 3$) quantum Hall state at $V_g = -0.2$ V and $n_f/n_b \simeq 0.55$, as shown in Fig. 5(b). In this case, the $N = 0$ LL in the front layer and the $N = 1$ LL in the back layer are involved. In both cases, one of the LLs involved are spin split. It is inferred that the phenomenon is associated with complicated behavior of the exchange enhancement which may occur in the crossing region of the LLs originating from different layers.

4. Conclusion

We have investigated the magnetoresistance features of bilayer 2DEG systems in quantum Hall regime under asymmetric conditions where the electron densities of the two layers are off-balance. The temperature dependence of the maximum slope of $\rho_{xy}(B)$ follows $(\mathrm{d}\rho_{xy}/\mathrm{d}B)^{\max} \propto T^{-\kappa}$. The value of the exponent is $\kappa \approx 0.43$ for the spin-split LLs and $\kappa \approx 0.21$ for the spin-degenerate LL, in agreement with earlier reports. For the B1 ↑ +F1 ↓ peak, an anomalous value $\kappa \approx 0.50$ is observed. We have also found an anomalous resistance peak at around 9 T in the middle of the Hall plateau region. Although the insensitiveness of its position to V_g suggest that it is associated with the back layer, the origin of this anomalous peak is presently unknown. In the region of LL crossing, hysteretic transition has been found in the region of crossing of the LLs originating from different layers.

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