Hysteresis in the quantum Hall regimes in electron double quantum well structures

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We present here experimental results on magnetotransport coefficients in electron double quantum well (DQW) structures. Consistent with previous studies, transport hysteresis is is observed in the electron DQWs. Furthermore, in our gated DQW samples, by varying the top layer Landau level filling (ν_{top}) while maintaining a relatively constant filling factor in the bottom layer (ν_{bot}), we are able to explain the sign of R_{xx}(up) -R_{xx}(down), where R_{xx}(up) is the magnetoresistance when the gate voltage V_g is swept up and R_{xx}(down) when V_g is swept down. Interestingly, at small magnetic fields hysteresis is generally stronger when the top quantum well is in the even integer quantum Hall effect (IQHE) regime (e.g., $\nu_{top}=2$) than in the odd IQHE regime (e.g, $\nu_{top}=1$). While at higher B fields, the hysteresis at $\nu_{top}=1$ becomes the strongest. The switching occurs around the B field at $\nu_{bot}=3$.

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There is a great deal of current interest in the study of the double quantum well (DQW) structures.[1] Compared to a single layer of the two-dimensional electron or hole system (2DES or 2DHS), the existence of another layer introduces significant interaction effects between two quantum wells. Over the years, many novel physical phenomena have been observed.[2–15] In addition, since the distance (or the coupling) between the two quantum wells can be controllably tuned from a few tenths of a nanometer to several microns, DQW structures have shown promise as possible future electronic devices for next generation information processing.[16]

Recently, a new phenomenon has been discovered in the DQW structures: electronic transport hysteresis.[17–19] It was observed that, when the densities of two wells are different and tunneling is negligible, the magnetotransport coefficients show hysteretic behavior when the magnetic (B) field is swept up and down. This hysteretic behavior occurs when only one QW is in the integer quantum Hall effect (IQHE) regime, and is believed to be due to a charge transfer between the two layers.[18] Specifically, when one layer enters into an IQHE state, its Fermi level jumps from one Landau level to another. Consequently, the chemical potential between the two QWs becomes unbalanced. In reaching an equilibrium state, a charge transfer from one QW to the other will occur, via the ohmic contacts. Since one QW is in the IQHE regime where the bulk is insulating, redistribution of the transferred charges takes a finite time to reach completion. This finite time constant, combined with the finite sweeping rate of the B field, gives rise to a hysteresis in electronic transport.

This hysteretic electronic transport has been observed in a single, high electron mobility quantum well with a low mobility parallel conducting channel[18] and in hole DQW structures.[17,19] So far, no studies have been conducted in the most common DQW structures, the electron DQWs. Thus questions remain whether the hysteresis is universal and occurs in electron DQWs.

In this Brief Report, we present experimental results of the transport hysteresis in electron DQW structures. Exploring the measurement technique of fixing the magnetic field and sweeping a front gate voltage (V_g), we are able to study the hysteresis by varying the top layer Landau level filling (ν_{top}) while maintaining a relatively constant filling factor in the bottom layer (ν_{bot}), allowing us to tackle the question of the sign of R_{xx}(up)-R_{xx}(down), where R_{xx}(up) is the magnetoresistance when V_g is swept up and R_{xx}(down) when V_g is swept down. Furthermore, we observe that at small B fields hysteresis is generally stronger when the top quantum well is in the even integer quantum Hall effect (IQHE) regime than in the odd-IQHE regime. This, we argue, is due to a larger energy gap for an even-IQHE state, determined by the Landau level separation, than that for an odd-IQHE state, determined by the Zeeman splitting. Interestingly, at higher B fields, the hysteresis at $\nu_{top}=1$ becomes the strongest. The switching occurs around $\nu_{bot}=3$.

The electron DQW sample (EA1025) was MBE (molecular beam epitaxy) grown. The schematic diagram of the growth structure is shown in Fig. 1(a). The GaAs quantum well width is 20 nm. The two QWs are separated by an $Al_{0.3}Ga_{0.7}As$ barrier of 100 nm thick. Because of this large separation, the tunneling between the two wells is negligible and the symmetric-antisymmetric energy gap is virtually zero. Standard Hall structures with a Ti/Au Schottkey gate were fabricated. Ohmic contacts were made by alloying Au/Ge in a forming gas at $\sim$420 °C for a few minutes. Electron transport measurements were performed in a pumped ^{3}He system with a base temperature (T) of $\sim$0.28 K, using the standard low frequency ($\sim$13 Hz) lock-in detection techniques. The excitation current is 20 nA. Transport hysteresis was also studied in similar DQWs of different barrier thickness. It was observed in a sample of 25 nm barrier thickness. In another sample of 10 nm thickness, where the tunneling between two layers is finite, no hysteresis was observed.

Figure 1(b) shows the results of the total resistance of two layers, R, as a function of V_g at zero B field. As V_g is negatively biased, R first increases. Close to the situation where the top layer is nearly depleted, a shallow dip shows up. After the top layer is completely depleted, R then continuously increases as V_g is further negatively biased. This non-

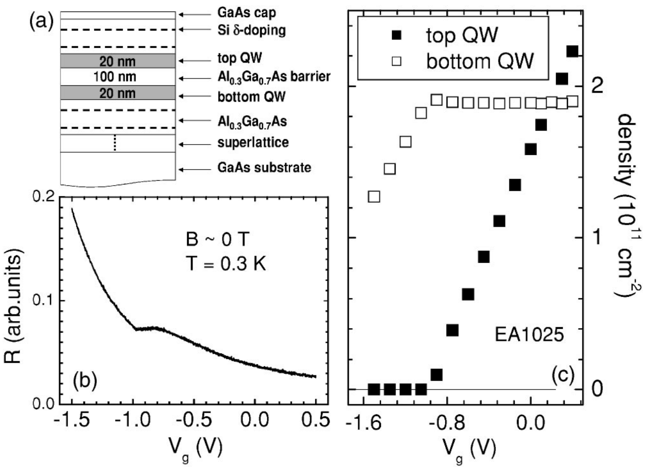

FIG. 1. (a) Schematic growth structure of sample EA1025. (b) Total resistance, R, as a function of V_g. A kink is apparent when the top layer is nearly depleted. (c) Top and bottom layers densities as a function of V_g. Electron densities are obtained from the FFT analysis of the low field Shubnikov-de Haas oscillations.

monotonic V_g dependence was also observed in previous studies.[20–22] In Fig. 1(c), the top layer density (n_{top}) and bottom layer density (n_{bot}) are shown as a function of V_g. The densities are obtained by performing the fast Fourier transform (FFT) analysis of the low-field Shubnikov-de Haas oscillations. It is clearly seen that n_{top} decreases linearly with V_g. From the slope of this linear dependence, a distance of $\sim$450 nm between the metal gate and the center of the top layer is obtained. This value is consistent with the growth parameter of $\sim$410 nm. When the top layer is totally depleted, the density of the bottom layer starts to decrease. The rate of decrease is slower than that of the top layer, consistent with a larger separation between the metal gate and the bottom layer.

Figure 2 shows the magnetoresistance R_{xx} vs B at $T=300$ mK in a bare sample cut from the same wafer. The traces were obtained after illuminating the sample with a red light emitting diode (LED).[23] The top layer electron density is $n_{top}=2.2\times10^{11}$ cm^{-2} and the bottom layer density is $n_{bot}=2.4\times10^{11}$ cm^{-2}. The total mobility is $\mu_{tot}=2.4\times10^{6}$ cm^2/V s. In this sample, only the even IQHE states are observed and the odd IQHE states are absent, where the even and odd refer to the total Landau fillings of both layers. Consistent with previous studies,[17–19] hysteresis is observed at these even IQHE states. In the temporal dependent measurements (not shown), R_{xx} in the hysteretic region shows the typical exponential decay with a time constant of 1 to 2 min.[18]

In our gated samples, the magnetotransport coefficients can be measured by fixing the B field while sweeping the front gate voltage (V_g). In general, as long as the Landau level filling factor is a good quantum number, sweeping B and sweeping V_g (or electron density) are equivalent. In the DQW structures, on the other hand, sweeping V_g has an extra benefit. Compared to sweeping B where both ν_{top} and ν_{bot} change simultaneously, sweeping V_g allows us to vary ν_{top} alone while maintaining a relatively fixed ν_{bot}. (Of course,

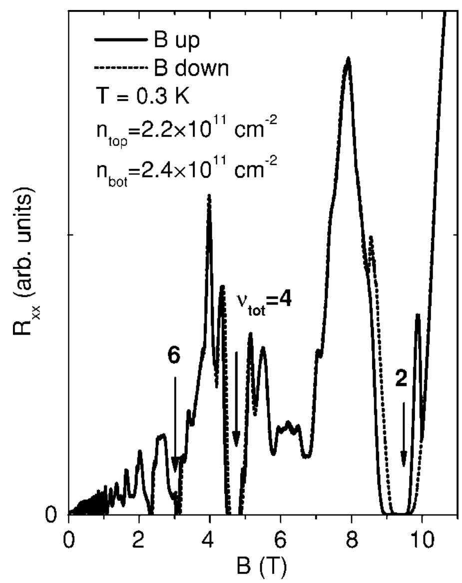

FIG. 2. Magnetoresistance R_{xx} measured in a bare sample of EA1025, after a brief LED illumination at 4 K. The top layer density and bottom layer density are $n_{top}=2.2\times10^{11}$ cm^{-2} and $n_{bot}=2.4\times10^{11}$ cm^{-2}, respectively. The total mobility is $\mu_{\text{tot}}=2.4\times10^{6}$ cm^2/V s. Hysteresis is seen at the total filling factor $\nu=2$, 4, and 6.

when charge transfers between layers, ν_{bot} changes slightly, causing the hysteresis.) In Fig. 3(a), we show the data taken at $B=2.36$ T, or $\nu_{bot}=3.31-R_{xx}$(up) (for V_g swept from -1.5 to 0.5 V) and R_{xx}(down) (for V_g swept from 0.5 to -1.5 V). Pronounced hysteresis is observed at $\nu_{top}=1$, 2, 3, and 4. In Fig. 3(b), R_{xx}(up)-R_{xx}(down) at various B fields is plotted as a function of V_g. The nonzero value indicates the occurrence of hysteresis. All the traces are shifted according

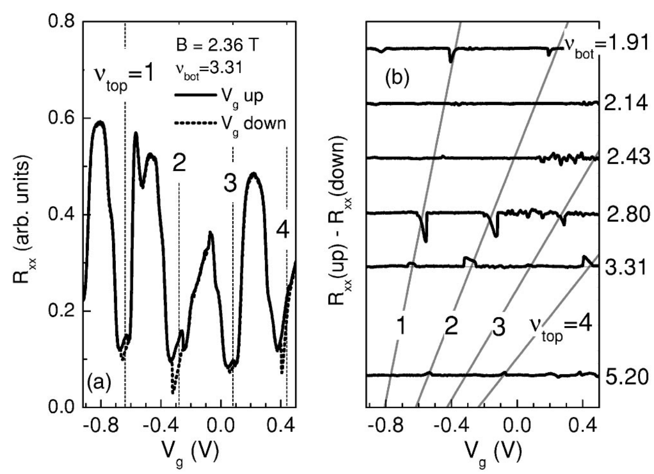

FIG. 3. (a) R_{xx} as a function of the front gate voltage. The dotted curve [R_{xx}(down)] is for V_g sweeping down from 0.5 to -1.5 V and the solid curve [R_{xx}(up)] for V_g sweeping up from -1.5 to 0.5 V. The vertical lines show the V_g positions of the Landau level fillings of the top quantum well. (b) R_{xx}(up)-R_{xx}(down) as a function of V_g. Traces are shifted vertically according to their B field values. The straight lines show the V_g dependence of $\nu_{top}=1$, 2, 3, and 4, respectively. ν_{bot} is also marked for each trace.

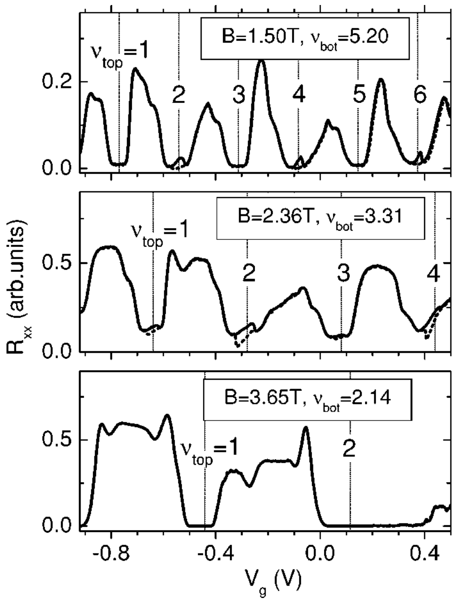

FIG. 4. R_{xx} traces at three selective B fields. The vertical lines show the V_g positions of the Landau level fillings of the top quantum well.

to their respective B field (or ν_{bot}). The four straight lines indicate the position of ν_{top} as a function of V_g. It is clearly seen that hysteresis occurs only along these lines, i.e., when the top layer is in the IQHE regime.

There are a couple of features worthwhile emphasizing in Fig. 3(b). First, R_{xx}(up)-R_{xx}(down) can be either negative or positive. As indicated in Fig. 3(b), the sign depends on ν_{bot}: It is positive when ν_{bot} is $[\nu_{bot}]+\delta$, and negative when $\nu_{bot}=[\nu_{bot}]-\delta$, where the square brackets denote the closest integer values to ν and $\delta < 0.5$. Second, while hysteresis only occurs when the top layer is in the IQHE regime, that the top layer is in the IQHE regime does not mean that a hysteretic electronic transport will always occur. It is also related to ν_{bot}. In Fig. 4 we plot R_{xx}(up) and R_{xx}(down) at three selective B fields. At $B=3.65$ T (or $\nu_{bot}=2.14$), no hysteresis occurs in the entire gate voltage range at the experimental temperature of 0.3 K. At $B=2.36$ T (or $\nu_{bot}=3.31$), hysteresis is seen at every IQHE state. At an even smaller B field, $B=1.50$ T (or $\nu_{bot}=5.20$), the situation is more interesting: Hysteresis only occurs at the even IQHE states.

Our experimental results clearly show the transport hysteresis in the electron DQW structures. Furthermore, the hysteretic behavior is discernable at temperatures as high as ~600 mK, much higher than the highest temperature (~250 mK) where hysteresis was previously recorded.[19] This probably is due to a larger electron density and a smaller electron effective mass (m^*) in our electron DQW than in the hole DQW. These two factors jointly result in a larger Landau level separation at the same ν. Consequently, the IQHE state and hysteresis can survive at higher temperatures.

That the sign of R_{xx}(up)-R_{xx}(down) can be either positive or negative has also been observed in previous studies[18,19] when B was varied. So far no systematic study has been conducted on this matter. In our measurements, where B is fixed and V_g varied, it is apparent that at small B fields the sign shows a systematic dependence on ν_{bot}: It is positive when $\nu_{bot}=[\nu_{bot}]+\delta$ and negative when $\nu_{bot}=[\nu_{bot}]-\delta$. In the following, we shall show that this dependence can be explained in a simple model. First, let us assume that the bottom layer is at the Landau level filling $[\nu_{bot}]+\delta$. When ν_{top} (or V_g) is, for instance, decreased from $[\nu_{top}]+\beta$ to $[\nu_{top}]$ (β is positive and <0.5), the Fermi level jumps down. In order to reach an equilibrium state in chemical potential between two layers, some electrons will move from the bottom QW to the top QW. In other words, the electron density of the bottom QW decreases. Consequently, its filling factor becomes smaller and is more close to $[\nu_{bot}]$. As a result, the resistance of the bottom QW is reduced. This, in turn, causes a reduction in R_{xx}, the total resistance of the two layers. On the other hand, when V_g is swept up and ν_{top} increases from $[\nu_{top}]-\beta$ to $[\nu_{top}]$, the Fermi level jumps up. Consequently, electrons will move from the top layer to the bottom layer. Thus, ν_{bot} increases and becomes closer to $[\nu_{bot}]+1/2$. Since the magnetoresistance generally displays a peak at half-fillings, the bottom layer resistance increases, resulting in an overall increase in R_{xx}. Together, when $\nu_{bot}=[\nu_{bot}]+\delta$, a positive R_{xx}(up)-R_{xx}(down) is the resulting effect. The same argument explains why the R_{xx}(up)-R_{xx}(down) is negative when $\nu_{bot}=[\nu_{bot}]-\delta$.

Another interesting observation can be made in Fig. 4: At small B fields, hysteresis is stronger in the even IQHE regime than in the odd-IQHE regime. This seems to suggest that electron spin may also play a role. We recall that the strength of hysteresis is related to the energy gap of an IQHE state. It is known that the energy gap of an even IQHE state is determined by the Landau level separation, while the odd IQHE state by the Zeeman splitting. Since the effective g-factor for GaAs is $|g|=0.44$, the Landau level separation ($\hbar\omega_c=\hbar eB/m^* \sim 20\times B$[T] Kelvin) is much larger than the Zeeman splitting ($|g|\mu_B B \sim 0.3\times B$[T] Kelvin). This explains why in Fig. 4 the hysteresis in the even IQHE regime is stronger than that in the odd IQHE regime. However, at higher B fields, hysteresis at $\nu_{top}=1$ becomes the strongest (e.g., at $B=2.79$ T or $\nu_{bot}=2.80$, in Fig. 3(b)). The switching occurs around $\nu_{bot}=3$. Its physical origin remains unclear.

In summary, in this Brief Report we present experimental results on transport hysteresis effects in electron double quantum well structures. The hysteresis is studied by varying the top layer Landau level filling while maintaining a relatively constant filling factor in the bottom layer. This measurement has allowed us to identify that the sign of R_{xx}(up)-R_{xx}(down) is positive when $\nu_{bot}=[\nu_{bot}]+\delta$ and negative when $\nu_{bot}=[\nu_{bot}]-\delta$, where δ is a positive number and $\delta<0.5$. A simple model is proposed to understand this sign dependence. Furthermore, it is observed that at small B fields hysteresis is generally stronger in the even-IQHE regime than in the odd-IQHE regime. This, we argue, is due to a larger energy gap for an even-IQHE state, determined by the Landau level separation, than that for an odd-IQHE state, determined by the Zeeman splitting. Interestingly, at higher B fields, hysteresis at $\nu_{top}=1$ becomes the strongest.

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[1] For a review of recent theoretical and experimental results on double quantum well structures, see, for example, the chapters by S. M. Girvin and A. H. MacDonald, and J. P. Eisenstein, in *Perspectives in Quantum Hall Effect*, edited by S. Das Sarma and A. Pinczuk (Wiley, New York, 1996), and references therein.

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[23] Except for the traces in Fig. 2, data present in this Brief Report were obtained without LED illumination.