PHYSICAL REVIEW B **68**, 201308(R) (2003)

Layer-charge instability in unbalanced bilayer systems in the quantum Hall regime

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(Received 4 September 2003; published 25 November 2003)

Measurements in GaAs hole bilayers with unequal layer densities reveal a pronounced magneto-resistance hysteresis at the magnetic-field positions where either the majority or minority layer is at Landau level filling factor one. At a fixed field in the hysteretic regions, the resistance exhibits an unusual time dependence, consisting of random, bidirectional jumps followed by slow relaxations. These anomalies are likely caused by instabilities in the charge distribution of the two layers.

DOI: 10.1103/PhysRevB.68.201308 PACS number(s): 73.50.−h, 71.70.Ej, 73.43.Qt

Hysteretic phenomena are widespread in nature. They are common in magnetic materials, and often indicate a nonequilibrium situation associated with a phase transition and the presence of domains.[1] Recently, hysteresis has also been reported in various two-dimensional (2D) carrier systems in semiconductor structures at low temperatures and high magnetic fields.[2–7] In these cases, magnetoresistivity ρ_{xx} hysteresis appears in the quantum Hall (QH) regime when two Landau levels (LL's) with opposite spin are brought into coincidence. While the 2D systems studied have been notably different, the common thread in these experiments is that there is a *magnetic* transition involving the carrier *spin*.[8]

Here we present hysteretic ρ_{xx} data in GaAs bilayer hole systems with unequal densities in the QH regime. The hysteresis in these systems has a different origin and is caused by a nonequilibrium charge distribution in the two layers. When the interlayer tunneling is sufficiently small, ρ_{xx} of the bilayer system exhibits a pronounced hysteresis at perpendicular magnetic-field B positions close to where either the majority or minority layer is at LL filling factor one. Most remarkable is the time dependence of ρ_{xx} at a fixed field in the hysteretic regime, when the two layers are closely spaced. As a function of time, ρ_{xx} exhibits large, random, sudden jumps toward higher and lower values, followed by a slow decay in the opposite direction. The data may signal an instability in the charge distribution of the two layers, i.e., an instability associated with the *pseudospin* (layer), rather than spin, degree of freedom.

We studied nine GaAs bilayer hole samples from six different wafers, all grown on GaAs (311)A substrates and modulation doped with Si. In all samples, the holes are confined to two 15-nm wide GaAs quantum wells which are separated by AlAs or AlAs/AlGaAs barriers with thickness $7.5 \leqslant W \leqslant 200$ nm. The rather thick barrier combined with the large effective mass of GaAs 2D holes reduces considerably the tunneling between the two layers.[9] As grown, the samples have layer densities of $\leqslant 7 \times 10^{10}$ cm^{-2}, and low temperature T mobilities of ~ 35 m^2/V s. Metallic top and bottom gates were added to control the densities in the layers. We studied several types of devices, including 2.5×2.5 mm^2 square samples and ones with patterned Hall bars. Except for one sample, as noted below, the ohmic contacts contact both layers. The measurements were performed in a dilution refrigerator down to $T = 20$ mK.

Data shown in Fig. 1 highlight some of the results of our study. In Fig. 1(a) we show a set of traces where ρ_{xx} was measured for a sample with $W = 11$ nm as B was ramped up or down. For the traces of Fig. 1(a) the total bilayer density p_{tot} is kept constant at 5.5×10^{10} cm^{-2} while charge is transferred from one layer to another using back-gate and front-gate biases. We define the charge transfer from one layer to another as $\Delta p = (p_B - p_T)/2$, where p_B and p_T are the densities of bottom and top layers, respectively.[10] At a given value of B, we define the filling factor ν of the bilayer system as the ratio between p_{tot} and the LL degeneracy, eB/h. We also introduce the filling factors for top and bottom layers, ν_T and ν_B, respectively, as the ratio between the layer density and eB/h.

The data in Fig. 1(a) show that when the bilayer system is balanced ($\Delta p = 0$; top trace) ρ_{xx} is independent of the direction B is ramped. However, as soon as the system is imbalanced ($|\Delta p| > 0$) a strong hysteresis develops in ρ_{xx}. For values of $\Delta p < 4.7 \times 10^9$ cm^{-2}, ρ_{xx} displays hysteretic behavior in two field ranges near $\nu = 2$, one near $\nu_T = 1$ and another near $\nu_B = 1$. When $\Delta p \geqslant 4.7 \times 10^9$ cm^{-2}, the hysteresis exists only near $\nu_B = 1$. For sufficiently large Δp, no hysteresis is observed. The amplitude of the hysteresis also decreases as T is increased (data not shown) and vanishes completely above $T \simeq 230$ mK, roughly independent of Δp.

To probe the contribution of the spin degree of freedom to the hysteresis in our bilayer systems, we performed measurements in tilted magnetic fields. In this experiment the direction of the field was kept at an angle θ with respect to the normal to the plane of the bilayer system. For θ ranging from $0°$ to $80°$, corresponding to a sixfold increase of the total field (and therefore of the Zeeman energy) in the hysteretic region, the position of the hysteresis in perpendicular magnetic field did not change at all. If the hysteresis were caused by an instability associated with the spin degree of freedom, one would expect[6,7] that the applied parallel field would change the position and magnitude of the hysteresis. These results rule out spin as being responsible for the hysteresis.

We then fabricated another sample from a different wafer, also with $W = 11$ nm, using a selective depletion scheme,[11] and aimed to independently probe each layer of the bilayer system. The data are shown in the right panel of Fig. 1. In (b) we plot ρ_{xx} for the bilayer system, that is, when the ohmic contacts are connected to both layers. In (c) and (d) we show

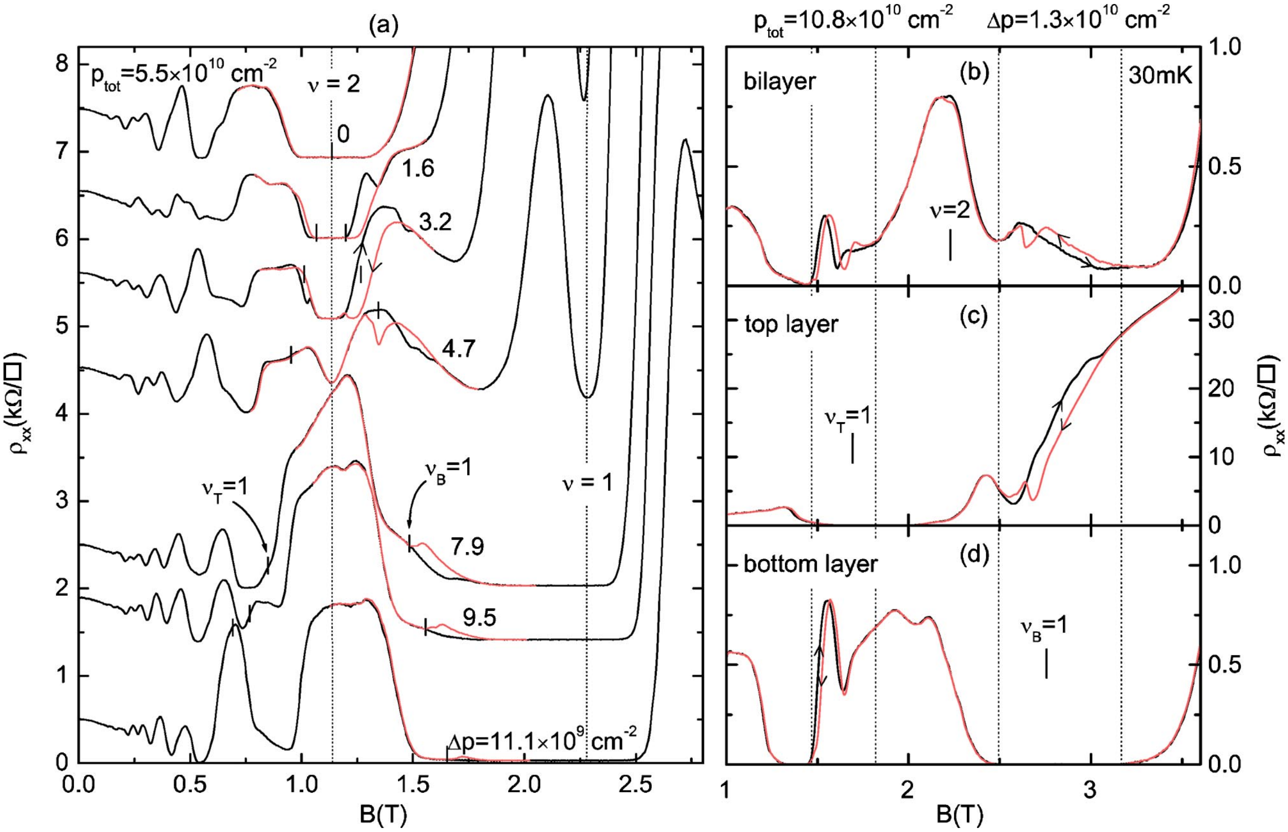

FIG. 1. (Color online) (a) ρ_{xx} vs B traces for a GaAs bilayer hole sample with a barrier width $W=11$ nm. Data are shown for different values of charge transfer Δp while p_{tot} is kept constant at 5.5×10^{10} cm^{-2}. The traces are shifted vertically for clarity. The dotted lines indicate the positions of bilayer filling factors $\nu=2$ and $\nu=1$. A strong hysteresis develops in ρ_{xx} when the bilayer system is imbalanced. The right and left tick marks in each trace indicate the estimated positions of filling factor one for layers with higher (bottom) and lower (top) densities, respectively. The right panel shows data for a similar sample but with independent layer contacts, and $p_{tot}=10.8\times10^{10}$ cm^{-2} and $\Delta p=1.3\times10^{10}$ cm^{-2}. (b) ρ_{xx} vs B traces measured when the ohmic contacts are connected to both layers. (c) and (d) ρ_{xx} of the top and bottom layers measured individually. In all figures the black (red) line represents the trace taken when B is swept up (down).

ρ_{xx} traces for the top and bottom layers, measured separately, but at the same pair of layer densities as in panel (b) traces. Two features of these data are noteworthy. First, the traces in (b) exhibit hysteresis in two ranges of B: one between 1.45 and 1.8 T that matches well the position of the $\nu_T=1$ QH state of the top layer as seen in (c), and another, between 2.5 and 3.2 T, which overlaps the $\nu_B=1$ QH state of the bottom layer [see (d)].[12] This observation confirms that the hysteresis in ρ_{xx} of the bilayer system takes place when one of the layers is at filling factor one. Second, data of (c) and (d) show that each individual layer exhibits hysteresis when the other layer is at filling factor one, i.e., ρ_{xx} of the top layer exhibits hysteresis when $\nu_B=1$, and vice versa.

The observation of hysteretic ρ_{xx} in unbalanced bilayer systems has precedence. Zhu *et al.*[13] reported hysteresis in 2D electron systems with a parallel conducting layer. In their case, the parallel layer was a parasitic, low-mobility, doping layer at a distance of 75–95 nm away from the high-mobility 2D electrons. Similar to our data, they observed hysteresis in ρ_{xx} when the layer containing the high-mobility 2D electrons was in a QH state. They also presented a simple model to explain the observed hysteresis. In their model, the hysteresis comes about because of a nonequilibrium charge distribution in the layers. As B is swept, thanks to the Landau quantization, the Fermi-levels of both layers oscillate. These oscillations lead to temporary imbalances between the chemical potentials of the two layers. The potential imbalance is particularly abrupt and large when the high-mobility 2D electrons enter a QH state as their Fermi level jumps by a significant amount, equal to the separation between the adjacent LL's. With increasing time, of course, the Fermi levels of the two layers have to come to equilibrium since the latter are shorted together via the ohmic contacts. But this equilibration can take a long time in the QH effect regime: it has to take place via the layers' edges and the ohmic contacts since the (bulk) states in the center of the 2D layer that is in the QH state are localized and the layer sheet conductivity is very small. As a result, ρ_{xx}, which is recorded as B is swept at a finite rate, can show a hysteretic behavior. Consistent with their model, Zhu *et al.* found that when the B sweep is interrupted in the hysteretic region and ρ_{xx} is monitored as a function of time, it decays approximately exponentially toward an equilibrium value. Moreover, they found the time constant of the decay in reasonable agreement with estimates based on the parameters of their experiment.

The hysteresis in our samples resembles what Zhu *et al.* have observed and likely has a similar origin. Our data in Fig. 1 in fact explicitly show that the hysteresis happens

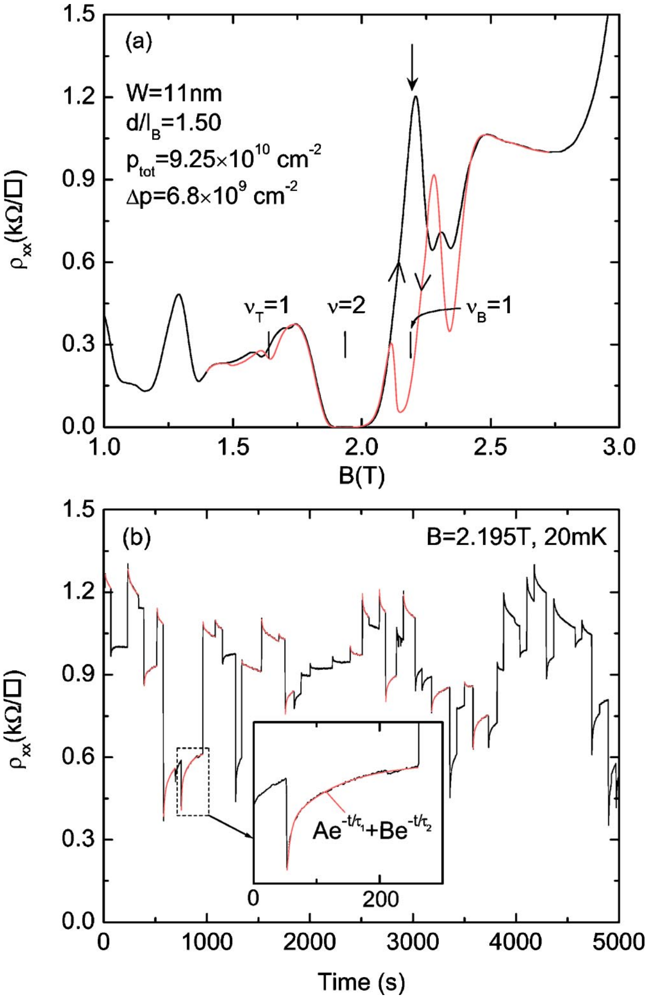

FIG. 2. (Color online) (a) ρ_{xx} vs B traces for another sample with $W=11$ nm, with p_{tot} and Δp as indicated. (b) ρ_{xx} vs time measured following an up-sweep of B and stopping B at 2.195 T. ρ_{xx} displays sudden jumps followed by a slow relaxation. The red lines represent double exponential fits to the slow relaxation component of the data, with time constants $\tau_1 \sim 5$ s and $\tau_2 \sim 90$ s.

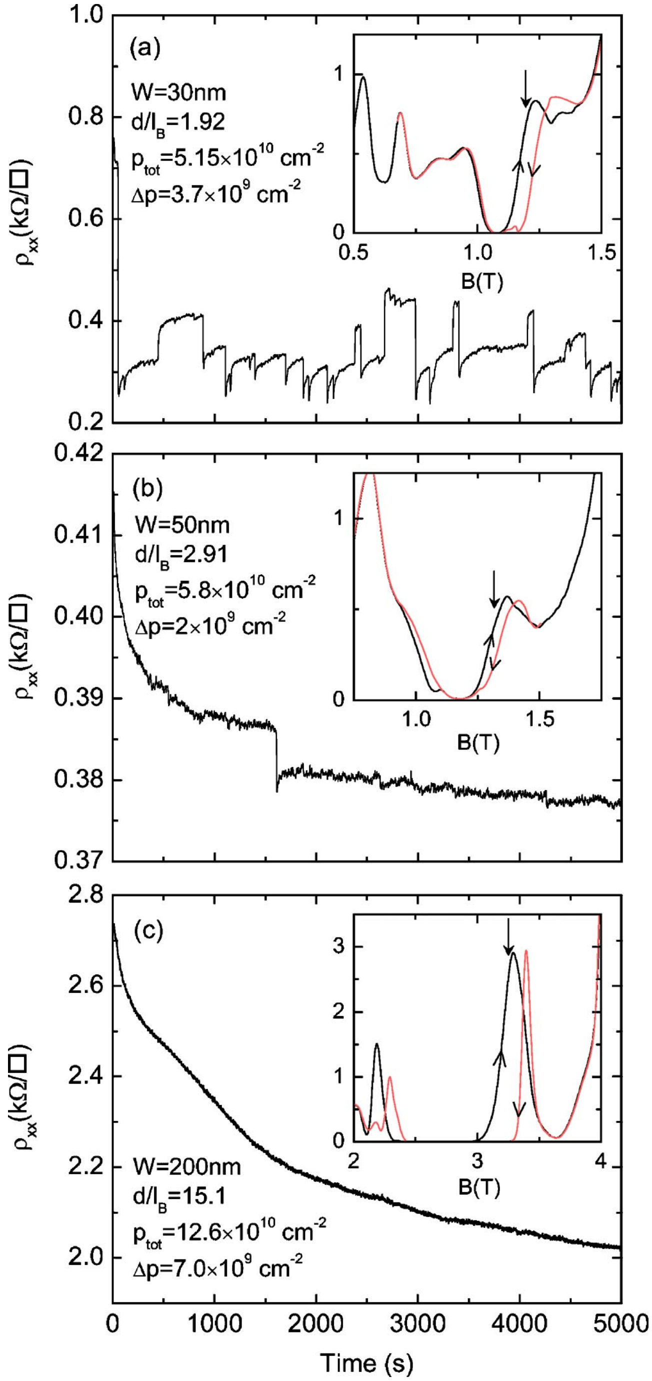

FIG. 3. (Color online) Time evolution of ρ_{xx} in the hysteretic region for samples with different W, p_{tot}, and Δp, as indicated. The insets show ρ_{xx} vs B for up- and down-sweeps. The arrow in each inset indicates the position at which the time evolution was recorded after an up-sweep of B.

when one of the layers is in a QH state, and it is the resistivity of the layer which is not in the QH state that is hysteretic. The interpretation that the hysteresis indicates a charge transfer between the two layers is also supported by our data: the hysteresis observed in ρ_{xx} of either the top or the bottom layer measured separately appears much like a horizontal shift of the trace in B, as if the layer had slightly different density when ramping B up or down [see, e.g., Fig. 1(c)]. The time evolution of ρ_{xx} in our samples, however, is qualitatively different from the observations of Zhu *et al.*, and points to a very unusual relaxation. In the remainder of the paper, we describe this evolution and speculate on its possible origin.

We studied a number of samples with varying p_{tot}, Δp, and barrier width $7.5 \leqslant W \leqslant 200$ nm. Samples with $W = 7.5$ nm do not show any hysteresis; this is likely because the interlayer tunneling is sufficiently large so that the two layers stay in equilibrium during the B sweep. We observe hysteresis for all samples with $11 \leqslant W \leqslant 200$ nm, but the time evolution of ρ_{xx} critically depends on W, as shown in Figs. 2 and 3. For samples with $W=11$ nm (Fig. 2), the time evolution is very unusual. It displays sudden, large jumps in ρ_{xx}, followed by a slow relaxation after each jump (note that outside the hysteretic region, ρ_{xx} is independent of time to within less than 0.3%). Surprisingly, ρ_{xx} jumps toward *both* higher and lower values, reminiscent of a bistability, although the jumps do not happen between fixed values of ρ_{xx}. In between jumps, ρ_{xx} follows a slow relaxation, almost always in the opposite direction of the jump, which can be fitted well by a double exponential [see Fig. 2(b) inset]. We emphasize that, even when measured over days (up to 2.5×10^5 s), there is no tendency toward a settling of the jumps.

We have attempted to quantify the characteristics of this evolution by two parameters: average frequency and amplitude of the jumps. At a fixed B, the average jump amplitude decreases as the temperature increases, but the T dependence does not appear to follow a universal behavior for different samples or at different B values. Not surprisingly, the jumps are no longer visible above the temperature where the hysteresis vanishes. On the other hand, the average frequency appears to be independent of T. Also, the jump frequency and amplitude are independent of the magnitude of the sample current, as long as the current is kept sufficiently small ($\leqslant 10$ nA) not to cause heating. Interestingly, the jumps and decays appear to continue even when the current is completely turned off.[14]

The sample with $W=30$ nm shows a behavior qualitatively similar to the one with $W=11$ nm, although both the frequency and size of ρ_{xx} jumps are smaller [Fig. 3(a)]. Data for the $W=50$ nm sample, however, are qualitatively different [(Fig. 3(b)]: there are by far fewer ρ_{xx} jumps (typically one jump every few 10^3 s), and ρ_{xx} appears to decay with time. Finally, for the $W=200$ nm sample [Fig. 3(c)], we typically observe a rather simple decay with time,[15] qualitatively similar to the observation of Zhu *et al.*[13,16] Interestingly, for the samples of Figs. 3(b) and 3(c), ρ_{xx} continues to decay with an ever increasing time constant.

The time evolutions for the samples with thin barriers ($W=11$ and 30 nm) are very unusual and cannot be understood in a simple model in which the bilayer system slowly and steadily relaxes to an equilibrium state. In these samples, ρ_{xx} displays sudden jumps that do not have any tendency to settle, at least over a time scale of days and even in the absence of current. The jumps may indicate a metastable charge distribution in the two layers. Our data also suggest that when a jump occurs, the charge density in the two layers changes over a large area of the sample.[17] These jumps bear some resemblance to the so-called Barkhausen jumps, which occur in magnetic materials when the system finds a lower energy state available and one or several domains change orientation.[1] However, unlike the Barkhausen jumps, the ρ_{xx} jumps in our samples are bidirectional, indicating a metastable state rather than an evolution toward equilibrium. It is possible that in the bilayer systems with small layer separation, the interlayer interaction acts as a force opposing the charge transfer caused by the Fermi-level difference.[18] In this scenario, the two opposing mechanisms may mediate a layer charge instability, leading to the creation of domains with different layer densities.

We thank DOE and NSF for support and D. Huse and D. Haldane for helpful discussions.

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[9] Using a GaAs hole effective mass of $0.38m_e$, a simple band calculation yields a tunneling energy of less than 1 μK for the bilayer system studied here.

[10] The total density is kept constant to within 3%. The charge transfer Δp is measured with an accuracy of 6%.

[11] J.P. Eisenstein, L.N. Pfeiffer, and K.W. West, Appl. Phys. Lett. **57**, 2324 (1990).

[12] The small hysteretic loop at $B \simeq 2.2$ T in Fig. 2(b) is not visible in all cooldowns; its origin is unclear.

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[14] For example, for the sample in Fig. 2(b), after a temporary turn-off of the current (or grounding of all contacts), ρ_{xx} does *not* recover to its value before the turn-off. If the off period is short ($\leqslant 1$ min), ρ_{xx} typically follows the same decay as before the current was turned off. For long off periods, ρ_{xx} attains a value that is much different than before, suggesting the occurrence of a jump even when the current was turned off.

[15] Even the $W=200$ nm sample shows ρ_{xx} jumps, but these are extremely rare. We measured four traces like in Fig. 3(c), taken over a total period of 5×10^4 s. In two traces we observed a single jump, followed by a decay.

[16] Also similar to the results of Zhu *et al.* (Ref. 13), this sample displays hysteresis when the individual layers are at integer fillings higher than one, i.e., when ν_B or $\nu_T = 2$, 3, and 4.

[17] This conclusion is based on the following observation. When studying L-shaped Hall bar samples, we have monitored the time dependence in the hysteretic region of ρ_{xx} and ρ_{xy} for the two arms of the Hall bar. All four quantities (ρ_{xx} and ρ_{xy} of the two arms) display jumps at the exact same times.

[18] As a measure of interalayer interaction, in Figs. 2 and 3, we have included values for d/l_B, the ratio between the interalayer distance d and the magnetic length l_B.