# Role of imbalance in GaAs two-dimensional hole bilayers

E. Tutuc, S. Melinte, E.P. De Poortere, R. Pillarisetty, and M. Shayegan

*Dept. of Electrical Engineering, Princeton University, Princeton, NJ 08540, U.S.A.*

When two layers of electrons are brought into close proximity so that interlayer interaction is strong, new physical phenomena, with no counterpart in the single layer case, can occur. Examples include unique collective quantum Hall states (QHSs) at even-denominator fractional fillings $\nu$=1/2 and 3/2 [1], and at $\nu$=1 [2] ($\nu$ is the total filling factor of the bilayer system). These states are stabilized by a combination of interlayer and intralayer Coulomb interaction. The *bilayer* $\nu$=1 QHS is a particularly interesting as it possesses unique, spontaneous, interlayer phase coherence: even in the limit of zero tunneling, the electrons spread between both layers coherently [2]. We report magnetotransport experiments on interacting bilayer *holes*, confined to two GaAs quantum wells with essentially no interlayer tunneling, with an emphasis on the properties of the system as the layer densities are made unequal (imbalanced) [3].

The results of our study are highlighted in Figs. 1 and 2. Data from two samples, A and B, consisting of two 150Å-wide GaAs quantum wells, separated by a 110Å-wide AlAs barrier, are shown here. The samples were fitted with back and front gates, which allow independent tuning of the density in each layer. In Fig. 1 the longitudinal resistivity ($\rho_{xx}$) vs. perpendicular magnetic field ($B$) traces are shown for sample A. When the densities in the two layers are equal (balanced), we observe a QHS at $\nu$=1, flanked by an insulating phase (IP) reentrant around this QHS and extending to filling factors as large as $\nu$ ~1.1 [Fig. 1(a)]. As we transfer charge from one layer to another while maintaining the total density constant, the IP at $\nu$ ~1.1 is destroyed but, surprisingly, the $\nu$=1 QHS becomes stronger [Fig. 1(b)]. The weakening of the IP with charge transfer indicates that this phase is stabilized by a delicate balance of interlayer and intralayer Coulomb interaction, and suggests a pinned, *bilayer* Wigner crystal. The strengthening of the $\nu$=1 QHS with increasing charge transfer, on the other hand, demonstrates the robustness of its phase coherence against charge imbalance.

Figure 2(a) reveals yet another very remarkable feature of transport coefficients in an imbalanced, interacting bilayer system: $\rho_{xx}$ exhibits pronounced hysteresis at lower magnetic fields near $\nu$=2, close to field values where either the majority or the minority layer is expected to be at (layer) filing factor 1. Furthermore, magnetoresistance measurements in tilted magnetic fields show that the position of the hysteresis in perpendicular magnetic field is independent of the applied parallel field. The hysteresis signals a first-order quantum phase transition and is, as we will demonstrate, caused by an instability associated with the layer index degree of freedom (pseudospin). In such scenario the hysteresis is caused by the formation of pseudo-spin (layer density) domains at the transition.

Of particular interest for the understanding of the morphology of these charge domains, is the time dependence of the resistivity at fixed value of magnetic field, at which the resistivity exhibits hysteresis. In Fig. 2(b) we show an example of such measurement, where the resistivity is measured as a function of time at fixed magnetic field. Most strikingly, the data exhibit sudden changes in sample resistivity to *both* higher and lower values. After each jump the resistivity follows a decay, which can be fitted well by a double exponential as shown in Fig. 2(b), thus showing that the hysteresis is associated with a bistability combined with a slow relaxation.

[1] Y.W. Suen *et al.*, Phys. Rev. Lett. **68**, 1379 (1992); J.P. Eisenstein *et al.*, Phys. Rev. Lett. **68**, 1383 (1992); Y.W. Suen *et al.* , Phys. Rev. Lett. **72**, 3405 (1994).

[2] S.Q. Murphy *et al.*, Phys. Rev. Lett. **72**, 728 (1994); I.B. Spielman *et al.*, Phys. Rev. Lett. **84**, 5808 (2000).

[3] E. Tutuc *et al.*, http://xxx.lanl.gov/abs/cond-mat/0209649.

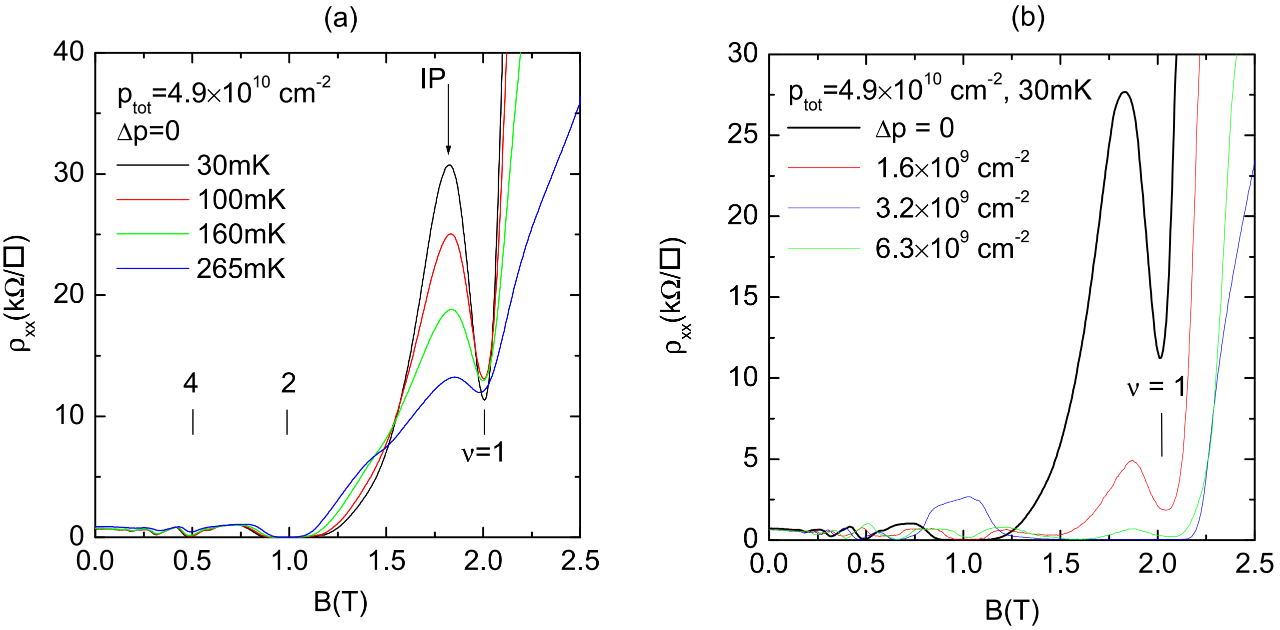

Fig. 1: Resistivity vs. magnetic field traces for sample A. (a) Temperature dependence of traces is shown; the total bilayer density is $p_{tot}=4.9\times10^{10}$ cm$^{-2}$, with both layers having equal densities. The vertical arrow points to the insulating phase developing near filling factor ν=1.1. (b) Data at temperature T=30mK for different values of the charge transfer, Δp, while the total charge density is kept constant at $4.9\times10^{10}$ cm$^{-2}$. Δp is defined as $\Delta p=(p_B-p_T)/2$, where $p_T$ and $p_B$ are the densities of the top and bottom layers.

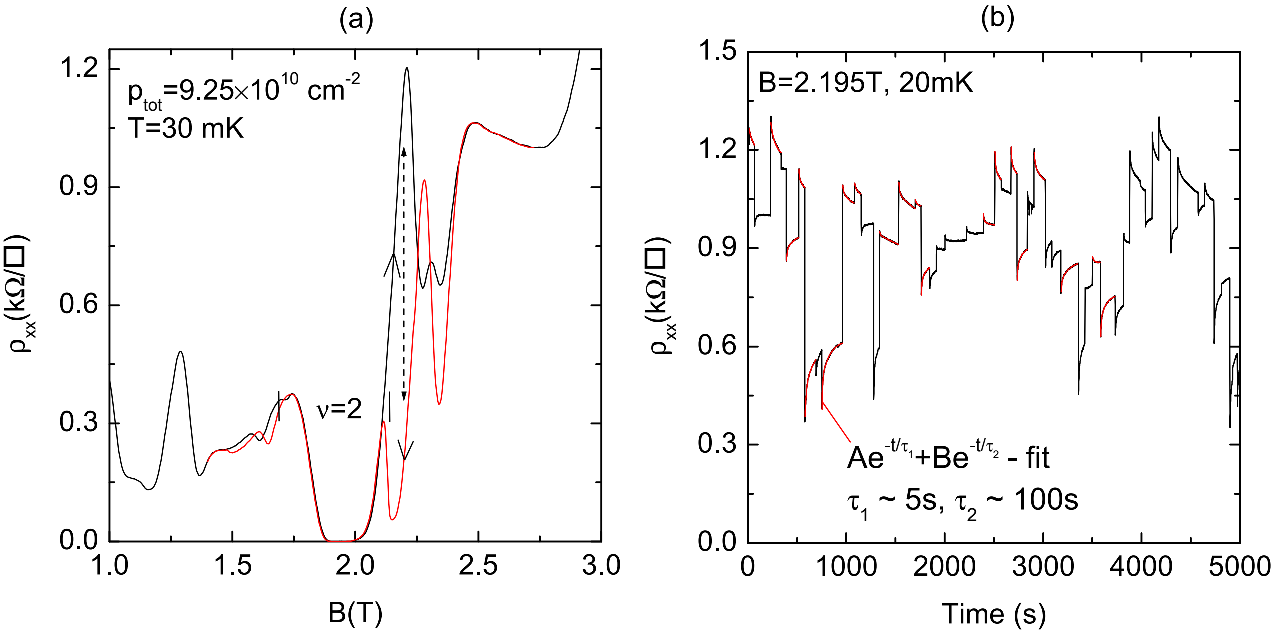

Fig. 2: Resistivity vs. magnetic field traces for sample B. (a) Data at a total density of $p_{tot}=9.25\times10^{10}$ cm$^{-2}$ revealing the development of a hysteresis in the magnetoresistance near total filling ν=2 when the bilayer is imbalanced. The magnetic field sweep direction is indicated by the arrows on each trace. The right and left vertical tick marks at 1.70T and 2.14T indicate the expected position of ν=1 for the two layers. The dashed line indicates the position of the magnetic field where the time dependence measurement of the resistance (see panel (b)) was performed.

(b) Resistivity vs. time at fixed magnetic field. The data shows sudden changes in resistivity combined with a slow relaxation. The red lines represent double exponential fits to the slow relaxation component of data.