# Hysteresis in Double Quantum Well Structure: Evidence for a Wigner Crystal

*by* ***W. Pan, J. L. Reno, and J. A. Simmons***

**Motivation**—There is a great deal of current interest in the study of the double quantum well (DQW) structures. Compared to a single layer two-dimensional electron system (2DES), the existence of another layer introduces significant interaction effects between the two wells. Over the years, DQWs have proven to be ideal for studying the charge and energy transfer over multi-length scales, and many novel physical phenomena have been discovered. In addition, since the coupling (or separation) between the two wells can be precisely tuned from a few tenths of a nanometer to several microns, DQW structures have shown promise as possible electronic devices for next generation information processing.

**Accomplishment**—The electronic state of a 2DES in the presence of a high magnetic (B) field is the result of a competition between electrostatic effects and subtle quantum mechanics. At very high B field and low carrier concentration electrons are forced into tiny orbits as compared to their separation. As a result, the mutual wave function overlap vanishes and electrostatics dominates. An electron crystal, analogous to a classical Wigner crystal (WC) of point charges, is expected to form. At lower B field, or higher carrier concentration, wave function overlap is appreciable. This leads to the fractional and integer quantum Hall effect (FQHE and IQHE) states at Landau level filling $\nu = n/s$, where n is the carrier concentration and s is the magnetic flux density. The hallmark of a quantum Hall state is the vanishingly small diagonal resistance $R_{xx}$ and precisely quantized Hall resistance $R_{xy} = (h/e^2)/\nu$.

In this research brief, we show experimental results of transport hysteresis in a DQW in the QHE regimes, and interpret it as the evidence of formation of a high B field WC. The sample structure is shown in Fig.1a. The ratio of top layer density ($n_t$) to bottom layer density ($n_b$), tuned by the front gate voltage ($V_g$), is $n_t/n_b \sim 1/6$ in Fig. 2a. Transport hysteresis is seen at the IQHE states $\nu = 1$ and 2. When $\nu < 1$ and the 2DES is in the FQHE regime, no hysteresis is seen. Surprisingly, in another type of measurement where B remains constant and $V_g$ is varied (Fig. 2b), prominent hysteresis is observed for $\nu < 1$ at the same experimental parameters, *e.g.*, $V_g$ = -0.79V and B =12.9T.

The huge transport hysteresis in the $V_g$ sweeps is striking. We believe it is new evidence of formation of a high B field WC, in the top layer. When $V_g$ is swept, electrons are added to or removed from the top layer. Since the WC is weakly pinned by residual disorders and the 2DES is insulating, it then requires a finite time for the carriers in the top layer to reorder and reach the final equilibrium state. This finite time constant, combined with a finite $V_g$ sweep rate, can cause hysteresis. On the other hand, in the B sweeps, there is no such charging/discharging process. Consequently, no hysteresis is expected or observed.

**Significance**—Adding a high-density, high-mobility 2DES close to a low-density one allows us to study some physical properties of WCs that might not be accessible in a single layer system. This novel approach, combined with other well-established experimental techniques, such as Coulomb drag and photoluminescence, is expected to shed more light on the physical properties of the high B field Wigner crystal phase, which has been a challenging problem for many decades.

**Sponsors for various phases of this work include:** DOE Office of Basic Energy Sciences

**Contact:** Wei Pan; Semiconductor Material & Device Sciences, Dept. 1123
Phone: (505) 284-9545, Fax: (505) 844-3211, E-mail: wpan@sandia.gov

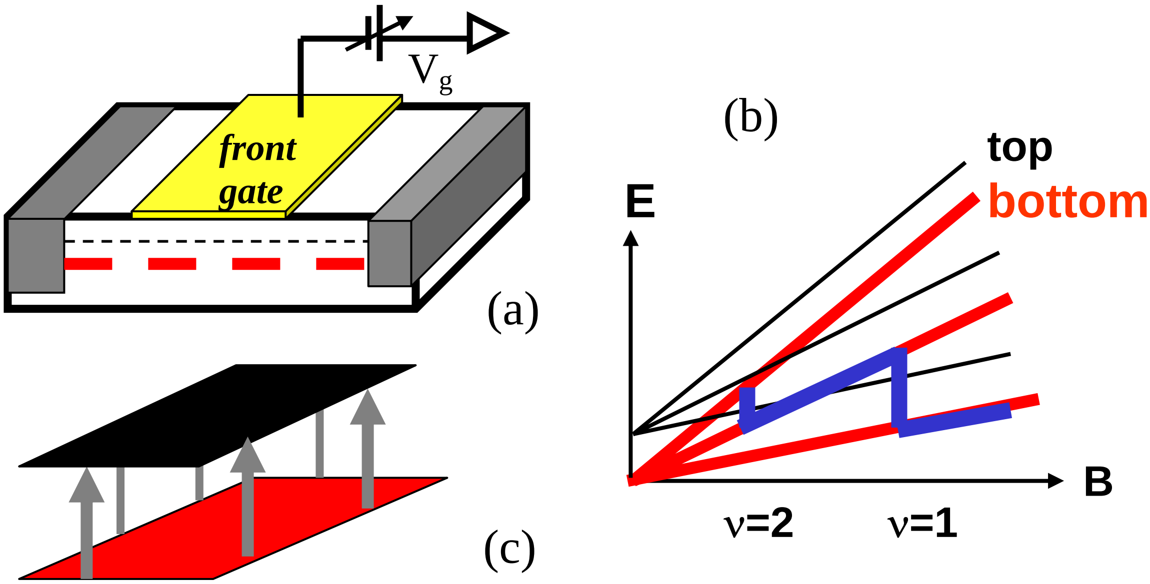


**Figure 1**. (a) Schematic of sample structure. The black thin dashed line represents the top layer and the red thick dashed line the bottom. (b) The transport hysteresis can be understood as spontaneous charge transfer between the two quantum wells. When the bottom layer enters into an IQHE state, its Fermi level (blue line) jumps from one Landau level to another. Consequently, the chemical potential between the two QWs becomes unbalanced. In reaching an equilibrium state, a spontaneous charge transfer from one QW to the other will occur, through ohmic contacts (Fig. C). Since the bottom QW is in the IQH regime and the bulk is insulating, redistribution of the transferred charges would take a finite time to finish. This finite time constant, combined with the finite sweeping rate of B field, gives rise to hysteresis in electronic transport. Once ν < 1 is reached, the Fermi level will stay in the lowest Landau level and experience no more sudden jumps. Thus, no hysteresis is expected, consistent with our results.

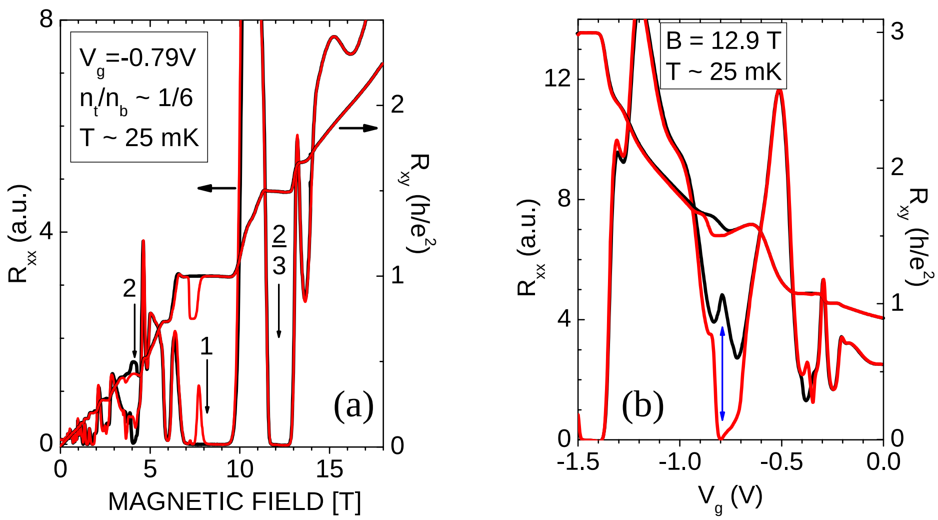


**Figure 2**. (a) No hysteresis is seen around V=2/3 at $V_g$ = -0.79 V and B = 12.9 T in B sweeps (black curve, B up; red, B down). (b) Huge hysteresis is seen in $V_g$ sweeps at the same experimental parameters, $V_g$ =-0.79 V and B=12.9 T (red curve, $V_g$ up; black, $V_g$ down).