Reentrant anisotropic phases in a two-dimensional hole system

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Anisotropic charge transport is observed in a two-dimensional (2D) hole system in a perpendicular magnetic field at filling factors $\nu=7/2$ and $\nu=11/2$ for temperatures below 150mK. In stark contrast, the transport at $\nu=9/2$ is isotropic for all temperatures. Our results for a two-dimensional hole system differ substantially from 2D electron transport where no anisotropy has been observed at $\nu=7/2$, the strongest anisotropy occurs at $\nu=9/2$, and reentrant behavior is not evident. We attribute this difference to strong spin-orbit coupling in the hole system.

For over a decade, investigation of the properties of half-filled Landau levels of clean two-dimensional (2D) systems has been the focus of intense research. In two-dimensional electron systems (2DESs) at half-filling, a surprisingly diverse set of ground states has been uncovered. In the N=0 Landau level (LL), at $\nu=1/2$ and $\nu=3/2$, compressible composite-fermion Fermi liquid states are observed \cite{12}. (Here $\nu=hce/EB$ is the filling factor with $B$ the magnetic field, and $n$ the carrier density). In the N=1 Landau level, DC transport measurements have convincingly demonstrated the presence of incompressible quantized Hall states at $\nu=5/2$ and $\nu=7/2 \cite{11,13,14}$. At half-filling in the $2 \lesssim N \lesssim 5$ Landau levels, electronic transport is anisotropic \cite{13,14} and is consistent with either a quantum smectic or nematic \cite{6} (i.e., “striped”) phase. While it is clear that all of these phenomena derive from strong electron-electron interactions, the exact relationship between the different ground states possible in half-filled Landau levels and the sample parameters necessary to stabilize one phase over another remain open questions \cite{6,10,11}. Access to a greater range of sample parameters than is currently available in high mobility 2DESs may enhance our understanding of these exotic states.

Transport studies of high mobility two dimensional hole systems (2DHSs) offer a complimentary approach to the investigation of correlation physics in 2D systems \cite{12}. The larger effective mass of holes ($m_e \sim 0.5$ vs. $m_e \sim 0.067$, in units of the free electron mass) reduces kinetic energy such that interactions play a more prominent role at a given 2D density. In addition, 2DHSs offer an ideal platform for the study of interesting spin phenomena \cite{13} since spin-orbit coupling plays a significant role through mixing of the light and heavy hole states. Yet, for several practical reasons, far fewer studies have been dedicated to the investigation of half-filled Landau levels in 2DHSs \cite{14}. First of all, it is difficult to produce hole samples of sufficient quality such that correlations at half-filling are evident. More importantly, the exploration of anisotropic behavior in excited hole Landau levels has been hindered by the presence of a significant mobility anisotropy at zero magnetic field. In the past, the highest mobility 2DHSs have been grown on the (311)A orientation of GaAs where the zero field mobility in the [233] direction often exceeds the mobility along the [011] direction by a factor of 2 to 4 \cite{15}. This zero field effect tends to obfuscate studies of anisotropic behavior at higher magnetic fields.

In this Letter we present low temperature magneto-transport measurements of a carbon-doped high mobility 2DHS \cite{16} grown on the (100) surface of GaAs where the zero field mobility anisotropy is approximately 20\%. (This residual anisotropy is also typical in high mobility 2DESs). At T=50mK we observe a pronounced anisotropy in transport at filling factors $\nu=7/2$ and $\nu=11/2$ while the transport at $\nu=9/2$ remains isotropic. At T=50mK, the resistance at $\nu=7/2$ in the [011] direction exceeds the resistance in the [011] direction by a factor \cite{17} of 16. The transport is extremely sensitive to temperature. Isotropic transport is restored at $\nu=11/2$ for temperatures greater than T\approx 80mK and at $\nu=7/2$ for temperatures greater than T\approx 160mK. These results are the first observation of anisotropic behavior in a 2D system in a perpendicular magnetic field at $\nu=7/2$, a state characterized by a quantized Hall effect in clean 2D electron systems. Our results further indicate that 2D hole systems can support an unusual alternating series of anisotropic/isotropic phases at half-filling which is quite distinct from the known behavior of 2D electron systems. We will interpret this new behavior as a result of strong spin-orbit coupling in the 2D hole system.

The samples used in this experiment are 15nm-wide GaAs/AlGaAs quantum wells grown on the (100) surface of GaAs by molecular beam epitaxy. The details of sample growth have been given elsewhere \cite{16}. The samples are symmetrically doped with carbon, yielding a sheet density $p=3.6 \times 10^{11}$cm$^{-2}$ and mobility $\mu=1 \times 10^{6}$cm$^2$/Vs when cooled to T=50mK in the dark. Cyclotron resonance studies of similarly grown carbon-doped quantum wells indicate that the hole effective mass is large, $m_e \sim 0.5$ \cite{18}. The high mobility of $10^{6}$cm$^2$/Vs in light of such a large effective mass attest to the quality of our 2DHS.

The samples are cleaved into 4mm by 4mm squares with eight In(Zn) contacts placed symmetrically around the perimeter of the square. The described transport ex-
FIG. 1: Overview of magnetoresistance in our high-mobility two-dimensional hole system at T=50mK. The blue trace is measured with current flowing in the [01\uparrow] direction. The red trace corresponds to the magnetoresistance with the current flowing in the [01\downarrow] direction. Anisotropic transport is clearly visible at ν=11/2 and ν=7/2 while ν=9/2 remains isotropic.

FIG. 2: Magnetoresistance along [01\downarrow] (red trace) and [01\uparrow] (blue trace) directions at temperatures T=160mK, T=100mK, and T=50mK. The resistance at ν=9/2 increases slightly with decreasing temperature but remains isotropic, while the anisotropies at ν=11/2 and ν=7/2 increase in strength below T=100mK.

FIG. 3: Temperature dependence of the resistance along the [01\downarrow] direction (red) and the [01\uparrow] (blue) exactly at ν=7/2. Below T~100mK, the resistance along [01\downarrow] rises rapidly and is not saturated at our base temperature T=50mK. The resistance along [01\uparrow] continues to decrease down to T=50mK.

Experiments have been conducted with three samples from two distinct wafers. Similar anisotropic behavior is observed in all samples. Magnetotransport measurements are performed in a dilution refrigerator with a base temperature T=45mK using standard low frequency (11Hz) lock-in techniques. The excitation current is kept to ≤10nA where no carrier heating is observed at T=50mK.

Figure 1 presents an overview of transport in our 2DHS for filling factor ν ≥ 2 at T=50mK along the [01\downarrow] and [01\uparrow] directions and contains the central findings of this work. At low magnetic field below B=2.5T the transport is isotropic – the zero magnetic field resistance ratio for this sample is R_{[01\downarrow]}/R_{[01\uparrow]} ≈ 1.4. We note that the resistances along [01\downarrow] and [01\uparrow] have not been scaled to have equal amplitude in the low magnetic field regime. At ν = 11/2 the first indication of anisotropic transport is evident. For current flow along the [01\downarrow] direction a local maximum in the longitudinal resistance is observed. In the [01\uparrow] direction, a weak minimum is present. This anisotropy is extremely sensitive to temperature. While it is clearly visible at T=50mK, the resistance at ν=11/2 is isotropic at T ≥ 80mK (see Fig. 2). At ν=9/2, the resistance is isotropic at our base temperature. At ν=7/2 the resistance again becomes anisotropic. In the [01\downarrow] direction a strong peak in resistance is observed, while in the [01\uparrow] direction a strong minimum in resistance is seen. At T=50mK, the resistance ratio R_{[01\downarrow]}/R_{[01\uparrow]} reaches ~16.

The temperature evolution of the magnetotransport for filling factors between ν=7 and ν=3 is shown in Figure 2. At T=160mK, the resistance at ν=11/2, 9/2, and 7/2 is largely isotropic with little indication of the presence of correlation effects. At T=100mK, ν=11/2 and
ν=9/2 remain isotropic, while a developing anisotropy is visible at ν=7/2. The resistance ratio R_{[011]}/R_{[01\overline{1}]} at T=100mK at ν=7/2 is only ~ 1.8. Upon reducing the temperature to T=50mK, the anisotropy at ν=11/2 becomes clearly visible, although its development is most probably limited by our relatively high base temperature of 50mK [8, 9]. Suprisingly, the resistance at ν=9/2 remains isotropic. At ν=7/2 no indication of a quantized Hall state is present, R_{xy} remains linear such that no developing plateau is evident (not shown). Moreover the longitudinal resistance ratio has risen to R_{[011]}/R_{[01\overline{1}]} ~ 16.

Figure 3 summarizes the rapid low-temperature evolution of the resistance at ν=7/2 from T=275mK down to T=50mK. Above T=150mK the resistance along both directions is approximately 125Ω and shows little variation with temperature. Below T=150mK the resistances change dramatically. Between T=150mK and 50mK the resistance along [011] increases by a factor of 7 and shows no indication of saturation at T=50mK. Conversely, the resistance along [01\overline{1}] has fallen by a factor of 2 from its value at T=150mK and also does not appear saturated.

The observation of isotropic transport for 2D holes at ν=9/2 flanked by anisotropic transport at ν=11/2 and ν=7/2 is the most striking feature of this study. In 2D electron systems which display anisotropic transport, the anisotropy only resides in the N≥2 LL’s and also shows the largest resistance ratio at ν=9/2. In addition, no alternating sequence of anisotropic/isotropic states is observed. Given these unexpected result for 2D holes one can ask if perhaps ν=9/2 is still anisotropic for holes, albeit with different principle axes than the [011] and [01\overline{1}] directions that prevail at ν=7/2 and ν=11/2. In order to investigate this possibility, we measured the resistance with current flowing primarily along the [001] and [010] directions. This configuration amounts to flowing current between two corner contacts, along the diagonal of the square sample. The voltage is monitored using two contacts at the midpoint of sample edges (see Fig. 4). The transport at ν=9/2 remains isotropic indicating that the principle axes of anisotropy has not switched in moving from ν=7/2 to ν=9/2. In addition we observe that the initial anisotropies observed at ν=11/2 and 7/2 are lost with current flow along the [010] and [001] directions, as expected.

Although 2D electron systems do not exhibit anisotropic transport in the N=1 Landau level at ν=5/2 and ν=7/2 in a perpendicular magnetic field, Lilly [4] and Pan [10] have observed that the incompressible quantum Hall states at ν=7/2 and ν=5/2 are replaced by compressible anisotropic states under the application of large tilting angles corresponding to in-plane magnetic field ~ 8T. These results suggest that the physics influencing the formation of compressible striped phases in the N≥2 LL’s may be active in the N=1 LL under the appropriate change of the effective interaction induced by the large in-plane field. In numerical studies, Rezayi and Haldane (RH) [11] have shown that the incompressible quantum Hall state at ν=5/2 is near to a phase transition into a compressible striped phase. In the pseudopotential formulation of the FQHE [19], the nature of the ground state is found to depend sensitively on the relative strengths of the pseudopotential parameters V_1 and V_3, where V_m is the energy of a pair of electrons in a state of relative angular momentum m. RH find that at ν=5/2, small variations in V_1 and V_3 can drive the phase transition and suggest that the proximity of the critical point to the Coulomb potential is the principle reason that transport becomes anisotropic in the tilting experiments.

What distinguishes our 2D hole system from the 2D electron system such that the fractional quantum Hall
state at $\nu=7/2$ is destabilized and replaced by an compressible anisotropic state and the transport at $\nu=9/2$ remains isotropic rather than displaying the anisotropy seen in electron systems? We claim that the strong spin-orbit coupling in the 2DHS is the critical difference. Spin-orbit coupling strongly mixes valence band states, which alters the orbital structure of hole Landau levels at $B \neq 0$ \[20, 21\]. The nature of the single particle wavefunctions that comprise a given LL alters the pseudopotential parameters, significantly influencing the correlations among the holes \[22, 23\]. Following Ref. \[23\], we have self-consistently calculated the Landau level structure in the Hartree approximation (while keeping axial terms as in \[20\]). Within this basis of single-particle states, the pseudopotential parameters for our 2DHS are then calculated. The 4x4 Luttinger Hamiltonian is used to describe the four highest valence bands and the effects of band anisotropy are included in the Luttinger parameters \[13\]. All of the valence LL’s are found to be strongly mixed. At $\nu=7/2$, the valence LL is comprised largely of the N=2 (50%) and N=4 (35%) oscillator functions. At $\nu=9/2$ the dominant oscillator components are N=1 (50%), N=2 (13%), and N=3 (24%). At $\nu=11/2$, N=3 (49%) and N=5 (36%) are most heavily weighted. The results of the pseudopotential calculations are shown in Fig. 5, plotted as $\sqrt{mV_n}/V_1$. For comparison, we also plot $\sqrt{mV_n}/V_1$ for the first five electron Landau levels (assuming an infinitely thin quantum well). Interestingly, the pseudopotential structure for our 2DHS differs significantly from the calculation for electron LL’s at several key filling factors. We begin consideration at $\nu=11/2$. For our 2DHS the pseudopotential structure at small $m$ is quite similar to the N=3 and N=4 electron LL’s. The anisotropic transport seen at $\nu=11/2$ in our 2DHS is thus consistent with the known correlations in the higher electron LL’s \[1, 2\]. At $\nu=9/2$ a quite remarkable change is seen. The pseudopotential ratios $\sqrt{3V_3}/V_1$ and $\sqrt{V_5}/V_1$ are appreciably below the N=2 electron LL, possessing ratios between N=1 and N=2 values. Our calculation indicates that 2DHS LL at $\nu=9/2$ has acquired correlations, at least in part, associated with N=1 LL, consistent with our observation of isotropic transport at $\nu=9/2$. At $\nu=7/2$, an even more dramatic difference between the electron and hole correlations is manifest. All of the pseudopotential ratios for $\nu=7/2$ are far above those of the N=1 electron LL. The calculated pseudopotential ratios rest between the N=2 and N=3 electron LL’s and are larger than those calculated at $\nu=9/2$. The calculated pseudopotential ratios at $\nu=7/2$ suggest an origin to the highly anisotropic transport observed in our 2DHS at $\nu=7/2$. The correlations operational at $\nu=7/2$ are in fact more closely related to the physics of the N$\geq 2$ Landau levels than the N=1 level. Thus our calculation of the pseudopotential ratios specific to our 2DHS provide, at least qualitatively, a consistent picture of the alternating sequence of anisotropic/isotropic transport observed

In conclusion, we observe an alternating sequence of anisotropic/isotropic transport at filling factors $\nu=11/2$, 9/2, and 7/2 in a high quality 2DHS. These results are quite distinct from the known behavior of 2D electron systems. The transport experiments combined with calculations of the Landau level structure and pseudopotential parameters of our 2DHS indicate that the type of correlated ground state observed at a particular filling factor depends sensitively on the nature of the single particle states available to the system. The great flexibility to tune the Landau level structure of a 2DHS through sample design suggests future experiments in which the correlated ground state observed at a given filling factor is constructed by judicious choice of 2DHS sample parameters.

M. J. Manfra thanks R. L. Willett for helpful conversations. Z. Jiang is supported by NSF under DMR-03-52738 and by the DOE under DE-AIO2-04ER46133.

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