Tilt-Induced Anisotropic Phases in Wide GaAs Quantum Wells

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Abstract. Tilt induced anisotropic transport is observed in a series of three wide GaAs quantum wells. In the absence of tilt the transport is isotropic and well developed quantum Hall states are observed. For large values of tilt ($\theta>60^\circ$) the quantum Hall states at $\nu=5$ and 7 are replaced by strongly anisotropic states in the two widest wells, occurring at slightly lower values of $\theta$ for the widest well. A similar transition is also seen at $\nu=9$ in the widest quantum well. This transition is not observed in the narrowest quantum well up to the largest tilt angle measured.

1. Introduction

Two-dimensional electron systems (2DESs) in high mobility GaAs quantum wells produce a variety of interesting quantum phases with increased magnetic field. Among them are the anisotropic states in the $N \geq 2$ Landau levels which occur at half values of the filling factor, such as $\nu=9/2$ [1,2]. These observed anisotropic states are believed to be due to the formation of a unidirectional charge-density wave state, also known as a stripe phase [3,4]. The orientation of these anisotropic phases has been observed to be sensitive to the application of an in-plane magnetic field [5,6].

Much of the experimental work involving stripe phases has been carried out in single layer systems. However in bilayer systems the presence of interlayer coupling may allow for the formation of more exotic phases. Indeed, the possibility of coherent stripe phases has been studied theoretically [7-13]. In particular, a tilt-induced transition from a quantum Hall state to various isospin stripe phases at odd values of filling factor in the $N \geq 1$ Landau levels has been predicted to occur for certain system parameters [9-11]. While experiments [14] with low mobility bilayer samples have shown some preliminary indications for anisotropy at odd $\nu$, unequivocal evidence is still lacking.

2. Summary of Results

In recent experiments we have examined anisotropic transport in three $\text{Al}_{0.25}\text{Ga}_{0.75}\text{As}/\text{GaAs}/\text{Al}_{0.25}\text{Ga}_{0.75}$ wide single quantum wells (WSQWs), with well widths $L=58$, 64, and 70 nm respectively. For sufficiently large values of $L$, the Coulomb interaction causes the electrons to collect near the walls of the quantum well forming an effective bilayer system. In the absence of an in-plane magnetic field, isotropic quantum Hall states are observed. When the two widest quantum wells are adequately tilted,
the quantum Hall states at $v=5$ and $v=7$ disappear and are replaced by anisotropic phases. These data clearly demonstrate a tilt-induced transition from a quantum Hall state to a compressible anisotropic state at $v=5$ and 7. For the widest quantum well, at the largest tilt angle studied, the quantum Hall states at $v=9$ and 11 are also replaced by compressible states with apparent anisotropy at $v=9$. Furthermore, in all samples investigated, anisotropic transport is also seen to emerge at half filling of the total filling factor and is particularly prominent at $v=9/2$ and $v=11/2$.

3. Samples

The WSQWs are modulation doped at a distance of 80 nm from both sides of the quantum well. The samples were cleaved into 5 mm × 5 mm squares and eight equally spaced ohmic contacts were positioned around the perimeter of each specimen to make contact to the conducting channel. The electron densities of each sample varied slightly but were all near $n_e \sim 2.7 \times 10^{11} \text{ cm}^{-2}$ and each had a mobility approaching $\mu \sim 10^7 \text{ cm}^2/\text{V}\text{s}$. Each sample was mounted in the mixing chamber of a dilution refrigerator with a base temperature of $T \approx 20 \text{ mK}$. Transport coefficients were measured as a function of the applied magnetic field, $B$, using a lock-in amplifier technique with an excitation frequency of $\sim 7 \text{ Hz}$ and current of 10 nA. The samples were tilted with respect to the direction of the applied magnetic field using an in situ rotator. The tilt angle, $\theta$, is defined as the angle between the normal vector perpendicular to the 2DEG and $B$ and is experimentally determined by aligning the quantum Hall effect minima at integer filling factors. The perpendicular (parallel) component of magnetic field is denoted by $B_\perp$ ($B_\parallel$).

In the data presented below we focus on results from the sample with a quantum well width of $L=70$ nm. The results of similar experiments conducted with $L=64$ and 58 nm samples will be discussed following the presentation of the $L=70$ nm data.

4. Experimental Results and Discussions

Figure 1 shows the diagonal resistance, $R_{xx}$, and the Hall resistance, $R_{xy}$, for the $L=70$ nm QW with $\theta=0^\circ$. Clear minima are seen at integer values of filling factor, both even and odd, for $v\geq 4$ and $v=2$. At $v=3$ the quantum Hall state is very weak and at $v=1$ the quantum Hall state is missing entirely. In addition, the fractional quantum Hall states surrounding $v=1$ all have even numerators. This behavior is very similar to previous observations in double quantum wells [15] and wide single quantum wells [16] and provides strong evidence that the $L=70$ nm QW is effectively a bilayer system.

Figure 1. $R_{xx}$ and $R_{xy}$ as function of $B$ for the $L=70$ nm quantum well at $T=22 \text{ mK}$. Several integer and fractional filling factors are labeled.
To detect the anisotropy, the diagonal resistance was measured with the current oriented in two perpendicular directions for each sample and each value of $\theta$. The resistance $R_{xx}$ is defined with the excitation current parallel to $B_{\parallel}$ and $R_{yy}$ is defined with the current perpendicular to the direction of $B_{\parallel}$. In the $L=70$ nm case only, $R_{xx}$ was multiplied by a scaling factor of 0.4 to make the amplitude at low field coincide with $R_{yy}$ at $\theta=0^\circ$. This discrepancy was most likely due to the specific contacts used, and does not effect the conclusions drawn from the data, though, it actually reduces the observed anisotropy.

Figure 2 displays typical data showing both $R_{xx}$ and $R_{yy}$ as a function of $B_\perp$ over a large range of $\theta$ for the $L=70$ nm sample. Initially when $\theta=0^\circ$, very little anisotropy is evident and well defined integer quantum Hall minima are present in the displayed range of $B_\perp$. As tilt increases to $\theta=40.3^\circ$, a slight disparity between $R_{xx}$ and $R_{yy}$ is discernable at half total fillings factors $v=9/2$ and $v=11/2$ and weakens with increasing $v$. This anisotropy grows with $\theta$ and is strongest at $\theta=55.4^\circ$. With further increase in tilt to $\theta=61.7^\circ$ the anisotropy weakens and the respective peaks and dips in $R_{xx}$ and $R_{yy}$ move slightly toward adjacent odd filling factors. With another increase in the $\theta$, by a mere 3.1 degrees, to $\theta=64.8^\circ$ a sudden transition occurs at $v=5$ where the minimum corresponding to the quantum Hall state is replaced by a strongly anisotropic state. Another small increase in tilt to $\theta=67.8^\circ$ causes a similar transition at $v=7$. When the tilt angle is increased to $\theta=74.0^\circ$ the quantum Hall states at $v=9$ and $v=11$ also disappear with $v=9$ exhibiting some anisotropy. The anisotropic states, especially at $v=5$ and 7, are characterized by a peak in $R_{xx}$ and a minimum in $R_{yy}$ or, in other words, the easy transport direction is perpendicular to $B_{\parallel}$ and the hard transport direction is parallel to $B_{\parallel}$. The disappearance of the
quantum Hall states and onset of transport anisotropy also corresponds to the disappearance of the quantized plateaus in the Hall resistance, $R_{xy}$. This is shown in Figure 3 where $R_{xy}$ is plotted as a function of $B_{\perp}$ near the transition to anisotropic states for the $R_{yy}$ current configuration. As the data show, the plateau at $v=5$ is absent for $\theta=64.8^\circ$ and both the $v=5$ and 7 plateaus are absent when $\theta=67.8^\circ$. Well defined plateaus at $v=9$ and 11 are not present when $\theta=74.0^\circ$, however, a visible minimum remains in the derivative of $R_{xy}$ at these two filling factors (not shown) in contrast to the situation at $v=5$ and 7. No anisotropy is observed in the Hall resistance.

The strong anisotropy at $v=5$ and 7 is presented in Figure 4 (a-d) at several different temperatures with $\theta=71.2^\circ$. The anisotropy is strongest at the lowest obtainable temperature of $T=22$ mK and rapidly weakens with increasing $T$. The easy direction ($R_{yy}$) increases while the hard direction ($R_{xx}$) decreases with increasing $T$, similar to the anisotropy observed at $v=9/2$ in single layer systems [1,2]. In Fig.4 (e) the ratio $R_{xx}/R_{yy}$ is plotted versus $T$ for both filling factors. Interestingly, the dramatic weakening of the anisotropy occurs for $T<300$ mK which may indicate the importance of correlations.

Before discussing the origin of the anisotropic transport, we argue that it is bilayer in nature. As discussed above, the transport in the absence of tilt suggests that the $L=70$ nm QW is effectively a bilayer system (see Fig 1). In addition to this sample, data were also acquired from $L=64$ nm and $L=58$ nm WSQWs. Magneto-transport data in the absence of tilt for the $L=64$ nm QW show that the bilayer characteristics appear to be weakened compared to the $L=70$ nm data [17]. Anisotropic transport at $v=5$ and 7 was observed in the $L=64$ nm sample but at a slightly larger value of tilt angle ($\theta \approx 70^\circ$) than for $L=70$ nm. In contrast, for the $L=58$ nm sample the transport [17] in the absence of tilt was very similar to what is expected for a single layer and no anisotropy was observed at odd values of $v$ up to the largest investigated angle of $\theta=80.4^\circ$. The presence of anisotropy at odd $v$ in the widest two samples and the absence of anisotropy in the narrowest sample suggest that the anisotropy is a bilayer phenomenon. We also note that a similar type of transition was observed at the even filling factors of $v=4, 6$ and 8 at larger tilt angles ($\theta>80^\circ$) in a narrower QW with $L=35$ nm by Pan et al [18]. This is in contrast to our results which show a tilt-induced transition to anisotropic states at odd values of $v$. The major distinction between our samples and that of Pan et al [18] is the relatively narrow QW width in
the case of the latter whose \( L=35 \) nm sample is basically single layer in nature, albeit with two occupied subbands.

Odd integer quantum Hall states in bilayer systems depend on coherent interlayer interaction and can be described by the so-called \{111\} state [19]. For sufficiently large values of \( B_{//} \) in WSQWs, increases in \( B_{//} \) result in reduced interlayer interaction and tunneling [20] as well as a modest increase in the interlayer separation [21]. Consequently, the \{111\} is suppressed and eventually destroyed with increased \( B_{//} \), and the system behaves as two independent single layer systems each with filling factor \( \nu/2 \). In single layer systems, in the presence of a large parallel magnetic field, the transport at \( \nu=5/2 \) and \( 7/2 \) is anisotropic [5,6]. Therefore it is possible that the onset of anisotropy in our samples at total filling factors \( \nu=5 \) and \( 7 \) may be the result of a transition to two independent layers each with filling factor \( \nu/2 \). In single layer systems, in the presence of a large parallel magnetic field, the transport at \( \nu=5/2 \) and \( 7/2 \) is anisotropic [5,6]. Therefore it is possible that the onset of anisotropy in our samples at total filling factors \( \nu=5 \) and \( 7 \) may be the result of a transition to two independent layers each with filling factor \( \nu/2 \). In single layer systems, in the presence of a large parallel magnetic field, the transport at \( \nu=5/2 \) and \( 7/2 \) is anisotropic [5,6]. Therefore it is possible that the onset of anisotropy in our samples at total filling factors \( \nu=5 \) and \( 7 \) may be the result of a transition to two independent layers each with filling factor \( \nu/2 \).

If the above scenario, i.e., a transition from a \{111\} quantum Hall state to two independent layers, is correct, a similar transition would be expected for larger odd filling factors, as well as for the \( L=58 \) nm sample, provided \( B_{//} \) is large enough. For the \( L=70 \) nm QW, possible evidence for this transition was observed at \( \nu=11 \) (see Fig.2). On the other hand, no anisotropy was observed in the \( L=58 \) nm quantum well up to \( \theta=80.4^{\circ} \), corresponding to a value of \( d/l_{//} \) beyond that of \( d/l_{//} \approx 4.2 \) observed in the other samples.
Another possible explanation for the observed anisotropy at odd $v$ is the tilt-induced onset of a stripe phase. Theoretical work [9-11] has considered the possibility of different stripe phases at odd integer quantum Hall states in WSQWs and bilayer systems. In particular Wang et al. [11] have shown that in a wide quantum well an isospin Skyrmion stripe phase can occur at odd $v$ when $B_y$ is large. A quantitative comparison between our experimental results and the theoretical calculations is not available at the present time, but the calculations at $v=1$ indicate that the transition from an integer quantum Hall state to a stripe phase occurs at large values of $B_y$ as well width is decreased, consistent with our experimental results. Further detailed numerical calculations taking into account our specific sample parameters are needed to shed more light on the observed anisotropy.

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References
[1] Lilly M P, et al. 1999, Phys. Rev. Lett. 82 394.
[2] Du R R, et al. 1999, Solid State Commun. 109, 389.
[3] Fogler M M, Koulakov A A, and Shklovskii B I 1996, Phys. Rev. B 54, 1853.
[4] Moessner R and Chalker J T 1996, Phys. Rev. B 54, 5006.
[5] Pan W, et al. 1999 Phys. Rev. Lett. 83 820.
[6] Lilly M P, et al. 1999, Phys. Rev. Lett. 83 824.
[7] Brey L and H.A. Fertig H A 2000, Phys. Rev. B 62, 10268.
[8] Côté R and H.A. Fertig H A 2002, Phys. Rev. B 65, 85321.
[9] Demler E, et al. 2002, Solid State Commun. 123, 243.
[10] Côté R, et al. 2002, Phys. Rev. B 66, 205315.
[11] Wang D W, Demler E, and S. Das Sarma S 2003, Phys. Rev. B 68, 165303
[12] Papa E, et al. 2003, Phys. Rev. B 67, 115330.
[13] Doiron C B, Côté R, and H.A. Fertig H A 2005, Phys. Rev. B 72, 115336.
[14] Gusev G M, et al. 2007, Phys. Rev. Lett. 99, 126804.
[15] Boebinger G S, et al. 1990, Phys. Rev. Lett. 64, 1793.
[16] Suen Y W, et al. 1991, Phys. Rev. B 44, 5947.
[17] Luhman D R, et al. 2008, Physica E 40, 1059.
[18] Pan W, et al. Phys. Rev. B 64, 121305.
[19] Halperin B I, 1983, Helv. Phys. Acta 56, 75.
[20] Hu J and MacDonald A H, 1992, Phys. Rev. B 46, 12554.
[21] T.S. Lay T S, et al. 1997, Phys. Rev. B 56, R7092.
[22] The value of $d$ was determined from the peak separation in the calculated electron density profile across the quantum well. Finite values of magnetic field were not taken into account, see Ref. [17].