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Fractional quantum Hall effect in high-mobility two-dimensional hole gases in tilted magnetic fields

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The fractional quantum Hall effect (FQHE) has been studied as a function of magnetic field in a series of high-quality p-type GaAs-Al$_x$Ga$_{1-x}$As heterojunctions. The magnetic-field dependence of the $\nu=\frac{4}{3}$ FQHE state, investigated by tilting the samples in the applied field, is consistent with a change in the spin polarization of the ground state. The behavior suggests that the Zeeman splitting of the interacting carriers forming this ground state is larger in this material, at a given magnetic field, than in comparable n-type samples. At high tilt angles, structure is observed to emerge in the second Landau level at $\nu=\frac{8}{3}$.

Recent experimental investigations of the fractional quantum Hall effect (FQHE) in n-type GaAs-Al$_x$Ga$_{1-x}$As heterojunctions have demonstrated that the interacting carriers in certain FQHE ground states are not necessarily fully spin polarized.[1-6] Although the FQHE has been observed in p-type GaAs-Al$_x$Ga$_{1-x}$As heterojunctions (hole gases),[7] this material has been neglected recently because of its relatively low quality in comparison with n-type heterojunctions. We present an investigation of the FQHE in a series of high-quality hole gases as a function of magnetic field, and study the spin polarization of the FQHE ground states of filling factors $1<\nu<2$.

Traditionally, hole gases are grown by molecular-beam epitaxy (MBE) on the (100) GaAs surface and are doped in the Al$_x$Ga$_{1-x}$As with beryllium. However, it is known that growth on the (311)A GaAs surface allows silicon to be used as an acceptor and much higher mobility material can be achieved.[8] We have grown modulation-doped p-type heterojunctions using this technique and have obtained samples with mobilities of up to $\mu=570000$ cm^{2}V^{-1}s^{-1} at 50 mK with carrier densities of $\approx 1.2\times10^{11}$ cm^{-2}.[9] The Fermi energy of such p-type heterojunctions is expected to lie within the heavy-hole band, the twofold degeneracy of which is lifted at the nonzero wave vector by the interface electric field.[10] After growth, the material was wet etched into standard Hall bar geometries orientated on the MBE wafer so that the source-drain current flowed along the $[\bar{2}33]$ crystallographic direction. Ohmic contact was made to the two-dimensional gas by means of annealed gold zinc. The samples were studied in a dilution refrigerator in magnetic fields of up to 13.5 T using conventional four-terminal low-frequency ac lock-in techniques with sample currents of 10 nA. The sample temperature was determined by means of a calibrated four-terminal germanium thermometer situated in a flux-canceled region of the dilution refrigerator mixing chamber.

The Hall (ρ_{xy}) and diagonal (ρ_{xx}) magnetoresistivity of sample No. 1 ($n=1.20\times10^{11}$ cm^{-2}, $\mu=540000$ cm^{2}V^{-1}s^{-1}) at dilution refrigerator base temperature (< 40 mK) are shown in Fig. 1. Minima are observed in the diagonal resistivity at filling factors $\nu=\frac{5}{3}$, $\frac{7}{5}$, $\frac{2}{3}$, $\frac{3}{5}$, $\frac{4}{7}$, $\frac{3}{7}$, and $\frac{2}{5}$, in conjunction with quantized plateaux in the Hall resistance for the more prominent states. The hierarchy of FQHE states is apparent; the $\frac{3}{5}$ and $\frac{4}{7}$ deriving from the $\frac{2}{3}$ parent, and the $\frac{2}{5}$ and $\frac{3}{7}$ deriving from the $\frac{1}{3}$ parent.[11] An unusual aspect of this data, however, is the absence of the $\nu=\frac{4}{3}$ FQHE state, which would have been expected to have occurred at the field indicated in the figure. The observation of the $\frac{7}{5}$ daughter state in the absence of the $\frac{4}{3}$ parent is not consistent with the fully spin-polarized hierarchical model.

Theoretical investigations of the FQHE have demonstrated that at sufficiently low magnetic fields certain FQHE ground states can contain interacting electrons with reversed spins.[12] Although the orbital parameters, such as the Landau-level splitting, depend only upon the normal component of the applied magnetic field in an ideal two-dimensional system, the electron Zeeman energy is independent of the magnetic-field orientation.[13] Thus, tilting the samples destabilizes the reversed spins and causes such FQHE ground states to undergo a transition into a more polarized form. Figure 2 shows the behavior of the FQHE structure $1<\nu<2$ of p-type sample No. 2 ($n=1.20\times10^{11}$ cm^{-2}, $\mu=360000$ cm^{2}V^{-1}s^{-1}) at 50 mK as a function of tilt angle θ—the angle between the sample normal and the magnetic-field direction deter-

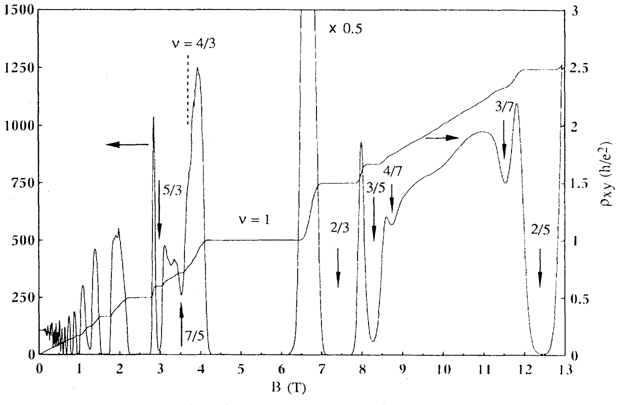

FIG. 1. The Hall (ρ_{xy}) and diagonal (ρ_{xx}) magnetoresistivity of p-type sample No. 1.

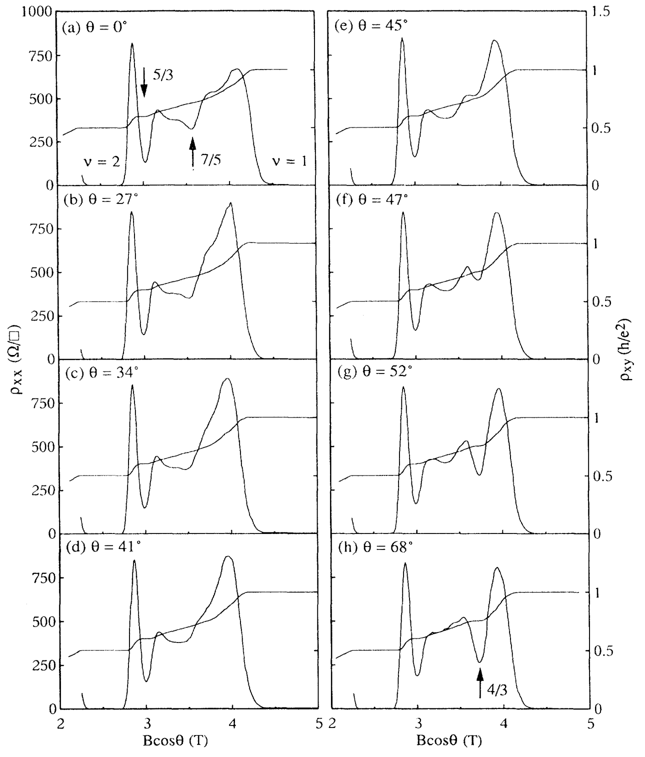

FIG. 2. The FQHE structure $1 < \nu < 2$ of sample No. 2 as a function of tilt angle θ at 50 mK.

mined from the magnetic-field position of prominent diagonal resistivity structure. Only eight tilt angles are shown in this figure, although 29 were investigated in total over the range $0° \leq \theta \leq 81°$. All samples were tilted *in situ* in the dilution refrigerator around an axis directed along the $[01\bar{1}]$ crystallographic direction, perpendicular to the direction of current flow.

In the normal orientation, $\theta = 0°$, a strong resistivity minimum and a quantized Hall plateau were observed at $\nu = \frac{5}{3}$ together with weaker structure at $\nu = \frac{7}{5}$ [Fig. 2(a)]. The $\frac{4}{3}$ FQHE state which would have been expected to have occurred at a total field $B_{4/3} = 3.7$ T was absent. As the sample was progressively tilted, the structure at $\nu = \frac{7}{5}$ weakened and by $\theta = 41°$, when $\nu = \frac{7}{5}$ occurred at $B_{7/5} = 4.7$ T, it was no longer discernible [Figs. 2(a)–2(d)]. At this tilt angle, however, a shoulder had started to become apparent between $\nu = \frac{7}{5}$ and $\nu = \frac{4}{3}$. By $\theta = 45°$ ($B_{4/3} = 5.3$ T), the shoulder had developed into a weak minimum and as the sample was tilted further, this minimum strengthened into a $\frac{4}{3}$ FQHE state, confirmed by the simultaneous development of a quantized Hall plateau at $h/(\frac{4}{3}e^2)$ [Figs. 2(e)–2(h)]. The $\frac{5}{3}$ resistivity minimum and quantized Hall plateau seemed to be largely unaffected upon tilting the sample, although the minimum weakened slightly.

The tilt-angle dependence of the FQHE structure in other p-type samples, No. 1, No. 3, and No. 4, was found to be very similar to that shown in Fig. 2 for sample No. 2, although the precise behavior, such as the field required to recover the $\frac{4}{3}$ state, depended upon the actual sample studied. An investigation of sample No. 3 ($n = 1.23 \times 10^{11}$ cm^{-2}, $\mu = 570000$ cm^{2}V^{-1}s^{-1}) at 50 mK revealed that when this sample was orientated perpendicular to the applied field, both the $\frac{4}{3}$ and $\frac{7}{5}$ FQHE states were absent, although a strong resistivity minimum and Hall plateau were observed at $\nu = \frac{5}{3}$. The $\frac{4}{3}$ FQHE state appeared very rapidly as the sample was tilted—a shoulder became apparent in the diagonal resistivity around $\nu = \frac{4}{3}$ at a total field of only $B_{4/3} = 3.8$ T ($\theta = 7°$), and a well-defined minimum was observed at $B_{4/3} = 4.1$ T ($\theta = 21°$). This minimum simply strengthened as the sample was tilted further, together with the development of a quantized Hall plateau. Again, the $\frac{5}{3}$ structure was not affected appreciably upon tilting. The tilt-angle dependence of the FQHE structure in sample No. 3 ($n = 1.22 \times 10^{11}$ cm^{-2}, $\mu = 450000$ cm^{2}V^{-1}s^{-1}) at 50 mK revealed the destruction of the $\frac{7}{5}$ state by $\theta = 44°$ and the emergence of the $\frac{4}{3}$ at a total field $B_{4/3} = 6.1$ T ($\theta = 52°$). The $\frac{7}{5}$ state was not originally observed in sample No. 4 ($n = 1.20 \times 10^{11}$ cm^{-2}, $\mu = 530000$ cm^{2}V^{-1}s^{-1}), studied at 85 mK, but emerged upon tilting. By $\theta = 52°$ the $\frac{7}{5}$ state had been destroyed and by $B_{4/3} = 6.7$ T ($\theta = 56°$) the $\frac{4}{3}$ started to develop.

To summarize, in all investigations of the FQHE in these hole gases, the $\frac{4}{3}$ FQHE state was absent when the samples were orientated normal to the field but appeared as the samples were tilted. The $\frac{7}{5}$ and $\frac{4}{3}$ FQHE states were never observed together in any of these *in situ* tilting experiments. The $\frac{5}{3}$ states were not observed to be affected appreciably upon tilting. It is noted that the diagonal resistivity zeros and Hall plateau quantization remained good even at the highest tilt angles.

Similar behavior has been observed in the magnetic-field dependence of the FQHE structure in n-type heterojunctions. The experimental data presented in Ref. 2 for an n-type heterojunction of carrier density 1.6×10^{11} cm^{-2} at 120 mK showed that the $\frac{4}{3}$ and $\frac{7}{5}$ FQHE states were present when the sample was orientated normal to the field. However, the $\frac{4}{3}$ state was progressively destroyed as the sample was tilted, and no longer was observed at around $B_{4/3} = 7$ T. Upon further tilting, the $\frac{7}{5}$ daughter state was destroyed prior to the reemergence of the $\frac{4}{3}$, which first became noticeable at around $B_{4/3} = 9$ T. The $\frac{5}{3}$ state was observed to be largely unaffected upon tilting of the sample. An empirical relationship, $B_c = 5.51\sqrt{n}$, has been proposed to relate the critical magnetic field required to destroy the $\frac{4}{3}$ FQHE state (B_c) to the n-type heterojunction carrier density ($n \times 10^{11}$ cm^{-2}).[6] This formula suggests that a critical magnetic field of 6 T ought to be required to destroy the $\frac{4}{3}$ state in heterojunctions of carrier density 1.2×10^{11} cm^{-2}—the carrier density of the p-type material presented here. However, in all of these p-type samples, the $\frac{4}{3}$ FQHE state was absent at $B_{4/3} = 3.7$ T with the sample in the normal orientation and had generally returned by $B_{4/3} = 6$ T, although this emergent field was found to be sample dependent, as detailed above.

The introduction of a parallel field component into a heterojunction can enhance the carrier scattering by pushing the confining wave function into the interface and can increase the FQHE energy gaps by squeezing the two-dimensional sheet, in addition to increasing the Zeeman splitting of the carriers.[14] It has been shown in *n*-type material that the magnetic-field dependence of the FQHE structure is insensitive to whether the samples are tilted or the sample carrier density is changed, demonstrating that the observed behavior is primarily a result of the enhanced Zeeman splitting.[2,5] However, it is known that an in-plane magnetic field can change the Landau-level separation in *p*-type material[15] and so there remains the possibility that the extent of Landau-level mixing[16] could be altered upon tilting. The persistent strength of the $\frac{5}{3}$ state and the destruction of the $\frac{7}{5}$ state demonstrate that neither this nor the effects of wave function squeezing can be the cause of the $\frac{4}{3}$ emergence reported here.

The magnetic-field dependence of the FQHE structure in the hole gases is therefore consistent with the findings in *n*-type heterojunctions and with the theoretical investigations. However, the fact that smaller magnetic fields are required to destroy and return the $\frac{4}{3}$ state in comparison with *n*-type heterojunctions suggests that the Zeeman splitting of the interacting carriers in the FQHE ground states is larger, at a given magnetic field, in the hole gases. In contrast to the behavior of the other FQHE structure that has been observed to undergo a spin transition upon tilting (at $\nu=\frac{8}{5}$ and $\frac{2}{3}$ in *n*-type material[3,5,6]), it is noted that in both *n*- and *p*-type material, the $\nu=\frac{4}{3}$ state remains absent over a finite range of magnetic field. Furthermore, the $\frac{7}{5}$ daughter state which is destroyed prior to the reemergence of the $\frac{4}{3}$ parent is not observed to be recovered at high tilt angles, again in common with studies of *n*-type samples. Clark *et al.*[2] attributed this to the formation of a partially polarized rather than a fully polarized emergent $\frac{4}{3}$ ground state.

At very high tilt angles, structure was observed to develop in the second Landau level. Figure 3 shows the behavior of the FQHE structure $2<\nu<3$ for sample No. 3 as a function of tilt angle θ at 50 mK. At a tilt angle $\theta=72°$, the Hall and diagonal resistivities in this region were featureless, but by $\theta=76°$, a strong minimum had appeared in the diagonal resistivity at filling factor $\nu=\frac{8}{3}$ together with weak structure in the Hall resistance [Figs. 3(a) and 3(b)]. Without a quantized Hall plateau, however, it is not possible to assign this structure conclusively to the $\frac{8}{3}$ FQHE state. Upon further tilting, additional structure was observed to develop on the high-field side of this minimum [Figs. 3(c) and 3(d)]. A similar effect was observed in the lower-mobility sample No. 2 (not shown). In this sample, though, a broader minimum was seen to appear as the sample was tilted between $\theta=78°$ and $80°$, centered at a slightly higher field than $\nu=\frac{8}{3}$. The splitting that was subsequently seen in sample No. 3 was not observed in this particular device.

The emergence of this structure is not understood, although several explanations could be considered. As outlined above, it is possible that the increased confinement caused by the in-plane magnetic field enhances the electron-electron interactions which drive the FQHE. Alternatively, the parallel field component might change the Landau-level mixing, thus, increasing the FQHE gaps as the samples are tilted. It might also be possible for this emergence to be Zeeman driven; the $\nu=\frac{8}{3}$ FQHE state is equivalent to the $\nu=\frac{2}{3}$ state in the lowest Landau level, which is thought to be spin unpolarized at low magnetic fields.[5,6] It is puzzling, however, that the $\frac{7}{3}$ state which is equivalent to the fundamental $\frac{1}{3}$ FQHE state in the lowest Landau level is not observed. The FQHE structure $2<\nu<3$ in *n*-type GaAs-Al$_x$Ga$_{1-x}$As heterojunctions also appears to be anomalous in comparison with that observed in the lowest Landau level.[17] Recent theoretical investigations have indicated that the $q=3$ denominator states are not as pronounced in the second Landau level as in the lowest Landau level.[18]

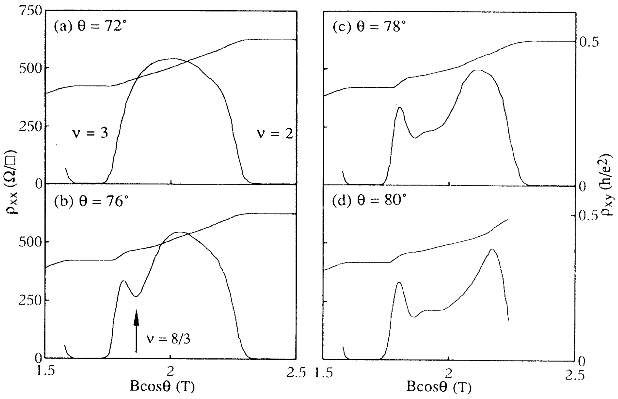

FIG. 3. The FQHE structure $2<\nu<3$ of sample No. 3 as a function of tilt angle θ at 50 mK.

In conclusion, we have studied the FQHE in a series of high-quality *p*-type heterojunctions. The magnetic-field dependence of the FQHE structure $1<\nu<2$ suggests that a spin transition occurs in the ground state of the $\nu=\frac{4}{3}$ FQHE state and is consistent with the behavior observed in *n*-type heterojunctions. The smaller magnetic fields required to destroy and return the $\frac{4}{3}$ state in the *p*-type material in comparison with *n*-type heterojunctions suggest that the Zeeman splitting of the interacting carriers in the FQHE ground states is larger, at a given magnetic field, in the hole gases. At very large tilt angles, structure has been observed to emerge in the second Landau level in the vicinity of $\nu=\frac{8}{3}$. A quantitative investigation of the tilt-angle dependence of the FQHE energy gaps determined from temperature activation studies will be presented elsewhere.

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