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LETTER TO THE EDITOR

Observation of a spin polarization phase transition of the 4/3 fractional quantum Hall state in a high-mobility 2D hole system

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Abstract. We report the observation of a spin polarization phase transition of the $\frac{4}{3}$ fractional quantum hall state of a high-mobility 2D hole system in a GaAs–(Ga, Al)As heterostructure. Mobilities in excess of 1 000 000 $\mathrm{cm^2\ V^{-1}\ s^{-1}}$ are achieved at a density of $0.86 \times 10^{11}\ \mathrm{cm^{-2}}$. The depth of the $\frac{4}{3}$ minimum is seen to weaken as the carrier density is increased before disappearing completely. Upon further increase in carrier density the $\frac{4}{3}$ minimum is re-entrant and proceeds to strengthen. The $\frac{8}{3}$ and $\frac{7}{3}$ states are observed to show apparently anomalous behaviour.

The fractional quantum Hall effect (FQHE) can be observed in sufficiently low-disorder two-dimensional electron or hole systems. This occurs when electron–electron interactions induce low-energy correlated liquid-like states at particular rational fractional values of the Landau level filling factor (ν). The strength of such states therefore depends upon the Coulombic energy. Initially it was assumed that such states would be fully spin polarized. Recently though it has been shown theoretically [1] and experimentally [2, 3, 4] that at sufficiently small magnetic fields, the ground state of certain FQHE states is partially polarized or spin-unpolarized. For such states a phase transition into a spin-polarized state can occur at a critical value of magnetic field (B), at which the Zeeman energy is equal to the difference of the Coulombic energy of the polarized and unpolarized phases. Good experimental evidence for such transitions in the $\frac{2}{3}$, $\frac{4}{3}$, $\frac{2}{5}$ and $\frac{8}{5}$ FQHE states has been found in high-mobility low-density 2D electron systems [2, 3, 4].

Experimentally one can observe such transitions by either varying the carrier density of the sample, which changes the magnetic field at which a given fraction occurs, or by applying a parallel magnetic field. The first approach changes the relative sizes of the Zeeman to Coulombic energies since the former has a B and the latter a $\sqrt{B}$ dependence. However the degree of disorder is also changed since the mobility is a strong function of carrier density in n-type GaAs–(Ga, Al)As heterostructures. In the second approach the Coulombic energy is assumed to be unchanged since, to a first approximation [5], it should depend only on the perpendicular B field component whilst the Zeeman energy depends upon the total B field. Such a parallel field will however also increase the confinement energy, decreasing the spatial extent of the wavefunction. It may also increase the scattering as the wavefunction is pushed into the interface. In either approach one expects a minimum in the FQHE energy gap at some critical magnetic field. Indeed it has been shown theoretically that it is possible for the FQHE energy gap to be zero for a certain range of B around the transition [6]. This effect was first observed for the $\frac{4}{3}$ state which though present at small and large B is absent

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around a critical field of $\simeq$ 8 T [2]. Similar behaviour has also been observed for the $\frac{2}{3}$ and $\frac{3}{5}$ states [3, 4]. Further evidence that helps to confirm the spin-unpolarized nature of the $\frac{4}{3}$ state at low Zeeman energy is provided by studies at high pressure [7] and in narrow quantum wells [8] for which the Landé g^* factor is reduced.

The FQHE effect in p-type GaAs–(Ga, Al)As heterostructures has not been extensively studied. This is because until very recently the quality of such heterostructures was very much poorer than the available n-type devices. Recently however much higher mobilities have been achieved by growth on the GaAs (311)A surface on which silicon is incorporated as an acceptor. Davies *et al* [9] were able to obtain mobilities up to 570 000 cm^2 V^{-1} s^{-1} at carrier densities of 1.2×10^{11} cm^{-2} on this plane. This has recently been further improved upon in a series of samples of exceptionally low density and high mobility ($n = 2.6$ to 12.5×10^{10} cm^{-2}, $\mu = 3$ to 8×10^5 cm^2 V^{-1} s^{-1}) [10] and a high-density gated sample which has $\mu = 1.2 \times 10^6$ cm^2 V^{-1} s^{-1} when the current direction is parallel to [$\bar{2}$33] and $\mu = 4.5 \times 10^5$ cm^2 V^{-1} s^{-1} when it is perpendicular to this direction at a carrier density of $n = 3.3 \times 10^{11}$ cm^{-2} [11].

Davies *et al* [9] present evidence for the $\frac{4}{3}$ state being unpolarized and the $\frac{5}{3}$ state being polarized for their hole gases. At zero parallel field they find the $\frac{4}{3}$ state is absent and the $\frac{7}{5}$ state is present for $n = 1.2 \times 10^{11}$ cm^{-2}. On tilting the $\frac{7}{5}$ disappears and the $\frac{4}{3}$ appears as happens for electron systems [2]. However, due to the high carrier density of their sample they were not able to see a re-entrant behaviour.

In this letter we present measurements on a GaAs–(Ga, Al)As 2D hole sample grown on the (311)A plane oriented with the current parallel to the [$\bar{2}$33] crystal direction. The carrier density could be increased by infra-red illumination providing a range $n = 0.84$ to 1.45×10^{11} cm^{-2} giving a mobility which increased with density from 1.26 to 1.34×10^6 cm^2 V^{-1} s^{-1} at 100 mK. The details of how such mobilities, which are the highest reported to date, are achieved will be discussed elsewhere. The fact that the mobility is a very weak function of density is particularly useful in the present study since the effect of disorder on the FQHE states should not change appreciably with density. Transport measurements using standard low-frequency lock-in techniques at excitation currents of 10 nA were made in a dilution refrigerator at a carefully maintained temperature of 100 mK.

Figure 1 shows the evolution of the FQHE states, indicated by minima in the longitudinal resistance (R_{xx}), in the second and third Landau levels as the carrier density is increased. At the lowest carrier density (0.86×10^{11} cm^{-2}, figure 1(a)) we see clear minima at both the $\frac{5}{3}$ and $\frac{4}{3}$ FQHE filling factor. The $\frac{5}{3}$ fraction is clearly present at all densities and can be seen to strengthen progressively as the magnetic field for this filling factor increases (figure 2(a)). In contrast the $\frac{4}{3}$ FQHE minimum slowly weakens with the increase in density until a density of $\simeq 1.35 \times 10^{11}$ cm^{-2} ($B = 4.18$ T) is reached, where it can no longer be seen (figure 1(h)). At the densities where the $\frac{4}{3}$ state has become very weak we see the onset of a weak minimum at $\frac{7}{5}$ (figures 1(g), (h) and (i)). As the density is further increased the $\frac{4}{3}$ minimum re-emerges at a density of $\simeq 1.40 \times 10^{11}$$cm^{-2}$ ($B = 4.34$ T) and then progressively strengthens.

The development of the $\frac{5}{3}$ and $\frac{4}{3}$ fractions can be more easily seen by plotting the difference between the FQHE minimum and the resistance peak nearest to this value, as a function of carrier density (figures 2(a) and 2(b) for the $\frac{5}{3}$ and $\frac{4}{3}$ fractions respectively). This is not an absolute measure of the strength of the fractional state and full activation studies are needed to quantify this effect. However it is a good qualitative measure of the strength of the features and enables the effects of small background increases in resistance with carrier density to be eliminated. It can clearly be seen that the $\frac{5}{3}$ fraction continuously strengthens

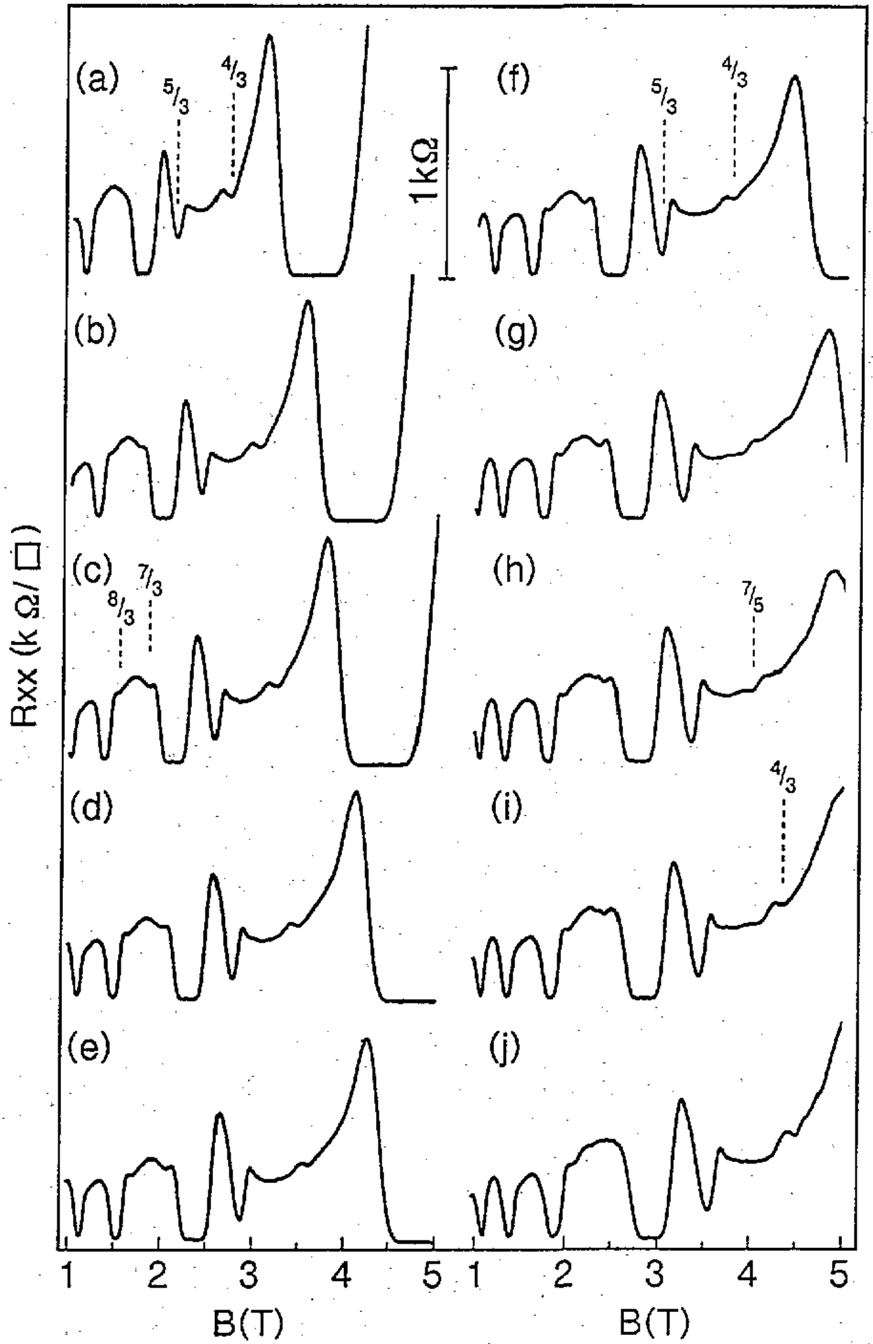

Figure 1. The magnetoresistance R_{xx} at a range of densities ((a) 0.86, (b) 0.98, (c) 1.04, (d) 1.09, (e) 1.17, (f) 1.21, (g) 1.32, (h) 1.36, (i) 1.40 and (j) 1.45 $\times 10^{11}$ cm^{-2}) showing the development of the $\frac{4}{3}$, $\frac{5}{3}$, $\frac{7}{3}$ and $\frac{8}{3}$ FQHE minima.

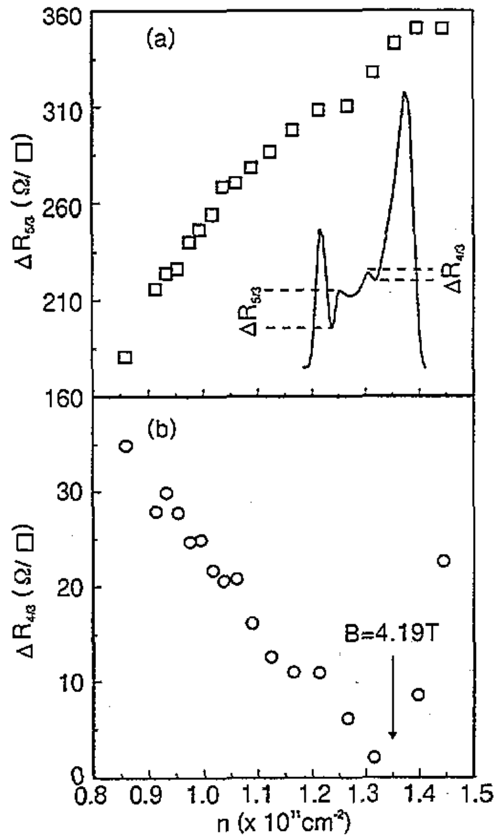

Figure 2. The development of the $\frac{5}{3}$ and $\frac{4}{3}$ FQHE minima (figures 2(a) and 2(b) respectively) as a function of carrier density. The definitions of $\Delta R_{\frac{5}{3}}$ and $\Delta R_{\frac{4}{3}}$ are shown in the inset to figure 2(a).

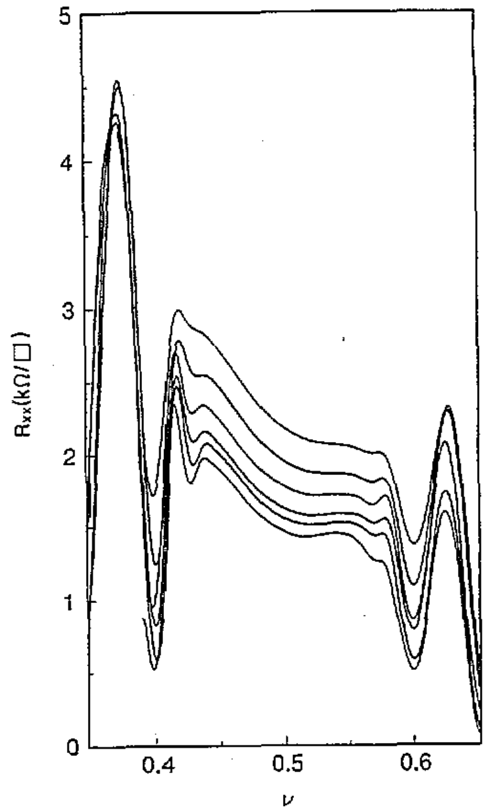

Figure 3. The magnetoresistance R_{xx} at a range of densities (from the top 1.14, 1.24, 1.30, 1.40, 1.50 and 1.55 $\times 10^{11}$ cm^{-2}) versus filling factor for the front gated sample.

with density (or equivalently magnetic field). The $\frac{4}{3}$ state shows a continuous weakening until it is no longer observable before rapidly strengthening again at higher densities.

The observed behaviour at higher densities is similar to that seen in 2D hole systems by Davies *et al* [9] who see the $\frac{4}{3}$ state emerge at *B*-field values of 4.1, 5.3, 6.1 and 6.3 T in different samples. They also find that the $\frac{7}{5}$ state is only ever present when the $\frac{4}{3}$ is absent. However our re-entrant behaviour occurs over a very narrow range of *B* yielding a well defined critical field of $B_c = 4.1 \pm 0.1$ T . In the re-entrant transitions of the $\frac{4}{3}$ state observed by Clark *et al* [2] the state was absent in the range 7 to 9 T for an electron gas with $n = 1.6 \times 10^{11}$ cm^{-2} in a tilted field study. They found similar behaviour when n was varied. Our observed sharp transition is very similar to that seen at *low* fields for the $\frac{2}{3}$ and $\frac{3}{5}$ states which occur over ranges of *B* as small as 0.1 T [3, 4]. The most significant difference in behaviour of the $\frac{4}{3}$ FQHE state in the hole gas is that B_c is about half the value.

The 2D hole system in GaAs–(Ga, Al)As heterostructures differs from the 2D electron system in several significant respects. The cyclotron effective mass at low field is $m^* \simeq 0.3\ m_e$ [12] which is about five times larger. This reduces the spatial extent of the wavefunction making the 2D hole system closer to the ideal 2D system. This would be expected to increase the FQHE gap energies but the effect on the *difference* in the Coulombic energy of the $\frac{4}{3}$ spin-unpolarized and spin-polarized states is unclear. The high mass will also lead to much stronger Landau level mixing and this results in very different behaviour at small filling factors where Wigner crystallization seems to occur at a density dependent filling factor [10, 13]. This could also lead to very different behaviour at low B in the 2D hole system and it is perhaps surprising that the FQHE results are so similar between the 2D electron and hole systems. The final difference is that it is believed that the Landé g^* factor is higher in the 2D hole system [14], calculations yield a value of $g^* \simeq 1.2$ compared with the value of $g^* \simeq 0.4$ for the electron case. As Davies *et al* argue this would be the most likely explanation of the lower B_c in this system since the Zeeman energy would reach the critical value at lower fields. A larger g^* would also lead to the Zeeman energy varying more rapidly with B which may partially account for the sharper transition we observe.

The high quality of the sample can be seen by the emergence of the $\frac{7}{3}$ and $\frac{8}{3}$ FQHE minima at fields below 2 T (figure 1(c)). This is the first reported observation of these states in a 2D hole system in non-tilted fields. Both states at first progressively strengthen with field but the $\frac{7}{3}$ is seen to disappear at the highest densities (figure 1(j)) with the $\frac{8}{3}$ also beginning to weaken at these densities. This behaviour would be consistent with an increase in disorder despite the apparent zero-field mobility. The behaviour at these fractions needs further investigations before the significance of the results can be assessed. It is however consistent with the behaviour seen by Davies *et al* who saw the emergence of the $\frac{8}{3}$ state but no $\frac{7}{3}$ state at large tilt angles. Such behaviour does not seem consistent with existing theory which suggests that the $\frac{8}{3}$ state should be unpolarized and the $\frac{7}{3}$ state polarized. However at these low fields in these high-mass systems the Landau level mixing will be extremely strong and the standard theory may not be a good guide to the expected behaviour.

We have also investigated the density dependence of the $\frac{2}{3}$, $\frac{3}{5}$, $\frac{2}{5}$, $\frac{1}{3}$ and $\frac{2}{7}$ FQHE states (figure 3). Measurements were made on a front gated high-mobility 2D hole system at 300 mK—the sample was a different GaAs–(Ga, Al)As (311)A plane heterostructure to that described above. By applying a positive bias to the gate the carrier density could be linearly reduced from 1.6 to 1.1×10^{11} cm^{-2} whilst the mobility remained constant at $\simeq 5.0 \times 10^5$ cm^2 V^{-1} s^{-1}. All the minima deepen monotonically with increasing magnetic field. The resistance of the minima all show very good $\ln R_{xx} \propto \sqrt{B}$ dependence. This is consistent with fully spin polarized ground and first excited states.

In conclusion we have made the first observation of re-entrance of the $\frac{4}{3}$ FQHE state in a 2D hole system. The behaviour is consistent with a spin polarization phase transition. The $\frac{8}{3}$ and $\frac{7}{3}$ FQHE states, which are observed for the first time in a 2D hole system without parallel field, are found to show apparently anomolous behaviour. All the lower filling factor FQHE states investigated are consistent with fully polarized states.

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