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LETTER TO THE EDITOR

Integer quantum Hall states in coupled double electron gas systems at mismatched carrier densities

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Abstract. We have used gated double two-dimensional electron gas (2DEG) samples in a study of the integer quantum Hall effect at mismatched carrier densities. For weakly coupled samples, the Landau level occupancy associated with the upper and lower 2DEGs may be identified for all gate voltages and magnetic fields. Strong integer states are only seen when an integer number of Landau levels are occupied in each subband. The strongly coupled sample has two magnetic field regimes with differing behaviour. At low fields, the quantum Hall states associated with two subbands are seen, and the device behaviour is similar to that of the weakly coupled sample, whilst at high fields, quantum Hall states are observed which are continuous over the full range of mismatched densities. The magnetic fields at which these quantum Hall states are seen correspond to the total number of carriers in the two subbands filling an integer number of Landau levels. Our studies show that the observed transition is driven by the degree of coupling between the 2DEGs rather than the inter-layer separation.

Devices with two two-dimensional electron gases (2DEGs) have been used to study a range of physical phenomena. With a large separation between the layers, Coulomb drag effects may be investigated [1, 2]. Reducing the inter-layer distance increases the coupling energy and allows electrons to tunnel from one 2DEG to the other. In this regime of coupling, observations have been made of resistance resonances [3, 4], and the formation of a Coulomb gap [5] at high magnetic fields. Of recent interest has been the observation of missing quantum Hall (QH) states [6, 7], at matched carrier densities, in coupled 2DEG devices. This result has been attributed to Coulomb interactions destroying the symmetric–antisymmetric energy gap (Δ_{SAS}) [8]. In addition, new QH states have been observed due to the presence of correlation between the layers [9]. These previous studies have focused on the behaviour at matched carrier densities, whereas here we report upon the development of QH states over a wide range of mismatched carrier densities. We find that in the weakly coupled samples, QH states due to the filling factors within the individual top and bottom 2DEGs may be identified. In contrast, as the coupling is increased features are seen at fields corresponding to the filling factor of the total carrier density. This transition is found to be driven by the combination of inter-layer coupling and magnetic field.

In our work, we have used GaAs/AlGaAs heterostructures grown by molecular beam epitaxy (MBE) upon (100) GaAs substrates. Electrons are confined to two GaAs quantum wells (QWs) of 150 Å width separated by a barrier layer of either $Al_{0.33}Ga_{0.67}As$ or AlAs. Carriers are supplied by modulation-doped AlGaAs layers situated above and below the two wells. Optical lithography and wet etching were used to define a Hall bar mesa and

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Table 1. Growth parameters of the samples including their mobilities and densities in the dark. Also shown are the self-consistently calculated coupling energies.

Sample	Barrier material	Barrier (Å)	Wells (Å)	Δ_{SAS} (μeV)	N_{Top} ($\times 10^{15}$ m^{-2})	N_{Bottom} ($\times 10^{15}$ m^{-2})	μ_{Top} (m^2 V^{-1} s^{-1})	μ_{Bottom} (m^2 V^{-1} s^{-1})
T225	$Al_{0.33}Ga_{0.67}As$	300	150	0.36	1.33	1.33	105	116
T224	$Al_{0.33}Ga_{0.67}As$	25	150	1600	0.80	0.85	70	54
T239	AlAs	25	150	514	1.19	1.06	158	114

AuGeNi ohmic contacts were made that penetrated both 2DEGs. A surface Schottky front gate enabled the density of the 2DEGs to be controlled. The growth characteristics of the three samples used in this work are shown in table 1, together with their calculated coupling energies Δ_{SAS}. Device T239 had an AlAs barrier, so the barrier height is 1050 meV compared with 270 meV in $Al_{0.33}Ga_{0.67}As$. Thus, the coupling energy is reduced whilst maintaining the same separation between the 2DEGs. Experimentally, we measured both the longitudinal resistance (R_{xx}) and the Hall resistance (R_H) of the device as functions of the front gate bias (V_{fg}) for different applied fields. Measurements were made with the sample at a temperature of 1.5 K and the magnetic field applied perpendicular to the growth plane.

Figures 1–3 show the longitudinal resistance for the different samples as functions of gate voltage and magnetic field. In these greyscale plots the darker the shading the lower the longitudinal resistance; thus the positions of resistance minima associated with the QH states appear black. As the gate voltage is made increasingly negative the upper 2DEG, closest to the gate, will screen the lower 2DEG from the applied bias until it is depleted. Thereafter the lower 2DEG density is decreased. Depletion of the upper and lower 2DEGs occurs at gate biases of -0.3 V and -0.8 V respectively for T224, and -0.5 V and -1.0 V respectively for T225 and T239.

Figure 1 shows the data for the most weakly coupled sample: T225. For gate voltages $V_{fg} < -0.5$ V, the top 2DEG is unpopulated and a set of dark lines are seen fanning back to the zero-field depletion point of the bottom 2DEG. This fan corresponds to the filling of Landau levels (LLs) in the bottom 2DEG. For $V_{fg} > -0.5$ V, the top 2DEG starts to populate and screens the bottom 2DEG from any further changes in the gate voltage. The Landau levels of the bottom 2DEG thus remain at fixed magnetic fields and so appear as horizontal lines. A second fan now emerges corresponding to the population of LLs in the top 2DEG. When both layers are occupied, we can, therefore, still identify the filling factors of the separate 2DEGs. Note that at the intersections of the integer LLs, a darker region is observed at which the resistance falls and a Hall plateau is obtained. The labelling of these intersections is of the form $\nu_{\mathrm{Total}}(\nu_B, \nu_T)$, where the total filling index ν_{Total} is determined from the Hall plateau and ν_T and ν_B are the filling indices of the top and bottom 2DEGs respectively. At these points, the Hall resistance is given by $R_H = (h/e^2)/(\nu_T + \nu_B)$. If we consider the matched carrier region, shown by the vertical dashed line, we only see even-integer filling factors indicating that the carrier densities in the two subbands are equal.

The same measurements were also performed on sample T224 (figure 2), which had a much smaller inter-layer separation than sample T225. By Fourier transforming the low-field magnetoresistance data from this sample we can identify the carrier densities of the two subbands as functions of gate bias. As seen in figure 4, the coupling causes an anticrossing of the two subbands at resonance. Self-consistent calculations show that in this region the wavefunctions have symmetric and antisymmetric forms. At resonance both the even and

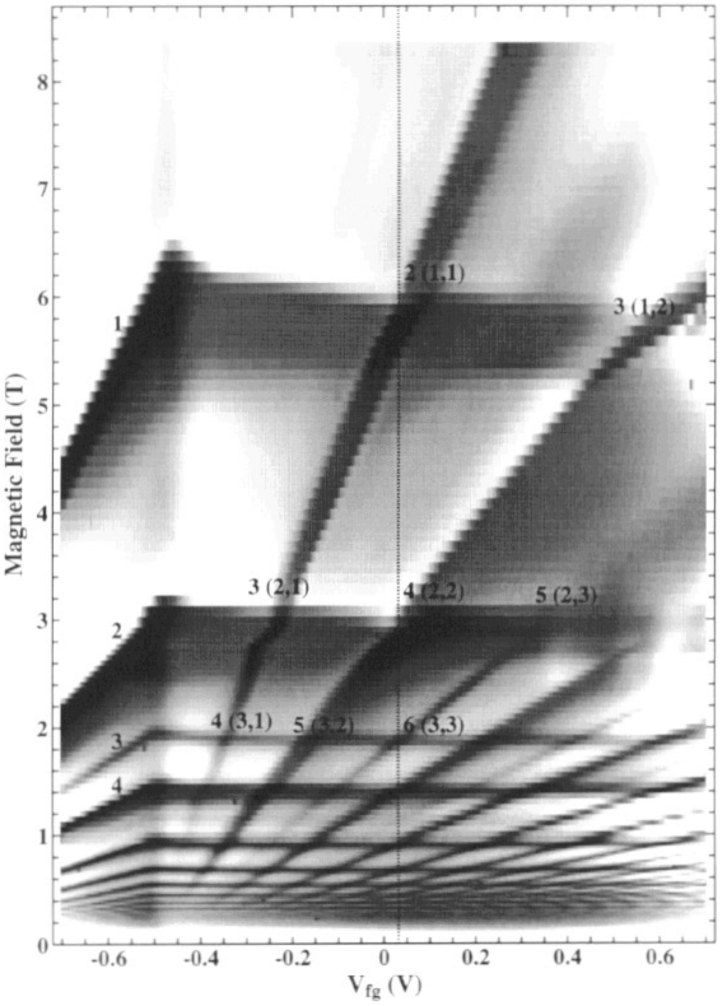

Figure 1. Data for the most weakly coupled device T225 at a temperature of 1.5 K. The greyscale shows the longitudinal resistance as a function of both the front gate voltage (V_{fg}) and the perpendicular magnetic field. The darker regions indicate a lower resistance. The labelling of the quantum Hall states is of the form $\nu_{\mathrm{Total}}(\nu_T, \nu_B)$. Here ν_{Total} is the filling index, determined from the Hall plateau, and ν_T and ν_B are the filling indices of the upper and lower 2DEGs respectively. The vertical dashed line indicates the resonance position.

odd QH states are visible. The odd states, however, are obscured by thermal broadening at 1.5 K and their appearance was confirmed by lower-temperature measurements. This is in agreement with the observation of odd-integer QH states [6, 7] due to the formation of symmetric–antisymmetric states separated by an energy gap Δ_{SAS}.

For sample T224 away from resonance, the development of the QH states may be divided into two regimes. At low magnetic fields, integer quantum Hall states are seen when both the upper and lower 2DEGs occupy an integer number of Landau levels. The two periods in the low-field magnetoresistance data (figure 4) confirm that the population of each subband may be identified. We can, therefore, see that the development of the quantum

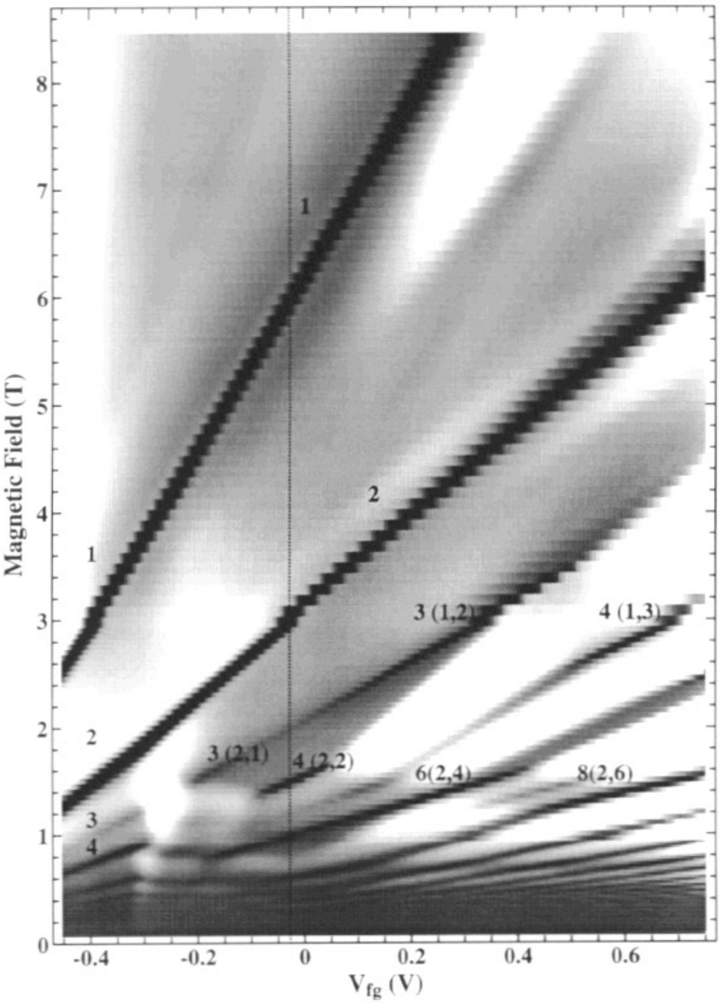

Figure 2. Data for the most strongly coupled device T224 at a temperature of 1.5 K. The greyscale shows the longitudinal resistance as a function of both the front gate voltage (V_{fg}) and the perpendicular magnetic field.

Hall states at low fields is similar in both the weakly and strongly coupled samples. At higher magnetic fields the $\nu_{\mathrm{Total}} = 1$ and $\nu_{\mathrm{Total}} = 2$ states are seen to be continuous across the full gate bias range. These bilayer QH states evolve continuously from the single-layer $\nu = 1$ and $\nu = 2$ states seen at large negative gate voltages $V_{fg} < -0.3$ V. For the filling indices $\nu_{\mathrm{Total}} = 1$ or 2 we are unable to assign separate filling indices to the two subbands, and the Fourier transform of the higher-field data shows only a single period. The behaviour of the QH states at high fields is thus very different to the development of the QH states in the weakly coupled sample.

Measurements, shown in figure 3, were also performed on a third sample, T239. This had an identical inter-layer separation to T224, but by using an AlAs barrier the coupling was reduced. In this device the $\nu = 1$ and $\nu = 2$ states are no longer seen to be continuous

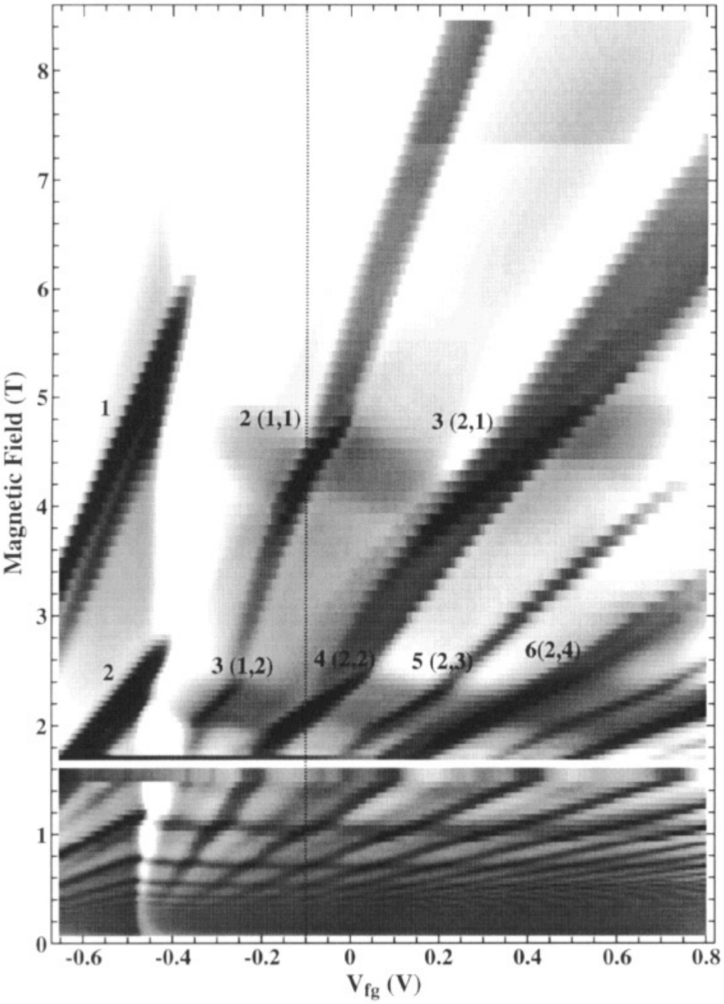

Figure 3. Data for sample T239 at a temperature of 1.5 K. The barrier width is the same as for T224 but the coupling is reduced by using an AlAs barrier. The greyscale shows the longitudinal resistance as a function of both the front gate voltage (V_{fg}) and the perpendicular magnetic field. There are no data for a magnetic field of 1.6 T and this is seen as a horizontal white line.

across the full carrier density range. As in device T225, the integer QH states now only form at the intersections of the upper and lower 2DEG Landau levels. The different behaviour of the samples is also illustrated in the magnetoresistance data shown in figure 5. The gate voltage at which each trace was taken was $V_{fg} = +0.2$ V. Both the weakly coupled T225 and AlAs barrier devices show characteristic interference in the magneto-oscillations due to different densities in each of the subbands. Sample T224 shows such interference at low fields, but very pronounced $\nu = 1$ and $\nu = 2$ states at high fields. The results from these samples indicate that the transition between the low- and high-field behaviour in the strongly coupled T224 device is related to the coupling energy, and hence the degree of tunnelling, rather than the wavefunction separation.

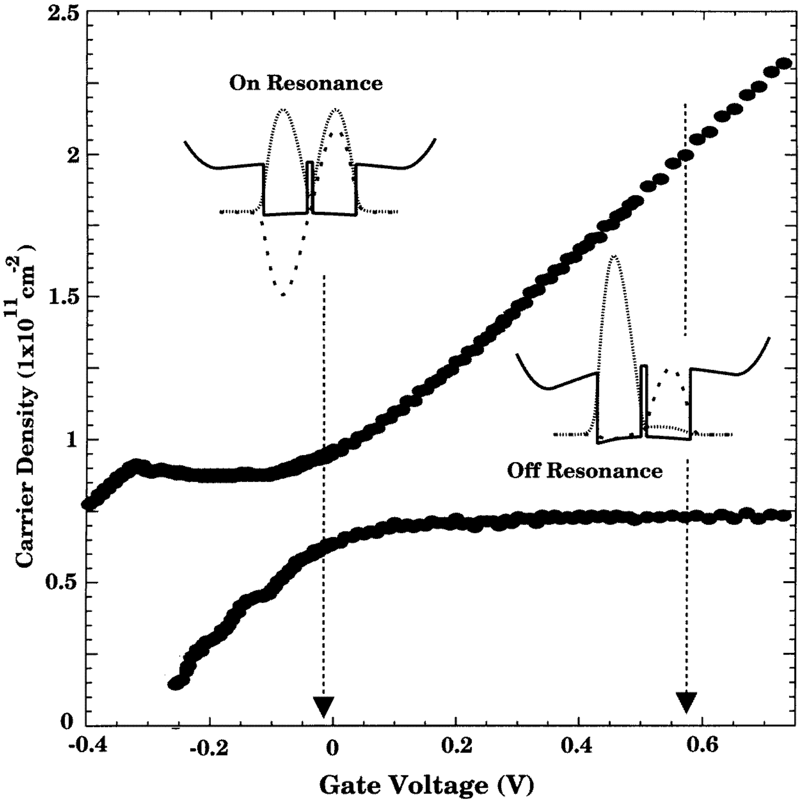

Figure 4. Upper and lower carrier densities in T224 as a function of the front gate bias as determined from the Fourier transformation of the magnetoresistance oscillations. The insets show self-consistent calculations of the wavefunctions on and off resonance.

This study of coupled 2DEGs is different to that in [5] and [6], which concentrated on matched carrier densities. In the latter work odd-integer QH states, seen due to the presence of the tunnelling gap Δ_{SAS}, were destroyed as the intra-layer Coulomb energy increased [8]. A phase diagram for this transition, comparing the single-particle tunnelling gap Δ_{SAS} with the inter-layer separation d (both scaled by $l_b^{-1} = (eB/\hbar)^{0.5}$), has been derived [8]. A further modification to this phase diagram included a transition to a many-body QHE in the limit where $d/l_b \approx 1$ and $\Delta_{SAS} \to 0$ [9]. For our strongly coupled sample (T224) all of the odd-index QH states are seen at resonance. This is in agreement with the theory of [8] where our sample with $\nu = 1$ ($d/l_b = 1.64$, $\Delta_{SAS}/(e^2/\varepsilon_0 l_b) = 0.14$) lies within the phase diagram's 'QHE' regime. This phase diagram, however, is for 2DEGs at resonance where the wavefunctions associated with each 2DEG are in their symmetric and antisymmetric forms. As shown in the insets to figure 4 the self-consistently calculated wavefunctions, away from resonance, are localized within the wells, as opposed to being extended across both. This phase diagram is thus inappropriate for describing our data away from resonance.

We suggest two possible explanations for the behaviour of the integer QH states in the strongly coupled sample. The first of these is the redistribution of charge with applied magnetic field. At mismatched carriers, the wavefunctions are predominantly localized within the QWs and filling factors may be identified in the upper and lower 2DEGs.

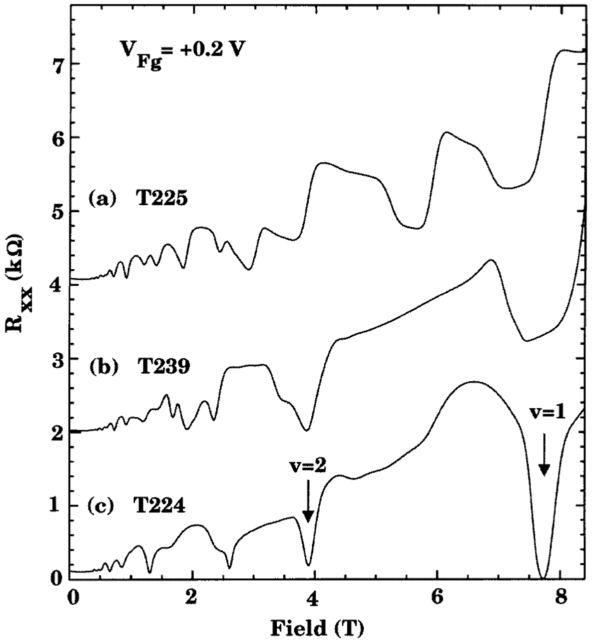

Figure 5. Data from (a) T225, (b) T239 and (c) T224 showing the magnetoresistance oscillations at 1.5 K. The gate voltage in each case was +0.2 V and the traces are offset by 2 kΩ for clarity.

Although the addition of a perpendicular field has little effect upon the form of the wavefunction, the magnetic quantization will affect the electrostatic band potentials. In order to maintain a constant total carrier density, the Fermi energy may oscillate; thus charge redistribution could occur and lead to the preferential population of one energy level [10]. This continual redistribution of charge would be enhanced at high fields when the LL spacing is large. It could, therefore, account for the continuity of the $\nu = 1$ and $\nu = 2$ states in T224. It is, however, unclear as to why the coupling should be so important. Alternatively, inter-layer correlations may play a part in stabilizing QH states. In this case, the total filling factor may determine the compressibility of the system, even at mismatched carrier densities. As illustrated on the phase diagram of [9], there is a transition to a many-body QHE as the conditions $d/l_b \approx 1$ and $\Delta_{SAS} \to 0$ are satisfied. It is possible that the lower QH states, $\nu \leqslant 2$ within our sample, enter such a regime as the device is taken off resonance. As Δ_{SAS} decreases, however, the sample would pass through a 'no QHE' region, contrary to our observations that the observed states are continuous. A study on the bilayer $\nu = 1$ state in [7] suggested a *continuous* evolution from a single-particle QHE to a many-body QHE as the coupling was altered which is more in agreement with our observations. Finally, we note that the $\nu = 1$ and $\nu = 2$ states are seen at comparatively high temperatures (1.5 K) for many-body effects.

In summary, we have studied the integer QH states in samples of differing coupling energy and wavefunction separation as a function of the mismatched carrier densities. The most strongly coupled sample ($\Delta_{SAS} = 1.6$ meV) showed continuous $\nu \leqslant 2$ QH states across the full gate range. The low-field behaviour of the same sample, though, is shown to be comparable to that of a weakly coupled device. The study of another sample, with $\Delta_{SAS} = 0.51$ meV, but the same barrier thickness, showed this observation to be related to the strength of the tunnelling between the 2DEGs, not the inter-layer separation. The cause of the transition in the strongly coupled samples is not fully understood, but we discuss the possibility of either (i) charge redistribution such that the system appears to behave as a single 2DEG, or (ii) stabilization of QH states off resonance by inter-layer correlations.

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