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# Observation of correlated $\nu = 1$ quantum Hall and insulating states in strongly coupled p-type double quantum wells

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**Abstract**

We present magnetotransport results for strongly coupled p-type double quantum wells which demonstrate the existence of a correlated $\nu = 1$ quantum Hall state in the limit of weak tunnelling. Our results are in good agreement with the finite-temperature phase transition predicted for this state. We also observe an activated insulating behaviour for $\nu < 1$, which may be evidence of a correlated bilayer Wigner state.

*Keywords:* Electrical transport measurements; Gallium arsenide; Heterojunctions; Magnetic measurements; Quantum effects; Semiconductor–semiconductor heterostructures

In single-layer two-dimensional (2D) conductors, the integer quantum Hall effect (IQHE) arises when the Fermi energy lies in the region of localised states between Landau levels. The fractional quantum Hall effect (FQHE) arises from the intra-layer Coulombic interaction which leads to transitions into correlated liquid-like ground-states when the Landau level filling factor $\nu$ has particular odd-denominator fractional values. In these cases, there exists a finite gap separating the many-body ground state from the lowest-lying excited state. When two such 2D layers are in close proximity, the interlayer Coulombic interaction can lead to further new correlated states. In particular, new FQHE states are possible when the filling factor in each layer is an even-denominator fraction.

In a double-layer system, the quantum Hall effect at a total Landau level filling factor $\nu = 1$ (i.e. $\nu = 1/2$ in each layer) can arise in two ways. If tunnelling is strong, a normal single particle state can occur in which the energy gap is that separating the lowest symmetric and antisymmetric states of the system ($\Delta_{SAS}$). A new many-body $\nu = 1$ state is also predicted to occur for sufficiently strong interlayer Coulombic interaction, even in the absence of tunnelling [1]. In n-type GaAs/GaAlAs double-layer systems at small layer separation, when the interlayer Coulombic energy is large, tunnelling also tends to be strong due to the small electron effective mass. This makes the unambiguous identification of the nature of the state difficult. $\nu = 1$ states consistent with the expected behaviour

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of the correlated state have been observed in a series of n-type double quantum wells which have $\Delta_{SAS}$ values as low as 0.8 K [2]. However, in these samples, tunnelling still plays an important role, as is shown in tilted field experiments [2]. Complex behaviour has also been observed in very wide quantum wells which have some bilayer character but which also have very large $\Delta_{SAS}$ [3]. It is clear from these studies that interlayer correlations are important in stabilising the observed $\nu=1$ states. However, the prediction of a $\nu=1$ state in the limit of small $\Delta_{SAS}$ has still not been directly demonstrated experimentally.

In this paper we will concentrate on results for high mobility p-type double quantum wells for samples from one MBE-grown (311) wafer (NU1174), though the $\nu=1$ state is observed in samples with appropriate densities from several wafers. Each quantum well is 100 Å wide and they are separated a 30 Å AlAs barrier, as shown in the insert of Fig. 1. The total carrier density and the relative densities in the two wells can be controlled using front and back gates, and can be accurately determined from the Fourier transform of the low-field Shubnikov–de Haas oscillations. As grown, the carrier density in each well for NU1174 samples is within 5% of $1.1\times10^{15}$ m$^{-2}$ and the average mobility is 400 000 cm$^2$/V·s. The mobility is found to be a very weak function of carrier density, as is the case for p-type heterostructures [4]. The high hole-mass leads to weak tunnelling, even at small layer separation. The potential and density distribution for this structure, shown in Fig. 1, was obtained by solving the Poisson equation and the one-electron Schrödinger equation self-consistently. A parabolic dispersion with a mass of $0.45m_0$ was used, and many-body effects were included in the local-density approximation. This yields a weakly hole-density dependent $\Delta_{SAS}$ of $\sim$70 mK.

Fig. 1 shows the typical behaviour of the longitudinal resistance $R_{xx}$ and the Hall resistance $R_{xy}$ when the hole number densities in the two wells are balanced. Fig. 2 shows the temperature dependence of $R_{xx}$ at $\nu=1$ for a series of total densities with equal hole densities in each well. As can be seen, strong $\nu=1$ quantum Hall states are observed which have activation energies of up fifty times $\Delta_{SAS}$. The states at $\nu=3, 5, 7$ ... are all absent, as expected for weak tunnelling. This is direct unambiguous proof of the existence of the correlated $\nu=1$ state in the limit of weak tunnelling. In the

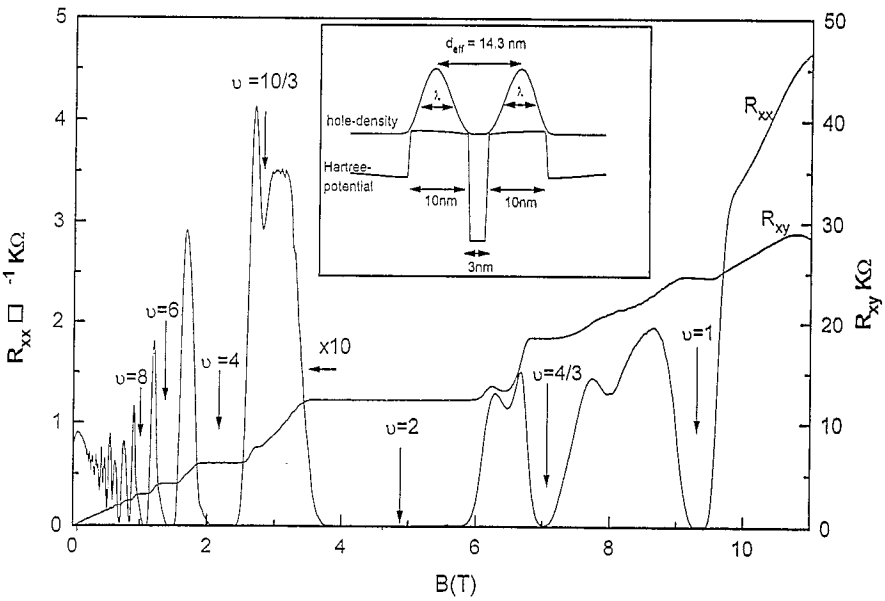


Fig. 1. Typical $R_{xx}$ and $R_{xy}$ results (at 60 mK) for equal hole number densities of $1.1\times10^{11}$ cm$^{-2}$ in each well. Insert: calculated potential profile and hole density distribution.

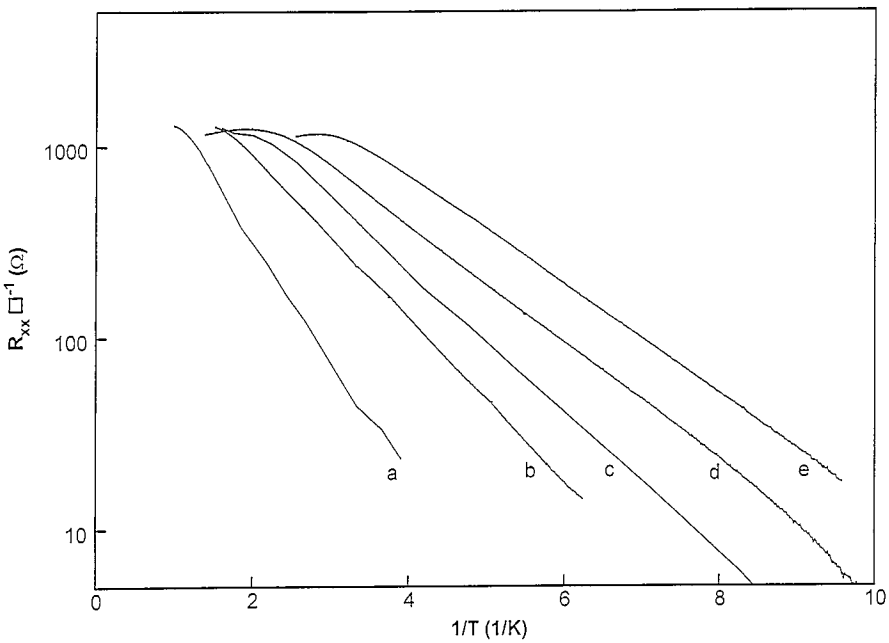


Fig. 2. Activation plots at $\nu=1$ ($\nu=1/2$ in each well) for a series of total number densities with activation energies $\Delta E$ (defined by $\rho_{xx} \propto \exp(-\Delta E/2k_BT)$) in K given in parentheses. (a) $1.61\times10^{11}$ cm$^{-2}$ (2.9 K), (b) $2.08\times10^{11}$ cm$^{-2}$ (1.9 K), (c) $2.23\times10^{11}$ cm$^{-2}$ (1.7 K), (d) $2.29\times10^{11}$ cm$^{-2}$ (1.4 K) and (e) $2.33\times10^{11}$ cm$^{-2}$ (1.3 K).

corresponding electron samples, less clear-cut behaviour is observed, with typically the higher order integers 5, 7 ... present, 3 absent and 1 present [2].

It is predicted that the correlated state should only be present when the ratio of the interlayer Coulombic energy is sufficiently large. A measure to the intralayer of this is the ratio of the layer separation $d$ to the magnetic length $l_B$. Recent theoretical calculations find that the state should only be present for $d/l_B<1.6$ [1]. We find that the state systematically weakens with increasing total carrier density, as shown in Fig. 3. This is in complete contrast with all the single-layer IQHE and normal FQHE states, which all strengthen with increasing density. It is, however, in agreement with the prediction that the correlated state will weaken with increasing $l_B$ since the increased density moves the $\nu=1$ state to higher $B$. We find that the state is destroyed as $d/l_B$ approaches $\sim1.7$, in agreement with theory. Previous results on 180 Å wide n-type double wells [2] indicate a critical value of $\sim2$. We attribute our better agreement with theory to the smaller finite thickness corrections for our 100 Å quantum wells and the smaller values of $\Delta_{SAS}$. In fact, as the insert to Fig. 1 shows, there are two effects which can be thought to modify the Coulombic interactions and lead to a new effective $(d/l_B)_{eff}$. First, repulsion between the holes in the wells moves the peaks in the probability densities apart, increasing the effective layer separation $d_{eff}$. Second, the finite thickness softens the intrawell Coulombic interaction. One can estimate this second effect by replacing $l_B$ by $(l_B^2+\lambda^2)^{1/2}$, where $\lambda$, the layer thickness, is taken to be the width at half height of the calculated probability density. This is about 5 nm. In our samples, these two effects are both small and also tend to cancel each other, giving $(d/l_B)_{eff}\approx(d/l_B)$, as is apparent from Fig. 3. This goes some way to account for the remarkably good agreement between our measurements and theory. The finite thickness correction will be more important for the wider well samples of Murphy et al. [2], increasing the critical $(d/l_B)$.

The correlated $\nu=1$ state is of particular interest since it is predicted that a finite-temperature Kosterlitz–Thouless transition may occur [1].

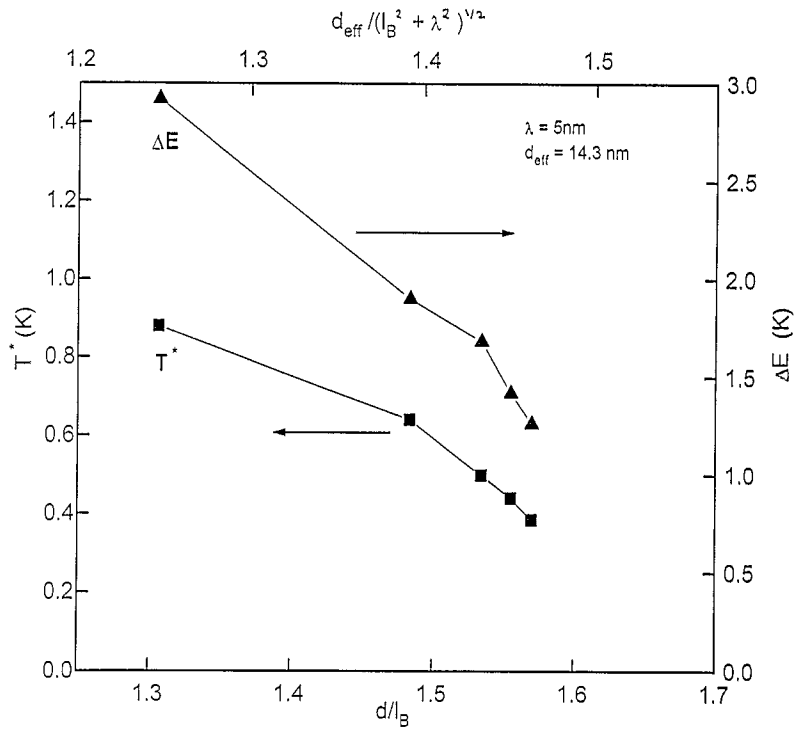


Fig. 3. Dependence of the activation energy $\Delta E$ and critical temperature $T^*$ on $d/l_B$ (lower scale) and $(d/l_B)_{eff}=d_{eff}/(l_B^2+\lambda^2)^{1/2}$ (upper scale) obtained for the same densities as those of Fig. 2. $T^*$ is taken as the point where the extrapolated activation line crossed the horizontal line through the saturation resistance value.

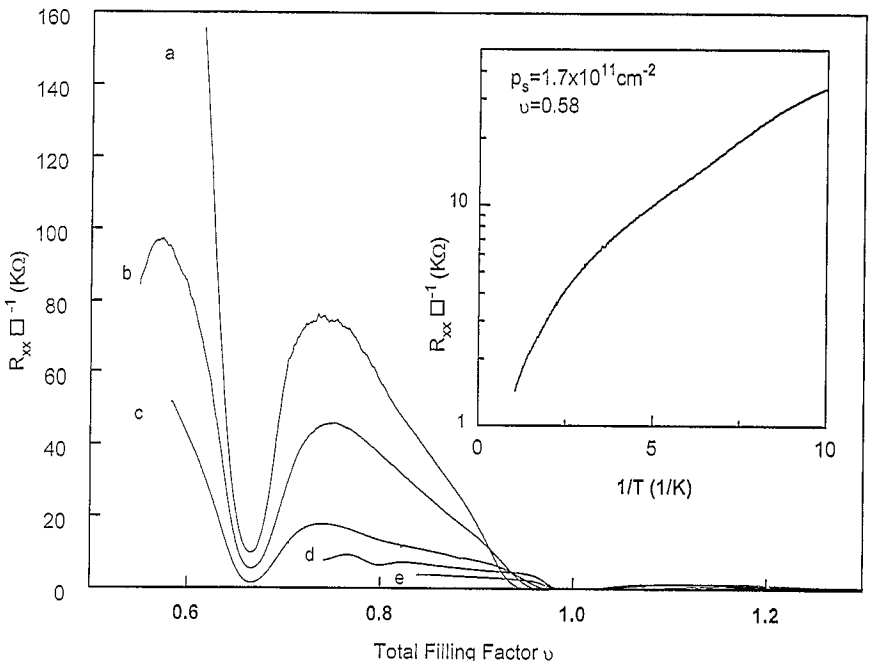


Fig. 4. Evolution of the insulating state with decreasing total hole density at 80 mK. (a) $1.49\times10^{11}$ cm$^{-2}$, (b) $1.59\times10^{11}$ cm$^{-2}$, (c) $1.65\times10^{11}$ cm$^{-2}$, (d) $1.69\times10^{11}$ cm$^{-2}$ and (e) $1.71\times10^{11}$ cm$^{-2}$. Insert activated behaviour at a single density.

Evidence for such a transition has been found recently in wide parabolic quantum wells [5]. We find qualitatively similar behaviour in our samples, but are also able to make direct comparison with theory since we are in the limit of small $\Delta_{SAS}$. As Fig. 2 shows, the state shows activated behaviour at low enough temperatures but is unobservable above a critical temperature $T^*$. This temperature is considerably less than the activation temperature, and so the behaviour is consistent with the predicted finite-temperature phase transition in which the activation gap disappears at $T^*$. As Fig. 3 shows, $T^*$ tends to zero as $d/l_B$ or $(d/l_B)_{\text{eff}}$ approaches $\sim 1.7$, in agreement with the theoretical prediction [1].

At the lowest densities, a direct transition from the $\nu=1$ quantum Hall state into an activated insulating state occurs, followed by a re-entrance of the fractional quantum Hall state at $\nu=2/3$ (1/3 filling factor in each well), as shown in Fig. 4. In single-layer electron gases, insulating behaviour for $\nu<2/9$ followed by a re-entrance of the 1/5 state has been shown to be consistent with Wigner crystallisation [6]. For single-layer hole gases, similar behaviour around for $\nu<2/5$ and re-entrance of the 1/3 state has been taken as evidence of stabilisation of the Wigner state by Landau level mixing [7]. The observed behaviour is consistent with a correlated bilayer Wigner solid in which the additional interlayer Coulombic interaction stabilises the solid state. The strength of the insulating state correlates well with that of the $\nu=1$ state, supporting the idea that it is also stabilised by bilayer correlations.

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