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# Studies of the extreme quantum limit of 2D hole systems

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**Abstract**

We present electrical transport and photoluminecence results for high mobility p-type GaAs/(AlGa)As systems. We observe transitions into an insulating state characterized by an activation energy and a threshold electrical field at a (density-dependent) Landau level filling factor. A new line also appears in the photoluminescence spectra at filling factors close to those at which the insulating state occurs. All our observations are similar to those in high mobility 2D electron systems but a larger filling factors as would be expected for a Wigner solid stabilised by the larger Landau level mixing.

At sufficiently low temperatures and disorder one expects two-dimensional electrons or holes to form a Wigner solid when $r_s$, the ratio of the Coulombic energy to the Fermi energy is large. $r_s$ is proportional to $m^* n_s^{-1/2}$ where $m^*$ is the effective mass and $n_s$ is the carrier number density. Calculation gives a critical value of $r_s > 37$ for zero magnetic field [1]. In the magnetic quantum limit the kinetic energy of the carrier is effectively quenched and a magnetically induced Wigner crystal is predicted to occur below a critical Landau level filling factor $\nu_c \sim 1/6.5$ [2] in the limit of *small* $r_s$. When $r_s$ is not small one has significant Landau level mixing which can stabilise the Wigner state leading to a larger $\nu_c$ [3]. In Fig. 1 we show a schematic zero temperature phase diagram for two-dimensional carriers drawn to be consistent with the calculated critical $r_s$ values for the fractional quantum Hall effect (FQHE)–Wigner transition at $\frac{1}{3}$ and $\frac{1}{5}$ [3] and the insulating transitions observed in two-dimensional electrons [4] and holes [5, 6]. For electrons in GaAs/AlGaAs heterostructure $r_s$ is always small since it is proportional to the effective mass. With increasing field (decreasing $\nu$) one goes through a series of FQHE states. Then for $\nu$ just above $\frac{1}{5}$ and again below $\frac{1}{5}$ a transition into an activated insulating state occurs though the FQHE is still the ground state at $\frac{1}{5}$. Coincident with the occurrence of the insulating state a new line in photoluminescence appears. Recently very high quality p-type GaAs/AlGaAs heterostructure and quantum wells with mobilities in excess of $10^6\,\mathrm{cm^2\,V^{-1}\,s^{-1}}$ have been produced [7, 8]. In such low disorder samples one expects to see similar behaviour to that observed for electrons except that the $r_s$ values will be about six times higher because of the high effective mass [9]. As indicated in Fig. 1 this opens up the possibility of observing the insulating state at large $\nu$, re-entrance of the insulating state around other fractions and since $r_s$ is inversely proportional to the square

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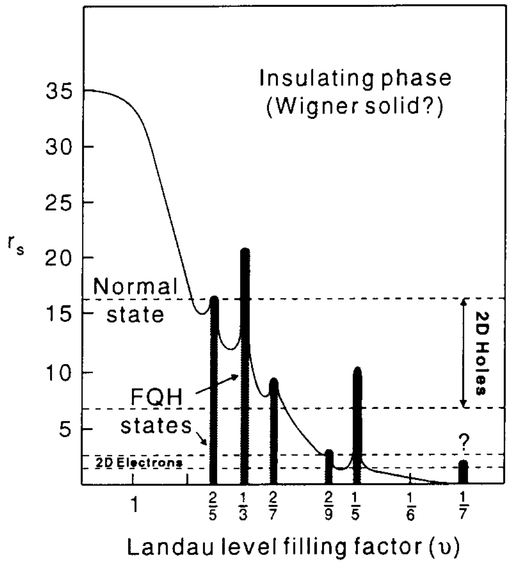


Fig. 1. A schematic representation of the zero temperature $r_s$–$v$ phase diagram of two-dimensional carriers.

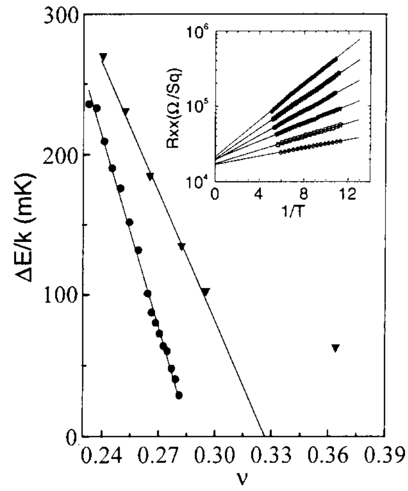


Fig. 2. Landau level filling factor dependence of the activation energy, $\Delta E$, for two hole samples with densities of $1.6 \times 10^{11}\,\mathrm{cm}^2$ (●) and $6.2 \times 10^{10}\,\mathrm{cm}^2$ (▼). Inset showing the activated behaviour ($\ln R_{xx} = \Delta E/k_B T$) for the lower density sample.

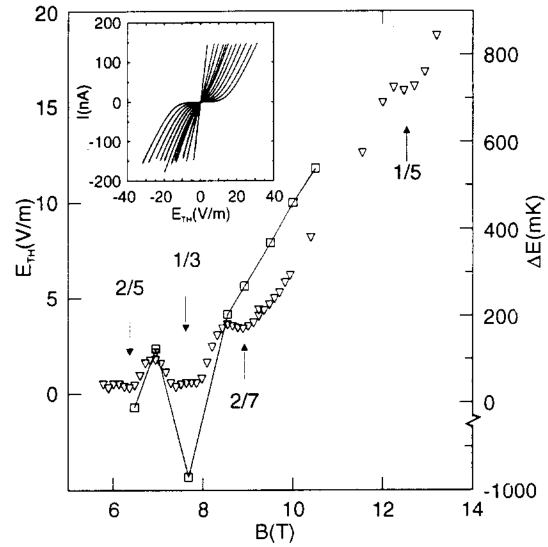


Fig. 3. Activation energy $\Delta E$ (□) and threshold electric field $E_{\mathrm{TH}}$ (▽) (determined from the non-linear $I$–$V$ characteristics measured at 85 mK shown in the inset for $B = 7.6\,\mathrm{T}$ ($v = \frac{1}{3}$, linear) to $B = 12\,\mathrm{T}$ (strongly non-linear)) showing re-entrant behaviour around $\frac{1}{5}$. For ease of display all the negative values are scaled by 1/10th.

root of the carrier density, a density-dependent transition.

For high hole densities ($> 10^{11}\,\mathrm{cm}^{-2}$) a transition into an insulating state is observed for $v < \frac{1}{5}$ with a weak re-entrance of the $\frac{2}{7}$ fraction [5, 6]. As the density is lowered the $r_s$ value at any given fraction only increases slowly since the cyclotron mass, which gives the Landau level separation and thus the Landau level mixing, falls with decreasing field [9]. However for densities of $\sim 5 \times 10^{10}\,\mathrm{cm}^{-2}$ $r_s$ is $\sim 13$ and one observes an activated insulating state, for $\frac{2}{5} > v > \frac{1}{3}$ as well as for $v < \frac{1}{3}$ while the FQHE state occurs at $v = \frac{1}{3}$ [5]. In order to try quantify the density dependence of $v_c$ we have studied in detail two samples with densities $6.2 \times 10^{10}\,\mathrm{cm}^{-2}$ ($\mu = 850\,000\,\mathrm{cm}^2\,\mathrm{V}^{-1}\,\mathrm{s}^{-1}$) and $1.6 \times 10^{11}\,\mathrm{cm}^{-2}$ ($\mu = 200\,000\,\mathrm{cm}^2\,\mathrm{V}^{-1}\,\mathrm{s}^{-1}$) (see Fig. 2). For $v < \frac{1}{3}$ we find that $R_{xx} = R_0 \exp\,(\Delta E/k_B T)$ with the activation energy given by $\Delta E = k_B T_0\,(1 - v/v_c)$. The $T_0$ values for the two samples, 1000 and 1400 mK, are a little over twice the classical melting temperatures of 433 and 660 mK. The critical filling factor inferred in this way is clearly higher for the lower density sample. However, around $\frac{1}{3}$ the FQHE is observed and $\Delta E$ is not simply linear in $v$ in the low density sample but is re-entrant. This is shown in Fig. 3. Between $\frac{2}{5}$ and $\frac{1}{3}$ $\Delta E$ rises to a maximum of $\sim 100\,\mathrm{mK}$ while it is negative at $\frac{2}{5}$ and $\frac{1}{3}$ (note change of scale in figure). In the insulating state one finds strong non-linear current–voltage behaviour of the form shown in Fig. 4. Here the continuous line is the data and the points are fits to the function $I = I_0 \sinh(E/E_0)$. If the fit is shown as a continuous line it also exactly overlays the data. This is the form expected for a pinned hole lattice for electric fields less than the critical value above which one has

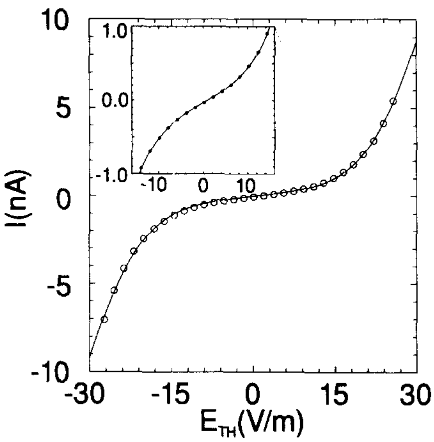


Fig. 4. Current–electric field behaviour in the insulating state at 85 mK and 12 T. The lines are the data and the points are a fit to $I = I_0 \sinh(E/E_0)$ with $E_0 = 9.9$ V/m.

strong de-pinning and a current proportional to applied voltage [10]. The fit is remarkably good until a value $E_{TH}$ above which we see an almost constant relatively low differential resistance. One can use $E_0$ or $E_{TH}$ to characterize this behaviour. Both show the same behaviour as a function of filling factor and temperature. Results for $E_{TH}$ are shown in Fig. 4. $E_{TH}$ is re-entrant around $\frac{1}{3}$ and also shows a minimum at $\frac{2}{7}$ FQHE state which also produces a clear minimum in the longitudinal resistance $R_{xx}$. Most interestingly $E_{TH}$ also has a minimum at $\frac{1}{5}$ despite the absence of a minimum in $R_{xx}$ which has risen to $\sim 50\,\mathrm{M\Omega}\,\square^{-1}$ at $\frac{1}{5}$ at 100 mK with $i = 0.1$ nA. This would seem to be an indication of the co-existence of the $\frac{1}{5}$ FQHE state and the insulating state. Such co-existence has been suggested as an explanation of photoluminescence result at $\frac{1}{7}$ and $\frac{1}{5}$ in electron gases [11].

We have performed photoluminescence (PL) measurements on two hole quantum well samples which have densities and mobilities similar to that of the low density sample considered above. In the low field regime the PL signal consists of two lines which we attribute to intrinsic recombination from the ground and first excited subband of the 2D holes. In both samples at high fields (estimated $\nu = 0.35$) we observe a dramatic decrease of the integrated intensity of the spectra accompanied by the appearance of a new line approximately 0.6 meV below the lower peak. This new line changes little with temperature up to 0.9 K and then shows activated behaviour before disappearing at about 2.5 K. This is similar to the behaviour observed for Be $\delta$-doped n-type heterostructures which has been attributed to Wigner solid formation [11]. The photo-luminescence results are presented in detail elsewhere [12]. Simulataneous transport and optical measurements are underway to clarify the relationship between the observed behaviour.

In conclusion we observe behaviour in both transport and PL around $\nu = \frac{1}{3}$ which are in very good agreement with observations made in 2D electron systems around $\nu = \frac{1}{5}$. This is consistent with the formation of a magnetically induced Wigner solid stablised by strong Landau level mixing.

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