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Physica B 249–251 (1998) 705–709

**PHYSICA B**

## Metal–insulator transition at $B = 0$ in an ultra-low density two-dimensional hole gas

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### Abstract

We have observed a metal–insulator transition in an ultra-low density two-dimensional hole gas formed in a high-quality GaAs–AlGaAs heterostructure at  $B = 0$ . At the highest carrier density studied ( $p_s = 2.2 \times 10^{10} \text{ cm}^{-2}$ ,  $r_s = 16$ ) the hole gas is strongly metallic, with an exceptional mobility of  $425\,000 \text{ cm}^2 \text{ V}^{-1} \text{ s}^{-1}$ . The low disorder and strength of the many-body interactions in this sample are highlighted by the observation of re-entrant metal–insulator transitions in both the fractional ( $\nu < \frac{1}{3}$ ) and integer ( $2 > \nu > 1$ ) quantum Hall regimes. On reducing the carrier density the temperature and electric field dependence of the resistivity show that the sample is still metallic at  $p_s = 1.3 \times 10^{10} \text{ cm}^{-2}$  ( $r_s = 21$ ), becoming insulating at  $p_s \approx 1 \times 10^{10} \text{ cm}^{-2}$ . Our results indicate that electron–electron interactions are dominant at these low densities, pointing to the many-body origins of this metal–insulator transition. We note that the value of  $r_s$  at the transition ( $r_s = 23 \pm 2$ ) is large enough to allow the formation of a weakly pinned Wigner crystal, and approaches the value calculated for the condensation of a pure Wigner crystal. © 1998 Elsevier Science B.V. All rights reserved.

**Keywords:** Metal–insulator transitions; Two-dimensional hole systems; Wigner solid

The scaling theory of localisation [1] predicts that there is no metallic phase in two-dimensional systems at zero magnetic field as  $T \rightarrow 0$ , and therefore there can be no metal–insulator transition (MIT), in agreement with early experiments on low-mobility silicon MOSFETs [2]. At low temperatures a dilute two-dimensional system is therefore always insulating and various models exist to

describe the nature of this insulating state. These range from the single-particle Anderson insulator in the case of strongly disordered systems [3] to the formation of a pinned Wigner crystal for clean systems with very low disorder [4].

In contradiction to the expectations of scaling theory however, several recent experiments on comparatively high-mobility electron gases in silicon MOSFETs have provided evidence of a metal–insulator transition at zero magnetic field [5,6]. The nature of this transition and its physical origins are not presently understood, however, it

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should be noted that in the original scaling theory electron–electron interactions were not included. In particular, electron–electron interactions become important at low densities in precisely the regime where the MIT is experimentally observed and will be dominant if the disorder is low enough.

This work provides the first evidence of a MIT at  $B = 0$  in GaAs/AlGaAs heterostructures. Using a back gate we study the transition from a strongly metallic state to an insulating state at  $B = 0$  in an extremely high-quality, low-density two-dimensional hole gas as the carrier density is reduced. The large effective mass ( $m^* \approx 0.3m_e$ ) and the extremely low disorder (with mobilities an order of magnitude larger than in Si MOSFETs) enhance interaction effects, the strength of which are characterised by the dimensionless parameter  $r_s$ , the ratio of the Coulomb interaction energy to the kinetic (Fermi) energy given by  $r_s = m^*e^2/(4\pi\epsilon\hbar^2\sqrt{\pi p_s})$ , where  $p_s$  is the sheet carrier density. The MIT observed in electron gases in Si MOSFETs occurs at  $r_s \approx 10$  [5,6]; in contrast, for our hole gas samples we observe strongly metallic behaviour at  $r_s = 16$  with a MIT occurring at  $r_s = 23 \pm 3$ . This value of  $r_s$  is significantly larger than that found for the MIT observed in Si MOSFETs and is approaching the value of  $r_s$  at which Wigner crystallisation is expected to occur in a perfectly clean 2D system ( $r_s = 37 \pm 5$ ) [7].

The heterostructure used in this study (T129) was fabricated by MBE growth on the (3 1 1) A surface of GaAs, utilising silicon as the acceptor dopant [8]. The structure consisted of a 300 Å p-type modulation doped GaAs quantum well with a 1600 Å  $\text{Al}_{0.33}\text{Ga}_{0.67}\text{As}$  spacer and an average distance of 2100 Å between the carriers and the remote impurities. Samples were patterned into Hall bars of size  $60 \times 600 \mu\text{m}$  aligned in the  $[\bar{2}33]$  direction. Two different samples were studied from the same wafer: Sample 1 was measured in the mixing chamber of a dilution refrigerator; sample 2 had an external metal plate approximately 500  $\mu\text{m}$  away from the 2DHG acting as a back gate and was measured on a cold finger. In both cases, magnetotransport measurements were made in the dark at a frequency of below 10 Hz, with a current of  $< 2 \text{ nA}$  (sample 1) or an excitation voltage of  $V_{\text{AC}} < 100 \mu\text{V}$  (sample 2).

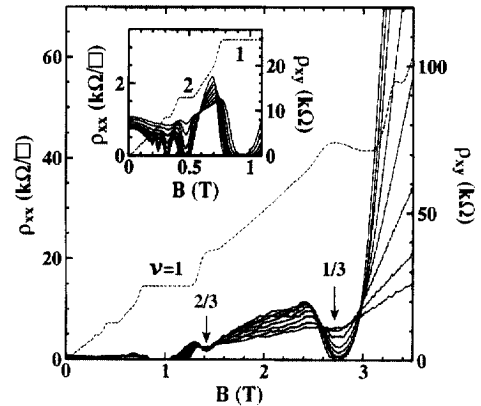


Fig. 1. Magnetotransport data for sample 1, measured at  $T = 50, 77, 98, 133, 180, 240, 333$  and  $425 \text{ mK}$ . The inset shows the low-field data.

Fig. 1 shows the temperature dependence of the magnetotransport data for sample 1 at a carrier density of  $p_s = 2.2 \times 10^{10} \text{ cm}^{-2}$  ( $r_s = 16$ ). The exceptionally high quality of this sample is highlighted by the clear observation of fractional quantum Hall (FQH) states at  $\nu = \frac{2}{3}, \frac{2}{5},$  and  $\frac{1}{3}$ . Indeed at the lowest temperatures studied, and with a current of 0.04 nA a clear  $\rho_{xx}$  minima at  $\nu = \frac{2}{7}$  was observed; evidence of this state can also be seen in the  $\rho_{xy}$  data at  $B = 3.3 \text{ T}$ . Several metal–insulator transitions can be seen in the data. Above  $B = 1.5 \text{ T}$  a weakly insulating state is observed, which is interrupted by the  $\nu = \frac{1}{3}$  FQH liquid, leading finally to a strongly insulating state at  $\nu < \frac{1}{3}$ .

The global phase diagram of Kivelson et al. [9] predicts a transition from a quantum Hall liquid at  $\nu = \frac{1}{3}$  to a Hall insulator. However, re-entrant insulating behaviour similar to that seen in Fig. 1 has been observed around  $\nu = \frac{1}{3}$  in higher density hole gases [10], and  $\nu = \frac{1}{5}$  in electron systems [11] and has been taken as evidence for the formation of a weakly pinned magnetically induced Wigner crystal.

The inset to Fig. 1 shows the low-field integer quantum Hall effect for  $\nu = 1-6$ . A second distinct metal–insulator transition occurs between  $\nu = 1$  and 2, with a critical point at which  $\rho_{xx}$  is  $T$  independent at  $B_c = 0.58 \text{ T}$  ( $\nu_c = 1.6$ ). Such a transition is expressly forbidden by the global phase diagram [9], and can only be accounted for by extremely

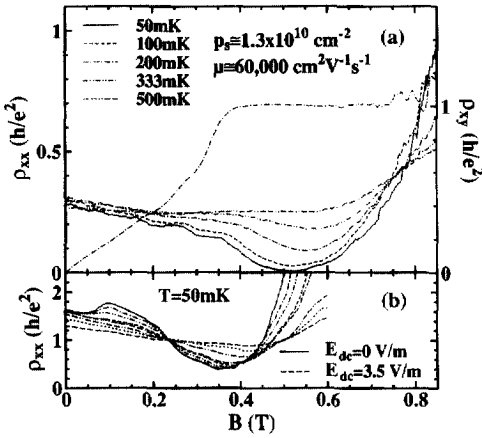


Fig. 2. Magnetotransport data for sample 2 at low densities, (a) at different temperatures ( $p_s = 1.3 \times 10^{10} \text{ cm}^{-2}$ ), and (b) at electric field values of  $E_{dc}$  from 0 to 3.5 V/m in steps of 0.5 V/m along the Hall bar ( $p_s \approx 8.5 \times 10^9 \text{ cm}^{-2}$ ).

strong many-body interactions [12]. We note in passing that this is the first time that metal–insulator transitions have been simultaneously observed both in the integer and fractional quantum Hall regimes.

We now consider the behaviour of these many-body metal–insulator transitions as the carrier density is reduced with the back gate. Fig. 2a shows magnetoresistance data at different temperatures for a carrier density of  $p_s = 1.3 \times 10^{10} \text{ cm}^{-2}$  ( $r_s = 21$ ). At this low density the sample is still metallic at  $B = 0$  ( $\mu = 60000 \text{ cm}^2 \text{ V}^{-1} \text{ s}^{-1}$ ) and  $\rho_{xx} \rightarrow 0$  as  $T \rightarrow 0$  at  $\nu = 1$ , but the relative disorder has increased. Thus, the QH-insulator–QH transition for  $2 > \nu > 1$  has disappeared, with the magnetically induced insulating phase now occurring at  $B = 0.8 \text{ T}$  ( $\nu < 1$ ).

Reducing the carrier density further, to  $p_s \approx 8.5 \times 10^9 \text{ cm}^{-2}$ ,  $r_s \approx 26$  (estimated from the minimum in  $\rho_{xx}$ ) causes the sample to become insulating at  $B = 0$  as shown in Fig. 2b. A transition to a  $\nu = 1$  quantum Hall liquid is observed at  $B = 0.24 \text{ T}$ . In these measurements we have varied the electric field  $E_{dc}$  along the Hall bar rather than varying  $T$ , since the sample was not stable over the large timescales required for a full temperature dependence. Nevertheless, a clear crossing point is seen at  $B = 0.24 \text{ T}$  with a critical resistivity of  $\rho_{xx}^c = h/e^2$ .

The metal–insulator transitions shown in Fig. 2 are consistent with that of a Hall insulator described by Kivelson et al. [9]. However, it does not follow that the insulating state observed at  $B = 0$  is of the same nature. Indeed the MITs observed in our data are also consistent with the formation of a pinned Wigner solid. In a perfectly clean system, the formation of a Wigner solid at  $B = 0$  is not expected to occur until  $r_s \geq 37$ . It has been shown, however, that disorder can stabilise the Wigner solid for  $r_s$  as low as 7.5 [7]. The multiple metal–insulator transitions observed in Fig. 1 highlights the strength of the many-body interactions in our samples and coupled with the large value of  $r_s$  suggest that the insulating state observed at zero field favours that of a Wigner crystal.

Fig. 3a shows the strong linear temperature dependence of the zero-field resistivity for the highest carrier density ( $p_s = 2.2 \times 10^{10} \text{ cm}^{-2}$ ) studied, characteristic of a metallic state. The change in the zero-field resistivity observed is too large to be caused by quantum interference effects and in the absence of phonon scattering (we are well within the Bloch–Grüneisen regime) we attribute this linear dependence to the temperature dependence of the screening [13,14].

To further examine the nature of the  $B = 0$  metal–insulator transition we show the temperature dependence of the zero-field resistivity as we reduce the carrier density in Fig. 3b. In the intermediate density range ( $p_s = 1.3 \times 10^{10} \text{ cm}^{-2}$ ) we observe a change in sign of  $\partial \rho_{xx} / \partial T$ , with  $\partial \rho_{xx} / \partial T > 0$  for  $T < 300 \text{ mK}$ , and  $\partial \rho_{xx} / \partial T < 0$  for  $T > 300 \text{ mK}$ . Similar behaviour near the MIT transition has been observed in Si MOSFETs [5] and has been ascribed to weak localisation. Whilst spin–orbit scattering for hole gases in GaAs is strong, and a combination of weak localisation and weak-antilocalisation could cause this non-monotonic behaviour [15], we do not believe this to be the case. In particular, we do not observe the strongly temperature-dependent low-field negative magnetoresistance that is characteristic of weak localisation in our data, (Fig. 2a), nor do we observe a change in the sign of the low-field magnetoconductance correction (where  $\sigma_{xx}$  was numerically calculated from  $\rho_{xx}$  and  $\rho_{xy}$ ) that would result in a change from weak localisation to weak

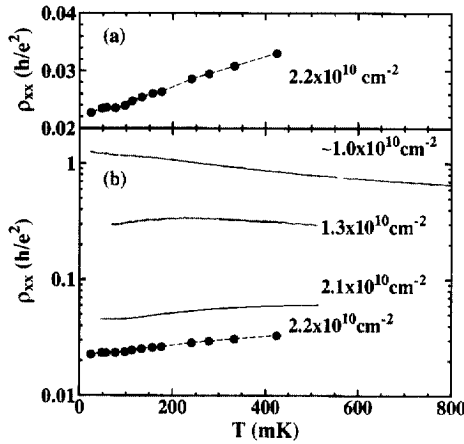


Fig. 3. (a)  $T$ -dependence of  $\rho_{xx}$  for sample 1 at  $p_s = 2.2 \times 10^{10} \text{ cm}^{-2}$  on a linear scale. (b)  $T$ -dependence of  $\rho_{xx}$  for sample 2 at different densities.

anti-localisation with decreasing temperature. We are therefore drawn to the conclusion that the temperature dependence of  $\rho_{xx}$  in this regime arises from the increasing importance of electron–electron interactions with decreasing temperature rather than disorder-related weak localisation effects.

Upon further reducing the hole density to  $p_s = 1 \times 10^{10} \text{ cm}^{-2}$ ,  $r_s = 23$ , the hole gas sample becomes insulating and  $\partial\rho_{xx}/\partial T < 0$  for all  $T$ . Whilst the value of  $\rho_{xx}$  at the transition ( $\rho_{xx} \approx h/e^2$ ) is similar to that reported in MITs observed in Si MOSFETs ( $\rho_{xx} \approx (2-3)h/e^2$ ), we do not observe the strong temperature dependence of  $\rho_{xx}$  on either side of the transition reported in Ref. [5].

Finally, we examine the effects of an electric field on the differential resistivity on either side of the metal insulator transition. In Fig. 4a we plot the differential resistance  $\rho'_{xx}$  for  $p_s = 2.1 \times 10^{10} \text{ cm}^{-2}$  at temperatures from 50–500 mK. At the lowest temperatures there is a sharp increase in  $\rho'_{xx}$  with  $E_{dc}$  consistent with metallic behaviour, which is washed out as the temperature increases, all the curves tending towards the same value of  $\rho'_{xx}$  at high  $T$  or  $E_{dc}$ .

Fig. 4b shows similar  $\rho'_{xx}(E_{dc})$  data for  $p_s = 1.3 \times 10^{10} \text{ cm}^{-2}$ . At the lowest temperatures metallic behaviour is seen similar to that shown in Fig. 4a. However, as the temperature is increased

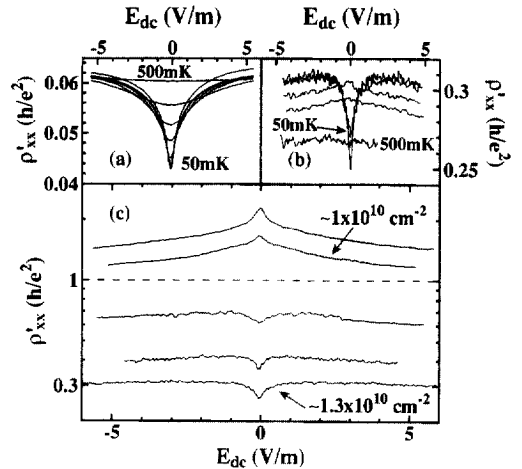


Fig. 4. (a) The differential resistivity  $\rho'_{xx}$  as a function of the electric field  $E_{dc}$  measured along the channel, for  $T = 50-500 \text{ mK}$  and  $p_s = 2.1 \times 10^{10} \text{ cm}^{-2}$ . (b) Similar data for  $p_s = 1.3 \times 10^{10} \text{ cm}^{-2}$ . (c)  $\rho'_{xx}(E_{dc})$  at  $T = 30 \text{ mK}$  for several different carrier densities.

this changes to insulating behaviour ( $\rho'_{xx}$  decreases with increasing  $E_{dc}$ ) consistent with the change in sign of  $\partial\rho_{xx}/\partial T$  seen in Fig. 3b at this density.

The overall trend of  $\rho'_{xx}(E_{dc})$  for different carrier densities at a fixed temperature of  $T < 30 \text{ mK}$  is shown in Fig. 4c, showing the transition from strongly metallic to insulating behaviour as  $p_s$  is reduced. The traces are symmetric about  $\rho'_{xx} = h/e^2$  (shown by the dashed line in the figure) in agreement with the value of  $\rho'_{xx}$  obtained from the temperature dependence data of Fig. 3b. Similar values of  $\rho'_{xx}$  and  $\rho'_{xx}(E_{dc})$  have recently been reported for high-mobility silicon MOSFETs at  $B = 0$  [16]. The data in Fig. 4 provides additional evidence for a true metal insulator transition in high-mobility hole gases in the absence of a magnetic field.

In summary, we have observed a MIT at  $B = 0$  in a very dilute, low-disorder two-dimensional GaAs/AlGaAs hole gas, characterised both by the  $T$  and  $E_{dc}$  dependence of  $\rho_{xx}$ . Although the physical origins of this transition are unclear, many-body interactions are shown to be extremely strong in our samples, with the value of  $r_s$  in the insulating phase large enough to allow the formation of a weakly pinned Wigner crystal. Our results confirm the universal nature of the MIT at  $B = 0$ ,

which has also been observed in different material systems and with different charge carriers.

This work was funded by the EPSRC. A.R.H. and M.Y.S. gratefully acknowledge financial support from the British Council in Japan; M.Y.S. acknowledges support from the British Association of Crystal Growth; and A.K.S., T.G.G., A.R.H. and M.Y.S. also acknowledge funding from the Exeter University research fund.

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