phys. stat. sol. (b) **230**, No. 1, 81–87 (2002)

Localisation in Strongly Interacting 2D GaAs Systems

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(Received September 6, 2001; accepted October 4, 2001)

Subject classification: 71.30.+h; 73.20.Fz; 73.40.Qv; S7.12

This paper presents a short review of localisation in strongly interacting, high quality dilute 2D GaAs systems. At zero magnetic field, studies of the temperature dependent resistance of both 2D electron and hole systems show a transition from insulating to metallic behaviour with increasing carrier density. However, careful examination of the 2D hole systems reveal the presence of localising quantum corrections to the conductivity which persist down to the lowest measurement temperatures. Our results highlight the importance of avoiding electron/hole heating at low temperatures and argue against the existence of a 2D metallic phase at $B = 0$.

The scaling theory of localisation [1] predicts that there is no metallic phase in non-interacting two-dimensional (2D) systems at zero magnetic field and therefore that there can be no metal–insulator transition at $T = 0$. Early experiments on weak localisation and interaction effects in 2D systems provided strong support for this theory, revealing a logarithmic increase in the low temperature resistance as $T \to 0$ [2, 3]. However, recent experimental studies of a wide variety of 2D semiconductor systems have demonstrated an unexpectedly large decrease in the resistance as the temperature is reduced below $T \sim 1$ K, suggesting the possible existence of a 2D metal (see Ref. [4] for a recent review).

In this paper, we present results from both high quality 2D GaAs electron and hole systems which exhibit this anomalous metallic-like behaviour at low temperatures. In the p-GaAs systems we use temperature dependent magneto-resistivity measurements to show that even in the metallic regime, both weak localisation and localising interaction corrections to the Drude conductivity are still present and increase logarithmically as $T \to 0$. The importance of sample heating is discussed. For the ultra-high quality electron systems it is extremely difficult to observe quantum corrections at experimentally accessible temperatures due to the long mean free path. In a separate work [5] we have used an alternative technique to ascertain the ultimate ground state of the n-GaAs system at $T = 0$. Results from both n- and p-type GaAs argue against the existence of a 2D metallic phase at $B = 0$.

The samples used in this study have been described in detail elsewhere [5–8]. Sample A is an electron device fabricated from an undoped GaAs/AlGaAs heterostructure where the carriers are induced with a gate [5], whereas samples B and C are p-type 2D GaAs hole devices fabricated from modulation doped heterostructures [7, 8]. The peak

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 0370-1972/02/23003-0081 $ 17.50+.50/0

mobilities were in excess of 10^7 and 10^6 $cm^{-2}\,V^{-1}\,s^{-1}$ for electron and hole systems, respectively. Measurements were performed using low frequency ac lock-in techniques with excitations as low as 0.01 nA or 6 μV to avoid heating effects.

Figure 1a shows the temperature dependence of the resistivity for the low density n-type sample A [5] for a range of different carrier densities. At the lowest density $n_s = 2 \times 10^9$ cm^{-2}, the sample shows insulating behaviour where the resistivity increases as $T \to 0$. At intermediate densities, $n_s = 4.5 \times 10^9$ cm^{-2}, the resistivity exhibits non-monotonic behaviour, with insulating-like behaviour ($dR/dT < 0$) at high temperatures and 'metallic'-like behaviour ($dR/dT > 0$) at lower temperatures. The transition between these two different behaviours occurs at $T/T_F \sim 0.16$, where T_F is the Fermi temperature, as the system becomes non-degenerate [9]. By increasing the density further to $n_s = 1 \times 10^{10}$ cm^{-2} the sample shows 'metallic' behaviour over the complete measurement range, with the resistivity dropping by 11% as $T \to 0$.

For comparison Fig. 1b shows data from the p-type sample B. This sample also shows insulating behaviour at low densities, with a cross-over region showing non-monotonic behaviour at densities of $p_s \sim 1.0 \times 10^{10}$ cm^{-2} (as the system becomes non-degenerate). At a density of $p_s = 2 \times 10^{10}$ cm^{-2} metallic behaviour is observed with the resistivity dropping by up to 50% as the temperature is reduced from 800 to 30 mK. At higher densities, away from the transition, the metallic behaviour becomes weaker and saturation at low temperatures becomes visible, with the resistivity being well described by the empirical relationship proposed in Ref. [10]. From this figure we can see that both the electron and hole systems exhibit similar behaviour but with the transition occurring at much lower densities in the high quality electron system. In addition the value of r_s at the critical density is much higher in the p-type samples than in the n-type sample due to the much larger hole mass.

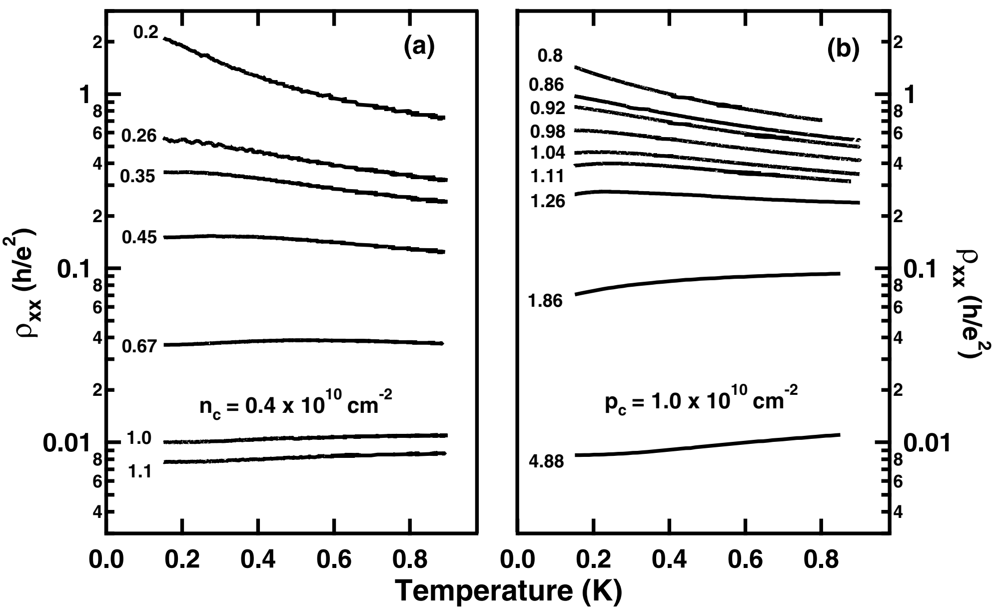

Fig. 1. Comparison of the temperature dependence of the resistivity at different carrier densities for a) electron sample A and b) hole sample B

Despite the drop in resistivity as $T \to 0$ the distinction between a metal and an insulator can only properly be made at $T = 0$ where there are no thermal excitations that might allow an insulator to conduct. If the resistance is finite at $T = 0$, the system is a metal – otherwise it is an insulator. Experimentally it is impossible to reach $T = 0$, so instead we must extrapolate the behaviour at low but finite temperatures down to $T = 0$. For this approach to be valid it is extremely important to ensure that the temperature of the electrons (or holes) does not deviate from the lattice temperature as the sample is cooled. This is particularly relevant in 2D systems since quantum corrections may only become visible at very low temperatures.

In all of our previously published data we have taken care to ensure that the excitation current is not causing unwanted heating of the 2D carriers by reducing the current until there is no change in the measured resistivity data. This is highlighted in Fig. 2 which shows the resistivity of p-type sample C [7] as a function of the lattice temperature at $p_s \sim 3.5 \times 10^{10}$ cm^{-2}. Initially we consider the raw data which shows insulating behaviour. For an excitation current I = 2 nA there is a monotonic increase in the sample resistance as the temperature is reduced, with a gradual saturation below 150 mK. By reducing the measurement current to 0.2 nA we obtain near identical results for higher temperatures, but the resistance only begins to saturate below 70 mK. This confirms that the saturation of the I = 2 nA trace below 150 mK is due to heating caused by the excitation current. Further reducing the current to 0.02 nA (not shown) yields data that is indistinguishable from the 0.2 nA trace, demonstrating that the excitation current must be 0.2 nA or lower for sensible measurements at this particular carrier density.

Although the above procedure ensures that the excitation current is not heating the 2D holes, it cannot verify that background noise is not causing heating. To check this we use the sample itself as a thermometer to monitor the hole temperature. In the insulating regime the resistance is well described as $\rho(T) = \rho_{\mathrm{VRH}} \exp\,[(T/T_{\mathrm{VRH}})^{-m}]$ characteristic of variable range hopping with the exponent m taking the value 1/2 deep in the insulating regime and 1/3 close to the transition [7]. For the carrier density shown in Fig. 2a we are in a cross-over regime between these two limits, and have therefore plotted fits to the data with both $m = 1/2$ and 1/3. Whilst these two fits are almost identical the main point is that both traces continue to become steeper as $T \to 0$. Despite ensuring that the excitation current is not heating the holes at I = 0.2 nA we still

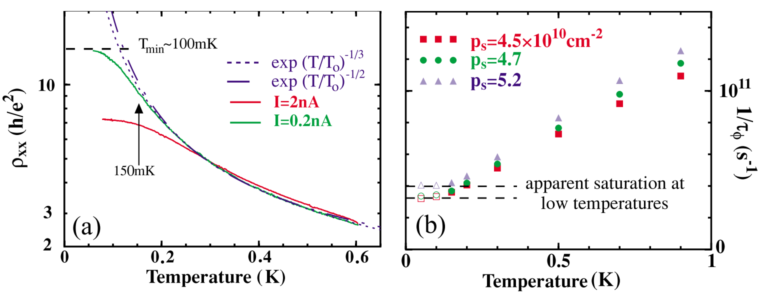

Fig. 2 (online colour). a) Temperature dependence of the longitudinal resistivity of p-GaAs sample C at $p_s = 3.5 \times 10^{10}$ cm^{-2} for different excitation currents as shown. The dotted line refers to fits to variable range hopping. b) Phase breaking rate $1/\tau_\phi$ versus temperature for densities close to the 'metal'–insulator transition ($p_s \sim 4.6 \times 10^{10}$ cm^{-2}) measured in the same sample observe deviation of the experimental data from the theory at 150 mK. Even though the resistance keeps increasing below 150 mK the holes are hotter than the lattice in this range. At the fridge base temperature of 50 mK, a comparison of the measured data with the theory indicates that the lowest hole temperature achieved is $T_{\min} \sim 100$ mK. In our analysis of the metallic behaviour, we therefore only concentrate on the regime where the hole temperature is well known, i.e. $T > 150$ mK.

Now that we have accurately determined the 2D hole temperature we can safely look at the low temperature behaviour of the system and extrapolate to $T = 0$. The first effect we consider is phase coherent backscattering or 'weak localisation'. In a previous study of 2D hole systems it was clearly demonstrated that these weak localisation corrections are present even in the so-called metallic regime and become stronger as T is reduced [7]. For high quality samples this correction is small (of the order of a few percent) and can be difficult to resolve even at very low temperatures. However, another characteristic signature of weak localisation is a strong temperature dependent negative magnetoresistance that causes a "cusp" around $B = 0$. In the earlier study of Ref. [7] the temperature dependent magnetoresistance data was fitted to the Hikami formula [11] to directly extract the phase relaxation time τ_ϕ at different densities and temperatures. Figure 2b summarises the phase breaking rate $1/\tau_\phi$ for three different densities on both sides of the transition from insulating to metallic behaviour for sample C. There are four important features of these results. Firstly the phase breaking rate falls approximately linearly with decreasing temperature in good agreement with that expected for disorder-enhanced hole–hole (Nyquiest) scattering $1/\tau_\phi \sim 2k_B T/(\hbar k_F l)$. We find that the measured phase breaking rate is approximately five times larger than that expected from theory but note that a similar enhancement of the phase breaking rate has been found in other experimental studies [12, 13]. Secondly the phase breaking rates measured in these low density p-GaAs samples with $k_F l \sim 3$ are almost identical to those found in n-type silicon MOSFETs with $k_F l \sim 1$ [14] despite a factor of 20 difference in the carrier densities. This suggests that the hole states are only mildly perturbed by the strong hole–hole interactions, and essentially remain Fermi-liquid-like. Thirdly, there is no reflection of the exponential decrease of the $B = 0$ resistivity with decreasing temperature in the phase breaking rate suggesting that whatever is causing the metallic behaviour does not destroy phase coherent weak localisation. Fourthly, a saturation of $1/\tau_\phi$ is observed at the lowest temperatures. However as shown in Fig. 2a this saturation is a direct consequence of the 2D holes not cooling below 150 mK. Such an apparent saturation highlights the care that has to be taken to ensure that the charge carriers are reaching the bath temperature. Indeed recent measurements on silicon MOSFETs [15] have also demonstrated the difficulties of cooling 2D electrons, with new data that now supports our earlier observations of weak localisation effects in the so-called metallic regime.

In addition to phase coherent weak localisation, hole–hole interactions can produce an additional correction to the Drude conductivity. However, as with weak localisation corrections it is extremely difficult to determine the presence (or absence) of interaction effects solely from the $B = 0$ $\rho(T)$ data, as the logarithmic correction can easily be masked by other semi-classical effects such as temperature dependent screening. It is possible to separate out the correction due to interactions by careful measurement of the low field Hall effect, if it can first be shown that the carrier density is constant with temperature. Figures 3a and b show the temperature dependence of the Hall and long-

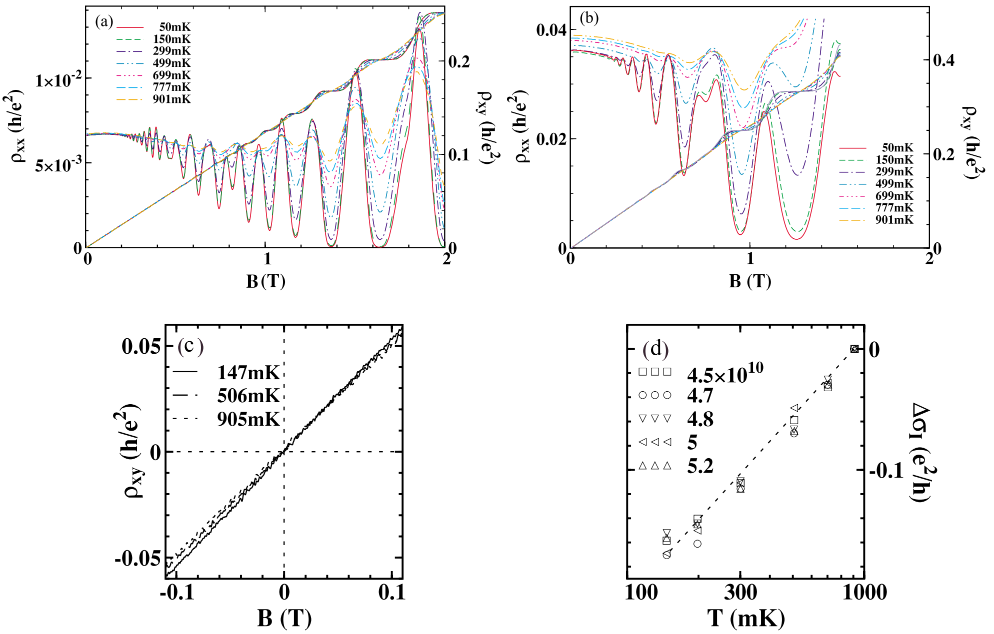

Fig. 3 (online colour). Temperature dependence of the Hall and longitudinal resistivity for p-GaAs sample C at fixed carrier densities of a) $p_s = 17.3 \times 10^{10}$ cm^{-2} and b) $p_s = 8.6 \times 10^{11}$ cm^{-2}. c) Hall resistivity at different temperatures for sample C at $p_s = 4.7 \times 10^{10}$ cm^{-2} and d) the interaction correction to the conductivity for densities close to the transition

itudinal resistance for the p-GaAs sample C at carrier densities of 17.3×10^{10} and 8.6×10^{10} cm^{-2}. In Fig. 3a we can see that the carrier density is constant from 50–900 mK, with minima in the Shubnikov-de Haas oscillations lining up at exactly the same magnetic field for all temperatures. It is also apparent that there is little difference between the 150 and 50 mK traces, consistent with the holes not cooling below $T_{\mathrm{min}} = 100$ mK.

At lower densities it is harder to determine the precise carrier density from the Shubnikov-de Haas oscillations. This is shown in Fig. 3b for $p_s = 8.6 \times 10^{10}$ cm^{-2}. If we were only to consider the $\nu = 3$ trace at $B \sim 1.2$ T then it would appear that the carrier density is changing with temperature since the Shubnikov-de Haas minima move to slightly lower fields as T increases. This is, however, an artifact caused by the presence of strongly localised states on the high B side of the minima which cause the resistance to increase rapidly on the right side of the $\nu = 3$ minima. However, for $\nu = 4$ at ~ 1 T the Shubnikov-de Haas minima line up perfectly at all temperatures confirming that the carrier density is indeed constant.

Interactions cause a correction to the conductance $\Delta\sigma_{\mathrm{I}}$ and to the Hall resistance ΔR_{H},

$$\frac{\Delta R_{\mathrm{H}}}{R_{\mathrm{H}}} = -2\,\frac{\Delta\sigma_{\mathrm{I}}}{\sigma}\,. \tag{1}$$

From the temperature dependence of the Hall resistivity we can therefore extract the interaction correction to the zero field conductivity, $\Delta\sigma_{\mathrm{I}}$. Figure 3c shows a plot of the

Hall resistivity ρ_{xy} on the metallic side of the transition at a carrier density of $p_s = 4.7 \times 10^{10}$ cm^{-2} for sample C [7]. The data reveals a small logarithmic decrease of the Hall slope with increasing temperature. Since Figs. 3a and b show that the carrier density of the sample is temperature independent, this change in the Hall slope must be due to interactions. Figure 3d shows the interaction correction $\Delta\sigma_I$ for different carrier densities on both sides of the transition obtained from Eq. (1). All the data collapses onto a single line, clearly demonstrating a $\log(T)$ dependence. The interactions will thus reduce the conductivity to zero as $T \to 0$, again suggesting that the 2D system will not be a metal at $T = 0$. Whilst it is surprising that a theory derived for weakly interacting systems applies to our system where interactions are strong ($r_s > 10$), we find reasonable agreement between the magnitude of the logarithmic corrections observed and those predicted by Altshuler and Aronov [16] (to within a factor of two). Furthermore, the logarithmic correction due to hole–hole interactions is independent of whether we are in the insulating or metallic phase, and is present despite the exponential drop in resistivity. This result shows that electron–electron interactions are not responsible for the 2D “metal“-insulator transition observed in high mobility systems.

The detection of logarithmic insulating behaviour is more difficult in n-GaAs samples since much lower carrier densities (and hence higher mobilities) are required to observe the metal–insulator transition. The mean free path is therefore longer in these high quality systems, which means even lower temperatures are required to observe quantum corrections than for p-GaAs. Recently, however, we have used an alternative technique to determine the ground state of the n-GaAs system where we track the position of the extended states at the centre of the Landau levels as a function of B to see whether they ‘float up’ or assume a finite energy as $B \to 0$ [5]. Again these results from n-GaAs are consistent with the absence of a 2D metal at $B = 0$.

In conclusion, we have performed a study of the metallic behaviour observed in high quality, low density 2D electron and hole systems. For p-type systems that show all the signatures of a $B = 0$ “metal”–insulator transition, detailed magnetoresistance measurements clearly demonstrate that neither phase coherent effects nor hole–hole interactions are responsible for the apparent 2D metal. Both of these effects are present in the metallic regime and both give rise to localising corrections to the classical Drude conductivity at low temperatures. By using the sample itself as a thermometer we demonstrate the difficulties inherent to cooling 2D systems to milliKelvin temperatures. Although the lattice and bath can readily be cooled to below 50 mK a careful analysis shows that the hole temperature begins to deviate from the lattice temperature at 150 mK, with the minimum hole temperature achieved being 100 mK. We observe no saturation of the phase breaking rate nor of the interaction correction down to 150 mK, which strongly suggests that there is no 2D metallic phase at $B = 0$ in these systems.

Acknowledgements This work was supported by the Australian Research Council and the UK EPSRC.

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