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Metallic behaviour and localisation in 2D GaAs hole systems

M.Y. Simmons^{a,*}, A.R. Hamilton^a, M. Pepper^b, E.H. Linfield^b, P.D. Rose^b, D.A. Ritchie^b^a*School of Physics, University of New South Wales, Sydney 2052, Australia*^b*Cavendish Laboratory, Madingley Road, Cambridge CB3 0HE, UK*

Abstract

We have investigated the apparent “metal”–insulator transition in a variety of high quality 2D GaAs hole systems. Central to the issue of whether such a transition can exist is the question of what happens to the localising quantum corrections to the conductivity predicted by one-parameter scaling theory. We demonstrate that in samples where the phase coherence length is greater than the mean free path, weak localisation corrections are observed in the so-called “metallic” phase. We also observe weak hole–hole interaction corrections close to but on the “metallic” side of the transition. Both these corrections are localising, becoming stronger as $T \rightarrow 0$. This suggests that despite the strong interactions ($r_s > 10$) these 2D GaAs hole systems still behave like Fermi liquids, and there is no true 2D “metallic” state. Instead, we find that conventional temperature dependent screening can account for many aspects of the metallic behaviour. © 2001 Elsevier Science B.V. All rights reserved.

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1. Introduction

The Quantum Hall effect is direct evidence for the existence of both localised and extended states in two-dimensional systems. It is still however unclear what happens to these extended states as $B \rightarrow 0$. In 1979 the one parameter scaling theory of localisation [1] showed that in the absence of a magnetic field the presence of any disorder in a non-interacting 2D system would localise all states at $T = 0$. Whilst a

2D system might appear conducting at high temperatures, quantum corrections would take over as $T \rightarrow 0$ at which point the sample would become completely insulating. However in 1994 experimental evidence emerged suggesting the possible existence of a metallic state at $B = 0$ in a strongly interacting, low disorder 2D system [2]. Since then metallic-like behaviour has been observed in other high quality 2D material systems including p-SiGe and p-GaAs [3–6].

In this paper, we address the question of what happens to the quantum corrections originally predicted by the scaling theory. The presence of these corrections are detected through careful magneto-resistance measurements. By subtracting these corrections from

* Corresponding author. Tel.: +61-9385-6313; fax: +61-9385-6060.

E-mail address: michelle.simmons@unsw.edu.au (M.Y. Simmons).

Table 1

Transport characteristics of three GaAs hole samples in which “metallic”-like behaviour has been observed and a comparison with other material systems

Sample	μ_{peak} (cm^2/Vs)	$\Delta\rho/\rho$ (%)	p_s^c ($10^{14}/\text{m}^2$)	ρ^c (h/e^2)	r_s^c	τ_{mfp}^c (ps)
A	1,100,000	50	1.5	0.5	20	5.5
B	250,000	15	4.5	0.4	12	2.3
C	160,000	10	7.3	0.2	9	2.8
n-Si [2]	71,000	88	8.5	2.8	8	0.1
p-SiGe [3]	15,000	50	10	0.5	6	0.7

the Drude conductivity a linear dependence of the conductivity on temperature is found for small T/T_F , similar to that predicted for temperature dependent screening where $\Delta\sigma/\sigma \propto T$ [7].

2. Experimental

The results from three different modulation doped p-type GaAs-AlGaAs heterostructures, exhibiting metallic-like behaviour, are summarised in Table 1. Included are the sample details such as the peak mobility, the maximum percentage drop in resistivity in the metallic regime, the hole density at the transition from insulating to metallic behaviour, the effective strength of the Coulomb interactions r_s , where $r_s \propto m^*/\sqrt{p_s}$ and the momentum relaxation time τ_{mfp}^c at the critical density. A comparison with n-Si and p-SiGe samples is also presented in the Table 1.

Three trends can be seen in Table 1: (a) The ‘strength’ of the metallic behaviour in p-GaAs samples, characterised by the magnitude of the drop in ρ with decreasing T is largest in the highest quality sample A. The magnitude of the drop in resistivity decreases as the sample quality (characterised by the peak mobility) decreases such that for sample C it is approximately 10%. (b) The hole density p_s^c at the transition is observed to decrease with increasing sample quality, with r_s^c growing correspondingly larger. (c) The value of the resistivity at the transition ρ^c increases from about $0.2e^2/h$ to $0.5e^2/h$ with increasing sample quality. Similar trends in p_s^c , ρ^c and the magnitude of the resistance drop have also been observed in studies of silicon MOSFET samples [2].

From Table 1, we can see that as the sample quality increases and the interactions get stronger a larger drop in the resistivity is observed. The question

remains whether this metallic-behaviour is a signature of a true metallic state (possibly due to strong interactions) or is it a finite temperature effect. To answer this question we investigate what happens to the quantum corrections to the resistivity—if they are still present in samples that show metallic behaviour, and they are localising, then we cannot have a true 2D metal.

3. Quantum corrections to the resistivity

To observe weak localisation effects the phase coherence time, τ_ϕ has to be greater than momentum relaxation time, τ_{mfp} , where

$$\tau_\phi = \frac{1}{2\pi k_B T} \frac{1}{\rho \ln(2\rho)} \quad (1)$$

and ρ is the resistivity in units of h/e^2 [8]. It can be seen that τ_ϕ only depends on the temperature T and the resistivity ρ . Therefore in order to observe weak localisation at experimentally accessible temperatures it is necessary to choose a sample with a small τ_{mfp} . For this reason we concentrate on Sample B for evidence of quantum corrections to the Drude conductivity.

Fig. 1 demonstrates the temperature dependence of the $B = 0$ resistivity at carrier densities from $3.5\text{--}5.6 \times 10^{10} \text{ cm}^{-2}$ for sample B. At low densities strongly insulating behaviour is observed, with the resistivity taking the familiar form for variable range hopping: $\rho(T) = \rho_{\text{VRH}} \exp[(T/T_{\text{VRH}})^{-m}]$, with $m = \frac{1}{2}$ far from the transition and $\frac{1}{3}$ close to the transition. Increasing the density causes a transition to metallic behaviour, where the resistance decreases exponentially as the temperature is reduced (this can be more clearly seen in Fig. 2d).

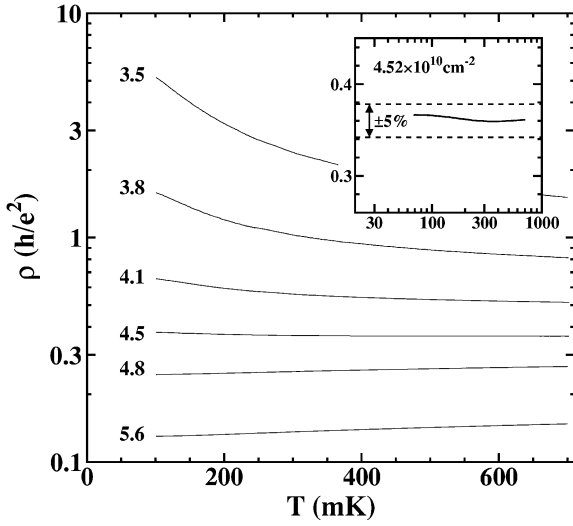


Fig. 1. Temperature dependence of the resistivity at densities ranging from $p_s = 3.5\text{--}5.6 \times 10^{10} \text{ cm}^{-2}$ for Sample B. The inset shows the temperature dependence of the resistivity on a linear scale at $p_s = 4.52 \times 10^{10} \text{ cm}^{-2}$ showing a small increase at temperatures below 300 mK.

The zero field conductivity $\sigma(T)$ of a Fermi liquid with $r_s < 1$ is given by [8]:

$$\sigma(T) = \sigma_D(T) + \Delta\sigma_{WL}(T) + \Delta\sigma_I(T) \quad (2)$$

where $\sigma_D(T)$ is the Drude conductivity, $\Delta\sigma_{WL}(T)$ and $\Delta\sigma_I(T)$ are the quantum corrections due to weak localisation and electron–electron (hole–hole) interactions, respectively. If quantum corrections are present then we would expect to observe a weak increase in the resistivity at low temperatures near the transition. On the logarithmic scale of Fig. 1 the resistivity data closest to the transition ($p_s^c = 4.52 \times 10^{10} \text{ cm}^{-2}$) shows no apparent evidence for any temperature dependence. Similar apparently temperature-independent resistivity traces have been reported in silicon MOSFET samples [9]. Indeed such a temperature independent separatrix between metallic and insulating behaviour was taken as further evidence for a zero temperature quantum phase transition. However if we zoom in and look in detail at this curve (inset to Fig. 1), we can clearly see a weak (approximately 2%) increase in the resistivity as $T \rightarrow 0$.

A small logarithmic increase in the resistivity of similar magnitude (1–5%) with decreasing temperature was observed in early studies of weakly

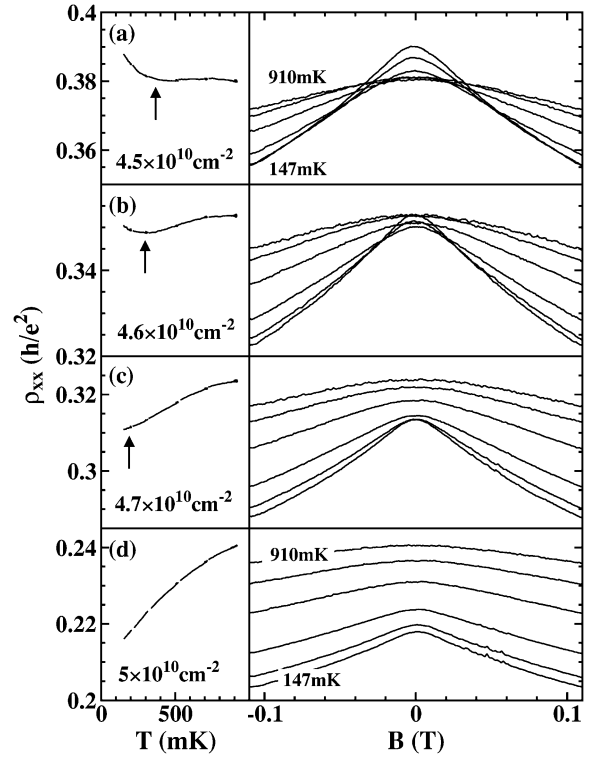


Fig. 2. (a–d) Left-hand panels show the $B=0$ resistivity as a function of temperature for Sample B, illustrating the transition from insulating to metallic behaviour with increasing density. Right-hand panels show corresponding magnetoresistance traces at $T = 147, 200, 303, 510, 705$ and 910 mK.

interacting, disordered 2D systems ($r_s \sim 4$) [10,11]. However, it is difficult to unambiguously detect the presence (or absence) of quantum corrections solely from $\rho(T)$ data at $B = 0$, particularly if σ_D is strongly temperature dependent. A more rigorous method is to study the temperature dependence of the magneto- and Hall resistivities.

3.1. Weak localisation

Fig. 2 shows the temperature dependence of the $B = 0$ resistivity (left-hand panel) and magnetoresistance (right-hand panel) at different densities on both sides of the “metal”–insulator transition. In Fig. 2a we are just on the insulating side of the transition. The left-hand panel shows that $\rho(T)$ is essentially T -independent down to 300 mK and then increases by 2.5% as the temperature is further reduced. The

origins of this increase can be ascertained from the magnetoresistance shown in the right-hand panel of Fig. 2a. Below ~ 300 mK a characteristic negative magnetoresistance peak develops as phase coherent weak localisation effects become important, mirroring the small increase in the resistivity at $B = 0$.

Increasing the carrier density brings us into the metallic regime (Fig. 2b) where the exponential drop in the resistivity with decreasing temperature starts to become visible. The upturn in $\rho(T)$ marked by the arrow has moved to lower temperatures and the negative magnetoresistance in the right-hand panel has become less pronounced. Further increasing the density (Fig. 2c) causes the metallic behaviour to become stronger, with the upturn in $\rho(T)$ moving to even lower temperatures, until at $p_s = 5 \times 10^{10} \text{ cm}^{-2}$ the upturn is no longer visible within the accessible temperature measurement range. However, the magnetoresistance still exhibits remnants of the weak localisation temperature dependent peak at $B = 0$. The weak localisation is therefore always present and is neither destroyed in the metallic regime, nor is it “swamped” by the exponential decrease in resistivity with decreasing temperature. Instead what can clearly be seen in the left-hand panel of Fig. 2, is that the upturn in $\rho(T)$ due to weak localisation marked by arrows, moves to lower T as the carrier density is increased. This is not surprising since as we move further into the metallic regime, the momentum relaxation time becomes longer, such that weak localisation corrections $\Delta\sigma_{\text{WL}} \propto \ln(\tau_\phi/\tau_{\text{mfp}})$ are only visible at lower temperatures (see Eq. (1)). Indeed this also explains why it would be more difficult to see weak localisation corrections in the higher quality sample A. Here the momentum relaxation time is ≈ 2.5 times larger than in sample B such that we would need to go to 2.5 times lower temperatures to have the same $\Delta\sigma_{\text{WL}}$. To clearly observe weak localisation would require the holes to be cooled below ~ 100 mK which is a difficult experimental task.

We can extract the phase relaxation time τ_ϕ by fitting the data to the Hikami formula for weak localisation [12]. Fig. 3a shows the temperature dependence of the phase breaking rate $1/\tau_\phi$ for three different densities on both sides and close to the “metal”–insulator transition. The phase breaking rate falls approximately linearly with decreasing temperature for all three traces in agreement with Eq. (1). This phase breaking mechanism only depends on ρ

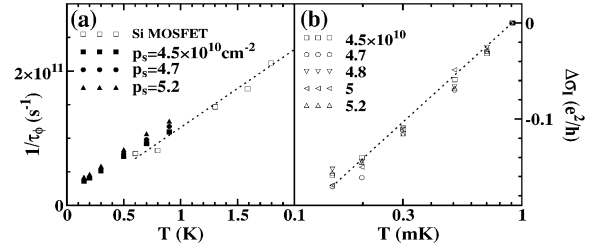


Fig. 3. (a) Phase breaking rate versus temperature for densities close to the “metal”–insulator transition for Sample B. Solid symbols are the data obtained from this study; open symbols are the data from Si MOSFETs [11]. (b) Logarithmic correction to the conductivity in Sample B due to hole–hole interactions, $\Delta\sigma_1$, plotted against temperature.

and it is therefore particularly noteworthy that the phase breaking rates in these low density p-GaAs samples, with $2.5 < k_F l < 5$, are almost identical to those found in n-type silicon MOSFETs [13] at similar resistivities, despite a factor of 20 difference in the carrier densities. This agreement with scattering limited electron lifetime suggests that the electron states are only mildly perturbed by the strong interactions and essentially remain Fermi liquid-like. Since all models of the resistivity in the metallic phase [14,15] predict that the exponential drop saturates at low temperatures, our data show that localisation effects will again take over as $T \rightarrow 0$.

3.2. Electron–electron interactions

It has been suggested that electron–electron interactions could counter the weak localisation corrections and stabilise a metallic state. To investigate this possibility we *directly* measure the interaction corrections from the low field Hall effect. Unlike weak localisation, interactions not only affect the $B = 0$ resistivity, but also cause a correction to the Hall resistance:

$$\Delta R_{\text{H}}/R_{\text{H}} = -2\Delta\sigma_1/\sigma_1. \quad (3)$$

From the temperature dependence of the Hall resistivity we extract the interaction correction to the zero field conductivity, $\Delta\sigma_1$ using Eq. (3). Fig. 3b shows a plot of the interaction correction for different carrier densities on both sides of the transition. All the data collapse onto a single line, clearly demonstrating a $\log(T)$ dependence of $\Delta\sigma_1$, which reduces the conductivity to zero as $T \rightarrow 0$.

It is perhaps surprising that results observed in, and derived from, weakly interacting systems apply to our system where interactions are strong and $r_s > 10$. Nevertheless, we find reasonable agreement between the magnitude of the logarithmic corrections due to interactions in our system and those predicted by Altshuler et al. [8] (within a factor of 2). As with the phase coherent effects this 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 suggests that electron–electron interactions are not responsible for the 2D “metal”–insulator transition observed in high mobility systems.

4. Temperature dependent screening

We can subtract the corrections due to weak localisation and hole–hole interactions from the measured zero-field conductivity to extract the bare Drude conductivity $\sigma_D(T)$ using Eq. (1). These results are plotted in Fig. 4 at a carrier density of $4.7 \times 10^{10} \text{ cm}^{-2}$ —just on the metallic side of the transition for Sample B. Immediately we can see that the resulting Drude conductivity shows a linear metallic temperature dependence in agreement with that expected for temperature-dependent screening in the clean limit [7,16]. Similar results have been reported previously in high quality p-GaAs [5] and more recently in p-SiGe samples [17].

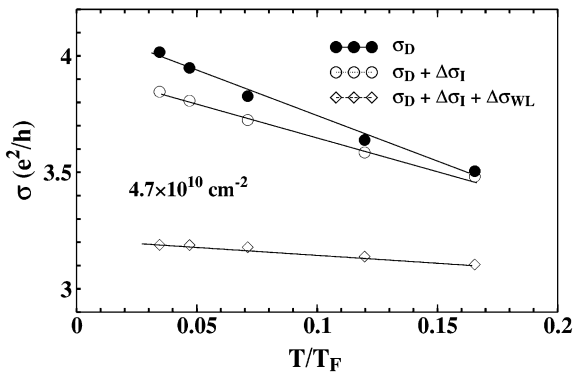


Fig. 4. Extracting the Drude conductivity $\sigma_D(T)$ in Sample B from the measured conductivity at $p_s = 4.7 \times 10^{10} \text{ cm}^{-2}$.

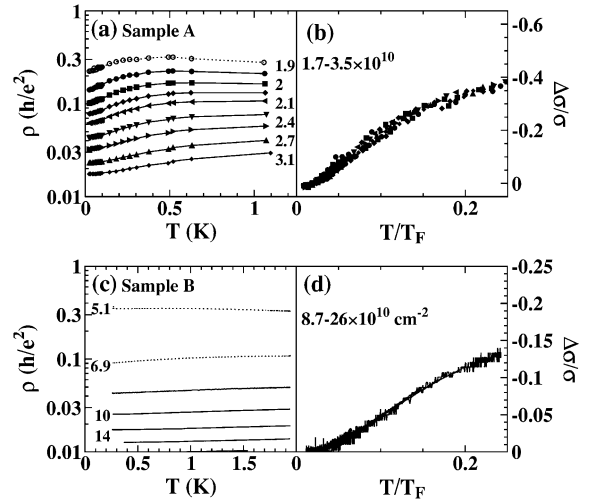


Fig. 5. Comparing the metallic behaviour in samples A and B. (a) Sample A: T -dependence of the $B=0$ resistivity for p_s in the range $1.7\text{--}3.5 \times 10^{10} \text{ cm}^{-2}$. (b) Corresponding fractional change in the conductivity $\Delta\sigma/\sigma$ against T/T_F . (c,d) Equivalent data for Sample B for $p_s = 8.7\text{--}26 \times 10^{10} \text{ cm}^{-2}$.

The universality of this result in p-GaAs is highlighted by comparing the results from Sample B with that from a higher quality sample—Sample A [18]. Fig. 5a shows the temperature dependence of the $B=0$ resistivity at different carrier densities in the so-called metallic regime for Sample A. This sample shows much stronger metallic-like behaviour than Sample B, with up to a factor of two decrease in resistivity as the temperature is reduced from 700 to 30 mK. In this high quality sample the quantum corrections are negligible for $T > 0.1 \text{ K}$ and we can replot the data (Fig. 5b) to show the fractional change in the Drude conductivity $\Delta\sigma/\sigma$ against T/T_F . Here $\Delta\sigma$ is the change in conductivity with increasing T , and T_F is the Fermi temperature. All the different density data collapse onto a common curve, which is linear at low T/T_F , and saturates at higher T/T_F as the system becomes non-degenerate.

Fig. 5(c) shows the T -dependent resistivity for a range of carrier densities from $8.7\text{--}26 \times 10^{10} \text{ cm}^{-2}$ for Sample B. The corresponding fractional change in conductivity is plotted in Fig. 5(d), where the data again collapse onto a common trace. In both cases $\Delta\sigma/\sigma$ is linear in T/T_F at low temperatures

($T/T_F < 0.2$), and flattens off at higher temperatures. This linear behavior between 0.5–2.0 T/T_F is consistent with temperature dependent screening [7]. The magnitude of the temperature dependent screening correction to the conductivity $\Delta\sigma/\sigma$ is larger for the higher quality Sample A than for Sample B. This is consistent with the theory of Ref. [7], which predicts that temperature dependent screening is more significant at low densities. It is only possible to reach such low densities in very high quality samples such as Sample A. These results demonstrate that the metallic behaviour observed in p-GaAs systems can be understood in terms of conventional disordered conduction mechanisms such as temperature dependent screening.

5. Conclusions

We have shown that both weak localisation and electron–electron interaction effects are present in the so-called metallic phase and give rise to localising corrections to the conductivity that increases as $T \rightarrow 0$. These corrections move to lower temperatures as the momentum relaxation time increases making them extremely hard to observe in ultra-high quality p-GaAs samples. Nevertheless, unless the corrections saturate at low (inaccessible) temperatures the results argue against the existence of a true metallic phase even when interactions are strong.

Instead, we have shown that temperature-dependent screening can account for many aspects of the

metallic-like drop in the resistivity observed in two different low disordered GaAs hole systems. The fractional change in the conductivity $\Delta\sigma/\sigma$ depends only on T/T_F such that the so-called metallic state can be described by conventional disordered conduction.

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