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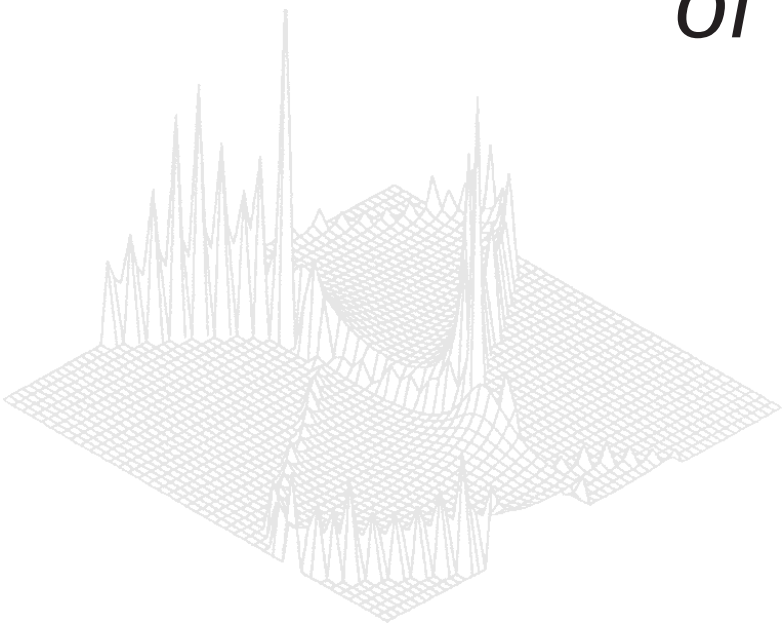

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Influence of Inversion Symmetry on the Metallic Behaviour in a Dilute Two-dimensional Hole System*

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Abstract

In the past five years numerous experimental studies of a wide variety of low disorder two-dimensional (2D) semiconductor systems have revealed an unexpectedly large decrease in the resistance as the temperature is lowered from $T \sim 1$ K, suggesting the existence of a 2D metal. Although numerous theories have been put forward to explain this metallic-like behaviour (which contradicts the expectations of one parameter scaling theory), its origins, and the question of whether it persists to $T = 0$, are still subjects of great debate. We present a detailed study of the influence of inversion symmetry on the $B = 0$ metallic behaviour in a low density GaAs hole gas close to the apparent two-dimensional metal–insulator transition. The strength of the metallic behaviour (determined by the size of the drop in resistance as $T \rightarrow 0$) is found to be almost independent of the electric field across the hole gas, and is predominantly determined by the magnitude of $k_F l$ at low temperatures (i.e. by the low temperature resistivity). These results suggest that the shape of the potential well and spin–orbit effects alone cannot account for the existence of metallic behaviour in low density, strongly interacting 2D systems.

1. Introduction

The scaling theory of localisation argues that there should be no metallic state in two dimensions for non-interacting electrons (or holes) (Abrahams *et al.* 1979; Gor'kov *et al.* 1979). This prediction has been revisited in recent years, with a growing interest in the possibility of a two-dimensional (2D) metal. Experimental studies of a wide variety of low disorder 2D semiconductor systems have revealed an unexpectedly large decrease in the resistance as the temperature is lowered from $T \sim 1$ K, suggesting the existence of a 2D metal (Kravchenko *et al.* 1994; Simmons *et al.* 1997*a*, 1998; Hanein *et al.* 1998). Although numerous theories have been put forward to explain this effect, the origins of this metallic behaviour, and the question of whether it persists to $T = 0$, are still subjects of great debate.

Recent experimental studies have shown that at high carrier densities, where interactions are weak (r_s is small) and $k_F l$ is large, a transition back to insulating behaviour occurs (Hamilton *et al.* 1999; Pudalov *et al.* 1999*a*). These results are in agreement with the early studies of weakly interacting 2D systems which revealed a logarithmic increase in the resistance as $T \rightarrow 0$ (Abrahams *et al.* 1979; Gor'kov *et al.* 1979; Altshuler *et al.* 1980; Uren *et al.* 1980). This logarithmic increase diverges as $T \rightarrow 0$, with the result that

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there is no true metallic state in weakly interacting 2D systems. Furthermore, it has also been shown that even in the 'metallic' regime in 2D hole systems, where the resistance drops sharply with decreasing temperature, quantum corrections to the conductivity are still present. These localising corrections, due *both* to phase coherent weak localisation (Simmons *et al.* 2000; Senz *et al.* 2000), *and* to weak carrier–carrier interaction effects (Simmons *et al.* 2000), indicate that the system is still a Fermi liquid, and that the drop in resistance with decreasing T is not quantum in origin. These recent studies therefore argue against the existence of a metallic phase even when interactions are strong ($r_s = 10$). In this paper we address the final remaining question: what then is the origin of the widely observed metallic-like drop in resistance in 2D systems?

A number of semi-classical mechanisms have been put forward to explain this effect, with the possibility of temperature dependent carrier–carrier scattering in a two-band system receiving particular interest (Pudalov 1997; Murzin *et al.* 1998). This model is attractive because it is independent of both the semiconductor material system and of whether the charge carriers are electrons or holes. Using a 2D GaAs hole system we investigate the relevance of this and other models, at low carrier densities, close to the transition from metallic-like to strongly localised behaviour. We show that, to first order, interactions, spin–orbit coupling and symmetry of the confining potential are not responsible for the metallic-like behaviour observed at low carrier densities.

2. Experimental Details

The heterostructure used here is similar to that described elsewhere (Simmons *et al.* 1997*b*), based on a high mobility modulation doped GaAs–AlGaAs heterojunction. Two samples were grown *simultaneously* on different (311)*A* GaAs substrates: Sample A was grown on an undoped substrate, whereas sample B had an *in-situ n*+ back gate buried 1.2 μm below the hole gas. The simultaneous growth ensures that the two samples have identical layer thicknesses, doping densities and impurity densities.

Measurements were performed using standard four terminal low frequency (4 Hz) ac lockin techniques, with the sample immersed in the mixing chamber of a dilution fridge. Temperature dependent data were taken both for increasing and decreasing T, to ensure accurate determination of the sample temperature. The hole density could be varied from $0 - 10 \times 10^{10}\text{cm}^{-2}$, with the metal–insulator transition occurring at a density of $\sim 1 \times 10^{10}\,\text{cm}^{-2}$. The heterostructures are of exceptionally high quality, with a peak mobility of $1.1 \times 10^6\ \text{cm}^2\text{V}^{-1}\ \text{s}^{-1}$.

3. Metallic-like Behaviour in Dilute 2D Hole Systems and the Two-band Model

In the two-band model the 'spin' degeneracy of the electrons (or holes) is lifted by a lack of inversion symmetry in a 2D system, creating two distinct bands. If the carriers in the two bands have different transport properties this can cause a metallic temperature dependence of the resistivity over a limited temperature range. Indeed studies of the metallic phase in high density hole gas samples, far from the metal–insulator transition, show a strongly temperature dependent positive magnetoresistance in a perpendicular magnetic field that is characteristic of conduction in a two-band system (Murzin *et al.* 1998; Papadakis *et al.* 1999; Yaish *et al.* 2000). Furthermore, the increase in resistance with magnetic field in these studies was almost identical in magnitude (~10%) to the increase of the $B = 0$ resistance with temperature. Both of these observations are consistent with the metallic behaviour resulting from scattering in a two-band system, and

not interaction effects, which are weak at high carrier densities. However, these experiments have been conducted at carrier densities in the range $(2-4)\times 10^{11}\mathrm{cm}^{-2}$, where the interparticle interactions, characterised by the parameter $r_s = 4 - 5.5^*$, are significantly weaker than in the studies which originally identified the 2D metallic behaviour: $r_s = 10 - 30$ (Kravchenko *et al.* 1994; Simmons *et al.* 1997*a*, 1998; Hanein *et al.* 1998). Furthermore, the metallic behaviour is much less visible in this high density regime than close to the 'metal'–insulator transition, with only a small drop in resistivity as the temperature is decreased ($\Delta\rho/\rho \sim 10\%$). It is not clear therefore that results obtained at high carrier densities can be related to the behaviour observed at much lower densities where the metallic behaviour is strongest and the transition to strong localisation occurs.

In this work we investigate the metallic-like behaviour, and the two-band model, immediately in the vicinity of the transition. The carrier densities investigated here are an order of magnitude smaller than used in previous studies, so that interactions are strong: $r_s \simeq 17$. This low density has the additional advantage that complications due to the anisotropy and non-parabolicity of the valence band-structure which occur at higher energies are avoided.

We begin by showing the marked decrease in the sample resistivity that characterises the metallic-like behaviour. The temperature dependence of the zero magnetic field ($B = 0$) resistivity ρ is plotted for sample B at a carrier density of 2×10^{10} cm^{-2} in Fig. 1*a*.

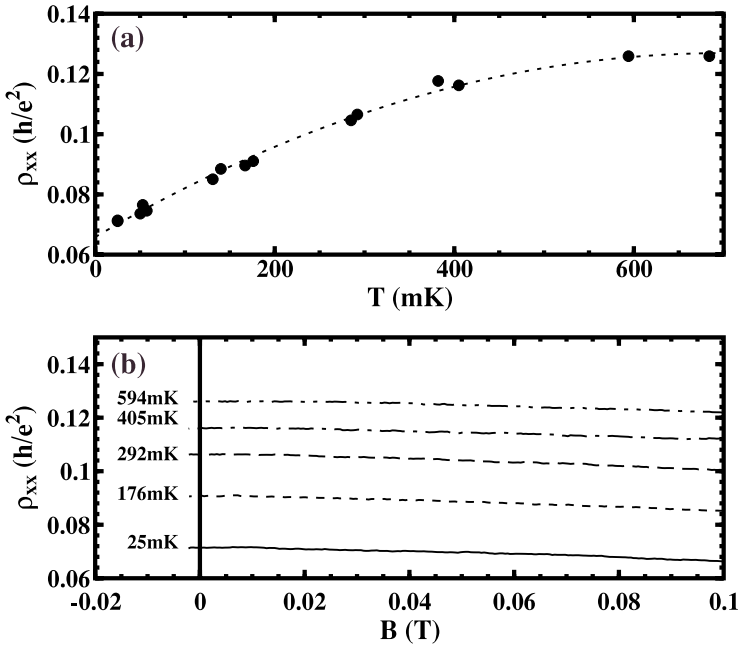

Fig. 1. (*a*) Temperature dependence of the zero field ($B = 0$) resistivity in the metallic regime for sample B. The carrier density is 2×10^{10} cm^{-2}, and the back-gate bias is 1.7 V. (*b*) Low field transverse resistivity ρ_{xx} as a function of perpendicular magnetic field over the same temperature interval.

* In 2D, $r_s \propto m^*/\sqrt{p_s}$, and so is strongly dependent on the effective mass, which is not a well known parameter for p-GaAs. In this paper we define $m^* = 0.3m_e$; using a larger effective mass will naturally increase the values of r_s calculated from the hole density p_s.

Strongly metallic behaviour is observed at this density, close to the 'metal'–insulator transition. The resistivity decreases by 50% as the temperature is reduced from 700 to 30 mK, with no signs of saturation as $T \to 0$.

In contrast to previous studies of high density hole systems, we find no evidence of the positive magnetoresistance that occurs in a two-band system. Fig. 1*b* shows the low field magnetoresistance for five different temperatures between 25 and 600 mK at $p_s = 2 \times 10^{10}$ cm^{-2}. Even though there is a factor of 2 drop in the zero field resistivity as T decreases from 700 to 30 mK, there is no sign of any positive magnetoresistance, confirming that the $B = 0$ 'spin-splitting' due to inversion asymmetry is extremely small. These results therefore show that the metallic behaviour observed at low densities cannot be solely due to temperature dependent scattering in a two-band system.

4. Effect of Symmetry on the Metallic Behaviour

We now examine what effect changing the symmetry has on the metallic state close to the transition. The symmetry of the potential confining the hole gas is determined by the electric field applied across the heterojunction. The combination of front and back gates makes it possible to tune the symmetry of the confining potential and the strength of the interparticle interactions independently. It is therefore possible to separate these two effects and determine which is responsible for the metallic behaviour observed in low density 2D systems. Sample A has been grown without a back gate (i.e. $V_{bg} = 0$) and represents the least asymmetric case, i.e where the electric field across the sample is minimal. The asymmetry is increased in sample B by the incorporation of an *n*+ back gate, which creates a large electric field across the hole gas. This built-in p–i–n structure gives rise to an effective back-gate bias equivalent to the low temperature GaAs band-gap of 1.5 V (Simmons *et al.* 1997*c*). The electric field, and hence asymmetry, in this sample can be further tuned over a limited range by biasing this back gate. The requirement that leakage currents should be below 1 pA limits the back-gate bias range to 1.25 – 1.7 V. It is not therefore possible to attain the flat-band condition $V_{bg} = 0$ in sample B.

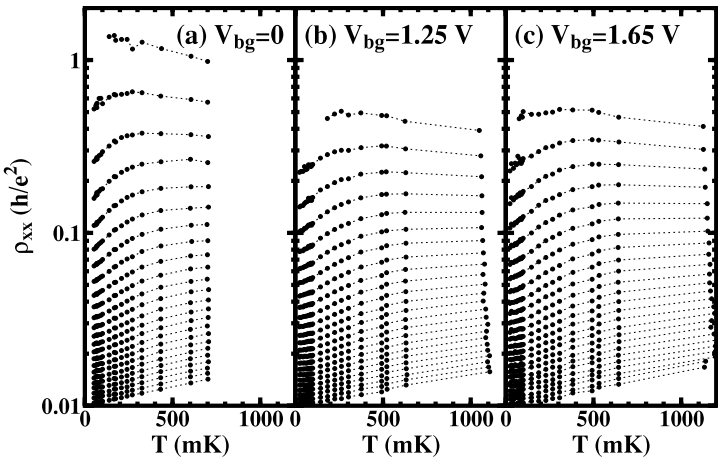

Fig. 2. Temperature dependence of the resistivity at carrier densities from $1 - 4 \times 10^{10}$ cm^{-2} in steps of 0.135×10^{10} cm^{-2}, for three different back gate biases: (*a*) $V_{bg} = 0$, $p_s = 0.9$, 1.04, 1.17, . . . , (*b*) $V_{bg} = 1.25$ V, $p_s = 1.47$, 1.6, . . . and (*c*) $V_{bg} = 1.65$ V, $p_s = 1.57$, 1.7, . . . $\times 10^{10}$ cm^{-2}.

Fig. 2*a* shows the temperature dependence of the $B = 0$ resistivity in sample A (where $V_{bg} = 0$) at carrier densities from $1 - 4 \times 10^{10}\text{cm}^{-2}$. Insulating behaviour is observed at the lowest carrier densities (top curve). The subsequent traces show the transition to metallic behaviour as the carrier density is increased. The resistivity at the transition is $\approx h/e^2$, as found in previous studies of extremely low disorder 2D hole gases (Simmons *et al.* 1997*a*). Figs 2*b* and 2*c* show the same measurements for sample B, with back-gate biases of 1.25 and 1.7 V. Increasing the back gate bias increases the electric field across the hole gas, causing the shape of the potential confining the holes to become more asymmetric. Despite altering the symmetry of the confining potential, the data in Fig 2 are remarkably similar with very little change in the magnitude of the temperature dependent resistivity. These results show that changing the symmetry does not affect the apparent strength of the metallic behaviour at this low carrier density.

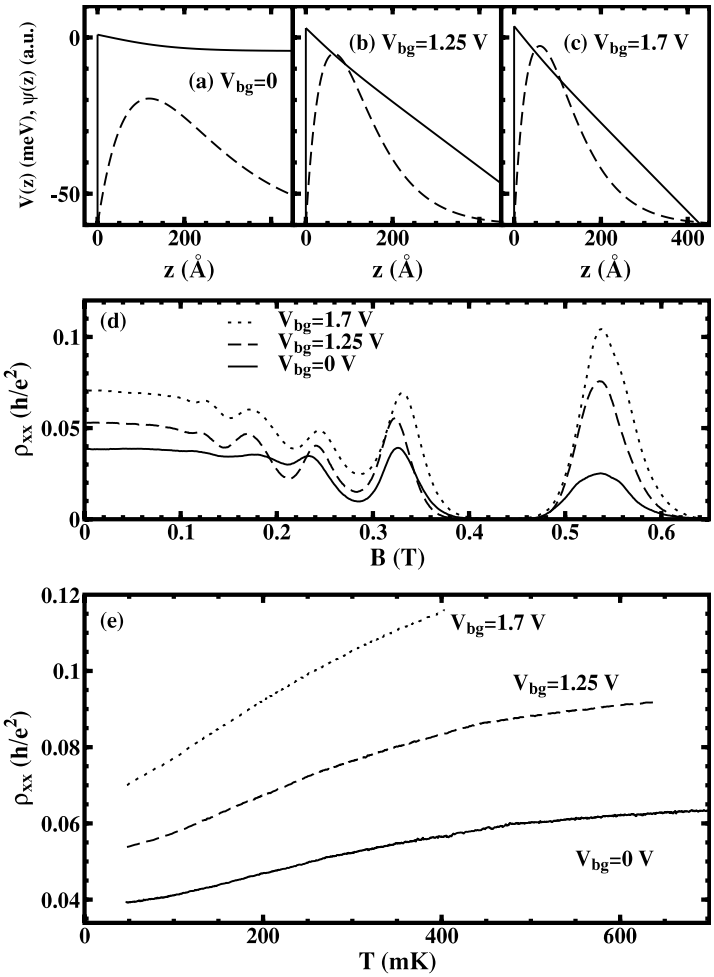

Fig. 3. Properties of the 2D hole gas at $p_s = 2.1 \times 10^{10}$ cm^{-2}: (*a*)–(*c*) Potential profiles $V(z)$ (solid curves) and hole wavefunctions $\psi(z)$ (dashed curves) calculated for three different back-gate biases, at constant density. (*d*) Magnetoresistance ρ_{xx} measured in a perpendicular magnetic field at $T = 30$ mK for the different back-gate biases. (*e*) Corresponding temperature dependence of the zero field resistivity.

The data in Fig. 2 show the metallic behaviour for three different back-gate biases at a series of different carrier densities. In order to quantify the effect of the back-gate bias we now concentrate on one particular carrier density, $p_s = 2.1 \times 10^{10}$ cm^{-2}, just on the 'metallic' side of the transition. We first calculate the potential profile and hole wavefunction for the three different V_{bg} (Kelly and Hamilton 1991). The net electric field across the hole gas is the sum of the field due to the back gate and the field due to the accumulation of the hole gas: $E = E_{bg} + ep_s/\varepsilon$. Here ε is the dielectric constant and $E_{bg} = V_{bg}/d$, where d is the distance from the substrate to the heterointerface. The results are plotted in Figs 3*a*–3*c*, with the solid curve showing the potential profile. There is a large change in the electric field E_{bg} from 0 to 14 kV cm^{-1} as the back-gate bias is altered from 0 to 1.7 V. In contrast the electric field due to the fixed carrier density is constant at only 3 kV cm^{-1}. Increasing the back-gate bias also pushes the holes up against the heterointerface, reducing the width of the wavefunction and making the hole gas more two-dimensional.

The effect of the changes in the symmetry of the confining potential shown in Figs 3*a*–3*c* on the transport properties of the hole system is now examined. Fig. 3*d* shows the magnetoresistance at a fixed density of 2.1×10^{10} cm $^{-2}$ for different V_{bg}. The three traces show Shubnikov–de Haas oscillations with the same periodicity, confirming that the density is constant. The oscillations show only a single frequency, with no sign of the beating that occurs when two bands are occupied. This indicates that in contrast to high density 2D hole gases the splitting of the heavy hole band is negligible at these low carrier densities.

To determine the influence of the electric field on the strength of the metallic behaviour, the temperature dependence of the $B = 0$ resistivity is plotted in Fig. 3*e*. Although metallic behaviour is observed in all three cases, it is not obvious how to quantify the strength of the metal because the different traces all start from different values of ρ at $T = 30$ mK. The change in resistance with T is clearly largest for the strongest electric field (top trace), where $\Delta\rho = 0.04\ h/e^2$ from $T = 30$ mK to 400 mK, compared to $0.02\ h/e^2$ for $V_{bg} = 0$. This comparison is not entirely fair, however, as the resistivity is larger for $V_{bg} = 1.7$ V than for $V_{bg} = 0$ V. This is because increasing the electric field due to the back gate pushes the holes closer to the heterointerface, enhancing the scattering from the remote ionised impurities in the AlGaAs. Thus, even though the carrier density (and hence k_F) are constant, the effective disorder becomes larger with increasing V_{bg}.

Nevertheless, the results clearly show that the metallic behaviour is affected by the back-gate bias. In these measurements the carrier density p_s, Fermi wavevector k_F and the strength of interparticle interactions r_s are all fixed, with only the disorder related mean free path l and symmetry varying. The metallic behaviour is therefore sensitive either to the symmetry of the confining potential, or to the disorder, or both.

5. Behaviour at Constant $k_F l$

To distinguish between the above two possibilities, we now compare $\rho(T)$ traces that originate from the same point at $T = 30$ mK—i.e. we fix $k_F l$ —and look for differences in the size of $\Delta\rho$ as T is increased. To do this we tune the hole density with the front gate, so that the resistivity, and hence $k_F l$, at 30 mK is the same for the three different back-gate biases. To achieve this the carrier density is increased from 1.8 to 2.3×10^{10} cm^{-2} as the back-gate bias is increased from 0 to 1.7 V. Although the carrier density and mean free path are now no longer constant in these measurements, they only vary by 30%, whereas the total electric field across the hole gas increases fivefold from 3 to 17 kV cm^{-1}. To

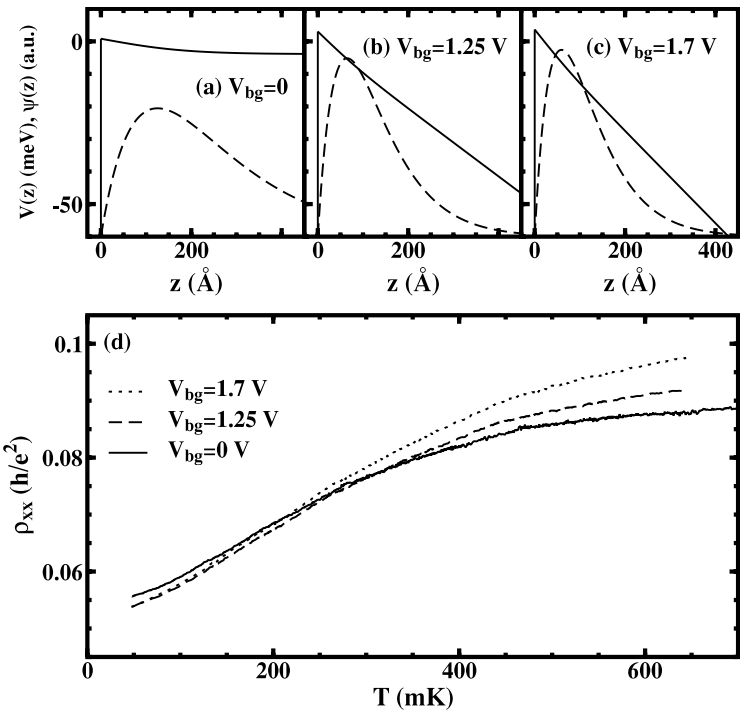

Fig. 4. Properties of the 2D hole gas with the $T = 30$ mK resistivity fixed at 0.055 h/e^2 ($k_F l = 18$), for three different back-gate biases: (*a*)–(*c*) Potential profiles and hole wavefunctions. (*d*) Corresponding temperature dependence of the zero field resistivity.

show this we plot the potential profiles and hole wavefunctions in Figs 4*a*–4*c*. These confirm that despite the small variation in p_s, the electric field across the hole gas is still predominantly determined by the back-gate bias. The corresponding temperature dependent resistivity traces for the three back-gate biases are shown in Fig. 4*d*. Despite the large change in the symmetry of the confining potential, the traces are almost identical. This confirms that the strength of the metallic behaviour at low densities is not determined by the symmetry of the confining potential, and is therefore not related to the degree of band splitting. Instead, the data indicate that the metallic state is primarily affected by changes in the disorder.

Alternative semi-classical models of the metallic behaviour include a temperature dependent density of charged scattering sites (Altshuler and Maslov 1999), and a combination of carrier freeze-out and temperature dependent screening (Das Sarma and Hwang 1999). The first of these two mechanisms is necessarily material dependent and cannot readily account for the metallic temperature dependence observed in three different material systems. The latter asserts that the number of free carriers contributing to electrical conduction is less than the total carrier density, with the apparent metal–insulator transition corresponding to the point where the free carrier density falls to zero. However, it is interesting to note that we find the free carrier density determined from low field Hall measurements is non-zero at the transition from metallic to strongly localised behaviour.*

* A similar observation has also recently been reported in the Si material system (Pudalov *et al.* 1999*b*).

6. Summary

The results presented here show that the two-band model of temperature dependent scattering does not describe the anomalous metallic behaviour observed in low density 2D hole gas systems. Furthermore, large changes in the electric field across the heterointerface, and hence the symmetry of the confining potential, do not produce significant changes in the strength of the metallic state. Instead, we find that at low carrier densities the temperature dependence of the resistivity is predominantly determined by $k_F l$, independent of the electric field across the heterojunction.

Although the origin of the metallic behaviour remains unexplained, these observations argue against interaction effects, the shape of the potential well and spin–orbit effects as the primary causes. Further work, both theoretical and experimental, will be needed before we can fully understand the nature of electrical conduction in dilute two-dimensional systems.

Acknowledgments

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