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Physica E 12 (2002) 646–649

PHYSICA E

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The fate of quantum Hall extended states as $B \rightarrow 0$ and the possibility of a 2D metal

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Abstract

We report the study of two-dimensional ‘metallic’ behaviour at $B = 0$ in ultra-high-quality n-GaAs ($\mu_{\text{peak}} > 10^7\ \text{cm}^2\ \text{V}^{-1}\ \text{s}^{-1}$), and in particular address the question of what happens to the quantum Hall extended states at the centre of Landau levels as $B \rightarrow 0$. In these high-quality electron samples we can reach extremely low carrier densities ($2 \times 10^9\ \text{cm}^{-2}$), allowing us to track the extended states down to very low magnetic fields (down to ~ 0.05 T). Our result suggests that as $B \rightarrow 0$ the extended states float up in energy as predicted by the scaling theory of localisation. © 2002 Elsevier Science B.V. All rights reserved.

PACS: 71.30.+h; 73.43.−f

Keywords: Metal–insulator transition; Quantum Hall effect

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1. Introduction

To date there remains a lot of controversy about the possibility of a ‘metallic’ ground state in two-dimensional (2D) systems. While the one-parameter scaling theory of localization [1] predicts that in the absence of a magnetic field all 2D systems are insulating (σ_{xx} vanishes) at $T = 0$, an anomalously strong ‘metallic’ behaviour ($\mathrm{d}R/\mathrm{d}T > 0$) has been observed in various high quality, strongly interacting systems over the last few years [2–7]. Despite numerous experimental and theoretical proposals, the questions as to what causes this ‘metallic’ behaviour and whether the 2D ground state is ‘metallic’ remain unresolved.

Another way to determine the ground state of the system is to relate the quantum Hall effect to the apparent ‘metal’–insulator transition (MIT) at $B = 0$ [8,9]. It is known that in a perpendicular B there exist extended states in the middle of the Landau levels, giving rise to the quantum Hall effect. The question is what happens to these extended states as $B \rightarrow 0$? If there are extended states below the Fermi energy at $B = 0$ then a metallic state exists, otherwise the system is an insulator. Following the scaling theory of localisation, Khmelnitskii and Laughlin have argued that these extended states ‘float up’ to an infinite energy as $B \rightarrow 0$ [10], eliminating the possibility of a metallic ground

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PII: S1386-9477(01)00421-0

state at $B = 0$. Thus one way to determine if there is a true 2D metal is to track the extended states and see what happens to them as $B \to 0$.

In this paper, we perform temperature-dependent magneto-transport measurement to track the position of the extended states as $B \to 0$, using an ultra-high-quality 2D electron system that exhibits an apparent MIT at $B = 0$. The samples were fabricated from an undoped GaAs/AlGaAs heterostructure where the carriers are induced by means of a gate voltage.

2. Experimental results

Fig. 1 shows the resistance of the sample as a function of temperature for different densities at $B = 0$. At the lowest density, the sample shows insulating behaviour where the resistance increases as $T \to 0$. As the density is increased, the sample shows an apparent 'metal'–insulator transition at a density of $n_s^c = 4 \times 10^9$ cm^{-2} where $r_s = 9$.

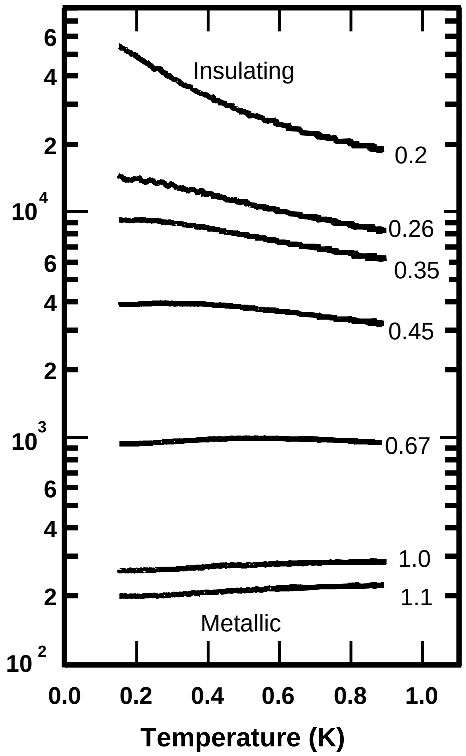

Fig. 1. Resistance versus temperature curves at $B = 0$ for carrier densities from 0.2×10^{10} to 1.1×10^{10} cm^{-2}.

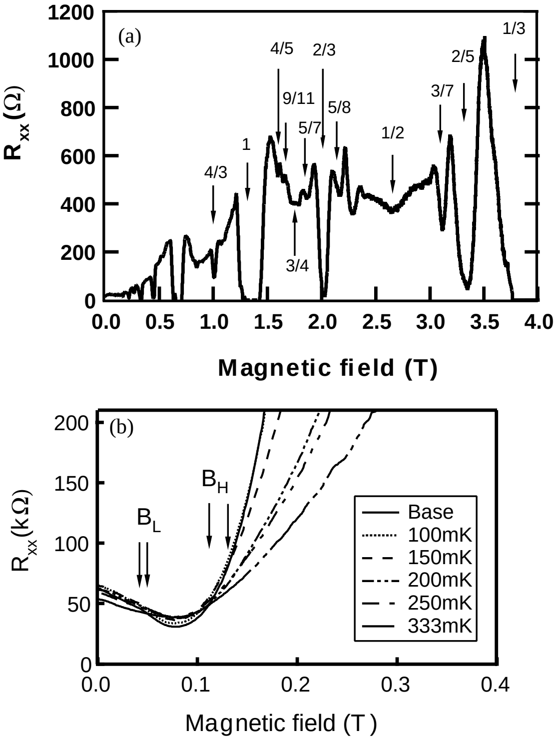

Fig. 2. Quantum Hall effect data at carrier densities of (a) 3×10^{10} cm^{-2} ($T = 100$ mK) and (b) 2×10^9 cm^{-2}.

Having demonstrated the existence of an apparent MIT at $B = 0$, we now examine the evolution of the extended states as $B \to 0$. Fig. 2 shows quantum Hall effect data at (a) $n_s = 3 \times 10^{10}$ cm^{-2}, and (b) $n_s = 2 \times 10^9$ cm^{-2}. The observation of the fractional states $\frac{9}{11}$, $\frac{5}{8}$ and the series around $\frac{3}{4}$ at a density of $n_s = 3 \times 10^{10}$ cm^{-2} and $T = 100$ mK (Fig. 2(a)) highlights the high quality of the sample.

In order to track the position of the extended states, the magneto-resistance data were used to produce a 3D grayscale as shown in Fig. 3. Here the x-, y- and z-axis are the magnetic field, density, and σ_{xx}, respectively. The dark regions represent the σ_{xx} peaks (i.e. the extended states) and the light regions represent the quantum Hall minima, also marked with dotted lines (with v the filling factor).

At very low carrier densities however, it becomes increasingly difficult to determine the positions of the extended states due to the expected broadening of the

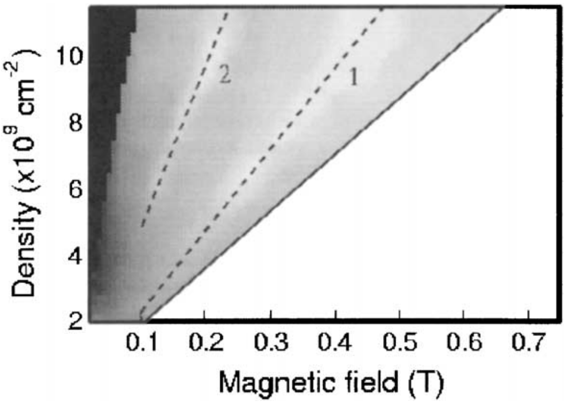

Fig. 3. 3D grayscale of the conductivity σ_{xx} as a function of carrier density and field, showing the evolution of the extended states.

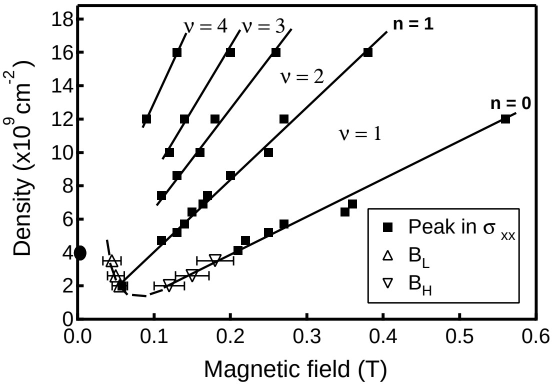

Fig. 4. Position of the extended states in the density-field plane. The circle marks the critical density at which the MIT occurs at $B = 0$.

σ_{xx} peaks. We have therefore used another method, by plotting the range in B over which the sample undergoes a transition from insulating behaviour ($\mathrm{d}R/\mathrm{d}T < 0$) to a quantum Hall state ($\mathrm{d}R/\mathrm{d}T > 0$), indicated by the arrows labeled B_{L} and B_{H} in Fig. 2(b). Fig. 4 highlights the positions of the extended states determined from both the crossing points B_{L} and B_{H} in Fig. 2, and from the peaks in σ_{xx} in Fig. 3. If we consider the $n = 0$ Landau level we see very good agreement between the two different methods of determining the position of the extended states. Using such a high-quality sample, we are able to reach extremely low carrier densities and hence track the extended states down to 0.05 T. This is approximately three times lower in B than previous studies in p-GaAs [8] where it was concluded that the extended states saturate to a finite energy at $B = 0$.

Our result shows that the lowest extended state ($n = 0$) starts to float up as $B \to 0$ and merges into the $n = 1$ state at $B = 0.05$ T. This leads to an insulator → $\nu = 2$ quantum Hall liquid direct transition at $n_{\mathrm{s}} = 3 \times 10^9\ \mathrm{cm}^{-2}$, in agreement with recent numerical calculations [11]. The observation that the extended states float up so rapidly as $B \to 0$ makes it difficult to relate them to the apparent $B = 0$ MIT. Thus, unless there is a sharp change in the trajectory of the extended states, there will be no extended states beneath the Fermi energy at $B = 0$, and hence no metallic ground state. This result is in agreement with previous studies of more disordered n-GaAs [9] samples where no metallic behaviour was observed at $B = 0$. It is also in agreement with the recent observations of weak localisation [12] which suggests that the $B = 0$ ground state is insulating.

3. Conclusions

In summary, we have observed an apparent MIT in an ultra-high-quality n-GaAs system. The sample is amongst the highest quality ($\mu_{\mathrm{peak}} = 2.4 \times 10^7\ \mathrm{cm}^2\ \mathrm{V}^{-1}\ \mathrm{s}^{-1}$) and lowest density ($n_{\mathrm{s}} = 2 \times 10^9\ \mathrm{cm}^{-2}$) sample in which the 2D MIT has been observed. Using such high-quality samples we are able to track the evolution of the extended states down to B of 0.05 T, three times lower than previous studies. Our result shows that the extended states merge and float up in energy as $B \to 0$, suggesting that there is no 2D ‘metal’ at $B = 0$.

Acknowledgements

This work was funded by the Australian Research Council. CEY acknowledges support from the IPRS scheme; MYS acknowledges support from the QEII Fellowship Scheme.

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