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LETTER TO THE EDITOR

Hopping in a low-mobility GaAs–AlGaAs heterojunction in the limit of low electronic concentrations

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Abstract. A gated low-mobility GaAs–$Al_{0.3}Ga_{0.7}As$ delta-doped heterojunction of large area is used to demonstrate a transition from diffusive to hopping transport as the electron concentration in the two-dimensional conducting layer is reduced. At helium temperatures ($1.3 < T < 4.2$ K), the hopping conductivity is well described by the variable-range-hopping law $\sigma \sim \sigma_0 \exp - (T_0/T)^{1/2}$ expected when electron–electron interactions are strong. At very low temperatures, ($T \simeq 100$ mK), conductance fluctuations are seen, indicating that under these conditions size effects are important and a description of transport by a macroscopic model of conduction is inappropriate.

GaAs–AlGaAs heterojunctions with a spacer layer can display a very high electron mobility as the two-dimensional (2D) electron gas and impurities are widely separated. Such low-disorder structures have been the object of extensive investigations. However, transport under conditions of high disorder, and when the conduction is thermally activated, has been examined in much less detail. Localisation and hopping conduction have been investigated in the presence of a magnetic field which establishes Landau levels [1–3], but localisation is hardly observable in the absence of such a field. In this paper we report experimental results obtained in the hopping regime of a low-mobility GaAs–AlGaAs heterojunction at low values of electron concentration.

The samples used were GaAs–$Al_{0.3}Ga_{0.7}As$ heterojunctions grown on an insulating substrate by molecular beam epitaxy. The layer composition is shown in figure 1. The structure is similar to a normal, high-mobility, structure but there is, in addition, a single layer doped with silicon at a concentration of $(5 \pm 1) \times 10^{10}\,\mathrm{cm}^{-2}$ situated two layers away from the interface on the AlGaAs side of the junction. The impurities in this delta-doped layer close to the 2D electron gas will act as scattering centres and hence lower the mobility. Several samples cut from different parts of the wafer were etched to form Hall bars, 100 μm × 750 μm, with evaporated Au–Ni–Ge ohmic contacts and a Au gate. At a gate voltage $V_G = 0$, the devices possessed an electronic concentration

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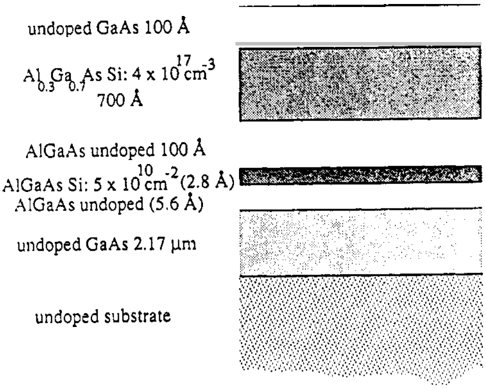

Figure 1. Cross-section of the heterojunctions used in the experiment.

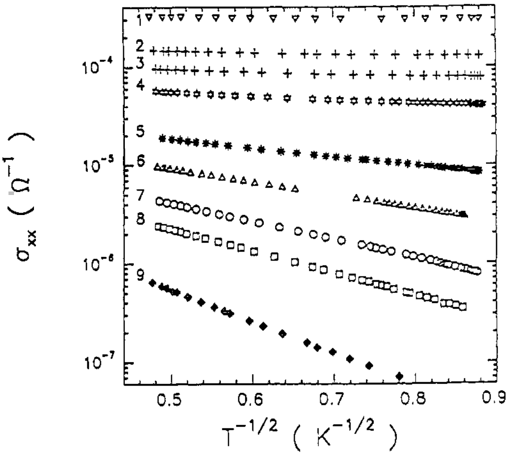

Figure 2. Conductivity as a function of gate voltage and temperature for sample S1. V_G = (1) −0.548 V, (2) −0.600 V, (3) −0.620 V, (4) −0.642 V, (5) −0.676 V, (6) −0.691 V, (7) −0.700 V, (8) −0.713 V, (9) −0.720 V.

$n \simeq 4 \times 10^{11}$ cm^{-2} and a low mobility, $\mu \simeq 5 \times 10^4$ cm^2 V^{-1} s^{-1}. The channel is completely depleted at $V_G \simeq -0.80$ V. Measurements in the regime of low resistivity were obtained using a four-terminal low-frequency technique and those obtained in the range $R \geq 10^5$ Ω, with a two-terminal low-frequency technique. The conductivity was studied in the temperature range $1.3 < T < 4.2$ K in a He^4 glass cryostat. The temperature was stabilized with a vapour pressure control system and measured with a calibrated resistor in good thermal contact with the sample via a copper block. All data were taken in the limit of low electric field ($E \simeq 1$ V m^{-1}). A top-loading dilution refrigerator was used for the measurements performed down to 100 mK. All samples that were investigated had similar properties.

At helium temperatures, we would expect a transition from diffusive to hopping transport to be observed in the highly disordered band tail, in a similar manner to results obtained with n-type and p-type MOSFETS [4], in view of the low value of mobility which results in a mean free time comparable with that found for the electron gas in the silicon structures studied earlier.

The temperature dependence of the conductivity of sample S1 is shown in figure 2 for different applied negative gate voltages. For $\sigma_{xx} \lesssim 10^{-4}$ Ω^{-1} this becomes increasingly strong as the negative gate voltage is increased, suggesting that a transition from diffusive (with a weak logarithmic dependence on temperature) to activated transport is occurring around this value of conductivity. At sufficiently low temperatures, phonon-assisted transport is expected to be by variable-range hopping (VRH), with a temperature dependence of the conductivity described by an equation of the form [5, 6].

$$\sigma = \sigma_0 \exp(-R_M/\xi) = \sigma_0 \exp[-(T_0/T)^X] \tag{1}$$

where R_M is the optimum hopping length, ξ is the localization length and X depends on the dimensionality of the system and the strength of the electron–electron interaction.

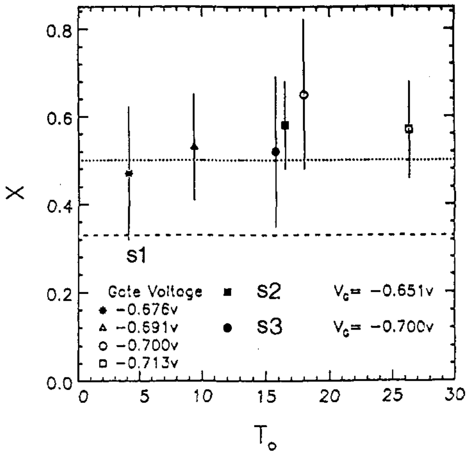

Figure 3. Best value of $X(V_G)$ and $T_0(X = \frac{1}{2}, V_G)$ for samples S1, S2 and S3. The upper horizontal line corresponds to the expected value $X = \frac{1}{2}$ for 2D interacting carriers or 1D non-interacting carriers, and the lower line corresponds to the expected value $X = \frac{1}{3}$ for 2D non-interacting carriers.

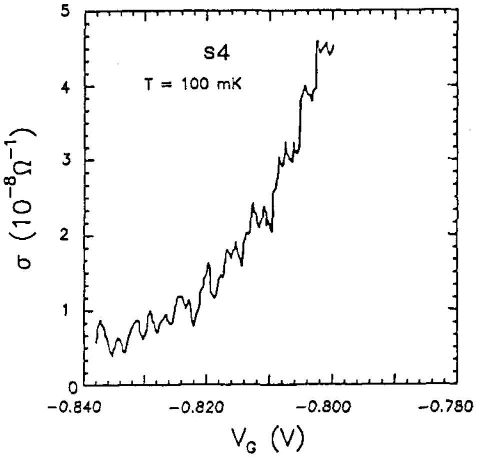

Figure 4. Gate voltage dependence of the conductivity for sample S4 in the insulating phase, at $T = 100$ mK and for a source–drain electric field of 1.3 V m^{-1}.

A least-squares-fit procedure [7] was used to evaluate the value of X in (1) which best describes the data taken in the regime of high resistivity. It is found that for $V_G \geqslant -0.676$ V, the value is close to $X = \frac{1}{2}$, a result consistent with the 2D VRH of interacting electrons [5] or possibly Mott hopping [6] in a 1D system. The best values of X and T_0 ($X = \frac{1}{2}$) are presented in figure 3. Results obtained from two other devices are also presented and good reproducibility is found. For sample S1 (figure 2) at $V_G = -0.642$ V the best value of X obtained is close to zero suggesting that a transition from hopping to metallic behaviour has occurred at $-0.676\ \mathrm{V} < V_G < -0.642$ V. It was found that in the regime $V_G > -0.642$ V, the temperature dependence of the conductivity is in agreement with that found in other disordered 2D systems in the diffusive regime [8–10]. The transition occurs when the electronic concentration $n = n_c \simeq (0.95 \pm 0.1) \times 10^{10}\ \mathrm{cm}^{-2}$, and is between diffusive and activated behaviour in contrast to very high-mobility heterojunctions where metallic behaviour persists for concentrations [11] down to $n \simeq 1 \times 10^{10}\ \mathrm{cm}^{-2}$. At the transition, the conductivity, σ_{xx}, $\simeq 5 \times 10^{-5}\ \Omega^{-1}$. This value is close to the critical (minimum metallic) conductivity measured in other 2D systems [4, 8, 9] and to the value $\sigma_{\min} \approx e^2/h \sim 4 \times 10^{-5}\ \Omega^{-1}$ originally suggested by Mott [12] and modified for a 2D system [4]. We note that we expect to find this result for 2D systems when the logarithmic corrections due to quantum interference or interactions are small [8].

The data obtained in the hopping regime suggest that in the strongly localised phase electron–electron interactions are important in 2D GaAs. There are a number of studies indicating that interactions are important in bulk GaAs [9, 13–16] and in various 3D crystalline and amorphous materials [16]. Fewer detailed experimental studies on 2D systems are available at present. In Na$^+$:Si MOSFET(s), results consistent with the hopping of non-interacting electrons were found under experimental conditions where a Coulomb gap was expected to be present [17]. Work on germanium bicrystals [18] showed transport according to (1) with $X = \frac{1}{2}$. However, this system becomes increasingly anisotropic below the metal–insulator transition and eventually becomes 1D, consequently the interpretation of the results is ambiguous. The Coulomb gap theory has also been questioned, and it has been suggested that in 2D there is no Coulomb gap unless the hopping rate is exactly zero [19]. Recently, transport according to (1) with $X = \frac{1}{2}$ was observed in a wide MOSFET in the limit of low electronic concentrations [20]. This was suggested to be due to hopping transport along a very few widely spaced 1D isolated optimal chains of impurities. The possible existence of this mechanism, even in large samples, was proposed by Raikh and Ruzin [21–22] and such a mode of conduction should give rise to conductance fluctuations with respect to an external parameter (for example a magnetic field or the gate voltage). The delta-doped heterojunctions used in this work do not show any measurable fluctuations of conductance with gate voltage, in the temperature range $1.3 < T < 4.2$ K, so lower temperatures were used to investigate this possibility.

The gate voltage dependence of conductance over a narrow range of gate voltages, in the insulating phase, is shown in figure 4 for sample S4, at $T = 100$ mK, with a source–drain electric field $E = 1.3\ \mathrm{V\ m^{-1}}$. At this temperature, reproducible conductance fluctuations are seen, although they are two orders of magnitude less important than in the results demonstrated in [21] (under similar experimental conditions but for a different value of aspect ratio). Given the size of the fluctuations in the heterojunctions and the size of the sample, it appears unlikely that transport is only along one, or a few, 1D chains in these structures. It is most probable that the fluctuations arise from fluctuations in the number of states available for the transport process. An estimate of the number of states available in an area of length $L = R_{\mathrm{M}}$ and width equal to the width of the channel, $W = 100\ \mu\mathrm{m}$, is instructive. Using the density of states equal to the free density D_{free}, $R_{\mathrm{M}} \simeq 2000$ Å and considering the energy range of width $\Delta E \simeq 2kT$, at $T = 100$ mK the number of states $N \simeq D_{\mathrm{free}}(2\,kT)WR_{\mathrm{M}} \simeq 100$. This is sufficiently small for fluctuations to become significant, resulting in conductance fluctuations. At $T = 4.2$ K, the number of states reaches several hundred and the system therefore behaves to a better approximation like an ideal 2D infinite system.

In conclusion, VRH transport is observed in the band tail of a low-mobility gated GaAs–AlGaAs heterojunction of large area ($7.5 \times 10^{-4}\ \mathrm{cm^{-2}}$). In the temperature range $1.3 < T < 4.2$ K, the temperature dependence of the conductivity is well described by the Coulomb gap theory which takes electron–electron interactions into account and which is valid for macroscopic 2D systems. At very low temperatures, of the order of 100 mK, reproducible but weak conductance fluctuations are observed indicating that under these conditions transport cannot adequately be described by a macroscopic model but is mesoscopic in nature.

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