One-Dimensional Conduction in the 2D Electron Gas of a GaAs-AlGaAs Heterojunction

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We present results on the transport properties of the 2D electron gas in a narrow channel formed by the split gate of a GaAs-AlGaAs heterojunction field-effect transistor. There are both quantum-interference and interaction corrections to the conductivity. We find that the temperature dependence of the phase relaxation length is in agreement with a recent theory based on scattering by electromagnetic fluctuations. Beyond the regime of quantum interference the conductivity varies with temperature as T^2.

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There has recently been considerable experimental interest in one-dimensional quantum interference (weak localization) and interaction effects.[1-5] Quantum-interference corrections in a two-dimensional electron gas become one dimensional when the phase coherence length, L_0, exceeds the width of the sample, W. The correction, expressed as a conductance per unit length δG, is given by

$$\delta G = -e^2 L_0/\pi\hbar. \tag{1}$$

When L_0 exceeds the localization length diffusive behavior will not occur as carriers are strongly localized[6] and conduction will proceed by hopping. If the overlap of electron states is small then transport is due to (phonon-assisted) variable-range hopping.

Thouless[7] suggested that if the overlap is significant the hops are caused by electron-electron collisions. The diffusion coefficient, D, is given by $L_o^2/12\tau_{\text{in}}$ where L_o is the localization length and τ_{in} the electron-electron scattering time. Therefore the conductivity will vary as τ_{in}^{-1}. It is well known that if $k_f l > 1$ the Landau-Baber T^2 behavior of τ_{in} is augmented by diffusion corrections with a weaker dependence on temperature. However, if electrons are strongly localized then these corrections may not apply and τ_{in} will vary as T^{-2}. Recently it has been suggested[8] that if the localization is one dimensional, a phonon-assisted hopping process could give a conductivity varying as T^2, provided the energy difference between hopping sites is less than the thermal energy kT.

Negative magnetoresistance is found in the regime of quantum interference; in one dimension the theoretical relation is[9]

$$\delta G(B) = \frac{-e^2}{\pi\hbar}\left(\frac{1}{L_0^2} + \frac{W^2}{3L_c^4}\right)^{-1/2}, \tag{2}$$

where W is the width of the conducting region and L_c is the cyclotron radius, $(\hbar/eB)^{1/2}$. Equation (2) arises from the change in the effective length scale and is due to the perturbation of the wave function by the magnetic field; it is only valid for $L_c > W$. Significant decrease of L_c below W results in 2D localization behavior; analogous 3D and 2D behavior has been discussed elsewhere,[10] as has the behavior of $G(B)$ in the presence of spin-orbit coupling and spin-flip scattering.[11]

In addition to quantum interference the electron-electron interaction produces a conductivity correction which is one dimensional when $(\hbar D/kT)^{1/2} > W$, where k is Boltzmann's constant. The interaction correction to the conductivity can be written

$$\delta G = (-e^2 g_{1\text{D}}/\pi\hbar)(\hbar D/2kT)^{1/2}, \tag{3}$$

where $g_{1\text{D}}$ is the 1D interaction parameter and D is the Boltzmann value of diffusion coefficient.[12,13] To first order the quantum-interference and interaction corrections are additive[14] when both are weak.

In this Letter we present results on one-dimensional conduction in narrow conducting channels in GaAs-AlGaAs heterojunctions. We find both the interference and interaction corrections together and, from the negative magnetoresistance, we confirm the existence of a recently predicted 1D electron-electron scattering mechanism.[15-17] Further narrowing of the channel results in the loss of these corrections and the conductance decreases as T^2, and a positive magnetoresistance is found. Eventually with even more narrowing a transition to variable range hopping is found.

The samples used were GaAs-AlGaAs heterojunctions, the carrier concentration was 4.0×10^{11} cm^{-2}, and the mobility at 4.2 K was 2×10^5 cm^2 V^{-1} sec^{-1}. The samples were in the form of Hall bars with Au-Ge-Ni Ohmic contacts. A gold gate of 700-Å thickness was fabricated on the 1500-Å thick AlGaAs with a small gap 15 μm long and 0.6 μm wide between the two halves, as in the inset of Fig. 1. The gates were fabricated by electron-beam lithography with use of PMMA positive resist. By application of a negative voltage to the two gates, the underlying GaAs is depleted of electrons and current flows through the narrow region not covered by gate metal. Further increase in the negative gate voltage results in a reduction in the width of the conducting channel until it is removed. The action of the gate is similar to the squeezing action of the P^+ regions in Si accumulation layers used previously.[18,19] However, the problem of gate overlap onto source and drain regions (which can give activated conduction at low temperatures) is removed here and the gate voltage now acts to narrow the conducting channel rather than to offset the squeezing action of the P^+ regions in the metal-oxide-semiconductor device. In the absence of a gate voltage, the device resistance was 700 Ω at 1.3 K, and when the gate voltage was such as to induce the one-dimensional behavior discussed later the device resistance was greater than 10^5 Ω. High-magnetic-field Shubnikov–de Haas measurements indicated that the carrier concentration remained constant as the channel width was reduced.

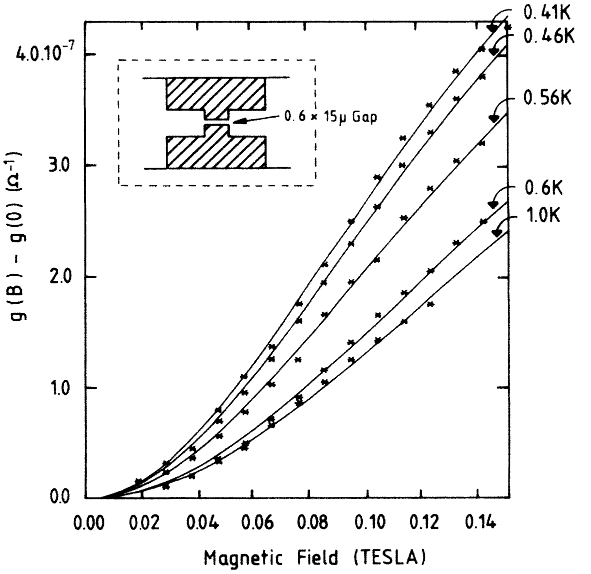

FIG. 1. The values of conductance as a function of magnetic field, indicated by crosses. The lines indicate the best fit of Eq. (2) at each temperature. Inset: The gate defining the narrow channel in the underlying heterojunction.

Conductance and magnetoconductance measurements were carried out below 1.2 K. The field across the channel was always less than 1 V/m to avoid electron heating. Figure 1 illustrates the increase in conductance induced by a magnetic field with −1.2 V on the gate. The results of Fig. 1 did not fit the 2D expression[20] whereas an excellent fit was obtained by use of Eq. (2). We note that it is not necessary to introduce spin-orbit coupling into the theoretical expression in order to obtain agreement with theory. In 2D the spin-orbit coupling in GaAs heterojunctions is only significant at very low temperatures and very low magnetic fields.[21] Analysis of a number of temperatures between 1.0 and 0.4 K yielded a constant value for the width of the conducting channel of 450 Å ± 10% and a temperature-dependent L_0 which is plotted in Fig. 2; this figure will be discussed later.

From the values of L_0 in Fig. 2, it is possible to obtain the value of δG due to quantum interference [Eq. (1)]. This was always small compared to G, having a maximum value of just over 20% at 0.41 K. In order to investigate the correction due to the electron-electron interaction we have added δg to the conductance g for each temperature and plotted the resultant value against $T^{-1/2}$, as shown in Fig. 3. A linear relation is

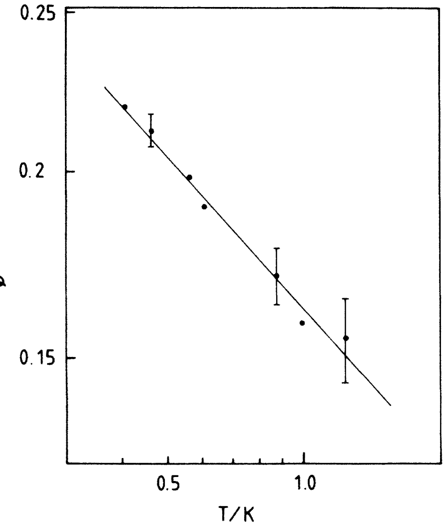

FIG. 2. The phase relaxation length plotted against temperature on a log-log scale.

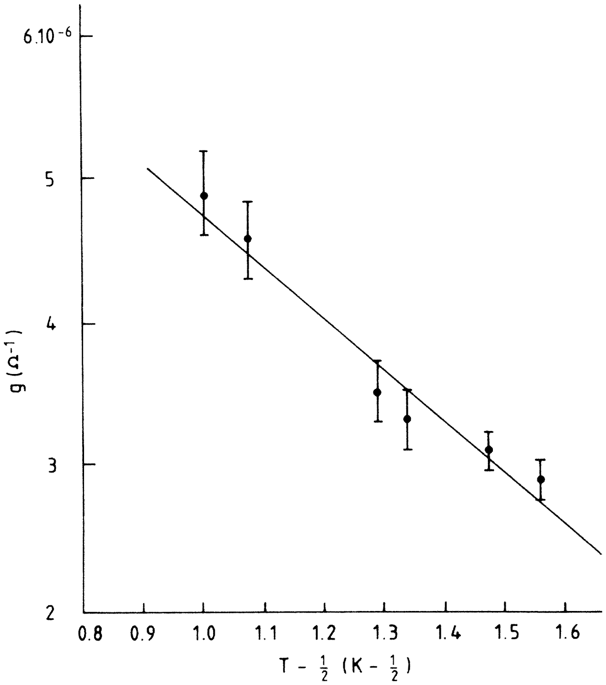

FIG. 3. The conductance after addition of the quantum-interference correction, plotted against $T^{-1/2}$.

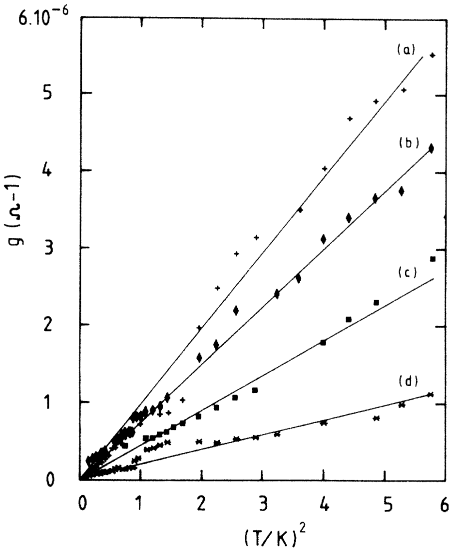

FIG. 4. The conductance for a number of gate voltages plotted against T^2. (a) $V_g = -1.210$, (b) $V_g = -1.215$, (c) $V_g = -1.220$, (d) $V_g = -1.225$. The error in g is approximately 5%.

found which gives a value of D of 660 $\mathrm{cm}^2 \cdot \mathrm{sec}^{-1}$ for an interaction parameter of 1.35 appropriate to this carrier concentration.[13] If we assume the two-dimensional density of states for GaAs, this Boltzmann value of D gives a value of $g_B \approx 8.9 \times 10^{-6}$ Ω^{-1} for a value of width of conducting channel of 450 Å. This is in satisfactory agreement with the value of 8.3×10^{-6} Ω^{-1} derived by extrapolation to zero $T^{-1/2}$. At all values of temperature the interaction length scale, $(\hbar D/kT)^{1/2}$, is considerably greater than the sample width. However, it is surprising that the $T^{-1/2}$ law is found for such large changes in conductance. The values of magnetic field were such that $g\mu B < kT$ and the interaction correction was not significantly enhanced.

We now consider the temperature dependence of the inelastic length shown in Fig. 2. The power of temperature for the best fit is -0.35 ± 0.06 which agrees with recent predictions that in 1D the dominant scattering of electrons is a low-energy process arising from electromagnetic fluctuations.[15–17] The fluctuations dominate over the disorder correction unlike the 2D situation where the disorder correction is strong giving a T^{-1} dependence of the phase relaxation time.[22] Altshuler *et al.* predict a phase relaxation length L_0 given by[15]

$$L_0 = (DgL\hbar^2/2e^2kT)^{1/3}, \tag{4}$$

where L is the sample length. If we assume the Boltzmann values of D and g derived from the interaction behavior, Eq. (4) predicts that $L_0 = 5.6 \times 10^{-5} T^{-1/3}$ cm in reasonable agreement with the experimental result of $1.6 \times 10^{-5} T^{-1/3}$ cm.

Decreasing the gate voltage in steps of 0.02 V resulted in the introduction of a strong temperature dependence as shown in Fig. 4. These results are consistent with the T^2 behavior discussed earlier. A further feature of this regime was a strong positive magnetoresistance at low fields, of magnitude 30% for $B = 0.1$ T. This behavior may indicate that a shrinkage of the wave function is lowering the conductance. Further reduction in the channel width results in hopping with an exponential dependence on temperature, i.e., phonon-assisted hopping. However, the experimental range was too limited for us to establish the precise power of temperature.[23] It is seen from Fig. 4 that the conductance shows oscillations about the T^2 line. We do not have an explanation for this but, in a similar manner to oscillations which occur as a function of carrier concentration, the effect may be related to the small number of conducting electrons $[N(E_F)kTLW]$. At the lowest temperatures this number can be of the order of unity.

In conclusion, these results show that the magnetic separation of quantum interference and interaction corrections can be achieved in 1D as well as 2D.[24–26] We have also found the existence of a recently predicted mechanism of electron phase relaxation and the transition from diffusive transport to hopping.

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