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Universal conductance fluctuations and electron coherence lengths in a narrow two-dimensional electron gas

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The conductance of a narrow two-dimensional electron gas in a GaAs:$Al_{0.3}Ga_{0.7}As$ heterojunction fluctuates as a function of magnetic field. The variance and correlation length of the fluctuations have been measured for a number of temperatures, and the electron phase-breaking length is found to vary as a small negative power of the temperature.

The observation that small, normal-metal wires and rings exhibit reproducible, aperiodic, oscillations in the magnetoconductance[1,2] has prompted a number of theoretical[3-7] and experimental[8-11] studies of small systems. It is now clear that the conductance fluctuations are universal in the sense that at $T=0$ the root-mean-square (rms) deviation from the mean $\langle \Delta g^2 \rangle^{1/2}$ is approximately e^2/h regardless of sample size and degree of disorder,[3,4] i.e.,

$$\langle \Delta g^2 \rangle^{1/2} = (\langle \delta g^2 \rangle - \langle \delta g \rangle^2) = \alpha e^2/h \ . \tag{1}$$

The angle brackets denote ensemble averaging and $\delta g = g(E_F,B) - \langle g(E_F,B) \rangle$. The constant α depends upon the shape of the sample and is of the order of unity but should be calculated numerically for the particular geometry being considered. For a quasi-one-dimensional wire ($W \ll L_\phi$) $\alpha = 0.729$ (Refs. 4 and 7) and this is the value that will be used here. At finite temperatures the temperature dependence of the fluctuations takes on a number of different forms depending upon the relative sizes of the interaction length $L_T = (hD/k_BT)^{1/2}$, the phase coherence length L_ϕ, and the device length L. In one dimension, when $W < L_\phi, L_T$, the rms amplitude of the fluctuations is given by

$$\langle \Delta g^2 \rangle^{1/2} = \begin{cases} \alpha \dfrac{e^2}{h} \left[\left(\dfrac{L_T}{L} \right) \left(\dfrac{L_\phi}{L} \right) \right]^{1/2}, & L_T \ll L_\phi < L \ , \quad \text{(2a)} \\ \alpha \dfrac{e^2}{h} \left(\dfrac{L_\phi}{L} \right)^{3/2}, & L_\phi \ll L_T < L \ . \quad \text{(2b)} \end{cases}$$

When the temperature is reduced to a value such that L_ϕ and L_T are larger than L, the amplitude of the fluctuations saturates at a value given by Eq. (1).

The fluctuations in the conductance are correlated in the magnetic field and it is useful to calculate the correlation function $F(B,\Delta B) = \langle g(B) g(B+\Delta B) \rangle - \langle g(B) \rangle^2$. For $\Delta B = 0$ the correlation function reduces to the variance $\langle \Delta g^2 \rangle$. For an arbitrary ΔB the correlation function $F(B,\Delta B)$ can be characterized by a magnetic correlation length B_c such that $F(B,B_c)/F(B,0) = \frac{1}{2}$. In a quasi-one-dimensional sample it is given by

$$B_c = \begin{cases} 1.2\phi_0/(WL_\phi), & L_\phi < L \ , \quad \text{(3a)} \\ 1.2\phi_0/(WL), & L < L_\phi \ , \quad \text{(3b)} \end{cases}$$

where ϕ_0 is the quantum of flux h/e. For the case $L_\phi < L$ the magnetic correlation length will vary with temperature, being a function of the phase coherence length.

In one dimension Altshuler, Aronov, and Khmel'nitskii have shown[12] that the dominant electron scattering mechanism is a quasielastic process in which the electrons scatter off fluctuations in the electromagnetic field (i.e., Nyquist noise). Scattering rates consistent with the Nyquist mechanism have been observed in Al and Ag wires[13] and in a narrow 2D EG in a GaAs:$Al_{0.3}Ga_{0.7}As$ heterojunction.[14] The phase relaxation length L_ϕ is determined by electron-electron interaction involving small energy transfer and is given by[12]

$$L_\phi = (DgLh^2/2e^2k_BT)^{1/3} \ , \tag{4}$$

where D is the diffusion coefficient and g is the Boltzmann conductance. In the paper we present results on the universal conductance fluctuations of a narrow 2D EG. The variance and correlation function of the fluctuations have been measured at different temperatures and used to determine the temperature dependence of L_ϕ.

The devices were split-gate heterojunction field-effect transistors (FET's) with a gate separation of 1 μm, length 15 μm, and have been discussed elsewhere.[14,15] The 2D EG under the gates can be removed by a negative gate voltage leaving only a narrow channel between the gates. Progressively reverse biasing the gates reduces the width of the channel until it is eventually removed by a gate voltage of -3.5 V. Low-field magnetoconductance measurements were carried out below 4.2 K, where it was necessary to use source-drain fields of less than 1 V m^{-1} to prevent electron heating.

The fluctuations in the conductance of a channel defined by a gate voltage of -3.010 V are shown in Fig. 1. As expected for a two terminal measurement the fluctuations are symmetric about $B=0$, i.e., $g(B) = g(-B)$.[16]

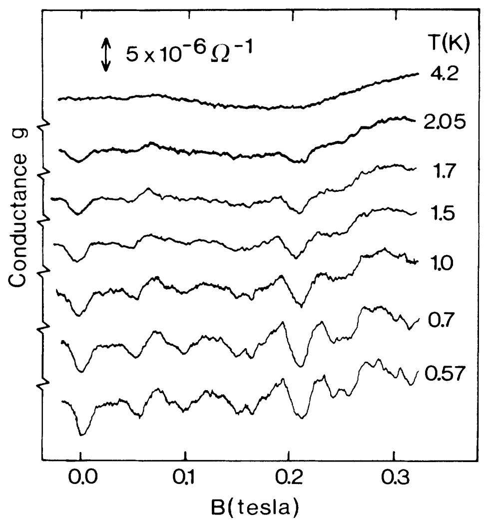

FIG. 1. Low-field magnetoconductance for a number of temperatures and a gate voltage of −3.010 V. At $B=0$ the conductance was $1.0\times10^{-4}\ \Omega^{-1}$ and changed by only a few percent in this temperature range.

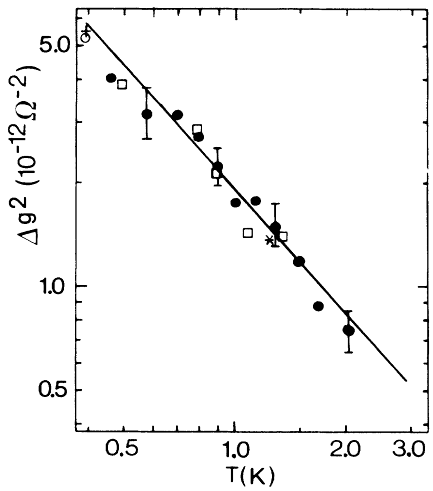

FIG. 2. The variance of the fluctuations for a number of gate voltages plotted against temperature on a log-log scale; (i) ● = −3.010 V, (ii) □ = −3.050 V, (iii) ○ = −3.100 V, (iv) * = −3.140 V, and (v) + = −3.150 V.

At 4.2 K the fluctuations are not developed and the conductance varies slowly with magnetic field. The background magnetoconductance for $T\geq4.2$ K does not vary significantly with gate voltage or temperature unlike the fluctuations which appear below 4.2 K. The latter grow in amplitude as the temperature is reduced and change to a different set of fluctuations when the gate voltage is changed by ∼10 mV (see Fig. 1 of Ref. 10). For gate voltages $V_g > -3.2$ V the channel resistance is not sufficient to dominate the magnetoconductance and the universal conductance fluctuations are superposed onto a smoothly varying background. The background may be due to localization and interaction effects in the high mobility regions between the channel and the source and drain[17] or they may result from resistance fluctuations in the diffused regions of the Ohmic contacts. Once the background is subtracted from the data the variance of the fluctuations can be calculated for each temperature and this is shown in Fig. 2 for a number of channel widths. It can be seen that although the fluctuations are different for different gate voltages, the variance at a given temperature is constant to within the accuracy of the measurement. The best fit to the data in Fig. 2 gives the variance as $\langle\Delta g^2\rangle=(2\pm0.2\times10^{-12})\ [T/(1\ \mathrm{K})]^{-1.2\pm0.2}\ \Omega^{-2}$. It will be shown later that $L_T=(hD/k_BT)^{1/2}$ is no longer than L_ϕ and using the above result in Eq. (2b) gives $L_\phi=(2.0\pm0.2)\ [T/(1\ \mathrm{K})]^{-0.4\pm0.07}\ \mu$m. The temperature dependence of L_ϕ is consistent with the expression given in Eq. (4) but in order to determine the prefactor we need to estimate the channel width and the diffusion coefficient.

The width of the channel can be obtained from the temperature dependence of the coherence area of the channel WL_ϕ. Because $L_\phi < L$, WL_ϕ is related to the half width of the correlation function according to Eq. (3a). Figure 3 shows the correlation function $F(B,\Delta B)$ at a number of temperatures of a gate voltage of −3.010 V. The width at half height gives the magnetic correlation length B_c and this is shown in Fig. 4. The temperature dependence for $V_g=-3.010$ V is best described by $B_c=(0.014\ \mathrm{T})\ [T/(1\ \mathrm{K})]^{0.35\pm0.03}$ (solid line). Equating this with Eq. (3) gives

$$WL_\phi=3.55\times10^{-13}[T/(1\ \mathrm{K})]^{-0.35\pm0.03}\ \mathrm{m}^2 \qquad (5)$$

and assuming a temperature independent width, Eq. (5) agrees with the temperature dependence given by Eq. (4). From Eq. (5), using the value of L_ϕ obtained from the variance of the fluctuations, the channel width is estimated to be ∼1800 Å. In Fig. 4 we also show results for a gate voltage of −3.050 V and the best fit in this case is $B_c=0.015\ \mathrm{T}^{0.35\pm0.5}$ (dashed line). This implies a narrower channel of width ∼1650 Å which is consistent with the more negative gate voltage.

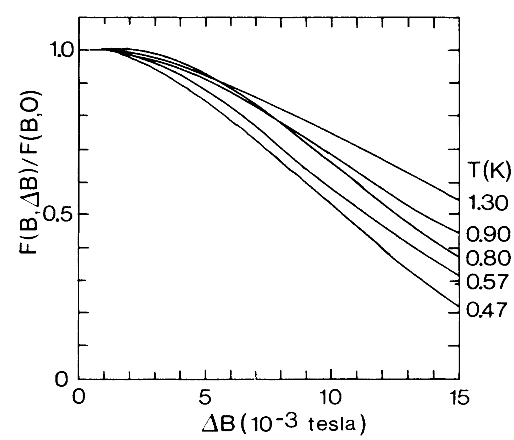

FIG. 3. The temperature dependence of the correlation function $F(B,\Delta B)$ normalized to the variance $\langle\Delta g^2\rangle=F(B,0)$.

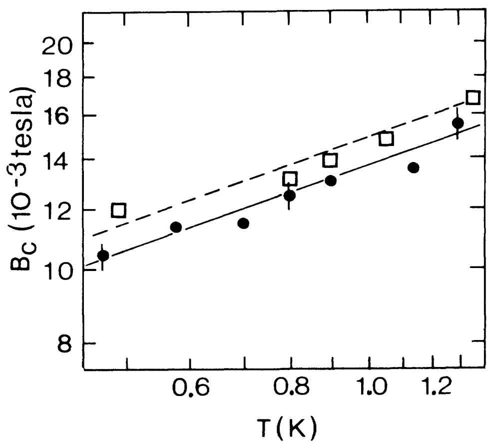

FIG. 4. The magnetic correlation length B_c as a function of temperature plotted on a log-log scale; (i) ● = −3.010 V—solid line, (ii) □ = −3.050 V—dashed line.

Numerical calculations of the subband structure of a narrow 2D EG have been performed by Berggren and Newson.[18] They showed that in the split gate device used for these experiments a channel of width 1500 Å has five subbands occupied and the Fermi wave number k_F approaches that of an ideal, infinite 2D EG so that the density of states is effectively two dimensional (2D). The channel conductance for a gate voltage of −3.010 V was $1.0\times10^{-4}\ \Omega^{-1}$ and changed by only a few percent from 4 to 0.4 K. Taking this as the Boltzmann conductance, $g=N(E_F)De^2W/L$, and assuming a 2D density of states, $N(E_F)=m^*/\pi\hbar^2$, gives the diffusion coefficient as $D\approx0.18\ \mathrm{m^2 s^{-1}}$. The measured value of L_ϕ is in quite good agreement with the result $L_\phi=1.2\ [T/(1\ \mathrm{K})]^{1/3}\ \mu\mathrm{m}$ calculated from Eq. (4) with $D=0.18\ \mathrm{m^2s^{-1}}$. It is of interest to compare the values of D and L_ϕ obtained above with the values $D\sim0.066\ \mathrm{m^2s^{-1}}$ and $L_\phi\sim0.16\ [T/(1\ \mathrm{K})]^{-0.35}\ \mu\mathrm{m}$ obtained from a channel of width ~450 Å.[14] The drop in the value of D is probably due to a reduction in mobility of the carriers in the very narrow channel because of the increased importance of boundary scattering in such channels. A reduced diffusion coefficient is reflected in the correspondingly small conductance of the narrow channel and, as expected from Eq. (4), this leads to a reduction in the value of L_ϕ.

At 1 K the values of L_T and L_ϕ are of similar size. Lee, Stone, and Fukuyama[7] define the interaction length as $(hD/k_BT)^{1/2}$. At 1 K this is ~2.9 μm for $D=0.18\ \mathrm{m^2s^{-1}}$ and justifies the use of Eq. (2b). However, Altshuler and Khmel'nitskii[6] have derived Eq. (2a) using an interaction length $L_T=(\hbar D/k_Bt)^{1/2}$. At 1 K this has a value of 1.2 μm so that $L_T<L_\phi$ and the amplitude of the fluctuations is given by Eq. (2a). We shall now calculate the values of L_ϕ, W, and D using the measured result $\langle\Delta g^2\rangle=2.0\times10^{12}\ [T/(1\ \mathrm{K})]^{-1.2\pm0.2}\ \Omega^{-2}$ in Eq. (2a). This gives

$$DL_\phi=0.177\times10^{-6}\ [T/(1\ \mathrm{K})]\ \mathrm{m^3s^{-1}}\ . \tag{6}$$

From the Boltzmann conductance we get

$$WD=3.3\times10^{-8}\ \mathrm{m^3s^{-1}}\ . \tag{7}$$

Solving Eqs. (5)-(7) gives $L_\phi=1.4\ [T/(1\ \mathrm{K})]^{-0.2\pm0.2}$ μm, $D=0.13\ \mathrm{m^2s^{-1}}$, and $W=2500$ Å. These results are similar to those obtained from Eq. (2b) except for the much larger uncertainty in the power of the temperature dependence of L_ϕ. The temperature dependence of the magnetic correlation length is the same in both cases.

In conclusion, we have measured the variance and correlation of the conductance fluctuations of a narrow 2D EG of width ~1800 Å. The variance suggests that the phase coherence length varies with temperature as $L_\phi\sim(2\pm0.2)\ [T/(1\ \mathrm{K})]^{-0.4\pm0.07}\ \mu\mathrm{m}$ and the half width of the magnetic correlation function gives $L_\phi\propto T^{-0.35\pm0.03}$. These results, like those from narrower channels, suggest that the dominant scattering mechanism in quasi-one-dimensional systems is Nyquist scattering due to electromagnetic fluctuations.

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[1]C. P. Umbach, S. Washburn, R. B. Laibowitz, and R. A. Webb, Phys. Rev. B **30**, 4048 (1984).
[2]G. Blonder, Bull. Am. Phys. Soc. **29**, 1761 (1984).
[3]B. L. Altshuler, Pis'ma Zh. Eksp. Teor. Fiz. **41**, 530 (1985) [JETP Lett. **41**, 648 (1985)].
[4]P. A. Lee and A. D. Stone, Phys. Rev. Lett. **55**, 1622 (1985).
[5]B. L. Altshuler and B. Z. Spivak, Pis'ma Zh. Eksp. Teor. Fiz. **42**, 363 (1985) [JETP Lett. **42**, 447 (1985)].
[6]B. L. Altshuler and D. E. Khmel'nitskii, Pis'ma Zh. Eksp. Teor. Fiz. **42**, 291 (1985) [JETP Lett. **42**, 359 (1985)].
[7]P. A. Lee, A. D. Stone, and H. Fukuyama, Phys. Rev. B **35**, 1039 (1987).
[8]J. C. Licini, D. J. Bishop, M. A. Kastner, and J. Melngailis, Phys. Rev. Lett. **55**, 2987 (1985).
[9]W. J. Scocpol, P. M. Mankiewich, R. E. Howard, L. D. Jackel, D. M. Tennant, and A. D. Stone, Phys. Rev. Lett. **56**, 2865 (1986).
[10]T. J. Thornton, M. Pepper, G. J. Davies, and D. Andrews, in *Proceedings of the Eighteenth International Conference on the Physics of Semiconductors, Stockholm, 1986*, edited by O. Engstrom (World Scientific, Singapore, 1987), p. 1503.
[11]G. P. Whittington, P. C. Main, L. Eaves, R. P. Taylor, S. Thomas, S. P. Beaumont, and C. D. W. Wilkinson, Superlattices Microstruct. **2**, 385 (1986).
[12]B. L. Altshuler, A. G. Aronov, and D. E. Khmel'nitskii, J. Phys. C **15**, 7367 (1982).
[13]S. Wind, M. J. Rocks, V. Chandrasekhar, and D. E. Prober, Phys. Rev. Lett. **57**, 633 (1986).

[14]T. J. Thornton, M. Pepper, A. Ahmed, D. Andrews, and G. J. Davies, Phys. Rev. Lett. **56**, 1198 (1986).

[15]K.-F. Berggren, T. J. Thornton, D. J. Newson, and M. Pepper, Phys. Rev. Lett. **57**, 1769 (1986).

[16]M. Büttiker, Y. Imry, R. Landauer, and S. Pinhas, Phys. Rev. B **31**, 6207 (1985).

[17]D. A. Poole, M. Pepper, and R. J. Glew, J. Phys. C **14**, L995 (1981); see also K. K. Choi, D. C. Tsui, and S. C. Palmateer, Phys. Rev. B **33**, 8216 (1986).

[18]K.-F. Berggren and D. J. Newson, Semicond. Sci. Technol. **1**, 327 (1986).