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Conductance fluctuations and non-diffusive motion in GaAs/AlGaAs heterojunction wires

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Abstract. We have measured the magnetoresistance of one-dimensional GaAs heterojunction wires at temperatures down to 0.04 K and in magnetic fields of up to 1.2 T. At low magnetic fields we observe universal conductance fluctuations with a temperature dependence consistent with a temperature independent phase breaking length. This unexpected result is not predicted by theory and we speculate that it may be related to the breakdown of diffusive motion.

1. Introduction

Advances in lithographic technology mean that it is now possible to fabricate devices in which electrons are confined on the scale of their Fermi wavelength [1]. In this regime semiclassical descriptions of electronic transport break down and it is more fruitful to consider the electron as a wave packet propagating coherently between phase breaking events. At low temperatures the distance between such events is relatively large and interference effects become increasingly important in determining the electrical properties of the device. In small metallic wires this interference manifests itself as large fluctuations in the conductance as the magnetic field or carrier density are varied [2]. The fluctuations are sample specific but are universal in the sense that at absolute zero they are predicted to have the amplitude e^2/h, independent of the sample size or the degree of disorder [3].

In this paper we describe the observation of universal conductance fluctuations in high mobility GaAs/AlGaAs heterojunction wires. An analysis of their temperature dependence reveals the phase breaking length to be temperature independent, an unexpected result which we relate to inadequacies in the existing theory.

2. The theory of universal conductance fluctuations

In a quantum mechanical approach to transport, the conductance of a disordered system is expressed in terms of simple transmission probabilities which in turn are determined

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by the many electronic trajectories across the sample [4]. Universal conductance fluctuations result from changes in the transmission probability as the relative phase of the paths, which does not average out to zero in small enough systems, is varied by a magnetic field or gate voltage.

The theoretical description of the fluctuations is complicated by their sample specific behaviour. However, by hypothesizing that the fluctuations in magnetic field and gate voltage are equivalent to those obtained on varying the impurity configuration, it is possible to derive expressions for the average amplitude and spacing of the fluctuations [5]. The basic technique is to define the correlation function

$$F(B, \Delta B, \Delta E) = \langle g(E_F, B) g(E_F + \Delta E, B + \Delta B)\rangle - \langle g(E_F, B)\rangle^2 \tag{1}$$

where the angle brackets denote an average over impurity configurations and g is the conductance expressed in units of e^2/h.

The size of the fluctuations is given by the variance $F(\Delta B = 0)$ and at finite temperatures is determined by the relative sizes of the phase breaking length l_φ (the distance over which the electron propagates with a well defined phase) and the thermal diffusion length L_T (the distance over which different paths remain unmixed). In most experimental situations the two lengths are comparable and Beenakker and van Houten [6] have shown that the RMS fluctuation is given by

$$g_{\mathrm{rms}} = \sqrt{6[l_\varphi/L]^3[1 + (9/2\pi)(l_\varphi/L_T)^2]^{-1}}. \tag{2}$$

The decay of the correlation function defines some basic correlation range, the average spacing of the fluctuations in magnetic field or gate voltage. In narrow wires the analysis is complicated by boundary scattering which leads to a flux cancellation effect. This results in an enhanced value for the correlation field which has been calculated by Beenakker and van Houten [6]

$$B_c = (0.38h/\gamma e l^2 l_\varphi^2 W^2)(1 + \sqrt{1 + 3.3\gamma l_\varphi^2 W/l^3}) \tag{3}$$

where

$$\gamma = \begin{cases} \gamma = \frac{1}{3} & l_\varphi \gg L_T \\ \gamma = [1/(4^{1/3} - 1)] & l_\varphi \ll L_T. \end{cases} \tag{4}$$

l is the mean free path of the electron and W is the wire width.

3. Experimental techniques

We have measured the magnetoresistance of GaAs/AlGaAs quantum wires in magnetic fields of up to 1.2 T and at temperatures down to 0.04 K. The heterojunction material was grown by molecular beam epitaxy at the Philips Research Laboratories, Redhill [7] and the wires were defined by a wet etching technique [8]. This leads to large sidewall depletion and a reduction in the carrier density which can be partially overcome by illumination at low temperatures.

After mounting to the base of a dilution unit the samples were cooled overnight to 4.2 K. Four terminal magnetoresistance measurements were made using standard audio-frequency techniques and the temperature was measured with a calibrated ruthenium oxide chip resistor [9]. Great care was taken to eliminate RF noise sources from the

Table 1. Transport properties measured in a narrow wire at 1 K. The geometrical width of the wire is 1.8 μm and the different conducting widths were obtained by progressive illumination at low temperatures.

Width (μm)	Carrier density (10^{15} m^{-2})	Mean free path (μm)	Mobility (m^2 V^{-1} s^{-1})	Diffusion constant (m^2 s^{-1})
0.45	1.40	0.33	5.3	0.027
0.55	1.82	0.68	9.6	0.062
0.55	3.73	0.97	9.6	0.128
0.74	3.71	1.31	12.8	0.177
1.25	4.56	3.60	32.3	0.527
1.22	5.43	5.93	48.8	0.947

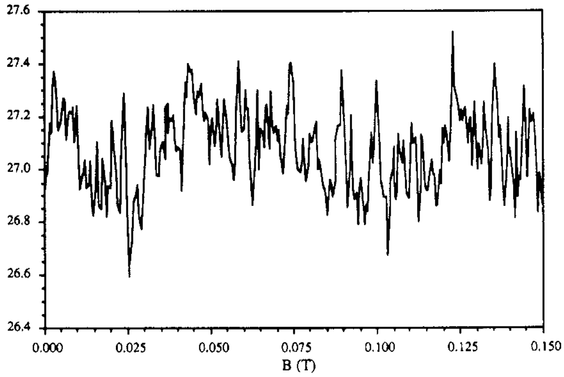

Figure 1. Universal conductance fluctuations (in units of e^2/h) measured at 0.058 K.

cryostat and spurious heating effects were avoided by keeping the voltage across the wires below $k_B T/e$.

4. Experimental results

In this paper we present the results of measurements on a wire of geometric width 1.8 μm and length 30 μm. At magnetic fields greater than 0.4 T, the observation of one-dimensional sub-band depopulation and Shubnikov–de Haas oscillations enabled us to determine the effective width of the wire and the carrier density [10]. The width and carrier density were varied by illuminating the device with short bursts of light from a red LED and a summary of the resulting transport properties is provided in table 1. An important feature is the quasi-ballistic nature of the wires; in most cases the mean free path exceeds the width and we expect boundary scattering to play an important role.

At low magnetic (<0.15 T) fields, we observe reproducible but aperiodic fluctuations in the magnetoresistance of the narrow wires (figure 1). The fluctuations are imposed upon a temperature independent parabolic background (figure 2) which has previously been associated with the formation of skipping orbits in a magnetic field [11]. In order to analyse the temperature dependence of the fluctuations we first need to subtract this

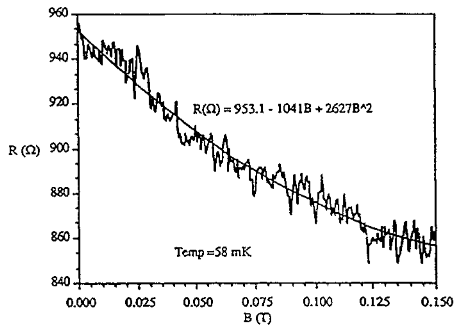

Figure 2. The fluctuations are imposed upon a monotonic background which remains temperature independent in the quasi-ballistic regime. The background is associated with the formation of skipping orbits and is subtracted from the magnetoresistance prior to analysis of the fluctuations.

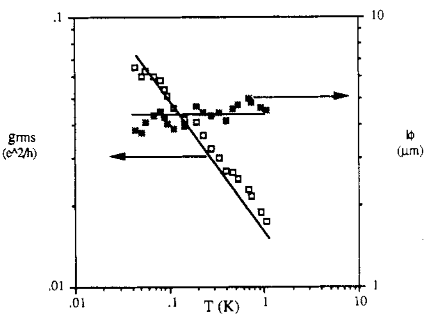

Figure 3. Root mean square fluctuation (in units of e^2/h) as a function of temperature and the corresponding phase breaking length in μm.

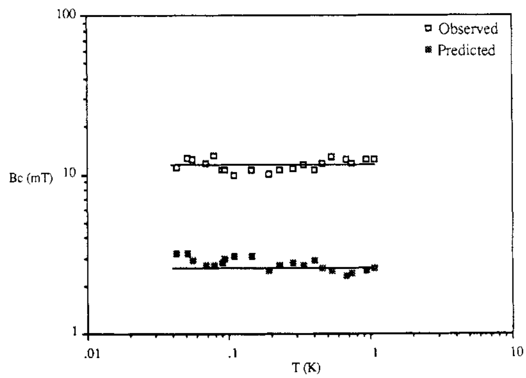

Figure 4. Observed and predicted values of the correlation field (mT).

background by fitting the magnetoresistance at higher temperatures to a second order polynomial. This is then subtracted from the lower temperature traces and the phase breaking length is obtained from the size of the fluctuations (equation (2)).

Typical results are shown in figure 3 where the size of the fluctuations and the resulting phase breaking length, as calculated from (2), are plotted as a function of temperature. The fluctuations have a $T^{-1/2}$ dependence over the entire range, indicating that the sample remains in good thermal contact at even the lowest temperatures. However, the most striking feature is the observation that below at least one degree kelvin the phase breaking length is almost temperature independent. This unexpected behaviour has been observed in all cases and we summarize the results in table 2.

Another gauge of the phase breaking length is provided by the correlation field (equation (3)). If the phase breaking length is truly temperature independent then we would expect that the correlation field should also be temperature independent. In figure 4 we plot the correlation field, determined from an analysis of the experimental data, as

Table 2. Variation of the phase breaking length (μm) as a function of mobility. In all cases a temperature independent l_φ was observed below 1 K.

Width (μm)	Mobility ($m^2 V^{-1} s^{-1}$)	l_φ (μm)	Temperature dependence
0.55	9.6	4	Independent
0.74	12.8	6	Independent
1.25	32.3	6	Independent
1.22	48.8	7	Independent

a function of temperature and see that it is indeed temperature independent. In addition, we plot the value of the correlation field predicted by (3), using the value of l_φ derived from (2). We see that there is a discrepancy between the observed and predicted values of as much as a factor of five.

5. Discussion

At low temperatures it is generally believed that the dominant phase breaking process is a quasi-elastic one in which electrons scatter off fluctuations in the electromagnetic field (Nyquist noise) [12]. In one dimension this produces the temperature dependent phase breaking length

$$l_\varphi = (D^2 W m^* / \pi k_B T)^{1/3} \tag{5}$$

where D is the electronic diffusion constant. This has already been observed in GaAs/AlGaAs wires [13].

More recently, measurements of the weak localization correction in GaAs/AlGaAs heterojunction wires have revealed that the phase breaking length can actually be temperature independent at low temperatures [14]. While the authors were unable to explain the origin of this saturation they suggested that it might result from the presence of fixed defects introduced along the channel during fabrication. Measurements of universal conductance fluctuations in n^+-GaAs wires have also revealed a large temperature independent component to l_φ related to boundary scattering effects [15]. However, since the low field magnetoresistance of our samples indicates the formation of skipping orbits at the channel edges it is unlikely that the temperature independence we observe is related to boundary scattering [11]. Finally, Milliken *et al* [16] have shown that the phase breaking length of small metallic loops is temperatiure independent in the regime $l_\varphi \sim L$. In our highest mobility samples the phase breaking length saturates at less than a quarter of the channel length and so it is unlikely that we are observing any such phase coherent effects.

We suggest that the anomalous behaviour observed in our wires is due to a breakdown of diffusive motion. The theory of universal conductance fluctuations is derived for metallic systems in which the mean free path is typically much smaller than the phase breaking length. As a result the motion is diffusive and the path of the electron can be simplified to a random walk. However, in our high mobility samples the long mean free path means that the two length scales may only differ by a numerical factor between one and ten. We believe that in this high mobility regime the diffusive description of electronic motion is no longer valid, resulting in the observed anomalies.

6. Concluding remarks

We have observed universal conductance fluctuations in the low field magnetoresistance of our narrow wires. An analysis of the correlation and variance of the fluctuations is consistent with a temperature independent phase breaking length, although there is poor agreement between the observed and predicted values of the correlation field. The results suggest that the effect of boundary scattering cannot simply be expressed in terms of geometric flux cancellations and that a more rigorous description is required of fluctuations in the non diffusive regime.

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References

[1] Roukes M L, Scherer A, Allen S J, Craighead H G, Ruthen R M, Beebe E D and Harbison J P 1988 *Phys. Rev. Lett.* **59** 3011
[2] Umbach C P, Washburn S, Laibowitz R B and Webb R A 1984 *Phys. Rev.* B **30** 4048
[3] Lee P A and Stone A D 1985 *Phys. Rev. Lett.* **55** 1622
[4] Landauer R A 1970 *Phil. Mag.* **21** 863
[5] Lee P A, Stone A D and Fukuyama H 1987 *Phys. Rev.* B **35** 1039
[6] Beenakker C W J and van Houten H 1988 *Phys. Rev.* B **37** 6544
[7] Foxon C T and Harris J J 1986 *Philips J. Res.* **41** 313
[8] Hutchings K M, Grassie A D C, Lakrimi M and Bird J 1988 *Semicond. Sci. Technol.* **3** 1057
[9] Bosch W A, Mathu F, Meijer H C and Willekers R W 1986 *Cryogenics* **26** 3
[10] Berggren K F, Roos G and van Houten H 1988 *Phys. Rev.* B **37** 10118
[11] Choi K K, Tsui D C and Palmateer S C 1986 *Phys. Rev.* B **33** 8216
[12] Altshuler B L, Aronov A G and Khmel'nitskii D E 1981 *Solid State Commun.* **39** 619
[13] Thornton T J, Pepper M, Ahmed H, Davies G J and Andrews D 1987 *Phys. Rev.* B **36** 4514
[14] Hiramoto T, Hirakawa K, Iye Y and Ikoma T 1989 *Appl. Phys. Lett.* **54** 2103
[15] Taylor R P, Leadbeater M L, Whittington G P, Main P C, Eaves L, Beaumont S P, McIntyre I, Thoms S and Wilkinson C D W 1988 *Surf. Sci.* **196** 52
[16] Milliken F P, Washburn S, Umbach C P, Laibowitz R B and Webb R A 1987 *Phys. Rev.* B **36** 4465