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1990 J. Phys.: Condens. Matter 2 5641

(http://iopscience.iop.org/0953-8984/2/25/017)

J. Phys.: Condens. Matter 2 (1990) 5641–5645. Printed in the UK

LETTER TO THE EDITOR

Observation of the rectification fluctuations in a mesoscopic n^+-GaAs wire

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Received 17 April 1990

Abstract. We present the first observations of rectification fluctuations in a mesoscopic conductor; a small n^+-GaAs wire. The results obtained enable us to examine directly that part of the conductance fluctuation that is antisymmetric in the applied voltage. Analysis of the data in terms of the ratio of the antisymmetric and normal conductance fluctuations then gives excellent quantitative agreement with the theoretical predictions.

Fluctuations in electrical transport coefficients such as electrical conductance [1, 2], Hall coefficients [3] and thermopower [4] are observable in samples that have geometric lengths (L) comparable to the length (L_φ) over which an electron retains phase coherence. The fluctuations are attributed to the interference pattern created by the sum of possible electron paths through the device, which, for these small samples, does not average to a constant amplitude. Variations in the detail of the impurity potential in the sample will determine the values of these coefficients, but for an ensemble of macroscopically identical samples, or in a single sample as Fermi energy or magnetic field is varied, the variance in the observed property has a universal value. This type of effect was first seen in a solid state system in the electrical conductance. Aperiodic conductance fluctuations (ACF) were observed in metal wires [1] as a function of applied magnetic field, and in MOSFET [2] structures as a function of Fermi energy, these have a characteristic magnitude of e^2/h for any sample that has $L < L_\varphi$.

Al'tshuler and Khmel'nitskii [3] predicted that conductance fluctuations should also occur as the magnitude of the applied voltage (V) along a sample is changed. They noted that the intrinsic dependence of the conductivity on the applied voltage would lead to rectification phenomena and predicted that, for any sample with $L < L_\varphi$

$$\langle |G(V) - G(-V)|^2\rangle \simeq [(e^2/h)eV/E_c]^2 \tag{1}$$

provided that $eV \ll E_c$, where E_c is the energy scale of the conductance fluctuations. The angular brackets in equation (1) denote an average over a large number of macroscopically identical samples. This would be awkward to test experimentally but an equivalent average can be found for a single sample, since changing the magnetic field alters the phase difference associated with any pair of possible electron paths and so alters the interference pattern created. If the change in magnetic field is large compared

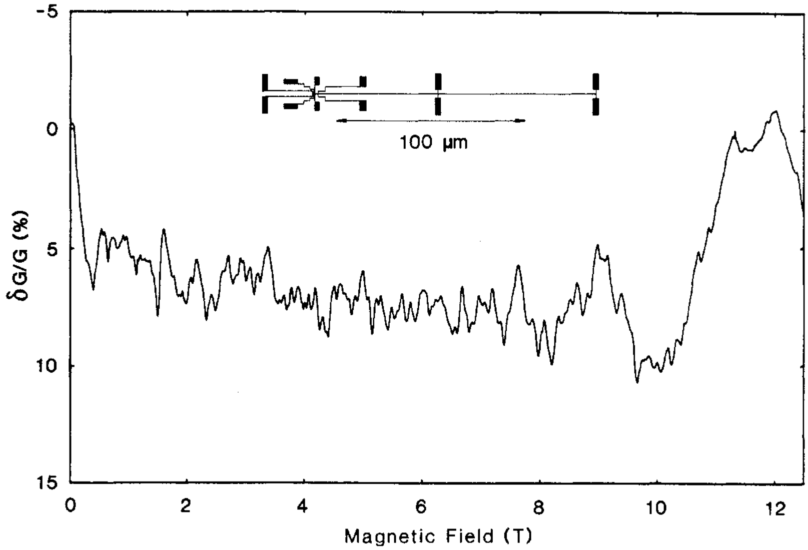

Figure 1. Two-terminal resistance fluctuations in a 9 μm section of the wire. Inset: the wire geometry. The resistance at zero field is 22 kΩ.

with a characteristic field scale, B_c, then the interference patterns are uncorrelated and device properties at the two fields would be independent.

Kaplan was the first to measure quantitatively non-Ohmic conductance in a mesoscopic device [5]. He measured the differential conductance as a function of magnetic field, of a silicon MOSFET with a length of 0.9 μm and a width of 0.5 μm. From this he was able to calculate $G(V)$ and so obtain $\delta G_a(V)$ and $\delta G_s(V)$, the antisymmetric and symmetric components of the conductivity. This measuring technique does not directly use the non-Ohmic properties of the sample to determine the detailed form of the conductivity. Harmonic generation due to the non-Ohmic conductance has been observed in metal [6] and semiconducting wires [7]. Such behaviour can in principle yield the terms in a power series expansion of $\delta G_a(V)$ and $\delta G_s(V)$. In practice only the first few harmonics can be observed. Such experiments give reasonable qualitative agreement with theory.

The aim of our experiment was to determine the antisymmetric component of the conductance fluctuations in an n^+-GaAs wire directly by measuring the DC voltage (V_{DC}) caused by the rectification of an applied AC voltage (V_{AC}).

The specimen that we have studied is the same as that in which thermopower fluctuations have been observed [4]. It is a 190 μm long wire with a physical width of 0.5 μm and a thickness of 50 nm with many side-arms. The wire was defined by electron beam lithography and dry etching of an MBE epitaxial layer of n^+-GaAs. From Hall and Shubnikov–de Haas measurements we have determined the electron concentration to be $1.09(5) \times 10^{24}$ m^{-3}. It is expected that the electrically conducting width of the wire will be reduced to $\simeq 0.44$ μm by electrostatic depletion. An electrical thickness of 30 nm is estimated from the Shubnikov–de Haas and Hall results using a model potential that allows for depletion from the surface and penetration into the undoped substrate.

In this experiment, 9 μm sections of the wire were used; these form pairs of side-arms perpendicular to the main wire. Figure 1 shows the conductance fluctuations that are seen in this device as a function of applied magnetic field. The ACFs are on a background negative magnetoresistance, and at higher fields they coexist with Shubnikov–de Haas oscillations.

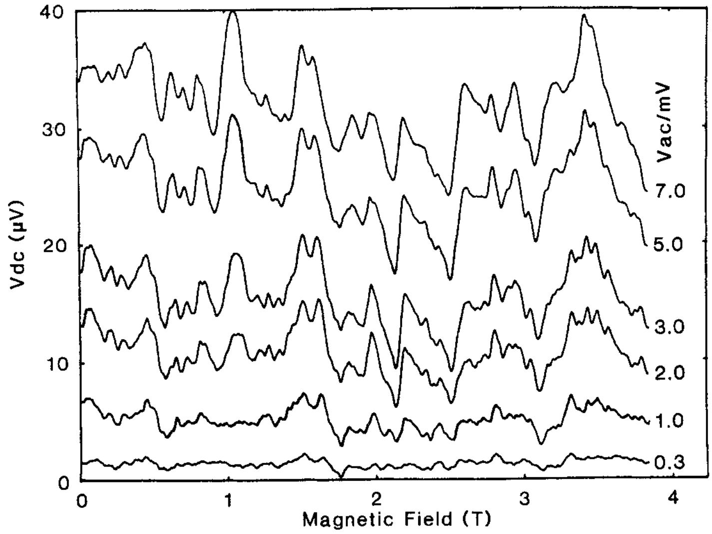

Figure 2. Fluctuations in the DC voltage rectified by the device. The applied voltage V_{AC} is indicated on the diagram. The traces are offset for clarity.

An AC voltage source with a very low harmonic distortion was capacitatively connected across this section of the sample. Capacitative coupling was used to isolate, at DC, the source from the sample. A DC voltage across the sample was measured as the applied magnetic field was increased. An EM Electronics nanovoltmeter, which has an input impedance of $\simeq 1$ GΩ and an offset current of typically 5 pA, was used to record the DC voltage, which was then stored digitally to allow numerical analysis.

By recording V_{DC} as a function of magnetic field whilst V_{AC} was held constant we were able to see fluctuations in the rectified voltage. Figure 2 shows a typical set of data in which the strong oscillations about zero are observed. The results obtained are independent of sweep rate and no change was noted in the shape of magnitude of these if the sample was kept at low temperature and in the dark. A calculation of the correlation† between two traces in nominally identical conditions but separated in time by two days gave 0.98, and the magnitudes were the same to within 2%.

The rectification of an applied alternating voltage by any non-Ohmic conductor is well known. Signals at harmonics of the applied voltage frequency are developed and a DC voltage can be set up across the device. Only the antisymmetric deviation of the conductance $G(V)$ from a constant value causes the DC potential. It is simple to show that if a conductance can be written as

$$G(V) = G_0 + \delta G_s(V) + \delta G_a(V) \tag{2}$$

then

$$V_{DC} = (V_{AC})_{RMS} 2(\delta G_a(V))_{RMS} G_0^{-1}. \tag{3}$$

By measuring the rectified signal it is therefore possible to obtain information about the form of $G(V)$. For our sample, in which the conductance fluctuates as the magnetic field is changed, we write

$$(V_{DC})_{RMS} = (V_{AC})_{RMS} 2(\delta G_a(V))_{RMS} G_0^{-1} \tag{4}$$

† The correlation figure quoted here is the result of a calculation of the RMS difference of two traces that have been normalised, expressed in such a way that two identical traces would have correlation 1.

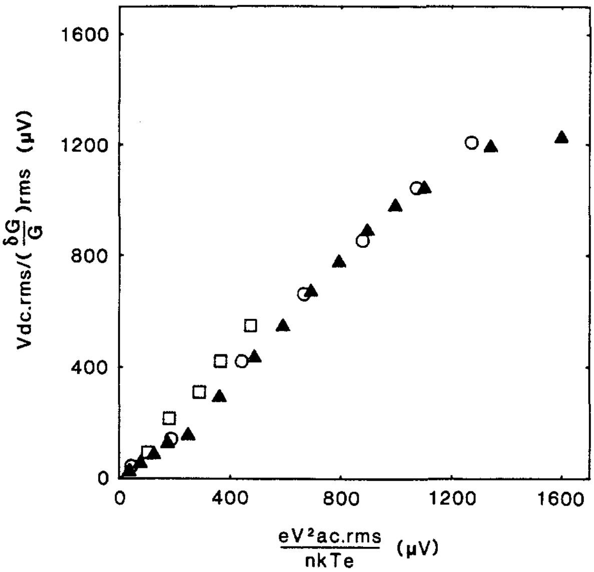

Figure 3. The magnitude of the DC voltage plotted to reveal the dependence on the applied AC voltage $T_l = 1.08$ K (▲), $T_l = 2.00$ K (○) and $T_l = 4.00$ K (□).

assuming that $(\delta G_a(B))_{RMS} = (\delta G_a(V))_{RMS}$. The RMS value of the DC voltage is calculated over a magnetic field range large compared with B_c.

Equation (1) contains an energy scale E_c which is set as the largest of kT_e, hD/L_φ and hD/L^2, where L is the sample length and D is the diffusion coefficient. For our sample in the temperature range studied the characteristic energy scale is the thermal energy kT_e.

Al'tshuler and Khmel'nitskii's expression is only valid for a sample with a width less than L_φ and $n = L/L_\varphi < 1$. For $n > 1$ the total applied potential difference must be replaced by that along a single phase-coherent sub-unit. In the current experiments n, which is obtained from the amplitude of the ACF's is between 20 and 50. At the highest temperatures L_φ is less than the width of the wire. Although the theory is not expected to be valid in this situation we believe any geometric averaging caused by $n > 1$ will affect the rectified voltage in exactly the same way as it will the magnitude of the conductance fluctuations, so the ratio is unaffected. Combining equations (1) and (4) and the scaling factors discussed above, we can write

$$V_{DC\,RMS}/(\delta G/G_0)_{RMS} = e(V_{AC\,RMS})^2/nkT_e. \qquad (5)$$

To allow comparison with equation (5), several calibrations were performed. Electron heating to temperatures (T_e) several K above the lattice temperature (T_l) occurred at the highest electric fields. To correct for this, calibrations of $G(T_e = T_l)$ and $G(V_{AC})$ were combined to determine $T_e(V_{AC})$, the electron temperature as a function of the applied potential. Measurements of $\delta G/G(T_e = T_l)$ could then be used to calculate $\delta G/G(V_{AC})$, the ACF amplitude. All of the calibrations were made using an ASL precision six-decade inductive divider bridge at 375 Hz.

The RMS magnitude of the measured voltage fluctuations, scaled by the size of the conductance fluctuations, are presented in figure 3. The data lie on a line of gradient one with excellent agreement over a wide range of V_{AC}. In this experiment, electron heating limits the maximum value of $eV_{AC\,RMS}/kT_e$ to $\simeq 0.2$, so we do not expect effects due to a change of energy scale, E_c, to be apparent. Such effects have been observed in a metal wire and MOSFETs [5, 6].

As the applied potential is increased the shape of the trace obtained changes, some features growing more rapidly than others. However, the theoretical predictions consider only averages of magnetic field ranges large compared with B_c, so the detailed form is not considered. There will be additional information in the way the traces decorrelate with increasing V_{AC}. We are currently investigating the correlation function along with the cross-correlations between the different transport coefficients.

Rectification is an integral part of the theory of the properties of mesoscopic devices. We have demonstrated that our experimental results can be understood using existing theory. The excellent agreement of our data with the predictions of Al'tshuler and Khmel'nitskii is highlighted by the way in which it has been analysed. Note that by expressing the prediction as a ratio of the rectified voltage and conductance fluctuation magnitude we have eliminated the geometrical and finite-temperature corrections that normally complicate the comparison with theory. This then allows the fundamental dependence of the rectified signal on the size of the conductance asymmetry to be easily seen. The universal aspects of the fluctuations are thus examined directly. These rectification fluctuations are very closely related to thermopower fluctuations, which we have recently observed in these samples [4].

We would like to acknowledge the useful contributions made to this work by Peter Main, Malcolm Carter and Melanie Cumpston and also the financial support of the SERC.

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