Thermoelectric effects in mesoscopic conductor

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(Submitted 31 December 1989)
Pis'ma Zh. Eksp. Teor. Fiz. **51**, No. 3, 151–153 (10 February 1990)

A thermopower of mesoscopic nature, which fluctuates with the magnetic field, has been observed in nanostructures fabricated on the basis of δ-doped gallium arsenide. The magnitude of the fluctuations has been found to be substantially greater than the regular component. It also depends strongly on the temperature.

It was shown theoretically in Refs. 1 and 2 that the disruption of the "electron-hole" symmetry in a mesoscopic Fermi system results in the appearance of fluctuations in the thermoelectric coefficients, in particular, the thermopower, with a magnitude which may be comparable to or greater than the regular component, even if the fluctuations in the resistance are small. However, no experiments have been carried out which have confirmed or refuted the theoretical predictions.

In the present letter we are reporting the first observation of a mesoscopic thermopower. We will show that its behavior agrees with the results of Refs. 1 and 2. The structure used in the present experiments was fabricated on the basis of δ-doped gallium arsenide with an electron density $N_s \approx 6\times 10^{12}$ cm^{-2} and a mobility $\mu \approx 2\times 10^3$ cm^2/(V·s). The structure is shown schematically in the inset in Fig. 1(a). It consists of a heater, in this case a macroscopic δ-doped layer of GaAs (with dimensions of 150×150 μm), and the mesoscopic sample ($L = 1$ μm, $W = 0.1$ μm), which was fabricated by electron lithography and reactive ion etching.

Let us outline the measurement procedure. An alternating voltage of frequency $f = 10$–40 Hz was applied to the macroscopic δ layer, and a thermopower signal was measured at the frequency $2f$. The heat flux from the heater was transferred to the mesoscopic sample by the lattice thermal conductivity of gallium arsenide. Since the thermal conductivity of GaAs is several orders of magnitude greater than that of the δ layer, the temperature gradient established in the sample was determined by the phonon flux in the substrate. This structure made it possible to achieved a complete electrical isolation of the heater from the mesoscopic sample and thus to avoid stray pickup from the voltage source feeding the heater. That stray pickup might have acted as a source of a parasitic signal at the frequency $2f$ as a result of rectification.

The experimental results are shown in Fig. 1(a) as a plot of the measured thermopower versus the magnetic field. Figure 1(b) shows the magnetic-field dependence of the resistance. We see aperiodic oscillations in both the resistance $R(B)$ and the thermopower $U_\alpha(B)$; there is no correlation between the oscillations in R and those in U_α. Furthermore, while the maximum fluctuation in the resistance is only 10% of the total value of R, the maximum amplitude of the fluctuations in U_α is equal to the mean value of the thermopower. We should point out that since the magnitude of the

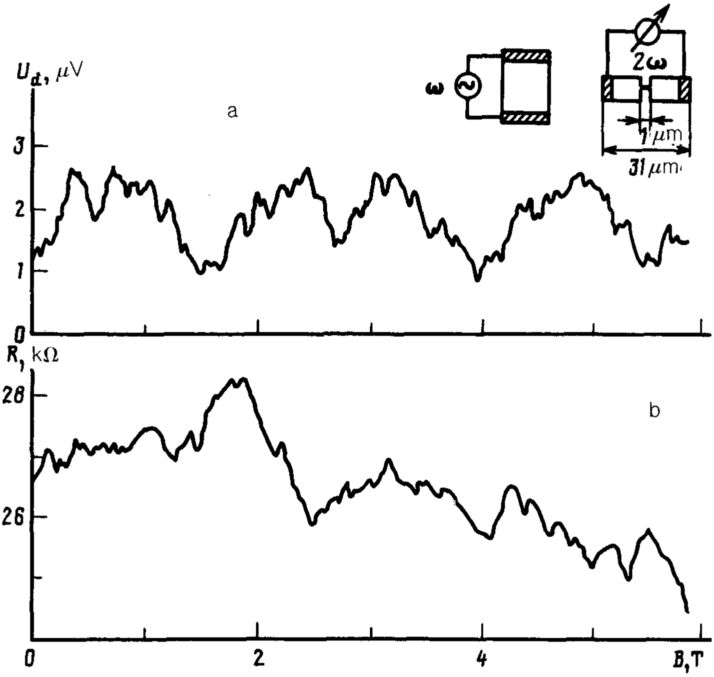

FIG. 1. a—Thermopower of a mesoscopic GaAs sample versus the magnetic field; b—resistance of the sample versus the magnetic field ($T = 4.2$ K). The inset shows the experimental geometry.

temperature gradient is determined not by the δ layer but by the lattice, the mean value of U_α is determined almost entirely by the nonmesoscopic part of the sample. The length of this part of the sample (as can be seen from this figure) is greater than the length of the mesoscopic bridge by a factor of 30. In other words, the fluctuations observed here are actually an order of magnitude greater than the regular value U_{α_M} of the mesoscopic conductor, and we have $\langle \Delta\alpha \}/\alpha_M \approx 10$. This value agrees well with an estimate from[1,2]

$$\frac{\langle \Delta\alpha \rangle}{\alpha} = k\,\frac{\langle \Delta\sigma \rangle}{\sigma}\,\frac{E_F}{E_c}, \qquad (1)$$

where $E_F \approx 200$ meV is the Fermi energy, $E_c \approx 1$ meV is the electron correlation energy, and k is a numerical factor, on the order of unity, which depends on the ratio T/E_c. The quantity $\langle \Delta\alpha \rangle/\alpha$ is convenient for analysis, since the temperature gradient in the mesoscopic conductor is essentially impossible to measure because of the small dimensionless of this conductor.

The temperature dependence of thermoelectric coefficients may be stronger than that of other kinetic characteristics of a mesoscopic conductor (its resistance, its rectification, etc.). This situation can be seen from relation (1), from which it follows that we have $\langle\Delta\alpha\rangle/\alpha\sim T^{-p-1}$, in contrast with $\langle\Delta\sigma\rangle/\sigma\sim T^{-p}$ if $E_c\sim T$ (the value of p depends on the dimensionality of the system and the scattering mechanisms). The dependence of $\langle\Delta\alpha\rangle/\alpha$ on T may be even stronger because of the temperature dependence of the coefficient k (Ref. 2).

Figure 2 shows $\Delta\alpha/\alpha$ as a function of B for two temperatures. We see that as the temperature is lowered from 4.2 K to 1.7 K, the value of $\langle\Delta\alpha\rangle/\alpha$ increases by nearly an order of magnitude. Such a pronounced increase in $\langle\Delta\alpha\rangle/\alpha$ cannot be explained on the basis of the temperature dependence of $\langle\Delta\alpha\rangle/\alpha$ described above. The apparent explanation is that the thermopower α of the δ-doped layer is caused not just by a drift of electrons due to the gradient in T but also by a phonon drag, which has a stronger temperature dependence. However, a more accurate analysis of the T dependence of $\langle\Delta\alpha\rangle/\alpha$ will require further research.

While this paper was being prepared for publication, a report of the observation of a mesoscopic thermopower was published.[3] The results found in Ref. 3, however, are questionable: In those measurements the alternating voltage used to create the temperature gradient was applied directly to the mesoscopic sample. The voltage should have caused another mesoscopic effect: a rectification, for which the voltage would have been substantially larger than the thermopower at the same applied power. In such a situation it would be an extremely complicated problem to single out the thermoelectric effect, and that problem was not solved satisfactorily in that study.

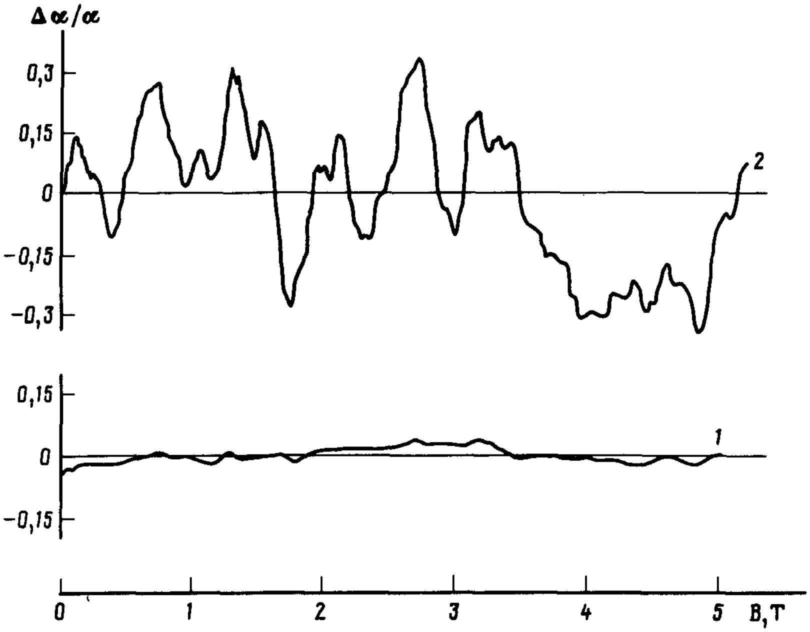

FIG. 2. Plot of $\Delta\alpha/\alpha$ versus the magnetic field for two temperatures. 1—T = 4.2 K; 2—T = 1.7 K.

We wish to thank D. I. Lubyshev and V. P. Migal' for furnishing the δ-doped GaAs samples, V. M. Kudryashev for carrying out the electron lithography, and V. Sh. Aliev and M. R. Baklanov for carrying out the ion etching.

[1] A. V. Anisovich *et al.*, Pis'ma Zh. Eksp. Teor. Fiz. **45**, 237 (1987) [JETP Lett. **45**, 295 (1987)].

[2] G. B. Lesovik and D. E. Khmel'nitskiĭ, Zh. Eksp. Teor. Fiz. **94(5)**, 164 (1988) [Sov. Phys. JETP **67**, 957 (1988)].

[3] T. Galloway *et al.*, in *Proceedings of the Eighth International Conference on Electronic Properties of 2D Systems*, Grenoble, 1989, p. 558.

Translated by Dave Parsons