Universal conductance fluctuations and impurity charge exchange in GaAs-based microstructures

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(Submitted 28 November 1991)
Zh. Eksp. Teor. Fiz. **101**, 1366–1375 (April 1992)

The sensitivity of the resistance of a mesoscopic sample to a change in the configuration of the random potential in microstructures prepared from δ-doped layers of GaAs was investigated experimentally. The effect of the state of a single impurity on the universal fluctuations of conductance was investigated. It was found that charge exchange of $\approx 0.1\%$ of the total number of impurities completely changes the pattern of mesoscopic fluctuations in a specific sample. The results obtained agree satisfactorily with the theory.

1. INTRODUCTION

Mesoscopic effects in semiconductors have been under intense study in the last few years. This is in many respects due to technological progress which has made it possible to fabricate submicron structures whose dimensions are comparable to the phase coherence length at liquid-helium temperatures. Under these conditions the properties of the sample are largely determined by the quantum interference of electron waves over all possible trajectories. It is important that although the number of trajectories can be very large the result of interference is not averaged, but rather it depends on the specific arrangement of the scattering centers in the given sample. When the parameters determining the conditions of interference, such as the configuration of the scattering potential, the magnetic field, or the Fermi energy, are varied the conductance of the mesoscopic sample fluctuates, and in addition the mean-squared amplitude of the conductance fluctuations $\langle \Delta G^2 \rangle$ is a universal quantity, $\langle \Delta G^2 \rangle \approx (e^2/h)^2$, if the characteristic size of the conductor satisfies $L < \min(L_\varphi, L_T)$, where L_φ is the phase coherence length, $L_T = (hD/kT)^{1/2}$, and D is the diffusion coefficient.[1–5] This property of mesoscopic samples raises the question of the sensitivity of their properties to a decrease of the parameters or the state of a separate scatterer. In Refs. 6 and 7 it was shown that if in the case $L < \min(L_\varphi, L_T)$ the charge state of a scattering center changes or the scattering center is displaced by a distance $r > k_F^{-1}$ (k_F is the momentum on the Fermi surface), the conductance changes by the amount $\approx e^2/h$.

The mesoscopic properties of small samples are now being quite intensively studied experimentally. Universal fluctuations of the conductance have been studied in metallic films and wires,[8,9] submicron MOS transistors,[10–13] submicron structures based on AlGaAs–GaAs heterojunctions,[14,15] and thin layers of degenerate semiconductors.[16–18] Effects associated with the sensitivity of a mesoscopic sample to small changes in the configuration of the random potential have also been observed. Observation of switching of the resistance between two levels (telegraph noise) in metallic nanostructures and submicron silicon MOS transistors were reported in Refs. 19–21, multilevel stimulated and spontaneous resistance switching in GaAs/AlGaAs-based structures and δ-doped GaAs layers was reported in Refs. 22 and 23, and interband mesoscopic photoconductivity was reported in Ref. 24. This question has nonetheless not been adequately studied.

In the present paper we present the results of experimental investigations of universal fluctuations of the conductance and the sensitivity of such fluctuations to changes in the configuration of the random potential in δ-doped-GaAs microstructures. The experimental results are compared with the theory of Refs. 1–7.

2. THEORETICAL QUESTIONS

At finite temperature the magnitude of mesoscopic fluctuations depends strongly on the ratio of the dimensions of the sample and the distance over which the propagation of electron waves is coherent, $L_i = \min(L_\varphi, L_T)$. Thus two-dimensional limits ($L_i < W, L$) and one-dimensional limits ($W < L_i < L$), where L is the length and W is the width of the sample, can be satisfied for a quasi-two-dimensional system in semiconductor structures. The corresponding formulas for the average amplitude of conductance fluctuations $\delta G = (\langle \Delta G^2 \rangle)^{1/2}$ in the case when the spin-orbital interaction can be neglected have the following form:[5,25]

$$1D:\ \delta G = a(e^2/h)(L_i/L)^{1/2}, \tag{1a}$$

$$2D:\ \delta G = a(e^2/h)(L_i/L)(W/L)^{1/2}, \tag{1b}$$

where the coefficient a is of order unity. In the temperature range studied, for our samples $L_\varphi < L_T$ and thus the length $L_i = L_\varphi$ is the determining length. In what follows, for purposes of estimation we use the formulas (1) with $a = 1$.

The question of the sensitivity of a mesoscopic sample to a change in the configuration of the scattering potential was studied in Refs. 6 and 7. It was established that at temperatures for which L_i is larger than the dimensions of the sample the displacement of a single scattering center by a distance $\delta r > k_F^{-1}$ results in a mean-square change in the conductance of a square sample given by the expression

$$\langle \Delta G_1^2 \rangle \approx (e^2/h)^2 (1/cl^2)\, a(k_F \delta r), \qquad \alpha(x) = 1 - \frac{\sin(x/2)^2}{x/2}, \tag{2}$$

where c is the concentration of impurity atoms and l is the mean-free path length.

The processes studied are of three types. In the first case the charge state of only a single impurity changes as a result of charge exchange between the impurity and the electron gas; this is equivalent to either removing the impurity from the sample or the reverse process and $a(x) = 1$. In the second case an electron is exchanged between the two close

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impurities, which is equivalent to a small change in the position of the impurity and $0<a(x)<1$. Finally, in the third case the conditions of screening of the scattering potential change as a result of a change in the number of charge carriers in the sample. In the existing theory,[6,7] however, this case is not studied and in the subsequent analysis we confine our attention to the first two processes. Then for the one-dimensional situation $W<L_i<L$ we have[6,7]

$$\langle \Delta G_1^2 \rangle \approx (e^2/h)^2 (1/cl^2)(L_i/L)^4 (L_i/W)\alpha(k_F \delta r). \qquad (3)$$

The important characteristics of mesoscopic fluctuations are the scales of parameters, such as the correlation magnetic field B_c and the correlation energy E_c, at which the conductance changes by an amount of order of e^2/h. These quantities can be obtained from the correlation function defined as follows:[5]

$$F(\Delta E, \Delta B) = \langle \delta G(E, B)\delta G(E+\Delta E, B+\Delta B)\rangle, \qquad (4)$$

where $F=0.5$ for $\Delta B = B_c$ and $\Delta E = E_c$. The correlation function for a gradual change in the configuration of the random potential can be determined similarly. In this case the correlation between the initial dependence and the dependence corresponding to the new configuration of the potential resulting from charge exchange of n impurities is calculated.

3. SAMPLES AND MEASUREMENT PROCEDURE

In the present work we employed samples prepared from δ-doped GaAs layers grown by the method of molecular-beam epitaxy. The parameters of the initial layers at 4.2 K were varied over the following limits: the mean-free path was $l = 400$–600 A, the phase coherence length obtained from measurements of the negative magnetoresistance was $L_\varphi = 0.45$–0.7 μm, the mobility was $\mu = 2000$–4500 cm^2/V·s, and the electron density was $N_e = (3.5$–$6)\cdot 10^{12}$ cm^{-2}.

Two types of samples were investigated (Fig. 1). Samples of the first type were fabricated by means of electron lithography and had the dimensions $L \approx 1$ μm and $W \approx 0.1$–0.2 μm. Samples of the second type, fabricated by the method of optical lithography, each had, in addition to pulling contacts, two potentiometric contacts separated by a distance of 2–4 μm. The width W ranged from 0.3 to 0.4 μm. An active ac bridge was used to perform the resistance measurements. The measurements were performed in the frequency band ~70–700 Hz. The voltage applied to the sample was less than kT/e, so as to eliminate heating effects. All measurements were performed at temperatures of 1.3–4.2 K in magnetic fields up to 8.1 T.

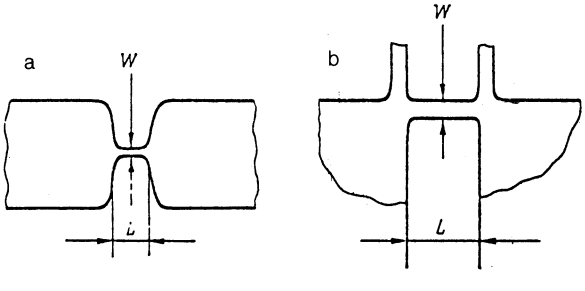

FIG. 1. Schematic diagram of the sample topology: a) samples prepared by the method of electronic lithography, $L = 1$ μm, $W = 0.1$ μm; b) samples prepared by the method of optical lithography, $L = 2$–4 μm, $W = 0.3$–0.4 μm.

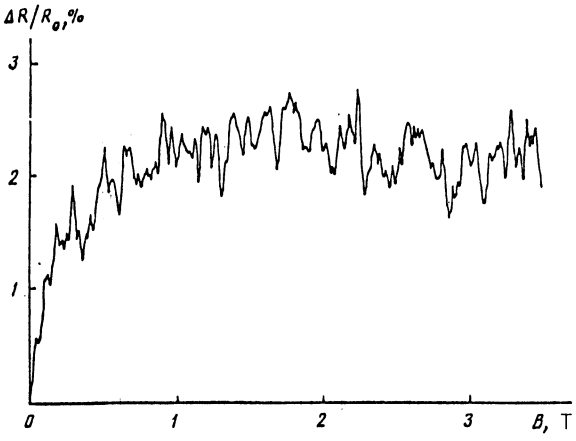

FIG. 2. Relative change in the resistance as a function of the magnetic field for a sample from the second group: $W = 0.36$ μm, $L = 3$ μm, $R = 2.45$ kΩ, $T = 4.2$ K.

4. CONDUCTANCE FLUCTUATIONS IN δ-DOPED GaAs BASED MICROSTRUCTURES

Figures 2 and 3 show the typical curves of $\Delta R/R_0$, where $\Delta R = R(B) - R_0$ and $R_0 = R(B=0)$, for the microstructures described in the preceding section. For all samples of this type, the quantity δG obtained from the curves in Fig. 2 agrees well with the theory. The quantity δG for samples fabricated by the method of electron lithography were not compared with the theory, since the resistance of these samples was measured by a two-point scheme and in so doing it is impossible to exclude the contribution of the contact resistance.

The temperature dependence of the quantities δG is determined by the behavior of L_φ. As follows from Ref. 26, $L_\varphi \sim T^{-1/3}$ in the one-dimensional limit and $L_\varphi \sim T^{1/2}$ in the two-dimensional limit. Substituting these expressions into the formula (1) we find that the temperature dependence of δG is the same in both the two- and one-dimensional cases: $\delta G \sim T^{-1/2}$. As follows from experiment, the temperature dependence $\delta G(T)$ for the samples studied on the whole agrees with the theory. Figure 4 shows the values of $\delta G(T)$ for two different samples of the second type. The sloped straight line in the figure is described by the expression

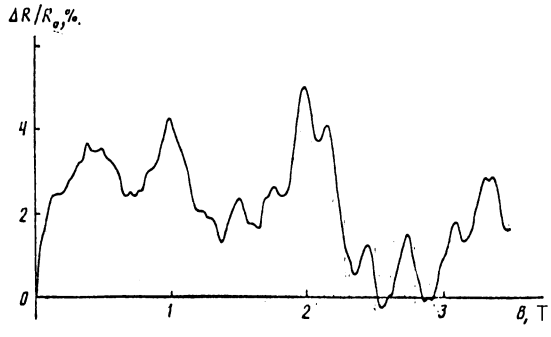

FIG. 3. Relative change in the resistance as a function of the magnetic field for a sample from the first group: $W \approx 0.1$–0.2 μm, $L \approx 1$ μm, $R = 11.37$ kΩ, $T = 4.2$ K.

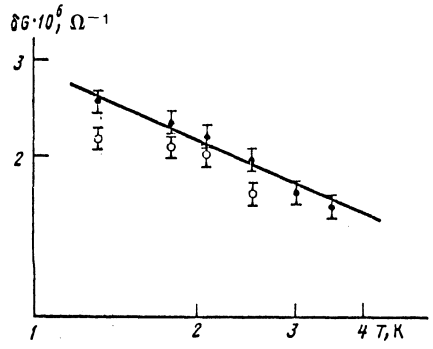

FIG. 4. Root-mean-square amplitude δG of conductance fluctuations as a function of the temperature for two different samples from the second group. The straight line corresponds to the temperature dependence $\delta G \sim T^{-\alpha}$ with $\alpha = 0.44$.

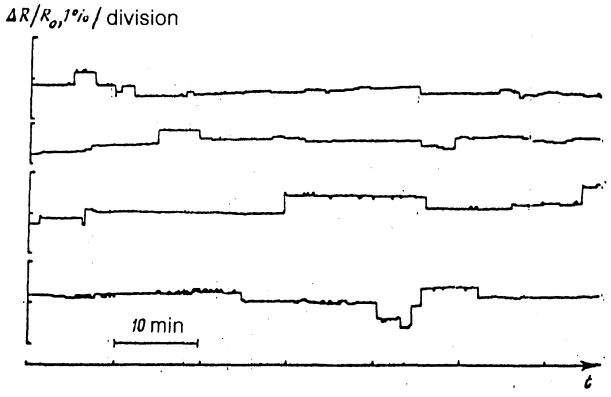

FIG. 5. Relative change in the resistance of a sample as a function of time. Here $T = 4.2$ K and $R = 16.11$ kΩ. The sample is the same one as in Fig. 3.

$\delta G \sim T^{-\alpha}$, where $\alpha = 0.44$. The behavior of the other mesoscopic quantity—the correlation magnetic field B_c—agrees qualitatively with the prediction of the theory in the case of the one-dimensional limit, i.e., it corresponds to the estimate $B_c \approx h/eL_i W$.[5]

Thus overall the theory satisfactorily describes the quantities δG and B_c for our samples. However, for different specific instances of the random potential obtained by means of "warming" and subsequent cooling of the sample, application of a high pulling voltage pulse, or irradiation with light, an appreciable spread in the values of B_c and R was observed for samples of the first type. According to the theory this spread should not be observed. This behavior could be caused by the presence of nonconducting clusters, comparable in size to the width of the sample and changing for each new realization of the random potential, in our structures.

5. UNIVERSAL CONDUCTANCE FLUCTUATIONS AND SPONTANEOUS CHARGE EXCHANGE OF IMPURITIES

For the smallest samples we observed spontaneous abrupt fluctuations (switching) of the resistance which were distinguished by a large range of frequencies and amplitudes.[23] The typical time dependence of the resistance $R(t)$ is shown in Fig. 5. Since with time such switching completely alters the curve $R(B)$, we assumed that the observed fluctuations are of a mesoscopic nature and are a consequence of single acts of charge exchange of impurity atoms in the δ layer that result in a change of the configuration of the random potential.

This behavior makes it possible to investigate the interesting question of the universality of the mesoscopic fluctuations in our samples. Indeed, according to the basic concept of the mesoscopic theory, the rms amplitude of conductance fluctuations δG, which is obtained by averaging over different configurations of the potential, should be equal, to within some constant factor $a \sim 1$, to the quantity δG obtained from the magnetic-field dependence of the conductance. A similar situation happens in our case. By observing the behavior of the sample in time we can find the average amplitude of the jump. This amplitude is essentially the average difference of the conductances of two samples which differ by the position or charge state of a single impurity. On the other hand, the same quantity can also be determined by a different method. Indeed, in accordance with what was said above, if the dependences $G_1(B)$ and $G_2(B)$ are obtained for two samples differing by the state of a single impurity or, which is the same thing, for the same sample but before and after a single-particle jump in the resistance, then the average amplitude of the fluctuations of the difference δG_1^B of these two curves should have the same value as that obtained as a result of averaging by the first method. In our case it should be noted that this comparison can also be performed in the presence of a contact resistance, since such a resistance affects only the absolute value.

The results of the corresponding experiment are presented below. In studying the switching described at the beginning of this section we found a state of high sensitivity in which the resistance was not observed to switch even once for a long time, and the curve $R_1(B)$ was reproduced completely within the limits of accuracy of the measurements. Increasing the pulling voltage by a factor of ten induced a single resistance jump, immediately after which a new curve

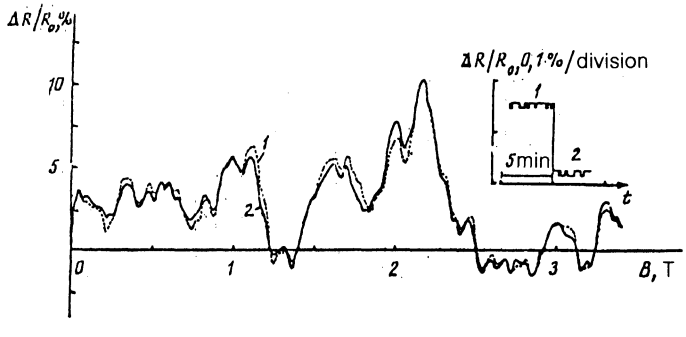

FIG. 6. Relative change in the resistance as a function of the magnetic field before (1) and after (2) a single switching. The inset shows the behavior of the sample at the moment of switching. Here $T = 1.3$ K and $R = 11.3$ kΩ.

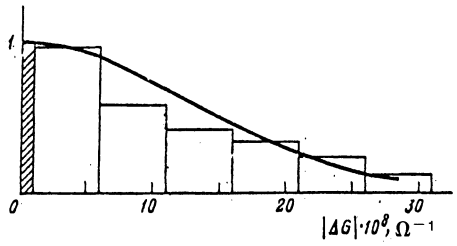

FIG. 7. Histogram of amplitudes of resistance jumps for the time dependence presented in Fig. 5. The normalized number of switching events is plotted along the ordinate. The Gaussian curve corresponds to $\sigma = 1.3 \cdot 10^{-7}\ \Omega^{-1}$ and the hatched region corresponds to the noise level.

$R_2(B)$, corresponding to the new realization of the scattering potential, was recorded.

Thus in this experiment we obtained two different curves corresponding to different realizations of the random potential in the sample, which, according to the assumptions made, differed by the state of a single scattering center (Fig. 6). According to what was said above, we find $\delta G_1^B \approx 5.5 \cdot 10^{-7}\ \Omega^{-1}$. On the other hand, analysis of the time dependence $R(t)$ in Fig. 5 gave the following value of the jump amplitude: $\delta G_1 \approx 1.3 \cdot 10^{-7}\ \Omega^{-1}$ (Fig. 7). Since the measurements of $R(t)$ were performed at $T = 4.2$ K and the measurements of $R(B)$ were performed at $T = 1.3$ K, a correction must be made for the temperature. For samples of the first type at these temperatures the condition $W < L_i < L$ is satisfied, i.e., the formula (3) is valid. Since for the one-dimensional case $L_\varphi \sim T^{-1/3}$, we have $\delta G_1^B \sim T^{-5/6}$. Therefore

$$\delta G_1^B(4{,}2\ \text{K}) \approx (4{,}2/1{,}3)^{-5/6} \quad \delta G_1^B(1{,}3\ \text{K}) \approx 2{,}1 \cdot 10^{-7}\ \Omega^{-1},$$

which, as expected, agrees satisfactorily with the value of δG_1. One other important conclusion follows from the results obtained: Each observed switching event indeed corresponds to the change in the charge state of a single impurity.

6. UNIVERSAL CONDUCTANCE FLUCTUATIONS AND PHOTOINDUCED CHANGE OF THE CONFIGURATION OF THE SCATTERING POTENTIAL

It was reported previously in Ref. 24 that interband photoconductivity σ_{ph} fluctuating in time is observed in the samples investigated. It was also found that when the sample is irradiated with light the form of the $R(B)$ dependence changes with time. On the basis of this observation it was suggested that the observed photoconductivity is of a mesoscopic nature and each maximum or minimum in the time dependence $\sigma_{\text{ph}}(t)$ corresponds to a single act of impurity charge exchange. It was established that on the average each photon incident on the sample induces a change in the state of ~ 1–2 impurities. This makes it possible to investigate the sensitivity of a mesoscopic sample to small changes in the configuration of the scattering potential.

This question appears as follows from the viewpoint of the theory of Refs. 5–7. Let δG_1 be the amplitude of the conductance fluctuations induced by a change in the state of a single impurity. Then when the state of more than one impurity changes the amplitude of the conductance fluctuations δG_n increases by a corresponding factor relative to δG_1, and this process continues until δG_n approaches the value δG corresponding to the conductance fluctuation induced by a complete change in the configuration of the scattering potential in the given sample. The fluctuation δG is determined experimentally as the amplitude of the fluctuation of G in a magnetic field. Further increase in the number of impurities whose state changes does not result in an increase of δG_n, which remains equal to δG. Therefore a change in the state of $n = \delta G / \delta G_1$ impurities makes the sample completely different from the viewpoint of mesoscopy, and this means that the corresponding dependences $R(B)$ are completely uncorrelated. The number n can be determined experimentally on the basis of the above behavior of the sample and our assumptions.

The experiment was performed at $T = 4.2$ K on a sample from the second group. The dimensions of the sample were $L \approx 3.5$ μm and $W \approx 0.4$ μm. The parameters of the starting δ layer were $c = 3.5 \cdot 10^{12}$ cm^{-2}, $l \approx 600$ A, and $L_\varphi \approx 0.45$ μm. The sample was illuminated with radiation from an AlGaAs light-emitting diode, having a maximum at the wavelength $\lambda = 6700$ A. A series of measurements was performed, in which the sample was exposed for a time Δt_i to light with fixed intensity, after which the dependence $R(B,t)$, where $t = \Sigma \Delta t_i$ is the total duration of the illumination, was determined. This gave a series of curves $R(B,t)$ which exhibit the buildup of changes with respect to the initial curve $R(B,0)$ as t increases. Figure 8 shows several $R(B,t)$ traces as well as the normalized correlation function

$$K(t) = \left[\frac{\int R(B,t) R(B,0)\, dB}{\int R^2(B,0)\, dB} \right]^{1/2}. \qquad (5)$$

The time $t = 46$ s at which $K(t) = 0.5$ holds corresponds to complete absence of correlation between them. It follows from the calibration of the radiation intensity $I \approx 1.3$ photons/sec that over this time approximately 60 photons were incident on the sample. According to the assumptions made, this should have resulted in charge exchange of approximately the same number of impurity atoms. Thus the experimentally determined number is $n \approx 60$. On the other hand, from the theory of Refs. 5–7 for the one-dimensional case we

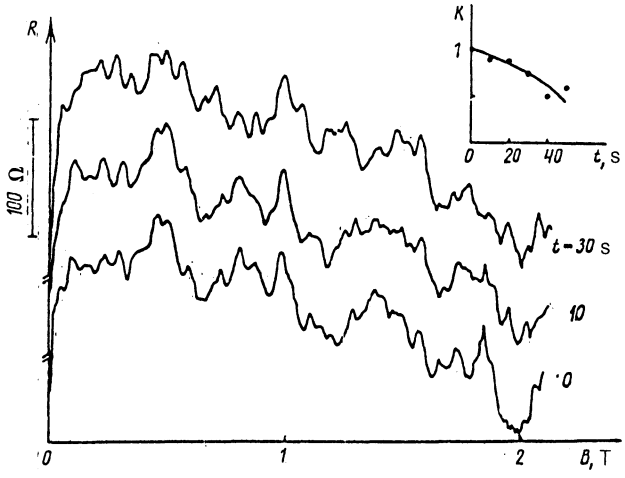

FIG. 8. Magnetic field dependences $R(B)$ corresponding to different illumination times. The inset shows as a function of time the normalized correlation function between the initial curve and the curve corresponding to the illumination time t. Here $R = 3.65$ kΩ and $T = 4.2$ K.

have

$$n=\delta G/\delta G_1=(Lcl^2W/L_\varphi^2)^{1/2}\approx 30,$$

which, taking into account the approximate character of our estimates, agrees well with the preceding results.

7. CONCLUSIONS

Our experimental investigation of the relation between the changes in the configuration of the random potential and the behavior of universal fluctuations of the conductance in micro- and nanostructures based on δ-doped layers of GaAs showed that a configuration can change 1) as a result of spontaneous charge exchange of impurities, 2) under the action of interband illumination, and 3) after the application of a strong electric-field pulse.

The results of the experiments on the whole confirm all predictions of the theory of mesoscopic systems concerning the sensitivity of the conductance of a mesoscopic conductor to small changes in the configuration of the random potential, and in particular to a change in the charge state of a single impurity.

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Translated by M. E. Alferieff