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LETTER TO THE EDITOR

Sensitivity of the universal conductance fluctuations in a GaAs microstructure to the state of a single scatterer

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Abstract. Discrete multilevel spontaneous resistance fluctuations have been observed in a microstructure fabricated on a δ-doped GaAs layer base. We suggest that this behaviour of the resistance is caused by random discrete changes of states of individual impurity atoms. We have been able to observe the influence of the change of the state of a single scatterer on the universal conductance fluctuations. Comparison with theory is made.

Interest in the physics of mesoscopic systems is unabated, since some essential questions still remain unanswered. Amongst the theoretical results as yet unverified experimentally, is an important prediction [1, 2]: this is that the motion or the change of the state of a *single* scatterer leads to a change in the value of the conductance of a mesoscopic structure of the order e^2/h. Measurements conducted in the present work enable comparison of this proposition with experiment for the first time.

The devices used are δ-doped GaAs layers with the following sizes: length $L \simeq 1\ \mu$m and width $W \simeq 0.15\ \mu$m. The original δ-layer parameters are: the two-dimensional carrier concentration, $n = 6 \times 10^{12}\ \text{cm}^{-2}$; mobility, $\mu = 2000\ \text{cm}^2\ \text{V}^{-1}\text{s}^{-1}$; NMR value of the inelastic scattering length, $L_{\text{in}} \simeq 0.7\ \mu$m; the two-dimensional concentration of Si atoms in the δ-layer, $c = 6 \times 10^{12}\text{cm}^{-2}$; mean free path, $l \simeq 460$ Å. The structures were prepared by electron beam lithography with subsequent anisotropic ion-stimulated etching by molecular Cl. The resistance of the devices was measured by an AC bridge scheme at a frequency of $f \simeq 700$ Hz. The AC voltage used to measure the sample resistance was kept at less than kT/e. The measurements were conducted over the temperature range 1.3–4.2 K and in magnetic fields of up to 3.5 T.

There have been investigations [3, 4, 5] of two-level resistance fluctuations (telegraph noise) in metal nanobridges and submicron Si MOSFETs, and recently a report has been published [6] concerning the observation of multilevel discrete resistance fluctuations in a GaAs/AlGaAs heterostructure stimulated by applied voltage impulses. In the present work both multilevel and two-level spontaneous discrete resistance fluctuations have been observed in a GaAs microstructure.

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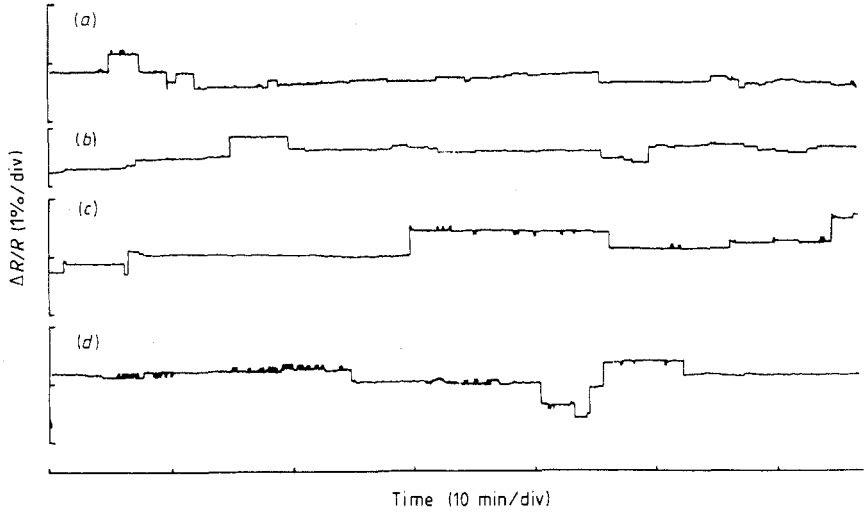

Figure 1. Time dependence of the sample resistance (quasi-equilibrum state): $T = 4.2$ K, $\bar{R} = 16.1$ kΩ.

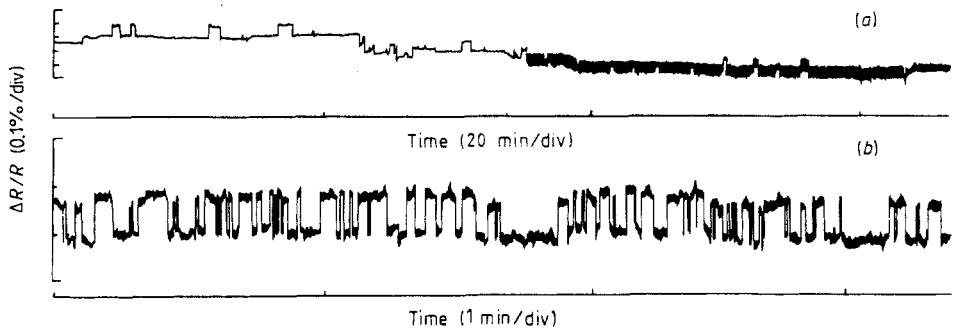

Figure 2. Types of two-level resistance fluctuations: $T = 4.2$ K, $\bar{R} = 14.7$ kΩ.

The results of the continuous 4.5-hour-long measurement of R are shown in figure 1. As may be seen, the value of the resistance changes randomly and spontaneously, with the amplitude of the jumps lying in a wide range: from 0.06% (noise level is about 0.03%) to 0.5%. The duration of the jumps is no more than 100 ms (this is the upper limit set by the time constant of the lock-in nanovoltmeter). The noise character features that appear from time to time on the $R(t)$ output are actually discrete two-level fluctuations with a low amplitude and of high frequency. Several types of the two-level fluctuations observed are shown in figure 2. In figure 2(a) there is a sharp transition from the low-frequency two-level resistance fluctuations to those of higher frequency and approximately the same amplitude. The dependence in figure 2(b) is the continuation of figure 2(a) with the susceptibility and the speed of the recording increased.

On the whole, it should be noted that the sample behaviour is very diverse and that at various rates of cooling different states of the sample may be obtained. The states differ from each other in the average values of the resistance $\bar{R}$ obtained (up to 70% variation) and in the frequency of the fluctuations observed. The states with a relatively

high frequency of fluctuations (up to 1 Hz) are noticeably non-equilibrum. As a rule, they appear immediately after the sample is immersed in the liquid helium, but may also be obtained by the temporal application of a sufficiently high source–drain electric field. At such states $\bar{R}$ gradually decreases and, after some time (two hours), the sample comes to a quasi-equilibrum state characterised by considerably less frequent fluctuations and a relatively constant value of $\bar{R}$. Figure 1 shows typical time dependences for such states. Their duration may be as long as 24 hours (observations longer than that were not made). Lastly, sometimes states are realised that are noticeably in equilibrum, when for several hours no jumps with an amplitude higher than the noise level are registered.

The possible explanation of the observed behaviour of the sample may be based on the well known fact that the resistance value of a mesoscopic sample depends substantially on the value of the interference correction, which is fully determined by the random potential configuration. So, even a very slight change in the scattering potential configuration may lead to a noticeable change in the resistance value. In the structures studied here the ionised Si atoms play the role of scattering centres. It may be supposed that the observed resistance jumps correspond to the separate acts of capture and recapture of electrons by the Si atoms. The probability of several such acts in different atoms leading to a single jump in the resistance is small, as it is proportional to the ratio of the upper estimate of the duration of a jump to the average interval between the jumps. On the other hand, supposing these jumps are the result of one-electron processes, they cannot be explained by classical reasoning (for example, by the change in the number of carriers or in the value of the mobility) because of the high magnitude of the effect. Moreover, as was found, if the discrete resistance jumps are present, the pattern of the mesoscopic magnetoresistance fluctuations gradually transforms, leading after some time to a quite different $R(H)$ dependence. This proves the mesoscopic nature of these jumps and gives us an opportunity of verifying the theoretical prediction concerning the sensitivity of the universal conductance fluctuations to the position or state of an individual scatterer.

We obtained a state of high stability where there was an absence of any jumps with amplitude higher than the noise level and, in the course of 2.5 hours, the $R(H)$ curve reproduced excellently, within experimental accuracy. In order to alter the state of the sample, the value of the AC voltage had been made ten times larger, leading to a corresponding increase in the susceptibility (even at this value of the AC current the sample showed Ohmic behaviour). The time dependence of the resistance was found to exhibit low-amplitude two-level fluctuations (see the insert to figure 3), which could not have been detected previously. However, as was established later, these did not lead to any noticeable changes in the magnetoresistance curve. About ten minutes after the AC voltage had been increased, a solitary resistance jump was detected (see the insert). Immediately, the voltage was brought back to its previous value and a new magnetoresistance dependence was obtained. Some minutes later, the resistance of the sample switched spontaneously back to its former value. Repeating the procedure, we were able to realise both the initial and the excited states several times, and to determine the corresponding $R(H)$ curves. Precise control of the resistance value had been made repeatedly in the process of the experiment, to be certain what state the sample was in. The results are shown in figure 3. One can see that for the two states of the sample the curves differ appreciably while, as it was found, the curves corresponding to each one of the states taken separately coincide perfectly. Thus, as follows from our suggestion, the two curves on figure 3 correspond respectively to two different scattering potential configurations, the only difference being the state of one scatterer. This provides the

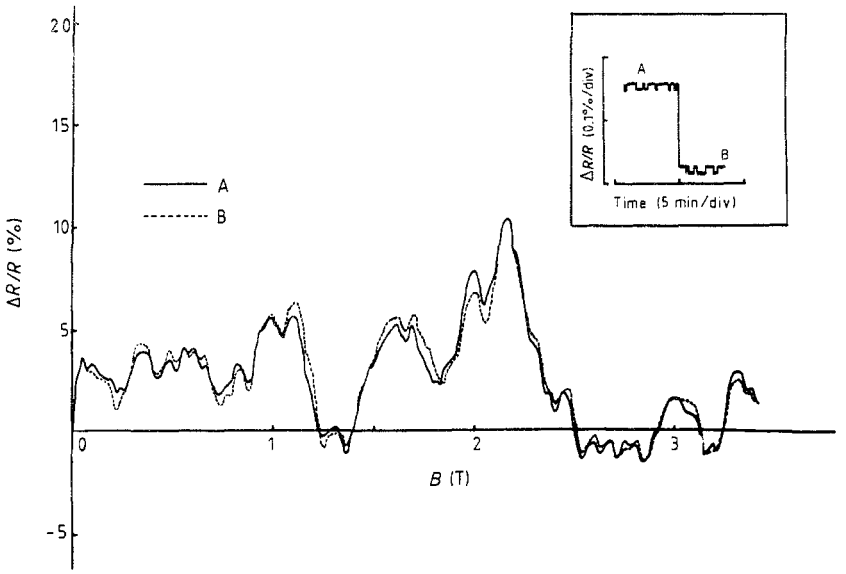

Figure 3. The magnetic field dependences of R before (full curve) and after (broken curve) the solitary resistance jump: $T = 1.3$ K, $R = 11.3$ kΩ.

possibility of finding the RMS value of the sample-to-sample conductance fluctuations $(\delta G_1)^2$, where the difference between the samples is in every instance the state of one scatterer, and of comparing the result with the theoretical prediction. Indeed, according to the ergodic hypothesis [7] it should be equivalent to the RMS magnitude of the curve, which is the difference between the two shown in figure 3. If, as in our case, $W < L_{in} < L$, the theoretical expression for $(\delta G_1)^2$ is [1, 2]

$$(\delta G_1)^2 \simeq (e^2/h)(L_{in}/L)(L_{in}/Wcl^2).$$

However, it would be more self-consistent to compare the theoretical and the experimental evaluations of the ratio $K = (\delta G_1)^2/(\delta G_2)^2$, where $(\delta G_2)^2$ is the RMS value of the conductance fluctuations as the magnetic field is varied and is given by the following expression [7]:

$$(\delta G_2)^2 \simeq (e^2/h)^2(L_{in}/L)^3.$$

Hence $K = L_{in}^2/WLcl^2$ and, taking for the parameters the values given above, one obtains $K \simeq 0.16$. The experimental result for K is about 0.15 to 0.23, and so the agreement is perfect.

Considering the results of our experiment, one more important conclusion may be made: the states of the impurity atoms in a heavily doped semiconductor that are realised after the cooling of the sample down to 4.2 K are *not* in thermodynamical equilibrium, and therefore the resistance of the sample has no fixed value.

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