Characteristic features of the current noise in the mesoscopic channel of a field-effect GaAs transistor

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Mesoscopic fluctuations in the power level of a current noise and a conversion of the $1/f$ noise to a "telegraph" noise of a single noise source, which occur as a result of a change in the electron density, have been detected in a short GaAs channel with a hopping conductivity.

Reproducible fluctuations of the conductivity G, which occur upon changing the gate voltage V_g and which stem from the fact that the conductivity cannot be averaged at the mesoscopic scale, have been observed in various micron transistors. In the present letter we report the results of a study of the current noise in a field-effect GaAs transistor, in which the fluctuations of $G(V_g)$ were detected near the hopping conductivity.[1]

The current noise is associated with the time-varying fluctuations of the conductivity. An elementary noise source of a channel with a metallic conductivity: a transfer of electrons between the channel and a capture center in an oxide, was clearly identified in an MIS Si structure of small area ($1\times0.1\ \mu$m).[2] In a channel with a large cross section the total effect gives rise to a $1/f$ noise. In the hopping-conductivity region the $1/f$ noise observed in a macroscopic MIS Si structure was attributed to the intrinsic properties of the conductivity, rather than to the capture of an electron at a capture center.[3] Our objective in the present study was to investigate the time-varying fluctuations of the hopping conductivity of a mesoscopic sample. The advantage of a transistor with a Schottky gate is that the surface has only a slight effect on the properties of the channel which is separated from the surface a distance equal to the thickness of the depleted layer, L.

The electron channel was situated in the doped GaAs layer ($N_d = 3$–10×10^{16} cm^{-3}). Its cross-sectional shape was that of a strip with the dimensions $l = 2\times20\ \mu$m, $W = 200\ \mu$m, and the current flowed through the short side (Fig. 1). At electron densities $n < 10^{11}$ cm^{-2} and $T < 20$ K, where the conductivity is determined by the hops between the donors, the $G(V_g)$ curve exhibits characteristic features which cause it to fluctuate rapidly as n decreases ($|V_g|$ increases): the mesoscopic conductivity regime.[1]

The time-dependent spectral fluctuation density of the voltage U across the channel, $S = \langle (U - \langle U \rangle)^2 \rangle / \Delta f$ was measured by a CK4-72 spectral analyzer in the frequency interval $f = 2$–2×10 Hz (the angle brackets denote averaging over time). The quadratic dependence of S on the average voltage in the voltage range $\langle U \rangle \leqslant 10$ mV means that the fluctuation of $U(t)$ is caused by the fluctuation of the resistance. In

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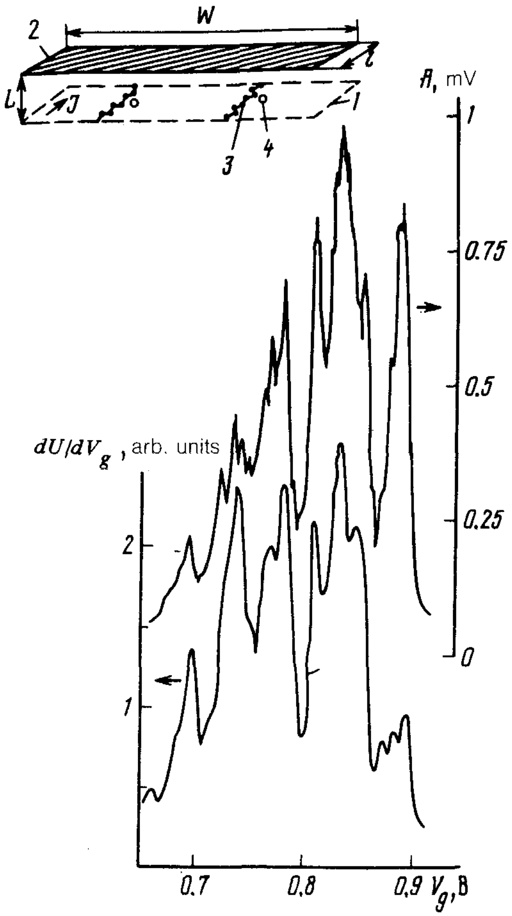

FIG. 1. The voltage fluctuation amplitude $A = \langle | U - \langle U \rangle | \rangle$ and the derivative dU/dV_g versus the gate voltage V_g. The inset: 1—Electron channel; 2—gate; 3—a series of jumps; 4—modulator.

addition, the quantity $A = \langle | U - \langle U \rangle | \rangle$ was measured by means of a selective voltmeter.

The noise power level depends nonmonotonically on the gate voltage. Figure 1 is a plot of the voltage fluctuation amplitude A measured at a frequency of 18 Hz in a band $\Delta f \approx 6$ Hz at 4.2 K. A comparison of the functional dependence $A(V_g)$ with the derivative $U_m(V_g) = dU/dV_g$ showed that the positions of most of the peaks on these curves are the same. The relationship between $A(V_g)$ and $U_m(V_g)$, however, is not constant. In addition, the amplitude of the noise peaks varies differently as the frequency is changed, suggesting that the noise spectrum is different in different $A(V_g)$ peaks.

Figure 2 is an example of how the noise spectrum changes with a change in the gate voltage. In the region of slight fluctuation of the average conductivity G as a function of V_g, the time-varying voltage-fluctuation spectrum behaves in a manner consistent with the $1/f$ law (curve 1). As the electron density decreases, the behavior

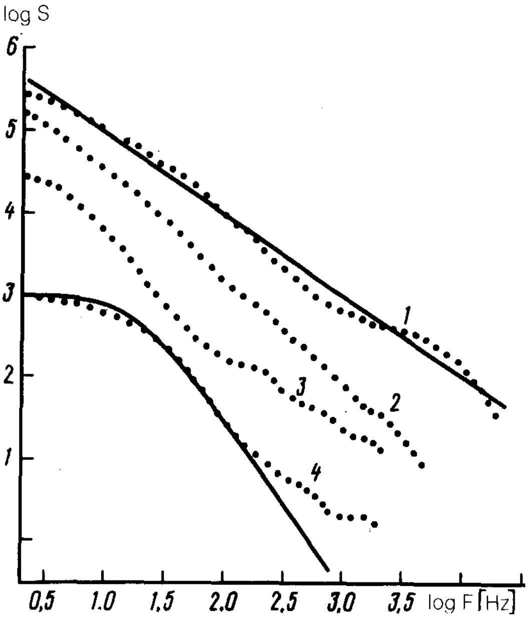

FIG. 2. Spectral density of the current noise for various values of V_g: 1—2.82; 2—2.90; 3—2.96; 4—2.99 V; $T = 4.2$ K. Solid lines—$1/f$ and $1/(1+\alpha f^2)$ plots.

of $S(f)$ changes and the spectral density of the voltage fluctuations can be described by the sum of several Lorentz curves $S_L \propto 1/(1+\omega^2\tau^2)$ with different values of τ (curves 2 and 3). In the region of strong fluctuations of $G(V_g)$ the fluctuation spectrum of $U(t)$ is similar to the spectrum of the relaxation process with one value of τ (curve 4).

As the temperature is raised to $T \approx 20$ K, while keeping V_g constant, the spectral density of the voltage fluctuations changes from a Lorentz shape to that of the $1/f$ law. The $1/f$ law was also observed in the case of a current noise in "long" samples of length $l = 200$ μm.

A single relaxation process manifests itself directly in the form of a jump in the resistance over time. Figure 3 is an example of the observable switching of the resistance between two stable states—"telegraph" noise. The resistance in this case is measured with an alternating current (18 Hz). The average pulse length and the ratio of the residence times in each state changes with changing V_g by an amount on the order of the characteristic scale value ΔV_g at which the conductivity $G(V_g)$ fluctuates.

It can be concluded from the coincidence of the positions of the noise resonances and the extrema of the derivative $U_m(V_g)$ that the noise is caused by the modulation of the conductivity by a stray electric field. This modulation is similar to the modulation of the conductivity by an alternating gate voltage when the derivative is measured. The stray electric field which displaces the levels of the localized states may appear when a center, which is situated near a conducting path, a "modulator," captures and releases an electron. The fluctuations associated with the filling of a center reach a peak level when the Fermi level is in the $\approx kT$ band near its energy level.

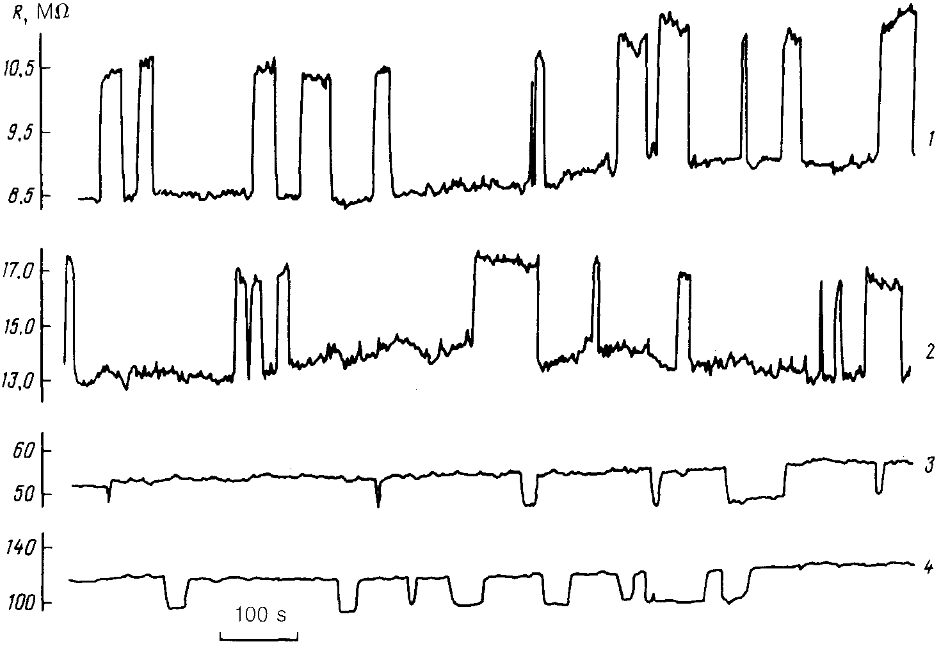

FIG. 3. The switching of the time-dependent channel resistance at various voltages V_g: 1—3.07; 2—3.08; 3—3.12; 4—3.14 V.

If the conductivity of the sample is determined by many paths, the spectral density of the voltage fluctuations is a sum of the Lorentz laws. We know that a $1/f$ spectrum can be obtained by summing the relaxation processes and an exponentially broad scatter of the time. In the hopping conductivity such a scatter may be linked with the scatter of the spacing r between the localized states,[4] between which the frequency of the electronic transitions is $\nu = \nu_0 \exp(-2r/a)$, where a is the effective Bohr radius.

A decrease in the electron density increases the average length of the jump and decreases the number of conducting paths (series of consecutive jumps). This process also leads to a reduction in the total number of modulators situated near these paths at distances on the order of the screening length: the distance from the metallic gate, L. Accordingly, when the conductivity is determined by a few jumps, we clearly see in the sample of relatively large cross section an elementary source of time-varying fluctuations of the hopping conductivity: fluctuations associated with the filling of a single localized state.

In a channel situated some distance from the surface, a modulator may be a donor which lies in the plane of the channel but which does not participate in the conductivity (Fig. 1). Assuming that the state density is smaller than a two dimensional state density by an order of magnitude, $m^*/\pi\hbar^2$, let us estimate the average number of states, N, in the channel which are situated in a band of width L and length l in the energy interval kT. For $T = 1.5$ K, $L = 2000$ Å, and $l = 2$ μm we find $N \sim 1$, the number of modulators near one series of jumps. Upon increasing the temperature to 20 K, the number of modulators increases by an order of magnitude, which accounts for the appearance of a noise with a $1/f$ spectrum.

A typical length of a jump between the centers due to the electron transfer may be $r = 1000$–2000 Å ($r \sim 1000$ Å is the length of a jump in a conducting series of jumps). An estimate of the corresponding transition frequency, with $\nu_0 = 10^{13}$ Hz and $a = 100$ Å, gives $\nu \sim 4 \times 10^{-5}$–$2 \times 10^{4}$ Hz. The experimentally observed frequencies of the noise sources, 10^{-2}–10^{4} Hz, lie in this range (Figs. 2 and 3).

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