Mesoscopic fluctuations in the current-voltage characteristic of a short sample with a hopping conductivity

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Oscillations have been observed in the differential conductance $\partial J/\partial U$ in a short (2-μm) electron channel of a GaAs field-effect transistor upon a change in the applied voltage U. The observations are explained on the basis of a change in the "main" hop, which determines the conductivity of the sample.

Mesoscopic effects have been observed in the ohmic conductivity of conductors, $G_0 = (\partial J/\partial U)(U=0)$ (U is the applied voltage), in one-dimensional (1D) Si transistor structures[1] and 2D GaAs transistor structures[2–4] with a conducting channel with dimensions $\lesssim 1$ μm. In a GaAs field-effect transistor, the value of G_0 oscillated during a variation of the number of electrons in the channel, which was set by the gate voltage V_g (Refs. 2 and 3), and also during a variation of the magnetic field.[4] In the plane, the channel took the form of a strip with dimensions of 2×200 μm. The current flowed along the short side. The oscillations on the curves of $G_0(V_g)$ and $G_0(H)$, which were manifested at low temperatures ($T<10$ K) and at low electron densities, where the conductivity was of a hopping nature, were explained[3,4] on the basis of a model of a "main" hop. The conductance of a short strip is equal to sum of the conductances of the various paths consisting of chains of hops. Because of the exponentially large spread in the resistances of the hops, the conductance of a sample is determined by one of the best-conducting chains, whose resistance is in turn determined by the largest of the series connection of resistances making up a chain.

Our purpose in the present study was to learn about the current-voltage characteristic of a short 2D channel in a GaAs transistor operated under conditions corresponding to oscillations in the ohmic conductivity. In the mesoscopic regime of "one hop," one can attempt to directly distinguish the elementary electronic processes which govern the hopping conductivity in a strong field.[5,6] Lee[7] called attention to the possible appearance of a nonmonotonic behavior on the current-voltage characteristic of a 1D chain of hops. Webb *et al.*[1] have observed an inflection point on the current-voltage characteristic of a 1D channel at a silicon surface.

At a frequency of 10 Hz we measured the differential conductance as a function of the applied drain-source field of a field-effect transistor based on an epitaxial layer of GaAs with a donor concentration of 3×10^{16}–10^{17} cm^{-3} (Refs. 3 and 4). The length of the Schottky gate was 2–5 μm, and its width was 200 μm. Figure 1 shows an example of the experimental dependence for various gate voltages in the region of the oscillations in $G_0(V_g)$. On the curve of $(\partial J/\partial U)(U)$ we see structural features, which correspond to the slope changes on the functional dependence $J(U)$. Interestingly, the

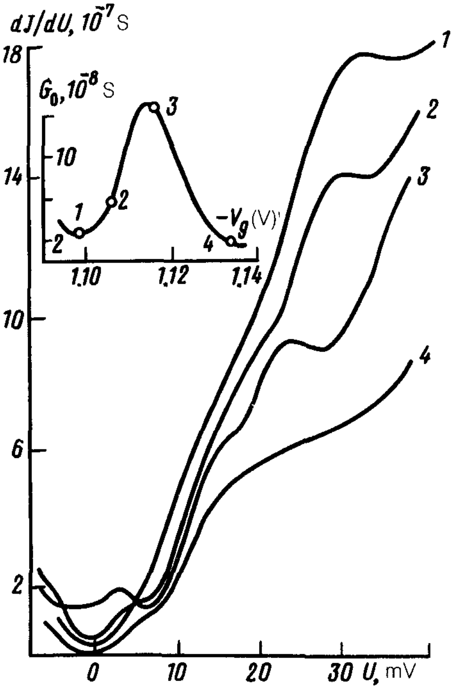

FIG. 1. The differential conductance of sample $D1$ versus the applied voltage U for various gate voltages V_g, corresponding to the numbered points in the inset ($T = 4.2$ K).

shape of the curves changes upon a change in the voltage V_g by an amount equal to the period of the oscillations in the ohmic conductivity; there is a change in the dominant chain of hops at this scale.

One possible reason for the appearance of slope changes on the current-voltage characteristic is a redistribution of the voltage among the resistances of the hops of the leading chain. According to Pollak and Riess,[5] the current-voltage characteristic of a single hop can be written as follows under the condition $(eU_n/kT) > 1$, where (U_n is the voltage across hop n:

$$J = \Gamma_0 \exp\left(- \xi_n + \frac{eU_n}{kT} \alpha_n \right). \tag{1}$$

The resistance of a hop in the ohmic regime is $\gamma \exp \xi_n$, and α is a coefficient which reflects the "softness" of the hop, in the terminology of Shklovskiĭ[6]: $\alpha = 1$ and $\alpha \ll 1$ for "soft" and "hard" hops, respectively. (The value of α is determined by the arrangement of energy levels of the localized states ϵ_i and ϵ_j which are participating in the hop and also by the position of the Fermi levels μ_i and μ_j.) We assume that at $U = 0$ the resistances of the hops in a chain are distributed uniformly in ξ over the interval $[0, \xi_{max}]$ with a step $\Delta\xi$. The entire voltage across the chain, U, falls across the largest resistance $\gamma \exp(\xi_{max} - \Delta\xi)$ which decreases with increasing U in accordance with expression (1). At a certain voltage, the resistance of the main hop becomes comparable to the resistance of the "substitute", $\gamma \exp(\xi_{max} - \Delta\xi)$, which is in the ohmic regime. From this time on, the voltage applied to the chain is divided between two resistances. As a result, whenever the resistance next in order of magnitude turns out to lie in the nonohmic regime, (1), we should observe a weakening of the current-voltage characteristic of the chain. If all the hops in a chain are soft ($\alpha = 1$), the distance between adjacent structural features on the current-voltage characteristic will increase in accordance with $\Delta U_{n,n-1} = (kT/e)\Delta\xi n$, where n is the order in which the feature appears. The smoothed current-voltage characteristic of a chain of this sort is described by

$$J \propto \exp(-\xi_{max} + (\Delta\xi eU/kT)^{1/2}). \qquad (2)$$

Actually, the current-voltage characteristics of different hops in a chain may be quite different. If a chain contains a hard hop ($\alpha \ll 1$), the entire voltage will fall across it as U is increased, and the increase in the current through the chain will be slowed substantially. As a result, another chain will become the lowest-resistance chain in the sample. A second possible reason for a change in the slope on the current-voltage characteristic (with an intensification of the dependence) might therefore be a replacement of a hard hop by a soft one, accompanied by a change in the leading chain.

Figure 2 shows curves of $G(V_g)$ for various values of the applied field. At $V_g = 1.165$ V we observe a nonmonotonic behavior on the plot of $(\partial J/\partial U)(U)$ with a minimum at $U = 7$ mV; this effect may be associated with a change in the leading chain. The dependence of the conductance on the gate voltage incorporates energy on a certain sequence of changes in the main hop in a sample. A single chain leads in the interval of V_g between adjacent minima of $G(V_g)$. We see that, as the applied field is increased, the sequence of changes in chains in the region $V_g = 1.165$ V changes significantly: The maximum on the $G(V_g)$ curve is replaced by a minimum. It can thus be concluded that the intensification of the dependence $(\partial J/\partial U)(U)$ at $U > 7$ mV

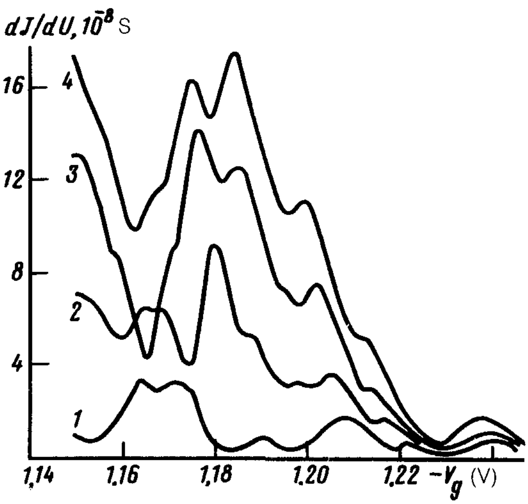

FIG. 2. The differential conductance of sample $D2$ versus the gate voltage for various values of the applied voltage: 1–$U = 0$; 2–$U = 4$ mV; 3–$U = 7$ mV; 4–$U = 9$ mV.

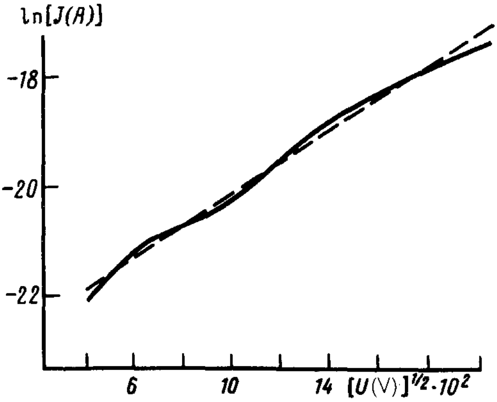

FIG. 3. Current-voltage characteristic of sample D 1. The dashed line is an approximating straight line.

in a region $V_g - 1.165$ V is due to a transition from a hard hop to a soft one with a simultaneous change in the leading chain.

Figure 3 shows a current-voltage characteristic with alternating changes in slope (found through an integration of curve 3 in Fig. 1). The current-voltage characteristics of the samples which were studied conform well to straight lines in the coordinates $\ln J(U^{1/2})$, in agreement with (2). This agreement can be taken as confirmation of the chain mechanism for the conductivity in these samples. The typical spread in the ohmic resistances, $\Delta\xi \approx 0.6$, found from the slope of the approximating straight lines agrees with an estimate of this quantity from the amplitude of the oscillations in the conductance: $\Delta\xi = \Delta[\ln G_0(V_g)] \approx 1$.

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