Oscillations of nonlinear characteristics of samples with small dimensions

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The detection of a low-frequency signal and the generation of a second-harmonic signal have been observed in the channel of a GaAs field-effect transistor with dimensions of $2\times200\,\mu$m. This second-harmonic signal oscillates as a function of (a) the number of electrons in the channel and (b) the magnetic field.

Samples with small dimensions should exhibit effects not seen in macroscopic samples: oscillations of the resistance upon a change in the Fermi level or the magnetic field, a detection (rectification) of an alternating current, and the generation of a second harmonic.[1–3] Some of these effects have been observed experimentally in one-dimensional structures: an oscillation of the conductivity of the electron channel at the surface of Si upon a change in the gate voltage, a nonlinearity of the current-voltage characteristic of a channel,[4] and fluctuations in the conductivity of metal samples upon a change in magnetic field.[5] It was suggested in Ref. 6 that oscillations of the conductivity G of the channel of a GaAs field-effect transistor upon a variation of the voltage across the Schottky gate, V_g, also stem from a mesoscopic nature of the two-dimensional samples. In the present letter we report a study of the nonlinear properties and magnetoresistance of such structures. The conductivity of the channel, $G(V_g)$, in

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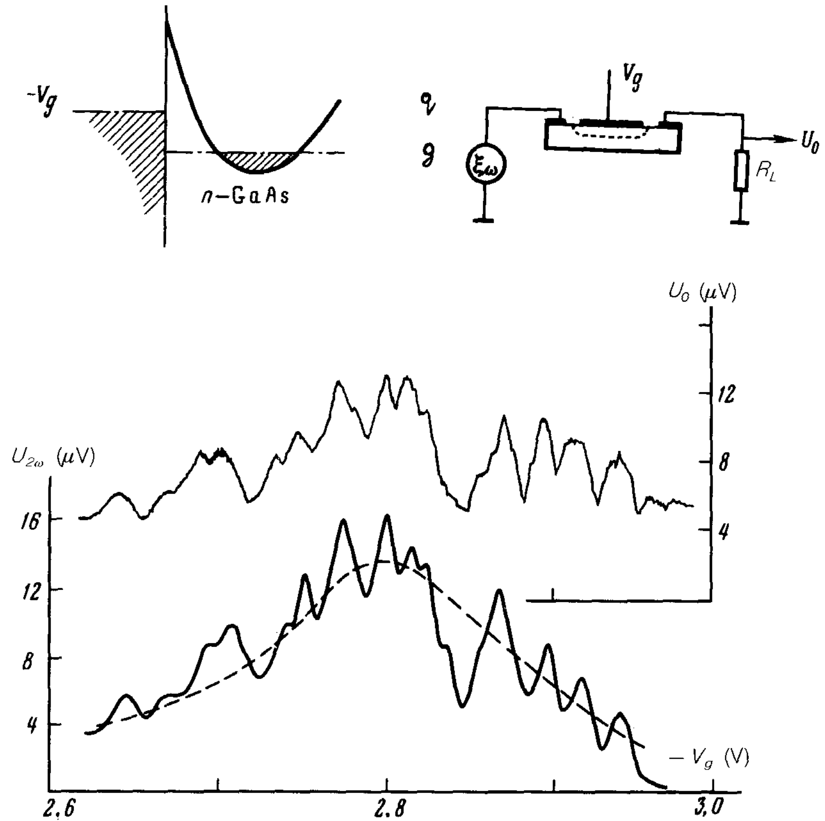

FIG. 1. Oscillations in the rectified voltage U_0 and in the second-harmonic signal $U_{2\omega}$ upon a variation in the gate voltage V_g ($T = 4.2$ K). The dashed line corresponds to $T = 25$ K. The insets show the band diagram of the device and the measurement arrangement; $\epsilon_\omega = 1.5$ mV, $\omega = 1$ kHz, $R_L = 100$ kΩ.

the oscillation region (at $T < 15$ K, with a narrow channel) is of a hopping nature, so that the test samples are of interest for observing an effect predicted in Ref. 3: fluctuations in the hopping conductivity of a sample of small dimensions upon a variation of the magnetic field.

Figure 1 shows the band diagram of the field-effect transistor and the experimental arrangement. The electron channel in an epitaxial layer of n-GaAs ($N_d \sim 10^{17}$ cm^{-3}) on a nonconducting substrate is bounded by a depletion region beside the Schottky gate. The thickness of the channel and the number of electrons in it can be controlled by means of the gate voltage V_g. The dimensions of the channel in the plane are determined by the shape of the gate: a length of 0.7–2 μm and a width of 200 μm. A voltage $\epsilon_\omega = 40$ μV to 1.5 mV of frequency $\omega = 20$ Hz to 1 kHz is applied to the sample. A constant voltage U_0, a voltage at the frequency ω (U_ω), and a voltage at twice this frequency ($U_{2\omega}$) are measured across the load resistance R_L. The voltage U_ω, determined by the differential conductivity of the channel, exhibits slight oscillations upon a variation in V_g. The signals U_0 (the rectified current) and $U_{2\omega}$ (the

FIG. 2. Oscillations of the second-harmonic signal $U_{2\omega}$ in a perpendicular magnetic field for various values of V_g: 1—3.09 V; 2—3.005 V; 3—2.95 V (the curves are displaced along the Y axis; two curves are shown for $V_g = 3.09$ V; $\epsilon_\omega = 1.5$, mV, $\omega = 23$ Hz; $R_L = 2$ MΩ).

signal determined by the value of $\partial^2 J/\partial V^2$ of the channel, where I is the current, and V is the source-drain voltage) exhibit well-defined oscillations with extrema which coincide along the V_g scale (Fig. 1). The oscillations in $U_\omega(V_g)$ and $U_{2\omega}(V_g)$ are seen in the same region of V_g, but we do not observe an unambiguous relationship between the positions of their extrema. The oscillations in the second-harmonic signal decrease with increasing temperature and with increasing external field, as do the oscillations of the channel conductivity.

The perpendicular magnetoresistance of the channel ($H \lesssim 60$ Oe) is measured at a fixed value of V_g in the region of the $G(V_g)$ oscillations at $T = 4.2$ K. The magnetoresistance of these samples has two regions: a negative magnetoresistance in weak fields, which gives way to a positive magnetoresistance in strong fields [the value of $\Delta R(H)/R(0)$ at the minimum is $\sim 40\%$]. Against the background of a monotonic change in $R(H)$ we can see two or three oscillations with a relative amplitude $\sim 1\%$. The second-harmonic signal oscillates as a function of the magnetic field with a typical amplitude on the order of the magnitude of the signal itself. The paths of the $U_{2\omega}(H)$ curves are quite different for different values of V_g. The rectified signal U_0 also oscillates as a function of the magnetic field.

It was shown in Ref. 3 that the probability for tunnel hopping with scattering by impurities (hopping conductivity with a variable hopping length) should fluctuate upon a variation of the magnetic field. The magnitude of the fluctuations would be on the order of the hopping probability itself. The typical oscillation period, $\Delta H_c = 2\pi e\hbar/r^{3/2}a^{1/2}$, is determined by the fluxoid, $\Phi_0 = ch/e$, through an area bounded by the longest trajectories: $S \sim r\sqrt{ra}$, where a is the localization length of the electron wave function, and r is the hopping length. This system may be thought of as a Miller/Abrahams network with many resistances ($N \sim 10^4$), with the result that the fluctuations in the probability for individual hops are averaged over, and the effect of the oscillations in the $R(H)$ dependence is small. The oscillations in $\partial^2 J/\partial V^2$, in contrast, should be on the order of the quantity itself, since the average value of $\partial^2 J/\partial V^2$ in a macroscopic system is zero. Consequently, measurements of the nonlinearity of the I–V characteristic would make it possible to see mesoscopic effects directly. Assuming the localization radius of the wave function to be $a_B \sim 100$ Å and also assuming $r \sim 600$ Å (in view of data on the temperature dependence of the resistance), we estimate the typical oscillation period to be $\Delta H_c \sim 25$ kOe. This value agrees with the typical oscillation period found experimentally (Fig. 2).

In summary, these experimental results can be explained as a manifestation of mesoscopic effects in a two-dimensional sample with a hopping conductivity. The anomalous negative magnetoresistance which has been observed can apparently also be explained by this model. According to Ref. 7, a system with a large number of hops with a variable hopping length should exhibit a negative magnetoresistance. This theory predicts a large negative magnetoresistance, in agreement with experiment. A quantitative analysis of the results will require a model which incorporates an averaging of the fluctuations in a mesoscopic two-dimensional sample, in particular fluctuations in $\partial^2 J/\partial V^2$.

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