Negative magnetoresistance and oscillations of the hopping conductance of a short *n*-type channel in a GaAs field-effect transistor

E. I. Laĭko, A. O. Orlov, A. K. Savchenko, É. A. Il'ichev, and É. A. Poltoratskiĭ

Institute of Radio Engineering and Electronics, Academy of Sciences of the USSR, Moscow
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An investigation was made of the magnetoresistance of short ($\approx 2\,\mu$m) n-type channels in GaAs transistors characterized by an oscillatory (at $T = 4.2$ K) dependence of the conductance G on the gate voltage V_g. It was found that in the region of strong oscillations of $G(V_g)$ the hopping conductance of the channel oscillated as a function of the intensity of the applied magnetic field. The oscillations of $G(H)$ changed to a negative magnetoresistance on approach to an insulator–metal transition. Both $G(V_g)$ and $G(H)$ oscillations were explained on the basis of a concept of mesoscopic channel conductance determined by a small number of electron jumps. The negative hopping magnetoresistance and the conductance oscillations for a single jump in a magnetic field were interpreted using a model of hopping conductance involving electron scattering by impurities.

INTRODUCTION

Electronic properties of samples of small (micron and submicron) dimensions are currently attracting much attention. Such samples are usually two-dimensional (thin films and n-type channels in metal–insulator–semiconductor transistors) formed by reducing one dimension in a plane by lithography. It has been established[1–6] that the conductance G of a submicron channel in a silicon metal–insulator–semiconductor (MIS) transistor oscillates when the gate voltage V_g, governing the number of electrons in the conducting channel, is varied. These investigations have stimulated studies of the properties of what are known as mesoscopic samples[7] whose dimensions are comparable with a characteristic length governing the conduction process and, consequently, are insufficient for averaging of microscopic fluctuations of the conductance associated with a random distribution of impurities. The characteristic conduction length in a metal at low temperatures is the coherence length of a normal metal L_T, whereas in the case of an insulator it is the length of an electron jump r.

The conductance of a channel in a field-effect transistor can be metallic or insulating, depending on the range of variation of the gate voltage.[8] An oscillatory dependence of the conductance $G(V_g)$ of a submicron silicon transistor has been observed in metallic[2–4,6] and insulating[1,5] conductance regimes. In the case of metallic systems (such as films[9] or channels in silicon MIS transistors[10–12]) an additional mesoscopic effect has been discovered: it is manifested by oscillations of the conductance as a function of the intensity of an external magnetic field.

The present investigation is concerned with oscillations of the conductance in a magnetic field when this conductance takes on a hopping nature. A brief report of the observation of this effect in a GaAs field-effect transistor with a short ($\leqslant 2\,\mu$m) channel was published by two of the present authors.[13]

A conducting channel in a GaAs field-effect transistor with a Schottky gate is formed in the interior of an epitaxial GaAs film.[14] Well before experiments on channels in silicon, Pepper[14] discovered an oscillatory dependence of the conductance on the gate voltage at $T = 4.2$ K; in contrast to one-dimensional channels in silicon,[1–6,10–12] a channel in a GaAs transistor was found to be of considerable width ($\approx 200\,\mu$m) and the current travelled along the short side of length $2\,\mu$m. We investigated earlier[16] a GaAs transistor structure similar to that studied by Pepper[15] and reached the conclusion that the oscillations of $G(V_g)$ were due to the mesoscopic nature of hopping conduction in the short two-dimensional channel. This was confirmed by the subsequent work,[13] where we reported not only oscillations of $G(V_g)$, but also oscillations of the second harmonic $U_{2\omega}(V_g)$ [it is known that second harmonic generation is a characteristic feature of a mesoscopic sample with an asymmetric current-voltage characteristic $G(V) \neq G(-V)$—see Ref. 7].

In the present study we found that the magnetoresistance $\Delta R(H)/R(0)$ of a channel in a GaAs transistor in the hopping conduction range depended strongly on the number of electrons in a channel. When the number of electrons was reduced by the gate voltage V_g, a negative magnetoresistance changed to an oscillatory dependence of the conductance on the magnetic field intensity.

The results obtained were in good agreement with the hypothesis that a characteristic feature of the hopping conductance of the investigated channels is the scattering of tunneling electrons by impurities. This situation had been investigated by Nguyen, Spivak, and Shklovskiĭ[17–20] in the specific case of variable-range hopping (VRH). They developed a fluctuation model of a hopping negative magnetoresistance[18] and predicted mesoscopic oscillations of the conductance for one jump due to a change in the magnetic field.[20]

The interpretation of the observed oscillations of $G(H)$ which we proposed is as follows: a reduction in the number of electrons modifies macroscopic conduction with a negative magnetoresistance to the mesoscopic regime when the process of conduction in a system is governed by a small number of jumps for which the conductance oscillates in a magnetic field. Oscillations of $G(H)$ confirm the validity of the fluctuation model[18] in the interpretation of the observed hopping negative magnetoresistance.

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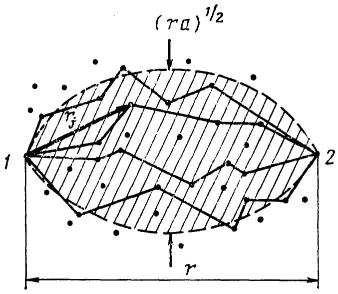

FIG. 1. Cigar-shaped region of the paths of an electron tunneling between states 1 and 2. The points represent the positions of impurities.

1. PHYSICAL DESCRIPTION OF HOPPING CONDUCTION WITH SCATTERING BY IMPURITIES

Following Refs. 17–20, we shall consider the tunneling of an electron in field of scattering impurities between two localized states 1 and 2 separated by a distance r (Fig. 1). The electron hopping conductivity σ is proportional to $|J|^2$, where J is the amplitude of the probability of tunneling from the point 1 to the point 2, which is the sum of the amplitudes of the probabilities J_i over all possible paths: $J=\Sigma J_i$. A characteristic region where the paths with nonexponentially small values of J_i are located has the shape of a cigar of length r and of transverse size $(ra)^{1/2}$, where a is the radius of localization of the wave function.

An impurity located at a point r_j is characterized by a scattering amplitude $\mu_j=\varepsilon_j/(\varepsilon_j-\varepsilon)$, where ε is the energy of the incident electron and ε_j is the energy of an impurity. The scattered electron wave ψ is related to the incident wave $\psi_{\rm inc}$ by

$$\psi(\mathbf{r})=\frac{\mu_j}{|\mathbf{r}-\mathbf{r}_j|}\,\psi_{\rm inc}\exp\left(-\frac{|\mathbf{r}-\mathbf{r}_j|}{a}\right).$$

It was shown in Ref. 18 that in the presence of a small number of scatterers with a negative amplitude the value of J has a randomly varying sign (this is known as the variable-sign regime in which the probabilities of positive and negative values of J are equal).

In a magnetic field the probability amplitudes J_i have additional factors $\exp(i\cdot 2\pi\Phi_i/\Phi_0)$, where $\Phi_0=ch/e$ is a magnetic flux quantum and Φ_i is the magnetic flux via an area bounded by the ith path and by a straight line joining the points 1 and 2. When the flux Φ_i becomes of the order of $\Phi_0/2$, the sign of J_i is reversed. When the magnetic flux through the cigar area becomes equal to Φ_0, the signs of the bulk of the terms in the sum $J=\Sigma J_i$ change. This is accompanied by a significant (by an order of magnitude) change in the sum in a random direction. Therefore, the resistance associated with one jump oscillates in a magnetic field with a characteristic "period"

$$\Delta H_c=2\cdot 2\pi\hbar c/er^{3/2}a^{1/2}. \tag{1}$$

It should be stressed that there is no rigorous periodicity of the oscillations: the quantity ΔH_c is the scale of the field ΔH in which the correlation function falls:

$$\langle G(H+\Delta H)G(H)\rangle-\langle G(H)\rangle\langle G(H+\Delta H)\rangle$$

(the angular brackets denote averaging with respect to H). However, periodic oscillations of the conductivity in a magnetic field (Aharonov–Bohm effect) should appear if all the electron paths surround the same area, as is true of a sample which is not singly connected and represents a conducting ring. (The Aharonov–Bohm oscillations for the hopping conduction in the VRH range were predicted in Ref. 19 and have been observed experimentally in PbTe films.[21])

We shall discuss the conditions in a sample with dimensions considerably greater than the average length of a jump (macroscopic conduction). The conductivity of such a sample can be described in terms of a network of random Miller–Abrahams resistances, where each element represents the conductivity of an electron jump σ_{ij} between a pair of localized states separated by a distance r_{ij} and by an energy gap E_{ij} (Ref. 22):

$$\sigma_{ij}\propto\exp[-(2r_{ij}/a+E_{ij}/kT)].$$

The total conductance G of such a network, which forms an infinite cluster, is governed by the average value of the random quantities $\sigma_0=\langle\sigma_{ij}\rangle$ and by their scatter $\delta=\langle(\sigma_{ij}-\sigma_0)^2\rangle$; an increase in δ reduces the conductance of the network. This is due to the fact that an increase of the scatter of σ_{ij} in a Miller–Abrahams network increases the proportion of high-resistance elements, which block some of the links in the network and reduce the total conductance.

In the theory of a fluctuation negative magnetoresistance[18] it was shown that in the case of variable-sign VRH conductance the application of a magnetic field reduces the dispersion δ of the hopping conductivities, but the average value of σ_0 is unaffected. This increases $\overline{G}$ in a magnetic field, i.e., it gives rise to a negative magnetoresistance. According to the model of Ref. 18, the fluctuation negative magnetoresistance has the following characteristic features: a) it varies linearly in weak magnetic fields; b) it reaches saturation as H increases; c) its value is large ($\approx$30–50% in the saturation region). In strong magnetic fields we can expect the magnetoresistance to become positive and the physical reason for this is the compression of the wave functions at right-angles to the magnetic field.[23]

2. EXPERIMENTAL METHODS AND RESULTS

a) Properties of samples

A field-effect transistor was made by forming an epitaxial structure on a conducting n^+-type GaAs substrate, a $GaAl_{0.2}As_{0.8}$ layer of thickness $d\approx 0.3\ \mu$m and a layer of n-type GaAs with $d\approx 0.2\ \mu$m and a Ge donor concentration $N_d\approx(1\text{–}2)\times 10^{17}$ cm^{-3} (Fig. 2). This structure was grown by the method of vapor phase epitaxy from metallorganic compounds; the GaAlAs layer was a semiinsulator with $\rho\approx 10^{11}\ \Omega\cdot$cm at $T=4.2$ K and it was separated from the n-type GaAs layer by a buffer of undoped GaAs ($N_d\approx 10^{15}$ cm^{-3}, $d\approx 0.5\ \mu$m). Two ohmic (Au–Ge) contacts (source and drain) were formed on the surface of the epitaxial GaAs layer and the distance between these contacts was $L\approx 14\ \mu$m. The width of the contacts ($w=200\ \mu$m) determined the width of the conducting channel. A Schottky gate (Al film) of length $l\approx 1.5\text{–}2\ \mu$m was deposited between the ohmic contacts.

The conducting channel of the transistor was located in the n-type GaAs layer and was confined across its thickness by two depletion layers: one of these was a space charge region under the Schottky gate and the other was a depletion

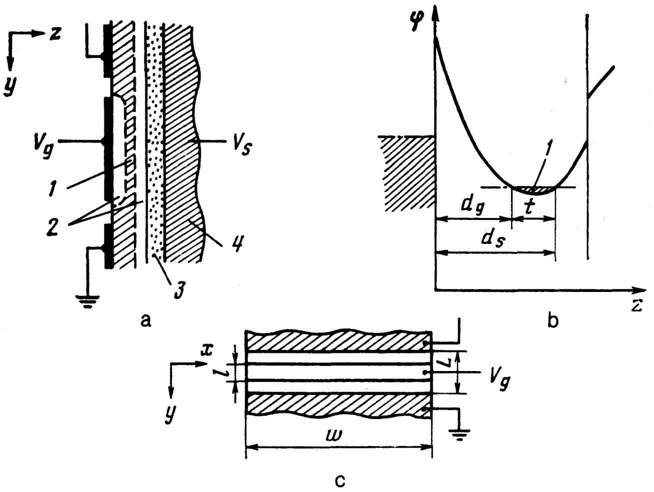

FIG. 2. a) Section through a structure: 1) conducting channel in GaAs; 2) depletion regions; 3) semiinsulating GaAlAs layer; 4) conducting substrate. b) Energy diagram of the channel. c) View of the structure from above.

layer near the GaAs–GaAlAs interface (Fig. 2). An increase of the Schottky gate (or substrate) potential which was negative relative to the drain increased the thickness of the corresponding depletion layer and reduced the channel thickness. A special feature of the investigated structures, which distinguished them from those investigated earlier,[14,15] was the presence of a thin semiinsulating GaAlAs layer, which provided means for effective control of the channel conductance by varying the gate potential or the substrate potential V_s. This double control made it possible also to shift the channel with depth in the GaAs layer without altering its thickness.

The channel parameters were determined by recording the dependence of the differential gate–source (or gate–drain) capacitance C (governed by the capacitance of the depleted Schottky layer) on the gate voltage in the frequency range $\omega/2\pi = 1$–100 kHz at temperatures $T = 4.2$ and 78 K. An analysis of the $C(V_g)$ capacitance-voltage characteristics by the standard procedure[24] made it possible to calculate a dopant profile in the n-type GaAs layer and also to determine the distance from the gate to the boundaries of the depletion regions (d_g, d_s) and the thickness of the conducting channel $t = d_s - d_g$. The values of d_g and d_s obtained for given values of V_g and V_s were estimated from the relationship describing the thickness of the Schottky layer[24]

$$d(V_g) = \varepsilon S / 4\pi C(V_g), \tag{2}$$

where $\varepsilon = 12.5$ and S is the gate area. We found the value of $d_s(V_s)$ by substituting in Eq. (2) the Schottky layer capacitance at a threshold gate voltage V_T which reduced the gate–source capacitance to zero (it was assumed that this complete depletion of the channel corresponded to coincidence of the boundaries of the two depletion regions in Fig. 2). The Schottky layer capacitance under the voltage V_T was found by extrapolation to V_T of the $C(V_g)$ curve in that range of voltages where the measured gate–source capacitance was governed by the Schottky layer capacitance. The error in the determination of the channel thickness by this method was governed by the error in the calculation of d_s and it amounted to ~ 100 Å.

The transistor channel conductance was measured at frequencies $\omega/2\pi = 5$–200 Hz using the lock-in detection method. The measured source–drain resistance R_{sd} included a contribution of the region under the gate and also the resistance of the source–gate and gate–drain regions. When the thickness t of the conducting channel under the gate was small, the total resistance was governed by the high-resistance region under the gate and the length of this region was determined by the gate length. We investigated in greatest detail this particular case and the channel conductance G was regarded as the conductance of the region under the gate. In the range of low gate voltages V_g, when the resistances of the three channel regions were comparable, the conductance of the region under the gate was calculated from the geometric relationships between the various regions.

b) Temperature dependence of the channel conductance and oscillatory dependence $G(V_g)$

Figure 3 shows a characteristic series of the temperature dependences log $G_\square(1/T)$ obtained for different voltages applied to the transistor gate. In the range of low values of $|V_g|$ (when the channel thickness was large) a weak temperature dependence of the conductance could be described by a theory of quantum corrections to the conductance of slightly disordered metal systems.[25–27] The metallic nature of the channel conductance in this range of gate voltages V_g was due to a strong overlap of the wave functions of electrons at neighboring donors: the critical concentration N_d deduced from the Mott criterion $N_d a^3 \approx 0.02$ was 3×10^{16} cm^{-3} for GaAs (when the Bohr radius in GaAs was of the order of 100 Å). An increase in $|V_g|$ enhanced the temperature dependence of the conductance and in the range $G_\square < G_{\min}$ it became exponential ($G_{\min}$ is the minimum Mott metallic conductance amounting to $3\times10^{-5}\ \Omega^{-1}$).

A reduction in the conductance on increase in $|V_g|$ in the metallic region was governed by a reduction in the thickness of the channel t for a constant bulk density of electrons, equal to the donor concentration. When the value $G_\square \sim 10^{-6}$ Ω^{-1} was reached, a steep fall of the channel conductance was observed on increase in $|V_g|$ and this was due to depression of the Fermi level and localization of electrons in a fluctuation potential. It was confirmed by a reduction (by several orders of magnitude) of the effective mobility of electrons μ^*, which was estimated from the formula

$$\mu^*(V_g) = l^2 G(V_g)/N(V_g), \tag{3}$$

where l is the channel length and N is the total number of electrons in the channel. The quantity $N(V_g)$ was calculated from

$$N(V_g) = -\int_{V_T}^{V_g} e^{-1} C(V_g)\, dV_g,$$

using the circumstance that the measured gate–source capacitance $C(V_g)$ was equal to edN/dV_g.

In this range of V_g, where the drop of μ^* began, the dependence $G(V_g)$ exhibited certain features which initially were in the form of inflections (manifested as oscillations in the dependence of dG/dV_g on V_g), but on increase in $|V_g|$ became clear oscillations whose order of magnitude was the same as that of the conductance. Estimates obtained of the

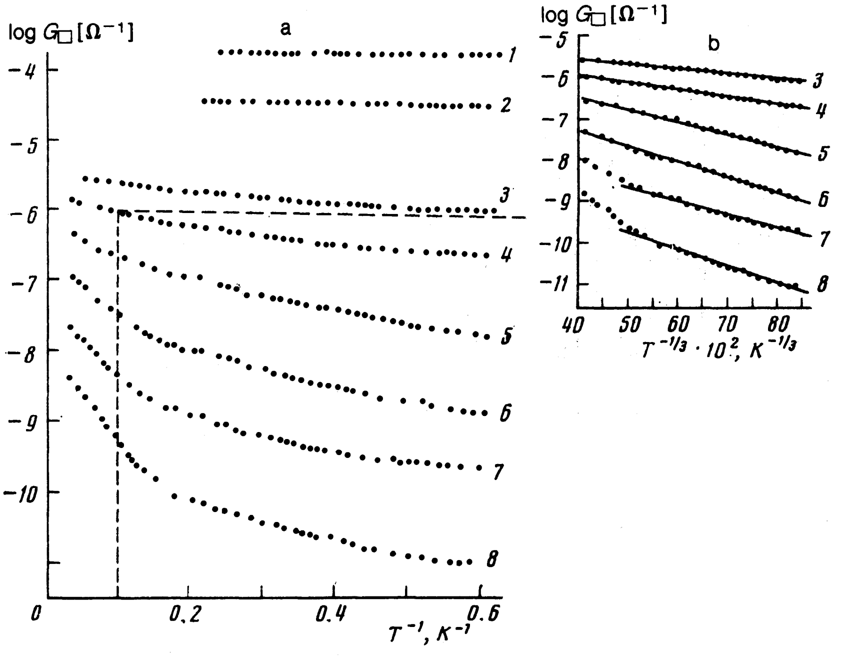

FIG. 3. a) Temperature dependences of the channel conductance (sample H1, $N_d = 1.0 \times 10^{17}$ cm^{-3}) obtained for different values of the gate voltage $- V_g$ (V): 1) 0; 2) 1; 3) 1.95; 4) 2.04; 5) 2.17; 6) 2.27; 7) 2.34; 8) 2.395. b) Curves 3–5 replotted using the coordinates log G and $T^{-1/3}$.

channel thickness and of the number of electrons at inflections and oscillations of the dependences $G(V_g)$ yielded the values $t < 300$ Å and $N_\square < 2 \times 10^{11}$ cm^{-2}.

We shall now list the main features of the observed behavior. The amplitude of the $G(V_g)$ oscillations increased on increase in $|V_g|$ (or on reduction in $N_\square$). The conductance oscillations did not have a clear period along the V_g scale, but one could identify a characteristic "period" of their repetition: $\Delta V_g \approx 20$–30 mV. The $G(V_g)$ oscillations were damped by an increase in temperature above 15 K. Cooling increased the oscillation amplitude and the $G(V_g)$ curves revealed new oscillations and this reduced the characteristic period ΔV_g (Fig. 4). It should be pointed out that oscillatory dependences of the conductance were also observed when the substrate voltage V_s was varied and the gate voltage V_g was kept fixed. The characteristic period of ΔV_s was several times greater than ΔV_g, which could be attributed to the lower rate of shift of the Fermi level in this case because of the lower substrate–channel capacitance.

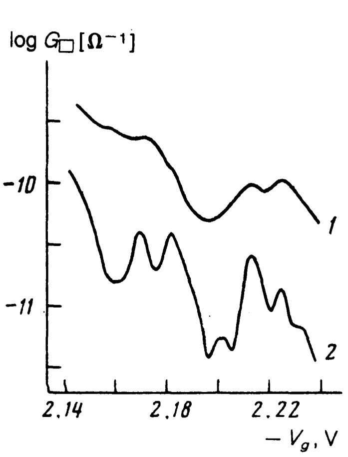

FIG. 4. Oscillations of the conductance (sample H4, $N_d = 1.1 \times 10^{17}$ cm^{-3}) observed at two different temperatures: 1) 4.2; 2) 1.5 K.

It should be noted that the voltage-capacitance characteristic $C(V_g)$ was smooth in the region of oscillations of $G(V_g)$. Hence, we concluded that it was the effective mobility of electrons and not their density which was oscillating.[16] An important feature of the observed effect was that the oscillations appeared only in channels with a short gate: when the gate length was $\approx 20\,\mu$m, the oscillation amplitude decreased strongly and there were no oscillations when the gate was $\approx 200\,\mu$m long.

The conditions under which the oscillations were observed (low temperatures and low channel conductances) are identified formally by dashed lines in Fig. 3. The temperature dependence of the conductance in the range $1.5 < T < 10$ K could not be described by a single activation energy, but the curves were readily rectified by plotting dependences $\log G(T_0/T)^\alpha$ with $\alpha = 1/3$ or $1/4$ (in this range of temperatures it was not possible to decide reliably between these two values of α). In the $\alpha = 1/3$ case the parameter T_0 was 500–1500 K in the range $G_\square \sim 10^{-9}\,\Omega^{-1}$. [Under these conditions we found that $\xi = (T_0/T)^{1/3} = 5$–6 at $T = 4.2$ K.]

The conductance at the boundary between the regions of weak ($\Delta G/G < 0.1$) and strong ($\Delta G/G \gtrsim 1$) oscillations was different for different samples. Typically, this boundary conductance was $G_\square \sim 10^{-9}\,\Omega^{-1}$. In the region of weak oscillations the slope of the log $G(1/T)$ curves rose monotonically on increase in $|V_g|$, whereas in the case of strong oscillations it fluctuated as a function of V_g (Fig. 3). Fluctuations of the change in G with temperature in the region of strong oscillations were observed clearly for sample H4 (Fig. 4). In particular, the temperature dependence of the conductance at the minima was stronger than at the maxima.

c) Magnetoresistance of the transistor channel

The channel magnetoresistance in weak fields was negative throughout the investigated range of the gate voltages V_g. The negative magnetoresistance of thick channels (me-

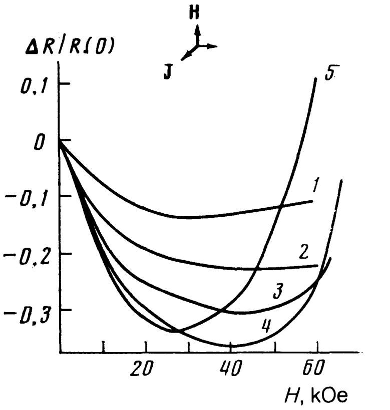

FIG. 5. Transverse magnetoresistance of a channel of sample H6 with $N_d = 1.8\times10^{17}$ cm^{-3} at $T = 4.2$ K recorded for different values of V_g and $R_\square$ ($H=0$): 1) 2.24 V, 160 kΩ; 2) 2.38 V, 270 kΩ; 3) 2.57 V, 1.7 MΩ; 4) 2.59 V, 2.7 MΩ; 5) 2.70 V, 28 MΩ.

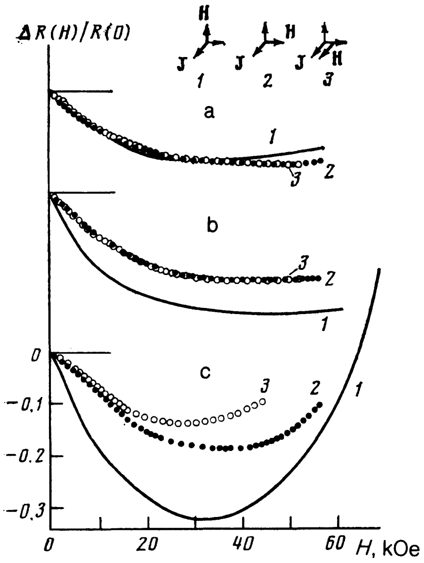

FIG. 6. Channel magnetoresistance (of sample H6) obtained for three orientations of the magnetic field: the continuous curves correspond to $H_\perp$; the black dots (●) correspond to $H_{\perp\parallel}$, and the open circles (○) correspond to $H_\parallel$. The curves were obtained for different values of V_g and $R_\square$ ($H=0$): a) 2.24 V, 160 kΩ; b) 2.38 V, 270 kΩ; c) 2.61 V, 7.0 MΩ (the curves are shifted along the y axis).

tallic range) was interpreted in Refs. 25–27 on the basis of a theory of weak electron localization. We investigated the magnetoresistance channels of thickness $t < 300$ Å, in which the effective mobility μ^* decreased on increase in $|V_g|$ and there were oscillations in the dependences $G(V_g)$. Measurements were carried out for three directions of the magnetic field relative to the normal to the surface of the structure **n** and the measuring current **J**:$\mathbf{H}\perp\mathbf{n}(H_\perp)$; $\mathbf{H}\parallel\mathbf{n},\mathbf{H}\perp\mathbf{J}(H_{\perp\parallel})$; $\mathbf{H}\parallel\mathbf{J}(H_\parallel)$. Figure 5 shows an example of the magnetoresistance curves $\Delta R(H)/R(0)$ obtained for different values of V_g in the range where the amplitude of the $G(V_g)$ oscillations was small. The magnetoresistance became more negative with increasing V_g (reduction in the number of electrons N) and, having reached 30–40%, it ceased to change as a function of V_g [The characteristic property of the channel in the region of weak oscillations was its resistance R at $H=0$ and not the quantity V_g, because the range of V_g was related directly to the position of the right-hand wall of the channel (Fig. 2), i.e., it depended on V_s and on the built-in charge in the semiinsulating layer.]

The channel magnetoresistance depended on the angle between the vector **H** and the normal to the surface **n**: an increase in $|V_g|$ increased the difference in the magnetoresistance for the $H_\perp$ and $H_{\perp\parallel}$ orientations (so that the magnetoresistance became two-dimensional), as shown in Fig. 6. It is clear from this figure that at high channel resistances there was also a difference between the negative magnetoresistance for different orientations of **H** relative to the direction of the current in the plane of the sample ($H_\parallel$ and $H_\perp$). (For some samples the anisotropy of the negative magnetoresistance for $H_\parallel$ and $H_{\perp\parallel}$ was manifested in a wide range of the channel resistances.)

The smooth dependence of the channel conductance on the magnetic field was obtained in the range of voltages where $G(V_g)$ exhibited inflections or small oscillations. However, in the range of high values of $|V_g|$, where the amplitude of the $G(V_g)$ oscillations was of the order of G itself, the channel magnetoresistance changed radically: an oscillatory dependence of the conductance on the magnetic field was observed. The dependence $G(V_g)$ shown in Fig. 7 gives the values of the gate voltages at which the channel magnetoresistance was measured (Fig. 8). In the region of weak oscillations (point 1) the negative magnetoresistance was smooth. At points 2–7 the magnetoresistance exhibited oscillations and the nature of the curves changed considerably as a result of a change in V_g by an amount equal to the characteristic period of the conductance oscillations on the gate voltage scale.

It should be pointed out that neither the smooth magnetoresistance curves nor the oscillatory dependence $G(H)$ was affected by a reversal of the direction of the field **H**: $G(H) = G(-H)$.

No magnetoresistance oscillations were observed when the magnetic field was oriented in the plane of the sample: the negative magnetoresistance then varied smoothly over the full range of V_g. However, in the region of strong oscillations $G(V_g)$ the negative magnetoresistance observed in the $H_{\perp\parallel}$ orientation exhibited nonmonotonic changes of the

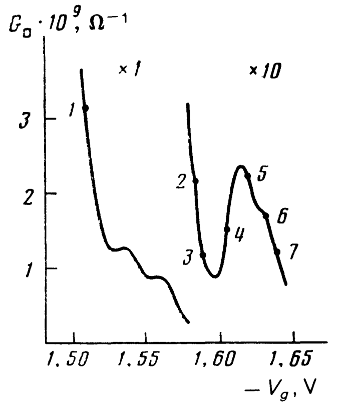

FIG. 7. Oscillatory dependence $G(V_g)$ obtained for the channel in the transistor sample H4. The points are the values of $G(H=0)$ at which the channel magnetoresistance plotted in Fig. 8 was measured; $T = 4.2$ K.

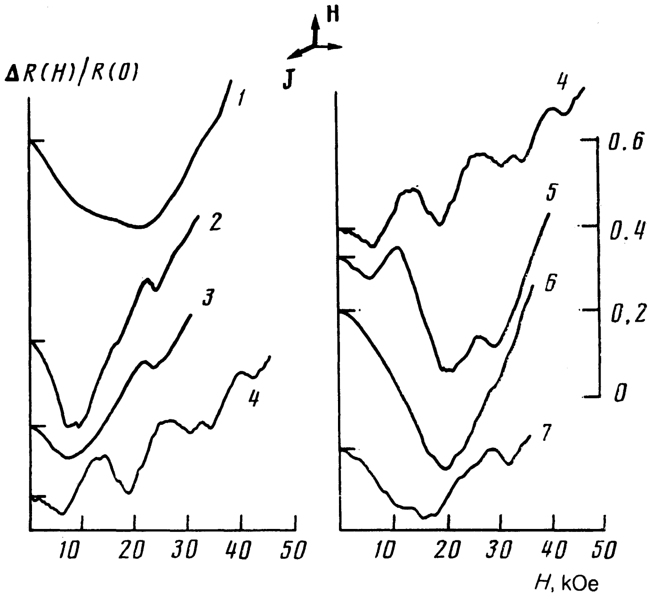

FIG. 8. Oscillatory dependence of the magnetoresistance $\Delta R(H_\perp)$ obtained for different channel resistances identified by numbers in Fig. 7 (the curves are shifted along the y axis).

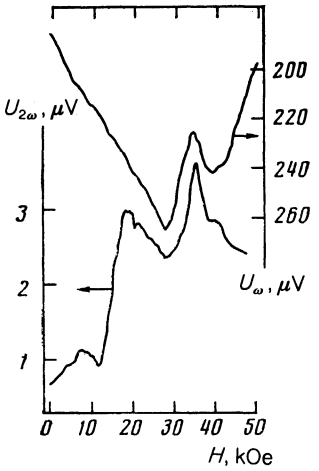

FIG. 10. Oscillatory magnetic-field dependence of the signals of the first (U_ω) and second ($U_{2\omega}$) harmonics ($\omega/2\pi = 13.4$ Hz) obtained using an oscillator subjected to a voltage $E_{osc} = 0.9$ mV; the voltages U_ω and $U_{2\omega}$ were recorded using a load resistance $R_L = 820$ kΩ connected in series with sample H4.

magnetoresistance itself and of dR/dH when the gate voltage was varied (Fig. 9a). In Fig. 9b we identified the values of V_g at which the magnetoresistance $\Delta R(H_{\perp\parallel})/R(0)$ was measured.

d) Oscillations of the second harmonic signal

We established that in the circuit of a sample with a thin channel the signal J_ω proportional to the channel conductance was accompanied by a constant current J_0 and a signal at twice the frequency $J_{2\omega}$, which oscillated in phase when V_g was varied.[13] The characteristic period of $J_{2\omega}(V_g)$ oscillations was close in magnitude to the period of the $J_\omega(V_g)$ oscillations, but the J_ω and $J_{2\omega}$ oscillations were not completely in phase.

A similar situation was observed in the case of oscillations of the signal $J_{2\omega}$ considered as a function of the transverse magnetic field. Figure 10 shows the dependence of the amplitude of the second harmonic on the magnetic field intensity alongside the conductance oscillations. The oscillations of $J_{2\omega}$ usually appeared more prominently.

In addition to samples with a donor concentration $N_d \sim 10^{17}$ cm^{-3}, we also investigated transistors with a lower dopant concentration: $N_d < 4\times10^{16}$ cm^{-3}. The results obtained for the latter samples were qualitatively similar to those obtained for the samples with the higher impurity concentration. The distinguishing feature of the lightly doped samples was a larger amplitude of the $G(V_g)$ oscillations. Figure 11 shows an example of the dependences $G(V_g)$ and $U_{2\omega}(V_g)$ obtained for a lightly doped sample. Figure 12a shows the damping of the $G(V_g)$ oscillations exhibited by a lightly doped sample on increase in temperature; Fig. 12b shows the magnetoresistance curves obtained at various

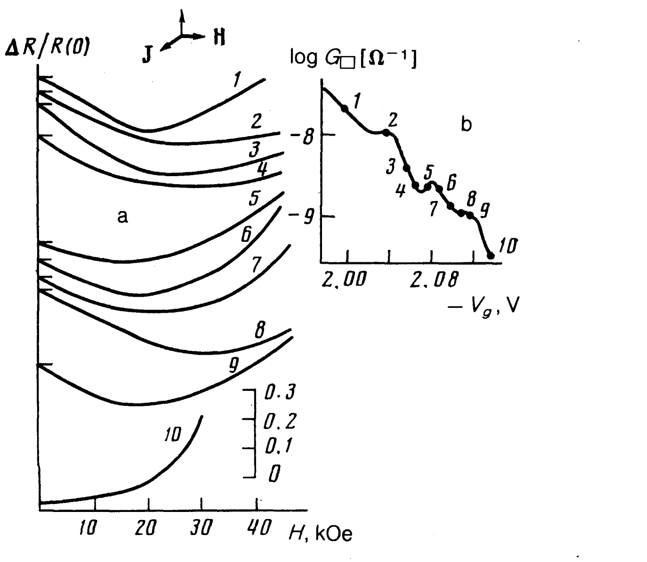

FIG. 9. a) Nonmonotonic variation of the channel magnetoresistance $\Delta R(H_{\perp\parallel})$ on increase in the gate voltage (sample H4); the curves are shifted along the y axis. b) Values of the channel conductance $G(V_g)$ at $H = 0$ are given under the relevant numbers which label the curves in Fig. 9a.

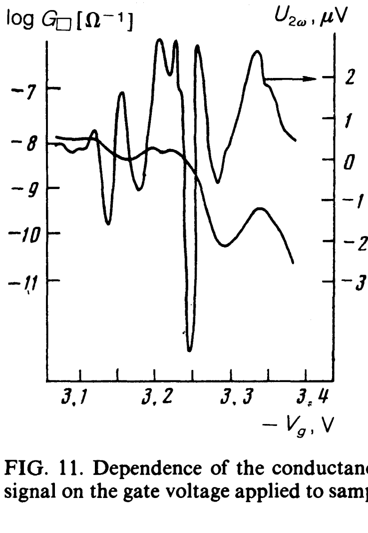

FIG. 11. Dependence of the conductance and of the second-harmonic signal on the gate voltage applied to sample PN6 ($N_d \approx 3\times10^{16}$ cm^{-3}).

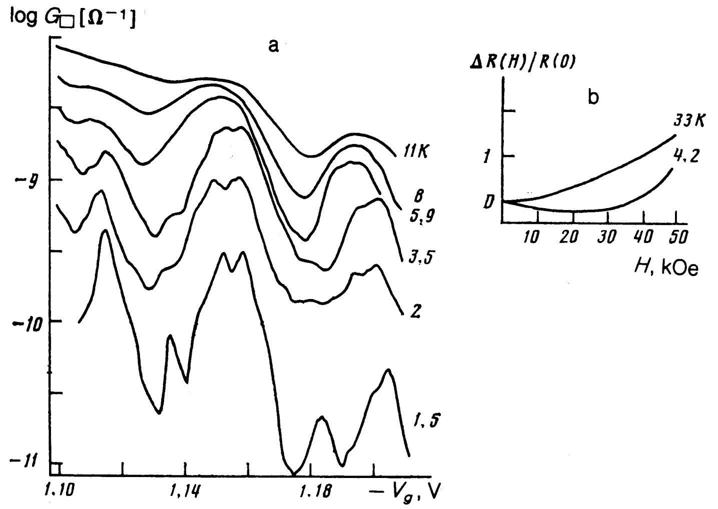

FIG. 12. a) Oscillations of $G(V_g)$ for sample DL1 obtained at different temperatures. b) Transverse magnetoresistance of sample PN3 with $R_{\square}^{4.2}(H=0) = 465$ kΩ.

temperatures and demonstrating the characteristic disappearance of the negative magnetoresistance with increasing temperature, which was exhibited by all the investigated samples.

3. DISCUSSION OF RESULTS

The temperature dependence of the conductance (Fig. 3) allows us to assume that a reduction in the channel thickness lowers the Fermi level in the region of localized states and that oscillations of $G(V_g)$ and $G(H)$ correspond to the insulating conduction regime. The temperature dependence is similar to the results obtained in a study of a metal–insulator transition on increase in the degree of compensation.[28] This is not surprising because the investigated system is characterized by an increase in the effective degree of compensation $1 - N/N_d S_d t$ (S_g is the gate area) as a result of depletion of the conducting channel. We can assume that at temperatures $T > 30$ K the main conduction mechanism is the activation at the mobility edge, whereas on lowering of the temperature T (i.e., in the oscillation region) the tunneling of electrons (hopping between localized states) becomes preferable.

In the analysis of our results we shall divide arbitrarily the whole range of the gate voltages where inflections or oscillations of $G(V_g)$ are observed into two regions: 1) region of inflections and weak oscillations ($\Delta G/G < 0.1$); 2) region of strong oscillations ($\Delta G/G \sim 1$). We shall assume that in the former case the properties of the samples are close to macroscopic, whereas the second region corresponds to the mesoscopic conduction regime.

a) Macroscopic conduction regime

It is shown above that the temperature dependence of the conductance observed in the region of weak oscillations is that expected for VRH in the two-dimensional case. We can use $\xi = 6$ to estimate the length of an electron jump: $r = a\xi = 600$ Å for $a = a_B = 100$ Å. An estimate of the channel thickness in the oscillation region gives $t = 170$–300 Å (the lower limit is the average distance between the donors $N_d^{-1/3}$ when $N_d = 2\times 10^{17}$ cm^{-3}). This estimate confirms the two-dimensional nature of the conduction process: $t < r$.

The transverse magnetoresistance and its contribution in weak fields (Fig. 5) are in agreement with the fluctuation model of the negative magnetoresistance in the VRH conduction case.[18] The difference between the magnetoresistances obtained for the $H_\perp$ and $H_{\perp\parallel}$ orientations (when the vector **H** is perpendicular to the plane of the sample and when **H** is in the plane of the sample—see Fig. 6) can also be explained on the basis of this model. The magnetoresistance observed in weak fields is governed by the area S of the cross section of the cigar-shaped region (Fig. 1) in a plane perpendicular to the vector **H**. In fields $H_c \sim \Phi_0/S$ the magnetoresistance saturates at a value $\Delta R(H)/R(0) \sim 50\%$. In the $H_\perp$ orientation we have $S_\perp \approx r(ra)^{1/2}$, whereas for $H_{\perp\parallel}$ the transverse size of the cigar is truncated by the thickness t of the conducting channel: $S_{\perp\parallel} \approx rt$. An estimate of the cigar diameter gives $(ra)^{1/2} \approx 250$ Å, which is of the order of the channel thickness. It therefore follows that the zone of the tunneling electron paths "senses" the boundaries of the channel and the magnetoresistance anisotropy should be observed experimentally.

According to this model, the negative magnetoresistance should reach saturation in fields $H_c \sim \Phi_0/S$. The experimental magnetoresistance curves show no saturation region: in high fields the negative magnetoresistance changes to positive, due to compression of the electron wave functions. If we assume that H_c is the field at the magnetoresistance minimum ($H_c \approx 30$ kOe), we can estimate the upper limit to the area of the cross section of the cigar in the range of voltages V_g under consideration: $S \leqslant 14\times 10^{-12}$ cm^2. An estimate of the value $r(ra)^{1/2}$ deduced from the temperature dependence of the conductance allowing for the jump length gives a similar value of the area of the cross section: 14.6×10^{-12} cm^2.

The magnetoresistance anisotropy for the $H_{\perp\parallel}$ and $H_\parallel$ directions may be related, in accordance with the theoretical model, to the difference between the areas of the corresponding cross sections $S_\parallel = ra$ for the field $H_\parallel$, parallel to the current and $S_{\perp\parallel} = r(ra)^{1/2}$ for the field $H_\perp$ in the plane of the sample perpendicular to the current [if we allow for the thickness of the layer, we have $S_\parallel = t(ra)^{1/2}$ and $S_{\perp\parallel} = tr$]. An estimate of the ratio of the areas $S_{\perp\parallel}/S_\parallel \approx 2.5$ leads to a prediction of a strong anisotropy, which is not confirmed by the experimental results (Fig. 6). This may be due to the fact that this estimate is based on the assumption that conduction occurs along a rectilinear chain of jumps, whereas in fact the current paths in a Miller–Abrahams network are complex (and this in particular is the reason for the anisotropy of the positive hopping magnetoresistance[22]). It should be pointed out that on approach to the mesoscopic regime the negative magnetoresistance becomes anisotropic for these two directions of the field, which provides evidence of rectification of the current paths.

b) Mesoscopic regime

In this range of voltages V_g the amplitude of the $G(V_g)$ oscillations is of the order of conductance itself. The proposed explanation of the oscillations is as follows. When the electron density decreases (i.e., when the Fermi level drops), the average value of the resistances in a Miller–Abrahams network increases and so does the characteristic length of a jump (because of an increase in the parameter ξ, which governs the VRH conduction process). Under these experimental conditions the conductance of a small sample is determined by a small number of hopping contributions to the conductance. When the Fermi level is depressed, changes in the jumps give rise to large oscillations of the conductance because of the exponentially large scattered resistances associated with the individual jumps.

The jump resistances may change as follows: the position of the channel shifts with depth in the epitaxial layer to a region with a different fluctuation potential when V_g changed. This effect has been observed in the case of simultaneous changes in the gate and substrate voltages.[16] In our case we have $V_s = \text{const}$ and the shift of the channel can be ignored when the characteristic oscillation period is $\Delta V_g \approx 20$ meV; it therefore follows that oscillations of the conductance $G(V_g)$ are due to the shift of the Fermi level.

Generation of the second harmonic signal is direct evidence of the mesoscopic nature of the samples (of the asymmetry of their current-voltage characteristics). The different positions of the extrema in the functions $J_{2\omega}(V_g)$ and $J_\omega(V_g)$ indicate that hopping conduction involves not one but several successive jumps. The $J_{2\omega}$ signal proportional to d^2J/dV^2 is determined by the nonlinearity of the current-voltage characteristics (and can therefore change its sign). The fact that the $J_\omega(V_g)$ and $J_{2\omega}(V_g)$ oscillations are not completely in phase for a system of several jumps reflects the fact that changes in the curvature of the resultant current-voltage characteristic and in its linear part do not occur simultaneously. In a system with one jump the "switching" of the jump would imply a transition to a different current-voltage characteristic, i.e., the linear part of the characteristic and its curvature should change simultaneously.

We now face the following question: how can the conductance of a sample of 2×200 μm dimensions be determined by a small number of jumps? For the sake of an estimate we shall assume that a jump length is 1000 Å ($r\approx600$ Å is obtained for the range of V_g preceding oscillations), which shows that 4×10^4 jumps occur in the area of the sample (20 jumps along the length and 2000 along the width). In the case of such a large number of hopping resistances the conductance oscillations of the sample should be completely averaged out. However, we must bear in mind that because of the exponentially large scatter of the hopping resistances, not all possible jumps participate in the conduction process. The current flows along the optimal paths characterized by the lowest resistances. In the case of a sufficiently short sample the optimal current paths represent rectilinear chains of jumps and the number of such chains in a sample is close to unity.[29,30] The magnetoresistance anisotropy observed for the $H_{\perp\parallel}$ and $H_\parallel$ orientations demonstrates the rectilinearity of the current paths and allows us to assume that the process of conduction in the investigated samples involves only a small number of chains connected in parallel. The conductance of each chain, each amounting to about 20 jumps, is governed by one (largest) hopping resistance. (A similar situation was considered in Ref. 31 using a one-dimensional model of VRH jumps and the results indicated that strong oscillations of the chain conductance should occur when V_g is varied.)

In the mesoscopic regime the transverse channel magnetoresistance oscillates with a period of 15–20 kOe. This is in agreement with the period of the conductance oscillations for one jump in a magnetic field given by Eq. (1): $\Delta H = 10$ kOe for $r = 600$ Å and $a = 100$ Å. The absence of $G(H)$ oscillation when the vector **H** is in the plane of the sample can be explained (like the anisotropy of the negative magnetoresistance in the macroscopic regime) by a reduction in the cross-sectional area of the cigar-shaped region and, consequently, by an increase in the oscillation period described by Eq. (1). The conductance oscillations with a period exceeding the investigated range of fields may be manifested experimentally as fluctuations of the quantity dR/dH when V_g is varied, as confirmed by the results in Fig. 9.

CONCLUSIONS

We concluded above that the negative magnetoresistance and the oscillations of the conductance in a magnetic field exhibited by a GaAs field-effect transistor are both manifestations of the same effect, which is the scattering of electrons by impurities, in two different hopping conduction regimes: macroscopic and mesoscopic. An analysis of the temperature dependences of the channel conductance and magnetoresitance demonstrated that the model of VRH with scattering is appropriate.[18,19]

However, it should be pointed out that similar effects may be exhibited by the magnetoresistance also in the case of a different hopping conduction mechanism involving tunneling electrons between neighboring wells in a large-scale fluctuation potential and scattering by impurities inside the potential humps. An increase in the jump length on increase in the gate voltage and the transition to the mesoscopic regime can then be explained by an increase in the spatial scale of the potential on reduction in the electron density in the channel. Additional experiments will be needed before these two mechanisms can be distinguished in detail.

The validity of the model of the fluctuation negative magnetoresistance in the hopping conduction region shows that the negative magnetoresistance of n-type channels in GaAs is of the same physical origin on both sides of the metal–insulator transition. In spite of the fact that electrons move in a metal in a diffuse manner, whereas in an insulator they tunnel between localized states, the cause of the negative magnetoresistance in both cases is the same: interference between electrons scattered by impurities.

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