Fluctuation properties of small silicon field-effect transistors

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Investigations were made of fluctuations of the conductivity and emf which appear when small silicon metal–oxide–semiconductor field-effect transistors are subjected to microwave radiation. The fluctuations were measured as a function of an external magnetic field and a voltage applied to the gate electrode, and were attributed to mesoscopic properties of the system. The correlation characteristics of mesoscopic fluctuations were determined. Variation of the magnetic field and of the chemical potential resulted in different behavior of fluctuations, which could be due to the dependence of the scattering of electrons on their density.

1. INTRODUCTION

Investigations of small conductors have now become a major field in solid-state physics. This is primarily due to the fact that their low-temperature properties are governed by quantum interference of electron waves in spite of the fact that the scattering defect concentration can be very high. It has been shown theoretically that even when the characteristic size of a conductor L is considerably greater than the mean free path of carriers l, the conductivity is governed not only by the average concentration of the scattering centers, but also by their actual configuration. A change in the configuration of such scatterers causes fluctuations of the conductivity of a mesoscopic (small) conductor and, most important, the mean-square amplitude of fluctuations of the conductance $\langle \Delta G^2 \rangle$ is a universal quantity $\langle \Delta G^2 \rangle = (e^2/h)^2$ (Refs. 1 and 2) if $L < \min(L_\varphi, L_T)$, where L_φ is the phase coherence length; $L_T = (hD/kT)^{1/2}$; D is the diffusion coefficient. Moreover, it is known that the conductivity of a mesoscopic conductor should fluctuate in the same way as a function of an external magnetic field and also due to variation of the Fermi energy.[1–5]

Experimental investigations of mesoscopic properties of small samples are being pursued sufficiently thoroughly. Universal fluctuations of the conductance have been observed in metallic films and wires,[6,7] in submicron metal–oxide–semiconductor field-effect transistors (MOSFETs),[8–11] submicron structures based on AlGaAs–GaAs heterojunctions,[12,13] and thin layers of degenerate semiconductors.[14–16]

Several new effects have been predicted and confirmed experimentally for mesoscopic conductors and they include fluctuations of the current-voltage characteristic,[17,18] rectification and harmonic generation,[4,19] and the photovoltaic effect.[20,21]

Submicron silicon MOSFETs occupy a special place among the whole range of mesoscopic objects, because only they provide an opportunity to investigate fluctuation properties not only when a magnetic field is varied, but also as a function of the Fermi energy. The properties of such MOSFETs were subjected by us to a detailed investigation reported below. The whole investigation differed from earlier studies in two respects: 1) a higher quality of our samples (carrier mobility in these transistors was three times higher); 2) the mesoscopic photovoltaic effect was investigated for the first time and, moreover, the correlation characteristics of fluctuations were determined simultaneously by several methods.

2. THEORETICAL ASPECTS

In the two-dimensional case when the spin–orbit scattering can be ignored, a theory[5,22] predicts the following expression for fluctuations of the conductance of a sample:

$$\delta G=\alpha(e^2/h)(L_i/L)(W/L)^{1/2}, \quad L_i=\min(L_\varphi, L_T),$$

$$\alpha=\begin{cases} 0.86, & B<B_q, \\ 0.61, & B_q<B<B_s, \\ 0.43, & B>B_s, \end{cases} \tag{1}$$

$$B_q=chT/4De, \quad B_s=kT/g\mu,$$

where g is the electron Landé factor, μ is the Bohr magneton, and W is the width of the investigated sample. A reduction in the average amplitude of fluctuations in a magnetic field observed in the range $B > B_q$ is due to suppression of the cooperon contribution to the conductance. This means, in particular, that fluctuations have a larger amplitude when the gate voltage is varied than fluctuations due to variation of the magnetic field B and in strong magnetic fields the average amplitudes differ by a factor of 2.

In addition to the average amplitude, the conductance fluctuations can be described also by scales of the magnetic field and energies in which the conductance changes by a value of the order of e^2/h: these are known as the correlation field B_c and the correlation energy E_c. According to Ref. 5, the general expression for the correlation function of the conductance is

$$F(\Delta E, \Delta B, E, B)=\langle \delta G(E, B)\delta G(E+\Delta E, B+\Delta B)\rangle; \tag{2}$$

by definition, we have $F = 0.5$ for $B = B_c$ and $E = E_c$. The existing theories failed to give exact values of B_c and E_c. According to Ref. 5, if $L_\varphi < L$ and $L_T < L$, we have

$$B_c=\beta\Phi_0/L_i^2, \quad E_c=\pi kT \quad \text{or} \quad E_c=h/\tau_\varphi, \tag{3}$$

where Φ_0 is a flux quantum and τ_φ is the relaxation time of the electron wave function.

This property of mesoscopic conductors makes them sensitive to the actual nature of the random potential and they should exhibit effects typical of noncentrosymmetric systems, such as the photovoltaic effect. The theory predicts that exposure of a sample to an hf electric field creates a

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photocurrent which can be estimated from:[20]

$$I_{ph} \approx \begin{cases} e(\omega/\tau_f)^{1/2}(EeL/\hbar\omega)^2, & \omega\tau_f \gg 1, \\ (e\pi/\tau_f)(EeL\tau_f/\pi^2\hbar)^2, & \omega\tau_f \ll 1, \end{cases} \quad (4)$$

where $\tau_f = L^2/D$. The photocurrent has the same correlation characteristics in respect of the magnetic field and Fermi energy as the conductance. A specific feature of the photovoltaic effect is its frequency correlation. This is manifested by the fact that fluctuations of the photocurrent observed on variation of the gate voltage or of the magnetic field are different for frequencies that differ by an amount $\Delta\omega \gtrsim \pi^2/\tau_f$. Therefore, a study of the frequency correlation properties can give additional information on the value of E_c.

3. SAMPLES AND MEASUREMENT METHODS

Our samples were silicon MOSFETs with inversion layers. They were prepared by a self-registration technology. Use was made of optical lithography and of ionic etching of a polycrystalline silicon (polysilicon) gate. The polysilicon layer thickness was 600 Å and the dopant concentration in the source–drain regions was $n^+ \approx 3\times 10^{20}$ cm^{-3}. The topology of a transistor with a channel of $1.5\times 2\,\mu$ dimensions is shown in Fig. 1. The contact resistance was measured after removal of the gate electrode. It amounted to 40 Ω, which was approximately 5 times less than the channel resistance 180 Ω at its minimum (at helium temperatures). Up to 20 structures with different gate dimensions were investigated. Their parameters and dimensions are listed in Table I. The electron density n_s was deduced from the Shubnikov–de Haas (SdH) oscillations. The threshold voltage was $V_{th} \approx 0.1$ V.

All measurements were carried out at temperatures 1.4–4.2 K in magnetic fields up to 7 T. We determined the conductance, the derivative of the conductance with respect to the gate voltage, and the emf generated by exposure of transistors to microwave radiation. The conductance was measured using an active bridge in accordance with the two-point scheme. A longitudinal field between the source and sink did not exceed kT/e and no heating effects were observed. Microwave radiation of 6–15 GHz frequency was amplitude-modulated and fed by cable directly to the current contacts. Higher frequencies in the range 30–80 GHz were delivered by a waveguide with a polarizer at the end. This polarizer was set so that the electric field vector of the incident microwave radiation was directed between the source–sink contacts. The microwave field intensity was determined by comparing the change in the transistor conductance under the influence of hf and lf electric fields.[23] In all experiments the microwave field intensity did not exceed 2 V/cm.

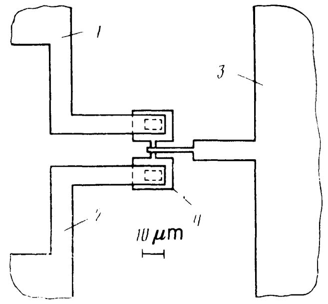

FIG. 1. Schematic diagram of a sample: *1*) drain; *2*) source; *3*) gate; *4*) heavily doped regions.

4. FLUCTUATIONS OF THE CONDUCTANCE OF METAL-OXIDE-SEMICONDUCTOR FIELD-EFFECT TRANSISTORS

Since the mesoscopic contribution to the conductance is due to interference of electron waves, any external perturbation altering the interference conditions induces fluctuations of the conductance. The interference conditions can be modified by the application of a magnetic field when the phase of the wave function can be increased additionally by varying the chemical potential which alters the electron wavelength λ. According to the ergodicity hypothesis, in such cases the conductance fluctuations are of the same magnitude as in the case when the scattering potential changes.[5] In the case of MOSFETs we can determine these fluctuations as a function of the magnetic field B and the chemical potential (gate voltage).

Figures 2a and 3a give the dependences of the conductance G of one of the transistors belonging to batch No. 2 on the magnetic field and on the gate voltage V_g. We can see that the conductance fluctuates both as a function of B and V_g. In Figs. 2b and 3b the same fluctuations are shown after subtraction of the monotonic component. Clearly, the amplitude of the conductance fluctuations $\Delta G(V_g)$ was 3–4 times greater than $\Delta G(B)$. In the range of V_g shown in Fig. 3b the fluctuation amplitude was independent of the gate voltage when the magnetic field was varied. Measurements of a negative magnetoresistance of a sample belonging to group No. 6 with 40×40 μm dimensions showed that L_φ and L_T were practically unaffected in the range $V_g > 5$ V. Hence, the difference between the amplitudes of the conductance fluctuations in Figs. 2 and 3 could not be due to the dependence of L_φ or L_T on the gate voltage in this range. We plotted in Fig. 4 the temperature dependences of the average amplitude of the conductance fluctuations $\delta G = (\langle \Delta G^2\rangle)^{1/2}$, determined from changes in the dependences $G(B)$ and $G(V_g)$ at different temperatures. Clearly, in both cases the value of δG increased approximately linearly on lowering of the temperature T, whereas the average

TABLE I. Parameters of investigated samples.

Sample group No.	L, μm	W, μm	Sample group No.	L, μm	W, μm
1	0.7	1.5	4	4	4
2	1.5	2	5	3	20
3	3	3	6	40	40

Note. The orientation of Si was (100); $N_{D,A} = 1.4\times 10^{15}$ cm^{-3}; $d = 320$ Å, $\mu_{max} = (8–9)\times 10^3$ cm$^2\cdot$V$^{-1}\cdot$s^{-1}; L is the length of the sample, W is the width of the sample, and d is the thickness of the SiO_2 layer.

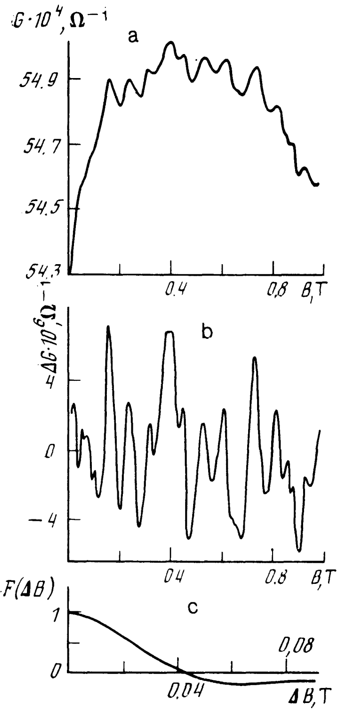

FIG. 2. a) Dependence of the conductance of a group No. 2 sample on B at $T = 1.4$ K, when $V_g = 13$ V. b) Dependence of fluctuations of the conductance on B. c) Dependence of the correlation function of the conductance on ΔB.

amplitude of the conductance fluctuations induced by the gate voltage was ~ 3 times greater than the amplitude δG of fluctuations due to the magnetic field.

We shall now consider these experimental dependences. As pointed out earlier, the fluctuations due to variation of the magnetic field and chemical potential could have different amplitudes because the magnetic field suppressed the cooperon contribution to the conductance. Determination of $\delta G(V_g)$ in different fields demonstrated that such suppression was indeed observed in magnetic fields up to 0.2 T and in this case δG decreased by a factor of 1.4. A further increase in B up to 1 T did not alter the fluctuation amplitude. Therefore, we could not attribute the difference between the fluctuation amplitudes induced by the magnetic field and by the gate voltage simply to suppression of the cooperon contribution to the conductance. Similar dependences of δG on B and V_g were reported in Ref. 11, but the similarity was not discussed at all.

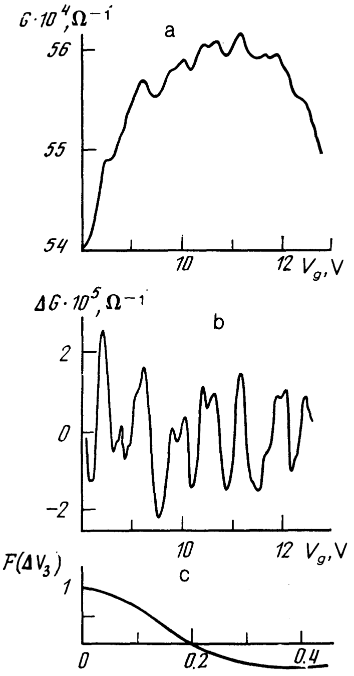

FIG. 3. a) Dependence of the conductance of a group No. 2 sample on V_g at $T = 1.4$ K, when $B = 0$. b) Dependence of fluctuations of the conductance on V_g. c) Dependence of the correlation function of the conductance on ΔV_g.

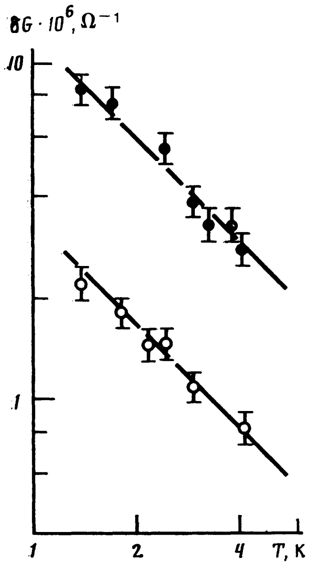

FIG. 4. ●) Average amplitude of the conductance fluctuations due to V_g plotted as a function of temperature for $B = 0$ T. ○) Average amplitude of the conductance fluctuations due to B plotted as a function of temperature when $V_g = 12$ V; group No. 2 sample.

One of the possible explanations can be the dependence of the elastic relaxation time on the density of two-dimensional electrons in a channel, which in the investigated samples could decrease on increase on n_s almost linearly in the range $V_g > 5$ V. It follows from the theory of Refs. 4 and 5 that the average amplitudes of the conductance fluctuations produced by B and V_g should be the same because of the equivalence of changes in the conditions of interference of electron waves as a result of a phase shift (advance) in the applied magnetic field and on increase in λ. The change in the relaxation time τ with the gate voltage is similar to a change due to variation in the random potential. This mechanism can increase the fluctuation amplitude considered as a function of the Fermi energy, because (like the change in the electron wavelength) it alters the interference conditions. This hypothesis can be checked by developing a theory of mesoscopic fluctuations of the conductance and considering the dependences of the scattering mechanisms on the electron energy.

The $\delta G(T)$ dependence is governed by the temperature dependence of the shorter of the lengths L_φ and L_T. The length L_φ is found from the negative magnetoresistance of macroscopic samples prepared by the same technology as the small samples. Unfortunately, it was difficult to find the temperature dependence of L_φ from the negative magnetoresistance of our samples because this magnetoresistance was not described by the theory of Ref. 24 in the range $T > 2.5$ K. This was clearly due to the fact that the intervalley relaxation time τ_v, which may determine the behavior of the negative magnetoresistance,[25] was in the case of our samples comparable with the time τ_φ at $T = 4.2$ K. The long intervalley relaxation time can be explained by an increase in the intervalley splitting, indicated by the unusual behavior of the SdH oscillations: both macroscopic and submicron samples exhibited dephasing on application of the magnetic field and gate voltage. This dephasing of the SdH oscillations in n-type inversion channels had been observed earlier in an oblique magnetic field,[26] where it was attributed to the intervalley splitting. In our case the observation of this dephasing in fields normal to the surface indicated an increase in the valley splitting. However, the reasons for this behavior were not clear and would require further investigations.

Cooling increased the relaxation time of the wave function phase and at $T = 1.7$ K the behavior of the negative magnetoresistance was described completely by the theory applicable to the $\tau_\varphi \gg \tau_v$ case. Comparison of measurements of the negative magnetoresistance of samples belonging to group No. 6 with the theory gave $L_\varphi = 0.36\ \mu$m. We found that $L_T = 0.6\ \mu$m and that the value of δG was governed primarily by the dephasing length.

According to Eq. (1), the linear $\delta G(T^{-1})$ dependence indicates that $\tau_\varphi \propto T^{-2}$. Hence, the dominant mechanism of relaxation of the phase of the electron wave function is the energy relaxation characterized by a large transferred momentum.[27] This does not quite agree with the results of an investigation of the relaxation time τ_φ in inversion layers on the surface of silicon,[28-30] which yielded the dependence $\tau_\varphi \propto T^{-3/2}$ because of the simultaneous effect of this mechanism and of the phase relaxation due to the interaction of electrons with the field of thermal electromagnetic fluctuations.[31]

The temperature length obtained in Ref. 4 is given by the expression $L_T = (\hbar D/T)^{1/2}$. In the present case we have $L_T \approx 0.25\ \mu$m, i.e., $L_T \lesssim L_\varphi$, and fluctuations of the conductance are governed primarily by the temperature length. Then, in accordance with Eq. (1), we have $\delta G \propto T^{-1/2}$ and the conflict with the theory is greater. Substitution of the values of L_φ or L_T into Eq. (1) and a comparison with the experimental results gives $\alpha = 0.25$–0.36. This is almost half the value of the coefficient α predicted in Refs. 5 and 22. However, this coefficient is still subject to discussion. In particular, a recent numerical experiment indicated that in the one-dimensional case this coefficient is $\alpha = 0.26$ (Ref. 32), whereas the values calculated using perturbation theory are 0.74 (Ref. 5) and 0.53 (Ref. 22).

Figures 3a and 2c show the dependences of the correlation functions F on ΔV_g and on ΔB calculated using the curves plotted in the same figures. The value $F = 0.5$ was then used to find the correlation gate voltage (energy) and the correlation magnetic field. We could determine B_c also by comparing the pattern of fluctuations of G as a function of V_g for different fixed values of the magnetic field. We found that B_c obtained in this way was an order of magnitude greater than the correlation magnetic field deduced from Fig. 2c. This could be due to the fact that the amplitude of the conductance fluctuations induced by V_g was greater than the value of δG representing fluctuations induced by the magnetic field, so that in order to alter the pattern of oscillations of G with V_g one would require fields higher than the values of B that simply alter the conductance. An analysis of the correlation characteristics will be made in the last part of the present paper when the various methods of determination of the correlations will be compared. It should be pointed out that the observed (Fig. 2c and 3c) nonmonotonic dependences $F(\Delta B)$ and $F(\Delta V_g)$ are due to the finite ranges of the magnetic field and of the gate voltage within which the experimental dependences were recorded.

In addition to determination of fluctuations of the conductance, we obtained the derivative of the conductance with respect to the gate voltage dG/dV_g. Since in the latter case there was some compensation of the monotonic component, determination of dG/dV_g enabled us to observe fluctuations throughout the investigated range of gate voltages. We plotted in Fig. 5a the dependence of dG/dV_g on V_g for a sample belonging to group No. 1. It is clear from this figure that the fluctuation amplitude increased on reduction in the gate voltage in the same manner as reported in Ref. 33. Figure 5b shows the dependences of dG/dV_g on V_g obtained in the range of high gate voltages for samples of different dimensions. Clearly, the fluctuation amplitude fell on increase in the channel dimensions. As in the case of the conductance, fluctuations of dG/dV_g due to variation of the magnetic field

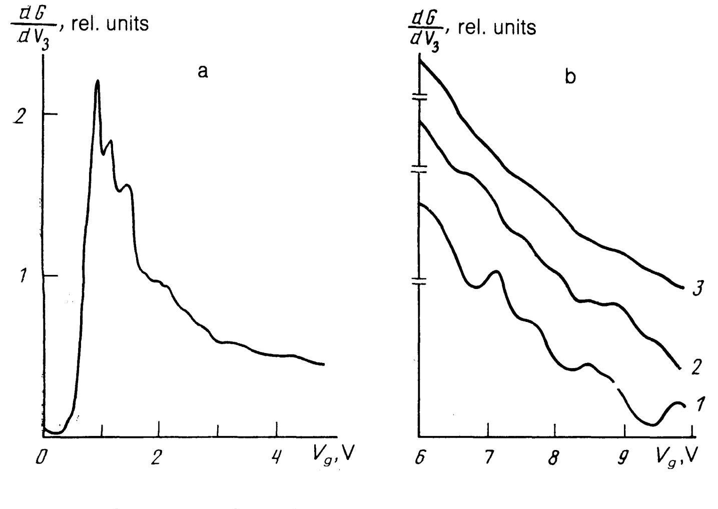

FIG. 5. a) Dependence of dG/dV_g on V_g for one of the group No. 1 samples at $T = 1.4$ K when $B = 0$. b) Dependence of dG/V_g on V_g at $T = 4.2$ K when $B = 0$ obtained for three different samples: *1*) group No. 2 sample; *2*) group No. 3 sample; *3*) group No. 5 sample (see Table I).

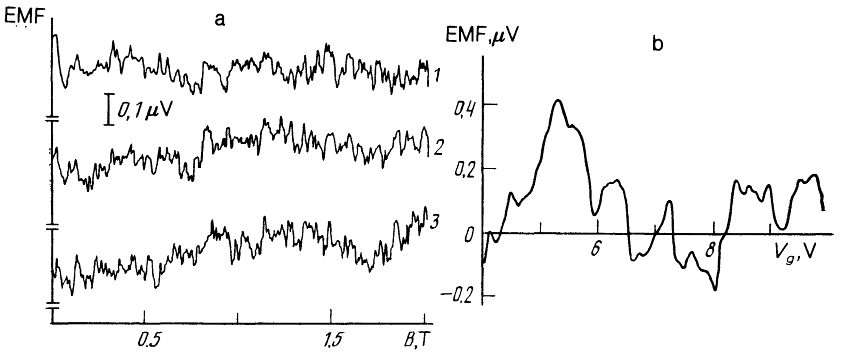

FIG. 6. a) Dependences of the emf, generated by exposure of a group No. 2 sample to microwave radiation of frequency $f = 7$ GHz, on the applied magnetic field obtained for different values of V_g at $T = 1.4$ K; *1*) $V_g = 9$ V; *2*) $V_g = 9.1$ V; *3*) $V_g = 9.2$ V. b) Dependence of the emf on V_g at $T = 1.4$ K when $B = 0$.

were 3–4 times less than fluctuations of dG/dV_g due to variation of the gate voltage.

5. PHOTOVOLTAIC EFFECT

As pointed out already in Sec. 2, the photovoltaic effect should appear in mesoscopic conductors. Figure 6 shows an example of an emf which appeared in MOSFETs when they were exposed to microwave radiation. Clearly, this emf oscillated as a function of the magnetic field and gate voltage. There was no correlation between the conductance fluctuations and the emf and this was true of variation of V_g and B. A comparison of Figs. 6a and 6b demonstrated that the amplitude of the emf fluctuation considered as a function of the magnetic field was, as in the conductance case, 3–4 times less than the amplitude of the fluctuations due to V_g. A quantitative comparison of the experiment and theory was difficult because the error in determination of the electric field of the incident microwave radiation was large. The absence of a monotonic component allowed us to determine the correlation characteristics of the fluctuations more accurately than in the case of the conductance. Moreover, the existence of the classical magnetoresistance hindered determination of fluctuations of the conductanee at high fields, whereas the photovoltaic effect was observed right up to quantizing magnetic fields when the SdH fluctuations were already visible.

We determined the correlation characteristics in the same way as in measurements of the conductance: we calculated the correlation functions $F(\Delta V_g)$ and $F(\Delta B)$ shown in Fig. 7. We determined $F(\Delta V_g)$ not only on the basis of the measurements of the emf as a function of V_g, but also from measurements of the emf as a function of B for different fixed values of the gate voltage V_g (Fig. 7a). These calculations were valid if the correlation energy did not vary in the investigated range of magnetic fields $B < 2$ T and gate voltages amounting to $V_g = 0.2$–0.4 V. It is clear from the magnetoconductance measurements that the coefficient D, the length L_φ, and, therefore, the value of E_c varied little in these ranges of fields and electron densities. The values of B_c and E_c deduced from the emf fluctuations were practically identical with the values of B_c and E_c deduced from an analysis of fluctuations of the conductance by the same methods (the values of B_c plotted in Figs. 2c and 7b were obtained for different samples). As in the conductance case, the correlation magnetic field deduced from a comparison of fluctuations of the emf as a function of V_g at fixed magnetic fields was an order of magnitude higher than the value of B_c deduced from Fig. 7b. The reason was still the same: the amplitude of the emf fluctuations due to V_g was greater than the amplitude due to B.

As pointed out above, the frequency dependences of the photovoltaic effect make it possible to determine the correlation energy of electrons. In fact, in the case of nonequilibrium carriers excited by radiation of frequency $\omega > E_c/\hbar$, the conditions for interference between electron paths (and, consequently, the pattern of fluctuations in the magnetic field) differed from the corresponding conditions in the case of nonequilibrium electrons of energy $\hbar\omega \ll E_c$. Figure 8a shows the dependences of the emf on B obtained for different frequencies of the incident microwave radiation. Clearly, a change in the frequency altered significantly the fluctuation pattern. Figure 8b shows the correlation function representing the dependence of the emf on B for $f = \omega/2\pi = 7$ GHz and other higher frequencies. Clearly, the correlation function fell rapidly on increase in the frequency ω.

In calculation of the correlation functions the average amplitude of the emf fluctuations considered as a function of the magnetic field was normalized at different frequencies to the value $[F(f = 7\text{ GHz})]^{1/2}$, so that there was no allowance for the fall of the amplitude on increase in the frequency in accordance with Eq. (4). The value $\hbar\Delta\omega_c = 0.4$ meV at which the function F fell by a factor of 2 was in this case the correlation energy of two-dimensional electrons. It should be pointed out that fluctuations of the emf due to a change in V_g, the amplitude of which was 4 times higher than the amplitude of fluctuations due to variation of the magnetic

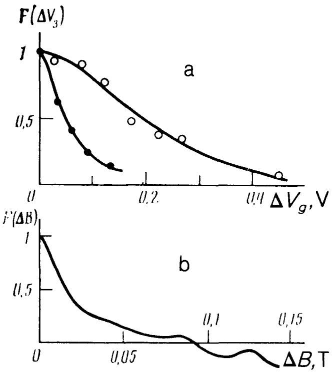

FIG. 7. a) Correlation functions of the fluctuations of the emf due to the magnetic field plotted as the dependence on ΔV_g when $V_g \approx 10$ V, obtained for different temperatures: ●) $T = 1.4$ K; ○) $T = 4.2$ K. b) Correlation function fluctuations of the emf due to the magnetic field plotted as the dependence on ΔB at $T = 1.4$ K; $V_g = 9.1$ V.

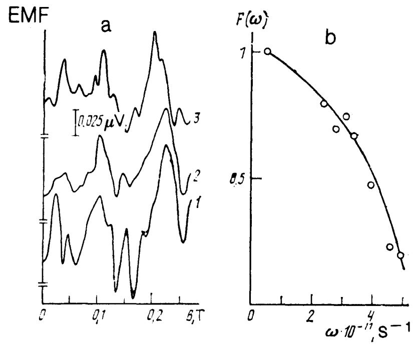

FIG. 8. a) Dependence of the emf on the magnetic field at $T = 4.2$ K for $V_g = 9.8$ V, recorded at different microwave radiation frequencies f: *1*) 7.4 GHz; *2*) 37.8 GHz; *3*) 70 GHz. b) Correlation function of the emf fluctuations due to the magnetic field plotted for $f = 7$ GHz and other frequencies; $T = 4.2$ K, $V_g = 9.8$ V, $\Delta B = 0$.

field, depended on the microwave radiation frequency much less strongly, but we were unable to determine E_c because the frequency range used in our experiments was insufficiently wide. Hence, the value of E_c, which could be determined from the frequency correlation of the emf fluctuations due to V_g, was considerably greater than E_c obtained from Fig. 8b.

The absence of a monotonic component of the emf enabled us to observe fluctuations right up to quantizing magnetic fields. We found that mesoscopic fluctuations gradually disappeared and changed to the SdH oscillations. The occurrence of the SdH oscillations in the emf is not yet fully understood: it may be due to heating of electrons. Another possible explanation is the macroscopic photovoltaic effect, because the inversion channel on the surface of silicon is noncentrosymmetric.[34] It should be pointed out that in spite of the possible macroscopic contribution to the emf, the emf fluctuations observed in weak magnetic fields were due to the mesoscopic properties of the system, because (as pointed out already) there was no correlation between the conductance and the emf and, secondly, because of the frequency dependence of the fluctuation pattern on the magnetic field. In the range $V_g < 4$ V the amplitude of the emf fluctuations increased in strong magnetic fields. This was probably due to the influence of the magnetic field on the mean free path of electrons (classical magnetoresistance).

Since the photovoltaic effect was entirely due to the mesoscopic properties of the system, then in contrast to the conductance which included a large average contribution, we could use the emf to study the mesoscopic fluctuations in the case when they were very small compared with the average conductance, for example, in the case of large samples. Figure 9 shows that the dependence of the emf on the magnetic field for a sample of dimensions 40×40 μm. Clearly, this sample exhibited the mesoscopic photovoltaic effect.

6. CORRELATION CHARACTERISTICS OF FLUCTUATIONS

As pointed out earlier, the correlation magnetic field was found by calculating the correlation functions of the magnetoresistance and emf. Figure 10a shows the dependence of B_c on the density of two-dimensional carriers in a channel in different samples at two temperatures. It is clear from this figure that there was some rise of B_c on decrease of n_s. Moreover, the theoretically predicted temperature dependence of the $B_c \propto T^{-p}$ type was not observed (p is the power exponent in the dependence $\tau_\varphi \propto T^{-p}$) and the value of B_c rose slowly on increase in the electron mobility, observed as a result of a detailed analysis. The absence or a weak dependence of B_c on T could be due to the anomalous behavior of the negative magnetoresistance associated, as pointed out in Sec. 4, with the intervalley splitting. However, in this case we would have to assume that the fluctuation amplitude and B_c depended in different ways on the characteristic length L_φ and on the intervalley relaxation time τ_v, governing the behavior of the negative magnetoresistance because, as demonstrated in Fig. 4, $\delta G \propto T^{-1}$. At $T = 1.4$ K the negative magnetoresistance of a macroscopic sample could be described satisfactorily by a theory ignoring the time τ_v and the experimental values of B_c could be compared with the theory. It is clear from Fig. 10 that that $B_c = 2 \times 10^{-2}$ T. Consequently, Eq. (3) gave $\beta = 0.6$, which differed by a factor of two from the theoretical calculations reported in Ref. 5. However, in view of the large scatter of the values of B_c and because of indeterminacy of the theory,[5,6] this difference could be difficult to analyze.

Figure 10b shows the dependence of the correlation energy of two-dimensional electrons and their density n_s at $T = 1.4$ and 4.2 K, determined by various methods. Clearly, the value of E_c deduced from the magnetic-field dependences of the emf and conductance obtained for different values of V_g (Fig. 7a) was proportional to the absolute temperature and depended on the electron density. On the other hand, the value of E_c deduced from measurements of fluctuations of the emf and conductance as a function of V_g (Fig. 3c) was independent of temperature. Clearly, the value of E_c

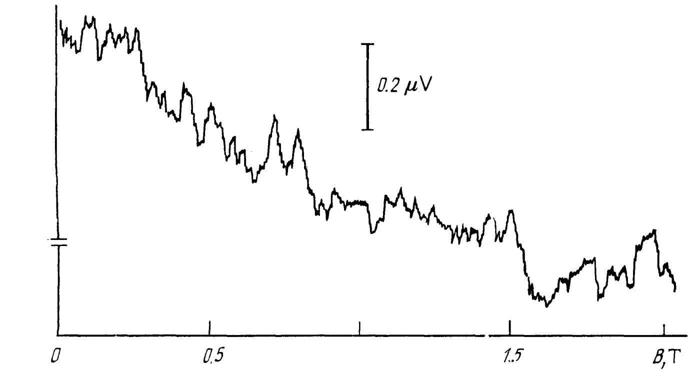

FIG. 9. Dependence of the emf on the magnetic field applied to a group No. 6 sample at $T = 1.4$ K, when $f = 6.8$ GHz and $V_g = 9.1$ V.

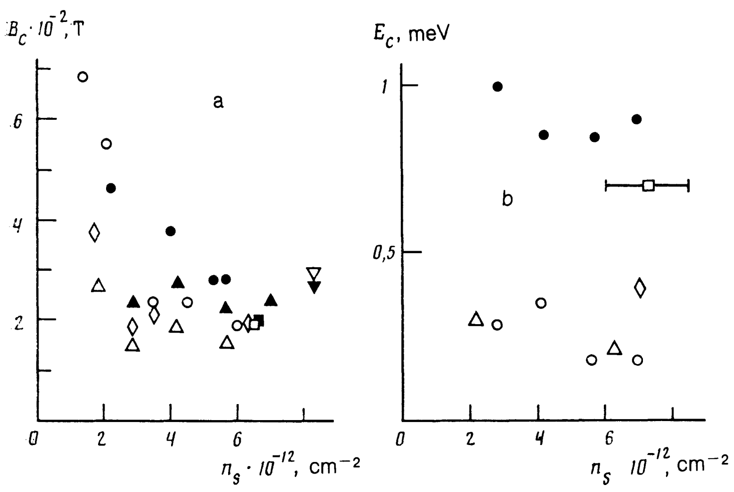

FIG. 10. a) Dependence of the correlation magnetic field on the electron density in a channel obtained for different samples; the black symbols represent the results obtained at $T = 4.2$ K and the open symbols correspond to $T = 1.4$ K. b) Correlation energy plotted as a function of n_s for different samples: ●) $T = 4.2$ K; open symbols $T = 1.4$ K; ◊) E_c deduced from the frequency dependence of the emf; □) E_c deduced from fluctuations of the emf and conductance due to V_g; ○), △) E_c deduced from fluctuations of the emf and conductance due to the magnetic field.

deduced from the frequency dependence of the emf (Fig. 8) was half the correlation energy found by other methods.

The correlation energy of MOSFETs should be governed both by a change in the scattering potential and a change in the energy of electrons with the applied gate voltage. The absence of the temperature dependence of E_c deduced from fluctuations of the conductance emf with V_g indicated that this dependence is entirely due to the change in the scattering potential. Therefore, the most direct method for the determination of the correlation energy is the frequency dependence of the emf because in this case there is only a change in the energy of nonequilibrium carriers and the number of these carriers is many times smaller than the energy of equilibrium carriers. The change in the scattering potential occurs because of a change in the energy of equilibrium electrons, which alter the degree of screening of the potential, or it happens because of amplification of the surface scattering on increase in V_g, when electrons are pressed strongly against a silicon–oxide interface. Estimates obtained for the correlation energies calculated from Eq. (3) give $E_c = \pi kT = 1.1$ meV or $E_c = h/\tau_\varphi = 0.4$ meV (if we assume that $\tau_\varphi \propto T^{-1}$) at $T = 4.2$ K, i.e., the smallest value of $E_c = h/\tau_\varphi$ corresponds to the energy deduced from the frequency correlation of the emf.

We shall now compare the results obtained with the correlation characteristics reported in other papers. The correlation magnetic field was determined in Refs. 10 and 11 and the values of the coefficient β [Eq. (3)], where 3.5 and 2.6, respectively, for samples of approximately the same quality. Our value of β is 4–6 times less and the mobility 3 times higher. This means that the value of β is not a universal parameter, but it clearly depends on the electron mobility. The correlation energy obtained for different samples is also different. It is reported in Ref. 8 that $E_c = 0.6$–0.2 meV ($T = 1.4$ K), whereas Ref. 9 gives $E_c = 1.1$–1.5 meV ($T = 0.047$ K) and Ref. 10 gives $E_c = 1.6$ meV ($T = 4.2$ K). The value reported in Ref. 11 is $E_c = 0.2$–0.4 meV ($T = 0.47$ K). This scatter of the correlation energy confirms that E_c is governed primarily by the scattering potential the behavior of which is a function of the technology used in the preparation of the samples. Therefore, a theoretical calculation of the conductance fluctuations as a function of V_g and determination of the correlation energy in the case when the scattering potential depends on the carrier energy, which would have to be made in any comparison with the experiments, should yield information on the scattering of carriers by the surface and on fluctuations of the scattering potential.

7. CONCLUSIONS

Our investigation of the fluctuation properties of the conductance and photovoltaic effect in small MOSFETs demonstrated that the behavior of these fluctuations as a function of the magnetic field, Fermi energy, and temperature, as well as their correlation characteristics is in full agreement with the theoretical predictions. The main discrepancy between the experimental results and the theory is the difference in the behavior of the fluctuations as a function of the magnetic field and the gate voltage. This discrepancy is probably due to the fact that a change in the electron energy alters the thickness of the inversion channel and, consequently, modifies the scattering of carriers on the surface irregularities which predominates in the investigated range of carrier densities.

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