Dynamic effect of a microwave field on weak localization

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(Submitted 26 November 1987)
Zh. Eksp. Teor. Fiz. **94**, 376–384 (May 1988)

An investigation was made of the conductivity of an inversion layer on the surface of silicon subjected to microwaves of different frequencies in the range 9–37 GHz. When the electron density was $n_s > 1.5\times10^{12}$ cm^{-2} it was found that dynamic suppression of weak localization occurred at the upper limit of the investigated frequency range. A study was made of the dependence of this effect on the applied magnetic field, on the amplitude and frequency of the waves, and on the electron density; a quantitative agreement with the theory was observed. Nonheating interaction of microwaves at low electron densities cannot be described by the theory of weak localization and the mechanism of the interaction remains unidentified.

1. INTRODUCTION

The discovery of quantum corrections to the conductivity due to the localization and interaction effects[1-3] has made it possible to gain a much better understanding of the phenomena occurring in disordered Fermi systems. In particular, it has been established that the role of coherent effects in the scattering of electrons by impurities is important.[4] It is these effects that are responsible for a negative magnetoresistance, the origin of which has remained unexplained for several decades. A theory of a negative magnetoresistance that has been put forward immediately after the discovery of quantum corrections to the conductivity attributes an anomalous magnetoresistance to the suppression of interference corrections to the conductivity by a magnetic field, which disturbs the phase coherence of electrons.[5] Somewhat later it has been shown in Ref. 6 that the phase coherence may be destroyed by an hf electric field of relatively small amplitude. A calculation of the simultaneous influence of a static magnetic field and an hf electric field on the interference effects was reported in Refs. 7 and 8; this is important in the interpretation of the experiments designed to reveal the dynamic interaction effect. The search for this effect in Cu and Nb films has been unsuccessful because of the heating of the samples.[9] Recent investigations of films[10] have demonstrated that at some temperatures the change in the conductivity under the influence of a microwave (8 GHz) field is in the expected direction, whereas at other temperatures there is no such agreement. The absence of measurements in a magnetic field and the consequent indeterminacy of the main parameters of the samples has prevented the drawing of firm conclusions on the observation of the dynamic destruction of the localization.[10] A convenient object for the detection of the dynamic effects of an hf field on weak localization is an inversion layer on the surface of silicon, because in a certain range of electron densities the Joule heating and dynamic destruction of the phase coherence causes conductivity changes which are of opposite signs. This was used in Ref. 11, where a nonheating mechanism of the effect of a microwave field on the conductivity of an n-type channel was observed. We shall consider this range of carrier densities in Sec. 4.3 but at this stage we shall note that the best quantitative agreement with the theoretical calculations of Refs. 7 and 8 was obtained by us at high densities $n_s > 1.5\times10^{12}$ cm^{-2}, when the heating and the dynamic interaction altered the conductivity in the same direction and the identification of the dynamic effect required the application of a magnetic field and of microwaves of several frequencies.

2. SAMPLES AND EXPERIMENTAL METHOD

Our samples were silicon metal-insulator-semiconductor (MOS) transistors with inversion and accumulation layers. At $T = 4.2$ K the electron mobility in these layers was within the range $(1.5–1.9)\times10^4$ cm$^2\cdot$V$^{-1}\cdot$s^{-1}. Coupling of an hf field to a two-dimensional (2D) electron gas was ensured by making the transistor gates of a semitransparent titanium film of thickness $d\sim100$ Å and a resistance 1–2 k$\Omega/\square$. The dimensions of a channel were 1200×1400 μm. The dopant concentrations in the substrates was $N_d = 2\times10^{13}–10^{15}$ cm^{-3}. Samples of MOS transistors prepared in this way were bonded to a pyroceramic substrate with contact areas, connected to the transistor contacts by ultrasonic soldering.

We determined the change in the conductivity of a channel in such MOS transistors subjected to a microwave field of frequency $\Omega/2\pi = 9.1–37$ GHz and magnetic fields of up to 10 kG at $T = 1.6–12$ K. We used an experimental setup shown schematically in Fig. 1. Microwave radiation generated by a klystron oscillator reached a rectangular resonator 1 along a waveguide and across an aperture 2. The microwave radiation amplitude was modulated by a diode

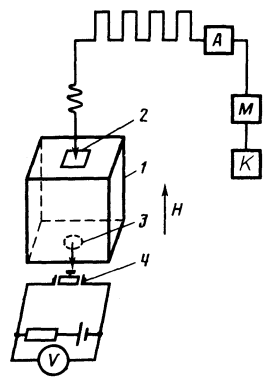

FIG. 1. Schematic diagram of the experimental setup: 1) cavity; 2) aperture for the coupling of the resonator to a waveguide; 3) aperture for the admission of radiation to a sample; 4) sample; V is an ac voltmeter; K is a klystron oscillator generating microwave radiation; M is a microwave radiation modulator; A is a calibrated attenuator.

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connected to one of the arms of a circulator. The power of the radiation reaching the system was controlled by a calibrated attenuator and was 10–20 mW at its maximum. A sample was located at a distance 1–2 mm from the plane of an aperture 3. The relaxation time of the wave function phase, needed in a comparison of the theory and experiment, was found by measuring a negative magnetoresistance. These measurements were carried out by a null method under dc and ac conditions. In studies of the effects of heating on the source-drain contacts in the presence of a static longitudinal voltage a sample was subjected to an alternating amplitude-modulated voltage of frequency from 100 kHz to 10 MHz.

3. INFLUENCE OF AN ALTERNATING ELECTRIC FIELD ON THE CONDUCTIVITY OF A SAMPLE

Quantum localization corrections to the conductivity appear because of interference between the probability amplitudes of an electron passing along a self-intersecting trajectory along opposite directions. External agencies suppressing this interference (such as inelastic processes), alternating electromagnetic and static magnetic fields reduced the quantum correction. In the two-dimensional case in the presence of an hf electric field E_Ω, applied along the film plane or along an inversion channel, and of a magnetic field H perpendicular to this plane, the change in the conductivity[1)] is described by the following expression[7,8]:

$$\delta\sigma(E_\Omega) = -\sigma_0 \int_{\Omega\tau}^{\infty} \frac{dx \exp(-2x/x_\varphi)}{(2/\xi)\,\mathrm{sh}(x\xi/2)} \exp(-\alpha B(x)) I_0(\alpha B(x)),$$

$$B(x) = x\left[1 + \frac{1-\xi^2}{1+\xi^2}\frac{\sin x}{x} - \frac{4\xi}{1+\xi^2}\frac{\sin^2(x/2)}{x\,\mathrm{th}(\xi x/2)}\right], \qquad (1)$$

where I_0 is a modified Bessel function, $\xi = 8DeH/\Omega c$,

$$\alpha = 2De^2E_\Omega^2/\Omega^3(1+\xi^2), \quad x_\varphi = \Omega\tau_\varphi,$$

τ_φ is the relaxation time of the phase of the wave function as a result of inelastic collisions, D is the diffusion coefficient, and τ is the momentum relaxation time, and $\sigma_0 = e^2/2\pi^2\hbar$.

At low electromagnetic field amplitudes and without allowance for the heating effects, the change in the conductivity

$$\Delta\sigma(E_\Omega) = \delta\sigma(E_\Omega) - \delta\sigma(0) = {}^1/_2\sigma_0\alpha \int \xi dx e^{-2x/x_\varphi} B(x)\,\mathrm{sh}^{-1}(\xi x/2) \qquad (2)$$

varies linearly with the power of the incident microwave radiation.

The absorption of the energy of the hf field by electrons increases the temperature of electrons T_e above the lattice temperature T. (The electron-electron collision time $\tau_{ee} \sim \tau_\varphi \ll \tau_e$ is the energy relaxation time,[12] because there is sufficient time for the establishment of the temperature inside the electron subsystem.) The time τ_φ depends on the temperature of electrons in accordance with T_e^{-p} (Refs. 13 and 14). The increase in T_e because of the heating by the electric field reduces τ_φ and, consequently, alters the quantum correction. The total conductivity of the system then increases, as in the case of the dynamic mechanism of suppression of weak localization effects. If the heating effect is small, so that $\Delta T_e \ll T$, the change in the quantum correction due to temperature

$$\Delta\sigma_T/\sigma_0 \propto \Delta\tau_\varphi/\tau_\varphi \propto \sigma_\square E_\Omega^2 \tau_\varepsilon / T c_\square \qquad (3)$$

is proportional to the power absorbed in the system and to the energy relaxation time. Here, $c_\square$ is the specific heat of electrons in a layer and $\sigma_\square$ is the conductivity of the sample. Therefore, the condition for reliable observation of the suppression of the quantum corrections to the conductivity $\Delta\sigma_\Omega \gtrsim \Delta\sigma_T$ by the microwave field is governed also by the magnitude and behavior of the time τ_ε in the case of scattering by acoustic phonons.

The total conductivity of two-dimensional electrons at the surface of silicon includes, apart from the quantum corrections, another contribution which depends on the electron temperature and has been investigated in detail by Dorozhkin and Dolgopolov.[15] This contribution, due to the temperature dependence of the conditions for the screening of impurities in n-type inversion channels,[15] increases the conductivity as a result of cooling approximately linearly in the range of electron densities $n_s < 10^{12}$ cm^{-2}. If $n_s > 10^{12}$ cm^{-2}, the effect decreases strongly, but may distort the logarithmic temperature dependence of the conductivity due to the localization effects.

The electron-electron interaction affects also the conductivity of two-dimensional layers.[3] However, these effects were not observed in our system.[16] The contribution of the dynamic mechanism to the change in the conductivity under heating conditions can be identified with the help of a magnetic field. In fact, in a magnetic field of just $H \approx 1$ kG the localization effects in the investigated systems are suppressed and the influence of microwave and lf electromagnetic fields on the conductivity reduces simply to the heating of the electron system. It is precisely this circumstance that will be used to separate the loss of phase coherence of the wave function of an electron in a microwave field against the background of a considerable contribution of the heating effects.

4. EXPERIMENTS AND DISCUSSION

4.1. Preliminary comments

It is clear from Eq. (1) that the suppression of the quantum corrections to the conductivity by an hf electromagnetic field, both in the presence and absence of a static magnetic field, depends strongly on the relaxation time of the wave-function phase. At low microwave field amplitudes, it follows from Eq. (2) that $\Delta\sigma(E_\Omega)$ increases on increase in the relaxation time τ_φ:

$$\begin{aligned} \Delta\sigma(E_\Omega) &\propto \sigma_0\alpha(\Omega\tau_\varphi)^5 \quad \text{for } \alpha(\Omega\tau_\varphi)^5 \ll 1,\ \Omega\tau_\varphi \ll 1, \\ \Delta\sigma(E_\Omega) &\propto \sigma_0\alpha\Omega\tau_\varphi \quad \text{for } \alpha\Omega\tau_\varphi \ll 1,\ \Omega\tau_\varphi \gg 1. \end{aligned} \qquad (4)$$

i.e., the effect will be maximal in the range of carrier densities n_s where the value of τ_φ is maximal. The time τ_φ can be determined from measurements of the negative magnetoresistance. The results of these measurements are plotted in Fig. 2a for the samples under investigation. It is clear that τ_φ increases with n_s and at $n_s = 5\times10^{12}$ cm^{-2} it reaches its maximum value and then falls. Such a behavior is in agreement with the results of Ref. 17 obtained for n-type inversion layers.

On the other hand, the optimal conditions for the observation of this effect require a reduction of the influence of

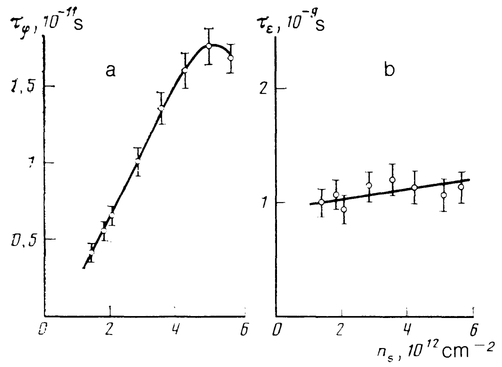

FIG. 2. a) Dependence of the dephasing time τ_φ of the wave function of an electron on the density of $2D$ electrons ($T = 4.2$ K). b) Dependence of the energy relaxation time τ_ε of the electron system on the density of $2D$ electrons n_s ($T = 4.2$ K).

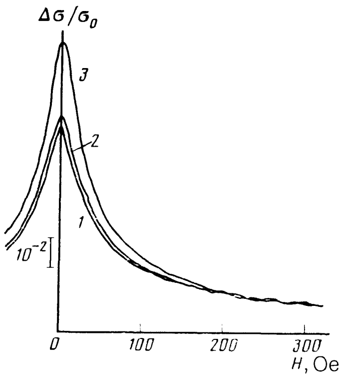

FIG. 3. Dependence of the correction to the conductivity of a sample $\Delta\sigma(E_\Omega)/\sigma_0$ on the applied magnetic field H ($T = 4.2$ K, $n_s = 4.2\times10^{12}$ cm^{-2}): 1) 10^6 Hz; 2) $\Omega/2\pi = 9.1$ GHz; 3) $\Omega/2\pi = 37$ GHz; $\sigma_0 = e^2/2\pi^2\hbar$.

heating, which as mentioned in the preceding section, is proportional to the energy relaxation time when electrons are scattered by phonons. As shown in Ref. 18, an effective method for the determination of the temperature of carriers heated by an electric field and, consequently, for finding the time τ_ε, is an investigation of the negative magnetoresistance in heating electric fields. Figure 2b shows the dependence of the time τ_ε on n_s, deduced from the negative-magnetoresistance measurements when electrons are heated by a longitudinal field. It is clear that τ_ε is practically independent of the carrier density. Equations (3) and (4) yield the following relationships which apply in the case of low amplitudes of the microwave field:

$$\Delta\sigma(E_\Omega)/\Delta\sigma_T \propto \alpha\tau_\varphi^5\Omega^5 c_\square T/\sigma_\square E^2\tau_\varepsilon, \quad \alpha(\Omega\tau_\varphi)^5 \ll 1,\ \Omega\tau_\varphi \ll 1, \tag{5a}$$

$$\Delta\sigma(E_\Omega)/\Delta\sigma_T \propto \alpha\tau_\varphi\Omega c_\square T/\sigma_\square E^2\tau_\varepsilon, \quad \alpha\Omega\tau_\varphi \ll 1,\ \Omega\tau_\varphi \gg 1. \tag{5b}$$

At sufficient high frequencies and intensities of the electric field the ratio $\Delta\sigma(E_\Omega)/\Delta\sigma_T$ increases with the relaxation time of the phase of the wave function of an electron and on reduction in the time τ_ε. At low frequencies and for relatively high intensities of a microwave field the ratio $\Delta\sigma(E_\Omega)/\Delta\sigma_T$ depends weakly on the time τ_φ and increases on reduction in τ_ε. Since in our case τ_ε is independent of the carrier density (Fig. 2b) and the intensity of the microwave field is low, the suppression of the quantum corrections by microwave radiation should be maximal at $n_s \approx 5\times10^{12}$ cm^{-2}, i.e., when τ_φ has its largest value.

4.2. Destruction of the phase coherence by a microwave field

In comparing the experimental results with the theory we have to know the microwave field amplitude. We can determine this amplitude in a magnetic field $H = 5$ kOe when

$$\Delta\sigma(E_\Omega) = \Delta\sigma(E_\omega), \tag{6}$$

where E_Ω is the amplitude of the high-frequency field and E_ω is the amplitude of an easily measured low-frequency field. As pointed out in the preceding section, the localization effects in such a magnetic field are suppressed and the influence of hf E_Ω and lf E_ω fields reduces to heating of electrons in a layer, whereas the conductivity changes because of a contribution that varies linearly with temperature. Since $\Omega\tau \ll 1$, the power absorbed by electrons at frequencies Ω and ω is the same if $E_\Omega = E_\omega$. Figure 3 shows the dependence $\Delta\sigma(E_\Omega)$ on the magnetic field at microwave radiation frequencies $\Omega/2\pi = 37$ GHz and 9.1 GHz and for an lf field of frequency 10^6 Hz when $n_s = 4.2\times10^{12}$ cm^{-2}. It is clear from this figure that the curves coincide completely in the range $H > 200$ Oe, which confirms the correctness of the calibration. If $H < 200$ Oe, the change $\Delta\sigma(E_\Omega)$ in a magnetic field of $\Omega/2\pi = 37$ GHz and two other curves for the high and low frequencies begin to differ: the curve for $\Omega/2\pi = 37$ GHz rises more rapidly. This behavior is due to the fact that additional (to heating) suppression of the localization corrections occurs at this frequency.

Figure 4 demonstrates the difference between the conductance of a sample in the two cases of illumination with fields of frequencies $\Omega/2\pi = 37$ GHz and $\omega/2\pi = 10^6$ Hz as a function of the magnetic field H:

$$\Delta_\Omega\sigma = \Delta\sigma(E_\Omega) - \Delta\sigma(E_\omega). \tag{7}$$

The time τ_φ necessary for the calculation of curve 1 was deduced from Fig. 2 when the gate voltage was $V_g = 30$ V. The diffusion coefficient was found from the conductivity using the Einstein relationship and the carrier density was

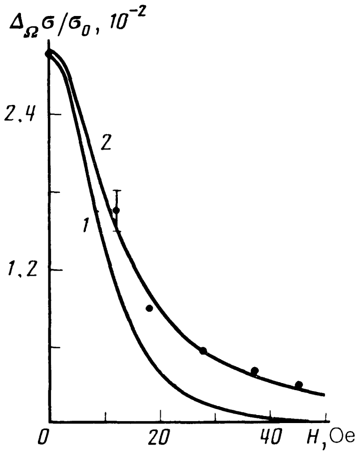

FIG. 4. Dependences of the difference between the conductivities of a sample in hf and lf fields $\Delta_\Omega\sigma/\sigma_0$ on the magnetic field H: $\Omega/2\pi = 37$ GHz, $\omega/2\pi = 10^6$ Hz, $n_s = 4.2\times10^{12}$ cm^{-2}, $D = 172$ cm^2/s; $E_\Omega = E_\omega = 1.9$ V/cm. Curve 1 represents the calculations made ignoring heating, whereas curve 2 allows for heating; $T = 4.2$ K.

found from capacitance measurements. The electric field determined by the method described above was 1.9 ± 0.2 V/cm. Therefore, we did not use any fitting parameters. The other curve in Fig. 4 was plotted allowing for the heating of electrons from 4.2 to 5 K. There was an allowance not only for the reduction in τ_φ because of increase in temperature, but also for the fact that the temperature of the electron system subjected to an lf field followed the amplitude of the heating field $\delta T \propto E^2(t)$. Therefore, after averaging over a period of the slow field in $\Delta_\Omega \sigma$, we have an additional term which can be estimated from

$$\left(\frac{\langle \delta T \rangle}{T}\right)^2 \int \frac{x^2}{x_\varphi^2} e^{-2x/x_\varphi} \frac{\xi\, dx}{2\,\mathrm{sh}\,(x\xi/2)}. \tag{8}$$

In the hf limit (37 GHz) we can ignore oscillations of the temperature of a sample and assume that $\delta T \propto \langle E^2(t) \rangle$ is independent of time. It should be noted that according to Eqs. (1) and (2) the magnetic-field dependence of $\Delta\sigma$ is governed by the factor $(1+\xi^2)^{-1}$ and the expression for α as well as the strong change in $\Delta\sigma$ occur on a scale of $\xi \sim 1$ ($H \approx 10$ Oe for our samples). This scale is independent of temperature. On the other hand, the scale of the negative magnetoresistance and of the heating contribution to $\Delta\sigma$ is different: $\xi \propto x_\varphi^{-1}$, i.e., it increases with temperature. Experiments carried out above 4.2 K demonstrated that the scale of the change in $\Delta\sigma$ with the magnetic field is practically unaffected (≈ 10 Oe).

Figure 5 shows the dependence of $\Delta_\Omega \sigma$ on the electric field E. Practically throughout the investigated range of fields the dependence is quadratic. Under these conditions Eq. (5a) is valid and, therefore, the change in temperature does not alter the ratio $\Delta\sigma(E_\Omega)/\Delta\sigma_T$.

Figure 6 gives the frequency dependence of $\Delta_\Omega \sigma$ when $H = 0$. Like Fig. 3, this figure demonstrates that the change in the conductivity of a sample due to illumination with a wave of frequency 9.1 GHz is practically of heating origin. The dynamic interaction is manifested clearly at the upper limit of the investigated range.

Figure 7 compares the experimental and calculated dependences of $\Delta_\Omega \sigma$ on the carrier density n_s. A change in the density makes it necessary to determine the parameters of a sample D, τ_φ, and τ experimentally.

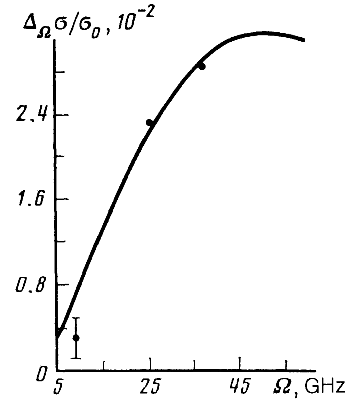

FIG. 6. Dependence of the difference between the conductivities $\Delta_\Omega\sigma/\sigma_0$ on the frequency Ω: $T = 4.2$ K; $n_s = 4.2 \times 10^{12}$ cm^{-2}; $D = 172$ cm^2/s; $E_\Omega = 1.9$ V/cm; $H = 0$; $\omega/2\pi = 10^6$ Hz.

We shall end this section by noting that the experimental dependences described above and involving a change in the conductivity of a two-dimensional electron gas under the influence of microwave and lf fields in the absence and presence of a static magnetic field may be described by a simultaneous effect of the heating and dynamic mechanisms of suppression of the localization corrections.

4.3. Effect of a microwave field on the conductivity at $n_s < 10^{12}$ cm^{-2}

It is clear from Fig. 7 that the dynamic suppression of weak localization in the investigated samples becomes weaker on reduction in n_s and disappears completely in the range $n_s < 2 \times 10^{12}$ cm^{-3}, owing to the linear dependence of τ_φ on n_s. However, if we reduce still further the electron density or, more exactly, operate within the range $2 \cdot 10^{11} < n_s < 10^{12}$ cm^{-2}, then—as found in Ref. 11—we can observe once again the nonheating interaction with the microwave field. It is clear from Fig. 8a that the $\Delta\sigma(n_s)$ dependence has a maximum at $n_s = (4\text{–}6) \times 10^{11}$ cm^{-2}, and that the position and magnitude of the maximum depend on the microwave radiation power. The parameter used in Fig. 8a is the power. The two upper dependences correspond to low powers, when the nonheating effect predominates. The third dependence $\Delta\sigma$ corresponds to the highest power,

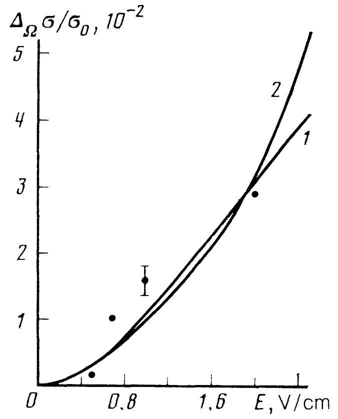

FIG. 5. Dependence of the difference between the conductivities $\Delta_\Omega\sigma/\sigma_0$ on the electric field $E_\Omega = E_\omega$: $T = 4.2$ K; $H = 0$; $n_s = 4.2 \times 10^{12}$ cm^{-2}; $D = 172$ cm^2/s; $\Omega/2\pi = 37$ GHz; $\omega/2\pi = 10^6$ Hz. Curve 1 was calculated ignoring heating, whereas curve 2 allows for the heating.

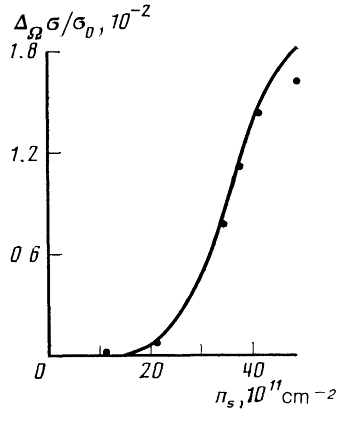

FIG. 7. Dependence of the difference between the conductivities $\Delta_\Omega\sigma/\sigma_0$ on the density of $2D$ electrons n_s: $T = 4.2$ K; $E_\Omega = 1.1$ V/cm; $H = 0$; $\Omega/2\pi = 37$ GHz; $\omega/2\pi = 10^6$ Hz.

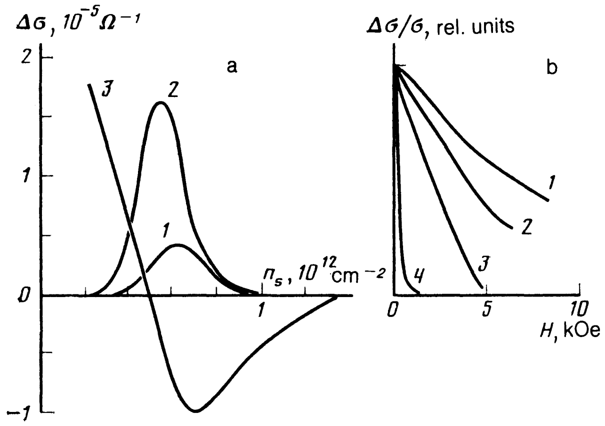

FIG. 8. a) Dependence of the correction to the conductivity $\Delta\sigma = \sigma(E_\Omega) - \sigma(0)$ on the carrier density: $T = 4.2$ K, $\Omega/2\pi = 9.1$ GHz. The curves differ in respect of the power of the incident microwave radiation: 1) $P_\Omega = 29$ dB; 2) $P_\Omega = 15$ dB; 3) $P_\Omega = 0$ dB. b) Dependence of the normalized correction to the conductivity $\Delta\sigma/\sigma$ on the magnetic field in the range of low carrier densities: 1) $n_s = 7.7\times10^{11}$ cm^{-2}; 2) $n_s = 8.4\times10^{11}$ cm^{-2}; 3) $n_s = 9.1\times10^{11}$ cm^{-2}; 4) $n_s = 9.8\times10^{11}$ cm^{-2}; σ is the total conductivity of the sample.

when the heating becomes the dominant effect. In this case the conductivity decreases under the influence of microwave radiation, exactly as a result of an increase in temperature, because—as mentioned above—in this range of carrier densities the main contribution to the dependence of σ on T comes from the term which is a linear function of temperature. Figure 8b shows the dependence of the nonheating effect at low microwave field powers on H, obtained for different values of n_s. It is clear from this figure that the effect decreases on increase in the magnetic field and, the higher the carrier density, the stronger the influence of the magnetic field, and for $n_s < 4\times10^{11}$ cm^{-2} the magnetic field does not influence $\Delta\sigma$. It should also be mentioned that for the same value of P_Ω the magnitude of the effect at the maximum is almost an order of magnitude greater than the largest change in $\Delta\sigma$ due to suppression of localization, which is observed at $n_s \approx 5\times10^{12}$ cm^{-2}. This nonheating effect is characterized by a strong temperature dependence. When T is reduced to 1.7 K the value of $\Delta\sigma$ rises by more than one order of magnitude and when T is increased to 15 K the effect is suppressed completely. It has not been possible to determine τ_φ in this range. If τ_φ is extrapolated to low densities in accordance with Fig. 2, the values obtained are $\tau_\varphi \sim \tau$ and in this region the approximation of weak localization is no longer justified. For $\tau_\varphi = 0.5\times10^{11}$ s the scale of the magnetic fields in which there is a change in the quantum correction to the conductivity is considerably less than the scales found experimentally (Fig. 8b). The change in the conductivity $\Delta\sigma$ is greater than that predicted by Eq. (1).

CONCLUSIONS

We observed dynamic suppression of weak localization by microwave radiation in the case when the carrier density is high and the results are shown to be in qualitative agreement with the theory. The nature of the observed nonheating effect at low carrier densities remains unjustified.

The authors are grateful to V.N. Ovsyuk for his encouragement of this investigation.

Note added in proof (March 4, 1988). It was reported recently[19] that a change in the phase relaxation time τ_φ occurred in Mg films subjected to a microwave field. In spite of the very controversial hypothesis that τ_φ can be found correctly from the magnetoresistance data at different microwave power levels and in spite of several discrepancies from the theory, the observed change in τ_φ is undoubtedly due to the dynamic suppression of the phase coherence of electrons by a microwave field.

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Translated by A. Tybulewicz