Dynamic effect of a microwave field on weak localization

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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 $n_e > 1.5 \times 10^{12}$ 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 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. 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 has been put forward immediately after the discovery of the interference effects. It is known that the role of coherent effects in 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. Somewhat later it was found that dynamic suppression of weak localization occurs 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.

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 $(1.5–1.9) \times 10^6$ cm$^2$ V$^{-1}$ 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 $d = 100$ Å and a resistance $1–2$ kΩ/Å. The dimensions of a channel were $1200 \times 1400$ μm. The dopant concentrations in the substrates was $N_d = 2 \times 10^{15}$ 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 $f/2\pi = 9.1–37$ 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

![Schematic diagram of the experimental setup](image-url)
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. 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 $E_{\text{hf}}$, 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 $\Delta \sigma$ is described by the following expression:

$$\Delta \sigma = -\sigma_0 \frac{e}{2 \hbar} \int \frac{dE}{(2\pi)^2} \frac{\sin x}{x} \left[ \left( 1 + \frac{1}{2} \frac{d}{dE} \right) B(x) \right],$$

where $\sigma_0 = 2\pi e^2 /\hbar$, $e$ is the elementary charge, $\hbar = \hbar /2\pi$, $B(x) = 1 + 1/(2x^2)$ is a modified Bessel function, and $r$ is the relaxation time of the phase of the wave function as a result of inelastic collisions. $D$ is the diffusion coefficient, and $r$ is the momentum relaxation time, and $\sigma_0 = e^2 /2\pi\hbar$. At low electromagnetic field amplitudes and without allowance for the heating effects, the change in the conductivity $\Delta \sigma$ is proportional to the power absorbed in the system and to the energy relaxation time $T_r$.

$$\Delta \sigma = \sigma_0 \frac{e^2}{2\pi\hbar} D \frac{1}{T_r},$$

where $\sigma_0$ is the conductivity due to the diffusion of electrons in a layer and $\sigma_0$ is the conductivity of the sample.

The electron-electron interaction affects also the conductivity of two-dimensional layers. However, these effects were not observed in our system. 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 $H = 1$ kG the localization effects in the investigated systems are suppressed and the influence of microwave and magnetic 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 $\Delta \sigma(E_{\text{hf}})$ increases in the relaxation time $T_r$:

$$\Delta \sigma(E_{\text{hf}}) = \sigma_0 \frac{e^2}{2\pi\hbar} D \frac{1}{T_r},$$

i.e., the effect will be maximal in the range of carrier densities $n$, where the value of $T_r$ is maximal. The time $T_r$ 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 $\alpha_{T_1}$ increases with $n$, and at $n = 5 	imes 10^{12}$ 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
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 \( \tau_{cl} \), is an investigation of the negative magnetoresistance in heating electric fields. Figure 2b shows the dependence of the time \( \tau_{cl} \), deduced from the negative-magnetoresistance measurements when electrons are heated by a longitudinal field. It is clear that \( \tau_{cl} \) 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:

\[
\Delta \sigma(E_{\omega})/\Delta \sigma_0 = \pi \tau_{cl} \omega \varepsilon F_{\omega} E_{\omega}, \quad \sigma(\Omega \tau_{cl}) < 1, \quad \Omega \tau_{cl} < 1, \quad \Delta \sigma(E_{\omega})/\Delta \sigma_0 = \pi \tau_{cl} \omega \varepsilon F_{\omega} E_{\omega}, \quad \sigma(\Omega \tau_{cl}) < 1, \quad \Omega \tau_{cl} > 1. \quad (5a)
\]

(5b)

At sufficient high frequencies and intensities of the electric field the ratio \( \Delta \sigma(E_{\omega})/\Delta \sigma_0 \) increases with the relaxation time of the phase of the wave function of an electron and on reduction in the time \( \tau_{cl} \). At low frequencies and for relatively high intensities of a microwave field the ratio \( \Delta \sigma(E_{\omega})/\Delta \sigma_0 \) depends weakly on the time \( \tau_{cl} \) and increases on reduction in \( \tau_{cl} \). Since in our case \( \tau_{cl} \) 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 \( n_e \approx 5 \times 10^{12} \) cm\(^{-2}\), i.e., when \( \tau_{cl} \) 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

\[
\Delta \sigma(E_{\omega}) = \Delta \sigma(E_{\omega}), \quad (6)
\]

where \( E_{\omega} \) is the amplitude of the high-frequency field and \( E_{cl} \) 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 \( E_{\omega} \) and If \( E_{cl} \) fields reduce to heating of carriers in a layer, whereas the conductivity changes because of a contribution that varies linearly with temperature.

Since \( \Omega \tau_{cl} \ll 1 \), the power absorbed by electrons at frequencies \( \Omega \) and \( \omega \) is the same if \( E_{\omega} = E_{cl} \). 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 If field of frequency 10\(^8\) Hz when \( n_e = 4 \times 10^{12} \) 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 \( \omega/2\pi = 10^8 \) Hz as a function of the magnetic field \( H \). The time \( \tau_{cl} \) 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
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 \( \tau_e \) because of increase in temperature, but also for the fact that the temperature of the electron system subjected to an If field followed the amplitude of the heating field \( \Delta T = E^2(t) \). Therefore, after averaging over a period of the slow field in \( \Delta_0 \sigma \), we have an additional term which can be estimated from

\[
\left( \frac{\langle \Delta T \rangle}{T} \right) f \sum_{j=0}^{\infty} x_j e^{-\omega_j n} \frac{1}{2 \sinh(x_j/2)},
\]

(8)

In the hf limit (37 GHz) we can ignore oscillations of the temperature of a sample and assume that \( \Delta T = E^2(t) \) 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 \( a \) as well as the strong change in \( \sigma \) occur on a scale of \( \xi \). Therefore, \( \xi = \pi \), i.e., it increases with temperature. On the other hand, the scale of the negative magnetoresistance and of the heating contribution to \( \Delta \sigma \) different: \( \xi = \pi \), 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 practical-

Figure 5 shows the dependence of \( \Delta \sigma \sigma \) 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 \( \Delta \sigma(E_0)/\Delta \sigma_{}\sigma_0 \).

Figure 6 gives the frequency dependence of \( \Delta \sigma_{}\sigma_0 \) 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 \( \Delta \sigma_{}\sigma_0 \) on the carrier density \( n_e \). A change in the density makes it necessary to determine the parameters of a sample \( B, \tau_e, \), and \( \tau \) experimentally.

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 If 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 \( n_e < 10^{10} \) cm

It is clear from Fig. 7 that the dynamic suppression of weak localization in the investigated samples becomes weaker on reduction in \( n_e \) and disappears completely in the range \( n_e < 2 \times 10^9 \) cm, owing to the linear dependence of \( \tau_e \) on \( n_e \). However, if we reduce still further the electron density \( n_e \), more exactly, operate within the range \( 2 \times 10^9 < n_e < 10^8 \) cm, 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 \( \Delta \sigma(E_{\sigma}) \) dependence has a maximum at \( n_e = (4-6) \times 10^9 \) cm, 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,
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 \( \sigma \) on \( T \) comes from the term which is a linear function of temperature.

The curves differ in respect of the power of the incident microwave radiation, as follows: 1) \( P_0 = 29 \text{ dB} \); 2) \( P_0 = 15 \text{ dB} \); 3) \( P_0 = 0 \text{ dB} \).

a) Dependence of the correction to the conductivity \( \Delta \sigma = \sigma(1) - \sigma(0) \) on the carrier density. \( T = 4.2 \text{K} \), \( \Omega/2\pi = 9.1 \text{GHz} \).

The curves differ in respect of the power of the incident 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 \( \sigma \) on \( T \) comes from the term which is a linear function of temperature. The curves differ in respect of the power of the incident microwave radiation, as follows: 1) \( P_0 = 29 \text{ dB} \); 2) \( P_0 = 15 \text{ dB} \); 3) \( P_0 = 0 \text{ dB} \).

b) Dependence of the normalized correction to the conductivity \( \Delta \sigma/\Delta \sigma_{\text{rel. units}} \) on the magnetic field in the range of low carrier densities: 1) \( n_i = 5.7 \times 10^{11} \text{ cm}^{-2} \); 2) \( n_i = 8.4 \times 10^{11} \text{ cm}^{-2} \); 3) \( n_i = 9.1 \times 10^{11} \text{ cm}^{-2} \); 4) \( n_i = 9.8 \times 10^{11} \text{ cm}^{-2} \).

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.

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Note added in proof (March 4, 1988). It was reported recently\(^{16}\) that a change in the phase relaxation time \( \tau_p \) occurred in Mg films subjected to a microwave field. In spite of the very controversial hypothesis that \( \tau_p \) can be found correctly from the magnetoereistance data at different microwave power levels and in spite of several discrepancies from the theory, the observed change in \( \tau_p \) is undoubtedly due to the dynamic suppression of the phase coherence of electrons by a microwave field.

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