Suppression of localization effects by microwave radiation in a 2*D* electron gas

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The effect of microwave radiation on the conductivity of an inversion channel at a silicon surface has been studied experimentally. A suppression of quantum-mechanical corrections to the conductivity of a 2*D* electron gas by an rf field has been discovered.

Altshuler *et al.*[1] have derived a theory for the effect of an rf electric field on the quantum-mechanical corrections to the conductivity which arise from localization effects. They showed that the rf electric field should disrupt the phase of the electron's wave function and suppress interference corrections to the conductivity. So far, however, there have been no experiments of any sort in which this interesting effect, of importance to an understanding of the localization problem, would have been observed.

In the present letter we report an experimental study of the effect of 9.1-MHz microwave radiation on the conductivity of electron inversion channels. The results reveal an increase in the conductivity of the 2*D* electron gas at low microwave power levels, providing evidence that localization effects are suppressed by the microwave field. The effects of the heating of the electron gas turn out to be negligible at low field amplitudes.

The samples are silicon metal-insulator-semiconductor transistors fabricated by the usual planar technology, with a maximum mobility $\mu = 1.7\times 10^4$ cm^2/(V·s) at 4.2 K and with channel dimensions of $1200\times 400\,\mu$m^2. The transistor gates are made of a semitransparent titanium film with a thickness $d < 100$ Å in order to couple the microwave field with the $2D$ electron gas. The samples are irradiated through a diaphragm 4 mm in diameter in the wall of a rectangular resonator. The rf electric field is directed parallel to the plane of the inversion layer. The experiments are carried out with various orientations of the field and the extracting current. The microwave radiation is produced by a klystron in cw operation at 9.1 GHz. The sensitivity is increased by modulating the amplitude of the microwave power incident on the sample at a frequency of 2 kHz. The modulator is a diode connected to one arm of a circulator.

In the experiments, we measure the change caused in the conductivity of the inversion layer by the microwave field, $\Delta G(P_\Omega) = G(P_\Omega) - G(0)$. These measurements are carried out at temperatures in the interval 2–10 K in magnetic fields up to 70 kG. Figure 1 shows the conductivity change (ΔG) at an electron density $N_S = 9.5\times 10^{11}$ cm^{-2} as a function of the microwave power P_Ω at 4.2 and 2 K. We see that at low power levels ΔG is positive; i.e., the microwave field increases the channel conductivity in this P_Ω range. As the power is raised further, ΔG goes through a maximum, decreases, and changes sign. This behavior of ΔG is due to specifically the effect of the microwave electric field, since heating by a direct current leads to a monotonic decrease in the conductivity. This behavior can be explained in a theory of weak localization. The increase in the conductivity at low microwave amplitudes is due to a suppression of localization corrections, as predicted in Ref. 1. With a further increase in the amplitude, effects of a heating of the electron gas come into play and reduce the conductivity.[1)]

We made a special effort to monitor the symmetry of the current-voltage characteristic of the transistor upon a reversal of the current. The observed symmetry of this characteristic rules out any influence of rectification effects on the conductivity.

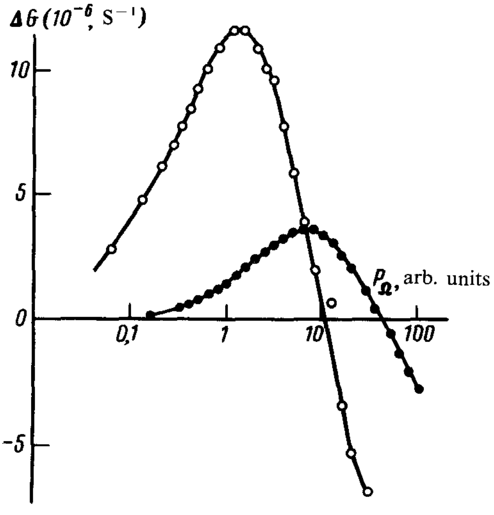

FIG. 1. Dependence of the change ΔG of the inversion channel on the microwave power P_Ω. $N_S = 9.5\times 10^{11}$ cm^{-2}. ○—$T = 2$ K; ●—$T = 4.2$ K.

We thus conclude that the observed behavior of the conductivity can be explained well by assuming that localization effects are suppressed by the microwave field in this system. The temperature dependence of ΔG at low power levels confirms this assumption. As can be seen from Fig. 1, a reduction of the temperature from 4.2 to 2 K leads to a pronounced increase in ΔG. An increase in the temperature, on the other hand, from 4.2 to 10 K leads to a disappearance of the effect. This behavior occurs because as T is increased, there is a decrease in the relaxation time for the phase of the electron's wave function,[3,4] τ_φ. The decrease in τ_φ has the consequences that (on the one hand) there is a decrease in the quantum-mechanical correction[5,6] and (on the other) there is a sharp drop in the strength of the effect of the alternating electric field on the interference process. We might note that the change ΔG caused by the heating varies to a much lesser extent as the temperature is changed.

An important experimental result, which confirms that the microwave field affects the conductivity of this system through a localization mechanism, is the effect of a magnetic field on ΔG. We know that a magnetic field, like a microwave electric field, suppresses quantum-mechanical localization corrections, giving rise to a negative magnetoresistance.[7] In a $2D$ electron gas, this effect was first studied in Ref. 8. Figure 2(a) shows ΔG as a function of the magnetic field for a case in which the suppression of localization by a microwave field is predominant. We see that ΔG falls off with increasing magnetic field, and at a field of only $H \approx 6$ kG the microwave radiation has essentially no effect on the channel conductivity, since the quantum-mechanical corrections to the conductivity have already been suppressed by the magnetic field. Figure 2(b) shows that at high P_Ω, at which the heating effect is dominant, ΔG depends much more weakly on H.

The positive value of ΔG, evidence of a suppression of the quantum-mechanical corrections by the microwave field, is not observed over the entire range of densities of the $2D$ electrons studied in these experiments. At $N_S < 3 \times 10^{11}$ cm^{-2} and $N_S > 1.2 \times 10^{12}$ cm^{-2}, ΔG is negative. In the former case, the reason is the decrease in τ_φ with decreasing N_S; in the latter case, the reason is apparently an increase in the importance of heating with increasing density.

Unfortunately, a quantitative comparison of the experimental results with the theory of Altshuler *et al.*[1] is hampered by the fact that we do not know the exact value of the microwave power absorbed by the channel. All we can do is estimate the magni-

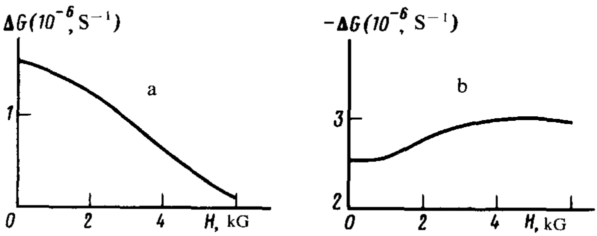

FIG. 2. a—Dependence of $\Delta G(P_\Omega)$ on the magnetic field at low microwave power levels ($P_\Omega = 1$ arbitrary unit); b—the same, at high microwave power levels ($P_\Omega = 100$ arbitrary units). $N_S = 9.5 \times 10^{11}$ cm^{-2}; $T = 4.2$ K.

tude of the effect on the basis of expression (5) in Ref. 1. Taking this approach, and setting $E_\Omega = 0.1$ V/cm and $\tau_\varphi = 2\times 10^{-11}$ s, we find $\Delta G = 1.5\times 10^{-6}$ S, in order-of-magnitude agreement with the experimental value [Fig. 2(a)].

In summary, the observed increase in the conductivity of a *2D* electron gas at a silicon surface during irradiation by a microwave field agrees with the predictions of the theory of Altshuler *et al.*[1]

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[1)] Over the temperature range studied, according to measurements of the temperature dependence, the conductivity decreases roughly linearly with increasing temperature.[2]

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