Submillimeter photoconductivity in inversion layers at a silicon surface

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A fast submillimeter photoconductivity has been detected in inversion layers at the Si surface. Because of the short photoresponse time (<40 ns) and the common properties of the resonant and nonresonant photoconductivities, this effect can be linked with the heating of a two-dimensional electron gas.

The negative submillimeter photoconductivity in a 2D electron gas at a silicon surface continues to be a topic of discussion (see , e.g., Refs. 1 and 2). Two mechanisms responsible for this photoconductivity are under discussion: photoconductivity which occurs as a result of heating the entire structure—the bolometric model—and photoconductivity which occurs as a result of purely electronic (including those involving heating) processes. Ambiguity stems, in particular, from the fact that until now there has been no direct experimental proof of either mechanism.

We have observed for the first time a fast (<40 ns) submillimeter photoconductivity resulting from Drude absorption (nonresonant photoconductivity) and from intersubband transitions (resonant photoconductivity). The presence of fast kinetics of photoconductivity (<40 ns) directly confirms that in each case the photoconductivity is of the same nature and that it is determined, as will be shown below, by the heating of electronic gas.

The experimental samples were metal-oxide-semiconductor transistors with the gate insulator thickness $d \sim 1200$ Å, assembled at the silicon surface which was deflected at an angle of 9.5° from the (100) surface with respect to the [011] direction. As was shown in Ref. 3, this arrangement makes it possible to excite optical transitions between the quantum subbands at a normal incidence of light. The maximum electron mobility μ in the inversion channel was 1.7×10^4 cm^2/(V·s) at the temperature of the experiment ($T = 4.2$ K). As the light source we used a pulsed submillimeter NH_3

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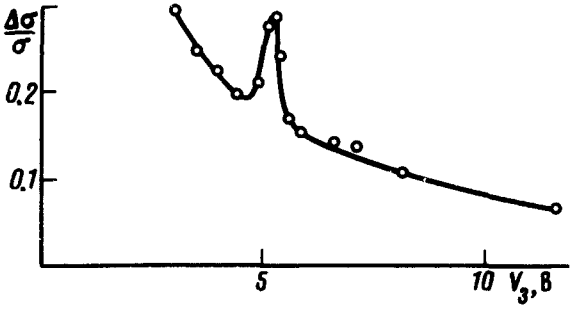

FIG. 1. Photoconductivity $\Delta\sigma/\sigma$ versus the gait voltage V_g, with $\mathbf{E}\perp[011]$.

laser which was optically pumped by a TEA CO_2 laser.[4] The wavelength of light was 90.55 μm ($\hbar\omega = 13.7$ meV) and the pulse duration was 40 ns. The power density level at the sample was varied from 10 to 10^3 W/cm^2. The sample was connected into the circuit for measuring the photoconductivity with a time resolution of 40 ns.

The curves for the photoconductivity versus the gate voltage varied, as expected, for various orientations of the electric vector **E** of light. When the vector **E** is oriented perpendicular to the [011] direction, the plot of the photoconductivity versus the gate voltage V_g (Fig. 1) has a sharp peak, suggesting the presence of an intersubband resonance between the "0" and "1" quantum subbands, the distance between which at $V_g = 5.1$ V corresponds to the photon energy of the radiation.[3] If **E** is oriented parallel to [011], there is no resonant increase in the photoconductivity.

The photoconductivity becomes saturated as the light intensity at the sample is increased (Fig. 2, a and b). Figure 2a shows that in the case of nonresonant photoconductivity there is a strong nonlinearity at small values of V_g, which decreases with increasing V_g and at $V_g = 7$ V it virtually disappears. Figure 2b shows plots for the total photoconductivity at the point corresponding to the exact position of the resonance ($V_g = 5.1$ V) and the point slightly shifted from it ($V_g = 5.2$ V). We see that the dependence on the light intensity is the same in each case. We also see that the ratio of the total photoconductivity to its nonresonant part is a constant in the investigated range of I near the resonance.

Let us discuss the results which we have obtained.

In the nonresonant region the photoconductivity is associated with the absorption by free carriers, for which the following expression has been derived in the case of scattering by irregularities:

$$\alpha = \frac{2e^3 g_v [\exp\Delta - 1]}{c m_{\parallel} \mu n \Delta^3 k T} \int_0^{\infty} \frac{(2x+\Delta)\,dx}{(1+\exp(x-\xi))(\exp(\xi-x)+\exp\Delta)}.$$

Here $\Delta = \hbar\omega/kT$ and $\xi = \epsilon_F/kT$, where e is the electron charge, g_v is the multiplicity of the valley degeneracy, c is the velocity of light, $m_{\parallel}$ is the effective longitudinal mass, n is the refractive index, ϵ_F is the Fermi energy, and k is the Boltzmann constant. The values of the absorption constant determined from the given expression are in good

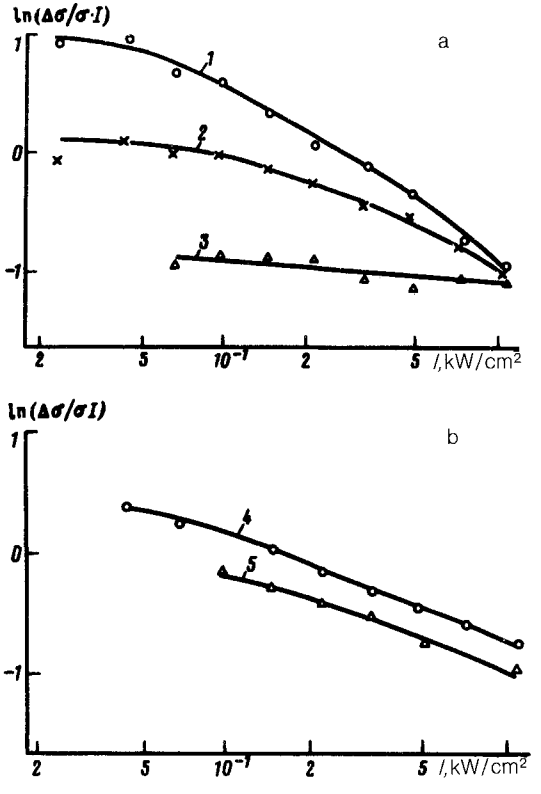

FIG. 2. Dependence of $(\Delta\sigma/\sigma)1/I$ on the light intensity, with E⊥[011] at various gait voltages. (a) Nonresonant photoconductivity, $V_g = 2$ V (curve 1), 4 V (curve 2), and 7 V (curve 3); (b) total photoconductivity at resonance (curve 4), $V_g = 5.1$ V, and near the resonance (curve 5), $V_g = 5.2$ V.

agreement with the available experimental data in the range of wavelengths[5] from 200 to 1000 μm.

The absorption of light in the indirect optical transitions causes photoexcitation of the charge carriers which transfer their energy to the bulk of the particles. This process increases the electron temperature T_e. In the test samples the value of μ decreases as the temperature is raised, which accounts for the observed negative sign of the photoconductivity. A decrease in the photoconductivity with increasing concentration of 2D electrons, n_s (Fig. 1) in this case causes the value $(1/\mu)\partial\mu/\partial T_e$ to decrease. The observed nonlinearity of the photoconductivity stems from a strong dependence of the energy loss on T_e (Ref. 6), which causes T_e, and hence the photoconductivity, to saturate with increasing I. The degree of nonlinearity changes with increasing V_g apparently because of the change in the dependence of the energy loss $\langle Q \rangle$ on the electron temperature. The possible dependence of $\langle Q \rangle$ on T_e and n_s was considered in Ref. 6.

The resonant photoconductivity occurs as a result of direct optical transitions between the zeroth subband and the first subband of the energy quantization. This photoconductivity occurs by means of two mechanisms.[7] The first mechanism involves a change in the mobility of the carriers, which participate in the absorption, due to the

difference in the mobilities of the carriers in the "0" and "1" subbands. In the second case the photoexcited carriers quickly go to the zeroth subband, releasing their excess energy, as in the nonresonant case, to the bulk of the particles, which accounts for the electron heating. The nonlinear dependence observed experimentally suggests that the resonant photoconductivity is caused by the electronic heating, since the nonlinearity of the photoconductivity at resonance and near it is the same only in this case (Fig. 2b).

We have thus observed for the first time a fast submillimeter photoconductivity and showed that both the nonresonant and resonant photoconductivities are caused by electron heating.

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