Oscillations in the photoconductivity of *n*-GaAs with monochromatic infrared illumination in a magnetic field

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The curve of the photoconductivity of *n*-GaAs versus the magnetic field during monochromatic infrared illumination reveals oscillations consisting of two series of extrema which are periodic along the inverse-field scale. One series of extrema stems from the nonmonotonic field dependence of the impurity magnetoabsorption coefficient, the other stems from a sharp step in the distribution function of nonequilibrium electrons.

In the present letter we report experiments which show that a feature at a fixed energy in the distribution function of nonequilibrium electrons leads to oscillations in the photoconductivity in a magnetic field. It thus becomes possible to detect a step in the distribution function which is associated with a change in the mechanism for energy relaxation as an electron undergoes a transition from the active region to the passive region.

The experiments are carried out at liquid-helium temperature in a magnetic field up to 70 kOe, produced by a superconducting solenoid. The samples of epitaxial *n*-GaAs, with a concentration $N_D - N_A = (2\text{–}5)\times 10^{14}$ cm^{-3}, with indium contacts, are illuminated by the beam from a cw CO_2 laser with a wavelength $\lambda = 10.6$ μm. In control experiments we also use a tunable CO_2 laser. The laser power is reduced to $\sim$0.5 W by means of a filter. Estimates based on the conductivity put the concentration of nonequilibrium electrons at $\sim 10^9$ cm^{-3} in our experiments at 1.3 K. The dependence of the derivative of the photocurrent, dJ/dH, on the magnetic field H is measured by the method of Ref. 1.

We see that the value of dJ/dH oscillates as a function of H. The shape of the observed lines corresponds to maxima of the photocurrent in fields where the derivative changes sharply. The shape and position of the extrema do not depend on whether the curves are recorded in a longitudinal geometry ($\mathbf{J}\|\mathbf{H}$) or a transverse geometry ($\mathbf{J}\perp\mathbf{H}$).

All of the observed lines can be put in two series, each of which is periodic along the scale of the inverse magnetic field (Fig. 2.). The arrows on curve 1 in Fig. 1 show extrema corresponding to the series with the longer period. The periods determined from the slope of the lines in Fig. 2 are $P_1 = 1.47\times 10^{-6}$ Oe^{-1} and $P_2 = 4.50\times 10^{-6}$ Oe^{-1}. The error in the determination of the period is 1%. The period of each series depends on the wavelength of the monochromatic light, falling off with decreasing λ, as can be seen from a comparison of curves 1 and 2 in Fig. 1. The first of these curves was recorded at $\lambda = 10.6$ μkm, while the second corresponds to a laser wavelength about 1% shorter.

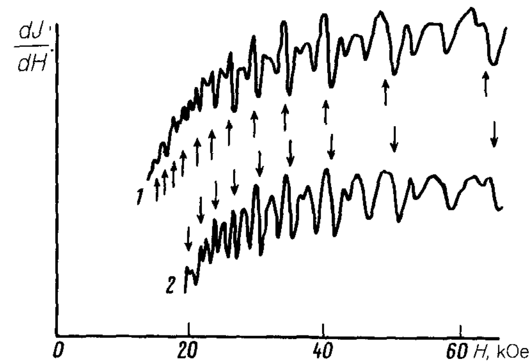

FIG. 1. The dependence $dJ/dH(H)$ for various wavelengths of the monochromatic illumination (see the text proper). $T = 1.3$ K.

What is the nature of the observed oscillations? It is easy to show that the series with the shorter period results from oscillations of the impurity magnetoabsorption coefficient. During photoionization of shallow donors by monochromatic infrared light, photoelectrons are produced at a fixed energy

$$E_0 = hc/\lambda - E_i \tag{1}$$

(E_1 is the donor ionization energy, equal to[2] 5.86 meV). Here and below, the energy in the conduction band is reckoned from the bandedge in the absence of a magnetic field. As H is varied, the optical absorption coefficient oscillates, increasing sharply whenever the carriers are produced near the bottom of the magnetic subband, i.e., when E_0 is equal to the energy of one of the Landau levels: $E_0 = \epsilon_n$. This relation, which is similar to the corresponding relation for the de Haas-van Alphen effect, describes oscillations with a period along the H^{-1} scale of[3]

$$P = 2\pi e / c\hbar S. \tag{2}$$

Here S is the area in k space of the extremal intersection of the isoenergy surface $\epsilon = E_0$ with the plane perpendicular to $\mathbf{H}$.

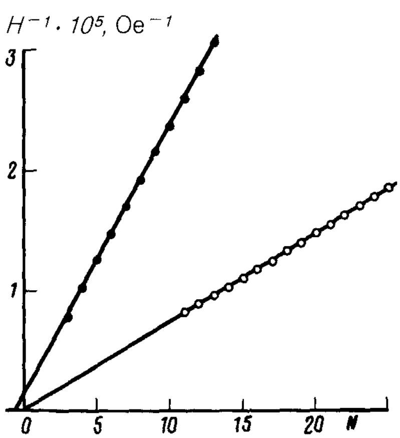

FIG. 2. Positions of the extrema along the H^{-1} scale versus the index for curve 1 in Fig. 1. Filled circles—Positions of the extrema of the series marked by the arrows in Fig. 1; open circles—positions of the extrema of the oscillations of the shorter period.

In our experiments, the thickness of the sample is considerably smaller than the reciprocal of the optical absorption coefficient, so that the oscillation in the absorption coefficient is accompanied by an oscillation in the total number of carriers produced by the illumination and thus an oscillation in the photoconductivity.

In our experiments, photoelectrons are produced at a significant distance from the bottom of the conduction band (at $\lambda = 10.6\ \mu$m, $E_0 = 112$ meV), where the nonparabolicity of the band has become important. The extent of the nonparabolicity can be determined by a method similar to that used in Ref. 4 in corresponding measurements for germanium. From the value of the period P_l we find $S_l = 6.48\times 10^{-13}$ cm^{-2}, which is $\sim 7\%$ greater than the value which would be obtained for a parabolic band with a mass $m(0) = 0.0665 m_0$, equal to the mass of electrons in GaAs near the band bottom.[2] On the other hand, the cross section calculated in the Kane model[5] is $S(E_0) = 6.54\times 10^{13}$ cm^{-2}, approximately the same as our measured value. Since the deviations from parabolicity are comparatively small, we need retain only the linear term in the energy dependence of the cyclotron mass, writing

$$m(\epsilon) = m(0)(1 + \alpha\epsilon)\,. \qquad (3)$$

Working from our measurements and expression (4) in Ref. 4, we find $\alpha = 0.96$ eV^{-1}.

Estimates show that the effect of quasibound Coulomb states in a magnetic field[6] and the incorporation of the dependence $E_i(H)$ do not change the results, within the experimental error.

What is the nature of the oscillations with the longer period? From the magnitude of their period (P_2) and (2) we find the corresponding cross section S_2; using it and the nonparabolicity of the band, we find the characteristic energy $E_2 = 38.0$ meV, reckoned from the bottom of the conduction band in the absence of a magnetic field. Although this energy is close to the energy of a longitudinal optical phonon ($\hbar\omega_0 = 36.75$ MeV; Ref. 7), the observed oscillation is not due to a magnetophonon resonance, since the period P_2 depends on λ (Fig. 1). We propose the following explanation for this effect. The energy E_2 is approximately equal to the difference $E_0 - \hbar\omega_0 = 38.5$ meV. Although this difference is greater than $\hbar\omega_0$, the photoproduced electrons lie in the passive region after the emission of two optical phonons in fields $H > 10$ kOe, because of the shift of the bottom of the conduction band up the energy scale. The subsequent relaxation of the electron energy can result only from impact ionization of donors and the emission of acoustic phonons. At an energy $E_0 - 2\hbar\omega_0$, a step should accordingly arise in the distribution function of the nonequilibrium electrons because of the dramatic slowing (by about two orders of magnitude) of the energy relaxation. Extrema are seen in the photocurrent whenever a Landau level intersects a step, i.e., under the condition $\epsilon_n = E_0 - 2\hbar\omega_0$.

We can also point out a specific mechanism for the appearance of the oscillations in the photocurrent.

Estimates show that for electrons with an energy $\epsilon \lesssim \hbar\omega_0$ the probability for impact ionization of donors exceeds the probability for the emission of acoustic phonons, except in energy regions with a high state density near the Landau level, where, according to the calculations of Ref. 8, the rate of energy relaxation with phonons increases, and the electron distribution function has minima. Impact ionization leads to, in addition to the energy relaxation, an additional generation of electrons into the conduction band. Each time a Landau level crosses the step in the distribution function as H is increased, there is an increase in the overall rate of this effective generation; this effect apparently leads to the oscillations of the photocurrent in our experiments.

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