Impact ionization in a semiconductor in a light wave

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(Submitted 7 July 1984)
Pis'ma Zh. Eksp. Teor. Fiz. 40, No. 5, 187–190 (10 September 1984)

Impact ionization due to heating of electrons in the field of a light wave has been observed in *n*-type InSb. The effect is analyzed theoretically.

The experiments reported here reveal the production of electron-hole pairs in *n*-type InSb ($\epsilon_g = 224$ meV) when excited by light with a photon energy ($\hbar\omega = 13.7$ meV) amounting to only 1/16 of the gap width. We will show that this effect results from an impact ionization caused by electrons heated in the electric field of the light wave.

The light source is an NH_3 laser optically pumped by the beam from a CO_2 laser.[1] The wavelength is $\lambda = 90.55\ \mu m$, the output pulse length is 40 ns, and the intensity of the light incident on the sample is varied up to 2 MW/cm^2. We study the kinetics of the photoconductivity, the relative photoconductivity $\Delta\sigma/\sigma$ as a function of the incident light intensity I, and the recombination emission of InSb in the intrinsic region. The measurements are carried out with *n*-type InSb samples with densities ranging from 9.3×10^{12} to 2.3×10^{15} cm^{-3} at $T = 78$ K.

The experiments on an *n*-type InSb sample with a density of 2.3×10^{15} cm^{-3} reveal that a luminescence appears in the region of the intrinsic absorption band of the indium antimonide during excitation by light with $\lambda = 90.55\ \mu m$. Figure 1 shows some corresponding oscilloscope traces. This luminescence is clearly evidence of the appearance of electron-hole pairs, despite the fact that the energy of the exciting photon is much smaller (by a factor of about 16) than the width of the energy gap. The appearance of these electron-hole pairs gives rise to a photoconductivity, whose kinetics is determined by the electron lifetime. We know that in InSb at $T = 78$ K this lifetime is determined by radiationless and radiative recombination channels and depends strongly on the density of dark carriers and the excitation level. The photore-

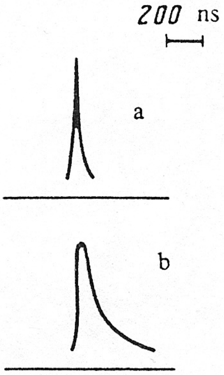

FIG. 1. a—Oscilloscope trace of the exciting pulse from the NH_3 laser ($\hbar\omega = 13.7$ meV); b—oscilloscope trace of the recombination emission of electron-hole pairs ($n = 2.3\times10^{15}$ cm^{-3}, $T = 78$ K).

sponse times observed by us in the various samples ranged from hundreds of nanoseconds to several microseconds and correspond well to data obtained on the lifetimes in InSb during ordinary excitation,[2] with $\hbar\omega \geqslant \epsilon_g$.

We attribute the appearance of electron-hole pairs to impact ionization by electrons heated in the intense light wave. Figures 2a and 2b show $\ln(\Delta\sigma/\sigma)$ versus E^{-2}, where E is the electric field amplitude of the light wave. There are two linear regions, in which the behavior of the relative photoconductivity can be described well by

$$\frac{\Delta\sigma}{\sigma} = A_i \exp\left\{-\left(\frac{E_{0i}}{E}\right)^2\right\}. \tag{1}$$

The characteristic fields here are $E_{01} = 7\times10^4$ V/cm and $E_{02} = 3\times10^4$ V/cm; these fields are essentially independent of the density according to experiments carried out over the density range from 9×10^{12} to 2.3×10^{15} cm^{-3}. The coefficients of the exponential functions, A_1 and A_2, on the other hand, increase substantially with increasing density. We believe that region 1′ is caused by interband impact ionization, while region 2′ is caused by the impact ionization of an impurity level of a structural defect roughly in the middle of the energy gap.

The pairs are produced by electrons with energies exceeding the threshold ϵ_i, which is 0.25 eV for direct interband impact ionization in InSb at $T = 78$ K (ϵ_i is greater than $\epsilon_g = 0.22$ eV because of the Kane nature of the spectrum in InSb). As the electrons are heated by the high-frequency field of the wave, the momentum distribution of the carriers is slightly asymmetric if the light frequency ω is far higher than the collision rate ν, and this momentum distribution can be characterized by the symmetric part of the distribution function, $f_0(\epsilon)$, averaged over the period. This average symmetric part depends on only the energy. To find $f_0(\epsilon)$ at high energies $\epsilon > \hbar\omega_0$ (ω_0 is the frequency of an optical phonon), we use the classical kinetic equation. This approach is legitimate under two conditions: $\hbar\omega \ll \bar{\epsilon}$ ($\bar{\epsilon}$ is the scale energy for the decay of the distribution function) and $(eE)^2/\hbar m\omega^3 \gg 1$. These stipulations are satisfied under the conditions under consideration here. From the kinetic equation we find

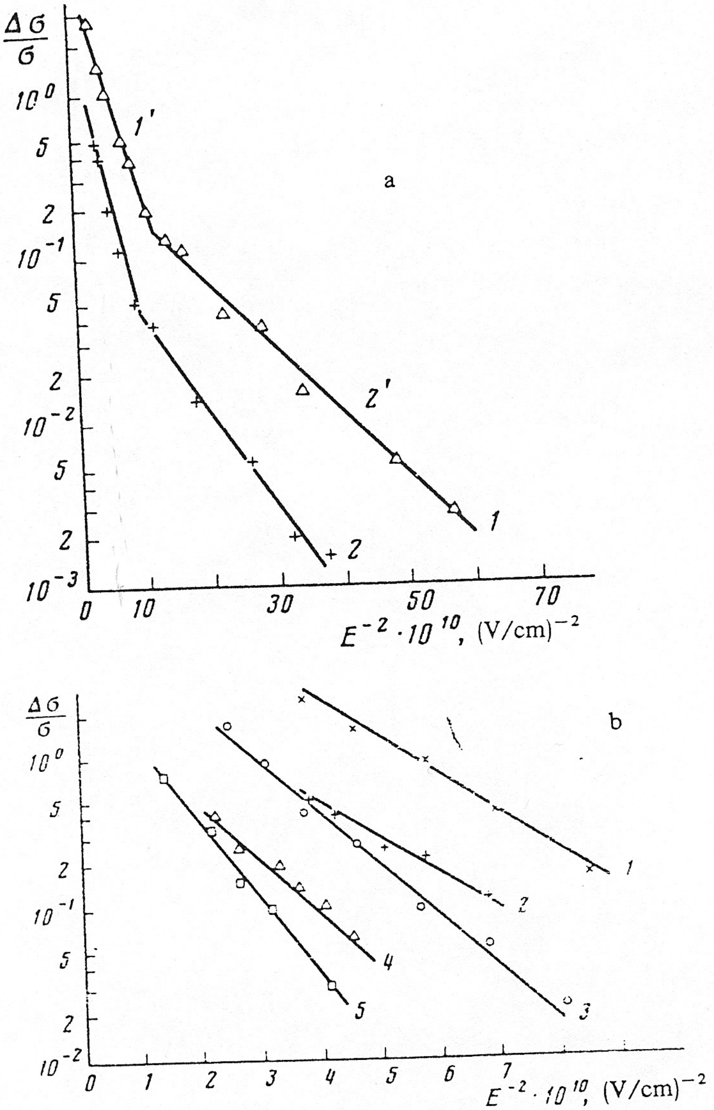

FIG. 2. Relative photoconductivity in *n*-type InSb at $T = 78$ K versus the electric field of the electromagnetic wave. a: 1—$n = 9.3\times10^{12}$ cm^{-3}; 2—3.67×10^{13}. b: 1—$n = 1.49\times10^{14}$ cm^{-3}; 2—3.67×10^{13}; 3—3.4×10^{14}; 4—2.3×10^{15}; 5—6.38×10^{14}.

$$\frac{e^2E^2\nu_t(\epsilon)v(\epsilon)}{6\omega^2}\,\frac{\partial f_0}{\partial\epsilon} + \hbar\omega_0\nu(\epsilon)f_0(\epsilon) = 0, \qquad (2)$$

where e is the electron charge, $v(\epsilon)$ is the velocity of an electron with an energy ϵ, $\nu(\epsilon)$ is the rate of collisions with optical phonons, and $\nu_t(\epsilon)$ is the transport frequency. Th first term in Eq. (2) describes the acquisition of energy by electrons in the high-frequency field of amplitude E. At $\omega\gg\nu$, the electrons can acquire energy only if elasti collisions occur and transfer kinetic energy from the longitudinal motion (longitudina with respect to the field) to the transverse motion. The second term in (2) describes th energy loss in collisons with longitudinal optical phonons. The derivation of (2) incorporates only the interaction with longitudinal phonons, which is quasielastic in th pertinent energy range. According to Kane's model we have

$$\epsilon(p) = \sqrt{\frac{\epsilon_g^2}{4} + \frac{p^2\epsilon_g}{2m_c}} - \frac{\epsilon_g}{2}\,; \qquad v(\epsilon) = \frac{\partial\epsilon}{\partial p} = 2\sqrt{\frac{\epsilon_g}{2m_c}}\,\frac{\sqrt{\epsilon(\epsilon+\epsilon_g)}}{2\epsilon+\epsilon_g}, \tag{3}$$

where m_c is the mass of an electron at the bottom of the conduction band. We then have the following expressions for the collision rates at $\epsilon \gg \hbar\omega_0$:

$$\nu_t(\epsilon) = \frac{e^2 m_c \omega_0}{\hbar\sqrt{2m_c\epsilon_g}}\left(\frac{1}{\kappa_\infty} - \frac{1}{\kappa_0}\right); \qquad \nu(\epsilon) = \nu_t \ln\frac{4\epsilon(\epsilon+\epsilon_g)}{\hbar\omega(2\epsilon+\epsilon_g)}.$$

In our case the condition $\omega \gg \nu_t$ is satisfied with a wide margin, since we have $\omega = 2\times10^{13}$, and $\nu_t(\epsilon)$ is $\sim 10^{11}$ at a typical value of the energies involved here.

From (2) we find the following expression for the distribution function:

$$f_0(\epsilon) \sim \exp\left\{ -\frac{6\hbar\omega_0\omega^2}{e^2E^2}\int_{\hbar\omega}^{\epsilon} \frac{\ln\dfrac{4\epsilon(\epsilon'+\epsilon_g)}{\hbar\omega_0(2\epsilon'+\epsilon_g)}}{v^2(\epsilon')}\,d\epsilon' \right\} \tag{4}$$

The impact ionization coefficient is proportional to the value of $f_0(\epsilon)$ at $\epsilon = \epsilon_i$. It follows that the relative photoconductivity is an exponential function of E^{-2} [Eq. (1)], and we find expressions for the characteristic fields E_{01} and E_{02}. For interband impact ionization we have

$$E_{01} = \left(\frac{3\hbar\omega_0\omega^2 m_c}{e^2\epsilon_g} \int_{\hbar\omega}^{\epsilon_i} \frac{(2\epsilon+\epsilon_g)^2 \ln\dfrac{4\epsilon(\epsilon+\epsilon_g)}{\hbar\omega_0(2\epsilon+\epsilon_g)}}{\epsilon(\epsilon+\epsilon_g)}\,d\epsilon \right)^{1/2} \tag{5}$$

If we assume that region 2 in Fig. 2a corresponds to impact ionization of impurities in the middle of the energy gap, then for E_{02} we have expression (5) with $\epsilon_i = \epsilon_g/2$.

Calculations from (5) yield $E_{01} = 6.2\times10^4$ V/cm and $E_{02} = 3.7\times10^4$ V/cm. We see that the field dependence of $\Delta\sigma/\sigma$ and the values of the fields E_{01} and E_{02} agree well with experiment.

It may be that impact ionization in the field of the light wave is responsible for the appearance of electron-hole pairs in Ge at $T = 300$ K during excitation with a CO_2 laser beam.[3,4]

We wish to thank V. I. Perel' for a useful discussion.

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Translated by Dave Parsons
Edited by S. J. Amoretty