Effect of cooling of carriers in semiconductors by light

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In the case of intraband absorption of light in semiconductors, the energy of some of the free carriers interacting with the light increases by an amount equal to the light quantum $\hbar\omega$. The photocarriers excited by the light relax in energy as a result of collisions with the bulk of the carriers and via emission of optical and acoustic phonons. The light energy transferred via the interelectron collision channel heats the equilibrium carriers and changes their mobilities, and leads as a result to the appearance of photoconductivity.[1,2]

However, one can visualize also a situation that is the exact opposite, namely cooling of free carriers by light; this situation can be realized in direct intraband transitions in semiconductors of the p-Ge type, when the initial photoelectron energy ϵ_i is fixed and is larger than the average carrier energy, and the energy-relaxation time of the photocarriers on the optical phonons is much shorter than the energy relaxation time in interelectron collisions. It is necessary here that the photocarrier have after emission of n optical phonons a final energy ϵ_f smaller than ϵ_i. The produced energy deficit, by virtue of the interelectron collisions, is distributed in the system of the majority carriers, which can be regarded as having an effective temperature T_e lower than the lattice temperature T_0.

We have experimentally observed this effect in p-Ge excited with a tunable Q-switched CO_2 laser. The measurement method was based on an investigation of the intraband photoconductivity following excitation by two emission lines with wavelengths $\lambda = 10.6$ and $9.54\ \mu$. If

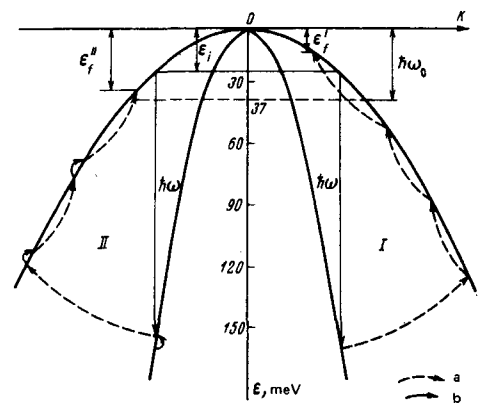

FIG. 1. Optical transitions and of energy relaxation of photoholes in p-Ge at $\hbar\omega = 130$ meV. I-Low hole densities, II-high hole densities; a-transitions with emission of optical phonons; b-multiple transitions resulting from interhole collisions; k-wave vector.

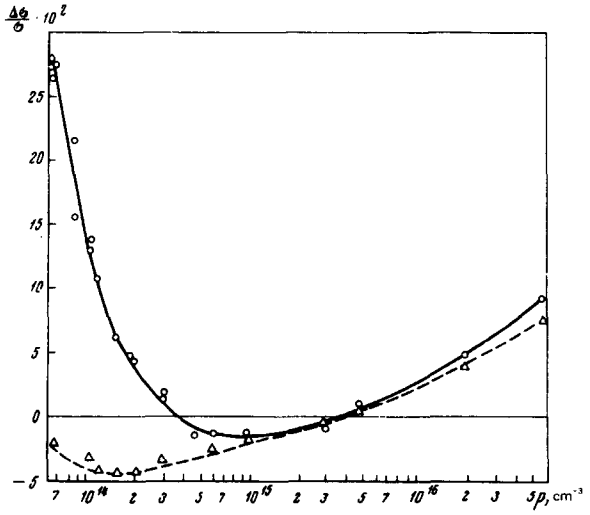

FIG. 2. Dependence of the photoconductivity on the concentration at $T = 77.3$°K: ○) $\lambda = 9.54\ \mu$; △) $\lambda = 10.6\ \mu$; $I = 10^{25}$ quanta/cm^2 sec.

$T_0 - T_e < T_0$, then it can be shown that the relative photoconductivity $\Delta\sigma/\sigma$, T_e, and the carrier mobility μ are connected by the relation

$$\frac{\Delta\sigma}{\sigma} = \frac{1}{\mu}\frac{\partial\mu}{\partial T_e}\Big|_{T_e = T_0}(T_e - T_0). \qquad (1)$$

Figure 1 shows the optical transitions and the subsequent relaxation of the energy of the photoholes in germanium for a 9.54-μ line ($\hbar\omega - 130$ meV) in a plane passing through the center of the Brillouin zone. The initial state from which the holes are excited, has an energy $\epsilon_i = 28$ meV for the 9.54-μ line and 22 meV for the 10.6-μ line ($\hbar\omega = 117$ meV).[3] When holes are excited by radiation having these quantum energies, the photoholes can emit respectively either four or three optical phonons ($\hbar\omega_0 = 37$ meV) and go over into final states with energies 10 and 20 meV. For the 9.54-μ line, we get cooling of the holes and a positive photoconductivity in the low-concentration region, in which the mobility is determined by scattering by the phonons. For the 10.6-μ line, to the contrary, under the same observations conditions, this leads to heating of the holes and to negative photoconductivity.

Plots of the experimental relative photoconductivity against the hole density and the temperature are shown in Figs. 2 and 3. It is seen from Fig. 2 that at $T_0 = 77.3$ °K the photoconductivity for the 10.6-μ lines remains negative from the very smallest densities up to $p = 4\times10^{15}$ cm^{-3}, at which it reverses sign as a result of the increase of the impurity-scattering fraction.[2] For the 9.54-μ line, on the other hand, at low densities the photoconductivity is positive and is more than six times larger in absolute magnitude than the value for the 10.6-μ line. With increasing hole density, $\Delta\sigma/\sigma$ decreases rapidly to zero and its subsequent density dependence is similar to that for the 10.6-μ line. With increasing temperature, the photoconductivity on the 9.54-μ line decreases and reverses sign near 180 °K. We note that at the same densities, the photoconductivity at the 117-meV radiation remains negative in the entire temperature range.

Convincing evidence that the observed photoconductivity is of intraband and not of the impurity type is afforded by the following facts: the linear dependence of $\Delta\sigma/\sigma$ on the light intensity up to the experimentally realized fluxes $I = 10^{25}$ quanta/cm^2 sec, the stationary character of the responses to the signals at light-pluse durations ~0.15 μsec, the superlinear dependence of $\Delta\sigma/\sigma$ on the density for the 9.54-μ line, and, most importantly, the qualitatively different character of the photoconductivity for two emission lines that have close quantum energies, the difference between which amounts to only 13 meV. If the observed photoconductivity were to be due to transitions to impurity levels, produced for example by structure defects, such deep levels would have an unusually small width, of approximately several meV, something that does not occur in semiconductors. Thus, the experimentally observed photoconductivity is of the intraband type, and the reversal of its sign under conditions of pure lattice scattering on going from the 10.6-μ line to the 9.54-μ line is due to a transition from heating of the hole gas to cooling. In addition to cooling of the bulk of the carriers as a result of the decrease in their average energy, there can also occur in the experiment a photoconductivity that is directly connected with a shift of a group of holes with energy ϵ_i to an energy ϵ_f, with a corresponding decrease of the mobility. However, even at the smallest densities realized in the experiment, this effect is estimated to be smaller in magnitude than the experimentally observed one. In turn, the conditions for Maxwellization are satisfied in our case. Using the experimental values of $\Delta\sigma/\sigma$ and formula (1), we find that for p-Ge samples with density 7×10^{13} cm^{-3} and light intensity ~10^{25} quanta/cm^2 sec, the cooling amounts to 30 °K. An estimate of the cooling temperature from the balance equation, with allowance for the losses to acoustic and optical phonons of the bulk of the carriers, yield for the effect a value that coincides within the limits of experimental error with that given above.

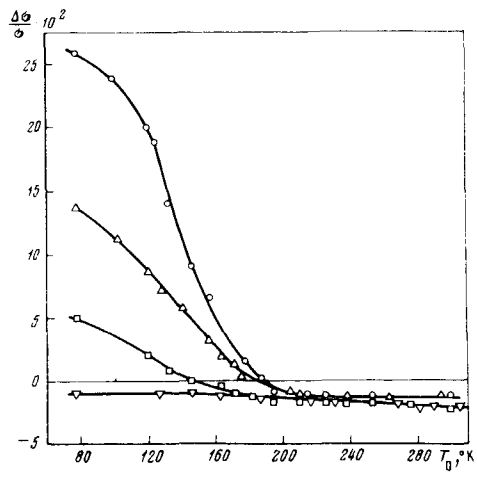

FIG. 3. Temperature dependence of photoconductivity: ○) $p = 6\times10^{13}$ cm^{-3}; △) $p = 10^{14}$ cm^{-3}; □) $p = 1.5\times10^{14}$ cm^{-3}; ▽) $p = 6\times10^{14}$ cm^{-3}; $I = 10^{25}$ quanta/cm^2 sec.

With increasing density, the cooling of the hole gas gives way to heating, on the one hand because of the increase in the fraction of energy introduced into the system of the majority holes by the photoholes with energy larger than $\hbar\omega_0$, and on the other hand as a result of the change in the number of emitted optical phonons from 4 to 3, and of the value of ϵ_f in accordance with Fig. 1, due to a shift in the energy of the photoholes as a result of the interhole collisions and as a result of emission of acoustic phonons by the holes. The observed transition takes place at lower densities than expected on the basis of simple estimates. The possible reason is that no account is taken of the real band structure (nonsphericity, nonparabolicity) in the indicated estimates.

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