INTRABAND PHOTOCONDUCTIVITY IN p-Ge

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Owing to the presence of optical transitions between the subbands V_1 and V_2 of the germanium valence band, intense absorption of infrared radiation occurs in the 9 - 25 μ band [1]. This changes the hole mobility, and a change of conductivity should be observable in principle. However, as a result of the very short relaxation times, the use of ordinary radiation sources is ineffective. In this respect, the CO_2 laser, with a wavelength 10.6 μ, is convenient. When a 0.117-eV quantum is absorbed, carriers with approximate energy 0.028 eV[1)] move from the heavy-hole band V_1 into the light-hole band V_2, the effective mass decreasing by a factor 5.7. Subsequently the light holes emit or absorb optical phonons within a time τ_ℓ, and return to the V_1 band, where they are thermalized after a time τ_h'' [3, 4]. In this case the photoconductivity can be expressed in the form:

$$\Delta\sigma = e[\mu_\ell \Delta p_\ell + \mu_h' \Delta p_h'' - \mu_h \Delta p] = kI \frac{e^2}{m_h}\left[\frac{m_h}{m_h} r_\ell^2 + r_h' r_h'' - (r_\ell + r_h')r_h\right] \tag{1}$$

$$\Delta p = \Delta p_\ell + \Delta p_h''$$

where Δp_ℓ is the concentration of the non-equilibrium "light" holes, $\Delta p_h''$ is the concentration of the "hot" heavy holes, τ_h' is the effective momentum-relaxation time of the "hot" hole in the V_1 band prior to its thermalization, m_ℓ is the mass of the hole with energy 0.145 eV in the V_2 band, m_h is the hole mass in the V_1 band, K is the absorption coefficient, and I is the intensity of the light in the sample.

At low impurity concentrations, when the hole mobility is determined by the lattice vibrations, the most significant term in (1) is the third. Indeed, according to [4], we have

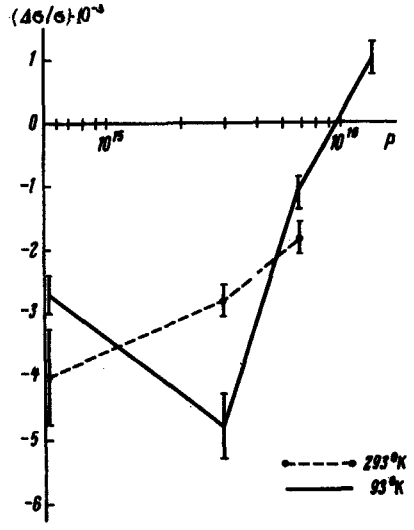
$$\frac{r_\ell(\epsilon_2 = 0{,}145\text{ eV})}{r_h(\epsilon = 0{,}028\text{ eV})}\Big|_{T=293^\circ K} \approx 0{,}2, \quad \frac{r_\ell(\epsilon = 0{,}145\text{ eV})}{r_h(\epsilon = 0{,}028\text{eV})}\Big|_{T=77^\circ K} \approx 0{,}05.$$

The relaxation time of the "hot" heavy holes τ_h' is likewise much shorter than the relaxation time of the "cold" ones τ_h. The relative photoconductivity should then have a negative sign and should depend little on the temperature between room and nitrogen temperatures.

At high concentrations, when scattering by charged impurities begins to play a role, all the foregoing relations between the times are altered. The relaxation times increase with increasing carrier energy. This, together with the decrease of the mass (on going over to the V_2 band), leads to a predominant influence of the first term in (1), and a changeover to positive photoconductivity becomes possible. Indeed, positive photoconductivity was indeed observed in [5] at room temperature in Ge with hole density 10^{17} - 10^{18} cm^{-3}.

1) The law of energy and momentum conservation with allowance for nonparabolicity of the band V_2 [2] is satisfied only for carriers with energy 0.028 eV.

To check on the foregoing considerations, we investigated the photoconductivity in p-Ge at room and nitrogen temperatures, using samples with different free-carrier concentrations. The light source was a Q-switched CO_2 laser with a pulse duration ~ 0.5 μsec and frequency 200 Hz. The pulse power was 2 kW. The radiation was focused with a long-focus lens on the samples (which measured 3 x 1 x 0.6 mm) perpendicularly to the applied external field, and the observed photoconductivity signals had exactly the same shape as the laser pulses.



Relative photoconductivity vs. free-carrier density

The figure shows plots of the relative photoconductivity $\Delta\sigma/\sigma$ vs. hole concentration at temperatures 293 and 93°K. As expected, negative photoconductivity was observed at low concentrations at both temperatures[1)]. With increasing carrier concentration, a transition to positive photoconductivity[2)] takes place at T = 93°K. It is also seen from the figure that the absolute values of $\Delta\sigma/\sigma$ obtained at different temperatures are close to each other.

Attention is called to the growth of the negative photoconductivity with concentration (T = 93°K) in the case when the latter is small. This may be connected with the fact that when the holes relax from band V_2 to band V_1 and are subsequently thermalized, an appreciable number of non-equilibrium phonons is produced, and these make an additional contribution to the carrier scattering process. Such a process can take place if: a) the time of interphonon interaction τ_{phph} is much longer than the time of electron-phonon interaction τ_{eph}, and b) if the spectrum of the nonequilibrium phonons includes a large number of them with momenta from 0 to $2k_h$ (k_h - momentum of hole in V_1 band).

Estimates show that both conditions are satisfied in our case. Naturally, this process can be significant only at low temperatures.

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[5] J. M. Feldman, Appl. Phys. Lett. 9, No. 5 (1966).

1) It should be noted that the absolute value of the observed photoconductivity turned out to be sensitive to the surface finish, particularly in the case of high-resistance samples. This is connected with the presence of a competing process, positive photoconductivity due to the presence of surface states. To obtain reliable and reproducible data, we have therefore performed measurements on a large number of samples of each concentration but with different surface finishes.

2) It was impossible to perform measurements on samples with high concentrations at room temperature, in view of the appearance of parasitic thermal effects connected with the large absorption coefficient.