Negative intraband photoconductivity in tellurium

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A negative photoconductivity has been observed in the intraband absorption region of tellurium at $T \lesssim 20$ K in both $\mathbf{E}\|\mathbf{C}_3$ and $\mathbf{E}\perp\mathbf{C}_3$ light polarization. The effect is comparable in magnitude to the photoconductivity in the fundamental absorption region. The relaxation times are ~ 10–10^3 sec. This effect is associated with dislocations.

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The band-to-band negative photoconductivity (NPC), which has been observed relatively rarely, is usually attributed to complicated relaxation processes of excited carriers in the presence of impurity levels.[1,2] NPC has also been observed in the presence of intraband absorption in a semiconductor as a result of illumination by a high-power laser source.[3–6] The effect, which is primarily due to "hot" carriers, is characterized by short relaxation times ($\sim 10^{-12}$ sec). The intraband photoconductivity is usually several orders of magnitude lower than the photoconductivity caused by transitions between the valence band and the conduction band.

We have observed an NPC as a result of intraband absorption in a semiconductor, which is comparable in magnitude to the photoconductivity in the fundamental absorption region. The test object is a tellurium single crystal ($\epsilon_g = 340$ meV, the distance between the two upper valence bands is $2\Delta = 126$ meV). The relaxation times are ~ 10–10^3 sec. The effect was observed at $T \lesssim 20$ K.

Ten samples with hole densities of $(2–90)\times 10^{14}$ cm^{-3} were investigated. Typical sample dimensions were $2\times1\times5$ mm. The samples were illuminated with a globar through the prism monochromator of the IKS-21 spectrometer. Direct incidence of light on the contacts was eliminated. The transmission and photoconductivity spectra were recorded simultaneously for $\mathbf{E}\|\mathbf{C}_3$ and $\mathbf{E}\perp\mathbf{C}_3$ light polarization ($\mathbf{C}_3$ is the trigonal symmetry axis of tellurium). The modulation frequency was 0–6000 Hz, the temperature was 1.7–40 K, the pressure was up to 4 kbar, and the spectral interval was 2–11 μm. The current through the sample was 0.1 mA.

The NPC effect was observed in the intraband absorption region in all the investigated samples. The resistance of the samples increased linearly with the intensity I of the incident light within the interval 10^{12}–10^{14} quanta/sec; the maximum increase amounted to $\sim 3\%$. At 1.5 K the steady-state, relative photoconductivity $\Delta\sigma/\sigma_0$, normalized to T, turned out to be only two to five times smaller than that in the fundamental absorption region.

The typical steady-state photoconductivity and absorption spectra measured simultaneously in the intraband-transition region are shown in Fig. 1. As Fig. 1 shows, the correlation between the NPC spectrum and the intraband absorption spectrum is

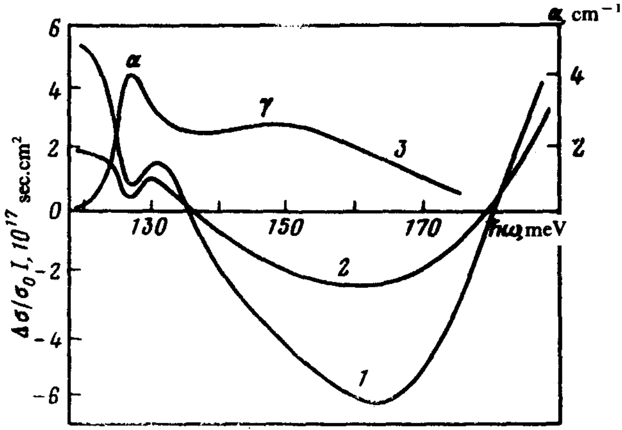

FIG. 1. Spectra of steady-state photoconductivity (1,2) and absorption (3) of tellurium in the intraband transition region. $p = 9 \times 10^{14}$ cm^{-3}, $T = 1.9$ K, light polarization E$\|C_3$ (1,3) and E$\perp C_3$ (2).

good. The NPC is observed in the region of the broad γ-absorption-peak. The α-absorption-peak ($E_\alpha = 2\Delta = 126$ meV) coincides in energy with the local minimum in the photoconductivity spectrum. This coincidence is not accidental, since both extrema are shifted at the same rate with the application of pressure.

There are, however, significant differences between these spectra. In accordance with the selection rules and the literature data, we detected no absorption in the transmission experiments for the E$\perp C_3$ light polarization (within an accuracy of 0.2 cm^{-1}). Nevertheless, NPC has been observed for E$\perp C_3$, where the magnitude is only about a factor of two smaller than that for E$\|C_3$ (Fig. 1).[1)]

Moreover, the NPC and the absorption spectra differ greatly in values of their absorption coefficient, which was estimated from the steady-state NPC and measured in the absorption experiments for E$\|C_3$. Since the observed NPC is unipolar, the recombination is linear and the absorption is small, for the steady-state case

$$\frac{1}{I}\ \frac{\Delta\sigma}{\sigma_0} = \frac{\beta\alpha\tau}{p_0}, \qquad (1)$$

where β is the quantum yield, α is the absorption coefficient, τ is the lifetime of the nonequilibrium holes, and p_0 is the equilibrium hole density. Assuming that τ corresponds to the relaxation time of the NPC signal (i.e., ignoring the trapping levels whose existence is difficult to establish in the picture of intraband transitions) and that $\beta = 1$, we determine $\alpha_\| \approx \alpha_\perp \sim (10^{-3}$–$10^{-5})$ cm^{-1} for the different samples from the experimental values of I, $\Delta\sigma$, σ_0, τ, p_0. The light transmission experiments give $\alpha_\| \sim 1$–10 cm^{-1}.

Before attempting to explain the observed effect, we would like to note that it cannot be explained by the bolometric effect or by a change in the hole mobility as a result of a simple transition of holes from the upper valence band to the lower, since in both cases a positive photoconductivity appears in tellurium at $T \lesssim 20$ K. It is unlikely that the effect is related to the presence of a known impurity level near the lower valence band, since in this case it is hard to explain the long relaxation times and the existence of the effect in the $E \perp C_3$ polarization.

Investigation of the NPC characteristics in samples subjected to an annealing (3 hours at 600 K), which had different doping levels and different surface conditions (natural cleavage, treatment in various etchants[2)]), showed that the point defects, doping impurities and surface states apparently cannot be the cause of the observed NPC.

A qualitative explanation of all the experimental data can be given if we assume that NPC is caused by absorption in the regions that are small in total volume, in which the selection rules for intraband transitions break down and in which there are traps for the excited holes. The regions near the dislocations can have such properties. Symmetry distortions[8] in our case are possible and hence violations of the selection rules. On the other hand, the deformation dislocation potential, together with the Coulomb potential of its center, can form a barrier-type potential. A hole with excess energy that is excited near the dislocation overcomes the potential barrier of the dislocation and is captured by a dislocation level, thereby excluding itself from the conduction process for a long time.

This assumption is consistent with the fact that a plastic deformation of the samples has a significant effect on the value of α that was estimated from Eq. (1). Thus, for example, a 3% deformation of a sample at 300 K led to an increase in α by a factor of 50–100 (the NPC spectrum in this case changes slightly and τ decreases). The density of electroactive dislocations determined from the etch pits increased in this case by more than an order of magnitude.

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[1)]The existence of a large photoconductivity under conditions when the transmission experiments indicate almost complete absence of absorption is another proof of the fact that photoconductivity sometimes is a more sensitive method than light absorption.

[2)]We also performed a special experiment[7] in which the light was incident at the center of the sample's end face in order to significantly reduce the influence of the surface of the photoconductivity.

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