
ELECTRONIC AND OPTICAL PROPERTIES
OF SEMICONDUCTORS

Specific Features of Intrinsic Photoconductivity Spectra of Copper-Compensated Indium Phosphide

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Abstract—The intrinsic photoconductivity of copper-compensated indium phosphide has been studied. It is found that mechanical polishing of a sample surface gives rise to an additional photoconductivity peak in the region of the fundamental absorption edge. This peak disappears upon storage of the sample. The dependence of the shape of the photoconductivity spectrum on the storage time, electric-field strength, and position of the light spot with respect to the contacts was determined. The results are explained in terms of variation in the lifetime of nonequilibrium carriers across the sample thickness. An expression qualitatively describing the photoconductivity spectra is presented.

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1. INTRODUCTION

Doping of gallium and indium phosphides with copper leads to pronounced compensation and makes these compounds highly sensitive to light. The particular interest in InP:Cu is due to the fact that its photoconductivity (PC) excitation spectrum coincides with the emission spectrum of commercial light-emitting diodes based on GaAs, which makes it possible to regard InP as a promising material for fabrication of high-efficiency resistor optical couplers. Reasons for the high photosensitivity of InP:Cu and GaP:Cu samples have not been elucidated conclusively, but there is evidence that two levels spaced by 0.2 eV lie in the energy gaps of the semiconducting phosphides above the valence band top [1]. Pribylov et al. [2] used the concept of the possible relationship between these levels and specific features of copper localization in the GaP lattice to explain why an additional photoconductivity peak appears for GaP:Cu samples in the range of the fundamental absorption edge. Assuming that the copper impurity behaves in about the same way in the above-mentioned semiconducting phosphides, we formulated the goal of our study as a search for conditions in which spectral anomalies of the intrinsic photoconductivity are observed in InP:Cu, because no data of this kind have been obtained previously.

2. MAIN EXPERIMENTAL RESULTS

Czochralski-grown indium phosphide with an electron density of $9.3 \times 10^{15} \text{ cm}^{-3}$ was doped with copper. The diffusion saturation with copper was performed from copper films deposited on both of the sample sur-

faces, in quartz cells evacuated to a residual pressure of 10^{-5} Torr at temperatures of 800–950°C over the course of 1–12 h.

After annealing, the cells were quenched in cold water and the samples were ground with an abrasive powder and polished with a diamond paste. Measurements of the free carrier density in quenched samples by the Hall effect method demonstrated that doping can yield both high-resistivity ($n = 2.5 \times 10^8$ – 10^9 cm^{-3}) and low-resistivity ($n = 1.5 \times 10^{16} \text{ cm}^{-3}$) materials. Contacts of a liquid In–Ga eutectic were deposited onto the polished surface of the samples in the form of two parallel 2.5–3-mm-long strips spaced by 2.6–2.8 mm. The photoconductivity signal was measured in a dc field with lock-in detection at modulation frequencies of 9–400 Hz. High-resistivity samples were taken for the study in order to obtain a current in an illuminated sample substantially exceeding the dark value.

Immediately after the mechanical polishing of the sample surface with an ASM-0.5 diamond paste, a two-peaked photoconductivity spectrum is observed in the region of the fundamental absorption band (Fig. 1). It was found that the short-wavelength peak disappears approximately two days after the polishing as a result of storage of a sample in air under normal conditions. We monitored the dynamics of disappearance of the short-wavelength peak in the course of time (see inset in Fig. 1). The peak completely disappeared on annealing a freshly polished sample at 405°C for 15 min.

We studied the influence exerted by the electric field on the shape of the PC spectrum of a given sample immediately after polishing. The experiment was performed at voltages of 70 to 460 V. For clarity, Fig. 2

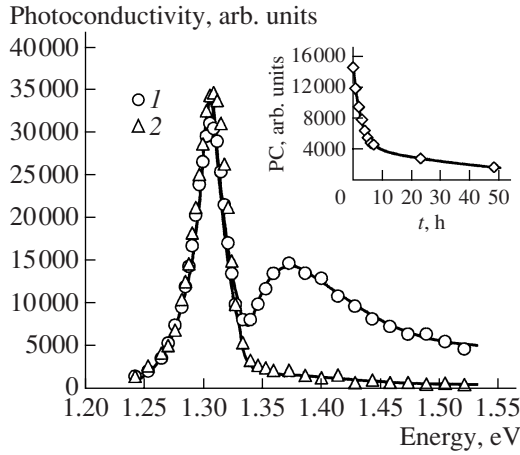


Fig. 1. Photoconductivity spectrum of an InP:Cu sample immediately after polishing and after two days in storage. Experimental data: (1) after polishing, at a voltage of 250 V; and (2) in 48 h at a voltage of 250 V. Solid lines represent approximation with expression (1). The inset shows the degradation dynamics of the short-wavelength ($E = 1.375$ eV) PC peak.

shows PC spectra only for voltages of 70 and 460 V. The inset of Fig. 2 shows how the PC increases with voltage at photon energies of 1.32 eV (near the maximum of the main peak) and 1.36 eV (near the maximum of the additional peak).

It was noticed that the short- or long-wavelength peak predominates if the light beam is focused onto the sample surface near the negative or positive contact, respectively (Fig. 3). The interval between the beginnings of the two experiments did not exceed 10 min.

3. DISCUSSION OF THE EXPERIMENTAL DATA

Previously, the additional peaks observed in PC spectra of GaP:Cu beyond the fundamental absorption edge have been attributed to the effect of distribution of the recombination parameter across the sample thickness [2]. Let us consider a model sample constituted by several layers. Similarly to [2], we assume that the quantum yield η in InP:Cu is constant within each layer and the mobility μ varies only slightly between layers. Then, the photoconductivity $\Delta\sigma$ of the entire sample can be described by the following expression:

$$\begin{aligned} \Delta\sigma(h\nu) = & Q_1[1 - \exp(-\alpha t_1)] \\ & + Q_2 \exp(-\alpha t_1)[1 - \exp(-\alpha t_2)] \\ & + Q_3 \exp(-\alpha t_1) \exp(-\alpha t_2)[1 - \exp(-\alpha t_3)] \\ & + Q_4 \exp(-\alpha t_1) \exp(-\alpha t_2) \exp(-\alpha t_3) \\ & \times \{1 - \exp[-\alpha(d - t_1 - t_2 - t_3)]\}, \end{aligned} \quad (1)$$

where $Q_i \propto e\mu\eta\tau_i$ is the coefficient proportional to the lifetime for the i th layer, $\alpha = f(h\nu)$ is the spectral dependence of the absorption coefficient of InP, t_i is the layer thickness, and d is the sample thickness.

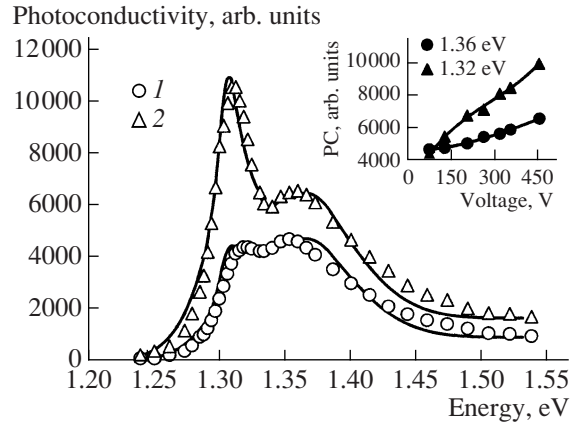


Fig. 2. Photoconductivity spectrum of a freshly polished InP:Cu sample at different voltages. Experimental data are obtained at voltages of (1) 70 and (2) 460 V; solid lines represent the approximation with expression (1). The inset shows how PC increases with voltage for photon energies of 1.32 and 1.36 eV.

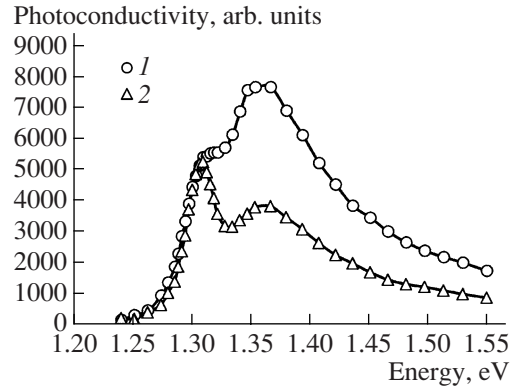


Fig. 3. Photoconductivity spectrum of an InP:Cu sample immediately after polishing, with the light beam focused near the positive or negative electrode at a voltage of 200 V. Experimental data are obtained with the beam focused near (1) negative and (2) positive contacts. Solid lines represent approximation with expression (1).

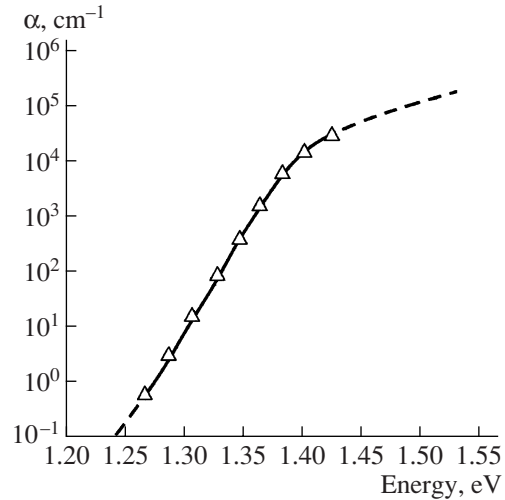


Fig. 4. Spectral dependence of the absorption coefficient in indium phosphide.

Table 1

t, h	Q_1	Q_2	Q_3	Q_4	$t_1, \mu\text{m}$	$t_2, \mu\text{m}$	$t_3, \mu\text{m}$	$t_4, \mu\text{m}$	$d, \mu\text{m}$
0	4730	14945	2878	51839	0.1943	21.02	210.1	1543.7	1775
1	3890	12545	2881	51840	0.1948	21.01	210.9	1542.9	1775
2	2890	10045	2880	51843	0.1947	21.09	210.6	1543.1	1775
3	2390	8295	2877	51846	0.1942	21.05	210.4	1543.4	1775
4	1890	6645	2882	51848	0.1945	21.02	210.2	1543.6	1775
5	1540	5995	2881	51851	0.1949	21.04	210.3	1543.5	1775
6	1440	5605	2879	51852	0.1942	21.03	210.5	1543.3	1775
7	1190	5455	2883	51854	0.1944	21.06	210.8	1542.9	1775
23	590	3105	2881	51855	0.1946	21.08	210.9	1542.8	1775
48	290	1605	2882	51857	0.1941	21.07	210.4	1543.3	1775

Table 2

Beam focused near indicated contact	Q_1	Q_2	Q_3	Q_4	$t_1, \mu\text{m}$	$t_2, \mu\text{m}$	$t_3, \mu\text{m}$	$t_4, \mu\text{m}$	$d, \mu\text{m}$
+	942	4035	1803	7258	0.3938	41.12	208.9	1524.6	1775
-	1852	7885	3903	5998	0.2951	61.09	210.8	1502.8	1775

We measured the absorption coefficient α of indium phosphide independently and the result we obtained (Fig. 4) is in good agreement with the data of [3]. The regions of weak and strong absorption were approximated.

In the range of the fundamental absorption edge, the absorption coefficient markedly increases as the photon energy becomes higher, which leads to a decrease in the light penetration depth. For the energy range from 1.25 to 1.55 eV, the sample can be conditionally divided into four layers: t_1 , t_2 , t_3 , and t_4 (see Table 1). Expression (1) was used to describe the PC spectra of samples stored after polishing for 0 to 48 h. The rms deviation did not exceed 4.287×10^{-3} . The values obtained for the parameters of expression (1) are listed in Table 1.

When approximating the PC spectra obtained at different voltages (Fig. 2) with expression (1), we noticed that, as the voltage is raised from 70 to 460 V, the parameter Q_1 increases by a factor of 1.8, Q_2 and Q_3 by a factor of 1.3, and Q_4 by a factor of 3. This means that, as the electric-field strength increases, the carrier lifetime grows to the greatest extent deep in the sample. The thickness of the first layer increased twice compared with the data in Table 1, but the thicknesses of the rest of the layers did not change significantly.

Table 2 lists the values of the parameters in expression (1) for approximation of the PC spectra obtained with the light beam focused near the negative (-) and positive (+) contacts (Fig. 3).

4. CONCLUSIONS

The appearance of the short-wavelength peak may be due both to stresses caused by polishing of the sample surface with a diamond paste and to the presence of

a space-charge layer, which is caused by interaction of the InP:Cu surface with air and changes in sample storage. The fact that the relative intensities of the two peaks are affected both by the electric field strength and by the position of the light spot with respect to the contacts means that the lifetime of nonequilibrium carriers varies across the sample thickness. Presumably, this is associated with changes in the depth of the space-charge region near the sample surface under the action of the factors studied, including the time of storage after polishing [4]. Also possible is the effect of carrier injection from the contacts, which leads to recharging of copper impurity centers.

Comparison of how the parameters Q_i vary between the layers for GaP and InP samples shows that the bulk lifetime is the longest in the latter case, but the common feature is that $Q_2 > Q_3$ (for t not exceeding 23 h).

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