Photoconductivity of semiconducting solid solutions $Bi_{1-x}Sb_x$

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(Submitted 29 July 1978)
Pis'ma Zh. Eksp. Teor. Fiz. **28**, No. 6, 401–404 (20 September 1978)

Intrinsic photoconductivity was observed in the solid solutions $Bi_{1-x}Sb_x$. The spectrum of this photoconductivity was measured. The frequency dependency of the photoresponse to 10 μm radiation in the range of several Hz to 100 MHz was investigated. It is shown that the photorelaxation time lies in the range from 10^{-7} to 10^{-9} sec.

PACS numbers: 72.40. + w

The solid solutions $Bi_{1-x}Sb_x$ with antimony concentration x in the range $8 < x < 25$ at.% are narrow-band semiconductors with gap width that depends on x and ranges from 0 to $E_g \sim 25$ meV at $x \sim 17$ at.%. It is possible at present to obtain, with good reproducibility, pure perfect single crystals of these semiconductors, in which the electron density at $T = 4.2$ K does not exceed 10^{14} cm^{-3} and their mobility reaches 10^7 cm^2/V-sec. Thus, the solid solutions $Bi_{1-x}Sb_x$ are at present the narrowest-band known pure semiconducting materials with high electron mobility. The electro-physical and galvanomagnetic properties of these materials were investigated quite substantially, a number of papers are devoted to the optical properties of $Bi_{1-x}Sb_x$, and there are reports of observation of coherent long-wave IR radiation from $Bi_{0.92}Sb_{0.08}$, but at present there are no published reports of observation of photoconductivity in this material, although interest in this property has been expressed long ago.[1]

The $Bi_{1-x}Sb_x$ samples investigated in the present study were single-crystal plates of area 10–20 mm^2 and thickness 50–100 μm, obtained by cleavage from single-crystal ingots in a direction perpendicular to the trigonal axis in liquid nitrogen. The electron density in the samples was $n_{4.2K} \lesssim 1 \times 10^{14}$ cm^{-3}, and the mobility was $\mu_{4.2K} \gtrsim 1 \times 10^6$ cm^2/V-sec. The sample resistance in liquid helium did not exceed 30 Ω. The contacts were soldered to the plates with indium. The samples were secured on the end of a stainless-steel light pipe and placed in a helium cryostat. To record the photoresponse spectrum, we used a long-wave vacuum lattice monochromator (FIS-21), in which the radiation was modulated by a mechanical chopper at a frequency 400 Hz.

Figure 1 shows the spectrum of the photoresponse of $Bi_{0.823}Sb_{0.177}$ and the spectrum of its optical transmission, measured by the procedures described in Ref. 2. In this sample, the width of the forbidden band was $E_g \sim 19$ meV at a photon energy $\hbar\omega > 19$ meV ($\lambda < 65$ μm) and the absorption coefficient was $K > 500$ cm^{-1}, so that $Kd > 1$ in the indicated spectral region (d is the sample thickness). Accordingly, the spectral dependence of the photoconductivity of $Bi_{0.823}Sb_{0.177}$, shown in Fig. 1, takes the form typical of "thick" samples: the entire curve lies in the region of the funda-

mental absorption edge, and its maximum lies in the IR region in which $Kd \sim 1$, and at large $\hbar\omega$ the photoconductivity decreases rapidly.

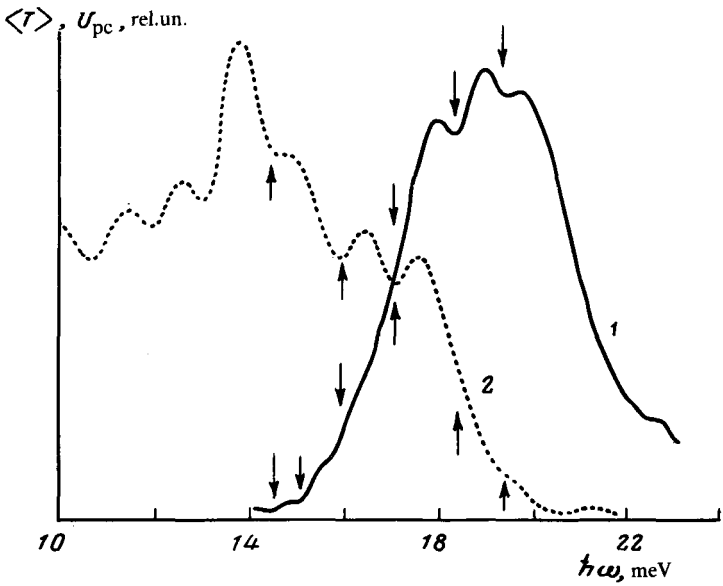

FIG. 1. Photoconductivity spectrum smoothed over the noise (curve 1) and transmission spectrum smoothed over the noise and over the interference (curve 2) of a $Bi_{0.823}Sb_{0.177}$ sample. The arrows indicate the phonon dips.

The photoconductivity spectrum reveals singularities (dips) corresponding to absorption bands in $Bi_{1-x}Sb_x$ at photon energies 14.3, 15.0, 15.8, 16.5, 17.2, 18.5, and 19.4 meV (see the table in Ref. 2). The agreement between the positions of the singularities in the photoconductivity and optical-transmission spectra was established by differentiating these spectra with a computer. The fact that the photoresponse decreases in the spectral region in which nonphotoelectronic radiation absorption takes place demonstrates that the observed photoresponse is due to photoconductivity and not to some thermal effect.

We investigated also the inertia of the photoconductivity in $Bi_{1-x}Sb_x$ samples. The initial measurements have shown that the time of the response is at the most less than 1 msec. Therefore, to measure the inertia for further response we mixed in the samples the radiation from two CO_2 lasers tuned with the aid of diffraction gratings to a single lasing line $\lambda = 10.6\ \mu m$. The power of the radiation incident on the sample was 10 mW. The method of mixing with frequency tuning within the Doppler width of the lasing line makes it possible to investigate the frequency dependences of the photoresponse up to a frequency $\sim 10^8$ Hz. In addition, the gain in the power of the incident radiation when a laser is used as an IR source instead of a monochromator is the 5–6 orders of magnitude. This makes it possible to investigate the frequency dependences of the photoresponse of low-sensitivity samples.

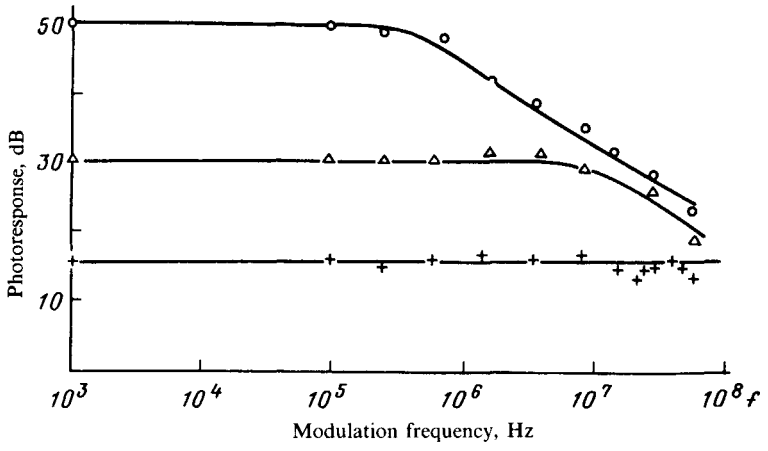

FIG. 2. Typical frequency dependences of the photoresponse $Bi_{1-x}Sb_x$ samples at liquid-helium temperature.

The tuning to the lasing line was monitored with a grating analyzer of the CO_2 spectrum. To obtain the required beat frequency one of the lasers was tuned within the limits of the lasing line width by varying the length of the resonator with the aid of a controllable dc voltage on a piezoceramic element.

The relaxation time of the photoresponse was determined from measurements of the dependence of the photoresponse on the beat frequency. Notice should be taken of one singularity of the performance of the measurements of the inertia of the photoresponse of the $Bi_{1-x}Sb_x$ samples. Inasmuch as in many of the samples the time of the photoresponse, and hence its magnitude, is small, it was necessary to use narrow-band receivers to register the beat signal. The voltmeter band width was ~ 10 kHz in the frequency range 10^5–10^8 Hz. Since the beat-frequency stability was ~ 5 MHz/min, the measured signal drifted with time out of the voltmeter band. This measurement difficulty was circumvented in the following manner. In addition to the dc voltage we applied to the piezoceramic element of one of the lasers also an alternating voltage of frequency 1 kHz. The further response at the output of the narrow-band voltmeter was then a series of pulses. The pulsed signal on the output detector of the receiver was compensated by a dc voltage, and measurement of the latter made it possible to determine the photoresponse.

The measurements have shown the following: 1) in $Bi_{1-x}Sb_x$ samples the relaxation time lies in the range 10^{-7} to 10^{-9} sec. Typical frequency dependences of the photoresponse are shown in Fig. 2. In samples having good photosensitivity, the photoresponse is independent of frequency in the range from 10 to 10^7 Hz. Some samples of low sensitivity reveal no decrease of the photosensitivity up to 160 MHz, from which it follows $\tau < 1.5 \times 10^{-9}$ sec. 2) The photosensitivity of the samples was measured by direct detection of CO_2 laser radiation amplitude-modulated by a mechanical chopper at a frequency 1 kHz. The measured values of the Volt-Watt sensitivity of the photoresponse are 10^{-1}–10 V/W (at 10^{-9}–10^{-7} sec, respectively).

It should be recognized that because of the large refractive index ($n > 10$, Ref. 2) a greater part of the incident radiation is reflected. If the sample surfaces could be made nonreflecting, the photosensitivity would be greatly increased.

The authors thank T.M. Lifshitz for constant interest in the work and for valuable discussions.

[1]Fotoprovodimost' (Photoconductivity), collected translations ed. by Sh. M. Kogan, Nauka, 1967.
[2]T.M. Lifshitz, A.B. Ormont, E.G. Chirkova, and A.Ya. Shul'man, Zh. Eksp. Teor. Fiz. **72**, 1130 (1977) [Sov. Phys. JETP **45**, 591 (1977)].