PbSnTe:In-Based Broadband Detector of Terahertz Radiation

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Abstract— Principles of operation of an injection-type terahertz photodetector based on PbSnTe:In films with adjustable spectral sensitivity range are described. Current-voltage characteristics of the photosensitive structures, defined by the electron trapping at localized states in the bandgap of PbSnTe:In and by the excitation of electrons from these states under the action of free-electron laser radiation, are reported.

I. INTRODUCTION AND BACKGROUND

A characteristic feature of narrow-gap (Eg≈0.06 eV) solid solution PbSnTe:In is its transition into the so-called «dielectric state» at certain composition of the material and its doping level with indium. This «dielectric state» is remarkable for very low concentration of free charge carriers at helium temperatures ($n<10^2$–10^7 cm^{-3}), the current through films in this situation being defined by monopolar injection of electrons from contacts in the presence of traps with space-charge limitation of the current [1]. With traps completely occupied with electrons, terahertz radiation of certain energy excited the trapped electrons from the localized states into the conduction band, these transitions affecting the value of the electric current flowing in the film. The population of traps depends on the bias voltage U applied to the structure. As a result, the spectral sensitivity range of the photodetector, defined by the energy spectrum of traps, turns out to be also dependent on U. The purpose of the present study was to investigate into the sensitivity of PbSnTe:In films to terahertz free-electron laser radiation, to determine the spectrum of localized states in the films, and to examine the possibility of adjusting the spectral sensitivity range of PbSnTe:In photodetectors via changing the bias voltage.

II. RESULTS AND DISCUSSION

We examined experimental structures fabricated on the basis of MBE-grown $Pb_{1-x}Sn_xTe$:In films with x≈25. The indium content of the films was about 2%. Schematic of the test structure is shown in the inset to Fig. 1. In the absence of background illumination the current-voltage characteristics of the structures measured at T=4.2 K exhibited regularities normally displayed by space-charge limited injection currents. In the range of voltages where the traps in the dielectric were completely filled with electrons (U>15 V) we were able to evaluate the electron mobility μ in the films by analyzing the current-voltage characteristics of the structures in terms of the theory of space-charge limited injection currents [2]. The average concentration of electrons in the gap between the contacts $n(U)$ was calculated from the expression for the electric current $I=q\mu nU(wd/l)$. In non-degenerate case such calculations allow one to determine the energy position of the quasi-Fermi level in the material E_{fn} as a function of voltage U using the expression $E_{fn}-E_c=kT\ \ln(n/N_c)$, where N_c is the effective density of states in the conduction band. In the step approximation of the Fermi function we then were able to calculate the energy distribution of traps in the material using the relation $g(E)=dn_t(E)/dE$, where $n_t(E)$ is the concentration of occupied traps at a voltage U, determined from measured capacitance of the structure and from the bias voltage applied to the structure.

The energy distribution of traps in the forbidden band of the dielectric turned out to be quasi-continuous in the energy interval from 0.001 to 0.01 eV below the conduction-band bottom, these energies corresponding to a broad range of terahertz frequencies.

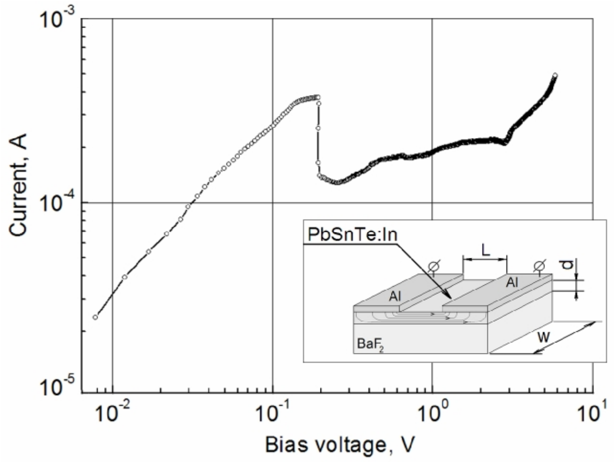

Fig. 1. Current-voltage characteristic of the structure illumi- nated with 300-K background radiation. Schematic of the structure is shown in the inset to the figure. L=0.003 cm, w=0.2 cm, d=0.0001 cm. Measurement temperature T=4.2 K.

In the presence of background illumination the trap levels can be filled with electrons due to the band-to-band excitation of electron-hole pairs already at zero bias voltage. In the latter case, at low bias voltages, with the injection of charge carriers out of contacts being negligible, the current-voltage characteristic of the structure will be defined by holes, and be linear (see Fig. 1).

At sufficiently high bias voltages (over 2 Volts in Fig. 1) the injected electrons will recombine with non-equilibrium holes. This is expected to lead at first to some reduction of hole concentration and, hence, electric current, and then to

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increased electric current. In the latter case, the electric current will be predominantly defined by electrons instead of holes. This model is supported by data obtained in Hall effect measurements of similar films; these data measured on one of the samples is shown in Fig. 2.

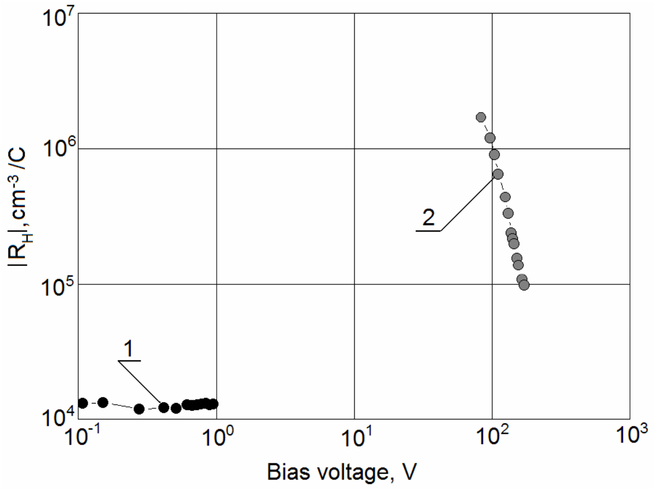

Fig. 2. Hall coefficient versus bias voltage for a PbSnTe:In film illuminated with 300-K background radiation. 1 – hole-type conductivity, 2 – electron-type conductivity. Measurement temperature T=4.2 K.

On optical excitation of the electrons captured at traps with submillimeter radiation, electric-current variations are to be observed. In the range of low bias voltages (U<2 V in Fig. 1) the electrons excited into the conduction band will recombine with non-equilibrium holes, which will lead to a reduced electric current (negative photoconduction). At bias voltages U>2 V, with no non-equilibrium holes present in the structure, the electric current is carried by electrons, and the excitation of electrons from traps should lead to an increase of the electric current (ordinary photoconduction).

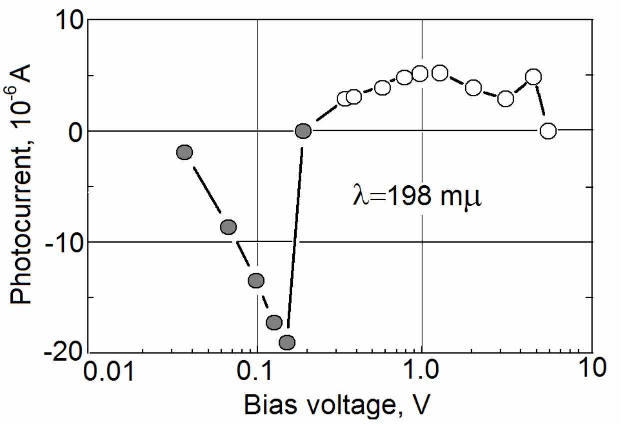

Fig. 3. Photosignal versus bias voltage in a sample illuminated with 300-K background radiation.

Figure 3 shows the curve of the photosignal in a sample illuminated with free-electron laser radiation at a wavelength λ=198 μm; the curve was measured at modulated signal, with chopping of the radiation flux. The photocurrent in the figure changes its sign when the phase of the modulated signal exhibits a change by 180^0. It is seen that the experimental data fairly well agree with the model, the range of bias voltages in which the photocurrent changes its sign in Fig. 3 being consistent with the behavior displayed by the static current-voltage curve in Fig. 1.

Under illumination with background radiation the occupancy of traps levels with different energies will be defined by the illumination intensity and by the bias voltage applied to the structure; the exact calculation of this occupancy presents rather difficult a problem. In the absence of background radiation the problem simplifies and, under some simple assumptions, one can determine how the occupancy of trap levels with different energies depends on the bias voltage. Thus, changing the bias voltage, or the injection level, one can smoothly adjust the spectral sensitivity range of the structure in the THz portion of the spectrum.

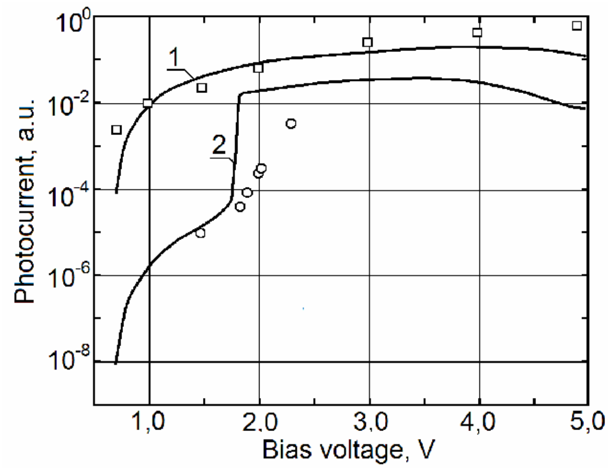

Fig. 4. Experimental (circles and squares) and calculated (lines) curves of the photocurrent versus bias voltage. Illumination with free-electron laser radiation at λ=130 μm (curve 1) and at λ=198 μm (curve 2).

Figure 4 shows the experimental (squares and triangles) and calculated (lines) photocurrent values in the structures exposed to free-electron laser radiation.The latter values were calculated using the energy distribution of traps in the samples extracted from measured current-voltage characteristics of the structures. The photosensitivity is seen to be strongly dependent on the bias voltage, with the predicted current values being in a good agreement with the experiment.

REFERENCES

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