Negative photoconductivity in $Pb_{1-x}Sn_xTe$:In

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Negative photoconductivity is detected in indium-doped (5×10^{17}–3×10^{19} atoms/cm^3) epitaxial films of $Pb_{1-x}Sn_xTe$ ($x\cong0.22$). The negative photoconductivity is observed at low temperatures ($\lesssim 30$ K) in the presence of background illumination. The kinetics of the negative photoconductivity is discussed in terms of the model of a Jahn-Teller center.

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A high photosensitivity has been found[1] in $Pb_{1-x}Sn_xTe$ ($x\cong0.2$) crystals containing large amounts of indium. In this Letter we report the observations of both positive and negative photoconductivity in epitaxial films of $Pb_{1-x}Sn_xTe$ which have been doped with indium to concentrations $n\sim5\times10^{18}$ cm^{-3}. It is at just such a doping level that a sharp drop in the photoluminescence intensity has been observed[2] in this material.

High-quality epitaxial films of $Pb_{1-x}Sn_xTe$:In ($x=0.22$–0.23) with thicknesses $d=0.5$–4 μm were grown on (111) BaF_2 substrates by the hot-wall method and by flash evaporation in a vacuum. In the first method the films were doped by diffusion, and in the second method they were doped during growth. The concentration of In atoms was varied from 5×10^{17} to 3×10^{19} cm^{-3}. The concentration and mobility of the current carriers at 77 K were $\sim10^{18}$ cm^{-3} and 10^4 cm^2/V sec for the p-type films and $(6$–$8)\times10^{16}$ cm^{-3} and 3×10^4 cm^2 V sec for the indium-doped n-type films. The photoconductivity was excited by a pulsed GaAs laser ($\lambda\cong0.9$ μm, $\tau_p=0.1$ μsec). The samples were placed on the cold stage of a cryostat with a regulated temperature T. The electric field in the sample was around 0.1 V/cm.

In the undoped and lightly doped (to $N\cong10^{18}$ cm^{-3}) samples a weak, positive photoconductivity was observed, with a relaxation time $\leqslant0.2$ μsec. When N was increased to 2×10^{18} cm^{-3}, the photoconductivity signal increased by more than two orders of magnitude, and in the presence of background illumination ($T\cong300$ K) the sign of the photoconductivity signal depended on T. For temperatures in the range 7–27 K we observed negative photoconductivity—the resistivity increased upon photoexcitation. Figure 1 shows the shape of the photoresponse signal for a sample with $N\cong2\times10^{18}$ cm^{-3} at various temperatures T. With increasing T the sign of the photoconductivity signal is seem to change from negative (Fig. 1a) to positive (Fig. 1c). The relaxation time of the negative photoconductivity decreases slightly in the process, while the amplitude of the corresponding signal first increases and then falls sharply to zero. At $T\cong25$ K a positive overshoot appears at the front of the negative-photoconductivity signal, and as T is increased further this overshoot comes to absorb the negative part of the signal. For $T\geqslant27$ K only the positive photoconductivity is ob-

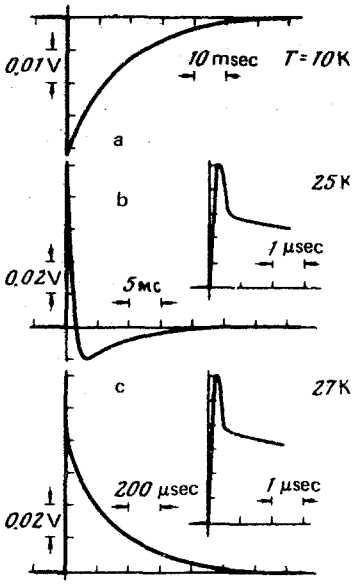

FIG. 1. The shape of the photoresponse signal for a sample with $N \cong 2 \times 10^{18}$ cm^{-3} and $d = 2.5$ μm.

served. The positive photoconductivity signal has two clearly expressed relaxation times, the shorter one being $\tau \lesssim 0.2$ μsec and the longer one $\tau \lesssim 1$ msec.

Figure 2 shows the T dependence of the relaxation times and photoresponse amplitudes of the negative photoconductivity (τ_- and A_-) and positive photoconductivity (τ_+ and A_+) for a sample with $N \cong 5 \times 10^{18}$ cm^{-3} in the presence of background illumination. It is seen that the relaxation time of the positive photoconductivity is of a thermally activated character. The activation energy decreases from 51 meV for samples with $N \cong 2 \times 10^{18}$ cm^{-3} to 35 meV for samples with $N \cong 3 \times 10^{19}$ cm^{-3}.

Figure 3 shows the temperature T_{tr} of the transition from negative photoconductivity to positive photoconductivity for samples with various doping levels. It is seen that T_{tr} decreases from 27 K at $N \cong 2 \times 10^{18}$ to 17 K at $N \cong 3 \times 10^{19}$ cm^{-3}.

To elucidate the effect of the background we studied the kinetics of the photoconductivity with the background completely screened off. In this case only positive photoconductivity was observed as T was changed from 8 to 200 K, with the relaxation time decreasing from 10 msec to 0.2 μsec. When the sample was simultaneously illuminated with the GaAs laser and a globar ($\lambda = 3.7$–5.5 μm), we observed a decrease in the relaxation time from 10 to 0.5 msec and a small increase in the amplitude in the case of negative photoconductivity, and a slight decrease in the relaxation time and a sharp drop in the amplitude in the case of positive photoconductivity. At $T > 50$ K the globar illumination had only a slight effect on the photoresponse signal. The photoconductivity was also measured under excitation by a CO laser ($\lambda \cong 5.3$ μm, $\tau_p \cong 1$ μsec). At temperatures in the range 2–27 K only positive photoconductivity was observed. At $T > 27$ K the curve of the relaxation time versus T coincided with the curve

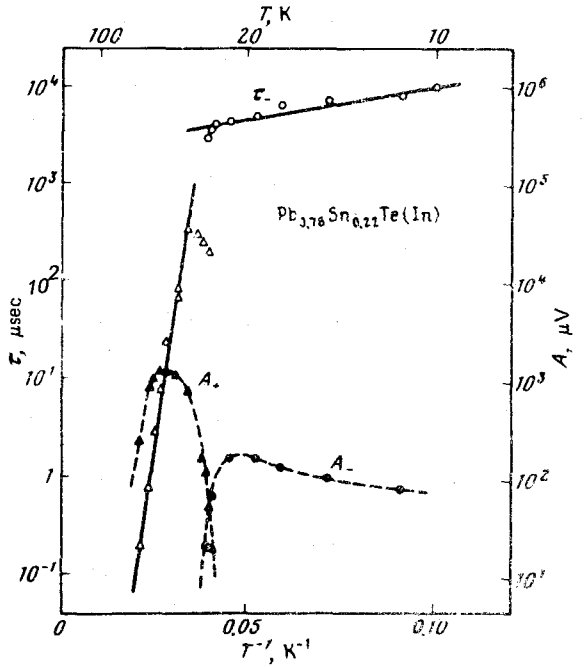

FIG. 2. Temperature dependence of the relaxation times and photoresponse amplitudes for the positive photoconductivity (τ_+, A_+) and negative photoconductivity (τ_-, A_-). $N = 5\times10^{18}$ cm^{-3}, $d = 2.0$ μm.

obtained under excitation by the GaAs laser. At $T < T_{tr}$ the ratio of the resistivity of the sample without the background to the resistivity with the background increased with increasing N, reaching two orders of magnitude at $N \cong 10^{19}$ cm^{-3}.

Our results, unlike those of Penchina *et al.*,[3] find a qualitative explanation in terms of the model of a Jahn-Teller center.[4] A center of this kind might be a Te vacancy or an In-atom–Te-vacancy complex. The indium impurity replaces metal vacancies, which are the main type of point defect in $Pb_{0.78}Sn_{0.22}Te$, and as the doping level is increased the hole concentration falls, leading eventually to an inversion of the

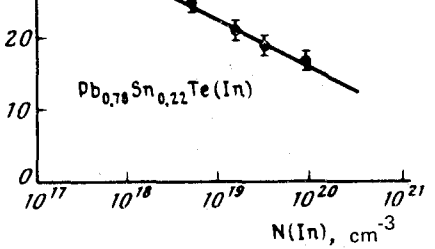

FIG. 3. The effect of the level of indium doping on the temperature of the transition from negative photoconductivity to positive photoconductivity.

type of conductivity at $N \cong 2 \times 10^{18}$ cm^{-3}. At this doping level the material has the maximum quantum yield of radiation, as compared with the undoped or heavily doped material.[2] A Jahn-Teller center comprises a local level above the bottom of the conduction band. The trapping of an electron by this level leads to a Jahn-Teller restructuring of the crystalline enviroment of the center, with the result that the level with the trapped electron sinks below the bottom of the conduction band. The electron can be extracted from this state by thermal activation or photoexcitation. Since the optical transitions occur at a fixed configuration of the Jahn-Teller center, the thermal activation energy is lower than the energy of the optical transition.

At $T < T_{tr}$ the electrons ejected from the Jahn-Teller centers into the conduction band by the background radiation cannot return to the centers because of the presence of a potential barrier ΔE. In this case the resistance of the sample is small. The absorption of a photon of higher energy than the distance from the top of the valence band to the level of the Jahn-Teller center ($\lambda < 5.3$ μm) leads to the trapping of an electron at this level, followed by a rapid rearrangement of the Jahn-Teller center. The holes formed recombine with conduction electrons in a time $< 10^{-7}$ sec, leading to an increase in the resistivity and the appearance of a negative photoconductivity. The relaxation of the negative photoconductivity occurs on account of the background radiation. Increasing the intensity of the background illumination with a globar accelerates the relaxation of the negative photoconductivity.

The complete screening of the background eliminates the mechanism responsible for the relaxation of the negative photoconductivity. As a result, each laser pulse will cause transitions of electrons to the Jahn-Teller centers until the forward and inverse transitions under the action of the radiation counterbalance each other. This will only change the value to which the resistivity relaxes. In the interval between pulses a fraction of the electrons will relax through the barrier ΔE. Here one observes a positive photoconductivity with a relaxation time ~ 10 msec at $T = 4.2$ K. This process corresponds to the intial stage of the relaxation of the long-term photoconductivity. The minimum relaxation time given by Vul *et al.*,[5] which was attributed to trapping by surface centers, was $\sim 10^2$ sec. According to the Jahn-Teller-center model the relaxation time depends strongly on the position of the Fermi level relative to the potential barrier and increases with the relaxation of electrons from the conduction band to the Jahn-Teller center.

At $T > T_{tr}$ the electrons undergo transitions to the Jahn-Teller center through the potential barrier ΔE as a result of thermal activation. Under laser illumination the electrons return to the conduction band and subsequently relax through the potential barrier ΔE; this leads to a positive photoconductivity with a relaxation time that is of a thermally activated character, with an activation energy $\cong 35$–51 meV.

The negative and positive photoconductivities observed in $Pb_{1-x}Sn_xTe$:In have thus been explained in terms of the model of Volkov and Pankratov.[4] From this point of view the negative photoconductivity represents the quenching of the photoconductivity excited by the background radiaton. We have estimated the height of the potential barrier for this model as $\Delta E \cong 35$–50 meV and determined the lower threshold for the level of the Jahn-Teller center as ~ 0.2 eV above the bottom of the conduction band.

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