Nature of the delayed photoconductivity in PbTe(Ga)

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The temperature dependence of the resistance and of the velocity and attenuation of ultrasound in PbTe and PbTe(Ga) was studied. The results are used along with an analysis of the effect of the Ga doping of the PbTe to propose a model for the delayed photoconductivity of this material.

Gallium-doped lead telluride is one of the materials which exhibit, at low temperatures, one of the most interesting manifestations of solid-state memory: a delayed photoconductivity. The solubility of Ga in PbTe is only slight: No more than 1 at. % of Ga can enter the lead sublattice as a substitutional impurity. Even in this narrow interval, the dopant exhibits an unusual behavior. With increasing Ga content in *p*-type PbTe sample, the hole density falls off linearly, putting the crystals in a compensated state at $N_{Ga} \approx 0.1$ at.%. Further doping, however, does not take PbTe(Ga) out of the insulating phase; the latter persists up to $N_{Ga} \approx 0.3$ at.%. Only when we leave this interval do we find the *p*–*n* conversion and a rapid increase in the density of electrons in *n*-type samples.[1] At $T \leqslant T_c = 80$ K, illumination of high-resistivity crystals by visible or IR light puts the crystals in a conducting state; this conducting state persists after the illumination is cut off. The relaxation time of this light-induced conductivity increases rapidly with decreasing temperature, reaching values $\tau > 10^5$ s at $T = 4.2$ K (Ref. 2). The importance of possible practical applications of this effect has stimulated a wide range of experimental studies (see the review article by Akimov et al.[3] and the papers cited there) and the derivation of several theoretical models. Prominent among these models are hypotheses involving a deformation of the nearest neighborhood of the dopant[4] and a Jahn–Teller restructuring of impurity centers.[5] An alternative explanation of the delayed photoconductivity is the suggestion[6] of a large-potential well due to inhomogeneity of the crystal.

Choosing among these hypotheses requires, along with electrical measurements, experimental data on the state of the crystal lattice. In this letter we are reporting a study of the temperature dependence of the velocity S and attenuation γ of longitudinal ultrasound in PbTe and PbTe(Ga). Since it was the intention in these experiments to detect the light-induced effect and the acoustic properties of the crystals simultaneously, we measured S and γ by a contactless method, based on a direct conversion of electromagnetic and ultrasonic waves in a magnetic field.[7] This approach differs from the conventional contact methods in that it does not prevent illumination of the working surfaces of the sample.

Measurements were carried out on plane-parallel, single-crystal PbTe and PbTe(Ga) platelets with transverse dimensions on the order of 1 cm and thicknesses of about 0.1 cm. The normal to the plane of the samples ran along the [001] fourfold

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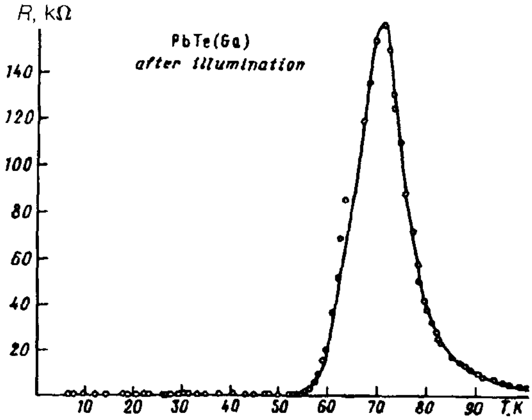

FIG. 1. Temperature dependence of the resistivity of PbTe (Ga) during warming after a low-temperature illumination.

symmetry axis. The behavior of an undoped PbTe crystal was studied in order to establish a baseline. The Ga content in the doped PbTe crystal was 0.3 at.%; this level corresponds to the region of the highest photosensitivity of this compound. The sample was inside a test chamber, shielded from external light. It was also inside two coaxial solenoidal inductance coils. One of these coils excited standing ultrasonic waves in the platelet, and the other detected them. Measurements were carried out over the temperature range 4–100 K in a magnetic field of 7 T. A miniature incandescent lamp, placed between the measurement coils, was used to briefly illuminate the crystal at liquid-helium temperature. Electrical contacts were soldered to the side faces of the test samples so that the resistance of the samples could be monitored. The temperature was detected by a CuFe–Cu thermocouple.

Because of the deviations from stoichiometry, the undoped PbTe sample has a high carrier density ($p > 10^{19}$ cm^{-3}) even at liquid-helium temperature. As the temperature is varied, the resistivity of the sample exhibits a metallic behavior, while revealing none of the effects associated with a delayed photoconductivity. The PbTe(Ga) single crystal, in contrast, has a resistivity with a semiconducting behavior, which reaches values $\rho \geqslant 10^5$ $\Omega \cdot$cm at low temperatures. At $T = 4.2$ K, the resistivity of the sample decreases to $\rho \sim 10^{-1}$ $\Omega \cdot$cm upon illumination. Figure 1 shows the temperature dependence of the resistivity of PbTe(Ga) during warming after illumination at a low temperature. The resistivity remains essentially constant over a broad temperature range; we then see a sharp increase in ρ, which gives way to an exponential decay at high temperatures.

Absolute values of the velocity of longitudinal ultrasound in the test samples were found by measuring the thickness of the platelet and the position of the acoustic resonance on the frequency scale. The velocity of longitudinal ultrasound, S, found in this manner at $T = 4.2$ K is $(3.8 \pm 0.1) \times 10^5$ cm/s for PbTe and $(1.7 \pm 0.1) \times 10^5$ cm/s for PbTe(Ga). It follows from these figures that the compressibility of PbTe(Ga) is five times that of PbTe. Figure 2 shows the temperature dependence of the velocity of longitudinal ultrasound in PbTe(Ga) measured after illumination at a low temperature. In the temperature interval corresponding to the anomalously rapid growth and

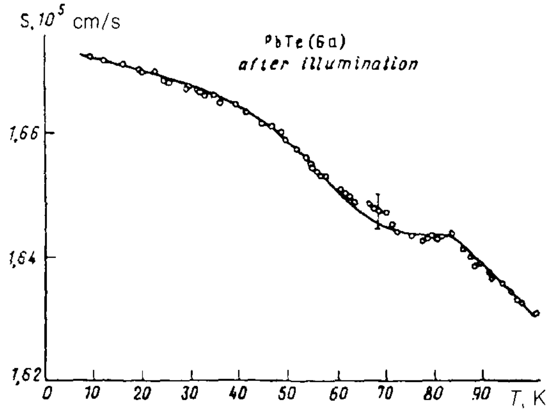

FIG. 2. Temperature dependence of the velocity of longitudinal ultrasound in PbTe (Ga) during warming after low-temperature illumination.

decay of the resistivity of the sample we see a slight additional softening of the bulk modulus, right at the sensitivity of the method.

It turns out that the attenuation of the ultrasound is the acoustic property of PbTe(Ga) which is the most sensitive to temperature changes (among those studied in the present experiments). Figure 3 shows the temperature dependence of γ in PbTe(Ga) after low-temperature illumination. On the $\gamma(T)$ curve we can see a clearly defined anomaly at $T_c = 80$ K. In the absence of illumination, we see only a monotonic increase in the attenuation in this region. The qualitative behavior of γ in this region is reminiscent of that of the attenuation in the course of a structural phase transition. However, since the absolute value of the attenuation remains fairly low at the critical temperature, and since there is no significant jump in the ultrasonic velocity, we are led to believe that a structural phase transition does not occur in the PbTe matrix.

The results found in this study allow us to make certain assumptions about the nature of the delayed photoconductivity of PbTe(Ga). We do not believe that this photoconductivity is associated with a large-scale inhomogeneity of the crystal. A potential well preventing a return of electrons from the conduction band to impurity centers after the illumination is cut off in an inhomogeneous crystal would not be characterized by any particular energy. This circumstance rules out the existence of a clearly defined critical temperature, and it contradicts the suggestion of a highly nonmonotonic temperature dependence of the resistivity and the attenuation of ultrasound.

We regard the most natural obstacle to a rapid relaxation of the photoconductivity to be a restructuring of the state of the impurity center in the lattice occurring as a result of a change in its charge state. Our reasoning here is that even during the doping step itself the Ga atoms replace Pb atoms with a variety of electron-shell configurations.[1] A first possibility is Ga^{s0p3}. In this case two electrons are expended on forming ionic–covalent bonds with Te, while one electron has a donor effect, compensating for acceptor centers of a different nature. A decrease in the hole density, to the level of the Ga content in the solid solution, on the order of 10^{19} cm^{-3}, is associated with this activity. With a further increase in the gallium content in the solid solution,

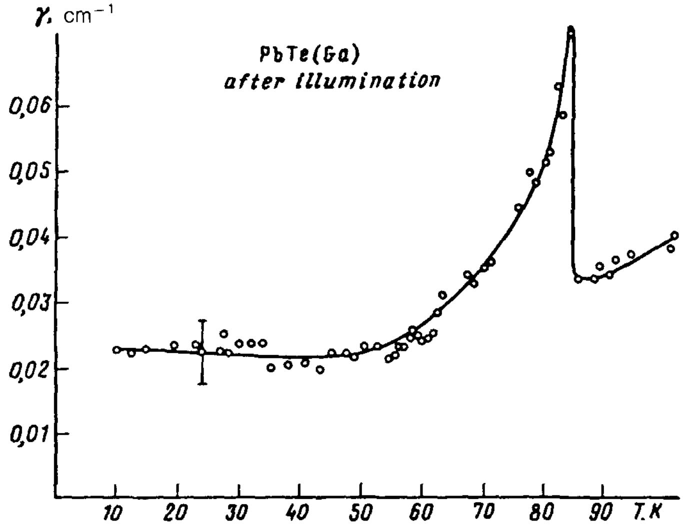

FIG. 3. Temperature dependence of the attenutation of longitudinal ultrasound in PbTe (Ga) during warming after low-temperature illumination.

the gallium replaces lead in the $Ga^{s^1p^2}$ configuration, which does not have a donor effect. During illumination, the gallium atoms in the $Ga^{s^1p^2}$ configuration can contribute one electron to the conduction band, thereby altering the state of the impurity center. The potential barrier which separates the ionized and un-ionized states of Ga opposes a return of electrons to the impurity centers. The height of this barrier can be estimated from the critical temperature $T_c = 80$ K. The total energy of an electron in the impurity band and of the impurity center in the new state is higher than the original energy of the un-ionized impurity; for this reason, the delayed photoconductivity is of a metastable nature.

As the temperature is raised, the kinetic energy of the electrons in the conduction band increases, as does the vibration amplitude of the atoms in sites of the crystal lattice. The probability for a transition of Ga to the original state, accompanied by a return of an electron from the conduction band, also increases. A compressional wave propagating through the crystal could in principle stimulate this process. The restructuring of the impurity centers causes an increase in the probability for the scattering of long-wave acoustic phonons, as can be seen from a peak in the attenuation of ultrasound at the critical temperature.

Our suggestions regarding the nature of the delayed photoconductivity in PbTe(Ga) have a very important implication: In the $Ga^{s^1p^2}$ configuration, the gallium atoms should have a net magnetic moment. Our preliminary studies of the magnetic susceptibility do not contradict that hypothesis.

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[1)]The possibility that group-III impurities exist in various electronic configurations in lead chalcogenides was pointed out by Volkov and Tugushev.[8]

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