Frozen conductivity of lead telluride

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The injection of hot electrons into an oxidized PbTe film at liquid-helium temperature, or illumination of the film, puts the film in a low-resistivity state. The inverse transition to the high-resistivity state can be induced by heating the sample to liquid-nitrogen temperature or by applying an electric field $E \geq 10^3$ V/cm.

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For a study of the passage of hot electrons through a lead film we used multilayer Al–Al_2O_3–Pb_1–PbTe–Pb_{II} film structures, which are briefly described in Ref. 1. The Al–Al_2O_3–Pb_I tunnel junction serves as an injector of hot (relatively high-energy) electrons when a constant voltage U_1 is applied between the Al and Pb_1 layers. The energy barriers in the Pb_I–PbTe–Pb_{II} structure are useful for detecting the hot electrons which have crossed the PbTe layer and which have created a potential difference U_2 between Pb_I and Pb_{II} (Fig. 1). Before the deposition of the Pb_{II} film, the PbTe layer was oxidized under standard atmospheric conditions to produce a nearly compensated semiconductor having a high resistivity at low temperatures.[2] The Pb and PbTe layers were ~1 μm thick.

Experiments at 77 K revealed that the application of the constant voltage U_1 causes a constant voltage U_2 (Ref. 1). When the temperature was lowered to ~1.3 K, it was found that the hot-electron injection can affect the resistivity of the PbTe layer. Figure 1 shows the time dependence of U_2, the voltage between the lead layers. The time at which U_1 is applied coincides with the initial jump in U_2. For as long as a voltage $U_1 < 0.4$ V is applied, U_2 remains constant. The resistance of the telluride layer is $R \approx 1 M\Omega$; this resistance can be determined by passing a current (independent of the injection circuit) between Pb_I and Pb_{II}, without changing the application and removal of $U_1 < 0.4$ V. Figure 1 shows that at high values of U_1 the value of U_2 decays over time at a constant U_1. After a voltage $U_1 > 0.5$ V is removed, measurements of the resistance of the PbTe layer reveal a reduced value R', so that the entire U_2 drop can be attributed to a lowering of the resistance of the barrier layer at a constant injection current. The decay in the PbTe resistance is observed for either sign of U_1, i.e., when either electrons or holes are injected. This new "low-resistivity" state is retained after the injection is stopped, so that no significant increase in R' is observed for several hours in experiments at liquid-helium temperature.

At the same time, the transition to the low-resistivity state is not a consequence of irreversible processes in the films. After the sample is heated to 77 K and recooled, the resistance returns to its original value. The inverse transition can also be induced without raising the temperature—by applying an external voltage U_3 to the PbTe

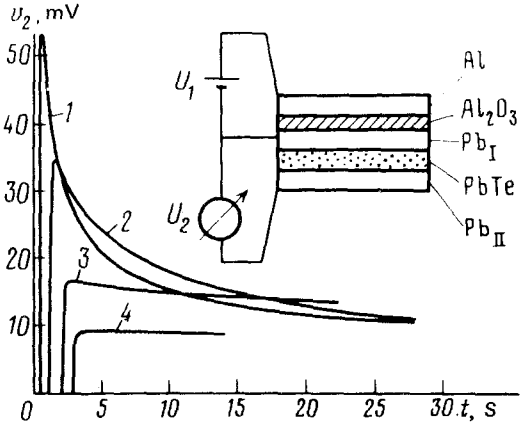

FIG. 1. Time dependence of the induced voltage U_2 at $T = 1.3$ K. The curves were recorded at the following injection voltages U_1: 1–0.95 V; 2–0.8 V; 3–0.5 V; 4–0.4 V.

layer (i.e., between Pb_I and Pb_{II}). The rate at which the high-resistivity state is reestablished depends on the magntitude of U_3; at $U_3 \sim 1$ V, this transition takes a few seconds, while at lower values of U_3 it takes minutes or even hours. The Joule heating power in the multilayer structure amounted to $< 10^{-6}$ W in these experiments and could not have caused a temperature rise sufficient to restore the high-resistivity state, since the multilayer structure was immersed along with its glass substrate in superfluid helium.

The increase in the conductivity of PbTe after the injection of hot electrons is analogous to an effect exhibited by many semiconductors: the appearance of a "frozen" or residual photoconductivity (see the bibliography in the review article of Sheĭkman and Shik,[3] for example). In PbTe this effect has not been studied previously at liquid-helium temperature. We accordingly carried out special experiments to observe the frozen photoconductivity of PbTe. For this purpose, a film of this semiconductor with dimensions $\sim 1 \times 1$ cm^2 was deposited on a glass substrate in a vacuum of 10^{-5} Torr. The contacts were Pb strips, deposited beforehand. After the PbTe film had been deposited, it was held under standard atmospheric conditions, i.e., it was oxidized to the stage of complete saturation. The oxidation of PbTe is known[2] to lead to a donor compensation and to a switch from the original n-type conductivity to a p-type conductivity. In experiments with these nearly compensated PbTe films we observed an increase in the resistance when the temperature was lowered, and we also observed a large frozen-photoconductivity effect (Fig. 2). The film was illuminated by a small lamp with a power ~ 1 W which, along with the film, was inside a closed copper cup immersed in liquid helium. The lamp was ≈ 5 cm from the film. When the lamp was turned on at a film temperature $T = 1.3$ K, the resistance of the PbTe decreased by six orders of magnitude within a few seconds. When the lamp was turned off, the PbTe remained in the new low-resistivity state for many hours at liquid-helium temperature. Heating the film to $T > 100$ K restored the original state. The effect of hot-carrier injection is thus qualitatively similar to the effect of optical excitation.

In some recent studies,[4,5] a frozen conductivity was observed in the complex compound $Pb_{0.8}Sn_{0.2}Te + In$ and attributed there to the indium impurity (present

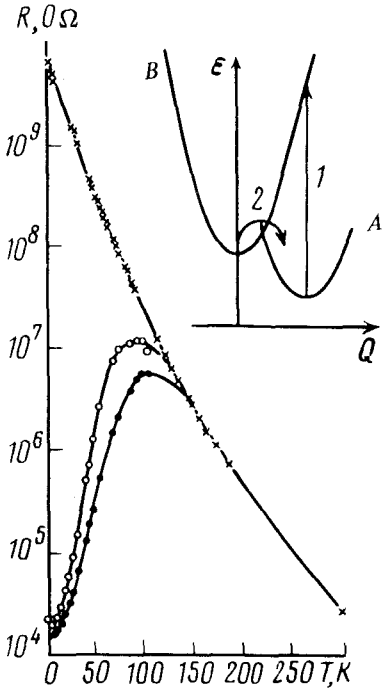

FIG. 2. Temperature dependence of the resistance of an oxidized PbTe film. +—Without illumination, upon cooling to 1.3 K; • and ○—steady-state value of R during heating at each temperature; •—during illumination of the film; ○—after the illumination has ended. The inset shows the dependence of the energy (ϵ) of the acceptor-electron system on the configurational coordinate Q. A—Energy of the state with a localized electron; B—energy of the state with a delocalized electron. Transition 1—upon optical excitation or electron-impact excitation; 2—upon thermal excitation.

in a definite concentration). Our own results show that the mechanism for the frozen photoconductivity in tellurides may be of a different nature. An explanation which seems plausible to us is that the oxidized PbTe contains self-localized acceptor states which move above the Fermi level when an electron is removed from an acceptor and transferred to the conduction band (see the inset in Fig. 2, where the configurational coordinate Q is a measure of the lattice deformation). Similar arguments regarding a pronounced change in the lattice deformation during the filling and emptying of a local level were offered by Lang *et al.*[6] with regard to donors in $Al_xGa_{1-x}As$; the possibility in principle of such an effect was raised even earlier by Rashba.[7]

A point which remains unclear is the qualitative difference between the effect of hot-carrier injection and that of ordinary current flow through the PbTe layer. While the carrier injection causes a transition to a low-resistivity state, the ordinary current flow causes the inverse transition. These effects can be explained only by appealing to a rather contrived argument: that the hot electrons, which have the relatively high energy ~1 eV required for crossing the barriers at the Pb—PbTe interface, have a higher probability for causing first-order transitions (as explained by the inset in Fig. 2), with an energy ~1 eV, than for causing above-barrier second-order transitions. On the other hand, the relatively weak electric fields, which appear in the PbTe film upon the flow of a current excited by an auxiliary external source, cannot cause first-order transitions; they simply cause the sample to return to its high-resistivity state, through second-order transitions with an energy ~0.01 eV.

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