Effect of additional doping with an acceptor impurity on the superconducting transition in PbTe ⟨Tl⟩

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The changes arising in the residual resistance, the critical temperature and magnetic field of the superconducting transition, and the density of states at the Fermi level with additional doping by an acceptor in PbTe ⟨Tl⟩, are investigated. It is concluded that quasilocal states of thallium play a determining role in the appearance of superconductivity.

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A superconducting transition in PbTe, doped with thallium, was discovered in Ref. 1. Analysis of the temperature dependences of the specific resistance and heat capacity and the effect of a magnetic field on them gave convincing proof of the volume nature of the superconductivity. For a thallium concentration $N_{\mathrm{Tl}} = 1.5$ at.%, the critical temperature is $T_c = 1.4$ K.

The characteristics of the electrophysical and optical properties of PbTe ⟨Tl⟩ were explained in Refs. 2–6 using a model of quasilocal impurity states, against the background of the resolved spectrum of the valence band. If the existence of the superconducting transition in PbTe ⟨Tl⟩ is related to the presence of these states, then we can expect a correlation in the dependences of the critical coefficients and the parameters of the superconducting transition on the degree of filling of the impurity band. The purpose of the present work is to verify this proposition experimentally. The degree of filling of the impurity states by Tl was varied by additional doping with an acceptor impurity, while maintaining the thallium content constant and equal to 2 at.%. Assuming that the impurity band contains two states per impurity atom and a single electron, which does not participate in the bonds with tellurium,[7] the degree of filling of the band can be written as follows:

$$k = \frac{1}{2} + \frac{N_A - p}{2N_{\mathrm{Tl}}}, \tag{1}$$

where p is the concentration of holes, determined from the value of the Hall coefficient at 77 K; N_A is the concentration of the additional acceptor impurity.

A transition to the superconducting state was deduced from the discontinuous drop (not less than by 2–3 orders of magnitude) in the specific resistance ρ, which could be returned to the starting value ρ_N by switching on a magnetic field, whose magnitude depended on the temperature and composition of the specimen. An exact determination of the critical temperature T_c, as in Ref. 1, is difficult due to the diffuseness of the transition in temperature $\Delta T \sim 0.1$ K. ρ returns to ρ_N in a magnetic field in a discontinuous manner and is likewise diffuse over the interval $\Delta H \sim 0.1$–0.5 kOe. For

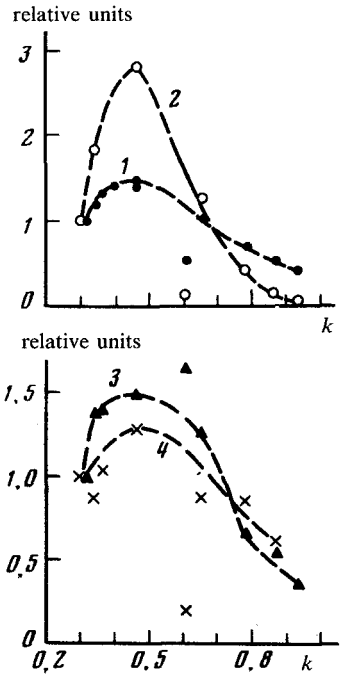

FIG. 1. The specific resistance ρ, critical temperature T_c, second critical field $H_{c2}(0)$, and the density of states in the normal state $N(0)$ as a function of the degree of filling of quasilocal impurity states of thallium in PbTe in relative units (refer to the corresponding values at $N_A = 0$). 1) T_c; 2) $H_{c2}(0)$; 3) ρ; 4) $N(0)$.

this reason, the values of T_c and H_{c2} (second critical field) are taken as the values corresponding to $\rho = 0.1\,\rho_N$.

As can be seen from Fig. 1, which presents the basic experimental data, there is a correlation between the dependences of the parameters of the superconducting transition and the resistance of the specimens on the degree of filling of the impurity states by holes. The maxima in the dependences shown correspond to a filling of the band by quasilocal states close to 0.5. The extremal nature of the dependence $\rho(k)$ corresponds to the representation of resonant scattering of holes in PbTe ⟨Tl⟩.[4] In the absence of a complicated structure of the band of quasilocal states, a maximum should be observed in ρ at the Fermi level, close to the center of the band, i.e., for $k \approx 0.5$. The dependence of the density of states at the Fermi level $N(0)$ in the normal state on the degree of filling has a similar character. The latter was estimated from the equation obtained from expressions (4.26), (4.30), (5.40), and (5.43) in Ref. 8 and is valid for large values of the Ginzburg-Landau parameter κ($\kappa \sim 100$ in PbTe ⟨Tl⟩[1]):

$$N(0) = 4.8 \times 10^{16} \frac{H_{c2}(0)}{\rho T_c}, \tag{2}$$

where $H_{c2}(0)$ is the critical field in T, extrapolated to 0 K from the experimental dependence $H_{c2}(T)$ (see Fig. 2), and ρ is the residual specific resistance in Ω m. In spite of the approximate nature of the estimates, we can conclude that the value of $N(0)$ determined by this method significantly exceeds the density of band states in PbTe not containing the thallium impurity.[9]

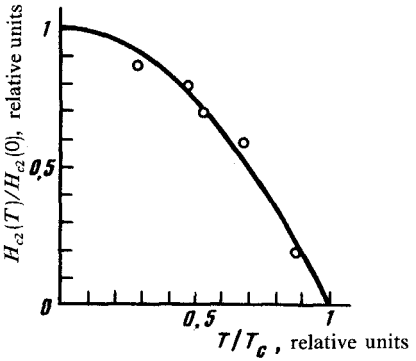

FIG. 2. Temperature dependence of the second critical field in the specimen with the degree of filling of the quasilocal states equal to $k = 0.46$. The points indicate the experiment and the line indicates a calculation using the equation $H_{c_2}(T) = H_{c_2}(0)[1 - (T/T_c)^2]$.

For one of the compositions, corresponding to $k \sim 0.6$, the values of T_c, H_{c2}, and ρ do not follow the general pattern. Whether this is a random effect or whether it is related to the complex structure of the band[10] is a question that must be answered by experiments currently in progress.

Thus, in our opinion, the data presented give additional confirmation of the presence of quasilocal states in PbTe ⟨Tl⟩ and indicate the fact that they play a determining role in the superconducting transition. The fact that the value of $N(0)$ greatly exceeds the density of band states in PbTe without Tl, as well as the form of the dependence $N(k)$, suggest that electrons located in hybridized (band + impurity) states, are paired. If we stay within the framework of the BCS theory, then the increase in T_c that accompanies the shift in the chemical potential to the maximum of the density of states (corresponding to $k = 0.5$) can be related both to an increase in the density of states at the Fermi level and to an increase in the electron-electron interaction constant with the increase in the resonant scattering intensity (decrease in the free path length).

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