Paramagnetism on the temperature-magnetization dependences in a superconducting semiconductor solid solution \((\text{Pb}_z\text{Sn}_{1-z})_{1-x}\text{In}_x\text{Te})

D V Denisov\(^1\), N Yu Mikhailin\(^1\), D V Shamshur\(^1\) and R V Parfeniev\(^1\)

\(^1\)Ioffe Institute, 26 Politekhnicheskaya st., Saint Petersburg 194021, Russian Federation

E-mail: ddenisov10@mail.ru

Abstract. In this work we studied magnetic properties of the semiconductor solid solution \((\text{Pb}_z\text{Sn}_{1-z})_{1-x}\text{In}_x\text{Te})\) in superconducting state. Peak-effect in magnetization vs magnetic field dependences was observed, and a paramagnetic response was obtained in superconducting state at certain magnetic fields and temperatures in a range of compounds. Possible relation between those effects is considered.

1. Introduction
Doping of a semiconductor solid solution of \(\text{Pb}_z\text{Sn}_{1-z}\)Te with In makes it possible to obtain materials with higher critical parameters of the superconducting (SC) transition (critical temperature \(T_c\) and critical magnetic field \(H_{c2}\)) compared to other SC semiconductors \([1]\). In addition, this material can exhibit properties of a topological crystalline insulator \([2]\). We studied magnetic properties of compounds in the region of maximum \(T_c\) based on previously obtained dependences of critical temperature on lead and indium content in the solid solution \([1]\): samples with indium content \(\text{In} (x) = 0.16, 0.2\) and lead content \(\text{Pb} (z) = 0.3, 0.4, 0.5, 0.6\) were used.

2. Experiment
Polycrystalline samples of \((\text{Pb}_z\text{Sn}_{1-z})_{1-x}\text{In}_x\text{Te})\) were obtained using the cermet method. The synthesis was carried out by fusion of the elementary In, Pb, Sn, Te materials taken in the appropriate proportions, in pumped and sealed quartz ampoules at a temperature of \(T \sim 900 - 1000^\circ\)C for 4 to 5 hours. Bulk samples have typical grain size \(d \leq 300\) \(\mu\)m. The homogeneity of the studied materials in terms of composition and concentration of dopants was monitored using an X-ray microanalyzer "Comebax". The deviation from stoichiometry is about 1-2 at. \%, and due to the fact that the content of In and Pb is high, it does not significantly affect the result. No noticeable traces of the second phase were detected in the studied samples. In addition to X-ray microanalysis, composition of the \((\text{Pb}_z\text{Sn}_{1-z})_{1-x}\text{In}_x\text{Te})\) thin films and the distribution of the components over the thickness was studied using the Auger method - electron spectroscopy with layer-by-layer etching with \(\text{Ar}^+\) ions. The difference of values between the values of taken elemental composition and Auger profiles in the depth of the sample is about 1-2 at. \% \([3]\).

Measurements were carried out on a Quantum Design Physical Property Measurement System 14 using a vibrating sample magnetometer option. Magnetization data is obtained by oscillating the sample near a detection coil and synchronously detecting the induced voltage, which is subsequently converted.
to magnetization. By using a compact gradiometer pickup coil configuration, a relatively large oscillation amplitude (1-3 mm peak) and sample oscillation frequency of 40 Hz, the system is able to resolve magnetization changes of less than 10⁻⁶ emu.

When Pb₃Sn₁₋₃Te is doped with In impurity, a band of deep quasilocal impurity states with energy level E_In is formed in the energy spectrum of the compound. The band spectrum in the solid solution shifts from direct band structure in Pb₁ₓInₓTe to reverse in Sn₁₋ₓInₓTe, passing through a zero band gap state at a lead concentration z = 0.65 (fig. 1). E_In also shifts from the conduction band of the material to its valence band with decreasing z. When the In level is located in the band gap, carriers in impurity states interact weakly with the band spectrum; at low temperatures (T < 20 K), long-term relaxation processes of nonequilibrium electrons are observed [4, 5]; solid solutions with In level located in the valence band are characterized with an extremely high critical SC transition temperature Tc ≤ 4.2 K for semiconductors [1, 6].

3. Results and discussion

Magnetization vs temperature m(T) and magnetization vs magnetic field m(H) dependences were obtained in the SC region of the materials at temperatures T > 2 K and in magnetic fields H < 30 kOe. An additional extremum is observed on the m(H) dependences in fields close to Hc₂ and temperatures below Tc, which we interpret as peak-effect (fig. 2). This effect is observed in (Pb₃Sn₀.5)₀.₈In₀.₂Te, (Pb₃Sn₀.₆)₀.₈In₀.₂Te, (Pb₃Sn₀.₇)₀.₈₄In₀.₁₆Te and (Pb₃Sn₀.₆)₀.₈₄In₀.₁₆Te compounds [7]. Peak amplitude increases with temperature decrease, and the secondary peak position on the m(H) dependence shifts to the region of lower magnetic fields.

![Figure 1. Band spectrum of a (Pb₃Sn₁₋₃)₁ₓInₓTe solid solution.](image1)

![Figure 2. Peak-effect in m(H) for (Pb₃Sn₀.₆)₀.₈In₀.₂Te sample at T < 3 K and H > 12 kOe](image2)
m(T) dependences are characteristic for a type-II superconductor in most studied samples - an increase of the diamagnetic signal with a decrease in the magnetic field (fig.3, 4). However, in (Pb$_{0.4}$Sn$_{0.6}$)$_{0.84}$In$_{0.16}$Te compound at H > 7 kOe and in (Pb$_{0.4}$Sn$_{0.6}$)$_{0.84}$In$_{0.16}$Te at H > 11kOe paramagnetic behavior can be observed on the curves obtained in zero field cooling (ZFC) regime (fig.5). This is commonly referred to as the paramagnetic Meissner effect (PME, Wohlleben effect) and can be caused by inhomogenous superconducting transition [8]. If the outer regions of the sample become SC first, the flux becomes trapped in the sample, and is further compressed, creating a critical Bean region inside the superconductor. The magnetic moment of the sample in this case is a sum of the diamagnetic moment created by outer shielding currents and the paramagnetic moment of the inner pinning currents, which can lead to a paramagnetic total response. In our samples PME occurs in the same range of temperatures and magnetic fields as the peak effect on the m(H) dependences. We assume that both phenomena are caused by specific properties of the vortex lattice and its interaction with pinning centers at certain H and T.

Figure 3. Characteristic m(T) dependences in samples (Pb$_{0.3}$Sn$_{0.7}$)$_{0.84}$In$_{0.16}$Te (a) and (Pb$_{0.4}$Sn$_{0.6}$)$_{0.84}$In$_{0.16}$Te (b), in which peak-effect on m(H) dependences was observed

Figure 4. Characteristic m(T) dependences in samples (Pb$_{0.4}$Sn$_{0.6}$)$_{0.84}$In$_{0.16}$Te (a) and (Pb$_{0.4}$Sn$_{0.6}$)$_{0.84}$In$_{0.16}$Te (b), at H=1kOe, H=2kOe, H=3kOe and H=4kOe in which peak-effect on m(H) dependences was observed
It should be noted however that some samples that show peak effect on m(H) dependences do not exhibit PME on m(T) dependencies in any magnetic fields in studied range of T. Since magnetization of the studied compounds in SC state depends on history of H and T changes, the effects that occur in m(H) and m(T) dependencies at the same T and H can’t be directly compared due to different history.

4. Conclusions
Magnetic properties of superconducting solid solution \((\text{Pb}_{0.4}\text{Sn}_{0.6})_{1-x}\text{In}_x\text{Te}\) with various concentrations of lead and indium were studied. In addition to the peak effect discovered earlier, paramagnetic Meissner effect was observed on the m(T) dependences obtained in the ZFC regime in \((\text{Pb}_{0.4}\text{Sn}_{0.6})_{0.8}\text{In}_{0.2}\text{Te}\) and \((\text{Pb}_{0.4}\text{Sn}_{0.6})_{0.84}\text{In}_{0.16}\text{Te}\) compounds. Since peak effect at m(H) and paramagnetism at m(T) appear in the same range of temperatures and magnetic fields, and since both effects are caused by features of vortex dynamics in the material, we can assume that those effects are related. Possible origins of both paramagnetism and peak-effect in \((\text{Pb}_{0.4}\text{Sn}_{1-x})_{1-x}\text{In}_x\text{Te}\) are still under discussion. We assume that PME in studied solid solutions is caused by flux capturing inside a superconducting sample and its consequent compression with lowering temperature due to inhomogeneities of SC transition.

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