Effect of pressure on superconductivity in the indium-doped topological crystalline insulator SnTe

This content has been downloaded from IOPscience. Please scroll down to see the full text.

2015 J. Phys.: Condens. Matter 27 242201
(http://iopscience.iop.org/0953-8984/27/24/242201)

View the table of contents for this issue, or go to the journal homepage for more

Download details:

IP Address: 14.139.60.97
This content was downloaded on 13/10/2015 at 06:18

Please note that terms and conditions apply.
Fast Track Communication

Effect of pressure on superconductivity in the indium-doped topological crystalline insulator SnTe

V K Maurya1, R Jha2, Shruti1, V P S Awana2 and S Patnaik1

1 School of Physical Sciences, Jawaharlal Nehru University, New Delhi 110067, India
2 National Physical Laboratory, New Delhi 110012, India
E-mail: spatnaik@mail.jnu.ac.in

Received 9 March 2015, revised 13 April 2015
Accepted for publication 27 April 2015
Published 22 May 2015

Abstract
We report on the impact of hydrostatic pressure on the superconductivity of optimally (indium)-doped SnTe which is established to be derived from a topological crystalline insulating phase. Single crystals of Sn1−xInxTe were synthesized by a modified Bridgman method that exhibited maximum superconducting Tc of 4.4 K for x = 0.5. Hydrostatic pressure up to 2.5 GPa was applied on the crystals of Sn0.5In0.5Te, and electrical resistivity as a function of temperature and pressure was measured. We observed a decrease in the onset superconducting transition temperature from 4.4 K to 2.8 K on increasing pressure from ambient to 2.5 GPa. The normal state resistivity also decreased abruptly by an order of magnitude at 0.5 GPa but for higher pressures, it decreased marginally. From onset, offset and zero resistivity values, dTc/dP of ∼−0.6 K GPa−1 was confirmed. The low temperature normal state resistivity followed T2 dependence suggesting Fermi liquid behaviour both for ambient and high pressure data. This increase in metallic characteristics accompanied by normal state Fermi liquid behaviour is in accordance with a ‘dome structure’ for Tc variation with varying carrier concentration.

Keywords: topological crystalline superconductor, superconductor phase diagram, high pressure measurements

(Some figures may appear in colour only in the online journal)

Introduction
Superconductors derived from topological insulators (TIs) and topological crystalline insulators (TCIs) have attracted considerable attention recently [1–3]. From a theoretical perspective they could bring to fruition the search for the elusive Majorana fermions (MFs) and from the technological point of view they are expected to have a significant impact on topological quantum computation [4, 5]. An example is the indium (In)-doped many-valley semiconductor telluride (SnTe) where a maximum superconducting transition temperature of ∼4.4 K is reported for x ∼ 0.5 in the series Sn1−xInxTe [3, 6, 7]. Several theoretical studies and detailed angle-resolved photo-electron spectroscopic (ARPES) measurements have established SnTe to be a TCI phase due to the underlying mirror symmetry of its crystalline lattice [8, 9]. Towards developing an understanding of how these bulk superconductors are different from BCS or cuprate superconductors, in this communication we report the effect of hydrostatic pressure on the superconducting properties of optimally doped Sn0.5In0.5Te.

The basic premise of measurements under high pressure is that they can effectively tune the electronic and phononic band structure. This has led to the discovery of superconductivity
in myriad compounds at high pressure [10–12]. With regard to optimally doped superconductors, such studies could reflect if there is a ‘dome structure’ associated with phase transitions vis-à-vis carrier concentration that relates to quantum criticality and correlation effects [13]. Further, if pressure could revert to the insulating bulk phase, then in principle one can have superconductor–topological insulator interfaces leading to the emergence of MFs. Moreover, a dome structure of increasing $T_c$ dependence with varying concentration of indium up to 50% was indicated earlier in SnTe [6], but the compounds were reportedly multiphase beyond $x = 0.5$ and therefore high pressure studies are essential to elucidate the full phase diagram of Sn$\textsubscript{1-x}$In$\textsubscript{x}$Te.

In particular, topological surface states have been investigated in Bi$\textsubscript{2}$Se$\textsubscript{3}$ and Bi$\textsubscript{2}$Te$\textsubscript{3}$ which have been driven to a superconducting state with application of external pressure [10–12]. In undoped topological insulators, superconductivity is achieved at relatively high pressure. For example, Bi$\textsubscript{2}$Se$\textsubscript{3}$ shows a turnover from semiconducting to metallic behaviour at $\sim$8 GPa accompanied by a structural phase transition [14]. Superconductivity appears in Bi$\textsubscript{2}$Se$\textsubscript{3}$ at $\sim$13.5 GPa at a transition temperature of 0.5 K, which gradually increases to a maximum of 7 K on increasing pressure up to 30 GPa. At higher pressures, the $T_c$ remains almost constant up to 50 GPa [10]. Bi$\textsubscript{2}$Te$\textsubscript{3}$ is another topological insulator, for which superconductivity is reported with application of 3 K under 3 GPa pressure that increases to 8 K at 15 GPa and for further higher pressures the $T_c$ exhibits a decreasing trend [12]. Like Bi$\textsubscript{2}$Se$\textsubscript{3}$, Bi$\textsubscript{2}$Te$\textsubscript{3}$ also undergoes several structural transformations from a rhombohedral (R-3m) phase to monoclinic (C2/m) at 3 GPa, to monoclinic (C2/c) at 8 GPa and finally to a bcc Im-3m structure above 16 GPa [12].

Superconductors derived from topological insulators through intercalation have also been subjected to various pressure studies [15]. Cu$_x$Bi$_2$Se$_3$ is a well-known topological insulator-based superconductor with a maximum $T_c$ of around 3.8 K [15]. Point contact spectra on the surface of Cu intercalated Bi$_2$Se$_3$ exhibit signs of unconventional superconductivity [16]. On applying pressure on Cu$_x$Bi$_2$Se$_3$ a gradual decrease in the superconducting transition temperature is reported and as pressure is increased further superconductivity disappears at $\sim$6.3 GPa [17]. With regard to TCI systems, a first-principles study on SnTe predicts a maximum superconducting $T_c = 7.16$ K by pressure tuning the electron–phonon coupling parameters in the bcc phase (Pm-3m) [18]. Further, very recently Wang et al have shown unconventional superconductivity in 3D Dirac semi-metal Cd$_3$As$_2$ which belongs to a new class of topological superconductors [19]. In this communication, we focus on the impact of pressure on superconducting and normal state conduction of the recently discovered optimally doped TCI superconductor Sn$_{0.5}$In$_{0.5}$Te. We found that the superconducting transition temperature ($T_c$) decreased monotonically with pressure ($\sim$0.6 K GPa$^{-1}$) and the normal state resistivity also decreased by an order of magnitude at 0.5 GPa. Such behaviour shows a surprising resemblance with the curious case of over-doped cuprates.

![Figure 1. Powder XRD pattern of crystals of Sn$_{0.5}$In$_{0.5}$Te. The inset shows crystal flakes. Experimental methods](image)

**Experimental methods**

Single crystals of Sn$_{0.5}$In$_{0.5}$Te were prepared by a modified Bridgman method. A series of compounds with varying indium concentration were prepared and optimum superconducting $T_c$ was achieved for Sn$_{0.5}$In$_{0.5}$Te [7]. We studied the electrical resistivity at high pressure on this composition. Single crystals were obtained by melting stoichiometric amounts of high purity elemental powder of Sn (99.99%), Te (99.999%) and shots of In(99.99%) at 900°C for 5 d in sealed evacuated quartz tubes. Intermittent shaking was performed for the homogeneity of the melt sample. The sample was cooled to 770°C over a period of 72 h followed by annealing at 770°C for 48 h. Silvery–shiny single crystals were cleaved along the $z$ axis. X-ray diffraction was carried out on the powdered samples by a RIGAKU powder x-ray Diffractometer (Miniflex 600) [7].

Pressure-dependent resistivity measurements were performed in the Physical Property Measurements System (PPMS-14T, Quantum Design) using an HPC-33 Piston type pressure cell with Quantum Design DC resistivity option. Hydrostatic pressures were generated by a BeCu/NiCrAl clamped piston-cylinder cell. The sample was immersed in a fluid (Daphne Oil) with pressure transmitting medium of Fluorinert in a Teflon cell. Annealed Pt wires were affixed to gold-sputtered contact surfaces on each sample with silver epoxy in a four-probe configuration.

**Results and discussion**

The powder XRD pattern of Sn$_{0.5}$In$_{0.5}$Te is shown in figure 1. It confirms pure phase synthesis in agreement with reference data from JCPDF (No. 089-3974). The specimen crystallizes in a rock-salt structure with space group Fm-3m. The calculated lattice parameter is $a = 6.265$ Å and the cell volume is 245.65 Å$^3$. We note that previous data have reported continuance of the rock salt structure of SnTe up to ($x = 0.5$) [6, 7]. Further band structure calculations indicate that structural changes are expected only above 5 GPa which is
considerably above our experimental range [18]. From these accounts we infer that \( x = 0.5 \) does not go into a new phase due either to pressure (less that 2.5 GPa) or dopant concentration. In the inset, as-grown crystal flakes are shown. The electrical resistivity as a function of temperature (\( \rho - T \)) for \( \text{Sn}_0.5\text{In}_0.5\text{Te} \) at ambient pressure is shown in figure 2. The inset shows resistivity up to room temperature. We mark \( T_{\text{onset}} \) by the intersection of the two extrapolated lines, one corresponding to the superconducting transition line and the other being an extended normal state resistivity line. Similarly, \( T_{\text{offset}} \) is indicated by the intersection of the transition line and a zero resistivity line. We define \( T_{\text{zero}} \) as the temperature where a zero resistivity state was achieved. This is schematically shown in figure 2. From figure 2, The values of \( T_{\text{onset}} \), \( T_{\text{offset}} \) and \( T_{\text{zero}} \) for single-crystal \( \text{Sn}_0.5\text{In}_0.5\text{Te} \) are found to be 4.4 K, 4.1 K and 3.6 K respectively. The superconducting transition is sharp with a transition width of \( \sim 0.3 \) K.

The resistivity versus temperature behaviour near the superconducting transition \( T_c \) for varying pressure is shown in figure 3(a). For clarity, the data for ambient pressure are not included as they are an order of magnitude higher. It is seen that both the superconducting transition temperature and normal state resistivity decrease with increasing pressure. It can be seen that at a maximum pressure of 2.5 GPa, the \( T_{\text{onset}} \) decreases to 2.8 K from 4.4 K (ambient pressure), while the \( T_{\text{offset}} \) and \( T_{\text{zero}} \) decrease to 2.6 K and 2.3 K from 4.1 K and 3.6 K respectively. The \( T_{\text{onset}} \), \( T_{\text{offset}} \) and \( T_{\text{zero}} \) for \( \text{Sn}_0.5\text{In}_0.5\text{Te} \) superconductor at intermediate pressure are summarized in figure 3(b). It appears that the decrease in the \( T_c \) is approximately linear for two markers (onset, offset) of the superconducting transition. The negative coefficients of \( T_c \) suppression with pressure for three markers (\( T_{\text{onset}} \), \( T_{\text{offset}} \) and \( T_{\text{zero}} \)) are estimated to be \(-0.66 \) K GPa\(^{-1}\), \(-0.61 \) K GPa\(^{-1}\) and \(-0.57 \) K GPa\(^{-1}\) respectively, and yield an average \( dT_c/dP \) of \(-0.6 \) K GPa\(^{-1}\) for the \( \text{Sn}_0.5\text{In}_0.5\text{Te} \) superconductor. In fact, in conventional superconductors, it is very common to see the decreasing \( T_c \) trend as a function of increasing pressure. Sn, In and Pb all have negative \( dT_c/dP \) of \(-0.4 \) K GPa\(^{-1}\) [20]. The principal reason for this decrease in simple metals is stiffening of the lattice and the consequent decrease in electron–phonon coupling rather than electronic effects. On the other hand, for high \( T_c \) cuprates generally \( T_c(P) \) first increases with pressure and beyond a critical pressure it starts to decrease, exhibiting a dome structure in accordance with the \( T_c \) dependence on carrier concentration [21].

In figure 4(a) we compare resistivity versus temperature \( \rho - T \) for \( \text{Sn}_0.5\text{In}_0.5\text{Te} \) taken at ambient pressure and applied pressures in the extended temperature range up to 250 K. This is done to visualize the impact of hydrostatic pressure on the normal state conduction of \( \text{Sn}_0.5\text{In}_0.5\text{Te} \). We see that at applied pressure 0.5 GPa the normal resistivity (resistivity just above the transition) decreases abruptly by nearly an order of magnitude. Quantitatively, a decrease of about 7.8 times (659.76 \( \mu \)Ω cm\(^{-1}\)–84.09 \( \mu \)Ω cm\(^{-1}\)) is observed. With further increase in pressure, while the normal state resistivity continues to decrease, the rate of change with pressure decreases substantially. Overall, the change in resistivity with temperature shows a metallic behaviour at both ambient and applied pressures up to 2.5 GPa and clearly the

**Figure 2.** Resistive superconducting transition of \( \text{Sn}_0.5\text{In}_0.5\text{Te} \) at ambient pressure. \( T_{\text{onset}} \), \( T_{\text{offset}} \) and \( T_{\text{zero}} \) are indicated by arrows.

**Figure 3.** (a) Resistive superconducting transition of \( \text{Sn}_0.5\text{In}_0.5\text{Te} \) at different pressures from 0.5 GPa to 2.5 GPa. An unambiguous decrease in superconducting transition temperature is seen. (b) Variation in superconducting \( T_c \) at various pressures for \( \text{Sn}_0.5\text{In}_0.5\text{Te} \). We can see a negative pressure coefficient \( (dT_c/dP) \) for all transitions \( T_{\text{onset}} \), \( T_{\text{offset}} \) and \( T_{\text{zero}} \).
metallic behaviour increases with higher pressure. This is in contrast to Cu$_4$B$_2$Se$_3$ where $\rho$ ($T_c$) increases by 7 times at 2.31 GPa. For low carrier density superconductors the BCS equation relates superconducting transition temperature with carrier concentration; $T_c \sim \theta_D \exp(-1/N(E_F)V_0)$ where $\theta_D$ is the Debye temperature, $V_0$ is the electron–phonon coupling calliper and density of state $N(E_F) \sim m^*n^{1/3}$ which is a product of effective mass $m^*$ and carrier concentration $n$. A decreasing carrier concentration (increasing normal state resistivity) with pressure can explain decreasing superconducting $T_c$.

But we find that normal state resistivity for Sn$_{0.5}$In$_{0.5}$Te decreases many-fold with pressure. Thus the controlling parameter for the $T_c$ suppression mechanism seems to be decreasing effective mass $m^*$ in Sn$_{0.5}$In$_{0.5}$Te under a simplistic s-wave correlation [7]. In figure 4(b) we show the change in the resistivity just above the transition temperature and at 250 K for ambient and various applied pressures. We can see that both decrease very rapidly on application of 0.5 GPa but for higher pressure, the change is relatively much smaller. The RRR (residual resistivity ratio) between resistivity at 250 K temperature and temperature just above the transition remains ~1.25 from ambient pressure to 2.5 GPa. This indicates that within experimental error, the impurity band contribution to the normal state conduction mechanism in Sn$_{0.5}$In$_{0.5}$Te remains mainly unaffected by applied pressure.

We note that both in high $T_c$ cuprates and in pnictide superconductors, the transition temperature varies in a so-called dome structure as a function of doping concentration. In the overdoped region, the normal state resistivity is well characterized by Fermi liquid behaviour. To study the appropriateness of Fermi liquid theory (negligible electronic correlations), in figure 5 we plot the resistivity versus $T^2$ curves in the temperature range 11–30 K for Sn$_{0.5}$In$_{0.5}$Te. In this theory, particularly with regard to heavy fermion systems, the strong interaction between charge carriers is replaced by weakly correlated quasi-particles with high effective mass. In figure 5, the resistivity data taken at various pressure are fitted to the equation $\rho = \rho_0 + AT^2$ where $\rho_0$ relates to impurity scattering and the coefficient A relates to square of the effective mass of the quasi-particles. The calculated values for $\rho_0$ and A are listed in table 1. We find that for the pressure 0, 0.5, 1, 1.5, 2, 2.5 GPa the data follow a $T^2$ behaviour in the temperature range 11–30 K and the curves deviate from linearity above 30 K. In the inset of figure 5 we plot the pressure dependence of coefficient A which indicates a decreasing trend with increasing pressure. This is suggestive of a weakening correlation between charge carriers in the overdoped region. But the origin of this correlation phenomenon in the semiconducting parent SnTe needs to be ascertained.

**Conclusion**

We have prepared single crystals of Sn$_{0.5}$In$_{0.5}$Te and applied pressures up to 2.5 GPa to check their superconducting properties under pressure. This is an optimally doped...
Table 1. The values for \( \rho_0 \) and \( A \) at various pressures for the equation \( \rho = \rho_0 + AT^2 \).

<table>
<thead>
<tr>
<th>Pressure (GPa)</th>
<th>0</th>
<th>0.5</th>
<th>1</th>
<th>1.5</th>
<th>2</th>
<th>2.5</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \rho_0 (\mu\Omega \text{ cm}) )</td>
<td>669.96</td>
<td>82.5</td>
<td>68.07</td>
<td>69.1</td>
<td>67.2</td>
<td>60.8</td>
</tr>
<tr>
<td>( A(\mu\Omega \text{ cm K}^{-2}) )</td>
<td>( 8.49 \times 10^{-3} )</td>
<td>( 3.71 \times 10^{-3} )</td>
<td>( 2.75 \times 10^{-3} )</td>
<td>( 2.49 \times 10^{-3} )</td>
<td>( 5.25 \times 10^{-4} )</td>
<td>( 1.58 \times 10^{-4} )</td>
</tr>
</tbody>
</table>

specimen derived from a topological crystalline insulating phase. We found that superconducting \( T_c \) (onset) decreased with pressure from 4.4 K (ambient) to 3.8 K (2.5 GPa). This suppression of superconducting transition temperatures was found to be almost monotonic with pressure and the overall \( dT_c/dP \) was estimated to be \(-0.6\) K GPa^{-1}. Fermi liquid behaviour was indicated in the temperature range 11–30 K and we found that the normal state resistivity of the sample varied as a function of \( T^2 \) with increasing pressure. Such a systematic decrease with \( T_c \) with increasing metallicity and normal state \( T^2 \) behaviour is reminiscent of overdoped high \( T_c \) cuprates.

Acknowledgments

SP thanks DST-FIST and VPSA thanks DAE-SRC for supporting research infrastructure at JNU and NPL respectively. VM, Shruti and RJ acknowledge financial support through senior research fellowships from UGC-BSR, UGC, and CSIR respectively. SP thanks GBaskaran and B Kumar for discussions on the experimental data.

References