Detailed magneto heat capacity analysis of SnAs topological superconductor

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Received 16 February 2022, revised 24 March 2022
Accepted for publication 5 April 2022
Published 22 April 2022

Abstract

In this article, we report magneto heat capacity analysis of superconducting SnAs. Magneto heat capacity analysis of superconductors is an important tool to determine bulk superconductivity as well as the pairing mechanism of Cooper pairs. SnAs crystal is characterized through x-ray diffraction and x-ray photoelectron spectroscopy. Magneto transport measurements of studied SnAs superconductor evidenced presence of superconductivity at around 4 K, which persists up to an applied field of 250 Oe. The bulk nature of superconductivity is determined through AC susceptibility ($\chi$) along with the heat capacity measurements. Magneto heat capacity measurements show SnAs to be a fully gapped $s$ wave superconductor. This finding is well supported by calculated physical parameters like $\alpha$ (3.36), $\lambda_{e-ph}$ (0.70) and $\Delta C_v/\gamma T_c$ (1.41). Calculation of residual Sommerfeld coefficient ($\gamma_{res}$) at different fields, confirms node-less superconductivity in SnAs.

Keywords: superconductivity, x-ray photoelectron spectroscopy, AC susceptibility, heat capacity, node-less superconductivity

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

1. Introduction

Ever since the discovery of superconductors, superconductivity continues to astonish the condensed matter scientists. In particular, the discovery of copper and iron-based high $T_c$ superconductors kept this field young and alive [1–3]. More recently, some superconductors were found to show topological effects in their normal state [4–6]. This class of superconductors is known as topological superconductors. Topological superconductors show fully gapped superconductivity below $T_c$ and the domination of topological surface states above [7, 8]. This unique combination of higher temperature topology and low temperature superconductivity enables superconductors to host Majorana fermions [8]. Majorana fermions are the fermionic particles, which are their own antiparticles, and realization of these particles is crucial in the field of fault tolerant quantum computing [8, 9]. Some of the doped TIs are found to show topological superconductivity with enhancement in the charge carrier density [10–14]. There are very few materials that show topological superconductivity in intrinsic form. Strong spin–orbit coupling (SOC) is the key parameter to realize topological superconductivity. Compounds with elements having higher atomic numbers, show strong SOC; this makes the study of superconductors containing heavier elements crucial to observe topological superconductivity. Some of the Sn based superconductors e.g. Sn$_{1-x}$Sb$_x$, In$_x$Sn$_{1-x}$Te and SnAs are studied recently in the context to topological superconductivity due to presence of strong SOC [15–19]. Apart from strong SOC in SnAs, the calculated Z2 invariants using first principle calculations do suggest the presence of strong topology as well in the same material [19].

The superconducting properties of SnAs are though known from a long time [20], but its type of superconductivity is yet inconclusive [18–23]. Though SnAs is reported to be type-I superconductor in reference [21], yet there are clear indications towards weak type-II superconductivity in
magnetization measurements in references [18, 19]. A similar
field dependence of heat capacity jump helps to determine the
nature of superconducting gap, which is discussed in reference
[18]. There exist only two reports on heat capacity measure-
ments of SnAs [18, 21]. The parameters obtained from heat
capacity measurements in references [18, 21] contradict each
other. In reference [21], SnAs is reported to be within BCS
weak coupling limit, on the other hand the same is shown to
be well above the BCS weak coupling limit in reference [18].
Also, the scanning tunnelling spectroscopic (STS) measure-
ments suggested SnAs to be a conventional superconductor
with isotropic gap [18, 22]. The order parameter obtained from
STS measurements in both available reports [18, 22], indicated
that the superconductivity of SnAs is well defined under BCS
weak coupling limit. The contradiction between the two avail-
able reports on heat capacity measurements [18, 21], motivates
us to study more about the nature of bulk superconductivity
of SnAs, through detailed analysis of magneto heat capacity
measurements.

In this article, we report magneto heat capacity analysis of
SnAs. Phase purity and surface chemistry of SnAs are anal-
ysed through x-ray diffraction (XRD) and x-ray photoelectron
spectroscopy (XPS) measurements. Magneto transport and AC
susceptibility measurements show the presence of supercon-
ductivity around 4 K. The parameters obtained from magneto
heat capacity measurements suggest SnAs to be a conventional
BCS superconductor with isotropic superconducting gap. The
obtained value of superconducting gap at absolute zero Δ(0) in
our report is in good agreement with that obtained from STS
measurements in references [18, 22]. Also the superconduc-
tivity is observed above 180 Oe in both magneto transport and
magneto heat capacity measurements as seen earlier in refer-
ence [18]. This strengthens our claim in reference [19] that
critical field of SnAs is higher than that as reported in ref-
ence [21]. Further magneto heat capacity analysis of SnAs
shows the same to be a fully gapped s wave superconductor.

2. Experimental

The studied SnAs crystal was synthesized by following a two-
step method based on solid state reaction process. Detailed
synthesis process is reported in our previous report [19].
X-ray diffraction spectra was recorded using Rigaku Mini-
flex II x-ray diffractometer equipped with Cu Kα, radiation of
1.5418 Å wavelength. XPS measurements are carried out using
PHI-5000 Versa Probe III made x-ray photoelectron spectrom-
eter. Al−Kα, radiation is used to analyse peaks of C 1s peak and
peaks of constituent elements of SnAs viz Sn 3d and As 3d.
Magneto transport measurements, AC susceptibility measure-
ments and magneto heat capacity measurements are carried out
on Quantum Design physical property measurement system
(QD-PPMS). Magneto transport measurements are performed
by following a standard four-probe method, the current was
limited to 5 mA. In AC susceptibility measurements the DC
background field was set to 0 Oe.

Table 1. Parameters obtained from Rietveld refinement.

| Cell parameters | Refinement parameters |
|-----------------|-----------------------|
| Cell type: face centred cubic (FCC) | χ² = 3.51 |
| Space group: Fm-3m | Rb = 10 |
| Lattice parameters: a = b = c = 5.721(0) Å | Rexp = 13.3 |
| Cell volume: 187.255 Å³ | Rexp = 7.10 |
| Density: 6.961 g cm⁻³ | |

3. Results and discussion

Phase purity and lattice parameters of synthesized crystal are
determined through Rietveld refined XRD pattern, shown in
figure 1. The refined XRD pattern shows that SnAs crystall-
izes in cubic structure with Fm-3m space group symmetry.
The model used for Rietveld refinement treats the observed
XRD peaks intensities as χ’ and the calculated intensities as
χ”. Basically, Rietveld refinement optimizes the model func-
tion in a way to minimize ∑i wi(χ’i − χ”i)². In this expression,
w_i represents the weight and given by 1/σ²i(yo_i−yo_i)⁰, where σ[yo_i] is
standard deviation of observed intensity. The weighted pro-
file R-factor (Rwp) is considered to be discrepancy index and
given by ∑i wi(χ’i − χ”i)²/∑i wi(χ’i)². The observed data is fitted to make the
expected value of w_i(yo_i − y_i)² to be equal to 1. In this con-
dition, the best possible value of Rwp is termed as expected
R-factor (Rexp) and given by Rexp² = N/ ∑i wi(χ’i−χ”i)². The observed data is fitted to make the
expected value of w_i(yo_i − y_i)² to be equal to 1. In this con
dition, the best possible value of Rwp is termed as expected
R-factor (Rexp) and given by Rexp² = N/ ∑i wi(χ’i−χ”i)². Here, the observed XRD
data is well fitted with NaCl-type structure. The obtained lat-
tice parameters along with the refinement parameters are listed
in table 1. The crystallographic information file (CIF) gen-
erated from Rietveld refinement is used to draw unit cell of
SnAs using VESTA software and the same is shown in inset of
figure 1. Sn and As atoms occupy respectively (0,0,0) and
(0,0,0) atomic positions in cubic unit cell of SnAs.

Figure 1. Rietveld refined powder XRD pattern of SnAs in which
the inset is showing the VESTA drawn unit cell of the same.
XPS spectra is recorded for chemical analysis of synthesized SnAs crystal. SnAs has two constituent elements viz Sn and As, hence the XPS spectra is recorded in Sn 3d° and As 3d° regions, which are shown in figures 2(a) and (b) respectively. The XPS peaks are calibrated with peak position of C 1s. The deconvoluted XPS spectra of SnAs in Sn 3d° region is shown in figure 2(a). Peaks of spin orbit doublet of Sn viz 3d5/2 and 3d3/2 are found to be at 484.20 ± 0.01 eV and 492.61 ± 0.01 eV respectively. These peaks are separated by 8.41 eV, which is in complete agreement with standard value of 8.41 eV as given in reference [27]. The XPS peaks in Sn 3d° region are accompanied by peaks of SnO, these peaks are generated due to surface oxidation and should not be treated as impurity in the sample, as no peak of SnO is observed in PXRD pattern. Figure 2(b) shows deconvoluted XPS spectra in As 3d° region. The spin orbit doublets of As 3d° viz 3d5/2 and 3d3/2 are merged into a single broad peak at around 40 eV. This broad peak is deconvoluted into two peaks to determine the positions of As 3d5/2 and As 3d3/2, the peak position for these spin orbit doublets are found to be 39.95 ± 0.03 eV and 40.65 ± 0.03 eV respectively. The peak positions of spin orbit doublets can be verified by matching the difference of binding energy of these peaks with the standard value. Here, XPS peaks of spin orbit doublet of As 3d° are found to be separated by 0.70 eV, which closely matches with the standard value of 0.69 eV as given in reference [27]. XPS peaks of As 3d° are also accompanied with peak of As2O3. The peaks of metal oxide in XPS spectra are occurred due to air exposure of the sample, which results in surface oxidation. All observed XPS peaks are listed in table 2 with their respective peak positions and full width at half maxima (FWHM).

**Table 2.** XPS peaks positions and FWHM of constituent elements of synthesized SnAs crystal.

| Element | Spin–orbit doublet | Binding energy (eV) | FWHM (eV) |
|---------|--------------------|---------------------|-----------|
| Sn      | 3d5/2              | 484.20 ± 0.01       | 0.97 ± 0.03 |
|         | 3d3/2              | 492.61 ± 0.01       | 0.75 ± 0.04 |
| As      | 3d5/2              | 39.95 ± 0.03        | 0.82 ± 0.09 |
|         | 3d3/2              | 40.65 ± 0.03        | 1.21 ± 0.06 |

AC susceptibility measurements at 0 DC background of synthesized SnAs crystal.

AC susceptibility measurements of SnAs are shown in figure 3. Bulk superconducting transition with $T_c^{\text{onset}}$ at 3.8 K is evident from both real ($M'$) and imaginary ($M''$) signals. DC magnetic field was set to 0 (within PPMS limits) throughout the experiment, while the AC field amplitude is varied from 1–11 Oe in steps of 2 Oe. It is important to maintain the DC field to close to 0 Oe because a slight change in DC field results in a change in $T_c$ of the superconductor. It is clear from figure 3 that $T_c^{\text{onset}}$ remains nearly unaltered, while changing the amplitude of AC field. It is quite common to observe a shift in $T_c^{\text{onset}}$ with AC amplitude, suggesting that the sample is crystalline in nature and granularity of the sample does not play a role in the superconductivity of the sample.

Figure 4(a) depicts the transport measurement of synthesized SnAs crystal. Superconducting transition is observed at around 4 K, the zoomed view of superconducting transition is shown in inset of figure 4(a). The normal state $\rho$–$T$ plot (up to 90 K) is fitted with the following equation,

$$\rho = \rho_0 + A \cdot T^n. \tag{1}$$

In above equation $\rho_0$ represents the residual resistivity and the value of $n$ determines the nature of scattering in the sample.
The value of $n$ is found to be 2.8, suggesting phonon assisted scattering in the synthesized SnAs crystal [29]. Further, the $\rho-T$ data is fitted in whole range using Bloch–Grüneisen formula, which is given as

$$\rho(T) = \rho_0 + \rho_{\text{el-ph}}(T)$$  \hspace{1cm} (2)

here $\rho(0)$ represents residual resistivity arising due to impurity scattering, the second term $\rho_{\text{el-ph}}(T)$ represents temperature dependent term, which depends on electron–phonon scattering. $\rho_{\text{el-ph}}(T)$ is given by the following formula

$$\rho_{\text{el-ph}}(T) = \alpha_{\text{el-ph}} \left( \frac{T}{\theta_D} \right)^n \int_0^\theta_D \frac{\theta_D}{1 - e^{-x}} \cdot \left( e^x + 1 \right) \, dx \hspace{1cm} (3)$$

here $\alpha_{\text{el-ph}}$ is electron–phonon coupling parameter, $\theta_D$ represents Debye temperature and $n$ is constant. $\rho-T$ data is well fitted with the above equation for $n = 5$, signifying dominant electron–phonon scattering. The observed value of Debye temperature $\theta_D$ from fitted resistivity plot is $151 \pm 0.1 \text{ K}$, this value is verified through heat capacity measurements in the later part. The residual resistivity ratio was found to be 3.54, which is comparable to other topological single crystals [30, 31]. Figure 4(b) depicts magneto transport measurements of synthesized SnAs crystal performed at different fields viz 0, 20, 40, 60, 100, 120, 140, 160, 180, 200, 250, 300 and 500 Oe. The superconducting transition temperature is gradually suppressed with the applied field. It is observed that superconductivity persists up to 250 Oe, which is well above the critical field ($H_c$), being suggested in reference [21]. Transition width of superconductivity transition tends to increase as the applied field is increased, this can be attributed to vortex pinning in the sample. The value of $H_c$ at 0 K i.e. $H_c(0)$, is determined by applying Werthamer–Helfand–Hohenberg (WHH) formalism, which is as follows

$$H_c(0) = -0.69 T_c \left[ \frac{\Delta H_c}{dT} \right]_{T_c}^{-1} \hspace{1cm} (4)$$

The obtained value of $H_c(0)$ is 381 Oe. Also, the obtained values of $H_c$ at different fields are plotted against temperature, and are fitted with the following quadratic equation known for conventional superconductors:

$$H_c = H_c(0) \cdot \left[ 1 - \frac{T^2}{T_c^2} \right] \hspace{1cm} (5)$$

The fitted quadratic and WHH plots are shown in inset of figure 4(b). The values of $H_c$ at different temperature are found to be well fitted with quadratic equation, indicating SnAs to be a conventional superconductor. The obtained value of $H_c(0)$ from this formula is 360 Oe, which is in agreement with the one as being calculated from WHH formalism. These values are also verified through heat capacity measurements in later part of this article.

Figure 5(a) represents heat capacity measurements results ($C/T$ vs $T$) of synthesized SnAs crystal in low temperature range of 2–6 K at different magnetic fields viz 0, 50, 100, 150, 200, 250 and 1000 Oe. The superconducting transition temperature gradually decreases as the magnetic field is increased; the $T_c$ here is observed to be 3.7, 3.4, 3.1, 2.8, 2.5 and 2.2 K at 0, 50, 100, 150, 200 and 250 Oe. No transition is observed at 1000 Oe. $T_c$ is found to have linear relationship with applied field, which is a trademark of conventional superconductivity. The inset of figure 5(a) shows the heat capacity measurements at zero field in temperature range 2–200 K. As mentioned earlier, there are only two reports available on heat capacity measurements of SnAs [18, 21]. Magnetic field dependent heat capacity is measured in reference [18], and the heat capacity transition is observed up to 250 Oe, which is certainly higher than the critical field suggested in reference [21]. Here also, the superconducting transition is visible up to 250 Oe, which is in agreement with reference [18]. Also, it is observed that the heat capacity transition becomes broader as the applied magnetic field is increased. The magnitude of heat capacity jump is also found to be suppressed on application of magnetic field; this signifies that the sample enters in a mixed state. This behaviour is also observed in some other type-I superconductors [32]. Magneto heat capacity measurements along with the magneto transport measurements establish that the critical field for SnAs is above 250 Oe. The value of upper critical
field at absolute zero is calculated in later part by calculating the Sommerfeld coefficient.

Figure 5(b) shows the $C/T$ vs $T^2$ plot of synthesized SnAs crystal. The inset is showing the zero field $C/T$ vs $T$ plot in temperature range from 2 to 6 K. A clear heat capacity jump is observed with $T_c^{\text{onset}}$ at 3.7 K. This signifies the presence of bulk superconductivity in the synthesized crystal at 3.7 K. Heat capacity of a material is a contribution of two terms at low temperatures viz electronic contribution ($C_{\text{el}}$) and phonon contribution ($C_{\text{ph}}$). To determine both these contributions $C/T$ vs $T^2$ plot is fitted with the following equation

$$\frac{C}{T} = \gamma_n + \beta_n \times T^2. \tag{6}$$

Here $\gamma_n$ represents the electronic contribution to heat capacity, also $\gamma_n$ is known as Sommerfeld coefficient and $\beta_n T^3$ represents phonon contribution to heat capacity. The obtained value of $\gamma_n$ and $\beta_n$ are found to be 4.92 ± 0.26 mJ mol$^{-1}$ K$^{-2}$ and 0.87 ± 0.01 mJ mol$^{-1}$ K$^{-4}$ respectively. These values can be used to determine various normal state parameters of the synthesized SnAs crystal. Sommerfeld coefficient $\gamma_n$ is associated with density of states (DOS) at Fermi level $[D_n(E_F)]$ by following formula

$$\gamma_n = \frac{\pi^2 k_B^2 D_n(E_F)}{3} \tag{7}$$

here $k_B$, represents Boltzmann constant and $D_n(E_F)$ is found to be 2.09 states eV$^{-1}$ f.u.$^{-1}$, Debye temperature of the sample is related to the coefficient of phonon term by following formula

$$\theta_D = \left( \frac{12\pi^4 n R}{5 \beta_n} \right)^{1/3} \tag{8}$$

here $n$ is the number of atoms and $R$ is ideal gas constant.

For SnAs, the value of $n$ is taken to be 2 and the calculated value of $\theta_D$ is found to be 161.6 ± 0.08 K. This value of $\theta_D$ in agreement with the obtained value from resistivity data which is 151 ± 0.1 K. Now, the value of Debye temperature and critical temperature $T_c$ are used to calculate constant of electron phonon coupling i.e. $\lambda_{e-\text{ph}}$, $\lambda_{e-\text{ph}}$ is related to $T_c$ and $\theta_D$ through McMillan formula [33], given below

$$\lambda_{e-\text{ph}} = \frac{1.04 + \mu^* \ln(\theta_D/1.45TC)}{(1 - 0.62\mu^*) \ln(\theta_D/1.45TC)} - 1.04 \tag{9}$$

here $\mu^*$ represents screened repulsive Coulomb potential. $\mu^*$ can take values from 0 to 0.2 for superconductors with $T_c$ between $10^{-3}$ K to 20 K as suggested in reference [33], while in the same report, the empirical value of $\mu^*$ is suggested to be 0.13. Here, we took the empirical value of $\mu^*$ to be 0.13 as suggested in reference [33]. $T_c$ is taken as the temperature at the middle of the heat capacity jump. The obtained value of $\lambda_{e-\text{ph}}$ is 0.70, which is comparable to the values obtained for a weakly or intermediately coupled superconductor [33]. The electronic contribution to heat capacity ($C_{\text{el}}$) is determined by subtracting the phonon contribution term from the total heat capacity. $C_{\text{el}}$ is normalized by dividing $\gamma_n T_c$ and plotted against $T/T_c$, which is shown in figure 5(c). The magnitude of specific heat jump i.e., $\Delta C_{\text{el}}/\gamma_n T_c$ is found to be 1.41. This value is certainly below the cutoff value for BCS weakly coupled superconductors, which is 1.43. This value is in agreement with reference [21]. The value of heat capacity jump is used to determine and verify the upper critical field at absolute zero obtained from WHH formalism. Sommerfeld coefficient and heat capacity jump are related to critical field through following formula [32, 34],

$$\Delta C = \frac{4H_c(0)^2}{\mu_0 T_c} = 1.43\gamma_n T_c \tag{10}$$

here, $\Delta C$ and $\gamma_n$ are taken in per unit volume. The molar volume of SnAs is 2.78 × 10$^{-3}$ m$^3$/mole. Here heat capacity jump, $\Delta C/\gamma_n$ is taken to be 1.41. The obtained value of $H_c(0)$ is found to be 333 Oe, which is nearly equal to the critical field obtained from WHH formalism which is 360 Oe. It is clear that the value of critical field is certainly higher than the reported value in reference [21].

Conventional or unconventional nature of superconductivity can be determined through normalized electronic specific heat by calculating the value of parameter, $\alpha = 2\Delta(0)/k_B T_c$. To calculate $\alpha$, the normalized heat capacity data is fitted with the s wave superconductivity equation, and is shown in figure 5(c). This suggests that SnAs is a bulk superconductor with conventional s-wave pairing. The obtained value of $\alpha$ from the fitted plot is 3.36, which is also lower than the BCS limit for weakly coupled superconductors. The obtained value of $\alpha$ corresponds to the superconducting energy gap $\Delta(0)$ of 0.54 eV, which is comparable to that is obtained from STS measurements on the same sample [22] and as in reference [18]. As mentioned before, the only two reports available on heat capacity measurements of SnAs do contradict each other [18, 21]. SnAs is shown to have BCS type weakly coupled superconductivity on the basis of heat capacity jump, which was observed below 1.43, while the value of $\alpha$ and superconducting gap were not calculated, which would have confirmed the statement. In reference [18], the value of $\alpha$ is calculated by fitting the heat capacity data, and was found to be 3.73, i.e., above BCS weak coupling limit, indicating towards moderately coupled superconductivity in SnAs. Here, in our study all calculated parameters viz $\alpha$, $\lambda_{e-\text{ph}}$, $\Delta(0)$ and $\Delta C_{\text{el}}/\gamma_n T_c$ are found to lie in BCS weak coupling limit, confirming SnAs to be a weakly coupled s wave superconductor, which is in agreement with reference [21].

In figure 5(d), $C_{\text{el}}/T$ is plotted against $T$ for different applied fields, and are fitted with the following equation [35] to calculate $\gamma_{res}$,

$$\frac{C_{\text{el}}}{T} = \gamma_{res} + A \times \exp \left( -\frac{\Delta}{T} \right) \tag{11}$$

The obtained values of $\gamma_{res}$ are further plotted against different applied fields. The variation of $\gamma_{res}$ with respect to applied field, yields an important information about the low energy excitations, which take place very near to Abrikosov vortex line. These low energy excitations determine, whether the superconductor has conventional isotropic superconducting gap or it has a nodal superconducting gap. For a superconductor with an isotropic superconducting gap, the low energy excitations take place inside the vortex cores of having their
radius proportional to penetration depth ($\xi$). For this, specific heat in superconducting state is proportional to vortex density and linearly depends on magnetic field giving $\gamma_{\text{res}}(H) \propto H$ [36]. While, in case of superconductors having nodal superconductivity, the DOS are found in the neighbourhood of gap nodes. This results in occurrence of the low energy excitations outside the vortex core and the specific heat is found to show square root dependence on magnetic field given as $\gamma_{\text{res}}(H) \propto H^{1/2}$, this is known as Volovik effect [37]. In the present case, $\gamma_{\text{res}}(H)$ is found to have a linear relationship with the applied field as shown in figure 5(e). This also confirms that the observed bulk superconductivity in synthesized SnAs crystal is of conventional nature with an isotropic superconducting gap. All the parameters obtained from heat capacity measurements are shown in table 3.

In our previous report, which was based on magnetization measurements, the SnAs was found to be a weak type-II superconductor. Interestingly, here also, superconductivity is found to persist well above type-I critical field, as suggested in reference [21]. To clear the discrepancy in nature of superconductivity in SnAs, here another exercise is made, which includes calculation of superconducting critical parameters at $T=0$ viz $\lambda(0)$ and $\xi(0)$. The unit cell of SnAs contains four formula units, while each formula unit provide three conduction...
Table 3. Parameters obtained from heat capacity measurements.

| Parameter | Obtained value |
|-----------|----------------|
| Tc onset  | 3.7 K          |
| γn        | 4.92 ± 0.26 mJ mol⁻¹ K⁻² |
| βp        | 0.87 ± 0.01 mJ mol⁻¹ K⁻² |
| Dc (Eg)   | 2.01 eV⁻¹ f.u.⁻¹ |
| θD        | 161.6 ± 0.08 K  |
| λ0,ph     | 0.70           |
| ΔC₀/T₀C   | 1.41           |
| α         | 2Δ(0)/kBTC     |
| Δ(0)      | 0.54 meV       |

...electrons, providing in total 12 electrons per unit cell. Electron density is calculated by the ratio of number of electrons and volume of one unit cell i.e., n = 12/V, where V = 187.25 Å³ (from Rietveld refinement). Electron density (n) is found to be 6.4 × 10²⁸ m⁻³. Fermi wave vector is calculated by considering a spherical Fermi surface using the formula kF=(3πn²)¹/³, and is found to be 1.24 Å⁻¹. Effective mass (m*) is calculated by taking the ratio of Sommerfeld coefficient obtained from heat capacity measurement (γn) and the same as being obtained from theoretical calculations (γcal) in reference [19].

DOS at Fermi level in theoretical calculations in reference [19] is found to be approximately 0.80 states eV⁻¹ f.u.⁻¹, providing γcal to be 2.34 mJ mol⁻¹ K⁻². The ratio of γn and γcal is given by ∆n / ∆cal, providing m* to be 2.10mₑ, where mₑ is free electron mass. The value of London penetration depth λ(0) can be calculated by using the relation λ(0) = (μn/μne)¹/². The obtained value of λ(0) is 30.4 nm. The BCS coherence length is calculated using the formula ξ(0) = (hν₀/T₀C)², and it is found to be 245.5 nm. Ginzberg Landau (G–L) κ parameter for a superconducting sample is given by the ratio of both the characteristic lengths viz London penetration depth and BCS coherence length i.e., ξ(0)/λ(0), κ parameter is found to be 0.12, which is certainly below the limit for type-I superconductivity which is κ = 1/2, suggesting SnAs to be a type-I superconductor. The obtained value of κ parameter is verified by calculating the mean free path (l), using the formula l = vFτ, here vF is Fermi velocity and given by vF = h/kF, another term τ is scattering time and given by τ = μn/mₑρ, here ρ is taken as residual resistivity ρ = 1.28 × 10⁻⁴Ω cm. The value of mean free path (l) is found to be 130.2 nm.

4. Conclusion

In this article, thermodynamic measurements are carried out to probe the nature of bulk superconductivity in the synthesized SnAs crystal. Bulk superconductivity is confirmed through magneto transport, AC susceptibility and heat capacity measurements. Some glimpses of intermediate state are observed in heat capacity measurements and a relatively high critical field is obtained in both magneto transport and heat capacity measurements. Also, the observed superconductivity in SnAs is found to be type-I, which is determined by calculating various superconductivity characteristics lengths. The heat capacity jump at the superconducting transition indicates SnAs to be a weakly coupled BCS superconductor. The value of parameter α is found to be 3.36, which also confirms that SnAs is a weakly coupled superconductor. Isotropic nature of superconducting gap is evident from linear dependency of Δ(0) upon critical field. Our report, establishes the fact that SnAs is a weakly coupled conventional BCS superconductor with an isotropic superconducting gap.

Acknowledgments

Authors would like to thank Director NPL for his keen interest and encouragement. Authors would like to thank Ms Prachi, IIT Roorkee, for XPS measurements. M M Sharma would like to thank CSIR-India for research fellowship and AcSIR for PhD registration.

Data availability statement

The data that support the findings of this study are available upon reasonable request from the authors.
Conflict of interest

Authors do not have any conflict of interest.

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References

[1] Maeda H, Tanaka Y, Fukutomi M and Asano T 1988 Japan. J. Appl. Phys. 27 L209
[2] Bednorz J G and Müller K A 1986 Z. Phys. B 64189
[3] Kamihara Y, Watanabe T, Hirano M and Hosono H 2008 J. Am. Chem. Soc. 130 3296
[4] Sasaki S, Kriener M, Segawa K, Yada K, Tanaka Y, Sato M and Ando Y 2011 Phys. Rev. Lett. 107 217001
[5] Leng H, Paulsen C, Huang Y K and de Visser A 2017 Phys. Rev. B 96 220506(R)
[6] Shen D, Kuo C N, Yang T W, Chen I N, Lue C S and Wang L M 2020 Commun. Mater. 1 156
[7] Sato T et al 2013 Phys. Rev. Lett. 110 206804
[8] Bezotosny P I et al 2019 Phys. Rev. B 100 184514
[9] Sharma M M, Karn N K, Sharma P, Gurjar G, Patnaik S and Awana V P S 2021 Solid State Commun. 340 114531
[10] Geller S and Hull G W Jr 1964 Phys. Rev. Lett. 13 127
[11] Wang Y, Sato H, Toda Y, Ueda S, Hiramatsu H and Hosono H 2014 Chem. Mater. 26 7209
[12] Howlader S, Mehta N, Sharma M M, Awana V P S and Sheet G 2021 arXiv:2111.14425
[13] Sleight A W 2009 Prog. Solid State Chem. 37 251
[14] Clark O J et al 2018 Phys. Rev. Lett. 120 156401
[15] Sirohi A, Das S, Adhikary P, Chowdhury R R, Vashist A, Singh Y, Gayen S, Das T and Sheet G 2019 J. Phys. Condens. Matter. 31 085701
[16] Le T, Yin L, Feng Z, Huang Q, Che L, Li J, Shi Y and Lu X 2019 Phys. Rev. B 99 180504(R)
[17] Sato T et al 2013 Phys. Rev. Lett. 110 206804
[18] Bezotosny P I et al 2019 Phys. Rev. B 100 184514
[19] Sharma M M, Karn N K, Sharma P, Gurjar G, Patnaik S and Awana V P S 2021 Solid State Commun. 340 114531
[20] Geller S and Hull G W Jr 1964 Phys. Rev. Lett. 13 127
[21] Wang Y, Sato H, Toda Y, Ueda S, Hiramatsu H and Hosono H 2014 Chem. Mater. 26 7209
[22] Howlader S, Mehta N, Sharma M M, Awana V P S and Sheet G 2021 arXiv:2111.14425
[23] Sleight A W 2009 Prog. Solid State Chem. 37 251
[24] Clark O J et al 2018 Phys. Rev. Lett. 120 156401
[25] Sirohi A, Das S, Adhikary P, Chowdhury R R, Vashist A, Singh Y, Gayen S, Das T and Sheet G 2019 J. Phys. Condens. Matter. 31 085701
[26] Le T, Yin L, Feng Z, Huang Q, Che L, Li J, Shi Y and Lu X 2019 Phys. Rev. B 99 180504(R)
[27] Moulder J F, Stickle W F, ‘Sobol P E and Bomben K D 1992 Handbook of X-Ray Photoelectron Spectroscopy (Eden Prairie, MN: Perkin-Elmer Corporation Physical Electronics Division)