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Fluctuation induced conductivity analyses of Cd doped $Cu_{0.5}Tl_{0.5}Ba_2Ca_2Cu_{3-y}Cd_yO_{10-\delta}$ ($y=0$, 0.5, 1.0, 1.5) superconductors

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Abstract

Fluctuation induced conductivity (FIC) analyses in the critical fluctuations region (cr), three dimensional (3D), two dimensional (2D) and zero dimensional (0D) region are reported for Cd-doped $(Cu_{0.5}Tl_{0.5})Ba_2Ca_3(Cu_{3-y}Cd_y)O_{10-\delta}$ ($y=0$, 0.5, 1.0, 1.5) superconductors. The coherence length along c-axis, $\xi_{c(0)}$, Fermi velocity, V_F, and Fermi energy of the carriers, E_F, were calculated from such analyses. Using the cross-over temperature (T_G) of critical to 3D regime the Ginzberg number, N_G, is determined. By using N_G, thermodynamic critical field, $B_{c(0)}$, the lower critical field, $B_{c1(0)}$, and critical current density, $J_{c(0)}$, are extracted. It was found from these analyses that widths of critical and 3D regimes are shrunken with the increased doping of Cd in the final compound. Also $\xi_{c(0)}$, V_F and the coupling constant J are suppressed with increased Cd doping. The decrease in important superconductivity parameters is suggested to be arising due to anharmonic oscillations induced by the heavier Cd atoms doped at Cu planar sites which in turn suppress the density of the desired phonons required for optimum superconducting properties. In these analyses we found that the critical magnetic fields ($B_{c(0)}$, $B_{c1(0)}$) and $J_{c(0)}$ increase with increased Cd concentration. The most likely reason for the improvement of magnetic properties is increased population of spin-less Cd atoms from which the magnetic field lines are not deflected and behave like pinning centers.

Keywords: Fluctuations induced conductivity; Critical magnetic field; Electron–phonon interactions

1. Introduction

Fluctuations induced conductivity (FIC) in oxide high temperature superconductors, HTSC, arise due to their short coherence length, high anisotropy and low carrier densities. There is a finite probability of the Cooper's pairs formation well above the critical temperature, T_c, which in turn causes excess conductivity, $\Delta\sigma_{(T)}$, and therefore FIC is expected to play a key role to investigate the microscopic properties of HTSC. Formation of Cooper's pairs above T_c is local and with decreasing the temperature, at $T=T_c$, a steady state generation rate of the Cooper's pairs formation becomes dominant over its decay rate where all the carriers are bosons and electrical resistance drops to zero [1–5]. This excess conductivity $\Delta\sigma_{(T)}$ is experimentally determined by the expression [6,7]

$$\Delta\boldsymbol{\sigma}_{(T)} = \left[\rho_{N(T)} - \rho_{(T)}/\rho_{N(T)}\rho_{(T)}\right]\rho_{(290\ \mathrm{K})} \tag{1}$$

Here, $\rho_{(T)}$ is the measured resistivity, and $\rho_{N(T)}=\alpha+\beta T$, is the extrapolated resistivity at 0 K, α is the resistivity at 0 K and β is slope of the line. Theoretically the excess conductivity is explained by the Aslamazov–Larkin (AL) model in thin films samples and by the Lawrence–Doniach (LD) model in polycrystalline samples [8,9]. The AL equation is Figs. 1–4

$$\Delta\boldsymbol{\sigma}_{AL} = A\varepsilon^{-\lambda D} \tag{2}$$

where $\varepsilon=(T-T_c^{mf})/T_c^{mf}$ is the reduced temperature and T_c^{mf} is the mean field critical temperature determined from the peak value of the temperature derivative of resistivity ($d\rho/dT$) in the transition region. λ_D is the dimensional exponent and is found from the slope of $\ln(\Delta\sigma)$ versus $\ln(\varepsilon)$ plot, $A=\{e^2/[32\hbar\xi_{c(0)}]\}$ and $\{e^2/[16\hbar d]\}$ while $\lambda_D=0.5$ and 1.0 for 3D and 2D excess conductivity, respectively [10,11].

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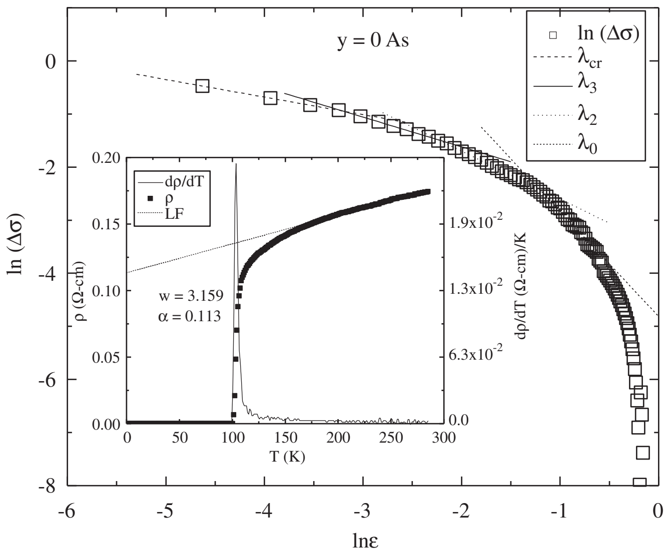

Fig. 1. ln($\Delta\sigma$) versus ln(ε) plot of $Cu_{0.5}Tl_{0.5}Ba_2Ca_2Cu_3O_{10-\delta}$ superconductors; the inset figure shows ρ versus T plot (scattered bold points' curve), the derivative dρ/dT (line graph with a sharp peak) and $\rho_{N(T)}$ (straight dashed line).

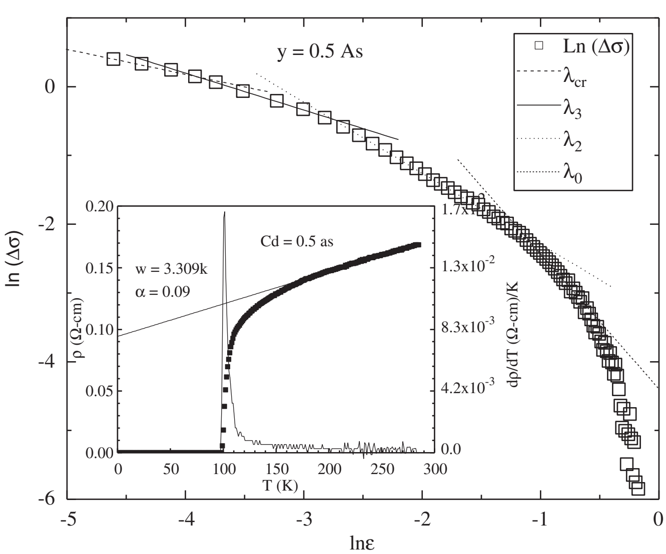

Fig. 2. ln($\Delta\sigma$) versus ln(ε) plot of $Cu_{0.5}Tl_{0.5}Ba_2Ca_2Cu_{2.5}Cd_{0.5}O_{10-\delta}$ sample; the inset figure shows ρ versus T plot (scattered bold points' curve), the derivative dρ/dT (line graph with a sharp peak) and $\rho_{N(T)}$ (straight dashed line).

λ_D and D are related as [6]:

$$\lambda_D = 2 - D/2 \tag{3}$$

The LD model is described by the equation

$$\Delta\boldsymbol{\sigma}_{\mathrm{LD}} = \left[e^2/(16\hbar d)\right]\left(1+J\varepsilon^{-1}\right)^{-1/2}\varepsilon^{-1} \tag{4}$$

where J=$[2\xi_{c(0)}/d]^2$ is a coupling parameter, $\xi_{c(0)}$ is the coherence length along c-axis and d is the inter layer separation between the conducting layer [12,13]. For $Cu_{0.5}Tl_{0.5}Ba_2Ca_3(Cu_{3-y}Cd_y)O_{10-\delta}$ superconductors, value of $d$is15 Å.

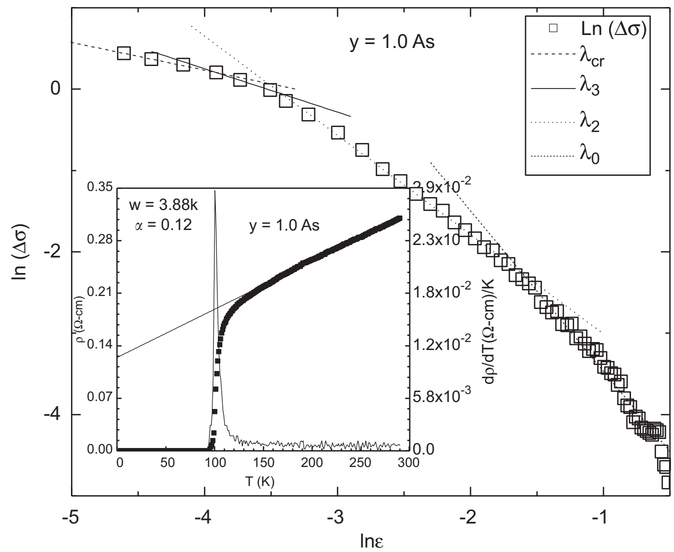

Fig. 3. ln($\Delta\sigma$) versus ln(ε) plot of $Cu_{0.5}Tl_{0.5}Ba_2Ca_2Cu_{2.0}Cd_{1.0}O_{10-\delta}$ sample, the inset figure shows ρ versus T plot (scattered bold points' curve), the derivative dρ/dT (line graph with a sharp peak) and $\rho_{N(T)}$ (straight dashed line).

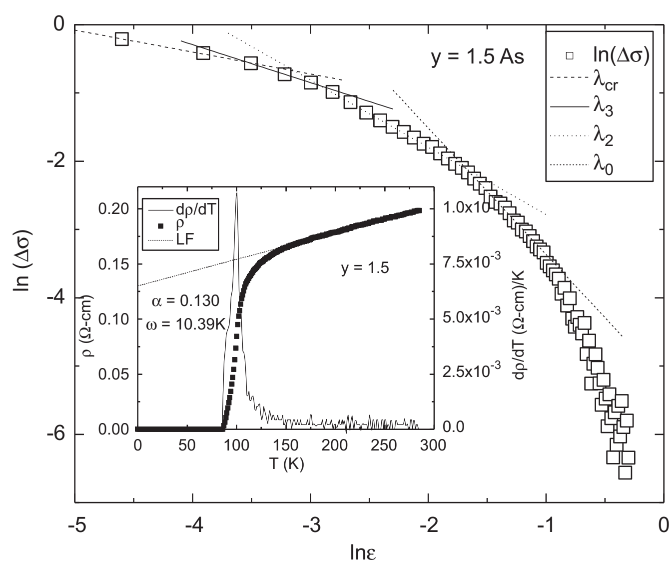

Fig. 4. In($\Delta\sigma$) versus ln(ε) plot of $Cu_{0.5}Tl_{0.5}Ba_2Ca_2Cu_{1.5}Cd_{1.5}O_{10-\delta}$ superconducting sample; the inset figure shows ρ versus T plot (scattered bold points' curve), the derivative dρ/dT (line graph with a sharp peak) and $\rho_{N(T)}$ (straight dashed line).

From the LD model, a cross-over from 3D to 2D occurs at $\varepsilon = T_{\mathrm{3D-2D}}$, from which we have calculated $\xi_{c(0)}$ as follows:

$$T_{\mathrm{3D-2D}} = T_{\mathrm{c}}[1+\left(2\xi_{c(0)}/d\right)^2] \tag{5}$$

At this temperature ($T_{\mathrm{3D-2D}}$) the system transforms from more isotropic three dimensional (3D) conducting state to a two dimensional (2D) an-isotropic state with increasing temperature. In oxide superconductors with conducting CuO_2 planes, the AL term dominates close to

T_c. The influence of superconducting fluctuations on the conductivity of normal electrons is explained by the Maki–Thompson (MT) term because formation of the Cooper pairs takes place in the background of normal electrons. The MT part depends on the phase-relaxation time τ_φ and becomes significant in 2D fluctuations regime accompanied by moderate pair-breaking [12,14].

Close to T_c, there exists the full critical regime, with an exponent denoted by λ_{cr} and equals to $-1/3$ [15]. Transition from critical to 3D regime occurs at T_G. From this cross-over very important physical parameters are calculated according to the Ginzburg–Landau (G–L) theory [16].

To find out the thermodynamic critical magnetic field $B_{c(0)}$, we have used the Ginzburg number N_G [17,18], which is determined by the equation

$$N_G = \left|(T_G - T_c)/T_c\right| = [1/2]\left[k_B T_c / B_{c(0)}{}^2 \gamma^2 \xi_{c(0)}{}^3\right]^2 \tag{6}$$

where K_B is the Boltzmann constant, $\gamma = \xi_{ab}/\xi_c$ is the anisotropy factor and its estimated value is about 4 for Cu–Tl-1223 system [19],and ξ_{ab} is the coherence length within the CuO_2/CdO_2 planes. Using the value of $B_{c(0)}$, the penetration depth $\lambda_{pd(0)}$, lower critical magnetic field $B_{c1(0),}$ upper critical magnetic field $B_{c2(0)}$ and critical current density $J_{c(0)}$ are calculated according to the following G–L equations [16, 17, 20]:

$$B_c = \Phi_0 / 2(\sqrt{2})\pi\lambda_{pd}\xi_{ab(0)} \tag{7}$$

$\Phi_0 = h/2e$ is the flux quantum.

$$B_{c1} = B_c \ln \kappa / (\sqrt{2})\kappa \tag{8}$$

$$B_{c2} = (\sqrt{2})\kappa B_c \tag{9}$$

$$J_c = 4\kappa B_{c1} / 3(\sqrt{3})\lambda_{pd} \ln(\kappa) \tag{10}$$

κ being the G–L parameter and is the ratio of penetration depth to coherence length.

In this paper we present the FIC analyses of our Cd doped $Cu_{0.5}Tl_{0.5}Ba_2Ca_3(Cu_{3-y}Cd_y)O_{10-\delta}$ ($y=0$, 0.5, 1.0 and 1.5) superconductors to investigate the causes of suppression of T_c and the underlying mechanism of superconductivity. Previously we have achieved enhanced superconducting properties for Zn doped $Cu_{0.5}Tl_{0.5}Ba_2Ca_3(Cu_{3-y}Zn_y)O_{10-\delta}$ and $Cu_{0.5}Tl_{0.5}Ba_2Ca_3(Cu_{4-y}Zn_y)O_{12-\delta}$ superconducting samples, with y content up to 3.5 [21,22]. There is a slight difference in the atomic masses of Cu and Zn. This small difference in the atomic mass does not affect the superconducting properties of the final compound. However, in $Cu_{0.5}Tl_{0.5}Ba_2Ca_3(Cu_{3-y}Cd_y)O_{10-\delta}$ ($y=0$, 0.5, 1.0 and 1.5) samples, the ground state electronic configuration of Cd atoms ($4d^{10}$) is identical to that of Zn ($3d^{10}$) atoms whereas the mass difference of these atoms (Cd) with Cu atoms in the CuO_2 planes is large. It was expected that if the role of mass of doped impurity atoms, such as Cd atoms, is passive their influence on the T_c (like Zn atoms) would be minimal. Contrary to our expectations we have observed a significant suppression in T_c of the final compound with the doping of Cd in $Cu_{0.5}Tl_{0.5}Ba_2Ca_3(Cu_{3-y}Cd_y)O_{10-\delta}$ ($y=0$, 0.5, 1.0 and1.5) superconducting samples. We have suggested in our previous studies that it arises due to the anharmonic oscillations produced by the heavier Cd atoms in the CuO_2 planes resulting in suppression of the desired phonon population, required for optimum superconducting properties [23]. The FIC analyses of the resistivity data of these samples would help in understanding these effects to the microscopic level and may provide further evidence in this belief.

2. Experimental

We have prepared $Cu_{0.5}Tl_{0.5}Ba_2Ca_3Cu_{3-y}Cd_yO_{10-\delta}$ ($y=0$, 0.5, 1.0 and 1.5) superconductors by the solid state reaction method [24]. These samples were characterized by dc-resistivity measurements; ac-susceptibility, X-ray diffraction (XRD) and Fourier transform infra-red spectroscopy (FTIR). The resistivity was measured by the four-probe method and ac-susceptibility was measured with the help of a lock-in amplifier SR530. For resistivity and susceptibility measurements, bar shaped rectangular samples were used. The electrical contacts were made by silver paste for resistivity measurement; a constant current of 1 mA was passed through the sample while the temperature was varied uniformly from 77 K to room temperature 290 K. The detailed method of preparation and characterization has already been reported elsewhere [24].

3. Results and discussion

For fluctuations induced conductivity analyses of our superconducting samples, we have followed the expression $\Delta\sigma_{(T)} = \sigma_{RT}\varepsilon^{-\lambda D}$ to fit the resistivity versus temperature data in the neighborhood of transition region and above. Values of T_c, T_c^{mf}, the dimensional exponent (λ_D) and cross over temperatures (T_G, T_{3D-2D}, T_{2D-0D}) between different fluctuation regimes from the log plot

Table 1
Superconducting parameters observed from the FIC analysis of $Cu_{0.5}Tl_{0.5}Ba_2Ca_3Cu_{3-y}Cd_yO_{10-\delta}$ ($y=0$, 0.5, 1.0 and 1.5) superconductors.

Sample	T_c (K)	T_G (K)	T_{3D-2D} (K)	T_{2D-0D} (K)	T_c^{mf} (K)	T^*(K)	$\alpha=\rho_n$(0 K) (Ω cm)	ΔT_c (K)	ξ_c (0) (Å)	$J=[2\xi_c(0)]^2/d^2$
y=0	100.05	107.37	114.39	132.45	103.35	187.64	0.113	3.159	2.287	0.106
y=0.5	98.03	103.35	107.37	133.46	101.34	177.61	0.09	3.309	1.707	0.059
y=1.0	94.44	102.35	103.36	118.41	100.34	163.56	0.12	3.88	1.214	0.030
y=1.5	86.01	103.35	105.36	119.41	100.34	159.55	0.13	10.39	1.565	0.050

Table 2
Dimensional exponents along with their temperature range for critical, 3D, 2D and 0D fluctuation regimes of $Cu_{0.5}Tl_{0.5}Ba_2Ca_3Cu_{3-y}Cd_yO_{10-\delta}$ (y=0, 0.5, 1.0 and 1.5) superconductors.

Sample	λ_{cr} (temperature range) (K)	λ_3 (temperature range) (K)	λ_2 (temperature range) (K)	λ_0 (temperature range) (K)
y=0	−0.33 (104.36–107.37)	−0.55 (107.37–114.39)	−0.90 (114.39–132.45)	−1.98 (132.45–158.54)
y=0.5	−0.36 (102.35–103.35)	−0.53 (103.35–107.37)	−1.03 (107.37–133.46)	−1.96 (133.46–156.54)
y=1.0	−0.34 (101.35–102.35)	−0.53 (102.35–103.36)	−1.22 (103.36–118.41)	−1.97 (118.41–154.53)
y=1.5	−0.32 (101.34–103.35)	−0.55 (103.35–105.36)	−0.98 (105.36–119.41)	−1.85 (119.41–136.47)

of excess conductivity versus reduced temperature are mentioned in Tables 1 and 2. λ_{cr} corresponds to the exponent value below T_G and has a value of 0.33. The exponent λ_{3D} refers to the 3D fluctuation region, between T_G and T_{3D-2D}, and λ_{2D} to 2D regime between T_{3D-2D} and T_{2D-0D} while λ_{0D} corresponds to exponent value of 2.0 above T_{2D-0D}. The exponent λ_{0D} refers to the 0D fluctuation regime where the Cooper pairs are formed and broken down instantly and their formation is not supported in any preferred direction. Values of all these exponents and their corresponding widths, for $Cu_{0.5}Tl_{0.5}Ba_2Ca_3Cu_{3-y}Cd_yO_{10-\delta}$ (y=0, 0.5, 1.0 and 1.5) superconductors, are given in Table 2. The values of λ_{cr} are found to be −0.33, −0.36, −0.34 and −0.32 for Cd-doping of y=0, 0.5, 1.0 and 1.5, respectively. The values of λ_{3D} for these samples are found to be −0.55, −0.53, −0.53 and −0.55 as in the above order, those of λ_{2D} are −0.9, −1.03, −1.22 and −0.98, and λ_{0D} are found to be −1.98, −1.96, −1.97 and −1.85, Table 2. The observed values of T_c for $Cu_{0.5}Tl_{0.5}Ba_2Ca_3Cu_{3-y}Cd_yO_{10-\delta}$ (y=0, 0.5, 1.0 and 1.5) samples are 100.05, 98.03, 94.44 and 86.01 K, respectively, Table 1. T_c^{mf}, determined from $d\rho/dT$, is found to be 103.35, 101.34, 100.34 and 100.34 K for y=0, 0.5, 1.0 and 1.5, respectively. It is observed that values of T_c, T_c^{mf} and T_G are suppressed as well as width of the critical and 3D regimes are shrunken with the increasing concentration of Cd, see Tables 1 and 2. Using the above values of T_{3D-2D} and T_c^{mf} in Eq. (5), the coherence length along the c-axis, $\xi_{c(0)}$, is determined. Values of $\xi_{c(0)}$ were found to be 2.287, 1.707, 1.214 and 1.565 Å for $Cu_{0.5}Tl_{0.5}Ba_2Ca_3Cu_{3-y}Cd_yO_{10-\delta}$ (y=0, 0.5, 1.0 and 1.5) samples, Table 1.

Values of the Ginzburg number, N_G, were calculated according to Eq. (6). These values were found to be 3.89×10^{-2}, 1.98×10^{-2}, 2.00×10^{-2} and 3.00×10^{-2} for Cd-doping of y=0, 0.5, 1.0 and 1.5, respectively. The values of $B_{c(0)}$ in accordance with Eq. (6) were found to be 1.62, 2.95, 4.89 and 3.02 T, respectively, for $Cu_{0.5}Tl_{0.5}Ba_2Ca_3Cu_{3-y}Cd_yO_{10-\delta}$ (y=0, 0.5, 1.0 and 1.5) samples. Values of $B_{c1(0)}$, determined from Eq. (8), are 0.08, 0.23, 0.54 and 0.024 T while the values of $J_{c(0)}$, found according to Eq. (10), are 0.988, 3.266, 8.944 and 3.410×10^3 A/cm^2, for y=0, 0.5, 1.0 and 1.5, respectively, as given in Table 4.

The cross-over observed from 2D to 0D occurs at T_{2D-0D} and this is actually cross-over from the LD to MT contribution when $\delta\cong\alpha$ as given in reference. [25],

Table 3
fermi velocity V_F, phase relaxation time τ_φ, coupling constant λ, and the Fermi energy E_F extracted from FIC analysis of $Cu_{0.5}Tl_{0.5}Ba_2Ca_3Cu_{3-y}Cd_yO_{10-\delta}$ (y=0, 0.5, 1.0 and 1.5) superconductors.

Sample	V_F (10^7 cm/s)	τ_φ (10^{-14} s)	λ	E_F (eV)
y=0	1.96	8.08	0.113	1.094
y=0.5	1.43	7.13	0.127	0.585
y=1.0	0.98	14.15	0.072	0.274
y=1.5	1.15	13.28	0.076	0.378

Table 4
Ginzberg Number N_G, critical magnetic field $B_{c(0)}$, the lower and upper critical fields $B_{c1(0)}$ and $B_{c2(0)}$, penetration depth λ_{pd} and critical current density $J_{c(0)}$ extracted from the FIC analysis of $Cu_{0.5}Tl_{0.5}Ba_2Ca_3Cu_{3-y}Cd_yO_{10-\delta}$ (y= 0, 0.5, 1.0, 1.5) superconductors.

Sample y=0.0	$N_G\times10^{-2}$	$B_{c(0)}$ (T)	$\lambda_{pd}\times10^2$ (Å)	κ	B_{c1} (T)	B_{c2} (T)	$J_{c(0)}\times10^3$ (A/cm^2)
y=0	3.89	1.62	8.94	56	0.08	128.70	0.988
y=0.5	1.98	2.95	4.92	31	0.23	128.70	3.266
y=1.0	2.00	4.89	2.97	19	0.54	128.70	8.944
y=1.5	3.00	3.02	4.81	30	0.24	128.70	3.410

which leads to the relation

$$\varepsilon_o \cong (\pi\hbar)/[1.203(l/\xi_{ab})(8K_B T\tau_\varphi)] \quad (11)$$

Increasing the temperature of a superconductor above T_c, at a particular point the mean free path l of the Cooper pairs approaches ξ_{ab} and they are separated apart into fermions. At this temperature the phase relaxation time of the Cooper pairs is investigated as under

$$\tau_\varphi = \pi\hbar/8k_B T\varepsilon_0 \quad (12)$$

Values of τ_φ found for our superconducting samples (y=0, 0.5, 1.0 and 1.5) are 8.08×10^{-14}, 7.13×10^{-14}, 14.15×10^{-14} and 13.28×10^{-14} s, respectively, see Table 4. These values are comparable with the values found for other oxides superconductors [26,27]. The above values of τ_φ were used in the following relation to find out the coupling constant λ:

$$\lambda = \hbar\tau_\varphi^{-1}/2\pi k_B T \quad (13)$$

The values determined for λ are 0.113, 0.127, 0.072 and 0.076, respectively, for Cd-doping y=0, 0.5, 1.0 and 1.5 in the final compound. The coupling constant λ has values greater than 0.04 which shows that the priority mechanism of superconductivity in our samples is electron-phonon interaction; the electron–electron correlation effect is minimum [7]. Fermi velocity of the carriers was found according to the following equation.

$$V_F = 5\pi k_B T_c \xi_{c(0)} / 2K\hbar \quad (14)$$

where $K \cong 0.12$ is a co-efficient of proportionality as used in reference [26]. Values of V_F determined from the above equation are 1.96×10^7, 1.43×10^7, 0.98×10^7 and 1.15×10^7 cm/s for $Cu_{0.5}Tl_{0.5}Ba_2Ca_3Cu_{3-y}Cd_yO_{10-\delta}$ (y=0, 0.5, 1.0 and 1.5) samples, respectively, Table 3. The Fermi energy of carriers was estimated by using the relation $E_F = (1/2)m^* V_F^2$, m^* being the effective mass of the carriers and $m^* = 10m_o$, for the Tl-1223 system [17]. Values of E_F determined from this relation are 1.094, 0.585, 0.274 and 0.378 eV for y=0, 0.5, 1.0 and 1.5 respectively, Table 3.

From the above results we see that T_c, T_G, $\xi_{c(0)}$, T^* and the coupling constant J are suppressed with the increased doping of Cd at CuO_2 planar sites. Also the width of the critical and 3D fluctuation regions are shrunken and shifted to lower temperatures as Cd concentration is increased in the sample. V_F and E_F values are decreased while τ_φ is marginally altered with increasing y content. The suppression in above superconducting parameters and shrinking of the widths of various fluctuation regimes, is suggested to arise due to anharmonic oscillations produced by the heavier Cd atoms doped at Cu planar sites, thereby suppressing the population of the desired phonons required for optimum superconductivity. On the other hand the critical magnetic fields ($B_{c(0)}$, $B_{c1(0)}$) and the critical current density $J_{c(0)}$ are enhanced as Cd concentration is increased. One of the reasons for the improvement of $B_{c(0)}$, $B_{c1(0)}$ and $J_{c(0)}$ is the enhancement in the population of spin-less Cd atoms [28] which act as pinning centers, due to which rest of the sample remains undisturbed and becomes capable of sustaining higher magnetic field.

4. Conclusions

We have synthesized $Cu_{0.5}Tl_{0.5}Ba_2Ca_3Cu_{3-y}Cd_yO_{10-\delta}$ (y=0, 0.5, 1.0 and 1.5) superconducting samples at 860 °C. Superconducting properties of these samples were studied. Fluctuations induced conductivity (FIC) analyses of these samples were carried out using the AL and LD models. Zero resistivity critical temperature T_c, T_G, $\xi_{c(0)}$, T_{3D-2D}, T^* and the coupling constant J were found to decrease with the increasing Cd-doping in the final compound. The critical and 3D fluctuation regimes were found to shrink and shift to lower temperature values with increasing Cd-doping. The V_F and E_F values are suppressed while τ_φ is marginally altered with increasing Cd content in the final compound. Suppression in the above parameters and shrinking of the width of critical and 3D regimes suggested to arise due to anharmonic oscillations produced by heavier Cd atoms which in turn suppress population of the desired phonons required for electron–phonon interactions. Values of critical magnetic fields ($B_{c(0)}$, $B_{c1(0)}$) and the critical current density $J_{c(0)}$ are enhanced with increasing Cd-doping in the final compound. A most likely explanation for the improved magnetic properties is that Cd atoms have zero net spin and the magnetic field lines are not deflected from Cd sites, so these sites behave like efficient pinning centers, due to which rest of the sample remains undisturbed and becomes capable of sustaining higher magnetic fields.

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