Thermoelectric power of (Cu$_{0.5}$Tl$_{0.5}$)-1223 superconducting phase added with BaSnO$_3$ nanoparticles

A Srour$^1$, W Malaeb$^1$, S Marhaba$^1$ and R Awad$^1$

$^1$Physics Department, Faculty of Science, Beirut Arab University (BAU), Lebanon
E-mail address: ali_sr@outlook.com

Abstract. In this study, we report the thermoelectric power (TEP) measurements of Cu$_{0.5}$Tl$_{0.5}$Ba$_4$Ca$_2$Cu$_3$O$_{10-\delta}$ added with BaSnO$_3$ nanoparticles. BaSnO$_3$ nanoparticles were prepared by chemical co-precipitation method, while (BaSnO$_3$)$_x$(CuTl)-1223 superconducting samples with 0.00 $\leq x \leq$ 1.50 wt% were prepared using the solid-state reaction method. The standard four-probe technique was applied to measure DC electrical resistivity in the temperature range from 300 to 77 K. Superconducting transition temperature ($T_c$) increases up to 117.5 K for $x = 0.25$ wt.% and then it decreases with further $x$ addition. The TEP coefficient was measured as a function of temperature in a wide temperature range from $\sim$77 K (liquid nitrogen temperature) up to 280 K using a standard differential technique. The behavior of the obtained TEP coefficient is suited with high-$T_c$ copper-oxide superconductors. The results were investigated according to two-band model with an extra linear term. Several parameters such as the pseudo-gap temperature ($T^*$), Fermi energy ($E_F$) and Fermi temperature ($T_F$) values were calculated and discussed in terms of nanoparticles BaSnO$_3$ addition.

1. Introduction
Doping of nanostructures was considered as an effective approach for improving the current capacity of high-$T_c$ superconductors (HTSCs). Among these HTSCs, CuTl-1223 superconductor phase is one of the most candidates in the field of power transmission electric energy and superconducting magnetic field sensors [1]. The study of transport properties on this phase such as electrical resistivity and thermoelectric power is important to explore its conduction mechanisms. Moreover, it provides information about the band width, scattering mechanism, nature of charge carries and electronic transport properties [2-4]. TEP sign and coefficient are strongly dependent on the oxygen content present in the compound [5, 6] and on the hole concentration within the CuO$_2$ planes [7]. This work studies the effect of adding different concentration of barium tin oxide nanoparticles to CuTI-1223 superconductor phase on its thermoelectric power.

2. Experimental and Investigation Techniques
The prepared superconducting samples added by $x$ BaSnO$_3$ nanoparticles (prepared by chemical Co-precipitation method) with different concentrations ($x = 0.00, 0.25, 0.50, 0.75$ and $1.50$ wt.%) using solid-state reaction technique at ambient pressure, reported in our previous work [8]. DC electrical resistivity was used to characterize the superconducting properties of the samples using standard four-probe DC technique, in the temperature range (77 to 300) K. TEP of the prepared superconductor samples was measured using the standard differential technique in the temperature range from 80 to 280 K. The sample, of dimensions $1.5 \times 0.3 \times 0.2$ cm$^3$, was clamped between two copper plates and each one supplied with a metal resistor heater. Two T-type thermocouples were used to monitor the temperatures of both blocks with accuracy $\pm 0.1$ K and record the thermoelectric motive force between the samples terminals using an accurate digital microvoltmeter and the data are carefully taken after removing the offset. Finally, the data was collected using the “DATA Studio” program and an interface (Pasco CI-7500).
3. Results and discussion

The prepared samples were characterized using X-ray Powder diffraction (XRD) and scanning electron microscope (SEM) in our previous work [8]. As a result from these characterizations, the BaSnO$_3$ nanoparticles set at the grain boundaries (no variation of lattice parameters was observed), and the addition of low content of nanoparticles enhanced the formation of (Cu$_{0.5}$Tl$_{0.5}$)-1223 phase [9]. Thus, increase in the inter-grain connectivity and grain size. The DC electrical resistivity as function of temperature for (BaSnO$_3$)$_x$/CuTl-1223 phase, with $x = 0.50$ wt.%, is shown in figure 1. The values of $T_c$ for all samples are listed in table 1. The enhancement in $T_c$ can be discussed according to the improvement in the volume fraction and inter-grain connectivity for $x = 0.25$ wt.% [8]. The hole-carriers concentration per Cu ion ($P$) is listed in table 1, calculated through the following relation [10]

$$ p = 0.16 - \left[ \frac{(1 - \frac{T}{T_{c_{max}}})}{82.6} \right]^{0.5}, \quad \text{(1)} $$

where $T_{c_{max}}$ is taken as 120 K for (Cu$_{0.5}$Tl$_{0.5}$)-1223 phase [11]. One can notice that both $T_c$ and $P$ enhance by increasing $x$ up to $x = 0.25\%$ followed by a suppression in their values with further increase in $x$. The pseudogap temperatures were also determined from the variation of $d\rho/dT$ with temperature for $x = 0.50$ wt.% sample as shown in the inset of figure 1, and the values for all samples are listed in table 1. $T^*$ represents the deviation point of resistivity from linear behavior at certain temperature, corresponding to the opining of pseudogap. It is also noticed from table 1, that the highest $T_c$ corresponds to lower $T^*$. This indicates that $T^*$ is probably affected by the oxygen content or the scattering of carriers at the grain boundaries and the change of carrier density in the CuO$_2$-planes [12, 13].

The temperature dependence thermoelectric power for the investigated set of (BaSnO$_3$)$_x$/CuTl-1223 samples with $x = 0.00$, 0.50, 0.75 and 1.50 wt.% superconductor samples is shown in figure 2. The inset of figure 2 represents the variation of $\text{TEP}_{\text{max}}$ as function of $x$ addition of BaSnO$_3$ nanoparticles. It is noticed that all the samples have positive TEP, suggesting that they are $p$-type conductive materials (holes in CuO$_2$-planes) [14]. It is well known that the BaSnO$_3$ nanoparticles possess $n$-type conduction character [15]. This means that BaSnO$_3$ does not affect the conduction mechanism of HTCSs [16]. TEP increases linearly as temperature decreases up to 150 K with a negative slope, resulting in the flow of the thermal excitation of extrinsic charge carriers at high temperatures. After that it has an optimum value at $T^*$, and their values are listed in table 1. Finally it decreases as the temperature decreases, consisting with the Mott formula [17].

A similar behavior of TEP was reported for several series of Bi-, Hg- and Tl cuprate superconductors [18-20]. $\text{TEP}_{\text{max}}$ decreases as $x$ increases up to 0.75 wt.%, followed by an increase in TEP at $x = 1.5$ wt.%. At low addition concentration (0.25 wt.%), the decrease in TEP is due to change in hole concentration to higher value (0.142), after that the followed decrease may be due to the negative conduction character (n-type) of the added nanoparticles. Then, TEP increases for $x = 1.5$ wt.%, which could be due to the growing of
impurities and inhomogeneous distribution with higher concentrations of nanoparticles. The measured TEP values are very small (5-10 µV/K), confirming the metallic behavior of (BaSnO$_3$)$_x$(CuTl)-1223 phase [21].

### Table 1. The variation of $T_c$, P and $T^*$, fitting parameters (A, B and $\alpha$), $E_F$, $T_F$ and $T^*$ estimated from TEP measurements.

| $x$ (wt.%) | $T_c$ (K) | P | $T^*$ (K) | A (µV) | B (K) | $\alpha$ (µV/K$^2$) | $E_F$ (eV) | $T_F$ (K) | $T^*$ (K) |
|---|---|---|---|---|---|---|---|---|---|
| 0.00 | 115.5 | 0.138 | 156.3 | 4000 | 50 | -0.06 | 0.4 | 0.4 | 154.1 |
| 0.25 | 117.0 | 0.142 | 147.1 | 900 | 70 | -0.0075 | 3.2 | 3.7 | 150.9 |
| 0.50 | 114.0 | 0.135 | 149.6 | 800 | 110 | -0.0085 | 2.8 | 3.3 | 153.3 |
| 0.75 | 112.5 | 0.132 | 152.1 | 720 | 128 | -0.009 | 2.7 | 3.1 | 154.7 |
| 1.50 | 111.0 | 0.129 | 155.4 | 1500 | 135 | -0.014 | 1.7 | 1.9 | 155.6 |

The measured TEP data were analyzed through the basis of the two-band model with an extra linear term on the decreasing part of the curves as shown in figure 2, which is developed by Forro et al. [22, 23] using

$$S = \frac{AT}{T^2} + \alpha T,$$

on the decreasing part of the curves, where $A$ is related to the contribution from the mobile holes in the Cu–O planes. The fitting parameters $A$, $B$ and $\alpha$ are listed in table 1. It is observed that the variation of $A$ and TEP$_{\text{max}}$ have the same trend. Assuming the term $\alpha T$, is the contribution of diffusion-like, the Fermi energy $E_F$ and temperature $T_F$ are given as

$$E_F = \frac{\pi^2 k_B^2}{3 e \alpha},$$

and their values are calculated and listed in table 1. The values of $E_F$ is consistent with other publish results for cuprates [25]. Also, the calculated values of $T_F$ are in the range of $10^4$ K, similar to those obtained for metals. According to the free electron theory, it was found that $E_F$ as well as $T_F$ are related to carrier concentration through equation 5:

$$T_F = \frac{E_F}{k_B}.$$
\[ E_F = \frac{\hbar^2}{2m} \left( \frac{3N^2 \pi^2}{V} \right)^{2/3}, \]  

where \( N/V \) is the carrier concentration at the Fermi surface, which confirmed the variation of \( P \) with both \( E_F \) and \( T_F \). The variation of Pseudogap temperature estimated from resistivity and TEP data as function of \( P \) is shown in figure 3. \( T^* \) is well fitted according to the relation \( T^* = aP - b \), by which \( a \) and \( b \) were determined to be 49.86 and 0.55 for resistivity, 79.96 and 0.42 for TEP, respectively.

4. Conclusion

The TEP of \((\text{BaSnO}_3)_x/(\text{CuTl})-1223 (0.25 \leq x \leq 1.5 \text{ wt.\%})\) was measured from 80-280 K using the standard differential technique. For all samples, TEP had positive value, which indicated the hole-like trend. Moreover, TEP decreased as the concentration of \text{BaSnO}_3 increased up to 0.75 wt.%, and then it increased with further increase in \( x \). \( T^* \) determined from TEP was consistent with that determined from resistivity. TEP results were well fitted according to two-band model with an extra linear term. Fermi Energy and Fermi temperature were estimated as function of \text{BaSnO}_3 concentrations. It was found that the variation of both \( E_F \) and \( T_F \) were confirmed the variation of \( P \) with \( x \).

References

[1] Jabbar A, Qasim I, Khan K, Ali Z, Nadeem K, and Mumtaz M 2015 J. Alloys Compd. 618 110
[2] Tokura Y, Torrance P, Huang T, and Nazzal A 1988 Phys. Rev. B 38 7156
[3] Kes P, Van den Berg J, and Narlikar A 1990 Nova Science Publ, New York. 228
[4] Okram G, Muralidhar M, Jirsia M, and Murakami M 2004 Physica C 402 94
[5] Lee S, Lee J, Suh B, Moon S, Lim C, and Kim Z 1988 Phys. Rev. B 37 2285
[6] Rao V, Rangarajan G, and Srinivasan R 1984 J. Phys. F 14 973
[7] Batlogg B, Hwang H, Takagi H, Cava R, Kao H, and Kwo J 1994 Physica C 235 130
[8] Srouj A, Malae W, Barakat M, and Awad R 2016 (submitted to Journal of temperature physics) “Physical properties of \((\text{BaSnO}_3)_x/(\text{CuTl})\)-1223 superconductor”
[9] Awad R, Abou-Aly A, Isber S, Malae W 2006 J Phys.: Conf. Ser. 43 474
[10] Presland M, Tallon J, Buckley R, Liu R, and Flower N 1991 Physica C 176 95
[11] Ihara H, Tanaka K, Tanaka Y, Iyo A, Terada N, Tokumoto M, Ariyama M, Hase I, Sundaresan A, Hamada N, and Miyashita S 2000 Physica C 341 487
[12] Francois I, Jaekel C, Kyas G, Dierickx D, Van der Biest O, Heeres R, Moshchalkov V, Bruynseraede Y, Roskos H, Borghs G, and Kurz H 1996 Phys. Rev. B 53 12502
[13] Mohammadizadeh M and Akhavan M 2003 Physica B: Condensed Matter 336 410
[14] Lin C, Chen M, Huang R, Cheng Y, and Lee P 2015 Energies 8 12573
[15] Duarte T, Buzolin P, Santos I, Longo E, and Sambrano J 2016 Theor. Chem. Acc. 135 1
[16] Al-Rasoul K 2012 Asian Trans, Basic. Appl. Sci. 2 1
[17] Fan X, Yang J, Zhu W, Bao S, Duan X, Xiao C, and Li K 2008 J. Alloys Compd. 461 9
[18] Chanda B, Ghatak S, and Dey T 1994 Physica C 232 136
[19] Orlando M, De Mello E, Passos C, Caputo M, Martinez L, Zeini B, Yuge E, Vanoni W, and Baggi-Saitovich E 2001 Physica C 364 350
[20] Mitra N, Trefny J, Yarar B, Pine G, Sheng Z, and Hermann A 1988 Phys. Rev. B:Condens. Matter 38 7064
[21] Gul I and Maqsood A 2008 J. Supercond. Nov. Magn 21 399
[22] Gottwick U, Gloss K, Horn S, Steglich F, and Grewe N 1985 J. Magn. Magn. Mater. 47 536
[23] Forro L, Lukatela J, and Keszei B 1990 Solid State Commun. 73 501
[24] Casquilho J and Teixeira P 2014 Introduction to Statistical Physics. Cambridge University Press
[25] Ghorbani S, Lundqvist P, Andersson M, Valldor M, and Rapp O 2001 Physica C 353 77