Studying the Partial Substitution of Pb Instead of Bi-O on Electrical Properties of the BBCCO System

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Abstract :This study investigates the effect of chemical substitution on the physical properties of the superconducting ceramic composite $Bi_{2-x}Pb_xBaCa_{1.85}Sb_{0.15}Cu_3O_{10+\delta}$ with varying amounts of lead substitution (x = 0.0, 0.1, 0.2, 0.3, 0.4). The main objective is to optimize the substitution conditions to enhance the structural and electrical properties of the composite and obtain the maximum superconducting transition temperature (high temperature). The samples were produced by the solid-state reaction (SSR) method under controlled conditions to facilitate gradual atomic diffusion. The four-probe technique was used to investigate the electrical resistivity as a function of temperature, facilitating the calculation of the critical transition temperatures (Tc) and energy gap (Eg) values for different substitution levels. The results show that all samples exhibit superconducting (metallic) properties at 780 °C. In comparison the best and most optimal sample was identified using the SSR method, and under optimal conditions compared to the samples with substitution (x = 0.4), it had the highest critical transition temperature (Tc = 121.8 K), the highest energy gap (Eg = 0.035192588 eV), the lowest bandwidth $\Delta T(K)$ = 1.2, and the highest hole concentration P(Hole) = 0.16. These changes reflect the improved superconducting properties upon substitution of lead at the sample (x = 0.4), making this composition ideal for high critical temperature applications.

Keywords: High-Tc, Partial Substitution, Electrical Resistance, Solid state reaction, Energy gap, Superconductivity

INTRODUCTION

Superconductivity is a significant physical phenomenon in materials science, characterized by the total elimination of electrical resistance at a threshold temperature (Tc) (Onnes, 1911)[1]. Following the identification of this phenomena, investigations into superconducting materials have intensified, particularly after the revelation of high-temperature superconductors in copper compounds and ceramic oxides (Muller-Bednerz) [2-4]. The correlation between resistivity and phase transitions in these materials is still a subject of contention, as the mechanisms of superconductivity differ based on crystal structure and electronic interactions. Superconductivity in ordinary materials is elucidated by the Bardeen-Cooper-Schrieffer theory (BCS, 1957), which is predicated on the production of Cooper pairs due to electron-phonon interactions[5-7]. This theory is inadequate to elucidate the behaviors observed in unconventional superconductors, necessitating the formulation of alternative models, including d-wave coupling in copper ferrites and electron-electron interaction theory[8-10]. Recent investigations indicate that structural variables, including lattice distortions, mechanical strains, and impurities, can substantially affect the critical temperature and phase transition behavior. The advent of high-temperature superconducting vehicles (HTSC) has ignited a new revolution in materials research and industrial applications[11, 12]. The examination of methods and processes for the replacement or addition of elements might broaden horizons.

Comprehending the methods by which superconductivity manifests in elements and compounds, particularly in relation to the composition of copper oxide cuprates [13, 14]. Despite extensive research on replacement and addition processes, no definitive approaches or mechanisms have been identified for the addition and replacement of elements in this material to far[15, 16] . This endeavour is driven by the desire to enhance research procedures and to fulfil the objectives outlined in this study. The objective of this study is to examine the impact of Pb substitution in Bi-based superconductors, which were synthesized by incorporating varying amounts of Sb into the $Bi_{2-x}Pb_xBaCa_{1.85}Sb_{0.15}Cu_3O_{10+\delta}$, with x values of 0.00, 0.1, 0.2, 0.3, and 0.4. Furthermore, the investigation encompasses the impact of this addition on the electrical properties of the compound.

EXPERMENTAL

Using the conventional solid-state reaction approach, samples of $Bi_{2-x}Pb_xBaCa_{1.85}Sb_{0.15}Cu_3O_{10+\delta}$ ceramic superconductors (x = 0.0, 0.1, 0.2, 0.3, and 0.4) were created, according to their molecular weights, and employing suitable weights for pure powders of Bi2O3, Sb2O3, BaO, CaO, and CuO. A sensitive balance was used to determine each reactant's weight. Utilizing an agate mortar, combine particles during the 45 minute grinding operation[17] . Utilizing hydraulic pressure and 8 tons/cm 2 for two minutes, the discs have a diameter of 1.5 cm and a thickness of 0.15 to 0.25 cm. Samples were sintered using the SSR method, which heats the air at 780 degrees Celsius for 22 hours at a rate of 10 degrees Celsius per minute. Resistance experiments using the prepared approach were used to analyse the samples' superconducting condition. The superconducting condition of the samples was assessed by resistance experiments conducted according to the established methodology. Figure (1) illustrates the circuit diagram for this technique.
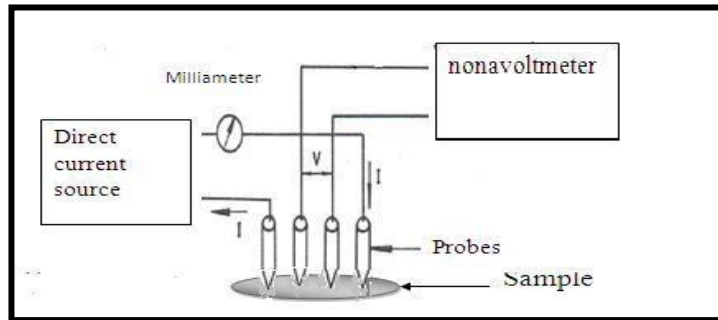

Figure 1: A diagram showing the four-sensor technique for measuring electrical resistivity as a function of temperature

When a current passes through the sample of (I), a voltage drop will occur across the electrodes. Thus, the resistivity of the sample can be ascertained using the subsequent equation: [18, 19]

$$\rho = \frac{V.t}{I.L} \tag{1}$$

Where (I) represents the current passing through the specimen, (V) denotes the voltage drop across the electrodes, (t) indicates the specimen thickness, (L) signifies the effective length between the electrodes, and (ω) refers to the width of the specimen. The following relationship is used :[9]

$$\rho = 4.5324 \ \frac{V}{I} \tag{2}$$

The critical transition temperature can be determined from the electrical resistivity curve plotted against temperature using the following equation:[9, 20]

$$Tc(mid) = \frac{T_{c_1} + T_{c_2}}{2} \tag{3}$$

Tc (Onset) is the starting transition temperature, Tc (Offset) is the ultimate transition temperature at ($\rho = 0$), and Tc (Mid) is the temperature at the halfway point between Tc (Onset) and Tc (Offset)[21].

$$Eg = 3.53 K_B Tc \tag{4}$$

Then, the energy gap of the superconducting samples was calculated through the following relationship:[22]

$$P= (0.16) - [(1- TC/Tcmax) / (82.6)] (1/2) \tag{5}$$

In this instance, p represents the gap concentration, and Tc (max) represents the system's maximum critical transition temperature (BBCCO). The architecture of the superconducting ceramic system (BBCCO) and its chemical formula (Bi2BaCa2Cu3O10) can be viewed as an electrically active entity, as both copper and oxygen create a series of copper oxide layers. The integration of these layers into the crystal structure allows oxygen to enter and exit the mixture more easily. The crystalline structure makes it easier to create a precise concentration of cavities, which is required for superconductivity to occur.

RESULTS AND DISCUSSION

One of the most important characteristics of matter is electrical resistivity as a function of temperature, which is used to calculate the value of the critical transition temperature (T_c). We can learn a lot about the nature of the interactions between the material's particles by examining this feature. The process of electron coupling and pairing (Cooper pairs) is necessary to reach the critical temperature (T_c), or the superconducting transition [22]. The solid-state reaction technique (SSR) was used to create samples (x=0, 0.1, 0.2, 0.3, and 0.4). Figure 2 shows how electrical resistance varies with temperature for the compound $Bi_{2-x}Pb_xBaCa_{1.85}Sb_{0.15}Cu_3O_{10+\delta}$. It is noted that all samples have metallic behavior in the region preceding (Tc(onset)), where superconducting behavior appeared with the preparation method [23].
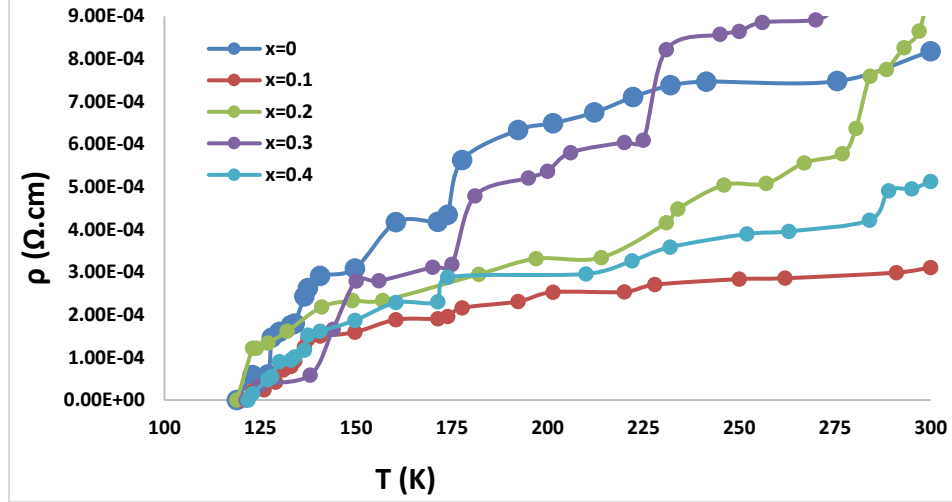

Figure 2 illustrates how electrical resistance changes with temperature for the compound $Bi_{2-x}Pb_xBaCa_{1.85}Sb_{0.15}Cu_3O_{10+\delta}$

The critical temperature of the doped samples was higher than that of the pure sample in the region before (T_{conset}), where the superconducting activity was seen, as Figure 2 illustrates, first Table. This suggests that with time, the superconducting samples' electrical resistance reduced. In the lead-substituted samples, we observed that the transition width had small values; these values were lower than those of the pure sample, indicating that the critical temperature was raised due to an improvement in the crystal structure. This suggests the homogeneity of the samples [24]. Table 1 shows that the critical temperatures change as the substitution ratios change. It shows that the critical temperature gradually increases from the pure sample's 118.9 K to 121.8 K at x = 0.4. This indicates that lead plays a crucial role in improving the superconducting properties by maintaining the high stability of the (2223) phase and reducing impurities and structural defects often found in materials with a high bismuth content. This behaviours is consistent with the results of previous studies on bismuth-based chemicals. Also, because of oxygen atoms join copper atoms in the formation of copper oxide levels Table 1 shows that the transition width ΔT (K) = Tc(on)- Tc(off) decreases. It observes that the bandwidth fluctuates and steadily drops between the samples, first from the pure sample x = 0 to the sample x = 0.4, from 5.1 to 2.1. This supports the superconducting state by showing a decrease in the electronic structure's dispersion and helping to increase the electronic concentration at the Fermi level [25]. The amount of energy gap rose from 0.034354669 in the pure sample to 0.035192588 in the x = 0.4 sample, indicating a minor yet consistent increase with the rising substitution ratio. This signifies an enhancement in the efficacy of the mechanism responsible for conduction (Cooper pairs) [26]. This signifies an improved association of electron pairs. This rise signifies the enhanced quality of the superconducting state in the lead-substituted samples. We also note that the concentration of gaps progressively increases from the pure sample to the varying percentages of replacement, indicating an enhancement despite alterations in electrical properties [27]. This improvement is not attributable to an increase in charged carrier concentration, but rather to an enhancement in the crystal structure and phase due to lead substitution [28]. This indicates that the conditions and method of preparation had a positive effect in terms of supporting the increased formation of the higher phase and thus increasing the critical temperature [29].

TABLE (1) shows a comparison of the critical temperature, energy gap, and concentration of gaps for the samples

X	$T_c(of)$ (K)	$T_{c(on)}$ (K)	ΔT (K)	$T_{c(mid)}$ (K)	E_g (eV)	$P_{(Hole)}$
0	118.9	124	5.1	121.45	0.034354669	0.159855875
0.1	119.8	122	2.2	120.9	0.034614713	0.159900603
0.2	118.9	123	4.1	120.95	0.034354669	0.159855875
0.3	121.3	125	3.7	123.15	0.035048119	0.159975151
0.4	121.8	123	1.2	122.4	0.035192588	0.16

CONCLUSION

When bismuth is substituted for lead in the superconducting ceramic composition $Bi_{2-x}Pb_xBaCa_{1.85}Sb_{0.15}Cu_3O_{10+\delta}$, the results of this investigation were examined. Sample ratios (X=0, 0.1, 0.2, 0.3, and 0.4) were used. It was discovered that every sample behaved like a metal. Lead further enhances superconducting, as evidenced by the rising critical temperature as the substitution ratios increase. Simultaneously, the bandwidth decreases as the substitution ratios increase, indicating an improvement in superconductivity. As substitution ratios rise, the energy difference widens, suggesting that superconductivity is becoming more stable. As the ratios rise, the gap concentration likewise rises, indicating an improvement in the charge carriers. Rather, the sample with replacement (x = 0.4) was the best and most stable. It possessed the best gap concentration ($P_{(Hole)} = 0.16$), energy gap ($E_g = 0.035192588$ E_v), critical temperature ($T_{c(off)} = 121.8$ K), and $\Delta T(K) = 1.2$. All of these are related to the high phase that gives it thermodynamic stability.

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