

*Araştırma Makalesi / Research Article*

**Determination of Possible Maximum Critical Transition Temperatures with Empirical Model Depending on Structural Disorders-Defects for  $\text{Bi}_{2.1}\text{Sr}_{2.0}\text{Ca}_{1.1}\text{Cu}_{2.0}\text{O}_y$  System**

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**Abstract**

In this study, we find a strong link depending on the preparation annealing ambient conditions between structural disorders-defects and characteristic transition temperature parameters (offset,  $T_c^{\text{offset}}$  and onset,  $T_c^{\text{onset}}$ ) of bulk  $\text{Bi}_{2.1}\text{Sr}_{2.0}\text{Ca}_{1.1}\text{Cu}_{2.0}\text{O}_y$  system for the first time. The superconducting samples are prepared at various annealing temperatures intervals 830°C -850°C with the temperature step of 10°C for annealing time ranging between 24 h and 48 h via traditional solid-state reaction route. The temperature-dependent resistivity measurements are conducted at temperature range of 30-140 K. The most ideal annealing ambient is obtained to be the combination of annealing temperature of 840 °C and annealing time of 24 h because of the enhancement in the formation possibility of strong cooper-pairs and optimization of itinerant charge carrier concentrations in the valence band. Similarly, the positive contributions are observed in the overlapping mechanism of wave functions between Cu-3d and O-2p electrons and especially logarithmic distribution of electronic state densities. The optimum annealing ambient makes the Bi-2212 system refine the structural problems and especially connectivity between the grains in the crystal structure. Conversely, the excess annealing ambient leads to increase considerably the grain misorientation, defects and grain boundary couplings due to the induced permanent problems in the crystal system. The highest correlated model shows that the Bi-2212 superconducting compounds with the minimum structural disorders in the short-range-ordered antiferromagnetic Cu-O<sub>2</sub> layers exhibit the maximum  $T_c^{\text{onset}}$  and  $T_c^{\text{offset}}$  values of about 85.347 K ( $R^2_{\text{adj}}=0.9882$ ) and 87.421 K ( $R^2_{\text{adj}}=0.97465$ ).

**Keywords:** Bi-2212 superconducting ceramic compound, Optimum annealing ambient, structural disorders-defects.

**$\text{Bi}_{2.1}\text{Sr}_{2.0}\text{Ca}_{1.1}\text{Cu}_{2.0}\text{O}_y$  İçin Yapısal Bozukluklara Bağlı Olan Empirik Model İle Olası Maksimum Kritik Geçiş Sıcaklıklarının Belirlenmesi**

**Öz**

Bu çalışmada, katı Bi-2212 süperiletken sisteminin yapısal bozukluklar-kusurlar ve kritik geçiş sıcaklıkları (başlangıç,  $T_c^{\text{başlangıç}}$  ve bitiş,  $T_c^{\text{bitiş}}$ ) arasındaki ilişki hazırlık tavlama ortam koşullarına bağlı olarak ilk kez güçlü bir ilişki kurduk. Süperiletken malzemeler, geleneksel katı hal reaksiyon yolu ile 24 saat ila 48 saat arasında değişen tavlama süresi için 10°C sıcaklık adımı ile 830°C - 850°C arasındaki farklı tavlama sıcaklık aralıklarında hazırlandı. Sıcaklığa bağlı direnç ölçümleri 30-140 K sıcaklık aralığında yapıldı. Tüm deneysel ve teorik bulgular, tavlama ortamının temel karakteristik özellikleri önemli bir şekilde etkilediğini göstermektedir. En iyi tavlama ortamı, aktif elektron-fonon bağlantı özelliklerinin oluşum olasılığındaki artış ve gezici yük taşıyıcı konsantrasyonlarının optimizasyonu nedeniyle 840°C'lik tavlama sıcaklığının ve 24 saatlik sürenin kombinasyonu olduğu bulunmuştur. Benzer şekilde, Cu-3d ve O-2p elektronları arasındaki dalga fonksiyonlarının örtüşme mekanizmasında ve özellikle elektronik durum yoğunluklarının logaritmik dağılımında pozitif katkılar gözlemlendi. Ayrıca, uygun koşullardaki tavlama ortamı, Bi-2212 sisteminin kristal yapı kalitesini ve kristal yapıdaki taneler arasındaki etkileşimin iyileştirilmesini sağlamaktadır. Tersine, aşırı tavlama ortamı, kristal sistemdeki kalıcı kristal yapı problemlerinin önemli ölçüde artmasına neden olur. Ayrıca, en yüksek ilişkili model, kısa menzilli antiferromanyetik Cu-O<sub>2</sub> katmanlarındaki minimum yapısal bozukluklara sahip Bi-2212 süper iletken malzemelerinin, maksimum  $T_c^{\text{başlangıç}}$  ve  $T_c^{\text{bitiş}}$  değerleri sırasıyla yaklaşık 85.347 K ( $R^2_{\text{adj}}=0.9882$ ) ve 87.421 K ( $R^2_{\text{adj}}=0.97465$ ) olarak belirlenmiştir.

**Anahtar kelimeler:** Bi-2212 süper iletken seramik bileşiği, Optimum tavlama ortamı, yapısal bozukluklar-kusurlar.

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## 1. Introduction

Until now, several science groups have searched on the improvement of fundamental characteristic properties (physical, electrical, superconducting, mechanical, electromechanical, flux pinning, structural, crystallinity, electronical and optoelectronics, etc.) of superconducting materials to find many places in the application fields [1-3]. Especially, the superconducting compounds are preferred to use in the metallurgical science, transformers, power transmission, particle accelerators, innovative energy infrastructure, medical diagnosis, energy-related sectors, refrigeration and heavy-industrial technology areas [4-7]. Historically, the first superconducting material was the mercury element that was discovered by Kamerlingh Onnes at the temperature of 4.2 K in 1911 [8]. Then, the researchers have made strong efforts to increase the critical transition temperature value up to such a temperature value higher than 77 K that is the boiling point of liquid nitrogen temperature and is further cheaper as compared to the other cooling material.

On this basis, Yttrium barium copper oxide (from the family of ceramic compounds) is the first superconductor showing the critical transition temperature larger than 77 K value and the date of 1987 was received as the essential turning-point of superconductivity phenomenon because of its transition temperature bigger than the boiling point of nitrogen temperature (in the liquid phase) of about 77 K [9]. In the literature, Bi-based superconducting material with three parent members (discovered by Maeda group in the year of 1988 [10]) is another crucial family of ceramic compounds. The critical transition temperature values are varied from 20 K until the value of 110 K [11] according to the active Cu-O<sub>2</sub> layer numbers of unit cell in the crystal structure. The values mentioned above can be developed by the change of preparation conditions [12-14]. In the current work, we scrutinize the role of annealing ambient (annealing temperatures between 830 °C and 850 °C and annealing time from 24 h until 48 h) on the fundamental characteristic electrical and superconducting quantities by means of temperature-dependent electrical resistivity measurements exerted in the temperature intervals 30 K-140 K. The experimental measurement results show that every characteristic feature is significantly affected by the annealing ambient conditions.

The best annealing ambient is measured as 840 °C annealing temperature for 24 h annealing duration. At the same time, we develop a strong empiric link between the preparation annealing ambient conditions and structural problems (disorders-defects) to detect the probable maximum onset and offset transition temperatures in our preparation conditions. The empirical model shows that the solid Bi-2212 superconducting sample with the perfect crystal structure displays the maximum offset and onset critical temperatures of about 85.34726 K and 87.42069 K, respectively.

## 2. Material and Method

### 2.1. Experimental Details for Bulk Bi<sub>2.1</sub>Sr<sub>2.0</sub>Ca<sub>1.1</sub>Cu<sub>2.0</sub>O<sub>y</sub> Superconducting Samples

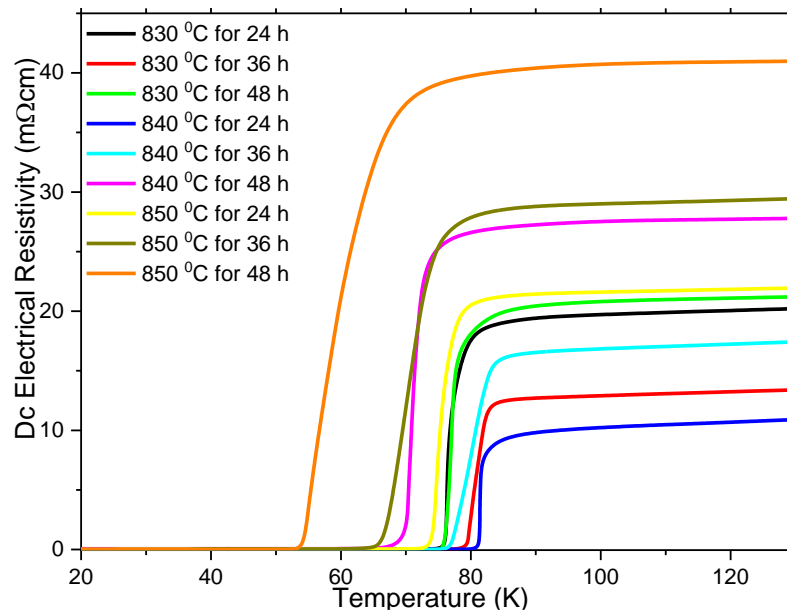
The bulk Bi-2212 superconducting ceramic compounds are prepared with the help of the standard solid-state method without any gas atmosphere under normal atmospheric pressure conditions. Initially, the main powders including carbonates and oxides, namely, the chemicals of CaCO<sub>3</sub>, CuO, SrCO<sub>3</sub> and Bi<sub>2</sub>O<sub>3</sub> within the high purity level of % 99.9 are weighed thoroughly with the assistant of electronic balance in medium of air to gather the powder of chemicals in the stoichiometric proportion of Bi, Sr, Ca, Cu and O: 2.1, 2.0, 1.1, 2.0 and y, respectively. After that, the powder obtained in the stoichiometric ratio is mixed well by a pounder for 9 h duration to possess the homogenous mixture of powders. Then, the mixture of powders is exposed to grinding process in the agate by a grinder for the period of thirty minutes. The grinding process is performed without any solvent or atmospheric gasses environment. Now, the particles of powders reach the desired sizes for the formation of solid Bi-2212 ceramics. The last form of powders put in the porcelain crucibles is pre-heated at 800°C for 36 h for the calcination process in a furnace under the atmospheric air with both heating-cooling rates of 5°C/m so that we can easily remove the foreign particles related to the impurity phase, carbon derivatives from the resultant form of powders. The blackish powders calcined are taken out of furnace are again subjected to the intermediate grinding for 30 min in the agate mortar under the atmospheric pressure for the improvement in the homogeneity of powder. Finally, the last powder with the nominal composition of Bi<sub>2.1</sub>Sr<sub>2.0</sub>Ca<sub>1.1</sub>Cu<sub>2.0</sub>O<sub>y</sub> are exhaustively pelletized as the solid bars within the rectangular volume sizes of

$1.5 \times 0.5 \times 0.2 \text{ cm}^3$  under 300 MPa applied load during 5 min in the normal atmospheric pressure condition. Hence, the fundamental principle (bringing the atoms closer together for bonding easily) is provided. The solid bars pelletized are separately sintered at various annealing temperatures (830°C, 840°C and 850°C) for the annealing times of 24h, 36 h and 48 h.

The alteration of electrical resistivity against the temperature for the solid Bi-2212 ceramic compounds prepared at varied annealing ambient is measured in the temperature intervals 30K-140 K with standard four-point contact route. The electrical test results on the surface are gathered by using 5mA dc current in a cryostat. The dc electrical curves of materials enable us to deduce some crucial electrical and superconducting parameter not only to find out the effect of annealing ambient on the general characteristics of solid Bi-2212 ceramic material and but to define a relation between structural problems (disorders-defects) and superconducting features so that we find the possible maximum onset/offset transition temperatures for the Bi-2212 system.

### 3. Results and Discussion

The crucial extracted parameters such as onset ( $T_c^{onset}$ ), offset critical transition temperature ( $T_c^{offset}$ ), degree of the broadening ( $\Delta T_c = T_c^{onset} - T_c^{offset}$ ), room temperature resistivity ( $\rho_{300K}$ ), residual resistivity ( $\rho_0$ ), residual resistivity ratios (RRR),  $\rho_{norm}$ , and  $\Delta\rho$  will sensitively be explained in following parts to point out the role of annealing ambient (annealing temperature and time) on the Bi-2212 superconducting system.



**Figure 1** Differentiation of dc electrical resistivity against temperatures intervals 30-140 K for every  $\text{Bi}_{2.0}\text{Sr}_{2.0}\text{Ca}_{1.1}\text{Cu}_{2.0}\text{O}_y$  superconducting material

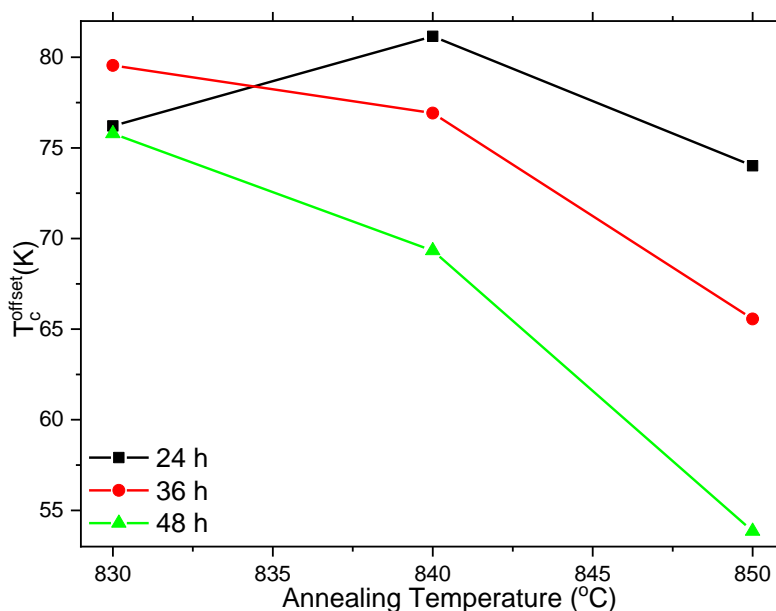
Besides, we determine the possible maximum  $T_c^{onset}$  and  $T_c^{offset}$  values with the aid of empirical approaches based on the general structural problems of impurity scattering and lattice strain in the active Cu-O<sub>2</sub> layers of bulk Bi-2212 superconducting crystal structure. On this basis, we firstly measure the electrical resistivity values over temperature varying between 30 K and 140 K and then thoroughly depict all the dc temperature-dependent electrical curves in Figure 1 clearly.

#### 3.1. Effect of Annealing Ambient on Fundamental Superconducting Properties Belonging to Bi-2212 Superconducting Crystal System

Prior to the serious discussions for electrical and superconducting quantities of Bi-2212 crystal system, the experimental findings pictured in Figure 1 show that the annealing ambient totally affects the

fundamental superconducting and electrical characteristic features of Bi-2212 superconductor. In this respect, we initially explain why and how the onset  $T_c^{onset}$  and  $T_c^{offset}$  and related parameter of broadening width  $\Delta T_c$  variation between  $T_c^{onset}$  and  $T_c^{offset}$  of superconducting ceramic materials change with the annealing ambient. It is well known that the  $T_c^{onset}$  parameter is in directly relation to the beginning of superconductivity phenomenon (the formation of active electron-phonon couplings) throughout the intra-grain regions (the isolated grains) [15].

In other words, the  $T_c^{onset}$  value is the vital temperature for both the formation of bipolaron mechanism in the polarizable lattices and hybridization mechanism (related the overlapping of wave functions between copper and oxygen electrons) in the superconducting system. Similarly, a number of mobile hole carrier concentrations are significantly affected by the onset critical transition temperature value [16]. It is received that the DOS (densities of electronic states) localization mechanism at Fermi energy level in the crystal structure and phase coherence ( $\varphi$ ) in the order parameter belonging to the super-electrons ( $\Psi = \Psi_0 e^{-i\varphi}$ ) are connected to the  $T_c^{onset}$  value for a superconducting ceramic material [17]. Accordingly, the formation of electron-phonon couplings is found to diminish with the augmentation of temperature and in fact could hardly any drive the superconductivity at the environment temperature values higher than the value of  $T_c^{onset}$ . On the other hand, the  $T_c^{onset}$  parameter is attributed to the inter-granular component features of Bi-2212 superconducting system and phase fractions in Bi-2223 superconducting system [18].

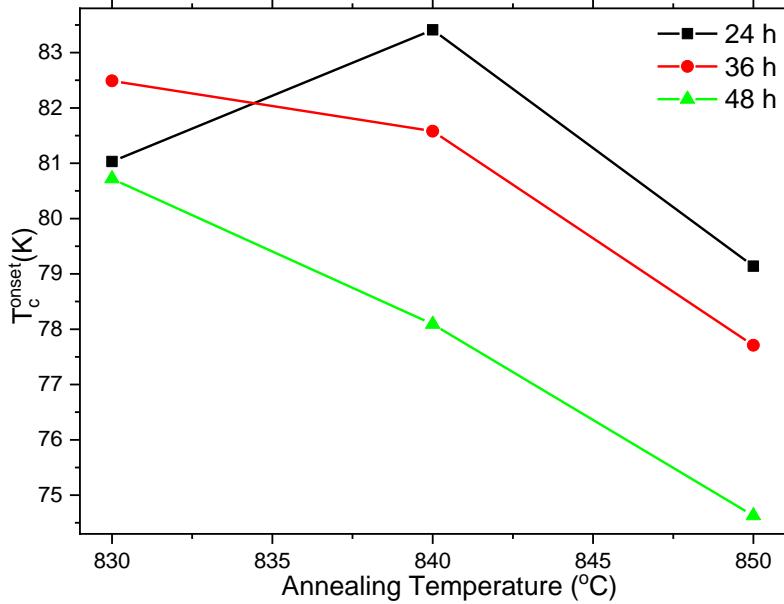


**Figure 2** Variation of  $T_c^{offset}$  parameters over annealing temperatures for all Bi-2212 superconducting ceramic material

At the vicinity of  $T_c^{onset}$  value, the bulk Bi-2212 superconducting material (with both the inter-granular and transgranular regions) transits into the superconducting state because of the presence of electron-phonon coupling cooper-pairs in the active Cu-O<sub>2</sub> layers [19]. One can see the  $T_c^{onset}$  and  $T_c^{offset}$  parameters (deduced from Figure 1) for all the superconducting compounds prepared at the varied annealing ambient in Figure 2 and Figure 3. It is obvious from the figures that both the critical transition temperatures (especially offset values) are recorded to be robustly dependence on the annealing temperature. On this basis, the bulk Bi-2212 superconducting material prepared at the constant annealing temperature of 830 °C for 24 h presents the  $T_c^{onset}$  value of 81.03 K and  $T_c^{offset}$  of 76.21 K.

Besides, the samples produced at 830 °C for the duration of 36 h and 48 h show the  $T_c^{onset}$  of 82.49 K and 80.72 K and  $T_c^{offset}$  of 79.55 K and 75.79 K, respectively. As for 840 °C annealing temperature value, the ceramic compounds fabricated at the annealing times of 24 h, 36 h and 48 h exhibit the  $T_c^{onset}$  parameters of 83.41 K, 81.58 K and 78.09 K and  $T_c^{offset}$  parameters of 81.16 K, 76.92 K and 69.33 K, respectively. In case of 850 °C, the superconducting ceramic materials prepared at the annealing periods of 24 h, 36 h and 48 h obtain the relatively smaller  $T_c^{onset}$  and  $T_c^{offset}$  of 79.14 K (74.01

K), 77.71 K (65.56 K) and 74.63 K (53.85 K), respectively. According to the experimental findings given, it seems that the highest  $T_c^{onset}$  and  $T_c^{offset}$  values are found to be about 83.41 K and 81.16 K, respectively for the Bi-2212 superconducting material produced at 840 °C for 24 h whereas the minimum  $T_c^{onset}$  and  $T_c^{offset}$  values of 74.63 K and 53.85 K are found for the bulk Bi-2212 compound prepared at 850 °C for 48 h annealing duration.



**Figure 3** Differentiation of  $T_c^{onset}$  parameters against annealing temperatures for every superconducting material prepared in this work

These results enable us to discuss why the superconducting characteristic temperatures of bulk Bi-2212 ceramic material change depending on the annealing temperature and time. Namely, the optimum annealing ambient (840 °C and 24 h) leads not only to form much more active and dynamic electron-phonon couplings throughout the intra-grain regions (meaning the increased order parameter regarding the super-electrons) and optimize the mobile hole carrier concentration in the active Cu-O<sub>2</sub> layers. Similarly, the ideal annealing temperature and time results in the enhancement of the DOS at Fermi energy level and overlapping of wave functions between copper and oxygen electrons in the superconducting system.

Morphologically, the general structural problems tend to dramatically decrease with the optimum production conditions [20]. However, the whole perfect mechanism collapses in case of the excess annealing ambient conditions. The deduced  $T_c^{onset}$  and  $T_c^{offset}$  parameters together allow us to define the crystal structure quality founded on the parameter of  $\Delta T_c$ . The minimum (best crystallinity)  $\Delta T_c$  parameter of 2.25 K ascribes to the solid Bi-2212 ceramic material fabricated at 840 °C for 24 h while the maximum one (20.78 K) is in association with the sample produced at the excess annealing ambient (840 °C for 48 h). The other compounds fabricated exhibit the moderate  $\Delta T_c$  values. It is apparent from the findings that the annealing ambient combination of 840 °C and 24 h makes the Bi-2212 superconducting material to be produced in the best crystal structure.

### 3.2. DC Electrical Findings for Bi-2212 Ceramic Samples Prepared at Various Annealing Process

In this part, we infer the dc electrical results as regards the parameters of  $\rho_{300K}$ ,  $\rho_0$ ,  $RRR$ ,  $\rho_{100K}$ ,  $\rho_{norm}$ , and  $\Delta\rho$  from the temperature-dependent resistivity curves provided in Figure 1. On can see all the experimental electrical findings in Table 1. Let us numerically discuss shortly the results founded on the maximum and minimum values. Namely, the Bi-2212 superconducting samples prepared at the constant annealing temperature of 840 °C for the annealing time of 24 h exhibits the global minimum  $\rho_{300K}$  (14.37 mΩcm),  $\rho_0$  (7.87 mΩcm),  $\rho_{100K}$  (11.16 mΩcm),  $RRR$  (1.29),  $\rho_{norm}$  (3.48), and  $\Delta\rho$  (3.21 mΩcm) parameters. On the other hand, the bulk Bi-2212 superconducting sample prepared at the annealing ambient combination of 850 °C annealing temperature and 48 h annealing time shows the maximum dc electrical

resistivity results (41.56 mΩcm, 39.39 mΩcm, 40.45 mΩcm, 1.03, 3.44 and 1.11 mΩcm for the  $\rho_{300K}$ ,  $\rho_0$ ,  $\rho_{100K}$ ,  $RRR$ ,  $\rho_{norm}$ , and  $\Delta\rho$  parameter, respectively). The other materials prepared possess the moderate resistivity values. We use all the experimental findings deduced from the temperature-dependent electrical resistivity curves to determine the ideal Bi-2212 superconducting ceramic material presenting the possible highest critical transition temperatures.

**Table 1** Deduced electrical quantities such as  $\rho_{300K}$ ,  $\rho_0$ ,  $RRR$ ,  $\rho_{100K}$ ,  $\rho_{norm}$ , and  $\Delta\rho$  parameters from the temperature-dependent resistivity curves

Dependence	$T_c^{offset}$ and $T_c^{onset}$ parameters extracted from correlation coefficient curves between structural disorders-defects and transition temperatures	
	$T_c^{offset}$ (K)	$T_c^{onset}$ (K)
$\rho_{100K}$	85.34726 $\pm 2.23008$ ( $R^2_{adj}=0.9882$ )	87.42069 $\pm 1.05553$ ( $R^2_{adj}=0.97465$ )
$\rho_{norm}$	83.56794 $\pm 1.0282$ ( $R^2_{adj}=0.98158$ )	85.63312 $\pm 0.84035$ ( $R^2_{adj}=0.97098$ )
$\rho_{res}$	82.64569 $\pm 1.87686$ ( $R^2_{adj}=0.9849$ )	84.29217 $\pm 0.49983$ ( $R^2_{adj}=0.95828$ )
$\rho_{300K}$	86.94921 $\pm 3.55148$ ( $R^2_{adj}=0.98495$ )	89.27739 $\pm 1.81947$ ( $R^2_{adj}=0.96213$ )

### 3.3. Determination of Possible Maximum Onset and Offset Critical Transition Temperature Values for Bulk Bi-2212 Superconducting Ceramic Compounds

In this part of this paper, we define a strong link between the annealing ambient conditions and structural disorders-defects (based on the fundamental electrical resistivity parameters) in the crystal system for the first time so that we find the highest maximum offset/onset critical transition temperatures pertaining to the bulk Bi-2212 superconducting ceramic compounds using the empirical approach. In this context, we examine the variation of  $T_c^{onset}$  and  $T_c^{offset}$  parameters against the  $\rho_{res}$ ,  $\rho_{100K}$ ,  $\rho_{300K}$ , and  $\rho_{norm}$  parameters, respectively. One can see the differentiation curves related to the  $T_c^{onset}$  and  $T_c^{offset}$  values in Figure 4a-d and Figure 5a-d. Besides, we depict the correlation parameters in the curves to realize the best approaching results. It is to be mentioned here that the high correlation coefficients are obtained for the fitting equations in the quadratic form of functions. Gather all the equations and provide in Table 2 in detail. It is apparent from the table that the extrapolated values founded on the  $\rho_{100K}$  values shows the highest correlation coefficients of  $R_{2adj}=0.97465$  and  $R_{2adj}=0.9882$  for the onset and offset critical transition temperature, respectively. According to the model, the maximum  $T_c^{onset}$  and  $T_c^{offset}$  values are obtained to be about  $85.34726 \pm 2.23008$  K and  $87.42069 \pm 1.05553$  K, respectively in case of the perfection of crystal structure for the Bi-2212 superconducting compounds. Secondly, we study on the empirical approach founded on the  $\rho_{norm}$  to find the maximum onset and offset critical temperature values.

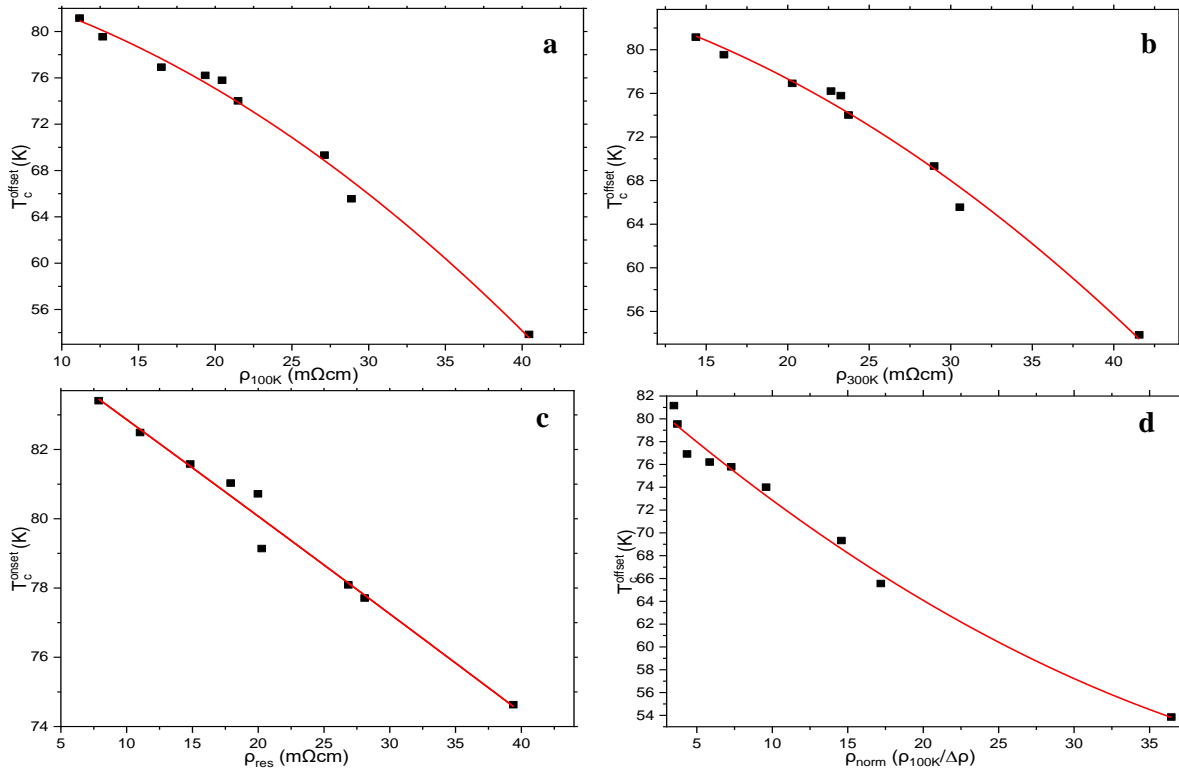
The correlation coefficients are found to be about  $R_{2adj}=0.98158$  for the  $T_c^{offset}$  parameter and  $R_{2adj}=0.97098$  for the  $T_c^{onset}$  parameter the related  $T_c^{onset}$  and  $T_c^{offset}$  values are deduced to be about  $85.63312 \pm 0.84035$  K and  $83.56794 \pm 1.0282$  K, respectively. Moreover, the empirical model focusing on the  $\rho_{res}$  parameters displays the possible highest  $T_c^{offset}$  of  $82.64569 \pm 1.87686$  K and  $T_c^{onset}$  of  $84.29217 \pm 0.49983$  K with the correlation coefficient of  $R_{2adj}=0.9849$  and  $R_{2adj}=0.95828$ . at the same time, the last model related to the  $\rho_{100K}$  values shows the highest offset ( $86.94921 \pm 3.55148$  K) and onset ( $89.27739 \pm 1.81947$  K) critical transition temperature values but within the moderate correlation coefficients of  $R_{2adj}=0.98495$  and  $R_{2adj}=0.96213$ . It is fair to conclude that all the  $T_c^{onset}$  and  $T_c^{offset}$  parameters are found to be closer to each other.

In this respect, the empirical model founded on the  $\rho_{100K}$  values (directly related to the impurity scattering and lattice strain in the crystal structure) illustrates the highest correlation coefficients with the relatively higher  $T_c^{onset}$  and  $T_c^{offset}$  values. Namely, the bulk Bi-2212 superconducting material with the ideal crystallinity and best grain boundary coupling quality exhibits the  $T_c^{onset}$  of about 87.42069 K

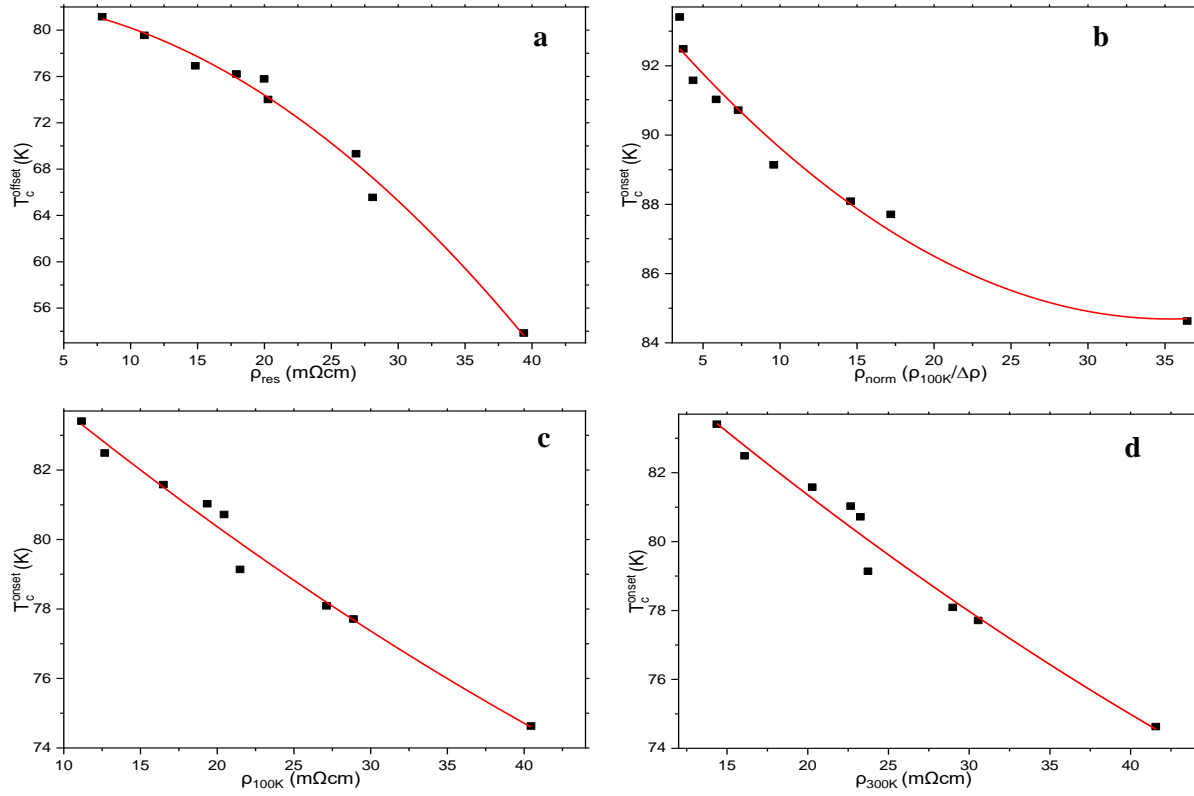
and  $T_c^{offset}$  of 85.34726 K in case of production of material in the most ideal annealing ambient conditions, being one of the most striking point inferred from this work.

**Table 2** Empirical approach findings extracted from correlation coefficient curves between structural disorders-defects and transition temperatures

Samples	$\rho_{300K}$ (mΩcm)	$\rho_{res}$ (mΩcm)	RRR ( $\rho_{300K}/\rho_{100K}$ )	$\Delta \rho$ ( $\rho_{300K} - \rho_{100K}$ ) (mΩcm)	$\rho_{norm}$ ( $\rho_{100K}/\Delta \rho$ )	$\rho_{100K}$ (mΩcm)
840°C for 24 h	14.37	7.87	1.29	3.21	3.48	11.16
830°C for 36 h	16.09	11.02	1.27	3.42	3.71	12.67
840°C for 36 h	20.28	14.83	1.23	3.79	4.35	16.49
830°C for 24 h	22.66	17.91	1.17	3.31	5.85	19.35
830°C for 48 h	23.26	19.98	1.14	2.81	7.28	20.45
850°C for 24 h	23.73	20.27	1.11	2.24	9.59	21.49
840°C for 48 h	28.98	26.85	1.09	1.86	14.58	27.12
850°C for 36 h	30.56	28.09	1.06	1.68	17.19	28.88
850°C for 48 h	41.56	39.39	1.03	1.11	36.44	40.45



**Figure 4** Correlation coefficient curves between (a)  $T_c^{offset}$  and  $\rho_{100K}$ ; (b)  $T_c^{offset}$  and  $\rho_{300K}$ ; (c)  $T_c^{offset}$  and  $\rho_{res}$  (d)  $T_c^{offset}$  and  $\rho_{norm}$  for definition of possible highest  $T_c^{offset}$  parameter. Inset: Fitting equations related to correlation graphics.



**Figure 5** Correlation coefficient curves between (a)  $T_c^{onset}$  and  $\rho_{res}$ ; (b)  $T_c^{onset}$  and  $\rho_{norm}$ ; (c)  $T_c^{onset}$  and  $\rho_{100K}$ ; (d)  $T_c^{onset}$  and  $\rho_{300K}$  for definition of possible highest  $T_c^{onset}$  parameter. Inset: Fitting equations related to correlation graphics

#### 4. Conclusions and Recommendations

In the current work, we discuss the effect of annealing ambient (combination of annealing temperature between 830°C and 850°C and annealing duration of 24-48 h for the bulk Bi-2212 superconducting ceramic compound) on the onset and offset critical transition temperature values with the aid of dc electrical resistivity versus temperature measurements in the temperature range of 30 K-140 K. It is found that the main electrical and superconducting characteristic features are dramatically affected by the annealing ambient conditions. According to the experimental measurement results, the combination of 840 °C annealing temperature and 24 h duration of is noted to be the best annealing ambient for the production of bulk Bi-2212 superconducting material. In more detail, the optimum annealing ambient leads to enhance rapidly the formation possibility of active and strong electron-phonon coupling properties throughout the intra-grain regions, and optimize the mobile hole carrier concentrations in the active Cu-O<sub>2</sub> layers. Besides, the DOS at Fermi energy level and overlapping of wave functions between copper and oxygen electrons in the superconducting system increase considerably in case of the optimum annealing ambient condition. At the same time, a strong empiric relation between the structural disorders-defects and critical transition temperatures demonstrates that the model depending on the  $\rho_{90K}$  parameter exhibits the best performance with the highest correlation coefficients of  $R^2_{adj}=0.97465$  and  $R^2_{adj}=0.9882$  for the onset and offset critical transition temperature, respectively. Accordingly, this study strongly shows that the solid Bi-2212 ceramic material produced in the ideal crystallinity and best grain boundary coupling quality possesses the maximum  $T_c^{onset}$  of about 87.42069 K and  $T_c^{offset}$  of 85.34726 K. In other words, it is not possible that the solid Bi-2212 ceramic material (produced in our condition) can exhibit the  $T_c^{offset}$  and  $T_c^{onset}$  values higher than about 85.34726 K and 87.42069 K, respectively.

#### Authors' Contribution

All the authors discussed the results and contributed to the final form of manuscript.



### Statement of Conflicts of Interest

The author has no conflict of interest regarding this article.

### Statement of Research and Publication Ethics

The author declares that this study complies with Research and Publication Ethics.

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