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## Original Research Article

# Remodeling engineering with high- $T_c$ superconductors: Resistivity and current-voltage (IV) characteristics in focus

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### ABSTRACT

The resistivity and current-voltage (IV) characteristics of doped rare earth (RE) based high  $T_c$  cuprate superconductors profoundly influence their applications in engineering and technology. The nonlinear IV characteristics over a wide temperature range around the onset of superconducting transition temperature and the superfluid phase stiffness (SPS),  $J_s(T)$  of a co-doped (Electron and hole doped) high  $T_c$  cuprate superconductor (REBCO) has been studied. SPS has been extracted in a co-doped layered bulk superconducting REBCO using the nonlinear exponent in zero field condition. Superfluid density in a co-doped cuprate changes as a result of the changing in the electron doping level. Co-doped superconductors having high superfluid density minimize energy dissipation in superconducting circuits, produce strong magnetic field, allow more compact and efficient superconducting motors and reduce the energy consumption of electric vehicles.

## 1. Introduction

The breakthrough discovery of high  $T_c$  superconductor significantly expanded the scope of real-world applications. The cuprate superconductors (RE-123 family) remain central due to their relatively high critical temperatures, layered crystal structure and strong anisotropic transport properties. The complex charge transport mechanisms of cuprates still pose challenges for scalable engineering applications. The electrical transport properties are crucial for understanding the superconducting phase transition, flux pinning and vortex dynamics and dissipative mechanisms near  $T_c$ . The nonlinear IV behaviour often reflects the vortex motion and Berezinskii-Kosterlitz-Thouless (BKT) like transitions especially in low dimensional or granular systems [1, 2]. A systematic investigation of these properties enables optimization of superconducting performance, improved critical current density ( $J_c$ ) and better material design for engineering applications. The objective of this work is to analyze the resistivity and IV characteristics in high  $T_c$  cuprates and to assess their role in remodelling the next generation engineering systems. BKT transition is associated with the variation of superfluid phase stiffness (SPS),  $J_s$  with temperature [1, 2]. The nonlinearity in IV characteristics below BKT phase transition is related to  $J_s$  of the superconducting system [3, 4]. Doping plays a crucial role to control the nature of  $J_s$  by following a suitable theory [5, 6]. In this paper we have studied the transport properties in  $\text{Eu}_{1-x}\text{Ca}_x\text{Ce}_y\text{Ba}_2\text{Cu}_3\text{O}_{7-\delta}$  (ECCBCO) system over a wide temperature range. The co-doping effect on SPS and its complex variation with temperature in ECCBCO within the BKT framework has been studied following a standard model [5].

## 2. Experimental

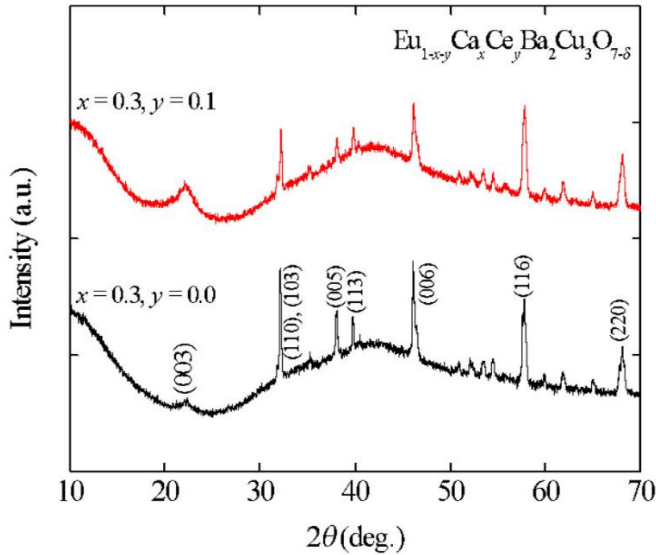
Synthesis of  $\text{Eu}_{0.7-x}\text{Ca}_{0.3}\text{Ce}_x\text{Ba}_2\text{Cu}_3\text{O}_{7-\delta}$  with  $x = 0.0$  (S1) and 0.1 (S2) has been done by using conventional solid-state reaction method. Typically, mixtures of required pure oxides have been used stoichiometrically to make pellets and then sintered after several intermediate grindings. In the last stage the samples are annealed in flowing oxygen [4]. Sample pellets have been characterized with the help of X-ray diffraction (XRD) technique. Resistivity and current-voltage (IV) measurements of bar shaped samples have been performed by using a closed cycle JANIS cryogenerator (10K-300K) with the help of four probe technique [7-10]. IV measurements have been carried out at constant temperatures around the phase transitions in the range of minimum and maximum current of 100 nA to 5.0 mA respectively [11-15].

## 3. Results and discussions

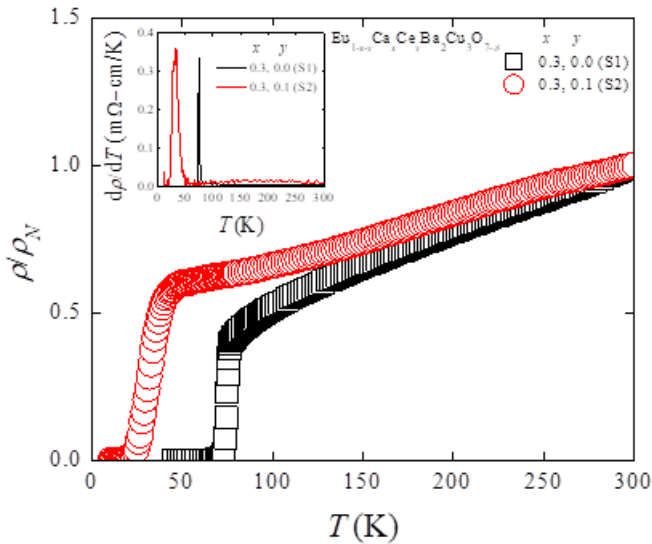
Fig. 1 shows the X-ray diffraction pattern of ECCBCO (S1 and S2) superconductors showing major peaks which corresponds to RE-123 (RE = Rare Earth) structure. The lattice constants of ECCBCO (S1 and S2) estimated from Intensity versus  $2\theta$  plot are  $a = 3.93\text{\AA}$ ,  $b = 3.78\text{\AA}$  and  $c = 11.78\text{\AA}$  which are comparable to the RE-123 system.

Ce doping causes no structural change in a given system. Fig. 2 shows the plot of normalized resistivity versus temperature of ECCBCO (S1 and S2) superconductors and inset shows the variation of  $dp/dT$  as a function of  $T$  from which  $T_{c,\text{onset}}$  values of S1 and S2 are obtained as 78.8K and 51K respectively.

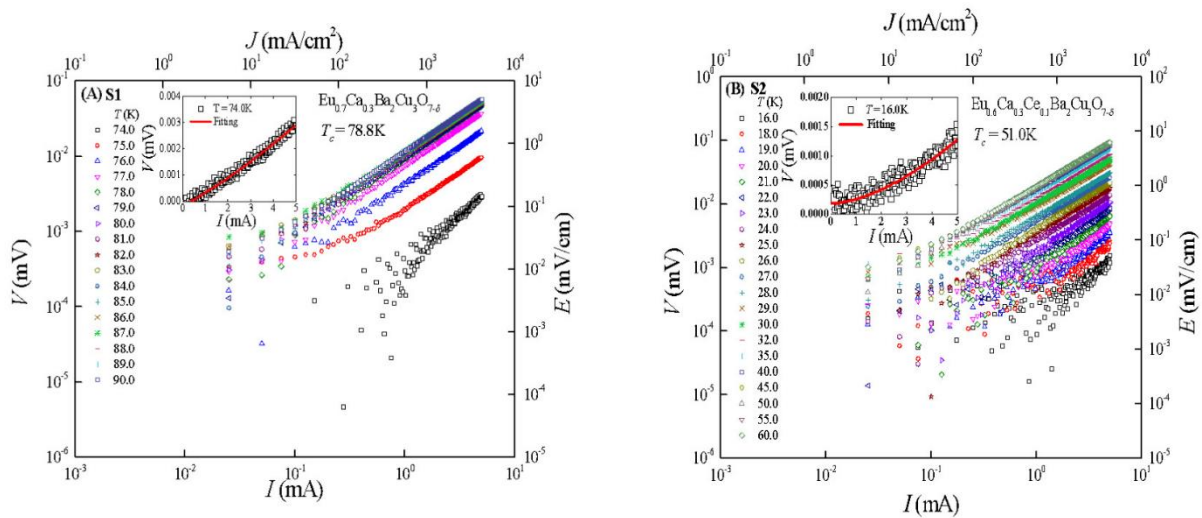




**Figure 1:** X-ray diffraction patterns of ECCBCO (S1 and S2) superconductors.



**Figure 2:** Normalized resistivity variations with  $T$  in ECCBCO (S1 and S2) system. Inset shows  $d\rho/dT$  versus  $T$  of respective samples.

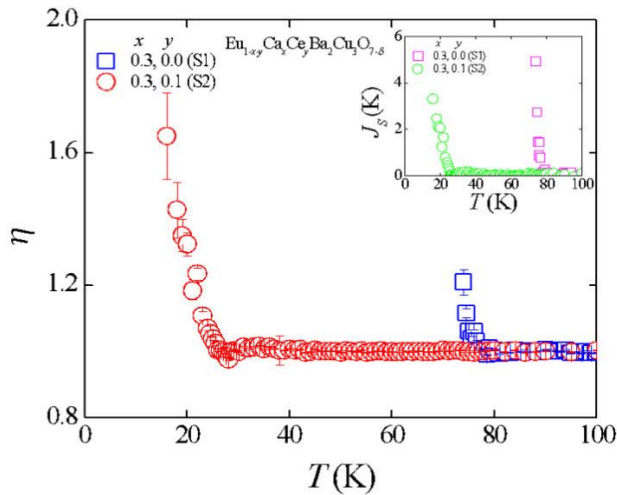


**Figure 3:** Current-voltage curves in log-log scale around  $T_c$  of (A)  $\text{Eu}_{0.7}\text{Ca}_{0.3}\text{Ba}_2\text{Cu}_3\text{O}_{7-\delta}$  (S1) and (B)  $\text{Eu}_{0.6}\text{Ca}_{0.3}\text{Ce}_{0.1}\text{Ba}_2\text{Cu}_3\text{O}_{7-\delta}$  (S2). Inset of each plot shows the  $IV$  characteristics of respective samples at lowest temperature in linear scale fitted by a power law equation of  $IV$  related to BKT transition.

Both samples exhibit a typical metallic behaviour in the normal state region, where resistivity decreases gradually with decreasing temperature prior to the onset of superconductivity. The higher  $T_{c,\text{onset}}$  of S1 suggests improved superconducting phase formation, better crystallinity, or enhanced carrier concentration compared to S2. The relatively lower transition temperature of S2 may be attributed to increased disorder, oxygen deficiency which suppress superconductivity. The broader peak in S2 suggests a distribution of transition temperatures, which may arise from compositional inhomogeneity or weak coupling between grains. The transition width ( $\Delta T_c$ ) of S1 is comparatively smaller than that of S2, reinforcing the improved superconducting quality of S1.

Fig. 3(A) and (B) shows the  $IV$  curves of S1 and S2 in log-log scale covering temperature zone around  $T_{c,\text{onset}}$ . As the temperature decreases below a characteristic temperature identified as  $T_{\text{BKT}}$ , a pronounced deviation from linearity is observed. This nonlinear  $IV$  behaviour is a hallmark of the vortex-antivortex unbinding mechanism described by the BKT transition [1, 16]. Nonlinear  $IV$  has been observed below  $T_{\text{BKT}}$  for using maximum current upto 5 mA and corresponding  $EJ$  range is also shown here. The emergence of nonlinearity below  $T_{\text{BKT}}$  reflects the establishment of phase coherence across the sample due to vortex pairing, while above  $T_{\text{BKT}}$ , free vortices lead to dissipative transport.

Each inset of Fig. 3 shows the nonlinear  $IV$  curve in linear scale at lowest  $T$  fitted by the power law equation related to BKT transition from which  $\eta$  can be extracted at each  $T$  [1].



**Figure 4:**  $\eta$  as a function of  $T$  in ECCBCO superconductors S1 and S2. Inset shows the SPS variation with  $T$  of ECCBCO superconductors S1 and S2 respectively.

Fig. 4 shows the BKT exponent  $\eta$  as a function of  $T$  in ECCBCO superconductors S1 and S2. Inset shows the SPS variation with  $T$  of ECCBCO superconductors S1 and S2 respectively following suitable (Ambegaokar-Halperin-Nelson-Siggia) theory. It is observed that  $\eta$  increases systematically with decreasing temperature, reflecting the strengthening of superconducting correlations. According to BKT theory, the transition temperature  $T_{\text{BKT}}$  is identified at the point where  $\eta \approx 3$ , marking the transition from ohmic ( $\eta = 1$ ) to nonlinear superconducting behaviour [16]. The relatively higher  $\eta$  value in S2 compared to S1 suggests comparatively stronger nonlinearity, which may arise from enhanced phase fluctuations, weaker grain coupling, or increased disorder in S2. On the other hand, S1, with its higher  $T_{\text{c,onset}}$  exhibits behaviour closer to ideal superconducting transport with comparatively weaker nonlinearity, indicating better phase coherence and improved intergranular connectivity. The  $IV$  characteristics indicate the presence of incipient nonlinear behaviour associated with vortex dynamics, although the absence of  $\eta \approx 3$  suggests that the system does not undergo a clear BKT transition in the investigated temperature range. The observed differences between S1 and S2 can be attributed to variations in microstructure, disorder, and superconducting coupling strength. The suppression of SPS due to Ce doping in ECBCO is observed [17-20].

The present study highlights that Ce doping in ECBCO superconductors effectively tunes resistivity, transition temperature, and nonlinear  $IV$  characteristics governed by phase fluctuations and vortex dynamics. These features are highly relevant to remodelling engineering, where material properties are deliberately engineered to achieve optimized performance under varying operational conditions. The controlled modulation of  $T_{\text{c,onset}}$  and resistive behaviour through Ce doping enables the design of superconducting components which is particularly useful in superconducting switching devices and fault current limiters.

The observed nonlinear  $IV$  characteristics below  $T_{\text{BKT}}$  suggest potential applications in current-controlled electronic elements, where nonlinearity can be exploited for designing sensitive detectors, superconducting diodes, and low-noise electronic circuits. The nonlinear temperature dependence of superconducting phase stiffness (SPS) indicates strong phase

fluctuation effects, which can be strategically used in designing devices operating near the superconducting transition region, such as bolometric sensors and thermal switches. Modelling based on phase fluctuation frameworks and Monte Carlo simulations could be employed to quantitatively describe the observed nonlinear  $IV$  behaviour and SPS variation. Microstructural characterization using advanced techniques such as TEM or SEM could also be correlated with transport properties to understand the role of grain boundaries and inhomogeneities.

#### 4. Conclusions

Ce doping in ECBCO system controls resistivity,  $T_{\text{c}}$  values and the nonlinearity in  $IV$  characteristics below the BKT phase transition temperature,  $T_{\text{BKT}}$ . The nonlinear to linear transition in  $IV$  is found at around 76.0 K and 25.0 K for S1 and S2 respectively. SPS is found to be nonlinear in  $T$  in co-doped superconductors, supporting the presence of strong phase fluctuations and reduced superfluid density. This behaviour is consistent with the observed deviation from ideal BKT characteristics and indicates that the superconducting state is governed by complex interplay between disorder, carrier concentration, and intergranular coupling. The study demonstrates that Ce doping is an effective parameter for controlling resistivity, transition temperature, and nonlinear transport behaviour in ECCBCO superconductors. The results provide valuable insight into the role of phase fluctuations and vortex dynamics in determining the superconducting properties of cuprate systems, which may be useful for optimizing their performance in practical applications.

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#### Authors' contributions

The author read and approved the final manuscript.

#### Conflicts of interest

The author declares no conflict of interest.

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#### Data availability

No new data were created.

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