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Interesting aspects of the analysis of resistivity in Li^{3+} irradiated Bi-2212

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Abstract

Differently heat treated and 55 MeV Li^{3+} beam irradiated $Bi_2Sr_2Ca_1Cu_2O_{8+\delta}$ (Bi-2212) high temperature superconductors have been studied from the analysis of resistivity in the normal state as well as near the superconducting transition. For all the unirradiated and irradiated samples the so-called linear temperature dependence of the normal state resistivity, in a wide temperature range, can well be understood within the variable range hopping (VRH) conduction scenario. Near and above the bulk superconducting transition, the fluctuation enhanced conductivity (paraconductivity) analysis shows a noteworthy modification of the conduction process due to radiation induced defects.

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1. Introduction

Defects and disorder in high T_c superconductors (HTSC) is one of the most discussed issues till date [1–3]. In such ceramic materials, there always exist some intrinsic defect centers like non-stoichiometric oxygen, vacancy defects, grain boundaries etc. Interestingly, defects are sometimes helpful from both technological and theoretical purposes and hence controlled defect creation in HTSC oxides has drawn prime attraction [4]. Particularly a defective but still superconducting system offers a scope to understand the pristine system as well. Near the superconducting transition temperature of such HTSCs, a large enough temperature region is found where thermodynamic fluctuations dominate resistivity and several other temperature

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dependent properties. Such fluctuation effects are strongly modified with defects due to smallness of the coherence length of these systems [5,6]. Analysis of this region, generally done by calculation of enhanced conductivity or paraconductivity, can deliver valuable information about role of defects on the conduction process [7,8]. The other typical feature of the HTSCs is linear, metal-like, temperature dependence of normal state resistivity in a vast temperature range. However, here the transport and scattering of carriers are far from being metallic [9]. The high T_c oxides can be viewed as a system of localized carriers which energetically interact through quantum percolation i.e. hopping process. In fact, signature of hopping conduction in HTSC system have been reported earlier [10,11] and till recently [3]. For hopping mediated carrier transport, the temperature dependence of resistivity can be obtained from well known Mott [12] formula $\rho(T) = \rho_0(T/T_0)^{2p}\exp(T_0/T)^p$ where ρ_0 and T_0 are constants. The value of p depends on the dimensionality of the hopping conduction. Mott's variable range hopping (VRH) theory predicts $p = 1/3$ for hopping only in two directions (2D VRH) and $p = 1/4$ for hopping in all three directions (3D VRH).

Importance of ion irradiation on HTSC materials lies on the fact that defects as low as one in several hundreds of unit cells can be produced. Hence subtle changes in the carrier transport are expected to be observable. The present article deals with a systematic analysis of the resistivity behavior for several Bi-2212 superconducting systems where defects have been incorporated by heat treatment(s) and Li^{3+} ion irradiation. To the best of our knowledge, similar analysis on irradiated HTSC oxides is rare.

2. Experiment and data analysis

Three types of polycrystalline Bi-2212 samples, Q1, SL1 and Q2, have been prepared by conventional ceramic route with different heat treatments. Sample Q1 and sample SL1 have been prepared from the same batch with Q1 quenched and SL1 slowly cooled (200 °C/h) from 825 °C to room temperature. Another batch of samples, Q2, has been prepared by similar quenching. Thickness of the samples has been optimized from TRIM [13] analysis to achieve implantation free radiation damage. The paraconductivity analysis near and above the bulk (or mean field) superconducting transition temperature (T_c) has been done under Aslamazov–Larkin (AL) formalism for Q1 and SL1 samples [14]. In this method the scaling of the paraconductivity, $\Delta\sigma$, with reduced temperature $\varepsilon = (T - T_c)/T_c$ is examined ($\Delta\sigma \sim \varepsilon^{-\lambda}$). The effective dimension of fluctuation in different temperature regimes can be understood from their respective scaling exponents (λ) where, AL theory predicts $\lambda_{2D} \sim 1$ for two-dimensional (2D) fluctuation and $\lambda_{3D} \sim 0.5$ for three-dimensional (3D) fluctuation. T_c is generally determined from the peak of the $d\rho/dT$ curve. Standard calculation of $\Delta\sigma$ can be found elsewhere [8]. Regarding the fitting of temperature dependence of normal state resistivity with VRH model, a free fit has been allowed for the parameters ρ_0, T_0 and p. As the best fit is achieved, p has been fixed to the nearest theoretically predicted value ($p = 1/4$ or 1/3 or 1/2) to get the refined values of ρ_0 and T_0.

3. Results and discussion

A brief outline on the nature of defects produced by 55 MeV Li^{3+} beam on Bi-2212 system should first be accounted. Usually in such ceramic systems [15] the electronic energy loss of Li^{3+} ions (energy few tens of MeV) is much greater than the corresponding nuclear energy loss except within the last 5 μm of the ion trajectory. Our sample thickness (~200 μm) being lower than the ion range (~222 μm), practically all the ion energy is lost by the electronic excitation which is much less than the columnar defect generation threshold (~1.44 keV/Å [16]). So there exists only possibility of vacancy or displacement like point defect production. Vacancies per ion produced in the sample are 22, 19, 8, 18 and 38, respectively for the Bi, Sr, Ca, Cu and O sites. For a fluence of 10^{15} ions/cm^2 one defect within 2–3 hundred-unit cells can be estimated.

Table 1
Table showing the defect dependence of VRH fit parameters ρ_0, T_0 for different Bi-2212 superconductors

Fluence (ions/cm^2)	T_{c0} (K)	1D VRH (p = 1/2)		2D VRH (p = 1/3)		3D VRH (p = 1/4)	
		ρ_0 (mΩ cm)	T_0 (K)	ρ_0 (mΩ cm)	T_0 (K)	ρ_0 (mΩ cm)	T_0 (K)
Sample Q1							
0	80.0			0.311	37.5		
2×10^{13}	72.5			7.024	132.7		
2×10^{14}	70.0			8.173	445.6		
2×10^{15}	68.5					41.635	6263.2
Sample SL1							
0	65.0	0.217	102.5	0.116	16.3		
2×10^{14}	65.0	0.265	79.0	0.170	15.5		
2×10^{15}	69.0	0.227	38.0	0.094	2.4		
Sample Q2							
0	84.0			0.696	30.8		
7×10^{13}	79.2			2.121	117.3		
2×10^{14}	78.4			3.452	144.2		
7×10^{14}	78.0			6.363	151.9		
1×10^{15}	76.6			6.862	114.2		

Table 1 and Fig. 1 show the change of $T_{c0}(\rho = 0)$ and room temperature resistivity (ρ_{300}) due to radiation induced defects for the three samples. To note firstly, the direction of change of T_{c0} due to irradiation is opposite for quenched (Q1) and slow cooled (SL1) samples. Like Q1, another quenched sample Q2 also shows a degradation of T_c with increasing fluence. Qualitative features of the variation of ρ_{300} with fluence are same for all samples. However, the increase of ρ_{300} (also for corresponding irradiated states) is different for the three samples. The changes for T_c and ρ_{300} of the samples together reflects the state of disorder introduced due to irradiation. It is also clear that the damage or modification of a system depends largely on its initial state. Similar results have also been observed by electron irradiation on differently heat treated Y-123 system [2].

To get an insight of the carrier transport and pairing in such disordered superconducting systems, paraconductivity analysis near and above T_c for Q1 and SL1 samples have been shown in Figs. 2 and 3. At the lower temperature side (lower ln ε) for all the unirradiated and irradiated samples, paraconductivity exponents λ_{3D} and λ_{2D} are clearly visible. Question of 3D fluctuations has often been debated in highly anisotropic Bi-2212. However, in polycrystalline samples with vacancy type defects, such as ours, defect mediated 3D fluctuation is favorable [6,17]. After the λ_{2D} region at higher temperatures, there exists a fluctuation regime (λ_1) which shows interesting consequences due to irradiation. It is due to the interplay between defects and the carrier pairing mechanism (as fluctuation occurs due to pairing and de-pairing of carriers). The length scale associated with the pairing of carriers i.e. coherence length $\xi(T)$, goes down as $\xi(T) = \xi(T = 0)\varepsilon^{-\lambda}$. Defect dependence of fluctuation is manifested if and only if $\xi(T) < L$, where L is length scale within which two defective regions exist. As $\xi(T)$ goes lower with higher ε, defect dependence of λ is becoming prominent. More interestingly, modification of the λ_1 value (towards 3) of sample SL1 with fluence (Fig. 3) is consistent with the growing short wavelength fluctuations [7,18]. The change of λ_1 (towards $1 + 1/3 = 4/3$) with fluence for sample Q1 resembles the development of a fractal behavior [6,17].

Radiation altered normal state resistivity and its temperature dependence for Q1, SL1 and Q2 samples has been shown in Figs. 4 and 5. There exist

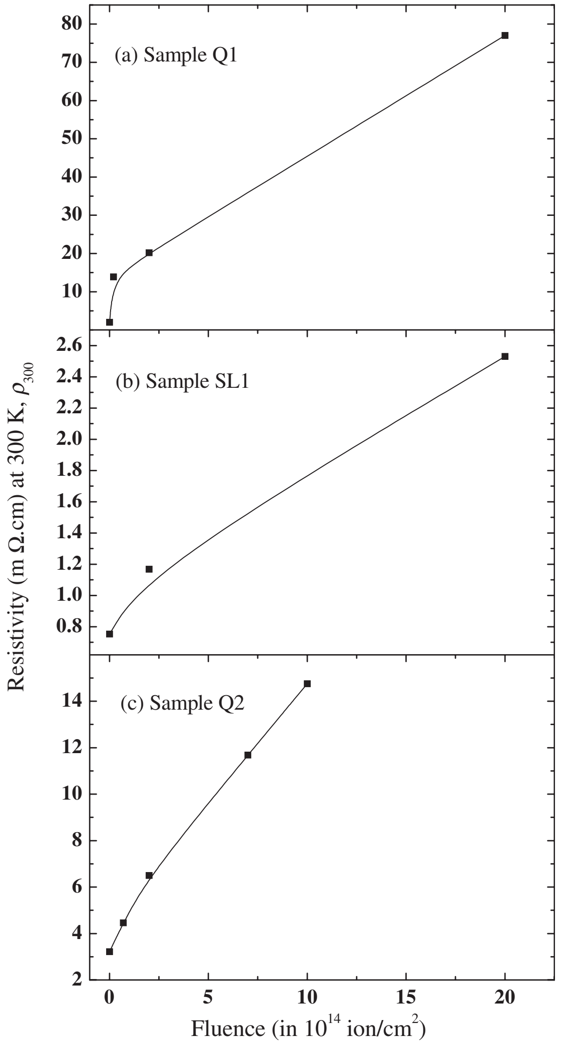

Fig. 1. Variations of room temperature resistivity (ρ_{300}) with irradiation fluence for (a) sample Q1, (b) sample SL1 and (c) for sample Q2.

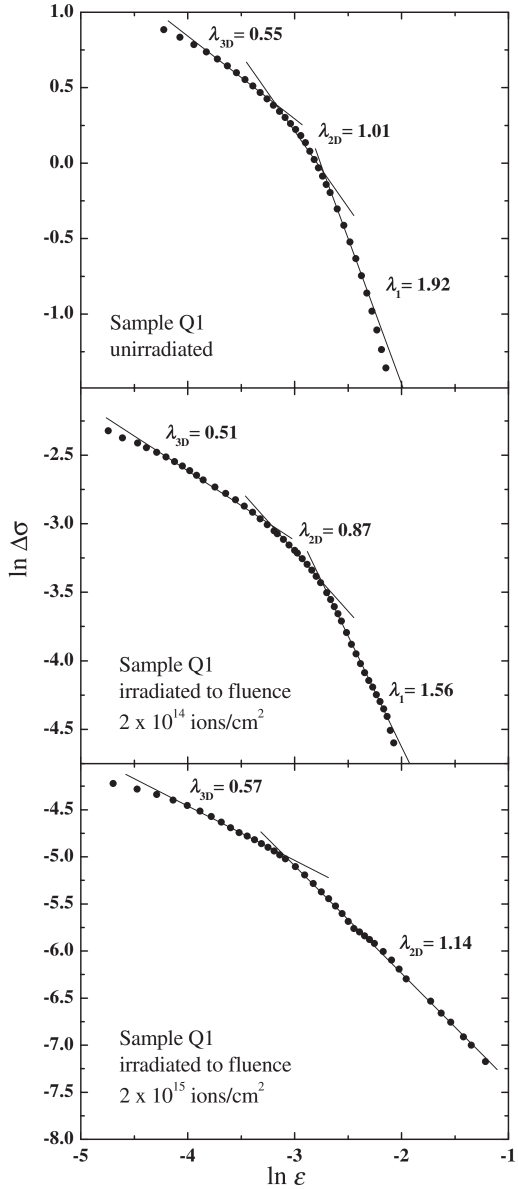

Fig. 2. Irradiation induced modification of different regions of paraconductivity for the sample Q1.

similar reports of driving a metal-like normal state to a semiconducting one either by heat treatment or by irradiation [2–4,9,10]. In our case, the Q1 sample with highest irradiation fluence is semiconducting down to 170 K from 300 K. All the other quenched (Q1 and Q2) samples, unirradiated and irradiated, show metal-like resistivity behavior in the normal state and have found an excellent fit with 2D VRH (p = 1/3) equation in a wide range of temperature. Of course, the values of ρ_0 and T_0 and their changes due to irradiation (Table 1) are not clear at this stage. The semiconducting region of the Q1 sample with maximum irradiation can well be fitted with 3D VRH model where p = 1/4. However, all the slow cooled (SL1) samples found best fit with p = 2/5, contrary to the

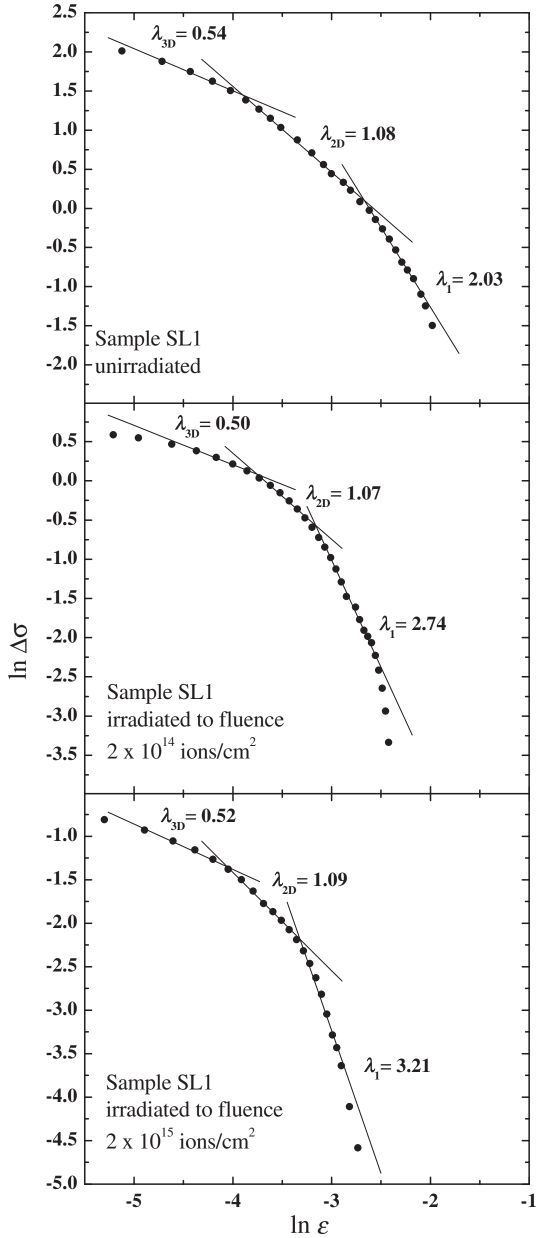

Fig. 3. Irradiation induced modification of different regions of paraconductivity for the sample SL1.

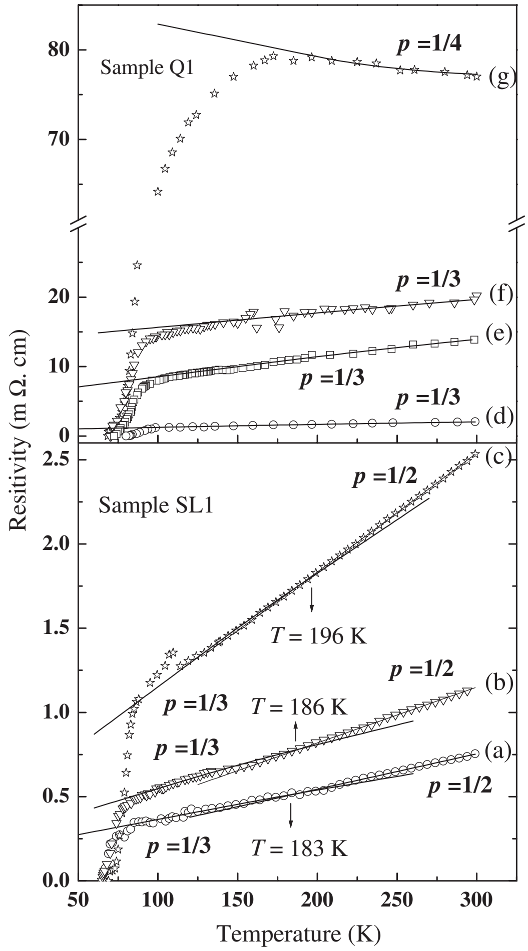

Fig. 4. VRH fit with the experimental temperature dependence of normal state resistivity for samples (a) unirradiated sample SL1, (b) sample SL1 irradiated to 2×10^{14} ions/cm^2, (c) sample SL1 irradiated to 2×10^{15} ions/cm^2, (d) unirradiated sample Q1, (e) sample Q1 irradiated to 2×10^{13} ions/cm^2, (f) sample Q1 irradiated to 2×10^{14} ions/cm^2 and (g) sample Q1 irradiated to 2×10^{15} ions/cm^2. The cross over temperature from 1D VRH to 2D VRH regime for sample SL1 is indicated.

theoretical predictions. Instead we found two separate regions in all SL1 samples as shown in Fig. 4. At higher temperature side, near 300 K, a region with $p = 1/2$ can clearly be distinguished. The value of $p = 1/2$ has been found earlier in overdoped Bi-2212 samples [10] and is consistent with a gap in density of states near the Fermi level [19]. From our preliminary results it is evident that hoping conduction dominates the normal state carrier transport of a HTSC superconductor. Any change in the nature of normal state resistivity behavior can successfully be accommodated within the framework of VRH conduction with changing values of ρ_0, T_0 and p.

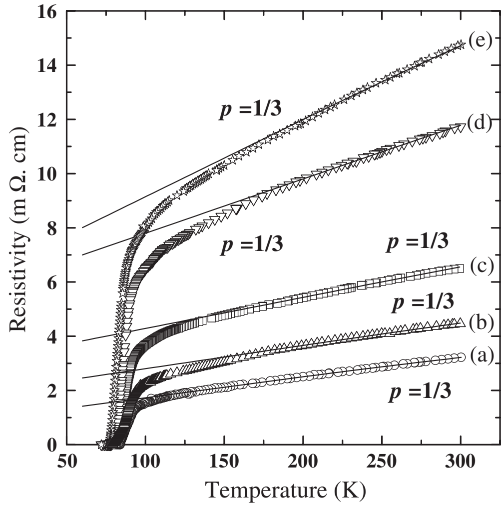

Fig. 5. VRH fit with the experimental temperature dependence of normal state resistivity for sample Q2 with fluence (a) zero, (b) 7×10^{13} ions/cm^2, (c) 2×10^{14} ions/cm^2, (d) 7×10^{14} ions/cm^2 and (e) 1×10^{15} ions/cm^2.

4. Conclusion

Analysis of the resistive behavior for differently heat treated and 55 MeV Li^{3+} irradiated Bi-2212 samples has been carried out near the bulk superconducting transition (T_c) and in the normal state. Irradiation induced defects lead to the evolution of different fluctuation regimes in slowly cooled and quenched samples as are clear from Figs. 2 and 3. In normal state, the experimental metal-like or semiconductor-like temperature dependences of the unirradiated and irradiated samples fit very well with VRH conduction scenario. However, the slowly cooled Bi-2212 system shows an anomalous dimensionality of hopping conduction near room temperature. This is a signature of a gap in the density of states near the Fermi level.

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