Correlations Between Critical Current Density and Penetration Depth in Ion Irradiated $YBa_2Cu_3O_7$ Thin Films

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Abstract—**Point defects have been introduced into $YBa_2Cu_3O_7$ through low energy helium ion irradiation in order to probe the origin of dissipation in a current-carrying superconductor. Resistivity, infrared reflectance and x-ray diffraction measurements indicate that the films are not chemically altered and that the induced point defects act as scattering centres. Measured electric field-current density characteristics are found to be well described by a model based on quantum current fluctuations. This description is used to extract the change in the superconducting carrier density with ion damage which agrees well with direct measurements of the same quantity by infrared reflectance. The implications of the relation between dissipation and the superconducting carrier density, or alternatively the magnetic penetration depth, are discussed.**

I. Introduction

Low energy, light ion irradiation can be used for the local modification of the superconducting properties of high temperature superconducting (HTS) thin films. Specifically, the critical current density, J_C, can be dramatically reduced and controlled [1]. The critical temperature, T_C, is relatively insensitive to ion damage compared to J_C [2]. This can be readily seen in Fig. 1, which demonstrates that even if J_C is measured at a fixed reduced temperature, $t=T/T_C$, it drops more rapidly with successives doses than T_C. Local control of the critical current could be important in the fabrication of a variety of high T_C devices including power limiters, SQUID's and switches.

Furthermore, because of its influence on J_C, ion irradiation can also provide insight into the mechanisms leading to dissipation in a current-carrying superconductor which are not well understood. This is particularly relevant to the case of zero applied magnetic field. In the absence of an accepted mechanism, the definition of J_C is ambiguous and often defined by an arbitrary electric field criterion. Identifying the mechanisms responsible for the onset of dissipation is an important step in developing optimized materials. Such materials will be important for overcoming power handling limitations in HTS wireless communications devices, one of the most promising applications of HTS thin films.

Both intrinsic and extrinsic [3] mechanisms can lead to dissipation in a current-carrying superconductor. However, key measurements [4], [5] suggest that in high quality thin films the origin of dissipation is intrinsic. Here, we take this viewpoint and treat dissipation arising from thermal and quantum current fluctuations. Current fluctuations correspond to the creation of vortices which move under the action of the Lorentz force and dissipate energy. In this paper we analyse electric field-current density (E-J) characteristics of irradiated $YBa_2Cu_3O_{7-\delta}$ microbridges within a model of current fluctuations. This allows us to extract the irradiation induced change in the superconducting carrier density which is compared to the results of infrared reflectance measurements on similarly irradiated samples.

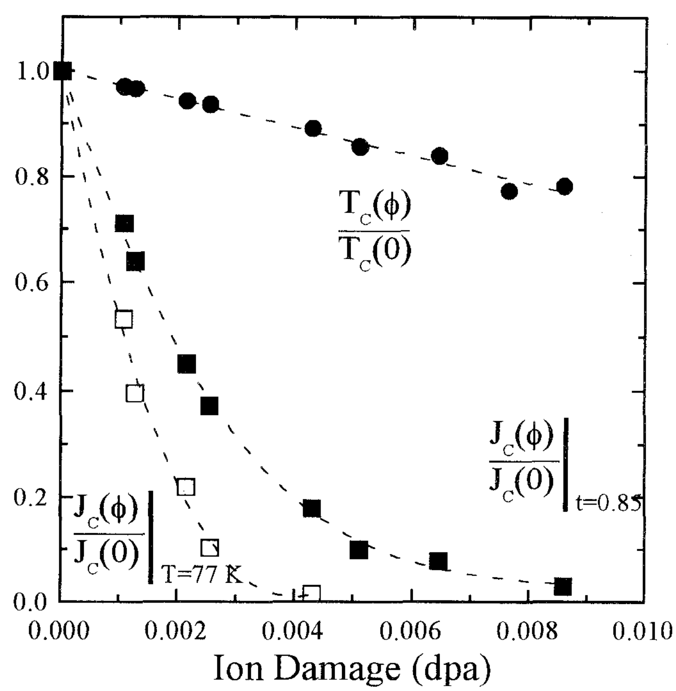

Fig. 1. The variation of T_C and J_C with ion damage in $YBa_2Cu_3O_7$ thin films. J_C is much more sensitive than T_C to ion damage. That T_C decreases with ion damage indirectly lowers J_C measured at a fixed temperature such as 77 K. The dashed lines are guides to the eye.

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II. Sample Preparation

The samples used in this study were 100 nm, high quality epitaxial thin films of $YBa_2Cu_3O_7$ grown by laser ablation on $LaAlO_3$ substrates as described elsewhere [6]. When required, films were etched into suitable structures using standard photolithographic techniques with 0.001M citric acid and gold contacts were applied by thermal evaporation.

Ion irradiation was performed at room temperature using 130 keV helium ions from an ion implanter. The ions were incident at approximately 7° to the surface normal to avoid channelling. A low beam current (< 50 nA/cm^2) was used to minimize sample heating. Monte Carlo numerical simulations [7] of the ion damage were performed to assess uniformity and quantify the damage level ,ϕ, given as the number of displacements per atom (dpa). These revealed that oxygen displacements were most common and that the damage is uniform through the film to within ten percent.

The change in the c lattice constant with ion damage, deduced from X-ray diffraction measurements, is shown in Fig. 2. The plateau between 0.005 and 0.018 dpa is consistent with other reports [8]. The origin of the plateau is not understood but may represent a saturation in the disordering of the Cu-O chains. Also shown is the variation of T_C with ion damage. It is interesting to note that this situation is dual to that found in oxygen reduced samples [9] where the c lattice constant increases smoothly and T_C exhibits a plateau. Nonetheless the broad similarity in the behaviour of the c lattice constant between ion damaged, oxygen reduced and impurity doped samples is consistent with modifications leading to point defects.

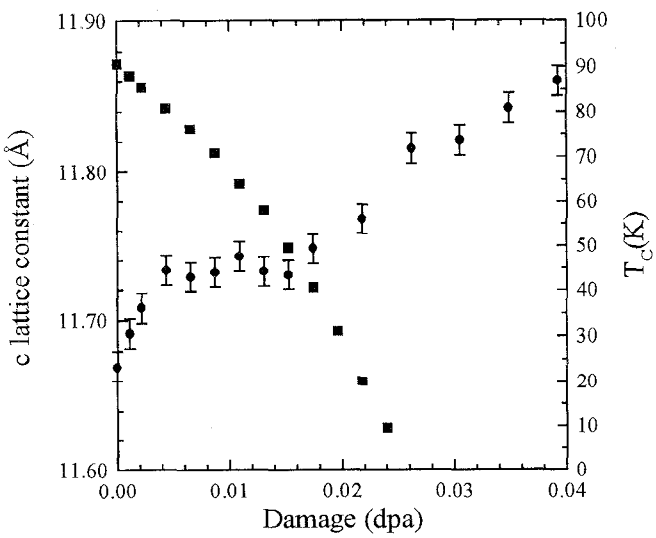

Fig. 2. The length of the c lattice constant (circles) and T_C (squares) as a function of ion damage. This behaviour is similar to what is seen when other types of point defects are incorporated in $YBa_2Cu_3O_7$.

III. Influence of Ion Irradiation on Transport Properties

A. Normal State

The influence of light ion irradiation on the ab-plane resistivity is shown in Fig. 3. At low doses the linear temperature dependence is unaffected and the data are well described by Matthiessen's rule in the form

$$\rho(T,\phi) = \frac{m}{n(\phi)e^2}\left[\frac{1}{\tau(T)} + \frac{1}{\tau_i(\phi)}\right] \tag{1}$$

where m is the carrier mass, $1/\tau$ is the temperature dependent scattering rate, $1/\tau_i$ is the temperature independent impurity or defect scattering rate and $n(\phi)$ is the total carrier density. From the slope of the linear portion of the $\rho(T)$ curves the change in $n(\phi)$ with ion damage can be deduced and is found to remain relatively unaffected in agreement with infrared results as shown in Fig. 4. In contrast, in oxygen reduced samples where T_C has been lowered by a similar amount the carrier density has been reduced much more significantly [10]. Thus, ion irradiation does not significantly affect the oxygen content or the doping level of the films. The primary effect of the ion damage is to create scattering centers as evidenced by the linear increase in the residual resistivity, ρ_0, with damage as shown in the inset of Fig. 3. For damage levels exceeding 0.01 dpa $\rho(T)$ starts to turn up just before T_C at which point this simple application of Matthiessen's rule breaks down.

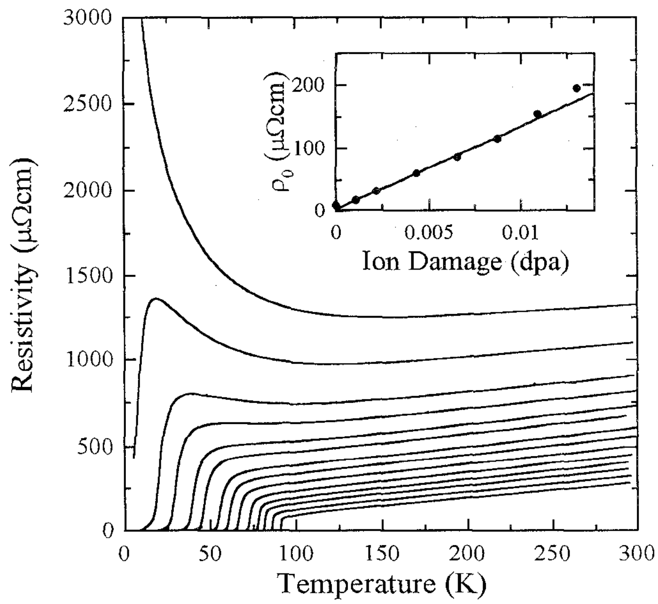

Fig. 3. The influence of ion damage on the temperature dependent resistivity, $\rho(T)$, of $YBa_2Cu_3O_7$ thin films. At low doses $\rho(T)$ remains linear and the residual resistivity, ρ_0 increases linearly with ion damage (inset), indicating that ion induced defects act as scattering centers. With sufficient irradiation superconductivity is completely suppressed and $\rho(T)$ develops insulating behaviour.

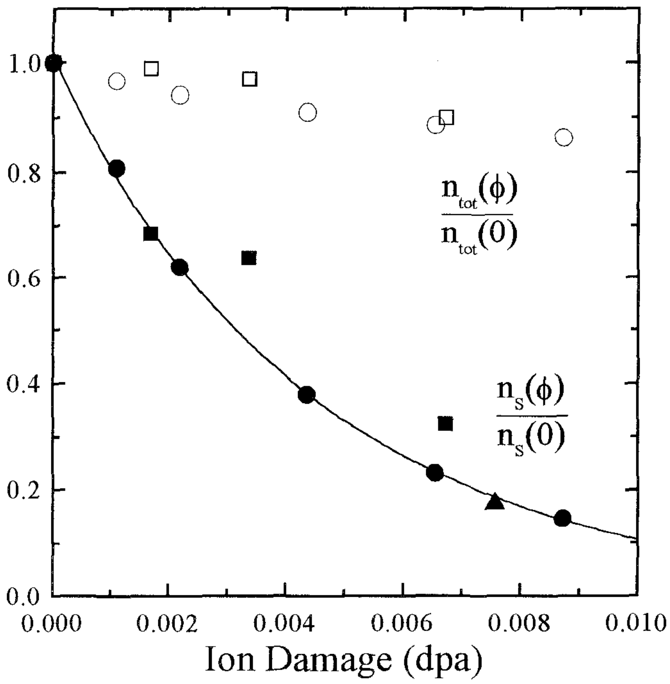

Fig. 4. The variation of the total carrier density with ion damage, ϕ, as obtained by infrared reflectance (open squares) and from the slope of $\rho(T)$ (open circles). The total carrier density varies little with ion damage. In contrast the superconducting carrier density, n_S, is reduced significantly by ion damage. Values obtained from infrared reflectance on a crystal (solid squares) and film (solid triangle) agree well with those obtained from an analysis of the E-J characteristics (solid circles). The solid line is an exponential fit.

B. Superconducting State

Two approaches were taken in the measurement of the superconducting properties. A non-contact, single-coil inductive technique [11], [12] was used to extract T_C and J_C as a function of ion damage for unpatterned films. As well, E-J characteristics in the superconducting state were measured using the patterned microbridge samples used for measuring $\rho(T)$. The details of the infrared reflectance measurements are reported elsewhere [13], [14].

Fig. 5 shows E-J characteristics of a microbridge measured at a fixed reduced temperature for a range of ion damage. It is apparent that while the curves shift to lower currents, they retain the same basic shape suggesting that the dissipation mechanism remains the same. Also shown in Fig. 5 are fits corresponding to one possible intrinsic current limiting mechanism discussed below.

The current fluctuations expected to lead to dissipation, in the absence of an applied magnetic field, are equivalently described in terms of the formation of vortex loops in a plane normal to the direction of the current. The free energy describing the formation of a loop of radius R given by

$$U = 2\pi R\tau - \pi R^2\phi_0 J\ , \qquad (2)$$

corresponds to a competition between the cost due to the

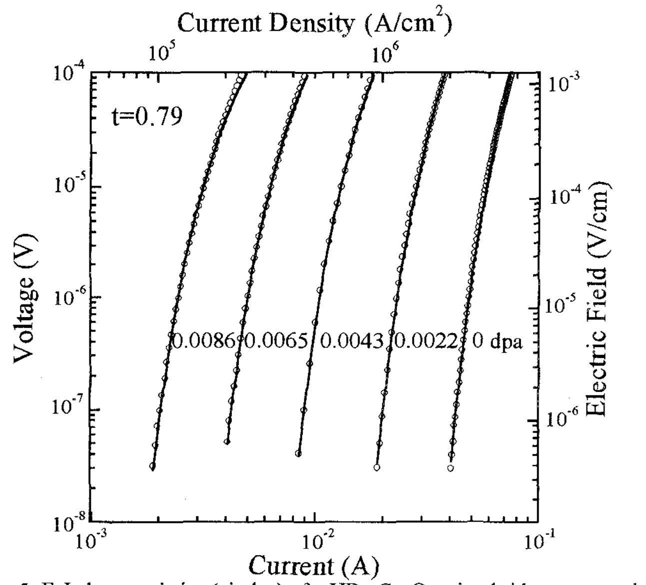

Fig. 5. E-J characteristics (circles) of a $YBa_2Cu_3O_7$ microbridge measured at a fixed reduced temperature of $0.79T_C$ after successive doses of ion damage. The solid lines are fits to the data using (4). The quality of the fits suggest that quantum fluctuations are responsible for the onset of dissipation.

line tension of the vortex, τ, and the gain due to a Lorentz force term proportional to the current density, J. The line tension of the vortex,

$$\tau = \frac{\phi_0^2}{4\pi\mu_0\lambda^2}(\ln\kappa + \eta)\ , \qquad (3)$$

is essentially determined by the penetration depth, λ, but also depends on κ, the ratio of the penetration depth to the coherence length and η, the contribution of the vortex core to the line tension.

Thermal and quantum nucleation of vortex loops over the free energy barrier in (1), lead to predictions [15], [16] for the E-J characteristics given by

$$\frac{E}{J} = \rho_0 e^{-\left(\frac{J_{C1}}{J}\right)}\ ;\ J_{C1} = \frac{\phi_0^3(\ln\kappa + \eta)^2}{16\pi\mu_0^2\lambda^4 k_B T} \qquad (4)$$

and

$$\frac{E}{J} = \rho_0 e^{-\left(\frac{J_{C2}}{J}\right)^2}\ ;\ J_{C2} = \frac{\phi_0^3(\ln\kappa + \eta)^{3/2}}{16\pi^2\mu_0^2 c\hbar\lambda^3} \qquad (5)$$

respectively. J_{C1} and J_{C2} are the critical current scales for dissipation from thermal and quantum fluctuations respectively. It should be noted that these are uniquely determined and do not require an arbitrary electric field criterion.

We found that the quantum nucleation model could give an excellent fit to our data while the thermal model could not. Fitting each E-J characteristic gives a value of J_{C2} for that reduced temperature and ion damage level. The temperature dependence of J_{C2} derived from the fits for several levels of ion damage is shown in Fig. 6. At all levels of ion damage J_{C2} is found to have a temperature dependence

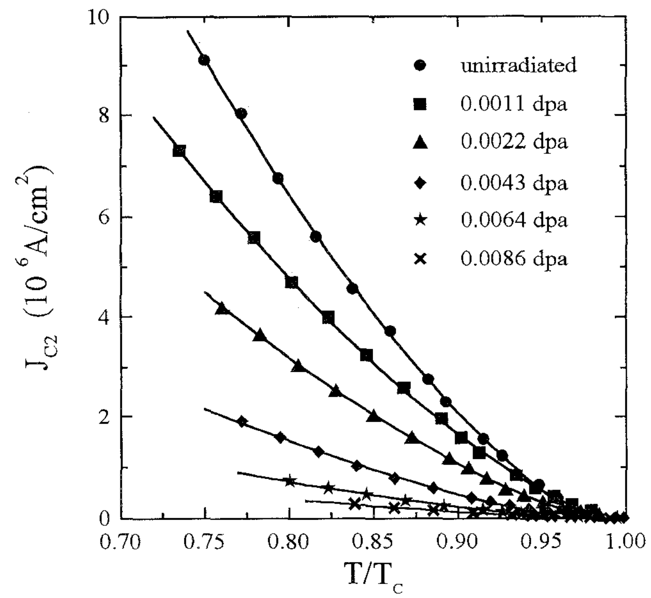

Fig. 6. The critical current density, J_{C2}, obtained from fitting E-J characteristics at several levels of ion damage and over a range of temperature. The solid lines indicate that $J_{C2} \propto (1-T/T_C)^{3/2}$ at all levels of ion damage.

of $(1-t)^{3/2}$, where $t=T/T_C$, as shown by the solid lines.

From (5) it can be noted that J_{C2} depends primarily on λ, or alternatively the superconducting carrier density $n_S \propto 1/\lambda^2$. Thus, the values of J_{C2} for different levels of ion damage can then be used to extract the relative change in n_S. The result of this procedure is shown in Fig. 4. The values obtained are compared with infrared measurements of n_S and found to be in good agreement. The solid line is an exponential fit to n_S derived from the E-J characteristics. It reveals that each ion-induced defect renders 2900Å^3 non-superconducting consistent with the idea that low energy ion irradiation results in point defects.

V. Conclusions

Low energy, light ion irradiation leads to point defects in high T_C materials. These point defects increase the resistivity in the normal state by increasing the scattering. In the superconducting state, the defects lead to a dramatic reduction in the superconducting carrier density and the critical current density. The shape of the E-J characteristics is consistent with a mechanism of quantum nucleated current fluctuations initiating the dissipation in the absence of an applied magnetic field. This mechanism can also quantitatively account for the connection between the superconducting carrier density and the critical current in ion irradiated films.

These results indicate that the materials with larger carrier densities should be sought for higher intrinsic current-carrying capacity. They also suggest that in cases where extended defects are added to increase the current-carrying capability in a strong magnetic field, consideration should be given to minimizing the increase in the penetration depth.

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