Role of pair-breaking and phase fluctuations in c-axis tunneling in underdoped $Bi_2Sr_2CaCu_2O_{8+\delta}$

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Abstract

The Josephson Plasma Resonance is used to study the c-axis supercurrent in the superconducting state of underdoped $Bi_2Sr_2CaCu_2O_{8+\delta}$ with varying degrees of controlled point-like disorder, introduced by high-energy electron irradiation. As disorder is increased, the Josephson Plasma frequency decreases proportionally to the critical temperature. The temperature dependence of the plasma frequency does not depend on the irradiation dose, and is in quantitative agreement with a model for quantum fluctuations of the superconducting phase in the CuO_2 layers.

Key words: Disorder, Interlayer coupling, Josephson Plasma Resonance, Quantum fluctuations
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1. Introduction

From the d-wave symmetry of the order parameter of cuprate superconductors, one expects an enhanced sensitivity of c-axis transport in the superconducting state to disorder, due to the enhancement of the quasiparticle density of states along the gap node directions, and due to impurity assisted hopping [1]. Both mechanisms lead to as yet unobserved T^2-dependences of the c-axis superfluid density ρ_s^c at low T, with coefficients that strongly depend on the scattering rate Γ. On the other hand, underdoped cuprates are sufficiently disordered for (quantum) fluctuations of the order parameter phase to play a prominent role [2], leading to a T-linear behavior of ρ_s^c. Here, we report on the effect of controlled point disorder on interlayer tunneling of Cooper pairs in underdoped $Bi_2Sr_2CaCu_2O_{8+\delta}$.

2. Experimental details

Single-crystalline rods of underdoped $Bi_2Sr_2CaCu_2O_{8+\delta}$ were grown using the travelling solvent floating zone technique under 25 mBar oxygen partial pressure [3]. The samples used for the study, with $T_c \approx 70$ K, were cleaved from the same crystalline piece. The crystals were then irradiated with 2.5 MeV electrons using the van der Graaf accelerator of the Laboratoire des Solides Irradiés. The irradiation produces homogeneously distributed Frenkel pairs, which have previously been identified as strong scattering centers [4].

The Josephson Plasma Resonance (JPR) frequency f_{JPR} of the crystals was then measured using the cavity perturbation technique, exploiting TM_{01n} harmonic modes to access different frequencies [6], and the bolometric technique using a waveg-

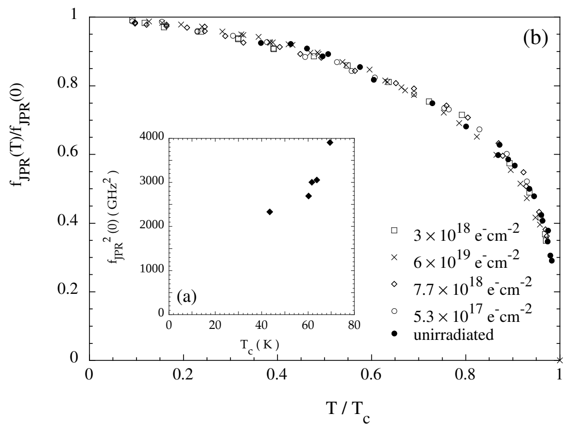

Fig. 1. JPR frequency of the e^--irradiated $Bi_2Sr_2CaCu_2O_{8+\delta}$ crystals, normalized to the JPR frequency at $T \to 0$, versus reduced temperature.

uide in the TE_{01} travelling wave mode [5]. The latter technique allows for swept-frequency measurements, necessary to elucidate the weak $f_{JPR}(T)$ dependence at low T [5]. Note that f_{JPR}^2 is proportional to the c-axis critical current j_c^c and to the c-axis superfluid density: $f_{JPR}^2 = j_c^c s/2\pi\epsilon_0\epsilon_r\Phi_0 = c^2/4\pi^2\epsilon_r\lambda_c^2 \propto \rho_s^c$, with ϵ_r the low-frequency dielectric constant and λ_c is the c-axis penetration depth.

3. Results and Discussion

Sharp JPR resonant peaks were measured for all samples under study. Both T_c and $f_{JPR}(T \to 0)$ decrease with irradiation dose. The sensitivity of f_{JPR} to even weak additional disorder contradicts the model of coherent interlayer Cooper pair tunneling [7]. Within the framework of a d-wave BCS model, the measured proportionality between f_{JPR}^2 and T_c can be understood as resulting either from (i) the dependence of the interlayer Josephson current $j_c^c \propto \Delta\sigma_{qp}$ on the gap magnitude Δ and the quasiparticle conductivity σ_{qp} [8], or (ii) from the decrease of the *in-plane* superfluid density due to strong phase fluctuations.

The origin of the temperature and disorder-dependence of f_{JPR} can be pinpointed using Fig. 1(b). Normalising all results to $f_{JPR}(T \to 0)$ and plotting these versus reduced temperature, reveals a common T-dependence independent of disorder. This contradicts the prediction of Ref. [1] that ρ_s should follow different powers of T depending on the ratio of T, Δ, and Γ. However, it agrees with a dominant role of quantum phase fluctuations. Then,

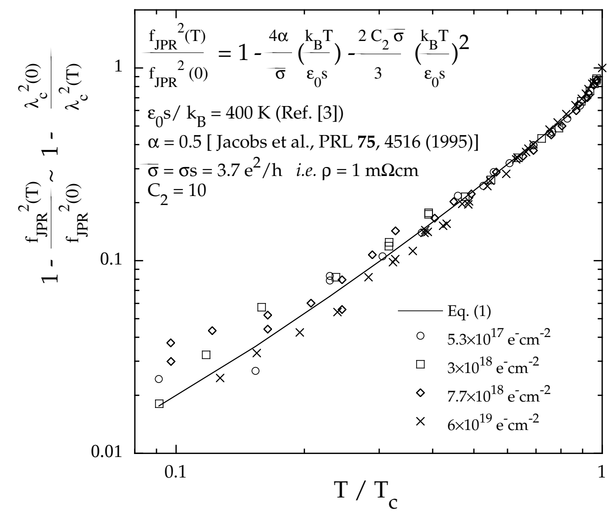

Fig. 2. JPR frequency of the e^--irradiated $Bi_2Sr_2CaCu_2O_{8+\delta}$ crystals, plotted as $1 - f_{JPR}^2(T)/f_{JPR}^2(0)$ in order to bring out the low temperature T-dependence. The line is a fit to Eq. 1 [9] with parameters as indicated.

$$\frac{f_{JPR}^2(T)}{f_{JPR}^2(0)} \approx 1 - \frac{4\alpha k_B T}{\varepsilon_0 s \overline{\sigma}} - C_2 \frac{2\overline{\sigma}}{3}\left(\frac{k_B T}{\varepsilon_0 s}\right)^2 \qquad (1)$$

where $\alpha = (\partial\varepsilon_0 s/\partial T)_{T\to 0}$, $\varepsilon_0 = \Phi_0/4\pi\mu_0\lambda_{ab}^2$ with λ_{ab} the in-plane penetration depth, s is the CuO_2 layer spacing, and $\overline{\sigma} = \sigma s$ is the CuO_2 plane sheet conductivity [9]. The temperature dependence of the JPR frequency arises from the temperature of the in-plane phase stiffness ε_0. Figure 2 shows that Eq. (1) describes the results very satisfactorily.

Summarizing, the temperature- and disorder dependence of the c-axis Cooper pair tunnel current in underdoped $Bi_2Sr_2CaCu_2O_{8+\delta}$ is well described assuming a strong effect of quantum phase fluctuations. A d-wave model without fluctuations cannot account for the T-dependence of c-axis coupling.

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