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Disorder and c-axis quasiparticle dynamics in underdoped $Bi_2Sr_2CaCu_2O_8$

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Abstract. We present measurements of the Josephson plasma frequency and the in-plane penetration depth of underdoped single crystalline $Bi_2Sr_2CaCu_2O_8$ with varying degrees of disorder introduced by irradiation with 2.3 MeV electrons. Increasing disorder drives T_c down, in agreement with in all model descriptions of high T_c superconductivity. However, the manner in which the JPR frequency, the square of which represents the zero-frequency spectral weight of the c-axis conductivity in the superconducting state, is driven down by disorder depends more strongly on the model description. We show that only the model of impurity assisted quasiparticle hopping in a d-wave superconductor, together with strongly scattering point defects in the superconducting layers, can explain the disorder dependence of the c-axis plasma frequency, the in-plane penetration depth, and T_c consistently. From the data, we extract the energy scale governing nodal quasiparticle excitations, $\Delta_0 \sim 2.5 k_B T_c$.

1. Introduction

The nature of the normal state in underdoped cuprates figures prominently among controversies concerning high temperature superconductivity. First, the temperature regime above the critical temperature T_c is characterized by the existence of the so-called "pseudo-gap", the origin of which is believed to be either due to preformed Cooper pairs [1,2], with Bose condensation at T_c, or, alternatively, to the onset of an electronically ordered state competing with superconductivity [3]. The "bosonic" preformed-pair scenario was invoked to explain the violation of the Glover-Tinkham-Ferell optical sum-rule by the c-axis conductivity[2], with the corollary that the zero-frequency peak in the c-axis spectral weight should be depressed due to in–plane quantum fluctuations of the phase $\phi_{||}$ of the superconducting order parameter.

Second, underdoped cuprates are, even more than their optimally doped and overdoped counterparts, prone to significant amounts of crystalline disorder [4-6]. Given the d-wave symmetry of the superconducting gap function, disorder is responsible for the enhancement of the quasiparticle density of states near the (π, π) direction of the gap nodes [6,7], but also for

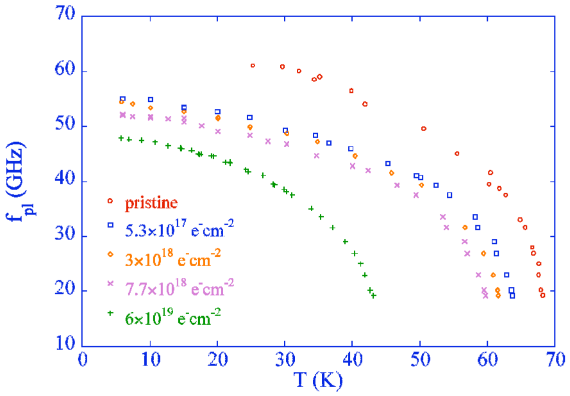

Figure 1. JPR frequency vs. temperature for underdoped $Bi_2Sr_2CaCu_2O_8$ single crystals irradiated with different fluences of high energy electrons.

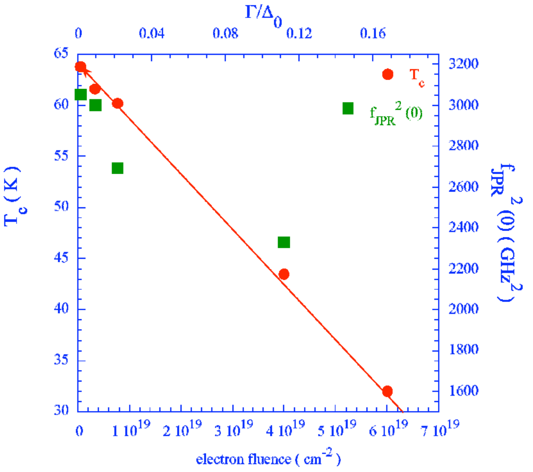

Figure 2. Critical temperature T_c, and square $f_{pl}^2(0)$ of the low temperature extrapolated JPR frequency, as function of the electron fluence.

quasiparticle scattering and, likely, an ensuing depression of T_c.

In this contribution, we study the decrease with disorder of the Josephson Plasma Resonance (JPR) frequency f_{pl}, which is a bulk probe of superconductivity, in single-crystalline underdoped $Bi_2Sr_2CaCu_2O_{8+\delta}$. Different levels of homogeneous disorder are artificially introduced by high energy electron irradiation. The results are cross-correlated with the behaviour of the penetration depth for supercurrents in the CuO_2 planes, λ_{ab}. We find that the evolution of T_c, f_{pl}, and $\lambda_{ab}(T)$ with the electronic scattering rate Γ is consistent with the d-wave Bardeen-Cooper-Schrieffer (BCS) model for superconductivity, in which f_{pl} is reduced with increasing temperature and disorder due to the impurity assisted hopping (IAH) of nodal quasiparticles [8-11]. results. Whereas the similar temperature dependence of λ_{ab}^{-2} and f_{pl}^2 is in good agreement with a model for strong quantum fluctuations [2,12,13], the disorder dependence is not.

2. Experimental details

Underdoped $Bi_2Sr_2CaCu_2O_{8+\delta}$ single crystals with 0.10 holes per Cu and $T_c = 65$ K were grown using the travelling-solvent floating zone method under 25 mBar O_2 partial pressure [14]. Different crystals cleaved from the same piece were irradiated to varying fluences of 2.3 MeV electrons using the van de Graaff accelerator of the Laboratoire des Solides Irradiés. The crystals were immersed in liquid hydrogen during the irradiation. The irradiation produces homogeneously distributed point defects (Frenkel pairs), both in the CuO_2 layers and in the BiO insulating blocking layers. The effect of the former is expected to be similar to Zn-doping [15]. The JPR frequency was measured by placing the sample on the centre of the top surface of a high conductivity copper resonant cavity, and measuring the cavity resonance as function of T; at the temperature at which the absorption is maximum, f_{pl} is equal to the resonant mode frequency. This procedure was repeated for different harmonic transverse modes TM_{01n}. Additional swept-frequency measurements were made at the University of Tokyo by exploiting the TE_{01} travelling wave mode of a waveguide together with bolometric detection of an increase in the surface resistance [16]. Finally, the temperature variation of λ_{ab} of the irradiated crystals was measured using a Pb resonant cavity at Kyoto University.

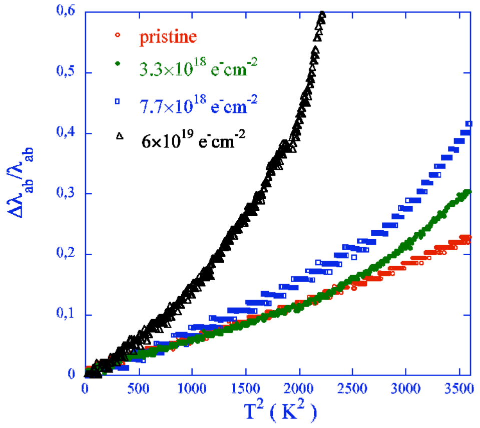

Figure 3. Temperature variation of the *ab*-plane penetration depth of underdoped $Bi_2Sr_2CaCu_2O_8$ crystals for different electron irradiation fluences.

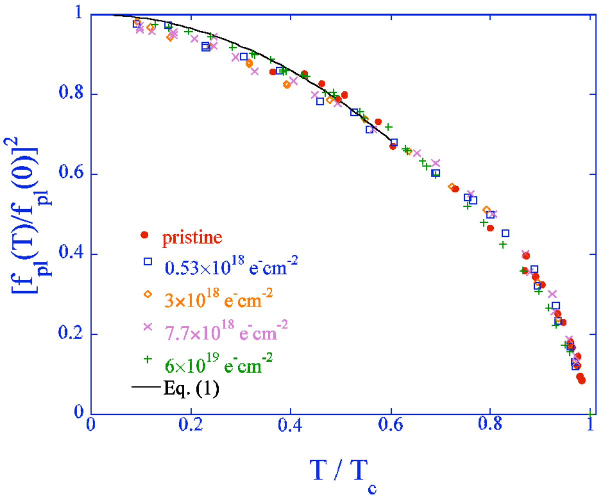

Figure 4. $f_{pl}^2(T)/f_{pl}^2(0)$ vs. reduved temperature T/T_c), for different elecgtron irradiation fluences.

3. Results

All crystals showed well-defined peaks in the *c*-axis surface resistance, permitting the identification of the JPR. The $f_{pl}(T)$ curves, depicted in Fig. 1, show that f_{pl} vanishes at the bulk T_c of the underdoped crystals, and allow for the determination of the low-temperature extrapolated value $f_{pl}(0)$. Fig. 2 shows that both T_c and $f_{pl}^2(0)$ decrease linearly as function of electron fluence. The linear decrease of T_c is expected from the pair-breaking effect of the irradiation-induced defects in the CuO_2 planes [17]. This is corroborated by the T^2–dependence of the *ab*–plane penetration depth (Fig. 3), which points to an important role of quasi-particle scattering in the unitary limit in all crystals [18]. We can then directly compare the evolution of T_c with fluence to the results [20] and obtain an estimate of the normal state scattering rate Γ normalized to the energy scale Δ_0 governing quasiparticle excitations (see Fig. 2).

In spite of the widely varying disorder levels, f_{pl}^2, which is proportional to the spectral weight of the zero-frequency peak in the *c*-axis conductivity in the superconducting state (or *c*-axis superfluid density ρ_s^c), has the same *T*-dependence for all crystals. Fig. 4 shows that all data overlap when plotted as $f_{pl}^2(T)/f_{pl}^2(0)$ vs T/T_c, and that $f_{pl}^2(T)/f_{pl}^2(0) \propto 1 - a(T/T_c)^2$.

4. Discussion

The observed temperature and disorder dependence of f_{pl}, T_c, and λ_{ab}, imposes important constraints on a model interpretation. Notably, the proportionality of $f_{pl}^2(0)$ with T_c excludes the scenario where the *c*-axis superfluid density is reduced through direct quasiparticle tunnelling [8]. Good agreement is obtained, however, by considering incoherent tunnelling of nodal quasiparticles mediated by interlayer impurity states. In this case, one expects [9,10]

$$\rho_s^c = 2\pi V_1 \Delta_0 N^2(E_F)\left[1 - 8\ln 2\left(\frac{T}{\Delta_0}\right)^2\right], \tag{1}$$

where V_1 is the anisotropic part of the interlayer impurity potential, and $N(E_F)$ is the density of states at the Fermi level. Eq. (1) consistently describes the temperature and the disorder dependence of f_{pl}, as well as the “scaling” observed in Fig. 4, if we assume that $\Delta_0 = 2.5k_BT_c$ regardless of the disorder level. This number is in very good agreement with that obtained from Scanning Tunnelling Spectroscopy [19,20] and B_{2g} Raman spectroscopy measurements [21], which also probe the nodal quasiparticle excitations. The data are also in agreement with the toy model of Ref. [11], which predicts $\rho_s^c \sim 1 - \frac{3}{14}(\Gamma/\Delta_0) - \ldots$. Note that in Fig.

4, the behaviour of the pristine crystal is indistinguishable from that of the irradiated ones. Hence, disorder plays an important role even without irradiation, and T_c of underdoped high temperature superconductors may be considerably suppressed with respect to a hypothetically "clean" material.

In a scenario where quantum fluctuations of the in-plane superconducting phase are predominant, the c-axis superfluid density is reduced by a "Debye-Waller" factor, $f_{pl}^2 \sim f_{pl}^2(0)\left(1-\frac{1}{2}\langle\phi_\perp^2\rangle\right) \sim 1-\frac{1}{2}C\langle\phi_{\|}^2\rangle$, while its T-dependence is only weakly affected ($\phi_\perp$ is the phase difference between adjacent layers and C is a constant of order 1). Developping this expression using the results [9,10], one has

$$f_{pl}^2 \propto 1-\frac{C}{2}\left(\frac{e^2}{\epsilon\xi_0}\frac{1}{\rho_s^{ab}s}\right)^{1/2}\frac{\lambda_{ab}(T)}{\lambda_{ab}(0)} \qquad (2)$$

(where $\rho_s^{ab}(0)$ is the low temperature in-plane superfuid density, ξ_0 the coherence length, s the CuO_2 layer spacing, e the electronic charge, and ϵ the relative dielectric constant). Eq. (2) well describes the similar temperature dependence of f_{pl}^2 and λ_{ab}^{-2}. However, it cannot reconcile the superposition of the curves in Fig. 4 with the linear decrease of $f_{pl}^2(0)$ vs. Γ - the two lead to different dependences of λ_{ab} on Γ.

Summarizing, we find that the temperature- and disorder dependence of the c-axis JPR in underdoped $Bi_2Sr_2CaCu_2O_8$ is in good agreement with a d-wave BCS model for impurity assisted nodal quasiparticle tunnelling between CuO_2 layers. We extract an energy scale governing nodal quasiparticle excitations that coincides with that found in other experiments [19-21].

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