Electronic compressibility and charge imbalance relaxation in cuprate superconductors

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Abstract

In the material SmLa 1−x Sr x CuO 4−δ with alternating intrinsic Josephson junctions we explain theoretically the relative amplitude of the two plasma peaks in transmission by taking into account the spatial dispersion of the Josephson Plasma Resonance in c direction due to charge coupling. From this and the magnetic field dependence of the plasma peaks in the vortex solid and liquid states it is shown that the electronic compressibility of the CuO 2 layers is consistent with a free electron value. Also the London penetration depth λab ≈ 1100Å near Tc can be determined. The voltage response in the IV-curve of a Bi 2 Sr 2 CaCu 2 O 8 mesa due to microwave irradiation or current injection in a second mesa is related to the nonequilibrium charge imbalance of quasiparticles and Cooper pairs and from our experimental data the relaxation time ∼ 100ps is obtained.

Key words: intrinsic Josephson effect, optical spectroscopy, transport, charge imbalance, Bi 2 Sr 2 CaCu 2 O 8, SmLa 1−x Sr x CuO 4−δ

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Theoretical analysis of optical and transport properties of intrinsic Josephson junctions in high-Tc superconductors allows to extract key microscopic parameters of the CuO 2 -layers, such as the electronic compressibility and the charge imbalance relaxation rate, which are hard to obtain otherwise.

In optical transmission or reflectivity experiments (cf. Fig. 1a) the Josephson Plasma Resonance (JPR) of Cooper pairs oscillating between the layers, creates a peak in the loss function L(ω) (e.g. in TBCCO [1]). Recently, in the novel material SmLa 1−x Sr x CuO 4−δ with alternating junctions two plasma peaks were observed with a high ratio of their amplitudes [2,3]. This can only be explained, if the spatial dispersion of the JPR in c direction due to charge fluctuations of the superconducting condensate, is taken into account, see Fig. 2 and Ref. [4]. Using the data in [2,3] we find that the electronic compressibility of the layers is consistent with a free electron value. This corresponds to a c axis disper-

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sion \sim \alpha of the (bare) JPR frequencies, \omega^2 = \omega_{cl}^2 (1 + \alpha k^2_f), f = 1.2 with \alpha = (\epsilon_0 / 4 \pi \varepsilon_0) (\partial \mu / \partial \rho) \approx 0.4 (\epsilon_0 background dielectric constant, \mu chemical potential, \rho 2d charge density). This result is confirmed by the magnetic field dependence of the plasma peaks [5], using the dependence of the critical current densities, which is well known in the vortex liquid state and has been newly derived for the vortex solid [6]. The parameter \alpha is not only relevant to understand the coupled dynamics of stacks of intrinsic Josephson junctions, e.g. for THz applications, but might also provide an important input for microscopic theories of high-T_c superconductivity. Beyond that, the c-axis quasiparticle conductivity \sigma_1 \sim 4 \sim 10/(1m)^{-1} and the London penetration depth \lambda_L = 1100\AA near T_c parallel to the layers can be accurately determined. Our theory for L(\omega) quantitatively improves Ref. [7] by taking into account the different conductivities \sigma_i in the junctions in accordance with their different current densities and the influence of the discrete atomic structure. Our results are in principle also applicable for microwave absorption experiments in a cavity (Fig. 1b).

From a theoretical point of view the inclusion of the wavevector dependence of the dielectric function \epsilon(\omega, \mathbf{k}) poses a nontrivial problem and requires to go beyond the conventional Fresnel theory [8]. Generally, for systems with spatial dispersion (e.g. phonons [9]), multiple eigenmodes with different group velocities are excited in the crystal and at certain extremal frequencies, where the group velocity vanishes, the atomic structure of the crystal enters explicitly in optical properties. The possibility to stop light dynamically by affecting the JPR in an external magnetic field might serve as a building block for a future magneto-optical device, e.g. to store photonic qubits [8].

Further, we perform two different transport experiments on Bi_2Sr_2CaCu_2O_8, in order to investigate nonequilibrium effects beyond the coupling \alpha [10]: (1) In 2-point measurements of the IV-curves in the presence of high-frequency irradiation (I_{rf}) of frequency f a shift of the voltage of Shapiro steps of \sim 3% from the canonical value V_s = hf / 2e has been observed due to the resistance at the NS-contact (Fig. 1c, first discussed in [11]). (2) In the IV-curves of double-mesa structures an influence of the dc voltage V_1 measured at one mesa on the dc quasiparticle current I_2 injected into the other mesa is detected (Fig. 1d). Both effects can be explained by charge-imbalance on the superconducting layers between resistive and superconducting junctions, where Cooper pairs and quasiparticles are transformed into each other. With the help of a recently developed theory [12] we get the charge imbalance relaxation time as \sim 70 \sim 450ps (depending on the sample).

In conclusion, the optical spectroscopy of the Josephson plasma resonance in SmLa_{1-x}Sr_xCuO_4-\delta suggests a free electronic compressibility of the superconducting CuO_2-layers and a London penetration depth \lambda_L = 1100\AA near T_c. From the analysis of the resistive state in the presence of microwave irradiation or current injection a charge imbalance relaxation time of the order \sim 100ps is obtained.

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