



Doping dependent time-reversal symmetric nonlinearity of $\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta}$ thin films

Sheng-Chiang Lee, Steven M. Anlage*

Center for Superconductivity Research, Physics Department, University of Maryland, College Park 20742-4111, USA

Abstract

We have measured the temperature dependent third harmonic response from a series of under-doped $\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta}$ thin films to address the mechanism of nonlinearity in these samples. We find that the intrinsic Ginzburg–Landau nonlinearity near T_c is doping dependent, with the sample becoming more nonlinear as it is under-doped. The results are consistent with the doping dependence of the condensation energy of $\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta}$.

© 2004 Elsevier B.V. All rights reserved.

Keywords: Microwave; Nonlinear; Superconductor; Doping

1. Introduction

The well-known Ginzburg–Landau description of superconductivity predicts an intrinsic third order nonlinearity of the superfluid response, which is enhanced tremendously near T_c . Another well-known third-order nonlinearity of interest in high-temperature superconductors (HTSC) occurs in the Andreev bound state (ABS). To explore and provide an alternative means to locally study these nonlinearities, we employ our near-field microwave microscope to study the local harmonic response from HTSC thin films.

The nonlinear dynamics of superconductors is manifested in different physical quantities in different ways. In the presence of a time-reversal symmetric (TRS), third order nonlinearity, the superfluid density ρ_s becomes dependent on the externally applied current density J through, $\rho_s(T, J)/\rho_s(T, 0) \cong 1 - (J/J_{\text{NL}}(T))^2$, where $J_{\text{NL}}(T)$ is the temperature-dependent, but experimental system-independent, scaling current density, which gives a quantitative measure of the nonlinear mechanism. Each mechanism of nonlinearity predicts its own value and temperature dependence for this scaling current density. For example, in the Ginzburg–Landau

(GL) description of s-wave superconductors, $J_{\text{NL}}(t)$ is expected to be $J_{c0}(1-t^2)(1-t^4)^{1/2}$, where J_{c0} is in the order of 10^{13} A/m² in HTSC, and $t = T/T_c$ is the normalized temperature.

2. Results

Details of the experimental setup (Fig. 1) are described elsewhere [1]. In summary, we apply microwave signals locally to the sample through a loop probe to induce localized microwave currents on the surface, and measure the third harmonic power (P_{3f}) in the signals reflected back from the sample.

The samples under study are a series of under-doped $\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta}$ (YBCO) thin films, with thickness around 1000 Å. The hole-doping concentration x is estimated from the T_c of each film, using the formula $T_c = 92 \text{ K}(1 - 82.6(x - 0.16)^2)$. The films were originally deposited on NdGaO_3 or SrTiO_3 substrates by the pulsed laser deposition technique at nearly optimal doping. Some of the films were subsequently re-annealed at different temperatures and oxygen pressures to change the oxygen content. All films have a transition width less than 5 K, as determined by ac susceptibility measurements.

In Fig. 2, measurements of the temperature dependent P_{3f} of a series of under-doped YBCO films are presented versus normalized temperature. The T_c values are determined by the peak P_{3f} response temperature.

* Corresponding author. Tel.: +1-301-405-7321; fax: +1-301-405-3779.

E-mail address: anlage@squid.umd.edu (S.M. Anlage).

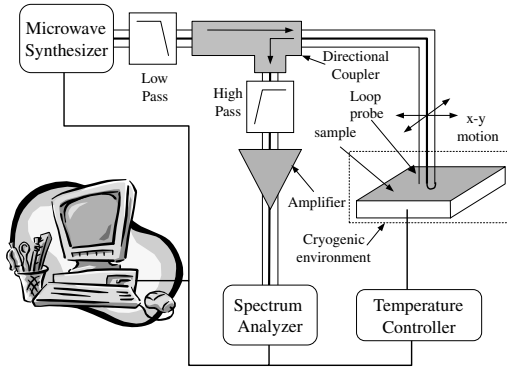


Fig. 1. System schematic (see Ref. [1] for details).

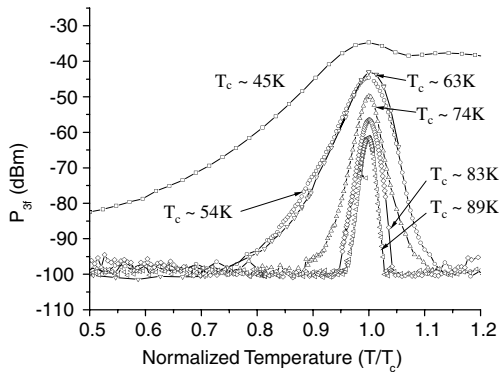


Fig. 2. $P_{3f}(t)$ of under-doped YBCO films versus normalized temperature.

The peaked behavior of $P_{3f}(T/T_c)$ near T_c is generally expected by all models of superconducting nonlinearity. Note the trend that $P_{3f}(T/T_c)$ gets stronger and broader around T_c as the samples are more under-doped (with one exception in Fig. 2). The strong persistence of P_{3f} above T_c in the under-doped materials is consistent with the observation of $\sigma_2 > 0$ above T_c in other under-doped materials [2].

3. Discussion

Using the algorithm described elsewhere [1], we can extract the $J_{NL}(T/T_c)$ which gives a model and system-independent means of quantifying the evolution of nonlinearity with temperature and doping. In Fig. 3, we present the extracted $J_{NL}(0.99T_c)$ at different doping levels from the P_{3f} data presented in Fig. 2, employing a doping-dependent penetration depth deduced from the literature [3].

Fig. 3 clearly shows a trend that the $J_{NL}(x, 0.99T_c)$ decreases with decreasing x . Here we consider an interpretation of $J_{NL}(x)$ in the context of GL theory, where it is the depairing critical current density $J_c(T)$. This critical

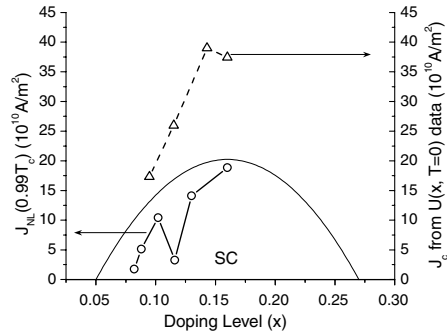


Fig. 3. Extracted J_{NL} at $0.99T_c$ of under doped YBCO films versus doping level (circles). Also shown is J_c deduced from condensation energy data $U(x)$ at $T = 0$ K (triangles).

current density should be on the scale of 10^{13} A/m² at an intermediate temperature range, consistent with our results. On the other hand, this quantity also relates to the condensation energy U of the superconductor through $J_c \sim H_c/\lambda$, and $U \propto H_c^2$, where H_c is the thermodynamic critical field, and λ is the GL magnetic penetration depth. According to the work of Luo et al. [4], $U(x)$ is peaked near optimal doping and decreases as the sample becomes under or over-doped. Taking the doping-dependent λ into consideration, we find the doping dependence of J_{NL} determined from our third order nonlinearity measurements is consistent with the $J_c(x, T = 0)$ deduced from the condensation energy results (Fig. 3).

We have measured the third harmonic response from HTSC thin films to study the local nonlinear mechanisms. We studied the trend of J_{NL} with doping level of the sample, and find that the samples are more nonlinear as they are under-doped. Our results are consistent with the doping dependent condensation energy U of YBCO.

Acknowledgements

This work was supported by NSF-GOALI DMR-0201261 the Maryland/Rutgers NSF MRSEC under DMR-00-80008, and NSF IMR under DMR-98-02756. We also thank Matt Sullivan for making the films, Ben Palmer for oxygen annealing and Greg Ruchti for supporting numerical calculations.

References

- [1] S.-C. Lee, S.M. Anlage, Appl. Phys. Lett. 82 (2003) 1893.
- [2] J.R. Waldram, D.M. Broun, D.C. Morgan, R. Ormeno, A. Porch, Phys. Rev. B 59 (1999) 1528.
- [3] C. Panagopoulos, J.R. Cooper, T. Xiang, Y.S. Wang, C.W. Chu, Phys. Rev. B 61 (2000) 3808.
- [4] J.L. Luo, J.W. Loram, J.R. Cooper, J. Tallon, Physica C 341–348 (2000) 1837.