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NONLINEAR MICROWAVE SWITCHING RESPONSE OF BSCCO SINGLE CRYSTALS

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Measurements of the surface impedance, Z_s, in $Bi_2Sr_2Ca_1Cu_2O_{8+\delta}$ single crystal with microwave currents flowing along the $\hat{c}$ axis show clear evidence of a step-like nonlinearity. The surface resistance switches between apparently quantized levels for microwave field strength changes of less than 1 mG. This non-linear response can arise from the presence of intrinsic Josephson junctions along the $\hat{c}$ axis of these samples driven by the microwave current.

The work described in this paper was motivated by a chance observation during the study of the microwave response of high quality $Bi_2Sr_2Ca_1Cu_2O_{8+\delta}$ (BSCCO) single crystals. While measuring the surface impedance, $Z_s(T)$, of these crystals, an unusual step-like switching feature was observed in the cavity resonances. (See Fig. 1) These effects are only observed in the presence of microwave currents induced along the $\hat{c}$ axis, and seem qualitatively consistent with the underdamped response of intrinsic Josephson junctions (JJs) in these samples.

The measurements are performed in a Nb cavity[1] operating in the TE_{011} mode at 10 GHz which is held at fixed temperature, $T \leq 4.2$ K. The sample sits on a sapphire rod at the center of the cavity so that its temperature can be varied independent of that of the cavity. The microwave field at the center of the cavity induces circulating microwave currents in the sample. By orienting the sample $\hat{c}$ axis $\parallel H_{rf}$ these currents flow entirely in the ab plane, while for $\hat{c} \perp H_{rf}$ current flows along the $\hat{c}$ axis as well as in the ab plane. All of the measurements reported here are for the latter geometry, and the $\hat{c}$ axis response dominates due to the large anisotropy.

The sample surface impedance, $Z_s = R_s + iX_s$, is typically determined from changes in the quality factor and resonance frequency of the perturbed cavity by $R_s = \Gamma(Q^{-1} - Q_b^{-1})$ and $\Delta X_s = \xi(f_b - f_0)$, where Γ and ξ are geometric

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factors, Q_b and f_b are the background Q and f_0. When the cavity resonance is Lorentzian, as is usually the case, f_0 is determined from the maximum of the peak, and the 3 dB (half power) width of the peak, Δf_{3dB}, gives $Q^{-1} = \Delta f_{3dB}/f_0$.

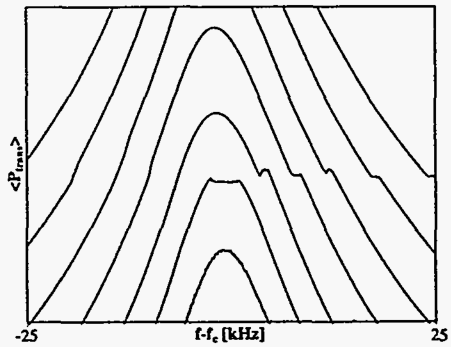

Figure 1: Typical non-linear response of BSCCO at 4 K presented for an 50 kHz frequency span centered at $f_c = 10.114738$GHz. The traces presented were taken in 3 dB increments of the input power.

Careful examination of the cavity resonances revealed clear step-like deviations from Lorentzian shape (See Fig. 1), and thus from linear response. At low input powers the resonance appears Lorentzian, and can thus be used with the ab plane results to extract the temperature dependence for the $\hat{c}$ axis alone.[2] An important feature of the data which can clearly be seen in Fig. 1 is the existence of a characteristic microwave power level at which the switching occurs, which stays constant over a wide range of input power.

When the cavity resonances are clearly no longer Lorentzian the usual relationships between the 3 dB bandwidth, quality factor Q and R_s cease to hold, and we must resort to other methods to relate the measurements to sample properties. We have developed a method[3] which relates the complex transmission through the perturbed cavity, S_{21}, directly to changes in surface impedance ΔZ_s of the sample.

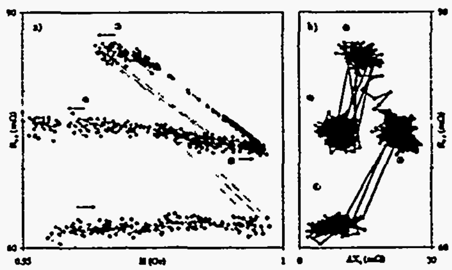

Figure 2: (a) $R_s(H_{rf})$ extracted from a resonance near $H_{rf\,switch}(4\text{ K})$ (b) $R_s(H_{rf})$ *vs.* $\Delta X_s(H_{rf})$

The results of our analysis applied to a resonance measured very near the initial onset of nonlinearities at 4 K is shown in Fig. 2a. The plot of R_s *vs.* H_{rf} shows that initially R_s is independent of H_{rf} as in the case of linear response, but an abrupt jump to increased dissipation occurs at a critical value of H_{rf}. This enhanced dissipation leads directly to the observed drop in H_{rf}. Interestingly the resistance almost appears quantized, being independent again of H_{rf} for $H_{rf} > H_{rf\,switch}$. The response is clearly hysteretic since the downward jump occurs at a different value of H_{rf}, giving rise to the observed asymmetry of the resonance. It is obvious that these features can only be quantitatively analyzed after the extraction of the R_s and X_s *vs.* H_{rf}. The changes in R_s are accompanied by simultaneous changes in X_s, as can be seen in Fig. 2b.

We were able to track $H_{rf\,switch}$ as a function of temperature (See Fig. 3) in a number of samples up to ~ 70 K where the signal strengths become too weak to clearly determine it. For a simple one junction model, one expects that $H_{rf\,switch} \propto 1/\lambda_c$, so for comparison $1/\lambda_c$ is presented on the right hand axis.

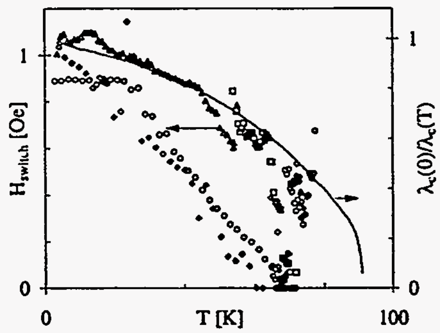

Figure 3: $H_{rf\,switch}(T)$, corresponding to the onset of nonlinearities. A line representing $\lambda_c(0)/\lambda_c$ with $\lambda_c(0) = 40\mu$m from a tunneling model are plotted on the right axis for comparison with single junction expectations.

$H_{rf\,switch} \sim 1$ Oe can be related to a critical current density by $J_c = H_{rf}/\lambda_c(T)$, where $\lambda_c(T)$ is the $\hat{c}$ axis penetration depth. Using $\lambda_c(0) \sim 40\mu$m, as estimated from fitting $\lambda_c(T)$ data to a tunneling model [2], we get $J_{c\,rf\,switch} = 200\,\mathrm{A/cm^2}$. This is well within the range obtained in mixed ac-dc experiments [4,5] with $70\,\mathrm{A/cm^2} \leq J_{c\,rf\,switch} \leq 1250\,\mathrm{A/cm^2}$ and corresponds to the value expected for optimally doped crystals with high T_c.

The *ab* plane critical current densities are much higher, $J_{c\,ab} \sim 7 \times 10^6$ A/cm^2.[6] The fact that similar switching behavior is not observed in our experiments when $H_{rf} \parallel \hat{c}$ (i.e. when only *ab* plane currents are induced) is entirely consistent with this large anisotropy in J_c.

The picture which emerges from these measurements is consistent with the previous results on BSCCO, being a highly anisotropic material composed of CuO_2 superconducting layers in the *ab* plane, coupled weakly along the $\hat{c}$ axis. The presence of JJs along the $\hat{c}$ axis is a distinct possibility and behavior consistent with this has also been observed in microwave emission and Shapiro step measurements in the presence of dc-currents. [7]

It is important to point out that the experiments described here differ from typical microwave experiments on JJs, in that we measure *dynamic* losses as a function of pure ac drive in the absence of any dc current or field bias. This problem has only recently begun to be studied on experiments in manufactured JJs and associated calculations. [9,8,10]

All of these consider the case of an overdamped nonlinear resistively shunted junction (RSJ), which does not seem to be able to describe our present data on

BSCCO, even qualitatively. The switching response and the rather complicated hysteresis observed may indicate that one needs to consider an underdamped junction for BSCCO, by inclusion of a mass term in the calculations. The equation ($\ddot{\phi} + \beta\dot{\phi} + \sin\phi = i_{\rm rf}\cos\omega t$) which arises has many complex solutions,[11] including regions of chaos, where such switching behavior may be observed. This distinguishes the nonlinearities observed in BSCCO from those observed in the *ab* plane of twinned YBCO single crystals[12] which do seem to be very well described by the overdamped RSJ model.[10] Overall, such nonlinear microwave response with JJ like behavior appears to be a characteristic intrinsic feature of the cuprates.

Acknowledgments

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