Observation of coherent Josephson response in the non-linear ab-plane microwave impedance of YBa$_2$Cu$_3$O$_{6.95}$ single crystals

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We report novel non-linear phenomena in the ab-plane microwave impedance of YBa$_2$Cu$_3$O$_{7-δ}$ single crystals. The $R_s$ vs. $H_{rf}$ data are well described by the non-linear RSJ model: $\dot{\phi} + \sin \phi = i_{rf} \cos \omega t$. The entire crystal behaves like a single Josephson junction. The extraordinary coherence of the data suggests an intrinsic mechanism.

We describe some striking observations associated with the microwave ab-plane response of high quality YBa$_2$Cu$_3$O$_{7-δ}$ crystals[1]. These result from our accidental observation that the microwave surface impedance $Z_s = R_s + iX_s$ of crystals is non-linear at very low applied microwave fields $H_{rf}$. The analysis[2] of the results implies that the entire crystal responds like a single Josephson junction to an ac drive current in the ab-plane.

Microwave experiments were carried out in a Nb cavity at 10 GHz with the microwave field $H_{rf} \parallel c$[3]. The $R_s$ vs. $H_{rf}$ ($\parallel c$) data in Fig. 1 shows a region of linear response at extremely low fields in which $R_s$ is independent of $H_{rf}$. The $T$-dependence of these high quality crystals is discussed in a separate publication[4]. As the microwave field $H_{rf}$ is increased, an onset of increased absorption is evident at a threshold value we call $H_{crit}$, which is about 200 mOe at low $T$ and decreases with increasing $T$. For further increase of $H_{rf}$ there is an overall parabolic rise of $R_s$, however there are definite jumps steps followed by plateaus at several values of the increasing $H_{rf}$. It should be noted that even at the highest field the overall change is very small and represents only a 50% increase of $R_s$. At 4.2 K, this overall change is still smaller by $10^3$ than the normal state value $R_n$.

Remarkably, a very simple model completely describes the essential features of the $R_s$ and $X_s$ data. Consider a resistively-shunted Josephson junction (RSJ). The junction phase $\phi$ obeys the dynamical “overdamped pendulum” equation $\beta^{-1}\dot{\phi} + \sin \phi = (i_{rf}/I_c) \cos \omega t$ where we consider a pure ac drive $i_{rf} \cos \omega t$, and $\beta = 2\pi I_c R/\hbar$. The RSJ equation is better analyzed in dimensionless form $d\phi/d\tau + \sin \phi = (i_{rf}/I_c) \cos \Omega \tau$, where $\tau = \beta t$, and $\Omega = \omega / \beta$. Unlike most junction mea-

Figure 1. Experimental data for $R_s$ vs. $H_{rf}$ at $T = 4.2 K$ for a YBCO crystal, and results (solid line) of numerical calculations using the non-linear RSJ model. The model results are displaced below the data for clarity.
measurements our experiments measure the dynamic ac impedance and not the dc I-V characteristics. The ac impedance can be calculated from the Fourier components at $\omega$ of the voltage $\delta$, $Z_\omega = R_\omega + iX_\omega = (\omega/2\pi R_f) \int_0^{\pi/\omega} e^{i\phi(t)} dt$. The result of numerical calculations for $R_\omega$ are also shown in Fig. 1 for $\Omega = \omega/\beta = 0.08$. All the features of the $R_\omega$ vs. $H_{fj}$ data are very well reproduced - the threshold rise and the occurrence of steps and plateaus for $i_{fj} > 1$.

From $\omega = 2\pi 10^{10} \text{rad/sec}$ and $\Omega = 0.08$, we deduce an $L/R$ product of $L/R = 0.3 mV$, remarkably close to those reported in the literature for fabricated Josephson junctions of YBCO. This value also implies that inertial effects associated with a $\phi$ term can only be observed at frequencies $\omega > \beta^{-1} \approx 125 GHz$.

The threshold value observed in Fig. 1 is $H_{crit} \approx 200 mOe$ at 4.2 K. This is an extremely low value compared to estimates of $H_{crit} \approx 250 Oe$ [3], even correcting by a factor of 10 for demagnetization, and hence cannot be associated with entry of Abrikosov vortices into the sample. Additional experiments have confirmed that trapped vortices are not responsible for the observed effect.

The excellent agreement between the experimental data and the very simple RSJ model strongly suggests that the entire macroscopic crystal behaves as a single Josephson junction.

The presence of "weak links" is well known to be responsible for the microwave response of ceramics but is less likely in crystals, even though they are twinned. However if defects are responsible, then they must respond in an extraordinarily coherent manner to account for the entire crystal responding like a single JJ, and this appears rather unlikely but cannot be ruled out.

The extraordinary coherence of the data in Fig.1 suggests the possibility that we are observing an intrinsic effect. Recently we have analyzed the linear response penetration depth $\lambda(T)$ and conductivities $\sigma_1(T)$ and $\sigma_2(T)$ of the same crystal [4], and observed new effects in the temperature dependence also. The $T$-dependent data suggest that a simple picture of a single order parameter (whether of $d$-wave or any other symmetry) is not correct, and instead there are at least two superconducting channels in $YBaCu_3O_7-\delta$.

The presence of multiple superconducting channels raises the possibility of coherent tunneling between them. The possibility of an "internal" or "bulk" Josephson effect in a two-band or two-gap superconductor has been suggested before [8-10]. In a multi-component superconductor an external current can induce a phase difference between the two order parameters and this could be responsible for the observed effects reported here.

Our experiment further suggests that magnetic fields penetrate at very low field strengths well below $H_{c1}$ in the form of fluxons even in high quality crystals. When the applied field is oscillating this leads to phase slip which we are able to observe as steps in the non-linear impedance data. Current relaxation at high frequencies takes place by this phase slip process and is responsible for the electrodynamic response at low applied fields and high frequencies.

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