Millimeter wave and microwave electrodynamic spectroscopy of $YBa_2(Cu_{1-x}Zn_x)_3O_y$ in the Meissner and mixed state

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Abstract

We performed the surface impedance measurement on almost optimally doped untwined $YBa_2(Cu_{1-x}Zn_x)_3O_y$ crystals under dc magnetic fields parallel to the $c-$axis, and determined the dependence of the vortex viscosity, η, and the pinning constant, κ_p on Zn concentration. Both η and κ_p changed dramatically from those of pure $YBa_2Cu_3O_y$ by 6%-Zn-doping. It can be explained by the strong overlap of the Zn potential and suppression of the amplitude of the superconducting(SC) order parameter caused by the pair-breaking effect of Zn. We also determined the relaxation time(RT) of quasiparticles(QP) in the vortex core, in the normal state, and in the Meissner state. It is suggested that the mechanism which determines the RT of the QP is different between outside and inside the vortex core. It is also suggested that RT of QP in the vortex core becomes smaller than in the normal state for the superconductors which have nodes in the SC gap.

Key words: vortex core; surface impedance; relaxation time

While the thermodynamic phase transition in the vortex system in the high-T_c superconductors have been made clearer by large amount of experiments, study of the dynamical aspect of the vortices have not been performed extensively, and remains a mysterious part to date. The dynamics of the vortex is closely related to the electronic state of the vortex core. The vortex viscosity, η, is represented as $\eta = \pi\hbar n\omega_0\tau_{\rm core}/(1 + (\omega_0\tau_{\rm core})^2)$ [1], where $\tau_{\rm core}$ is the relaxation time(RT) of the quasiparticles(QP) in the vortex core, n is the QP concentration and ω_0 is the cyclotron frequency at the upper critical field. To obtain information on the electronic structure in the mixed state, in this paper, we investigated the temperature and magnetic-field dependence of complex surface impedance, Z_s, for the almost optimally doped untwined $YBa_2(Cu_{1-x}Zn_x)_3O_y$(YBCZO)(x=0, 0.01, 0.06), and discussed the effect of Zn-doping on the electronic state in the vortex core.

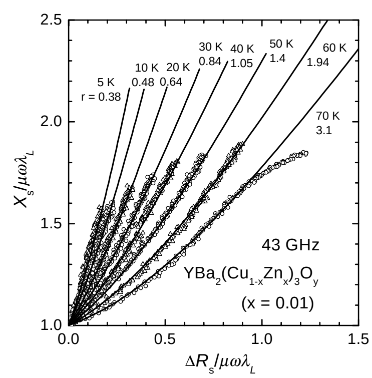

Fig. 1. Z_s data at 43 GHz(see the text for detail)

Single crystals of untwined YBCZO were almost op-

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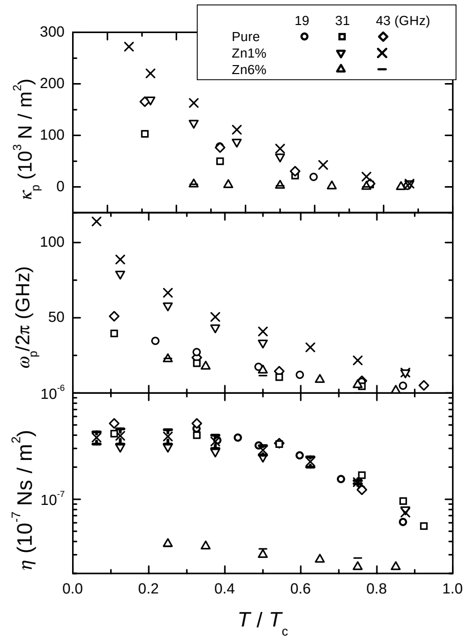

Fig. 2. Temperature dependence of (a)the viscosity, η, (b)the pinning frequency, ω_p, and (c)the pinning constant, κ_p.

timally doped with typical dimensions of $350 \times 300 \times 10$ μm^3. The critical temperatures, T_c's, were determined as 92 K for x=0, 80 K for x=0.01 and 20 K for x=0.06 by magnetization measurement.

The microwave surface impedance, $Z_s(= R_s + iX_s)$, where R_s and X_s are surface resistance and surface reactance, respectively, was measured by the cavity perturbation technique with a cylindrical oxygen free Cu cavity resonators operated at 19 GHz, 31 GHz and 43 GHz in the TE_{011}mode [2].

In Fig. 1, we show the $\Delta R_s/\mu\omega\lambda_\text{L}$ *vs.* $X_s/\mu\omega\lambda_\text{L}$ data, where λ_L is the penetration depth in zero magnetic-field at each temperature. The effective penetration depth $\tilde{\lambda} \equiv Z_s/\mu\omega$ is expressed simply as[3]

$$\frac{\tilde{\lambda}^2}{{\lambda_\text{L}}^2} = \left(1 + \frac{r}{1+r^2}b\right) - i\left(\frac{r}{1+r^2}b\right) \quad (1)$$

where $b = \phi_0 B/(\mu\omega{\lambda_\text{L}}^2\eta) \equiv B/B_\eta, r = \omega\eta/\kappa \equiv \omega/\omega_p$, ω_p is pinning frequency, and κ_p is pinning constant. By fitting the data to Eq. (1) given by the solid lines in Fig. 1, we can determine r which gives ω_p. Then, using the obtained r value, and fitting $Z_s(B)$ data to Eq. (1), we can determine B_η, which, in turn, gives η [2].

In Fig. 2, we showed the temperature dependence of the obtained η, ω_p, and $\kappa_p(\equiv \eta\omega_p)$. It is remarkable that for the x=0.06 sample, both η and κ_p change dramatically from those of x=0, whereas 1%-Zn-doping did not change them largely. It can be explained as follows. In the x=0.06 sample, there are strong overlap of the Zn potential and suppression of the amplitude of SC order parameter caused by pair-breaking effect of Zn because of high Zn concentration. As a result, dependence of the energy of a vortex on the position becomes weaker, and quasi free flux flow state might realize. Zn concentration x=0.01 is still too high to pin the vortex more effectively than the x=0 sample.

Table 1
The value of τ_norm, τ_Meis and τ_core for each Zn concentration.

	Zn0%	Zn1%	Zn6%
$\tau_\text{norm}(s)$	$\sim 2 \times 10^{-13}$	$\sim 2 \times 10^{-13}$	-
$\tau_\text{meis}(s)$	$\sim 10^{-11}$	$\sim 10^{-13}$	-
$\tau_\text{core}(s)$	$\sim 10^{-14}$	$\sim 10^{-14}$	$\sim 10^{-15}$

In table I, we show τ_core derived from η. We also show RT of QP in the Meissner state, τ_Meis, and in the normal state, τ_norm, derived from the analysis based on two-fluid model. It is interesting that the change of τ_Meis caused by 1%-Zn-doping is larger than the change of τ_core. These suggests that the mechanism which determines the RT of QP is different between outside and inside the vortex core. It is also interesting that τ_core is shorter than τ_norm, which means that there is more scattering for QP in the vortex core than for QP in the normal state. We consider this extra shortening of τ_core is a general property of superconductors which have nodes in the superconducting(SC) gap, taking account of the fact that the magnetic field dependence of the free flux flow resistivity is always larger than the value expected from the normal core model[4] in $\text{YNi}_2\text{B}_3\text{C}$[5] and UPt_3[6] which have anisotropic SC gap with nodes.

In conclusion, Z_s was studied in almost optimally doped untwined YBCZO crystals under dc magnetic fields parallel to the $c-$axis, and determined the dependence of η and κ_p on the Zn concentration. Both η and κ_p changed dramatically in 6%-Zn-doped sample, while in 1%-Zn-doped sample, it did not change them largely. It can be explained by the strong overlap of the Zn potential and suppression of the amplitude of SC order parameter caused by pair-breaking effect of Zn. We also determined τ_core, τ_norm and τ_Meis. It is suggested that the mechanism which determines the RT of QP is different between outside and inside the vortex core. It is also suggested that τ_core becomes smaller than τ_norm in the superconductors which have nodes in the SC gap.

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