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MICROWAVE CONDUCTIVITY OF THIN YBCO FILM IN MAGNETIC FIELD

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Dedicated to Professor Boran Leontić on the occasion of his 70$^{\mathrm{th}}$ birthday

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The microwave response of a thin film of high temperature superconductor $YBa_2Cu_3O_{7-\delta}$ was measured for a wide region of temperatures and magnetic fields. From the measured complex frequency shift, the complex conductivity was calculated. The model for effective conductivity in the mixed state was fitted to the complex conductivity data and the values of upper critical fields $B_{c_2}(T)$ and depinning frequencies $\omega_0(T)$ have been obtained as fitted parameters.

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1. *Introduction*

Measurements of the microwave response can be very important in the study of superconductors. From this type of measurements one can extract the complex conductivity which is an intrinsic property of superconductors. In the Meissner state of classical superconductors, for microwave frequencies lower than the superconducting gap ($\hbar\omega < 2\Delta$), the only contribution to the real part σ_1 of the complex conductivity $\widetilde{\sigma}$ arises from thermally activated quasipartical excitations, while the imaginary part σ_2 determines the superconducting penetration depth. In the case of high temperature superconductors (HTSC), microwave measurements gave the first evidence of the existence of nodes in the pairing states [1], thus indicating that the superconducting gap has no longer the symmetry of an isotropic s-wave.

When a DC magnetic field is applied, driving a type-II superconductor into the mixed state, unpaired electron states are excited in the vortex cores in addition to those thermally excited in the bulk. These unpaired states give a remarkable rise to the real part of the microwave conductivity. The contribution of the vortices to the complex conductivity depends on whether they are pinned or not. There is a characteristic frequency, the so called depinning frequency ω_0, above which the vortices are practically in the flux flow regime, i.e. for such high microwave frequencies the viscous drag force exceeds the pinning force. For classical type-II superconductors, the depinning frequency is lower than 100 MHz [2], and one can consider the vortices at all microwave frequencies to be in the flux-flow regime. On the contrary, HTSC have been reported to have depinning frequency in the microwave region [3] and it is, therefore, very important to investigate the microwave response of HTSC in the mixed state, giving valuable information about the vortex dynamics.

In this paper we present temperature and magnetic field dependent microwave response measurements on a thin YBCO film, giving the upper critical fields and depinning frequencies of the sample.

2. *Experimental*

The investigated sample was an epitaxially grown, c-axis oriented, $YBa_2Cu_3O_{7-\delta}$ film on MgO substrate. The film thickness was 200 nm, grown on the substrate whose thickness was 0.5 mm [4]. For the purpose of measurements, we have cut a piece of the film of area 1 mm $\times$3 mm.

The sample was placed on a sapphire rod in the centre of a cylindrical microwave cavity operating in the TE_{111} mode at 9.28 GHz. The longest side of the sample (ab-plane) was oriented along the microwave electric field at the position of its maximal strength. The c-axis of the sample was parallel to external DC magnetic field.

Microwave response was measured in terms of the complex frequency shift

$$\frac{\Delta\widetilde{\omega}_p}{\omega} = \frac{\Delta f_p}{f} + \mathrm{i}\Delta\left(\frac{1}{2Q_\mathrm{p}}\right) \ , \tag{1}$$

where $f_p = \omega_p/2\pi$ and Q_p are the frequency and Q-factor, respectively, of the cavity loaded with a perfect conductor of the same geometry [5].

The Q-factor was measured by using frequency modulation of the microwaves about resonant frequency. The modulation was in the audiofrequency range so that the signal could be detected first in the microwave detector, and the output then analysed by a lock-in detector at the modulation frequency and its second and fourth harmonics [4]. The value of the modulation depth was adjusted to be less than the half width of the Lorentzian line. The output of the lock-in detector at the modulation frequency was minimized by automatic adjustment of the klystron frequency to the centre of the Lorentzian line. This provided the means of measuring the frequency shift by a microwave counter.

3. Results and discussion

The temperature dependence of the complex frequency shift in the absence of DC magnetic field is shown in Fig. 1. The sharp minimum in $\Delta f/f$ just below T_c is characteristic for samples thinner than normal-state skin depth, placed in a microwave electric field [5].

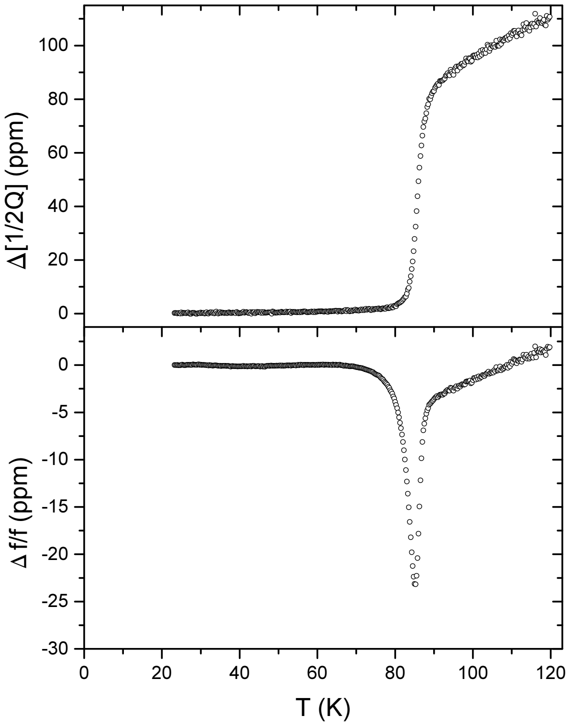

Fig. 1. Zero field temperature dependence of the imaginary and real parts of the complex frequency shift $\frac{\Delta\widetilde{\omega}}{\omega} = \frac{\Delta f}{f} + \mathrm{i}\Delta\left(\frac{1}{2Q}\right)$ *for a thin film* $\mathrm{YBa_2Cu_3O_{7-\delta}}$ *on* MgO *substrate.*

The extraction of complex conductivity from thin film data should be carefully conducted. The complex frequency shift for a superconductor of an arbitrary thickness is given by

$$\left(\frac{\Delta f_\mathrm{p}}{f}\right) = -2\frac{\mu_0 H_{\|\mathrm{e}}^2 V_\mathrm{s}}{W_\mathrm{cp}}\left[\frac{\frac{\lambda_1}{d}\sinh\left(\frac{\lambda_1}{|\widetilde{\lambda}|^2}d\right) - \frac{\lambda_2}{d}\sin\left(\frac{\lambda_2}{|\widetilde{\lambda}|^2}d\right)}{\cosh\left(\frac{\lambda_1}{|\widetilde{\lambda}|^2}d\right) - \cos\left(\frac{\lambda_2}{|\widetilde{\lambda}|^2}d\right)}\right], \tag{2}$$

$$\Delta\left(\frac{1}{2Q_{\rm p}}\right) = 2\frac{\mu_0 H_{\parallel {\rm e}}^2 V_{\rm s}}{W_{\rm cp}} \left[\frac{\frac{\lambda_2}{d}\sinh\left(\frac{\lambda_1}{|\widetilde{\lambda}|^2}d\right) + \frac{\lambda_1}{d}\sin\left(\frac{\lambda_2}{|\lambda|^2}d\right)}{\cosh\left(\frac{\lambda_1}{|\widetilde{\lambda}|^2}d\right) - \cos\left(\frac{\lambda_2}{|\widetilde{\lambda}|^2}d\right)} \right], \tag{3}$$

where d is the sample thickness, and $\widetilde{\lambda} = \lambda_1 - {\rm i}\lambda_2$ is the complex penetration depth [5]. These relations are approximations which neglect minor effects of the substrate on the field solutions in the superconductor. The relation between the complex penetration depth $\widetilde{\lambda}$ and the complex conductivity $\widetilde{\sigma} = \sigma_1 - {\rm i}\sigma_2$ is given by

$$\lambda_{1,2} = \sqrt{\frac{|\widetilde{\sigma}| \pm \sigma_2}{2\mu_0\omega|\widetilde{\sigma}|^2}}, \tag{4}$$

thus giving, together with (2) and (3), the relation between $\Delta\widetilde{\omega_p}/\omega$ and $\widetilde{\sigma}$. If the sample were thick, the expressions in brackets of relations (2) and (3) would reduce to λ_1/d and λ_2/d, respectively, and the values of σ_1 and σ_2 could be analytically extracted. In the case of a thin film, however, the extraction should be done numerically. The curves in Fig. 1 were given offsets so that the extrapolations to zero temperature are consistent with zero absorption and London penetration depths of 140 nm. The Newton-Raphson method [6] was used for the extraction of σ_1 and σ_2. The results are shown in Fig. 2. One can note the strong growth of σ_1 below $T_{\rm c}$ which could not be ascribed to the BCS coherence peak. Similar data have been observed in good single crystals [7]. The growth in σ_1 was ascribed to the growth of scattering time for the quasiparticle excitations, probably due to the opening of

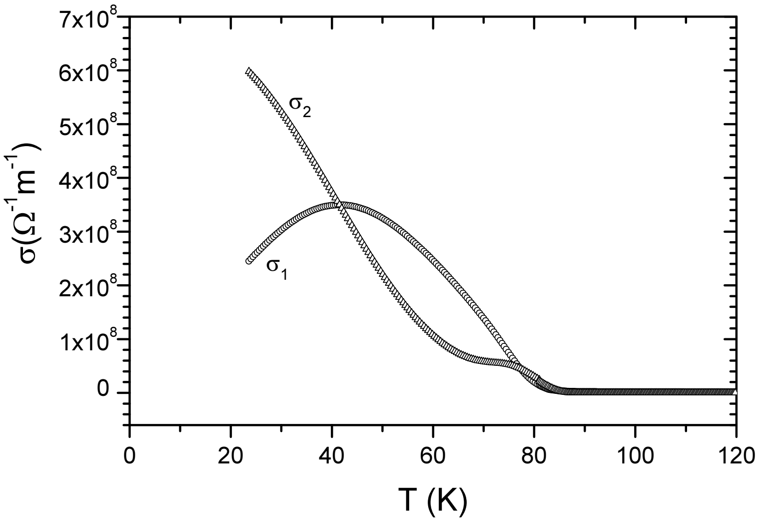

Fig. 2. The real (σ_1) and imaginary (σ_2) parts of the complex conductivity extracted from the data in Fig. 1.

a spin gap, which is still a question of debate. Just above T_c, the real part of the conductivity was close to $1 \times 10^6\ \Omega^{-1}\mathrm{m}^{-1}$, which appears negligible on the scale of Fig. 2.

Much more interesting experimental data have been obtained by imposing a DC magnetic field on the sample. For a given temperature, the magnetic field was swept and the complex frequency shift was measured. The curves for some of the temperatures are shown in Fig. 3. There was no hysteresis in sweeping the magnetic field up and down. This is consistent with the demagnetizing effect in the geometry of a magnetic field which is perpendicular to a thin film.

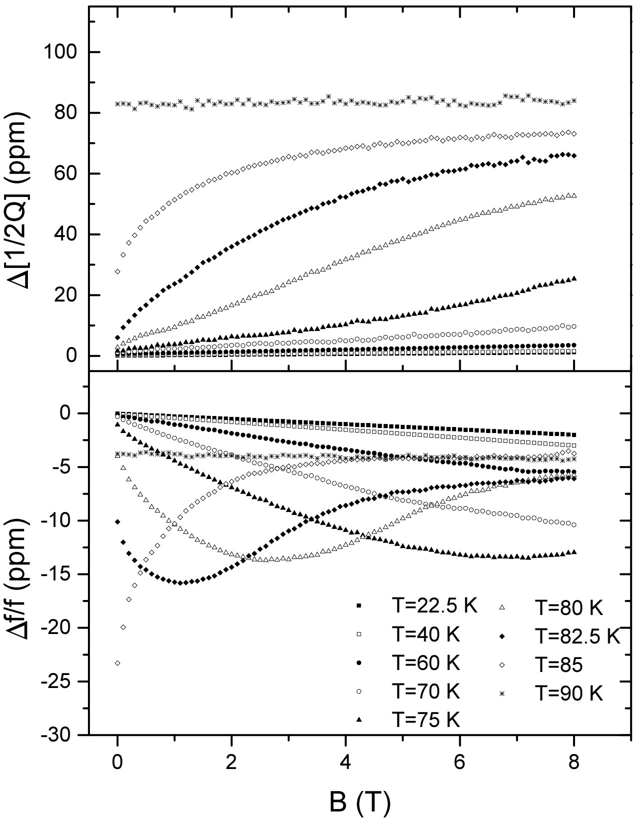

Fig. 3. Magnetic field dependence of the imaginary and real parts of the complex frequency shift at various temperatures.

From the data on the complex frequency shift, the complex conductivity can be numerically obtained for every point in the field-temperature space. The obtained field dependence of the complex conductivity can be successfully modelled using the effective conductivity approach for the mixed state, as described by Dulčić and Požek [8]. According to the model, the effective complex conductivity $\widetilde{\sigma}_{\text{eff}}$ in the mixed state is given by

$$\frac{1}{\widetilde{\sigma}_{\mathrm{eff}}} = \frac{1 - b\left(\dfrac{v}{v_{\mathrm{f}}}\right)}{(1-b)(\sigma_1 - \mathrm{i}\sigma_2) + b\sigma_{\mathrm{n}}} + \frac{b}{\sigma_{\mathrm{n}}}\left(\frac{v}{v_{\mathrm{f}}}\right) , \qquad (5)$$

where $b(T) = B_{\mathrm{dc}}/B_{\mathrm{c}_2}(T)$ is the reduced field, $B_{\mathrm{c}_2}(T)$ is the upper critical field, $\sigma_1(T) - \mathrm{i}\sigma_2(T)$ is the complex conductivity of the Meissner state, and $\sigma_{\mathrm{n}}(T)$ is the normal state conductivity in the vortex core. The ratio of the actual vortex velocity v to the maximum velocity v_{f} in the flux flow regime is given by [2]

$$\frac{v}{v_{\mathrm{f}}} = \frac{1 + \mathrm{i}(\omega_0/\omega)}{1 + (\omega_0/\omega)^2} , \qquad (6)$$

where ω_0 is the depinning frequency.

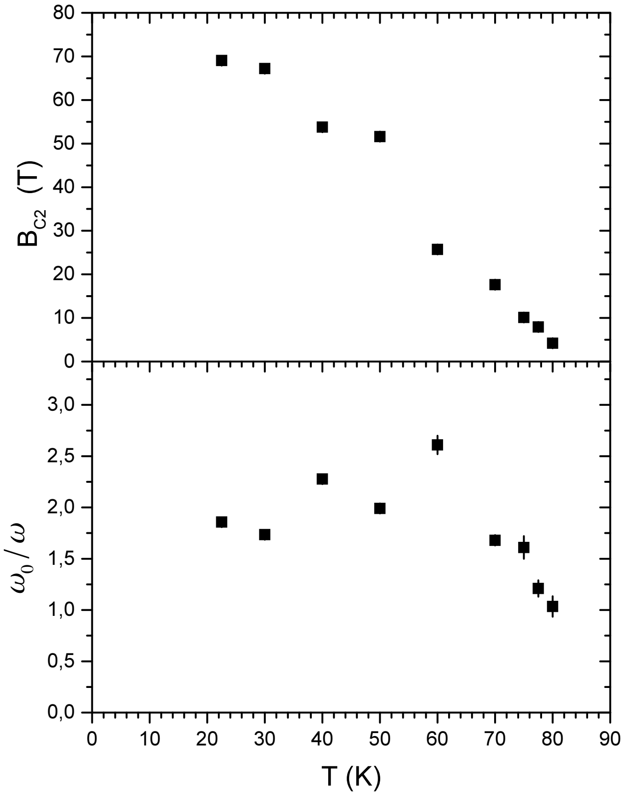

Fig. 4. The upper critical field $B_{\mathrm{c}_2}(T)$ and the ratio of the depinning frequency $\omega_0(T)$ to the measurement frequency $\omega = 2\pi \times 9.28$ GHz, obtained as the best fit parameters for the curves in Fig. 3.

For each measured temperature, we have fitted the field dependence of $\widetilde{\sigma}_{\text{eff}}$ from Eq. (5) to the measured conductivity. The parameters $\sigma_1(T)$ and $\sigma_2(T)$ have been taken from the zero-field measurements (Fig. 2), and $\sigma_n(T)$ is the extrapolated value of the normal state conductivity above T_c. The parameters B_{c_2} and ω_0 have been left as fit parameters. The real and imaginary parts of $\widetilde{\sigma}_{\text{eff}}$ have been fitted simultaneously, i.e., the two experimental curves have been fitted by only two free fit parameters. The best fit parameters $B_{\text{c}_2}(T)$ and $\omega_0(T)$ are plotted in Fig. 4.

One can notice that we have extended the determination of the upper critical field to considerably lower temperatures in comparison to the previous measurements on a single crystal [9]. The upper critical fields up to 70 T have been determined, although the field range used in the measurements was only up to 8 T. For temperatures above 80 K, the fitting procedure could not give satisfactory results. This is an indication of the fluctuation regime for which our mean-field model for the mixed state does not apply. One can notice that the mean-field B_{c_2} vanishes at $T \approx 84$ K. It was shown earlier that the mean-field T_c can be equally well determined by the temperature dependence of B_{c_2} and/or by the critical scaling of the data in the fluctuation regime [9, 10]. By comparison of Figs. 1 and 4, one can conclude that the mean field T_c corresponds to the minimum in the real frequency shift and to the T_c defined as the half absorption in the plot of $\Delta(1/2Q)$.

The lower part of Fig. 4 shows that depinning frequency for the measured thin film actually lies in the region 10 – 30 GHz, thus confirming the initial assumption that microwave frequencies are characteristic for vortex dynamics in HTSC. Although the depinning frequency decreases slightly above 60 K, it does not vanish up to 80 K, showing that the vortex lattice remains rigid and strongly pinned in practically the whole of the superconducting region.

4. *Conclusions*

We have examined the microwave response of a superconducting YBCO thin film in magnetic fields up to 8 T and at temperatures down to 20 K. Both the real and imaginary parts of the complex frequency shift were measured, enabling the determination of both the real and imaginary parts of the complex conductivity in the field-temperature space. The zero-field complex conductivity shows the behaviour characteristic of good single crystals, indicating that our thin film sample is suitable for determination of intrinsic properties.

From the measured field dependences, the upper critical fields up to 70 T have been determined, extending the $B_{\text{c}_2}(T)$ curve down to 20 K. The values of B_{c_2} are slightly lower than those usually reported in the literature, but still reasonable for a thin-film sample. From the $B_{\text{c}_2}(T)$ curve, the mean-field T_c is estimated to be 84 K although the onset of superconductivity occurs above 88 K, indicating the wide temperature region of fluctuations.

The depinning frequencies were also determined for the measured temperatures. They are larger than 10 GHz in the whole temperature region, in agreement with the observations of Golosowsky et al. [3].

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MIKROVALNA VODLJIVOST TANKIH LISTOVA YBCO U MAGNETSKOM POLJU

Mjerili smo mikrovalni odziv tankog filma visokotemperaturnog supravodiča $YBa_2Cu_3O_{7-\delta}$ u širokom području temperatura i magnetskih polja. Iz izmjerenog kompleksnog frekventnog pomaka izračunali smo kompleksnu vodljivost. Numeričkom prilagodbom modela efektivne vodljivosti u miješanom stanju odredili smo vrijednosti gornjeg kritičnog polja $B_{c_2}(T)$ i frekvencije opuštanja $\omega_0(T)$.