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Impedance properties and microwave magnetic field dependence of surface resistance of YBaCuO

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The microwave magnetic field H_ω dependence of the surface resistance R_s for a $YBa_2Cu_3O_{7-\delta}$ ceramic and thin film has been studied in 8 mm wave band. It is shown that for the film one of mechanisms consistent with the obtained dependence $R_s(H_\omega)$ may be microwave-induced flux motion. For the ceramic specimen, the above dependence is in agreement with the model of Sridhar for the nonlinear high-frequency response of a planer superconductor in a current-induced critical state and with Gurevich's theory of the nonlinear dynamics of vortices in high-J_c overdamped Josephson contacts. An approach was applied which allows us to perform measurements without preliminary patterning of the samples.

1. Introduction

Microwave surface impedance Z_s measurement of the superconductors is a powerful tool for study of the mechanisms of interaction of the materials with electromagnetic fields. For these purposes, exploring the response to elevated microwave irradiation is quite an effective approach, as it allows us to intensify the dissipation processes and make them to be easier observable.

Up-to-date nonlinear theories usually treat particular states of the materials and are not always consistent. The weakly coupled grain model, previously formulated by Hylton et al. [1], has been modified for the nonlinear regime by Attanasio et al. [2] and by Chin et al. [3]. It treats the Meissner state of a medium, consisted of superconducting grains connected via Josephson (J) contacts, and predicts for both real R_s and imaginary X_s parts of the Z_s quadratic dependence on the magnetic field H_ω. A theory of Halbritter [4], in addition to the Meissner phase, also considers J vortices penetration into the weak links (WL) and the vortex motion which leads to linear or sublinear behavior of R_s with H_ω depending on the state of the vortices (pinning or flux-flow). Portis [5] considers HTSC as a transmission-line network and distinguishes five regimes for the magnetic flux state. These are also characterized by either linear or sublinear dependence of Z_s on H_ω. Lately, Sridhar [6] has extended the critical state model for description of the nonlinear microwave impedance of superconductor in the form of a cylindrical wire and a rectangular strip. For the strip geometry, which is mostly close to the experiments on thin films in parallel ac magnetic field, dependence of R_s (and X_s) on H_ω has the form $R_s = aH_\omega^2 + bH_\omega^4$. Gurevich [8] has treated the dynamics of Abrikosov's vortices with a Josephson core in high-J_c J-contacts, which could model coherent planar crystalline defects (twins, stacking faults, low-angle grain boundaries etc.). The resulted mean power dissipated by the oscillating vortex is represented by a linear combination of complete elliptic integrals as a function of H_ω^2.

The lack of a proper understanding of the nonlinear microwave properties of HTSC is partially connected with a small number of experimental works in this field, which in turn is caused by the unavailability of high microwave power generators, especially in the millimeter wave band. The stripline resonators, which easily allow us to achieve large H_ω, have an extremely non-uniform field distribution. In addition, patterning of the samples leads to a weakening of the superconducting properties at the edges of the strip, where the H_ω has a sharp peak. The points mentioned above make analysis of the obtained results difficult.

We present here the results of the investigation of the microwave magnetic field dependence of surface resistance R_s for a $YBa_2Cu_3O_{7-\delta}$ ceramic and thin film in 8-mm wave band. A technique was used which permitted us to carry out the measurements of unpatterned samples. This allows us to exclude the impact of the treatment defects upon resulting behavior of the surface impedance.

II. Samples and experimental equipment

An epitaxial YBaCuO thin film of 300 nm thickness was deposited directly onto the quasioptical dielectric resonator (QDR) [9] in the form of a disk from $LaAlO_3$. The transition width $\Delta T = 1.3$ K from dc measurements and $T_{c0} = 89$ K. X-ray studies have shown that the film consisted of small-size grains connected via a large number of WL. A layer of the film near the substrate was mostly c-axis oriented, although the remainder of the film has the c axis tilted to the plane of the substrate. The YBaCuO ceramic sample has been prepared as a target for thin films deposition. The superconducting powder was strongly pressed into a disk-shaped form with a diameter 16 mm with 300 μm thickness. The critical temperature (about 93 K) and the transition width ($\Delta T \sim$ 1–1.5 K) were determined by the radio-frequency (rf) inductive technique. R_s of the ceramic at 77 K was about 100 mOhm at 35 GHz, which is only about three times worse than R_s of OFHC copper at this temperature (see Fig. 1).

A block-diagram of the experimental set-up consists of three channels: two microwave ($\sim$ 35 GHz) and a radiofrequency channel ($\sim$ 9 MHz). Microwave circuit makes use of QDR, which has multimode equidistant spectrum and allows us to use two different resonances at frequencies of probe and pump microwave signals. The peak microwave magnetic field at the surface of the sample was estimated to be $\sim$ 10 Oe.

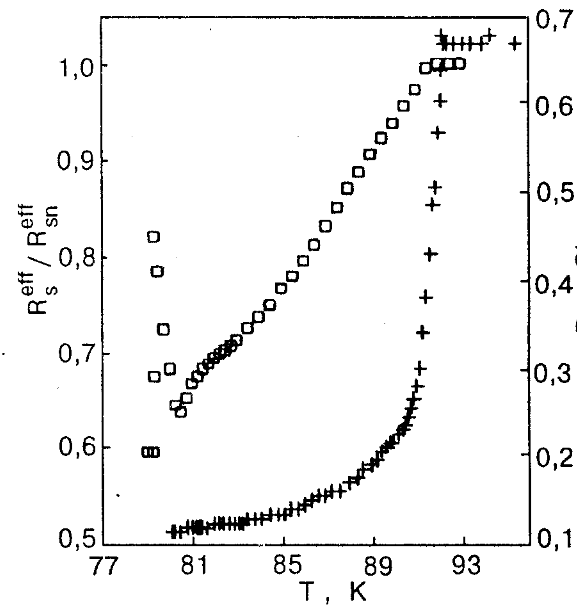

Fig. 1. Temperature dependence of the microwave surface resistance for YBaCuO ceramic (+), and the effective surface resistance normalized by the normal state value for YBaCuO thin film on $LaAlO_3$ (□) substrate (resonator).

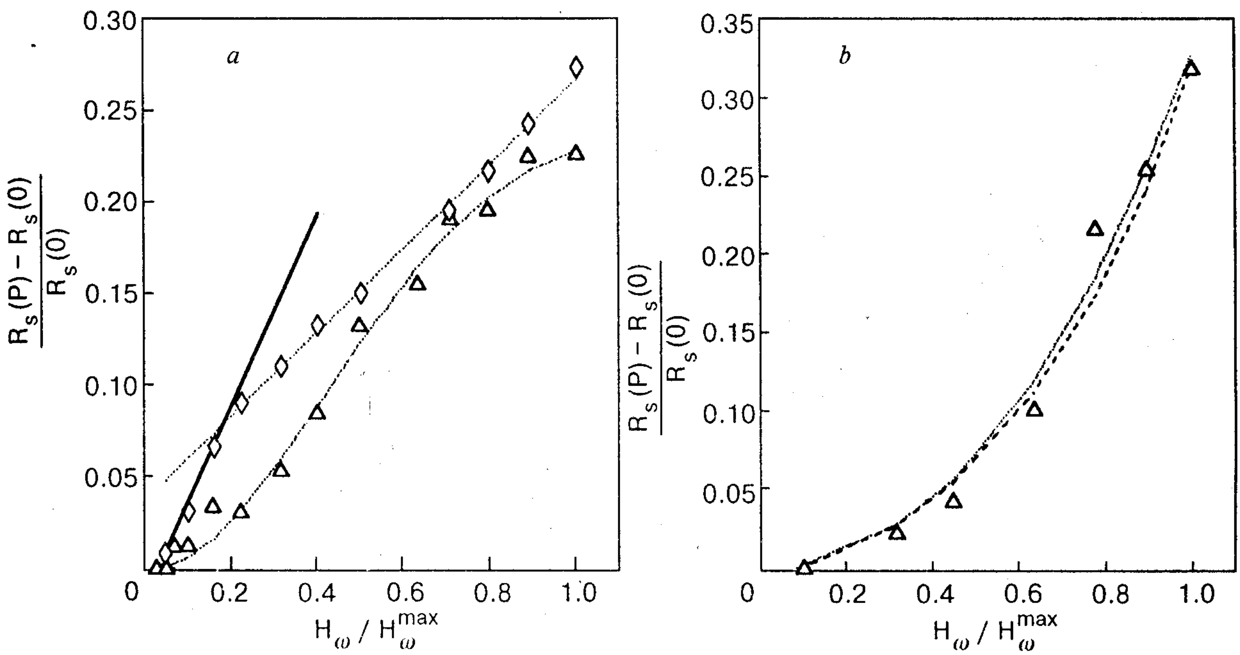

Fig. 2. Microwave magnetic field H_ω ($H_\omega^{max} \sim 10$ Oe) dependence of R_s normalized by its value at minimum irradiation amplitude ($H_\omega < 0.3$ Oe): *a*) for the film: at 87.5 K (△) and 88.9 K (◇) and their approximation by Eq. (1) and Eq. (2) (solid and dashed lines); *b*) for the ceramic: △ — experimental data; dotted and dashed curves are approximations using Sridhar's and Gurevich's theories, respectively.

III. Experimental results and discussion

The surface resistance depends exponentially (see Fig. 2,*a*) on squared magnetic field amplitude:

$$R_s(H_\omega) = R_{s0}(1 - \alpha \exp(-H_\omega^2/H_{\omega c}^2)) \qquad (1)$$

at low temperatures (about 10 K lower the critical temperature T_c) and this dependence turns into one consisting of two linear regions with different slopes

$$R_s(H_\omega) = R_{s0}(1 + \alpha H_\omega) \qquad (2),$$

(see Fig. 2,*a*) at temperature close to T_c. Here R_{s0}, α and $H_{\omega c}$ are constants. These relations are found empirically and written under the assumption that microwave power $P_\omega \sim H_\omega^2$. In accordance with Ref. 4 a linear behavior of R_s with $H_{\omega c}$ is characteristic for a regime of J-vortex penetration into WL and the vortex motion both in process of flux creep and flux flow. Here, the dependence in the latter case may be both linear (with a slope reduced as compared with that for the pinning regime) and sublinear in fields $H_\omega > H_{sat}$, where H_{sat} is the saturation field. It should be also emphasized that in a weak dc magnetic fields H (< 150 Oe) R_s is practically independent of H within the experimental accuracy.

It's well known that at temperatures close to T_c thermally activated flux motion may significantly affect high frequency dissipation. In accordance with Anderson-Kim theory [10], the magnetization decreases in time logarithmically after magnetic field removal due to flux creep and so does the surface resistance [11]:

$$R_s(t) = R_s(t{=}0^+)\left(1 - \frac{k_B T}{U}\ln t/\tau\right)^{1/2} =$$

$$= R_s(t{=}0^+)\left(1 - \frac{k_B T}{2U}\ln t/\tau\right), \qquad (3)$$

where $R_s(t{=}0^+)$ is a value measured immediatly after the field is removed; U is the thermal activation energy; τ is a characteristic time. It is obvious, that in a case when a strong microwave field leads to vortex nucleation (in WL), one should observe an exit of the vortices from a superconductor after the field is removed, owing to the flux creep. Experimental dependence of $R_s(t)$ was found to behave linearly with logarithm of time t, what is a characteristic feature of the flux creep process. A value of U extracted from the dependence $R_s(t)$ is estimated to be of the order of 0.08–0.2 eV which is consistent with data in literature (see, e.g., [11]).

The results of the R_s dependence on the microwave magnetic field H_ω are presented in Fig. 2,*b*. The dotted line corresponds to the best least-square fit to the data by the following law:

$$\frac{\Delta R_s}{R_s(0)} \equiv \frac{R_s(P) - R_s(0)}{R_s(0)} = aH_\omega^2 + bH_\omega^4, \qquad (4)$$

where a and b are constants. Such behavior has been predicted by Sridhar [6] for stripline geometry with a rectangular cross-section. According to the theory for the superconducting strip, R_s in the critical state is described by Eq. (4) with $b/a = 2/5$. One can note that the calculated curves agree well with the experimental points. However, the theory describes the hysteretic ac response of a current carrying strip, for which the critical state may be valid for frequencies $< 10^9$ Hz. This estimation was made by Sridhar, proceeding from the maximum vortex velocity, but it seems to be inconclusive, because other experimental works indicate that the depinning frequency for HTSC may be as high as 40 GHz [7]. The dashed curves in Fig. 2,*b* represent a fit by Gurevich's theory [8] for a moving Abrikosov's vortex with J-core (AJ vortex). Such vortices are formed in overdamped high-J_c J-junctions when $\lambda_j(J_c) < \lambda$, where λ_j and λ are Josephson and London penetration depths, respectively. The oscillation of AJ vortex driven by ac current of large amplitude is followed by a mean dissipated power, described as

$$Q = Q_0[K(\beta_0^2) - E(\beta_0^2)], \qquad (5)$$

where $Q_0 = \Phi_0 J_c c^2 R/4(\pi\lambda)^2$; Φ_0 is the flux quantum; J_c is the critical current density; R is the sheet resistance of J contact; $K(\beta_0^2)$ and $E(\beta_0^2)$ are complete elliptic integrals of first and second kind, respectively, $\beta_0 = J_\omega/J_c$. One can see that both models give good agreement with the experimental data. It is not clear, however, how a ceramic may possess high-J_c contacts. If we pay attention to the fact that there is no observable dependence of R_s on H_ω for the ceramic up to temperatures close to the transition, and only small relative increase of R_s with dc magnetic field, we may suppose that, in addition to extrinsic WL such as defects, pores etc., which are easily damped by a small magnetic field, there exist an ac current passing through the direct contacts between grains. Such contacts may be formed by oxygen-deficient layers at the surface of grains and behave as high-J_c WL. This possibility is confirmed by very sharp superconducting transition, the small effect of dc magnetic field on the R_s, the valve of R_s, which is very low for ceramics, and the R_s independence of H_ω up to temperatures close to T_c.

In addition, we have examined temperature dependence of J_c of the ceramic using a well known procedure [13] and the theory of Clem and Sanchez [12]. This dependence shows that, at T higher than about 92 K, predominant character of WL is *SNS*, which proves our assumption that the observed nonlinear behavior of R_s seems to be connected with high-J_c junctions, which may be formed by direct contacts between grains or by intragrain defects. At lower temperature we clearly observe a linear behavior of J_c on T, which is evidence for *SIS* type WL. We should also stress, that in the low temperature range, we have not observed a nonlinear behavior of the R_s even at maximum available microwave power.

IV. Conclusion

The impedance measurement that have been performed have shown that the YBaCuO film seems to contain a large amount of defects, which leads to a high residual surface resistance, whereas the ceramic sample investigated, having much lower R_s (~ 120 mOhm) and a much steeper superconducting transition, appears to be a more perfect sample than the film. The conclusion was inferred that the main mechanism of the dissipation for the film is microwave-induced flux motion of Josephson vortices within weak links with poor superconducting properties. At the same time the nonlinear behavior of R_s observed for the strongly pressed YBaCuO ceramic is consistent with both the nonlinear current-induced critical state model of Sridhar and the nonlinear electrodynamics of vortices in high-J_c Josephson contacts developed by Gurevich. This proves that the dependence $R_s(H_\omega)$ for the ceramic, which is observed only near the superconducting transition region, is probably connected with J- or AJ-vortices motion within high-J_c Josephson WL either intragrain ones or those, formed by direct contacts between grains.

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