Edge barrier manifestation in the nonlinear microwave response of thin YBaCuO films

M. R. Trunin[1)] and A. A. Zhukov
Institute of Solid-State Physics, Russian Academy of Sciences, 142432 Chernogolovka, Moscow Region, Russia

(Submitted 20 April 1995; resubmitted 16 May 1995)
Pis'ma Zh. Éksp. Teor. Fiz. **62**, No. 1, 39–44 (10 July 1995)

The initial cubic-law regime $H_{3\omega} \propto H_\omega^3$ in the amplitude dependence of the third harmonic $H_{3\omega}(H_\omega)$ was found to change when the microwave field H_ω perpendicular to the surface of the YBaCuO film reached the value H_ω^*. The observed dependences $H_\omega^* \propto R_i^{1/2}(T_c-T)$ on the film radius R_i and on the temperature T close to the critical temperature T_c and comparison of H_ω^* with the computed value of the field, in which the current density at the film edge reaches the critical value, make it possible to identify H_ω^* as the field that suppresses the edge surface barrier.

1. Experiments with films or crystals of high-temperature superconductors are often performed in the so-called perpendicular geometry, where the alternating magnetic field is perpendicular to the surface of the sample. The electromagnetic response of the superconductor in this case is much stronger than in the longitudinal geometry (field parallel to the surface). In each case an energy barrier impedes flux penetration into a bounded superconductor. This barrier corresponds to the maximum in the dependence of the Gibbs energy $G(X)$ of a flux line on its distance X from the boundary of the superconductor and vanishes in the field H_p determined by the condition $(\partial G/\partial X)_{X=0}=0$. The value of H_p has been determined for a semi-infinite sample in a longitudinal geometry by Bean and Livingston[1] and for a thin film by Shmidt.[2] In the perpendicular geometry for thick superconducting films of width w and thickness d ($\lambda \ll d \ll w$) the geometric barrier is large.[3,4] In Ref. 5 Likharev showed that the edge potential barrier prevents flux entry into a thin strip ($d<\lambda \ll w$). The barrier is suppressed by a field H_p, approximately equal to the amplitude of the magnetic field perpendicular to the surface of the film for which the maximum Meissner current density $j_s(w)$ at the edge of the film reaches the Ginzburg–Landau (GL) critical pair-breaking current density $j_c=cH_c/(3\times 6^{1/2}\pi\lambda)$, where c is the speed of light, H_c is the thermodynamic critical field, and λ is the London penetration depth. The relation $j_s \simeq j_c$ gives the correct order of magnitude of H_p even in the longitudinal case.[6]

The destruction of the Meissner state is accompanied by nonlinear processes. The amplitude of the microwave magnetic field perpendicular to the thin film, measured in Ref. 7 and corresponding to the formation of a dynamic mixed state in the film, was found to be much smaller than H_p. In Refs. 5 and 7 it was asserted that the barrier vanishes because of irregularities of the film edges and the nonlinear effects were attributed to the onset in the film of periodic motion of vortices whose axes are perpendicular to the plane of the film,[8] but not to the pair-breaking action of the microwave field. In Ref. 9 the current induced by the high-frequency field reached the value j_c, which resulted in threshold generation of odd harmonics. However, rf currents did not flow along the edges of the film, and both components of the alternating magnetic field (parallel and perpendicular to the film) participated in the formation of the nonlinear signal. Therefore, explicit evidence for the manifestation of an edge barrier and the associated GL nonlinearity has still not been found for thin superconducting films in the perpendicular geometry.

In the present paper we report the results of an experimental study of the generation of the third microwave harmonic $H_{3\omega}$ in epitaxial YBaCuO films of different radii and the same thickness $d < \lambda \ll R$. As the microwave field H_ω incident perpendicular to the surface of the film increases, the cubic regime $H_{3\omega} \propto H_\omega^3$ corresponding to the GL nonlinearity breaks down in a field H_ω^*. The observed dependences of H_ω^* on the film radius and the temperature and comparison of the value of H_ω^* with the value calculated from the condition $j_s(R) \simeq j_c$ permit us to conclude that H_ω^* is the field H_p that suppresses the edge surface barrier.

2. The experiments were performed on YBaCuO films with a thickness of $d \simeq 1000$ Å and the normal directed along the C axis. The films were deposited on the $NdGaO_3$ substrate by the method of laser epitaxy. The width of the resistive superconducting transition did not exceed 1.5 K. After deposition, the ring was cut into two halves, each of which was subjected to further lithographic processing. As a result, a regular grid of nonoverlapping superconducting circles — films was produced on the substrate. The radius of the circles on one half of the ring was $R_l \simeq 5 \times 10^{-2}$ cm and the radius on the other half was approximately ten times smaller — $R_s \simeq 5 \times 10^{-3}$ cm. Next, a sample with an area of about 2 mm^2, containing only one entire film with radius R_l, was carefully cut from the first half with a thin diamond saw and a sample with almost the same area was cut from the other half.

The prepared samples were alternately placed in a 24-mm-diameter bimodal cylindrical cavity, tuned simultaneously to two frequencies $\omega/2\pi = 9.33$ GHz (E_{010} mode) and 3ω (H_{111} mode). A block diagram of the high-frequency circuits and the construction of the cavity are shown in Refs. 10 and 11 . Here we indicate only some details referring to the experiments described below. The magnetic flux lines of the mode E_{010} are concentric circles. For this reason, the sample was placed on the bottom of the resonator near the walls in such a way that, allowing for the smallness of the sample, the field H_ω near its surface would be as uniform as possible and directed perpendicular to the surface of the film. The amplitude of this field was calculated from the formula

$$H_\omega(\mathrm{Oe}) \simeq 1.5 \times 10^4 (P_\omega Q/\omega)^{1/2} \simeq 1.13 \times 10^2 \langle P \rangle^{1/2}, \tag{1}$$

where the numerical factor was found from the known structure of the cavity fields, the cavity dimensions, and the location of the sample; $Q \simeq 1000$ is the Q of the resonator; P_ω (in watts) is the pulsed microwave power entering the cavity at the frequency ω. The average power $\langle P \rangle \simeq 0.3 \times 10^{-3} P_\omega$ was regulated continuously at the required rate and simultaneously measured with a wattmeter. The maximum power $\langle P \rangle$ did not exceed several milliwatts. Because of the uncertainty in the placement of the samples, the tem-

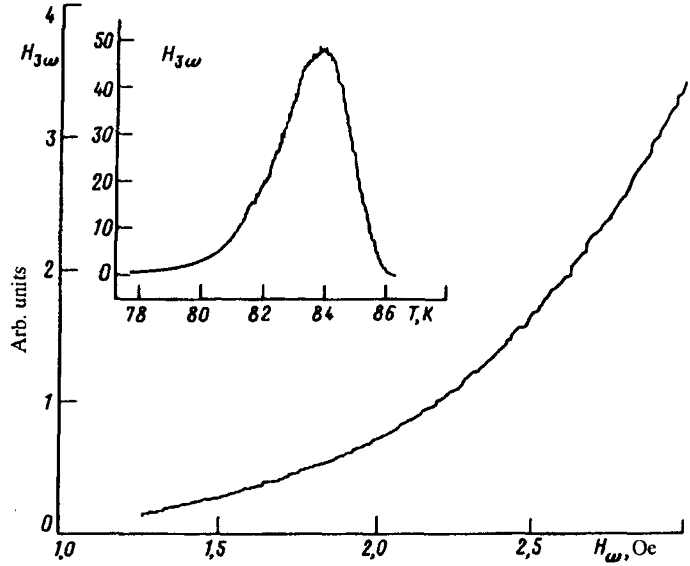

FIG. 1. Example of the field dependence $H_{3\omega}(H_\omega)$ at $T=0.905T_c$ for an l film of radius $R_l \simeq 5\times10^{-2}$ cm. Inset: Temperature dependence $H_{3\omega}(T)$ of the same film in the field $H_\omega \simeq 1.7$ Oe.

perature dependence of Q, and other reasons, the error in determining the field H_ω from Eq. (1) can reach 10–20%. The pulsed power $P_{3\omega} \propto H_{3\omega}^2$ reflected from the film at the frequency 3ω was measured experimentally. We note that the signal $P_{3\omega}$ in the perpendicular geometry was 3–4 orders of magnitude greater than in the longitudinal geometry on the same film with a fixed power level P_ω.

The temperature dependence $H_{3\omega}(T)$ for the large ($l-$) film of radius $R_l \simeq 5\times10^{-2}$ cm placed in a field $H_\omega \simeq 1.7$ Oe perpendicular to the surface of the film is shown in the inset in Fig. 1. The signal has the shape of an asymmetric peak with a width of several degrees. We observed this peak in a previous work while studying the generation of the third microwave harmonic in high-quality YBaCuO single crystals.[12,13] In the normal state of the sample $H_{3\omega}=0$. Generation starts at the critical temperature $T_c \simeq 86.5$ K and reaches a maximum at $T_m \simeq 84$ K (Fig. 1). The signal $H_{3\omega}(T)$ on the small (s-) film ($R_s \simeq 5\times10^{-3}$ cm) had the identical shape and the same values of T_c and T_m. This shows that the s and l films possess the same internal structure. Just as in the experiments with single crystals,[12,13] the harmonic $H_{3\omega}$ is very small at temperatures below the temperature of liquid nitrogen. For this reason, the experiments were performed mainly in the interval $77<T<87$ K. The temperature could be recorded to within ±0.02 K and automated amplitude measurements could be performed at a fixed temperature. An example of the curve $H_{3\omega}(H_\omega)$ obtained in this manner at $T=78.3$ K for the l film is shown in Fig. 1. Ultimately, a collection of curves $H_{3\omega}(H_\omega)$ was recorded for s and l films at different temperatures. This set of curves was analyzed by the following procedure. First, a plot of $H_{3\omega}(H_\omega^3)$ was constructed. Then an optimal comparison was made with a linear function passing through the origin. The field H_ω^* was determined as

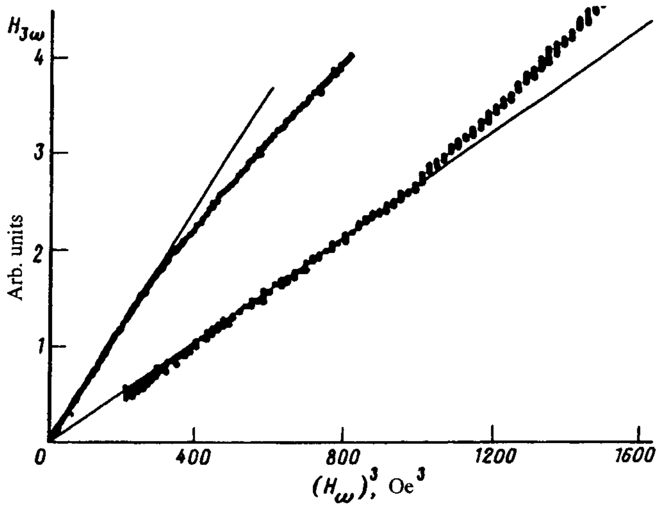

FIG. 2. $H_{3\omega}(H_\omega^3)$ for an s film ($R_s \simeq 5\times 10^{-3}$ cm) at different temperatures: $T/T_c = 0.960$ for the top curve and $T/T_c = 0.916$ for the bottom curve.

the field corresponding to a 10% deviation of this straight line from the experimental dependence $H_{3\omega}(H_\omega^3)$ (see Fig. 2). As one can see from Fig. 2, the initial cubic regime $H_{3\omega} \propto H_\omega^3$ breaks down in the field H_ω^*, and the nonlinearity mechanism changes. As the temperature decreases, the field dependence $H_{3\omega}(H_\omega)$ changes at $T \simeq 0.95T_c$ from weaker to stronger than cubic in both s and l films in fields H_ω exceeding H_ω^*.

The reasons for this transition and the deviations from the cubic dependence $H_{3\omega} \propto H_\omega^3$ should be sought in the nonlinear process which arises in fields $H_\omega > H_\omega^*$ and which is most likely associated with flux penetration into the film. The heating of the film is weak, so that in the entire experimental microwave power range no changes were observed in T_c and the curves $H_{3\omega}(H_\omega)$ had a reversible character. According to the calculations of Ref. 14 , the development time of the instability of the Meissner state, which results in the formation of vortices at the edge of the film, is equal in order of magnitude to the relaxation time τ of the order parameter.[15] The time $\tau \simeq 5.6\times 10^{15}(1-T/T_c)^{-1}$ s measured in Ref. 12 for YBaCuO is very short compared with the period of the electromagnetic wave ($\simeq 10^{-10}$ s). Integrating numerically the nonstationary GL equations,[15] the authors of Ref. 16 demonstrated how in the absence of pinning at a fixed temperature a vortex structure forms over a time $\sim 10^{-10}$ s in a thin square ($d \leqslant \lambda < w$) film of a type-II superconductor placed in an alternating magnetic field perpendicular to its surface: In the first half period of the microwave, as H_ω increases, the magnetic flux penetrating from the lateral walls of the film for $H_\omega > H_p$ transforms into vortices which propagate from the corners toward the center of the film, and they leave the film as H_ω decreases; when the sign of the field H_ω changes, antivortices appear at the locations where the vortices exit the film, and these antivortices, which penetrate into the film, annihilate with the vortices which remain in the film. The fact that the deviation of the curves $H_{3\omega}(H_\omega^3)$ in the direction of smaller and greater values than

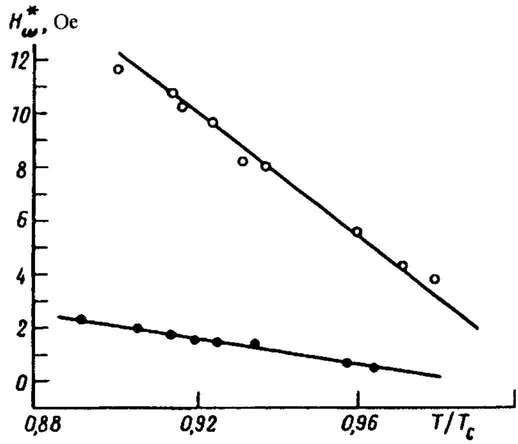

FIG. 3. Crossover field $H^*_\omega(T/T_c)$: ● — l film and ○ — s film.

the straight line $H_{3\omega} \propto H^3_\omega$ in Fig. 2 occurs for both l and s films at the same temperature is a consequence of the fact that these films possess the same internal structure. Calculations such as those in Ref. 16 , performed taking into account the pinning of vortices at different temperatures, would be very helpful for explaining the field dependences $H_{3\omega}(H_\omega)$ which we observed in strong fields $H_\omega > H^*_\omega$.

The temperature dependences of the measured values of H^*_ω for l and s films are shown in Fig. 3. The straight lines drawn through the experimental points correspond to the temperature dependences

$$H^*_{\omega s}(\mathrm{Oe}) \simeq 87(1 - T/T_c), \quad H^*_{\omega l}(\mathrm{Oe}) \simeq 26(1 - T/T_c). \tag{2}$$

In both films H^*_ω decreases linearly as the temperature approaches T_c, and their ratio $H^*_{\omega s}/H^*_{\omega l} \simeq (R_l/R_s)^{1/2}$.

3. In Figs. 1 and 2 the cubic dependence $R_{3\omega} \propto H^3_\omega$ in weak fields H_ω is caused by the manifestation of the GL nonlinearity. In the Meissner state the source of the third harmonic is the nonlinear term at the tripled frequency 3ω in the expression for the quasistationary current density of the GL theory:

$$j = (-cA_\omega/4\pi\lambda^2)[1 - c^4A^2_\omega/(108 \times \pi^2\lambda^4 j^2_c)], \tag{3}$$

where $A_\omega \propto \exp(i\omega t)$ is the vector potential at the frequency ω. In YBaCuO $\lambda \simeq 1500$ Å, the coherence length is $\xi \simeq 15$ Å , $\kappa = \lambda/\xi \simeq 100$, $H_c(0) \simeq 10^4$ Oe, $j_c(0) \simeq 3 \times 10^8$ Å/cm^2, and the first critical field $H_{c1}(0) \simeq 330$ Oe.

As the field H_ω increases, the maximum current at the edge of the film reaches the value j_c, the Meissner state of the film becomes unstable, and deviations are observed from the cubic regime $H_{3\omega} \propto H^3_\omega$. We calculated this edge current, using the algorithm proposed in Ref. 17 for solving numerically Pearl's equation[8] for the vector potential of a round film of constant thickness $d < \lambda$ in a magnetic field oriented perpendicular to the surface of the film. The characteristic distance along which the field changes in this problem is $\lambda_{\text{eff}}=\lambda^2/d$. For the values of interest to us $\lambda_{\text{eff}}/R<0.005$ the expression for the vector potential $A(R)$ at the edge of the film has the form $A(R)=1.1\times H_\omega(\lambda_{\text{eff}}R)^{1/2}$. The Meissner current density $j_s(R)$ at the edge of the film is found by substituting this expression into Eq. (3). When $j_s(R)$ becomes equal to j_c, it should be expected that vortices will start to enter the film. This occurs in the field $H_\omega=H_p$ equal to

$$H_p=H_{\text{c1}}\times 4\times 3^{1/2}\kappa(d/R)^{1/2}/(1.1\times 9\ \ln\kappa). \tag{4}$$

The quantity H_p is many times greater than the value $H^e_{\text{c1}}=H_{\text{c1}}\times 3\pi d/8R$ of the field in which a mixed state is formed. This field was computed taking into account the demagnetization factor in the ellipsoidal model of a disk.

4. Near the critical temperature we obtain the following expression from (4) with the parameters κ and H_{c1} for YBaCuO

$$H_p(\text{Oe})\simeq 5\times 10^3(d/R)^{1/2}(1-T/T_c). \tag{5}$$

Substituting into Eq. (5) the dimensions of the films employed in our experiments and comparing to the expression (2), we see that the measured values of H^*_ω are approximately three times smaller than H_p; i.e., the edge Meissner current density in the field H^*_ω reaches a value of the order of the critical density. The inverse square-root dependence of H^*_ω on the radius of the film $H^*_\omega \propto R^{-1/2}$ and the linear temperature dependence $H^*_\omega(T) \propto (T_c-T)$ near T_c also Eq. (5). We conclude that the present investigation proves the existence of an edge surface barrier in thin YBaCuO films in a magnetic field oriented perpendicular to their surface.

We thank G. I. Leviev for assisting in this work, E. Borovitskaya, V. Genkin, V. Krasnov, and D. Shovkun for their helpful discussions, and L. Mazo (Institute of Metal Physics, Russian Academy of Sciences, Nizhniĭ Novgorod) for providing the films for the experimental research. This work was performed as part of the Project No. 94-02-03236 of the Russian Fund for Fundamental Research and was supported in part by a Grant (REY000) from the George Soros Fund.

[1)]e-mail: trunin@issp.ac.ru

[1]C. P. Bean and J. D. Livingston, Phys. Rev. Lett. **12**, 14 (1964).
[2]V. V. Shmidt, Zh. Éksp. Teor. Fiz. **57**, 2095 (1969) [Sov. Phys. JETP **30**, 1137 (1970)].
[3]E. Zeldov, A. I. Larkin, V. B. Geshkenbein *et al.*, Phys. Rev. Lett. **73**, 1428 (1994).
[4]M. V. Indenbom and E. H. Brandt, Phys. Rev. Lett. **73**, 1731 (1994).
[5]K. K. Likharev, Izv. Vyssh. Uchebn. Zaved., Radiofiz. **14**, 909, 919 (1971).
[6]V. V. Shmidt and G. S. Mkrtchyan, Usp. Fiz. Nauk **112**, 459 (1974) [Sov. Phys. Usp. **17**, 170 (1974)].
[7]V. N. Gubankov, K. K. Likharev, and N. M. Margolin, JETP Lett. **11**, 157 (1970); V. N. Gubankov and K. K. Likharev, Fiz. Tverd. Tela (Leningrad) **13**, 125 (1971) [Sov. Phys. Solid State **13**, 99 (1971)].
[8]J. Pearl, Appl. Phys. Lett. **5**, 65 (1964).
[9]V. A. Berezin, S. V. Govorkov, S. K. Tolpygo, and V. A. Tulin, Fiz. Tverd. Tela (Leningrad) **27**, 1953 (1985) [Sov. Phys. Solid State **27**, 1173 (1985)]; S. V. Govorkov, S. K. Tolpygo, and V. A. Tulin, Zh. Éksp. Teor. Fiz. **89**, 1704 (1985) [Sov. Phys. JETP **62**, 983 (1985)].
[10]V. F. Gantmakher, G. I. Leviev, and M. R. Trunin, Zh. Éksp. Teor. Fiz. **82**, 1607 (1982) [Sov. Phys. JETP **55**, 931 (1982)].
[11]M. R. Trunin and G. I. Leviev, J. Phys. France III **2**, 355 (1992).
[12]G. I. Leviev, A. V. Rylyakov, and M. R. Trunin, JETP Lett. **50**, 88 (1989).

[13] I. Ciccarello, C. Fazio, M. Guccione *et al.*, Phys. Rev. B **49**, 6280 (1994).
[14] L. G. Aslamazov and S. V. Lempitskiĭ, Zh. Éksp. Teor. Fiz. **84**, 2216 (1983) [Sov. Phys. JETP **57**, 1291 (1983)].
[15] L. P. Gor'kov and G. M. Éliashberg, Zh. Éksp. Teor. Fiz. **54**, 612 (1968) [Sov. Phys. JETP **27**, 328 (1968)].
[16] R. Kato, Y. Enomoto, and S. Maekawa, Phys. Rev. B **47**, 8016 (1993).
[17] E. S. Bakhanova and V. M. Genkin, J. Appl. Phys. (to be published).

Translated by M. E. Alferieff