Size effect in nonlinear rf properties of thin superconducting films

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There is a lower limit on the amplitude for the appearance of that nonlinearity of thin superconducting films which stems from the creation of vortex pairs near T_c. This limitation is determined by the transverse dimensions of the film.

It has been established that the order parameter approaches zero as the critical temperature T_c is approached from below. The critical quantities characterizing the superconductivity (the critical magnetic field, the critical current, and so forth) also tend toward zero. If the amplitude of the alternating magnetic field acting on a superconducting object (more precisely, a film or thin wire) or the current which this field induces exceeds a critical value, the properties of the object will vary periodically at the frequency of the alternating field. This circumstance is manifested in nonlinear effects. Since the critical parameters tend toward zero as T_c is approached, it is reasonable to assume that the amplitude required of the alternating field for the occurrence of nonlinear effects can be arbitrary if we are suitably close to T_c. In the present letter, however, we show that one of the nonlinear effects in superconducting thin films arises after a threshold is passed (this circumstance was discovered previously[1]), and the amplitude of the rf field at which the nonlinearity arises is related to the transverse dimensions of the film by

$$h_c^{min} D^{3/2} = \text{const} ,$$

where $h_c^{\min}$ is the minimum critical amplitude of the rf field at which the nonlinearity arises, and D is the transverse dimension of the film (e.g., the diameter, in the case of a circular film). The amplitude $h_c^{\min}$ tends towards zero in the limit $T \rightarrow T_c$ only if $D \rightarrow \infty$.

We have studied third-harmonic generation in a thin superconducting film ($d \ll \lambda, \xi$, where d is the film thickness, λ is the penetration depth of the magnetic field, and ξ is the coherence length) during "single-sided" irradiation[1] near T_c. The object in these experiments was an aluminum film synthesized by vacuum deposition in a "diffusion" vacuum, $\sim 10^{-5}$ Torr, on a glass substrate. The thickness of the films was found to be about 45 nm by means of a quartz balance. The temperature of the superconducting transition of the films was ~ 1.4 K. The experimental apparatus is described in Ref. 1.

A small region of a large-area aluminum film was irradiated through a diaphragm in a copper screen. The receiving coil was positioned on the other side of the film. The signal at the third harmonic of the irradiation frequency, 123 MHz ($3f = 369$ MHz), was fed from the coil to a receiver with a sensitivity of 10^{-15} W and recorded as a function of the irradiation power and the dimensions of the diaphragm as the temperature crossed T_c. We used diaphragms of two sizes: 1.9 and 3.5 mm in diameter.

After the synthesis of the sample, we carried out measurements, initially with a diaphragm of one size. The sample was then repositioned on the screen with the diaphragm of the other size, and the measurements were repeated. We monitored the coupling between the circuit and the conducting line in order to keep the power entering the circuit constant at this change in diaphragm. Since all the other parts of the arrangement were fixed during the measurements, it can be assumed that the amplitude of the rf magnetic field near the surface of the film was reproduced within an error on the order of 10% from one experiment to the next. The sample, the resonant circuit, the receiving coil, and the screens were all immersed in superfluid helium during the measurements. The temperature was changed by changing the rate at which the cryostat was evacuated. The relative temperature was measured and recorded on a chart recorded by means of a carbon thermometer.

Figure 1 shows some representative recordings of the amplitude of the third harmonic emitted by the film as a function of the bath temperature for several values of the irradiation power. From these results we find the dependence of the maximum amplitude of the third harmonic on the amplitude of the field at the film. This dependence is shown for the diaphragms of the two sizes, for the same film, in Fig. 2. Extrapolation of the linear regions to the abscissa intercept gives us the threshold irradiation amplitude at which this nonlinear effect occurs. An increase in the dimensions of the diaphragm (or an increase in the dimensions of the irradiated part of the film) results in a decrease in the threshold power. For the two diaphragms used, with diameters of 1.9 and 3.5 mm, the threshold power decreases to 8.2 dB and 7.1 dB for two different samples. We carried out measurements with seven films; within the experimental errors, the results correspond to those reported here for the first samples.

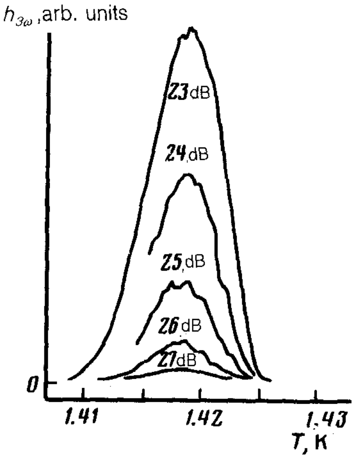

FIG. 1. Maximum power of the third-harmonic emission from the superconducting film versus the temperature near T_c.

In this experimental situation, the film in its normal state was transparent to the rf field, while in its superconducting state it was essentially opaque. At a temperature slightly below the critical temperature, the magnetic field does not penetrate through a diaphragm covered by the superconducting film. In this case we have a single-sided irradiation of the film. Let us assume, as in Ref. 1, that when the current induced by the rf magnetic field in the film reaches the critical value J_c, pairs of vortices of opposite sign are created in the film. These vortices annihilate in a reversible fashion as the magnetic field decreases in the next part of the period. The most important quantity with the dimensionality of a length in this case is the penetration depth of the perpendicular magnetic field in the film, $\lambda_\perp = 2\lambda^2/d$. The same quantity determines the size of a vortex in the film. Near the critical temperature for the superconducting transition, $\lambda_\perp(T)$ can reach macroscopic dimensions.

We have two temperature-dependent quantities: $J_c(T)$ [or $P_c(T)$] and $\lambda_\perp(T)$. Here we may have two different situations. If the rf power is of such a level that it is critical at a temperature at which $\lambda_1 \ll D$, where D is the size of the diaphragm, then the vortex-antivortex pairs that arise will lead to nonlinear effects, and we will observe the third harmonic. If, on the other hand, the rf power is low, so that it is critical at a temperature at which $\lambda > D$, we cannot see the individual vortices making up the pairs.

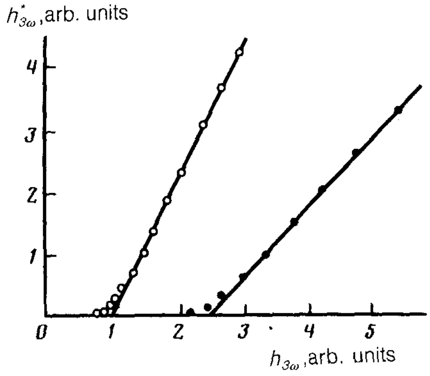

FIG. 2. Maximum power of the third-harmonic emission from the film versus the amplitude of the rf field irradiating the film for diaphragms of two diameters: ○—3.5 mm; ●—1.9 mm.

The screening currents of the vortices of the opposite signs overlap and annihilate each other. This action implies that the superconducting component of the film does not screen out the rf magnetic field. In this case, the nonlinear effects associated with the perturbation of vortex pairs should not be seen. As the temperature is lowered, the sizes of the vortices will become smaller than the sizes of the diaphragm, but the established power will be below the critical power, and nonlinear effects will not be seen.

It was shown in Ref. 2 that the critical power in a situation analogous to that under discussion here is $\lambda_\perp = 2\lambda^2/d \sim (T_c - T)^{-1}$. Using the temperature dependence $P_c(T) \sim (T_c - T)^3$, and introducing a nominal boundary for the disappearance of the nonlinear effects associated with the creation of vortex pairs, $\lambda_\perp = D$, we can derive the following relation for a given film which is irradiated through different diaphragms:

$$\frac{D_2}{D_1} = \frac{\lambda_{\perp 2}}{\lambda_{\perp 1}} = \left(\frac{P^{min}_{c1}}{P^{min}_{c2}}\right)^{1/3} \quad \text{or} \quad D^{3/2}\,(h^{min}_{c}) = \text{const}.$$

The critical power for the onset of this nonlinearity is inversely proportional to the cube of the diameter of the diaphragm. Substituting the dimensions of the diaphragms used, we find $P^{\min}_{c1}/P^{\min}_{c2} = 6.25$, which corresponds to 8 dB. In other words, the result agrees well with the experimental values.

The results of this study indicate that as the temperature (or some other parameter on which $\lambda_\perp$ depends) is varied, there are changes in the electrodynamic properties of the film at $\lambda_\perp \approx D$. As a result, one should use caution in interpreting results of studies of phase transitions in quasi-2*D* superconducting systems (the Kosterlitz-Thouless transition).

[1] S. A. Govorkov, S. K. Tolpygo, and V. A. Tulin, Zh. Eksp. Teor. Fiz. **89**, 704 (1985) [*sic*].
[2] V. A. Berezin, S. A. Goverkov, S. K. Tolpygo, and V. A. Tulin, Fiz. Tverd. Tela (Leningrad) **27**, 1953 (1985) [Sov. Phys. Solid State **27**, 1173 (1985)].

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