Macroscopic quantum microwave interference in single crystals of high-T_c superconductors

A. A. Bugaĭ, A. A. Bush, I. M. Zaritskiĭ, A. A. Konchits, N. I. Kashirina, and S. P. Kolesnik

Institute of Semiconductors, Academy of Sciences of the Ukrainian SSR

(Submitted 4 July 1988)
Pis'ma Zh. Eksp. Teor. Fiz. **48**, No. 4, 209–211 (25 August 1988)

A threshold (in p_{mw}) excitation of the periodic, with respect to the magnetic field H, microwave power absorption peaks has been detected for the first time in the single crystals of the high-T_c superconductor $RBa_2Cu_3O_{7-\delta}$ (R = Gd, Dy, or Y) at $T = 4.2$–77 K. The experimental data are interpreted as macroscopic quantum interference effects in which the substructures, most likely the twinning boundaries, are involved.

The study of high-T_c superconductor ceramics has revealed the presence of strong nonresonant microwave absorption signals in small magnetic fields[1,2] H, whose origin is now being vigorously discussed. Quite recently such effects were detected in $YBa_2Cu_3O_{7-\delta}$ single crystals.[3]

We have studied the low-field microwave response of several $RBa_2Cu_3O_{7-\delta}$ (R = Gd, Dy, Y) single crystals. The experiments were carried out using a superheterodyne ESR spectrometer ($\nu \approx 9.4$ GHz) without rf modulation of the field H. The response proportional to the change in the microwave power reflected from the resonator was detected by an oscilloscope directly from the wide-band output of the detector. The high-T_c superconductor single-crystal samples with typical dimensions $0.5 \times 0.5 \times 0.05$ mm were placed at the antinode H_1—the microwave component—of the resonator's field.

At a certain threshold value of the decaying microwave power P^+, which depends on the external magnetic field H, we found conditions that lead to a generation of an

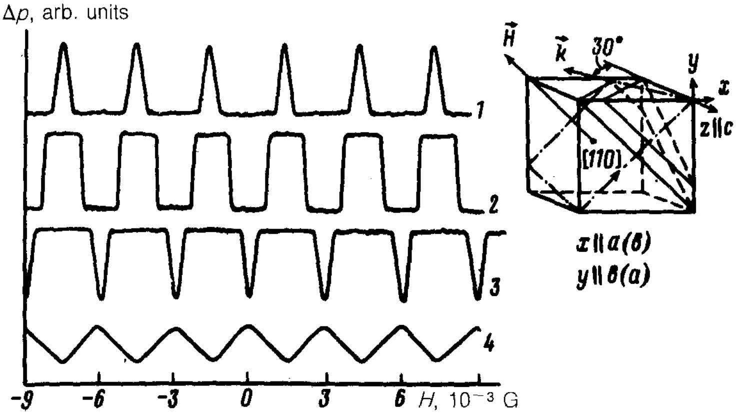

FIG. 1. Periodic series of absorption peaks for the $GdBa_2Cu_3O_{7-\delta}$ sample at $p_{mw} > p^*$ ($p^* \approx -50.5$ dB). $T = 4.2$ K. p_{mw} (in dB): 1—50; 2—49.5; 3—49; 4—48.5. Zero dB corresponds to 0.1 W. Also shown is a schematic drawing of the test single crystal, with the substructures discussed in the text proper marked accordingly.

H-periodic reflected-power pulse train (Fig. 1), whose signal is critical to p_{mw}. The peak pulses were measured in the interval $\sim \pm 1$ dB relative to the maximum power $p^{max} \approx p^* + 1$ dB (Figs. 1 and 2). At $p_{mw} > p^{max}$ the signal peaks of the same pulse train are weaker.

We found that microwave power absorption retains its threshold nature even when H is kept constant (Fig. 2). The maximum intensity of the absorption peaks in a varying H field corresponds to the total amplitude of "step 1" in Fig. 2 when p^{max} is at its half-maximum.

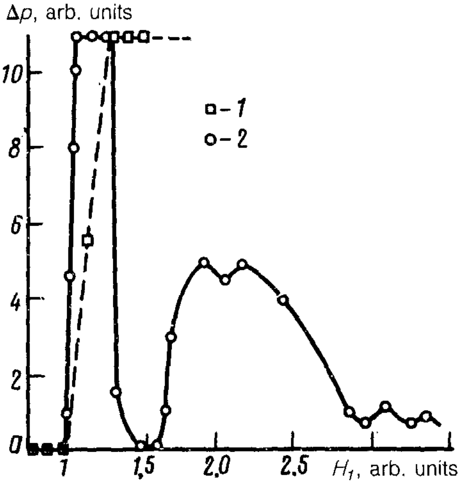

FIG. 2. Strength of the signals of the microwave absorption in a $GdBa_2Cu_3O_{7-\delta}$ sample versus the amplitude of H_1: the component of the microwave field in an external static H field (1) and in an external variable field (2).

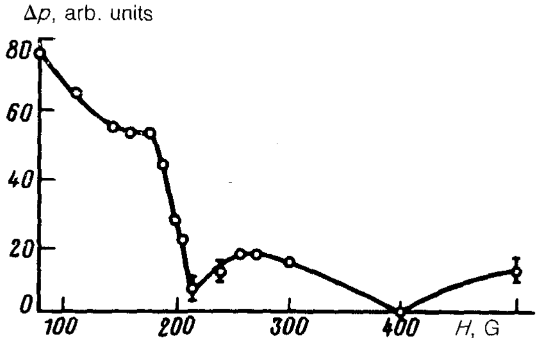

FIG. 3. The amplitude of the periodic signals versus the strength of the H field. $T = 4.2$ K. The orientation of the crystal is the same as that in Fig. 1.

Analysis of the angular dependence of the period of the measured oscillations, ΔH, showed that $(\Delta H)^{-1} = (\Delta H_0)^{-1} |\sin\theta|$, where $\Delta H_0 \approx 3 \times 10^{-3}$ G is the minimum oscillation period, and θ is the angle between the direction of **H** and the vector **k** (Fig. 1) or the [110] direction when **H** rotates in the zx and xy planes, respectively.

We see in Fig. 1 that the position of each peak of the pulse train is rigidly bound to the value of H.

The effect persists to $H \approx 500$ G. The amplitude of the peaks in this case is illustrated by the curve in Fig. 3, where $p_{\rm mw} \approx p^{\rm max}$. The amplitude of the periodic signals and the corresponding value of $\sqrt{p^{\rm max}}$ decrease linearly at the same rate with increasing T to $T \approx 65$ K. At $T < 65$ K the signal decays sharply and at $T \approx T_c \approx 75$ K it vanishes (in the case of the crystal under study).

Similar excitation of the periodic series of signals was also observed in other superconducting crystals. The value of ΔH_0, however, differed appreciably in different samples. In $DyBa_2Cu_3O_{7-\delta}$ sample, for example, $\Delta H_0 \approx 4$ G. Weak signals of the type under discussion were also observed in $Bi_2Sr_2CaCu_2O_{8-\delta}$ single crystals.

In addition to the signals generated at a certain threshold value of $p_{\rm mw}$, we observed in some samples typical "triangular"-shaped signals which are not critical to $p_{\rm mw}$ (see curve 4 in Fig. 1).

The experimental data which we have obtained are typical of the data associated with quantum-interference phenomena in superconductors with Josephson junctions.[4] This suggests that some high-T_c superconductor single crystals form natural "SQUID structures," in which the weak links may be the twinning boundaries, whose directions in Fig. 1 are indicated by the thin solid lines, or some other extended defects such as the growth steps.

The area of the SQUID can be estimated from ΔH_0, $\Delta S_0 = (\Phi_0/\Delta H_0) = 0.7 \times 10^{-4}$ cm^2 ($\Phi_0 = 2 \times 10^{-7}$ G·cm^2 is the fluxoid). Making use of the linear dimension of the single crystal in the [110] direction, $l \approx 0.07$ cm, we find the second linear dimension, $\sim 10^{-3}$ cm, which is smaller than the crystal thickness by several factors. If it is assumed that the $\sim 10^{-6}$-cm-thick twinning boundary is the weak link, we find, from the period $\delta H \approx 200$ G (Fig. 3), the length of the weak link to be $\sim 10^{-3}$ cm, consistent with the data on the twin sizes in high-T_c superconductor single crystals published in the literature.

The threshold nature (with respect to p_{mw}) of the excitation of the periodic series of pulses is apparently related to the induction of the current $I \gtrsim I_c$ by the H_1 component of the microwave field, at $p_{\mathrm{mw}} \approx p^*$, in the circuit which includes the Josephson junction, where I_c is the critical current of the weak link. It follows from these data that I_c determines both the value of $p^{\max}$, which is close to p^*, and the maximum amplitude of the peaks of the periodic series (see Figs. 1 and 2). The experimentally determined temperature dependence of these quantities is a consequence of the decrease in I_c as T is raised.

Our interpretation differs from that of Refs. 2 and 3, where the pinning and depinning of fluxoids, which can be induced only in the presence of a variable H field and which should not depend critically on p_{mw}, were analyzed. It is conceivable that the threshold nature (with respect to H_1) of the onset of the absorption peaks in high-T_c superconductor single crystals stems from the parametric excitation of special kind of surface waves which are associated with the superconducting screening currents whose interference gives rise to the effects which we have observed.

The true nature of this phenomenon is now being clarified.

[1] L. S. Vlasenko, M. G. Semenchenko, and Yu. P. Stepanov, Pis'ma Zh. Tekh. Fiz. **13**, 1435 (1987) [Sov. Tech. Phys. Lett. **13**, 600 (1987)].

[2] A. M. Portis, K. W. Blazey, K. A. Müller, and J. G. Bednorz, Europhys. Lett. **5**, 467 (1988).

[3] K. W. Blazey, A. M. Portis, K. A. Müller *et al.*, Preprint of the Proceedings of Int. Conf. MMHTSC, Interlaken, 1988, Switzerland.

[4] A. Barone and G. Paterno, *Physics and Applications of the Josephson Effect*, Wiley, New York, 1982.

Translated by S. J. Amoretty