Nondissipative rf response of Y-Ba-Cu-O microcrystals due to phase matching of the Josephson currents in weak magnetic fields

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Induction effects which depend on the size of Y-Ba-Cu-O microcrystals and which are associated with the nondissipative component of the Josephson currents whose phases become aligned in weak (< 1 Oe) magnetic fields, have been observed. These induction effects have been studied.

Many studies, in which the effect of weak magnetic fields on the rf and microwave properties of high-T_c superconductors at temperatures below the critical temperature has been investigated, have considered various energy-loss mechanisms which are related to the Josephson junctions.[1–4] In particular, the experimental observation of a series of narrow microwave absorption lines in high-T_c superconducting single crystals has been attributed to the dissipative fluxon motion.[2]

The experimental data which we are reporting here for the samples with isolated Y-Ba-Cu-O microcrystals of various sizes can be used to identify the nondissipative component of the Josephson currents whose phases in different particles differ only slightly from each other in magnetic fields $H_0 < 1$ Oe.

In the experiments we used samples of the composition $Y_1Ba_2Cu_3O_{6.9}$. These samples were obtained by ceramic synthesis with additional thermal treatment at the sintering stage at a temperature of 950 °C for 46 h. As a result, the grains with a size of up to 100 μm acquired a crystal structure. They were then ground and the particles were separated according to size. The sizes were in the range 1–4 μm, 2–6 μm, 3–10 μm, and 10–50 μm, respectively, for samples 1, 2, 3, and 4. Each sample weighed ~ 40 mgf. The particles were isolated from each other in a paraffin matrix. The samples were inserted into a coil of an oscillatory circuit which was tuned to a frequency of 9 MHz, while the alternating field $H_1 \sin \omega t$ was produced by another coil which was axially aligned with the coil of the recording circuit. The static magnetic field $H_0 \| H_1$ varied within $\pm$ 100 Oe. The experiments were carried out either in a magnetic screen or the external magnetic field components directed at right angles to H_0 were canceled. The signals corresponding to the change in the voltage U across the circuit with the sample upon scanning the field H_0 were recorded experimentally. The signals were observed in the case of low-frequency modulation of the field H_0 with simultaneous detection and directly from an rf detector. The voltage U is the sum of the voltage, U_I, induced by the alternating field H_1 and the total voltage, $U_\Sigma = \Sigma U_c$ (where U_c corresponds to the contribution from a single particle), induced by the currents in the sample, i.e., $U = U_\Sigma + U_H$.

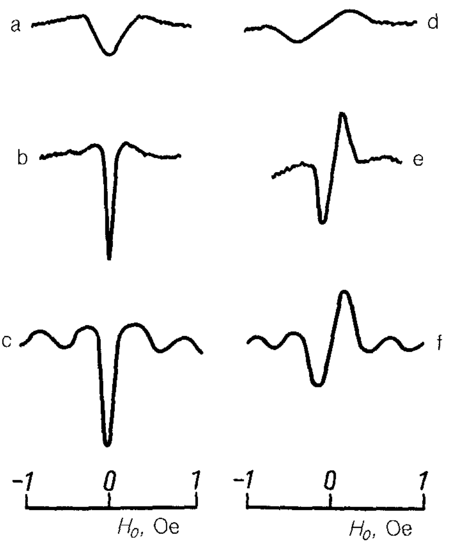

FIG. 1. Rf response signals of sample No. 3(a, d) and sample No. 4(b, e) at the first harmonic (a, b) and the second harmonic (d, e); (c, f)—signals determined from calculations.

Figures 1a and 1b show the signals at the rf detector output for samples 3 and 4 cooled in zero magnetic field (ZFC) upon scanning the field H_0 through zero. As can be seen in the figure, with an increase in the particle size, the signal amplitude increases, while the widths of the corresponding lines decrease. The line width measured between the maxima of the derivative dU/dH_0 was 0.97, 0.72, 0.45, and 0.27 Oe for samples 1, 2, 3, and 4, respectively. The width of the observed lines is comparable to the fields which produce one flux quantum in an average cross-sectional area S of the particles in the sample.

The results which we obtained can be explained by assuming that the microcrystals have currents which flow along paths with an area S_p in which there are weak links. In a static field H_0 and in an alternating field $H_1 \sin \omega t$ the Josephson current flowing along such a path is given by[5]

$$i_k(t) = -I_c \sin(\alpha_0 + \alpha_1 \sin \omega t + \gamma), \tag{1}$$

where $\alpha_0 = 2\pi S_k H_0/\Phi_0$, $\alpha_1 = 2\pi S_k H_1/\Phi_0$, $\gamma = 2\pi L_k i_k(t)/\Phi_0$, I_c is the critical current of the weak link, $\Phi_0 = 2 \times 10^{-7}$ G·cm is a flux quantum, and L_p is the inductance of the path with an area S_p. The term $L_p i_p/\Phi_0$ determines the scatter of the phases of the Josephson currents in zero field for particles with different values of L_p. Assuming this term to be small, after expanding (1) in a series with the help of the Bessel functions, we obtain

$$i(t) = -I_c[J_0(\alpha_1)\sin\alpha_0 + 2J_1(\alpha_1)\cos\alpha_0 \sin\omega t + 2J_2(\alpha_1)\sin\alpha_0\cos 2\omega t + \ldots]. \tag{2}$$

In a measurement oscillatory circuit tuned to the frequency ω this current induces a voltage $U_p = -M_1 S_p (di_p/dt)$ which combines with the voltage induced by an alternating field $U_p = -M_2\omega \cos \omega t$ (where M_1 and M_2 are the proportionality coef-

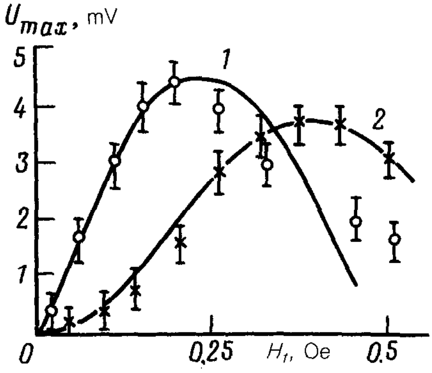

FIG. 2. The amplitude of an rf response at the first harmonic (curve 1) and the second harmonic (curve 2) vs the amplitude of the alternating field H_1 for sample No. 4. Solid curves—Calculation; points—experiment.

ficients). For a signal of frequency ω we find from (2)

$$U_{\omega} = -M_2\omega\cos\omega t + 2M_1 I_c \omega\cos\omega t \sum_k S_k J_1(\alpha_1)\cos\alpha_0. \tag{3}$$

The nondissipative response of the Josephson currents thus leads to the appearance of an induction signal whose phase is opposite to that produced by the field H_1. This circumstance causes the voltage detected by an amplitude detector in the circuit at $H_0 = 0$ to decrease. The sign of the signal in this case is opposite to that of the rf and microwave power absorption signals usually observed in high-T_c superconductors in weak magnetic fields.[1]

Figure 1c shows the shape of the signal calculated according to (3). Allowance for the spread in the phases of the currents i_p, which occurs as a result of the spread in the induction values L_p [see the term $L_p i_p/\Phi_0$ in Eq. (1)], and for the decrease in I_p with increasing H_0 leads to additional flattening of the oscillations on the $U_\omega(H_0)$ curve in Fig. 1c and to a better agreement with the experimental shape of the signal.

The nonlinearity of the Josephson currents leads to the appearance of signals at the harmonics of the fundamental frequency which were recorded experimentally up to the fourth harmonic. Figures 4d and 4e show that the signals recorded at the second harmonic for various samples, and Fig. 1f shows the shape of the calculated signal, $U_{2\omega} \sim 4M_1 I_p \omega \sin 2\omega t \Sigma_p S_p J_2(\alpha_1)\sin\alpha_0$. Note that the strength and phase of the signals at even harmonics depends on the relative orientation of the fields H_0 and H_1.

The model we are considering has also been confirmed by the plots of the signal strength vs the amplitude of the alternating field H_1, which are described by the Bessel functions. The corresponding experimental data and the calculated curves are shown in Fig. 2. In the calculation we used the average area $\overline{S}$ which was determined for the given sample from the line width at the fundamental frequency. As the particle size was reduced, the maximum signal strengths at the first and second harmonics were attained at large values of the field H_1.

The maximum intensity of the induced signals was observed in all the samples at ZFC. When the samples were magnetized in a field H_0^* after ZFC and also at FC, the signal strength decreased in zero field, as indicated in Fig. 3. Such a behavior of the

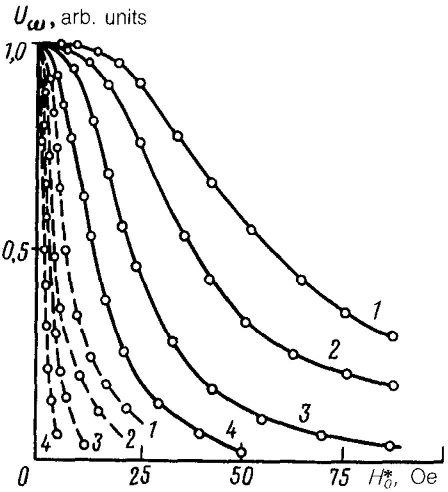

FIG. 3. The amplitude of the signal at the first harmonic in zero magnetic field vs the strength of the magnetizing field H_0 after ZFC (solid lines) and after FC (dashed lines) for samples 1–4.

signals is attributable to the capture of the magnetic flux by the particles, which accounts for the spread in the phases of the currents at $H_0 = 0$.

The peculiar rf properties of the particles of the high-T_c superconducting microcrystals, which have been observed in fields < 1 Oe, can thus be explained by the nondissipative variation in the Josephson currents whose phases are similar in zero field. The narrow lines in weak fields, which have been observed in microwave absorption experiments, apparently are similar in nature.[4] The specific physical model of the Josephson junctions and current paths in single particles of high-T_c superconducting microcrystals requires a separate study.

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