Liquid-nitrogen-temperature superconductor magnetometer

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An interference superconductor magnetometer which operates at liquid-nitrogen temperatures is described. It is made from a $YBa_2Cu_3O_7$ ceramic and is intended for measuring weak magnetic fields, down to 10^{-6} G. The characteristics of the weak link of the interferometer are similar to those of a single Josephson junction. Some possible explanations of this similarity are proposed.

Numerous experiments have shown that ceramic samples of oxide superconductors consist of a system of granules coupled by Josephson junctions. As a particular consequence of this structure, the voltage across these samples exhibits a periodic dependence on the external field when the samples are in their resistive state. This periodic dependence is explained, as are Little-Parks experiments,[1] in terms of interference phenomena. In samples made of high-temperature superconductors, the period of these oscillations can reach[2] 10^{-1}–10^{-2} G. These periods correspond to a magnetic-flux quantization area $\sim 10^{-6}$ cm^2, which agrees in order of magnitude with the characteristic dimensions of the particles making up the sample. In addition, we have shown[3] that interference effects can be observed at a quantization area of 10^{-2} cm^2; the implication is that it would be possible to fabricate a magnetometer which would operate at liquid-nitrogen temperature from a high-temperature-superconductor ceramic. An interferometer using a film system with a quantization area $\sim 10^{-5}$ cm^2 has been fabricated at an IBM research center.[4]

The sensitive element of the rf interferometer was a ring made of the ceramic $YBa_2Cu_3O_7$ with a hole $\approx 2.2 \times 10^{-2}$ cm^2 in area, with a weak link. Specifically, this weak link was a thinning of the cross section of the ring to 10^{-3}–10^{-4} cm^2 over a distance $\sim 10^{-2}$ cm. Measurements were carried with standard SQIMP apparatus.[5] The coil of the resonant rf circuit was positioned in the hole in the ceramic ring. The current through the circuit was set by an rf oscillator (with a frequency ≈ 20 MHz; Fig. 1a). Since the superconducting ring was inductively coupled with the resonant circuit, we were able to determine the superconducting transition temperature of the weak link by measuring the characteristics of this circuit. In particular, for the interferometer whose characteristics are shown in the inset in Fig. 2, this transition had a width of 0.7 K and was completed at 79.5 K. Below this temperature, an increase in the oscillator output voltage V_{rf} made it possible to put the weak link in a resistive state. This event was accompanied by the appearance of a periodic dependence of the rf voltage across the circuit on the external magnetic field; we used a low-frequency modulation of the magnetic field, in the customary way, to bring out this periodic dependence. The ratio of the useful signal to the noise was 3–5 for most of the samples;

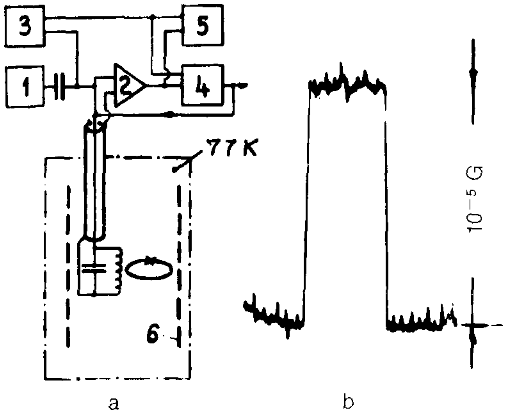

FIG. 1. a: The experimental layout. 1—Radio-frequency oscillator; 2—rf amplifier with detector; 3—low-frequency oscillator for the field modulation; 4—low-frequency amplifier and phase detector; 5—oscilloscope; 6—solenoid for determining this sensitivity to the magnetic field (the magnetic shielding is not shown). b: Illustrative recording of the output signal of the magnetometer upon the application of a magnetic-field pulse (the current in the solenoid).

for three out of the dozen studied this ratio was 10–20. In other words, these values were close to those typical of point-contact rf interferometers operating at 4.2 K (Ref. 6).

The particular value of V_{rf} at which the system under study responds to a change in the external magnetic field varies with the temperature in a complicated way. Near T_c, the value of V_{rf}, which corresponds to the maximum signal-to-noise ratio, increases with increasing value of the difference $T_c - T$. At the same time, there is an increase in the working voltage range (in which the effect of the magnetic field can be

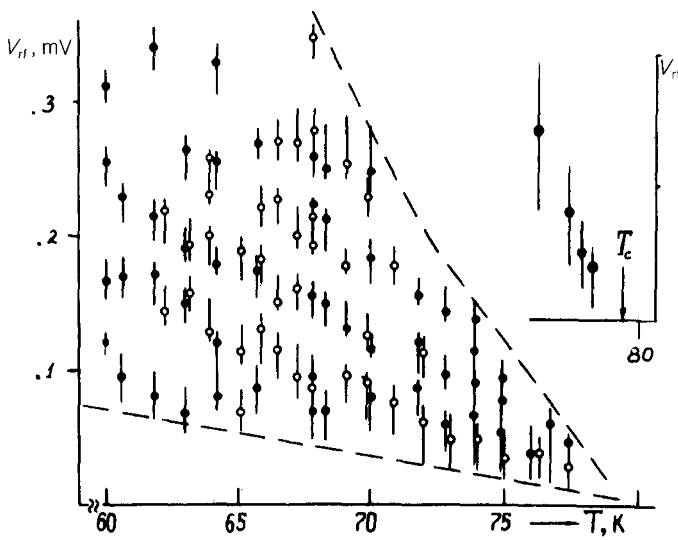

FIG. 2. Temperature dependence of that value of V_{rf} at which there is a response of the ceramic rf interferometer to the magnetic field. Open and filled circles—best signal-to-noise ratio (from two independent experiments); vertical bars—regions in which the effect of the field can be seen; dashed lines—boundaries outside which the field has no effect. The inset shows the characteristics of a second interferometer.

seen; Fig. 2). With a further lowering of the temperature, several working regions may appear, separated by intervals in which there is no response to a magnetic field (at $T \lesssim 72$ K in Fig. 2). The phases of the response to a low-frequency alternating field in working regions that lie close together differ by[1] π. In this temperature region the characteristics of this ceramic rf interferometer are very similar to those customarily observed in rf SQUIDs with a single point contact (Ref. 6, for example).

The functions of the weak link in a ceramic interferometer have yet to be conclusively explained. In terms of its geometric dimensions, a weak link is many orders of magnitude larger than the coherence length of the particular superconductor which is being used. It apparently contains a set of Josephson junctions between distinct granules. If this is the case, the fact that the ceramic rf interferometer exhibits a large signal-to-noise ratio and the fact that the phase of the response to the external magnetic field changes with the level of the rf field, V_{rf}, can be explained only by assuming that the entire set of Josephson junctions responds as a single junction to the external stimulus. The following factors might be responsible for this behavior:

a) A specific feature of the technique by which the ceramic was prepared, which results in identical characteristics of the junctions between the granules.

b) A manifestation of mesoscopic effects, which occur because there are not enough junctions in the weak link to achieve a complete averaging of their characteristics (see, for example, Subsection II.C.3 in Ref. 7).

c) The appearance in a set of coupled Josephson junctions, upon a variation in V_{rf}—amid the chaos of responses to the external stimulus—of regions (along the V_{rf} scale) of a mutual synchronization of the ensemble, as occurs in nonlinear dynamic systems.[8]

Among these possibilities, the last two seem the most likely to us. Further research will be required to choose among them.

We studied the possibility of using this instrument for magnetic measurements in a system consisting of two interferometers similar to that described above. The two interferometers differed in the area of the hole, by a factor of 1.77. They were closed by a common weak link. The external magnetic field was directed perpendicular to the area of the interferometers. In the smaller hole, with an area of 2.2×10^{-2} cm^2, we inserted a coil of the resonant circuit of a SQIMP, and we took measurements in a regime of feedback through the field. Figure 1b is an example of the readings of the output signal from the magnetometer upon the application of a magnetic-field pulse ~ 2 min long. We see that the noise level of the apparatus is $\sim 10^{-6}$ G. We assume that this noise is due in large part to fluctuations of the laboratory magnetic field, which were weakened (but not adequately) by external shielding. There is reason to assume that this magnetometer could also be used in measurements of fields substantially weaker than 10^{-6} G.

The superconducting ceramic $YBa_2Cu_3O_7$ rf interferometer studied in the present experiments has stable characteristics when stored in liquid nitrogen for prolonged periods of time (several months). It withstands repeated thermal cycling (77–300 K) with minimal precautions, and it can be kept at 300 K for a matter of weeks. However, even a brief heating (for ~ 30 min) to 340 K in water vapor erases the superconductivity of the weak link at 77 K. This result agrees with studies[9,10] of the decomposition of a $YBa_2Cu_3O_7$ ceramic in water.

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[1)]At 77 K in one of the interferometers ($T_c \approx 85$ K), we were able to observe up to eight such regions in the interval $V_{rf} = 0.06$–0.3 mV.

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