Operation of a massive $YBa_2Cu_3O_x$ SQUID

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In SQUIDs made of massive ceramic $YBa_2Cu_3O_x$ with a constriction as a weak link, quantization contours which do not envelop the aperture of the SQUID operate. A magnetic flux is produced in them by induced currents; i.e., the body of the SQUID operates as a flux transformer, while the role of the constriction reduces to one of increasing the density of the induced current.

Immediately after the first reports of the superconductivity of metal oxide ceramic samples at liquid-nitrogen temperatures and above, attention was attracted to the possibilities of making practical use of these superconductors to fabricate Josephson-effect devices. It was soon shown, in many experimental studies, that there is a macroscopic quantum interference in these materials (Refs. 1–3, for example), and it was suggested that the ceramic is a system of granules coupled by Josephson junctions.

The presence of Josephson junctions in the ceramic itself has made it possible to fabricate a two-hole Zimmerman SQUID[4,5] and also single-hole SQUIDs[6,7] which have operated satisfactorily in liquid nitrogen. The role of weak link was played by a constriction of macroscopic dimensions in those devices. It was suggested by Zavaritskiĭ *et al.*[7] in this connection that the entire set of Josephson junctions in the constriction responds as a single junction to an external agent. However, the characteristics of SQUIDs made of a metal oxide ceramic differ in many ways from those of conventional SQUIDs. Despite the various measurement procedures which have been used, these differences are seen in SQUIDs fabricated in various laboratories, so they characterize the properties of the material itself.

In this letter we are reporting experiments on the particular features of the characteristics of massive SQUIDs made from a $YBa_2Cu_3O_x$ ceramic. We studied cylindrical pickups 4–6 mm long with an aperture of 1.4 mm in diameter and a wall thickness of 0.5–1 mm, with a slit parallel to the axis, which held a crosslink.[6,7] A coupling coil consisting of 20.1-mm-diam copper wire wound in a single layer to a diameter of 1 mm, was placed in the aperture. This coil was connected to a circuit with a resonant frequency of 25–30 MHz and a quality factor $Q \cong 60$. We recorded the amplitude of the voltage across the circuit, $u_\sim$ as a function of the pump current $I_\sim$ (rf current-voltage characteristics) and also the derivative of the rf characteristics, i.e., the dynamic impedance of the circuit ($du_\sim/dI_\sim$) as a function of $I_\sim$ and also as a function of the direct current through the coupling coil, $I_=$. For the impedance measurements we used an amplitude modulation of $I_\sim$ at a frequency of 300–100 Hz. The measurement arrangement is described in more detail in Ref. 4. All the measurements were carried out in liquid helium at 4.2 K in superconducting shields.

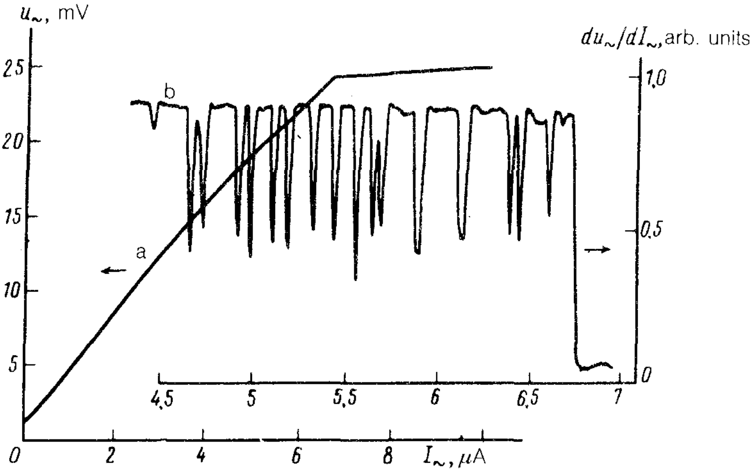

FIG. 1. a—Voltage across the resonant circuit of the SQUID, $u_\sim$; b—the derivative $du_\sim/dI_\sim$ on the part of the rf current-voltage characteristic coming before the plateau, versus the circuit pumping current $I_\sim$.

Figure 1 shows an rf I-V characteristic and its derivative for one of the pickups. As for the two-hole SQUID of Ref. 4, this characteristic has structural features which correspond to an additional power absorption. These structural features are seen particularly clearly, as minima, on the derivative of the rf current-voltage characteristic. In contrast with Ref. 4, the rf I-V characteristic acquires a plateau at sufficiently large values of $I_\sim$; this plateau is ordinarily observed for conventional rf SQUIDs[8] and corresponds to the attainment of the critical current in the SQUID ring. In contrast with a conventional SQUID, however, the introduction of a static magnetic flux Φ in the ring is not reflected in the position of the plateau, while the minima shift. In other words, the SQUID is sensitive to the magnetic field not on the plateau but at lower levels of $I_\sim$.

Figure 2 shows the positions of the minima versus the flux through the SQUID ring; specifically, this figure shows a series of curves of $du_\sim/dI_\sim(I_\sim)$, for which the parameter is $I_=$. It can be seen from this figure that when $I_=$ or $I_\sim$ is swept (when we look at a vertical or horizontal section through the pattern) there is an alternation of regions which are and are not sensitive to a small modulation of $I_=$. The same result was observed in Ref. 7. It corresponds to the signal characteristic reported in Ref. 4. The pattern in which the minima move is similar to the triangular dependence which was in fact found by Zimmerman,[9] for a niobium SQUID with a point contact. The pattern acquires a corresponding meaning if we assume that the coefficient of the coupling of the resonant circuit with the SQUID quantization circuit, k, is small: $k^2Q \ll 1$. In this case,[8] the plateaus on the rf current-voltage characteristics are narrow and are seen only as minima on the derivative.

The pattern in which the minima are positioned should be periodic in Φ with a period $\Phi_0 = \pi\hbar/e$. The pattern in Fig. 2 is not strictly periodic in $I_=$, but one can

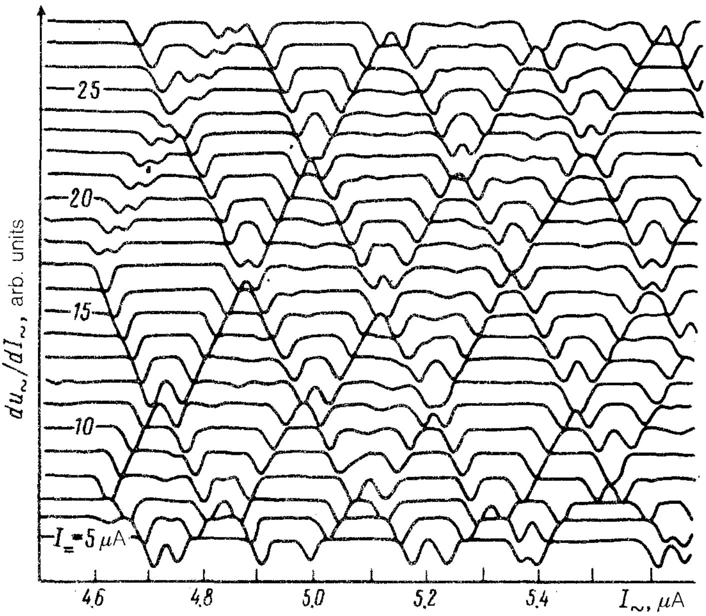

FIG. 2. The derivative $du_\sim/dI_\sim$ for various values of the direct current $I_=$, plotted against the circuit pumping current $I_\sim$. During the recording of the series of curves, $I_=$ was increased in steps of 1 μA (the values are the curve labels), the curves have been displaced upward for clarity.

make out a characteristic distance between similar curves: $\Delta I = 10\,\mu$A, corresponding to a flux $\Delta\Phi = 50\Phi_0$ through the cross-sectional area of the coil. If we assume that ΔI corresponds to Φ_0 in the SQUID quantization circuit, we find $k \sim 0.02$; in other words, the condition $k^2Q \ll 1$ does indeed hold. On the other hand, when we compare the dimensions of the coil and the aperture of the pickup and when we examine the change in the resonant frequency of the circuit when the coupling coil is placed in the SQUID, we conclude that we should have $k \geqslant 0.5$. It follows from these estimates that the SQUID quantization circuit (or circuits) does not coincide with the pickup aperture.

It might be suggested that the quantization circuits lie in the connecting piece and that their weak link with the coil is a consequence of fringing fields. A check showed, however, that in the magnetic field produced by an external solenoid there is a shift of the minima which corresponds to the same value of $\Delta\Phi$, referred to the area of the pickup aperture. We are thus left with the assumption that quantization circuits which lie in the ceramic itself, in the connecting piece or near it, are operating in the pickup. A magnetic field is produced in them by the screening currents, whose density is relatively high near the connecting piece. In other words, the body of the SQUID pickup operates as a flux transformer, and the role of the connecting piece reduces to one of increasing the density of the induced current (a current concentrator). This interpretation contradicts the suggestion by Zavaritskiĭ *et al.*[7] that all of the Josephson junctions in the connecting piece operate as a single junction.

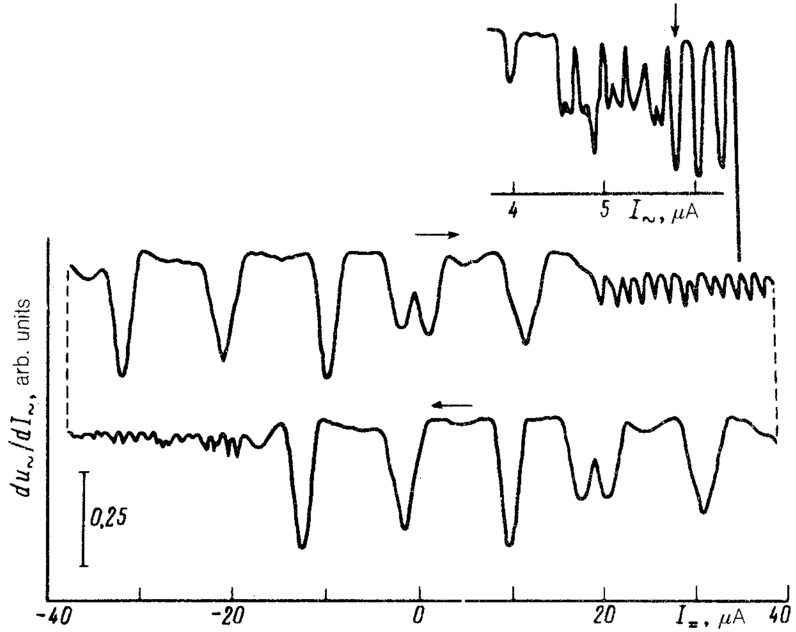

FIG. 3. The derivative $du_\sim/dI_\sim$ at a fixed pump $I_\sim$ versus the direct current $I_=$. The horizontal arrows show the direction in which $I_=$ is swept. The curves have been displaced vertically for clarity. The inset shows part of the derivative of the rf current-voltage characteristic; the pumping current is marked.

Figure 3 shows $du_\sim/dI_\sim$ as a function of $I_=$ at a constant pump level $I_\sim$ near the beginning of the plateau on the rf current-voltage characteristic. As $I_\sim$ is swept, the curve first acquires structural features which are a consequence of the passage of minima; later on, when the sum of the currents induced in the pickup reaches the critical current of the connecting piece, the curve acquires jumps which correspond to an escape of flux from the pickup aperture. When a sweep is made in the opposite direction, all the structural features of the first curve are initially and completely repeated (the curve in a sense shifts along the $I_=$ axis), and then some corresponding jumps appear. This behavior is unambiguous evidence that the magnetic flux through the quantization circuits is determined by the current induced in the pickup, not by the field of the coupling coil.

The curves are shifted along $I_=$ by an amount which is precisely equal to the region of the jumps. In other words, in this region the current induced in the pickup remains essentially constant. This behavior corresponds to Bean's model[10] and is characteristic of hard type II superconductors.

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