Superconducting quantum interference devices based on YBaCuO nanobridges

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Direct current SQUIDs based on YBaCuO thin film nanobridges have been investigated. Critical current densities J_c of the devices are up to 3×10^6 A/cm² at $T=77$ K and show a temperature dependence of $(1 - T/T_c)^{1.6 \pm 0.1}$. High values of the voltage-flux modulation are observed (8 μ V peak to peak at 77 K, 45 μ V at 4.2 K). The temperature dependence of the SQUID modulation is found to be essentially different from the one of the conventional weak link SQUID. We discuss our results by considering degradation of the nanobridge area during structuring, which leads to a transition from SNS to SS'S type junction with decreasing temperature. © 1996 American Institute of Physics. [S0003-6951(96)02608-5]

Most high- T_c SQUIDs are based on grain boundary weak links or ramp-type junctions. The techniques to prepare such structures have been developed extensively and often face technological problems caused by an extremely short coherence length ξ in high- T_c superconductors. Recent results show that nanobridges, although having dimensions significantly exceeding ξ , manifest a true Josephson behavior and are suitable for SQUID fabrication.¹⁻³ The concept of the coherent motion of flux quanta has become a standard for nanobridge description, and explains a wide variety of effects.⁴ However, the periodic supercurrent-phase relation, which is a principal element of SQUID operation, does not follow obviously from this model.

We investigated SQUIDs based on high- T_c thin film nanobridges systematically. We explain the Josephson nature of these devices by considering degradation of the bridge area during structuring, which leads to a transition from SNS- to SS'S-type junctions with decreasing temperature.

SQUIDs were structured in 50 nm thick YBa₂Cu₃O_{7- δ} films by electron beam lithography (EBL) and direct focused ion beam milling (FIB). An inductively shunted dc SQUID geometry was chosen.³ The T_c of unstructured films is (90 ± 1) K. The superconducting transition curves $R(T)$ of the investigated devices show the presence of a "foot" that grows rapidly with the decrease of the bridge width w , with an onset at $w \approx 250$ nm [Fig. 1(b)]. For wider bridges no degradation of T_c has been observed. The current voltage characteristics (I - V) of SQUIDs at zero external magnetic field [see Fig. 1(a)] are similar to those of single nanobridges discussed elsewhere.⁵ The critical current I_c is a linear function of the nanobridge width w for $50 \text{ nm} < w < 350 \text{ nm}$. The critical current density J_c is up to 3×10^6 A/cm² at 77 K and follows $J_c \propto (1 - T/T_c)^{1.6 \pm 0.1}$ in a wide range of temperatures from T_c down to at least $T_c/2$.

For $w < 300$ nm, voltage-flux modulation was observed in our SQUIDs. For a device based on 250 nm bridges, the maximum measured peak-to-peak voltage modulation U_{mod} is 8 μ V at 77 K (see Fig. 2). For a SQUID with 100 nm bridges ($T_c = 60$ K), the maximum U_{mod} is 45 μ V at 4.2 K.

In Fig. 3 the experimental data for the temperature dependence of the voltage modulation $U_{\text{mod}}(T)$ are given. $U_{\text{mod}}(T)$ of the nanobridge SQUID is essentially different from the one of conventional weak link SQUIDs described by the RSJ model. For wider bridges with decreasing temperature starting from T_c of the bulk material, the amplitude of the modulation increases rapidly, and reaches quite a narrow maximum at $T \approx 0.9T_c$. With further decrease of temperature, the amplitude of modulation drops and vanishes, remaining zero at lower temperature. Narrower bridges, where T_c is suppressed significantly, show a maximum at higher temperature, a decrease of the voltage modulation in intermediate temperature range, and an abrupt raise at low temperatures (typically below 20 K) (see also Fig. 5). This behavior cannot be explained by an increase of the SQUID screening parameter $\beta_L = 2I_c L_{\text{sq}} / \Phi_0$ due to the I_c increase with decreasing temperature. The increase of β_L leads to a saturation of the modulation amplitude and not to a suppression.

FIG. 1. (a) The $I(V)$ and (b) $R(T)$ characteristics of SQUIDs with nanobridges of different widths.

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FIG. 2. A typical voltage-flux modulation of a nanobridge SQUID for different bias voltages (here, $w=250$ nm and $T=77.4$ K).

It is reasonable to assume that superconducting properties of YBaCuO change in the vicinity of a trench patterned by either FIB or EBL. Earlier experiments demonstrated that a superconductor shows degradation of T_c after irradiation by high energy ions.⁶ We assume the spatial distribution of T_c in a region close to the trench follows the formula:

$$T_c(x) = T_{cb}(1 - e^{-x/x_0}), \quad (1)$$

where T_{cb} is the critical temperature of bulk, x is the distance from the trench, and x_0 is the characteristic length of the T_c variation. Applying this formula to nanobridges (i.e., two trenches at distance $w=2x$), decrease of T_c of the nanobridge with decreasing w is expected. This is confirmed by the experimental results [see Fig. 1(b)], taking x_0 in the order of 50 nm.

Let us assume that a nanobridge behaves like an SNS-type junction in the temperature range $T_{c2} < T < T_{c3}$, and like a bulk superconductor below T_{c2} , where T_{c2} is the critical temperature of the central region of the bridge, and T_{c3} is T_c of the layer next to it (see Fig. 4). Such system can be described by the “two fluid” model, where the Josephson component of the supercurrent I_j is gradually substituted by a “strong” term (i.e., nonperiodic with the phase difference $\Delta\phi$) with decreasing temperature. We calculated the tempera-

FIG. 3. Voltage-flux modulation U_{mod} as a function of temperature for SQUIDs with bridges of different widths ($w=100, 150, 200$, and 250 nm).

FIG. 4. Schematic critical temperature distribution inside the nanobridge area.

ture dependence I_j [see Fig. 6(a)] using an expression derived by Likharev and Kupriyanov *et al.*^{7,8} for long SS'S junctions:

$$I_j = \frac{\text{const } I_c(T)}{(1 + \sqrt{1 + A^2/2})^2} \exp\left(-\frac{L}{\xi}\right). \quad (2)$$

Here, $A^2 = (T_{cs} - T)/|T_c - T|$, where T_{cs} is the critical temperature of the junction electrodes and T_c is that of the junction area itself. L is the length of the junction. We substituted in the model T_{cs} by T_{c3} and T_c by T_{c2} , where both T_{c2} and T_{c3} are functions of the bridge width w according to Eq. (1).

The SQUID voltage modulation is proportional to the critical current I_c (assumed to be the Josephson current) and can be written as⁹

$$U_{\text{mod}} = \frac{7}{\pi^2} \frac{I_c R_n}{1 + \beta_L} \left(1 - 3.57 \frac{\sqrt{k_b T L_{sq}}}{\Phi_0} \right). \quad (3)$$

This expression explains the vanishing of U_{mod} of the SQUIDs with decreasing temperature due to the decline of the Josephson term I_j of the full supercurrent of the nanobridge. By assuming a T_c distribution along the bridge according to Eq. (1), the temperature range where the modulation is observed can be calculated and agrees with the experiment for bridges of all widths.

FIG. 5. The amplitude of the SQUID voltage-flux modulation U_{mod} and its dynamic resistance R_{dyn} ($U_{\text{bias}} = 10$ μV) as a function of temperature.

FIG. 6. Calculated Josephson current component I_j (a) and the amplitude of the voltage-flux modulation U_{calc} (b) for SQUID with bridges of different widths ($w=100, 150, 200$, and 250 nm).

The difference between our SQUIDs and the conventional Josephson weak link devices described by the RSJ model is that the nanobridge SQUID is a typical “flux-flow” device with the corresponding I - V characteristics [see Fig. 1(a)]. Instead of a single and well-defined RSJ-like resistance parameter R_n , the nanobridge SQUID is characterized by its bias-dependent dynamic resistance R_{dyn} , which is determined by effects of vortex flow in the bridge and can depend on temperature in a rather complicated way. In Fig. 5, R_{dyn} of a SQUID with 150 nm bridges, measured experimentally, is presented. It raises strongly in both low and high temperature regions. By substituting in Eq. (3) R_n the approximation of the experimental values of R_{dyn} and I_c by the calculated $I_j(T)$, the SQUID voltage modulation U_{calc} was calculated as a function of temperature for bridges of different width [Fig. 6(b)]. A qualitative agreement between the experimental data and the calculated ones has been obtained for all temperatures and bridge widths (compare Figs. 3 and 6(b)).

A more realistic assumption would be that even at high

temperatures, only a small fraction of total supercurrent in the bridge is of Josephson origin. This coincides with the high observed values of J_c at 77 K and explains why we did not see any significant suppression of I_c by a weak magnetic field. The above discussion brings up the idea that vortices in the nanobridge are not always of the pure Abrikosov type, but can gain properties of Josephson fluxons, like increase of the vortex size and gradual disappearance of the normal vortex core with decreasing w .⁷ This could also explain the low value of the viscous drag coefficient η of vortex motion in a nanobridge.⁵ The proposed $T_c(x)$ distribution near the bridge edge leads to a more complicated shape of the edge barrier for a vortex to enter the bridge than usually assumed.⁴

In summary, SQUIDs based on high- T_c thin films have been made. They show well-reproducible voltage-flux modulation U_{mod} with amplitude comparable to that of conventional weak link SQUIDs. The temperature dependence of U_{mod} is found to be essentially different from that known for weak link SQUIDs. To explain this phenomenon, we considered degradation of superconductor in the nanobridge area, which leads to a local suppression of T_c and to a transition from SNS to SS'S-type junctions with decreasing temperature. This approach allows us to explain the experimental data for T_c and $U_{\text{mod}}(T)$ for SQUIDs with nanobridges of different widths.

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