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Design and realization of an all *d*-wave dc π-superconducting quantum interference device

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The predominantly $d_{x^2-y^2}$-pairing symmetry in most high-T_c superconductors provides the opportunity to fabricate Josephson junction circuits in which part of the junctions are biased by a phase difference of the superconducting order parameter of π. We present fabrication and measurements of an all high-T_c dc superconducting quantum interference device (dc SQUID) realized with thin-film technology, of which the Josephson junctions consist of one standard junction and one junction with a π-phase shift. The characteristics of the π-SQUID are compared with the properties of a standard high-T_c SQUID. © *2000 American Institute of Physics.* [S0003-6951(00)02906-5]

A predominantly d-wave symmetry of the order parameter[1] influences many basic properties of high-T_c superconductors, including characteristic features of Josephson junctions.[2–4] The unconventional order parameter symmetry offers the possibility to fabricate electronic circuits in which the phase differences of selected Josephson junctions are in equilibrium biased by π. For convenience, for the rest of the letter such junctions will be termed π junctions, with the understanding that it is not the microscopic transport across the junction,[5] but the superconducting circuit consisting of the junction and the superconducting quantum interference device (SQUID) loop, which creates the π-phase shift. Such π junctions have been considered first by Geshkenbein *et al.*[6] in studies of heavy fermion superconductors and by Sigrist and Rice investigating high-T_c superconductivity.[7] As suggested by Terzioglu and Beasley,[8] π junctions are useful for the fabrication of so-called complementary Josephson junction circuits, which, e.g., are characterized by small power dissipation and large circuit margins. Likewise, circuits containing π junctions have been used with outstanding success for analyses of the order parameter symmetry.[9–15] For practical reasons, it is desirable to realize such circuits in an all high-T_c thin-film technology using standard growth processes. In bicrystalline films, π junctions occur naturally at grain boundary facets.[16,17] Although these π facets strongly affect the properties of the grain boundaries, they have not been used for the fabrication of devices, as it has not been possible to control their growth with the required accuracy.

The first intentionally fabricated π junctions were built by contacting single crystals of $YBa_2Cu_3O_{7-\delta}$ with a conventional s-wave superconductor. In these studies, done by Wollman and van Harlingen *et al.*,[9] and subsequently by Brawner and Ott,[14] dc SQUIDs or corner junctions combining standard junctions (0 junctions) and π junctions have been fabricated. All-high-T_c π junctions were first designed and used by Tsuei and Kirtley *et al.* in their tricrystal ring experiments.[10,11] Likewise, SQUID rings which consisted of $YBa_2Cu_3O_{7-\delta}$ and Pb films and contained π junctions were fabricated by Mathai *et al.*[12] $YBa_2Cu_3O_{7-\delta}$ tricrystal junctions, which included 0 and π junctions, were investigated by Miller and coworkers.[13]

In the work presented here, we aimed to fabricate a thin-film high-T_c dc SQUID which includes one π junction and one 0 junction [see Fig. 1(a)] and to unambiguously verify its operation. This device will be referred to as "π-SQUID." For symmetric π-SQUIDs with small inductance L, the phase shift across the π junction causes a minimum of the magnetic-field-dependent SQUID critical current $I_c(H)$ at small applied magnetic fields H, as compared to the maxi-

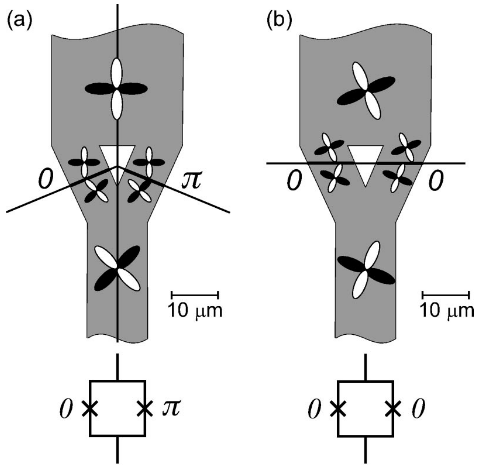

FIG. 1. Schematics of (a) the π-SQUID and (b) the standard SQUID investigated. For both SQUIDs, the junctions straddle symmetric 45° [001]-tilt grain boundaries. As sketched by the vertical line, there is an additional boundary with nominal misorientation of 0° present in the π-SQUID.

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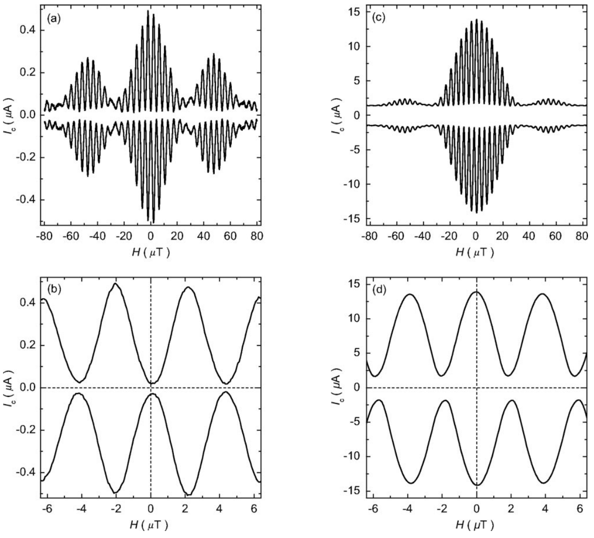

FIG. 2. Dependencies of the critical current on applied magnetic field of the π-SQUID (a) and (b) and of the standard SQUID (c) and (d) at 77 K.

mum shown by the $I_c(H)$ patterns of standard SQUIDs. However, the mere observation of such a minimum does not serve as an unambiguous proof of proper device operation, because a minimum may be mimicked by shifts of the SQUID oscillations along the magnetic-field axis, caused by trapped magnetic flux, background magnetic fields, or SQUID asymmetries.

To prove the correct operation of the π-SQUID, it was designed as a distributed-junction SQUID with a small inductance L. This design offers three essential advantages:[18] First, unequal critical currents of the two Josephson junctions of a SQUID, or unequal inductances of the two SQUID arms, lead to shifts of the $I_c(H)$ patterns only in case the screening parameter $\beta_L = LI_c/\phi_0$ is non-negligible, as the asymmetry-induced shifts are proportional to β_L. Here, ϕ_0 is the magnetic-flux quantum. Therefore, a small screening parameter guarantees that such possible asymmetries cannot mimic a minimum of the $I_c(H)$ dependence. Second, distributed-junction SQUIDs allow simultaneous measurements of potential background magnetic fields, and of the SQUID oscillations. This is the case as the period of the SQUID oscillations is sizable compared to the periodicity of the $I_c(H)$ dependencies of the individual junctions, which give rise to the envelope of the SQUID $I_c(H)$ characteristic. A measurement of this envelope provides the value of the background magnetic field H_0, to which the $I_c(H)$ pattern is symmetric. Third, a symmetric envelope proves that trapped magnetic flux or other inhomogeneous fields are not affecting the SQUID oscillations.[18]

The design of the π-SQUID is illustrated in Fig. 1(a). It is based on two ≈ 9-μm-wide, symmetric $45° \pm 1°$ [001]-tilt grain boundaries formed by a ≈ 100-nm-thick, c-axis oriented $YBa_2Cu_3O_{7-\delta}$ film grown by pulsed-laser deposition at 760 °C in 0.25 mbar of O_2 on a $SrTiO_3$ tetracrystal.[15] Due to the orientation of the grain boundaries, one of the junctions is a π junction. In practice, this will be the junction with the smaller critical current, as it has the smaller Josephson coupling energy. Because a symmetric design of the SQUID is preferable for our goals, we did not define specifically which one of the two Josephson contacts is the π junction. To optimize the symmetry of the device, the grain-boundary angle was chosen to be as close to 45° as possible, which is not a general requirement for the design of the π-SQUIDs. The design was aimed for an inductance $L \cong 20$ pH, corresponding to $\beta_L \cong 10^{-1}$ at 77 K.[19] For comparison, we also fabricated a standard SQUID containing conventional Josephson junctions only, as sketched in Fig. 1(b). All characteristics, measured in a magnetically shielded room, were reproduced over several weeks and after numerous thermal cycles to room temperature.

The current–voltage, $I(V)$ characteristics of the π-SQUID and of the standard SQUID at 77 and 4.2 K follow the behavior expected according to the resistively shunted junction model, with additional self-induced resonances. The maximum values reached by the critical current of the π-SQUID as a function of applied magnetic field were approximately 15 μA at 4.2 K and 0.5 μA at 77 K. The critical currents of the standard SQUID were considerably larger, approximately 200 and 14 μA, the current densities remaining in the range common for symmetric 45° grain boundaries. Clear differences between the π-SQUID and the standard SQUID are revealed by the magnetic-field dependencies of the critical currents, which are shown in Fig. 2. These $I_c(H)$ characteristics have been obtained from the $I(V)$ dependencies using a voltage criterion of 5 μV. Both devices show clear SQUID modulations bounded by the envelope given by the $I_c(H)$ dependencies of the grain-boundary junctions. As is typical for 45° grain boundaries,[17] the envelopes deviate from a Fraunhofer pattern. It was noted that at 4.2 K the $I_c(H)$ dependence of the π-SQUID is slightly asymmetric, suggesting that at this temperature β_L is not completely negligible. For both devices, the SQUID oscillations and the envelopes at 77 K are highly symmetric with respect to a small offset field $H_0 < 0.2\ \mu$T.

As discussed, the symmetry and the small value of H_0 prove that the influence of trapped magnetic flux and of magnetic background fields on the measurements are small. It is noted that for the π-SQUID an asymmetry of the SQUID oscillations with respect to H_0 may be caused by small admixtures of non-$d_{x^2-y^2}$-wave components to the $d_{x^2-y^2}$-wave dominated order parameter, e.g., $d_{x^2-y^2} + \alpha_1 is + \alpha_2 id_{xy}$,[18] and thus yields information about the admixture coefficients α_i as analyzed elsewhere.[20] The large modulation depths of the SQUID oscillations indicate a large degree of symmetry in both the critical currents and inductances of the SQUID arms. Analysis of the SQUID modulation at 4.2 K yields for the π-SQUID an upper limit to the screening parameter $\beta_L(4.2\ \text{K}) < 0.15$. By considering the temperature dependence of I_c from this value an upper limit $\beta_L(77\,\text{K}) < 5 \times 10^{-3}$ is derived. Therefore, as designed, at 77 K the π-SQUID is in the limit of small β_L, and the $I_c(H)$ characteristic is not influenced by possible small SQUID asymmetries.

As expected, the $I_c(H)$ pattern of the π-SQUID shows a minimum at small fields exactly opposite to the behavior of the standard SQUID's critical current, which goes through a maximum. This effect demonstrates unambiguously that the π-SQUID operates correctly. The π-SQUID investigated, therefore, represents a practical realization of the complementary junction technology proposed by the Stanford group.[8]

According to the sample design, the ground states of the π-SQUID are characterized by two states of comparable energy, differing only by which is the π junction, or potentially by the coherent superposition of these states. As the switching time between the ground states is short and because the π-SQUIDs allow coupling into logically interconnected systems, it is worthwhile to investigate whether π-SQUIDs are useful for potential future devices, such as superconducting qubits. In that case, to obtain sufficiently long coherence times, the π-SQUID parameters are to be adjusted.

In conclusion, we have designed and measured a high-T_c thin-film dc SQUID, which is based on a standard Josephson junction and on a π-junction. This technology is extendible for the design of circuits with a larger number of π Josephson junctions, fabricated, for example, by using a template biepitaxial process or ramp-type Josephson junctions.

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