Magnetic Phase Shifter for Superconducting Qubits

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We have designed and investigated a contactless magnetic phase shifter for flux-based superconducting qubits. The phase shifter is realized by placing a perpendicularly magnetized dot at the center of a superconducting loop. The flux generated by this magnetic dot gives rise to an additional shielding current in the loop and induces a phase shift. By modifying the parameters of the dot an arbitrary phase shift can be generated in the loop. This magnetic phase shifter can, therefore, be used as an external current source in superconducting circuits, as well as a suitable tool to study fractional Josephson vortices.

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Various solid state structures can exhibit quantum behavior, potentially interesting for quantum computing [1]. A typical example is a superconducting flux qubit based on Josephson junctions, which operates by utilizing the degeneracy of the two equal and opposite persistent currents at half-integer flux $(n + 1/2)\Phi_0$ through the superconducting circuit, where Φ_0 is the superconducting flux quantum ([2] and references therein). The degeneracy is lifted by the charging energy, and the two distinct quantum states $|0\rangle$ and $|1\rangle$ are associated with the opposite circulation of the superconducting condensate. A resonant external excitation can make the superconducting condensate oscillate coherently between these two states [2]. Although an external applied field has been used in the experiments to generate the flux necessary a for π shift in the superconducting qubit, it is thought that the fluctuations of the external flux (flux noise) present a major source of decoherence [3]. Therefore, it has been a challenge to incorporate π shift in the qubit and enable its operation without an external bias field. A number of structures using high-T_c superconductors have been proposed ([4] and references therein). In high-T_c superconductors, due to the predominant $d_{x^2-y^2}$ symmetry of the order parameter, π shift can inherently be gained if, for example, the interfaces of the Josephson contacts are made of two superconductors rotated by $\pi/2$ in the *ab* plane. However, this particular symmetry poses a fundamental constraint on the overall coherence of the high-T_c superconducting qubits. Since the superconducting gap Δ is zero along the nodal directions, normal quasiparticles that are inherently incoherent are present even at very low temperatures. For this reason, the application of high-T_c superconductors is a trade-off in terms of coherence: decoherence due to the flux noise is eliminated, but an additional source of decoherence related to the presence of normal quasiparticles is introduced.

In this Letter we propose a new practical realization of a phase shift for the superconducting qubit. The phase shift is achieved by placing a magnetic dot with the perpendicular magnetization at the center of a loop made of a *conventional* *s*-wave superconductor. The flux generated by the dot creates an additional current in the superconducting loop giving rise to a phase shift. We believe that the proposed design has several advantages. First and foremost, the phase shift is a result of a quite basic and general property of superconductors and can be implemented without any limitations. It does not require *d*-wave symmetry of the order parameter, nor does it put any constraints on the interfaces of Josephson junctions, as with high-T_c superconductors. More importantly, the phase shift is achieved with an *s*-wave superconductor, and, therefore, no additional decoherence appears in the system, as in the case of the *d*-wave superconductors. As the magnetic dot is separated from the superconducting loop it cannot, by all means, adversely affect the operation of the qubit. The generated flux and, consequently, the persistent current in the loop are stable. Technologically, the fabrication procedures for conventional nanostructured superconductors and ferromagnets have been mastered and can be carried out routinely. By conveniently varying the parameters of the dot it is possible to introduce *any* phase shift in the loop. The magnetic phase shifter can, therefore, be used as an external current source with a high stability. Furthermore, it may well be applied for phase biasing in the experimental study of fractional Josephson vortices [5]. Since the phase shifter can be used with *s*-wave superconducting circuits, the integrability and scalability of the qubit are not deteriorated.

The sample was prepared with electron beam lithography in three phases. For the details on the fabrication procedure we refer to Refs. [6,7]. The superconducting loop is made up of 46 nm thick Al, with the inner and outer radii 680 and 915 nm, respectively, whereas the radii of magnetic dots are 174 nm (hereafter "sample *A*") and 350 nm (hereafter "sample *B*"), respectively. The dots consist of ten bilayers of 0.4 nm Co and 1 nm Pd, with a 2.5 nm Pd buffer layer. This composition

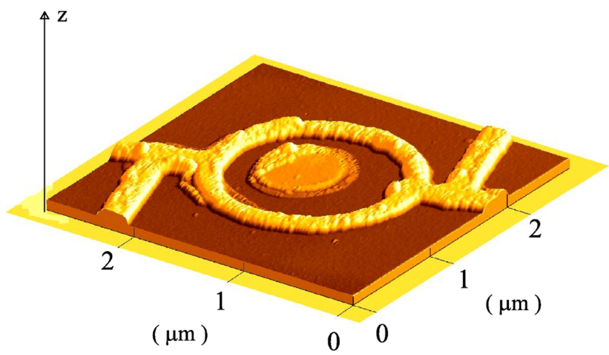

FIG. 1 (color online). An AFM image of sample *B*.

of the dots has been chosen since it provides a sufficiently high coercive field of approximately 150 mT, as well as a complete remanence and nearly perfectly rectangular shape of the hysteresis loop. Prior to the measurements the dot was saturated in the field of 800 mT. The external magnetic field was being varied within the range $-30 \leq B_a \leq 30$ (mT), so that the magnetization of the dot remained unaltered during the measurements. The mean free path of Al, estimated from the resistance of the coevaporated Al sample at 4.2 K, is $l \approx 16$ nm, whereas the Ginzburg-Landau coherence length is $\xi(0) \approx 138$ nm. Figure 1 shows an atomic force micrograph of sample *B*. The surface of the Al loop, as well as a part of magnetic dot, seem to be corrugated. This is just due to the presence of the remains of the electron beam resist after the lift-off procedure, as ascertained by the atomic force microscopy, and we do not consider them to have any impact on the properties of the samples.

The superconducting properties of these structures were investigated with transport measurements, applying the magnetic field perpendicularly to the sample surface and using a transport current with the effective value of 100 nA and frequency of 27.7 Hz. The measurements were taken with the field and temperature resolution of 10 μT and 0.4 mK, while the resolution of the dc current was 0.01 μA. Special attention was being paid to eliminate any possibility of a trapped flux in the setup before a set of measurements was started up.

Figure 2 shows the critical current of the structures (filled symbols) versus the normalized applied flux, taken with the step of $0.1\Phi_a/\Phi_0$ within the range $\Phi_0 \leq \Phi_a \leq \Phi_0$ at 99.5 % of the maximum critical temperature of the structures $T_{cm} = 1.3105$ K. The solid lines are the theoretical curves obtained by using de Gennes–Alexander theory for superconducting micronetworks [8]. The flux has been calculated with respect to the mean radius of the loop $r_m = 797.5$ nm, taking the field parallel to the z direction as positive (Fig. 1).

A homogeneous mesoscopic superconducting loop whose width w and thickness t are much smaller than the coherence length $\xi(T)$ [$w, t \ll \xi(T)$, 1D regime] exhibits an oscillatory dependence of the critical

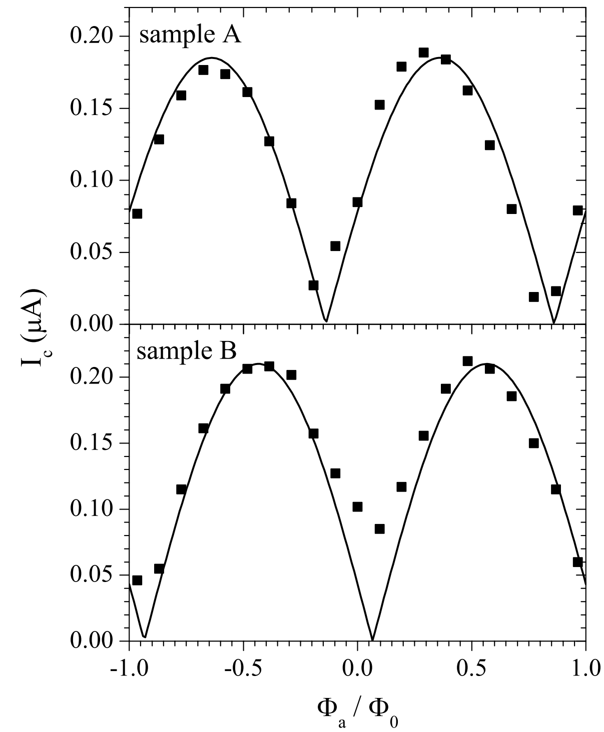

FIG. 2. The critical current of the structures versus the normalized applied flux. The measurements were taken with the field step of $0.1\Phi_a/\Phi_0$ at 99.5 % of the maximum critical temperature $T_{cm} = 1.3105$ K. The solid line is the theoretical curve [Eq. (1)].

current [9,8]

$$I_c = I_{cm} \left| \cos\left(\pi \frac{\Phi}{\Phi_0} \right) \right|, \tag{1}$$

where Φ is the total flux through the loop and I_{cm} is the maximum critical current. Close to the zero-field critical temperature the influence of self-inductance can be neglected and the flux through the loop equals the applied flux. As the coherence length at $T = 0.995T_{cm}$ is $\xi(T) \approx 1.9$ μm and the width of the loops is $w = 0.235$ μm, the samples are in the 1D regime and the de Gennes–Alexander theory is applicable. In order to take into account the magnetic dots, Eq. (1) has to be modified by adding the flux generated by the dots to the applied flux. The stray fields of the dots were obtained by magnetostatic calculations [6,10]. Using the saturation magnetization of the bulk Co, it has been estimated that the flux generated by the dot in sample *A* is $-0.4\Phi_0$, whereas in sample *B* the flux equals $-1.6\Phi_0$. Both values are in a good agreement with the experimental $I_c(\Phi/\Phi_0)$ data (Fig. 2). Close to the zero applied flux $\Phi_a/\Phi_0 = 0$, sample *A* has a finite resistance, which is lower than the residual resistance in the normal state, and its critical current has therefore been taken as zero. On the other hand, for the same applied flux sample *B* remains in the superconducting state and has a finite value of the critical current. A very good agreement in the periodicity of the critical current, but similar discrepancies in the amplitude of the critical current, have already been observed in Ref. [9].

The loops have a minimum in the critical current in the vicinity of zero applied flux and maxima for finite applied fluxes around $\pm\Phi_0/2$. This is a clear evidence that phase shifts are introduced in the loops. More importantly, given that the superconducting loops are identical and that the minima and maxima are attained for different values of the applied flux, it is evident that the phase shift is governed by the flux of the dot. Neither of the curves displays exactly π shift, but we have convincingly demonstrated that magnetic dot can efficiently be used as a phase shifter, as well as that the phase shift can be controlled by changing the parameters of the dot. The flux of the dot necessary for π shift can be tuned by changing the radius of the dot or by varying the number of Co/Pd bilayers. By increasing the number of Co/Pd bilayers the magnetization, as well as the coercive field of the dot, increase, whereas the direction of the magnetization, remanence, and the shape of the hysteresis loop remain unchanged. Moreover, the dependence of the coercive field on the number of Co/Pd bilayers makes it possible to ensure that an externally applied magnetic field, used for instance for the readout of the qubit, does not affect the flux generated by the dot.

Even though electron beam lithography introduces to some extent manufacturing errors, additional lithographic step with an accurate alignment, needed to place a magnetic dot at the center of the loop, as well as optimization of the radius of the dot in order to generate flux needed for exact π shift, do not constrain applicability of the phase shifter. A magnetic dot as a phase shifter is intended for superconducting flux qubits that are also fabricated by electron beam lithography and, therefore, posses their own variability in dimensions, as well as properties of the Josephson junctions [2]. Equally importantly, superconducting flux qubits are typically loops with the area of approximately 20–25 μm^2. In this range, dedicated electron beam lithography tools are very accurate and there is effectively no discrepancy between the designed and achieved dimensions of a structure.

Figure 3 presents the superconducting phase boundary of sample *A*. The data are given as the normalized critical temperature $1 - T_c(\Phi)/T_{cm}$ versus the normalized applied flux Φ_a/Φ_0. The open symbols are experimental data and the solid line is the theoretical curve, whereas the dashed line is the theoretical curve obtained for the reference loop with the same parameters, but without magnetic dot. The theoretical $T_c(\Phi/\Phi_0)$ dependence, found from the Ginzburg-Landau theory, shows good agreement with the experimental data. For the details of our method we refer to Ref. [7]. The real dimensions of the loop, as well as the aforementioned values of the flux generated by the dots, have been used in the calculations and the best agreement with the experimental data has been obtained for the coherence length of $\xi(0) = 100$ nm. The discrepancy between this value of $\xi(0)$ and the estimation from the reference sample $\xi(0) = 138$ nm is typically encountered in mesoscopic Al structures and is accounted for by the influence of the contacts, which effectively increase the radius of the superconducting loop, as well as by minor nonuniformity in the width of the loop [11]. The $T_c(\Phi)$ phase boundary is pronouncedly modified by the stray field of magnetic dot, displaying a phase shift (Fig. 3). It should be noted here that, due to its inhomogeneity, the stray field affects the phase boundary in a nontrivial way bringing about an additional asymmetry in the phase boundary, as discussed in Ref. [7]. For this reason, two consecutive minima in the phase boundary of the loop with magnetic dot (corresponding to local maxima of the critical temperature) have different values and appear at different fluxes. The inhomogeneity of the stray field, however, does not prevent the application of the proposed phase shifter. In order to operate, the superconducting qubit has to be driven to the state where the flux is $\Phi_0/2$. Other states are less important for the operation of the qubit, provided that they are well separated from the relevant state so that the interference between them can be ruled out. Irrespective of its inhomogeneity, the stray field of the dot can generate $\Phi_0/2$, thus providing the necessary conditions for the qubit to operate. We mention that in our experiment the $T_c(\Phi)$ phase boundary may be slightly affected by the displacement of magnetic dot from the center of the opening, which is for both samples approximately 125 nm and is caused by the limitations of the electron beam writer at our disposal.

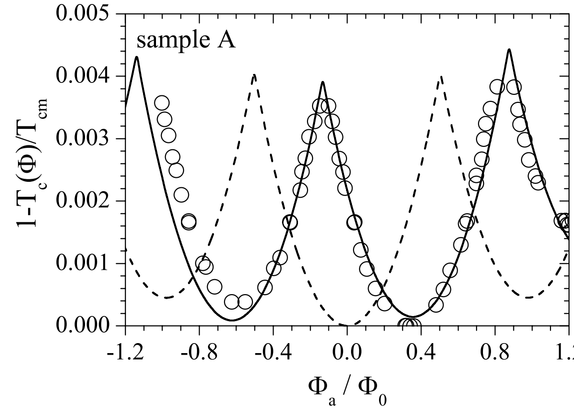

FIG. 3. The superconducting phase boundary of sample *A* presented as $1 - T_c(\Phi)/T_{cm}$ versus the Φ_a/Φ_0. The open symbols are experimental data, the solid line is the theoretical fit, and the dashed line depicts the theoretical phase boundary of the loop without magnetic dot.

Figure 4 presents $I(V)$ curves taken at the values of the applied flux which correspond to the maxima and minima

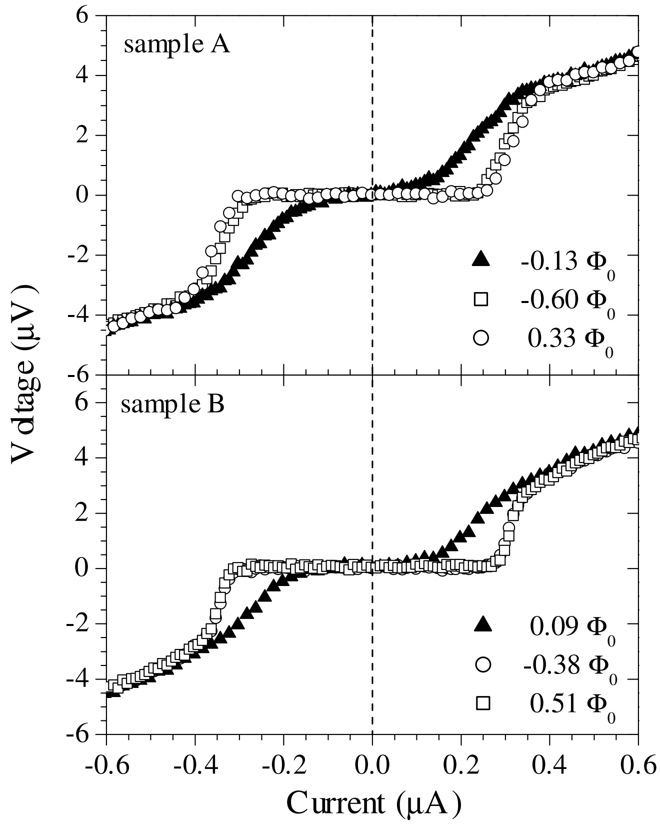

FIG. 4. $I(V)$ curves of the samples taken at the field values corresponding to the minima and the maxima of the phase boundary within the range $-\Phi_0 \leq \Phi_a \leq \Phi_0$.

of the superconducting $T_c(B)$ phase boundary (the phase boundary of sample B is not shown) at $0.995T_{cm}$. The values of the fluxes are indicated in the figures. The presence of the phase shifts is unambiguously and directly demonstrated for both samples, as the critical currents for finite applied fluxes are higher than the critical currents around the zero applied flux.

In conclusion, we have fabricated and investigated a contactless magnetic phase shifter for flux-based superconducting qubits. It has been demonstrated that a phase shift can be induced in the superconducting circuit, as well as that it can be controlled by modifying the parameters of the magnetic dot. As the magnetic phase shifter can generate an arbitrary phase shift, it can be used as an external high stability current source for superconducting elements, or may serve as a tool to investigate fractional Josephson vortices. The experimental results have been interpreted in the framework of de Gennes–Alexander theory for superconducting micronetworks and the Ginzburg-Landau theory.

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