Controllable π SQUID

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We have fabricated and studied a promising kind of direct current superconducting quantum interference device (dc-SQUID) in which the magnitude and sign of the critical current of the individual Josephson junctions can be controlled by additional voltage probes connected to the junctions. We show that the amplitude of the voltage oscillations of the SQUID as a function of the applied magnetic field can be tuned and that the phase of the oscillations can be switched between 0 and π in the temperature range of 0.1–4.2 K using a suitable control voltage. This is equivalent to the external application of $(n+1/2)$ flux quantum. [DOI: 10.1063/1.1414304]

The direct current (dc) superconducting quantum interference device (SQUID) is the most sensitive magnetic flux sensor currently available. It combines two phenomena: Flux(oid) quantization and the Josephson effect.[1–3] The critical current of the SQUID is an oscillatory function of the applied magnetic flux ϕ_{app} with a period given by the flux quantum $\phi_0 = h/2e = 2.07\times 10^{-15}$ Wb. Using a suitable current I_{Bias} a little larger than the sum of the critical currents of the two Josephson junctions, the oscillating critical current is transformed into an oscillatory voltage. The SQUID can be designed to meet various demands. However, once fabricated, the properties of the device, in particular, the critical currents of the two Josephson junctions, are fixed. On the other hand, a recent development in the field of mesoscopic superconductivity is the controllable Josepshon junction. In such a junction it is possible to change the magnitude of the critical current I_c,[4–6] and even reverse its direction with respect to the phase difference φ between the superconducting electrodes.[7–12] This corresponds to an extra phase factor of π in the Josephson supercurrent (I_{sc})-phase relation $I_{\mathrm{sc}} = I_c \sin(\varphi) \Rightarrow I_{\mathrm{sc}} = I_c \sin(\varphi+\pi)$. This π-junction behavior is well known in the field of high-T_C superconductors,[13] and has also been observed in ferromagnetic weak links.[14] However, the state (normal or π) of the junction is fixed once the device has been made, this in contrast with a *controllable* π junction. We have implemented such a *controllable* Josephson junction in a dc-SQUID, which leads to a controllable π SQUID, in which the critical currents of the individual junctions,[15] and hence, the symmetry of the SQUID, can be fine tuned. More interestingly, the device can be switched from a state where no circulating current is running around the SQUID loop (at $\phi = n\phi_0$ with n an integer), to a state with a circulating current running around the SQUID loop, without the application of an external magnetic field, but by switching one of the weak links into the π state. This is a consequence of the condition of a single-valued wave function around the SQUID loop:

$$\frac{2\pi\phi}{\phi_0} - \varphi_1 - \varphi_2 = 2\pi n, \tag{1}$$

where the total flux $\phi = \phi_{\mathrm{app}} + LI$, the flux due to the screening current. Switching, for example, junction 1 in the π state changes φ_1 with π, which leads to the same solution of Eq. (1) if the junction would be in the normal state and $\phi = (n + \frac{1}{2})\phi_0$.

In this letter, we propose and demonstrate experimentally the controllable π SQUID and show that the magnitude of the voltage oscillations as a function of the applied magnetic field (V–B oscillations) can be tuned and shifted a factor of π in phase.

The only realization so far of a controllable π junction is based upon a superconductor–normal metal–superconductor (SNS) junction in which the normal region is made of gold or silver and the superconductor is made of niobium.[11,12] The normal region of the junction is connected to the center of a short mesoscopic wire ($\sim$1 μm), that we will call the control channel, which is attached also to two large electron reservoirs. In practice, the device has a cross shape, with the control channel crossing the normal region of the junction. The principle of operation is the following: A control voltage V_c is applied over the control channel, resulting in a change in the electron energy distribution in the channel, and therefore, the normal region of the SNS junction. As a consequence, the occupation of the quantum states that carry the supercurrent though the normal region is also changed. If the control channel is sufficiently short, so that both electron–phonon and electron–electron interactions can be neglected, the electron energy distribution in the center of the control channel will not be a Fermi distribution, but the renormalized superposition of the electron distribution functions of the two reservoirs. This distribution is a double step function, with a separation of eV_c between the steps if $eV_c \gg k_b T$.[16]

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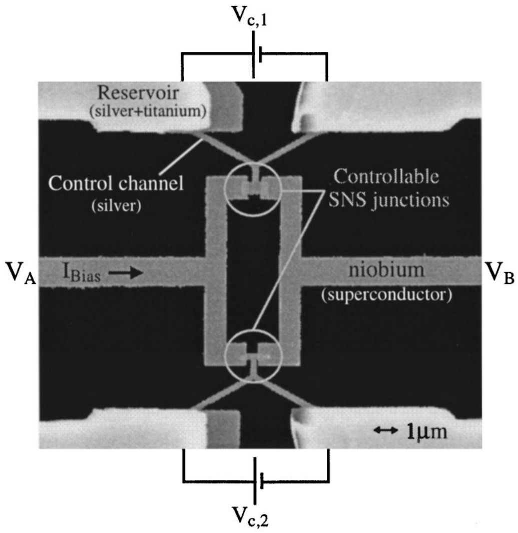

FIG. 1. Scanning electron microscope picture of the controllable π SQUID. The currents and voltages used in the experiment are also indicated, with the voltage over the SQUID, $V_{\mathrm{SQUID}}=V_B-V_A$.

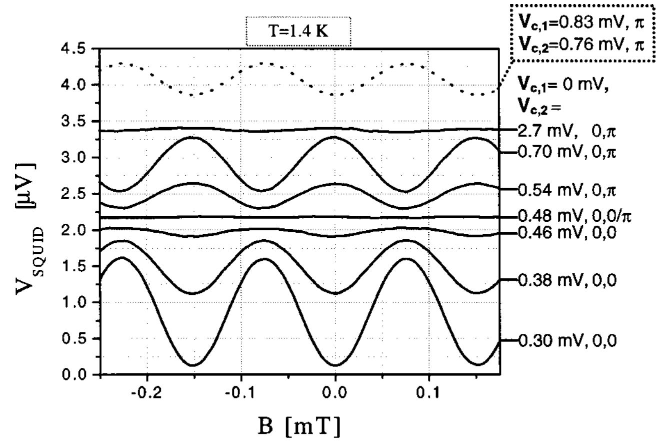

FIG. 2. Voltage over the controllable SQUID as a function of external magnetic field B for different values of $V_{c,1}$ and $V_{c,2}$ (curves offset for clarity).

Here, T is the electron temperature in the reservoirs and k_b is Boltzmann's constant. The effect of this specific electron distribution in the normal region of the SNS junction on the magnitude of the critical current is a reduction of the critical current to zero and a subsequent sign reversal with increasing V_c. In the limit of strong electron–electron interaction and still negligible electron–phonon interaction, the electron energy distribution in the control channel will be a thermal one with, however, an elevated effective temperature proportional to V_c (hot-electron regime). The effect of such a distribution on the critical current of the junction is a monotonic decrease to zero, analogous to a rise in temperature.[4,17]

A practical realization of a controllable π SQUID is shown in Fig. 1. A niobium loop (thickness: 50 nm, surface area: 12 μm^2) has two metallic weak links made of silver (thickness 50 nm). The length of the normal regions of both junctions is 1100 nm with a Nb separation of 420 nm. The width of the normal regions is 520 nm for the top junction and 220 nm for the bottom junction. The silver weak links are each connected to a V-shaped silver control channel with a total length of $5+1$ μm, which connects to two large silver reservoirs 475 nm thick and a surface area of about 1 mm^2. The size of the reservoirs is needed because they should act as effective cooling fins to prevent unwanted electron heating at $T<1$ K.[18,19] The resistance per square of the normal region of the junction and the control channel is 0.4 Ω, which yields, using free-electron theory, an elastic mean-free path of 46 nm with diffusion constant $D=0.02\,\mathrm{m}^2/\mathrm{s}$. The Thouless energy, estimated from the junction dimensions, is identical for both junctions and given by $E_{\mathrm{th}}=12\,\mu\mathrm{eV}$.

The geometry of the controllable Josephson junction used in the controllable SQUID differs from the conventional cross shape. The disadvantage is that length L of the control channel is much larger than in the case of a cross-shaped device, resulting in a diffusion time $\tau_D=\sqrt{L^2/D}\approx 2$ ns. As a consequence, a material with a long electron–electron relaxation time is needed to be able to maintain a nonthermal energy distribution in the control channel. For this reason silver is used as the normal metal.[20,21]

We now describe the sample fabrication, again referring to Fig. 1. The samples have been realized on a thermally oxidized Si wafer that is covered with a 150 nm layer of sputter-deposited Al_2O_3 to improve the adhesion of Ag. In the first step the Nb ring is deposited using standard e-beam lithography on a double layer of PMMA, dc sputtering, and subsequent lift-off. The critical temperature of the sputtered film is 8.1 K. Subsequently, the silver normal region, control channel, and the reservoirs are deposited in one single step using shadow evaporation. This is needed because the adhesion of Ag is so poor that it is not possible to bake this film to be able to do another lithography step. We use a double layer of PMMA–MA and PMMA with e-beam lithography and wet etching to create a PMMA-suspended mask. The deposition is done in an UHV deposition system with a background pressure of 5×10^{-10} mBar, the pressure in the system during the evaporation steps is $\leqslant 5\times10^{-8}$ mBar.

Prior to deposition, we use argon etching ($P_{\mathrm{Ar}}=1\times10^{-4}$ mBar, 500 V) for 3.5 min to clean the Nb surface. After that, we deposit 10 nm of a Ti adhesion layer under a large angle (47°), with the result that the Ti layer is only deposited on the substrate at the position of the reservoirs, whereas it will be deposited on the sides of the resist at the position of the thin openings defining the control channel and the normal region of the junction. Subsequently, we deposit 50 nm Ag perpendicular to the substrate, thus creating the control channel and the normal region of the junction. As a last step, 700 nm of Ag is deposited again at 47° to form the reservoirs with an effective thickness of 475 nm. To measure the quality of the Nb–Ag interface we have made, in the same run, a cross of a 200-nm-wide Nb and Ag wire. The resistance of the 200×200 nm interface has been determined to be 0.1 Ω, which is smaller than the square resistance of the silver (0.4 Ω), indicating that the interface is clean. The SQUID shown in Fig. 1 has a normal-state resistance of 0.55 Ω and, at 1.4 K, an equilibrium supercurrent ($\phi=0$, $V_{c,1}=V_{c,2}=0$ mV) of 10 μA. The theoretical prediction of the I_cR_n/E_{Th} is 0.5,[22] which corresponds well with the measured value of $\frac{5.5}{12}=0.46$.

In the experiment, we bias the SQUID with a low-frequency ac bias current (I_{Bias},80 Hz) with an amplitude a little larger than the critical current of the SQUID (see Fig. 1)

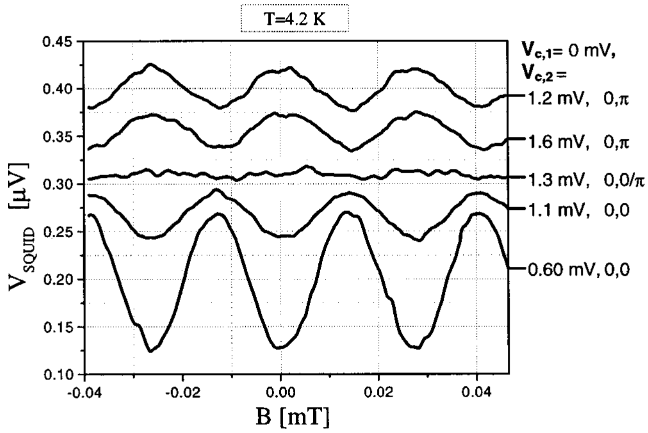

FIG. 3. Voltage over the controllable SQUID as a function of the external magnetic field at 4.2 K for different values of $V_{c,2}$ with $V_{c,1}=0$ mV (curves offset for clarity).

and measure the voltage over the SQUID, V_{SQUID}, as a function of the applied magnetic field B using a lock-in amplifier. This lock-in technique strongly reduces the noise compared to a dc-biased measurement. Simultaneously, we send a dc current through the top and/or bottom control channel and measure the resulting control voltage $V_{c,1}$ and/or $V_{c,2}$. Measurements are performed at 100 mK, 1.4 K, and at 4.2 K. A typical result, taken at 1.4 K using the device shown in Fig. 1, is shown in Fig. 2. The solid lines represent the V_{SQUID}–B oscillations for increasing values of $V_{c,2}$ ($V_{c,1}=0$) using $I_{\mathrm{Bias}}=4\ \mu$A. At first, the amplitude of the oscillations decreases with increasing $V_{c,2}$ and reaches zero at $V_{c,2}=0.48$ mV, indicating that the critical current of the bottom junction is equal to 0. At higher values of $V_{c,2}$ the V_{SQUID}–B oscillations reappear, with a shift π in phase with respect to the oscillations at lower values of $V_{c,2}$. The bottom junction, and hence, the SQUID, are now in the π state. At zero field we now measure a voltage maximum instead of a minimum, indicating that a circulating current is now flowing around the SQUID loop. If the bottom junction is now kept in the π state ($V_{c,2}=0.76$ mV), and $V_{c,1}$ is increased to 0.83 mV, the top junction switches to the π state as well. This corresponds to an addition of 2 times π to the phase of the SQUID loop. In this case, the original phase of the $V-B$ oscillations is regained, as shown by the dashed line in Fig. 2. Similar measurements at 100 mK in a dilution refrigerator have shown similar results with, however, larger amplitudes of the $V-B$ oscillations due to the temperature dependence of the critical current of the Josephson junctions.

The question now arises whether the transition to a π state would be possible at 4.2 K. To be able to observe the effect at these higher temperatures, we have made another set of samples, which differ only in the fact that the Josephson junctions are shorter (length of the normal region: 870 nm, width 500 nm, separation of the Nb electrodes: 260 nm, $Rn=0.29\ \Omega$, $E_{\mathrm{th}}=19\ \mu$eV) and that the surface area of the SQUID is 70.5 μm^2. We performed a measurement of the $V-B$ oscillations as a function of $V_{c,2}$ ($V_{c,1}=0$) at 4.2 K, with an ac current bias of 1.5 μA. The results are shown in Fig. 3. It is clear from Fig. 3 that despite a reduction in the signal amplitude, due to the lower critical current and the lower normal-state resistance, the transition to the π state is observed at $V_{c,2}>1.3$ mV. This is a much higher value than in the previous experiment, caused by the elevated temperature and the larger Thouless energy. The observation of the π state at this temperature is somewhat surprising, for the transition to a π junction has so far only been observed at $T<100$ mK.

In summary, we have shown that it is possible to fabricate a controllable π SQUID, based on Nb–Ag, which operates in the temperature range of 0.1–4.2 K. The critical current of each junction can be controlled by means of the application of a control voltage V_c over additional contacts attached to the normal region of the specific junction. Moreover, the role of the magnetic field, to apply $[(n+\frac{1}{2})\phi_0]$, and thereby to induce a circulating current in the SQUID, can be played by V_c, which induces a screening current at integer external flux if its value is large enough to cause the junction enter a π state.

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