Fabrication of SQUIDs with Nb/Ru/Sr$_2$RuO$_4$ junctions

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Abstract. We have fabricated superconducting quantum interference devices (SQUIDs) using Nb/Ru/Sr$_2$RuO$_4$ hybrid dc-SQUIDs. The superconducting loop of a Nb-Sr$_2$RuO$_4$ hybrid dc SQUID is composed of Nb, Sr$_2$RuO$_4$ and two Nb/Ru/Sr$_2$RuO$_4$ junctions, and made by building a Nb bridge between two individual Ru micro inclusions on the $ab$-plane surface of the Ru-Sr$_2$RuO$_4$ eutectic system. We measure the critical current between Nb and Sr$_2$RuO$_4$ parts of such dc-SQUIDs, which oscillates with every flux quantum through the SQUID loop.

1. Introduction

A number of experimental and theoretical studies indicate that Sr$_3$RuO$_4$ with $T_c = 1.5$ K is a spin triplet chiral $p$-wave superconductor with time reversal symmetry breaking [1, 2]. It is considered as an electronic analogue of superfluid $^3$He–$^3$A in a narrow parallel plate [3]. SQUIDs built from a conventional $s$-wave superconductor and bulk Sr$_3$RuO$_4$ behave as $\pi$-junction SQUIDs ($\pi$-SQUIDs), demonstrating that the orbital symmetry of superconductivity of Sr$_3$RuO$_4$ is indeed odd parity, consistent with $p$-wave superconductivity [4, 5]. Very recently, magnetization jumps corresponding to half-integer quantum fluxoid states are observed in sub-micrometer rings of Sr$_3$RuO$_4$ single crystals [6], giving strong evidence for the equal-spin-pairing (ESP) state consistent with the proposed spin triplet chiral $p$-wave state. Because of the intrinsic degeneracy of two states in zero external field, a $\pi$-SQUID used as a quantum bit is expected to have various advantages including robustness against environmental noises. Aside from enhancement in flux sensitivity, it is preferable to fabricate a small device of Sr$_3$RuO$_4$ in order to avoid the presence of multiple chiral domains which complicates the junction behavior [7].

We have fabricated Nb-Sr$_3$RuO$_4$ hybrid dc-SQUIDs using Ru-Sr$_3$RuO$_4$ eutectic crystals and measured the field dependence of its critical currents. The superconducting phase of Ru-Sr$_3$RuO$_4$
eutectic is called the 3-Kelvin phase because of its enhancement of $T_c$ up to 3 K \cite{8, 9}, although the mechanism of the $T_c$ enhancement has not been understood well. Recently, in an SNS junction using Pb/Ru/Sr$_2$RuO$_4$ containing many Ru inclusions, peculiar temperature dependence of the critical current attributable to topological phase interference is reported \cite{10}. The device configuration presented in this paper uses an individual Ru inclusion in a well-defined SQUID geometry. With some further design refinement, this opens a way towards operation as a $\pi$-SQUID having easy coupling to an external field for the phase control.

2. Experimental

We fabricate SQUIDs with Nb/Ru/Sr$_2$RuO$_4$ junctions on a polished $ab$ surface of a high quality eutectic single crystal of Sr$_2$RuO$_4$-Ru, cut from a crystalline rod grown by a floating-zone method \cite{8}.

![Figure 1. (a) A schematic of a dc-SQUID with Nb/Ru/Sr$_2$RuO$_4$ junctions. Electrodes from Sr$_2$RuO$_4$ are extracted through Ru inclusions. The square indicates a SQUID loop. (b) An optical microscope image of a sample before Nb deposition. Square holes made though SiO$_2$ layer on top of Ru inclusions can be seen. (c) An optical microscope image of two SQUIDs after Nb electrode deposition.](image)

Figure 1 (a) shows a schematic of a dc-SQUID. There are four Nb/Ru/Sr$_2$RuO$_4$ junctions. Two of the junctions are used for two weak links of a dc-SQUID loop. The other two are used as contacts for four-terminal measurements. Figure 1 (b) shows an optical microscope image of the sample coated with an SiO$_2$ layer of 300-nm thickness before niobium electrode deposition. Bright regions are Ru micro inclusions with a typical size of 1 $\mu$m $\times$ 10 $\mu$m exposed on the $ab$ surface. There are 6 square holes for the contact windows through the SiO$_2$ layer. Figure 1 (c) is a top view of the sample after Nb deposition. This device was fabricated by employing the following technique.

Firstly, an SiO$_2$ insulating film is deposited on the polished $ab$ surface of a Sr$_2$RuO$_4$-Ru eutectic crystal. For contacting electrodes, windows of 2 $\mu$m $\times$ 2 $\mu$m are etched through the SiO$_2$ film by using photo lithography and a reactive ion etching technique, ensuring that the contact windows are placed exactly above the Ru lamellae. For SQUID A, the distance between the centers of the windows for the two junctions forming the SQUID loop is 11.5 $\mu$m. Secondly electrodes of niobium are patterned by photo lithography and a lift-off technique. Just prior to the evaporation of niobium, the contact surface is treated by argon sputter cleaning. The niobium coating is inevitably depressed around the contact windows. To improve coverage at these depressed steps, thereby ensuring high critical current...
throughout the niobium layer, the thickness of the niobium film was made sufficiently thick, about 400 nm.

Superconducting transition temperatures of the bulk niobium, ruthenium and Sr$_2$RuO$_4$ are respectively 9.2 K, 0.5 K and 1.5 K. In this paper, the results for SQUID A at 0.6 K are presented. At this temperature the Nb/Ru/Sr$_2$RuO$_4$ junctions should behave as an SNS junction. The magnetic field direction is arranged to be perpendicular to the plane of the SQUID loop. For the data presented here no magnetic shielding was employed, but we confirm that the essential features remain the same in experiments performed using magnetic shielding.

3. Results and discussions

Figure 2 shows the $I$-$V$ characteristic of SQUID A at 0.6 K in the absence of an applied field. The duration of a bias current cycle is 1 s. The $I$-$V$ characteristic indicates a clear supercurrent with the critical value $I_c$ of about 200 $\mu$A with no hysteretic behavior. Reflecting the proximity junction configuration employed in this SQUID, the $I_cR$ product of the junction, several $\mu$V, is much smaller compared to that calculated by the Ambegaokar-Baratoff theory.

![Figure 2](image1.png)

**Figure 2.** The $I$-$V$ characteristic of SQUID A at 0.6 K in the absence of a magnetic field.

![Figure 3](image2.png)

**Figure 3.** The field dependence of the critical current of Nb/Ru/Sr$_2$RuO$_4$ SQUID A at 0.6K.
As a function of an external field, a periodic oscillation of the critical current $I_c$ is observed, as shown in Fig. 3. The critical current is defined at the threshold voltage of 0.5 μV in the $I$-$V$ curves. The observed period of about 0.6 mT is consistent with the addition of a flux quantum $\Phi_0 = h/2e$ to the effective SQUID area of 0.3 μm × 11.5 μm. This result confirms that the loop containing Nb/Ru/Sr$_2$RuO$_4$ junctions operates as a SQUID.

The field positions of the maxima of the $I_c$ positive and the minima of the $I_c$ negative are shifted with each other and moreover shifted from zero external field. The mutual shift between positive and negative $I_c$ can be quantitatively explained by the self-induced flux produced by the bias current. From the present data, the intrinsic field position of the maximum magnitude of $I_c$ cannot be extracted.

4. Conclusion

In conclusion, we have fabricated a micro hybrid dc-SQUID with Nb/Ru/Sr$_2$RuO$_4$ junctions. The observed clear oscillations with the period of a flux quantum establish a characteristic as a SQUID.

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