Shapiro steps observed in a dc superconducting quantum interference device with multiple junctions in each arm

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A high-T_c dc superconducting quantum interference device (SQUID) with three Josephson junctions (JJs) in series in each of its arms has been fabricated. Its Shapiro steps were studied using microwave (rf) radiation of 10 GHz and weak magnetic fields. The appearance of giant Shapiro steps and of some of half-integer steps was observed. Separation between the adjacent Shapiro steps could be tuned by rf magnetic fields and small external dc magnetic fields. This phenomenon was analyzed by phase locking the JJs in the SQUID. [DOI: 10.1063/1.1447598]

A Shapiro step is a step-like structure that displays the $I-V$ characteristics of a Josephson junction (JJ) in rf radiation with frequency ω_s. It appears at voltage of $nh\omega_s/4\pi e$, where $n=1,2,\ldots,n$. However, for JJ arrays, a space (or separation) between adjacent Shapiro steps can be equal to a half-integer Shapiro space, other fractional numbers of normal Shapiro space, known as fractional giant Shapiro steps, or equal to a multiple of the normal Shapiro step space, known as giant Shapiro steps.[1–6] It is of great interest to study the Shapiro step in a dc superconducting quantum interference device (SQUID), which is a nonlinear current oscillator whose frequency is controlled by the voltage that appears across its terminals. In work done by Vannesta *et al.* they observed both normal separation and half-integer separation of Shapiro steps in a low-T_c dc SQUID.[7]

In order to study the behavior of Shapiro steps, we propose a high-T_c dc SQUID, in which the usual single junction in each arm is replaced by three junctions in series in the present letter, and study its behavior in rf radiation and external magnetic fields. Multiple JJs in a dc SQUID decrease the failure rates of the SQUID, enhance the signal to noise ratio, and increase the internal impedance of the SQUID to match the external impedance and raise the output power. We also suggest that the separation between adjacent Shapiro steps of the SQUID is tunable by small external dc magnetic fields as well as by rf magnetic fields. A SQUID, a very sensitive magnetic sensor, has been employed in our experiment exclusively.

The dc SQUID was fabricated on $YBa_2Cu_3O_{7-\delta}$ (YBCO) thin film grown on a 24° bicrystal $SrTiO_3$ substrate by pulsed laser deposition (PLD),[8] plotted in Fig. 1. In Fig. 1, shown by an arrow is the magnified center portion of the SQUID. Black denotes YBCO thin film and white shows the places where the films are etched away. The superconducting transition temperature T_{c0} of the film is higher than 90 K and its critical current density J_c is larger than 1.6×10^6 A/cm^2. A conventional photolithographic technique was used to pattern the SQUID. After etching, the width of each JJ was 9 μm, while the area of the SQUID loop was about 1×10^4 μm^2. The area of its square washer was 8×8 mm^2. The magnetic field period of the SQUID was around 2×10^{-3} G. The period became 8.4×10^{-5} G when flux focus was considered.[9]

The rf power dependence of the Shapiro steps on the $I-V$ curve of the SQUID is presented in Figs. 2(a)–2(d) in order of increasing microwave power. Consequently, the rf magnetic field that entered the SQUID varied. All the measurements were carried out at 77 K in three layers of a μ-metal shielding environment. A 500 MHz oscilloscope was used to collect the data from the electronic circuit of the SQUID directly. The rf power with frequency of 10 GHz was capacitively introduced into the Dewar used by a coaxial cable. The distance between the SQUID and the end of the coaxial line was about 10 cm. The separation between the adjacent Shapiro steps of a single JJ was calculated to be 20.7 μV in rf radiation of 10 GHz. In Fig. 2(a), both of the first Shapiro steps in the positive and negative current sweeps were observed when current with a triangular wave

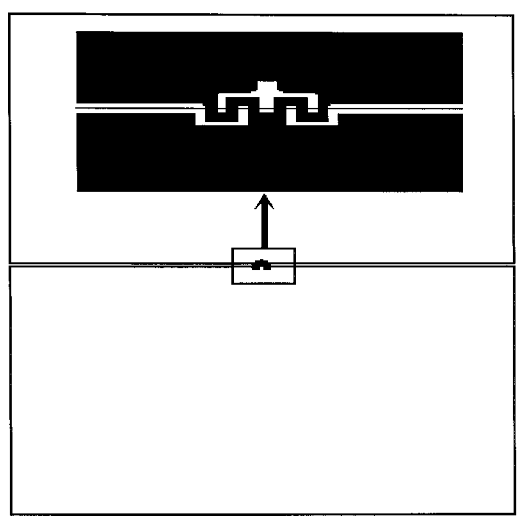

FIG. 1. Picture of the dc SQUID with three JJs in series in each arm. Arrow points to magnification of the SQUID loop (white). A black line indicates the position of the bicrystal boundary. The six junctions form when the strips of YBCO film cross the bicrystal boundary.

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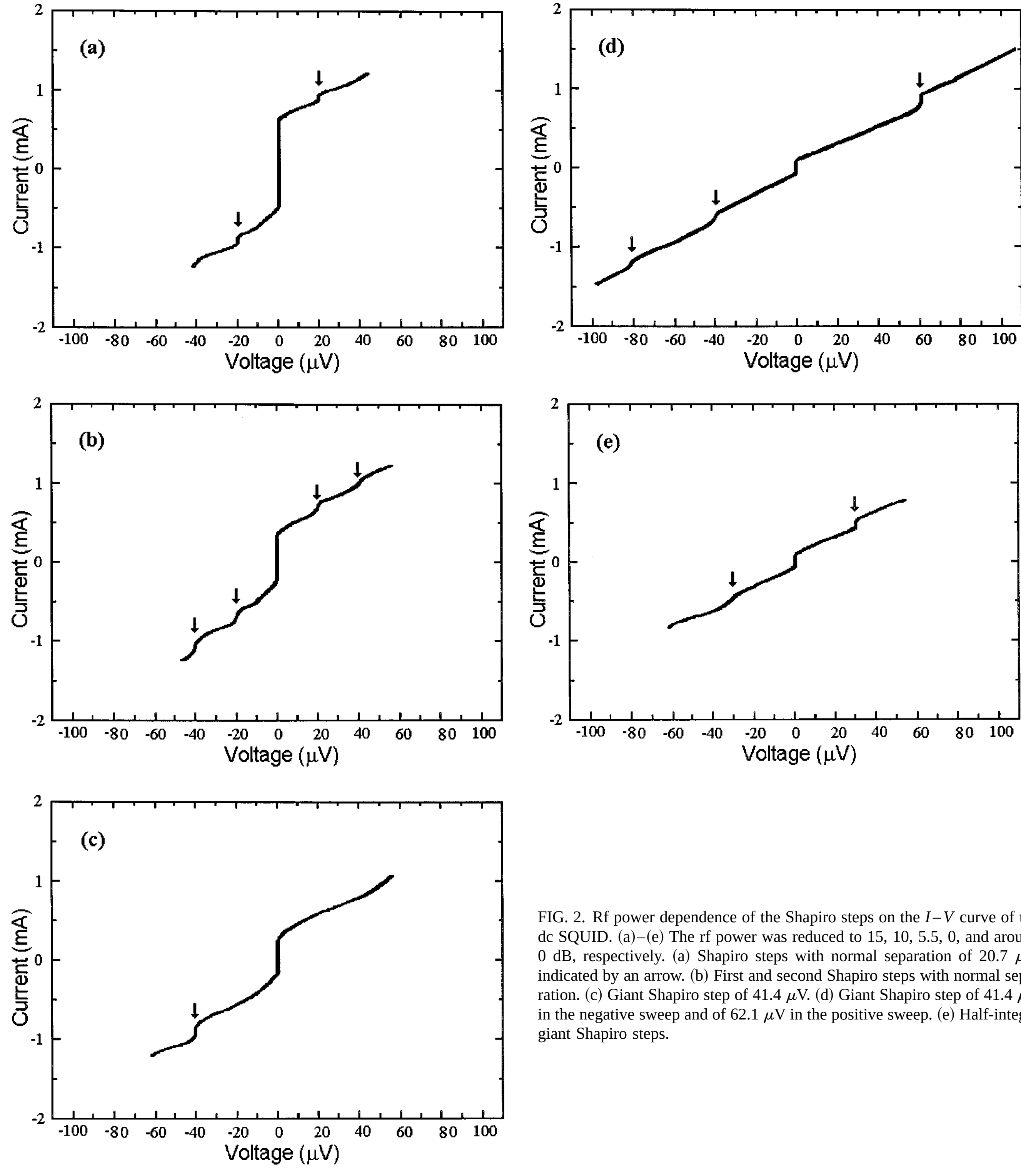

FIG. 2. Rf power dependence of the Shapiro steps on the $I-V$ curve of the dc SQUID. (a)–(e) The rf power was reduced to 15, 10, 5.5, 0, and around 0 dB, respectively. (a) Shapiro steps with normal separation of 20.7 μV, indicated by an arrow. (b) First and second Shapiro steps with normal separation. (c) Giant Shapiro step of 41.4 μV. (d) Giant Shapiro step of 41.4 μV in the negative sweep and of 62.1 μV in the positive sweep. (e) Half-integer giant Shapiro steps.

form was swept from a negative peak to a positive peak and the rf power was attenuated at 15 dB. This corresponded to locking of one JJ in each branch of the SQUID. The normal integer Shapiro steps observed were consistent with the results in a low-T_c SQUID[7] and in high-T_c SQUID.[1–6]

In Fig. 2(b), the rf power was attenuated to 10 dB. When the critical current was decreased to 0.35 mA, first and second Shapiro steps were observed. This is consistent with that in Fig. 2(a), where one JJ in each branch of the SQUID was locked. In Fig. 2(c), where the rf power was attenuated to 5.5 dB, a giant Shapiro step with separation twice that of the normal space was observed in the negative current sweep. This corresponded to locking of two JJs in each branch of the SQUID during the negative current sweep. However, no step was observed during the positive current sweep. This was probably due to the self-field effect of the junctions.

In Fig. 2(d), as the rf power was attenuated to 0 dB, the giant Shapiro steps with separation twice that of the normal separation barely appeared in the negative sweep and the giant Shapiro steps with separation three times that of the normal separation were clearly observed in the positive current sweep. Therefore, three JJs were locked in the positive

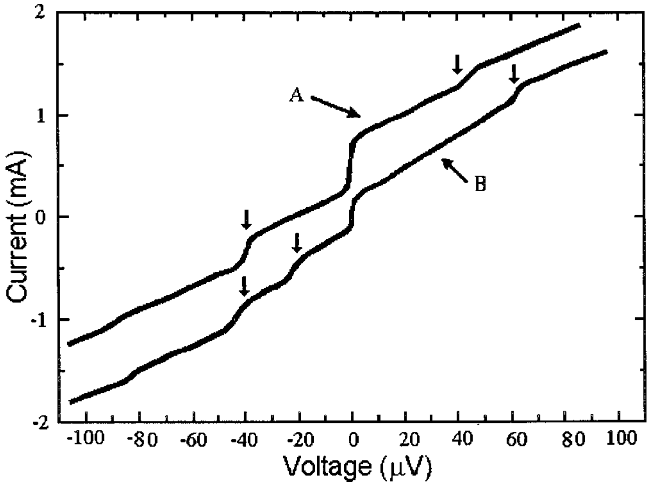

FIG. 3. Shapiro steps on the $I-V$ curve of the three JJ SQUID under two different external magnetic fields. In curve (A), a giant Shapiro step was observed, denoted by an arrow. In curve (B) two normal steps were observed in the negative sweep and one giant Shapiro step was observed in the positive sweep.

current sweep and two JJs were locked in the negative current sweep.

When the rf power shown in Fig. 2(d) was adjusted slightly to the center of the magnetic field period, the $I-V$ curve observed is shown in Fig. 2(e). The half-integer giant Shapiro steps at 31.03 μV for the three locked JJs appeared in both the negative and positive current sweeps.

We also performed experiments by applying small external dc magnetic fields normal to the substrate when the rf power was attenuated to 0 dB. The results are presented in Fig. 3 for two different magnetic fields. Curve (A) was the result of a larger applied magnetic field. Giant Shapiro steps corresponding to two locked JJs were observed in the negative sweep as well as in the positive sweep. In curve (B), when the magnetic field was decreased, two normal Shapiro steps were observed in the negative current sweep and one giant Shapiro step corresponding to three locked JJs was observed in the positive sweep. The number of locked JJs in the SQUID estimated was further supported by calculation of the internal resistance.

In order to understand the appearance of giant Shapiro steps, we use the Bessel function solution for a JJ given in standard textbooks.[10] Current through a JJ is given by

$$I_j(t)=I_c\sum_{n=-\infty}^{\infty}(-1)^n J_n\left(\frac{2eV_s}{\hbar\omega_s}\right)\sin[(\omega_j-n\omega_s)+\phi_0]. \tag{1}$$

Spikes in the dc current occur at the Josephson oscillation frequency (ω_j) and satisfy

$$\omega_j-n\omega_s=0, \tag{2}$$

where ω_s is the frequency of the rf source applied. We assume $\omega_j=\omega_{j1}+\omega_{j2}+\omega_{j3}$ to reflect the fact that we have three JJs connected in series. When one JJ is locked, $\omega_j=\omega_{j1}=\omega_s$. No voltage step appears in the second and the third JJ, i.e., $\omega_{j2}=\omega_{j3}=0$. Therefore, only Shapiro steps of 20.7 μV are observed [see Fig. 2(a)]. When two JJs are locked, $\omega_j=\omega_{j1}=\omega_{j2}$ and $\omega_{j3}=0$. We get $2\omega_{j1}=n\omega_s$. Giant Shapiro steps corresponding to 41.4 μV occur at voltage twice that of the normal Shapiro step [see Fig. 2(c)]. When three JJs are locked, $\omega_{j1}=\omega_{j2}=\omega_{j3}$. Giant Shapiro steps of 62.1 μV are observed [Fig. 2(d)]. In Fig. 2(e), the appearance of half-integer Shapiro steps of three JJ phase locking is the result of a flip flop between two fluxoid states of the SQUID synchronized to the microwave field, which also agrees with the results of Ref. 7.

In conclusion, we proposed a high-T_c dc SQUID consisting of three JJs connected in series in each of its arms to study the effect of rf and dc magnetic fields on the Shapiro steps. Shapiro steps of the SQUID can be tuned by microwave fields and very small dc magnetic fields. The appearance of giant Shapiro steps and some half-integer ones was observed under 10 GHz rf radiation. Their origins were explained in terms of phase locking of the JJs connected in series in the SQUID.

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