The Observation of Non-integral Shapiro Steps of a High- T_c Superconducting dc SQUID

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An unusual oscillatory behavior of the magnitude of non-integral Shapiro steps versus applied magnetic fields was observed, on a bi-epitaxial dc SQUID, illuminated by a microwave source. Preliminary results suggest that the expected position of the first Shapiro step was splitted into two steps; one is larger, while the other smaller than the magnitude of the expected step. A proposed reason for the observation of non-integral steps is attributed to the possible existence of a finite resistance, connected in series to one of the single Josephson junctions, in the asymmetric dc SQUID circuitry, causing a splitting effect of the Shapiro steps.

1. INTRODUCTION

It is well known that the current-voltage (I-V) characteristic of a Josephson junction is modified in the presence of an applied microwave field. Observation of constant voltage steps on a single Josephson junction, namely *Shapiro steps*, has been confirmed for both *low- T_c* [1] and *high- T_c* [2] superconducting samples at integer multiples, n , of the voltage, $h\nu/2e$, where ν is the microwave frequency. Vanneste et al. [3] reported the observation of *half-integral* Shapiro steps on dc SQUID samples, which have been associated with the flip-flop between two fluxoid states of the dc SQUID synchronized to the microwave field when the applied dc magnetic flux is close to half integral numbers of flux quanta Φ_0 . Half-integral steps of single grain boundary junctions [4] and step-edge junctions [5] were also observed and concluded to be likely due to a result of grain boundaries being composed of multiple junctions in parallel [6], similar to the results of Vanneste et al. [3]. Apart from half-integral steps, *higher order subharmonic steps* on bi-epitaxial grain boundary junctions were observed by Terpstra et al. [7], as concluded to be caused by the synchronized motion of Josephson vortices along the junction, not by an array of weaker

regions in the barrier. In this work we report the unusual effect of microwave and magnetic field on the I-V characteristics of a bi-epitaxial dc SQUID.

2. EXPERIMENTAL RESULTS

The I-V curves of several YBCO bi-epitaxial dc SQUIDs [8] (Mr. SQUID from Conductus Inc.) were measured under magnetic fields and microwave irradiation to investigate the characteristics of constant voltage steps to be expected in these samples. Only integral steps on most of the samples without any noticeable fractional steps were observed in the temperature range between 4.2 K and 77 K. However, unusual non-integral steps on one of the specimens were noticed with and without applied dc magnetic fields. The special sample with a SQUID hole area of about $7 \times 10^{-10} \text{ m}^2$ initially showed usual integral steps in the I-V curves for several measurements, before the appearance of the non-integral steps. The geometry of the sample and some experimental results were presented by Horng et al. [9]. Fig. 1 shows the I-V curves of non-integral steps at various applied magnetic inductions up to $2 \mu\text{T}$. The magnitude of magnetic induction was estimated by a simple calculation of an

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Figure 1. Experimental I-V curves at 26 K of the SQUID, irradiated by a 12 GHz microwave source at a fixed input power level of -3dBm, under various applied dc magnetic inductions as indicated. The curves are deliberately displaced horizontally for clarity. The positions of the expected $n = \pm 1$ steps are indicated by dash lines.

ideal short solenoid without further calibration, where the solenoid and the specimen were both covered by a mu-metal shield. It is noted that the voltage steps are not appeared at the positions of the steps near $n = \pm 1$, but shifted upward and downward. Fig. 2 shows the dependence of the voltage difference (between the zero voltage and the first non-integral voltage steps near $n = \pm 1$)

Figure 2. The dependence of the magnitude of the first non-integral steps as a function of applied magnetic induction, by using the data points near $n = \pm 1$ in Fig. 1 and others (not shown in Fig. 1).

versus magnetic induction. After more results measured at different microwave frequencies, it is noticed that the magnitude of both the smaller and larger steps near $n = \pm 1$ oscillates with the applied magnetic field, with an average value close to the value of the first integral step, within an error of $\pm 0.8 \mu V$. The reason of the appearance of the non-integral steps is proposed to the possible existence of a finite resistance, connected in series to one of the single junctions in the dc SQUID circuitry. The voltage across the finite resistance is suggested to be able to disturb the I-V characteristics of the dc SQUID, causing a splitting effect of the Shapiro steps. More work is required to identify this suggestion.

3. CONCLUSION

We observed an anomalous and interesting effect, namely the splitting of one Shapiro step into two steps, one is larger, while the other is smaller than the magnitude of the expected step. A possible reason of this effect is suggested to be due to the existence of a finite resistance, connected in series to one of the junctions in the dc SQUID.

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