Observation of Half-Integer Shapiro Steps in Step-edge $\text{YBa}_2\text{Cu}_3\text{O}_y$ Josephson Junctions

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Current-voltage (I-V) characteristics of step-edge $\text{YBa}_2\text{Cu}_3\text{O}_y$ junctions on $\text{MgO}(001)$ substrates were measured over various temperature and frequency ranges to examine the effects of microwave irradiation and magnetic fields on the I-V behaviors of the junctions. In addition to the usual integer Shapiro steps, half-integer Shapiro steps were observed under microwave irradiation. Both the integer and half-integer Shapiro steps were sensitive to the applied magnetic field and the microwave power. The results are discussed.

There has been much research¹⁻³ on the effects of microwave radiation in high- T_c step-edge Josephson junctions and superconducting quantum interference devices (SQUIDs). Recently, Early et. al⁴ reported the observation of half-integer constant voltage steps in high- T_c grain boundary junctions. In this work we reported in addition to the usual integer Shapiro steps, half-integer Shapiro steps were observed under microwave irradiation in step-edge Josephson junctions and SQUIDs. Both the integer and half-integer Shapiro steps were sensitive to the applied magnetic field and the microwave power.

Step-edge Josephson junctions and SQUIDs were prepared by the techniques of photolithography and Ar^+ ion milling. The step height on $\text{MgO}(001)$ was 200 - 300 nm. YBCO films grown on the substrate was patterned to Josephson junctions or SQUIDs. The width of the junction was 5 - 20 μm . The effects of the applied magnetic field and microwave irradiation on the current-voltage (I-V) characteristics were examined at various temperatures. The magnetic field was applied perpendicular to the substrate and the

microwave was coupled to the junction by a dipole antenna.

Figure 1 shows typically an I-V characteristic for a step-edge Josephson junction at 81 K. The I-V curve can be described by a resistively shunted junction model; the critical current density was $5 \times 10^4 \text{ A/cm}^2$ and $I_c R_n = 88 \mu\text{V}$ at 81 K. Figure 2 shows I-V curves for a step-edge Josephson junction with different irradiation of microwave powers at $T = 70 \text{ K}$, $\nu = 9.4 \text{ GHz}$. In addition to the usual Shapiro steps resulting

Figure 1. Current-voltage characteristic for a typical step-edge Josephson at $T = 81 \text{ K}$.

This work is supported by National Science Council of Republic of China under grant NSC83-0212-M002-070

from ac Josephson effects, constant voltage steps halfway between the voltages of Shapiro steps were clearly present, i.e. $V_n = nh\nu/2e$ with $n = 1/2, 3/2, 5/2, \dots$ where ν is the frequency of microwave radiation, h is the Planck constant, e is the electronic charge. These constant voltage steps were sensitive to microwave powers and magnetic fields.

Figure 2. I-V curves for a step-edge Josephson junction at $T = 70$ K under 9.4 GHz microwave irradiation. The irradiated microwave powers were 5.5, 6.5, and 8 dbm for curves (a), (b), and (c) respectively.

Figure 3 shows a I-V characteristic of a SQUID (area of the SQUID hole is $60 \times 200 \mu\text{m}^2$) under microwave radiation at $T = 65$ K with $\nu = 7.5$ GHz. In addition to the usual Shapiro steps resulting from ac Josephson effects, constant voltage steps halfway between the voltages of Shapiro steps were also present.

Half-integer Shapiro steps have been observed on a Nb-based SQUID by Vanneste et al.⁵ By using a resistively shunted junction model (RSJ) and including capacitive and inductive elements, they were able to reproduce the experimental results. In present work, it is reasonable to consider the step-edge junctions or SQUIDs to be composed of multiple junction in parallel. The half-integer Shapiro steps in step-edge junctions are most likely to be a result of the step edge being composed of multijunctions in parallel.

Figure 3. An I-V curve for a step-edge dc SQUID under 7.5 GHz microwave irradiation at $T = 65$ K. Half-integer voltage steps with $n = 1/2, 3/2, \dots$ were present.

In summary, we have examined the effects of microwave radiation and magnetic field on I-V characteristics of step-edge Josephson junctions. Large junctions show self-field effects. In addition to the usual Shapiro steps constant voltage steps halfway between the voltages of Shapiro steps were present in a single junction or a SQUID. These steps were most likely caused by the multiple weak links present at the step edge of the junctions.

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