Proceedings of the Korean Superconductivity Society Meeting 1999
(KSS 99), YongPyung, Kangwondo, Korea, Aug. 18-20, 1999

# Effect of an additional resistance on Shapiro steps of the Josephson junction

# 조셉슨 접합의 샤피로 계단특성에 대한 부가저항의 효과

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We have investigated the microwave properties of a high-$T_c$ superconducting Josephson junction by Shapiro step measurements. A Josephson junction was fabricated on the bicrystal MgO substrate using pulsed laser deposition method. We have measured Shapiro steps in the I-V characteristics under the irradiation of 1.36 cm wavelength up to 45 K and found inclined current steps above 50 K. In order to understand these results, we introduced an additional resistance connected in series to RSJ model. Using this modified RSJ model, we could explain the inclined current steps as a result of superposition of the junction and an additional resistance above certain temperatures. Also, we presented the received power of the Josephson junction above 50 K.

## 1. Introduction

The Josephson junction devices based on ac Josephson effect[1] are potentially important for microwave device applications as voltage-controlled oscillators (VCO), ultra-precise voltage standards, and sensitive receiving devices operated in millimeter and sub-millimeter wavebands.[2-5] A high-$T_c$ Josephson junction is a candidate for a sub-millimeter waveband mixer and local oscillators. Upper frequency limit of the Josephson devices made of a high-$T_c$ superconducting materials is known about order of tens THz, covering over sub-millimeter wavebands. However, the self-radiation powers of the Josephson junctions are low, and they are required to become higher at least from nW to $\mu$W for real applications. The radiation powers have continuously enhanced; flux flow oscillators in on-chip detection have reached up to a few $\mu$W[6,7] and Josephson junction array using waveguide detection system are about order of tens pW.[2,8]

Suceessful implementation of a high-$T_c$ Josephson devices requires reproducible fabrication of junctions with appropriate values of electrical properties as well as microwave properties. Up to now, it was reported on non-integral Shapiro steps of a high-$T_c$ Josephson junctions, but the reason is still not clear yet. Some reporters think that the reason of the appearance of an anomalous steps may be the possible existence of a finite resistance connected in series to the junction in the circuitry.[9,10]

In this paper, we report the effect of an additional resistance on Shapiro steps of the high-$T_c$ Josephson junctions. We measured the temperature dependence of the critical current, the normal resistance, I-V (current-voltage) characteristics of the junction, Shapiro steps, and R-T characteristics. In order to explain non-Shapiro steps, we considered anomalous I-V characteristics and inclined current steps above 50 K. We introduce an additional resistance connected in series to the junction in the RSJ model fot the explaination of the non-Shapiro steps.

## 2. Theory

### 2-1. RSJ model

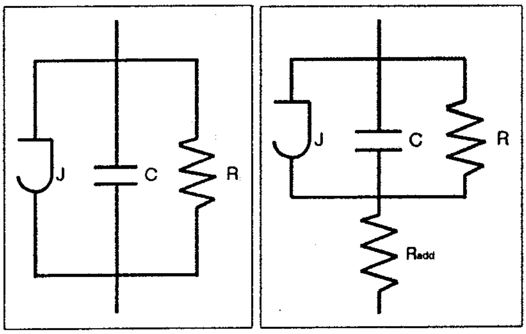
RSJ(Resistively-Shunted Junction) model[11,12] describes correctly the relationships between the current and voltage measured at the terminals not only qualitatively, but also quantitatively. Shown Fig. 1(a), we may write a dimensionless differential equation using Kirchhoff's current law and voltage-phase relation,

$$\frac{I}{I_c} = \sin\phi + \frac{d\phi}{d\tau} + \beta_c \frac{d^2\phi}{d\tau^2} \qquad (1)$$

$$\tau = \frac{2eI_cR_n}{\hbar} t, \quad \beta_c = \frac{2eI_cR_n^2C}{\hbar}$$

where I is the bias current, $I_c$ is the critical current of the junction, $\varphi$ is the phase difference of the junction, $\tau$ is the characteristic time constant, and $\beta_c$ is McCumber-Stewart parameter. This equation can explain all properties of the junction in principle.

In the presence of an external microwave radiation, vertical current steps called *Shapiro steps*,[13] are induced on the I-V characteristics of the Josephson junction at voltages given by



(a) (b)

Fig.1. A equivalent circuit of (a) RSJ model (resistively shunted junction model) (b) RSJ model including an additional resistance.

$$V_n = n\left(\frac{h}{2e}\right) f_a \qquad (2)$$

where $n$ is an integer, $h$ is Plank constant, $2e$ is the electronic charge of the Cooper pair, and $f_a$ is the frequency of the external radiation.[1] Because we used microwave with 22 GHz or 1.36 cm wavelength, voltage intervals of current steps are about 46 $\mu$V from eq. (2). Shapiro step measurements can inform us to compare a characteristic frequency and real upper frequency of the Josephson junction.

### 2-2 Modified RSJ model including an additional resistance

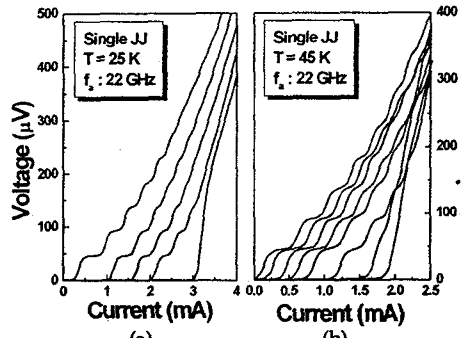
We introduce modified RSJ model, including an additional resistance connected to the junction in the equivalent circuit of the RSJ model as shown Fig. 1(b). The modified RSJ model is the same as the conventional RSJ model, except a linear voltage drop below certain low bias current. Later we use this modified model to explain the possible orgin of the non-Shapiro steps.

## 3. Experiment

We used high-$T_c$ superconducting grain boundary Josephson junctions on MgO bicrystal substrates with 24° tilt angle because of their low loss tangent and low dielectric constant for microwave device applications. YBCO thin films have a lattice mismatch with MgO substrates, but are deposited with good quality under best condition.[14,15]

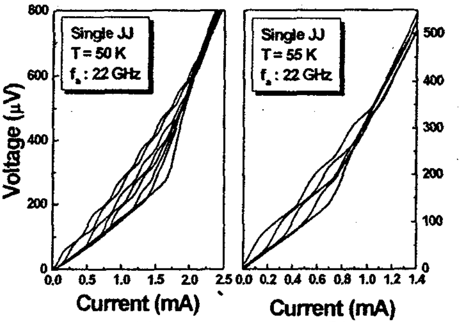
Deposit conditions are followings ; A KrF excimer laser with 248 nm was used at a pulse rate of 10 Hz and an energy density of $1J/cm^2$. During deposition, the substrate was held at 800 ℃, and the oxygen pressure in the chamber was 480 mTorr. A film thickness was about 2000 Å. The film was patterned by conventional photolithography and ion milling technique.

The Josephson junctions are sensitive to magnetic field and thus mounted in a $\mu$-metal shielded cold head at a distance of 20 mm from a dielectric horn antenna with focal length of 20 mm, which enables a external microwave to couple to the sample. The detailed setup and system were the same as those used in Ref. 16.



(a) (b)

Fig.2. Typical current-voltage characteristics of the Josephson junction with and without 22 GHz varying microwave radiation at 25 K and 45 K, respectively.



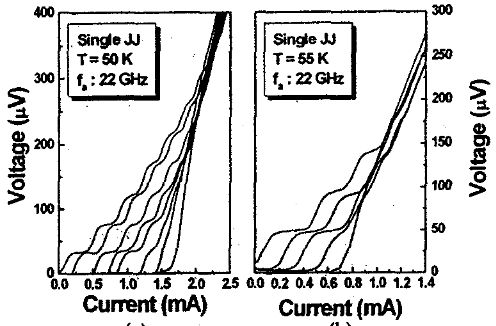
(a) (b)

Fig.3. Typical current-voltage characteristics of the Josephson junction with and without 22 GHz varying microwave radiation at 50 K and 55 K, respectively.

## 4. Results and discussion

Figure 2 shows I-V characteristics and the conventional Shapiro steps of the Josephson junction under microwave irradiation having 22 GHz with various power at 25 K and 45 K, respectively. The constant voltage intervals, about 46 $\mu$V, satisfied the Josephson voltage-frequency relation. This shows that the Josephson junction is formed well. From Shapiro step measurements, upper frequency limit at 45 K is about 250 GHz. This is about 70 % of the upper frequency of the characteristic voltage($V_c$) of the junction at 45 K. The temperature dependence of $V_c$ decreased from 11 K to 45 K, according to Two Fluid Model.

Figure 3 shows I-V characteristics and current steps under irradiation of 22 GHz with various powers at 50 K and 55 K, respectively. These are exotic and different from the conventional Josephson junction behavior. There is a linear voltage drop at a low current bias and a nonlinear behavior above certain bias currents. This kind of I-V characteristics has not been reported ever in study of the Josephson junction. It is strange that the high-$T_c$ Josephson junction shows linear voltage drops.



(a) (b)

Fig.4. Current-voltage characteristics of the Josephson junction after compensating the voltage due to an additional resistance at 50 K and 55 K, respectively.

In order to explain this, we modified the RSJ model. Considering a linear voltage drop, We put an additional resistance connected in series with junction into the model as shown 1(b). Voltage drop across the junction due to RSJ model is

$$V_s = R_s I_0 \tag{3}$$

where $I_0$ is a current flowing through the junction, and $R_s$ is the effective resistance of the junction, respectively. Linear voltage drop is

$$V_{add} = R_{add} I_0 \tag{4}$$

due to an additional resistance, where $R_{add}$ is an additional resistance. Thus total voltage drop including an additional resistance is

$$V_{total} = R_s I_0 + R_{add} I_0 = R_{eff} I_0 \tag{5}$$

where $R_{eff}$ is a effective resistance of the sample. There is no voltage drop through a shunted resistance when a bias current is smaller than a critical one. But these experimental results are different from what we expected. When a small bias current is applied to the junction a linear voltage drop appears due to an additional resistance. And when a bias current exceeds a critical one of the junction, a nonlinear voltage drop is shown as superposition of the junction and an additional resistance. The junction behaviors follow a RSJ model, while an additional resistance follows Ohm's law. Therefore the modified RSJ model could explain the usual results above certain temperatures.

This model can explain also non-Shapiro steps, which are not satisfied with Josephson relation. Generally speaking, a microwave cannot affect the properties of the Ohmic and shunted resistance. Under microwave irradiations, RSJ prediction are still effective as eq. (2) is satisfied. Shapiro steps are tilted due to a superpositon of an additional resistance. These effects are shown in Fig. 3. After substraction of an additional resistance effect, I-V characteristics and current steps of the junction are shown in Fig. 4. The shape look like conventional I-V characteristics following RSJ model.

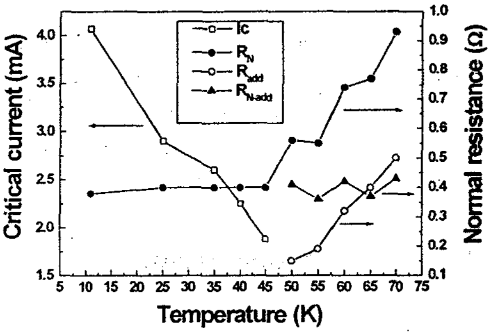


Fig. 5. Temperature dependences of the critical current( $I_c$), junction normal resistance( $R_N$), and an additional resistance( $R_{add}$).

Figure 5 shows the temperature dependence of the critical current, the juntion normal resistance and an additional resistance. The dependence of critical current is conventional, but the junction normal resistance is not. The junction normal resistance is nearly constant, 0.4 $\Omega$, up to 45 K, but from 50 K to 70 K linearly increased. This is aeffected by an additional resistance. We subtracted an additional resistance from the junction normal resistance. Then normal resistance is nearly constant up to 70 K, 0.4 Ω. From Fig. 4 and 5, we may convince an existence of an additional resistance connected in series to the junction in RSJ model above 50 K.

We also found an additional resistance from the resistance-temperature(R-T) characteristics. $T_{(c,onset)}$ is about 89 K, but a resistance tail reaches to about 52 K. The second phase may consist of the bias line except the junction, etc. We think that this second phase causes an additional resistance above its critical temperature.

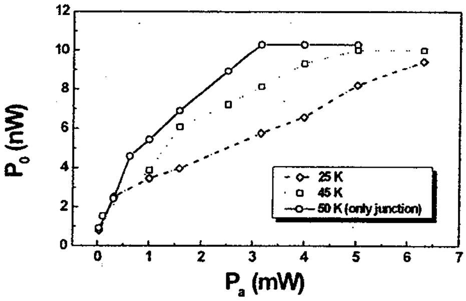


Fig. 6. The received power of the junction as function of temperature and microwave power.

From Shapiro steps, we can calculate the received power of the Josephson junction. The received power after compensation of an additional resistance is shown Fig. 6 as function of temperature and irradiation power of 22 GHz. The received power at 50 K shows the same tendency as the low temperature behaviors. This also show clearly the superposition effect of two components above 50 K.

The origins causing an additional resistance are considered as followings;

1) Some impurities are included in thin films and may cause a critical temperature to decrease.

2) Due to oxygen deficiency, there exists a second phase or localized states having lower critical temperatures.

These origins are understood generally as the results of the complexity of the high-$T_c$ superconducting materials and the oxygen deficiency.

Our analyses clearly support the suggestion of ref. 11 in which a finite resistance connecting to the junction exists. This means that the microwave properties of Josephson junctions are very sensitive to a second phase, in addition to TAPS(Thermally Activated Phase Slippage) effect[17] and rounding effect of the Shapiro steps due to thermal noise.[18]

## 5. Conclusion

In this paper, we investigated electrical and microwave properties of the high-$T_c$ Josephson junction. We have obseved an additional Ohmic properties and inclined current steps above 50 K. These results could be accounted for using a modified RSJ model, which consists of a junction and an additional resistance.

## Acknowledgements

This work was supported by the Korean Ministry of Science and Technology, Republic of Korea. We would like to thank professor Jaejun Yu at Seoul National University, Dr. Yunsung Huh at Hanvac corporation, Jinhyung Lee at Sogang University for useful discussions.

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