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Microwave Properties of Superconductor-Constrictions-Superconductor Devices

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1. Introduction

Many authors have developed special techniques to fabricate non-tunneling-type Josephson devices built from low-T_C and high-T_C materials [1-5]. However, most of these devices generally exhibit a broad variety of poorly reproducible current-voltage (I-V) curves. Thus, there is relatively poor knowledge of its transport mechanism and microwave properties on the experimental level, especially when compared with well-understood high-quality Nb/Al-Al_2O_3/Nb tunnel junction.

Recently, we have reproducibly fabricated all-thin film superconductor-constrictions-superconductor (S-c-S) devices [6, 7]. The quasiparticle characteristics of these devices were well explained by the theory of Blonder, Tinkham and Klapwijk (BTK) [8] for the case of non-effective scattering potential, i.e., in the clean and ballistic limit.

Aberle and Kümmel (AK) calculated for relation to Andreev reflection and microwave, and predicted to occur the integral sharp steps in SNS junction [9]. Experimental study of microwave properties in the S-c-S devices, however, have not yet been done.

In this paper we report on new microwave-induced steps in current-voltage (I-V) characteristics of S-c-S devices.

2. Device fabrication and measurement system

The Nb-constrictions-NbN (S-c-S) devices were fabricated by "field-assisted growth" method [6, 7], where the constriction diameter is about 10nm, and that length is less than 20nm. By this method, we could continuously vary the I-V characteristics from insulator to tunnel-contact and up to perfectly metallic-contact. The gradual evolution of the quasiparticle characteristics of the contact can be well explained by the BTK theory [8].

The microwave irradiation was performed on the S-c-S device mounted on Al block using Cu-Ni semirigid cable as an antenna. The irradiated microwave frequency was 8-12GHz. The maximum rf-power P_{rf} of HP-8620C sweep oscillator was 10mW.

3. Microwave properties

Figure 1 shows P_{rf} dependence of normalized differential resistance dV/dI vs. V characteristics in an Nb-c(2nm)-NbN device. Inset shows the enlarged view in the range of -1.2mV to 1.2mV.

In the absence of microwave irradiation the dV/dI curve, except for near the gap voltage, is good agreement with the theoretical curve calculated from BTK single-Andreev reflection model for effective scattering potential Z=0 [8].

Critical current I_C of this device was 30μA at 4.2K. As increasing of P_{rf}, the differential resistance below superconducting energy gap is gradually increased, while dV/dI above gap, i.e., normal resistance R_N is not changed. This result indicates that the Andreev reflection was disturbed by external microwave.

Many dV/dI peaks are observed in the dV/dI vs. V curves as shown in Fig. 2. Inset shows the dV/dI curves below V=0.4mV. For V<0.4mV, the voltage positions of periodic dV/dI peaks were correspond to the Josephson conditions $2eV = m\hbar\omega$, where, m is the integer, ω is the microwave frequency and other symbols retain their standard meaning.

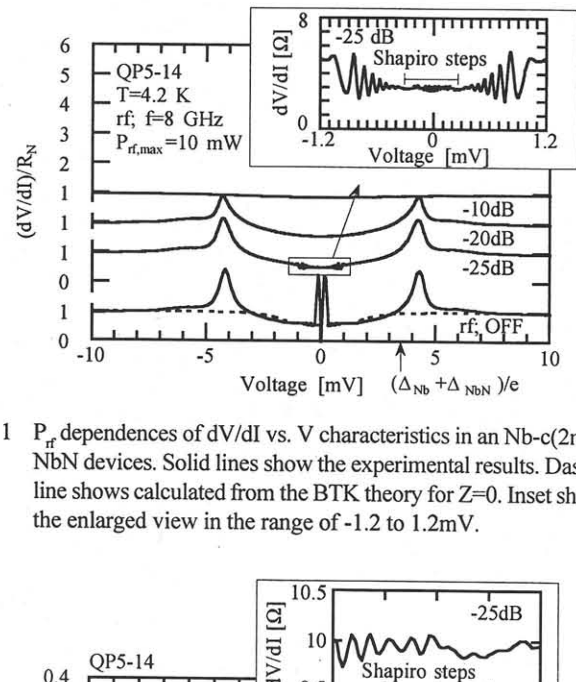

Fig. 1 P_{rf} dependences of dV/dI vs. V characteristics in an Nb-c(2nm)-NbN devices. Solid lines show the experimental results. Dashed line shows calculated from the BTK theory for Z=0. Inset shows the enlarged view in the range of -1.2 to 1.2mV.

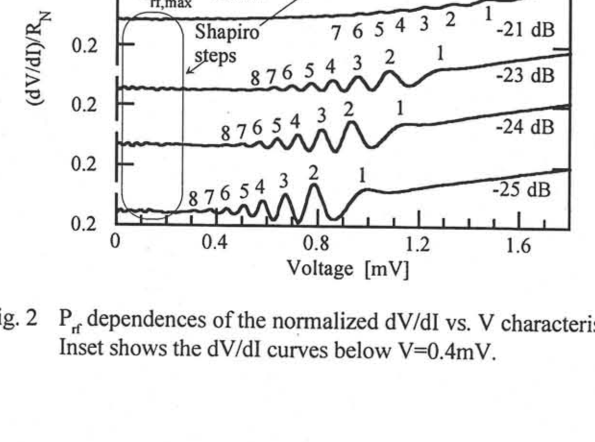

Fig. 2 P_{rf} dependences of the normalized dV/dI vs. V characteristics. Inset shows the dV/dI curves below V=0.4mV.

The dV/dI peaks for V<0.4mV were the well-known "Shapiro steps".

For V>0.4mV, the voltage spacing of the dV/dI peaks are increased with bias voltage. Also, the voltage positions V_n of dV/dI peaks are continuously shifted to higher voltage regime as increasing of P_{rf}. Figure 3 shows the dependence of the V_n on $P_{rf}^{1/2}$. Dashed lines are eye-guide drawings. The V_n are linearly increased as $P_{rf}^{1/2}$ increased. The voltage spacing, however, is not depend on $P_{rf}^{1/2}$. From these experimental results, we concluded that the dV/dI peaks for V>0.4mV are not Shapiro steps.

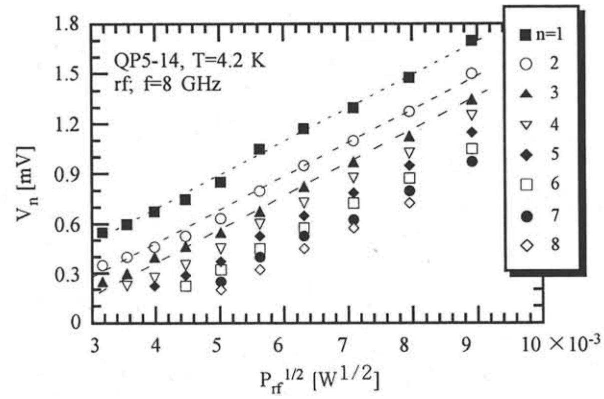

Fig. 3 P_{rf} dependence of the dV/dI peak positions V_n of the "microwave-induced" steps.

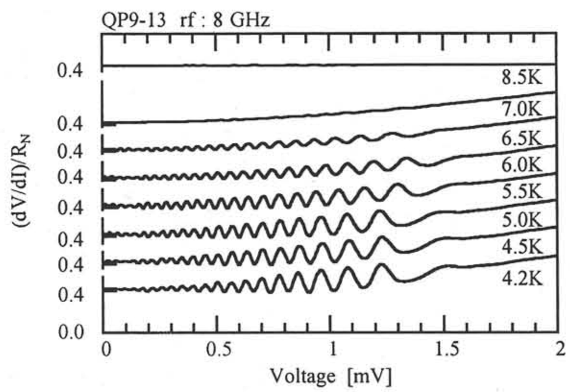

Fig. 4 Temperature dependences of $(dV/dI)/R_N$ vs. V characteristics.

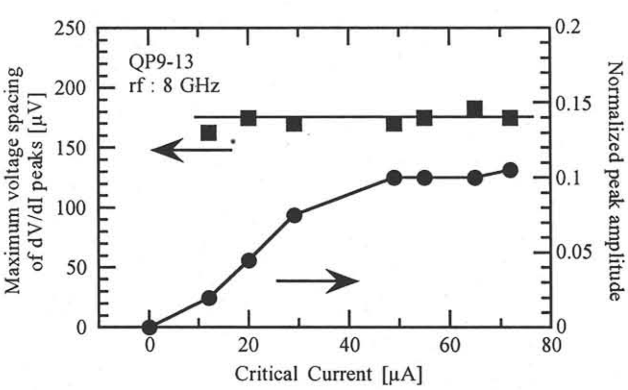

Fig. 5 Critical current I_C dependences of maximum voltage spacing of dV/dI peaks and normalized peak amplitude.

Temperature dependence of dV/dI peaks in Nb-c(4nm)-NbN device is shown in Fig. 4. The I_C of this device was 70μA at 4.2K. The dV/dI peaks are disappeared with I_C above 7.0K. Below 7.0K, dV/dI peaks are clearly observed. The voltage positions V_n of dV/dI peaks are not constant at the various temperatures. This is due to the changing of the coupling efficiency of device and microwave irradiation system for technical reason.

Figure 5 exhibits the I_C dependence of peak amplitude and voltage spacing in new microwave-induced steps. Normalized peak amplitude is increased as increasing I_C and saturated. The maximum voltage spacing of dV/dI peaks ($|V_2-V_1|$), however, is not depend on I_C. We also found that these qualitative features of new microwave-induced steps were not depend on the constriction length.

The voltage spacings and the P_{rf} dependence of V_n in the observed microwave-induced steps can not be explained by the AK theory [9], existing LC resonance [10] or microwave-assisted tunneling [11].

4. Summary

For S-c-S devices, the observed microwave-induced steps up to 2.5mV differ from the features of the well-known "Shapiro steps". The voltage spacing of the dV/dI peaks increased with bias voltage. The voltage positions of dV/dI peaks continuously shifted to higher voltage regime as increasing of P_{rf}. The voltage spacing did not depend on P_{rf} and I_C. These features of the microwave-induced steps can not be explained by other existing models, e.g., LC resonance step model. The mechanism of this new microwave-induced steps may be related to modulation of Andreev reflection by microwave irradiation.

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