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Quasiparticle Characteristics and Noise Properties of Superconductor-Normal Metal-Superconductor Quantum Well Devices

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All-thin film superconducting Nb-Nb nanoconstrictions-NbN quantum well devices with improved low-frequency noise properties have been successfully fabricated. The quasiparticle current characteristics are well explained using the Andreev reflection current.The low-frequency noise parameter η in the Hooge's empirical theory decreases quickly with decreasing the devices quality factor $Q_{eff}=R_D(1mV)/R_N(10mV)$, i.e., with decreasing the effective strength of the barrier potential at the superconductor (Nb, or NbN)-nanoconstriction interface.

1. INTRODUCTION

In recent years, there has been much theoretical work on Andreev reflection at normal metal-superconductor (NS) interface. Compared to the theoretical development, the experimental situation for SNS device remains rather unclear. This is because it is difficult to prepare an SNS contact with a contact size of the order of electron mean free path ℓ_e and superconducting coherence length ξ. These conditions are necessary to fill the Blonder, Tinkham and Klapwijk (BTK) theory,[1] and also the Likharev theory.[2] In order to avoid the difficulties in the conventional preparation technique for a thin-film metallic point contact, we have developed a new technique.[3]

In this paper, we report the quasiparticle-current characteristics and low-frequency noise properties of Nb-nanoconstriction-NbN devices prepared by this technique.

2. DEVICE FABRICATION

Nb-Nb nanoconstriction -NbN quantum well devices were prepared by applying electric pulses to an insulating Nb/MgO/NbN edge-sandwich with small area of $0.2\mu m^2$. The process allows for remarkable device improvement in the reproducibility of its quasiparticle characteristics.[4] The thickness of the MgO insulator layer of the sandwich is 7nm as estimated from the deposition rate.

We consider that changing of the shape of I-V curves is attributed to the growth of Nb nanocostriction in the pinholes of MgO insulator layer in the Nb/MgO/NbN edge-sandwich assisted by electric field. To obtain a clear evidence, one should estimate the size and the density of the pinholes in the edge-sandwich area. However, for a practical device (area $0.2\mu m^2$), to observe these quantities is extremely difficult, if not completely impossible.

We mention here that electron mean free path ℓ_e of 100 nm thick Nb film was about 7nm as estimated from the film reistivity at 10K. Hence, if the length L of the nanoconstriction is taken to be defined by the thin MgO layer, Nb constrictions roughly satisfy the ballistic condition.

3. ENERGY DIAGRAM

A superconductor-insulator-normal metal-insulator-superconductor (SINIS') and a superconductor-constriction-superconductor (S-c-S') geometries are shown in Figs.1 (b), and (d). Figures 1(a), and (c) show schematic energy diagrams of these devices. If one neglects the proximity effect at N-S interface and the thickness of N layer (or the length of the constriction in S-c-S') is small compared to the inelastic scattering length, these structures can be characterized as ideal superconducting quantum well devices, i.e., step-like BCS pair potential $\Delta(r)$.[5]

For SNS, however, this step-function model is not correct because of inevitable proximity effect at the NS interfaces.[1,5]

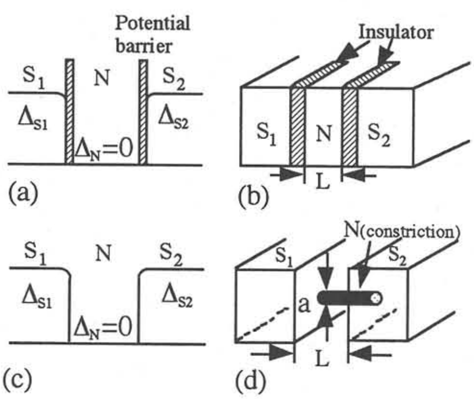
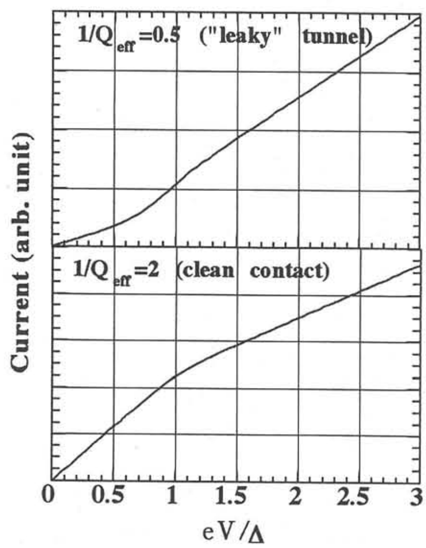


Fig.1 Schematic configuration and energy diagram of SINIS', and S-c-S'.



Fib.2 Calculated I-V curves using Eq.(1).

In the case of Fig.1(b), i.e., for S-c-S' device, the BTK theory give us a useful theoretical explanation for a quasiparticle current through a nanoconstriction. In this theory, the quasiparticle current through a constriction is given by [1]

$$I_{qp} = \frac{1}{eR_N}\int_{-\infty}^{+\infty}\left[f_0(E-eV)-f_0(E)\right]\times\left[1+A(E)-B(E)\right]dE \qquad (1)$$

where A(E) is the Andreev reflection probability and B(E) is normal scattering probability, and other symbols have their usual meanings.

In the clean contact limit, i.e., A(E)=1 and B(E)=0, if $eV-\Delta >> k_BT$, one finds,

$$I_{qp} = \frac{V}{R_N} + \frac{4\Delta}{3eR_N}\tanh\left(\frac{eV}{2k_BT}\right) \qquad (2)$$

where $I_{qp}-R_N/V$ gives the excess current. When the S-S' (or S-c-S') device can be thought of as a series combination of an SN and a NS' nanoconstrictions, Δ in Fig.2 can be substituted by $\Delta+\Delta'$. [1]

Figure 2 shows the calculated current-voltage curve for Z_{eff}=0, 0.5 using Eq.(1), where Z_{eff} denotes the BTK's effective barrier strength. In the similar manner to tunnel junction, we denote the device quality factor, $Q_{eff}=R_D(\text{subgap})/R_N(\text{super gap})$.[6] The $1/Q_{eff}$ value of the case shown in Fig.2 is 0.5 and 2, respectively.

4. EXCESS CURRENT

For the S-c-S' device, one should calculate the quasiparticle current using two values of Z associated with the two interfaces. It seems to be, however, very difficult to estimate these values experimentally. It can be in principle done by analysis of characteristics of leaky tunnel-like devices. Such devices, however, can be expected to have poor noise properties and consequently a precise estimation of the two values of Z is not much practical importance. Hence, in this study, we use only Z_{eff} as a practical figure of merit. This procedure is of practical for $Z_{eff}\sim 0$, i.e., clean contact.

Figure 3 shows a normalized excess current $(R_NI_{qp}-V)/R_N$ vs voltage curves. In this figure, the closed symbols show the experimental excess current, and the solid line shows the predictions of the BTK theory for the clean contact ($1/Q_{eff}$=2) and "leaky" tunnel junction ($1/Q_{eff}$=0.43). The experimental data are found to agree closely with the BTK prediction. Thus, it may be possible to conclude that our device is a superconducting quantum well device with step-like pair potential Δ(r).

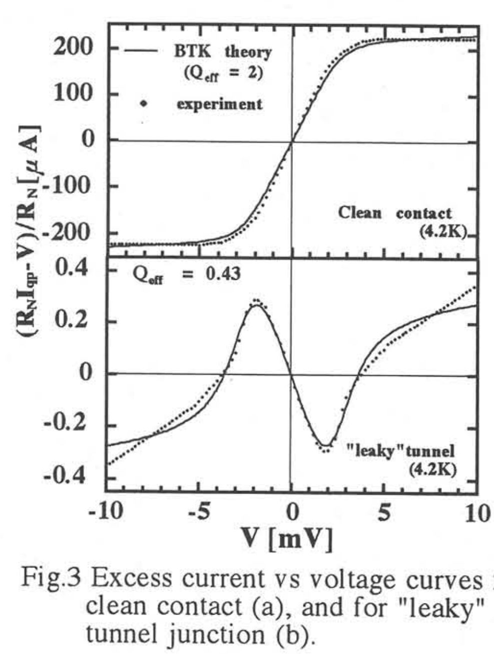


Fig.3 Excess current vs voltage curves for clean contact (a), and for "leaky" tunnel junction (b).

5. LOW-FREQUENCY NOISE

The study of low-frequency noise in metal nanoconstrictions, especially in ballistic quantum point contacts, is very important both for physics and practical device applications. However, the origin of two level fluctuation process (TLF) and 1/f noise is not yet well-understood. Also, the low frequency noise of S-c-S' with Andreev reflection currents has not yet been investigated.

We studied the low-frequency noise properties of the device as a function of device quality Q_{eff}. Noise measurements were performed at 4.2K in a rf-shielded room, and the device was additionally shielded by a superconductive Nb can. The voltage noise of the device was preamplified by a cooled LC resonant circuit, and then amplified by an amplifier with voltage noise V_n=1.4nVHz$^{-1/2}$. To get a quantity that would characterize well the noise magnitude and allow for direct comparison with Roger and Buhrman work for tunnel junctions,[6] we recall the Hooge's empirical theory for voltage noise power spectral density S_V[6]

$$S_v(f) = (\eta / A \cdot f) \cdot R_D^2 \cdot I_{qp}^2 \qquad (3)$$

Where, η is a quantity characterizing the magnitude of low-frequency noise. A is the junction area (here,0.2μm^2). Other symbols have their usual meanings. Roger et al. found a linear dependence of the magnitude η on the inverse junction quality factor $1/Q_{eff}$.[6]

Figure 4 shows the experimental dependence of η on $1/Q_{eff}$ for four samples.

Regularly during the adjustment process of the I-V characteristics of the S-c-S'[3,4], we observe an evolution of the voltage noise spectrum from a highly featured one, consisting of a single or a few clearly pronounced Lorentzian bumps for $1/Q_{eff}$<<2 device, to almost featureless, nearly 1/f dependence in $Q_{eff}\sim$2 samples. In the former case, the two-level fluctuations (TLFs) are clearly observed in the time trace. these results suggest that the observed TLFs are closely related to the proportional fluctuation of Taylor-cone-like Nb microtips.[7,8]

6. SUMMARY

We have successfully fabricated an all-thin film superconducting Nb-Nb nanoconstriction-NbN quantum well device with improved low-frequency noise properties. The quasiparticle current of the device is interpreted having the contribution from the Andreev reflection current. The excess current is in a good agreement with the BTK prediction.

Low-frequency noise for the device was also investigated and two level fluctuations (TLFs) were observed for tunneling-type contacts, but, for our experimental sensitivity, no apparent TLF is observed for clean metallic contact. We first found that low frequency voltage noise power spectral density Sv(f) decreases quickly with increasing $1/Q_{eff}$ i.e., with decreasing the effective barrier potential Z_{eff}.

7. REFERENCES

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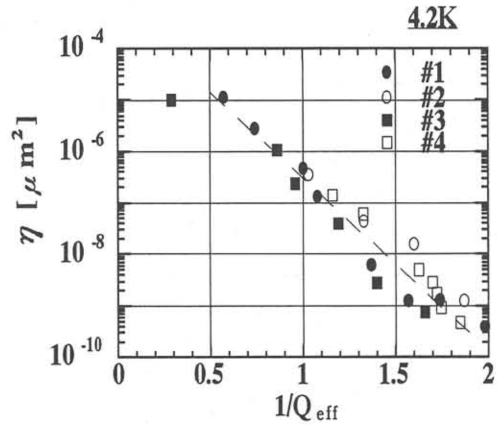

Fig.4 η vs $1/Q_{eff}$ at various stages of the adjustment process of device characteris tics for four samples.