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# Crossover of Noise Power from Thermal to Shot Noise in Superconducting Mesoscopic Devices

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Low-frequency noise properties of all-thin film superconducting Nb-(constrictions)-NbN point contacts have been investigated. This type contact can be regarded as a superconducting mesoscopic system, and its quasiparticle characteristic is well analyzed by Blonder, Tinkham and Klapwijk (BTK) theory [Phys. Rev. B25,4515(1982)] based on Bogoliubov-de Gennes equation. We also discuss on white noise in Nb-(constrictions)-NbN point contact, which is in clean and ballistic limit. The temperature dependence of crossover voltages between thermal noise and shot noise in ballistic system is in good agreement with calculated values.

## 1. INTRODUCTION

Many undesirable noise properties of low-Tc and high-Tc superconducting short weak link (SWL) devices are related to the structural and chemical defects in weak link region. The knowledge of physical process is, however, rather insufficient. This is due to the lack of both sufficient experimental data and a relevant theory to explain consistently current(I)-voltage(V) characteristics of these structure. [1]

In recent years , we have reproducibly fabricated all-thin film superconducting mesoscopic devices, with the structure of Nb-(contrictions)-NbN. [2,3] The quasiparticle of these devices can be well explained by the theory of Blonder, Tinkham and Klapwijk (BTK) [4] for the case of no effective scattering potential, i.e., in the clean and ballistic limit.

We wish to discuss in this report the experimental study on the temperature dependence of crossover of noise power from thermal to shot noise in Nb-(contrictions)-NbN.

## 2. NOISE MEASUREMENT SYSTEM

Noise measurements were performed in an rf-shielded room, and with superconducting Nb can. The voltage noise of low resistance device(<200 Ω ) amplified by a low noise preamplifier(LI-75A, NF Circuit Block; Gain=100) with noise voltage $V_n$=-137dBV/Hz$^{1/2}$ at f=58kHz. During the noise measurements, the device is current biased. A special care is taken in order to minimize all external noise sources.

In case of sufficiently high resistance(>200 Ω ) device, the noise is directly measured with spectrum analyzer (TR-9402, ADVANTEST;Vn=-154dBV/Hz$^{1/2}$ at f=58kHz) in the frequency band from 1Hz up to 100kHz. For measurement of the device voltage noise at levels well below our preamplifier noise, a different scheme is used.

Here, the noise signal is fed to a cooled LC resonant circuit, amplified by the low noise amplifier(LI-75A) and detected by a lock-in amplifier (model 124A, EG & G Princeton Applied Research) in ACVM mode in a narrow frequency band around the LC circuit resonant frequency of 58kHz. The system was carefully calibrated against thermal noise in a metal thin-film resistor to check the performance. At a given bias voltage point, the Q is estimated from experimental dynamic resistance $R_d$ taking into account the parasitic damping in LC circuit, $R_{damp}\sim$ 2 Ω . The corrections for the noise of the preamplifier and for the effective bandwidth of the whole measurement chain are applied to get correct device voltage noise magnitudes. In order to obtain a sufficient Q factor of the LC circuit, this procedure is restricted only to devices with lower resistances(<20 Ω ).

## 3. LIU AND YAMAMOTO THEORY [9]

Previous study of the transition between the mesoscopic and macroscopic conduction regimes has yet to recover the generalized Nyquist expression for the nonequilibrium noise in the heavily dissipative regime. [5-8]

Recently, R.C.Liu and Y.Yamamoto (LY) have treated the current noise in the transition from mesoscopic to macroscopic circuit using a coherent scattering approach which assumes an energy-independent scattering matrix.[9] According to the LY theory, a generalized Nyquist current noise spectral density is given by

$$S(\omega)=\frac{1}{(M+1)^2}S_\delta(\omega)+4\,k_B\,\Theta\frac{T\,G_Q}{T\,M+1}\frac{\Omega}{2}\coth\frac{\Omega}{2} \quad (1)$$

where

$$S_\delta(\omega)=2\,k_B\,\Theta\,T\,G_Q\left(1-T\right)$$
$$\times\left[\left(\frac{\Omega+\nu_M}{2}\coth\frac{\Omega+\nu_M}{2}\right)+\left(\frac{\Omega-\nu_M}{2}\coth\frac{\Omega-\nu_M}{2}\right)-2\frac{\Omega}{2}\coth\frac{\Omega}{2}\right] \quad (2)$$

and M is the number of inelastic scattering reservoirs, $\Theta$ is the temperature, T is the transmission probability of the conductor, $G_Q=e^2/h$ is the quantum unit of conductance. $\Omega=\hbar\omega/k_B\Theta$, $\nu_M=(eV/k_B\Theta)/(TM+1)$.

Figure 1 shows the two-terminal device model proposed by LY. The nonequilibrium current noise spectral density $S(\omega)$ is shown in Figure 2 for a frequency of 1kHz, and temperature of 50mK.

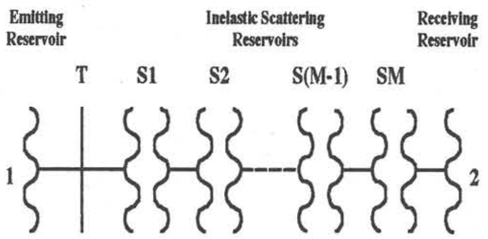


Fig. 1 Model of two-terminal device with an elastic scatterer having a finite transmission probability,T. [9]

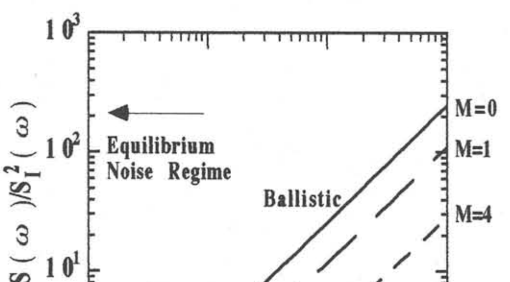


Fig. 2 Normalized current noise power spectral density for the two-terminal device for f=1kHz and T=0.5. $S_I^2$ is given by Eq. 4.8 in Ref. 9

## 4. RESULTS AND DISCUSSION

### 4.1 FABRICATION AND CHARACTERIZATION

For the interpretation of noise properties of superconducting mesoscopic devices, at first, one should evaluate the normal resistance, i.e., quasiparticle characteristics.

Nb-(constrictions)-NbN were prepared by applying electric field to an insulating Nb/MgO($\sim$7nm)/NbN sandwich. The changing of the shape of I-V curves is attributed to the growth of Nb constriction in the pinholes of MgO insulator layer assisted by electric field. [3]

Figure 3 shows the I-V curves for the Nb-(constrictions)-NbN metallic contact measured at 4.2K and 7.0K, respectively. This characteristic was obtained at the final stage of the field adjustment process. Dashed curves was calculated by Eq.17 in Ref. 3 using experimental $R_N$, and gap parameter $\Delta_{fitted}$ and $Z_{eff}$ as fitting parameters.

As shown in Fig. 2, the experimental curves closely agree with the theoretical prediction for $Z_{eff}=0$ through a wide temperature range. In the framework of the above mentioned BTK theory, our S-c-S' device shown in Fig. 3 is in ballistic limit. Also, the normal resistance $R_N$ is based on the Andreev reflection. The $R_N$ was independent on temperature below 13K which is the critical temperature of NbN film.

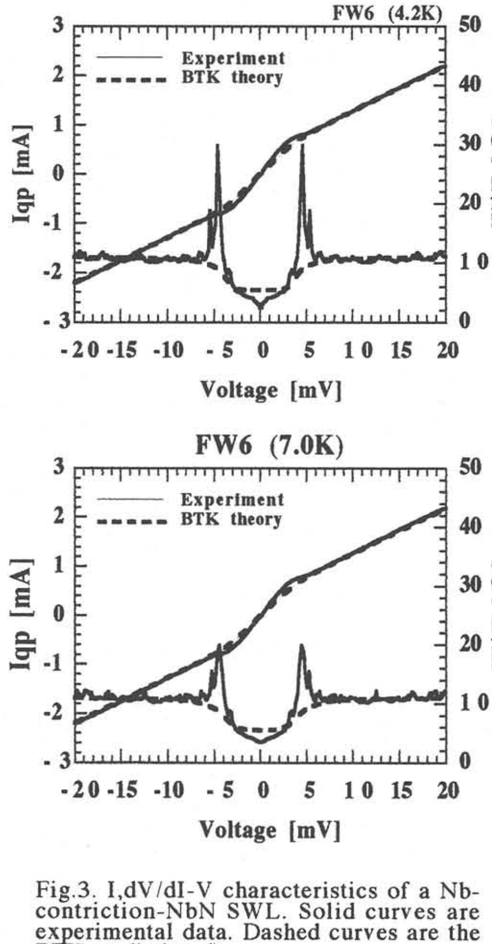


Fig.3. I,dV/dI-V characteristics of a Nb-contriction-NbN SWL. Solid curves are experimental data. Dashed curves are the BTK prediction [4].

### 4.2 NOISE PROPERTIES

Figure 4 shows the bias voltage dependence of the voltage noise power spectral density, Sv, at 58kHz for a $Z_{eff}$=0 contact. As shown in Fig. 4, in the region of bias voltage less than 1mV, the Sv is independent on bias voltage, (i.e., current), indicating thermal noise limit. For $V_{bias}$>1mV, apparent excess noise is on background thermal noise. This excess noise may be shot noise in ballistic contact. The dotted line in Fig.4 shows the LY prediction for f=58kHz,M=0,T~0. Our results is agreed with the LY prediction for T~0. The possible origin of this value(T~0), however, is not apparent yet.

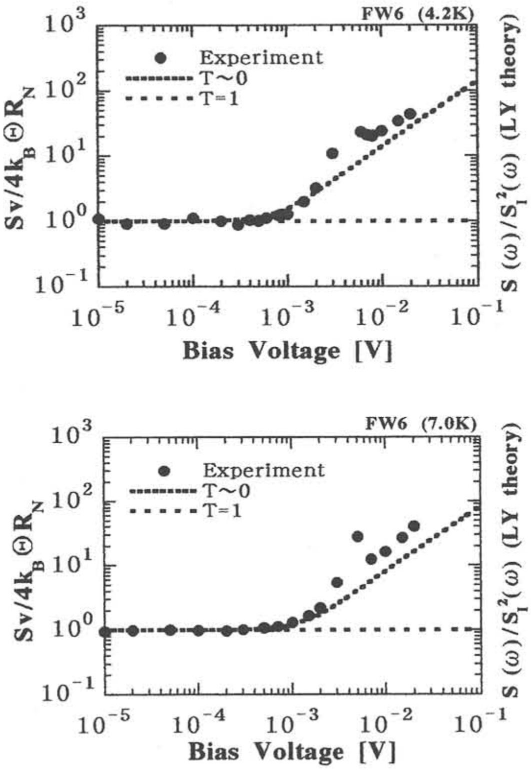


Fig.4. Bias voltage dependence of the normalized voltage noise power spectral density. Dotted(T~0) and broken(T=1) curves are LY prediction for M=0.

Likharev and Semenov, [10] predicted the crossover voltage $V_c$ between thermal and shot noise in Nb-(constriction)-NbN weak link. If an energy associated with a single scattering event becomes comparable to the average thermal energy, i.e., $eV/(\ell e/L)=k_B\Theta$, the $V_c$ is expected to be

$$V_C = k_B \Theta / (e \frac{\ell_e}{L}) \qquad (3)$$

Figure. 5 shows the temperature dependence of $V_c$ values for BTK's ballistic contact mentioned above. The solid line shows the calculated curve using from Eq. (3) for $\ell e/L$=1 and 2. As is apparent from Fig.5, Eq. (3) fits well experimental data for temperature below 10K.

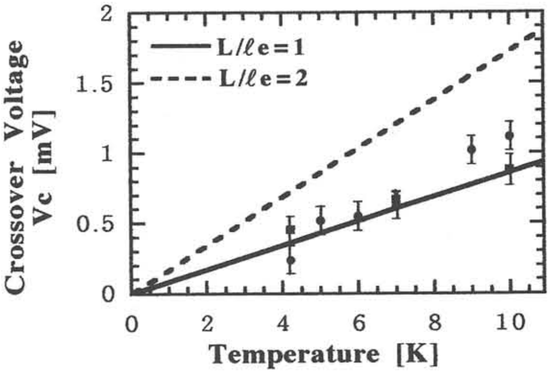


Fig.5. Temperature dependence of crossover voltage Vc. Solid and dotted lines shows the theorecal curves calculated from Eq. (3) for $\ell e$/L=1 and 2.

In conclusion, we have fabricated and characterized all-thin film superconducting Nb-(constriction)-NbN point contact, and measured low-frequency voltage noise. Our result was agreed with the LY prediction. We took notice of the crossover from thermal to shot noise, and the temperature dependence of the crossover voltage $V_c$. Temperature dependence of $V_c$ values were in agreement with calculated values for $L/\ell e$=1. From the quasiparticle and low frequency noise properties, we found that our device is in ballistic limit.

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