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Realization of Primary Thermometer from Electrical Shot Noise in a Metal-Insulator-Metal Tunnel Junction

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Metal-Insulator-Metal 터널접합의 산탄잡음을 이용한 일차 온도계 구현

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Abstract

We measured electrical shot noise in a metal-insulator-metal tunnel junction, which was made by using electron-beam lithography and double-angle evaporation technique. Since the dependence of the shot noise on bias voltage and temperature is theoretically well known, we can determine the temperature of the junction by measuring the noise as the voltage across the junction is changed. A cryogenic low noise amplifier was used to amplify the noise signal in the frequency range of 600-800 MHz, which enabled fast measurement of noise signal and thus temperature. With further study, this method could be useful for primary thermometry in cryogenic temperatures.

Keywords : tunnel junction, shot noise, thermometry

I. Introduction

Temperature of a system can be measured with a variety of thermometers, which can be divided into two groups; primary thermometers such as constant volume gas thermometer or acoustic gas thermometer, and secondary thermometers such as platinum resistor thermometer or diode thermometers.

For primary thermometers, we can determine temperature by measuring the physical properties of the system, which we know the physical principles governing the system. Since the physical laws are predictable in primary thermometers, they don't suffer the problem of calibration or long term drift. However, secondary thermometers, in which the equation of the system is not known explicitly, need calibrations with the primary thermometers to

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maintain the accuracy of the temperature [1].

In this paper, we introduce a shot noise thermometry (SNT) that relates the electrical noise of a tunnel junction to the temperature of the system. Since we can determine the temperature by measuring the electrical shot noise, which comes from the well known physical laws, SNT can be regarded as primary thermometer.

When bias voltage V is applied across the tunnel junction of resistance R, the electrons from electrodes of the tunnel junction tunnel across the barrier. The spectral density of the current noise is given by the following equation.

$$
\begin{aligned}
&S_I(V) \\
&= \frac{2}{R}\int\left\{f_l(E)\left[1-f_r(E)\right]+f_r(E)\left[1-f_l(E)\right]\right\}dE \qquad (1)\\
&= \frac{2eV}{R}\coth\left(\frac{eV}{2k_BT}\right) = 2eI\coth\left(\frac{eV}{2k_BT}\right)
\end{aligned}
$$

where $f_{l,r}(E)$ is energy-dependent Fermi function on the left and the right electrodes, and T is temperature [2].

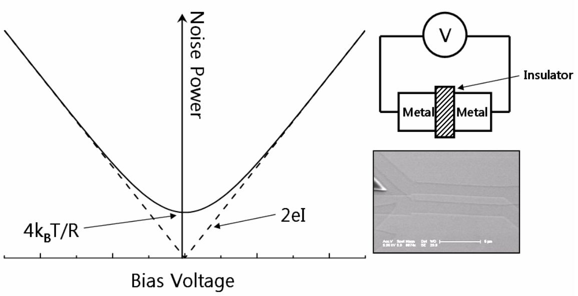

Fig. 1. Theoretical plot of the noise power as a function of bias voltage in a metal-insulator-metal tunnel junction. The dashed lines indicate the shot noise curve without the thermal noise. At zero voltage, voltage-independent Johnson (thermal) noise of $4k_BT/R$ appears. Upper inset indicates the measurement schematic. Lower inset indicates the top view of the fabricated tunnel junction.

When the voltage is close to zero, Eq. 1 yields Johnson (thermal) noise $4k_BT/R$. For high voltage bias limit ($eV \gg k_BT$), the equation reduces to temperature-independent shot noise *2eI* [3].

II. Experimental setup

The tunnel junction in our study consists of two aluminum electrodes and a thin insulating layer (AlO_x) that separated two electrodes. To make the sub-micron scale Al-AlO_x-Al tunnel junctions, suspended bridge structure of double-layer resist were fabricated by electron beam lithography [4]. After the first layer evaporation, tunnel barrier was formed between top and bottom deposition [5]. The junction area was 10×0.2 μm^2 and resistance-area product at room temperature was 3 x 10^{-6} Ω·cm^2. The resistance increased from 125 Ω at room temperature to 163 Ω at 4 K as the bath temperature decreased (In most of our samples, they show increasing resistances with decreasing temperature). The superconducting transition temperature of our aluminum thin film is typically 1.2 K. Since our experiments were performed above 4 K, the aluminum electrodes were not superconducting.

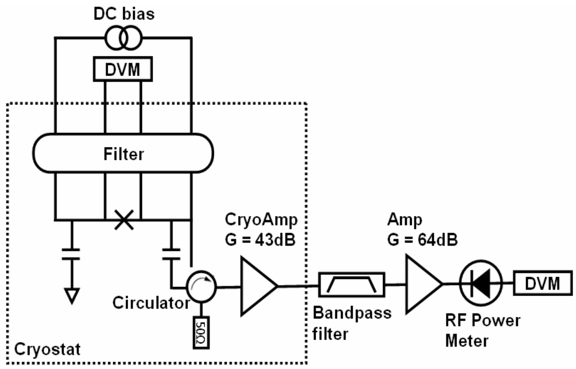

Fig. 2. Experimental setup for noise measurement of the tunnel junction. The interference from DC bias and DVM is blocked by a filter. The shot noise signal is first amplified by a cryogenic HEMT amplifier of 43 dB gain. The signal, passed through bandpass filter of 600 and 800 MHz, undergoes further amplification by the room temperature amplifiers of 64 dB gain. The amplified noise power is then converted to a DC voltage by a Schottky diode detector.

Figure 2 shows the schematic experimental setup to measure the RF signal from the tunnel junction. For DC parts consisting of a current source and voltmeters, it is important to prevent external interference from reaching the tunnel junction. Therefore, we inserted low pass filters between room temperature electronics and the junction. To block high frequency signal in DC chain, we used 120 nH inductors near the leads of the junction.

For RF chain, impedance matching should be considered to reduce the reflection of the signal between different parts in our system. The shot noise signal from the junction passed through blocking 33 pF capacitors, which removed DC signal in RF chain. The signal went through a circulator, which was used for removing the backward noise from the cryogenic HEMT amplifier [6]. After the noise signal was amplified by 43dB in the HEMT amplifier, it underwent a bandpass filter with the passband of 600 ~800 MHz. Following further amplification of 64 dB by room temperature amplifiers, the output signal is converted to DC voltage by a Schottky diode detector. Finally the output DC voltage is measured by a digital voltmeter.

The tunnel junction was mounted on a copper sample holder inside a vacuum can, where the temperature can be adjusted from 4 K to room temperature [7]. We measured the shot noise from 4 K to 150 K.

III. Results and discussion

The shot noise data taken at several different temperatures are shown in Fig. 3a in the unit of temperature. At zero bias voltage, the zero-bias noise goes up as the temperature increases since the zero bias limit of shot noise curve is the thermal noise $4k_BT/R$. In the high bias region, all the curves coincide with each other, which agree well with conventional Poissonian shot noise *2eI*. The transition from thermal to shot noise occurs at higher voltage as the temperature goes up. From curve fitting of the data using Eq. 1, the temperature of the junction can be extracted as a fitting parameter.

Figure 3b shows normalized shot noise curves versus the normalized voltage eV/k_BT. The shot noise curves were normalized by dividing shot noise RF power by RF power at zero voltage. All the normalized data agrees well with the universal form of $(x/2)\coth(x/2)$, ($x=eV/k_BT$), which indicates that the measured shot noise follows theoretical predictions well.

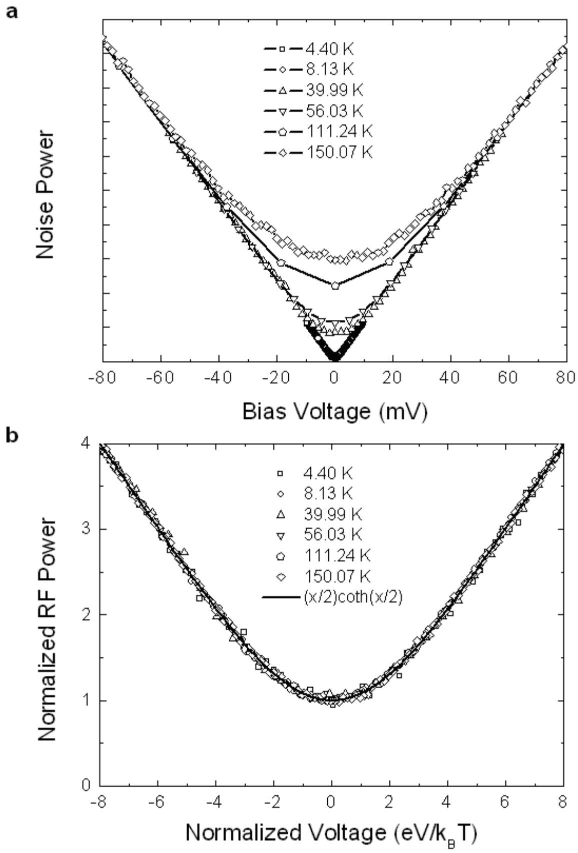

Fig. 3. Bias-dependent noise for several temperatures **a.** The lowest points near at zero bias-voltage go up as the temperature increases. In the high bias-voltage region, the noise power is independent of temperature. **b.** With normalized voltage $x = eV/k_BT$, all the temperature -dependent data falls on the same curve of $(x/2)\coth(x/2)$.

To test reliability of the inferred temperature from the tunnel junction, we compared the T_{SNT} to the secondary thermometer (Lakeshore DT-670) for the range from liquid helium temperature to 150 K as shown in Fig. 4. Most of the fitting temperatures are located near the solid line that corresponds to $T_{SNT} = T_{secondary}$ line. To see the detail of the difference from the secondary thermometer, we evaluated relative uncertainty δT / $T_{secondary}$ = (T_{SNT} - $T_{secondary}$) / $T_{secondary}$. $\delta T/T_{secondary}$ lies in the range of ± 0.2; we have relative uncertainty ± 0.2 at 4.2 K and lower relative uncertainty at higher temperatures. Another systematic error comes from the nonlinearity of the Schottky diode detector, which we can correct by careful diode calibration.

Eq. (1) assumes a perfect tunnel barrier and direct tunneling without any scattering in the barrier. However, if there are defect states in the barrier, inelastic tunneling can occur so that it will modify the noise-voltage curve. Verification of the junction quality would be measuring it below the superconducting transition of the aluminum, and evaluating the sub-gap leakage. Indeed, since this kind of thermometry is more useful at ultra low temperatures, we are pursuing to set up a system in He-3 refrigerator so that we can reach down to 0.3 K. Below the transition temperature of aluminum electrodes, magnetic field needs to be applied to suppress the superconductivity in aluminum. Also, blocking thermal photons and hot electron injection is essential that requires carefully anchoring each wiring. We are currently under progress in low temperature measurement setup, and the result will be presented later.

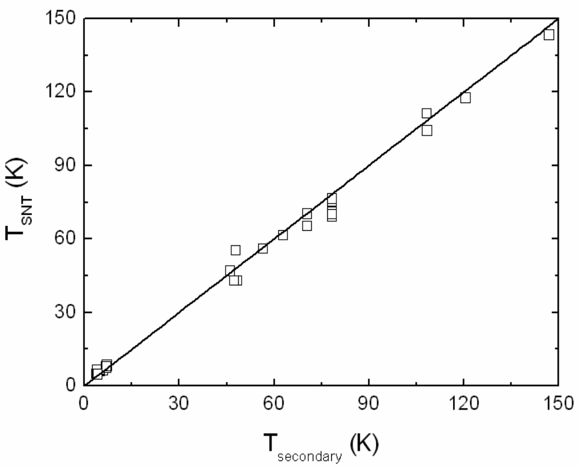

Fig. 4. Comparison of the measured temperature from noise (T_{SNT}) with the secondary thermometer (Lakeshore DT-670). The solid line indicates $T_{SNT} = T_{secondary}$.

In summary, we have fabricated sub-micron scale metal-insulator-metal tunnel junction and measured the shot noise in the frequency range of 600~800 MHz. The measured results agree well with the theoretical shot noise curves, which enabled us to determined temperature of the junction. Compared with conventional Johnson noise thermometry at kHz range, we can measure the temperature relatively quickly by using broadband measurement. Further study will be focused on the improvement in the accuracy of the shot noise thermometer. The physical properties of the tunnel junction itself can be studied by the noise measurement study, which will include the transport phenomena in superconducting tunnel junctions.

Acknowledgments

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