ALL-NbN QUASI-OPTICAL SIS MIXERS AT TERAHERTZ FREQUENCIES

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Abstract

We have theoretically and experimentally investigated submillimeter-wave receiver performances employing NbN/AlN/NbN tunnel junctions with high current density and high energy gap. The receiver noise based on parameters for our typical NbN SIS junction were analyzed using Tucker's quantum theory of mixing, which showed that DSB receiver noise temperatures of below $3h\nu/K_B$ can be achieved by using the NbN SIS junctions for frequencies up to 2 THz. An experimental receiver has been designed and tested for the 1 THz band. The mixer consists of a MgO hyperhemispherical lens with anti-reflection cap, a NbN twin-slot antenna, and NbN tuning circuits. The prepared NbN/AlN/NbN junction size was about 0.5 μmφ, and the current density was about 30 kA/cm^2 ($\omega C_J R_N$ = 11 at 1 THz). Although the junctions showed good dc I-V characteristics with a small sub-gap leakage current, the receiver noise temperature measured by the standard Y-factor method was about 2700 K(DSB) at 761 GHz, which is much larger than the theoretical prediction. The relative high noise performance may be caused by the large RF losses in the tuning circuit of polycristalline NbN on the SiO.

1. Introduction

Superconductor-insulator-superconductor (SIS) tunnel junction based on NbN is the best candidate for terahertz mixer elements, because NbN has a large gap frequency of up to 1.4 THz compared to about 700 GHz for conventional Nb. According to theoretical calculations by Feldman [1], SIS mixers should exhibit good performance at frequencies up to twice the superconducting gap frequency, which is 2.8 THz for all-NbN tunnel junctions. SIS mixers using all-NbN junctions can therefore almost cover the whole submillimeter wave band. However, simple scaling arguments pose some problems in fabricating SIS mixers based on NbN at the end of submillimeter wave-lengths. This issue is discussed in Ref. [1], which is that the NbN junctions must have small junction area of 0.1 μm^2 and the critical current density of 40 kA/cm^2 at 1 THz for the condition of $\omega C_J R_N = 4$, assuming the specific capacitance of 60 $fF/\mu m^2$.

We have developed NbN/AlN/NbN tunnel junctions with high quality and high current density up to 54 kA/cm^2 [2,3], and demonstrated excellent noise performances in the 300 GHz band by using these junctions with Nb tuning circuits[4,5]. In order to develop the great potential of the high current density NbN SIS junctions at terahertz frequencies (above the gap frequency of Nb), it is essential to fabricate all-NbN mixers or NbN mixers with normal metal tuning circuits. In this report, we show the theoretical prediction of the receiver noise temperature based on an experimental I-V curve of the typical NbN junctions, and the preliminary results on fabrication and testing of all-NbN quasi-optical SIS mixers at terahertz frequencies.

2. Theoretical Noise Performance

We have made simulation of the DSB receiver noise temperatures employing quasi-five port model based on Tucker's quantum theory of mixing at frequencies up to around twice the gap frequency of NbN [6]. The I-V curve of a NbN/AlN/NbN tunnel junction used in our simulation is shown in Fig. 1. This was obtained from the measurement for the NbN SIS junction with the current density of 20 kA/cm^2 and the size of 1 $\mu m\phi$. The junction has the small leakage current and the strong non-linearity at the gap voltage of about 5.3 mV which corresponds to the gap frequency of 1.3 THz. We assumed that the junction capacitance with the specific value of about 100fF/μm^2 was tuned out at each simulation frequency by an external circuit. Both the RF embedding admittance and the IF load resistance seen by the intrinsic SIS junction were taken to be $1/R_N\ \Omega^{-1}$ and 50 Ω, respectively. The IF frequency is 1 GHz and IF amplifier noise temperature is 2 K. The results for optimum receiver noise temperature at the physical temperature of 4.2 K are shown in Fig. 2. At each frequency, the pumping strength α and bias voltage were optimized. As seen in Fig. 2, the simulation predicts that sensitive SIS receiver noise temperature of below $3h\nu/K_B$ can be achieved by using the NbN/AlN/NbN junctions for frequencies up to 2 THz. This result is encouraging.

3. Experimental Results

3.1 Mixer Design

In our mixers, a quasi-optical structure employing a substrate lens is used to couple the RF radiation to the junctions. An optical micrograph of our mixer chip is shown in Fig. 3. On a 0.3-mm-thick single-crystal MgO substrate, two NbN/AlN/NbN junctions in parallel were integrated with a single-crystal NbN twin-slot antenna and NbN tuning circuits. The procedures for fabricating the junctions are described in Ref. [5]. The mixer designs utilizing twin-slot antennas and two-junction tuning circuits have successfully demonstrated low noise performances and wide-band operations as described in many papers [7-10]. We chose the antenna dimensions as followings: the slot length is L = 0.33λ, the width is W = 0.05L, and the separation is S = 0.17λ. Here λ is the free-space wavelength at the center frequency. These dimensions are originally for the silicon substrate (ε_r = 11.5), and the antenna impedance become a value of Z_{ant} = 33 Ω at the center frequency [8]. In case of our mixer using the MgO substrates (ε_r = 9.6), the antenna impedance may be a little bit different from 33 Ω at the design frequency, but we assumed the antenna impedance to be 35 Ω. The slot antennas are connected to the NbN SIS junctions with NbN coplanar-waveguide (CPW) transmission lines having the characteristics impedance of 35 Ω.

The NbN/AlN/NbN tunnel junctions are assumed to be the size of 0.7 μmϕ and the current density of 30 kA/cm^2. The capacitance for the 30 kA/cm^2 junction was calculated from the following expression obtained by measurements for our high current density NbN SIS junctions ;

$$\mathrm{Log}C_S = 1.85 + 0.16\log J_C,$$

where C_S is the specific capacitance in $fF/\mu m^2$, and J_C is the current density in kA/cm^2 [11]. Thus, the assumed junction has the normal state resistance of 37 Ω and the junction capacitance of 47 $fF/\mu m^2$, which gives the $\omega C_J R_N$ product of 11 at 1 THz.

The two-junction tuning circuit employing a NbN microstripline is used to tune out the SIS junction capacitance, and connected to the center conductor of CPW-lines. The NbN microstripline consists of a 300-nm thick NbN for the strip, a 250-nm thick SiO ($\varepsilon_r = 5.5$) for the microstrip dielectric, and a 180-nm thick NbN for the ground plane on the single-crystal MgO substrate. Since we had not measured the penetration depth of NbN thin films fabricated on the SiO underlayers, we assumed the penetration depth to be 180 nm measured for NbN films on the single-crystal MgO [12, 13].

The mixer chip, whose dimensions are 4 x 4 x 0.3 mm, is clamped on the flat surface of a 3-mm radius hyperhemispherical MgO lens. As MgO has a relatively large dielectric constant of 9.6, the reflection loss at the surface of the lens is about 26 % in case of no matching layer. To reduce the reflection loss, we put a thermoformed matching layer of polyimide film [14]. This material has not only a dielectric constant of 3.46, necessary for the $\lambda/4$ matching layer, but also excellent physical, electrical, and mechanical properties at cryogenic temperature. We used the 50-μm thick film which corresponds to the $\lambda/4$ thickness at around 800 GHz.

3.2 Noise Performances

The receiver set-up is basically the same as described in Ref. [5]. The incoming radiation entered the dewar through a 0.5-mm-thick Teflon vacuum window. Thin Zitex infrared filters cooled to 77 K and 4.2 K were used to block infrared radiation from the 4.2-K components in order to reduce thermal load and temperature gradients. Local oscillator (LO) power was provided by a optically pumped HCOOH laser [15], and was introduced into the signal path through a 16-μm-thick mylar beam splitter. LO power was adjusted by rotating a wire-grid in front of the LO source. The heterodyne receiver noise measurements were made using the standard Y-factor method with room-temperature (295 K) and liquid-nitrogen-cooled (77 K) loads. No corrections were made for losses in front of the receiver.

The prepared junctions have current density of around 30 kA/cm^2, and the size of 0.5 μmϕ, lower than the design value of 0.7 μmϕ. Fig. 4 shows I-V characteristics for the receiver at 761 GHz with and without LO power. The receiver IF output in response to hot and cold loads is also shown in Fig. 4 as a function of bias voltage. The small subgap leakage current and large gap voltage as used in our noise simulation are observed in the unpumped I-V curve. The gap voltage is 5.2 mV, corresponding to a gap frequency of 1.26 THz. The normal state resistance for each junction is about 72 Ω, which is twice the design value. Photon-assisted tunneling steps were clearly observed with LO applied.

The IF responses to hot and cold loads show a receiver noise temperature of 2700 K (DSB), which is much larger than the theoretical prediction. Moreover, the measured receiver noise at around 1 THz using a optically pumped CH_3OD laser was much worse. The relative high noise performances may be caused by the large RF losses in the tuning circuit of polycrystalline NbN on the SiO. In addition, the penetration depth used in our design may be different from that of actual value. It is very difficult to fabricate single-crystal NbN thin film on the SiO. Polycrystalline NbN film has larger surface resistance and longer London penetration depth compared to single-crystal NbN film [16]. To overcome this problem, we will attempt to use single-crystal NbN for tuning circuits or self-compensated NbN SIS junction [17].

4. Conclusion

Submillimeter-wave receiver performances employing our high current density NbN/AlN/NbN tunnel junctions have been investigated theoretically and experimentally. The theoretical prediction showed that DSB receiver noise temperatures of below $3h\nu/K_B$ can be achieved by using the NbN SIS junctions for frequencies up to 2 THz. However, the experimental receiver designed for the 1 THz band showed poor performances with the noise temperature of 2700 K at 761 GHz. The main reason for the high noise performance may be the large RF losses in the tuning circuit of polycristalline NbN on the SiO. Thus, the existing problem for developing low noise terahertz receivers is material properties of tuning circuits rather than NbN SIS junction properties. We are continuing to explore the fabrication of NbN/AlN/NbN tunnel junctions with single-crystal NbN tuning elements or self-tuned NbN SIS junctions, and to test their noise performance at terahertz frequencies

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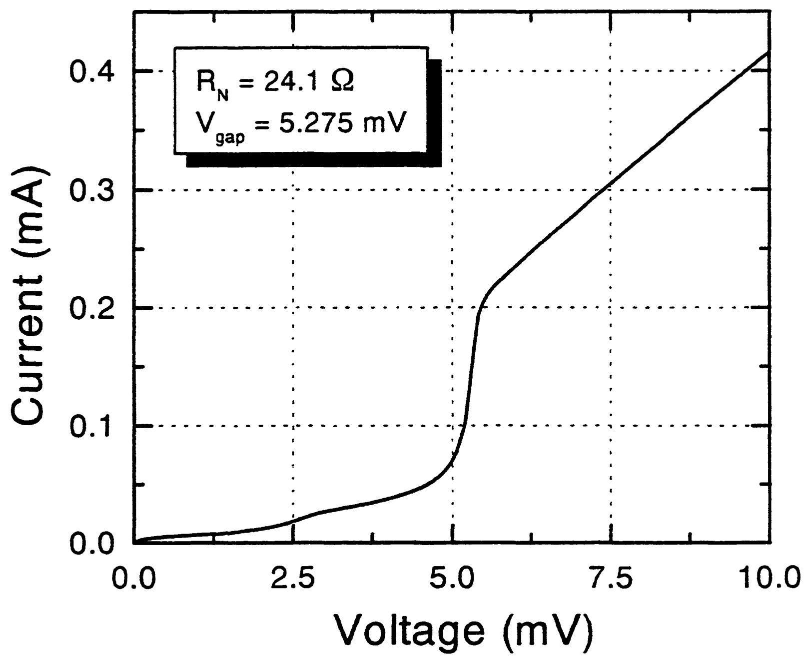

Fig. 1. I-V curve of a practical NbN/AlN/NbN tunnel junction for the performance simulation of the SIS receiver.

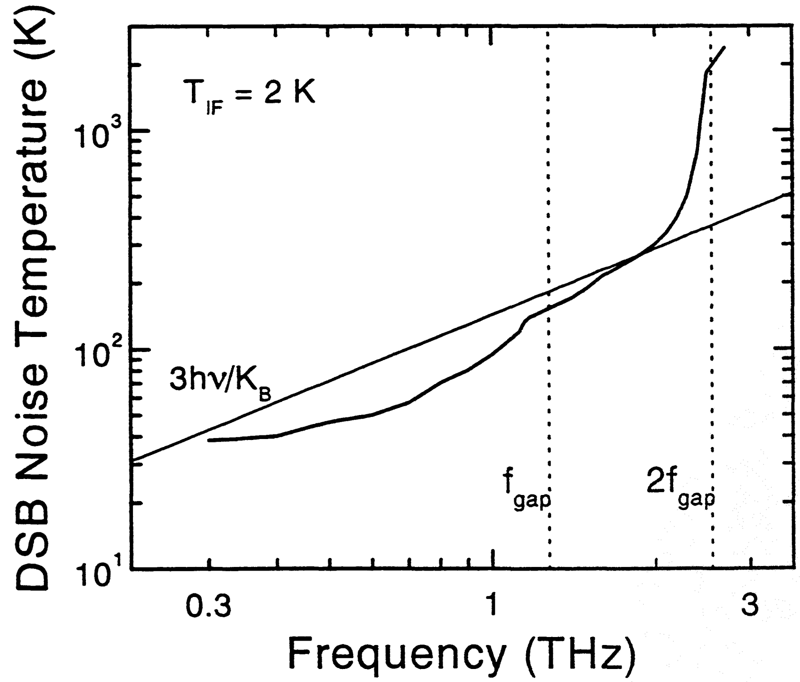

Fig.2. Theoretical sensitivity of the NbN SIS receiver based on the practical I-V curve

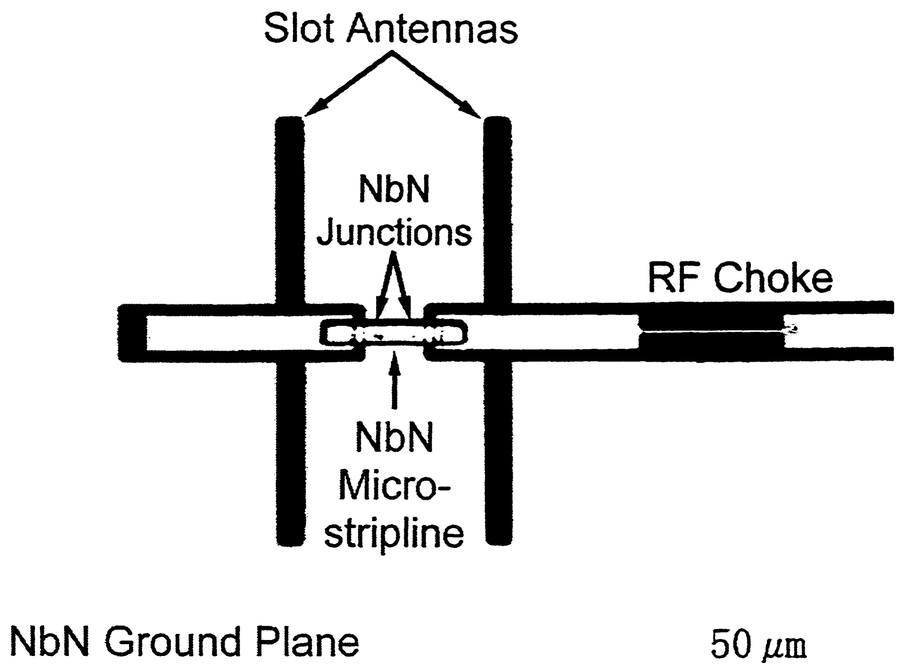

Fig. 3. Optical micrograph of the 1 THz NbN/AlN/NbN mixer. Two NbN junctions in parallel with integrated tuning circuits are fabricated with a twin-slot antenna. Each junction is approximately 0.5 μm in diameter.

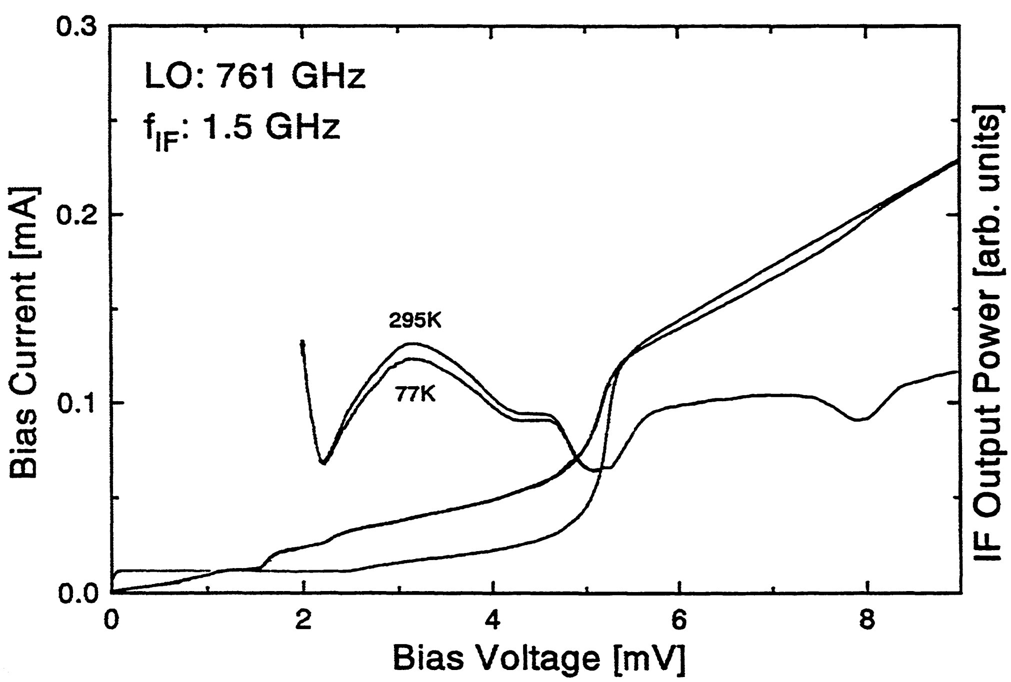

Fig. 4. Heterodyne response of the receiver at 761 GHz. Shown are the I-V curve for the parallel NbN/AlN/NbN junctions with and without LO power. Also shown is the IF power as a function of bias voltage for hot (295 K) and cold (77 K) loads.