Electrical NEP in hot-electron titanium superconducting bolometers

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ABSTRACT

We are presenting the current progress on the titanium (Ti) hot-electron transition-edge devices. The ultimate goal of this work is to develop a submillimeter Hot-Electron Direct Detector (HEDD) with the noise equivalent power NEP = 10^{-18}-10^{-20} W/Hz$^{1/2}$ for the moderate resolution spectroscopy and Cosmic Microwave Background (CMB) studies on future space telescope (e.g., SPICA, SAFIR, SPECS, CMBPol) with cryogenically cooled (~ 4-5 K) mirrors. Recently[1], we have achieved the extremely low thermal conductance (~ 20 fW/K at 300 mK and ~ 0.1 fW/K at 40 mK) due to the electron-phonon decoupling in Ti nanodevices with niobium (Nb) Andreev contacts. This thermal conductance translates into the "phonon-noise" NEP ≈ 3×10^{-21} W/Hz$^{1/2}$ at 40 mK and NEP ≈ 3×10^{-19} W/Hz$^{1/2}$ at 300 mK. These record data indicate the great potential of the hot-electron detector for meeting many application needs. Beside the extremely low phonon-noise NEP, the nanobolometers have a very low electron heat capacitance that makes them promising as detectors of single THz photons[2]. As the next step towards the practical demonstration of the HEDD, we fabricated and tested somewhat larger than in Ref.1 devices (~ 6 μm × 0.35 μm × 40 nm) whose critical temperature is well reproduced in the range 300-350 mK. The output electrical noise measured in these devices with a low-noise dc SQUID is dominated by the thermal energy fluctuations (ETF) aka "phonon noise". This indicates the high electrothermal loop gain that effectively suppresses the contributions of the Johnson noise and the amplifier (SQUID) noise. The electrical NEP = 6.7×10^{-18} W/Hz$^{1/2}$ derived from these measurements is in good agreement with the predictions based on the thermal conductance data. The very low NEP and the high speed (~ μs) are a unique combination not found in other detectors.

Keywords: hot-electron detector, transition-edge sensor, terahertz astronomy, superconducting bolometer

1. INTRODUCTION

Several advanced space submillimeter astronomy missions (SAFIR[3,4], SPECS[5], SPICA[6,7]) have been recently proposed. These missions would make a dramatic impact on the sensitivity achievable for the moderate resolution spectrometry ($\nu/\Delta\nu$ ~ 1000) due to active cooling of telescope mirrors down to ~ 4 K. This deep cooling would significantly reduce the telescope emissivity and enable realization of background-limited noise equivalent power (NEP) ~ 10^{-19}-10^{-20} W/Hz$^{1/2}$ at submillimeter wavelengths. However, the NEP of state-of-the-art direct detectors needs to be improved by almost two orders of magnitude to meet this goal. Membrane supported bolometers have come close to meeting the sensitivity goals [8]: a low phonon conductance has been achieved in long (~ 1-8 mm) Si_3N_4 beams suggesting an *NEP* = 6×10^{-20} W/Hz$^{1/2}$ at 50 mK. The further decrease of the thermal conductance seems to be hindered by the weakening temperature dependence of the thermal conductance due to a transition to the 1-D phonon transport [9].

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Kinetic inductance detectors[10] are another perspective approach. It is based on the microwave reading of a Q-factor change in a λ/4 coplanar waveguide caused by the absorbed radiation. Despite the difficulties associated with the excess phase noise the sensitivity gradually improves having reached a respectful electrical NEP ≈ 3×10^{-18} W/Hz$^{1/2}$ at 100 mK [11]. Even lower NEP values have been just reported [12].

We have been pursuing an alternative approach [13],[14] to enhance the sensitivity of bolometers based on the hot-electron effect [15,16] in superconducting nanostructures. Recently, we have fabricated hot-electron superconducting nanobolometers with an ultra-low electron-phonon thermal conductance and showed that this approach can both significantly increase the sensitivity and reduce the response time [1,17]. In the current work, we demonstrate that the electrical noise in such devices is well explained by the conventional noise mechanism associated with the fluctuations of electron thermal energy in the device.

2. THERMAL CONDUCTANCE

It is well known that the fundamental sensitivity limit of a bolometer depends on its thermal conductance, G. The corresponding component of the NEP is given by:

$$NEP = \sqrt{4k_B T^2 G}\,, \tag{1}$$

where T is the bolometer temperature. A traditional way to reduce G is to suspend the absorber and the thermometer with low thermal conductive beams or membranes. Si_3N_4 is commonly used as the membrane material. This material can be made very thin and microfabricated into narrow beams thus reducing the cross section of the thermal link to a small fraction of a square micron. In this way, very low thermal conductance has been achieved in bolometeric devices of Ref.8.

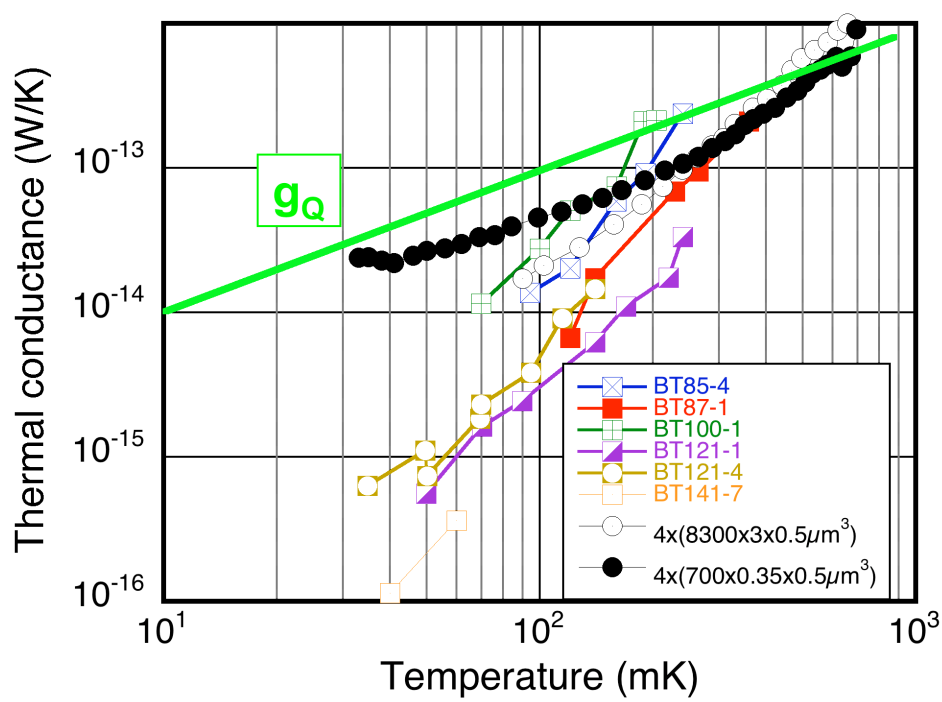

Fig.1. Comparison of the thermal conductance in Si_3N_4 beam suspended bolometers of Ref. 8 (round symbols) and in Ti hot-electron nanobolometers similar to those of Ref. 1 (square symbols). The Ti devices were 40 nm thick, 0.1-0.14 μm wide and 0.5-1.0 μm long. $G_Q = \pi^2 k_B^2 T/3h$ is the so-called "quantum of thermal conductance".

In the hot-electron bolometers, $G = G_{e\text{-}ph} = C_e/\tau_{e\text{-}ph}$ (C_e is the electron heat capacity, $\tau_{e\text{-}ph}$ is the electron-phonon relaxation time in the material). Since C_e is proportional to the device volume, $G_{e\text{-}ph}$ can be made very small in nanoscale devices. This idea[13] has been proven in our recent work[1] where we obtained extremely low $G_{e\text{-}ph}$ values in submicron size (down to 0.5μm × 0.1μm × 0.04μm) Ti devices. It turned out that because of the stronger temperature dependence, $G_{e\text{-}ph}$ in the hot-electron devices is two orders of magnitude smaller at 40 mK than G in Si_3N_4 suspended bolometers of Ref.8 (see Fig. 1). $G_Q = \pi^2 k_B^2 T/3h$ is the so-called "quantum of thermal conductance". This is a limiting value for the ballistic transport of phonons[9] or photons[18,19] and is shown in Fig.1 as a convenient benchmark.

The low $G_{e\text{-}ph}$ values suggest the very low *NEP* due to the "phonon noise" (see Fig. 2). The NEP is below 10^{-18} W/Hz$^{1/2}$ for $T < 0.3$ K and reaches below 10^{-20} W/Hz$^{1/2}$ for $T < 60$ mK. These values are sufficiently small for all foreseeable astronomical applications at submillimeter wavelengths.

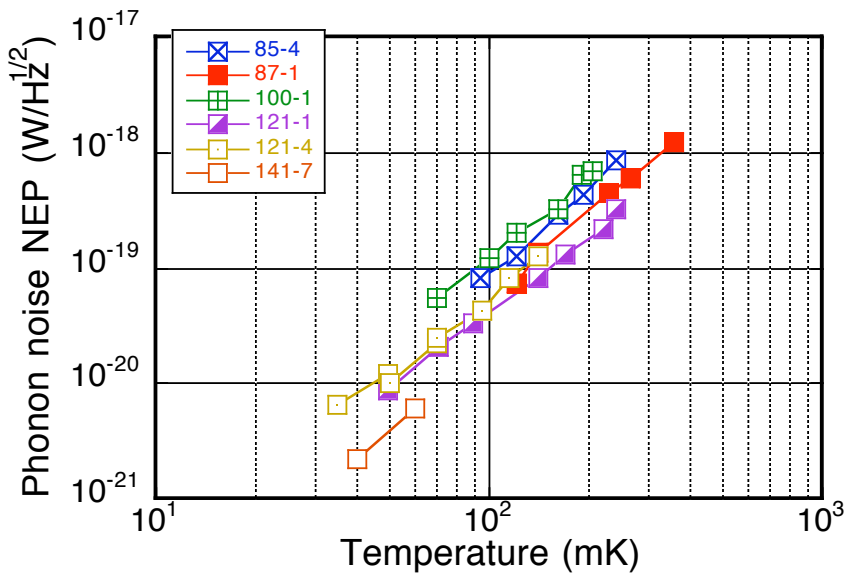

Fig. 2. NEP due to the phonon noise in Ti hot-electron nanobolometers calculated using the G values of Fig.1.

3. CURRENT-VOLTAGE CHARACTERISTICS AND ELECTRICAL NOISE

The small devices described above had rather low T_C values, that was likely the result of contamination of Ti material during e-beam evaporation of Ti though an organic mask (see Ref. 1 for fabrication details). The critical current in the devices was also small. In order to avoid this deterioration of superconducting parameters we fabricated somewhat larger devices from a thicker (60 nm) Ti film. The same as in Ref.1 process was used for *in situ* deposition of Ti and Nb Andreev contacts. Below we discuss the results for a device whose lateral size was 6μm × 0.35μm.

The device was tested in a dilution refrigerator. The external bias current was passed though a 1-Ohm resistor situated in the vicinity of the device on the mixing chamber. This resistor was connected in series with the device and a dc SQUID thus simulated the constant voltage bias. The SQUID amplifier was placed at the 1-K pot of the dilution refrigerator and connected to the device circuit via a magnetically shielded superconducting twisted pair. The device circuit was in an rf tight superconducting shield in order to avoid overheating of the device by uncontrolled rf interferences and noise. The entire experimental volume was surrounded by a Cryoperm-10® magnetic shield immersed in liquid He4. The bias lines and the SQUID wires were put through the custom low-pass filters (LPF), which were built from discrete element LPFs placed inside metal tubes filled with Emerson&Cuming CRS-124 microwave absorbing compound. This approach was inspired by a recent work [20].

A family of the current-voltage (IV) characteristics for the Ti device is shown in Fig. 3 as function of temperature. The device normal resistance, R_N, was 55 Ohm and the residual resistance was much less than 1 Ohm. One can see that the critical current is very pronounced below T_C (≈ 332 mK) and quickly collapses as the temperature increases by a few mK. Because of the dc stability condition $|dV/dI| > R_L$ (=1 Ohm) it was not possible to bias the device below 324 mK.

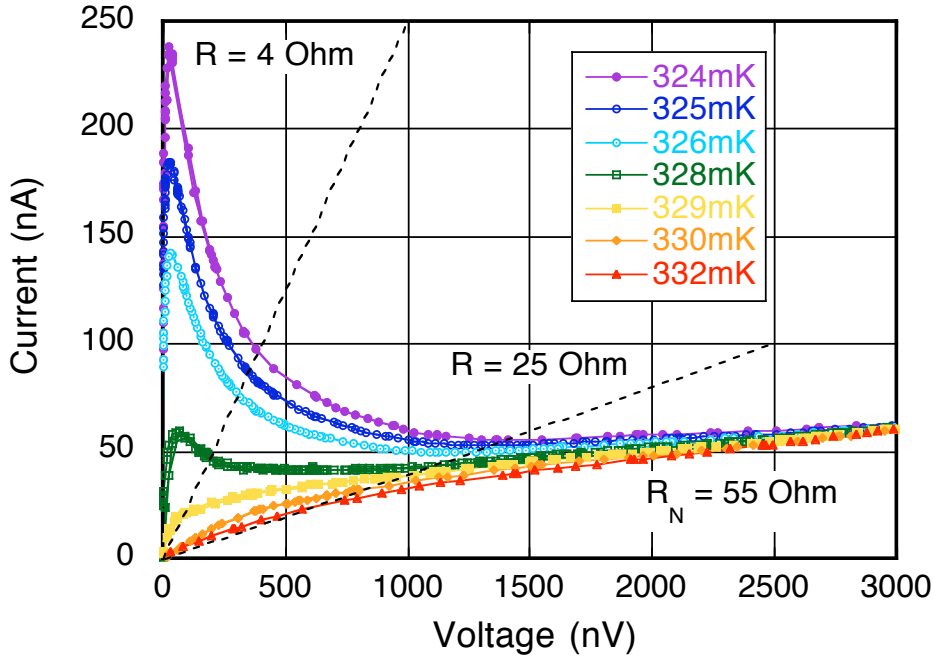

Fig. 3. IV characteristics of a 6μm × 0.35μm × 0.06μm Ti hot-electron bolometer. The dashes show the constant resistance lines along which the calculations of the thermal conductance were made.

From the IV curves of Fig.3 the thermal conductance in the device was estimated. Here we used the so-called "isothermal" technique[21,22] which has been commonly used in superconducting hot-electron heterodyne detectors. The idea is based on an assumption that the resistance of the device is a function of its electron temperature, T_e, only. If we take two bias points at two different bath temperatures T_1 and T_2 then the following heat balance equations are valid:

$$P_1 = G(T_{e1} - T_1), \qquad P_2 = G(T_{e2} - T_2) \tag{2}$$

Here P_1 and P_2 are Joule powers dissipating in the device in each bias point and T_{e1} and T_{e2} are the corresponding electron temperatures. If both bias points correspond to the same resistance then $T_{e1} = T_{e2}$ and

$$G = \frac{P_2 - P_1}{T_2 - T_1}. \tag{3}$$

The calculations of G for two different resistances (4 Ohm and 25 Ohm) are shown in Fig. 4. The same thermal conductance value 7.8 pW/K was derived in both cases. This G figure is in good agreement with the data of Ref.1 where the thermal conductance above 0.3 K could be well approximated by the expression:

$$G_{e-ph}(T) = 1.56 \times 10^9 T^3 v, \tag{4}$$

where v is the device volume. From Eq.4 we obtain $G_{e\text{-}ph}(0.33\text{K}) = 7.1$ pW/K.

Finally, we measured the electrical noise in the device as function of bias for two close temperatures: 324mK and 326mK. The measurements of bias and temperature dependencies were done using a lock-in amplifier for detecting the

SQUID output noise. The calibration was made in a few points using the full noise spectrum and making sure that the measurement frequency (900 Hz) corresponds to the "white noise" segment of the spectrum and does not coincide with some spurious resonances or interference peaks.

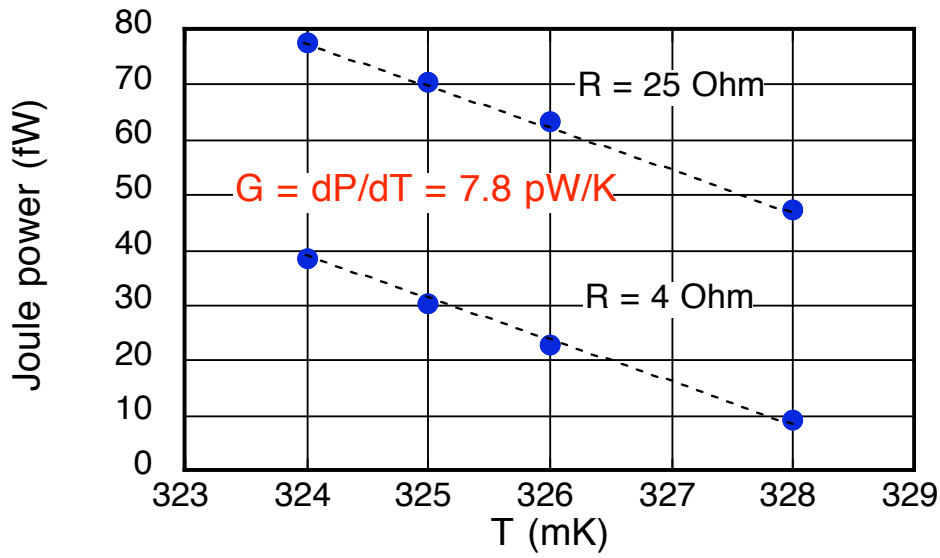

Fig. 4. Determination of the thermal conductance using the "isothermal" technique.

We should mention that at this stage we could not reliably establish any device dependent roll-off of the noise spectrum. The main reason was that in order to provide better stability for the SQUID we used the SQUID feedback setting reducing the SQUID bandwidth to several kHz. This is a significantly lower bandwidth than the Ti device relaxation time (~ μs) allows for. The aspect of the device noise bandwidth will be addressed in the future work using a faster array SQUID amplifier.

The results of the noise measurements are shown in Fig.5. Here two IVs of Fig. 3 (324mK and 326 mK) are shown along with the corresponding noise date points. The maximum noise values 50-60 pA/Hz$^{1/2}$ are observed at low bias voltages. The noise gradually decreases with bias. This is easy to understand qualitatively since the responsivity of a voltage-bias bolometer (and its phonon noise) is higher towards the low bias values. The maximum noise far exceeds the SQUID noise (2.5 pA/Hz$^{1/2}$). Also, despite the bias current collapses by a factor of 2 between 324 mK and 326 mK, there is no apparent change in the output noise.

In order to get a better idea about the origin of the device noise we calculated the output noise using the model for a lumped element bolometer developed in [23,24,25,26]. In this model, the negative electro-thermal feedback (ETF) plays a role modifying the output noise and the thermal relaxation time. The dimensionless parameter characterizing the feedback (the loop gain, L) was derived from the IV characteristics using the expression:

$$L = \frac{dV/dI + V/I}{dV/dI - V/I}. \tag{5}$$

We noticed that the part of the IV below 200 nV (where the responsivity is greater) can be approximated as $I \sim 1/V^m$. The extreme theoretical case $m = 1$ (strong negative ETF) has been considered, e.g., in[24]. In was not the case in our measurements where we obtained $m \approx 0.25$ for $T = 324$ mK and $m \approx 0.42$ for $T = 326$ mK. The loop gain relates to exponent m:

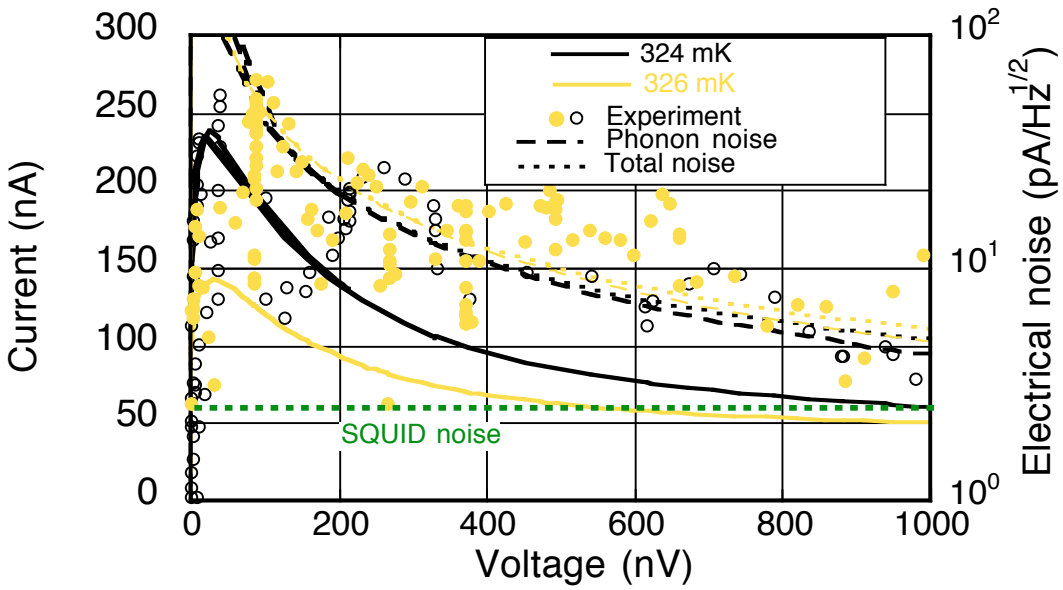

Fig.5. Output electrical noise in Ti hot-electron devices. Experimental noise: open symbols – 324 mK, closed symbols – 326 mK. IVs and modeled noise: dark lines – 324 mK, light lines – 326 mK.

$$L = \frac{1+m}{1-m} \tag{6}$$

yielding L = 2.45 at 326 mK and L = 1.67 at 324 mK. Using these values, the phonon noise and the Johnson noise have been calculated:

$$i_n^{phon} = \frac{\sqrt{4k_B T^2 G}}{V}\frac{L}{1+L}, \qquad i_n^J = \sqrt{\frac{4k_B T}{R(1+L)}}. \tag{7}$$

The results of calculations of the phonon noise contribution and also of the total noise are plotted in Fig.5. One can see that the total noise agrees very well with the experimental values. The modeling suggests that the phonon noise dominates and two other noise components (SQUID noise and Johnson noise) are negligibly small. This is an indication that the intrinsic responsivity in the bias points below 200 nV is sufficiently high (it nearly reaches 1×10^7 A/W), and that the total NEP can be estimated using Eq.1. This estimate gives NEP = 6.7×10^{-18} W/Hz$^{1/2}$.

The bolometer time constant can be found as

$$\tau = \frac{C_e/G_{e-ph}}{1+L} = 1.9\ \mu\text{s}. \tag{8}$$

(we used the bulk Sommerfeld constant value γ = 310 J m^{-3} K^{-2} for Ti).

It is interesting to note that this time constant is practically of the same magnitude as the electrical time constant of the circuit $\tau_{el} = L_{SQUID}/(R+R_L)$. The SQUID input coil inductance was L_{SQUID} = 1.8 μH and the device resistance was well under 1 Ohm for small bias voltages. Still the operating point was stable in the region where $dV/dI < 0$. Previous analytical papers[27,28] derived a more conservative stability condition: $\tau > (3\text{-}6) \times \tau_{el}$.

4. CONCLUSIONS

The obtained results demonstrate a very good potential for hot-electron bolometers to become a competing detector technology in low background submillimeter applications. Although more technological work is needed in order to improve the basic superconducting characteristics of the smallest devices, the "medium-size" devices studied in this work have already sufficiently good characteristics having reached the noise limit set by the fundamental thermal energy fluctuations. The next step would be to perform optical NEP measurements with similar devices integrated with planar antennas. The device normal resistance of about 50 Ohm is a perfect match for the typical planar antenna impedances.

The electrical NEP < 10^{-17} W/Hz$^{1/2}$ achieved at 330 mK sets the record for this temperature. Other types of detectors may be that sensitive only a temperatures 50-100 mK. Temperatures higher than 300 mK can be readily achieved using sorption coolers, which are simple and inexpensive. The very short detector time constant is instrumental for eliminated the 1/f-noise and increasing the data rate from the instrument.

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