Analysis of a normal metal nano-HEB THz array

Boris S. Karasik[1] *, Christopher B. McKitterick[2], Theodore J. Reck[1], and Daniel E. Prober[2]
[1]*Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA 91109, USA*
[2]*Yale University, New Haven, CT 06520, USA*
*Contact: boris.s.karasik@jpl.nasa.gov +1 (818) 393-4438

Abstract— **We will present an analysis of the sensitivity and a preliminary design of a multiplexed THz direct detector array utilizing normal metal titanium (Ti) hot-electron nanobolometers (nano-HEB) as sensing elements. The readout technique employs direct reading of the electron temperature via a correspondent Johnson noise. In contrast to its superconducting transition-edge sensor (TES) counterpart, the normal-metal nano-HEB can operate within a very broad range of cryogenic temperatures (0.05 - 9 K) depending on the anticipated radiation background. The array does not require bias lines, 100s of nano-HEBs can be read by a single low-noise X-band amplifier via a filter bank channelizer. The modeling predicts that the Noise Equivalent Power (NEP) is fundamentally limited by the amplifier noise, with a NEP = 3 × 10^{-20} W/Hz$^{1/2}$ expected at 50 mK.**

I. INTRODUCTION

Moderate resolution spectroscopy in space will require very sensitive THz detectors in order to take advantage of the ultra-low radiation background expected under the condition of the cryogenically cooled primary telescope mirror. Superconducting nano-HEB detector (= hot-electron TES) made from Ti is one of the most sensitive THz detectors demonstrated to date [1]. Because of its small (submicron) size and a weak electron-phonon coupling constant in the material, a much lower thermal conductance than in a SiN membrane suspended TES has been achieved [2]. A low NEP ≈ 3×10^{-19} W/Hz$^{1/2}$ has been demonstrated via direct optical measurements [3]. However, the operation of an array of superconducting nano-HEBs requires individual SQUID amplifiers instrumented into some multiplexed scheme as well as numerous circuits for dc bias and flux bias of the SQUIDs [4], [5]. Also, the detector material's critical temperature, T_C, must be tuned uniformly across the array to some low value (~ 0.1 K) desirable for operation.

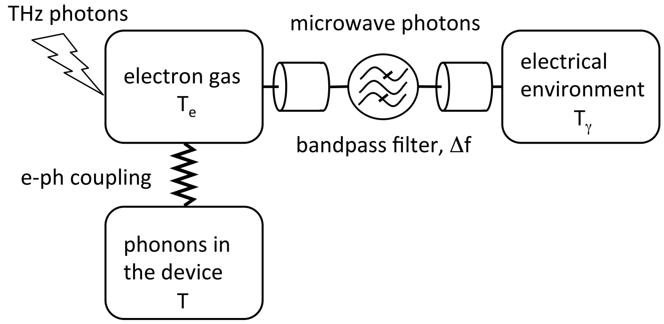

Fig. 1. Cooling pathways for hot electrons in a normal metal nano-HEB. As in TES HEBs, electrons cool via emission of acoustic phonons in the device. Also, because of the necessity to read the Johnson noise within a bandwidth Δf, additional cooling occurs via emission of microwave phonons.

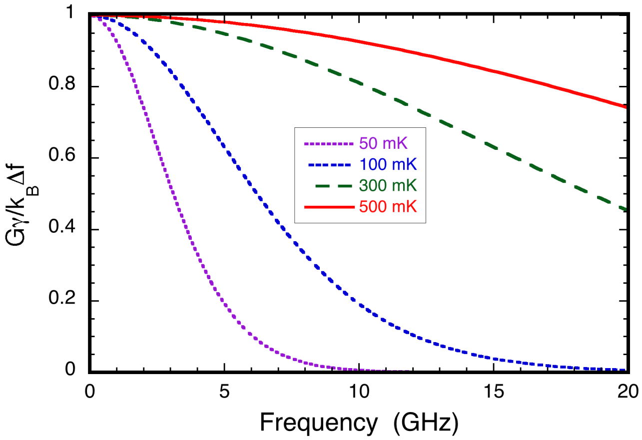

Fig. 2. Microwave photon mediated thermal conductance as function of temperature and frequency (Δf = 10 MHz).

In this paper, we analyze an alternative approach to the nano-HEB, which combines the high thermal sensitivity inherent in this type of detector with the simplicity of the readout offered by the Johnson Noise Thermometry (JNT) [6]. In order to achieve that, the nano-HEB must be made from a normal metal (non-superconducting) material with superconducting contacts made from the material with high critical temperature (e.g., Nb, NbTiN) in order to facilitate the Andreev reflection mechanism preventing fast diffusion of hot electrons. THz photons absorbed in an antenna-coupled nano-HEB raise the electron temperature that leads to an increase of the Johnson noise. The latter is read by a sensitive (ideally, quantum-noise limited) rf amplifier connected to the detector via a transmission line and a bandpass filter.

II. COOLING MECHANISMS FOR ELECTRONS

In bolometers, low thermal conductance is the key for achieving the lowest NEP fundamentally limited by the thermal energy fluctuations (TEF or "phonon" noise). The electron-phonon (e-ph) thermal conductance $G_{e\text{-}ph}$ in Ti has been thoroughly studied [2], [7]. It is so low in submicron-size devices that the TEF noise limited $NEP_{TEF} < 10^{-20}$ W/Hz$^{1/2}$ can be expected at 40-50 mK.

Because of the nature of the readout, the normal metal nano-HEB has an additional pathway for cooling, an emission on microwave photons [8]. The corresponding thermal

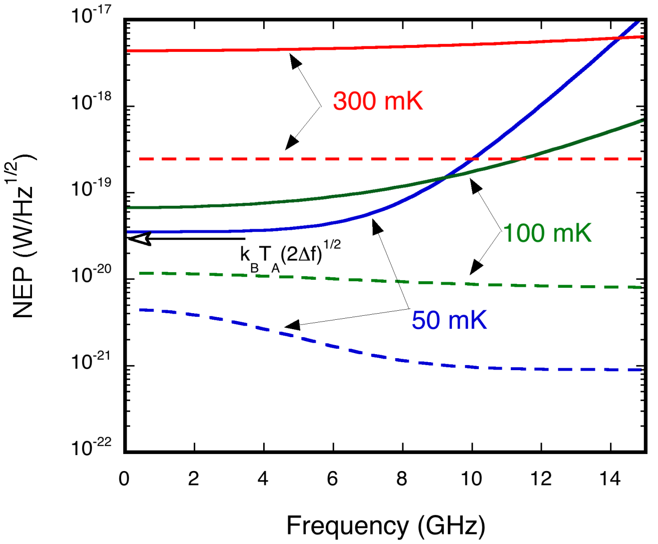

Fig. 3. Modeling results for NEP$_{TEF}$ (dashes) and NEP$_{JNT}$ due to the readout noise (solid lines). At 50 mK, a contribution of the Gγ (larger NEP$_{TEF}$) can be seen below 7 GHz. At higher temperature, G$_{e\text{-}ph}$ dominates (NEP$_{TEF}$ does not depend on the readout frequency). At any temperature, NEP$_{JNT}$ dominates exceeding the corresponding NEP$_{TEF}$ by an order of magnitude.

conductance Gγ is shown in Fig. 2. Whereas at low readout frequency Gγ (~ 0.1 fW/K for Δf = 10 MHz) can be larger than G$_{e\text{-}ph}$ (~ 0.01 fW/K @ 50 mK for a 0.5μm × 0.25μm × 20nm Ti device), the role of the photon cooling diminishes as the readout frequency increases. A readout frequency f ~ 10 GHz is also desirable for instrumenting a large number (100s) of 10-MHz-wide frequency bands using a single low noise amplifier (e.g., kinetic inductance parametric amplifier [9]).

III. NOISE EQUIVALENT POWER

Details of the NEP analysis can be found in [6]. It turns out that the filter bandwidth and the summing amplifier noise temperature, T$_A$, define the overall system sensitivity. The lowest NEP value which can be achieved with this detector at 50 mK (and below) is limited by $\mathrm{NEP}_{JNT} \approx k_BT_A(2\Delta f)^{1/2} = 3 \times 10^{-20}$ W/Hz$^{1/2}$. (see Fig. 3). The analysis shows that the noise bandwidth (the readout frequency range within which NEP is constant) of the Ti HEB is about 7-10 GHz even at temperatures of 50-100 mK. Materials with weaker e-ph coupling (Bi [10], graphene [11]) may have even larger noise bandwidth at 50 mK since the ratio Gγ/G$_{e\text{-}ph}$ at f = 0 will be higher in those cases.

IV. POWER SATURATION AND DYNAMIC RANGE

By employing a normal (non-superconducting) absorber, we allow a significant increase of the electron temperature in the normal metal HEB without hard saturation of the output signal. The practical limit is set by the critical temperature of superconducting Andreev contacts (9.3 K for Nb) and corresponds to an optical load ≈ 7 nW per pixel. This is a huge number in comparison with that for TES detectors with similar sensitivity. The dynamic range of the sensor can be as large as 100 dB. The parametric amplifier [9] will not limit the output signal even for a 1000-pixel HEB array since it has a very large 1-dB gain compression input power level of -52 dBm.

Beside the high sensitivity application on a space telescope, such a detector can be employed with practically any background expected in suborbital and ground based receivers. Depending on the expected photon noise NEP the operating temperature can be chosen in the range 0.05-9 K.

V. CONCLUSIONS

The proposed nano-HEB offers an attractive combination of qualities not found in other sensitive THz detectors, namely high sensitivity, large dynamic range, large multiplexing ratio, absence of dc or rf bias, relative simplicity of fabrication and suitability of the same detector element for multiple applications. Beside the high sensitivity, the normal metal bolometer does not have any hard saturation limit and thus can be used for imaging with arbitrary contrast. Using a broadband quantum noise limited kinetic inductance parametric amplifier, 100s of normal metal HEBs can be read simultaneously without saturation of the system output.

ACKNOWLEDGMENT

This research was carried out in part at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration. The work at Yale was supported by NSF Grant DMR-0907082, an IBM Faculty Grant, and by Yale University.

REFERENCES

[1] B. S. Karasik, A. V. Sergeev, and D. E. Prober, "Nanobolometers for THz photon detection," *IEEE Trans. THz Sci. & Technol.*, vol. 1, pp. 97-111 (2011).
[2] J. Wei, D. Olaya, B. S. Karasik, S. V. Pereverzev, A. V. Sergeev, and M. E. Gershenson, "Ultrasensitive hot-electron nanobolometers for terahertz astrophysics," *Nat. Nanotechnol.*, vol. 3, pp. 496-500 (2008).
[3] B. S. Karasik and R. Cantor, "Demonstration of high optical sensitiivty in far-infrared hot-electron bolometer," *Appl. Phys. Lett.*, vol. 98, pp. 193503 (2011).
[4] B. S. Karasik, S. V. Pereverzev, D. Olaya, M. E. Gershenson, R. Cantor, J. H. Kawamura, et al., "Development of the nano-HEB array for low-background far-IR applications," *Proc. SPIE*, vol. 7741, pp. 774119 (2010).
[5] B. S. Karasik, P. K. Day, J. H. Kawamura, B. Bumble, and H. G. LeDuc, "Multiplexing of Hot-Electron Nanobolometers Using Microwave SQUIDs," *AIP Conf. Proc.*, vol. 1185, pp. 257-260 (2009).
[6] B. S. Karasik, C. B. McKitterick, T. J. Reck, and D. E. Prober, "Normal-metal hot-electron nanobolometer with Johnson Noise Thermometry readout," *IEEE Trans. THz Sci. & Technol.* (2015), in press, doi: 10.1109/TTHZ.2014.2370755
[7] M. E. Gershenson, D. Gong, T. Sato, B. S. Karasik, and A. V. Sergeev, "Millisecond electron-phonon relaxation in ultrathin disordered metal films at millikelvin temperatures," *Appl. Phys. Lett.*, vol. 79, pp. 2049-2051 (2001).
[8] D. R. Schmidt, R. J. Schoelkopf, and A. N. Cleland, "Photon-mediated thermal relaxation of electrons in nanostructures," *Phys. Rev. Lett.*, vol., 93, pp. 045901 (2004).
[9] B. H. Eom, P. K. Day, H. G. LeDuc, and J. Zmuidzinas, "A wideband, low-noise superconducting amplifier with high dynamic range," *Nat. Phys.*, vol. 8, pp. 623-627 (2012).
[10] Y. F. Komnik, V. Y. Kashirin, B. I. Belevtsev, and E. Y. Beliaev, "Temperature variation of the time of inelastic electron relaxation in disordered bismuth films," *Phys. Rev. B,* vol. 50, pp. 298-303 (1994).
[11] A. C. Betz, F. Vialla, D. Brunel, C. Voisin, M. Picher, A. Cavanna, et al., "Hot electron cooling by acoustic phonons in graphene," *Phys. Rev. Lett.*, vol. 109, pp. 056805 (2012).