THz Hot-Electron Photon Counter

Boris S. Karasik and Andrei V. Sergeev

Abstract—**We present a concept for the hot-electron transition-edge sensor capable of counting THz photons. The main need for such a sensor is a spectroscopy on future space telescopes where a background limited NEP ~ 10^{-20} W/Hz$^{1/2}$ is expected at around 1 THz. Under these conditions, the rate of photon arrival is very low and any currently imaginable detector with sufficient sensitivity will operate in the photon counting mode. The Hot-Electron Photon Counter based on a submicron-size Ti bridge has a very low heat capacity which provides a high enough energy resolution (~140 GHz) at 0.3 K. With the sensor time constant of a few microseconds, the dynamic range would be ~ 30 dB. The sensor couples to radiation via a planar antenna and is read by a SQUID amplifier or by a 1-bit RSFQ ADC. A compact array of the antenna-coupled counters can be fabricated on a silicon wafer without membranes.**

Index Terms—**radiation detectors, submillimeter wave detectors, bolometers, superconducting devices.**

I. INTRODUCTION

Several new advanced space submillimeter (SMM) astronomy missions (Single-Aperture FIR Observatory – SAFIR [1,2], Submillimeter Probe of the Evolution of Cosmic Structure – SPECS [3], Space Infrared Telescope for Cosmology and Astrophysics – SPICA [4]) have been recently proposed. What they all have in common is a dramatic impact on the attainable sensitivity in the moderate resolution mode ($R = \nu/\Delta\nu \sim 1000$) which is typical for application of direct detectors in spectroscopy. This will be achieved by active cooling of telescope mirrors in space to 4-5 K. For all existing platforms, the temperature of the telescope and radiation of the atmosphere set the limit of the sensitivity. Deep cooling of a telescope mirror to ~4K would almost completely eliminate the effect of the telescope emissivity. Then the limiting noise equivalent power (*NEP*) would be set by the background fluctuation at the level of *NEP* ~ 10^{-19}-10^{-20} W/Hz$^{1/2}$ in the most of the SMM range (see Fig. 1). Below 1 THz, the radiation is from the Cosmic Microwave Background. At higher frequencies, the radiation from the galactic core and dust clouds dominates.

The required *NEP* is two-three orders of magnitude lower then that currently achieved by the state-of-the-art (SOA) micromachined bolometers. Although it has been speculated that more than order of magnitude improvement of the performance could be achieved for such devices [2,5], we show that the required improvement of the bolometer sensitivity is restricted by the quantum limitations imposed on the phonon conductance in 1-D channels below 1 K. Alternative approaches for achieving the *NEP* ~ 10^{-20} W/Hz$^{1/2}$ include a number of superconducting concepts, namely a superconducting [6] or normal metal [7] hot-electron bolometer, a kinetic inductance detector [8,9], a superconducting tunnel-junction device with single-electron transistor readout [10], and a hot-spot superconducting detector [11].

Data of Fig. 1 show that the low *NEP* above 1 THz corresponds to a very low photon arrival rate $N_{ph} < 100$ s^{-1}. This makes integration of weak signals impossible for the most of the above detector concepts. Indeed, the time constant cannot be easily engineered and is determined by either the electron-phonon relaxation time [6,7,11] or by the quasiparticle recombination time [8,9,10] which are of the order of millisecond at 100 mK where the low *NEP* can only be achieved. This circumstance makes photon counting a preferable mode of operation at least for detection of weak signals. The photon counting mode has been considered for devices [10] and [11]. The only experimental demonstration of the detection of single SMM photons was done using

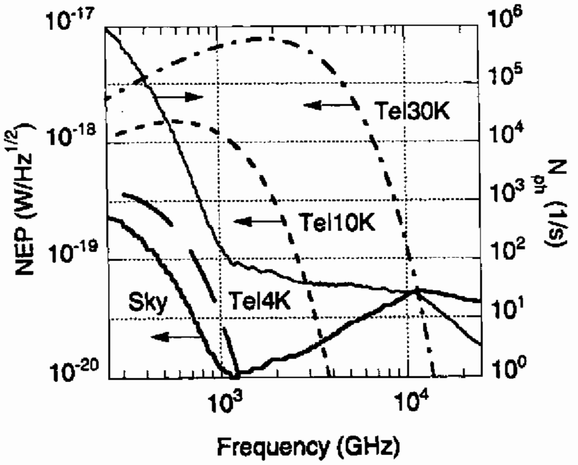

Fig. 1. The *NEP* corresponding to the background limit for the moderate resolution spectrometer (R = 1000) and the corresponding rate of photon arrival. The later is less than 100 sec.$^{-1}$ above 1 THz.. The dashed and dotted line show contributions to the *NEP* of a telescope mirror with a 5% emissivity at different temperatures (4K, 10K, and 30K).

Manuscript received October 5, 2004.

This research was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration. The work of A.V.S. was supported by a NASA grant.

B. S. Karasik is with the Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA 91109, USA (phone: 818-393-4438; fax: 818-393-4683; e-mail: boris.s.karasik@jpl.nasa.gov).

A. V. Sergeev is with the University at Buffalo, Buffalo, NY 14260, USA (e-mail: asergeev@eng.buffalo.edu).

quantum-dot devices [12]. The low operation temperature of the devices (50 mK) and potential difficulties associated with coupling of radiation to such devices and with their readout make alternative approaches worth of pursuing.

In this paper, we analyze the photon counting regime for a Hot-Electron Direct Detector (HEDD) [6], which is a transition-edge sensor (TES) operated in the hot-electron regime and whose sensitivity is enhanced due to the material disorder [13]. The main advantage of this approach is that the *NEP* ~ 10^{-20} W/Hz$^{1/2}$ can be actually achieved at 300 mK instead of 100 mK that makes a huge difference for space applications. The proposed Hot-Electron Photon Counter (HEPC) can be planar antenna coupled and fabricated on bulk *Si* substrate. The readout circuits can use either SQUIDs or RSFQ devices. Both readout technologies are compatible with the detector technology and relatively well developed.

II. SENSITIVITY LIMIT IN MICROMACHNIED BOLOMETERS

Bolometers are currently detectors of choice for SMM astronomical instruments. The state-of-the-art design of a SMM bolometer represents a very fine mesh ("spider-web") etched from a 1 μm thick Si_3N_4 membrane that suspends a sensitive Neutron-Transmutation-Doped Ge (NTD-Ge) thermometer. The mesh plays simultaneously the role of the thermal conductance to the bath and of the radiation absorber. One of the most important applications of these bolometers will be the High-Frequency Instrument (HFI) on the NASA/ESA Planck Surveyor Mission where a typical background-limited Noise Equivalent Power *NEP* ~ 10^{-17}-10^{-16} W/Hz$^{1/2}$ will be utilized in several frequency bands between 100 GHz and 857 GHz [14]. The fundamental *NEP* of a bolometer is set by the minimum possible thermal conductance between the absorber of radiation and the thermal sink. "Spider-web" bolometers use several (~10) 500 μm long, 1 μm thick and 3 μm wide Si_3N_4 legs, each of which contributes ~ 1 pW/K into the thermal conductance at 100 mK.

A further decrease of the thermal conductance might be seen via an increase of the leg length and decrease of the number of legs and their crossection assuming that the "classical" T^3-dependence of the thermal conductivity still holds at lower temperatures There is, however, new data on the thermal conductance of dielectrics nanowires at low temperatures setting some doubts about the realism of this approach for increase of the detector sensitivity. Theory [15], which takes into account the quantization of phonon modes in thin wires, gives the following low temperature limit for the thermal conductance:

$$G_Q = 4\pi^2 k_B^2 T / 3h. \qquad (1)$$

Remarkably, this quantity does not depend on the length of the wire and its material properties. The experiments with Si_3N_4 [16], GaAs wires [17] and nanotubes [18] confirm the theory demonstrating the crossover of the conductance from the T^3-dependence to the linear dependence of (1). Though the crossover temperature depends on the material purity, the lowest possible conductance is given by (1). If we assume a hypothetical leg-suspended bolometer with just three legs then the intrinsic quantum conductance limited NEP_Q will be given by:

$$NEP_Q = \sqrt{4k_B T^2 \cdot 3G_Q} \qquad (2)$$

At 100 mK, (2) yields an *NEP* which is slightly less than 10^{-18} W/Hz$^{1/2}$. It approaches the 10^{-20} W/Hz$^{1/2}$ only below 10 mK, which is an impractically low temperature for space instruments.

III. RELAXATION TIME IN NON-EQUILIBRIUM SENSORS

Since conventional micromachined bolometers cannot in principle achieve the low enough *NEP* other alternatives must be considered. Two other actively pursued approaches to sensitive integrating SMM detectors are the Hot-Electron Direct Detector (HEDD) [6] and the Kinetic Inductance Detector [9]. Both use non-equilibrium phenomena in superconducitng films. The HEDD relies on a weak electron-phonon coupling in disordered Hf or Ti superconducting films. Its sensitivity is limited by the same thermal energy fluctuation noise mechanism as in ordinary bolometers but with $G_{e\text{-}ph} = C_e/\tau_{e\text{-}ph}$ (C_e is the electron heat capacity, $\tau_{e\text{-}ph}$ is the electron-phonon relaxation time) playing a role of the thermal conductance. $\tau_{e\text{-}ph}$ is the material parameter and does not depend on the geometry. C_e is proportional to the volume therefore the sensitivity of the detector becomes greater for small devices. A previous analysis [6] shows that the corresponding *NEP* can be as low as 10^{-20} W/Hz$^{1/2}$ at 100 mK.

The relaxation time in, e.g., *Ti* HEDD greatly increases at low temperature [13]:

$$\tau_{e-ph} = 0.2 \cdot T^{-4} [\mu\text{sec}]. \qquad (3)$$

Exponent 4 in the dependence of (3) arises due to the scattering on defects in a metal at very low temeperautres that additionally slows down the relaxation [19]. If an HEDD device operated at 100 mK, $\tau_{e\text{-}ph}$ would be ~ 2 ms. This is still too short to integrate photons arriving at as low as in Fig. 1 rate.

The situation with the KID is somewhat similar. Here the detection mechanism uses a number of Cooper pairs broken by photons. This causes a decrease of the kinetic inductance of the superconducting film that can be detected by either an inductive bridge with a SQUID [8] or via a shift of the resonance frequnency in a strongly coupled microstrip resonator [9]. The fundamental sensitivity limit is set by the quasiparticle generation-recombination noise and can, in principle, yield the *NEP* below 10^{-19} W/Hz$^{1/2}$ [8]. This would, however, require a very small number of quasiparticles N_{qp} < 1000 in the entire volume of the detector. The response time is given by the quasiparticle recombination time modified by phonon trapping effects in the film. This time has a very strong temperature dependence

$$\tau_{qp} \propto \exp\left(\frac{\Delta}{k_B T}\right), \qquad (4)$$

and can, on the first sight, be very long. Thus, e.g, in Al [9], this time has been found to follow the dependence of (4) reaching ~ 0.1 ms at 250 mK. An extrapolation of (4) to 100 mK would bring τ_{qp} to ~ 30 s that is sufficient for integration of rare single photon events. However, in the experiment, a saturation of τ_{qp} has been seen at lower temperatures. There are a number of reasons causing a saturation of τ_{qp} and of N_{qp} at low temperatures. They can be internal traps with lower gap in the material, strain radiation or diffusion. It is unclear at this time if the material properties and conditions for operation of KID devices can be improved to the extent necessary to obtain both a low *NEP* and a long time constant.

IV. HOT-ELECTRON BOLOMETRIC PHOTON COUNTER

It is quite obvious from the above that it will be very difficult if possible at all to realize a combination of the *NEP* ~10^{-20} W/Hz$^{1/2}$ and the time constant ~ 1 s. Thus, the photon counting mode for THz radiaiton becomes unavoidable and needs more attention and study. Superconducting photon counters have been successfully developed from X-ray to near-IR wavelengths. The main motivation is to achieve useful energy resolution without using external wavelength dispersing elements. In many cases they are also the most sensitive detectors at these wavelengths. TES devices have been in particular of great interest for such applications in view of their robust thin-film technology, compatibility with low-noise SQUID readout and the presence of the negative electro-thermal feedback improving the energy resolution. When the wavelength increases the energy resolution of the photon-counters degrades and the only remaining advantage of the photon counters over the integrating detectors is an ability to detect very weak radiation fluxes with a small photon count rate.

Just recently, submicron-size (down to 0.5 μm × 0.1 μm × 0.020 μm) Ti HEDD devices have become available for our work [20]. This has created a situation when we can realistically evaluate a performance of the Hot-Electron Photon Counter (HEPC) in the THz regime. The envisioned HEPC device is a submicron size superconducting bridge made from thin disordered Ti film, which has a critical temperature, $T_C \approx 350$ mK. The bridge is fabricated on silicon or sapphire substrate between Nb contacts which block the diffusion of hot electrons out of the bridge due to Andreev reflection. A planar antenna provides coupling to THz radiation. The Ti nanobridge will operate in the voltage-biased TES mode, that is, its operating temperature T will be somewhat lower than the critical temperature, T_C, and the resistance at the operating point will be much smaller than the normal resistance. An absorbed photon causes a fast increase of the electron temperature in the device, $\delta T_e = h\nu/C_e$, within the characteristic time $\tau_R \approx L^2/\pi^2 D$ (L is the bridge length, D is the electron diffusivity). Then the relaxation of electron temperature occurs with the time constant $\tau = \tau_{e\text{-}ph}/(\mathcal{L}+1)$ where $\mathcal{L}$ is the electro-thermal feedback (ETF) loop gain [21]. For strong ETF, $\mathcal{L} = \alpha/n$ ($\alpha \approx 2T_C/\delta T_C$, δT_C is the superconducting transtion width). The response time does not vary significantly over the range where the sensitivity is high. The value of $N_{max.} = 1/(\pi\tau)$ determines the maximum count rate. This would provide a large dynamic range for the counter: $DR = N_{max}/N_{ph}$. The ability of the device to detect a single photon will depend on the magnitude of the intrinsic thermal fluctuations compared to the photon energy. The rms energy fluctuation for a TES with srtrong ETF is given by [21]:

$$\delta E \approx \sqrt{4\sqrt{n/2}\,k_B T_e^2 C_e/\alpha}\,. \qquad (5)$$

Here $n = 6$ is the material exponent in the temperature dependence of the electron-phonon thermal conductance. This value of n corresponds to the T^{-4} temperature dependence of (3). Frequency $\nu_R = \delta E/h$ can be treated as the "red boundary" or the low frequency limit for the detection mechanism.

In order to detect low energy photons, the temperature must be low and the volume of the device must be small. On the other hand, $T \geq 0.3$ K is quite desirable for space applications since this tremendously simplifies the cryocooling. Minimization of the device length is limited by the proximity effect: for shorter microbridges, the superconducting order parameter will propagate from Nb contacts in Ti microbridge and raise its critical temperature. The lower limit on the microbridge length corresponds to the thermal length in normal metals $L_C = \sqrt{hD/\left(4\pi^2 k_B T\right)}$. For the experimental value $D = 2.4$ cm^2/sec [13], this estimate gives $L_C \approx 30$ nm. The available device length of 500 nm is by an order of magnitude greater, therefore the proximity effect can be neglected.

In order to realize the photon-noise limited *NEP*, the dark count rate imposed by the energy fluctuations in the electron subsystem should be below the count rate due to the background radiation. This is achieved by choosing the corresponding level of the discrimination threshold, $E_T = \zeta h\nu$ ($\zeta < 1$), in the photon counter or/and in the readout electronics. Then the counts are caused only by the energy fluctuations, which exceed the discriminator threshold. The corresponding dark count rate is approximately given by [22]:

$$N_d = \frac{1/(\pi\tau)}{\sqrt{2\pi}} \cdot \int_{E_T/\delta E}^{\infty} \exp\left(-x^2/2\right) dx. \qquad (6)$$

The results of a numerical modeling demonstrating the parameters of the Ti HEPC for detection of 1 THz phototns at 300 mK are summarized in Table I.

With the above parameters the probability to detect a 1-THz photon is 95% (see Fig. 10.2 in [22]). Since N_d depends very strongly on the lower integration limit (see (6)) it can be varied broadly by choosing ζ or adjusting the device volume. That may be necessary in order to increase the range of frequencies where the counter would operate ($\nu_{max} = C_e \delta T_C/h$).

TABLE I
MODELED PARAMETERS OF THE HEPC

α	ν_R (GHz)	N_{max} (s^{-1})	ζ	N_d (s^{-1})	DR (dB)

It is important to mention that the limited device speed is a key condition for keeping the dark count rate low. In another concept [23], a similar counting device was considered using a small piece of normal metal absorber capacitively coupled to a superconducting antenna through a pair of normal metal–insulator–superconductor tunnel junctions. In that device, the absorption of a photon in the normal metal produces a spike of the electron temperature, which is measured by a normal metal-insulator-superconductor (NIS) junction. Since the device does not have superconducting contacts its thermal relaxation is governed by the electron diffusion with the characteristic time τ_R ~ ns rather then the electron-pohonn relaxation as in our case. Under conditions of the above example, this would result in a very high rate of dark counts exceeding the background photon arrival rate.

V. CONCLUSION

The paper demostrates the importance of the photon counting detector for a specific application in the space THz astronomy where this kind of technology is currently lacking. A proposed HEPC approach is promising for meeting sensitivity needs while operating at 0.3 K. Beside the astronomical applicaitons, such sensors might be of interest for laboratory molecule spectroscopy, quantum information applications, and nanoscale physics of thermal processes.

ACKNOWLEDGMENT

The authors acknowledge useful discussions with G. N. Goltsman and M.E. Gershenson.

REFERENCES

[1] 1. http://safir.jpl.nasa.gov/technologies/index.asp

[2] 2. D.J. Benford and S.H. Moseley, "Cryogenic detectors for infrared astronomy: the Single Aperture Far-InfraRed (SAFIR) Observatory," Nucl. Instr. Meth. Phys.Res. A **520**, pp. 379-383 (2004).

[3] 3. http://space.gsfc.nasa.gov/astro/specs; D. Leisawitz, J.C. Mather, S.H. Moseley, Jr., and X. Zhang, "The Submillimeter Probe of the Evolution of Cosmic Structure (SPECS)," *Astrophys. & Space Sci.*, Vol. 269–270, pp. 563–567 (1999).

[4] 4. T. Matsumoto, "Large aperture cooled telescope mission: SPICA" *Proc. SPIE*, Vol. 4850 (2003), pp. 1091-1096.

[5] 5. J.J. Bock et al., "Antenna-coupled bolometer array for astrophysics," *Proc. Far-IR, SubMM & MM Detector Technology Workshop, April 1-3, 2002, Monterey, CA*, pp. 224-229.

[6] 6 B.S. Karasik, W.R. McGrath, H.G. LeDuc, and M.E. Gershenson, "A hot-electron direct detector for radioastronomy," *Supercond. Sci. Technol.* Vol. 12, pp. 745-747 (1999); B.S. Karasik, W.R. McGrath, M.E. Gershenson, and A.V. Sergeev, "Photon-noise-limited direct detector based on disorder-controlled electron heating," *Journal of Applied Physics*, Vol. 87(10), pp. 7586-7588 (2000).

[7] 7 A. Vystavkin, D. Chouvaev, L. Kuzmin, M. Tarasov, E. Aderstedt, M. Willander, and T. Claeson, "Andreev reflection based normal metal hot-electron bolometer for space applications", *Proc. SPIE* **3465**, pp. 441-448 (1998).

[8] 8. A.V. Sergeev, V.V. Mitin, and B.S. Karasik, "Ultrasensitive Hot-Electron Kinetic-Inductance Detectors Operating Well Below Superconducting Transition", *Appl. Phys. Lett.* **80**, pp. 817-819 (2002).

[9] 9. P.K. Day, H.G. LeDuc, B.A. Mazin, A. Vayonakis, and J. Zmuidzinas, "A broadband superconducting detector suitable for use in large arrays," *Nature* **425**, pp. 817-821 (2003).

[10] 10. R.J. Schoelkopf S.H. Moseley, C.M. Stahle, P. Wahlgren, and P. Delsing, "A concept for a submillimeter-wave single-photon counter," *IEEE Trans. Appl. Supercond.* **9**(2), Part 3, pp. 2935-2939 (1999).

[11] 11 A. Semenov, A. Engel, K. Il'in, G. Gol'tsman, M. Siegel and H.W. Hubers, "Ultimate performance of a superconducting quantum detector", *Eur. Phys. J.* **AP21**, pp.171-178 (2003).

[12] 12 S. Komiyama, O. Astafiev, V. Antonov, T. Kutsuwa, and H. Hirai, "A single-photon detector in the far-infrared range," *Nature* **403** pp. 405-407 (2000); O. Astafiev, S. Komiyama, T. Kutsuwa, V. Antonov, Y. Kawaguchi, and K. Hirakawa, "Single-photon detector in the microwave range," *Appl. Phys. Lett* **80**, pp. 4250-4252 (2002).

[13] 13 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.* **79**(13), pp. 2049-2051 (2001).

[14] 14. M. Yun, J. Beeman, R. Bhatia, J. Bock, W. Holmes, L. Husted, T. Koch, J. Mulder, A. Lang, A. Turner, and L. Wild, "Bolometric Detectors for the Planck Surveyor," *Proc. SPIE*, Vol. 4855, pp. 136-147 (2002); W. Holmes et al., "Preliminary Performance Measurements of Bolometers for the Planck High Frequency Instrument," *Proc. SPIE*, Vol. 4855, pp. 208-216 (2002).

[15] 15. L.G.C. Rego and G.Kirczenow, "Quantized Thermal Conductance of Dielectric Quantum Wires," *Phys. Rev. Lett.* **81**, pp. 232-235 (1998).

[16] 16. K. Schwab et al., "Measurement of the quantum of thermal conductance," *Nature* **404** (6781), pp. 974-977 (2000); K. Schwab et al., "Thermal conductance through discrete quantum channels," *Physica* E **9**, pp. 60-68 (2001).

[17] 17. C.S. Yung, D.R. Schmidt, and A.N. Cleland, "Thermal conductance and electron-phonon coupling in mechanically suspended nanostructures," *Appl. Phys. Lett.* **81**, pp. 31-33 (2002).

[18] 18. Y. Xiao et al., "Specific heat and quantized thermal conductance of single-walled boron nitride nanotubes," *Phys. Rev.* B **69**, 205415 (2004); T. Yamamoto et al., "Universal features of quantized thermal conductance of carbon nanotubes," *Phys. Rev. Lett.* **92**, 075502 (2004).

[19] 19. K.S. Il'in, N.G. Ptitsina, A.V. Sergeev, G.N. Gol'tsman, E.M. Gershenzon, B.S. Karasik, E.V. Pechen, and S.I. Krasnosvobodtsev, "Interrelation of resistivity and inelastic electron-phonon scattering rate in impure NbC films," *Phys. Rev. B* **57**(24), pp. 15623-15628 (1998); B.S. Karasik, A.V. Sergeev, and M.E. Gershenson, "Electron-Phonon Relaxation in Hot-Electron Detectors below 1 K", in *Low Temperature Detectors - Proc. 9th Int. Workshop on Low Temperature Detectors, Madison, WI, 2001, AIP Conf. Proc 605*, pp. 75-78; J.J. Lin and J.P. Bird, "Recent experimental studies of electron dephasing in metal and semiconductor mesoscopic structures," *J. Phys.: Condens. Matter* **14**, pp. R501-R596 (2002).

[20] 20. The devices were fabricated by the group of Prof. M.E. Gershenson at Rutgers University, Piscataway, NJ 08854. The experimental study of these samples will be published elsewhere.

[21] 21. K.D. Irwin, "An application of electrothermal feedback for high resolution cryogenic particle detection," *Appl. Phys. Lett.* **66**(15), pp. 1998-2000 (1995).

[22] 22 R.H. Kingston, "Detection of Optical and Infrared Radiation," Springer Ser. in Opt. Sci., Ed.D.L. MacAdam, Springer-Verlag, 1978, Ch. 10.

[23] 23. D.V. Anghel and L. Kuzmin, "Capacitevely coupled hot-electron nanobolometers as far-infrared photon counter," *Appl. Phys. Lett.* **82**(2), pp. 293-295 (2003).