Ultrasensitive Graphene Far-Infrared Power Detectors

D. E. Prober[1,*], C. B. McKitterick[1], M.J. Rooks[1], B. S. Karasik[2], H. Vora[3] and X. Du[3]
[1]*Yale University, New Haven, CT 06520, USA*
[2]*Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA 91109, USA*
[3]*Department of Physics, Stony Brook University, Stony Brook, NY 11790, USA*
*Contact: daniel.prober@yale.edu, phone +1-203-432 4280

Abstract— **We discuss the prospects for using graphene as an ultrasensitive detector of THz photons. In our analysis, we examine two contacting schemes: superconducting contacts which make good Ohmic contact to the device and superconducting contacts with a thin insulating barrier. We perform thermal measurements of large area graphene devices to extract information on the electron-phonon coupling in graphene. Using these results, we develop predictions for optimum detector performance. With ideal biasing conditions and device parameters, we find that an NEP of 2×10^{-19} W/$\sqrt{\text{Hz}}$ should be achievable.**

I. Introduction

The far-infrared contains the majority of all photons in the universe [1]. Transition edge sensors (TESs) [2], kinetic inductance detectors (KIDs) [3], and quantum capacitance detectors [4] have been successfully developed, but have not yet demonstrated the necessary sensitivity to detect single terahertz (THz) photons.

To address the challenge of detecting individual THz photons, we propose graphene as the detector element. Due to the very low heat capacity of a single atomic layer of carbon atoms, a single incident THz photon will substantially raise the temperature of the electron system in the graphene layer. Unlike a TES or KID, in which the resistance or microwave impedance changes following the absorption of a THz photon, the resistance of graphene is largely temperature independent at cryogenic temperatures. As a result, Johnson noise has been proposed as the method to read out the temperature of the graphene electron system [5].

II. Photon Detection Model

We have carefully modeled the absorption of a THz photon by graphene [6] and have found that, with an appropriately small doped graphene device, graphene can make an effective single-photon counter for THz photons. In order to adequately distinguish between no photons (zero-photon events) and one-photon events, it is necessary to use a graphene sample of sufficiently small area such that the absorption of a THz photon raises the temperature of the electron system significantly higher than the equilibrium temperature, $T_b = 0.1\,K$. Thus, the device no longer behaves linearly. This is seen in the different widths of the two theoretical detection histograms plotted in Fig. 1.

The performance of this detector depends critically on graphene having a very low thermal conductance. This allows slow decay of the elevated electron temperature, giving a longer measurement time for a more accurate measurement of the average temperature rise, ΔT. Superconducting contacts can contain the hot electrons in the graphene, constraining the system to relax through the slow electron-phonon process. With non-superconducting contacts, hot electrons rapidly diffuse out of the graphene [5]. The strength of the electron-phonon coupling has been measured by various groups. Their results vary considerably [5,7,8].

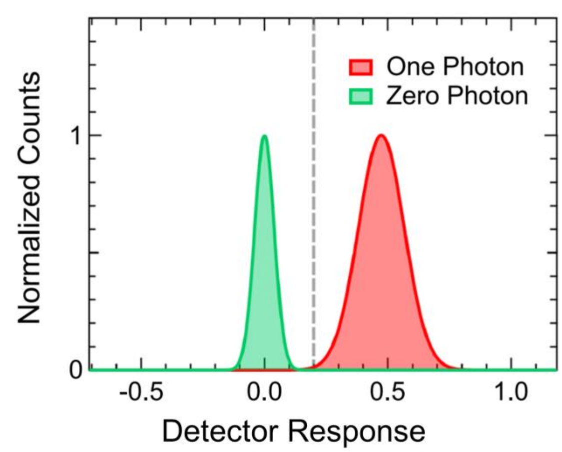

Fig. 1: Theoretical normalized histogram of counts of THz photons by the graphene detector described in [6]. Value of Σ in (1) is taken to be $\Sigma = 0.5\ \mathrm{mW/K^4m^2}$ as reported by [8]; we take n = 10^{12} electrons/m^2, A = 5 μm^2. Detector response is the measured temperature rise, in K, averaged over the pulse.

III. Johnson Noise Measurements of Electron-phonon Cooling

To establish the viability of graphene as a THz photon detector, we have performed Johnson noise thermometry measurements of graphene samples. These measurements probe the thermal conductance of graphene down to sub-Kelvin temperatures. The devices are fabricated with superconducting contacts with the goal of preventing out-diffusion cooling the electron system. We use commercially-available CVD-grown graphene to lithograph large areas of graphene, allowing us to emphasize the contribution of electron-phonon cooling in our measurements. We report the results of these measurements and the performance that should result. Using the thermal cooling model of

$$P_{\mathrm{eph}} = \Sigma A(T^4 - T_0^4), \quad (1)$$

expected for clean graphene devices [6], we extract a value of $\Sigma = 30\ \mathrm{mW/K^4m^2}$, with the fit shown in Fig. 2. Here $n = 2.4 \times 10^{12}/\mathrm{m}^2$. The electron-phonon thermal conductance is $G_{\mathrm{eph}} = dP_{\mathrm{eph}}/dT$. These data indicate that $\Sigma = 19\ \mathrm{mW/K^4m^2}$ for $n = 10^{12}/\mathrm{m}^2$; for that value of Σ the histograms for single-photon detection would partially overlap (see Fig. 1).

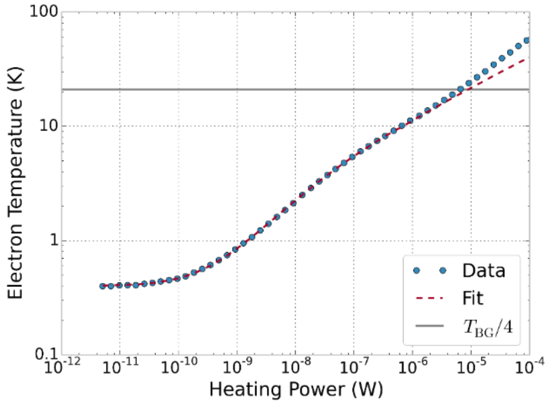

Figure 2: Average electron temperature as a function of DC Joule heating power, calculated from device resistance R. The dashed line is a calculation of electron temperature using the device resistance, heating power, and $\Sigma = 30\ \mathrm{mW/K^4m^2}$; n = 2.4 x $10^{12}/\mathrm{m}^2$. Numerical calculations [9] demonstrate that the low temperature limit is valid below $T_{\mathrm{BG}}/4$, where T_{BG} is the Bloch-Gruneisen temperature. For this measurement, $T_{\mathrm{BG}} \approx 85$ K; $T_{\mathrm{BG}}/4$ is denoted by a solid horizontal line.

IV. Conclusions

We have developed projections for device performance based on our measurements for two device geometries—graphene contacted with transparent superconducting contacts (SNS) and graphene contacted with superconducting contacts, but with a tunnel barrier in between (SINIS). In neither geometry is graphene found to be an effective counter of single THz photons. The relatively high electron-phonon coupling results in a readout noise greater than the photon signal.

Power measurements of a relatively weak THz signal (count rate $\leq 10^5$/s) can be performed with high sensitivity using a graphene detector with superconducting contacts. In Table 1, the performance of both types of detectors is summarized. T_0 is the base temperature. The values of NEP quoted are for device NEP including readout noise, but do not take into account possible optical or antenna inefficiencies.

Both Johnson noise thermometry with a 1 GHz readout, and low-frequency measurements of $R(T)$ employing a SINIS junction, can allow for very sensitive measurements of THz photon power. There remain challenges of device fabrication for eventual implementation in a detector.

V. Acknowledgment

The research of BSK was carried out 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. Facilities use at Yale was supported by YINQE and NSF MRSEC DMR 1119826. X. Du and H. Vora acknowledge support from AFOSR-YIP Award No. FA9550-10-1-0090.

TABLE I
CALCULATED OPTIMUM PERFORMANCE FOR GRAPHENE DEVICES

Noise properties for power measurement		
Device Configuration	**Cryogenic Amplifier**	***NEP*** **($\mathrm{W}/\sqrt{\mathrm{Hz}}$)**
SINIS $T_c = 0.45$ K 300 $\mu\mathrm{m}^2$ $T_0 = 100$ mK	Low frequency current amplifier	2×10^{-19}
SINIS or SNS $T_c \geq 9$ K 400 $\mu\mathrm{m}^2$ $T_0 = 50$ mK	Microwave amplifier, 1 GHz, $T_N = 0.3$ K	7×10^{-19}, $B = 10$ MHz 2×10^{-19}, $B = 100$ MHz

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