Graphene holds promise for hot-electron bolometers

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The superior capability of graphene to limit electronic energy from being dissipated within the lattice makes it a fast photon detector with unprecedented sensitivity.

A bolometer is an electronic device that converts light into heat, which can then be detected by a thermometer. The thermal resistance, $R^h$, provides the coefficient linking incident power $P$ and change in temperature $\Delta T$, such that $\Delta T = PR^h$. An important consideration in designing a bolometer is the time taken for it to recover, given by $\tau = R^hC$, where $C$ is the heat capacity. This has influenced the design of bolometers, which often used thin metal films with low $C$ as absorbers that were suspended in vacuum with a spiderweb of fine nylon or Kevlar fibers to minimize thermal leak to the environment.

In contrast, a hot-electron bolometer uses a simpler approach. At low temperature, the electron gas in a material becomes increasingly decoupled from the phonons or lattice vibrations, leading to a large $R^h$, while $C$ of the electrons becomes small and proportional to $T$. Currently, the most sensitive hot-electron bolometers are transition edge sensors (TES), which make use of a metal near its superconducting phase transition as both the absorber and thermometer, with the sharpness of the superconducting transition providing excellent sensitivity.1

We considered that graphene, a single atomic layer of carbon atoms,2 has properties that should make it an excellent hot-electron bolometer. Graphene is well-known for its broadband absorption of photons from far infrared to ultraviolet,3 and it has the highest specific interaction strength (absorption per atom of material) known. The electron-phonon interaction in graphene is also the weakest of any material.4 There is a problem, however. Graphene’s electrical resistance is nearly independent of temperature. To overcome this, we chose to use bilayer graphene, which has a tunable bandgap.5 Application of a perpendicular electric field (accomplished through gates above and below the graphene) gives rise to strongly electron-temperature-dependent resistance at low temperatures, making the device suitable for thermometry.6

In our graphene bolometer device, the bilayer graphene is surrounded by a silicon dioxide dielectric that is sandwiched between electrical gates on top (nichrome) and bottom (doped silicon): see Figure 1. Light from above heats up the graphene and decreases its resistance.5 This gives rise to a measurable change in the voltage drop $AV$ across the sample when it is biased with a dc current $I_{dc}$. Figure 1c shows the voltage responsivity of one of our devices $\frac{AV}{P}$ where $P$ is the absorbed laser power. At high currents ($I_{dc} = 200\text{nA}$) the responsivity is as high as $2 \times 10^5\text{VW}^{-1}$ which is similar to the performance of a commercial silicon bolometer. We estimate that the noise equivalent power (NEP—the minimum detectable signal

Figure 1. (a) Schematic side view of the bilayer graphene hot-electron bolometer. (b) Optical micrograph of the device (top view). The central area is the thermally evaporated, semitransparent nichrome top gate covering the graphene device. The larger ‘L’ shaped area surrounding it is the top-gate dielectric (silicon dioxide). The yellow features are chromium/gold electrodes, which connect to the graphene and the nichrome gate. In this image, the graphene cannot be seen as it is under the nichrome gate. The scale bar (white) is 20$\mu$m. (c) Responsivity of the device as a function of dc bias current. The measurement was taken at 5.2K.

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per square root bandwidth) of our graphene bolometer at 5K is $3.3 \times 10^{-14} \text{WHz}^{-1/2}$, which is similar to or better than the best silicon or TES bolometers operating at that temperature. $^7$

Figure 2a shows the heat resistance of our graphene bolometer. For the $100 \mu m^2$ device, the heat resistance is about $2 \times 10^9 \text{KW}^{-1}$ at 5K and is strongly dependent on the temperature. Previous theoretical work$^8$ predicted a $T^3$ dependence of the heat resistance, which is close to our observation. The heat resistance determines the ultimate signal-to-noise-ratio of the graphene bolometer due to thermal energy fluctuations in the flux-integrating regime, $\text{NEP} = \sqrt{4k_B T^2 / R_h}$. From our data, if we extrapolate to 100mK for a $1 \mu m^2$ sample (an achievable sample size), the NEP is $\sim 5 \times 10^{-21} \text{WHz}^{-1/2}$, similar to or better than the state-of-the-art TES. $^3$

We also found that our graphene bolometer has a very fast operating speed. Measuring the thermal energy relaxation time of the graphene bolometer using a two-pulse correlation study, we compared the response of the sample due to pulse one $\Delta V_1$, pulse two $\Delta V_2$, and both pulses $\Delta V_{12}$. We found that the non-linearity of the response as a function of power gives rise to a dip in the signal when the pulses are coincident within a time $\tau$. $^6$ We measured a time constant $\tau \approx 0.1 \text{ns}$ at 10K, and 0.25ns at 4.55K. These results suggest gigahertz operation of the device in this temperature range, which is approximately six orders of magnitude faster than TES devices at similar temperature. $^7$ The ultimate energy resolution of a bolometer is given by $\Delta E = \text{NEP} \sqrt{T}$. For a $1 \mu m^2$ sample at 100mK, $\tau$ is about 1$\mu$s and $\Delta E$ is 30$\mu$eV, less than 1% of the energy of a 1THz photon. The high speed of the graphene bolometer should thus give it an edge in energy resolution over the best TES designs.

Challenges remain in applying graphene to bolometry. One is that graphene’s absorption, while large on a per-atom basis, is small for two layers of carbon atoms. Graphene’s absorption can be increased by simply using multiple layers of material. $^9$. Alternatively, placing graphene in an optical cavity $^{10}$ or micro-patterning graphene to produce a plasmonic resonance $^{11}$ at the desired THz frequency can increase the absorption without increasing the amount of material. Another challenge is that graphene has a high resistance at low charge carrier densities desirable for bolometer operation, and high-impedance devices are traditionally difficult to read out at high speed. However, Fong and Schwab$^{12}$ successfully used an impedance-matching scheme and noise thermometry to measure a graphene bolometer at 1.2GHz with an 80MHz bandwidth. We therefore see no insurmountable barriers to the adoption of graphene-based bolometry for ultra-sensitive detection of sub-millimeter wave photons. Future work will include efforts to demonstrate the ultrahigh sensitivity of graphene bolometers at lower temperatures. Other mechanisms, such as plasmons in graphene, may also be explored to make the graphene detector work at room temperature. $^{13}$

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