**Introduction:** The terahertz (THz) frequency range of the electromagnetic spectrum (sub-mm to mm wavelengths) has tremendous potential for applications in security, spectroscopy, astronomy, and medicine.1 Yet, there is a lack of affordable and efficient devices for the generation and detection of THz radiation. Thus, there is a huge push to develop better THz optoelectronic devices for scientific, defense, and everyday applications.

Graphene, a one-atom-thick carbon allotrope with unique electrical and optical properties, has shown theoretical and experimental promise for the creation of sources and detectors of THz light. **I propose a research plan to develop high-sensitivity, room-temperature graphene THz detectors, and first graphene THz lasers.**

**INTELLECTUAL MERIT:** Graphene has no bandgap which gives it a broadband optical response.2 A variety of graphene THz detectors have been built, including devices that work at room-temperature.3 Some of the most promising of these room-temperature devices are those that rely on the hot-electron photothermoelectric effect. In such detectors, THz radiation increases electron temperature, forcing hot electrons to diffuse to colder regions. Cai, Fuhrer, *et al*. have created a photothermoelectric graphene THz detector that uses electrodes of dissimilar metals to create an asymmetric potential across the graphene strip.4 An electron temperature gradient induced by incident THz radiation drives electron diffusion and the asymmetry forces the diffused electrons across the detector, producing a net current. This detector shows impressive sensitivity unparalleled by other graphene THz room-temperature detectors, yet significantly worse than some cryogenic graphene THz bolometers.

The electrons in graphene interact very little with its tightly-bound lattice atoms. Collective oscillations (plasmons) in the population of electrons can be generated that have resonant frequencies that depend on the size of the graphene channel. When incident radiation excites these collective oscillations, there is a large boost to the photoresponse. This effect has been used in a variety of detectors,5 but has not been fully exploited in photothermoelectric detectors. A combined photothermoelectric and plasmonic THz detector would have sensitivity better than any room-temperature detector, comparable to that of the high-sensitivity low temperature bolometers.

Another exciting property of graphene is its ability to sustain population inversion: the essential phenomenon for the construction of a laser. V. Ryzhii, *et al*, have shown that due to its non-linear carrier dynamics, graphene can support population inversion.6 This group has proposed a method to achieve population inversion via a forward-biased p-i-n junction. Graphene has no bandgap, so in this type of device, oppositely biased gate electrodes are used to build up electrons in one area (n region) and holes in another (p region). A forward source-drain bias current is applied which forces electrons and holes to the intrinsic (ungated) region between the n and p regions, achieving population inversion. In the intrinsic region, the electrons and holes can recombine and emit photons. The emitted photons excite plasmon waves, emitting radiation in the THz frequency range. Simulations suggest that this phenomenon could exist at room temperature, and in a wide frequency range (2-18 THz).7 Ryzhii *et al* have made a proof-of-concept device8, but this phenomenon has not been utilized to make robust graphene emitters and needs to be studied further. Furthermore, stimulated emission in graphene has not yet been observed at room temperature.

**Objectives: 1)** Develop higher-sensitivity graphene THz photothermoelectric detectors that are sensitive at room temperature by exploitation of plasmonic resonances. **2)** Create graphene forward-biased p-i-n junction THz emitters that are tunable and functional at room temperature.

**Research Plan**: **1)** I will design and fabricate photothermoelectric THz detectors with standard methods of electron-beam lithography on chemical vapor deposition (CVD), and commercial epitaxial graphene samples. I will test the response of these detectors to mm-wave radiation at a variety of temperatures. I will work toward improving the characteristics of these devices, and developing better, more scalable fabrication methods. **2)**  I will create devices similar to the split-gate p-i-n junction devices by Ryzhii *et al*. to study THz emission of graphene at a variety of temperatures, including room temperature. I will incorporate these designs into optoelectronic structures and collaborate with engineers to develop functional and efficient graphene lasers.

Much of my research experience as an undergraduate has involved THz optics and graphene. I spent a summer at Caltech developing an on-chip mm-wave spectrometer for use in far-IR telescopes. My work in the lab of Professor Paola Barbara at Georgetown University has been in graphene microelectronics and optoelectronics. Through over three years of research with Professor Barbara I have gained the essential skills that I will need to complete this research project, namely: photo and electron-beam lithography, metal deposition, mm-wave optical testing of micro and nanoelectronics, and cryogenic electrical testing. The resources I will need will be those of any group working in microelectronics, e.g., clean-room fabrication equipment, and cryogenic testing equipment. My graduate schools of choice are MIT and Columbia University, where there are strong research efforts in graphene optoelectronics.

**BROADER IMPACTS:** THz technology allows screening for dangerous substances such as narcotics and explosives. These substances have characteristic chemical signatures in the THz range. The only way to create and detect THz radiation is with expensive machines that have to be kept at cryogenic temperatures. My research will improve our ability to detect these types of dangerous substances. Graphene-based THz detectors and sources that work at room temperature will promote new, efficient and portable, drug and bomb detection devices.

My research will also enable new science to be pursued. One way is that high-sensitivity graphene THz detectors could be implemented in new telescopes for probing the cosmic far-IR background radiation. Much of the information about the early formation of galaxies is intelligible only through the sub-mm light emitted by dust in the early stages of the universe. Recent work by scientists I worked with at Caltech has been in using graphene to make THz detectors for use in telescopes that measure this light.9 My research would enable the creation of better far-IR telescopes, so that we can learn more about this earliest era of the universe.

**Conclusion:** This project in graphene-based THz detectors and lasers promotes the development of new technologies that will enable improvements in security systems and defense, further scientific endeavors, and impact everyday lives. I have the insight and skills needed to be successful in this work that I have acquired through my undergraduate research. The NSF GRFP will allow me to continue my work immediately in graduate school, and help me to further the development of these exciting properties of graphene that will have large impacts on the future.

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