Partnerships for International Research and Education

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Mitchell Trafford - NanoJapan 2012 Student Profile
University of Tulsa
Major/s:Chemical Engineering and Mathematics
Anticipated Graduation: May 2015
Prof. Yukio Kawano, Tokyo Institute of Technology
"Low-temperature THz Photo-conductivity and Mesoscopic Conductance Fluctuations in Graphene" – *Recipient of $250 Best Poster Presentation Prize at 2012 RQI Colloquium*

Why NanoJapan?
I discovered in high school that I had a knack for math and chemistry, and that's why I'm currently studying chemical engineering. However, I'm also a hands-on person, and I am very interested in technology and discovering how things work. NanoJapan is such an exciting experience because it integrates all of these passions into one program, with the added benefit of an international experience. It gives me the opportunity to apply my knowledge and understanding to contribute to cutting-edge research in an industry that fascinates me.

I am at the beginning of my college education and I am looking for opportunities to learn as much as I can to develop myself as a competent student and researcher. I like the fact that research doesn't have a "back of the book" answer- it forces me to synthesize everything I know in order to systematically approach a problem. Not only will NanoJapan provide an opportunity to develop these skills, it will also teach me how to conduct myself professionally in a laboratory environment.

I think science is an international endeavor, so it is very important to promote cross-cultural experiences. Not only does this collaboration lead to international friendships, it also allows several researchers to come together and share their individual perspectives of a given problem. Outside of the lab, I look forward to immersing myself in a culture that is completely different from my own. This experience will broaden my perspective, not only educationally, but culturally as well.

My goals for this summer include:

- I want to get as much out of this experience as possible; I don't want to miss out on all of the opportunities that are not available back in the United States.
- I hope to learn much more about nanotechnology and contribute to Prof. Kawano's research to the best of my ability.
- I want to learn how to speak Japanese, at least to the point where I have a working understanding of the language.
- I am seriously excited to try some authentic Japanese sushi.

Note: This student has not yet submitted his updated NanoJapan Student Profile or authorized the release of excerpts from his weekly reports.

LOW TEMPERATURE THz PHOTO-CONDUCTIVITY AND MESOSCOPIC CONDUCTANCE FLUCTUATIONS IN GRAPHENE

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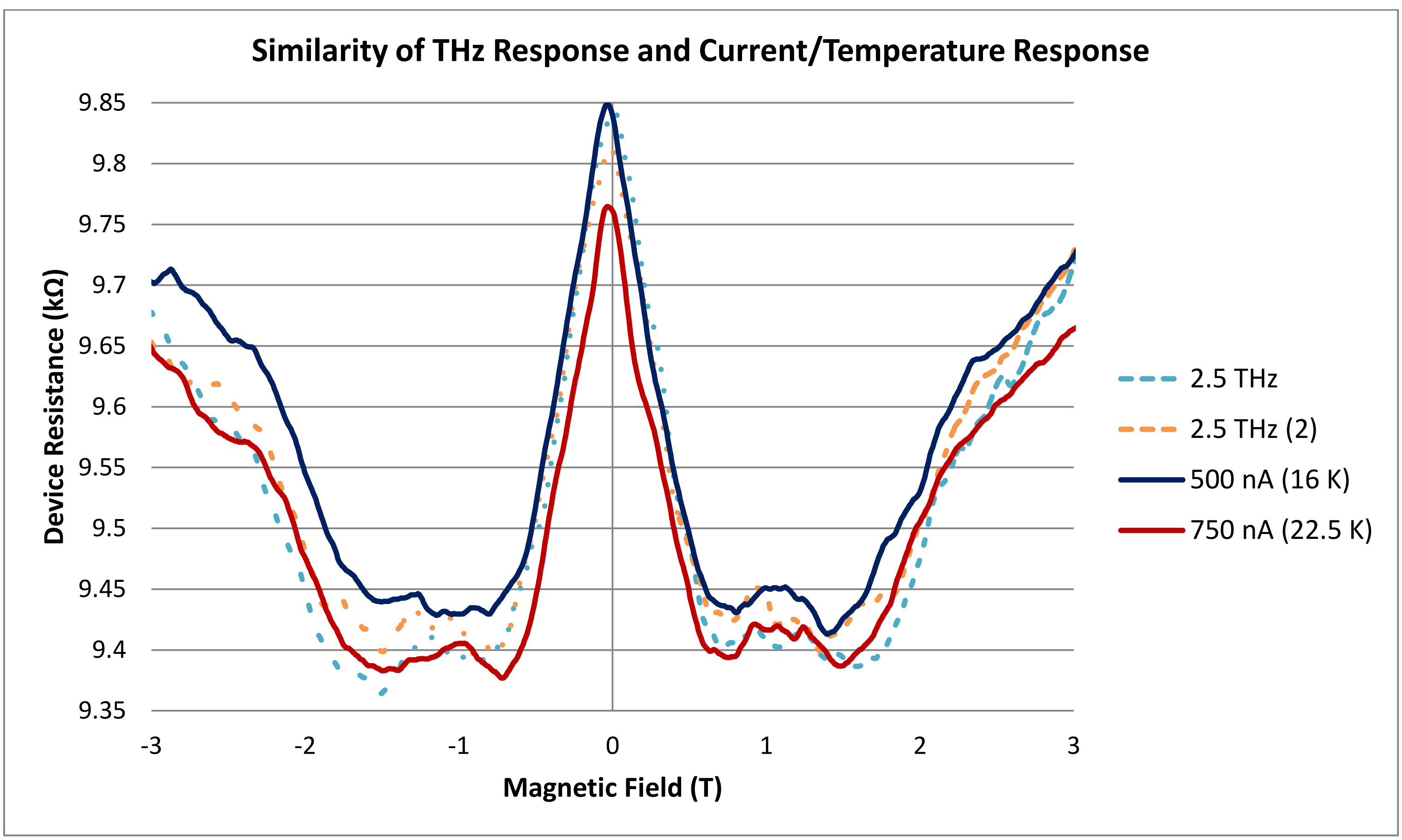
The ability to alter the conductance fluctuations in graphene will expose brand new fields of research in THz detection, semiconductor technology, and quantum computing. Graphene exhibits many unique properties, and our research explores fundamental questions about the nature of electron waves in disordered graphene. Researchers have discovered that significantly disordered mesoscopic metal and semiconductor samples exhibit “universal” conductance fluctuations with amplitude e^2/h. However, graphene does not exhibit ergodicity in terms of conductance fluctuations and therefore does not conform to the “universality” observed in other materials. Graphene’s fluctuations are influenced by the puddles of charge carriers in its potential landscape, and the energy of a photon of THz radiation roughly corresponds to this energy difference. Therefore, by radiating a graphene device with THz waves, it may be possible to control the electron interference patterns. Additionally, the effect of THz radiation may be observed as an increase in the temperature of the lattice or a sudden non-linearity in the device resistance due to the electric field component of the THz wave. Not only is this research fundamental to our understanding of graphene, but it may serve as a precursor for THz detectors and qubit operations.

INDICATION OF BOLOMETRIC THZ RESPONSE:



THz Photo-conductivity and Mesoscopic Conductance Fluctuations in Graphene

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[2]Department of Physical Electronics, Tokyo Institute of Technology

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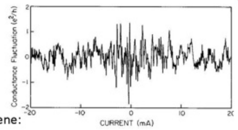
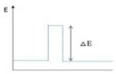
[4]NanoJapan Program, Rice University

Project Overview

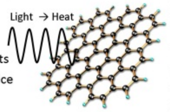
- Mesoscopic metal and semiconductor devices with significant disorder all exhibit a "Universal Conductance Fluctuation" of amplitude e^2/h †
- Graphene's fluctuations are much smaller than this and do not follow the "universal" trend ‡
- THz radiation may have several different effects on graphene:



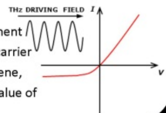


Quantum: The energy of a photon of THz radiation roughly corresponds to the potential energy wells and barriers within the graphene potential landscape (photon-assisted tunneling)

Bolometric: The energy from THz radiation heats the graphene lattice

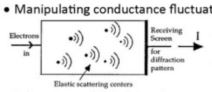


Rectifying: The electric field component of the THz wave causes carrier oscillations within graphene, and the time-averaged value of this current is nonzero



Motivation & Application

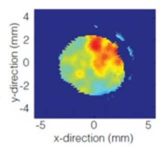
- Graphene has many unique properties that remain to be explored
- Manipulating conductance fluctuations in graphene is advantageous:



– Indicates ability to manipulate electron interference patterns

– Precursor to smaller, more effective THz detectors

- Advantages of THz detection:
  – High-resolution imaging without dangers of X-rays
  – THz waves pass through clothing, but are absorbed by metals

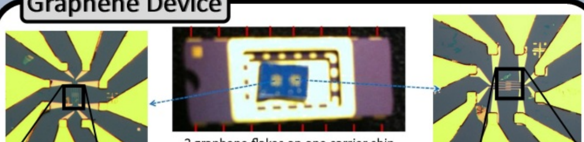


– Most explosives have a distinct THz fingerprint

– Non-destructive evaluation of materials

– Non-invasive medical screening

Graphene Device



2 graphene flakes on one carrier chip

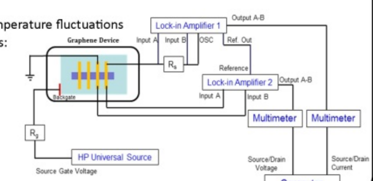
- Fabricated by Hari Ramamoorthy and Ann Somphonsane from the University at Buffalo, State University of New York.
- Exfoliation of natural graphite onto a Si/SiO_2 substrate

Flake 1: Bilayer, 5 μm long, 3 available contacts

Flake 2: Monolayer, 7 μm long, 4 available contacts

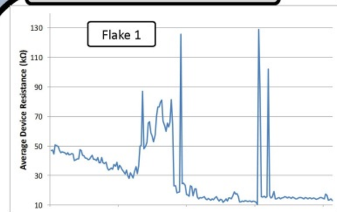
Experimental Process

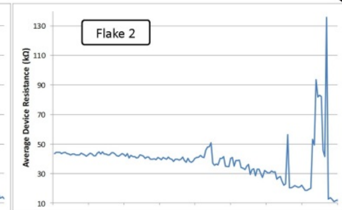
- **Current annealing**—remove impurities by and lower the overall resistance by locally heating the sample with high current
- **Measure fluctuations**—test low-temperature fluctuations affected by the following parameters:
  – Sweeping gate voltage (**trans-conductance**)
  – Sweeping magnetic field (**magneto-conductance**)
  – Exposure to THz radiation (**photo-conductance**)



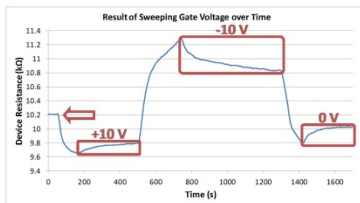
Equipment setup for measurements

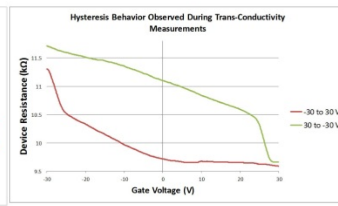
Experimental Results



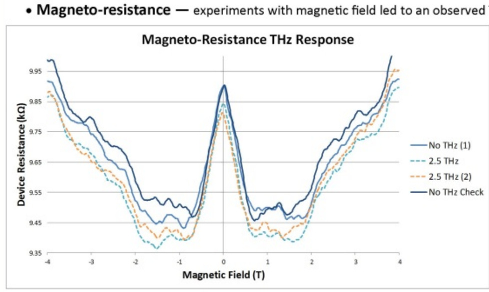


- **Current annealing** — Successful reduction in average device resistance
  – Resistance changes- Flake 1: 48 → 13 kΩ, Flake 2: 44 → 11 kΩ
  – Sudden peaks in resistance are due to Schottky type behavior near device contacts





- **Trans-conductance** — remaining impurities in the sample lead to undesired stored charge and hysteresis
  – Impairs reproducibility and stability needed for THz measurements
  – Experimental conditions are static yet device resistance continues to change
  – Exponential change in resistance is an indication of stored charge in the oxide layer
  – Sweeping gate voltage in different directions results in different resistances → indication of hysteresis behavior
- **Magneto-resistance** — experiments with magnetic field led to an observed THz response from the device



– Source current is 100 nA

– Magnet sweep rate: 0.568 T/min

– 2.5 THz radiation

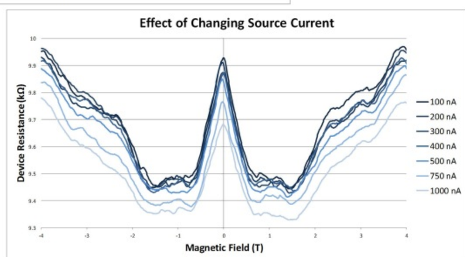
– 5 mW outside of cryostat

– Peak at 0 T is due to quantum interference in the sample: Weak Localization

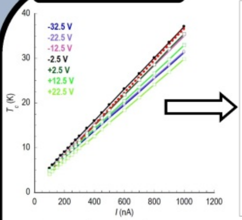
– Interference is suppressed by magnetic field (translates to a drop in resistance)

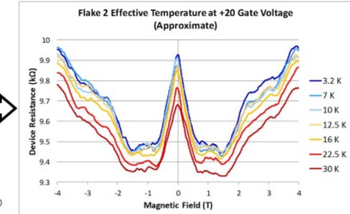
– Effect decreases at higher magnetic fields where Quantum Hall Effect is more prevalent

- **Current dependency:**
  – Varying levels of source current simulates heating the sample lattice
  – Shows an effect very similar to that of THz radiation exposure

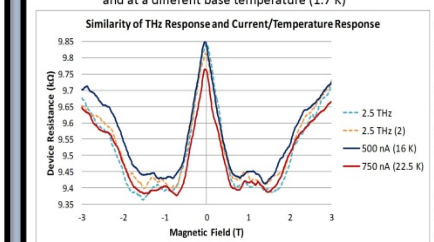


Conclusions





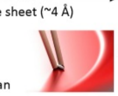
- Linear relationship between source current level and effective heat applied to the lattice¥
  – Values represented above are only **approximate**; current → temperature conversion is based upon research performed on a different device (with a different Dirac position) and at a different base temperature (1.7 K)



- The device response from increasing current resembles the response to THz radiation
- Suggests that THz radiation increases the effective temperature of the graphene lattice → a bolometric mechanism for THz response
- Does not rule out other mechanisms; only indicates the bolometric response
- It is likely that further device purification will allow observation of quantum responses
- Need temperature– and power– dependent measurements to determine a relationship between THz radiation and effective temperature increase
  – Can also lead to determining the energy relaxation time for the sample

Future Research Possibilities

- Conduct temperature– and power– dependent tests to determine actual THz temperature change
- Perform time-dependent current annealing to remove impurities and lower the hysteresis effect
- Measure trans-conductance fluctuations
- Determine the amount of radiation absorbed by the sample; the wavelength of 2.5 THz radiation (~120μm) is 300,000 times the thickness of the graphene sheet (~4 Å)
- Investigate THz frequency dependency
- Repeat tests for a bilayer graphene device
- Investigate the effect of a THz pulse (rather than continuous exposure) using pump-probe spectroscopy



If Mt. Fuji represents the wavelength of 2.5 THz radiation, then the thickness of graphene is about the length of 1-2 grains of rice!

Acknowledgements & References

- ¥D. F. Holcomb, "Quantum electrical transport in samples of limited dimensions," Am. J. Phys., **67** (4), 278-297, (1999)
- †G. Bohra, R. Somphonsane, N. Aoki, Y. Ochiai, R. Akis, D. K. Ferry, and J. P. Bird, "Non-Ergodicity & Microscopic Symmetry Breaking of the Conductance Fluctuations in Disordered Mesoscopic Graphene"
- ‡R. Somphonsane, G. Bohra, H. Ramamoorthy, G. He, D. K. Ferry, N. Aoki, Y. Ochiai, and J.P. Bird, "Dramatically Enhanced Energy Relaxation of Non-Equilibrium Carriers Near the Dirac Point of Graphene"

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