TOKYO TECH
Pursuing Excellence

TOKYO INSTITUTE OF TECHNOLOGY

Summer 2012 Research Internship in Japan

Mitchell Trafford

NanoJapan
International Research Experience for Undergraduates

World of Physics Meeting

- **Orientation in Tokyo**
- **Summer Internship at Tokyo Tech**
  - Introduction to Conductance Fluctuations
  - Motivation and Applications for Project
- **Why Should I Apply?**
- **Pictures from Experience in Japan**

NanoJapan Program

Orientation in Tokyo

- **We spent the first three weeks of the program in Tokyo**
- **The orientation program consisted of:**
  - Japanese Language Classes
  - NanoScience Seminars
  - Japanese Culture Lectures
  - Company Visits
  - Discussions with Other Japanese Students
  - Trips to Kamakura, Nikko, and Minami-Sanriku

Up in Tokyo Tower

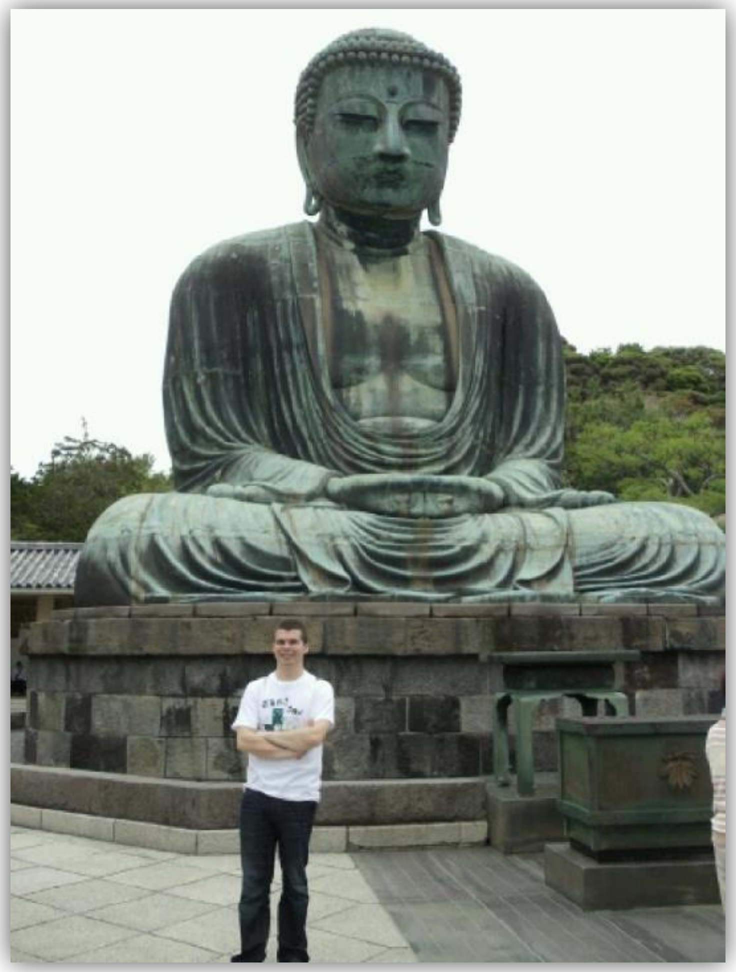
View from Tokyo Tower

Asakusa (Sanja Matsuri)

Okonomiyaki in Asakusa

SkyTree – Still not open!

Trip to Kamakura

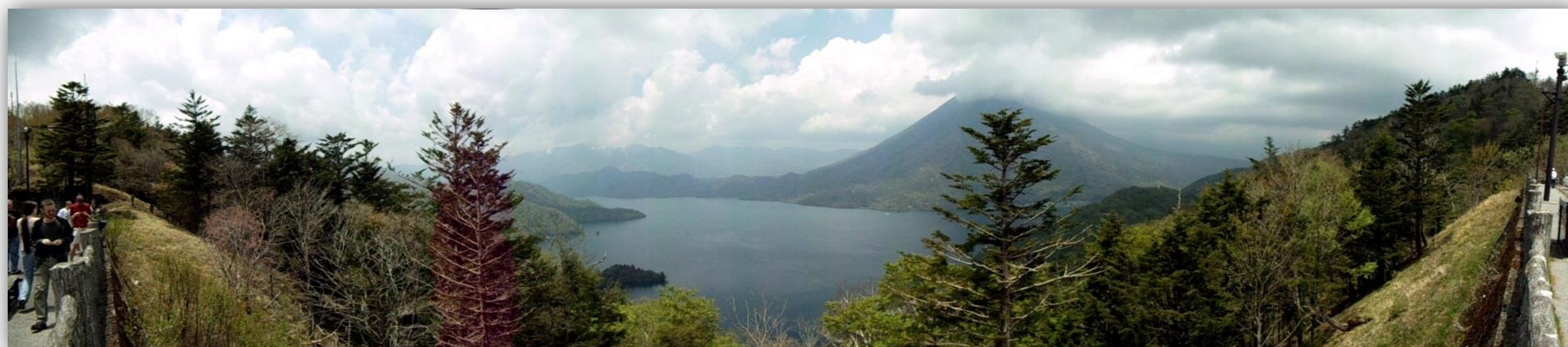


Trip to Nikko

Fun in Nikko!


Heart
Pride
Attitude
Tulsa
The University of Tulsa
Service Day 2012
Cooperation
Willpower
HOPE
SERVE

Mountains in Nikko



Kegon Falls, Nikko

Trip to Minami-Sanriku

Summer Internship

- **Project:**
  THz Photo-Conductivity and Mesoscopic Conductance Fluctuations in Graphene
- **Japanese Advisor:**
  Kawano-sensei
- **US Advisor:**
  Prof. Jon Bird, University at Buffalo, SUNY
- **Japanese Mentors:**
  Kuga-san and Suzuki-san

Influential Research

- 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"

THz Photo-conductivity and Mesoscopic Conductance Fluctuations in Graphene

M. Trafford[1,4], T. Kuga[2], D. Suzuki[2], H. Ramamoorthy[3], A. Somphonsane[3], Y. Kawano[2], J. Bird[3,4]

[1]Department of Chemical Engineering, University of Tulsa

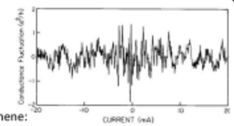
[2]Department of Physical Electronics, Tokyo Institute of Technology

[3]Department of Electrical Engineering, University at Buffalo – State University of New York

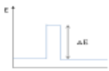
[4]NanoJapan Program, Rice University

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 [‡]

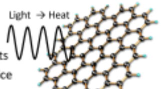


- THz radiation may have several different effects on graphene:

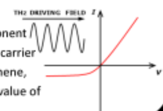


Quantum: The energy of a photon of THz radiation roughly corresponds to the potential energy wells and barriers within the graphene potential landscape (photon-assisted tunneling)

Bolometric: The energy from THz radiation heats the graphene lattice

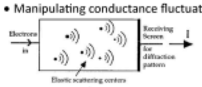


Rectifying: The electric field component of the THz wave causes carrier oscillations within graphene, and the time-averaged value of this current is nonzero



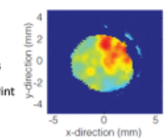
Motivation & Application

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

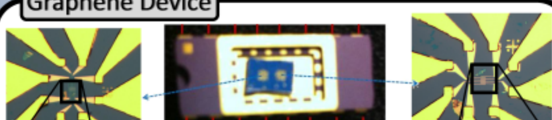


  - Indicates ability to manipulate electron interference patterns
  - Precursor to smaller, more effective THz detectors
- Advantages of THz detection:
  - High-resolution imaging without dangers of X-rays
  - THz waves pass through clothing, but are absorbed by metals

  - 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

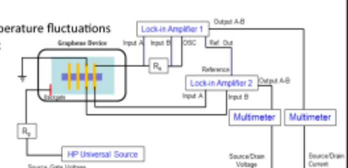
- Fabricated by Hari Ramamoorthy and Ann Somphonsane from the University at Buffalo, State University of New York.
- Exfoliation of natural graphite onto a Si/SiO_2 substrate

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

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

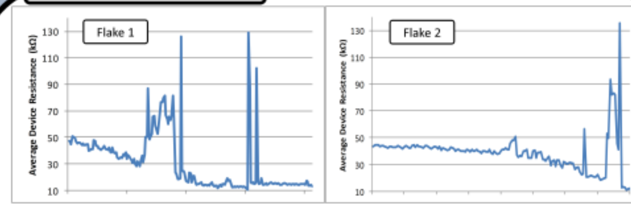
Experimental Process

- **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**)

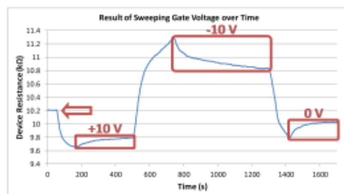


Equipment setup for measurements

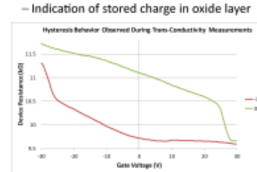
Experimental Results



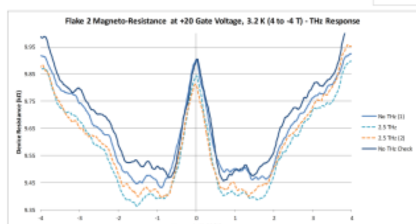
- **Current annealing** — Successful reduction in average device resistance
  - Resistance changes- Flake 1: 48 → 13 kΩ, Flake 2: 44 → 11 kΩ
  - Sudden peaks in resistance are due to Schottky type behavior near device contacts
- **Trans-conductance** — remaining impurities in the sample lead to undesired stored charge and hysteresis



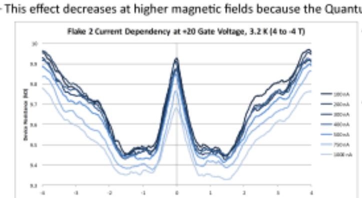
  - Impairs reproducibility and stability, which are necessary to observe a THz response
  - Enclosed areas are at constant gate voltage; experimental conditions are static yet device resistance continues to change
  - The arrow shows unchanging device behavior before voltage is applied to the back gate
  - Exponential appearance in these regions is similar to capacitor charge/discharge
  - Indication of stored charge in oxide layer
  - In the plot to the right, sweeping gate voltage in different directions results in different resistances
  - Indication of hysteresis behavior



- **Magneto-resistance** — data obtained by sweeping magnetic field was very reproducible and led to an observed THz response from the device

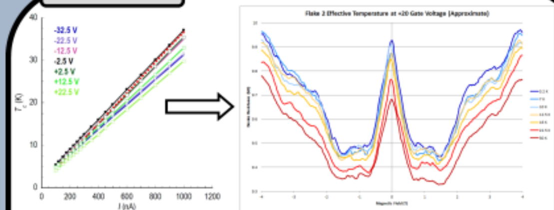


  - Source current is 100 nA
  - Magnetic field sweep rate: 0.568 T/min
  - 2.5 THz radiation, at about 5 mW outside of cryostat (translates to a few µW at the sample due to filtering)
  - Peak at 0 T due to quantum interference in the sample: Weak Localization
  - Interference is suppressed by magnetic field; backscattering electron waves are not in phase, so overall interference caused by backscattering is lowered (translates to a drop in resistance)
  - This effect decreases at higher magnetic fields because the Quantum Hall Effect begins to dominate device behavior

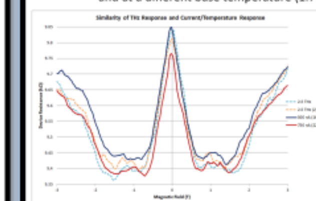


- **Current dependency** — device behavior at constant temperature and varying levels of source current show an effect similar to the THz response
- **Photo-conductivity** — tests involving switching THz radiation on and off were inconclusive
  - Signal noise at constant gate voltage and magnetic fields was too large to observe a clear response to THz radiation
  - Laser output power was also very weak

Conclusions



- Previous research has established a linear relationship between source current level and the effective heat it applies to the sample 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, indicating a bolometric mechanism for THz response
- Does not rule out other mechanisms for THz response, only indicates the presence of a bolometric response
- To determine a relationship between THz radiation and effective temperature increase, both temperature-dependent measurements and THz power-dependent measurements need to be conducted
  - 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"

- Graphene photos courtesy of H. Ramamoorthy, and A. Somphonsane, Department of Electrical Engineering, University at Buffalo, State University of New York
- Special thanks to my graduate mentors, Takayoshi Kuga and Daichi Suzuki, Prof. Jon Bird, and Prof. Yukio Kawano for all of their help and guidance with my project this summer. I would also like to thank the entire Kawano-Oda lab for supporting me and making me feel welcome in Japan. This program is made possible by the hard work of Sarah Phillips, Dr. Cheryl Matherly, Keiko Packard, and Prof. Junichiro Kono.

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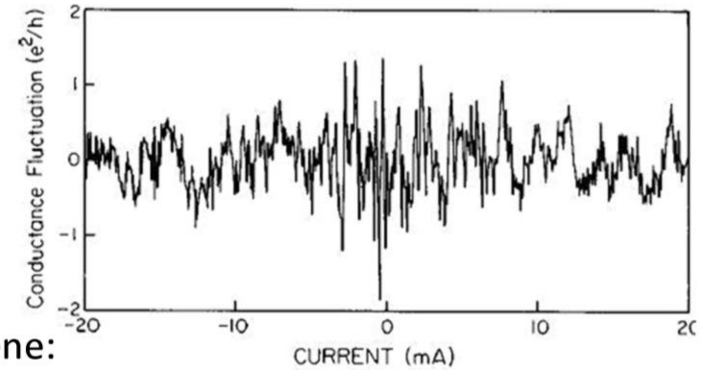

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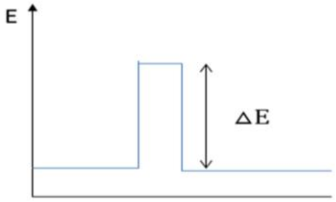

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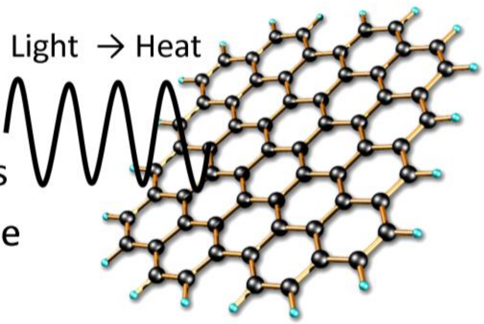

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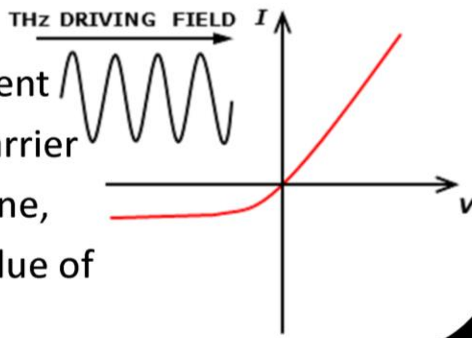

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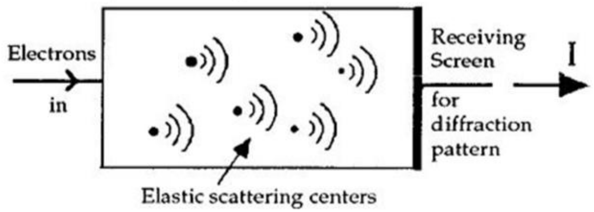

  — Indicates ability to manipulate electron interference patterns

  — Precursor to smaller, more effective THz detectors

- Advantages of THz detection:
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  — Most explosives have a distinct THz fingerprint

  — Non-destructive evaluation of materials

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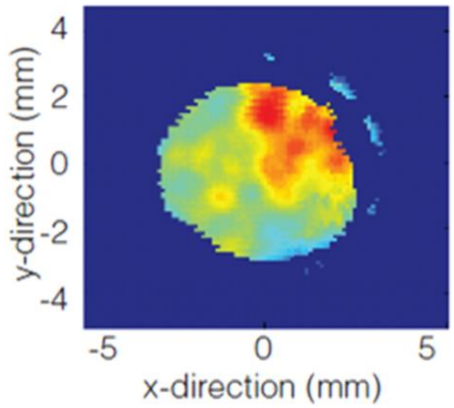
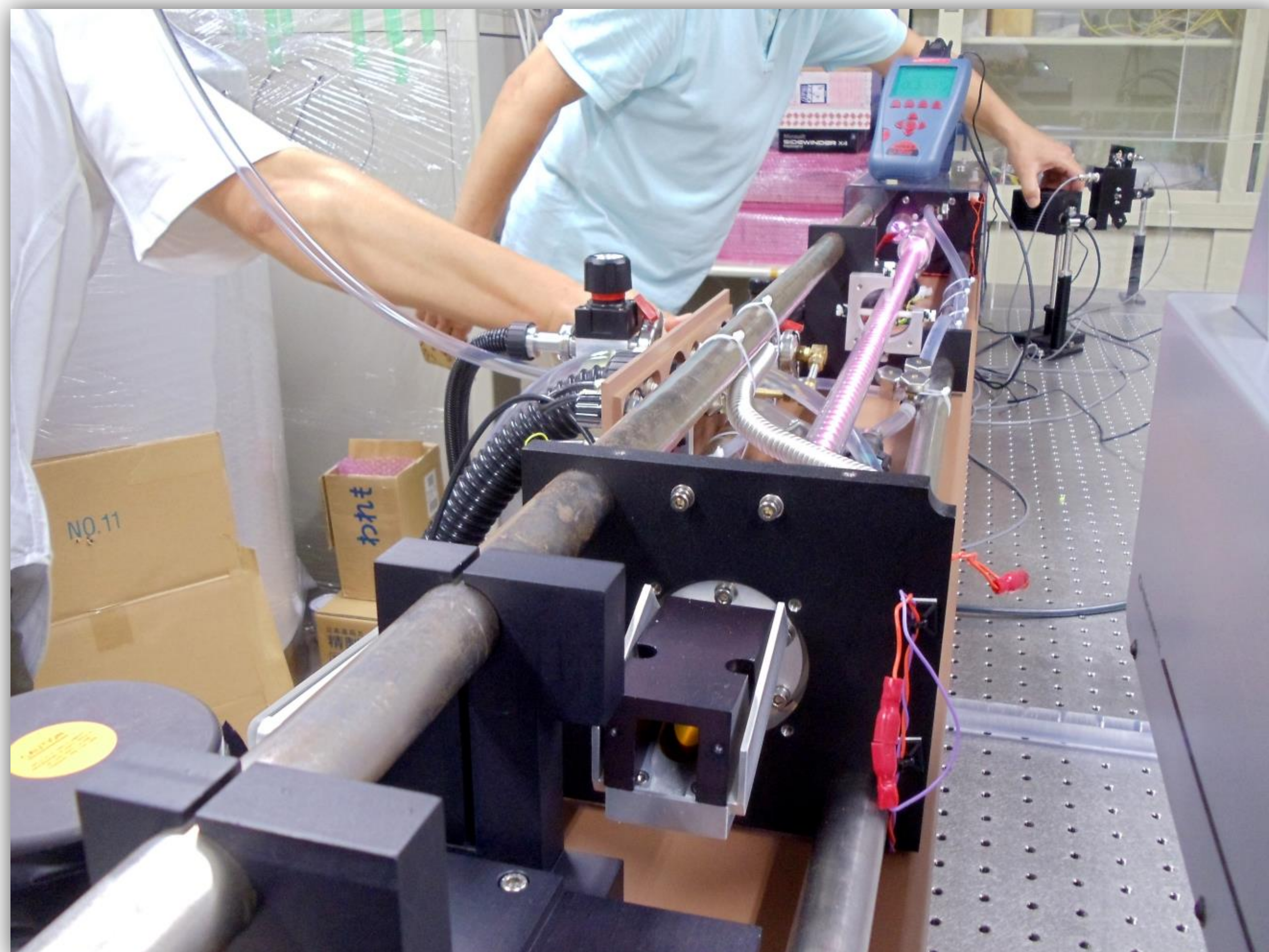


Why Should I Apply?

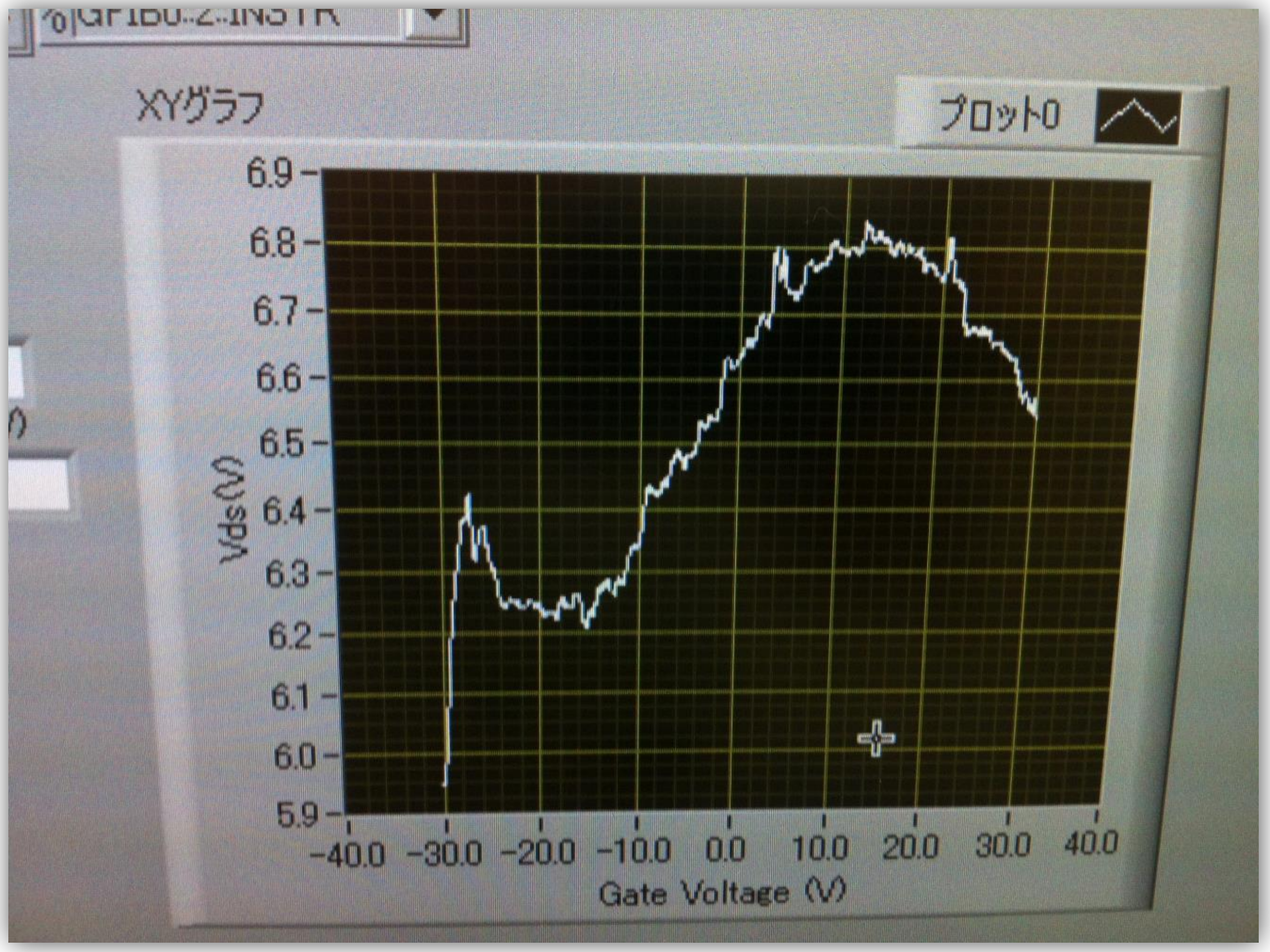
- **Specifically for Freshmen and Sophomores**
  - Not required to know quantum mechanics or Japanese
  - You just need to have a passion for Japanese culture and nanotechnology!
- **Introduction to International Research**
  - NanoJapan is an IREU – **I**nternational **R**esearch **E**xperience for **U**ndergraduates
  - Hands-on experience in a cutting-edge Japanese laboratory
  - Guidance from Japanese and American researchers at the front of their fields
  - Exposure to current research in nanotechnology

Japanese Lab

Japanese Lab



Japanese Lab



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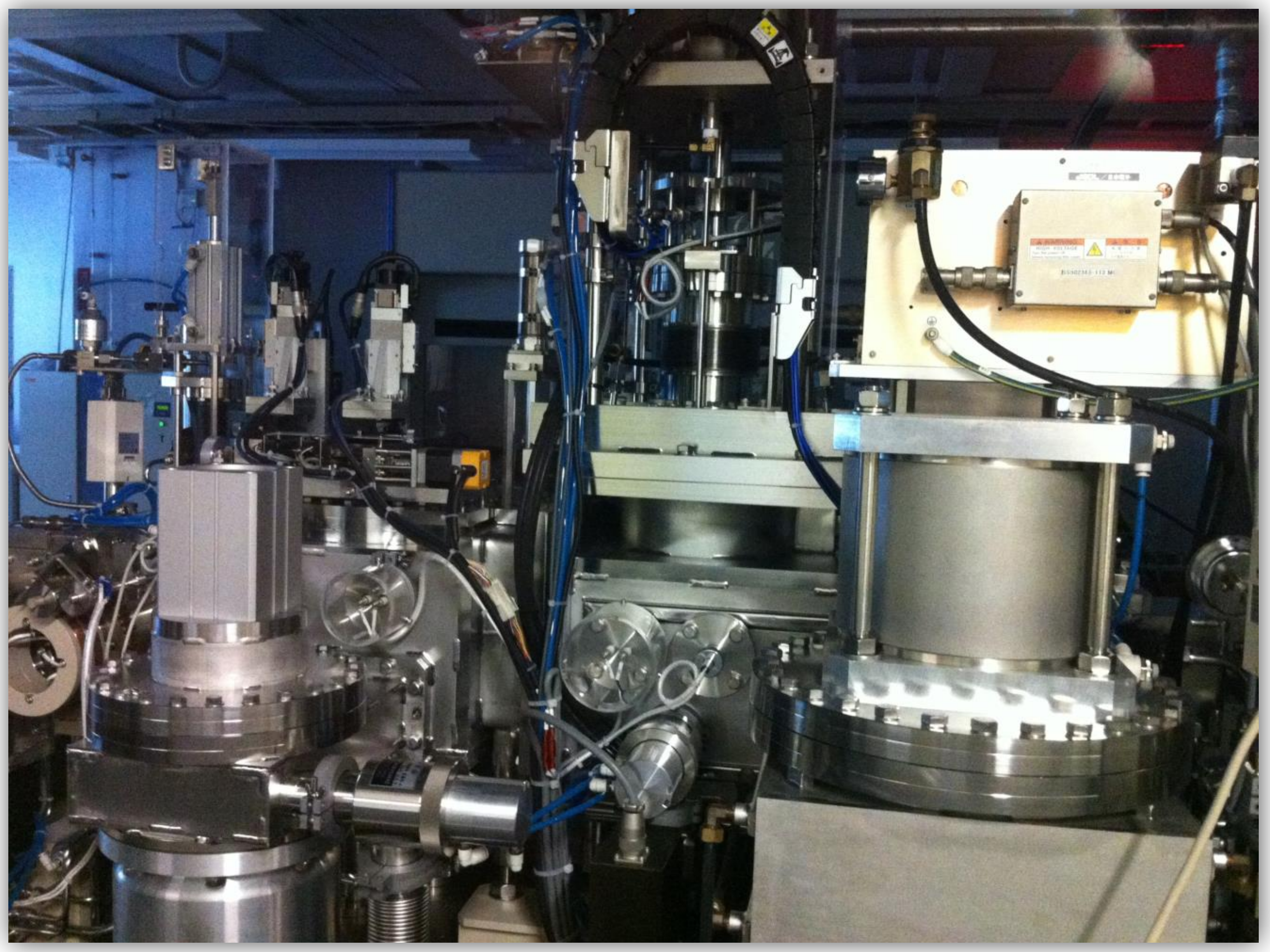

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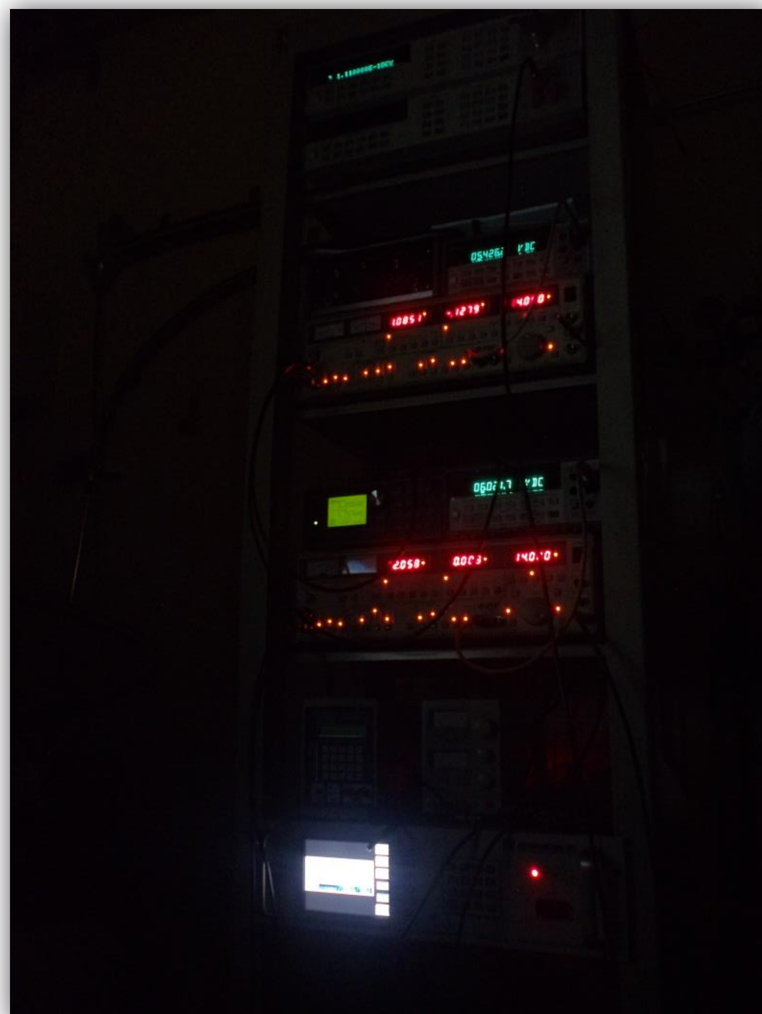

Why Should I Apply?

- **Exposure to Japanese Culture**
    - This summer isn't entirely about the research!
    - Time to explore Japan – see and experience new things
    - Get to know a culture very different from your own
    - Learn about different perspectives
- **Development as a Student and a Researcher**
    - Learn about International Research, its pros and cons
    - Gain competency with maintaining your own project
    - Learn how to deal with complete immersion in a subject
    - Cross cultural boundaries to arrive at solutions
    - Start a network of international research collaborators

Pictures from Japan

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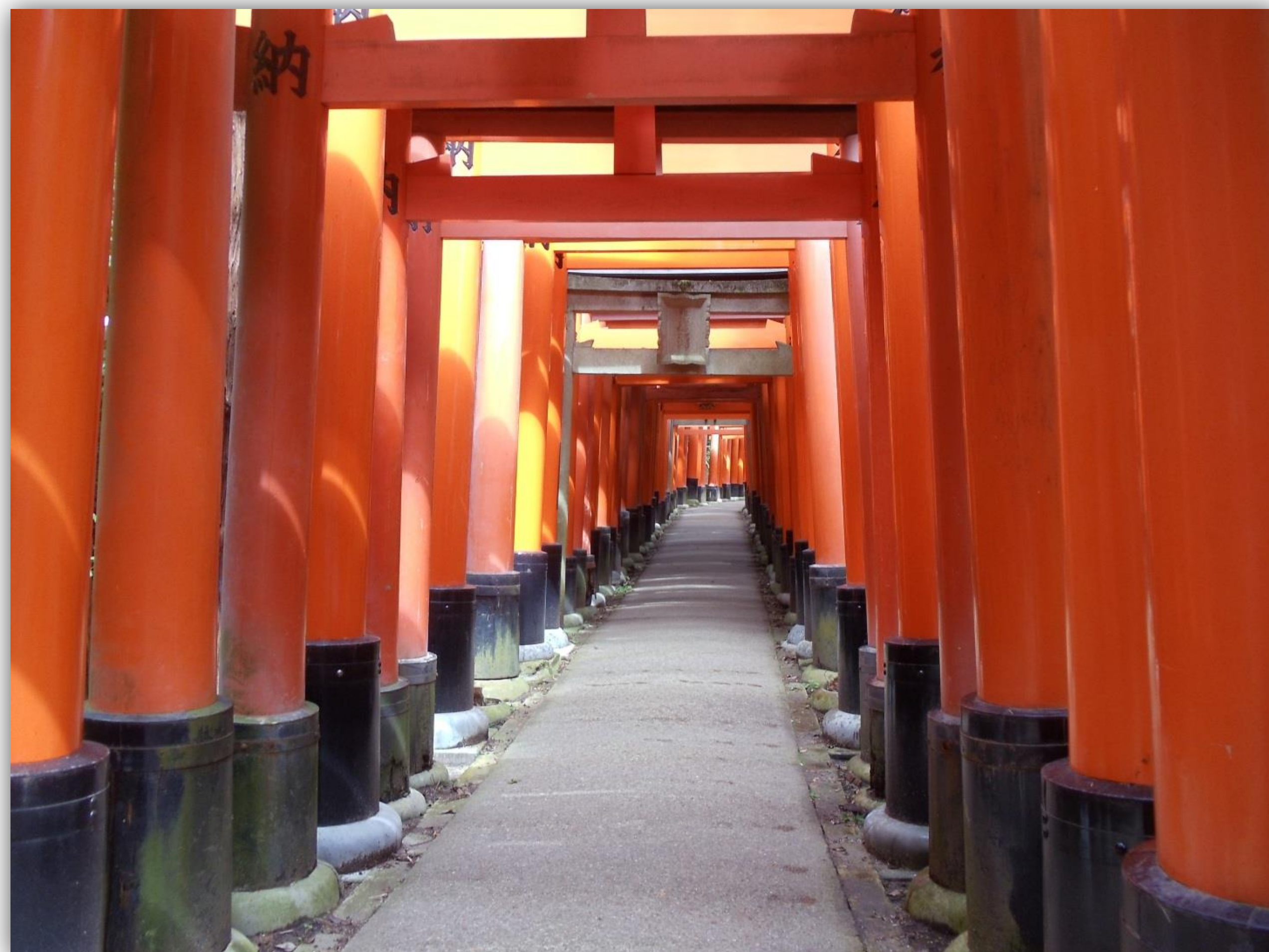

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