Photothermoelectric p-n Junction Photodetectors Based on Macroscopic Films of Aligned Carbon Nanotubes in the Terahertz Range

J. M. Lloyd,[1] N. Fujimura,[2] T. Kuga,[2] X. He,[3] R. Hauge,[4] Y. Kawano,[2] and J. Kono[3,5]
[1]*Department of Electrical and Computer Engineering, Carnegie Mellon University, Pittsburgh, PA and the NanoJapan Program, Rice University, Houston, TX, U.S.A.*
[2]*Department of Physical Electronics, Tokyo Institute of Technology, Tokyo, Japan*
[3]*Department of Electrical and Computer Engineering, Rice University, Houston, TX, U.S.A.*
[4]*Department of Chemistry, Rice University, Houston, TX, U.S.A.*
[5]*Department of Physics and Astronomy, Rice University, Houston, TX, U.S.A.*

Terahertz (THz) technologies are quickly developing for non-invasive sensing, characterization, and communication applications. Lasers and modulators in this region have been studied extensively though THz detection systems remain relatively unexplored. Carbon nanotubes (CNTs) exhibit strong absorption in the THz, making them promising for THz detection. Studies in the ultraviolet (UV) to near-infrared (NIR) have demonstrated CNTs' capability of absorbing light via interband transitions, whose excitonic origin and diameter/chirality dependence basically are well understood. The origin of THz absorption in CNTs is relatively unclear, remains rather controversial, though promising for detection applications. Here we investigate photothermoelectric p-n junction photodetectors based on macroscopic films of aligned CNTs [1]. CNTs were grown via chemical vapor deposition and rolled down, creating horizontally-aligned films, then transferred to substrates. Two films were used in device fabrication. One was unintentionally p-doped by atmospheric molecules, while the other was n-doped using benzyl viologen and placed over the p-doped film, creating a p-n junction. Two electrodes contacted each side, allowing the voltage across to be measured. A broadband photoresponse was previously found in these devices in the UV to NIR [1]. We aim to further characterize these devices' functionality in the THz range. Our setup consists a CO_2 laser that pumps a far-infrared molecular gas laser, which emits various THz wavelengths. The beam was focused on the sample's p-n junction. From previous experiments, we know this junction is significantly the most responsive area. We will discuss our results as a function of THz laser power, polarization, and wavelength.

[1] Xiaowei He, Xuan Wang, Sébastien Nanot, *et al.*, "Photothermoelectric p–n Junction Photodetector with Intrinsic Broadband Polarimetry Based on Macroscopic Carbon Nanotube Films," *ACS Nano,* published online on June 30, 2013. DOI: 10.1021/nn402679u.

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NanoJapan International Research Experience for Undergraduates

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[1]Department of Electrical and Computer Engineering, Carnegie Mellon University, Pittsburgh, PA, U.S.A and the NanoJapan Program, Rice University, Houston, TX, U.S.A.

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

[3]Department of Electrical and Computer Engineering, Rice University, Houston, TX, U.S.A.

[4]Department of Chemistry, Rice University, Houston, TX, U.S.A.

[5]Department of Physics and Astronomy, Rice University, Houston, TX, U.S.A.

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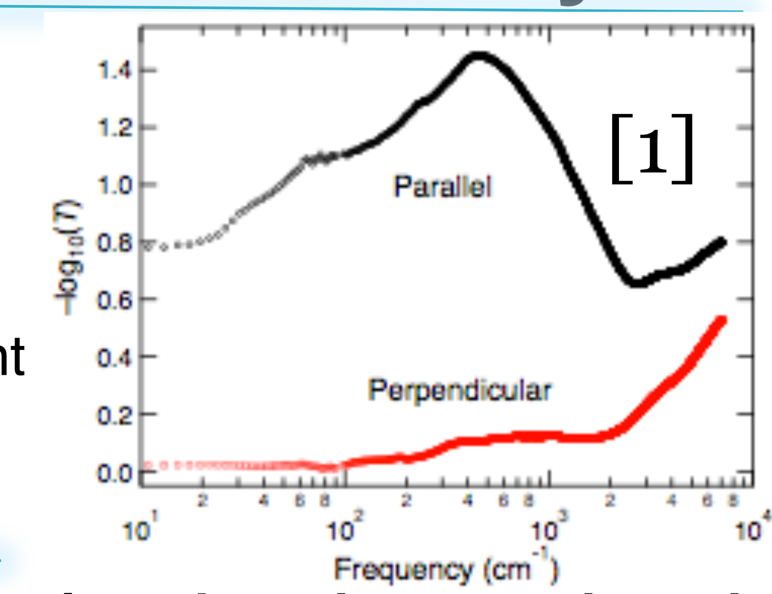
Material & Device History

Previous carbon nanotube (CNT) work shows:

- Interband absorption in UV and IR
- → Diameter/chiral dependent
- Strong absorption peak at ~ 4 Terahertz (THz) [1]



Previous studies of p-n junction photodetectors based on CNTs have shown:

- Broadband photovoltage (PV) up to 3.3 μm
- Max. sensitivity at junction

Project Aim:

- Characterize device functionality via power, wavelength, and polarization dependences.

Methods and Measurement

Sample Fabrication:

1. CNT growth by CVD
2. Rolled down → Two horizontally-aligned CNT films
3. N-doped film with benzyl viologen
4. Overlayed on an p-doped film
5. Contacted by silver electrodes

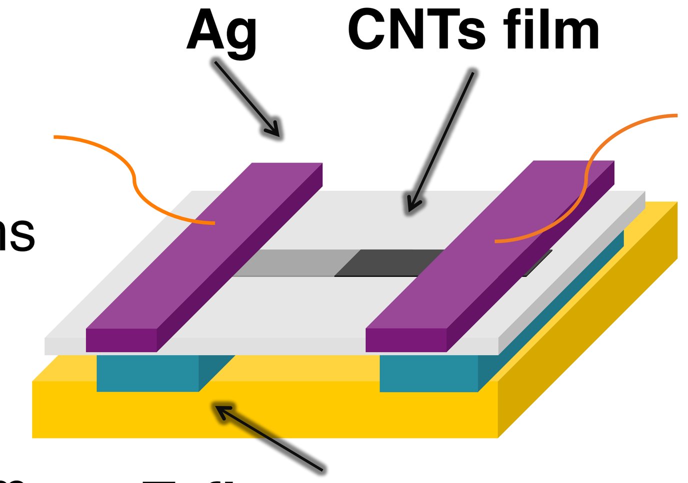
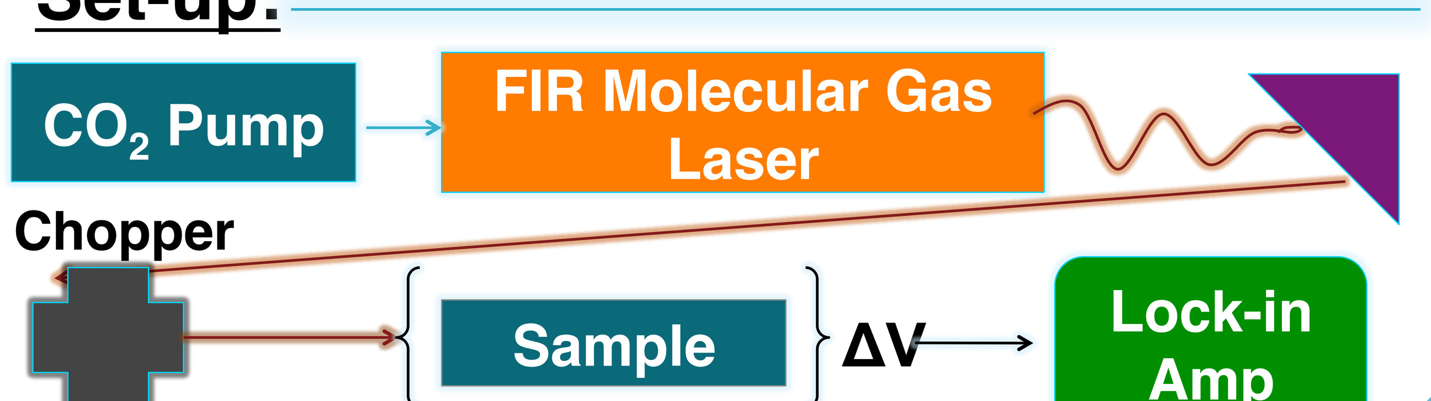


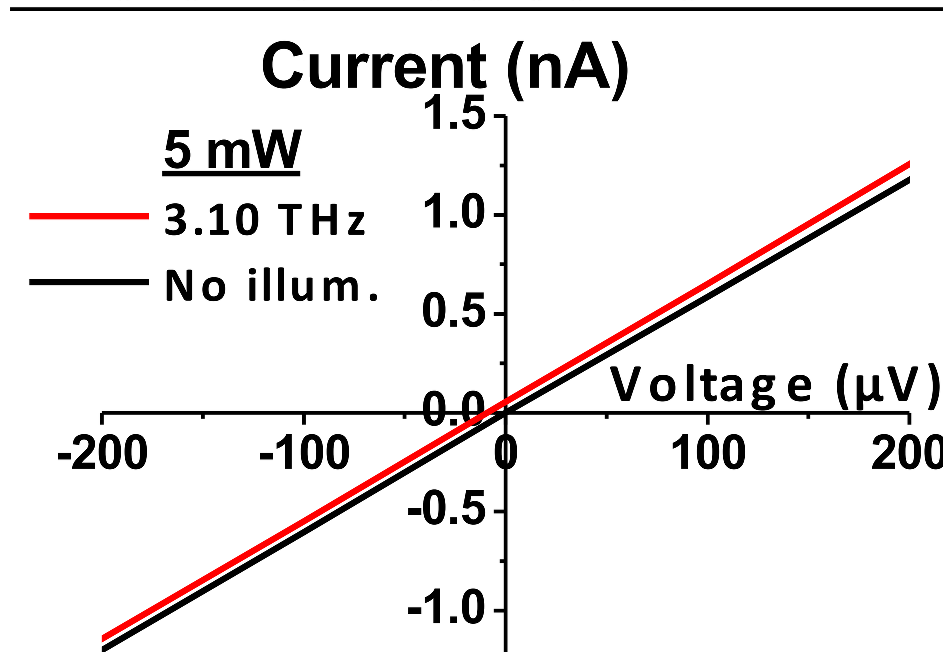
Image: Xiaowei He[3]

Set-up:



Results & Discussion

Photothermoelectric THz I-V Curve

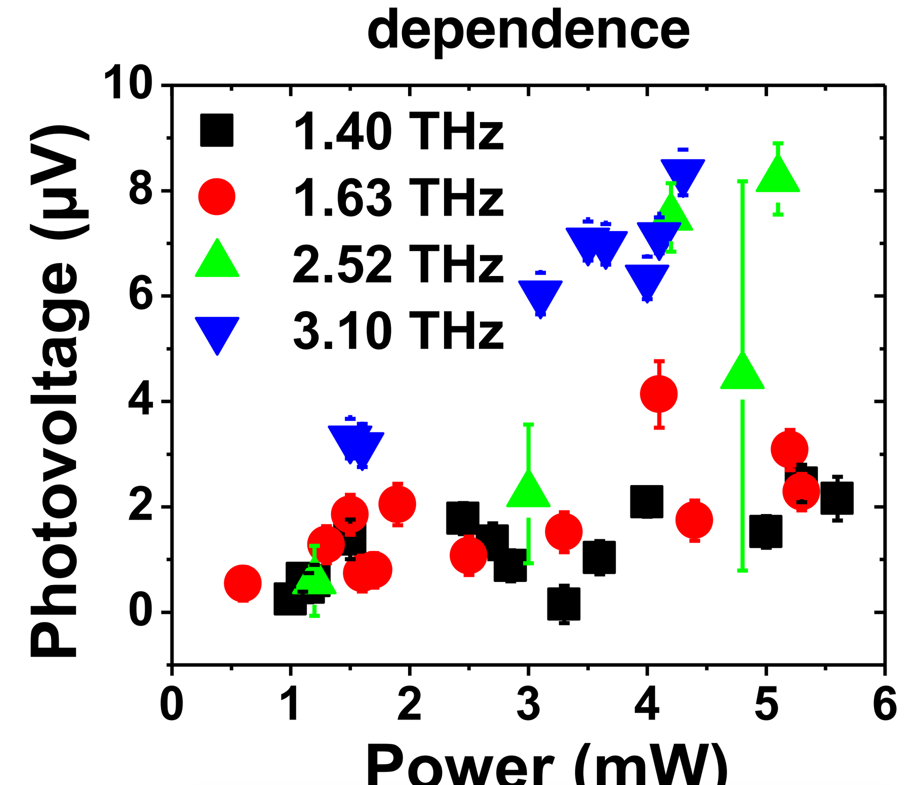


- Shift of I-V →photothermoelectric effect [2]
- $\Delta V = \Delta V_p + \Delta V_n$
- Thermocoupling → Dominant PV near the junction

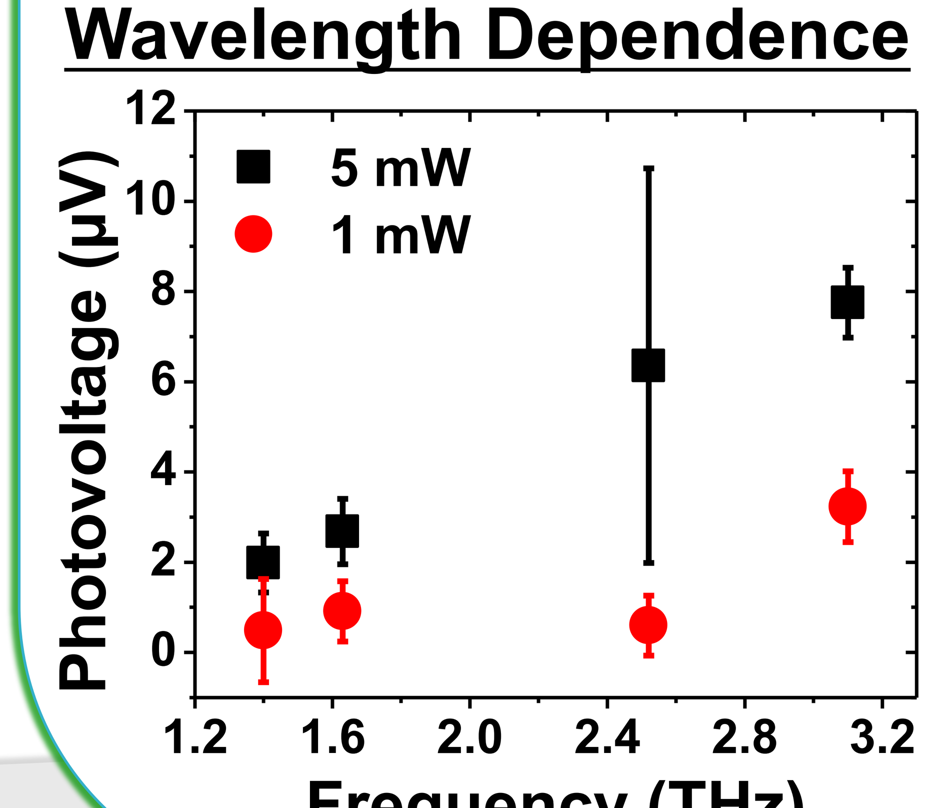
THz Power Dependence

- Possible linear power dependence in 1.40, 1.63, 2.52, and 3.10 THz
- **Trend:** Higher frequency, higher photoresponse:
  - Shorter λ's, higher photon energy → bandgap coorespondance
  - CNT absorp. peak ~ 4 THz

Absolute valued power dependence



Wavelength Dependence



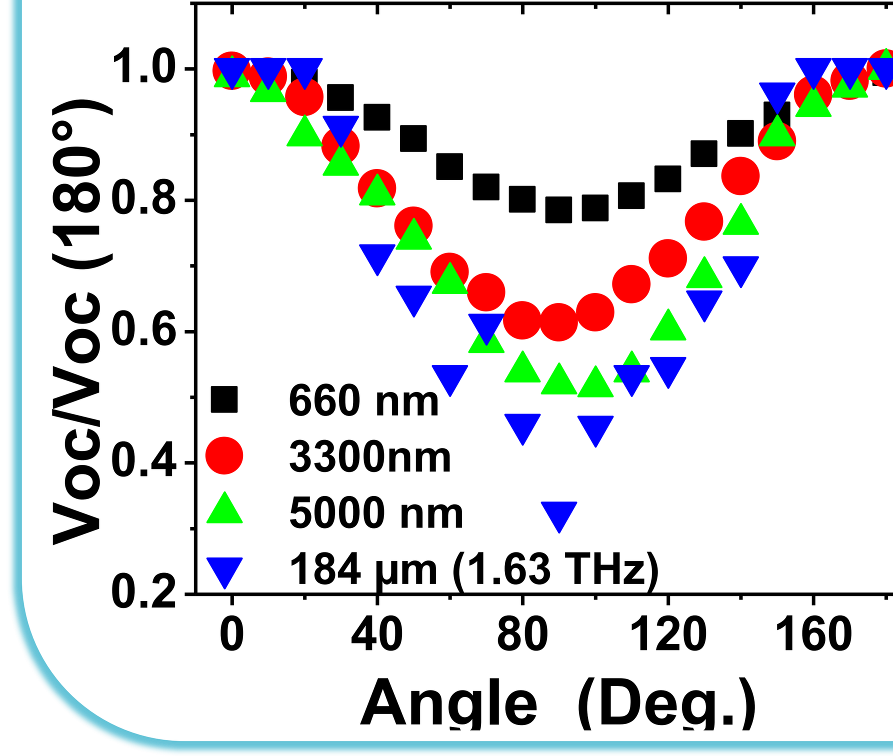
- **Trend:** Increase in PV with frequency

Possible mechanisms of THz peak:

- Intraband absorption in THz → assisted by junction
- Radiation scattering between aligned tubes [1]

Results & Discussion Cont.

Polarization Dependence



Previous polarization ratios/figures (ll : ⊥) [2]:

- 660 nm – 0.78
- 3300 nm - 0.61

This study's findings:

- 1.63 THz - 3.5
- Possible mechanism for signal → radiation scattering [1]

THz Response & Conclusions

- THz signal in p-n junction photodetectors based on CNTs
- Photothermoelectric-indicative shift
- Photovoltage increase with frequency and power

Future Work:

- Improve alignment system
- Map sample w/ mid-IR Near-Field Scanning camera
- Continue with various frequencies & low temperature
- Study in mid- to far-infrared for systematic comparison.

Acknowledgments:

This research project was conducted as part of **the 2013 NanoJapan: International Research Experience for Undergraduates Program** with support from a National Science Foundation Partnerships for International Research & Education grant (NSF-PIRE OISE-0968405). For more information on NanoJapan see: http://www.nanojapan.rice.edu

[1] L. Ren, et al., *APS,* Physical Review B 87, 161401(R), (2013)

[2] Xiaowei He, et al., "Photothermoelectric p–n Junction Photodetector with Intrinsic Broadband Polarimetry Based on Macroscopic Carbon Nanotube Films," ACS Nano, published online on June 30, 2013. DOI: 10.1021/nn402679u.