Terahertz Photoconductivity in Disordered Single-Wall Carbon Nanotube Films

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The terahertz (THz) frequency range, from 0.1 to 10 THz, is the latest frontier of the electromagnetic spectrum to be exploited by solid-state technologies. Given their unique properties of exhibiting characteristics of both infrared and microwave waves, THz waves have provoked much interest in the scientific and engineering communities. Recently, single-wall carbon nanotubes (SWCNTs) have emerged as important materials for THz device applications such as THz polarizers [1], detectors [2], and sources. SWCNTs absorb THz radiation across a wide spectral range in a strongly polarization-sensitive manner; in addition, they are flexible, mechanically strong, and highly conductive both electrically and thermally. Here, we are investigating the photoconduction properties of a macroscopically aligned SWCNT film in response to THz radiation as a function of temperature to probe signs of quantum mechanical transport processes such as quantum tunneling in the presence of strong disorder. We first measured the resistance of the SWCNT film as a function of temperature in a temperature range of 3-20 K with particular interest in the 3-4 K range, observing a variable-range hopping transport mechanism. To perform a comparative study of how THz radiation influences the conductivity, we are also performing resistance measurements under THz illumination. Furthermore, to understand how THz radiation of varying frequencies may influence the transport mechanisms, we are performing the measurements in this temperature range with THz waves of varying frequencies. Given that the transport mechanisms under similar conditions have yet to be investigated, we are interested in understanding the terahertz induced response.

1. L. Ren *et al*., "Carbon Nanotube Terahertz Polarizer," Nano Lett. **9**, 2610 (2009).
2. X. He *et al*., "Carbon Nanotube Terahertz Detector," Nano Lett. **14**, 3953 (2014).

Terahertz Photon-Assisted Variable Range Hopping in Macroscopically Aligned Single-Wall Carbon Nanotube Films

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◊Introduction

Background

Objective:

- Investigate SWCNT film conductivity as a function of temperature
- Identify the effect of THz radiation on photoconductivity

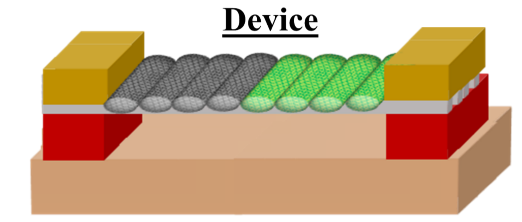
Motivation:

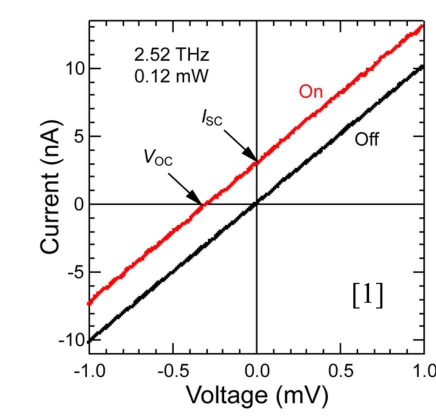
- Reveal new information about the effect of THz radiation has on the conductivity and electron transport mechanisms of a system with high disorder

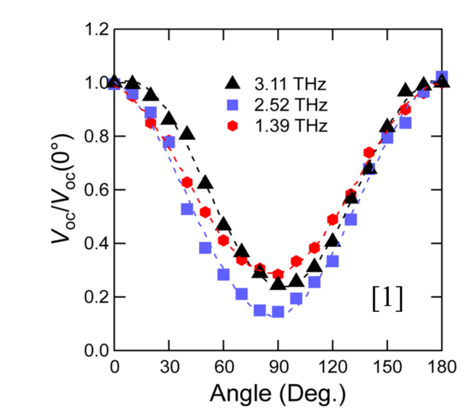
Device History

Previous Research:

- Observed a photothermoelectric effect shift in I-V curve
- Strong polarization dependence of photovoltage

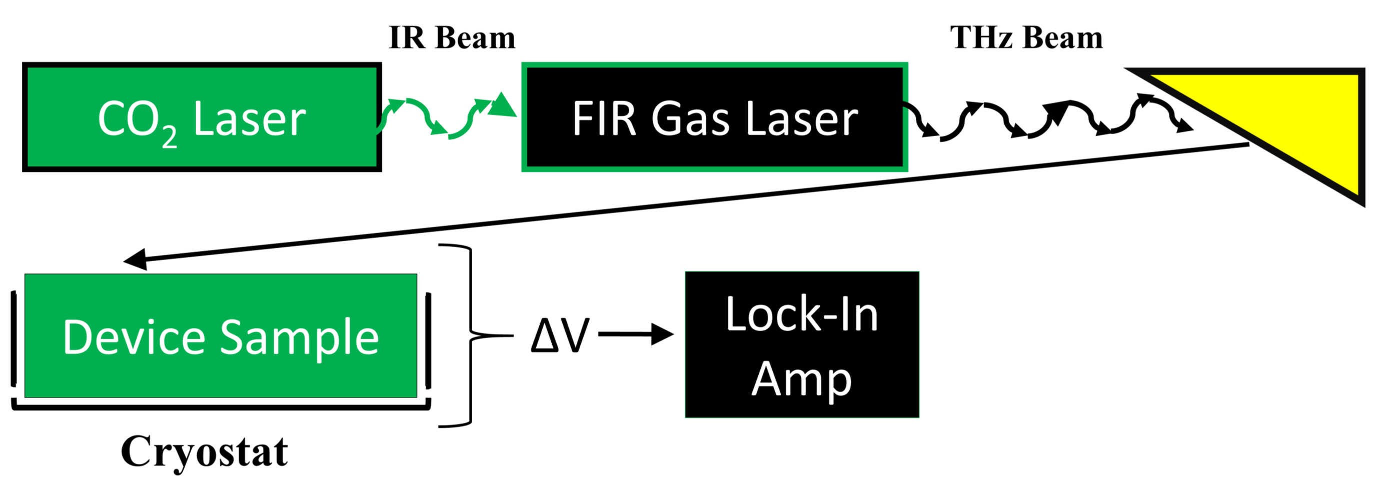






◊Methods

Experimental Setup



Producing THz Radiation for Device Illumination

1. Pump CO_2 gas into CO_2 laser
2. CO_2 laser -> IR beam
3. IR Beam -> FIR laser -> THz beam
4. THz beam illuminates device in cryostat
5. Amplifier connected to device records output current

Measurement Process

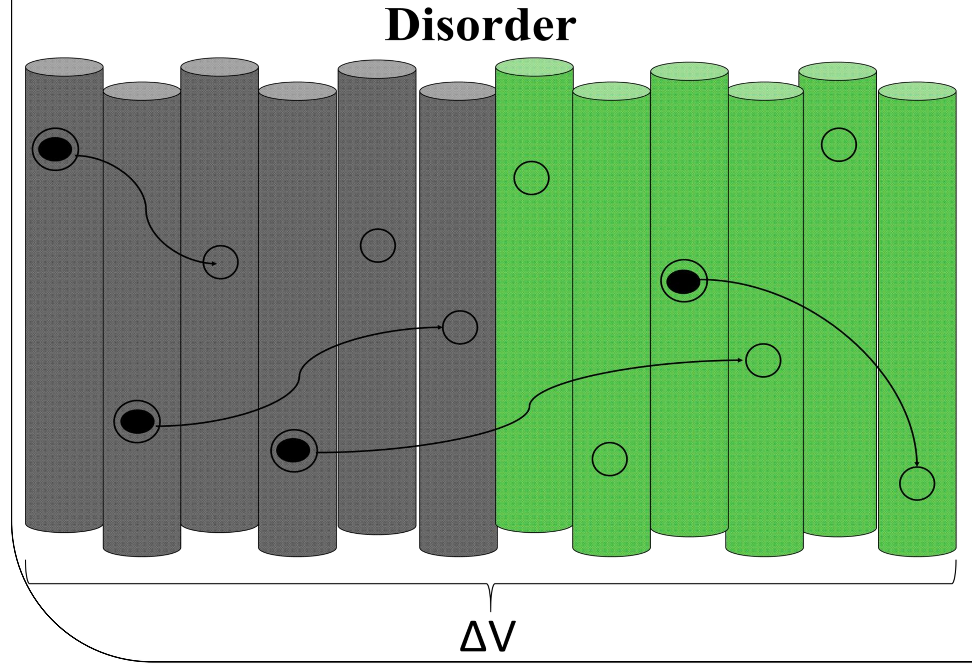
1. Exposed unilluminated device to 2.9-300°K temperatures
2. Recorded I-V characteristics for each temperature value to determine resistance
3. Repeated measurements with THz exposure in the temperature range of 2.9-20°K
4. Recorded the effect of different THz frequencies on the conductivity via I-V characteristics

*The resistance was calculated by recording the current generated by a constant voltage through the sample

◊Results and Discussion

Localization in SWCNTs

Variable Range Hopping in Strong Disorder



Mott's Law for VRH Conductance

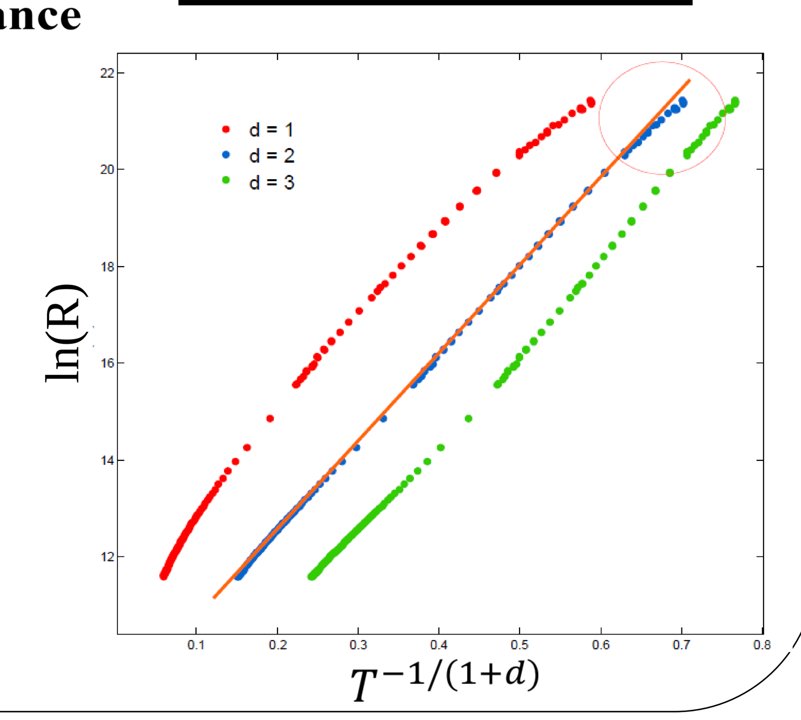
$$R(T)=R_0\exp[(\frac{T_0}{T})^{1/(d+1)}]$$

- Used to fit experimental data for d =2
  - Exact reasons why d=2 for our device are still not known

Types of Disorder in the SWCNT System:

- PN junction interactions
- Potential energy barriers (e.g. Schottky barriers)
- Material impurities
- Random diameters
- Nanotube contact points

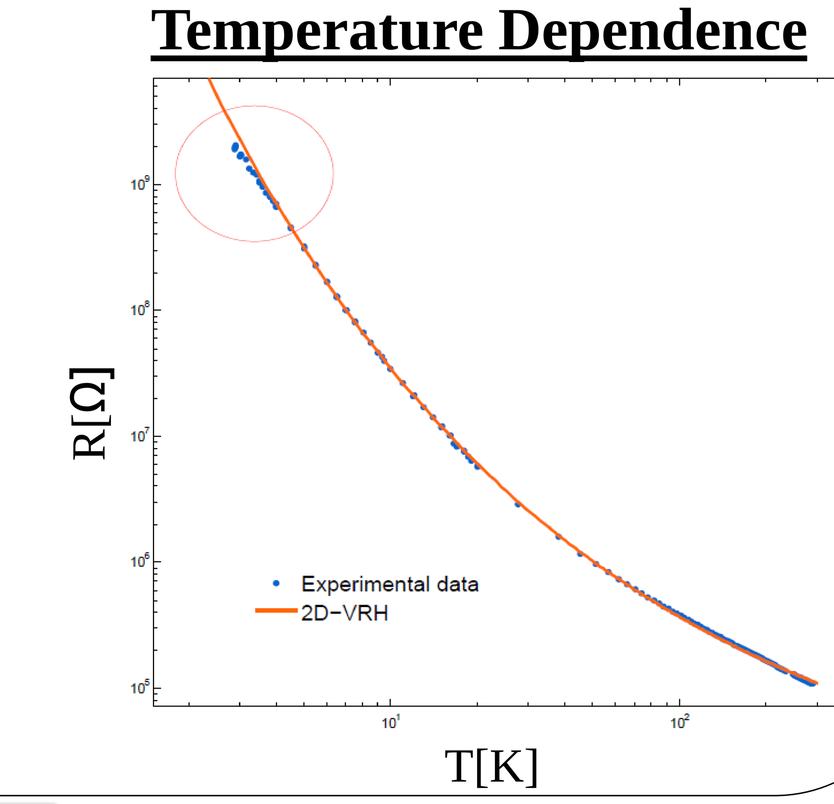
Mott's Law Fit Line



Device Conductivity & Temperature Dependence

- Strong correlation between experimental data and Mott's Law for 2D-VRH
- Slight discrepancy in the 3-4°K range
- Trend: higher temperature, less resistance
- Data resembles the behavior of a logarithmic function; as expected from Mott's Law

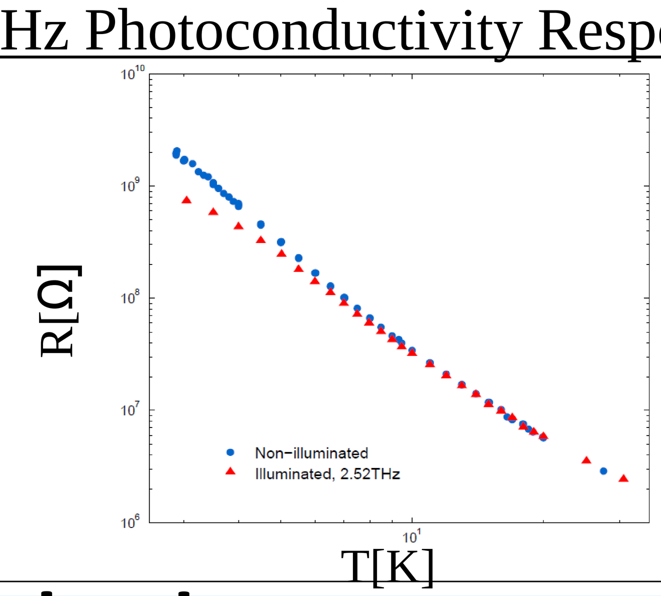
Temperature Dependence



THz Photoconductivity Response

- General trend is that the two graphs show the same behavior and are approximately equivalent in resistance value
- Two plots noticeably diverge in what appears to be the temperature range of 1-5°K
- Interested in observing the effect of different THz frequencies

THz Photoconductivity Response



Outlook and Future Study

- Perform comparative measurement of THz frequencies
- Investigate real-time response mechanism of the device under THz illumination

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[1] Xiaowei He, et al., "Carbon Nanotube Terahertz Detector," Nano Letters (ACS Publications), published online on May 29th, 2014. DOI: 10.1021/nl5012678