Terahertz Detection at Room Temperature Using Highly Aligned Single-Wall Carbon Nanotube Films

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Terahertz (THz) radiation has a broad range of potential applications in the medical, security, industrial, and agricultural fields. However, current technology for generating, modulating, and detecting THz radiation is unsuitable for commercial applications because of its limited performance, high cost, and cryogenic temperature requirements. Single-wall carbon nanotubes (SWCNTs) are a candidate for developing high-temperature-operating THz detectors due to their wide range of absorption at room temperature, high charge carrier mobility, flexibility, and strength. Additionally, SWCNTs come in various species, called chiralities, including metallic and semiconducting types, which have differing band gaps, conductivities, and Seebeck coefficients allowing for different responses to THz radiation. In this study, we set out to characterize the effects of back gate control on THz absorption of highly aligned single-chirality and metal/semiconductor mixture SWCNT films [1]. Each of our devices consisted of a SWCNT film on a Si/SiO_2 substrate with four Cr/Au electrodes deposited by electron beam evaporation and an Al back gate deposited by thermal evaporation. Because aligned SWCNT films exhibit different values of absorption and conductivity depending on the direction of polarization/current flow with respect to the films' alignment, we characterized the current-voltage relationship for each orientation with and without a back gate bias voltage and with and without THz irradiation.

[1] X. He, W. Gao, *et al*., *Nature Nanotechnology* **11**, 633 (2016).

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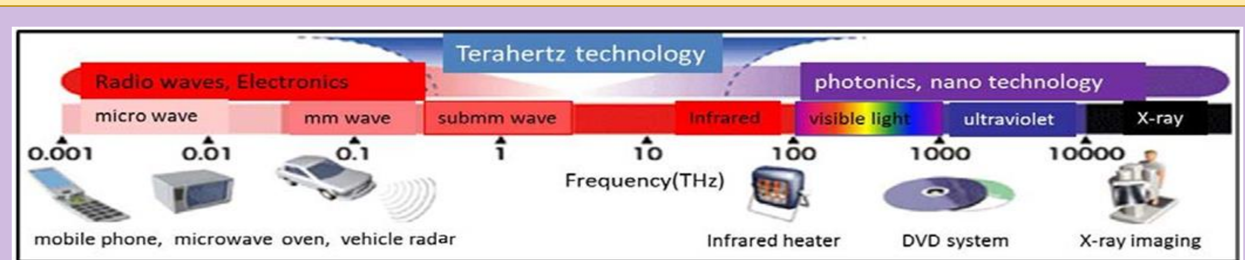
Terahertz: The Final Frontier



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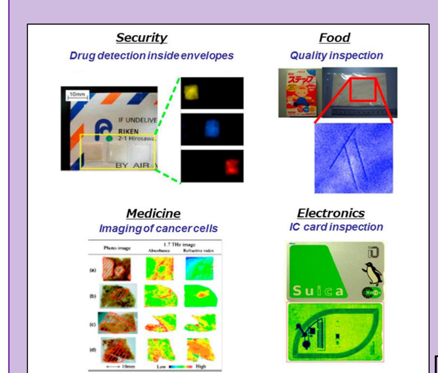

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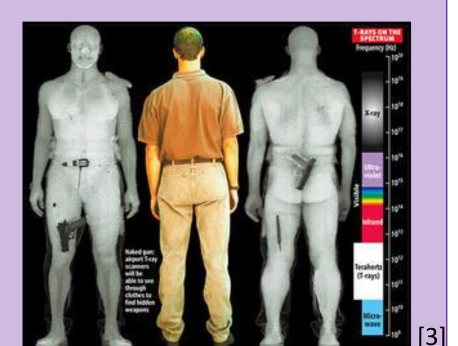
Current Technology:

- Limited performance
- Expensive
- Cryogenic operating temperature



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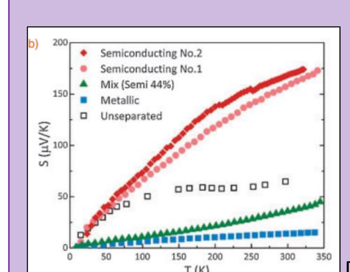

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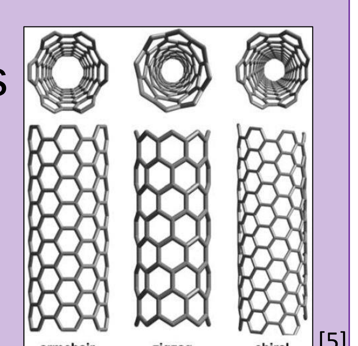
Single-Wall Carbon Nanotubes (SWCNTs):

- Strong, flexible, high charge carrier mobility
- Terahertz (THz) absorption at room temperature
- Metallic and Semiconducting species



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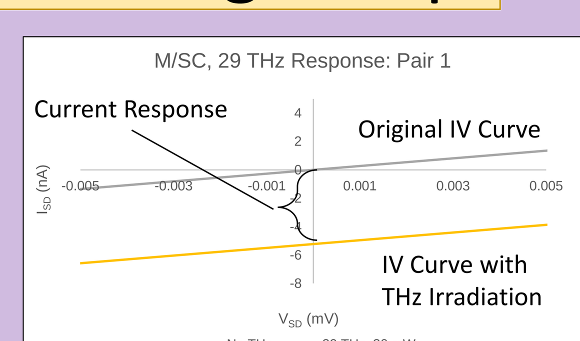
Purpose

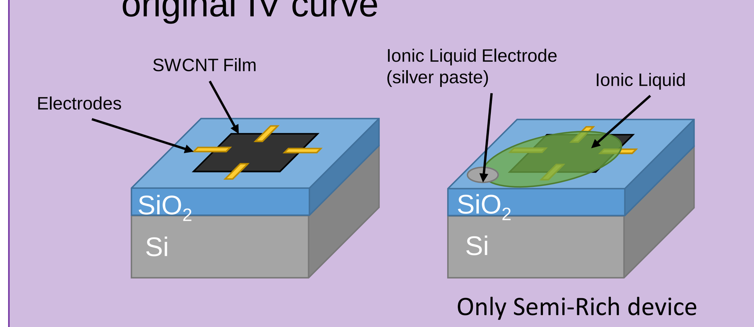
Characterize the effects of gate control on THz absorption in two types of highly aligned SWCNT films: semiconductor enriched (semi-rich) and metal/semiconductor mixture (M/SC).

Device Design and Testing Setup

Terahertz Irradiation:

- 1.4 THz: THz laser pumped by CO_2 gas laser, polarized
- 29 THz: CO_2 gas laser, non-polarized
- THz absorption causes a shift in the original IV curve



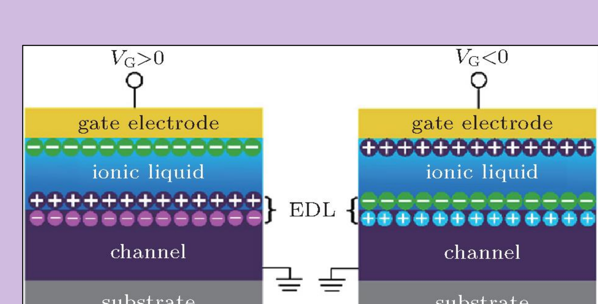


Device Design:

- Electrode deposition:
  - Shadow masking
  - Electron Beam Evaporation

Ionic Liquid:

- EDL – Electrical Double Layer
  - Ions align with applied voltage
  - Causes a change in Fermi level in semiconductor



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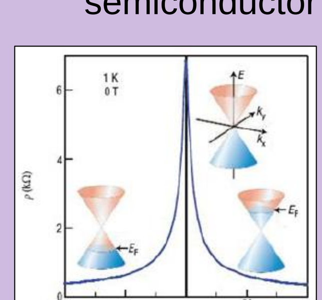

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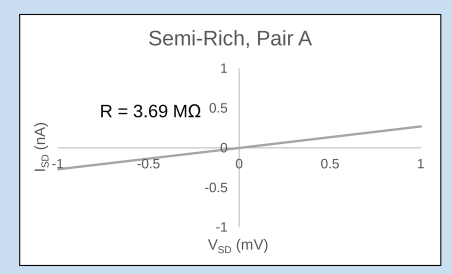
Gate Control:

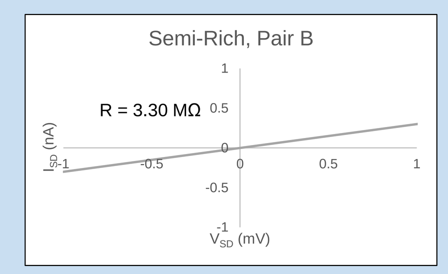
- Applying a voltage to change the Fermi level
- Changes amount/type of available charge carriers

Effects of Ionic Liquid on Semi-Rich Device

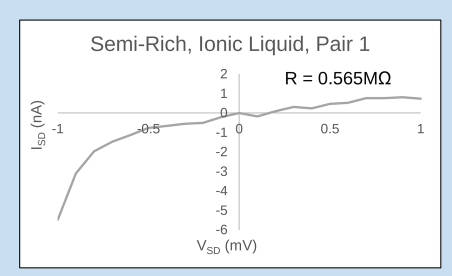
IV Characteristics

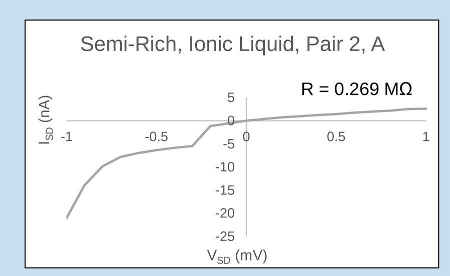
Before Application of Ionic Liquid





After Application of Ionic Liquid



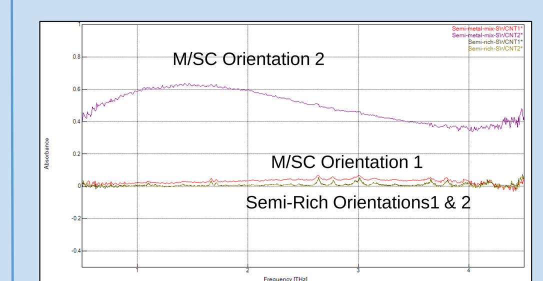


- No gate voltage
- Resistance reduced by ~10%

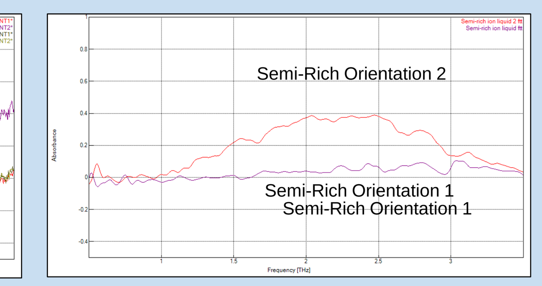
- Possible causes of rapid rise in current:
  - Time delay
  - Impurities

THz Absorption Spectroscopy

Without Ionic Liquid



With Ionic Liquid



M/SC film:

- Polarization dependent

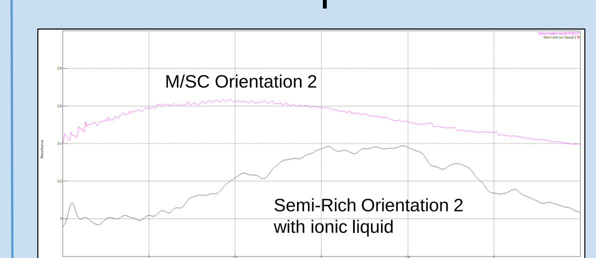
Semi-Rich film:

- No absorption

Semi-Rich film:

- Absorption from 1 to 3.5 THz
- Polarization dependent
- No gate voltage

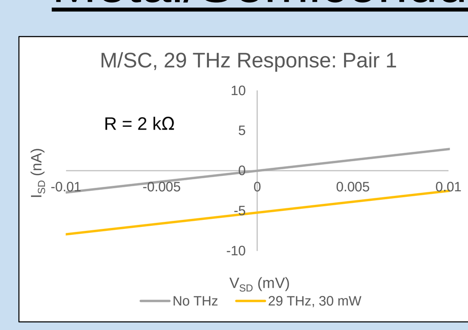
Comparison: Zero Gate Bias

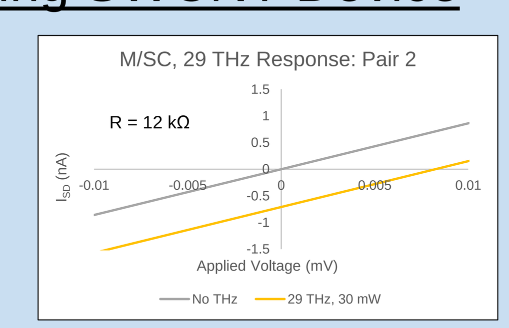


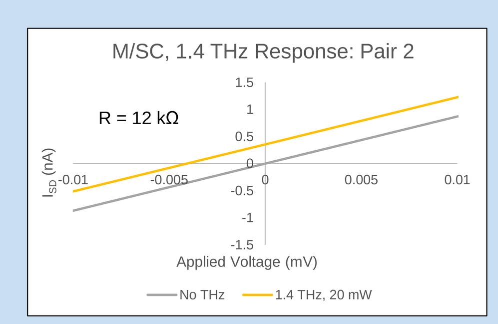
- M/SC device:
  - Broader range
  - More absorption
- Semi-Rich Device:
  - Zero gate voltage
  - Gate control may change absorption characteristics

THz Detection in M/SC and Semi-Rich Films

Metal/Semiconducting SWCNT Device



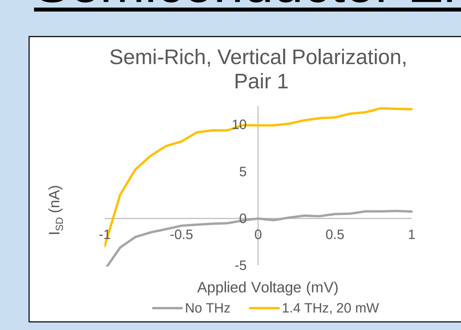


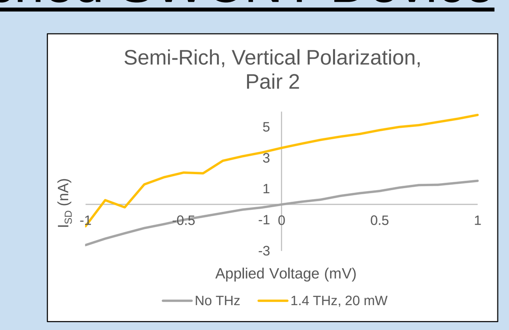


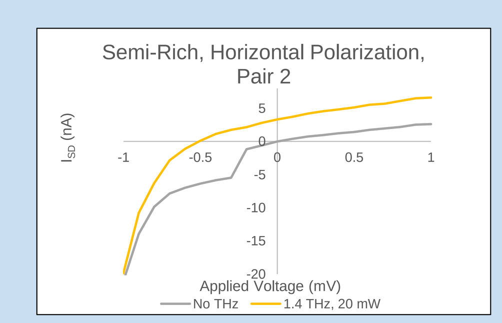
- Resistance of Pair 1 is 1/10 of Pair 2
- Pair 1 has the highest current response
  - Suggests Pair 1 is closer to the parallel orientation

M/SC Device	29 THz, 30 mW, Non-Polarized		1.4 THz, 20 mW, Vertical Polarization
	Pair 1	Pair 2	Pair 2
Current Response (nA)	5.23	0.710	0.356
Responsivity (nA/W)	174.3	23.7	17.8
NEP (W/√Hz)	7.66e-8	7.03e-6	6.75e-7

Semiconductor Enriched SWCNT Device







- Resistance values are similar
- Highest current response in Pair 1
  - Suggests parallel to CNT alignment

Semi-Rich Device	1.4 THz, 20 mW		
	Pair 1, Vertical Polarization	Pair 2, Vertical Polarization	Semi-Rich, Pair 2, Horizontal Polarization
Current Response (nA)	9.93	3.65	3.31
Responsivity (nA/W)	496.5	182.5	165.5
NEP (W/√Hz)	9.77e-9	1.04e-8	1.47e-8

Acknowledgements

NAKATANI FOUNDATION
for advancement of measuring technologies in biomedical engineering

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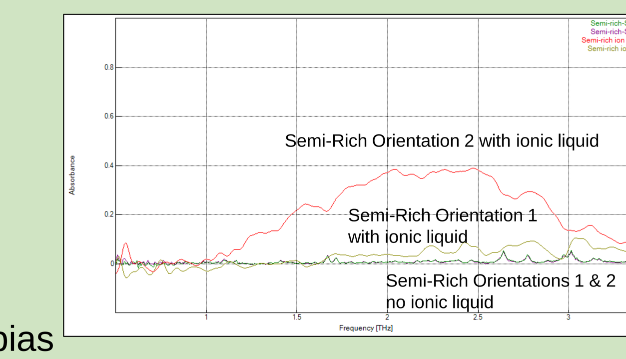
Discussion

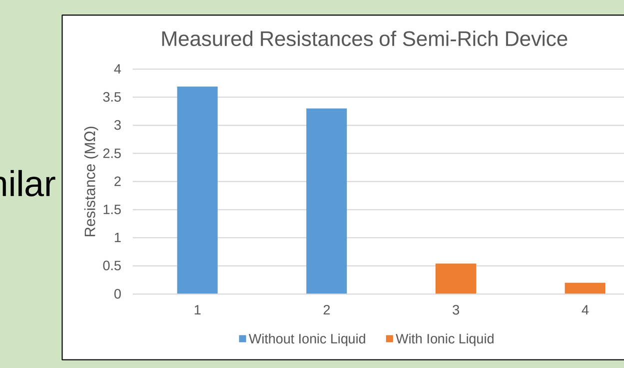
Effects of ionic liquid:

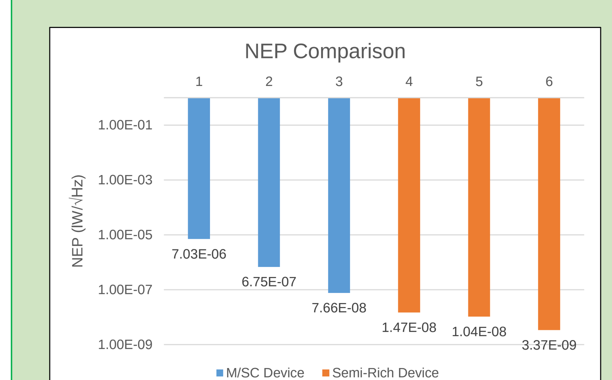
- Before application of ionic liquid
  - No THz or IR (29 THz) absorption
    - Band gap >1eV
  - Resistance ~3 MΩ
    - Very few/no charge carriers
- After application of ionic liquid, no gate bias
  - Resistance reduced to ~10%
  - Absorbs 1–3.5 THz



Detection Mechanism:

- Shift in IV curve of Semi-Rich device similar shift observed in M/SC device
  - Same detection mechanism
  - Photothermoelectric effect





NEP Comparison:

- Noise Equivalent Power
  - Distinction between a measured signal and background noise
  - Smaller is better
- The Semi-Rich device has better NEP values at smaller frequencies

Conclusions

- Ionic liquid causes a shift in the fermi level of semiconductor enriched SWCNT films with no applied voltage.
- THz absorption in semiconductor enriched SWCNT films is due to intraband absorption by free charge carriers.
- THz radiation can be detected in semiconductor rich SWCNT films via the photothermoelectric effect.
- Semiconductor enriched SWCNT films are a more effective means to detect THz than metallic/semiconductor mixed films when charge carriers are present.

Future Plans

- Characterize the SWCNT films at more polarization angles
- Establish gate control in SWCNT films
- Investigate cause of rapid rise in current in samples with ionic liquid.

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