INL/CON-19-52964-Revision-0

Non-Destructive Terahertz Imaging and Spectroscopy

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September 2019

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Non-Destructive Terahertz Imaging and Spectroscopy

Topics:

Nonlinear THz Spectroscopy Using Plasmonic Induced Transparency

THz Field Induced Metal-Insulator Transition in Vanadium Dioxide

Non-Destructive Evaluation of Microprocessors using THz Radiation

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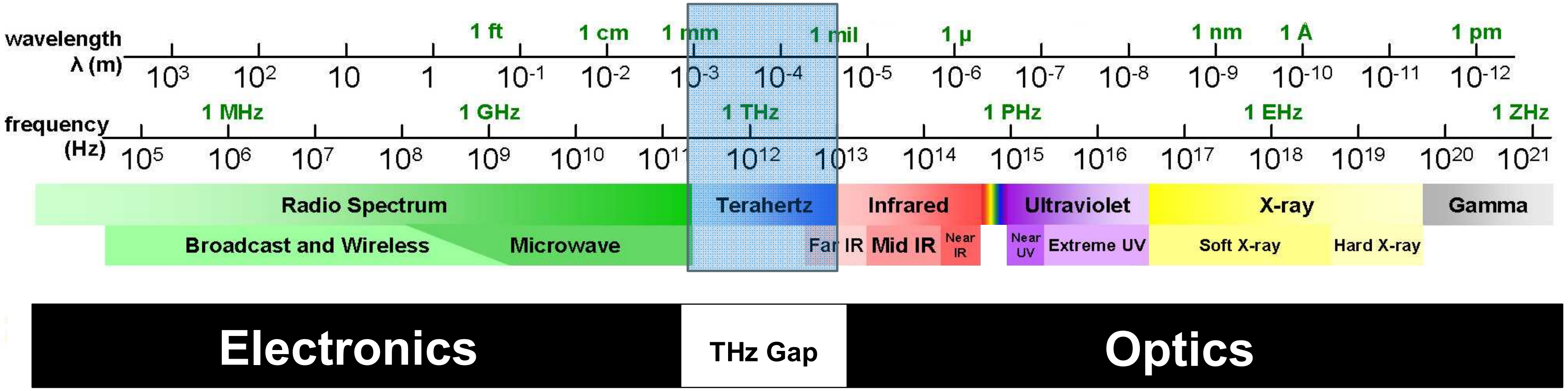
Idaho National Laboratory

Motivation

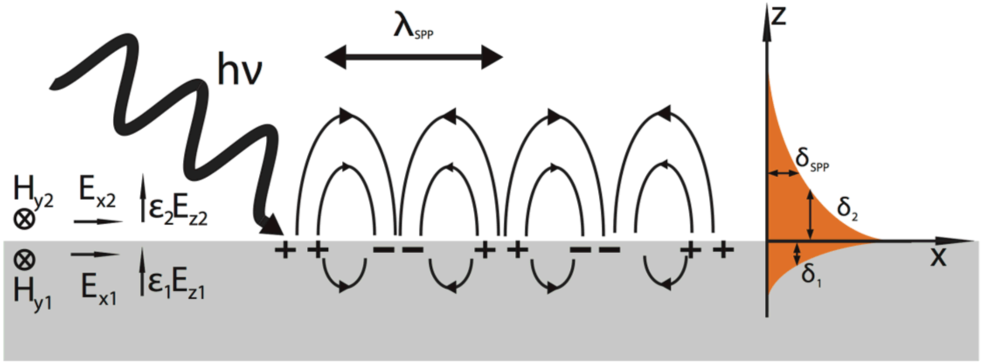


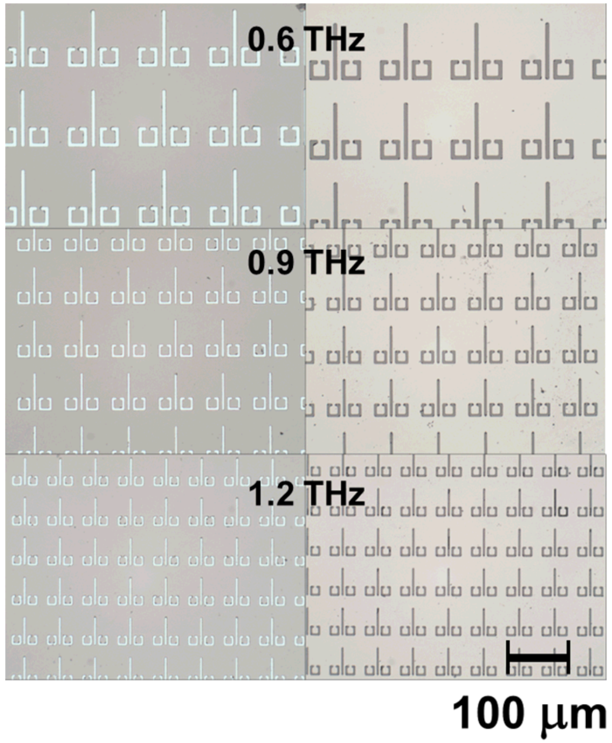
- Low energy, Non-ionizing
  - 1 THz photon carries 4.1 meV
  - Generally corresponds to rotations and vibrations of molecules
- Difficult to generate and detect
  - Requires pulsed lasers and/or cryogenic systems
- Relatively unutilized region
  - Table-top sources have only recently been realized

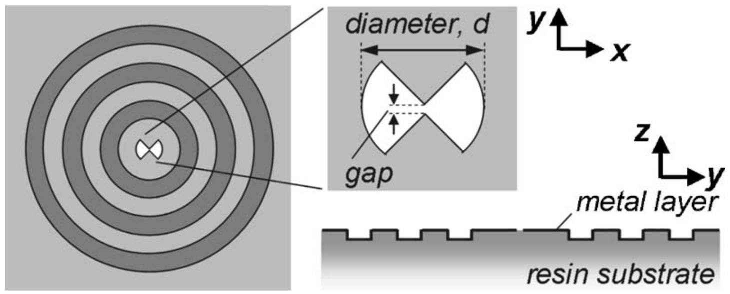
INTRO:
Motivation
TOPICS:
PIT
VO_2
ICE
FUTURE

Plasmonic Induced Transparency

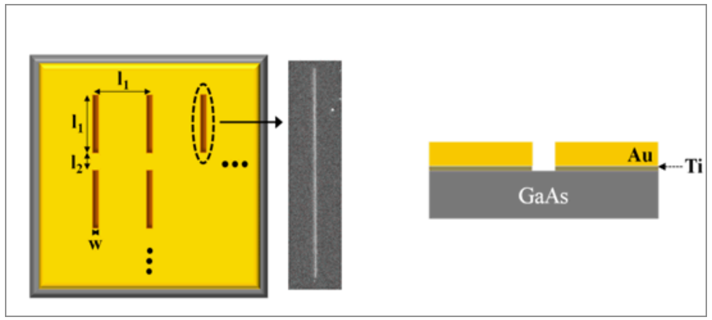
- Plasmonic Metamaterials
  - Sub-diffraction limit imaging
  - Electric field enhancement
  - Plasmonic Induced Transparency





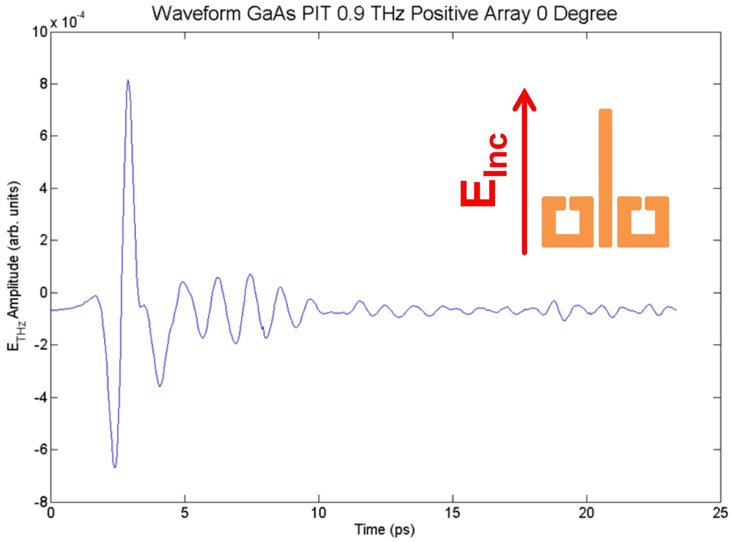


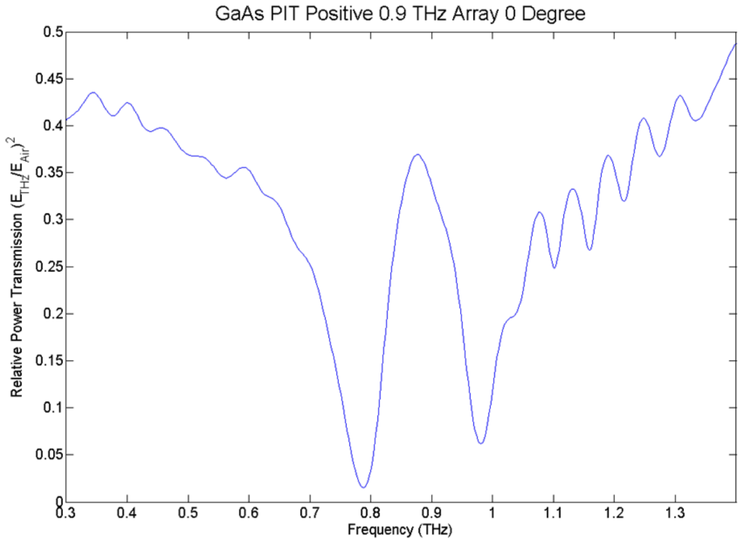
Ishihara et al. APL **89,** 201120 (2006)

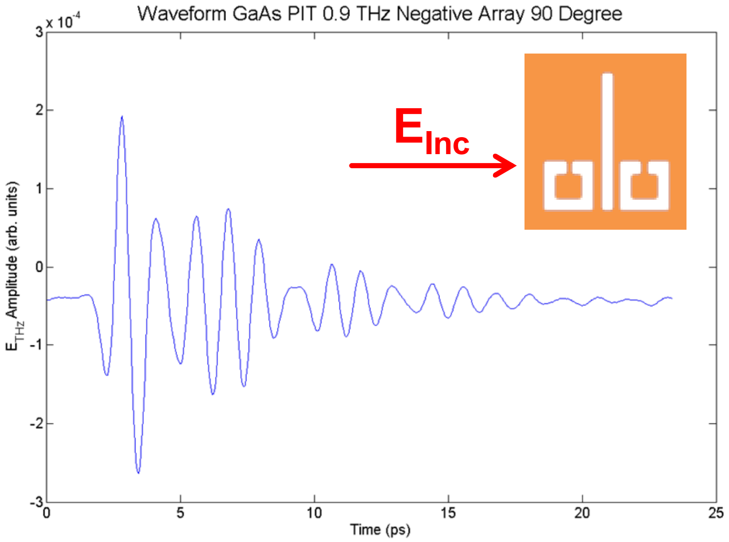


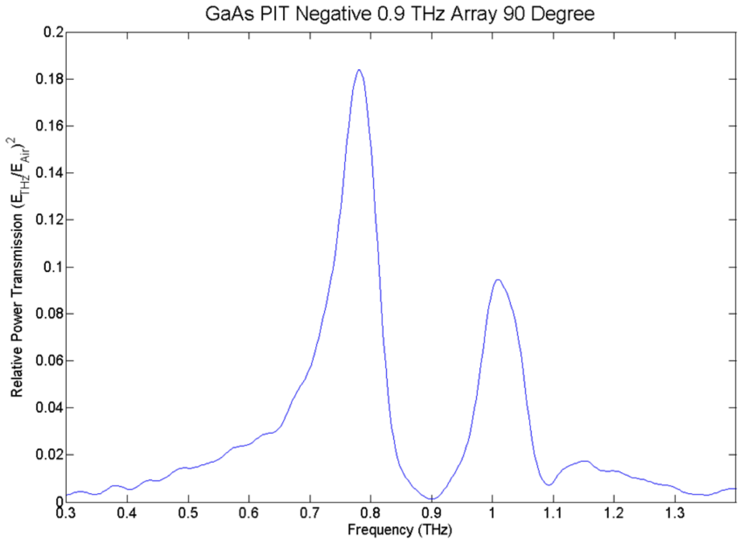
Y. G. Jeong et. al. accepted to CLEO 2013

Plasmonic Induced Transparency





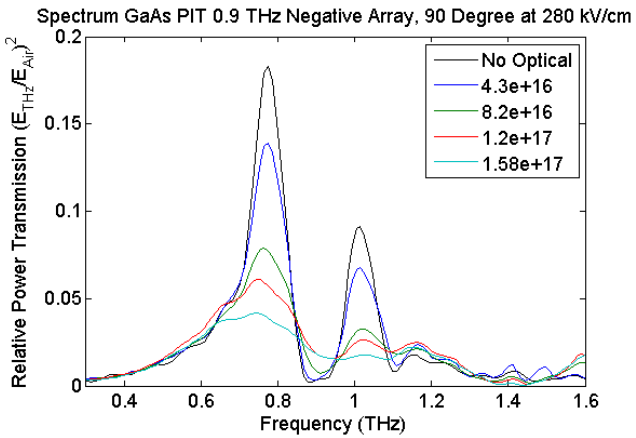


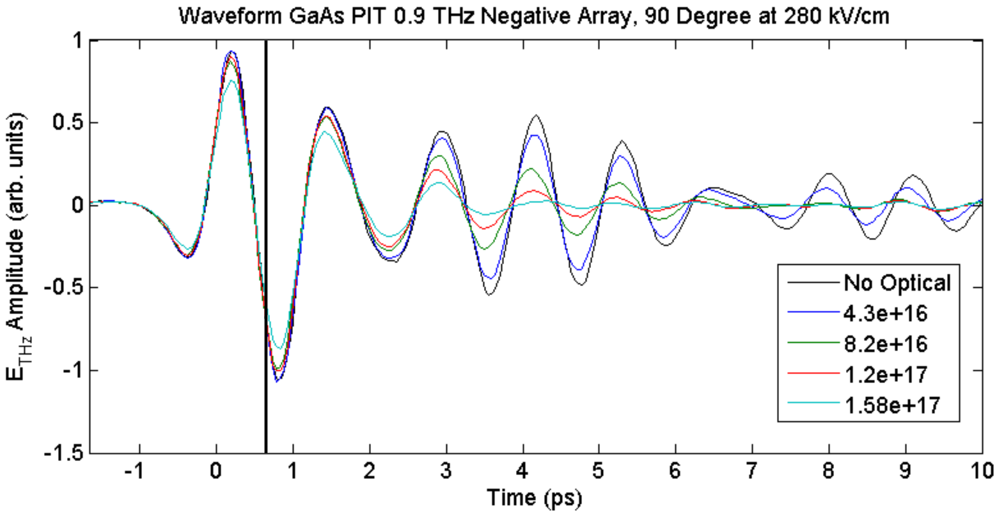


Plasmonic Induced Transparency

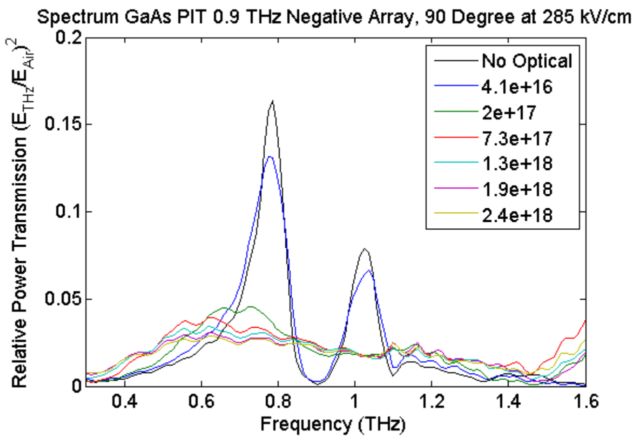
Optical Excitation

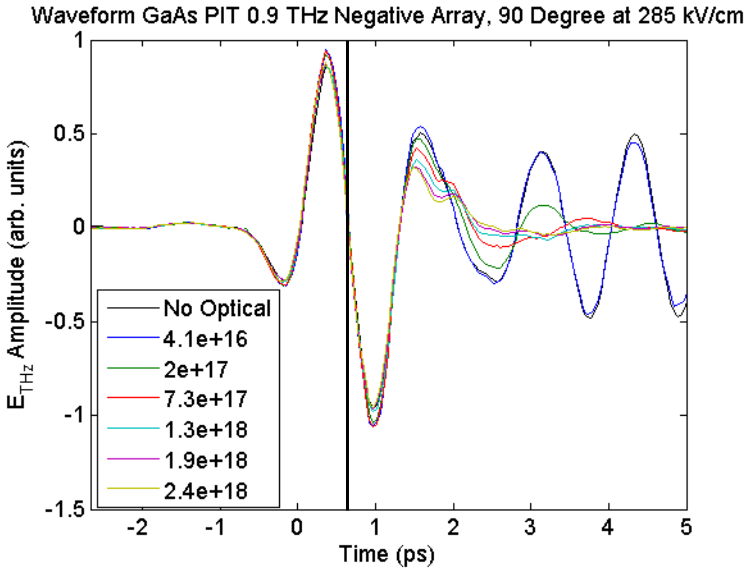
Low Optical





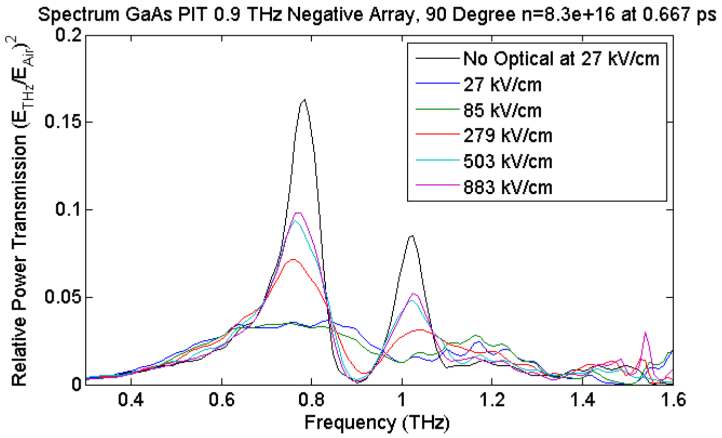
High Optical

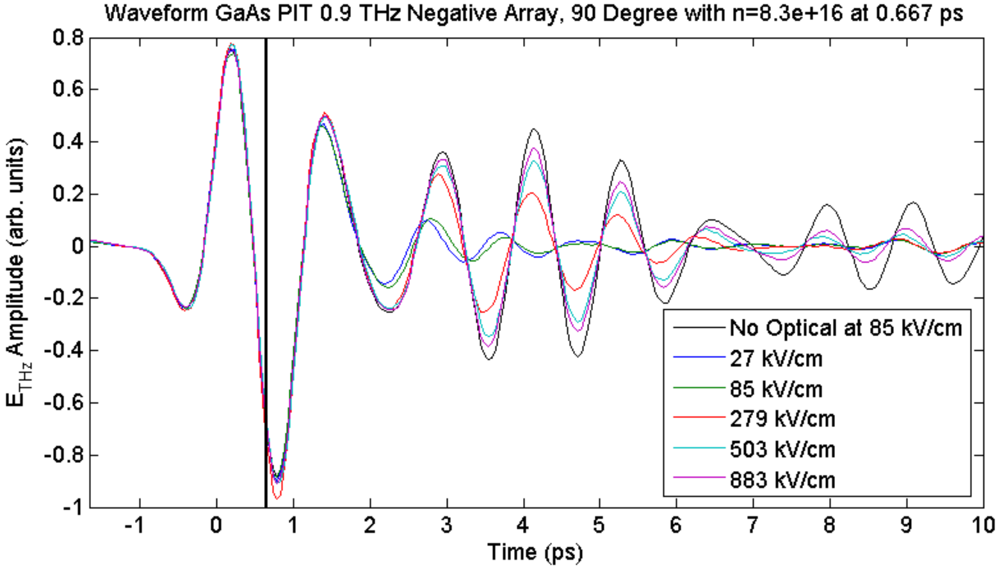




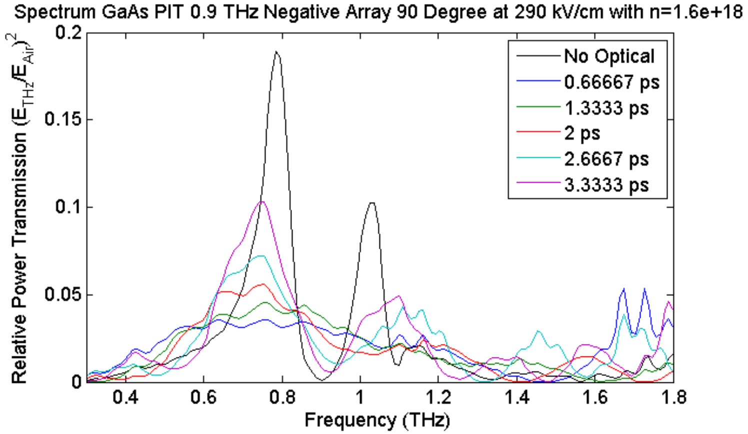
Plasmonic Induced Transparency

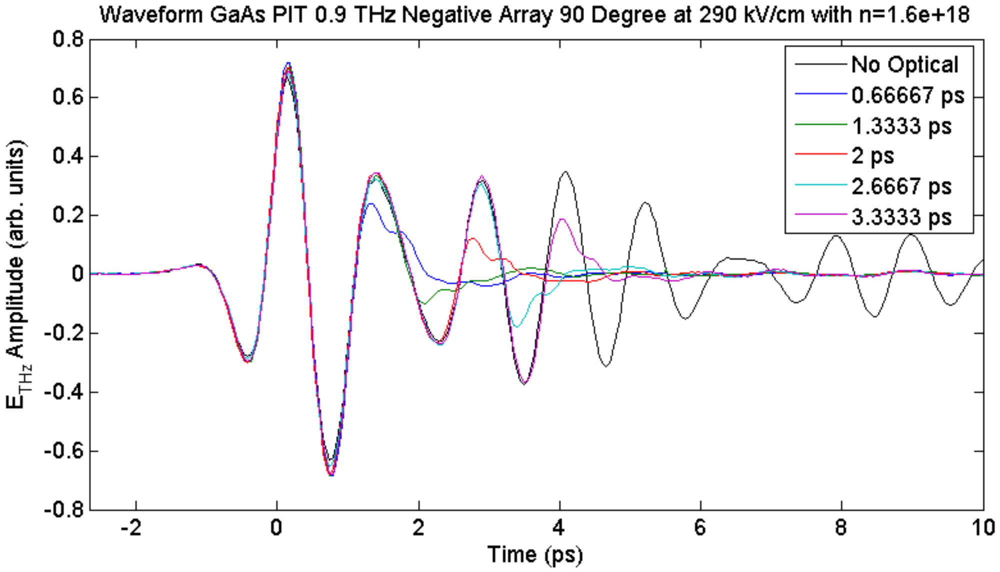
THz Control





Pulse Shaping

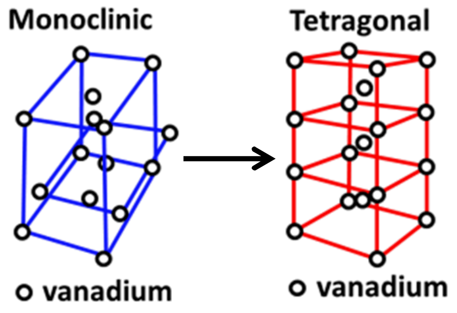




Vanadium Dioxide

Material Properties

- Mott Insulator with Near Room Temperature (343 K) Insulator-to-Metal Transition (IMT)
- Transition can be excited in 2 ways
  - Lattice Distortion
  - Electronic Correlations

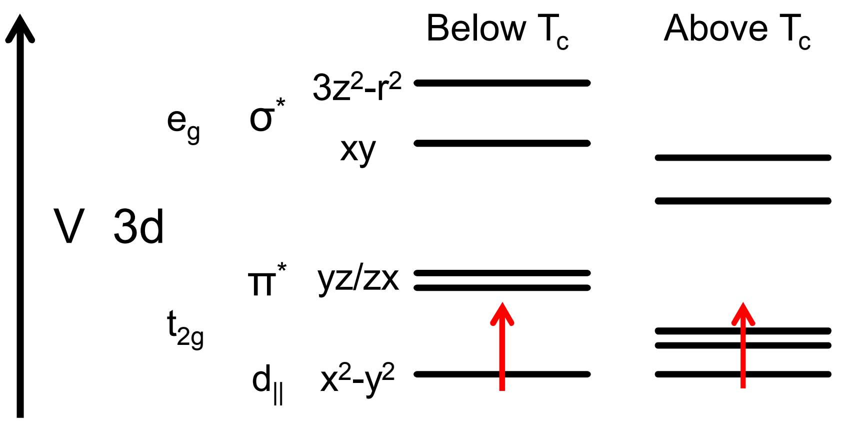


Mott Insulators

- Conventional band theory assumes independent non-interacting electrons.
- Mott insulators account for electronic correlations.

$$H = -\sum_{\langle ij\rangle,\sigma} t_{ij}\left(c^{\dagger}_{i\sigma}c_{j\sigma} + c_{i\sigma}c^{\dagger}_{j\sigma}\right) + \sum_{j\sigma} E_j c^{\dagger}_{j\sigma}c_{j\sigma} + U\sum_i n_{i\uparrow}n_{i\downarrow}$$

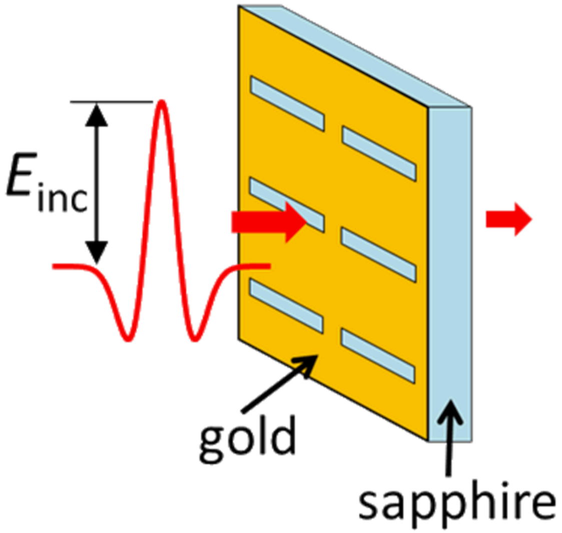
Orbitals for the Equilibrium IMT



Vanadium Dioxide

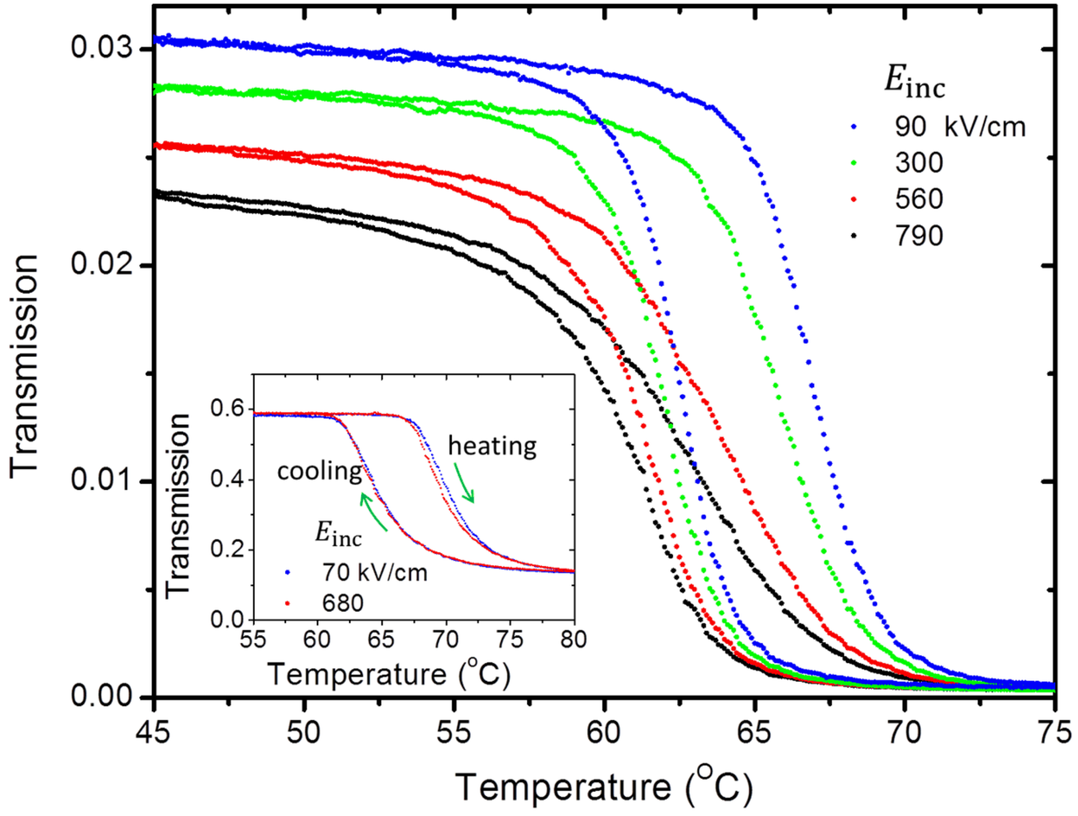
Sample Structure and THz Field Dependence

Nanoslot Sample



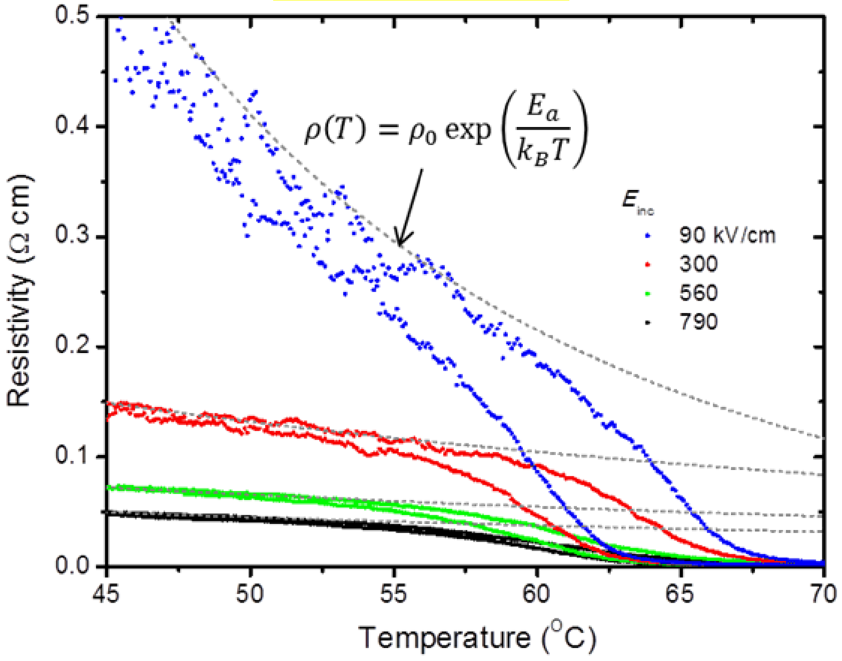
$$\alpha = \frac{E_{near}}{E_{inc}} = \frac{1}{\beta}\sqrt{\frac{T}{\tau_r}}$$

Hysteresis



Vanadium Dioxide

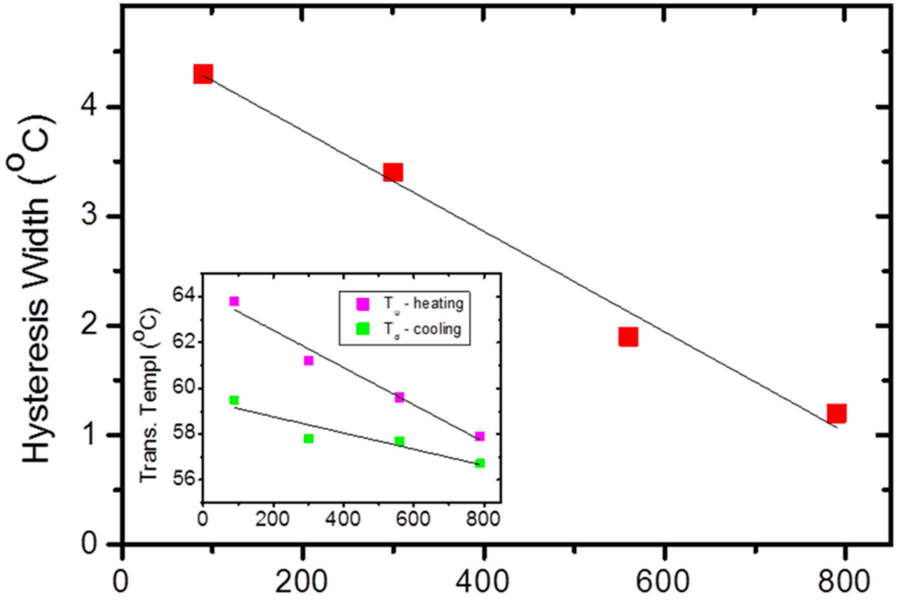
Resistivity



Activation Energy

E_{THz} (kV/cm)	E_A (eV)
90	0.60
300	0.22
560	0.17
790	0.16

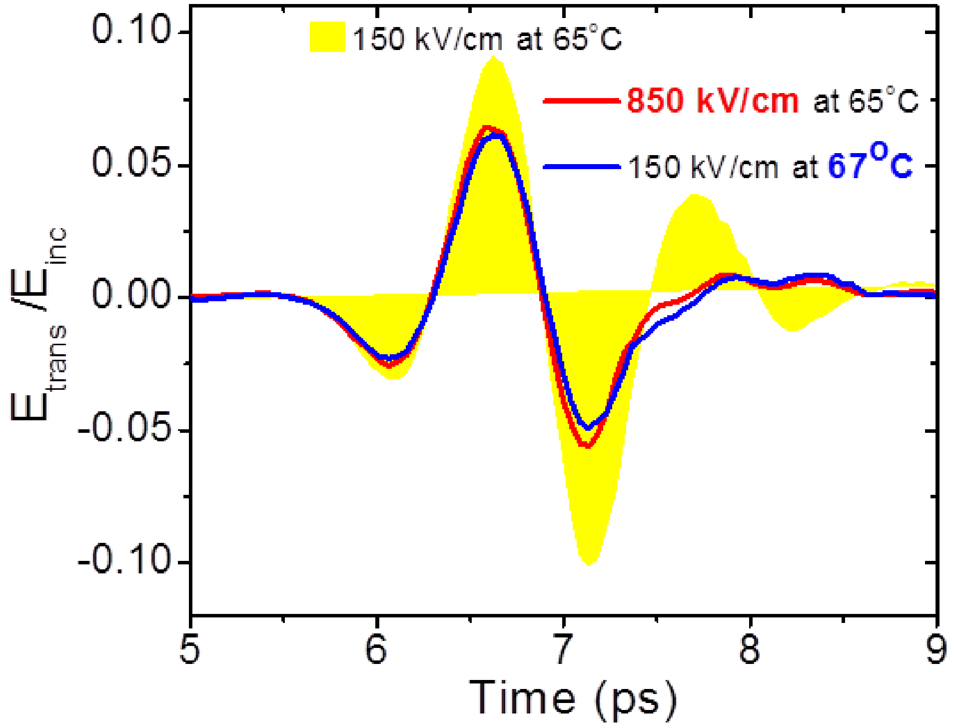
Hysteresis Width



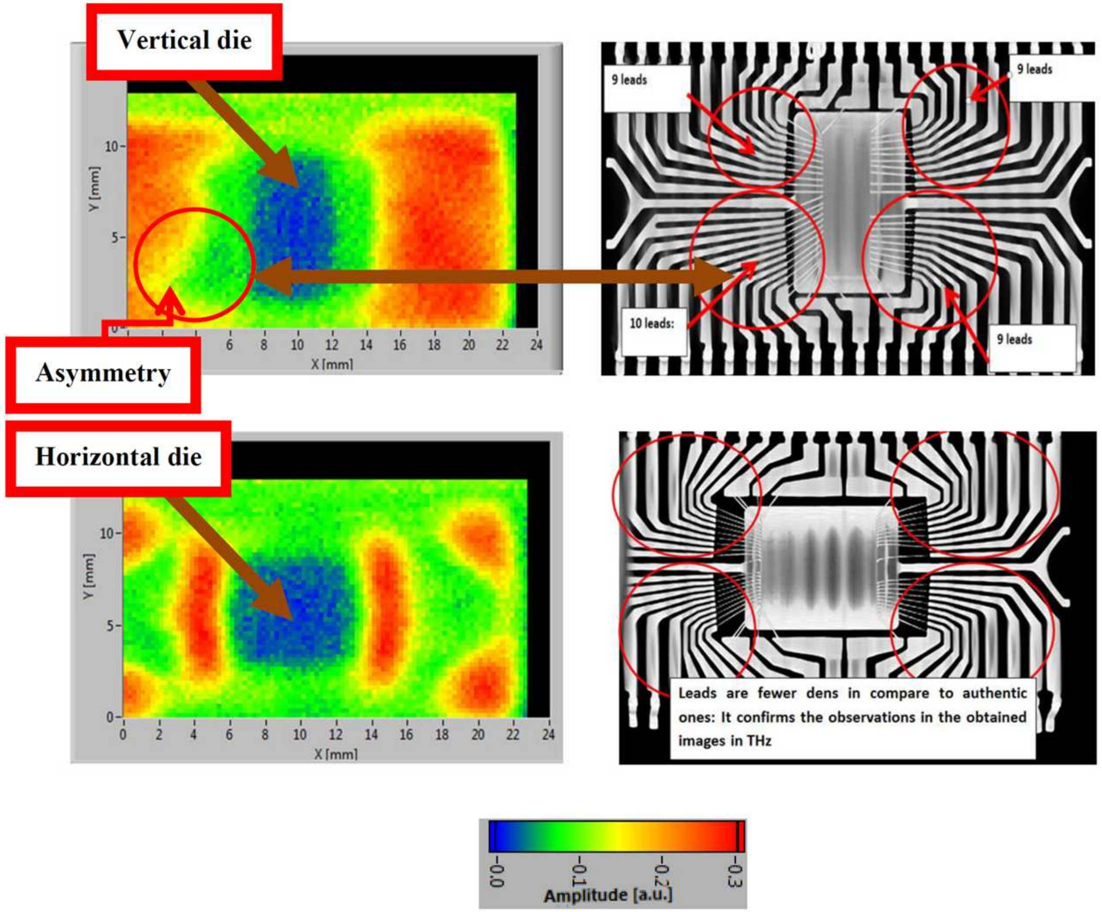
$$\Delta T = T_h - T_c = \frac{\eta G \gamma^2}{2\Delta S}$$

Vanadium Dioxide

Transient Phase Transition



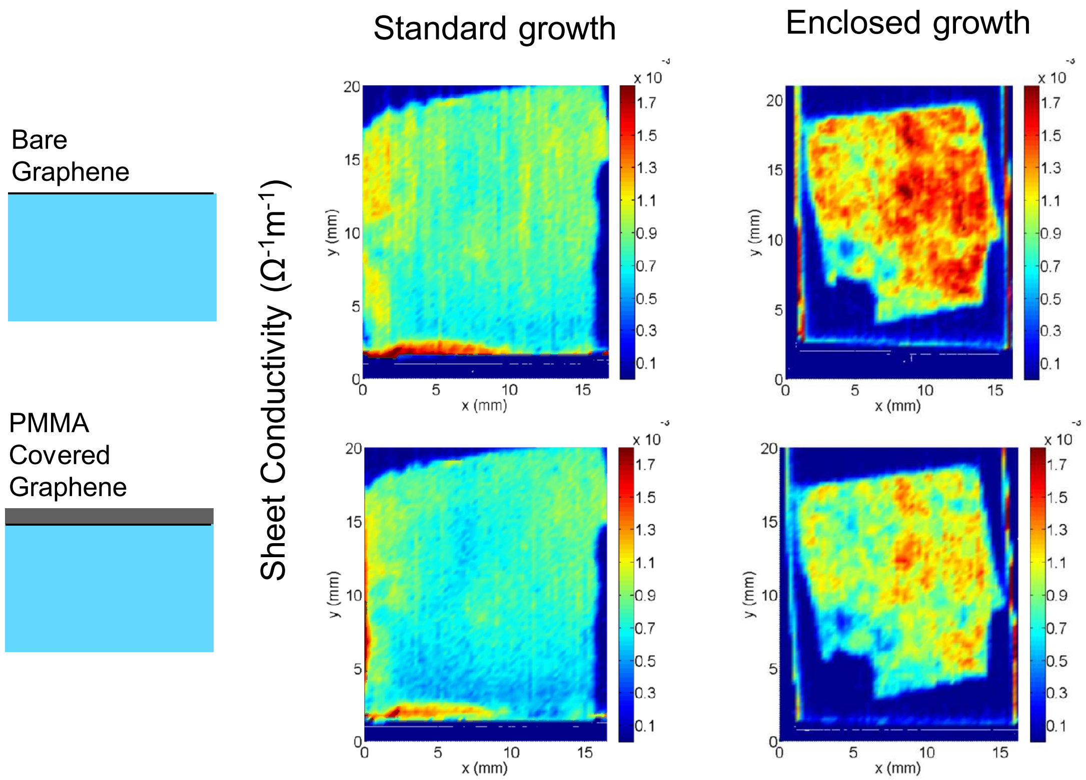
Integrated Circuit Evaluation

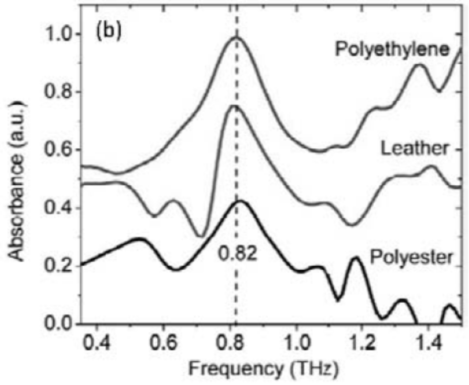


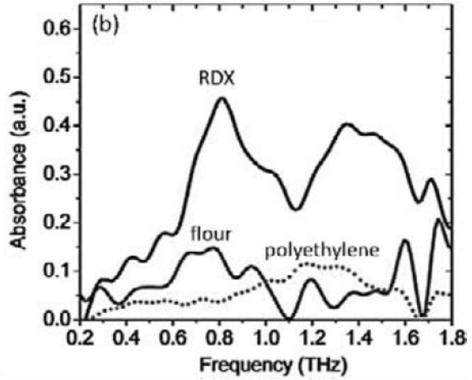
Ahi, Kiarash, et al. "Terahertz characterization of electronic components and comparison of terahertz imaging with x-ray imaging techniques." *Terahertz Physics, Devices, and Systems IX: Advanced Applications in Industry and Defense*. Vol. 9483. International Society for Optics and Photonics, 2015.

Future THz Applications

- Material Identification and Characterization
  - Unique Rotational and Vibrational Spectra
  - Non-contact conductivity measurements
  - Possible for direct phonon excitation



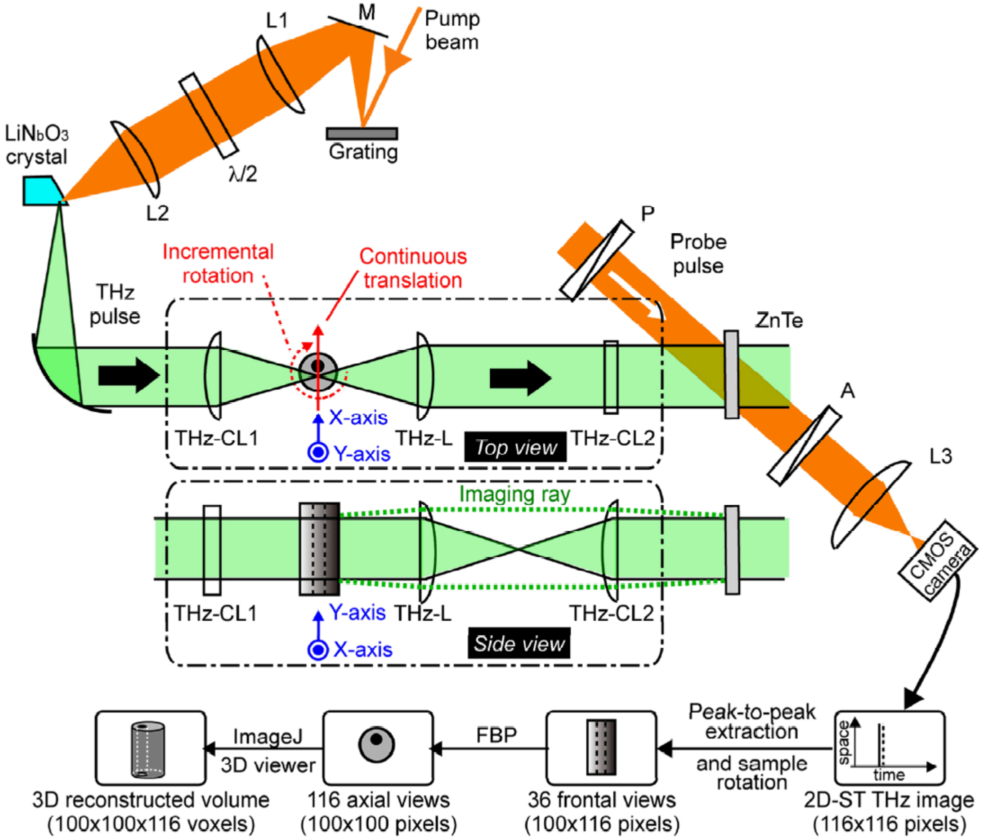




Lee *Principles of Terahertz Science and Technology*

Future THz Applications

- Non-ionizing imaging
  - Computed tomography

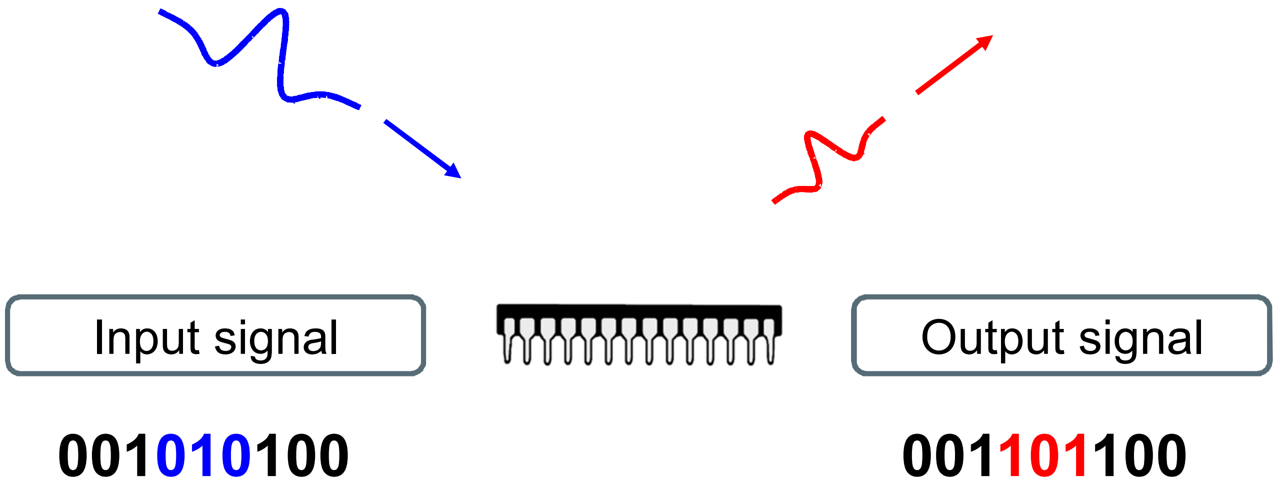


Mukesh Jewariya, et al, "Fast three-dimensional terahertz computed tomography using real-time line projection of intense terahertz pulse," Opt. Express 21, 2423-2433 (2013)

Future THz Applications

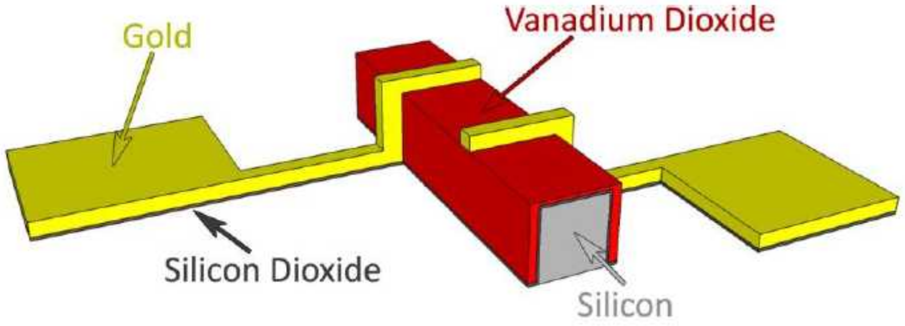
- High-Speed, Secure Wireless Communication
  - Bandwidth scales with frequency
  - Low photon energy makes it difficult to detect
  - Highly directional

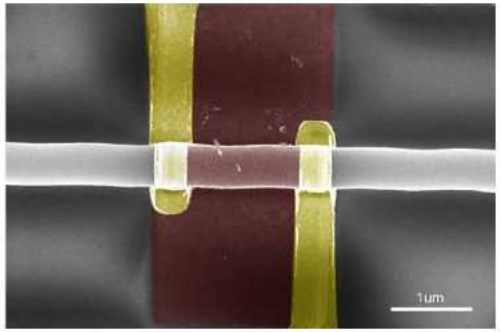
- Cybersecurity
  - Side Channel Analysis
  - Functional Imaging
  - Code Injection



Future THz Applications

- Highspeed optical switching using metamaterials





P. Markov, et al, "Silicon-VO2 hybrid electro-optic modulator," *CLEO: 2013*, San Jose, CA, 2013, pp. 1-2.

- Manipulation of entangled quantum systems
  - Nitrogen vacancy centers in diamond
  - Inorganic quantum well systems (GaAs/AlGaAs, etc.)

Questions?

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