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Power generation from direct conversion of infrared radiation from a thermal source.

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Applied Photonics

Sandia National Labs

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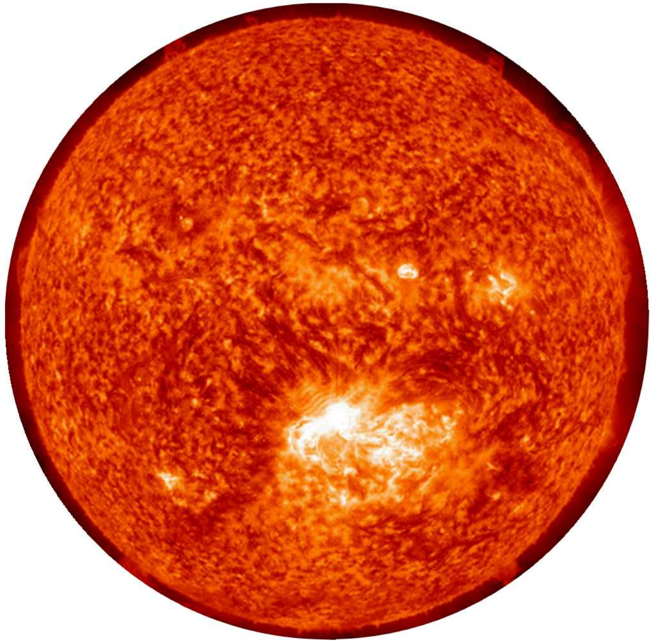
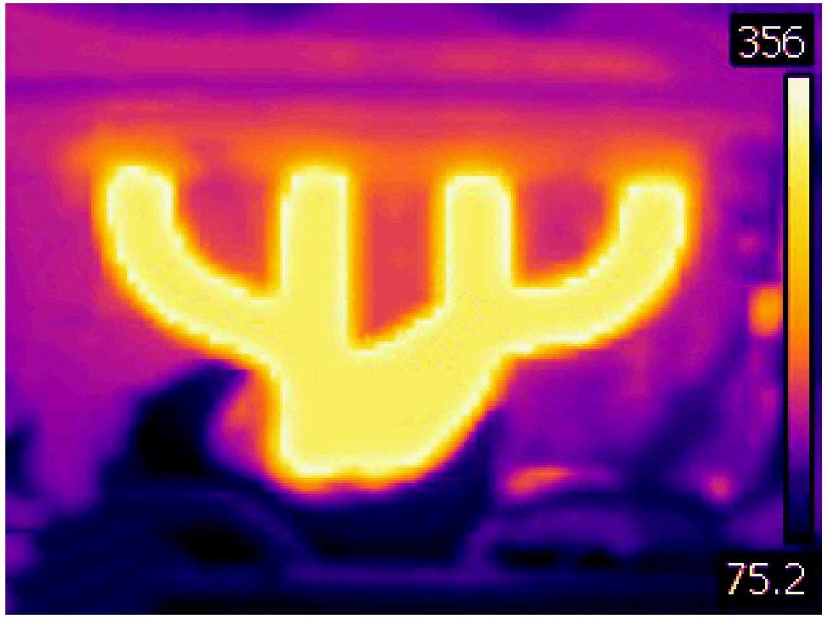
Outline

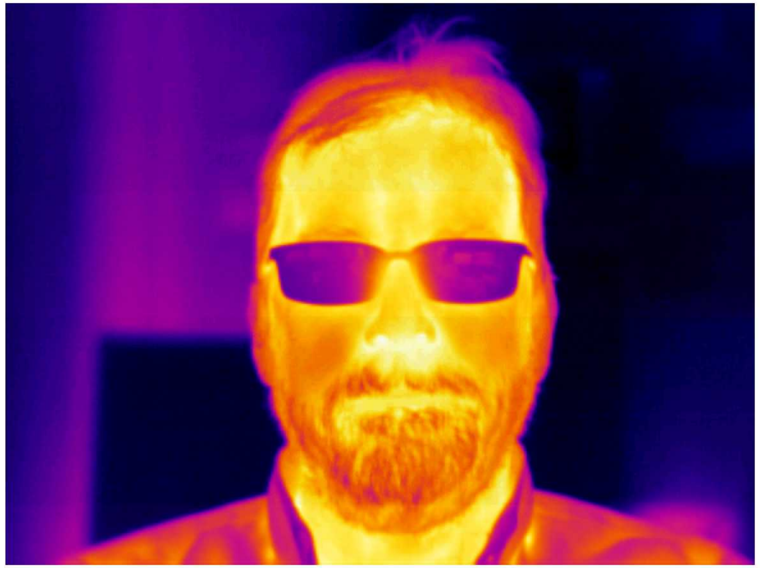
- Intro & Motivation
- Epsilon near-zero enhanced photonic coupling and tunneling
- Photon-assisted tunneling
- Electrical power generation from radiated waste heat
- Outlook and Conclusions

Introduction

- *All objects at finite temperature radiate due to fluctuations of their constituent atoms.*
- *Considerable power radiated from waste heat is available for recovery and conversion.*





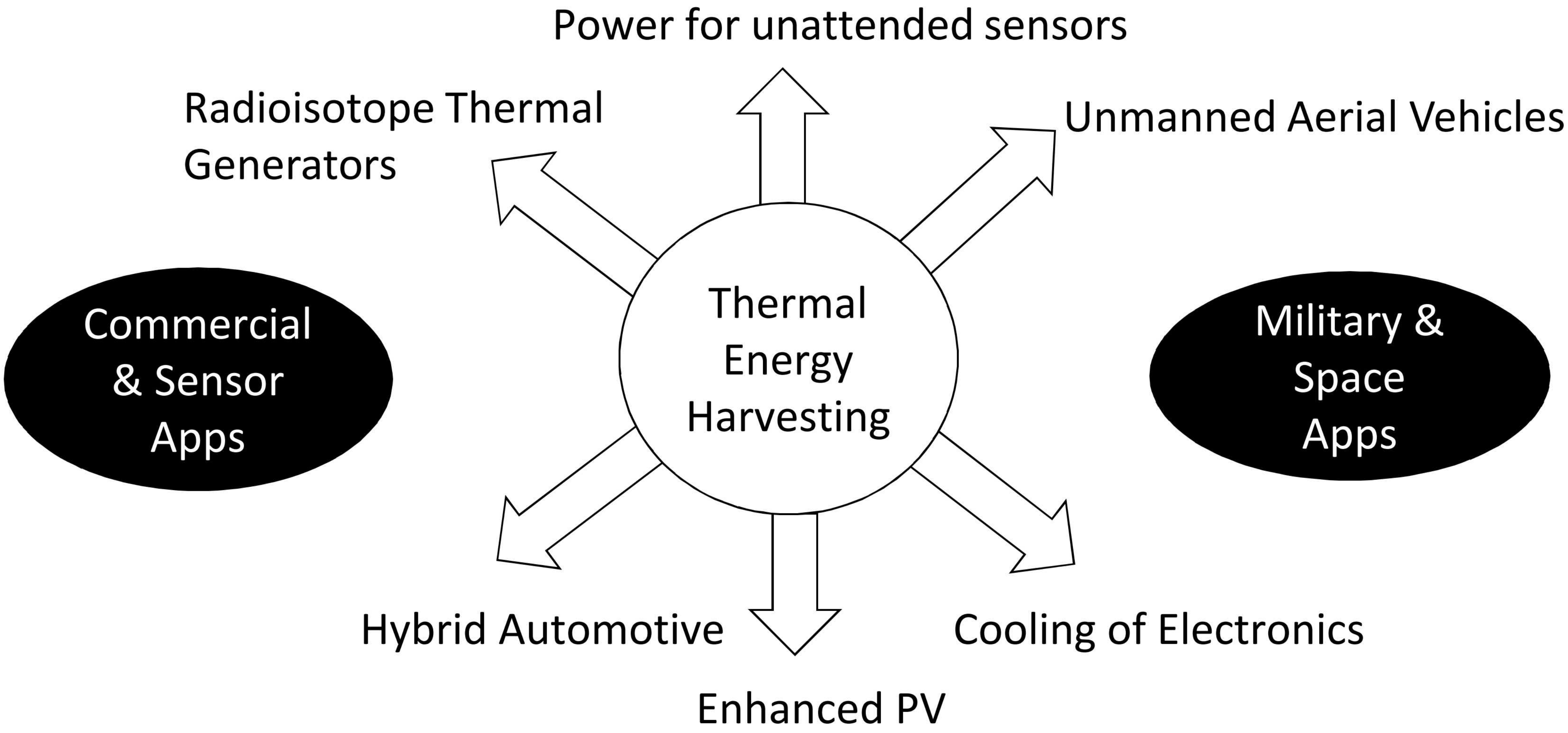


Motivation

New nanoscale thermal to electric energy conversion method based on direct conversion of radiated infrared light from a moderate temperature thermal source.

- Radiative energy harvesting from a thermal source:
  - View of thermal source.
  - Scalable to large area.
- Direct conversion: IR photon converted to electrical current
  - Infrared metamaterials for large area photonics coupled to ->
  - Epsilon near zero materials for enhanced field confinement
  - Ultrafast tunneling for rectification and charge separation.
- Integrated tunnel diode
  - Photon-assisted tunneling rectification in MOS tunnel diode.
  - Leverages CMOS processes to make and improve device.

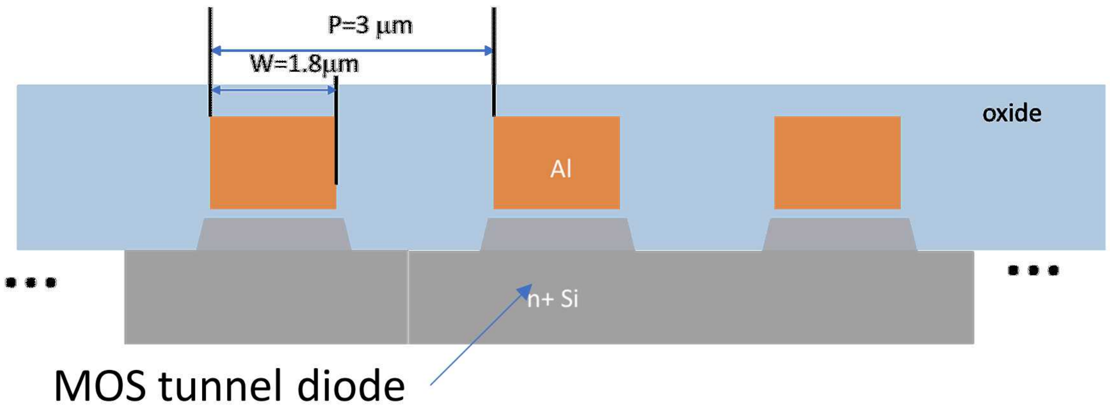
Applications



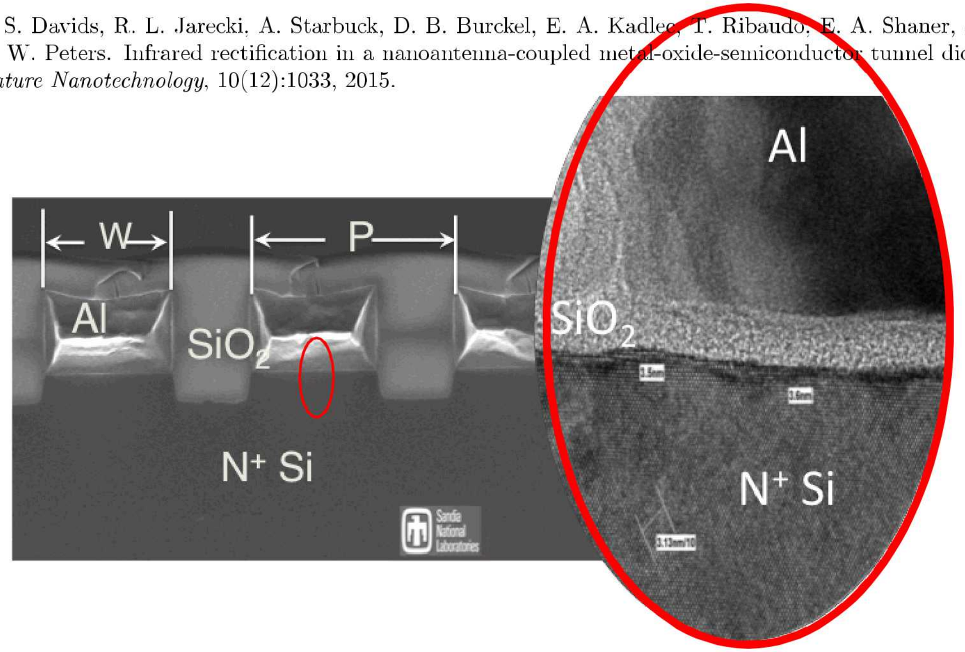
Epsilon near zero photonic device

- Idea: Couple material ENZ and photonic resonances to enhance transverse fiel confinement in nanoscale tunnel gap.
- CMOS compatible photonic coupled large area tunnel diode
  - Based on MOS capacitor with 3-4 nm tunnel oxide.
  - Simplest photonic antenna structure is metal grating.
- Photon-assisted tunneling current model.
  - Transverse confined Electric field in gap enhances asymmetric tunneling current.

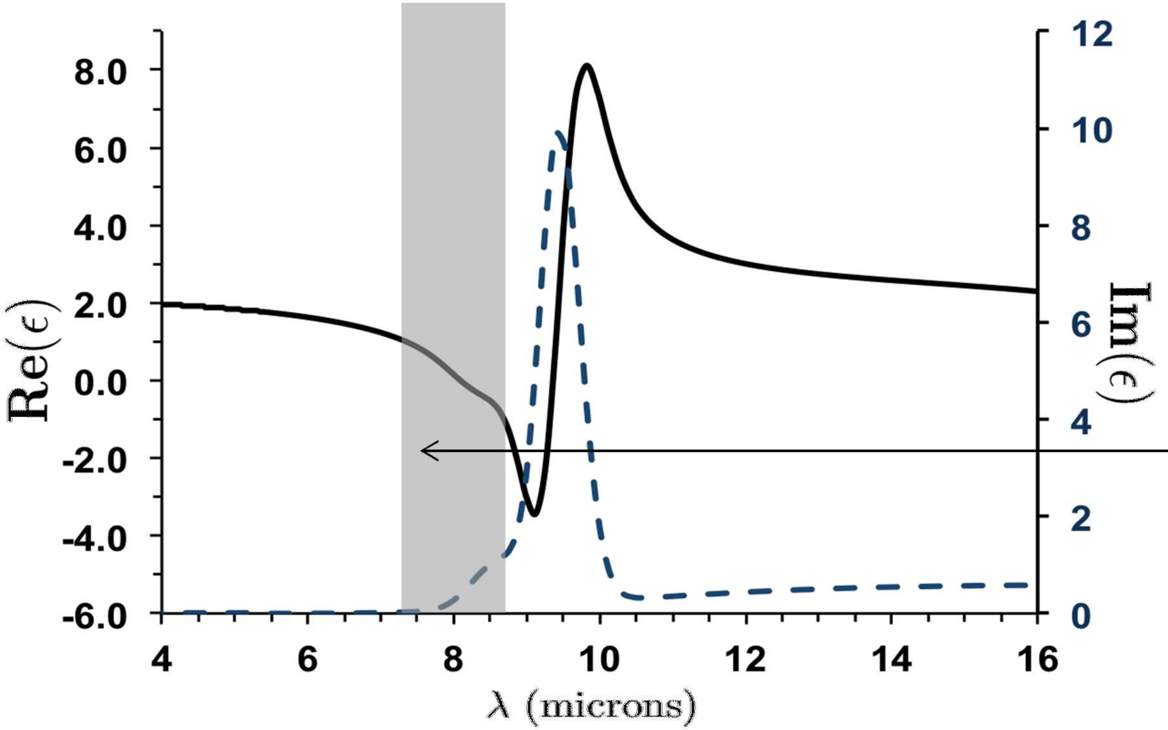
Simple large area grating



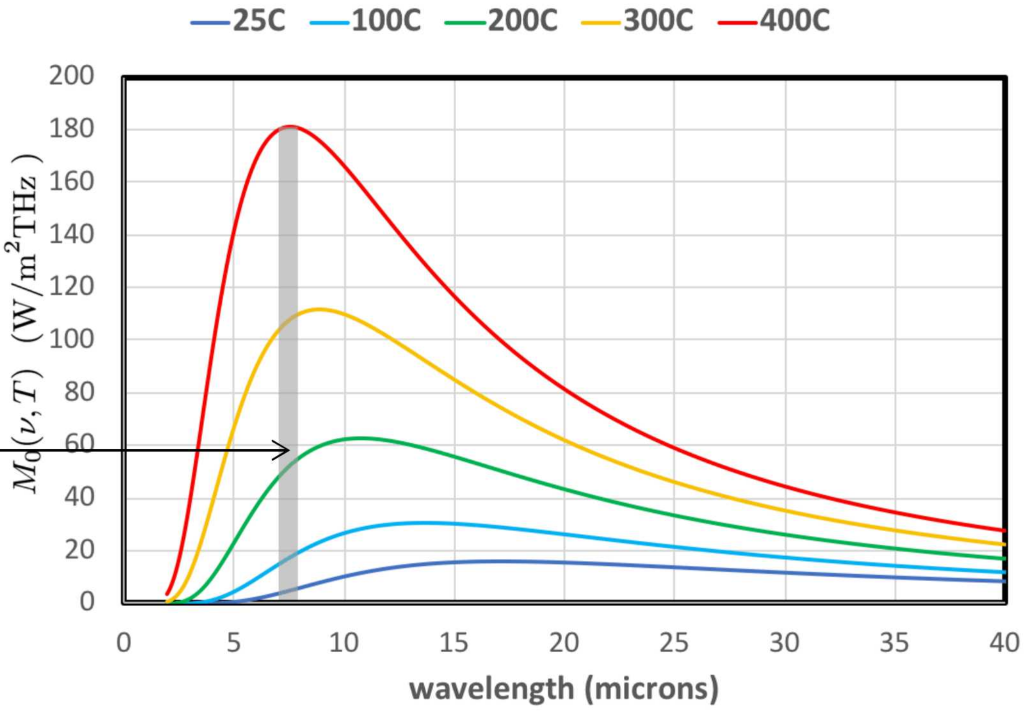
[1] P. S. Davids, R. L. Jarecki, A. Starbuck, D. B. Burckel, E. A. Kadlec, T. Ribaudo, E. A. Shaner, and D. W. Peters. Infrared rectification in a nanoantenna-coupled metal-oxide-semiconductor tunnel diode. *Nature Nanotechnology*, 10(12):1033, 2015.



Infrared LO/TO phonon in SiO_2



Blackbody spectral exitance



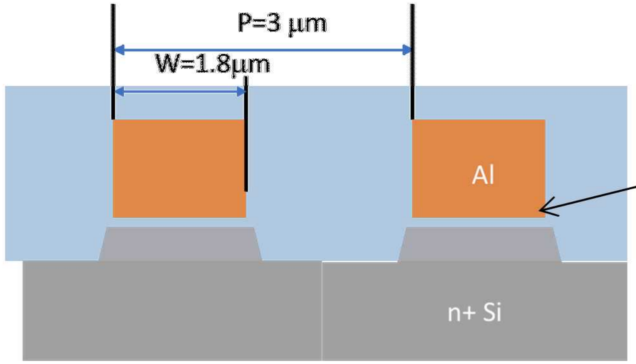
$$M_0(\nu, T) = \frac{2\pi h\nu^3}{c^2}\frac{1}{\exp(\beta h\nu) - 1}$$

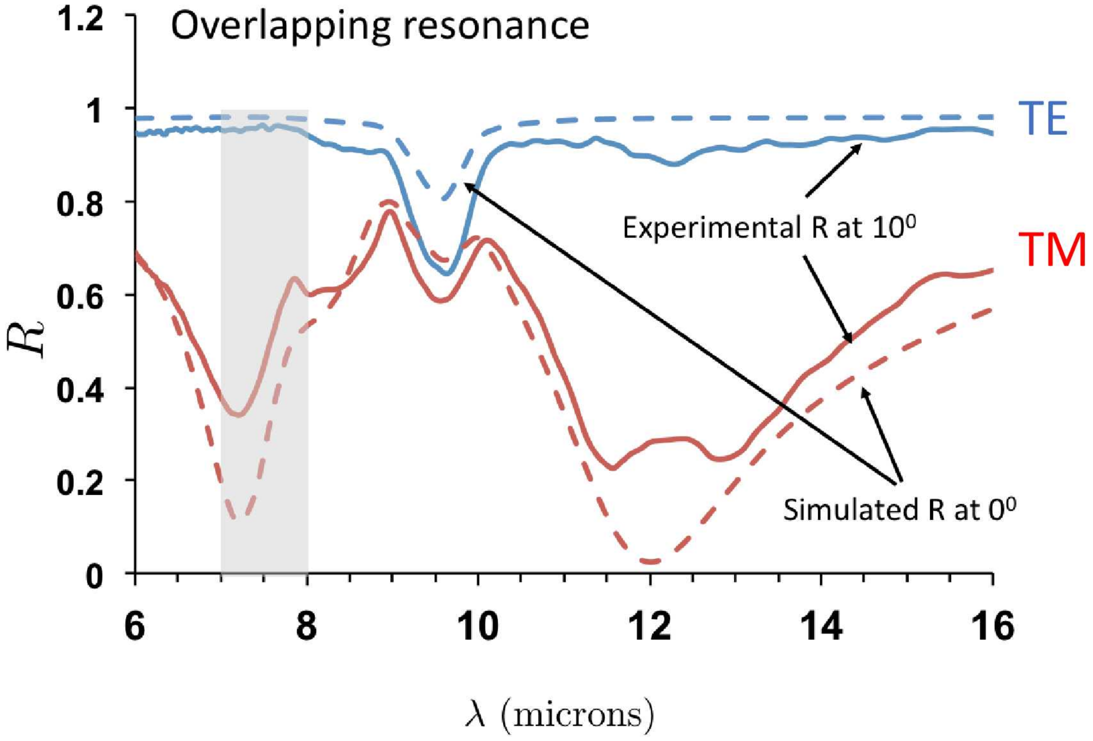
Power radiated from a blackbody per unit Area Per unit bandwidth

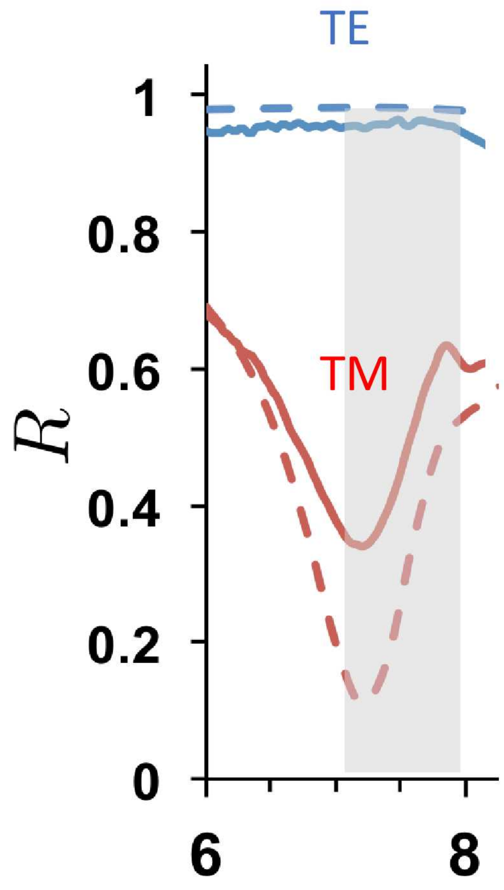
Bandwidth in thermal infrared

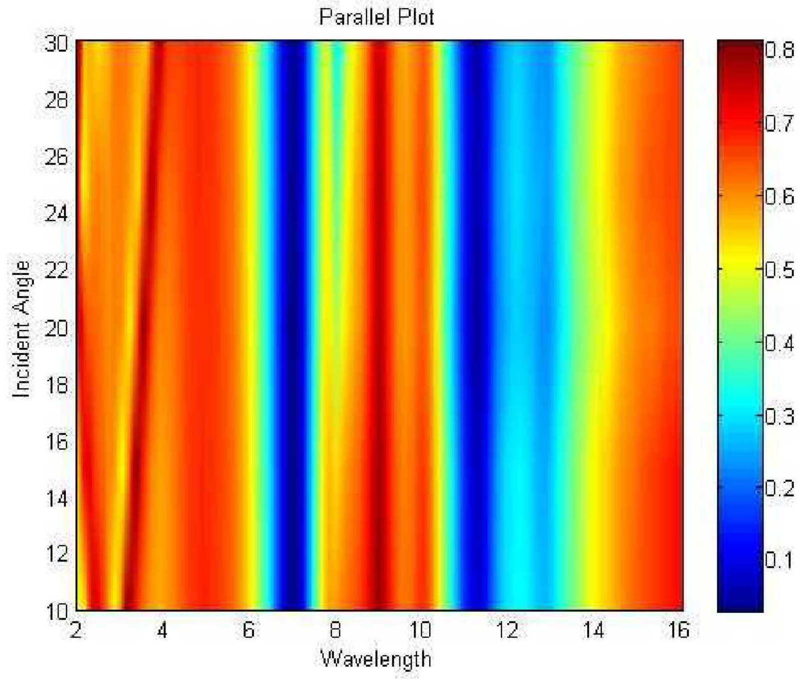
$\lambda = 7 - 8\ \mu m$

Resonant Grating Antenna





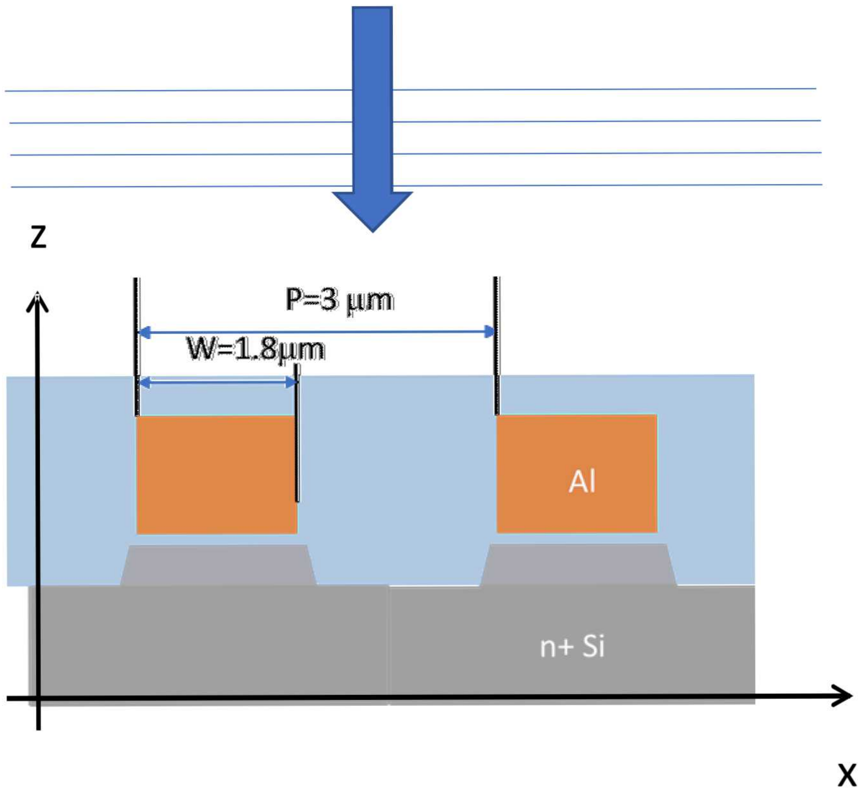




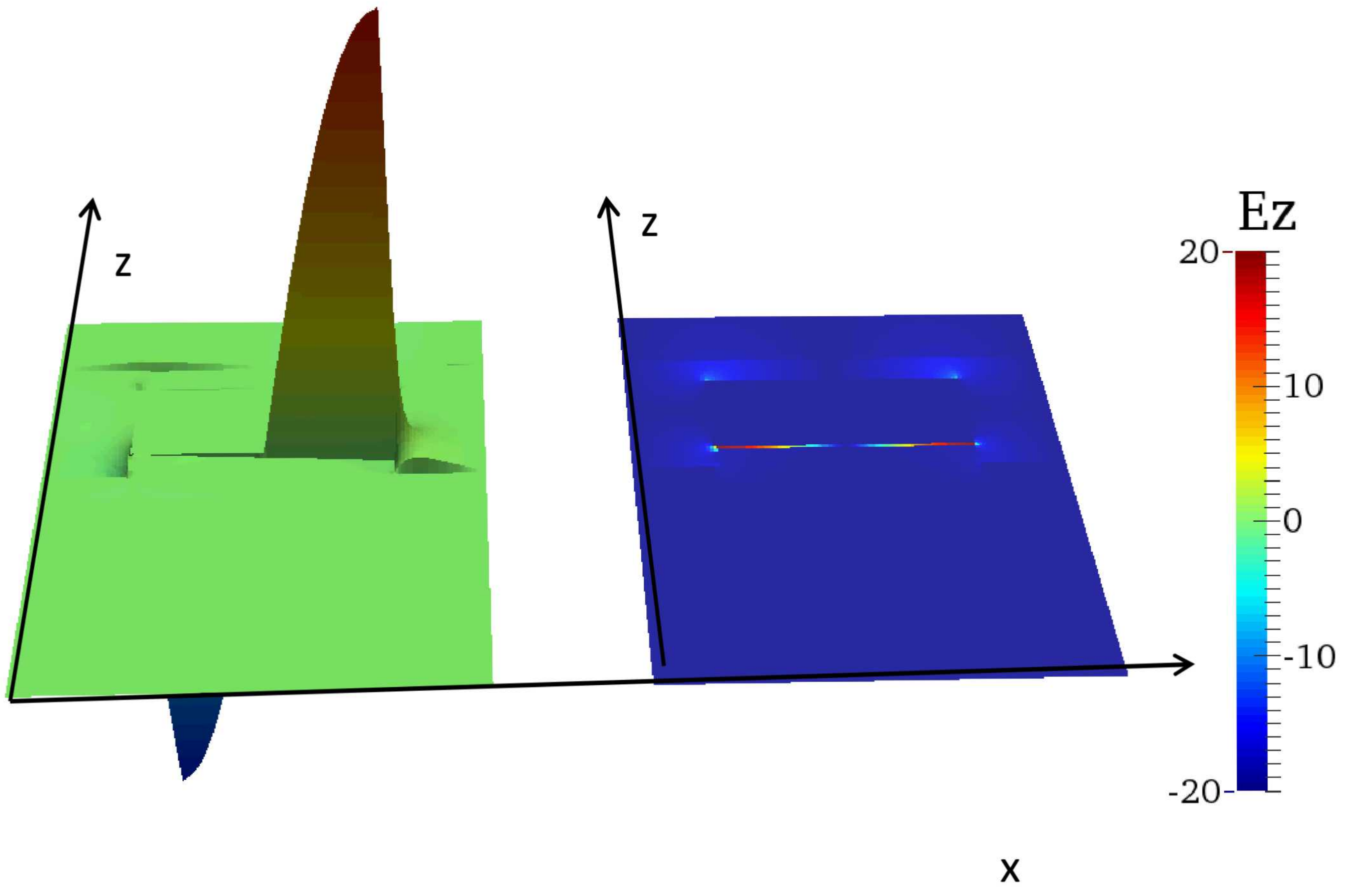
Measured TM Reflectance map

Field Confinement in gap

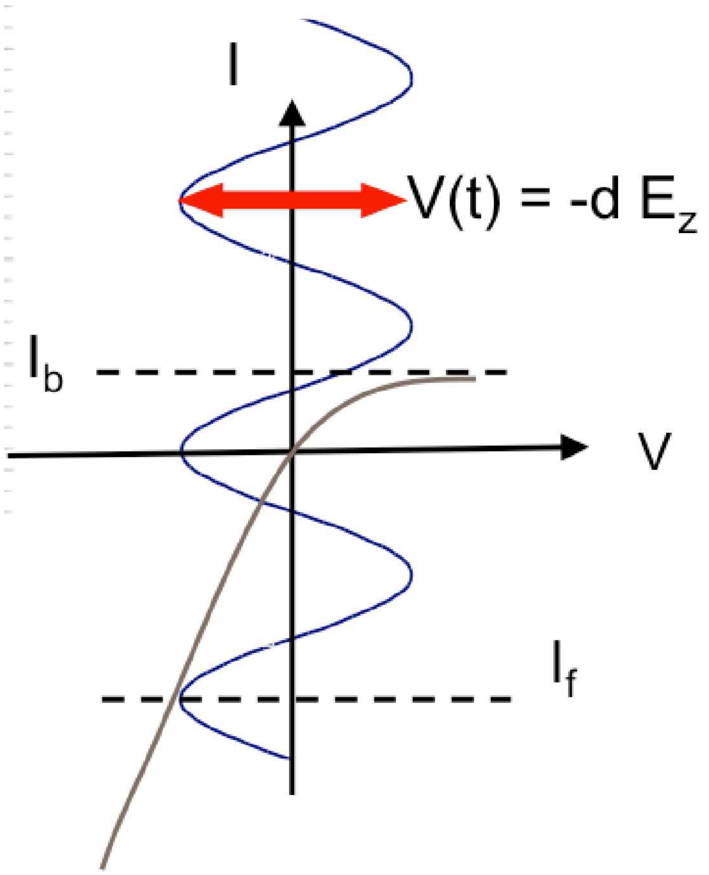
Planewave incident on structure
Polarized along x (grating) direction.

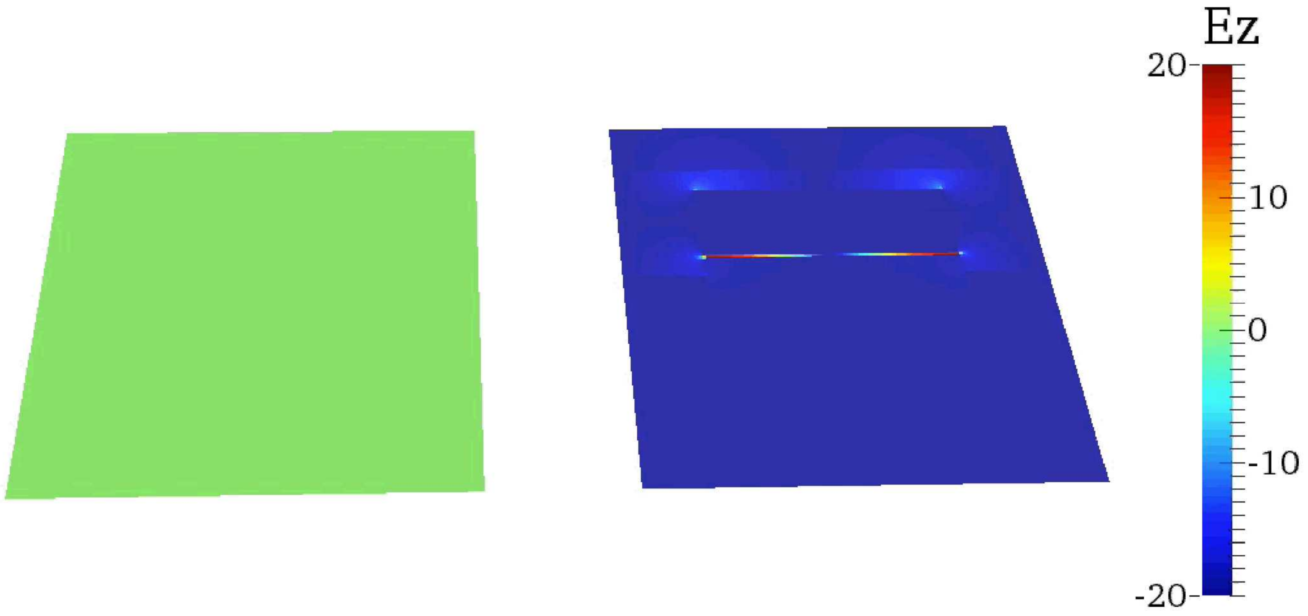


Enhance Ez field in 3 nm gap.

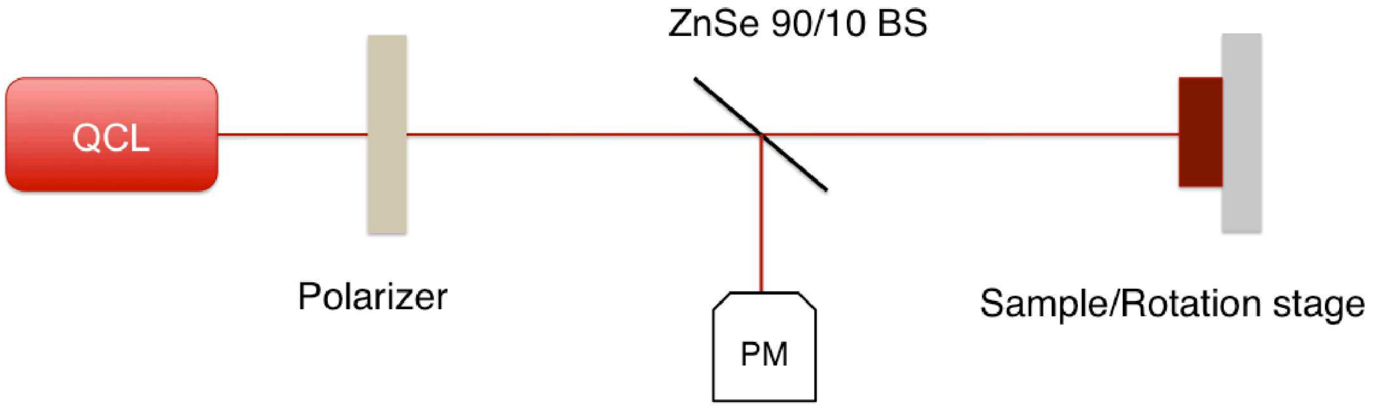


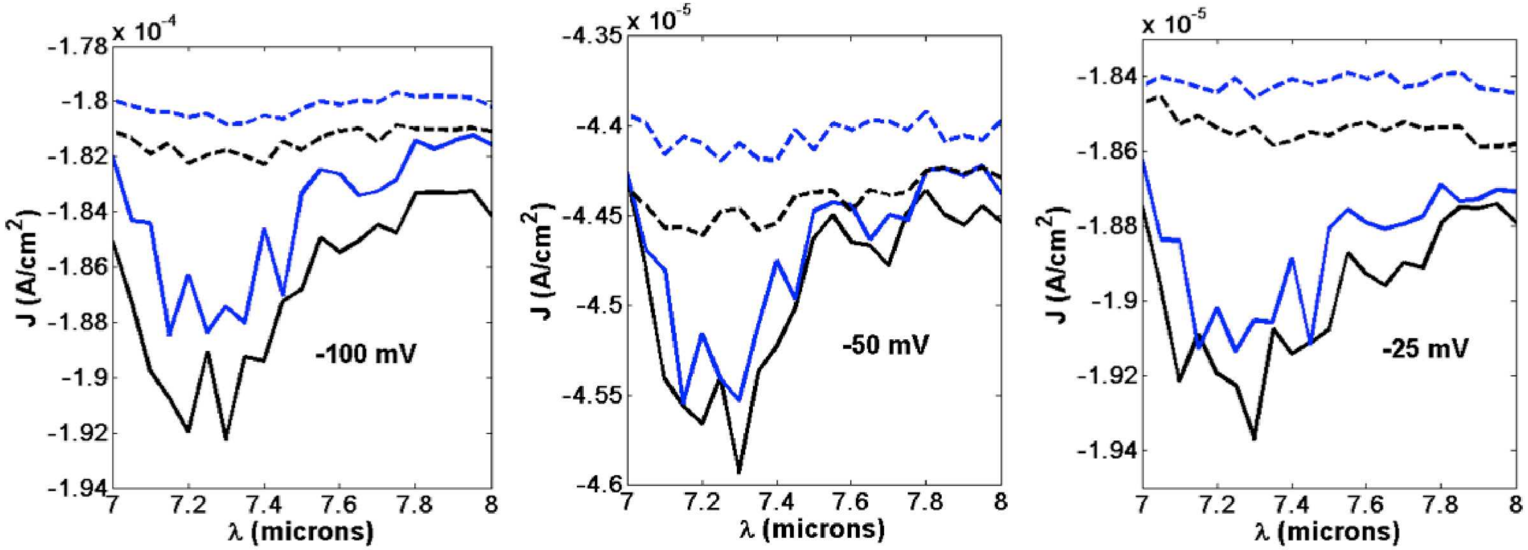
Field Confinement in gap





Measured Infrared Photoresponse

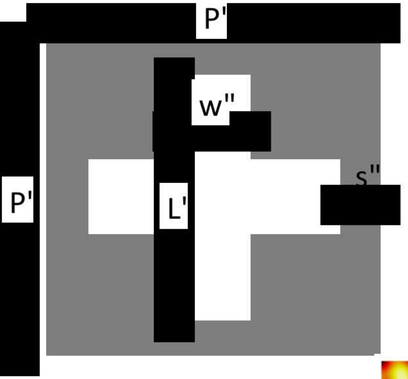


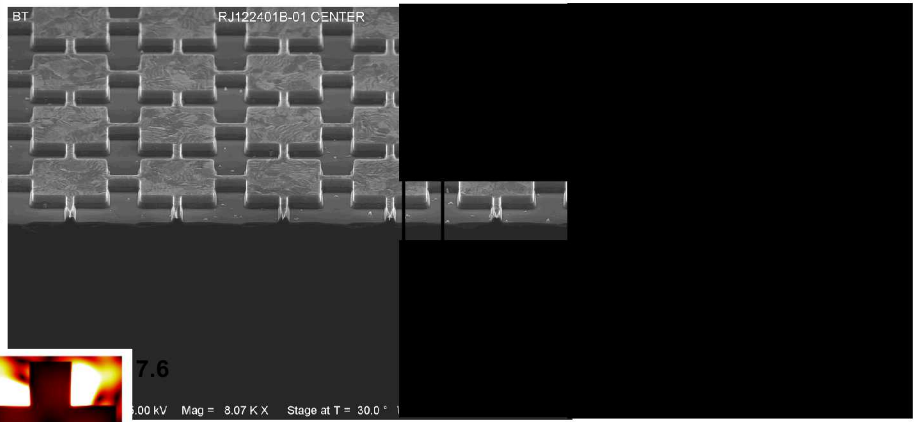


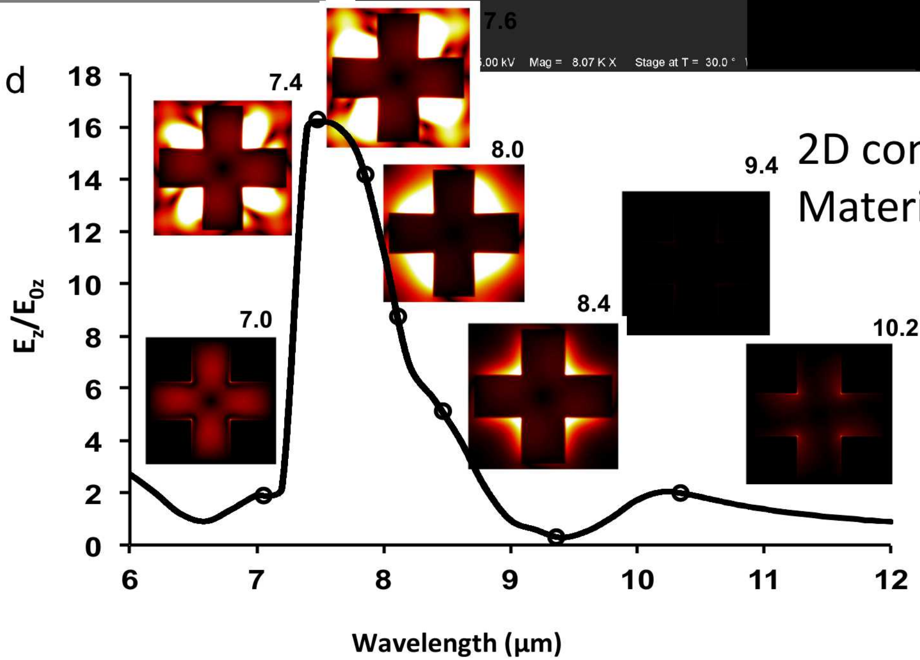
- Sample 3mm x 3mm large area 1D grating coupled tunnel diode.
- Tunable QCL tuned across IR resonance.
- Observed photo-current for TM polarization

[1] P. S. Davids, R. L. Jarecki, A. Starbuck, D. B. Burckel, E. A. Kadlec, T. Ribaudo, E. A. Shaner, and D. W. Peters. Infrared rectification in a nanoantenna-coupled metal-oxide-semiconductor tunnel diode. *Nature Nanotechnology*, 10(12):1033, 2015.

2D IR Antenna coupled tunnel diode

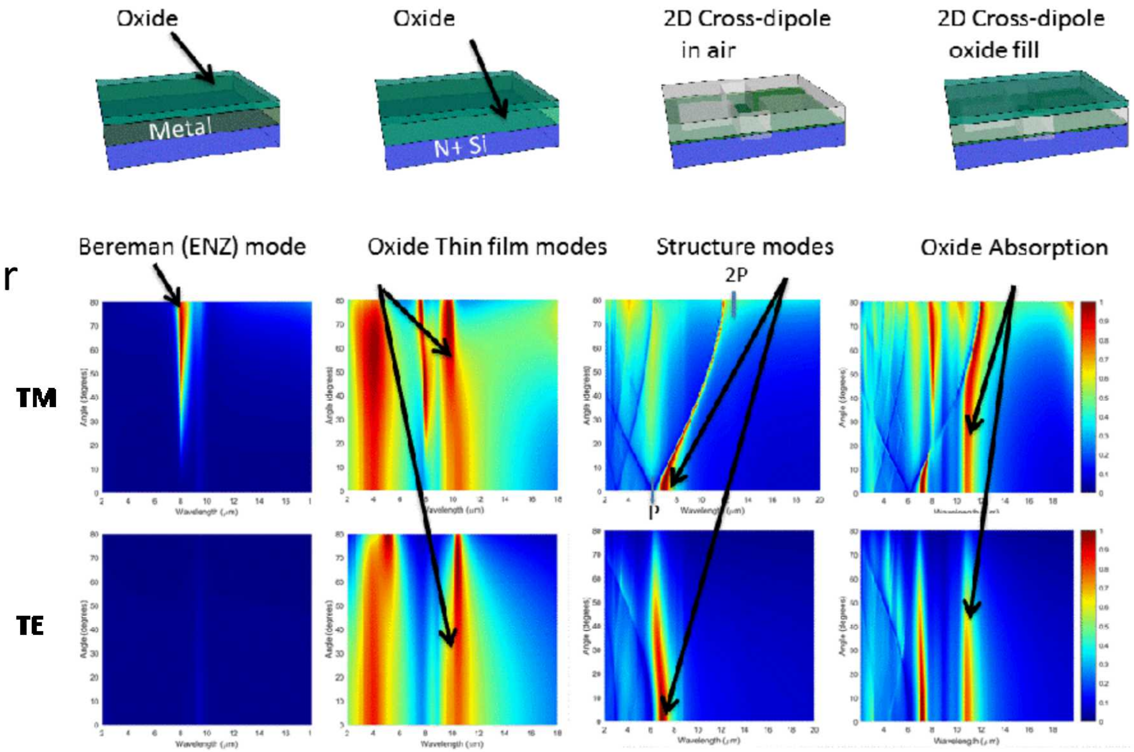






2D confined Ez field near Material ENZ

Complex 2D modal structure with TE and TM resonances.

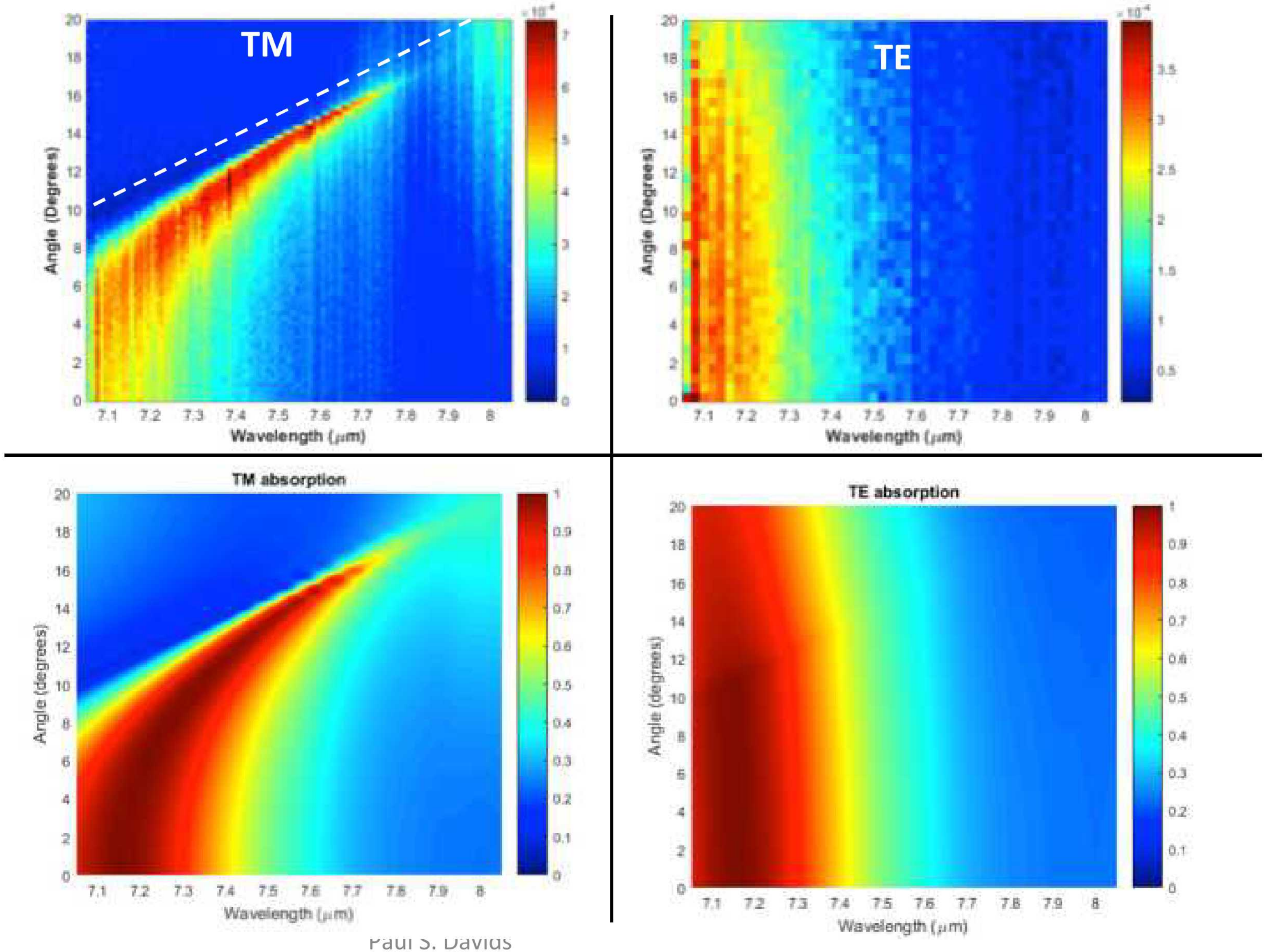


[1] E. A. Kadlec, R. L. Jarecki, A. Starbuck, D. W. Peters, and P. S. Davids. Photon-phonon-enhanced infrared rectification in a two-dimensional nanoantenna-coupled tunnel diode. *Phys. Rev. Applied*, 6:064019, Dec 2016.

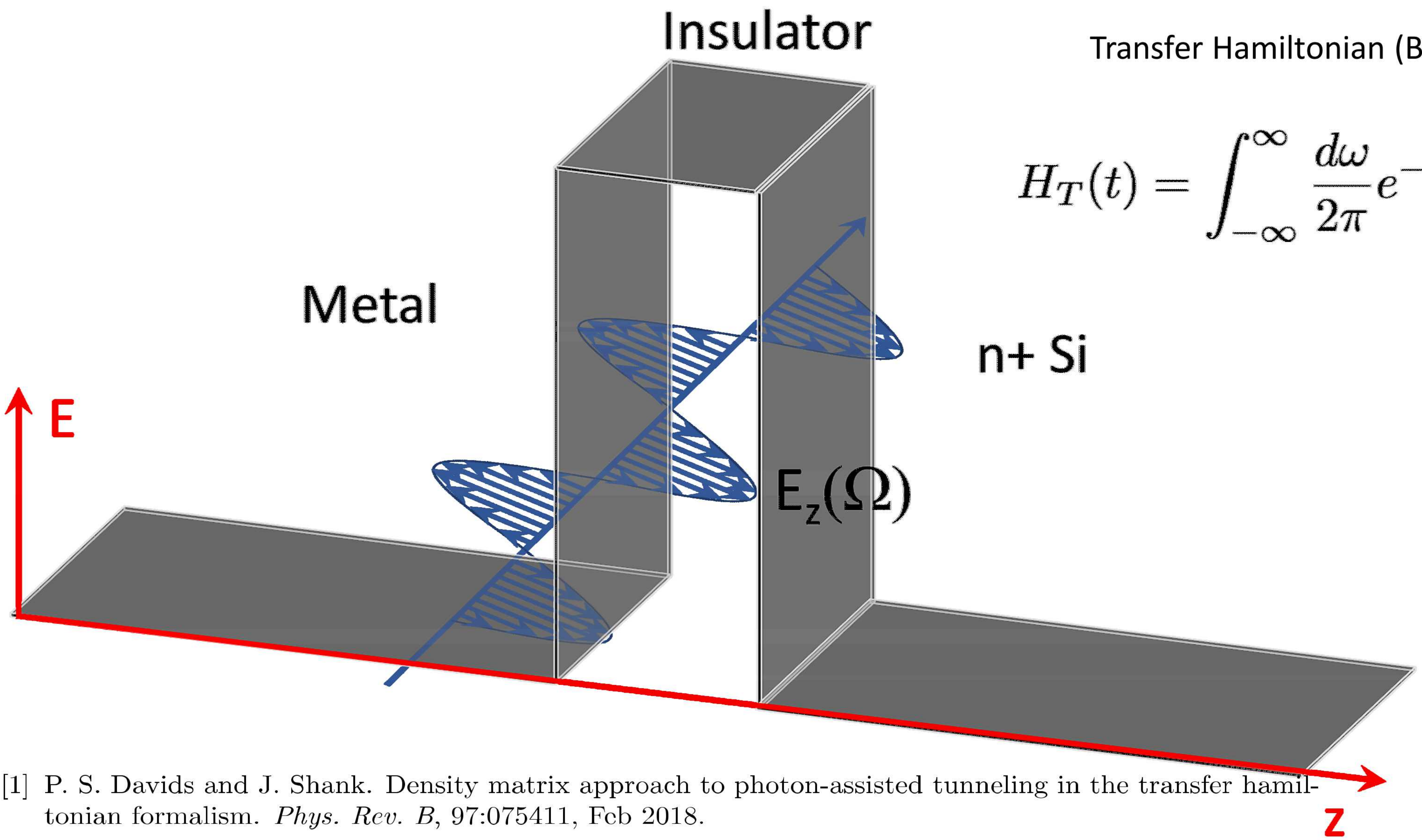
Photocurrent spectrum at V=0

Measured Angular Photocurrent Spectra at V=0

Simulated Absorption



Photon-assisted tunneling



Transfer Hamiltonian (Bardeen)

$$H_T(t) = \int_{-\infty}^{\infty} \frac{d\omega}{2\pi} e^{-i\omega t} \frac{e\hbar}{m\omega} \mathbf{E}(\omega) \cdot \nabla$$

[1] P. S. Davids and J. Shank. Density matrix approach to photon-assisted tunneling in the transfer hamiltonian formalism. *Phys. Rev. B*, 97:075411, Feb 2018.

Photon-assisted tunnel current

- First order expansion of single particle density matrix in Bardeen's transfer Hamiltonian approach.
- Analytic expression for DC current.
- Photon-assisted tunnel current for partially coherent thermal radiation.

$$J^{(1)} = \frac{4\pi e m_e}{h^3 \beta^2} \left(\frac{m_r m_l}{m_{ox}^2} \right) \int_0^\infty \frac{d\omega}{2\pi} \left(\frac{e t_{ox}}{\hbar \omega} \right)^2 |E(\omega)|^2 \mathcal{T}(\omega),$$

$$\mathcal{T}(\omega) = \beta \int dE_l \; t(E_l, E_l + \hbar\omega) \log \left[\frac{1 + \exp(-\beta E_l)}{1 + \exp(-\beta(E_l + \hbar\omega))} \right] + (\omega \to -\omega)$$

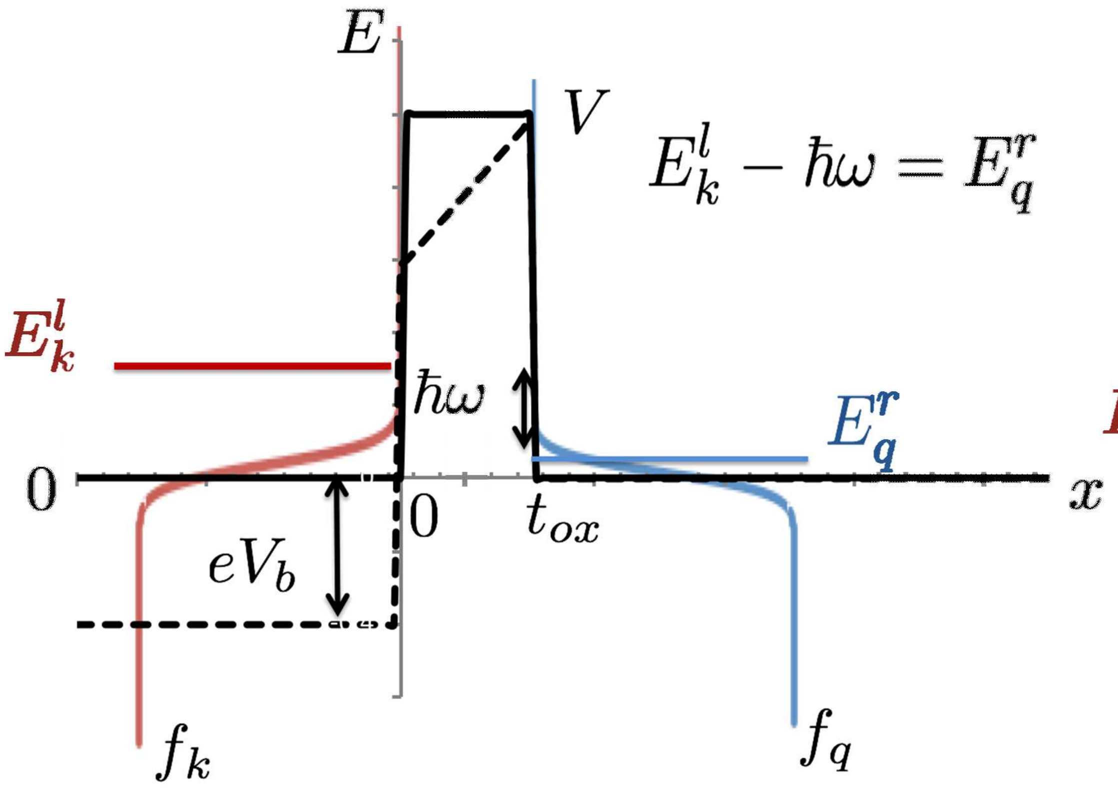
absorption

emission

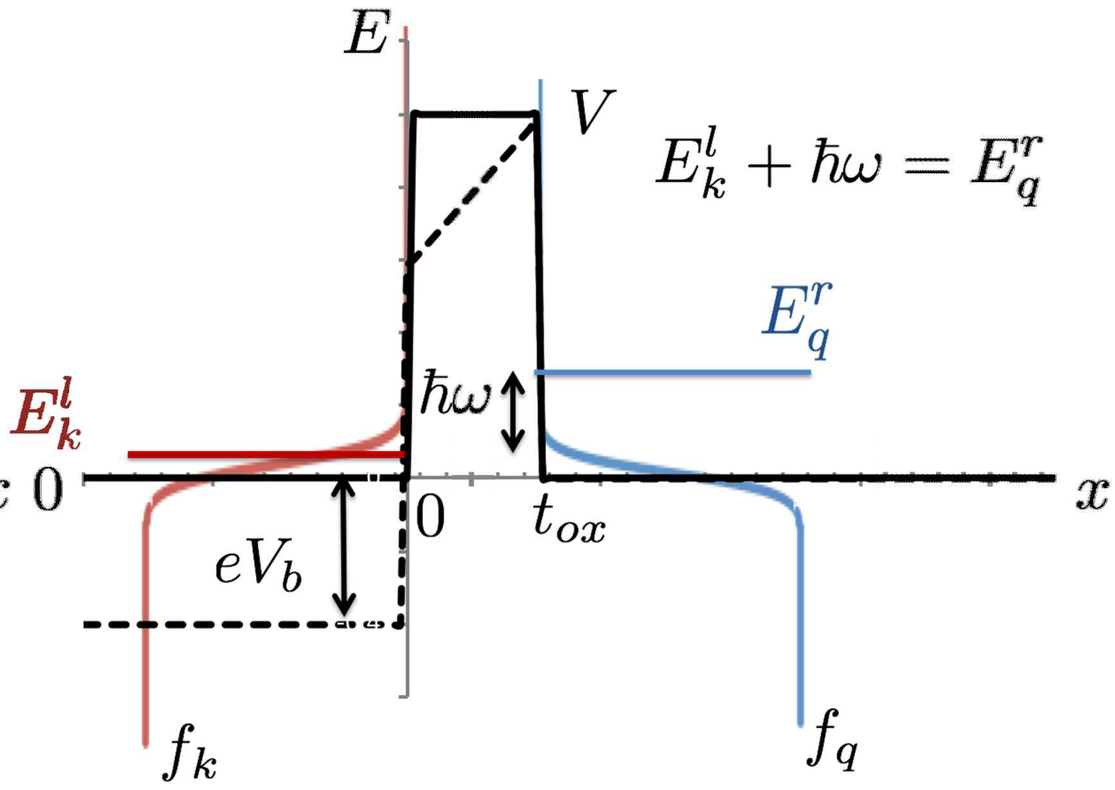
[1] J. Bardeen. Tunnelling from a many-particle point of view. *Phys. Rev. Lett.*, 6:57–59, Jan 1961.

Photon absorption & emission

Photon emission in barrier



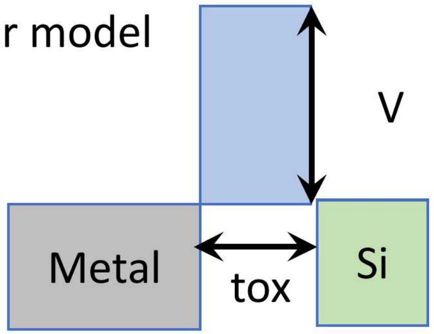
Photon absorption in barrier



$$J^{(i)} \propto f(E^l_k) - f(E^r_q)$$

Parametric Study of PAT Current

Uniform barrier model



Locus of current sign change

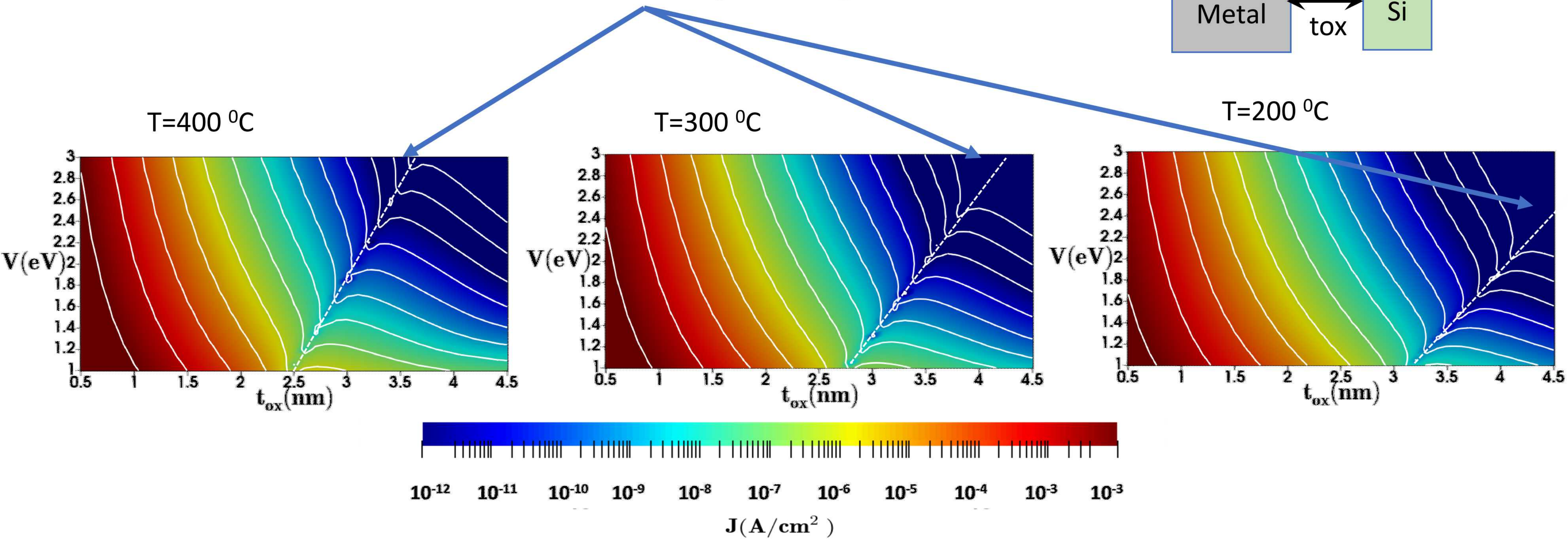
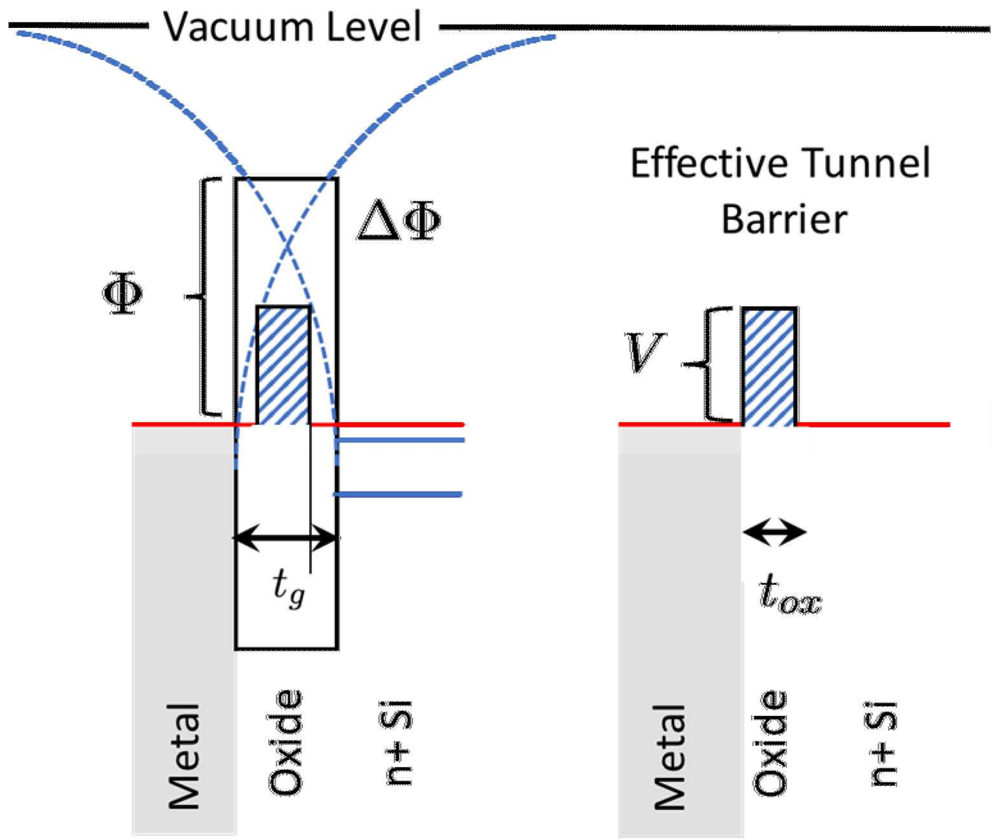
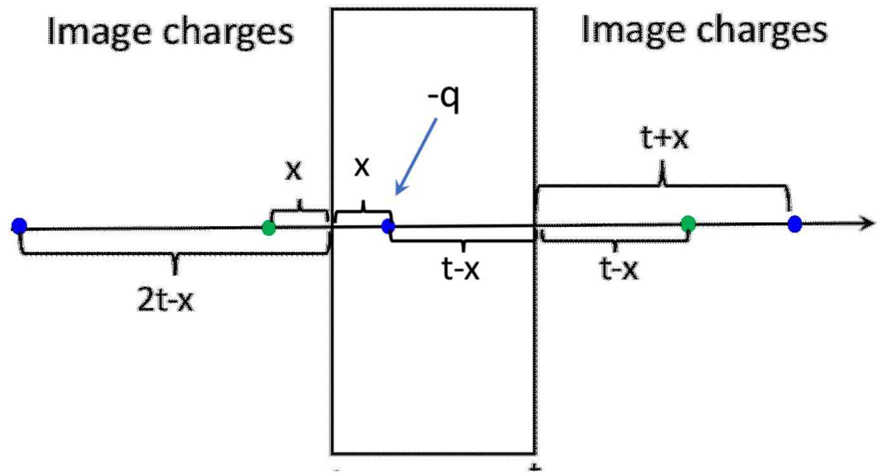
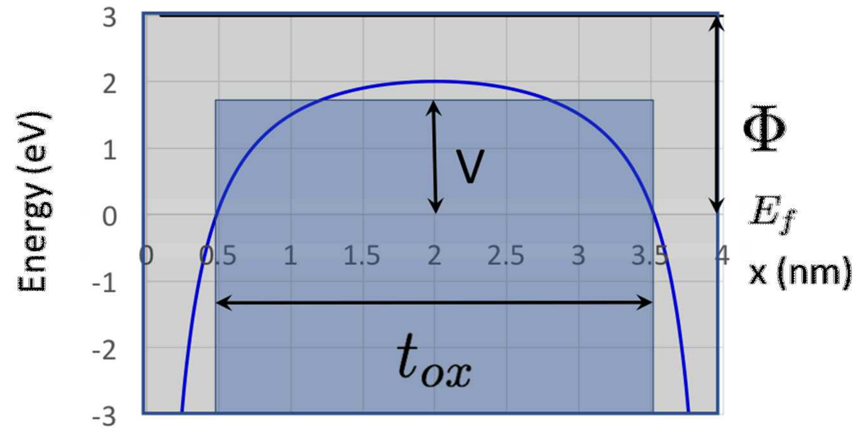


Image force barrier lowering

$$\Phi_e(x) = \Phi + W(x).$$



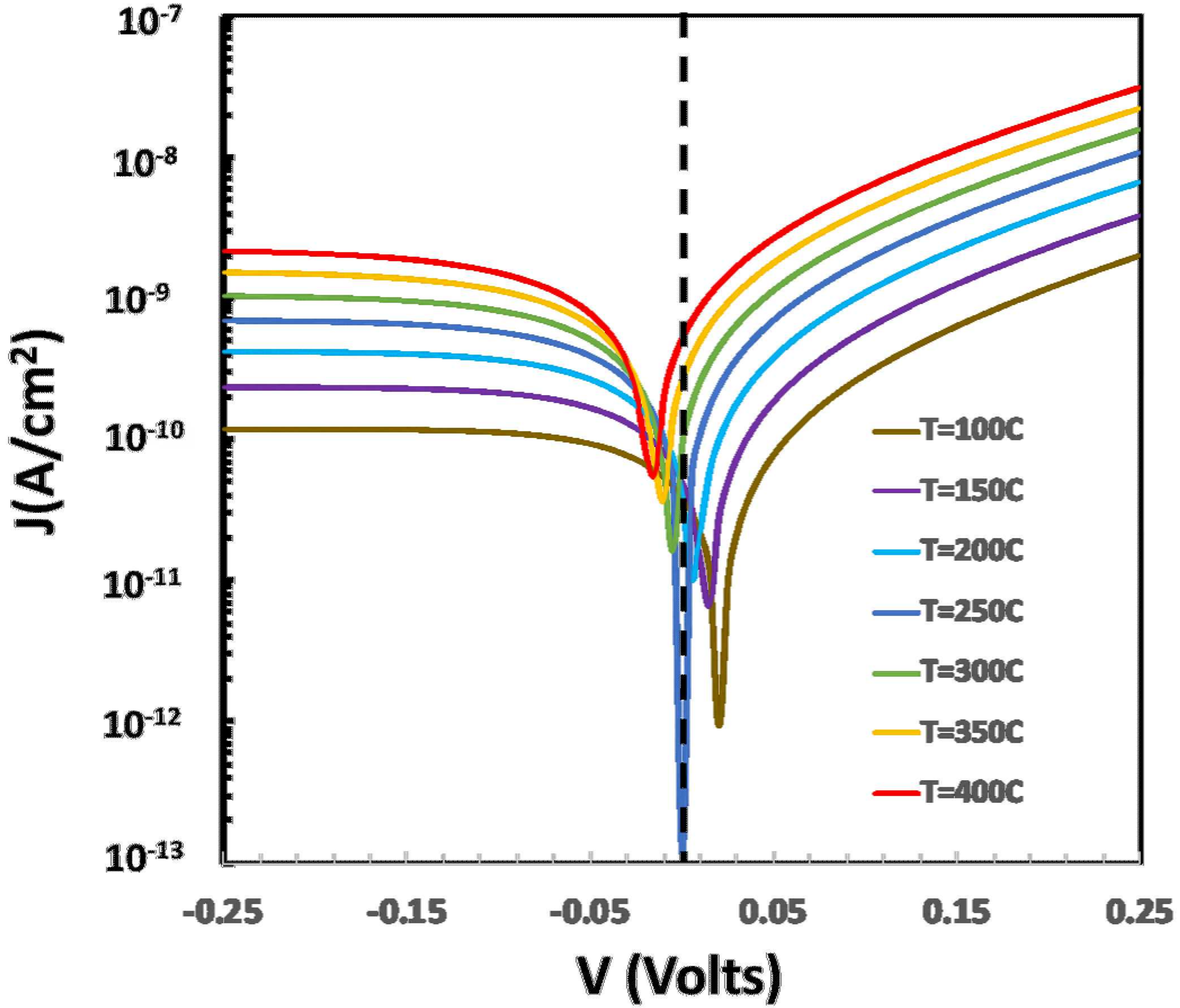


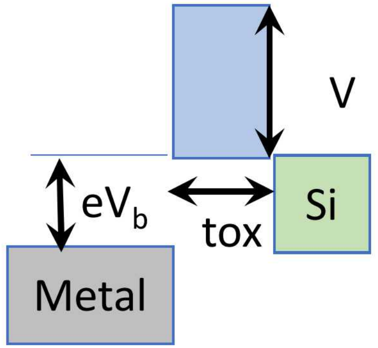


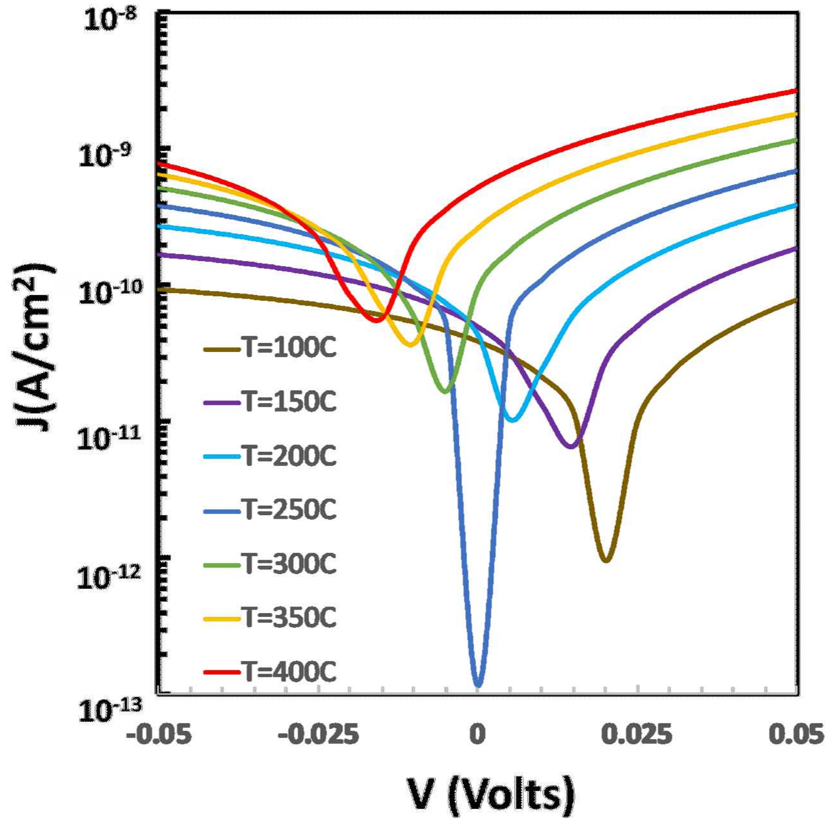
$$W = -\frac{q}{8\pi\epsilon_0\epsilon}\left\{\sum_{n=1}\left(\frac{nx}{(nt)^2 - x^2} - \frac{1}{nt}\right) + \frac{1}{2x}\right\},$$

$$V \cdot t_{ox} = \int_{x0}^{x1} dx\,\Phi_e(x),$$

Photon-assisted IV characteristics







MOS parameters: Barrier height 1.65, tox= 3.5 nm , wavelength = 7.5 um , bandwidth 1THz

Infrared Rectenna Power Supply (IRPS)

Half-wave rectifier

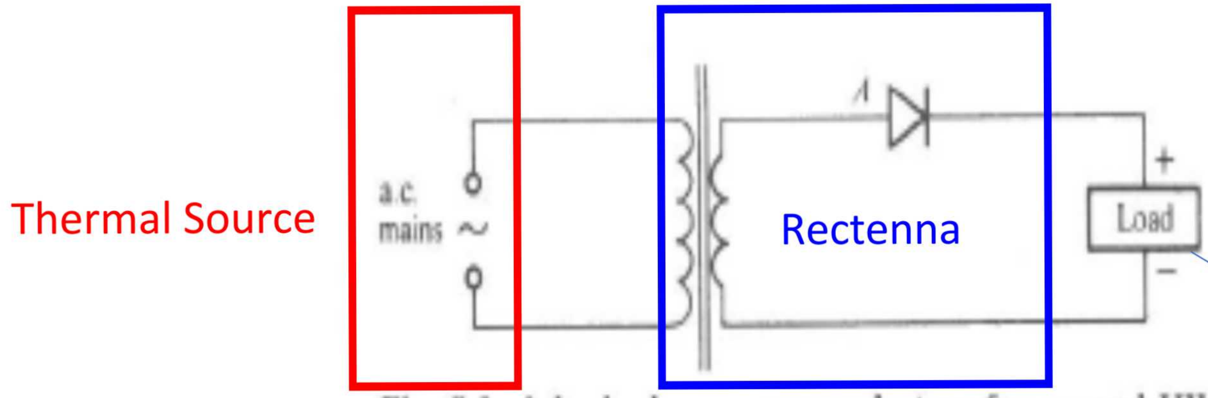


Fig. 9.1. A basic d.c. power-supply transformer and HW rectifier

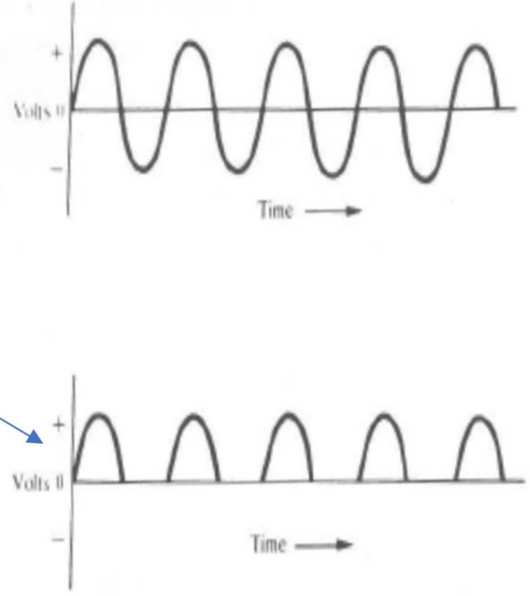
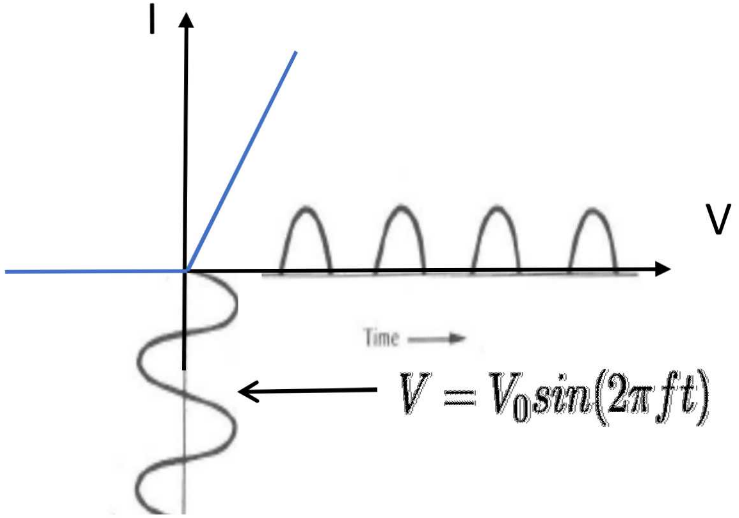
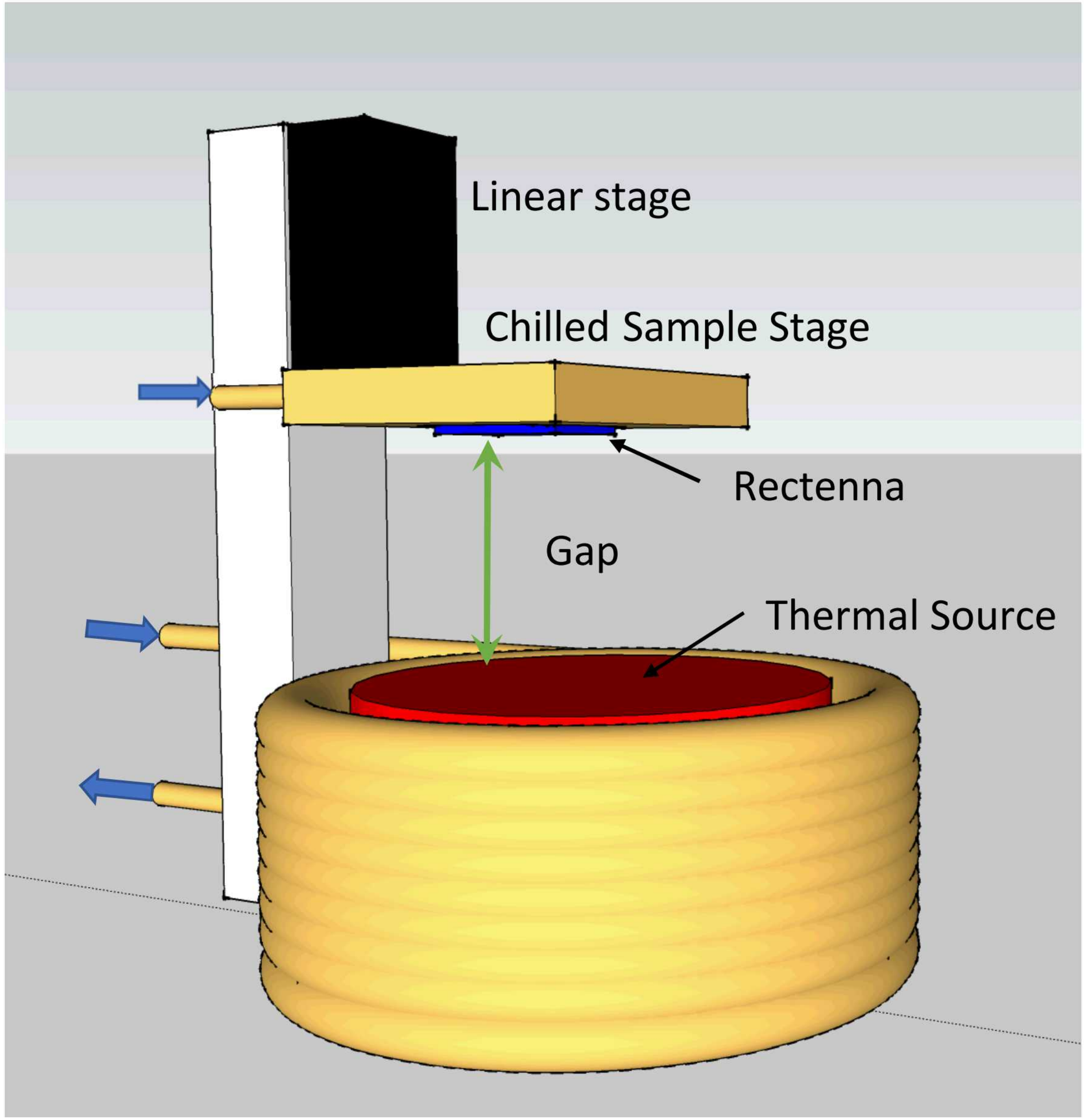


Fig. 9.2. Waveforms in HW rectifier circuit: (*a*) a.c. input waveform, (*b*) rectified unidirectional waveform across load.

Rectification in ideal diode

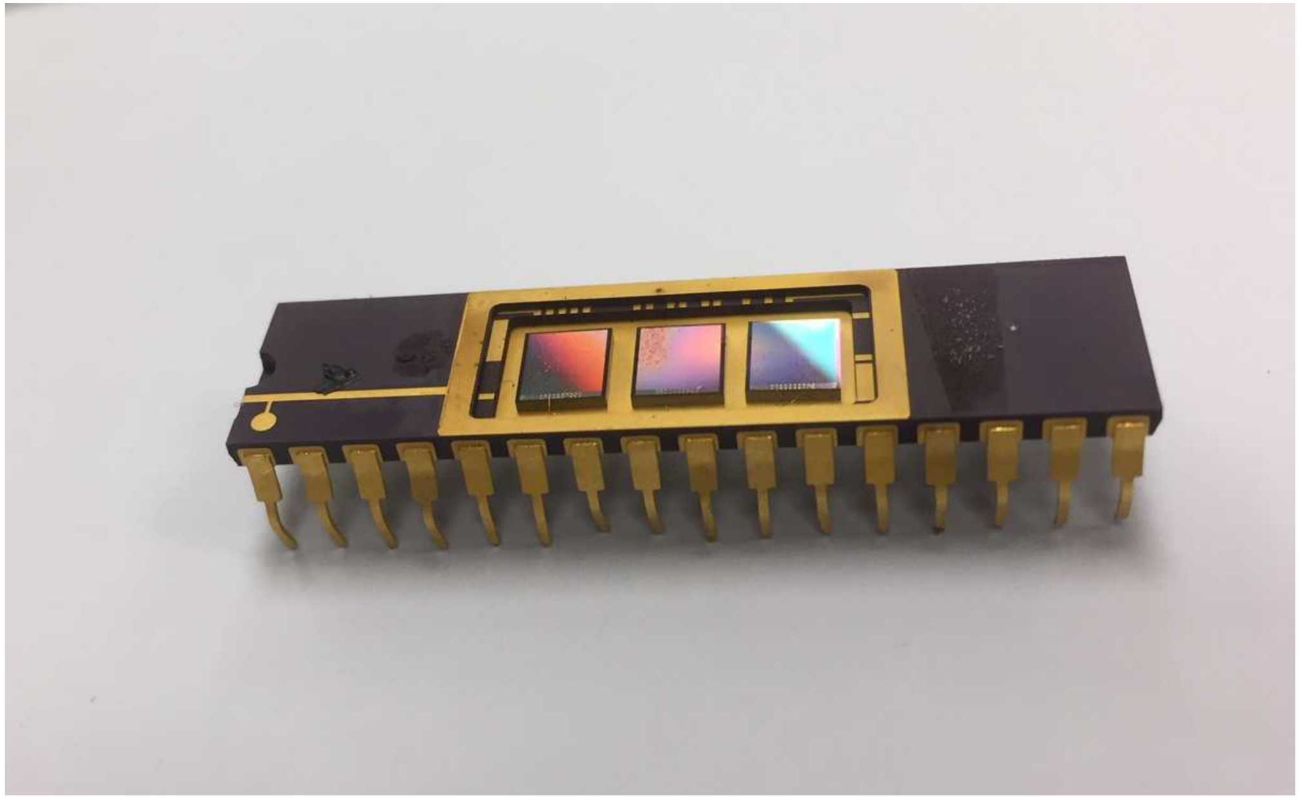


Radiometric thermal measurement

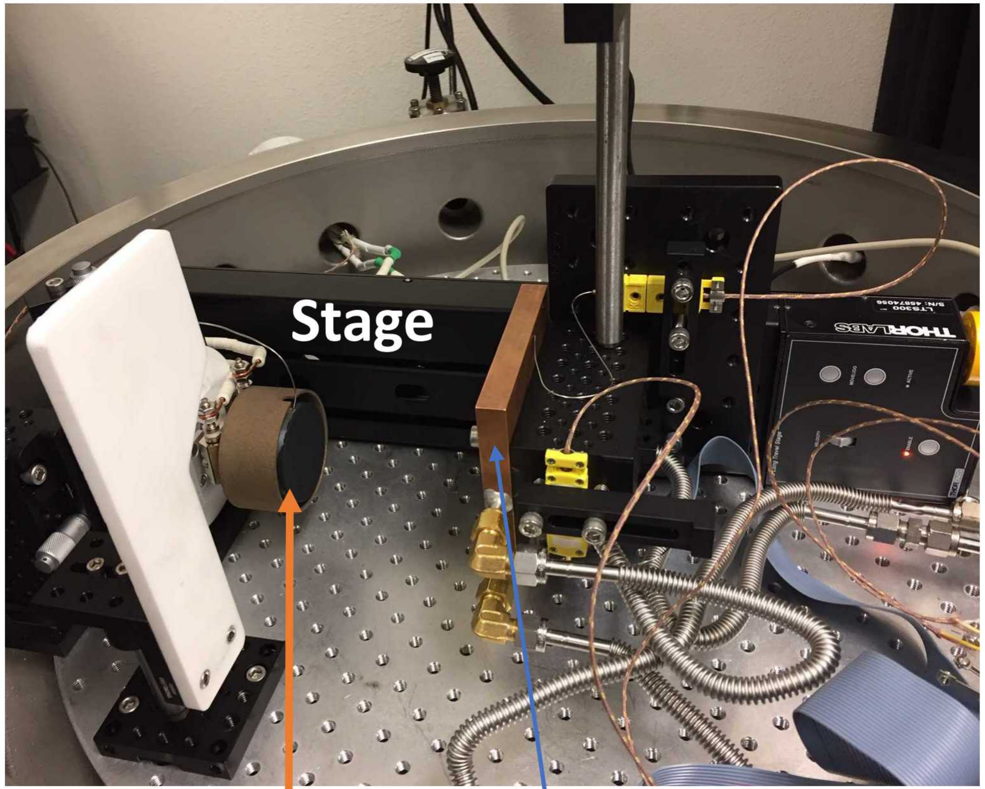


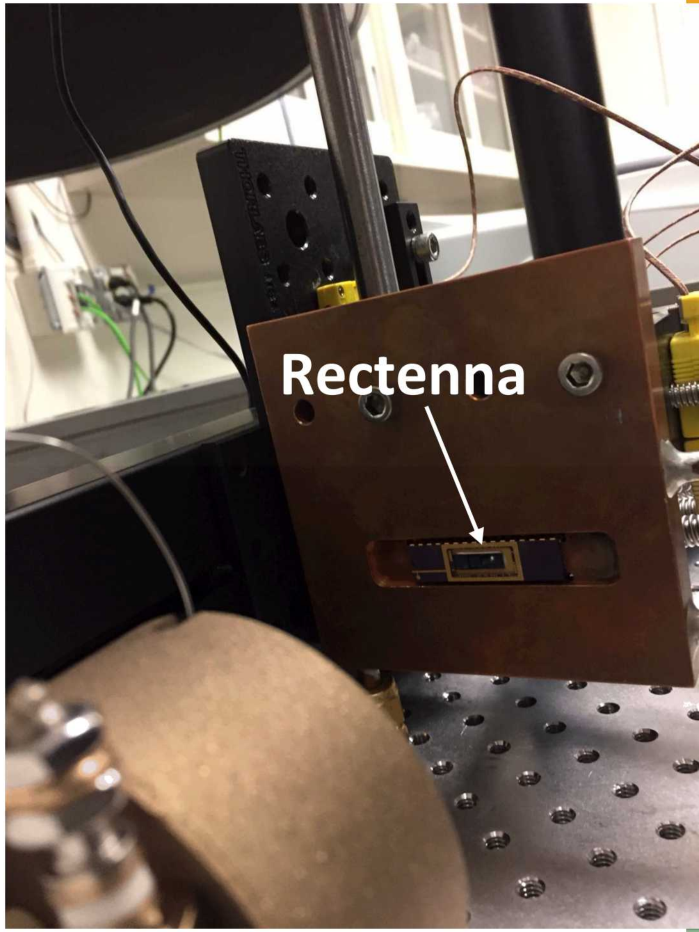
Energy conversion only needs to view thermal source

Packaged devices for thermal test

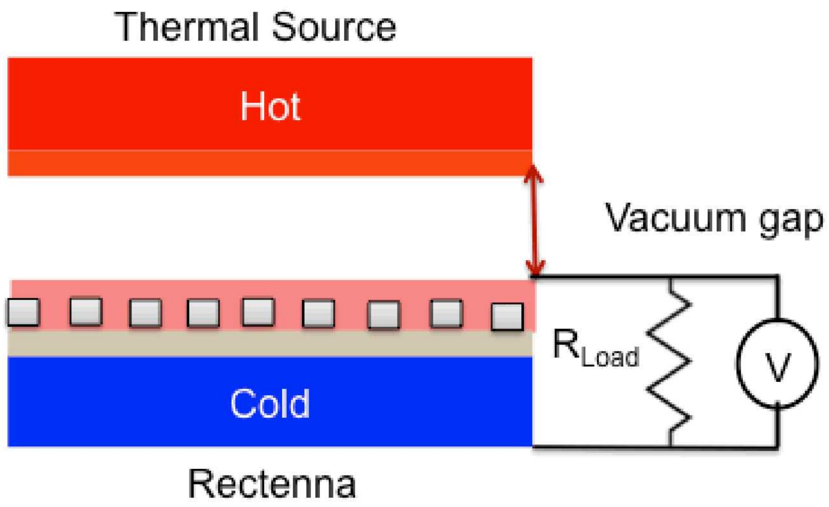


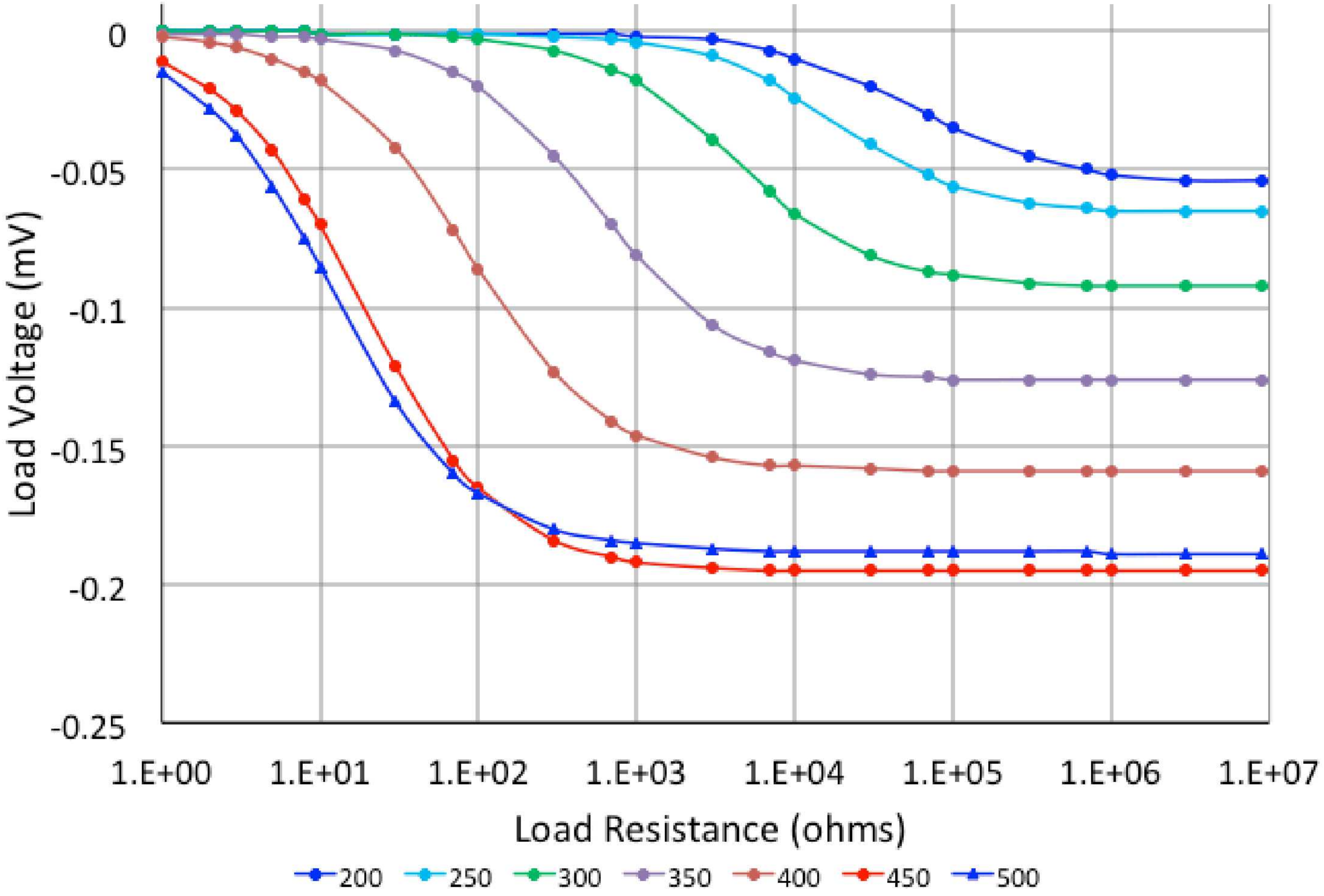
Vacuum Radiometric Setup





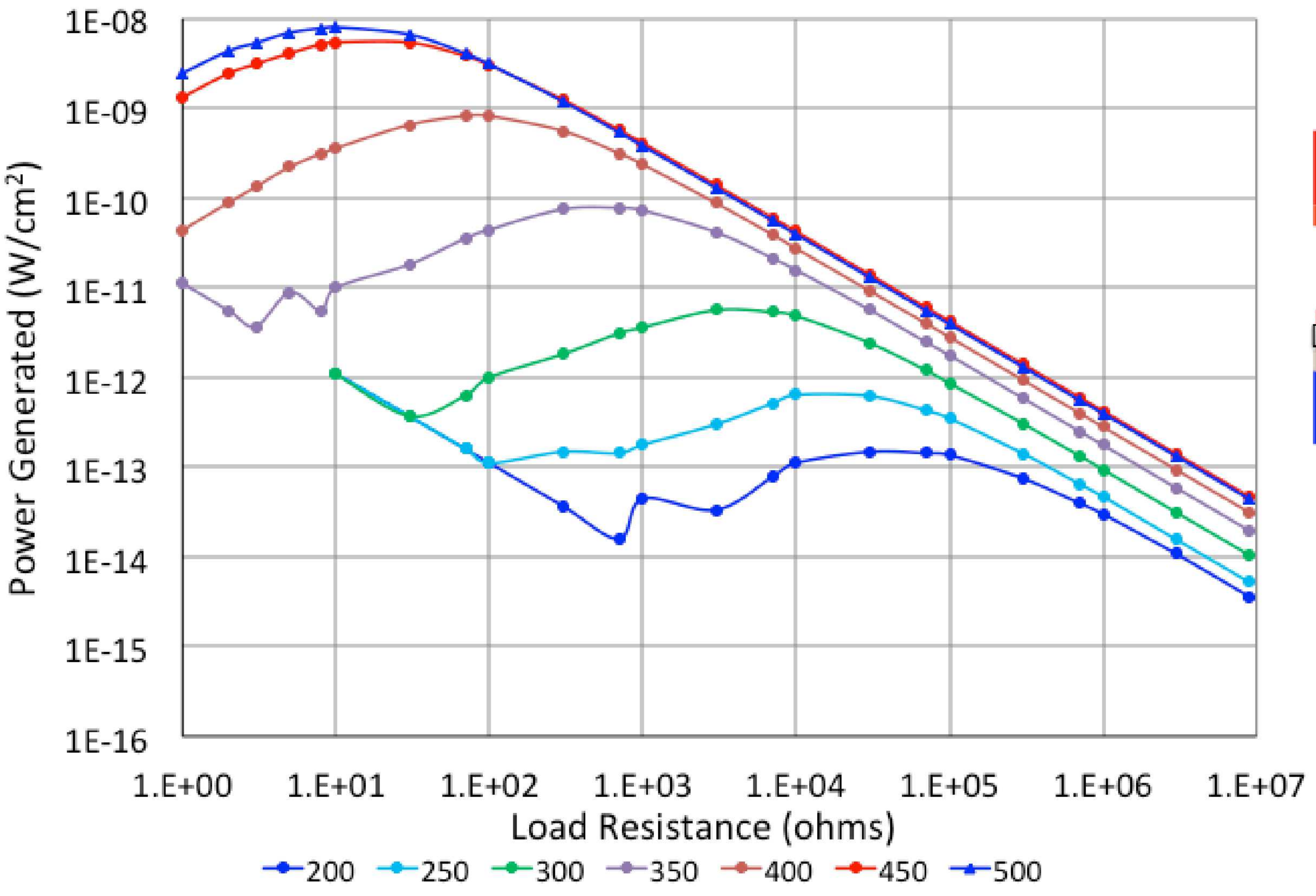
Generated Voltage across Load Resistance

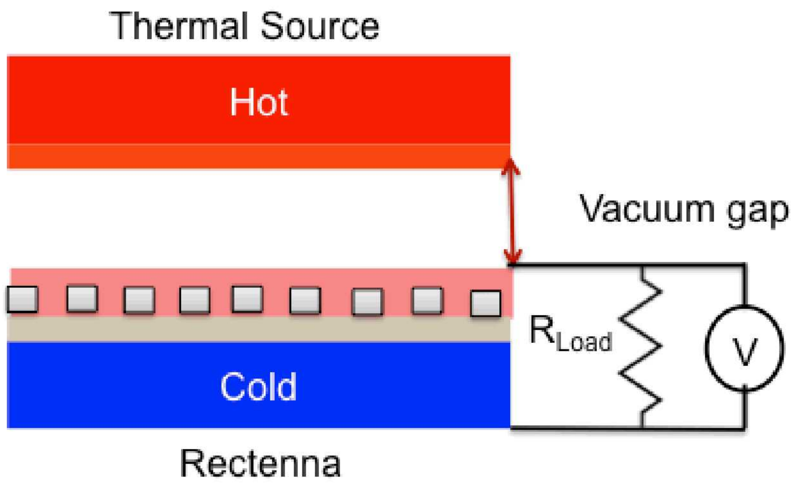




[1] J. Shank, E. A. Kadlec, R. L. Jarecki, A. Starbuck, S. Howell, D. W. Peters, and P. S. Davids. Power generation from a radiative thermal source using a large-area infrared rectenna. *Phys. Rev. Applied*, 9:054040, May 2018.

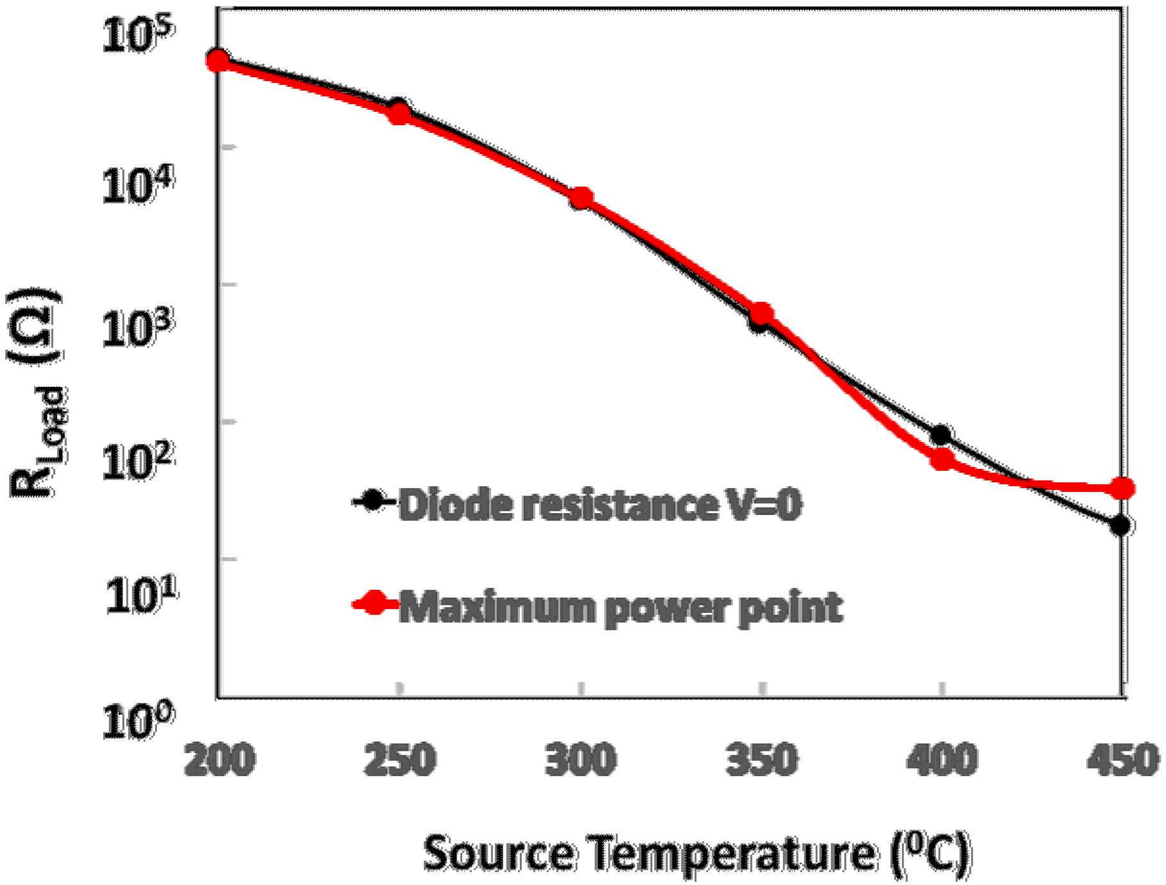
Power generation

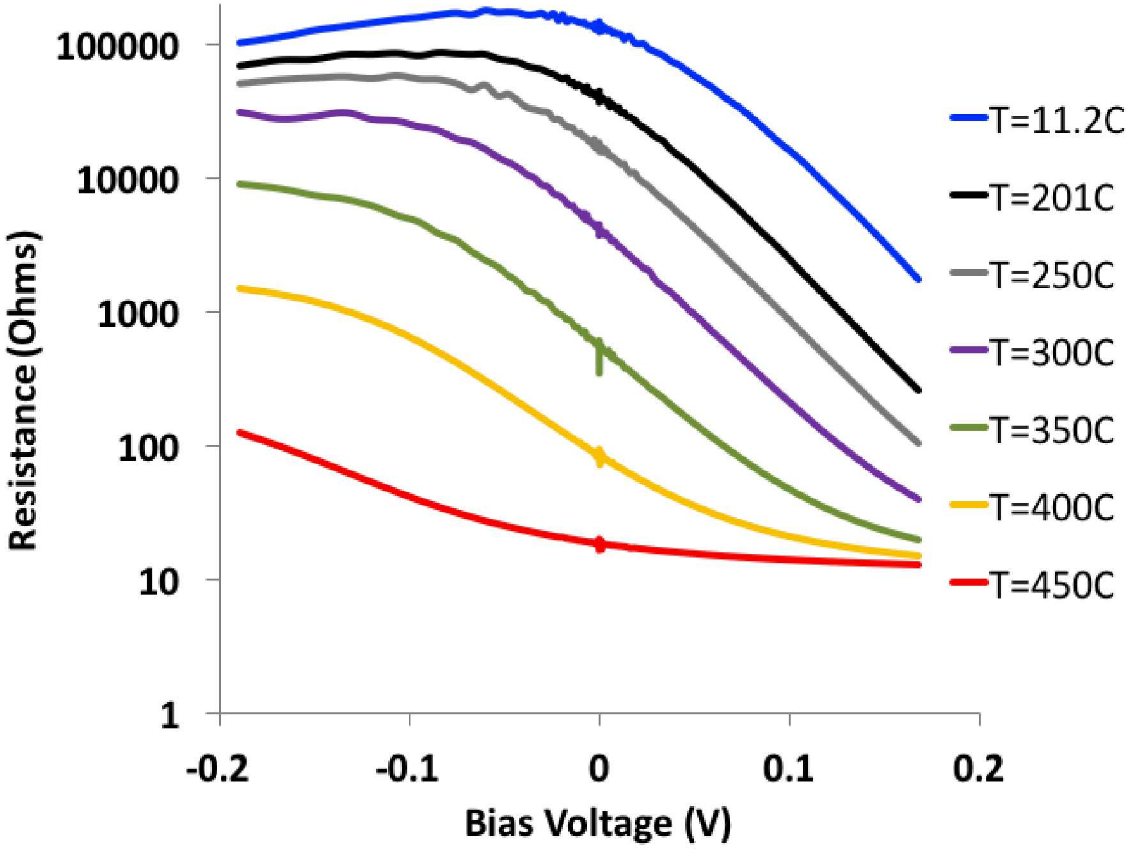




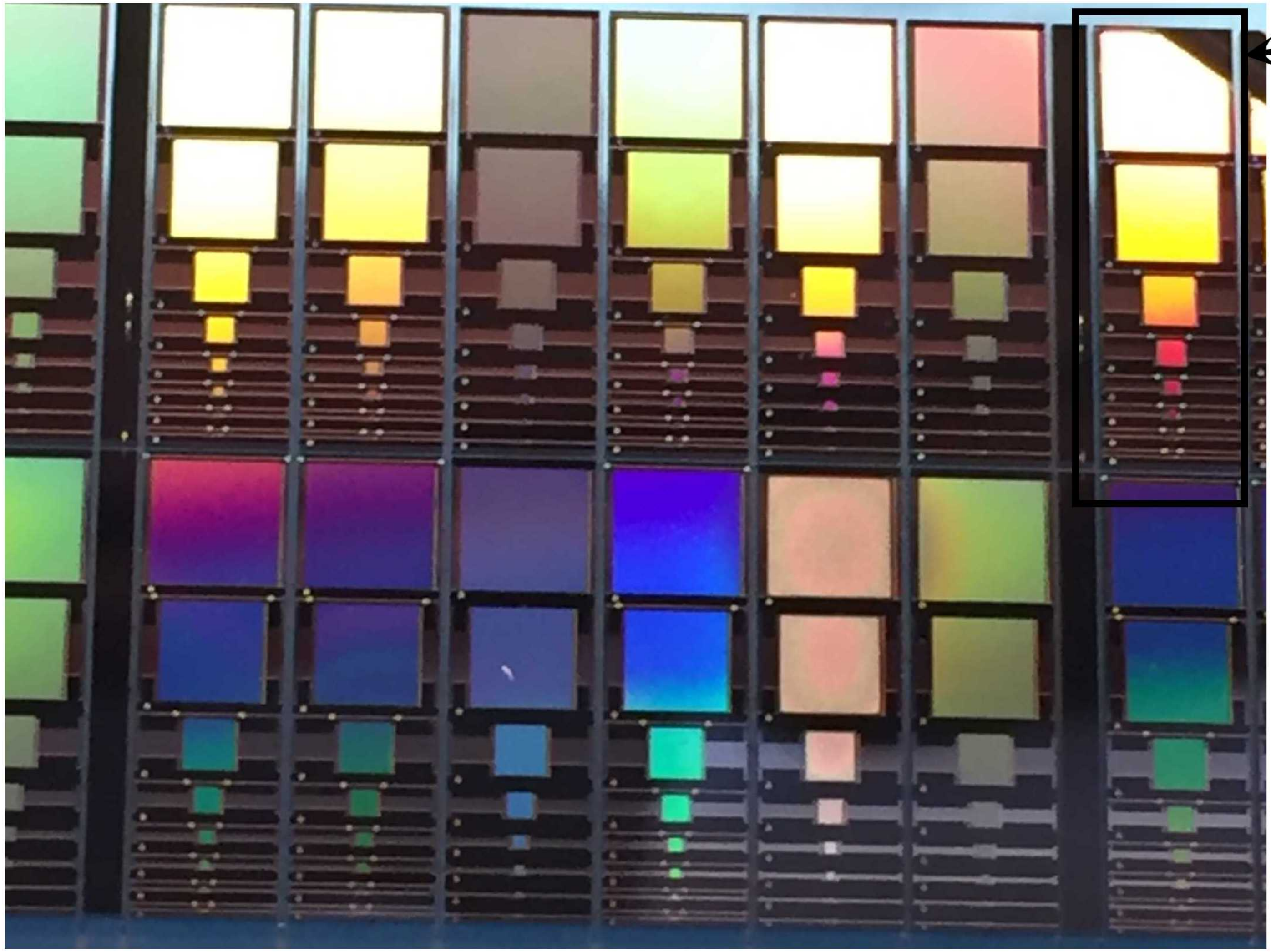
Impedance match

Peak power generated for load resistor matched to zero bias diode resistance.





Next generation rectenna

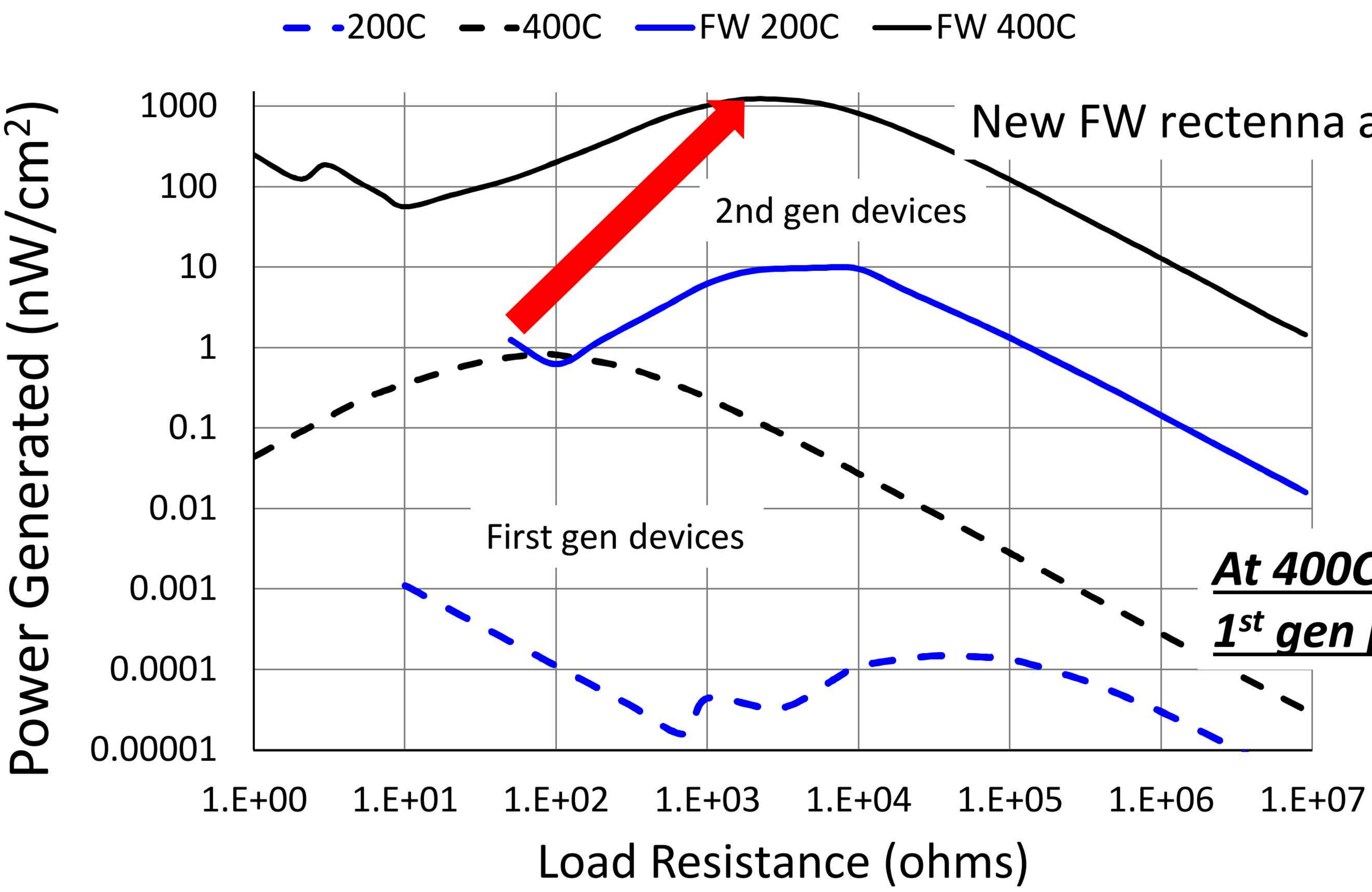


Diced for packaging
4mm x 14mm

Multiple designs with varying size

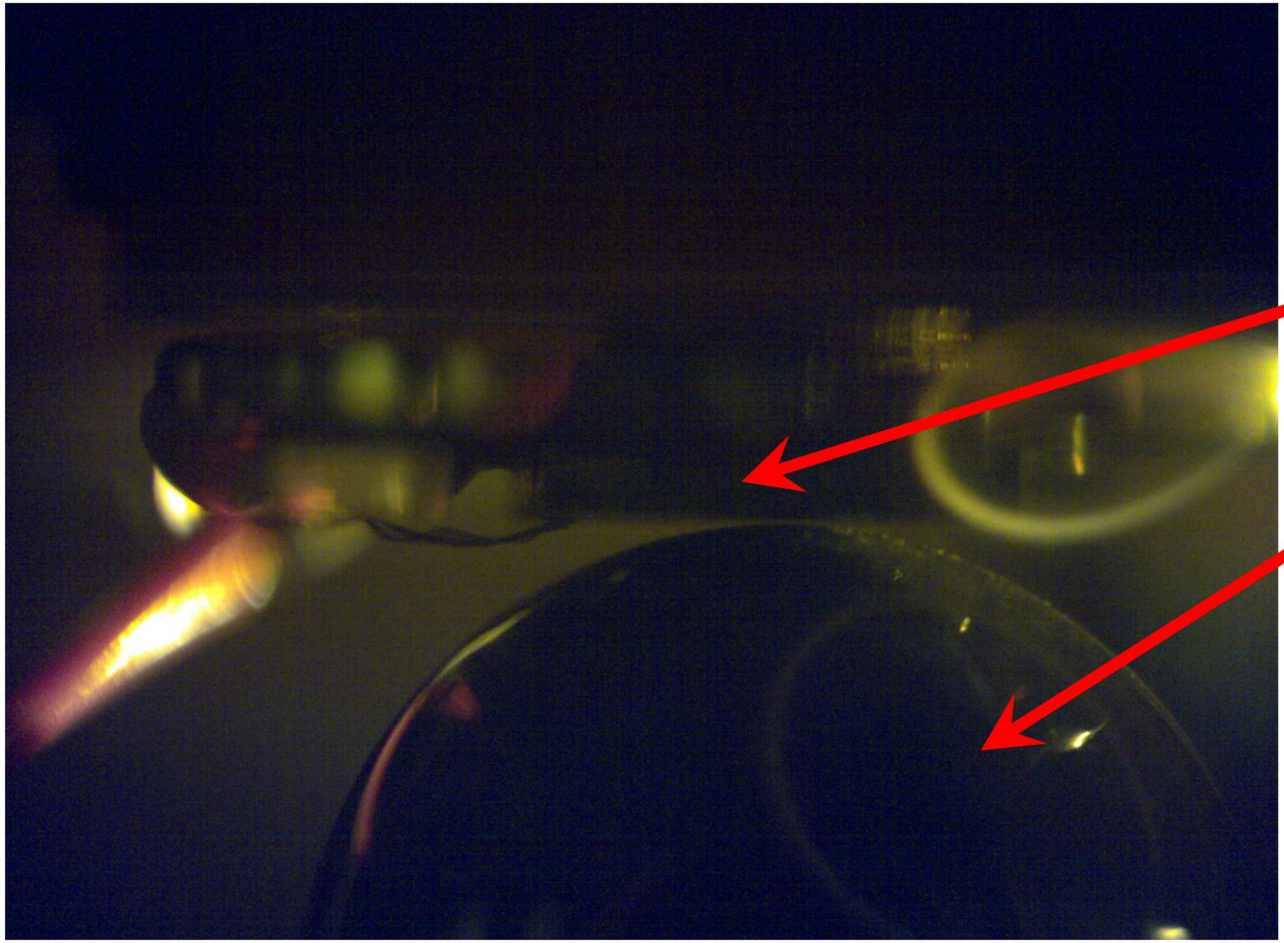
Evaluate area scaling and yield

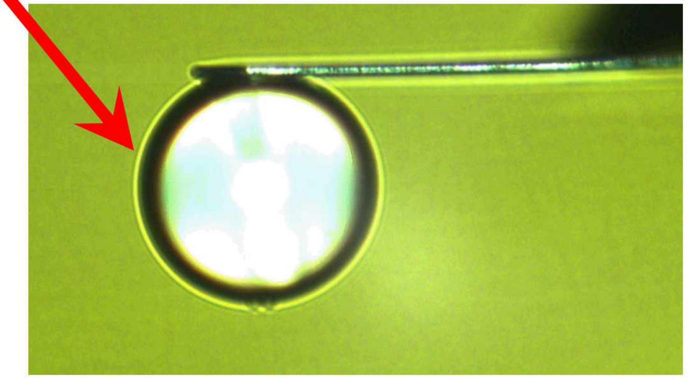
Comparison of 1st Gen devices to 2nd Gen



At 400C FW rectenna is over 1000X 1st gen power generation

Enhanced near-field radiative heat transfer





Conclusions

- Developed a large-area nanoantenna coupled tunnel diode rectifier that resonantly converts infrared radiation into photocurrent.
- Demonstrated power generation from a thermal source in a large-area antenna coupled tunnel diode.
- Developed a model based on photon-assisted tunnel
  - Shows clear indication of sign change in current as a function of radiation temperature.
  - Qualitative agreement with simple uniform barrier model predicts IV vs temperature characteristics.
- Future:
  - New devices using full design capability of CMOS shows large improvement
  - Near-field enhanced power generation