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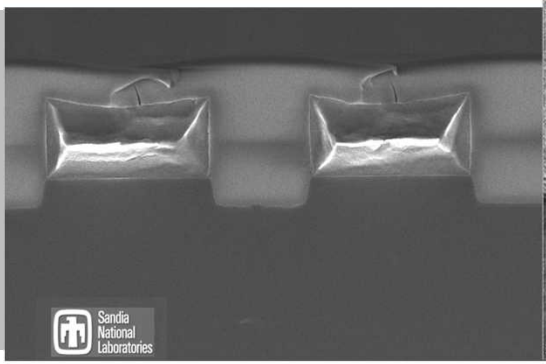

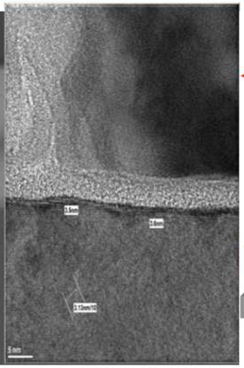

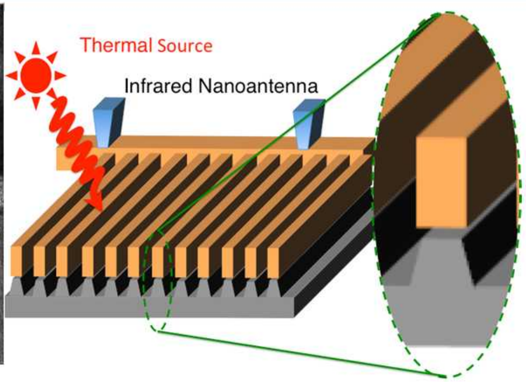

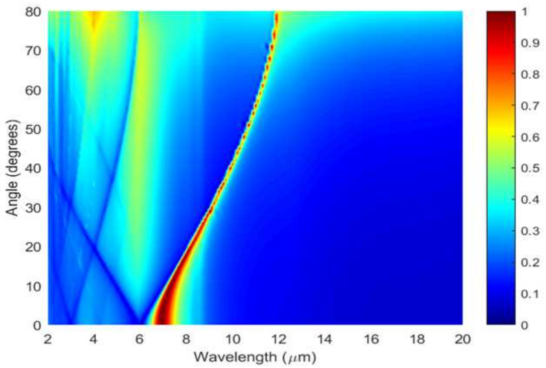

Tunneling rectification in an infrared nanoantenna coupled MOS diode

Paul Davids, Emil Kadlec, Steve Howell, David Peters

U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

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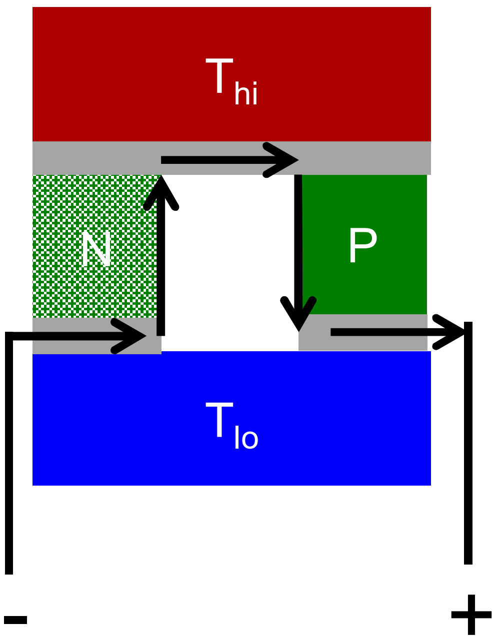
Motivation

A new thermoelectric conversion mechanism (heat to electrical power) based on direct conversion of infrared radiation from a thermal source into electrical power.

- ***Large area infrared antenna coupled metal-oxide-semiconductor (MOS) tunnel diode rectifier.***
- ***Strong Photon-Phonon coupling gives large transverse field enhancement in nanometer scale tunnel gaps.***
- Advantages of new **Rectenna** device technology:
  - Uses well established mature Si manufacturing technology for large area devices.
  - Radiative approach: non-contacting of thermal source; needs only view of thermal source to generated power.

Thermoelectric Generation



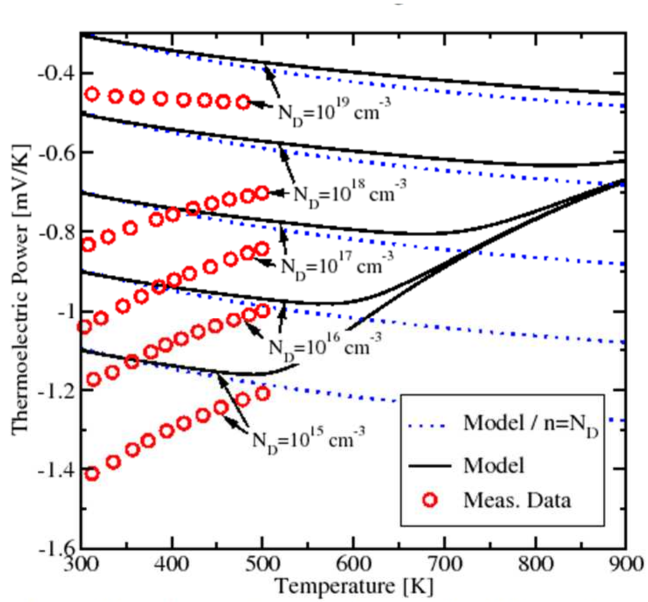


Figure 3.8: *Seebeck* coefficients for differently doped n-type silicon samples.

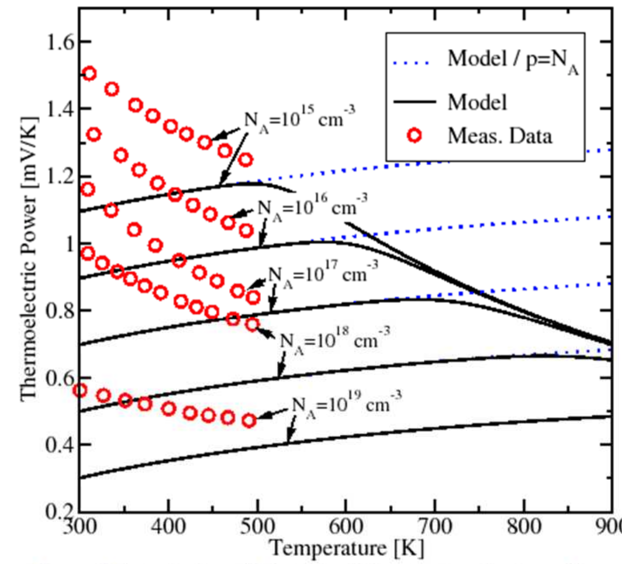
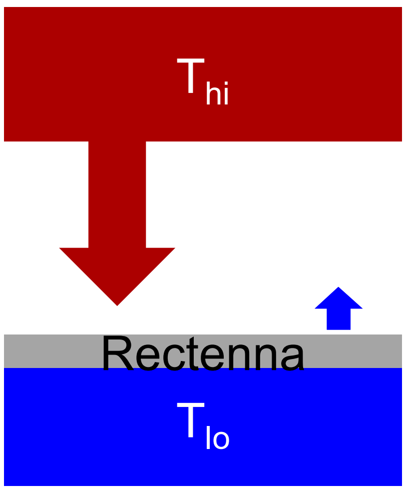
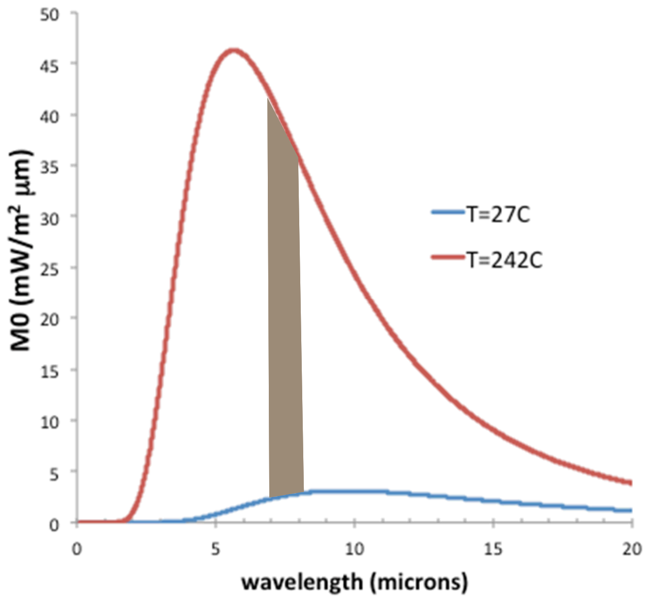


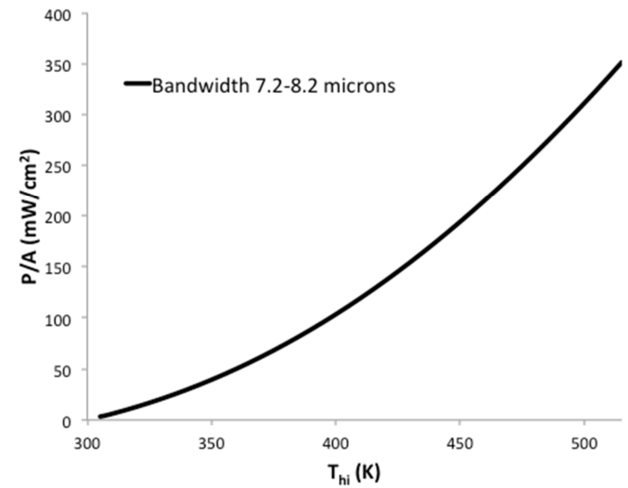
Figure 3.7: *Seebeck* coefficients for differently doped p-type silicon samples. Solid lines depict the theoretical models, whereby the decrease for elevated temperatures results from the increased hole concentration in the intrinsic range.

- **Seebeck effect**: Thermal induced EMF due to temperature difference.
- Load Resistor: Current flow
- Thermoelectric figure of merit: ZT
  - Maintain Temperature difference – low thermal conductivity
  - High electrical conductivity

New Radiative Thermoelectric Generation



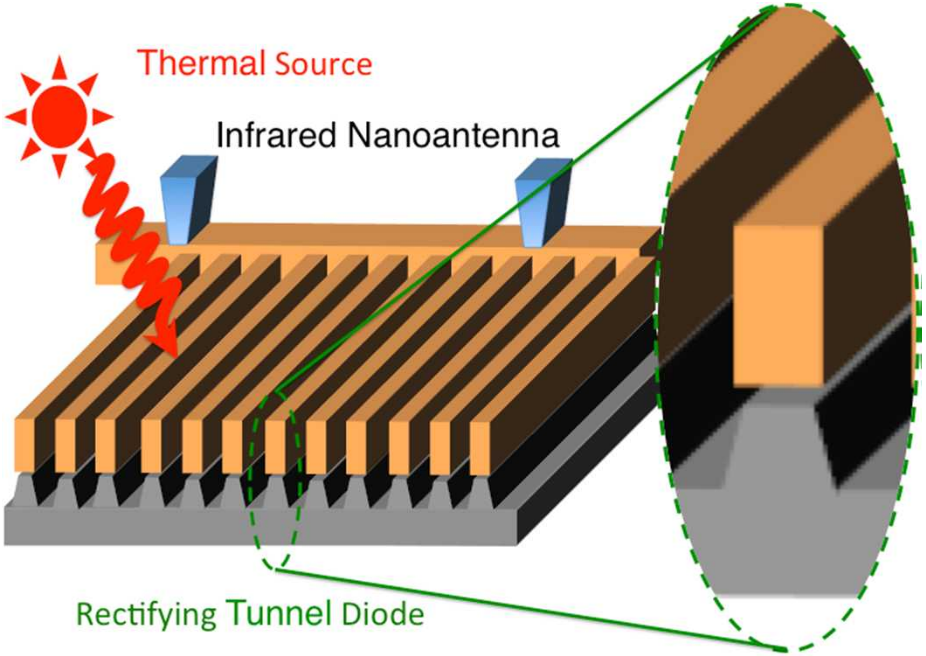


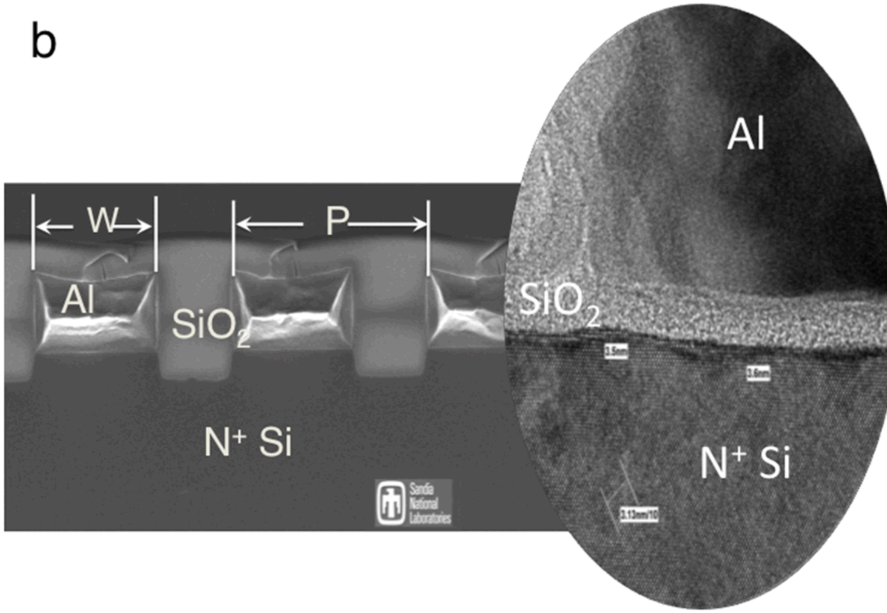


<u>Rectenna</u>: New device that directly converts broadband incident infrared radiation into dc electrical current.

- Antenna coupled coupled metal oxide semiconductor tunnel diode.
- Key insight
  - Optical phonon polariton creates enhanced field in tunnel barrier.
  - Large field in tunnel diode gives large DC rectified current.

Infrared Rectenna



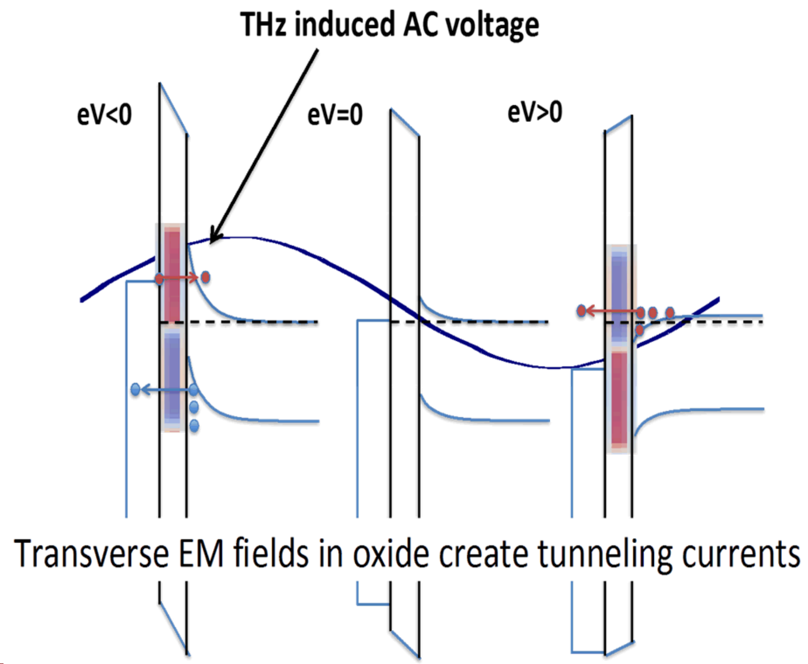


1D large area grating coupled MOS tunnel diode.
4mm x 4 mm square
Grating Pitch P = 3.0 microns
Width 1.8 microns
Tunnel Oxide thickness ~ 3.5 nm

[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):1033–1038, 2015.
[2] J. C. Ginn, R. L. Jarecki, E. A. Shaner, and P. S. Davids. Infrared plasmons on heavily-doped silicon. Journal of Applied Physics, 110(4):043110, 2011.

How it works

- Large area antenna coupled MOS diode.
- Coupled Material and Photonic Resonances
  - Polar oxide Restrahlen peak.
  - Photonic surface mode resonances.
- Enhanced transverse field confinement in tunnel barrier.
- Tunneling rectification.
  - Direct tunneling



Material Dispersion: Oxide Optical Phonons

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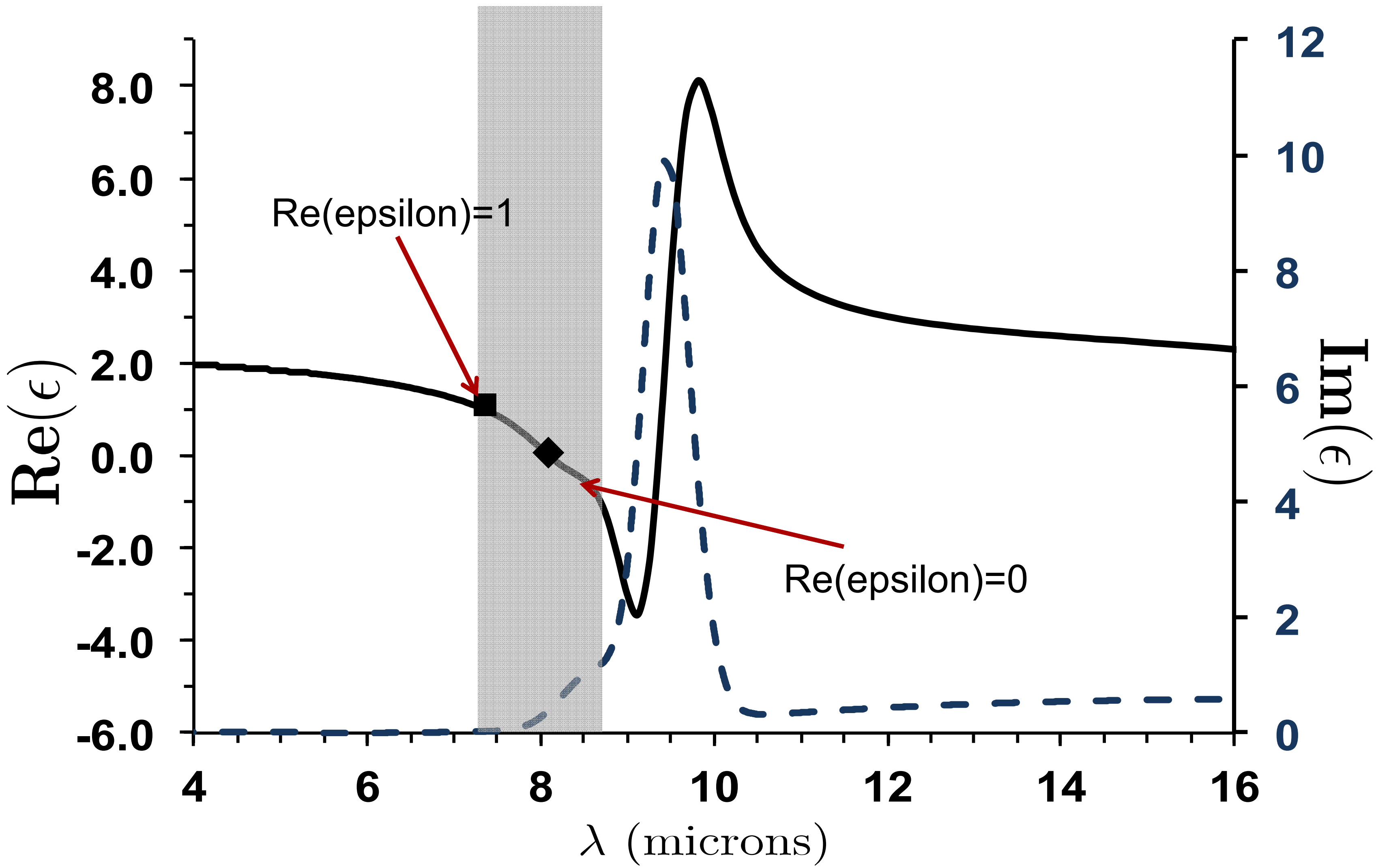
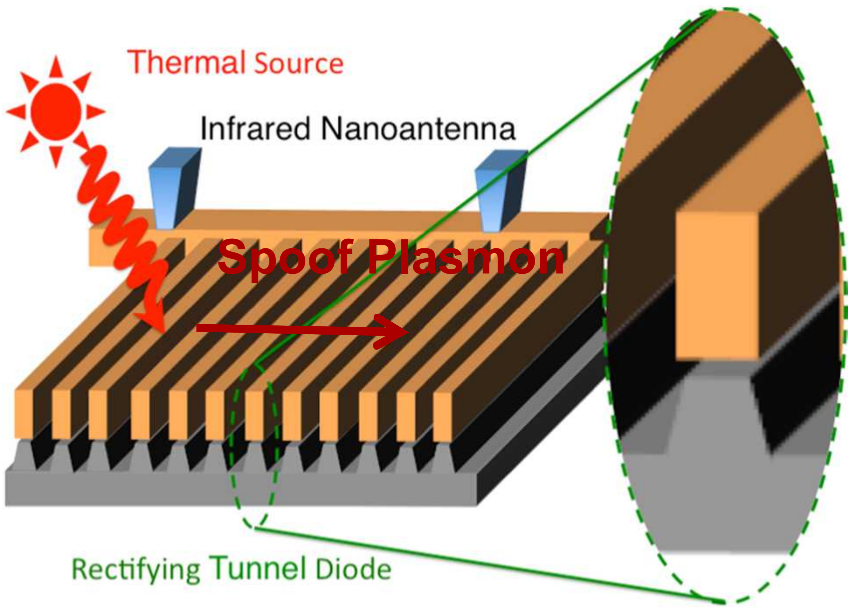
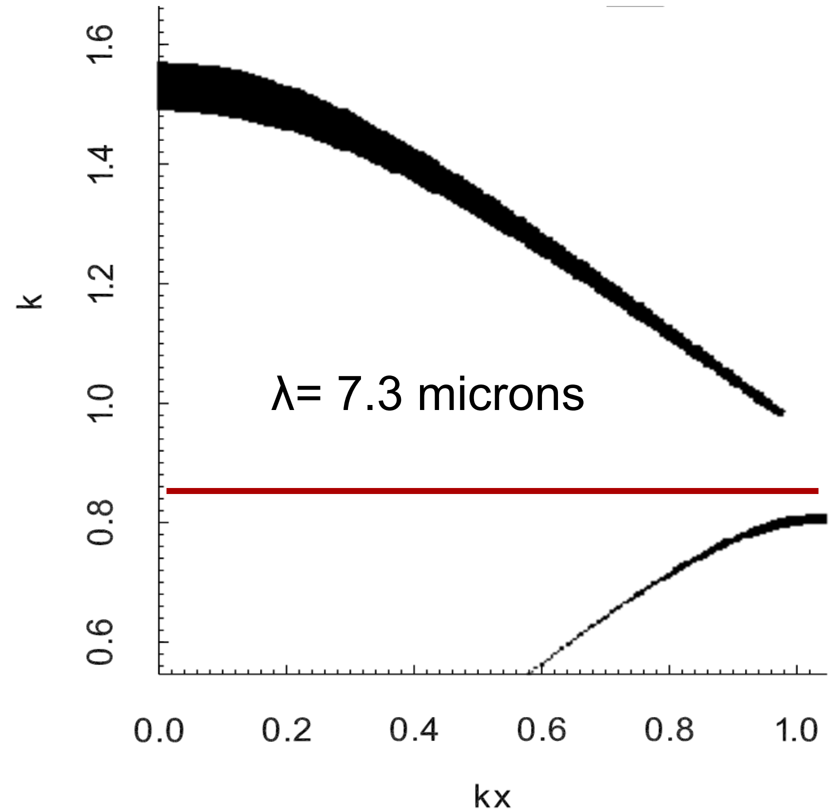


Photonic Surface Mode



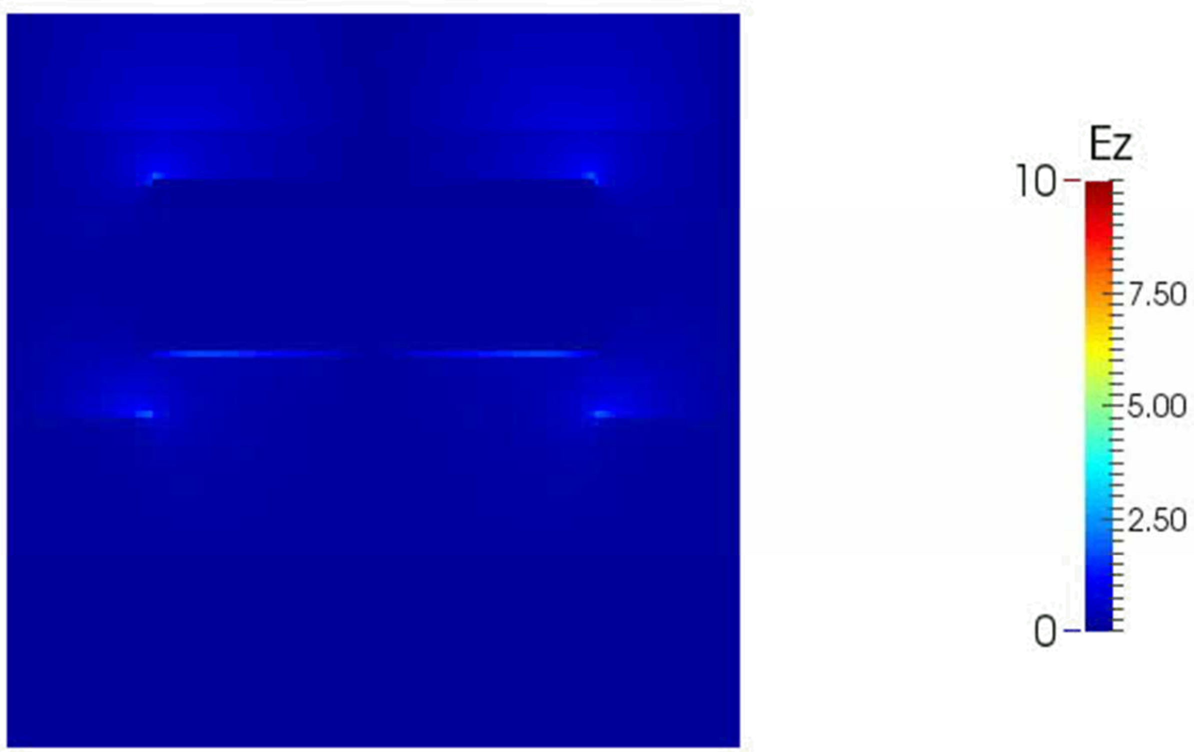
Spoof Plasmon Mode in 1D grating

$$\frac{w}{L_x} s_0^2 \tan(kh) = \frac{\sqrt{k_x^2 - k^2}}{k},$$



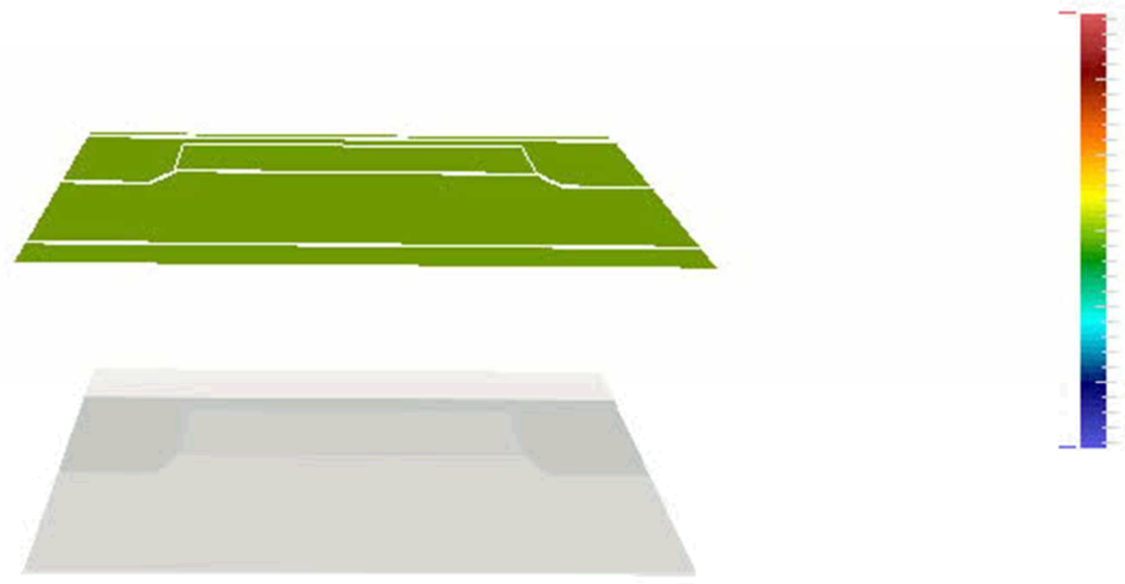
[1] P. Davids, F. Intravaia, and D. Dalvit. Spoof polariton enhanced modal density of states in planar nanostructured metallic cavities. Optics Express, 22(10):12424–12437, 2014.
[2] F. J. Garcia-Vidal, L. Mart ́ın-Moreno, and J. B. Pendry. Surfaces with holes in them: new plasmonic metamaterials. Journal of Optics A: Pure and Applied Optics, 7(2):S97–S101, Feb. 2005.

Field Enhancement in Tunnel Gap



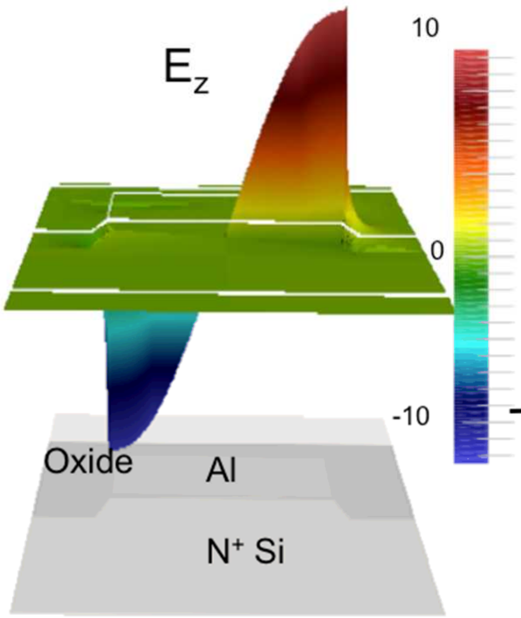
Ez versus wavelength (6 -12 microns)

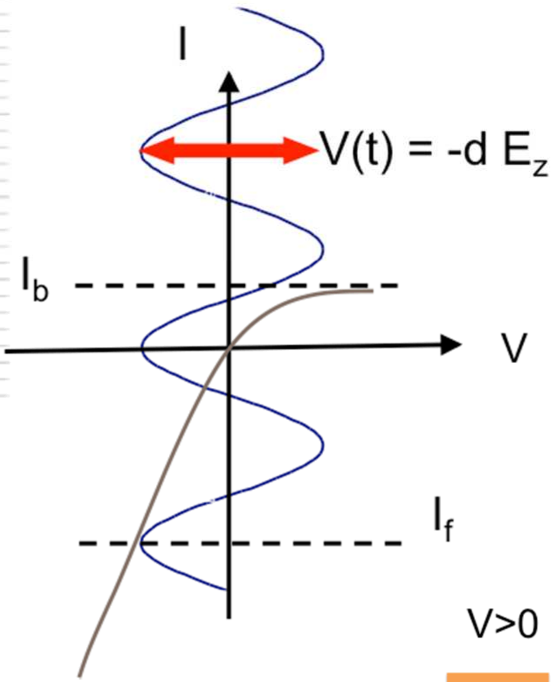
Field Enhancement in Tunnel Gap



Ez at 7.3 microns Re(epsilon) = 1 Peak field enhancement

Tunneling Rectification

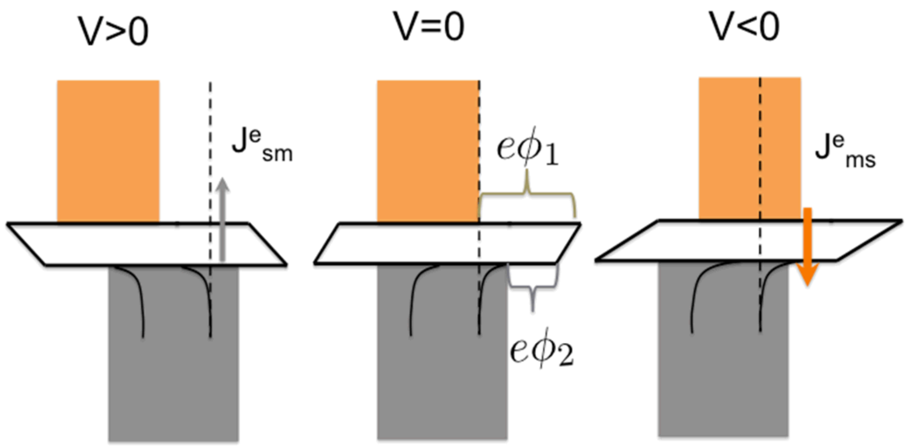




Distributed Current in MOS Tunnel Diode

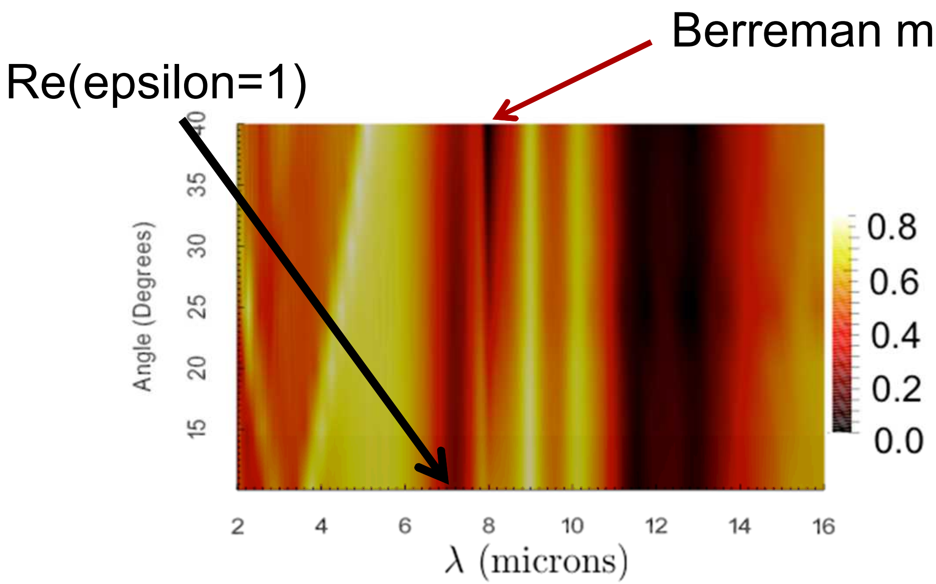
Half-wave DC current

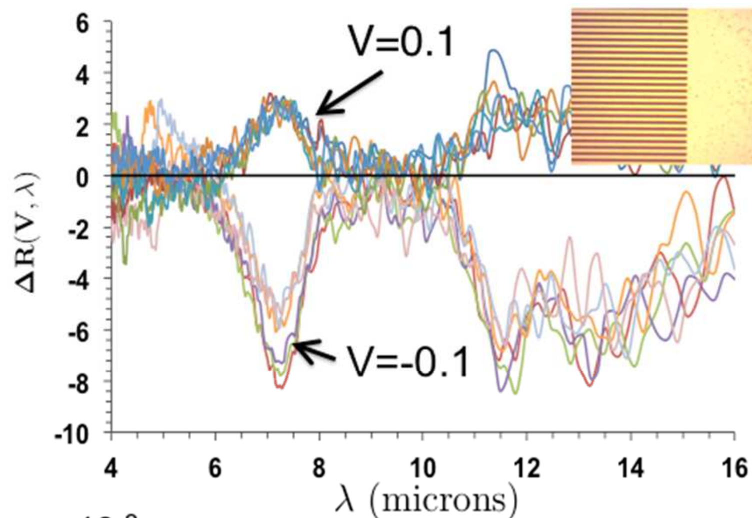
$I_{DC} = I_f - I_b$

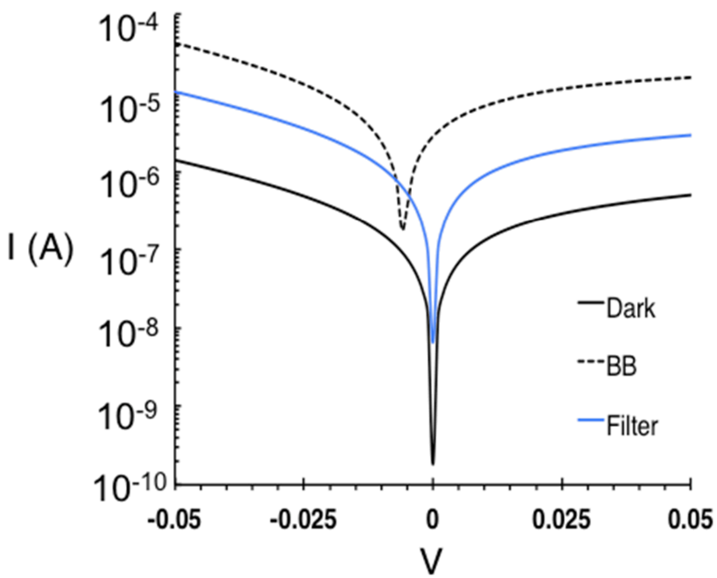


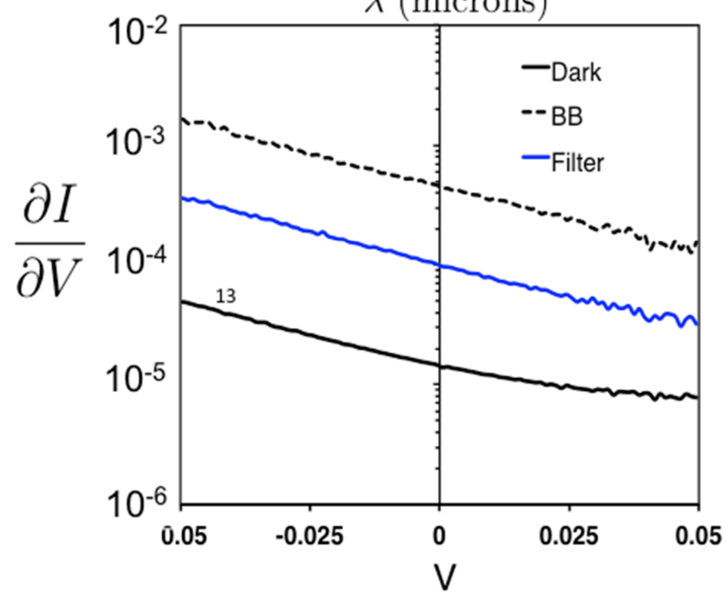
Tunneling current in MOS diode is Asymmetric due to different density of states

Experimental Data

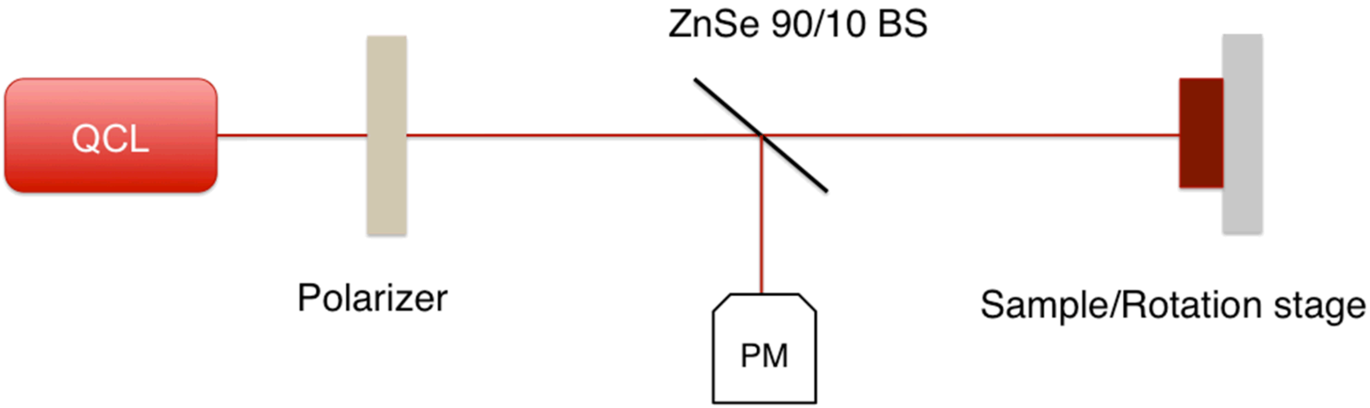


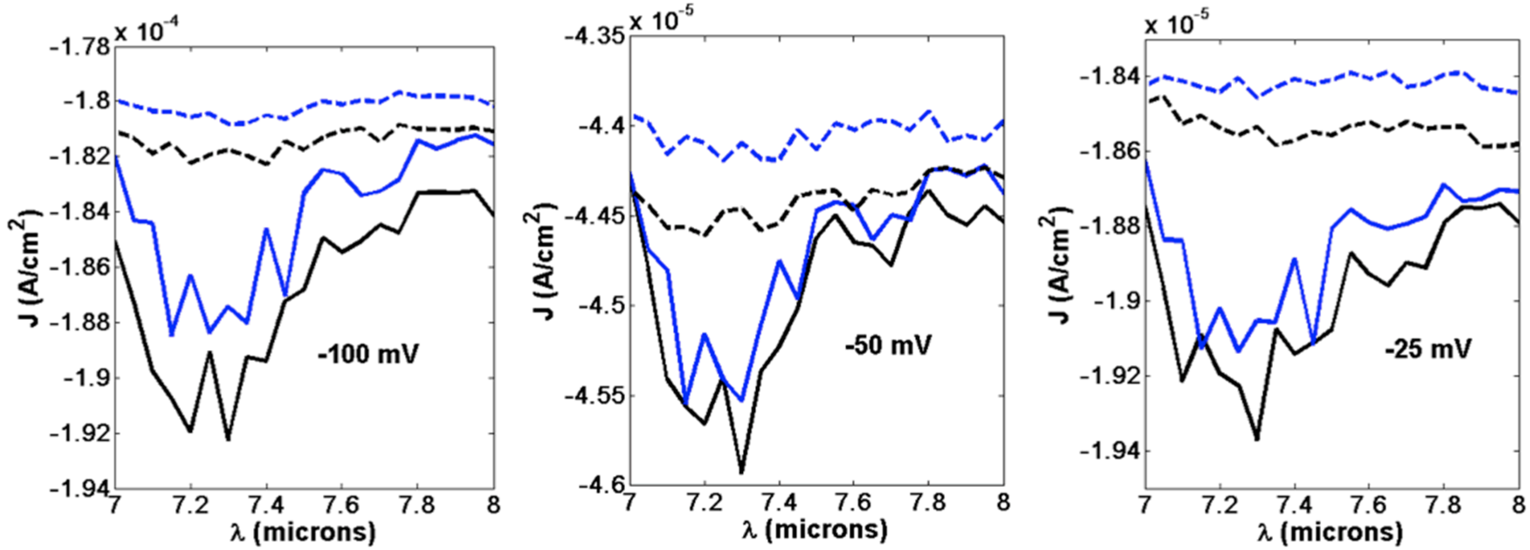






QCL Illuminated Sample





Photoresponse of large area antenna coupled diode

1D Tunneling Rectification

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- Large transverse field confinement in tunnel gap
  - ***Maximum field at Re(ε)=1***
- Engineered Spoof Surface Rlasmon Resonance overlap with SiO_2 optical phonon resonances.
- Photocurrent seen under broad-band (black-body) illumination with infrared only light.
- QCL photoresponse signal in photon-phonon enhancemed tunneling regime.
- 1D TM polarization only coupling into tunnel gap.

Details in reference

nature nanotechnology

LETTERS

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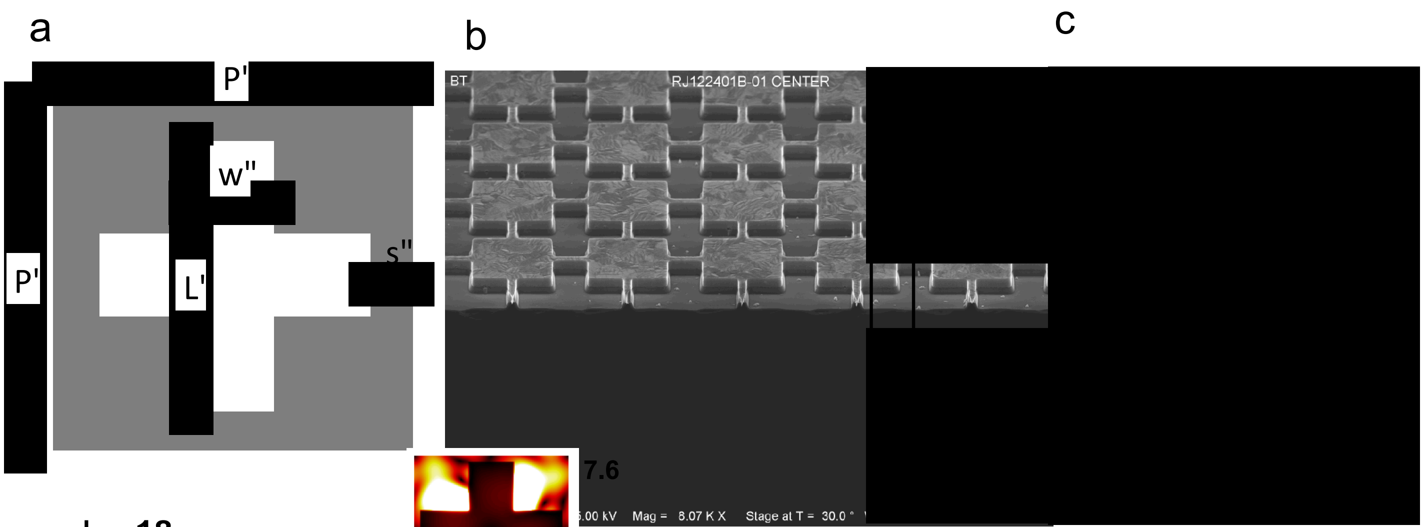
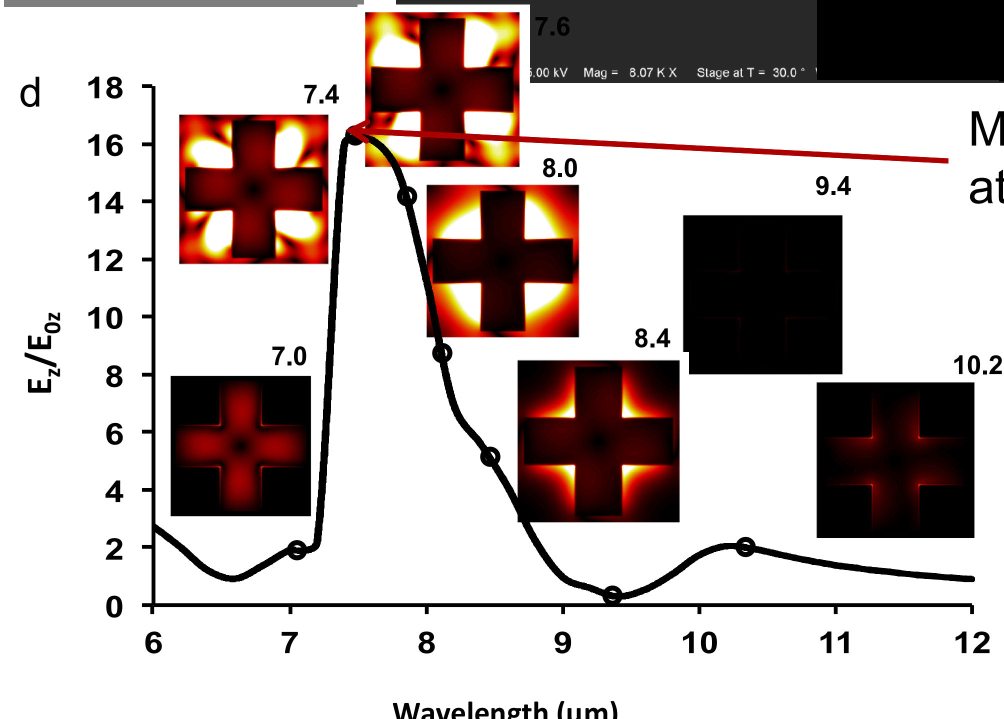
2D Tunneling Rectification

- Drawbacks of 1D Antenna design
  - Polarization sensitive (TM couples but not TE)
  - Spoof surface mode to couple into epsilon near unity
  - Difficult to optimize field confinement
- 2D Antenna structure
  - Polarization and angular independence (cone of incidence)
  - Higher field confinement in larger area
  - Use Surface diffracted mode to couple into epsilon near unity
- Challenges:
  - Fabrication
  - Yield
  - Testing

2D Antenna coupled tunnel diode



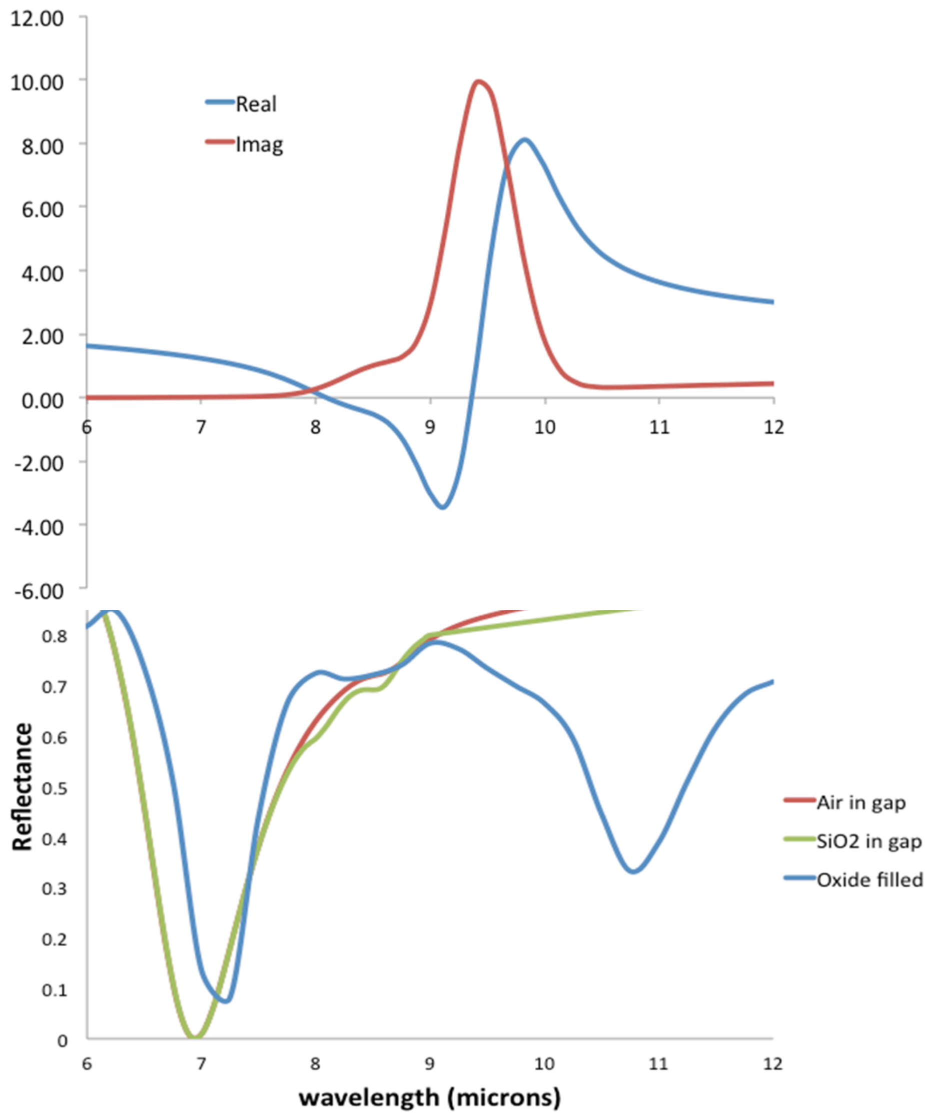


Max transverse field enhancement at Re(ε)=1

Large area 2D MOS diode

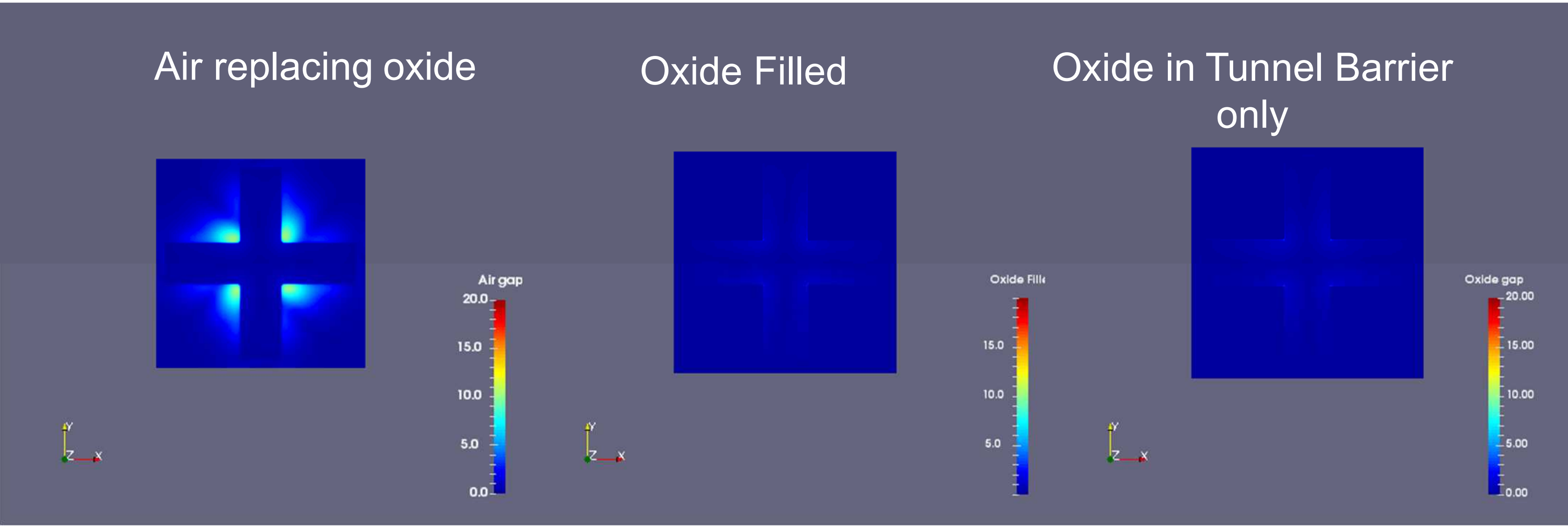
4 mm x 4 mm area

Re(ε) ≅ 1: Resonance matching

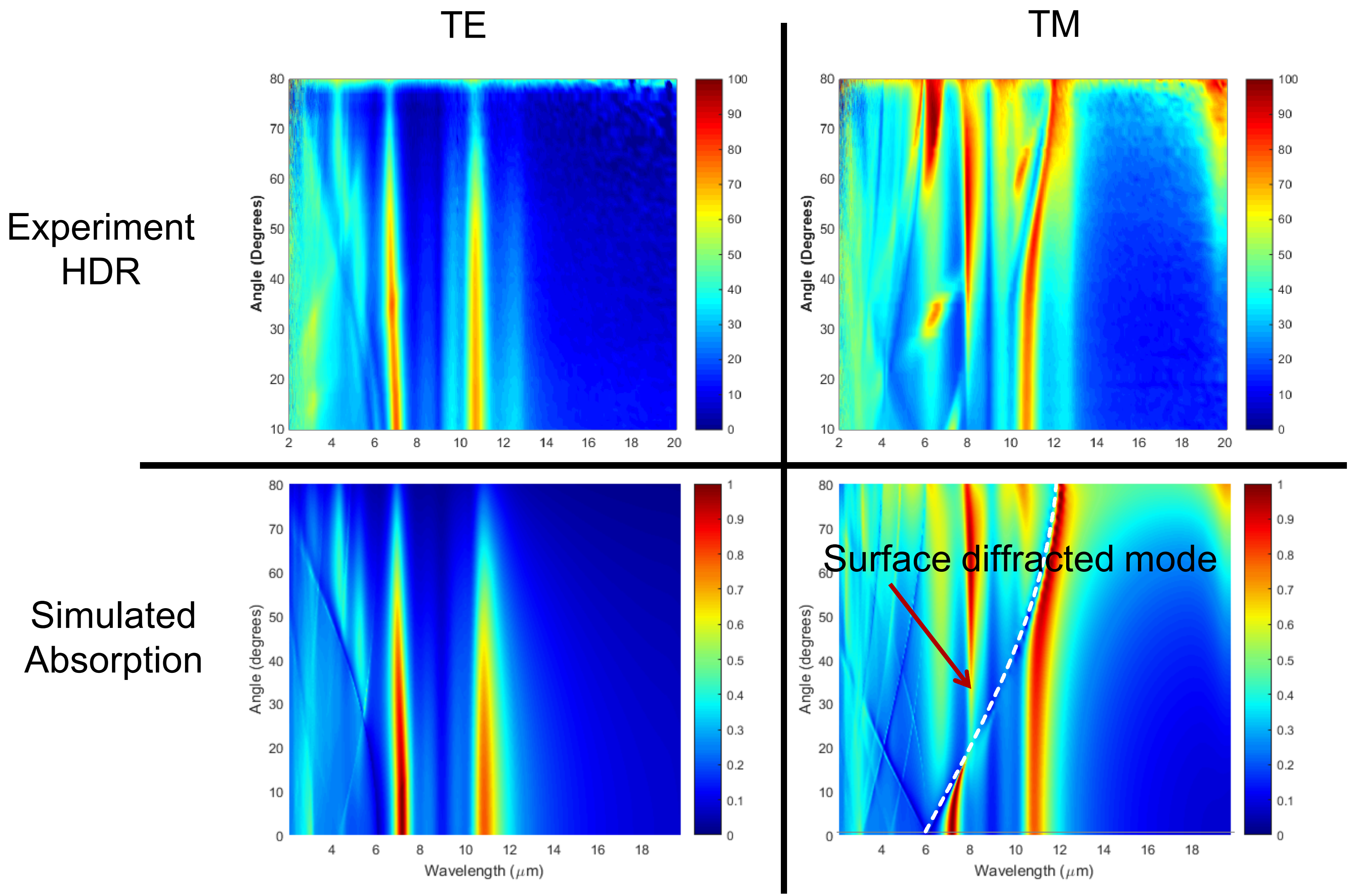


- Goal: Overlap photonic resonance with Re(ε)=1
- Examine Transverse field concentration in gap for
  - Oxide filled structure (experiment)
  - Oxide in tunnel gap only
  - Vacuum/Air in tunnel gap and filled structure

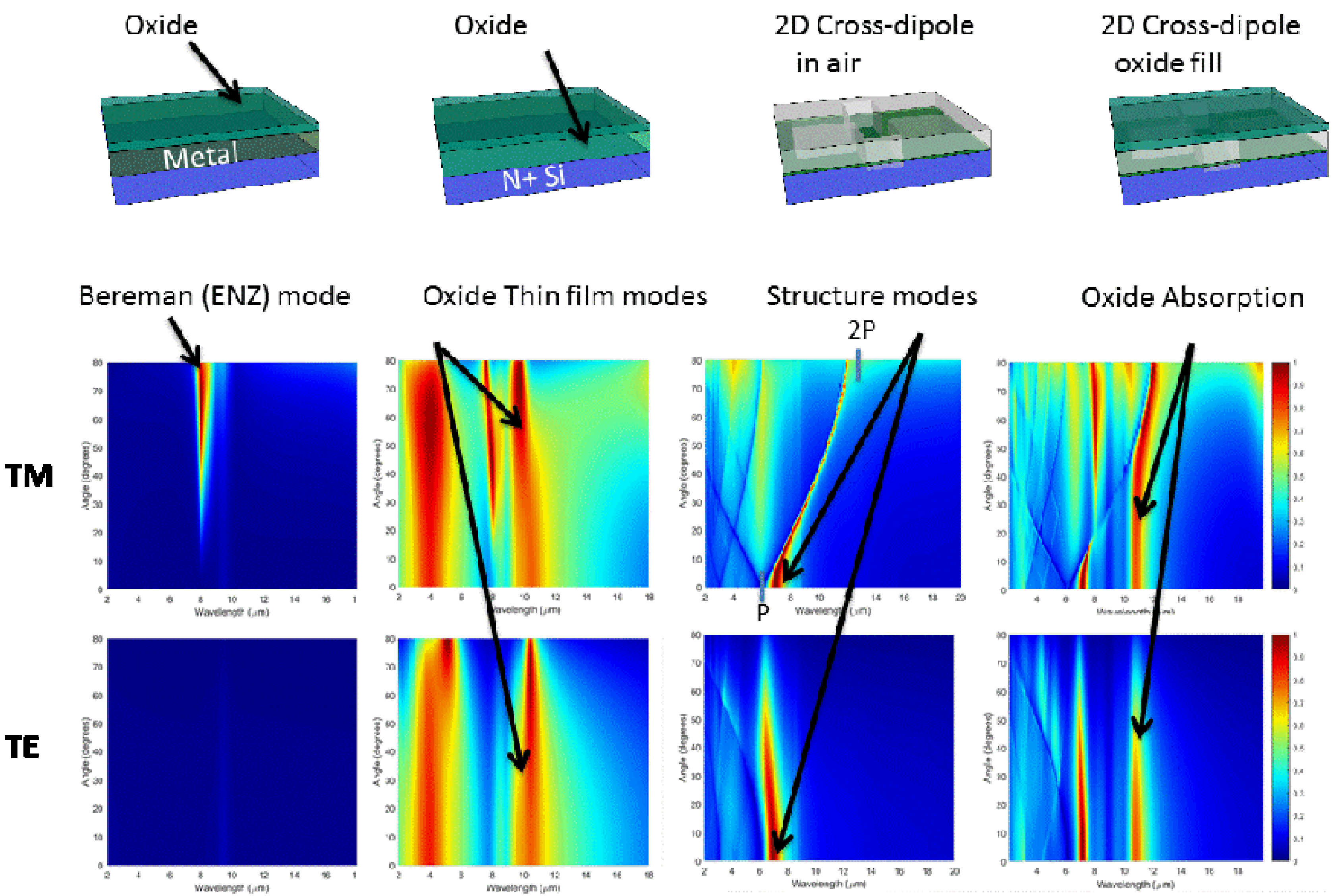
Re(ε) ≅ 1 : Field Concentration



2D Angular Absorption Spectra



2D Photonic Modes

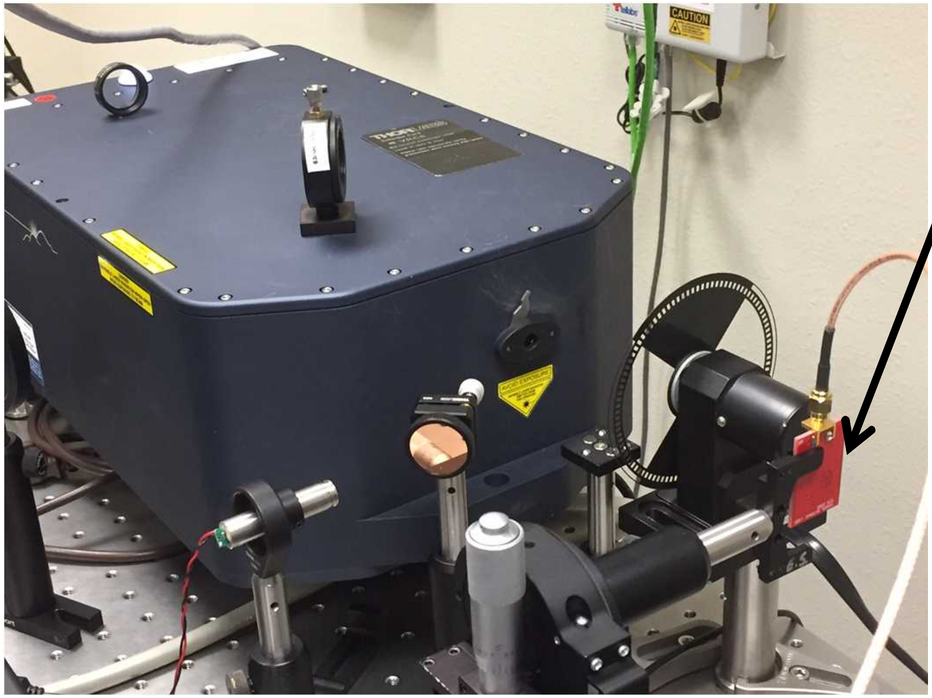


Photocurrent spectrum

2D Rectenna Angular Photocurrent Spectrum at V=0

QCL wavelengths 7-11 microns

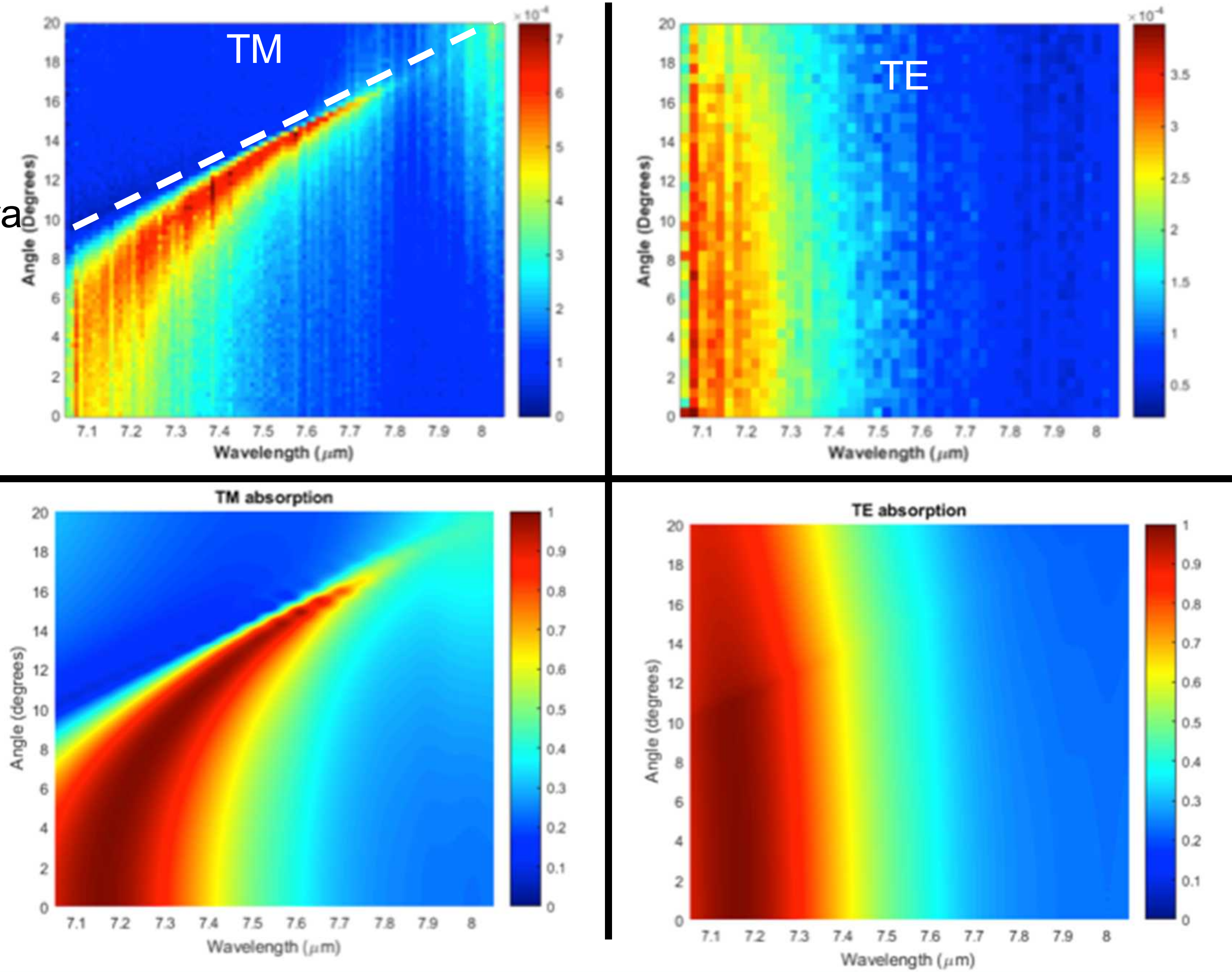
Rectenna mounted



Photocurrent spectrum

Measured Angular Photocurrent Spectra at V=0

Simulated Absorption



Summary

- ***SiO_2 optical phonons give epsilon near unity Re(ε) ≅ 1 (ENU) result in large transverse field enhancement in tunnel barrier.***
- Photonic surface modes couple thruENU dispersion to create large field in device.
  - 1D -- Spoof surface plasmon mode (2P < λ)
  - 2D – Surface diffracted mode (P ≅ λ)
- Leads to enhanced IR tunneling photocurrent in ENU region.
- Potentially new large area heat to electrical current (Thermoelectric) conversion method.

Oxide Optical Phonons

$$\epsilon(\omega) = \epsilon_\infty \left(1 - \frac{\omega_{pl}^2}{\omega^2 - \omega_T^2 + i\gamma\omega} \right),$$

$$\omega_{pl}^2 = 4\pi e^2 n / m_e \epsilon_\infty$$

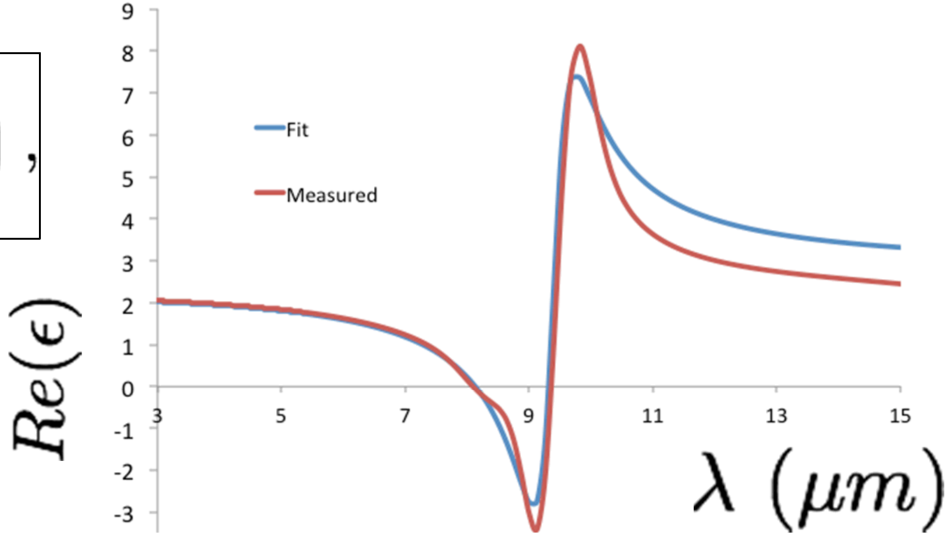
$$\epsilon_\infty = 2.1$$

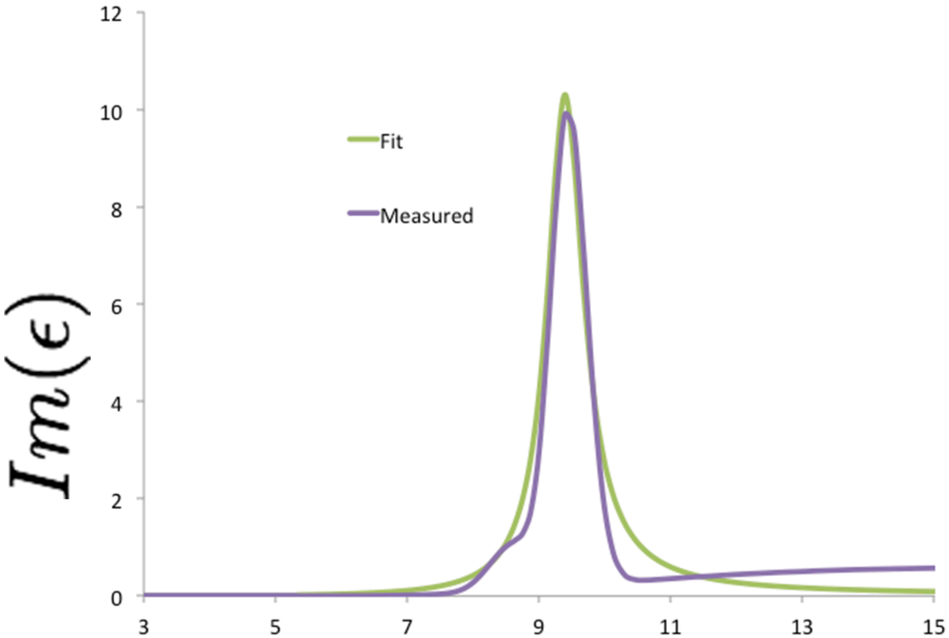
$$\omega_T = 1/9.38 \quad (\mu m^{-1})$$

$$\omega_{LO} = 1/7.96 \quad (\mu m^{-1})$$

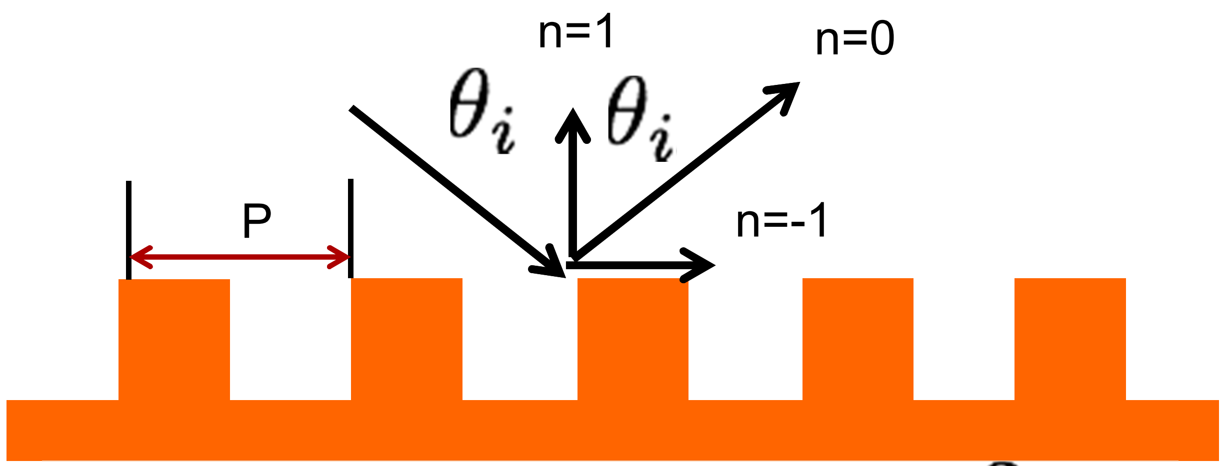
$$\omega_{pl} = 1/15.77 \quad (\mu m^{-1})$$

$$\gamma = 0.0077 \quad (\mu m^{-1})$$





Surface diffraction mode



$$k(\sin(\theta_i) - \sin(\theta_r^n)) = \frac{2\pi}{P} n,$$

$$\sin(\theta_r^{-1}) = 1$$

$$\theta_i = \sin^{-1}(1 - \lambda/P)$$

$$P \leq \lambda < 2P$$