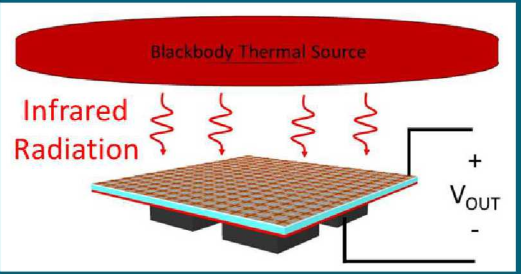
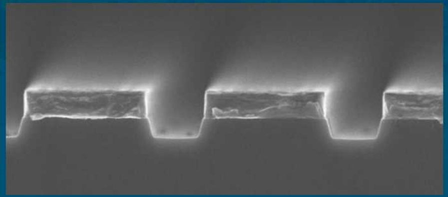
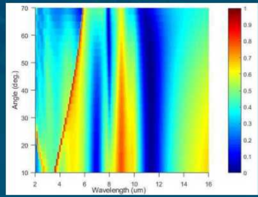
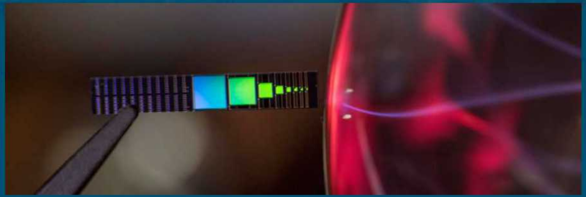
SAND2019-2427C

Infrared Nanoantenna-Coupled Rectenna for Energy Harvesting









PRESENTED BY

Joshua Shank

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The Problem

We have systems that require:

- Low levels of power
- For a very long time
- Solar power is not available

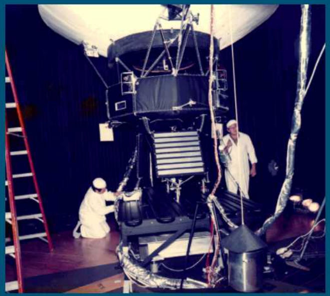
Space Systems

- Satellites
- Probes
- Landers
- Extraterrestrial Experiments

Terrestrial Systems

- Remote Outposts
- Cars
- Hot Machinery

(Cars, Hot Machinery) } Waste heat recovery


Voyager 1 and 2


Apollo ALSEP


Viking 1 and 2


Cassini


New Horizons


Curiosity Rover

*all images courtesy of Wikipedia

State-of-the-Art Solutions

Need to convert heat into electricity

Thermoelectrics
- Materials are difficult to manufacture, fragile, and expensive
  - BiTe, PbTe, $CoAs_3$
- Require high temperatures to operate
- Must physically touch the hot source → Cracking

Thermophotovoltaics
- Difficult materials to work with
  - InGaAsSb
- Require high temperatures to operate
- **Non-contact (use radiated IR light)**

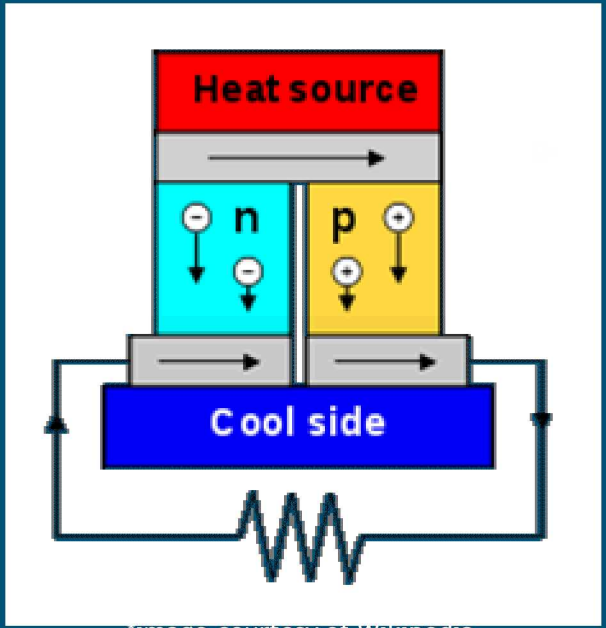


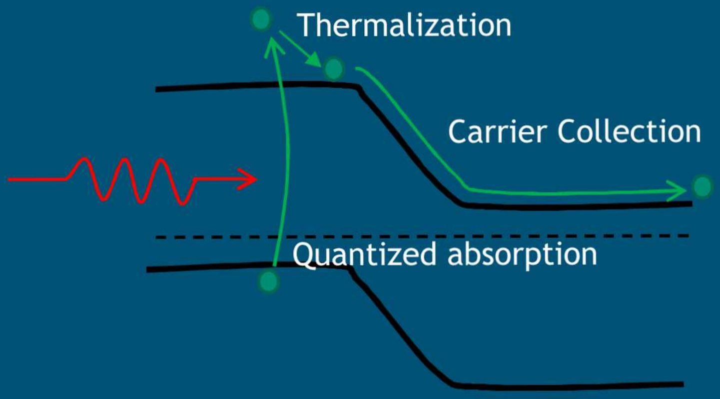
*image courtesy of Wikipedia

New Solution - Rectennas

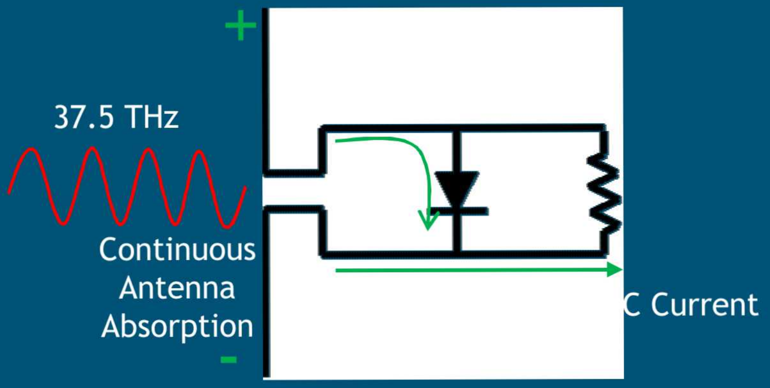
Take the non-contact idea from thermophotovoltaics

Use the continuous (wave) properties of light instead of the quantum (particle) properties

Photovoltaics



Rectennas



Rectenna History

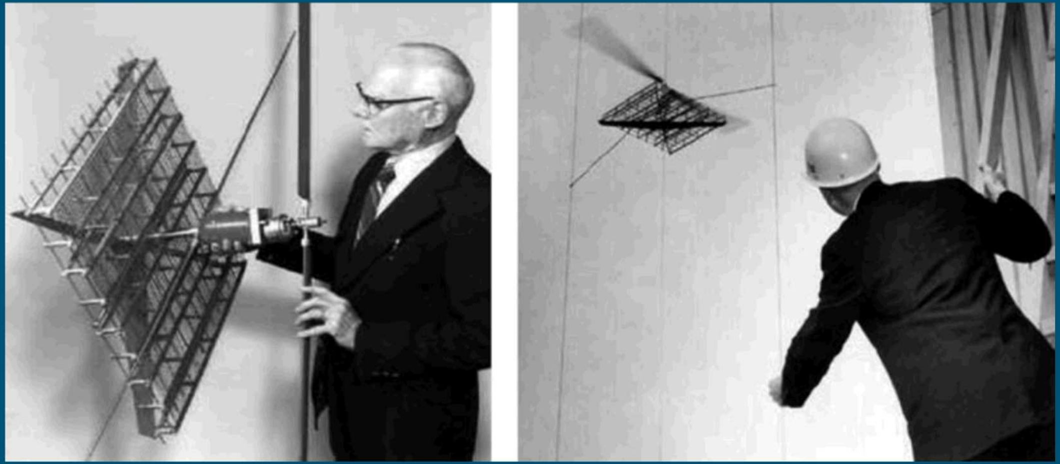
Developed in 1960's for RF power transmission

Highest reported efficiency > 92%

- Carnot Efficiency Limits?
- **Narrow Band Sources**

Made possible by a new high speed diode (Schottky diode)

- **This problem gets worse at optical frequencies**



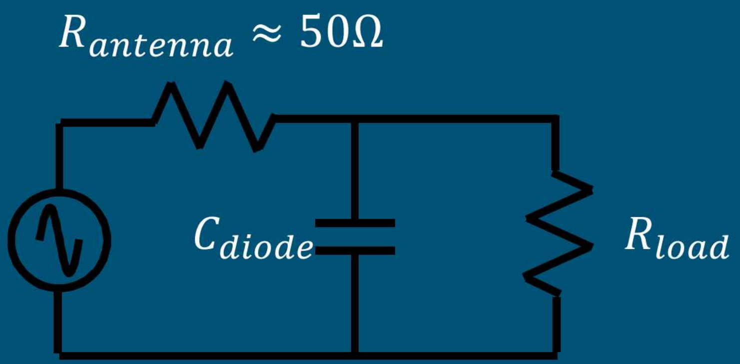
An early rectenna powered helicopter
Brown, *J. Microwave Power*, 1966

$$f_c = \frac{1}{2\pi RC}$$

$f = 2.45\ GHz$

$\tau \approx 400ps$

$C < 1.3pF$



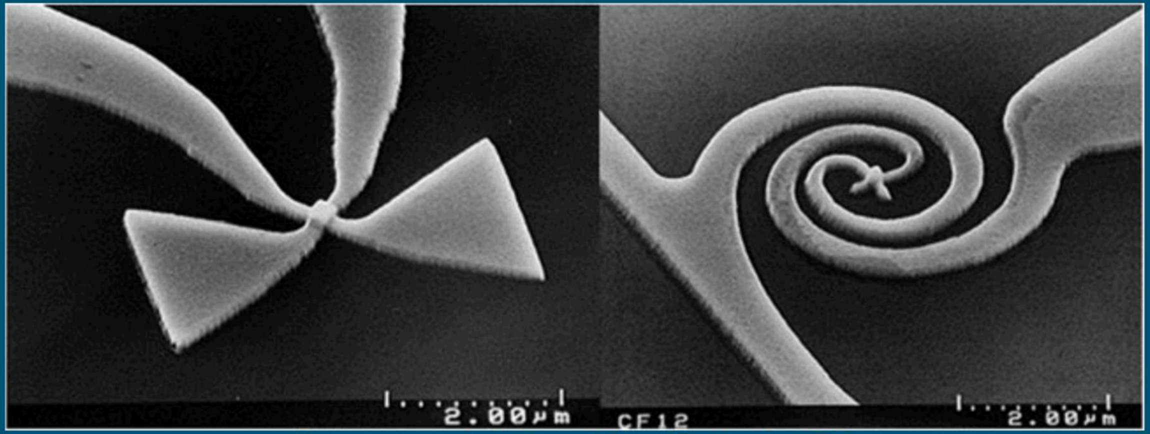
Infrared Rectenna Problems

RC time constant and transport speed

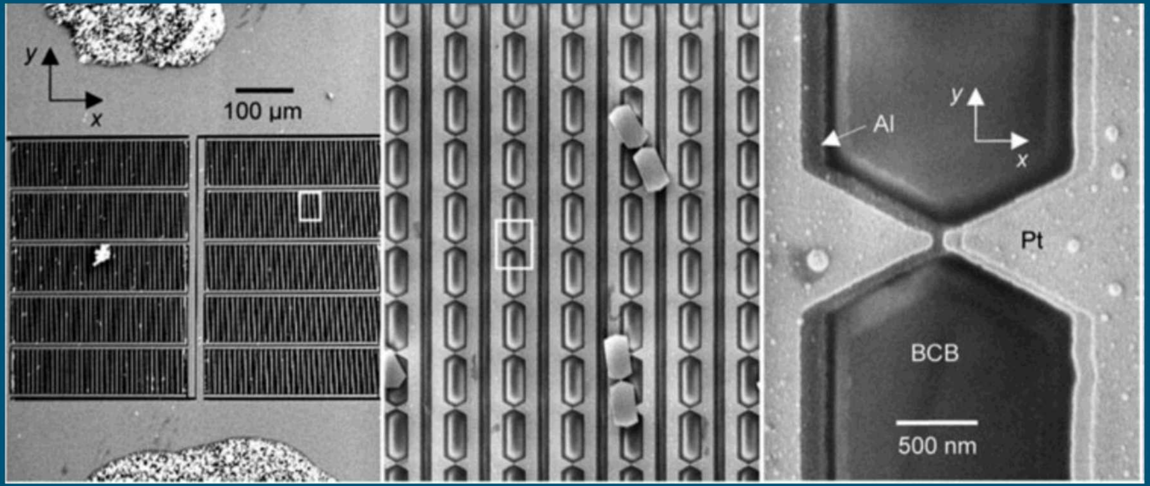
- $f \approx 40\, THz$
- $C < 80\, aF$ → **limited by parasitic capacitance**
  - Really small devices
- $\tau \approx 25\, fs$ → **limited by electron saturation velocity**
  - Tunnel diodes

Manufacturability

- Need large area manufacturing
  - Antenna dimensions must match wavelength
  - Capacitors must be really small
- Avoid exotic materials for tunnel diodes



Fumeaux et. al. *Infrared Phys. Technol.*, 1998



Kinzel et al., *Microwave Opt. Technol. Lett.*, 2013

Our Solution

Travelling wave design

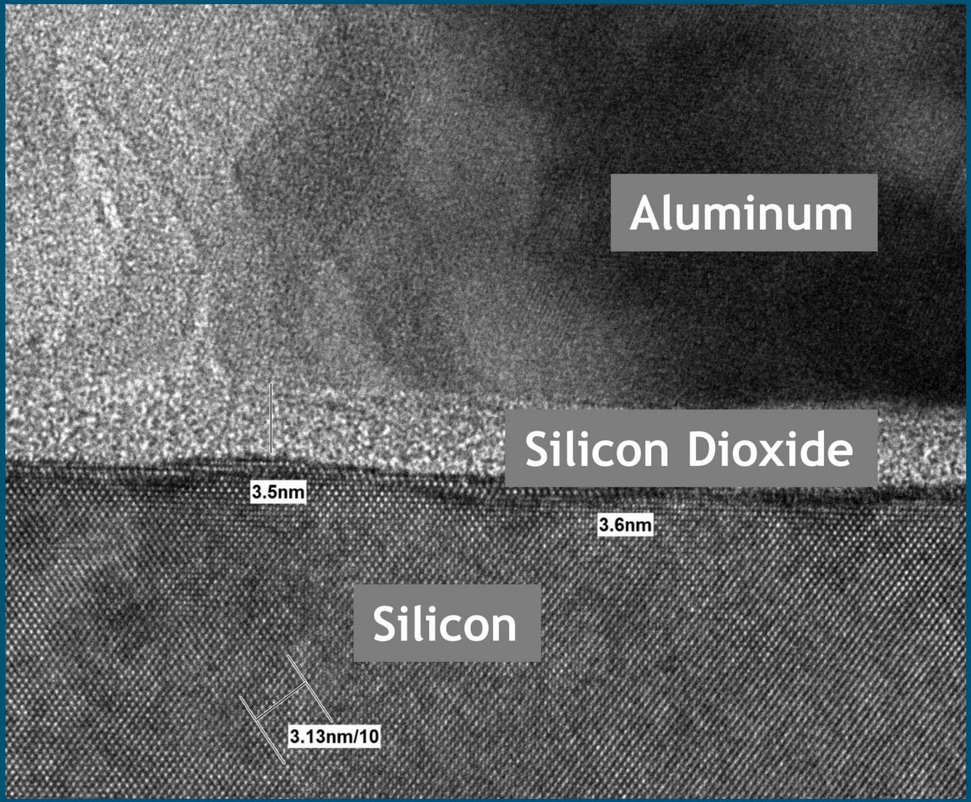
- Use distributed R and C rather than discrete devices

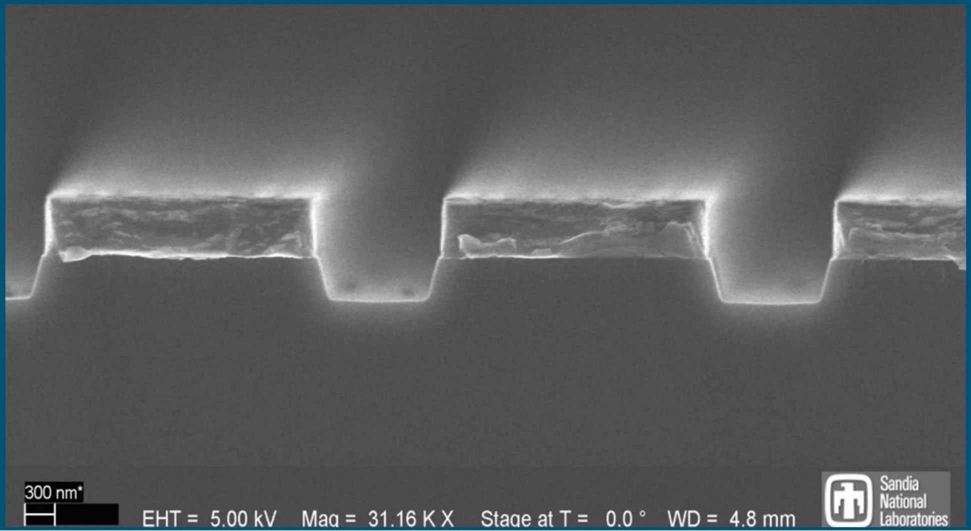
MOS tunnel diode

- CMOS compatible process
- Controlled tunnel oxide (Thermal SiO_2 on Si)
- Large area manufacturing
- Standard, cheap materials (Si, Sio_2, Al)

Structured surface antenna

- Easy planar geometry
- Design light coupling with spoof plasmons





Tasks

Get light in

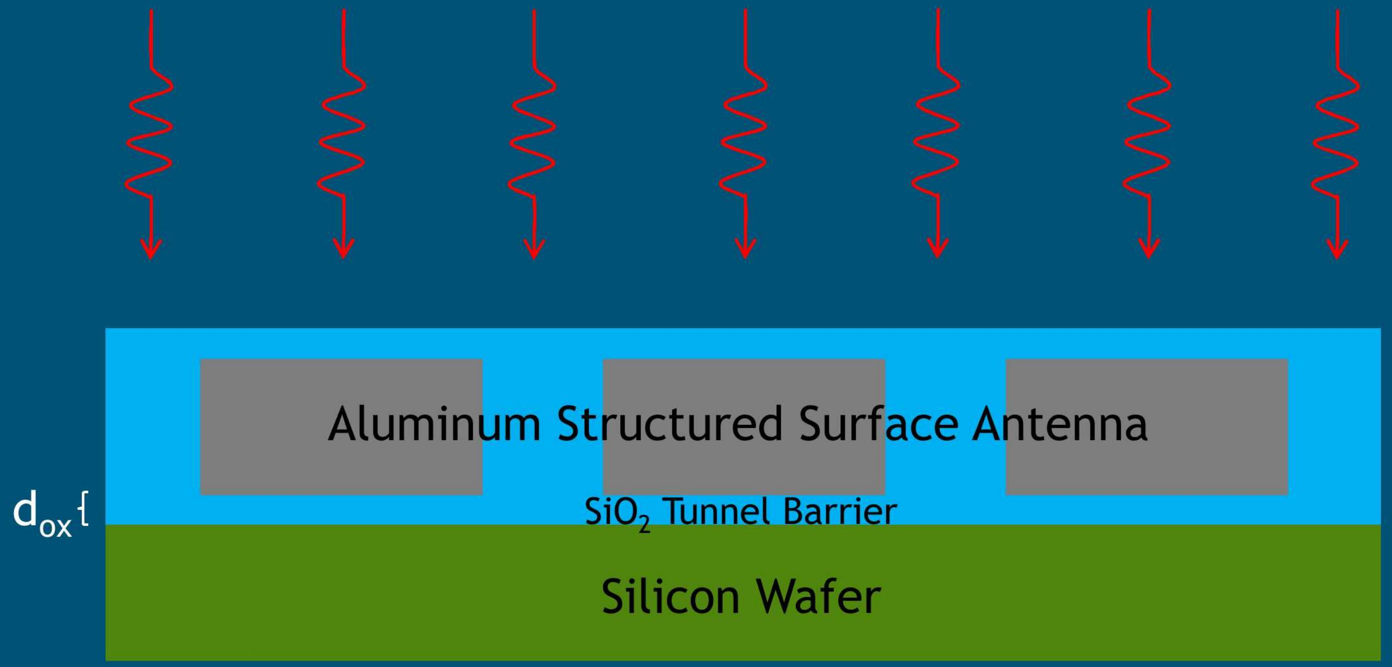
- Reflected light generates no power

Concentrate E-field

- $V = E \cdot d_{ox}$

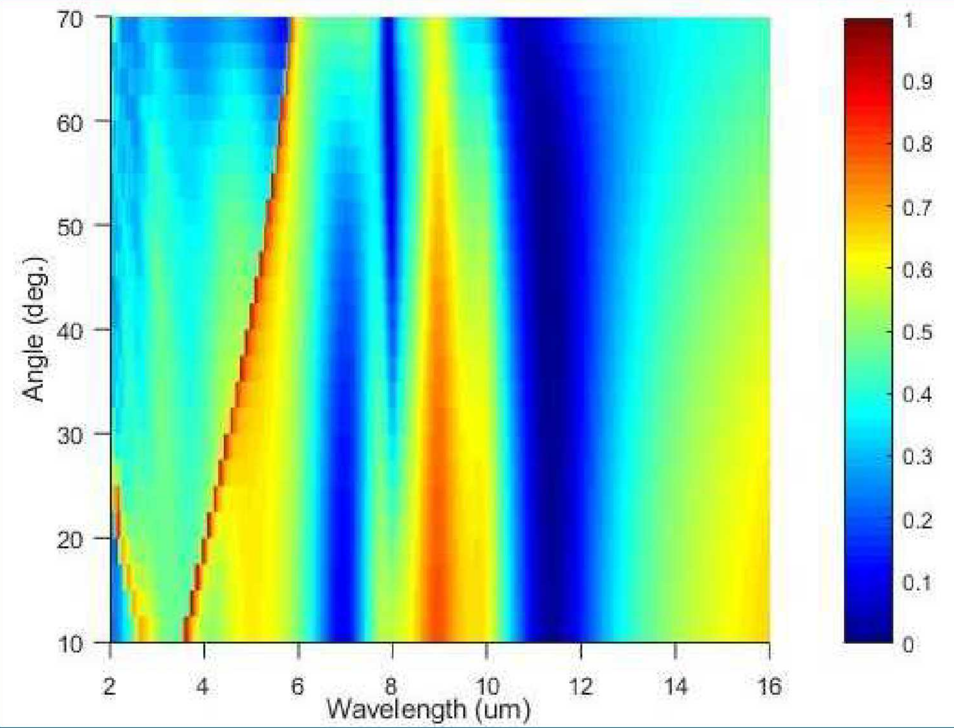
Rectify

- Turn an AC field into DC current

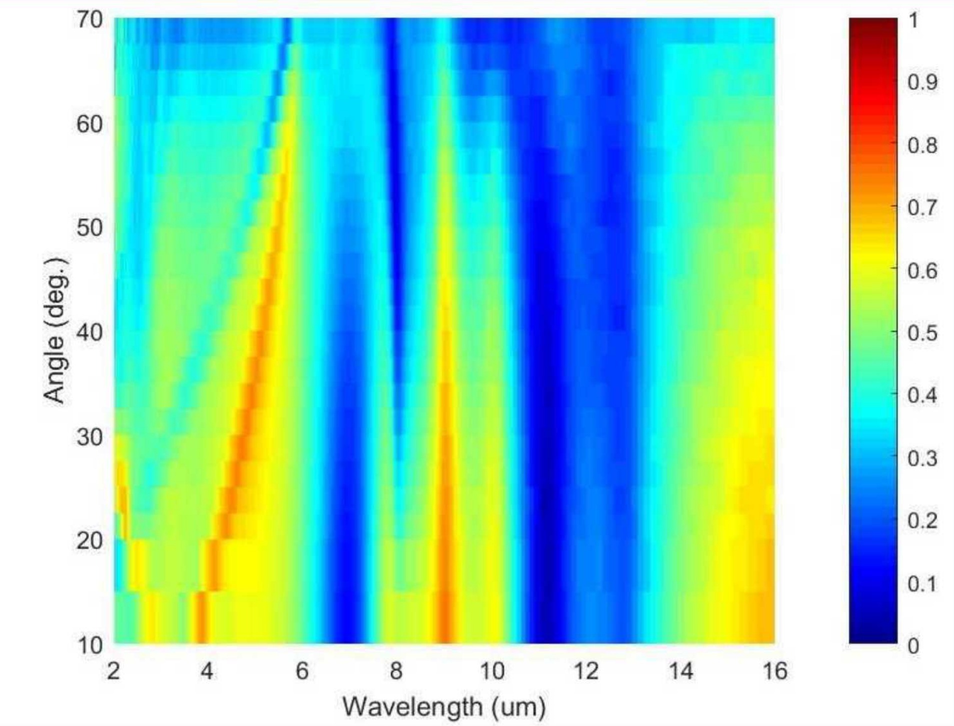


Getting Light In

Structured surface designed to couple light in at 7 – 8 um to match low-temperature thermal sources



Simulated Reflection Map



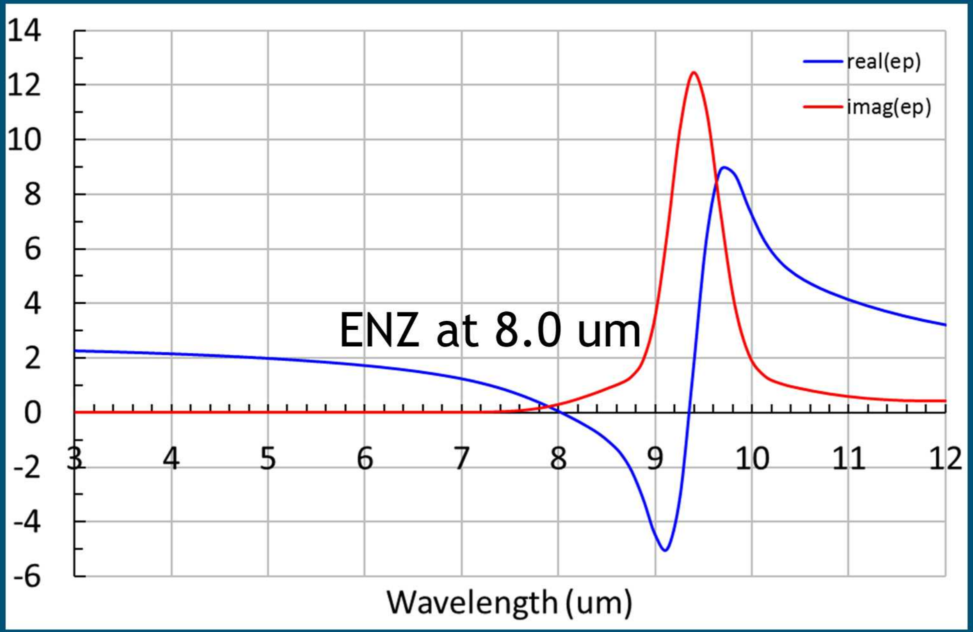
Measured Reflection Map

Spoof plasmon mode observed around 7 um at low angles

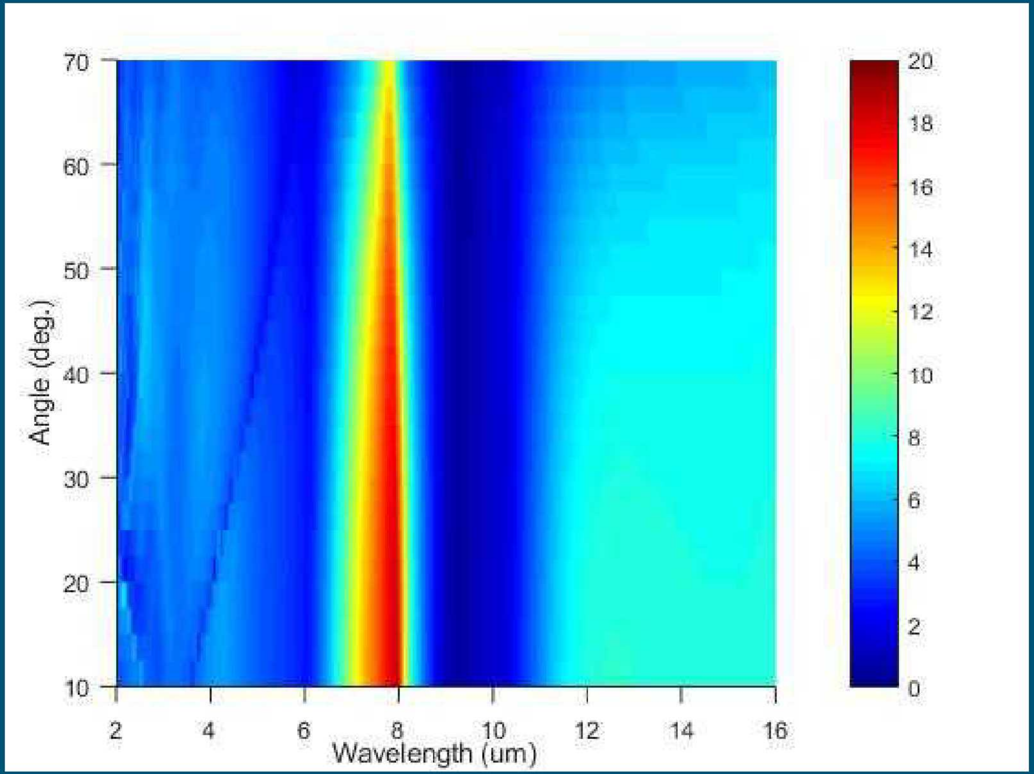
Berreman mode observed around 8 um at high angles

Concentrating the E-field

Use an Epsilon Near Zero (ENZ) material



Real and Imaginary Permittivity of SiO_2



Simulated Field Concentration

Field concentration due to Poisson's equation: $E_I = \frac{\varepsilon_M}{\varepsilon_I} E_M + \frac{\rho_S}{\varepsilon_I}$

$$\lim_{\varepsilon_I \to 0} E_I \to \infty$$

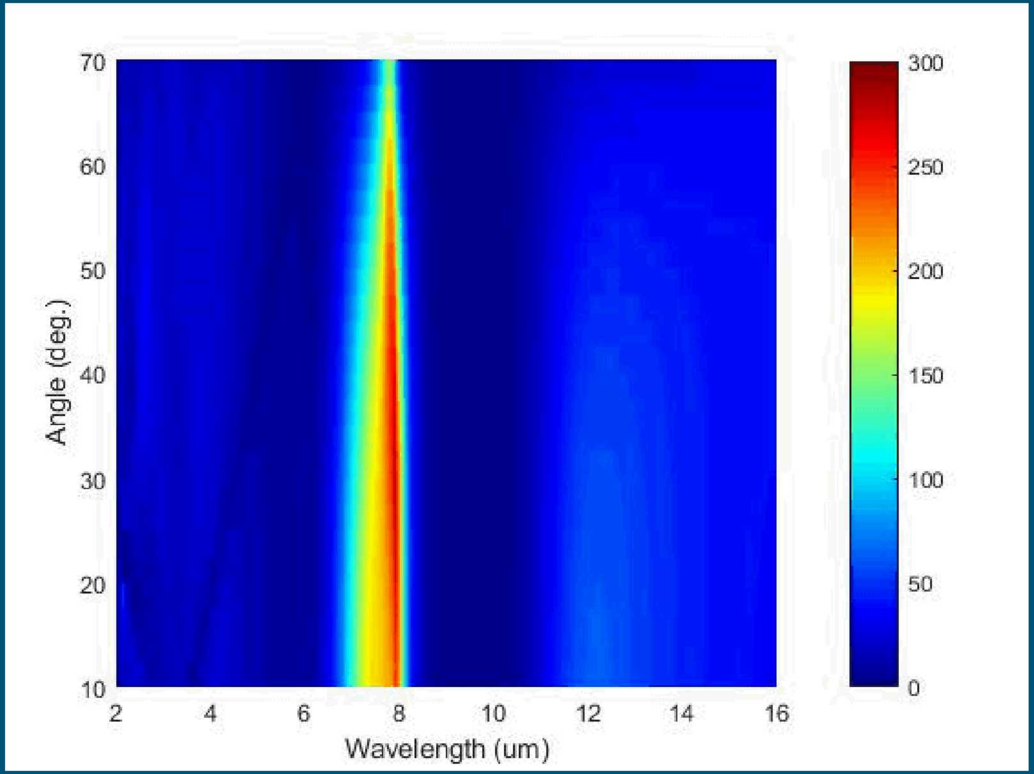
Figure of Merit

Electron Tunneling Current

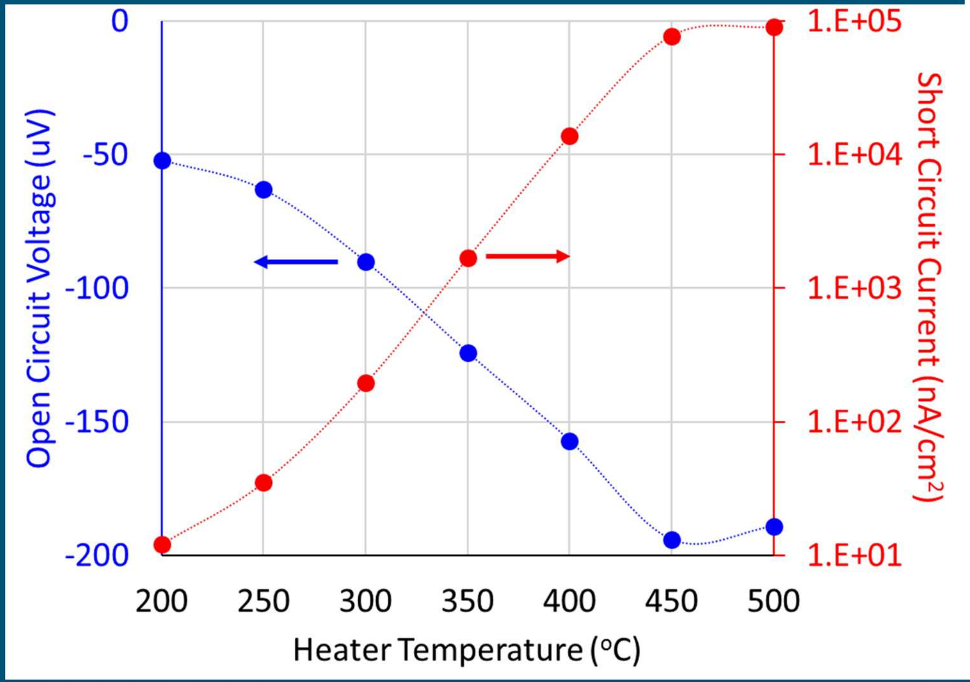
Couple Light In

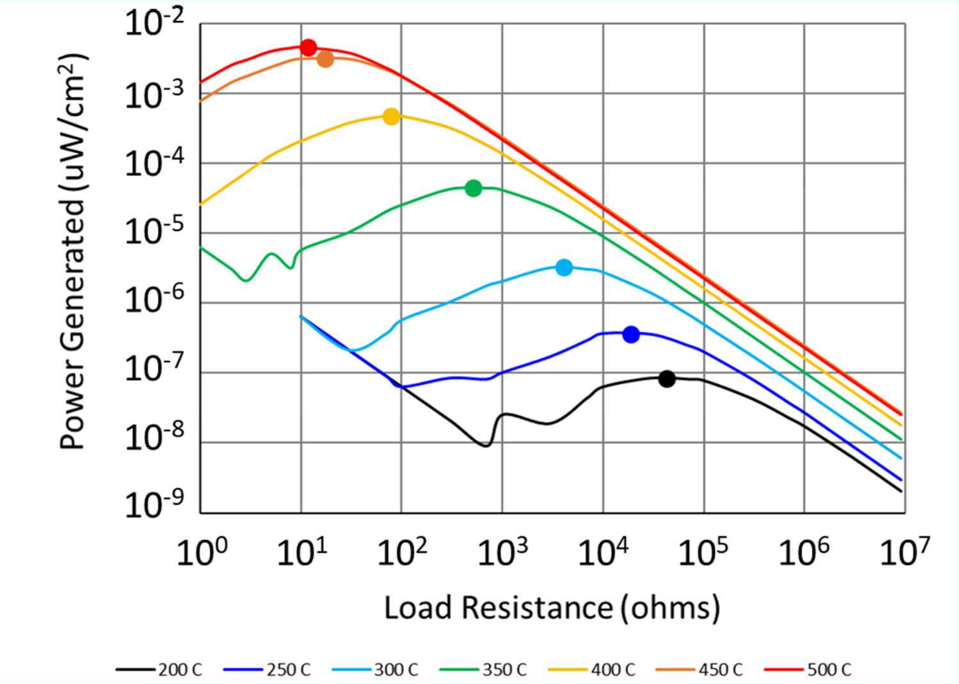
Concentrate Electric Field

$$J^{(1)} = AT^2 \left(\frac{m_r m_l}{m_{ox}^2}\right) 2Z_o \int_\nu (\mathbf{1} - \mathbf{R^2})\gamma^2 \left(\frac{q t_{ox}}{h\nu}\right) M_\nu^0(T)\mathrm{T}(\nu)\, d\nu$$



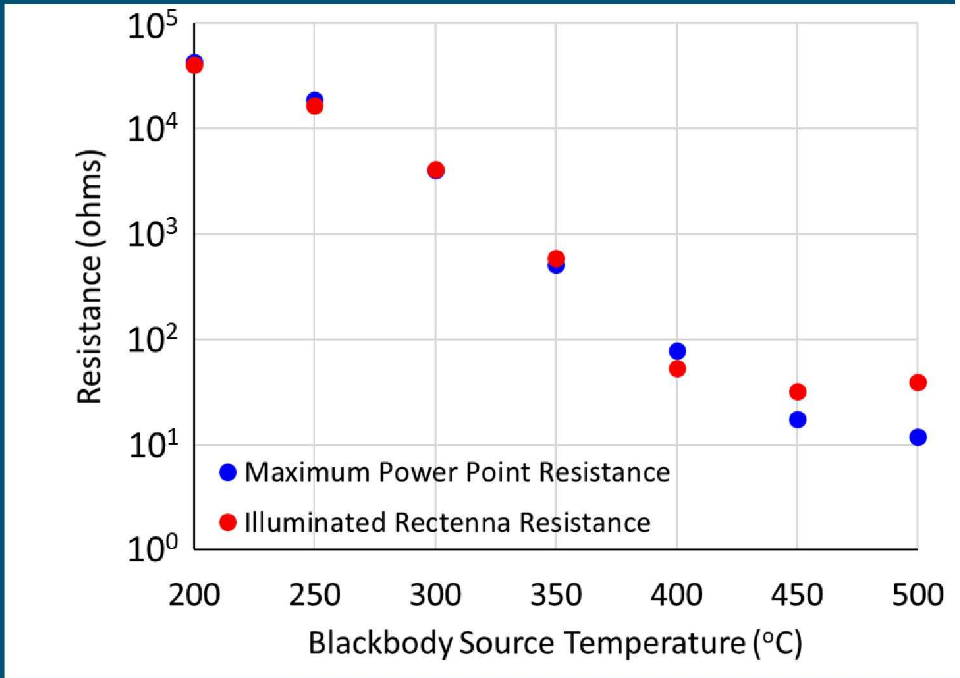
Power Generation

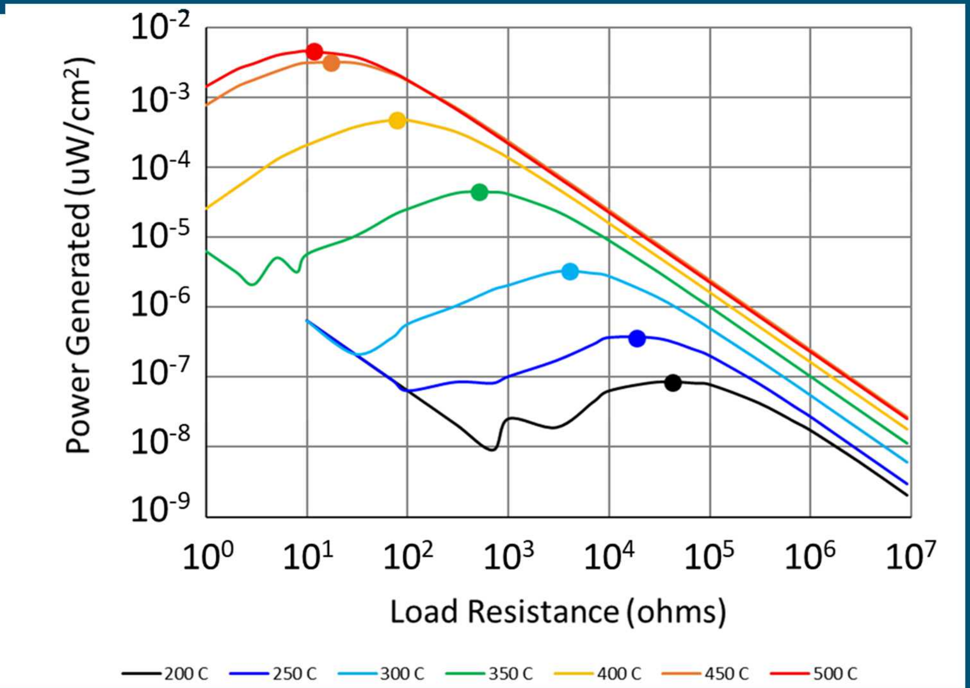




Generate power in the 2nd Quadrant → Rectenna

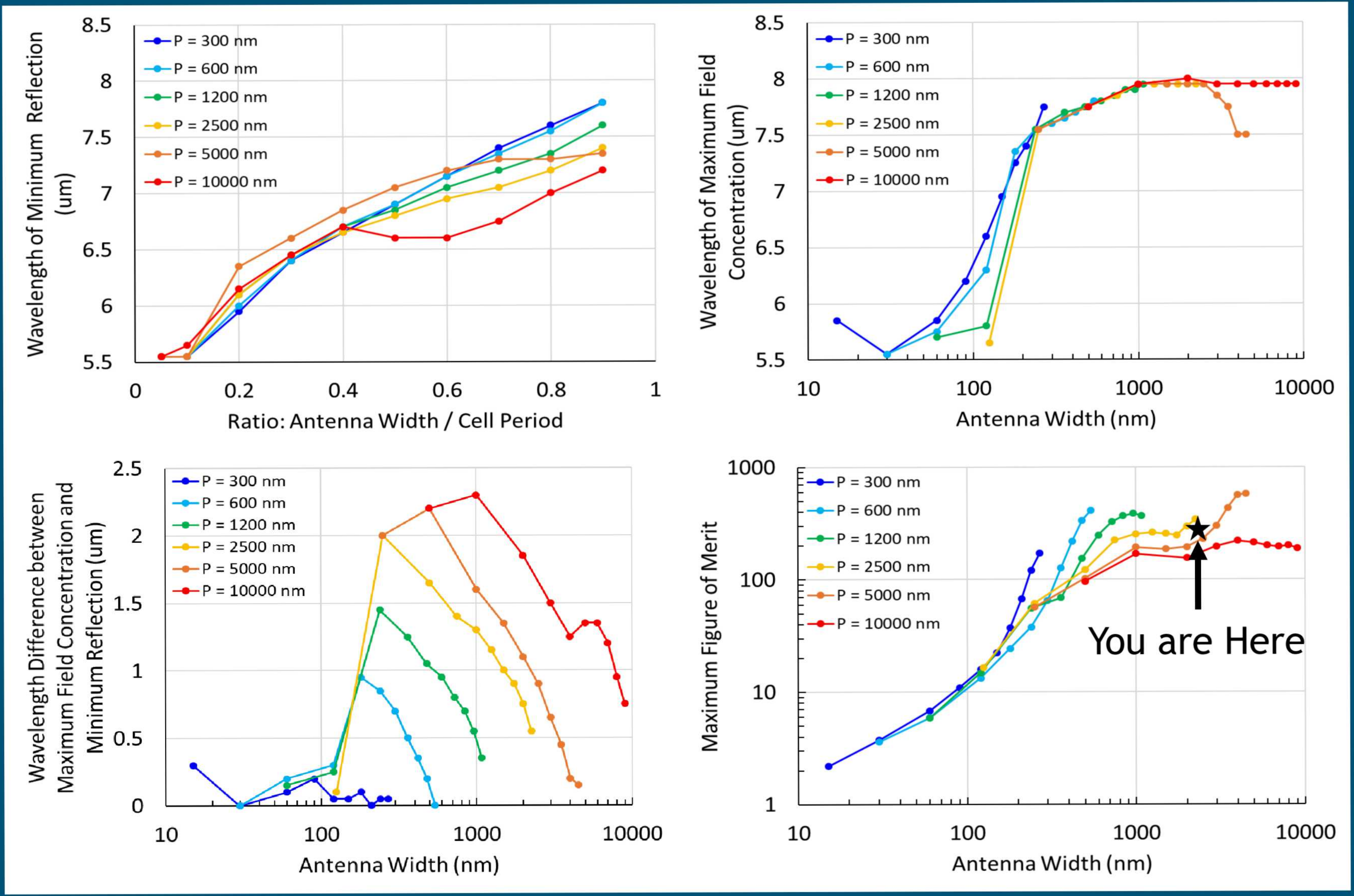
Impedance Matching





System behaves like an antenna/transmission line system

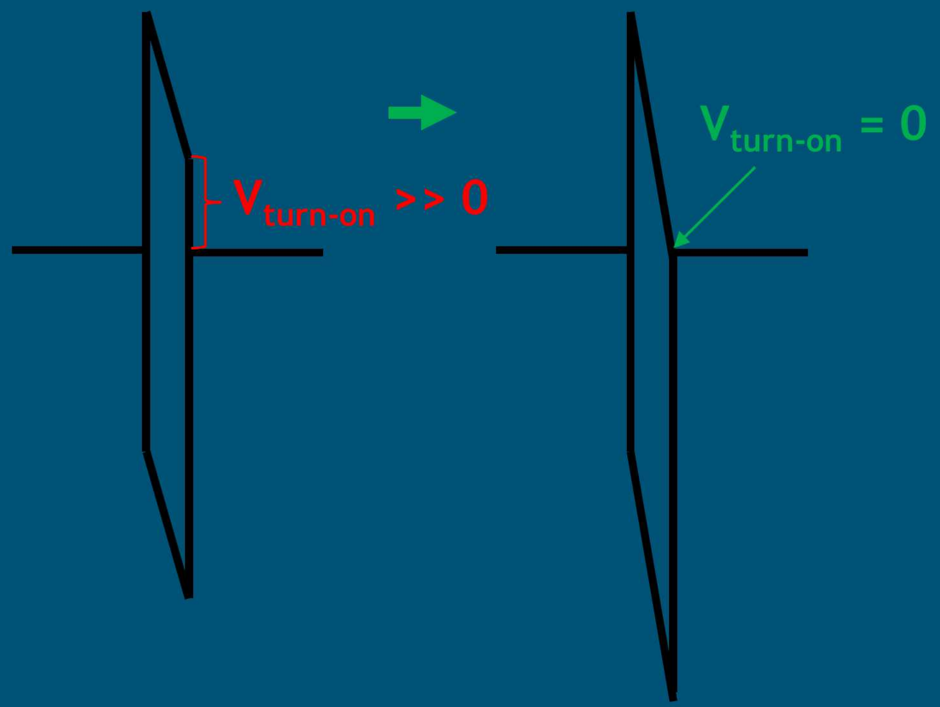
Spectra Matching



Ideas for Future Research

Improve MIM diodes at low voltages

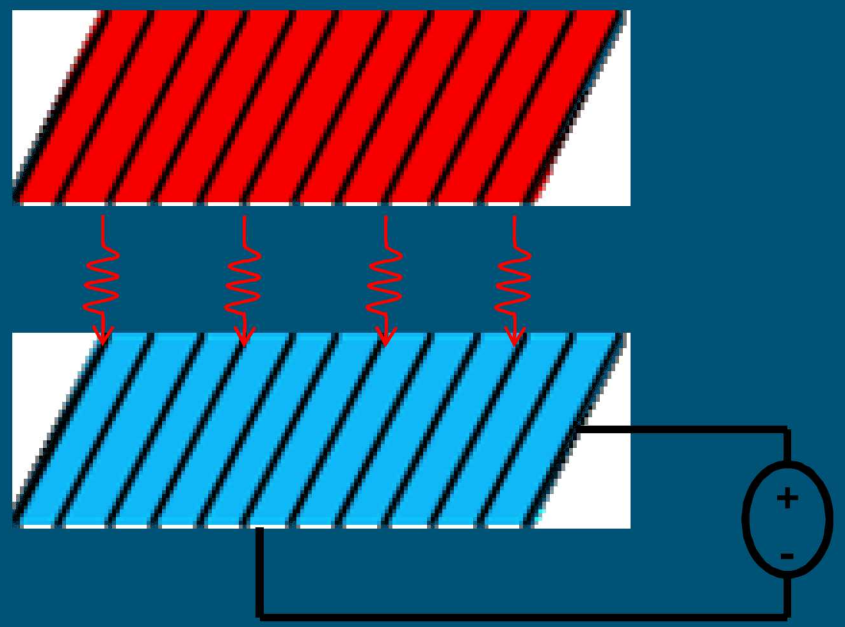
Requires materials work
- Work-function control
- Defect / trap management



Band limit emissions

RF Rectennas achieved high efficiency from narrow sources

Structured emitter on thermal source
- Match polarization
- Match coupling spectra



More Information

Davids et al. “Infrared rectification in a nanoantenna-coupled metal-oxide-semiconductor tunnel diode”, Nat. Nano, v. 10, 2015.

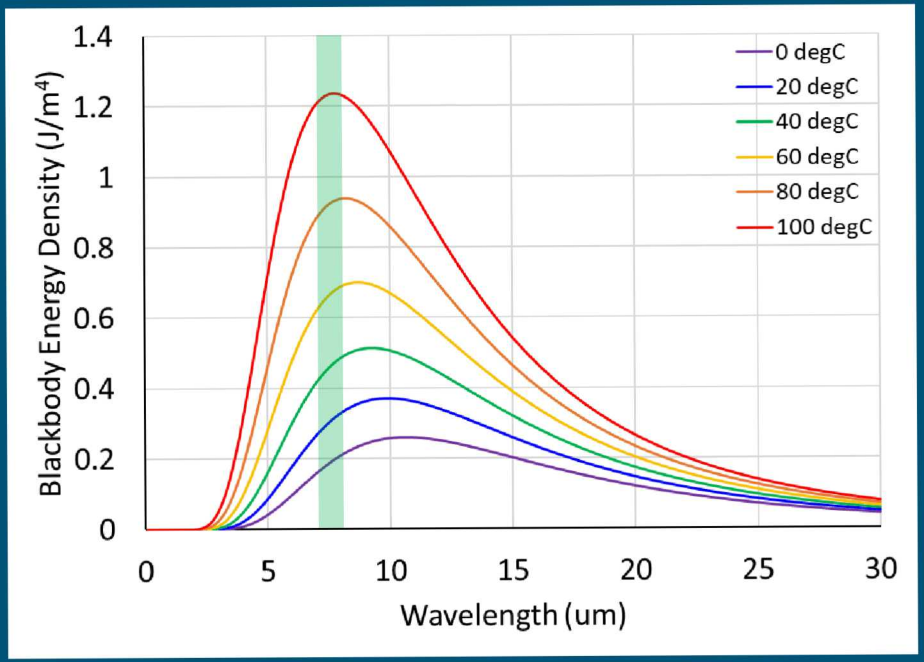
Kadlec et al. “Photon-Phonon-Enhanced Infrared Rectification in a Two-Dimensional Nanoantenna-Coupled Tunnel Diode”, Phys. Rev A, 2016.

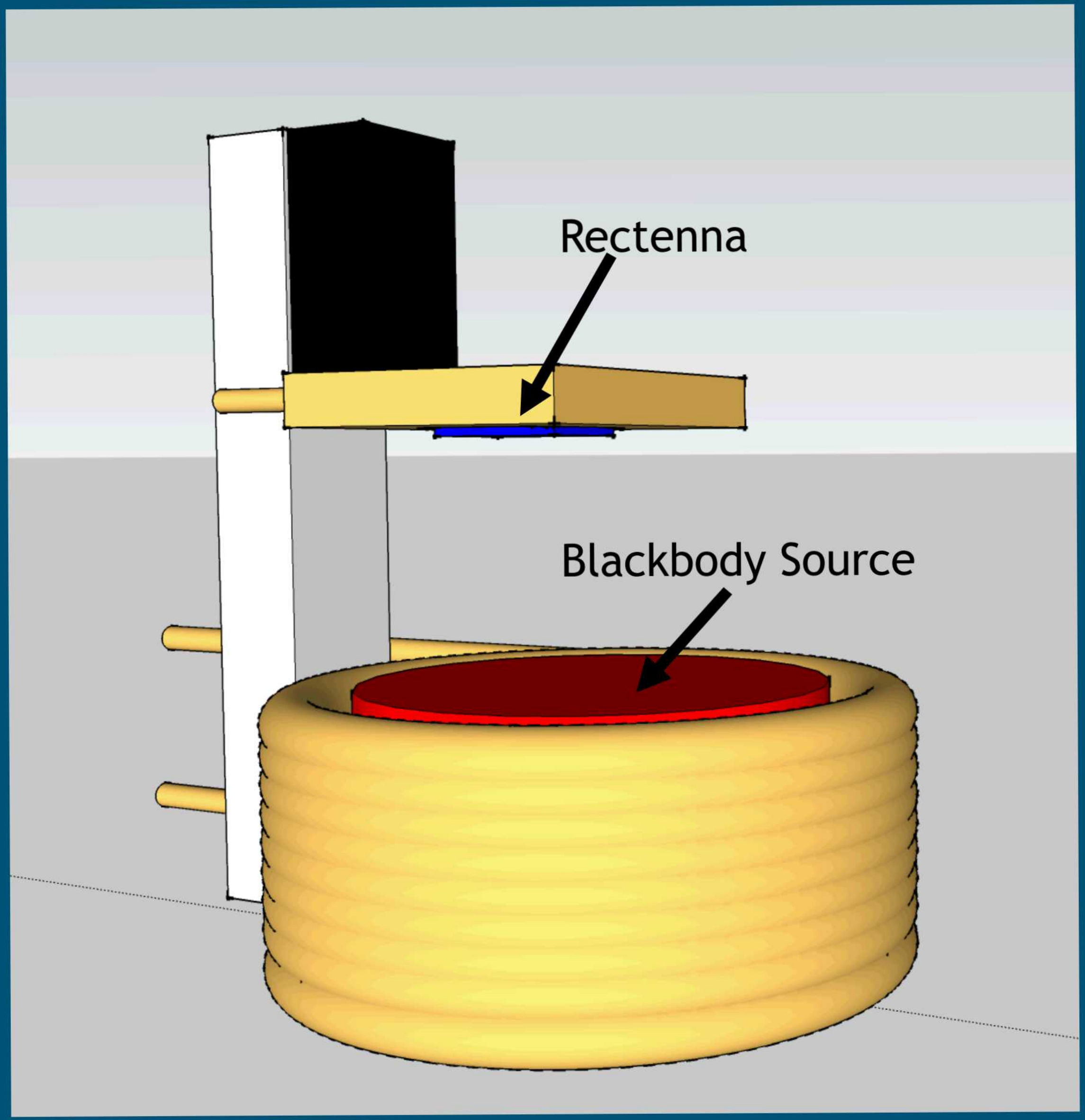
Davids et al. “Density matrix approach to photon-assisted tunneling in the transfer Hamiltonian formalism”, Phys. Rev B, 2018.

Shank et al. “Power generation from a radiative thermal source using a large-area infrared rectenna”, Phys. Rev A, 2018.

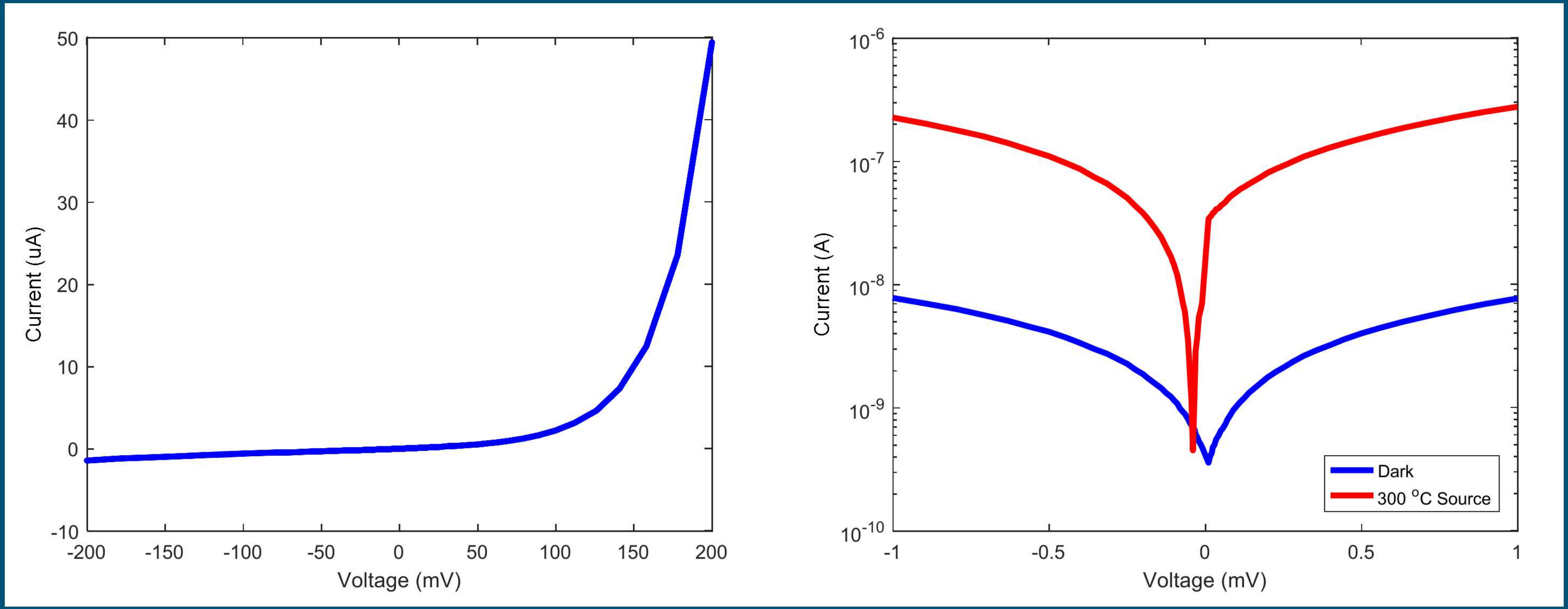
Come talk to me

Experimental Setup





Is it a diode?

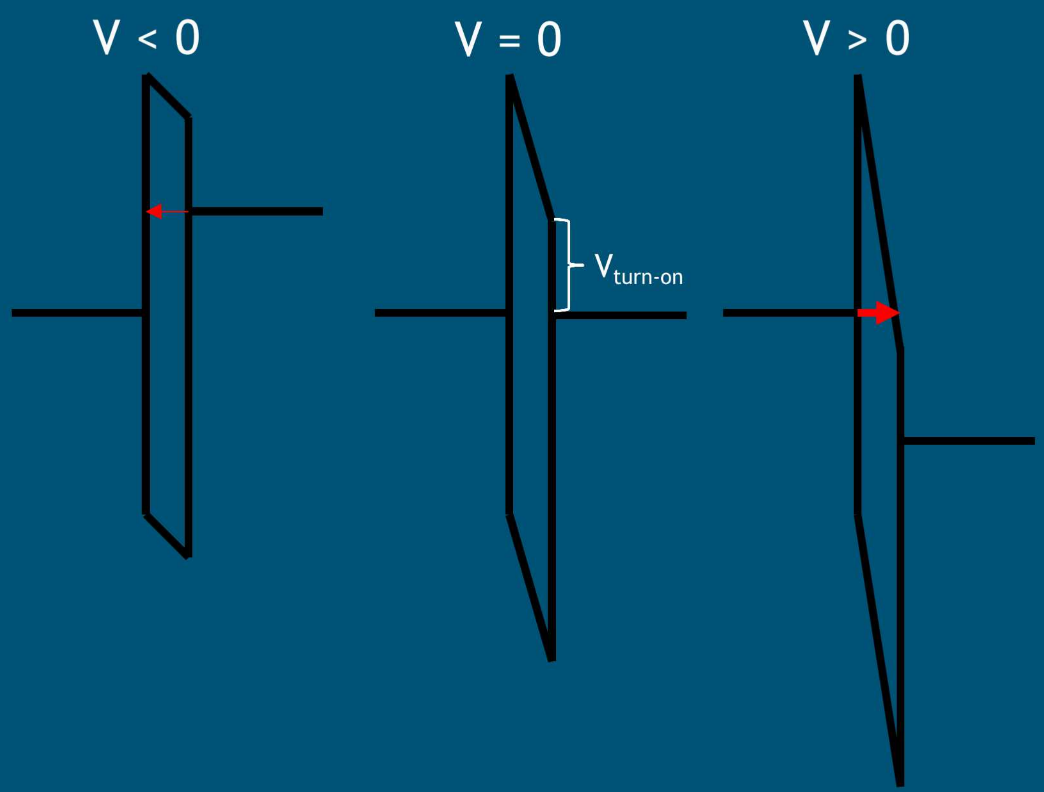


Substantial rectification around 100 mV

Induced voltage around 100 uV

Tunnel Diodes

Metal-Insulator-Metal (MIM)

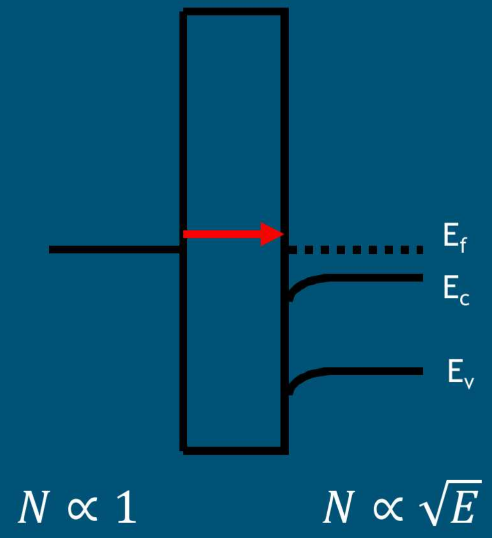


Fowler-Nordheim Tunneling

Shows greater asymmetry

Exhibits asymmetry at higher voltages

Metal-Insulator-Semiconductor (MIS^{deg})

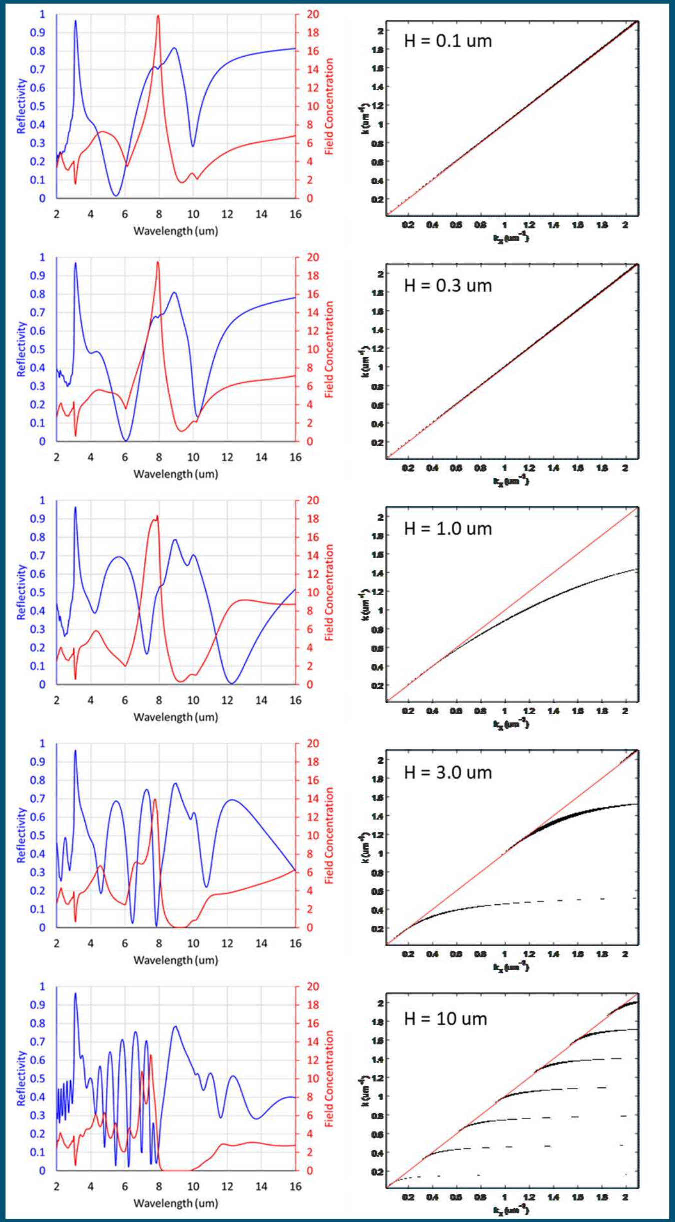


Differential Density of States Tunneling

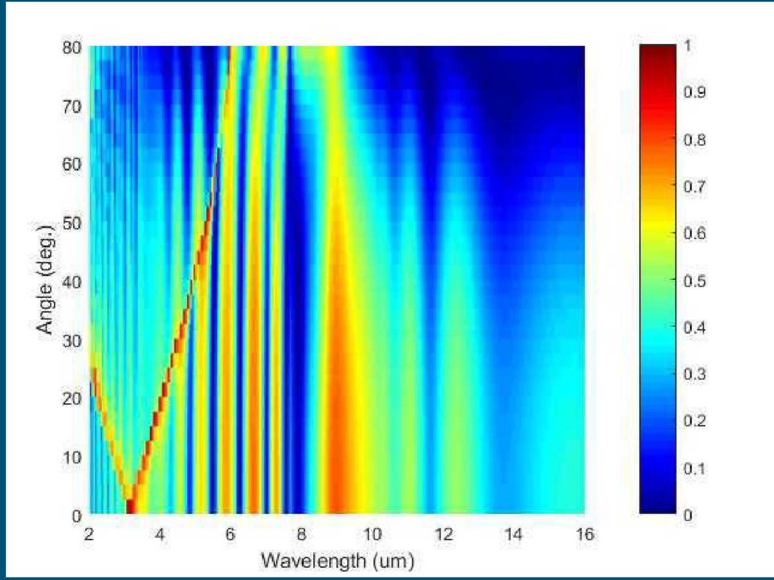
Should exhibit asymmetry at lower voltages

Shows less asymmetry

Multi-mode Rectennas



Reflection



Field Concentration

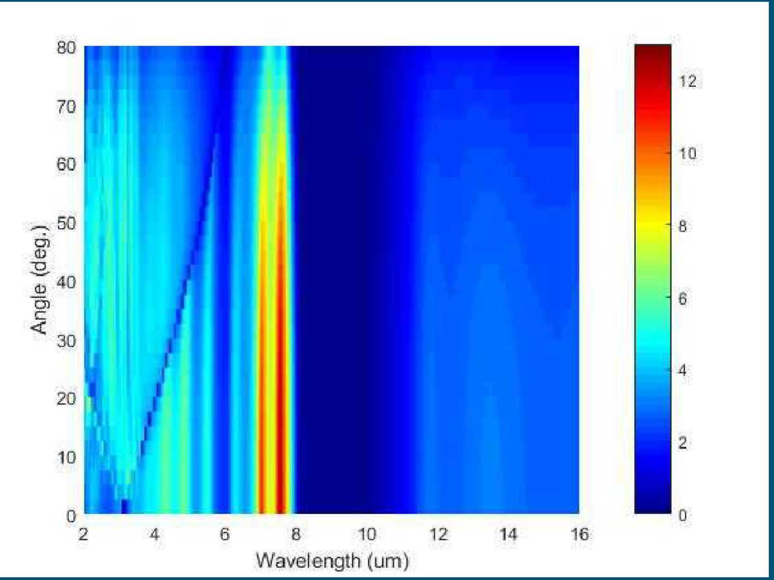
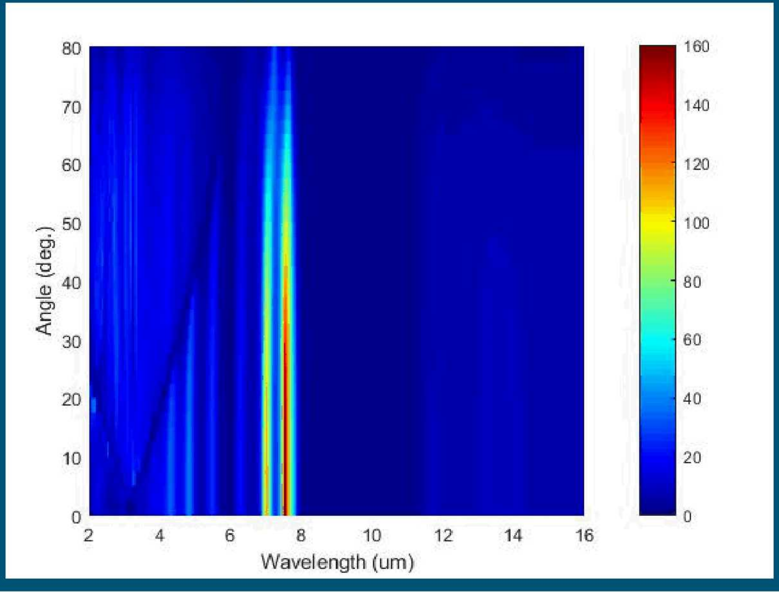


Figure of Merit



Process Variations