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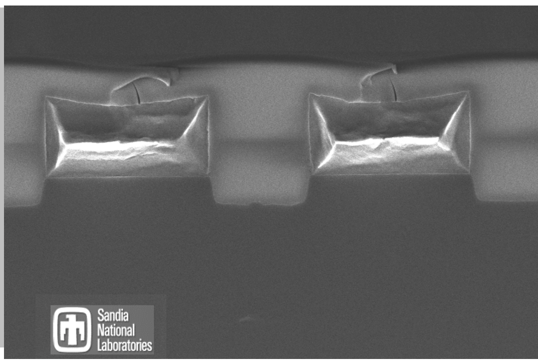

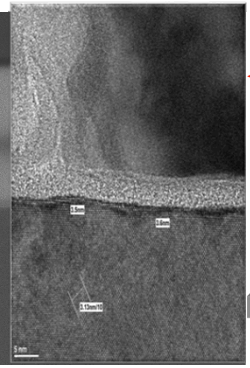

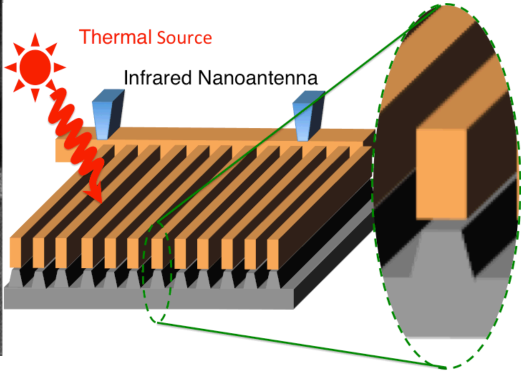

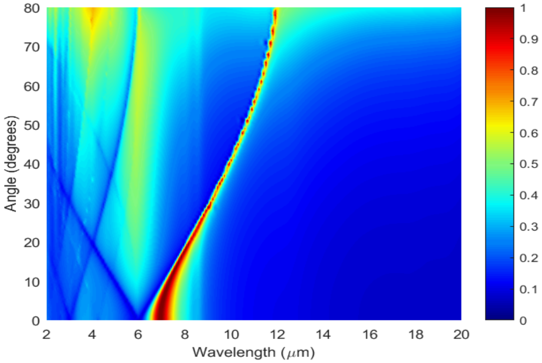

Vacuum radiometry of an infrared nanoantenna-coupled tunnel diode rectenna

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U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

Motivation

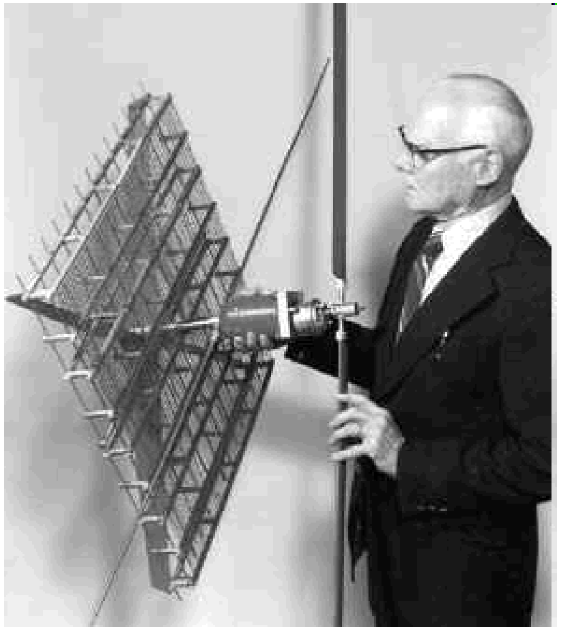
A new thermoelectric conversion mechanism (heat to electrical power) based on direct conversion of infrared radiation from a thermal source into electrical power.

- ***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.

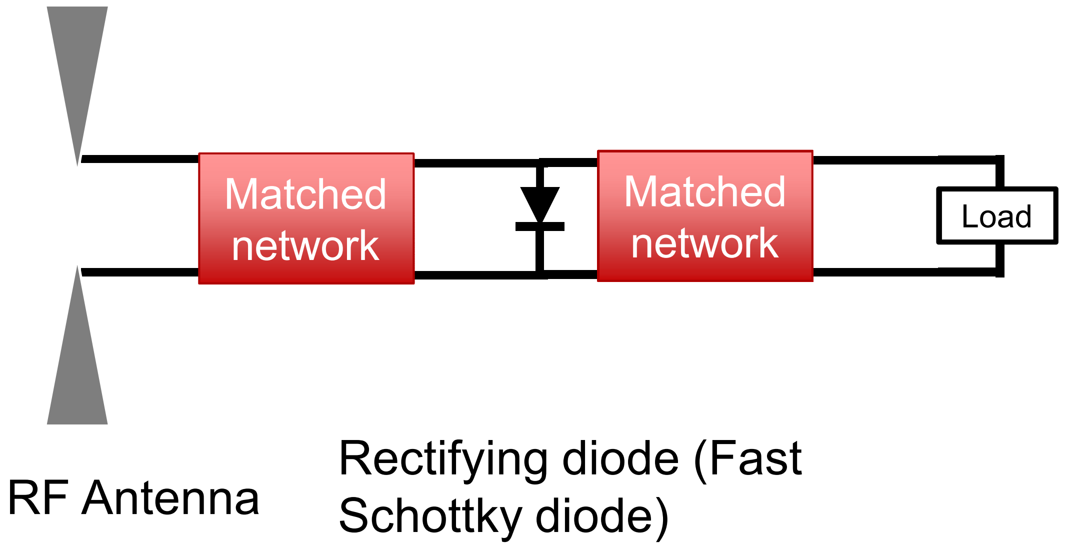
Outline

- Rectenna and direct conversion
  - RF rectenna
  - Scaling to infrared and optical regimes.
- Infrared rectenna
  - Different approach
    - Large-area antenna coupled MOS tunnel diodes
    - Photon Phonon enhanced tunneling (Field concentration)
    - 1D and 2D examples
- Radiometric measurement of rectennas
  - Thermal power supply
  - Radiometric measurement
  - Diode characteristics under thermal illumination
  - Power generation
- Summary and future directions

RF Rectenna & Wireless Power Transfer



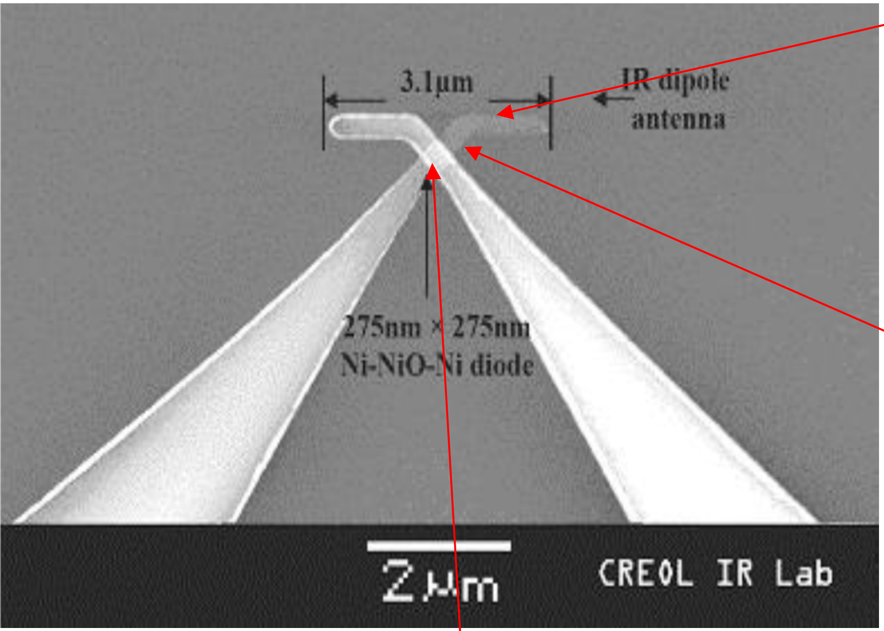
Bill Brown and RF rectenna powered helicopter.



- Rectenna concept has been around since 1966 and has demonstrated direct microwave power conversion.
- Power conversion efficiency is > 85%

Can it be scaled to IR and Visible frequencies?

Direct scaling of RF designs to IR



Antenna

- Vis-IR dipole antenna is small and requires advanced lithography.
- Effective area is very small ➔ weak signal.

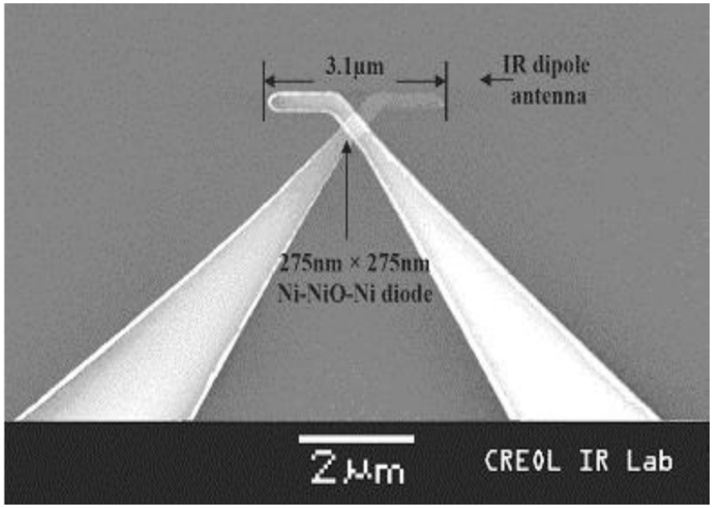
Transmission line

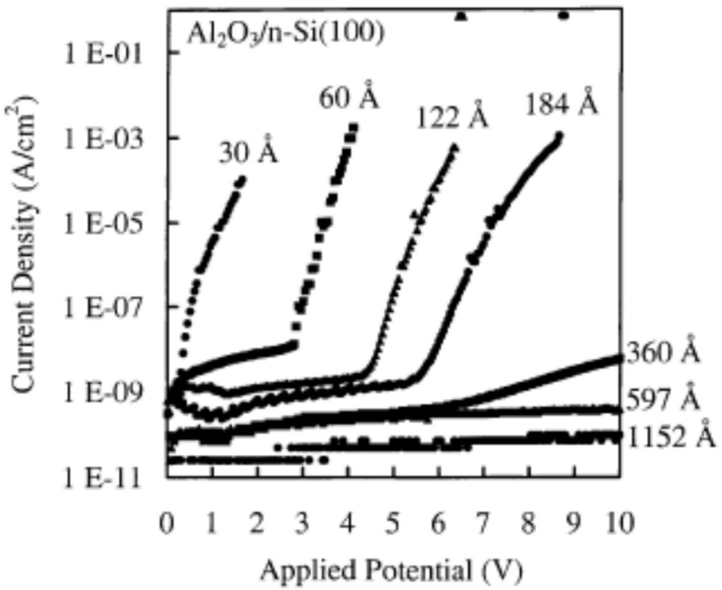
- Vis-IR transmission line is very lossy: must integrate diode very closely with antenna.
- Impedance matching into diode is difficult.

Rectifying Diode

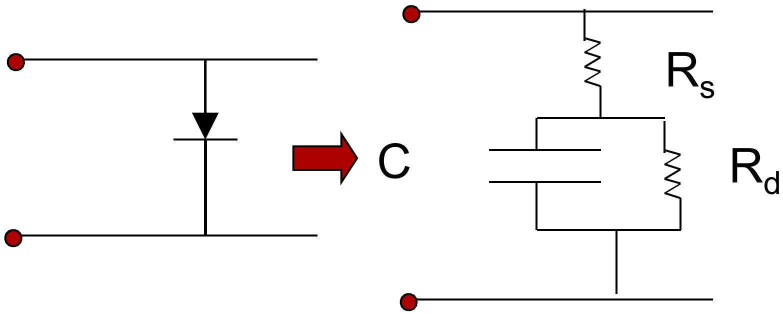
- Treated as lumped element as in RF designs.
- Capacitance needs to be small (attofarad) for Vis-IR speeds.
- Carrier based drift-diffusion is too slow to rectify Vis-IR signal.
- Resulting efficiency is less than 1%.

RC Scaling problems





Diode circuit model



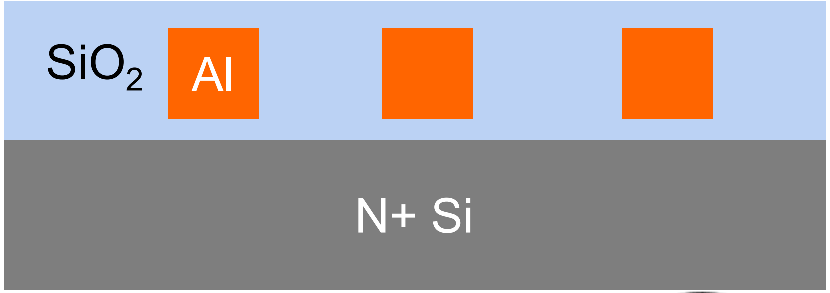
R_s is series resistance and R_d is diode differential resistance.

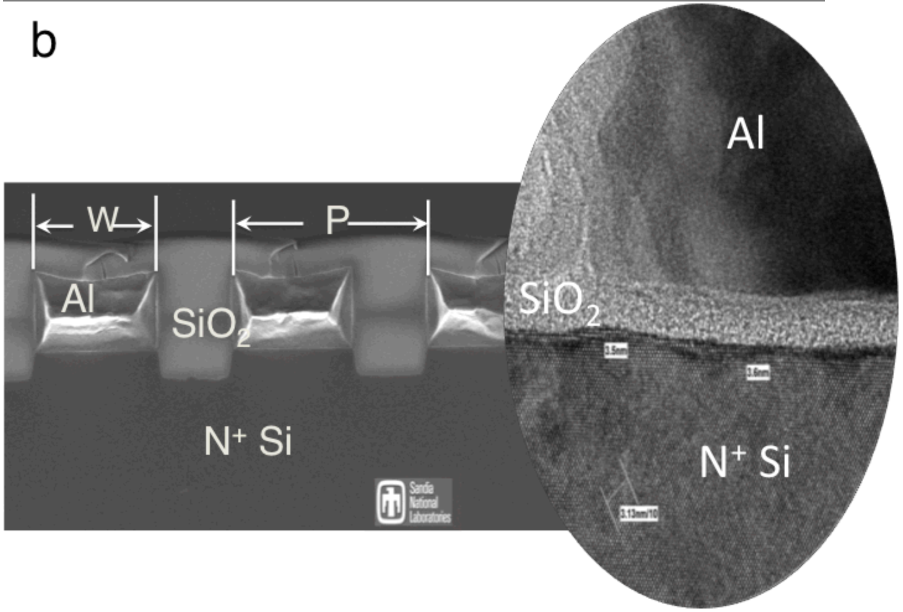
C is the diode capacitance.
For a MIM tunnel diode, thickness of insulator is between 30-50A.

Lumped element circuit model leads to problems

New Type of IR Rectenna

- Overcome limits of lumped elements.
- Direct rectification of infrared radiation.
- Large Area Distributed Antenna-coupled Tunnel Diode.
  - Leverage CMOS
- High Field concentration in nanoscale gaps.
  - Use SiO_2 Restrahlen band

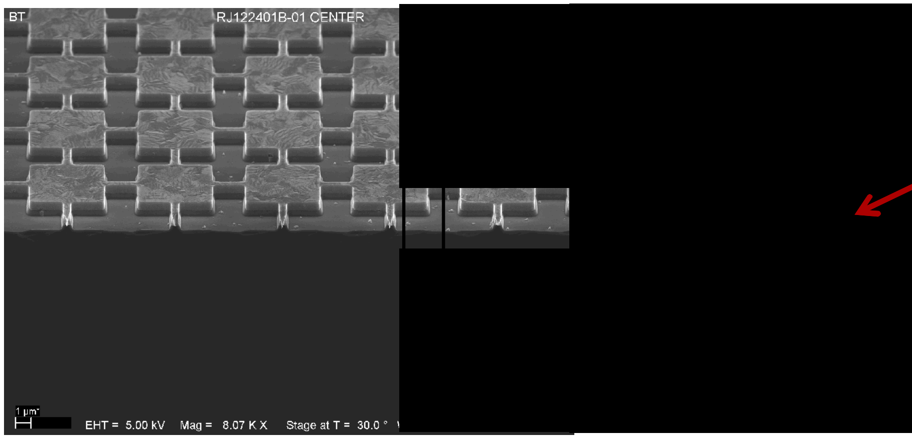




[1] P. S. Davids,et.al., Nature nanotechnology, 10(12):1033–1038, 2015.
[2] J. C. Ginn,et.al., Journal of Applied Physics, 110(4):043110, 2011.
[3] E. A. Kadlec,et.al., Physical Review Applied, 6(6):064019, 2016.

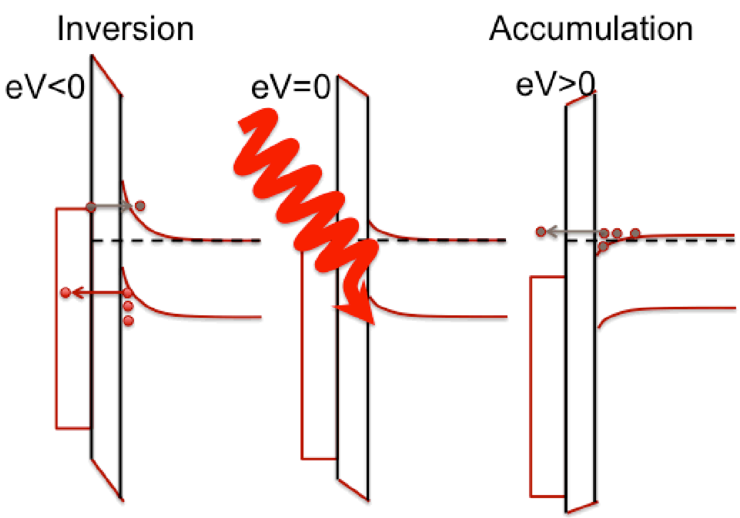
IR Rectenna: New Approach

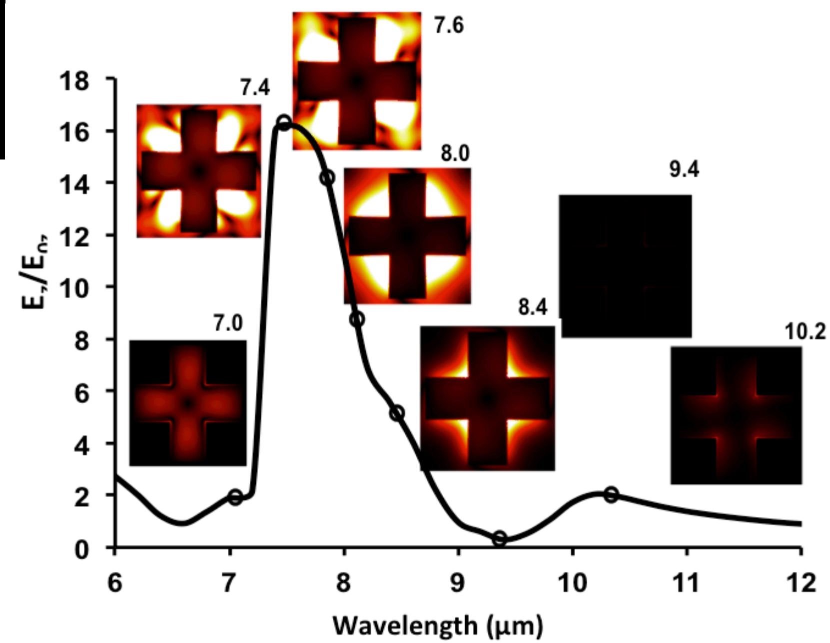
Large area distributed antenna-coupled tunnel diode



3-4nm thick oxide

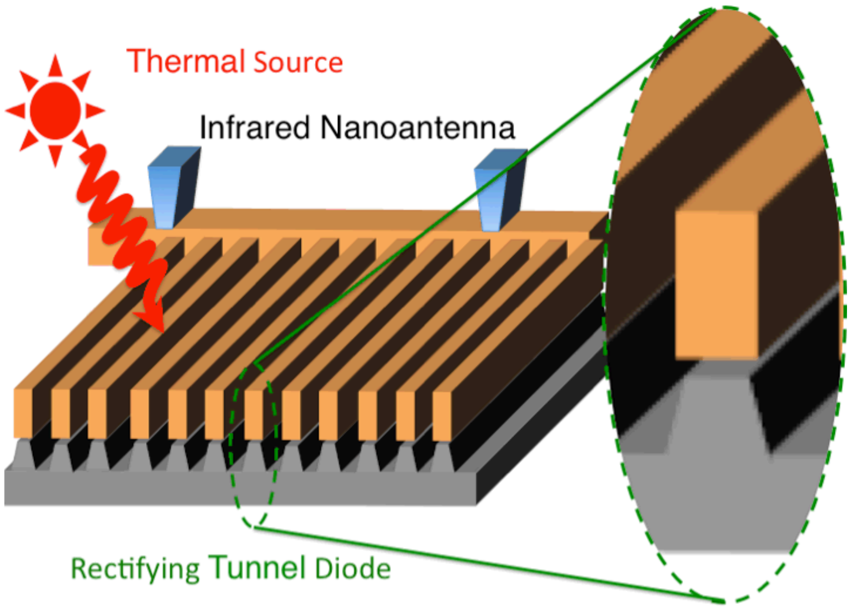
Photon-phonon enhancement

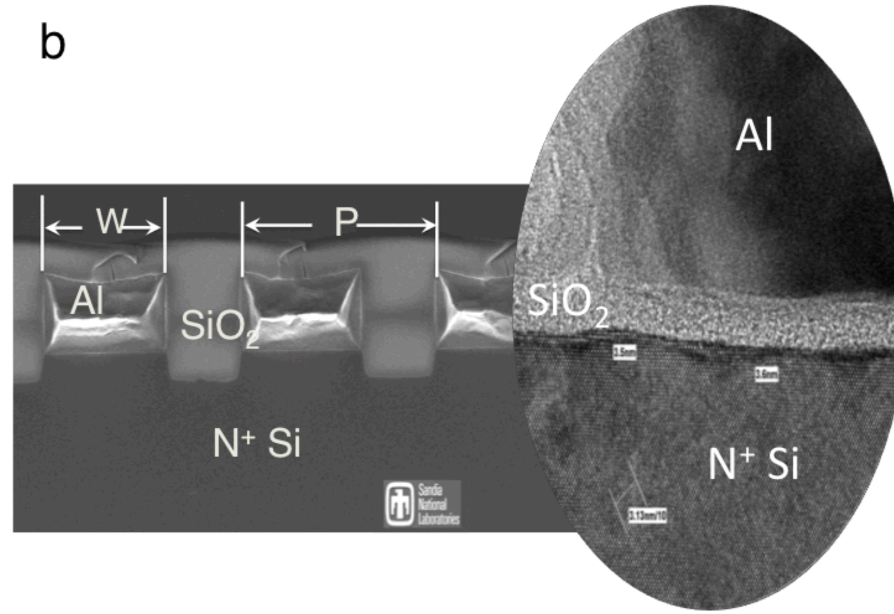


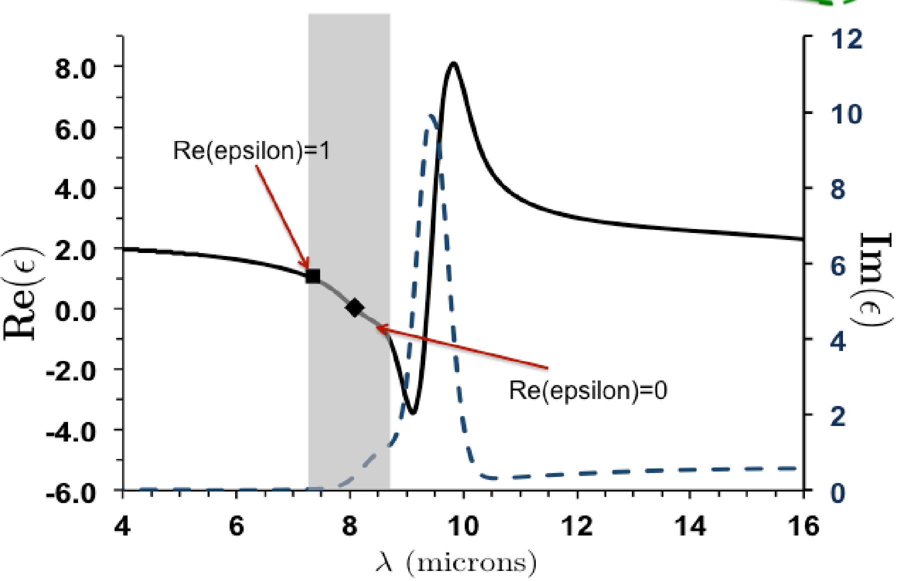


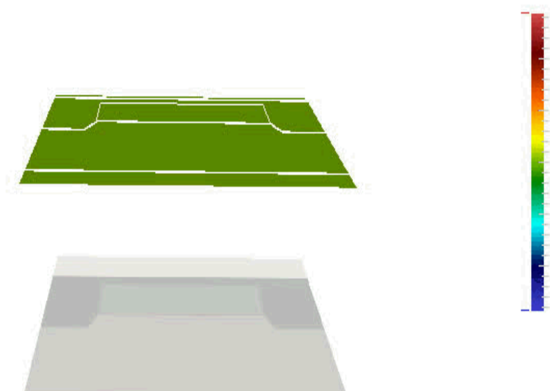
Tunneling rectification in MOS tunnel diode

Enhanced field in 1D rectenna

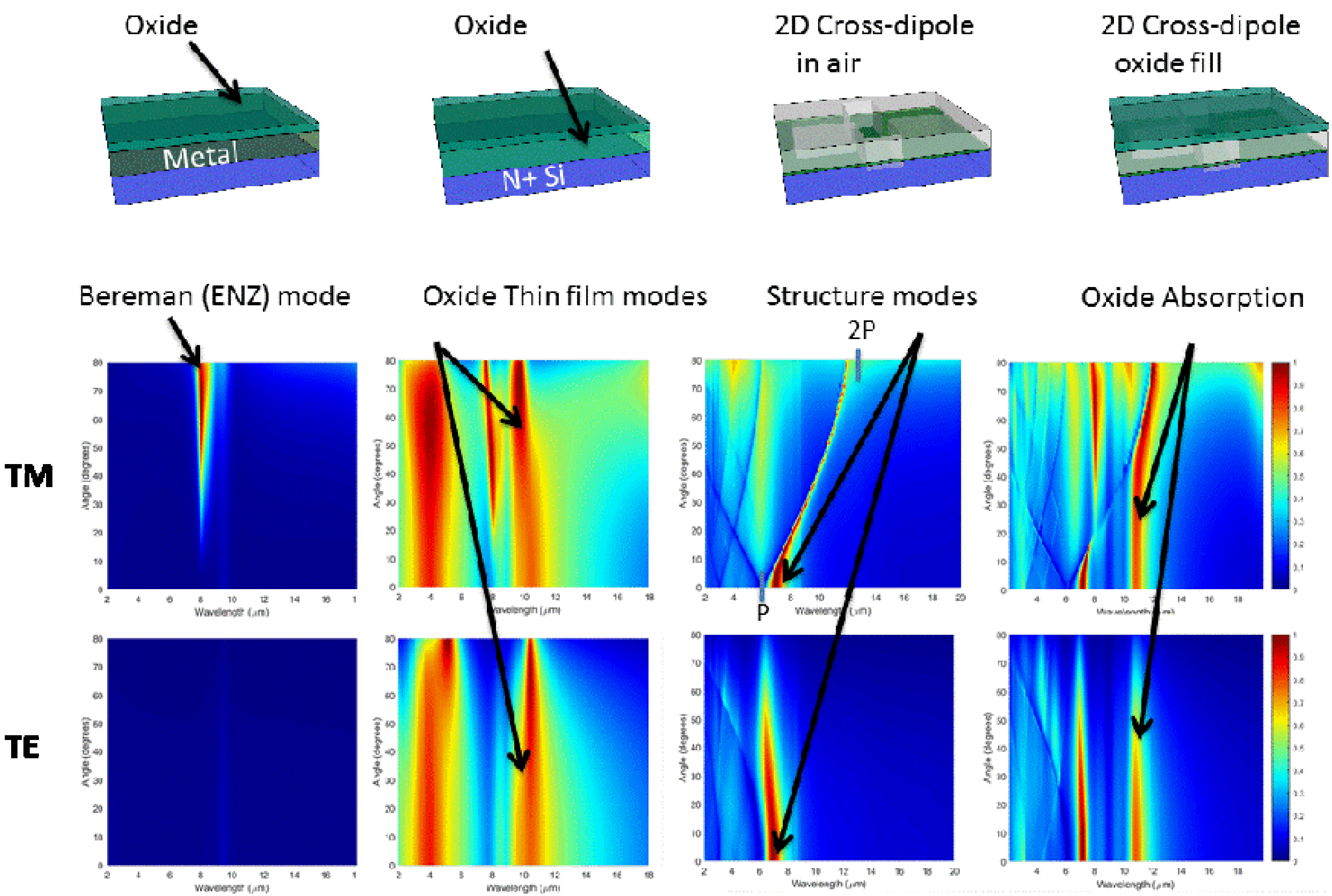








2D IR Rectenna Photonic Modes

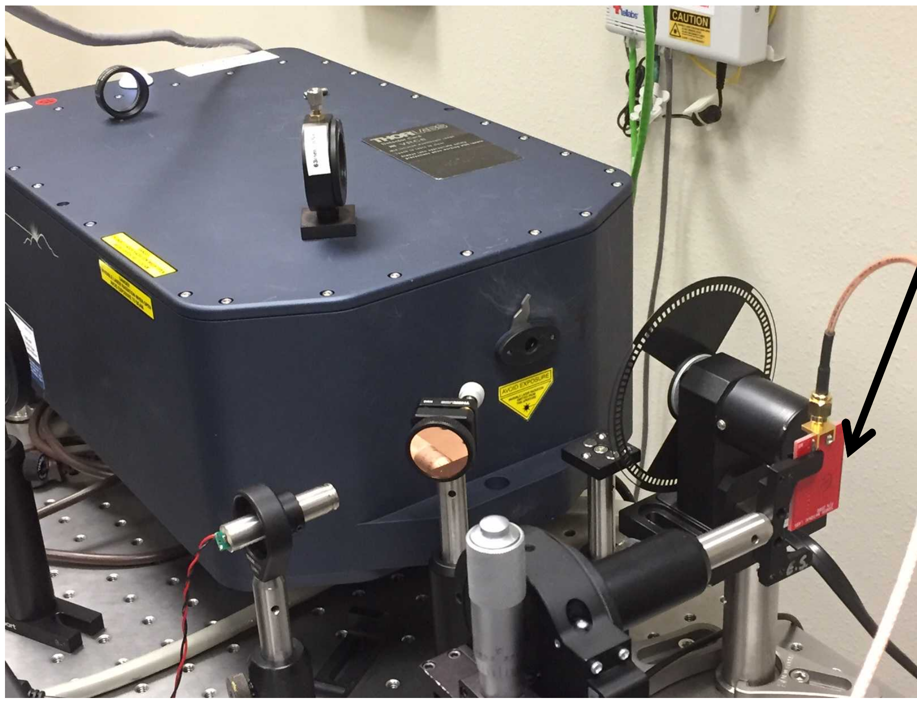


Photocurrent spectrum

2D Rectenna Angular Photocurrent Spectrum at V=0

QCL wavelengths 7-11 microns

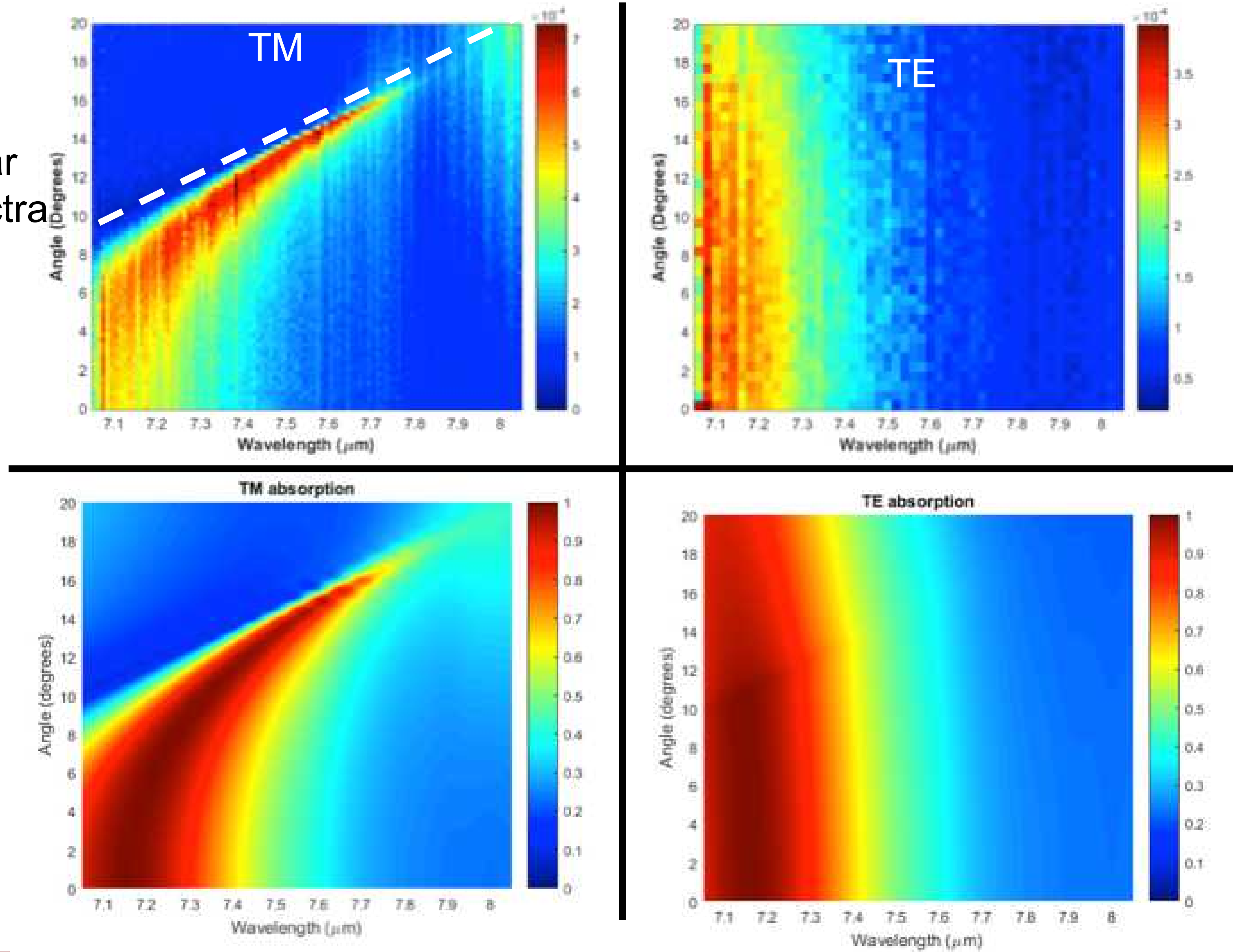
Rectenna mounted



2D Photocurrent spectrum at V=0.0

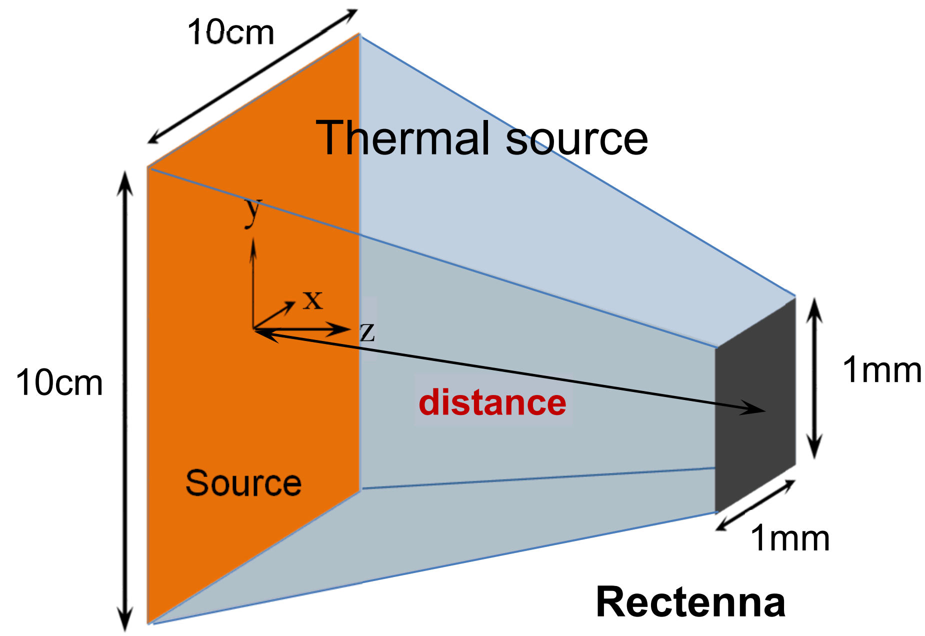
Measured Angular Photocurrent Spectra at V=0

Simulated Absorption



Radiometric Measurement of Rectenna

- Examine thermal source illumination of rectenna in vacuum .
- Finite size thermal source and rectenna as a function of distance.
- Built 2 vacuum radiometry setups.
  - One capable of near-field measurement.



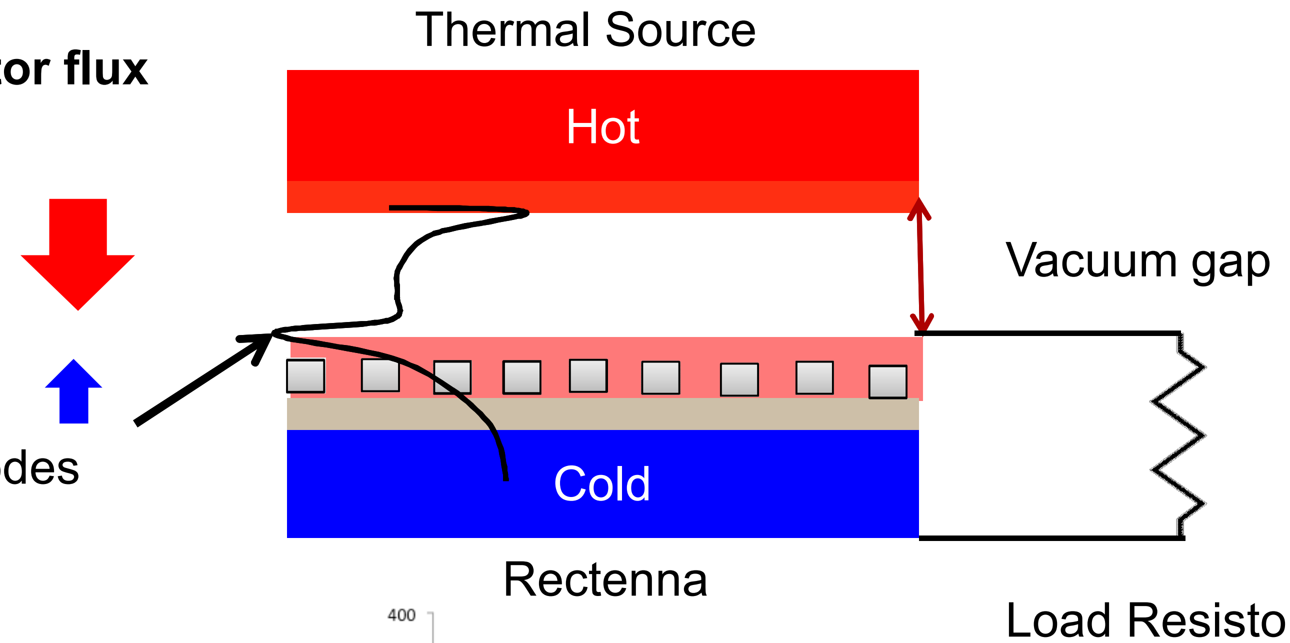
Measure1D Rectenna device characteristics and power generation as a function of source temperature and vacuum gap spacing.

Radiative heat transfer

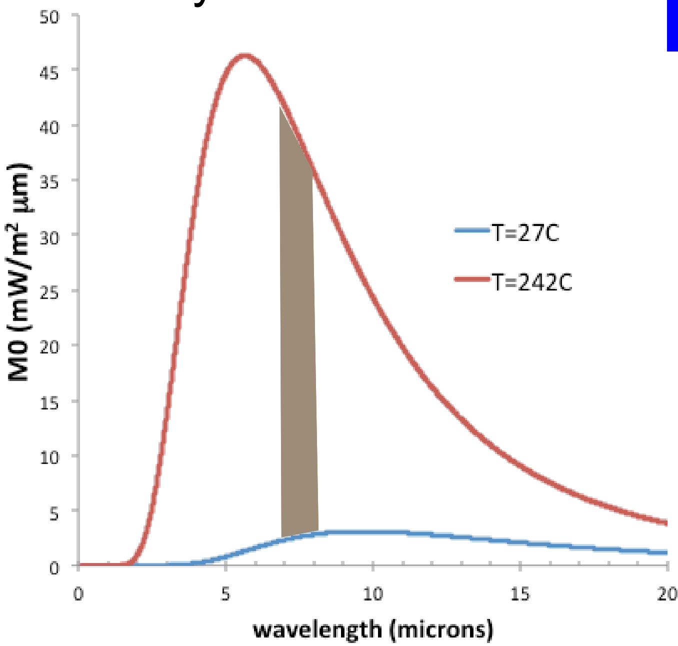
Net Poynting vector flux

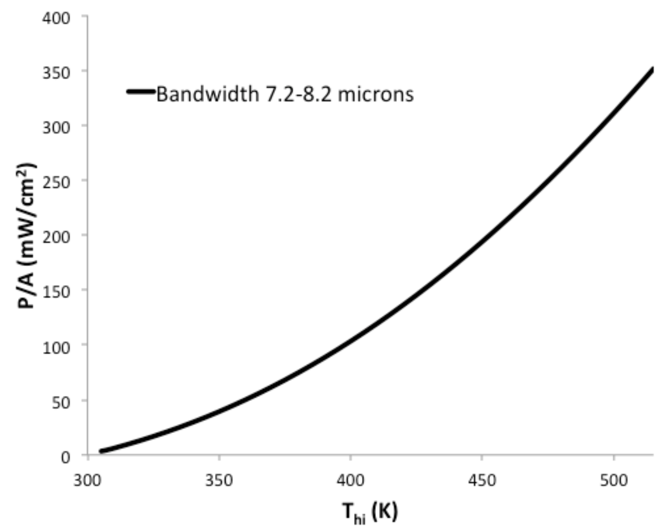
Heat Transfer Rate

$$W = \frac{S_z(T_2) - S_z(T_1)}{T_2 - T_1}$$



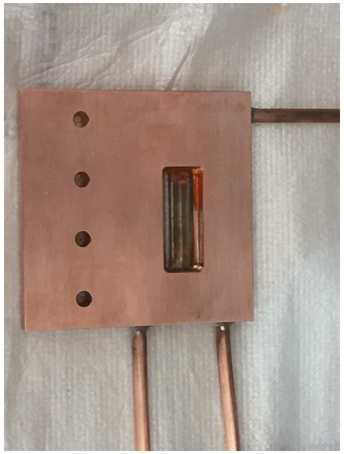
Cavity EM modes





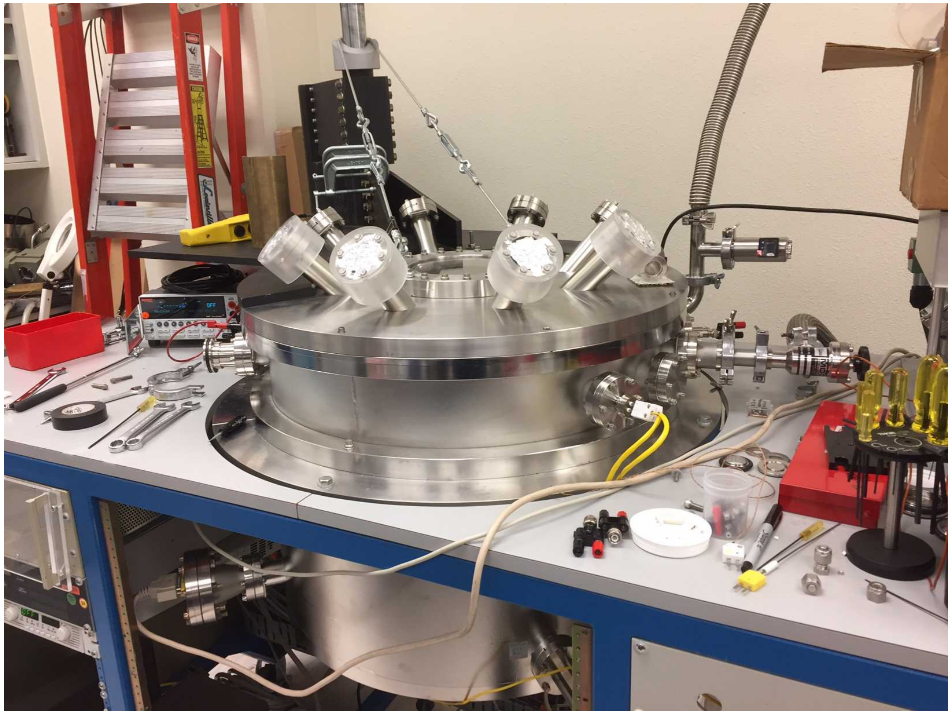
Vacuum Radiometric Setup

Water cooled sample

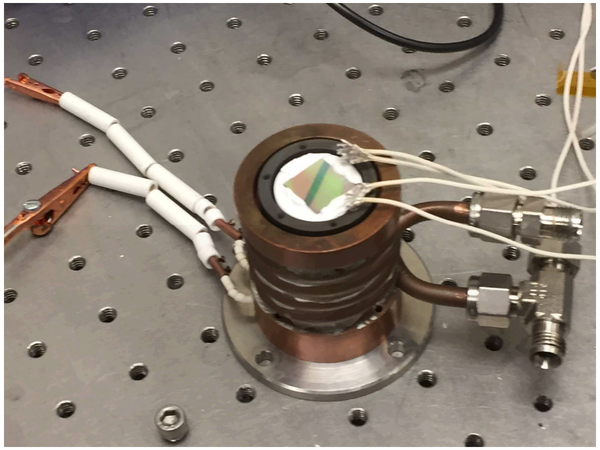


Packaged sample

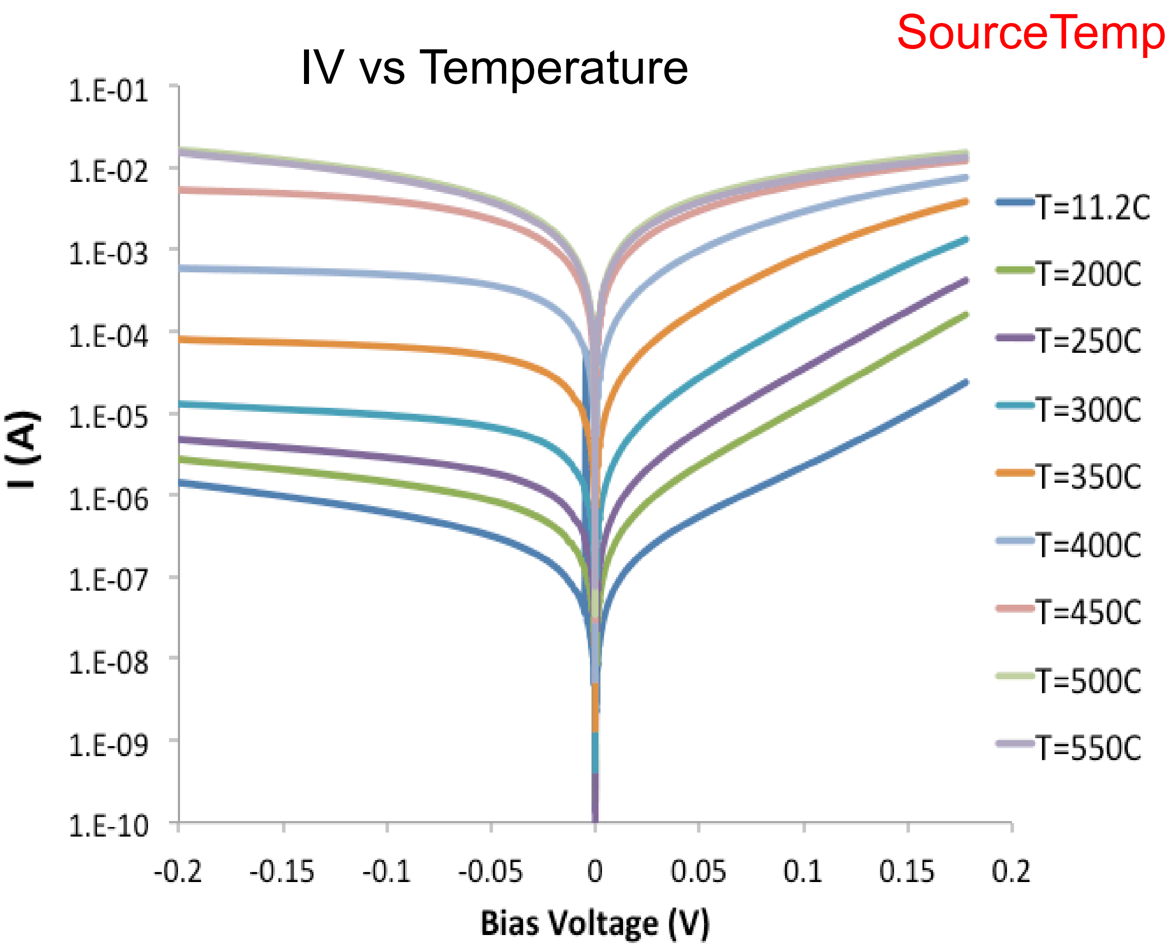
Vaccum setup

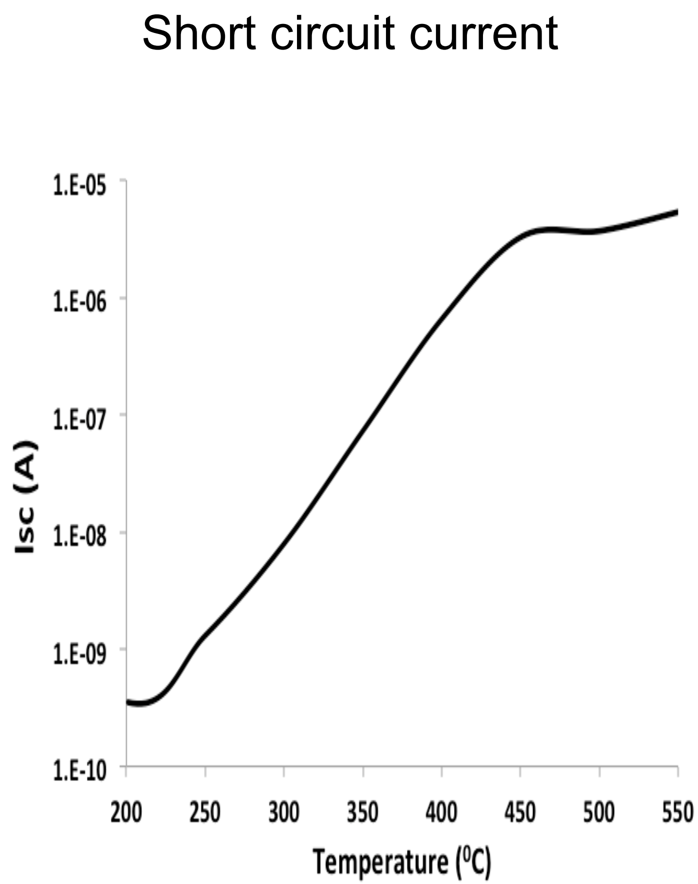


Thermal source

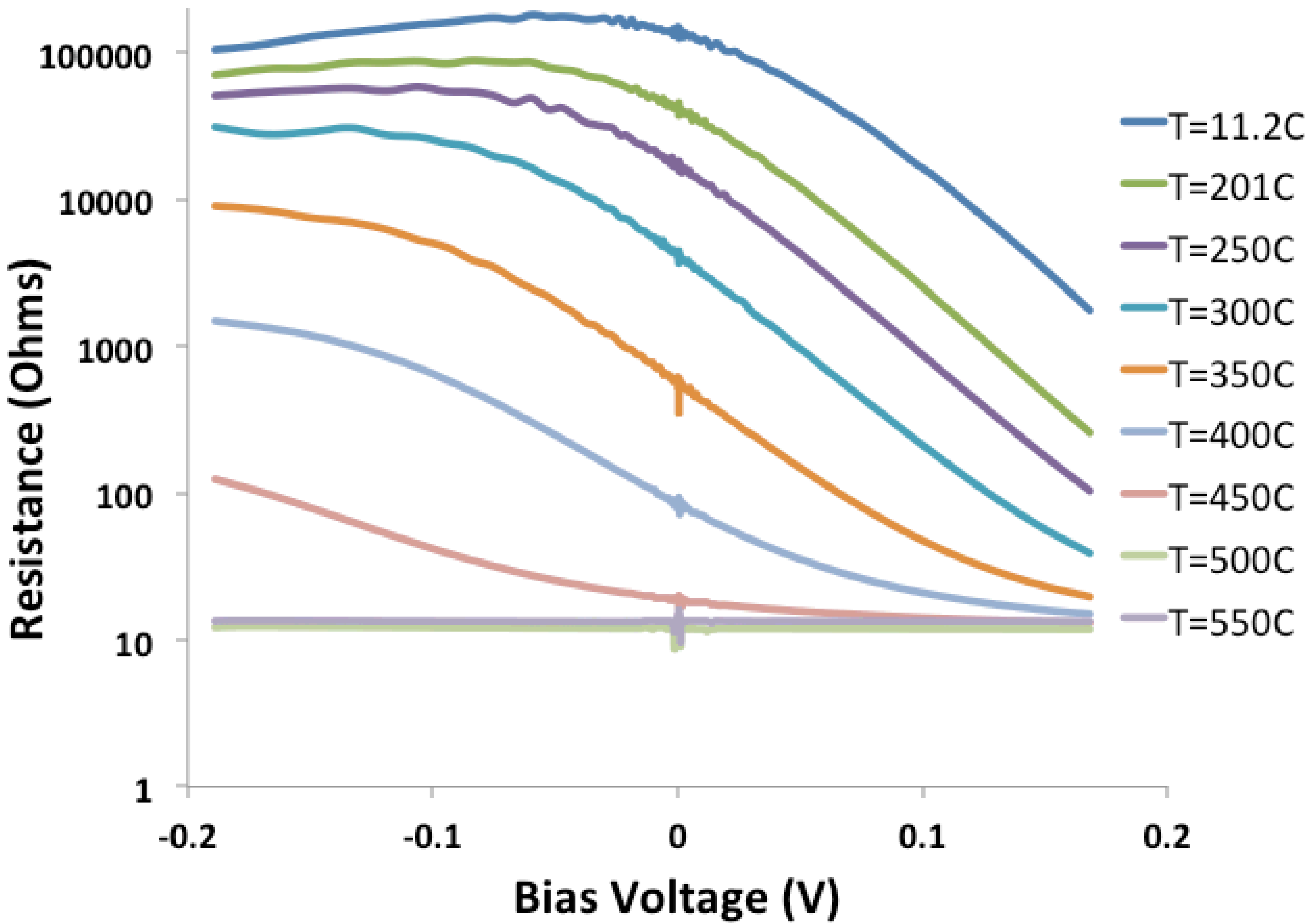


IV under thermal illumination



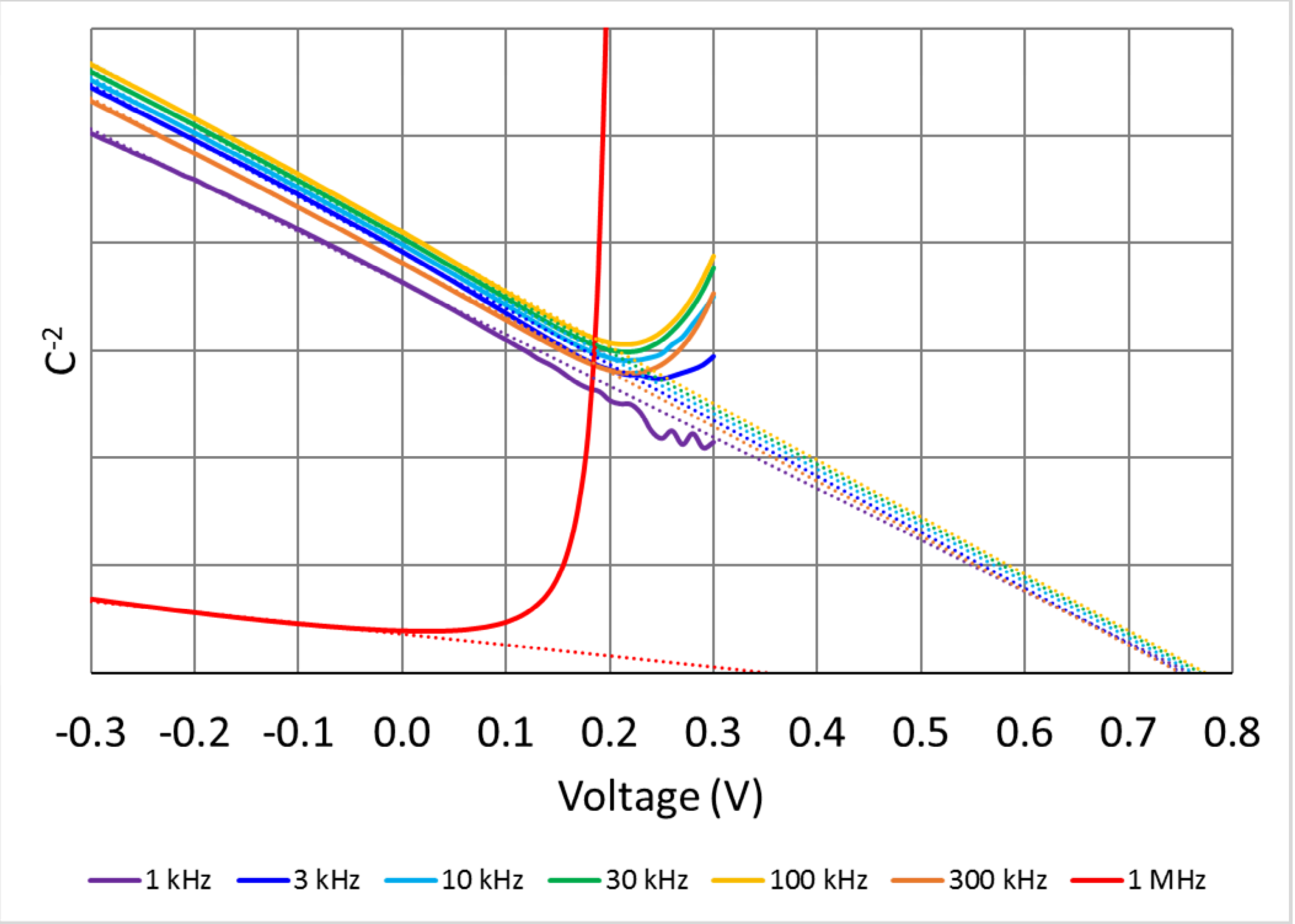


Diode Resistance



Capacitance

CV at various source temperatures



DC Power Supply

Half-wave rectifier

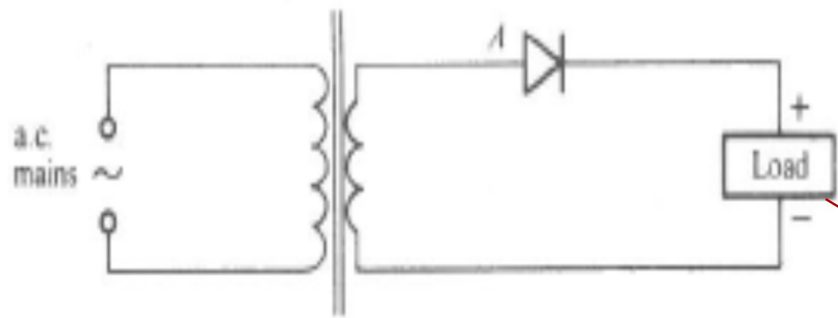


Fig. 9.1. A basic d.c. power-supply transformer and HW rectifier

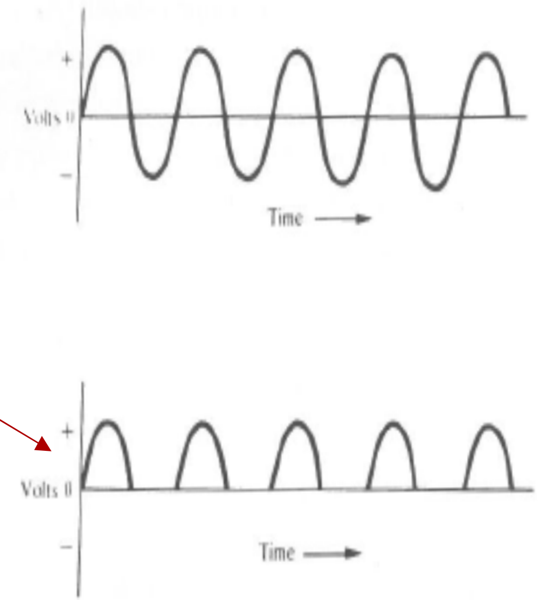
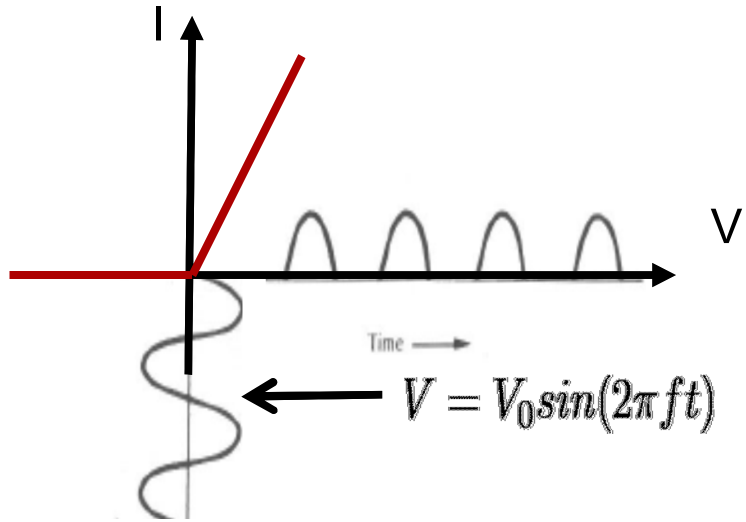


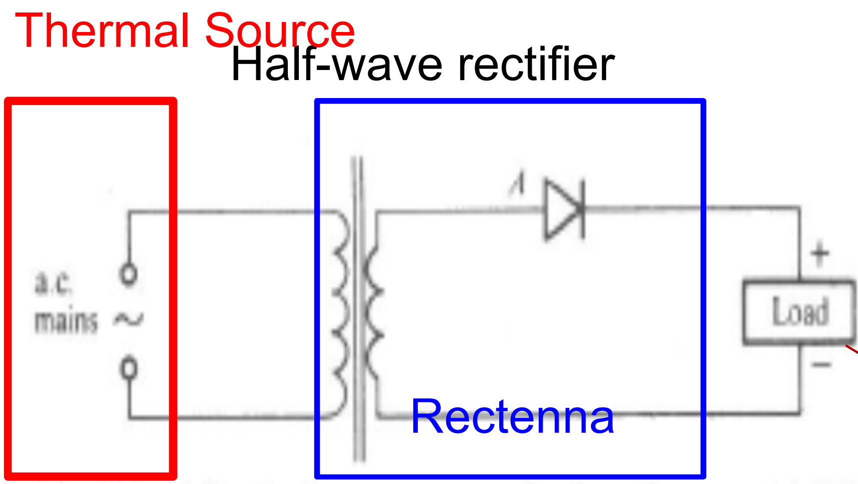
Fig. 9.2. Waveforms in HW rectifier circuit: (*a*) a.c. input waveform, (*b*) rectified unidirectional waveform across load.

Rectification in ideal diode



$V = V_0 sin(2\pi f t)$

DC Power Supply



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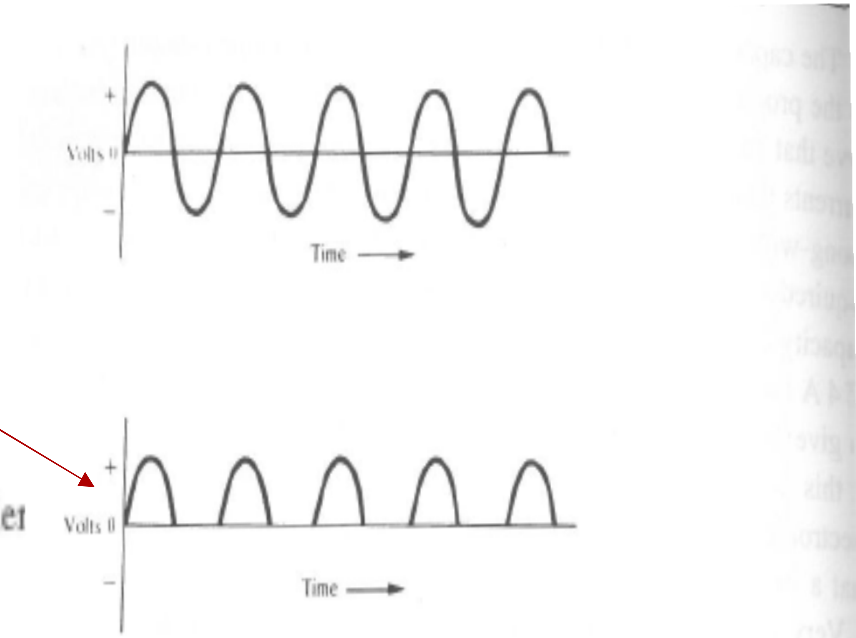

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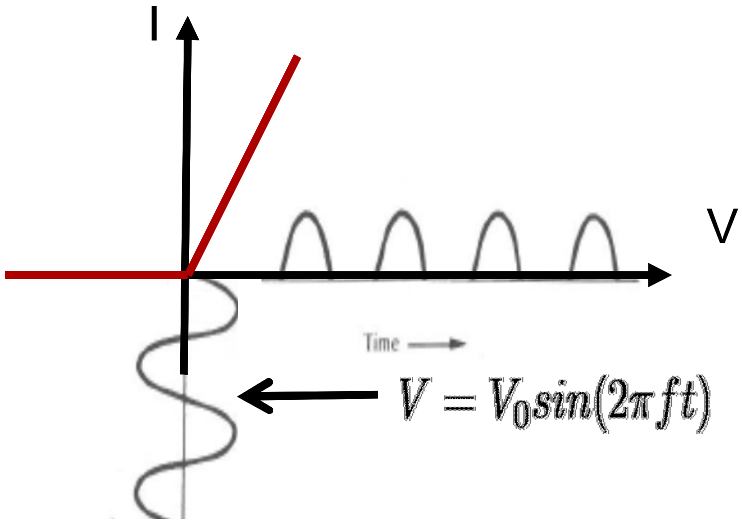
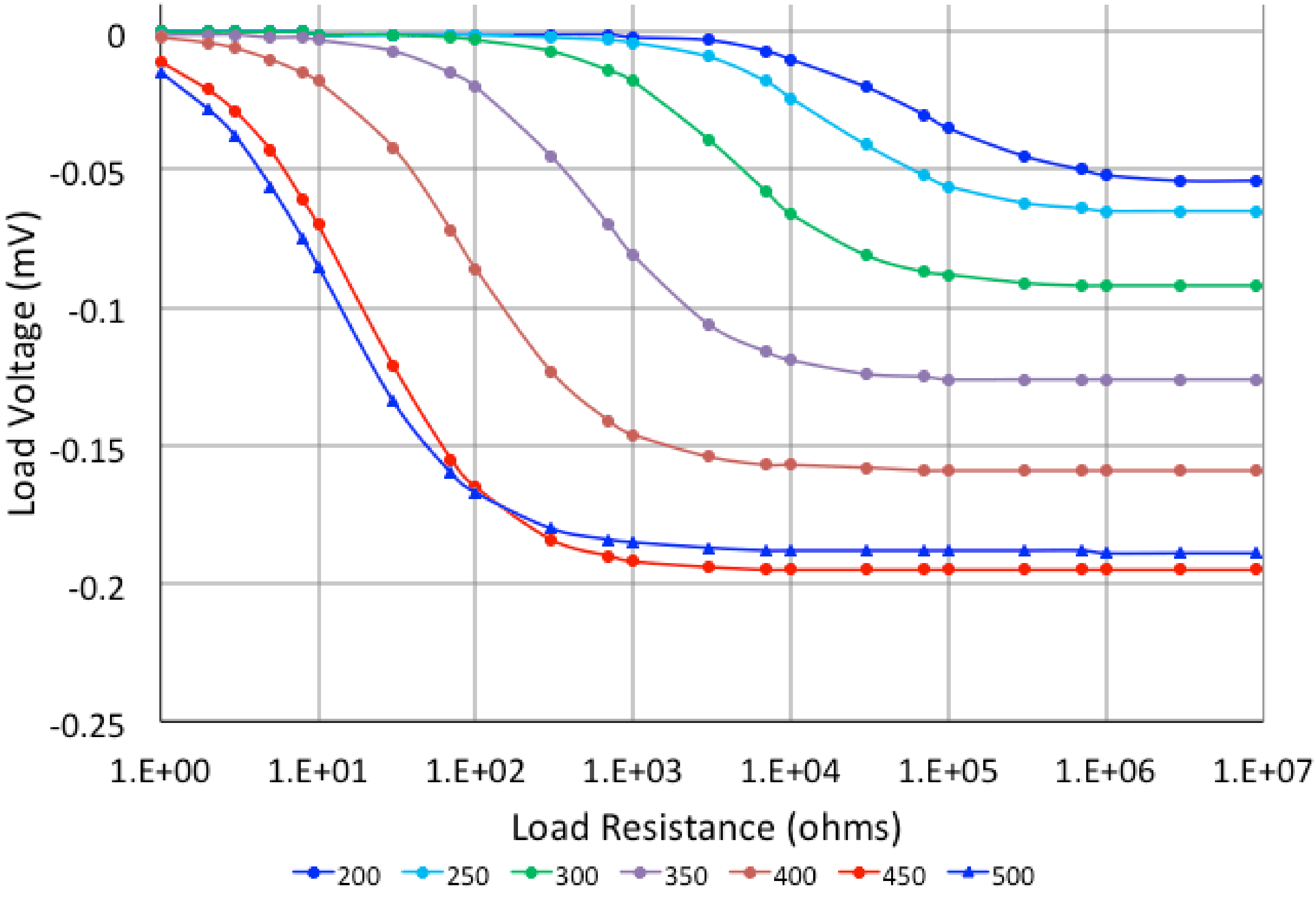
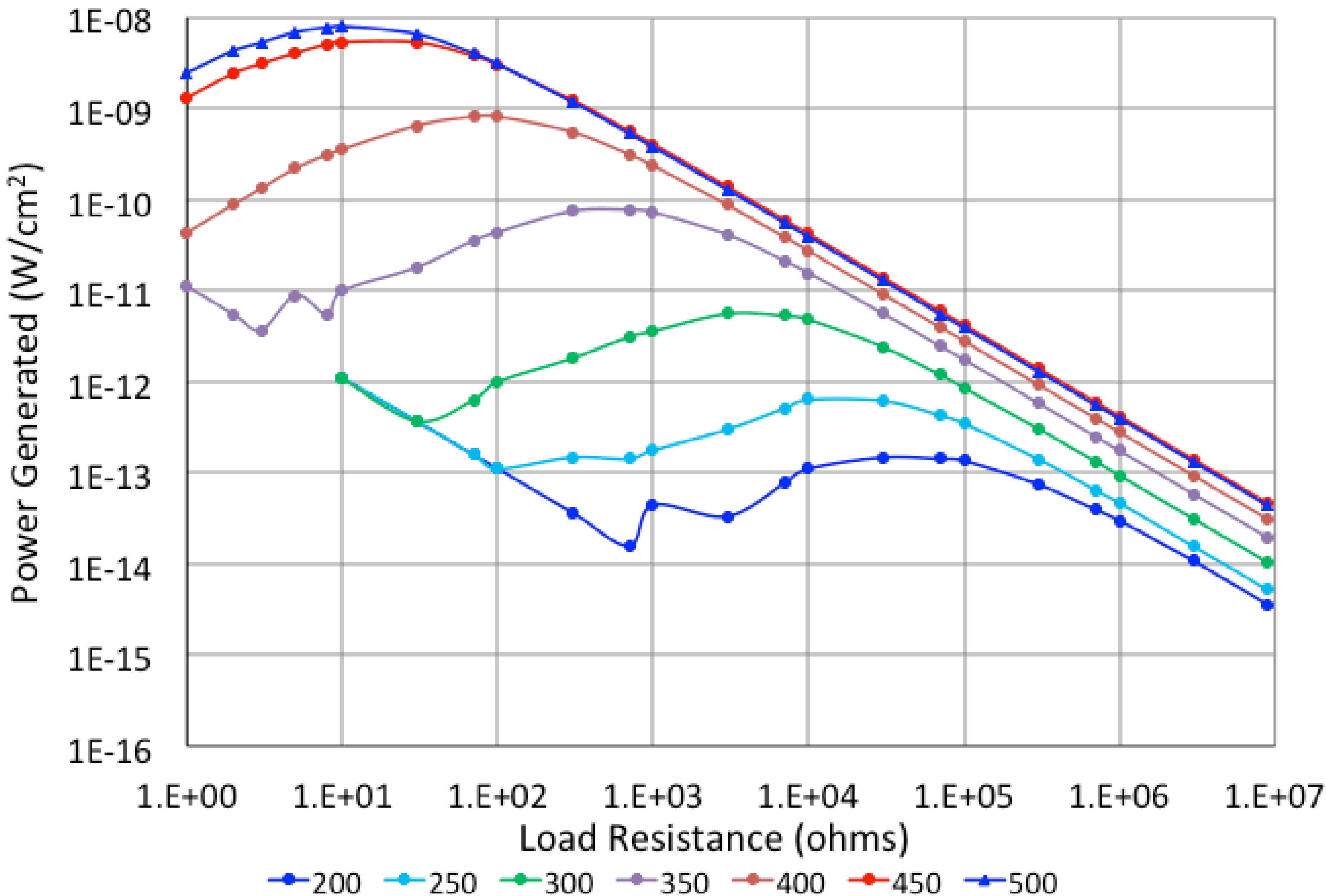


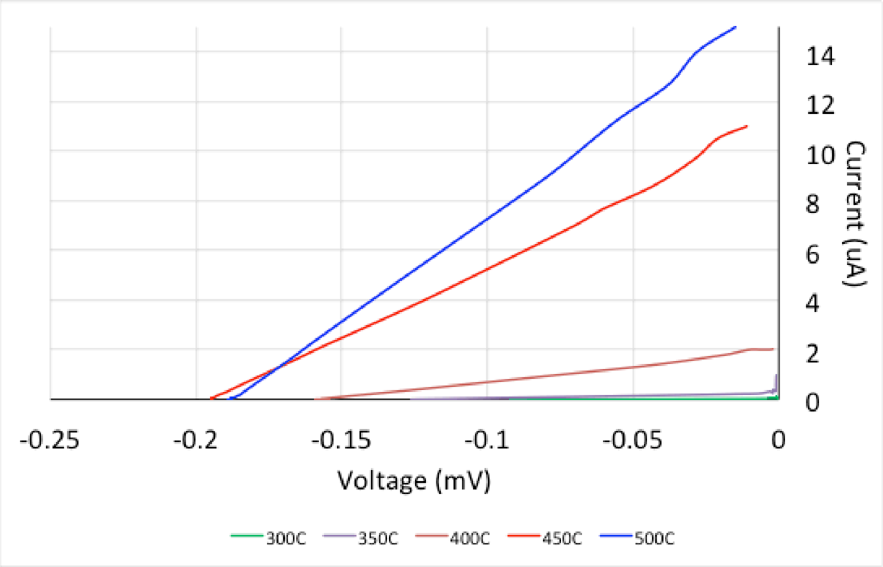
Power generation



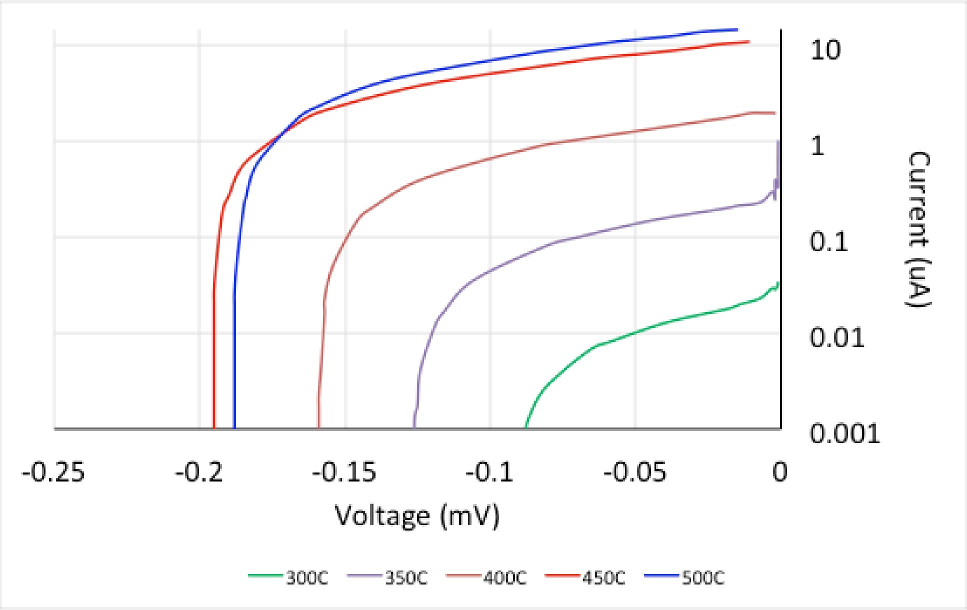
Power generation



Load Line

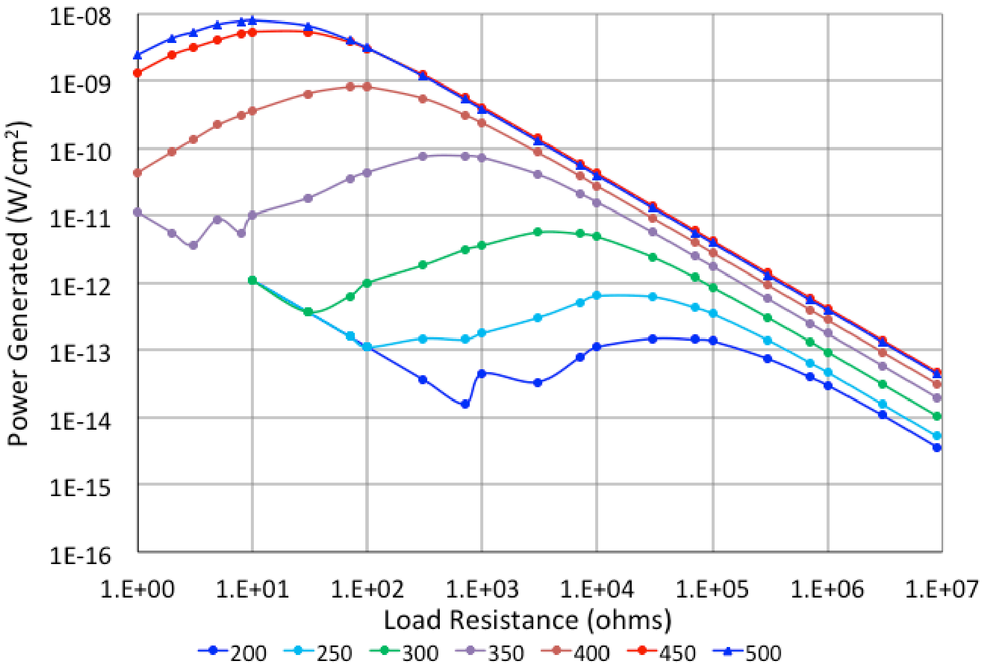


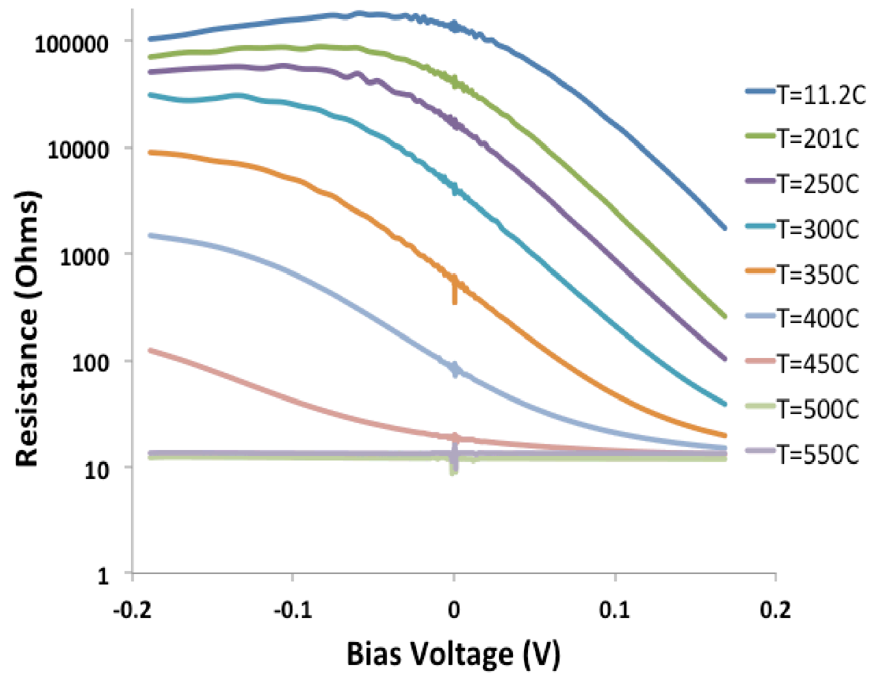
14
12
10
8
6
4
2
0
Current (uA)
-0.25
-0.2
-0.15
-0.1
-0.05
0
Voltage (mV)
300C
350C
400C
450C
500C



10
1
0.1
0.01
0.001
Current (uA)
-0.25
-0.2
-0.15
-0.1
-0.05
0
Voltage (mV)
300C
350C
400C
450C
500C

Impedance match





Diode resistance at V=0 is approximately the peak power load resistance

Summary and Future work

- Reviewed new type of IR direct converter: IR rectenna
- Radiometric characterization of IR rectenna under thermal illumination.
- ***Demonstrated Power Generation in 1D Rectenna.***
- Next steps
  - 2D and with structured emitters.
  - Improved efficiency
  - Near-field enhancement and measurements