(Micro) Rectenna Arrays for Infrared Power Conversion

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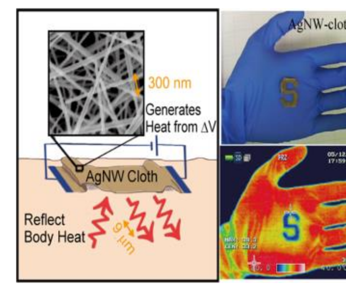
Brown University



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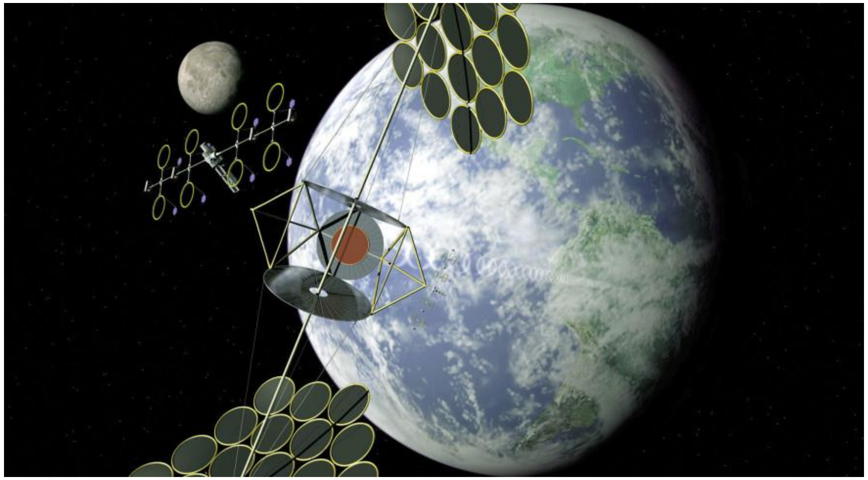
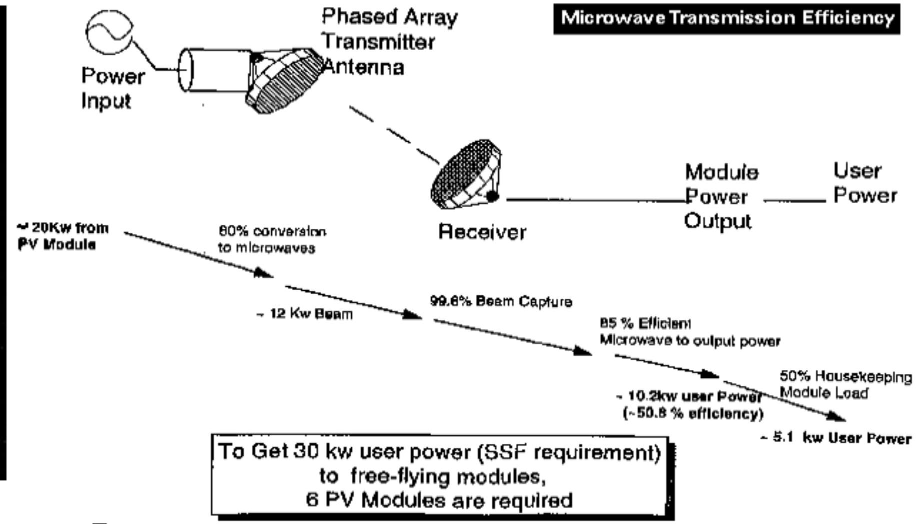
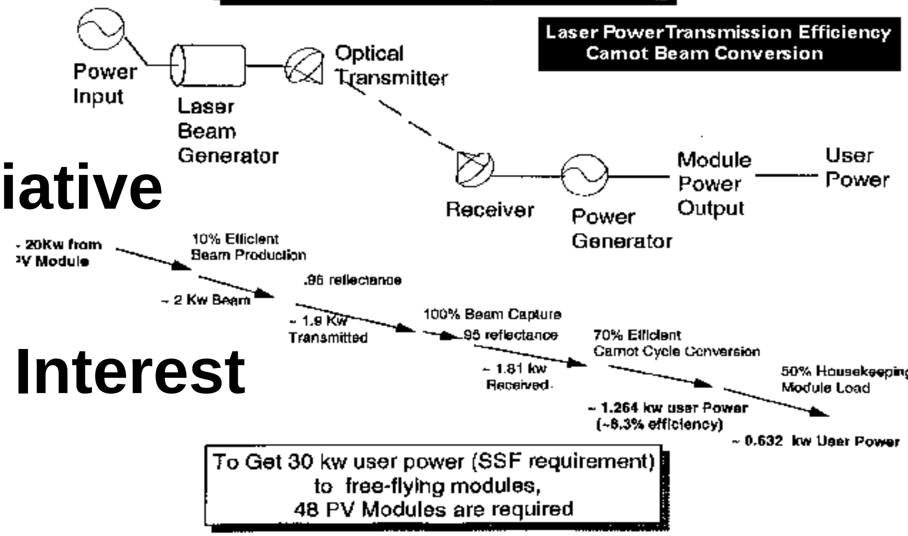
Mr. Mathew Chin, Dr. Madan Dubey, Dr. Barbara Nichols

Army Research Laboratory (ARL) – Sensors and Electron Devices Directorate

Rectenna Arrays for Infrared Power Conversion – Power Beaming in Space



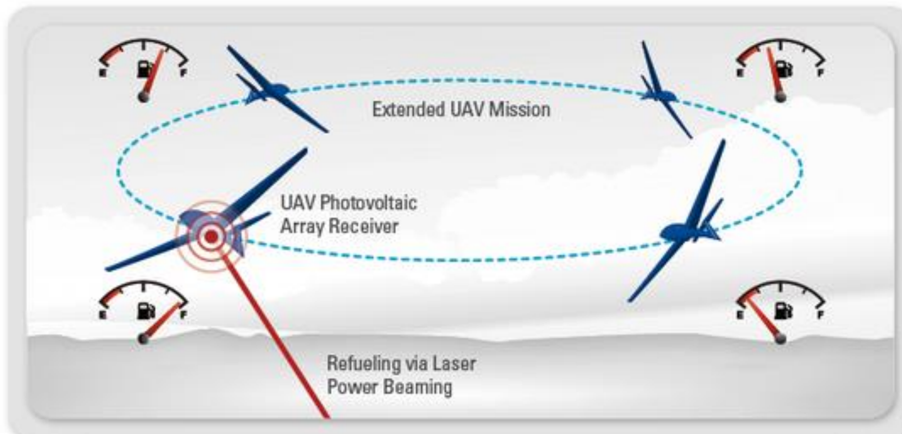


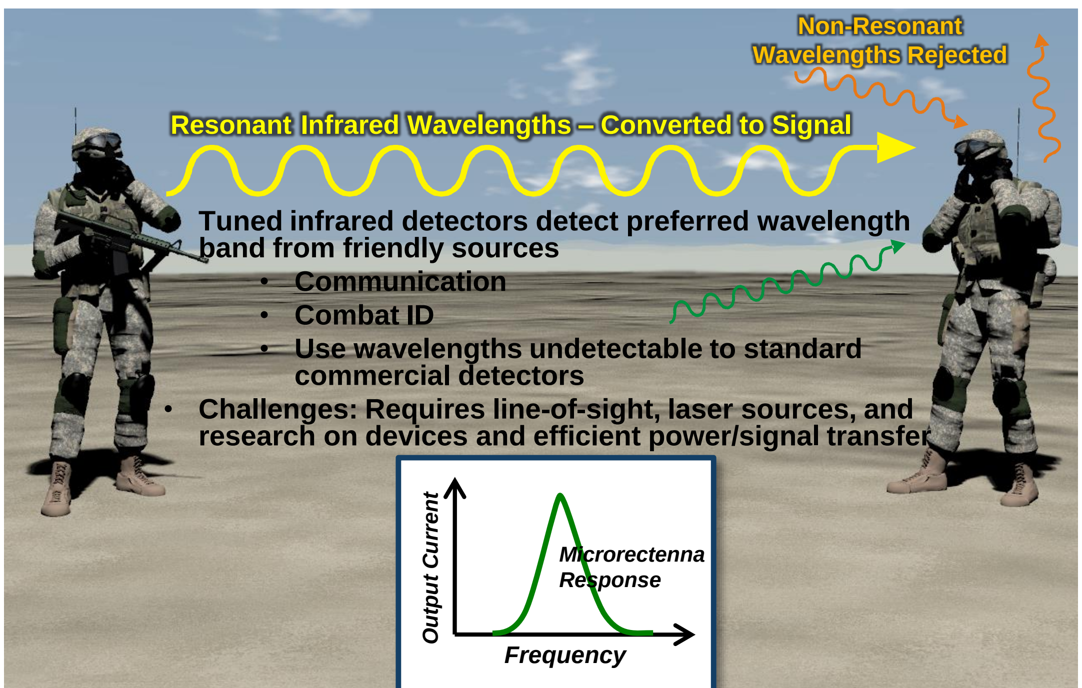


- **Space Solar Power Initiative**
- **Solar Power Satellite**
- **Japanese Government Interest**
- **Also Infrared Sensing**

(Micro) Rectenna Arrays for Infrared Power Conversion – Terrestrial Power Beaming

- **UAS sustainment**





Other applications: Battlefield Data Transfer and Identification

(Micro) Rectenna Arrays for Infrared Power Conversion

- What are microrectennas and microrectenna arrays?
- Materials for microrectenna arrays
- Vertical MIM diode rectifiers
  - J-V curve experiments and modeling
  - Estimation of responsivity and direct current
- Horizontal stripe-teeth metamaterial arrays
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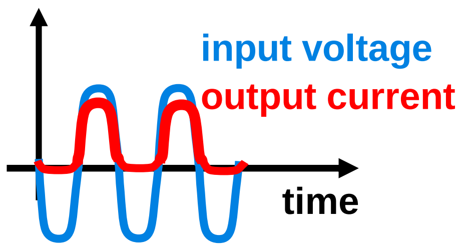
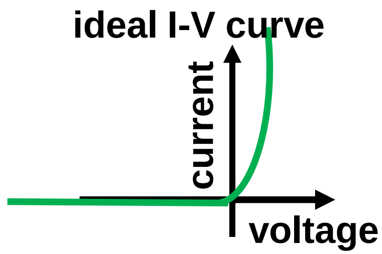
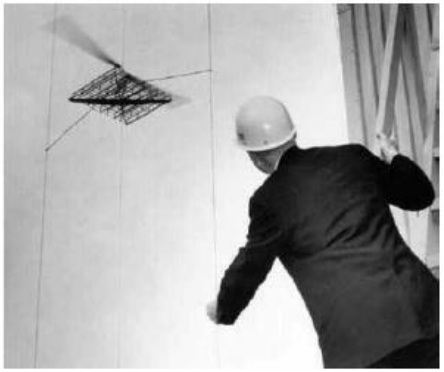
  - Analysis
  - Response to cw lasers

Antenna-coupled rectifiers for GHz





Diode rectification (assumes ideal , highly non-linear I-V curve)



Dr. W. C. Brown, Raytheon Corporation (1964)

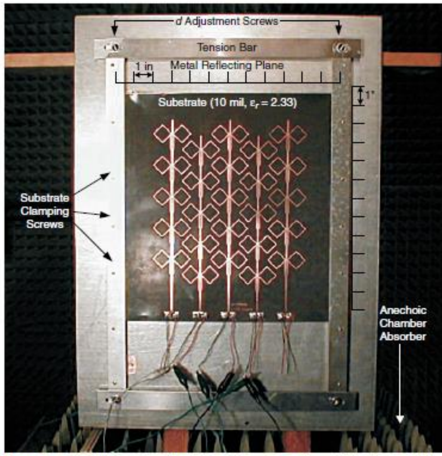
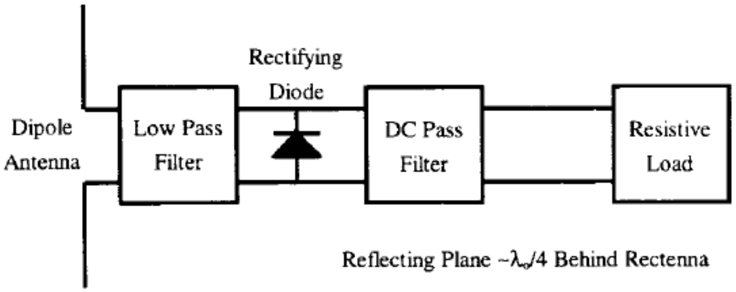


Figure 9. *5.61-GHz circular polarized printed rectenna with over 78% efficiency [38].*

>75% efficient 5.61 GHz rectenna array (TAMU) – IEEE Microwave Journal (2002)

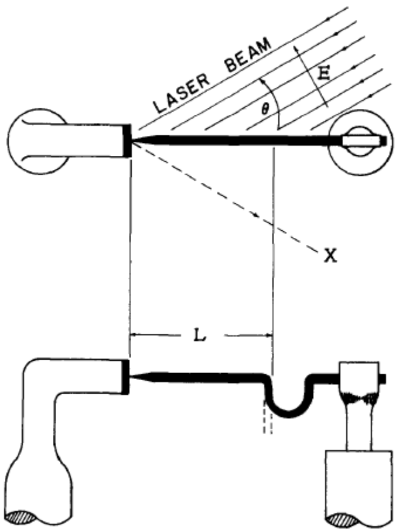


McSpadden *et. al.*, IEEE Trans. Microw. Theory Tech. v. 46 p.2053 (1998)

η > 80% for 5.8 GHz!

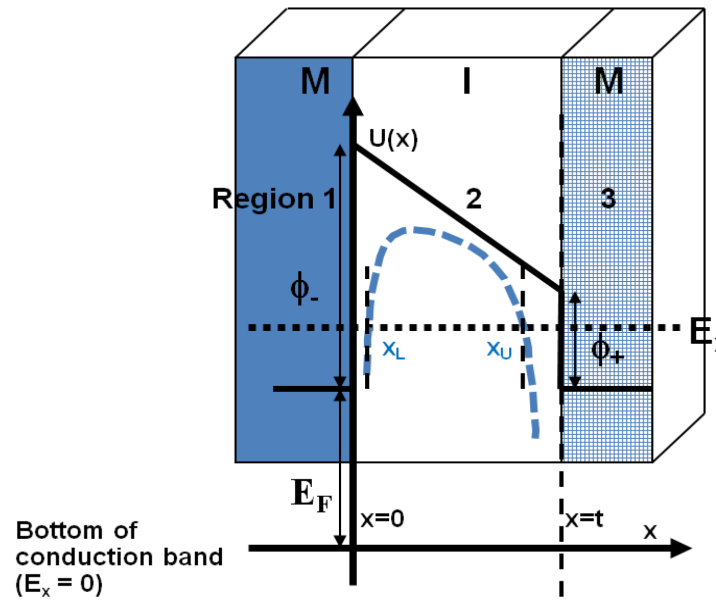
High frequency Metal-Insulator-Metal (MIM)-based diodes for detection

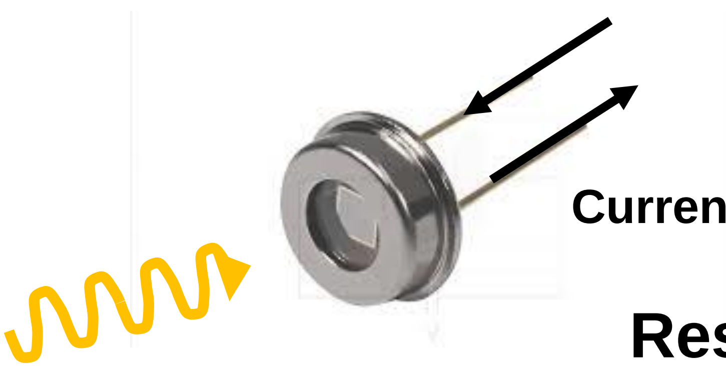
- **Accurate measurements of infrared/visible frequencies**



Point-contact devices (1960s and 1970s)

"Improved coupling to infrared whisker diodes by use of antenna theory" Matarrese and Evenson, Appl. Phys. Letts. 17, 8 (1970)





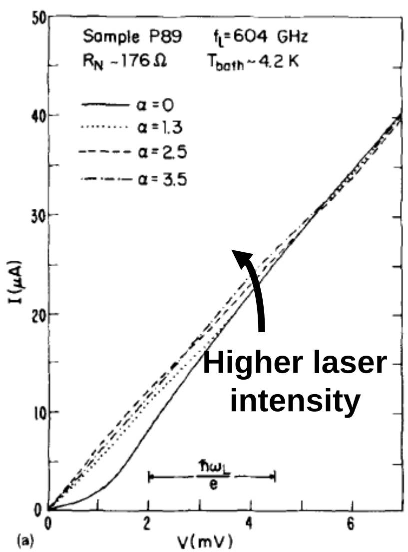
Current in Amperes

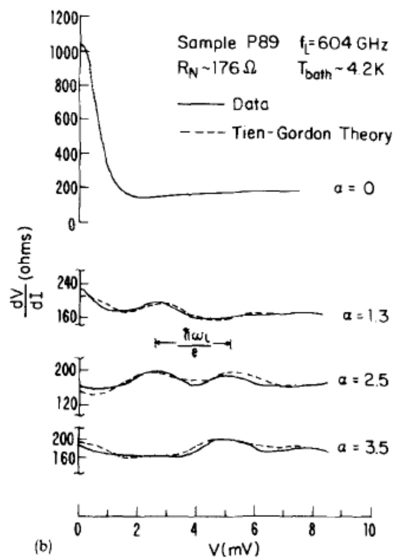
Responsivity R in A/W [1/V]

Radiative power in Watts

Responsivity of Metal-Insulator-Metal (MIM) Diodes

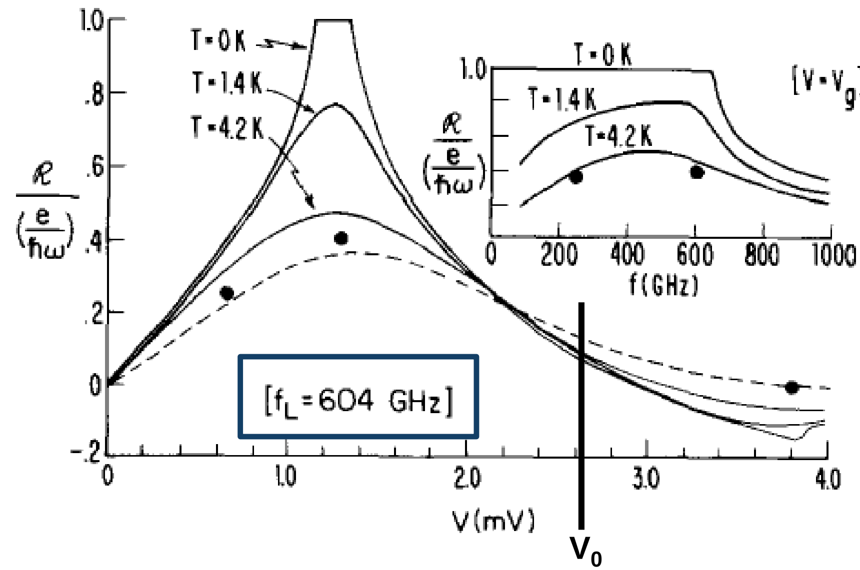
- **Tinkham: Responsivity of Superconductor – Insulator – Superconductor/Normal junctions (1982)**





Steps in dV/dI separated by photon voltage = (photon energy)/e

α **= V_{AC}/photon voltage**



$$R_Q = \frac{e}{\hbar\omega}\left[\frac{I_{dc}\left(V_0 + \hbar\omega/e\right) - 2I_{dc}(V_0) + I_{dc}\left(V_0 - \hbar\omega/e\right)}{I_{dc}\left(V_0 + \hbar\omega/e\right) - I_{dc}\left(V_0 - \hbar\omega/e\right)}\right]$$

Rectification responsivity R_Q in A/W

Quantum responsivity of MIM diodes

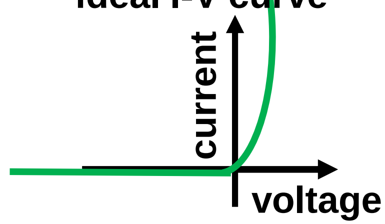
$$R_Q = \frac{e}{\hbar\omega}\left[\frac{I_{dc}\left(V_0 + \hbar\omega/e\right) - 2I_{dc}(V_0) + I_{dc}\left(V_0 - \hbar\omega/e\right)}{I_{dc}\left(V_0 + \hbar\omega/e\right) - I_{dc}\left(V_0 - \hbar\omega/e\right)}\right]$$

0.45 A/W maximum for green light (higher in infrared)

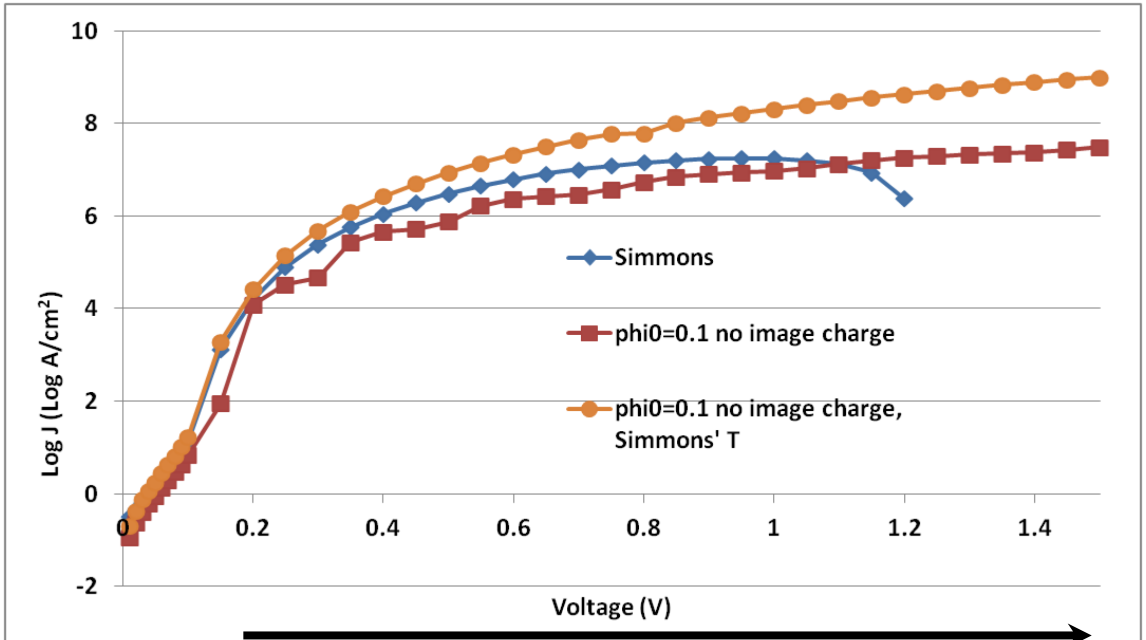
$$= \frac{1}{2}\frac{\partial^2 I_{dc}/\partial^2 V}{\partial I_{dc}/\partial V}\Big|_{V=V_0}$$

Approximation! Valid only in classical case

ideal I-V curve

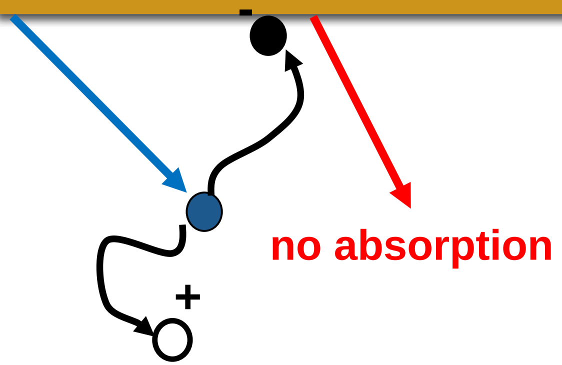


Must model I-V curve to predict rectification responsivity (A/W), especially at high voltages for R_Q!



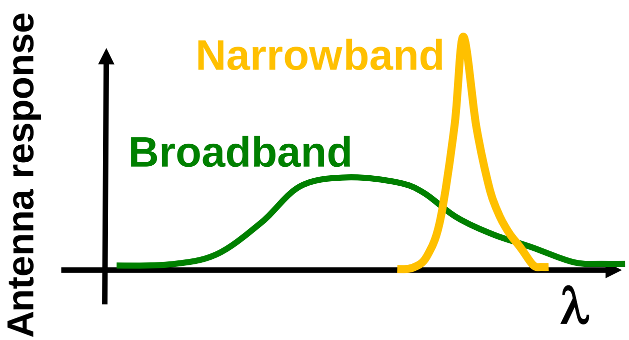
photon voltage $\hbar\omega/e$ (visible light)

What are microrectennas and microrectenna arrays?

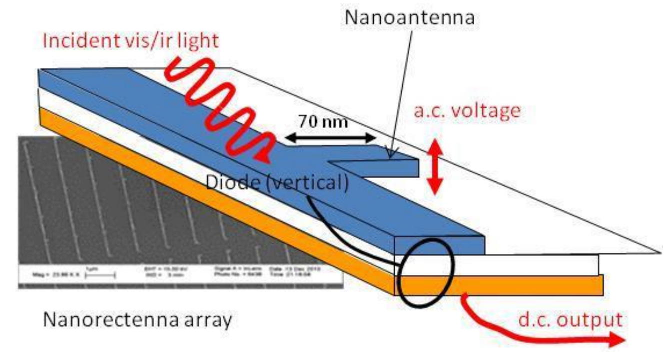


Photovoltaic (electron-hole generation with semiconducting bandgap)

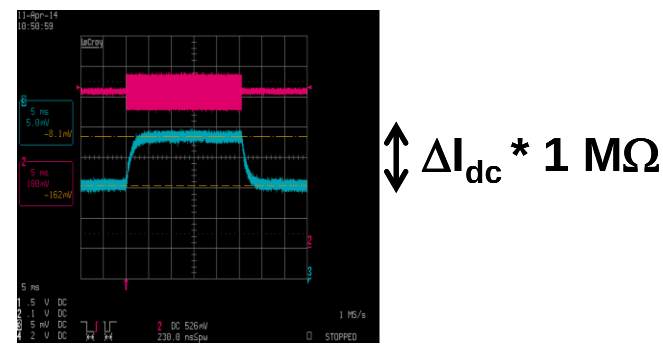
PV doesn't absorb photon energies less than bandgap



Dependent on dimensions and conductivity (no bandgap)



Perspective view of microrectenna



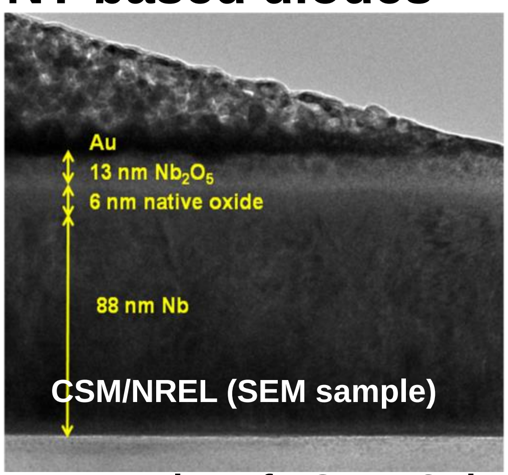
Simple rectification verification at 1 MHz (NbOx – based diode)

(Micro) Rectenna Arrays for Infrared Power Conversion

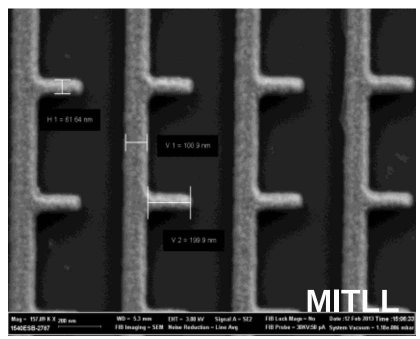
- **What are microrectennas and microrectenna arrays?**
- **Materials for microrectenna arrays**
- **Vertical MIM diode rectifiers**
  - **J-V curve experiments and modeling**
  - **Estimation of responsivity and direct current**
- **Horizontal stripe-teeth metamaterial arrays**
  - **Design and fabrication**
  - **Analysis**
  - **Response to cw lasers**

Materials for microrectenna arrays

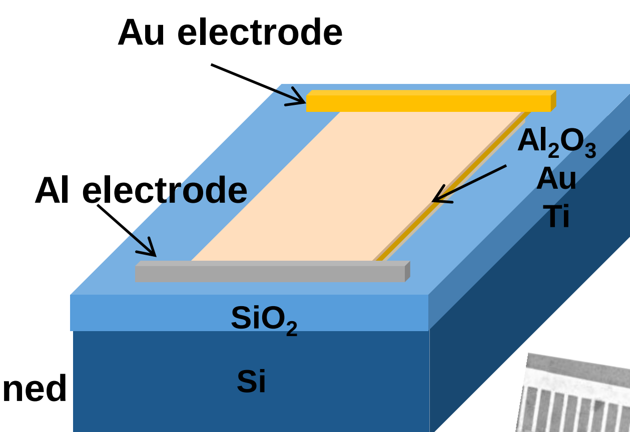
- Materials systems investigated:
  - M/Nb_2O_5/NbO_x/Nb, M = Ag/Ti, Au/Ti, Pt/Ti, others
  - M/Al_2O_3 (ALD)/Al, M = Al, Au
- Al or Nb ground planes
- Au wire antennas underneath Al electrode
  - Small cluster of nanorectennas
  - Antennas run between electrodes in top plane, vertical MIM diode (same as other cases)
- CNT-based diodes

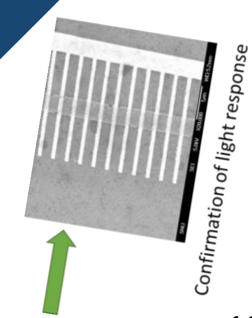


Cross-section of NSRDEC-designed microrectenna array (metal-insulator-metal (MIM) diode)

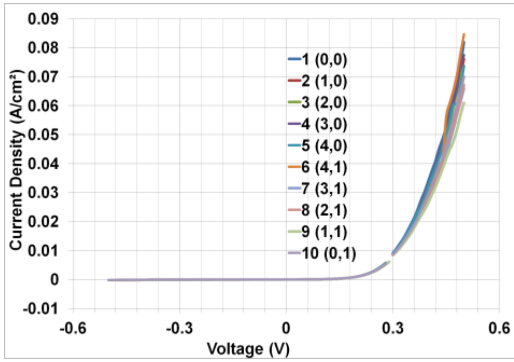


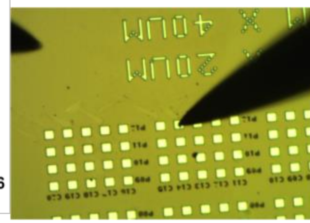
Plan view of NSRDEC-designed microrectenna array (Al stripe-teeth antennas)



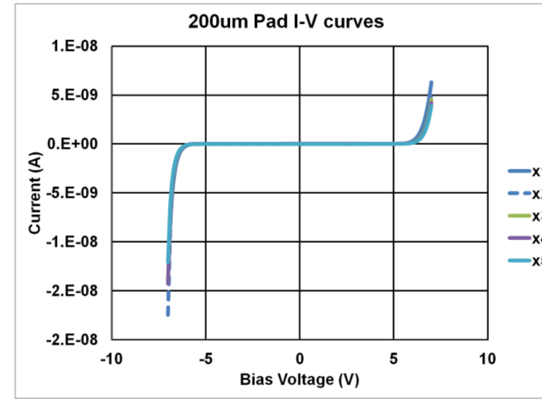


Vertical MIM diode rectifiers (Al- and Nb-based)

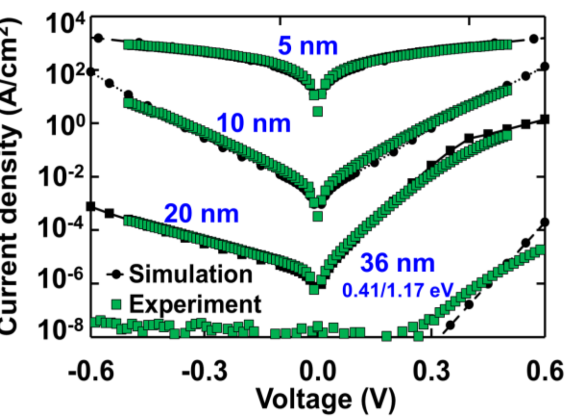




Pt/NbO_x/Nb test diodes (ARL)

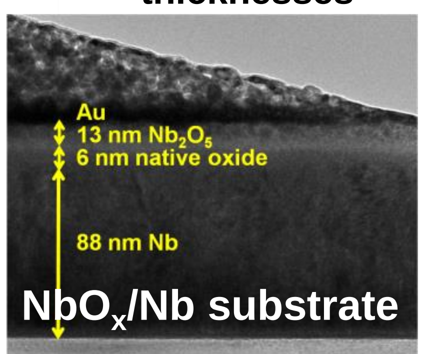


Al-Al_2O_3-Al test diodes



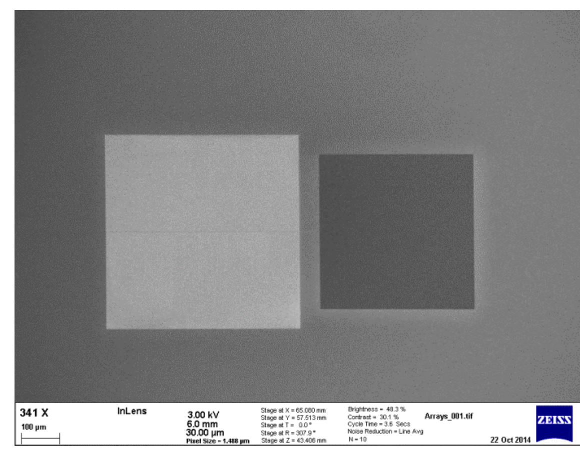
NSRDEC measurement, analysis, modeling

Pt/Nb_2O_5/(NbO_x)Nb test diodes with various barrier (oxide) thicknesses



Derived material parameters for Pt/Nb_2O_5/(NbO_x)Nb diodes:

- ϕ_+/ϕ_- = 0.41/0.77 eV
- K= 6
- m_2 = 0.16 m_0



Antenna-coupled Al-Al_2O_3-Al array

(Micro) Rectenna Arrays for Infrared Power Conversion

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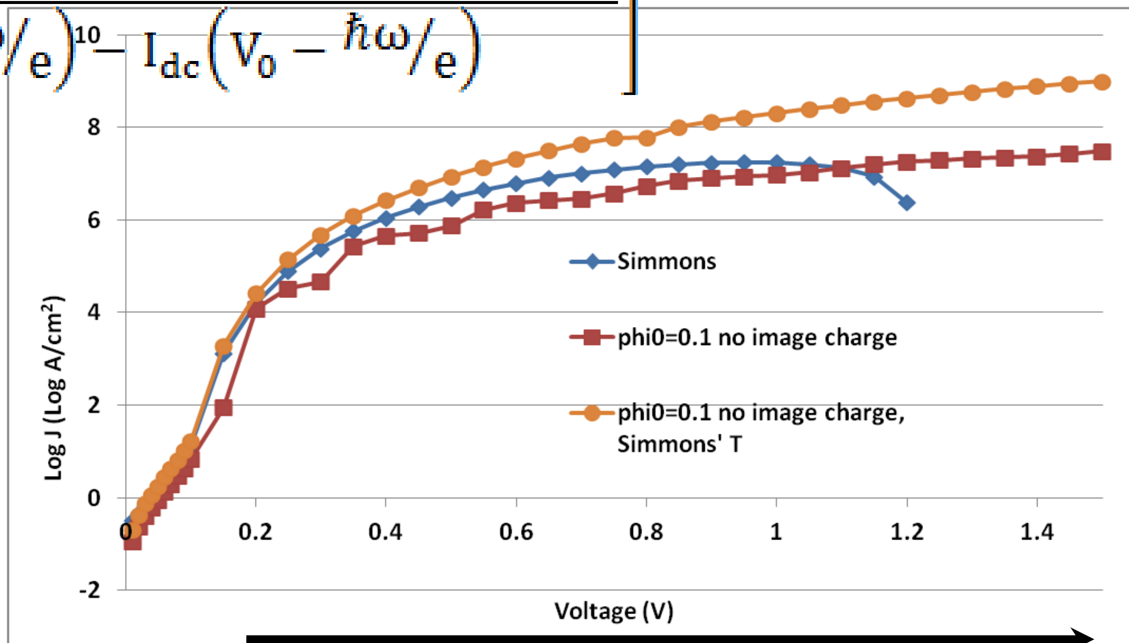
Need accurate knowledge of MIM diode's I-V curve to predict R_Q

Vertical MIM diode rectifiers

$$R_Q = \frac{e}{\hbar\omega}\left[\frac{I_{dc}\left(V_0 + \hbar\omega/e\right) - 2I_{dc}(V_0) + I_{dc}\left(V_0 - \hbar\omega/e\right)}{I_{dc}\left(V_0 + \hbar\omega/e\right) - I_{dc}\left(V_0 - \hbar\omega/e\right)}\right]$$

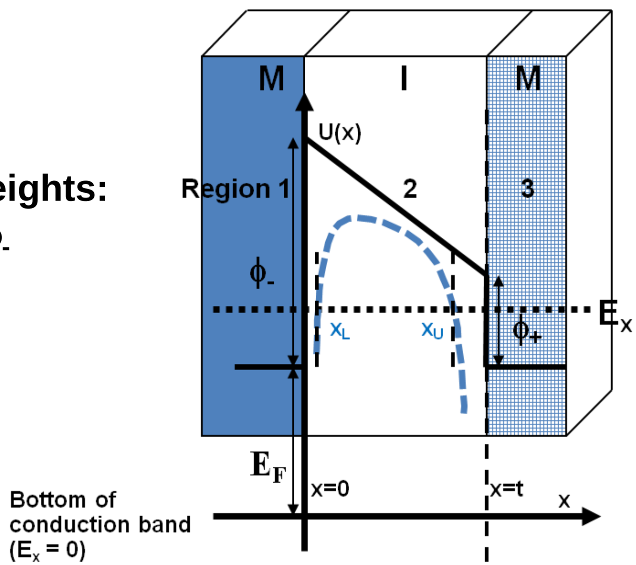


photon voltage $\hbar\omega/e$ (visible light)

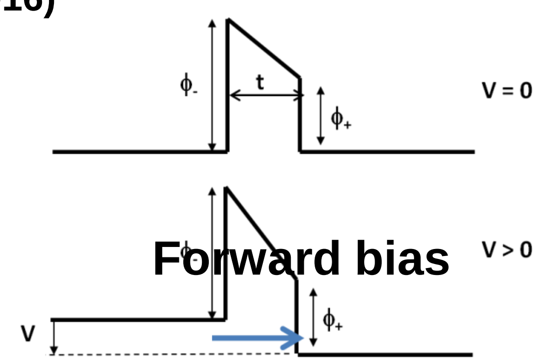
Must model I-V curve to predict rectification responsivity (A/W), especially at high voltages for R_Q!

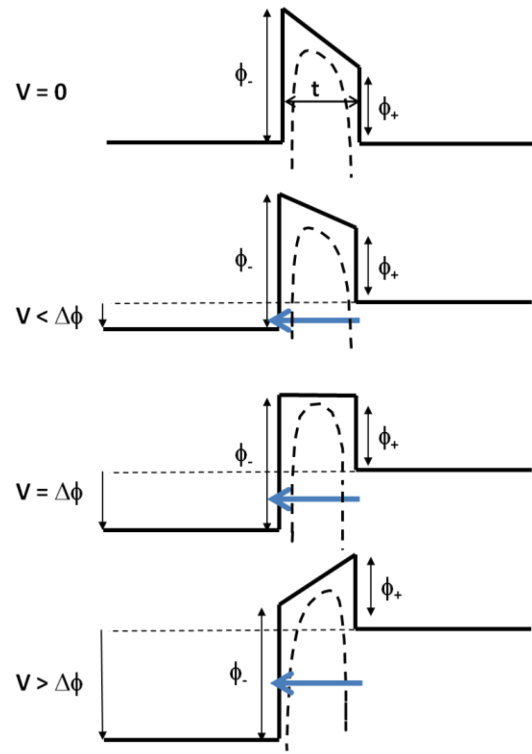
NSRDEC MIM diode model

Barrier heights:
ϕ_+, ϕ_-



Osgood, Giardini, *et. al.*, JVSTA 34, 0151514 (2016)



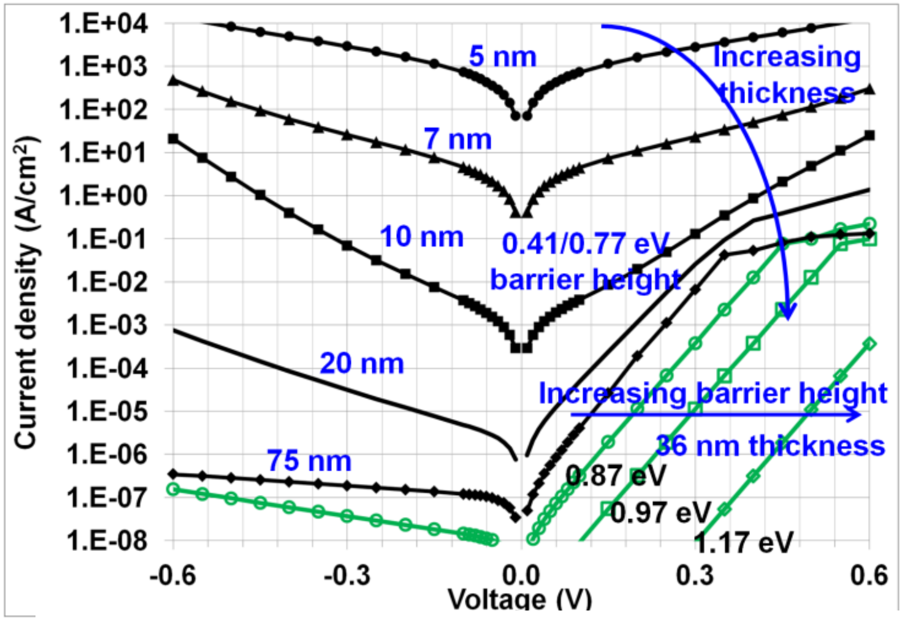


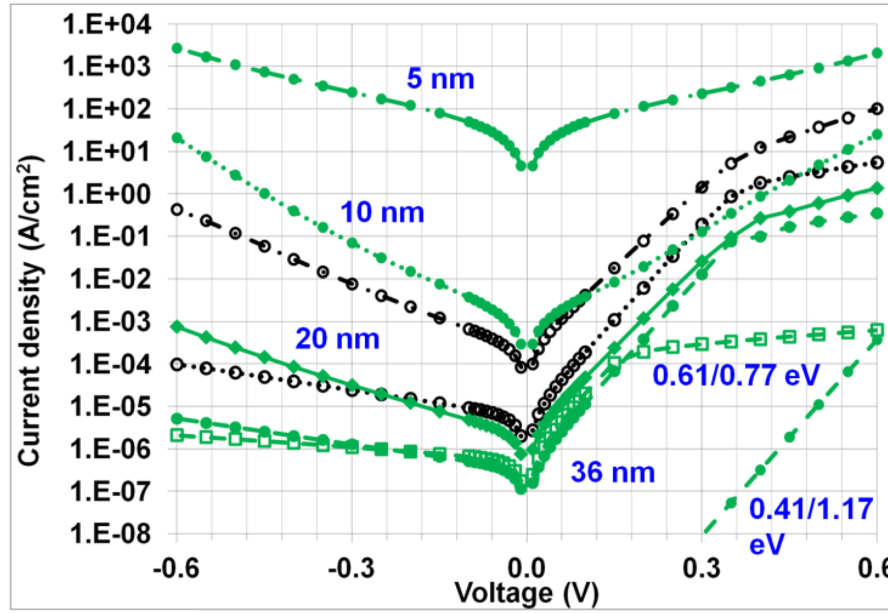
Reverse bias

New physics in model

- **Exact solution to trapezoidal potential barrier: no WKB approximation**
- **Principle of "equal action" to solve image force problem**
- **Effective mass not equal to electron rest mass**
- **Note convention: larger barrier on left**

Trends with thickness and effective mass





Conduction and rectification in NbO_x- and NiO-based metal-insulator-metal diodes

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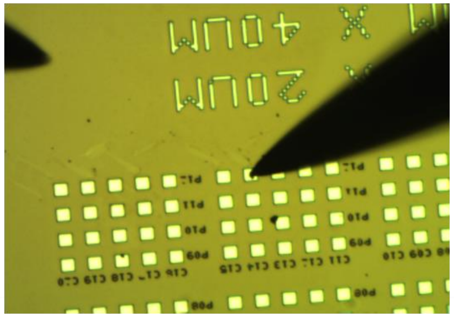
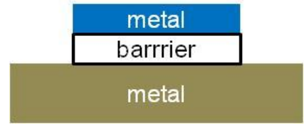
(Received 18 January 2016; accepted 1 August 2016; published 25 August 2016)

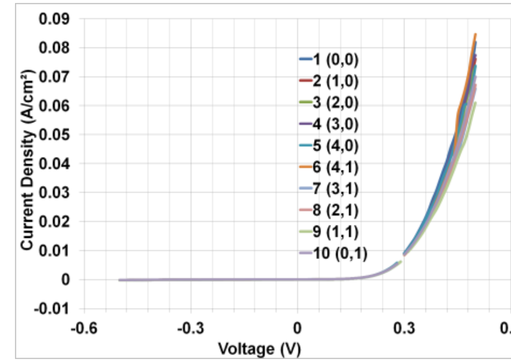
Barrier heights in format: ϕ_+/ϕ_-

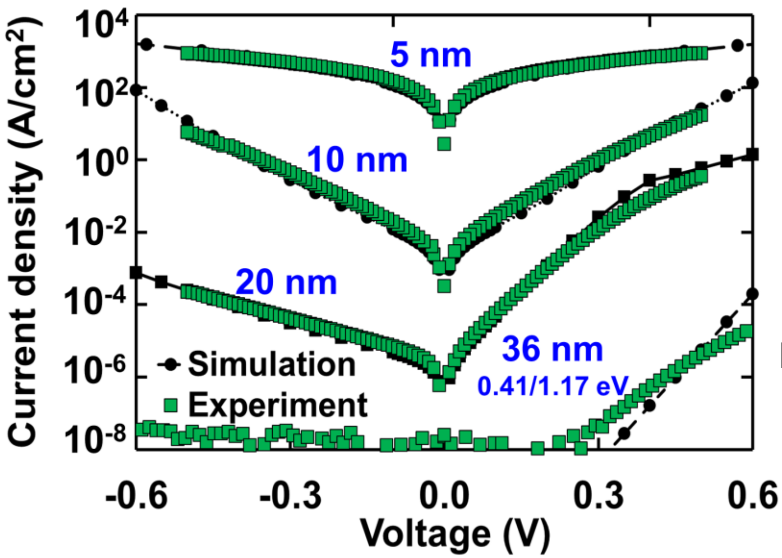
Eleven orders of magnitude in current through NbOx – based diodes





Pt/NbO_x/Nb test diodes (ARL)

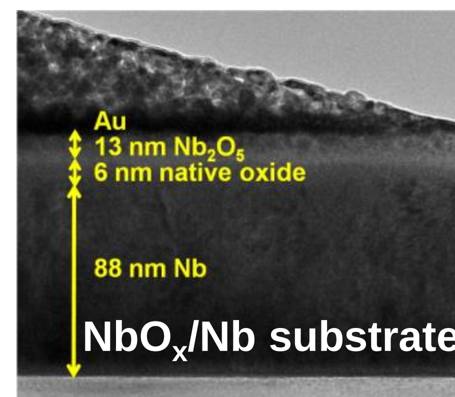




Barrier heights in format: ϕ_+/ϕ_-

NSRDEC measurement, analysis, modeling

Pt/Nb_2O_5/(NbO_x)Nb test diodes with various barrier (oxide) thicknesses



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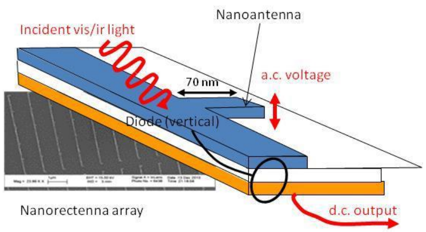
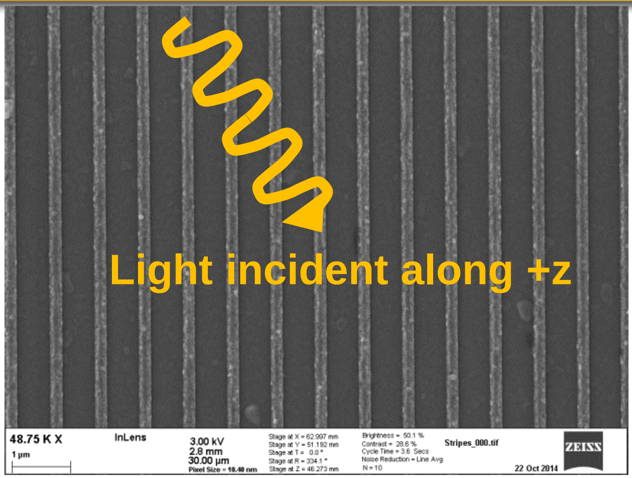
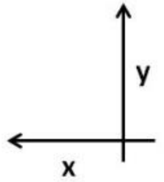
Stripe arrays exhibit cross-stripe resonances

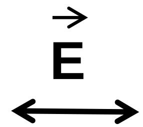


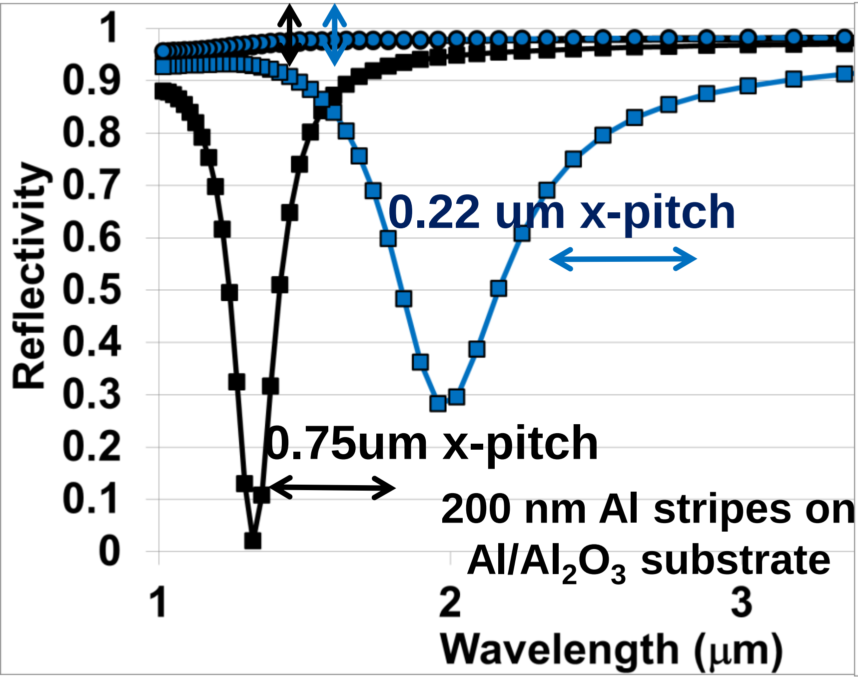
Microrectenna

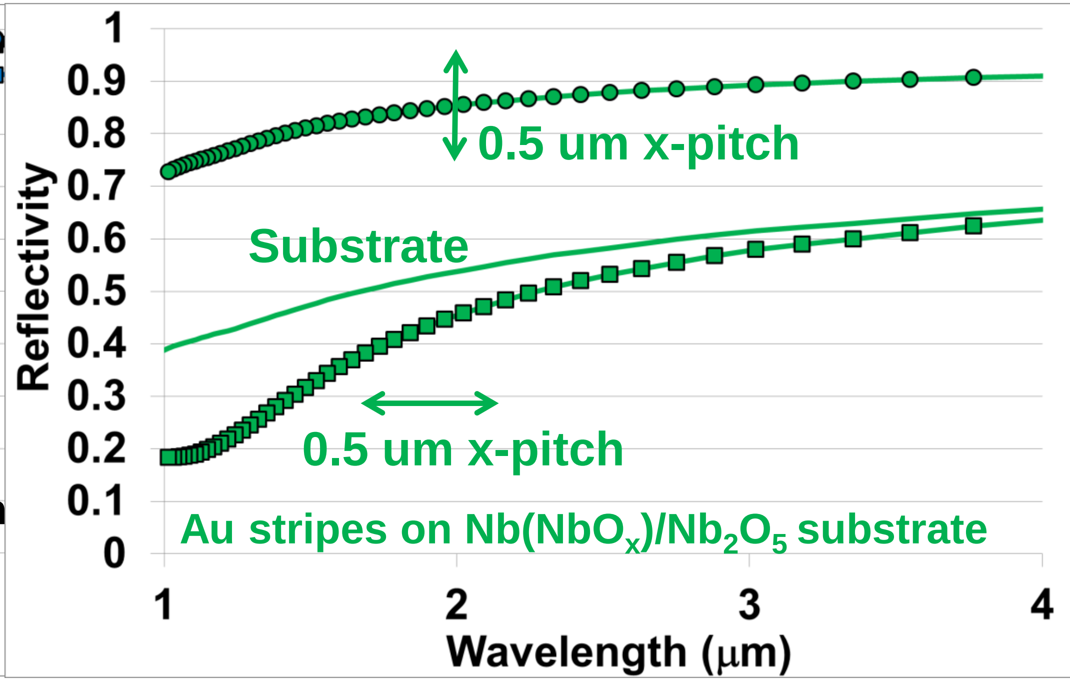
Top view of stripe array



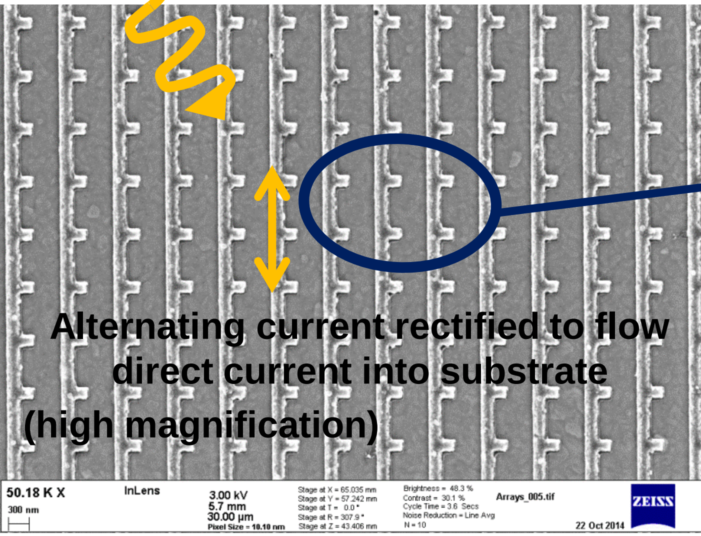


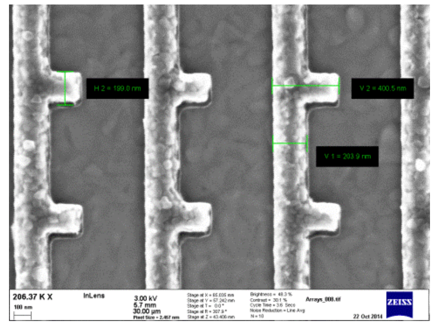






Stripe-teeth resonances (Al-Al_2O_3-Al microrectenna arrays)

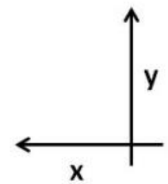


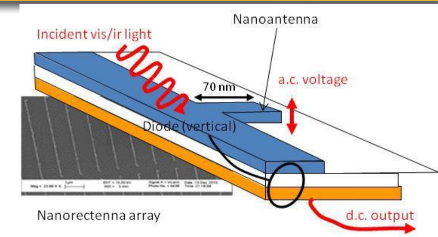


Top view

LINCOLN LABORATORY
MASSACHUSETTS INSTITUTE OF TECHNOLOGY

US Army NSRDEC design

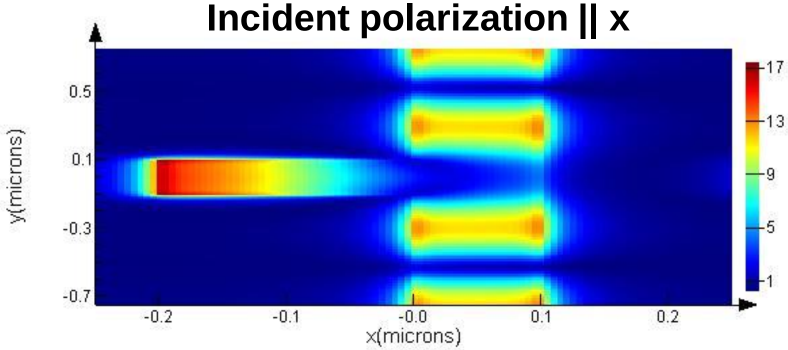




Microrectenna

2.25 μm resonance

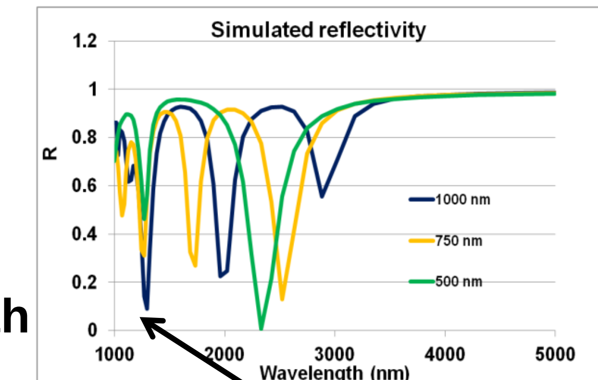
Incident polarization || x

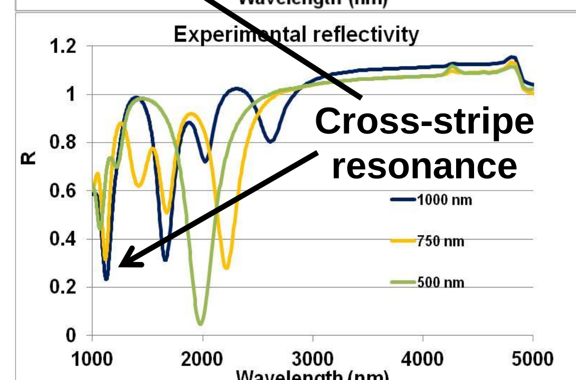


200 nm long Al teeth and stripes

E || x

⟷

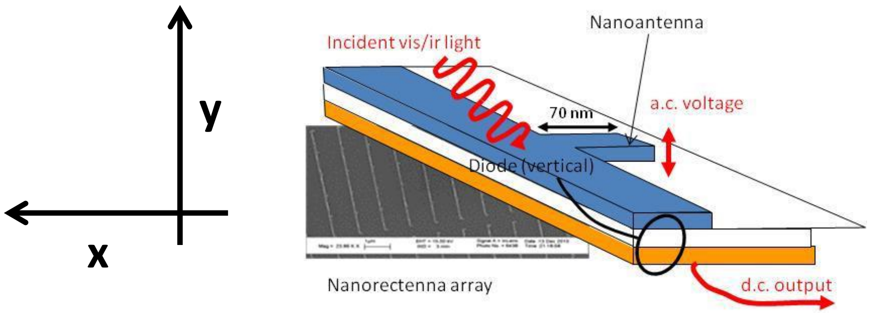


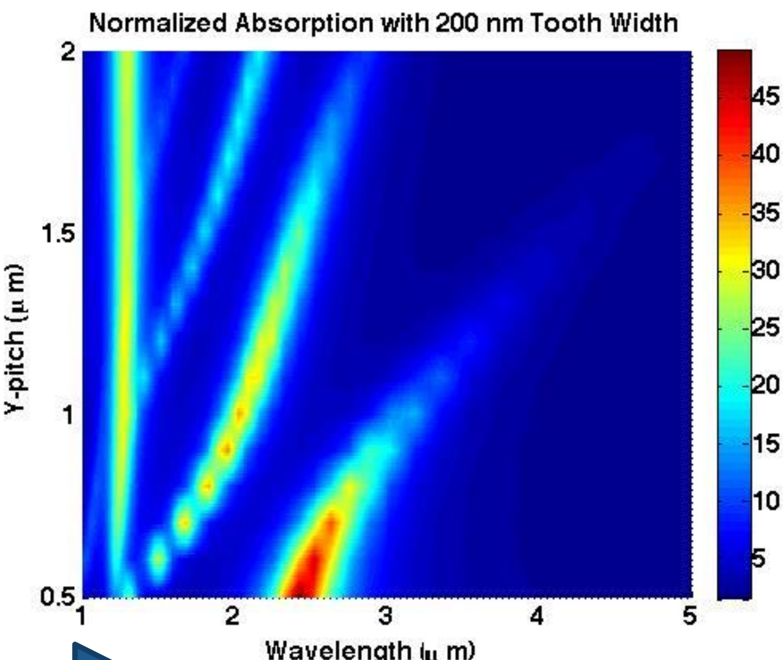


Cross-stripe resonance

"Teeth" add additional cross-stripe resonances!
(dependent on teeth separation)

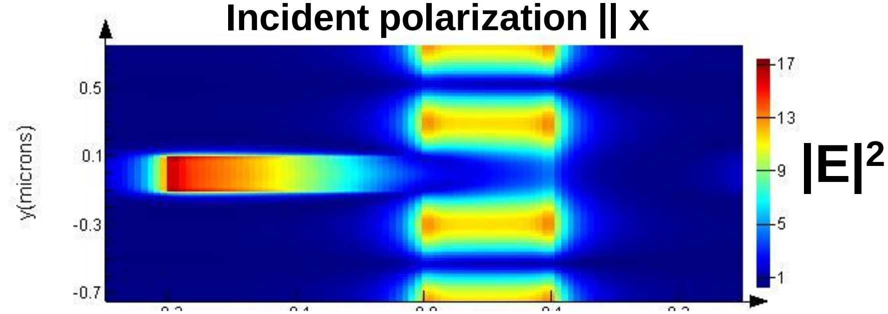
Stripe-teeth resonances (Al-Al_2O_3-Al microrectenna arrays)

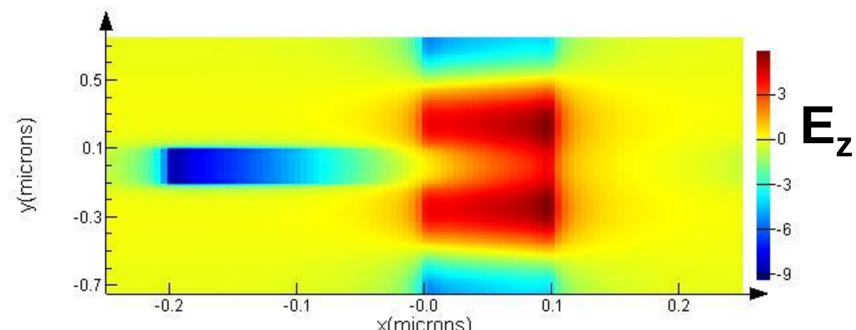




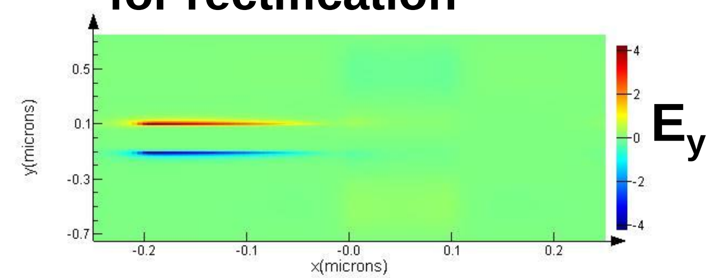
2.25 μm resonance

Incident polarization || x



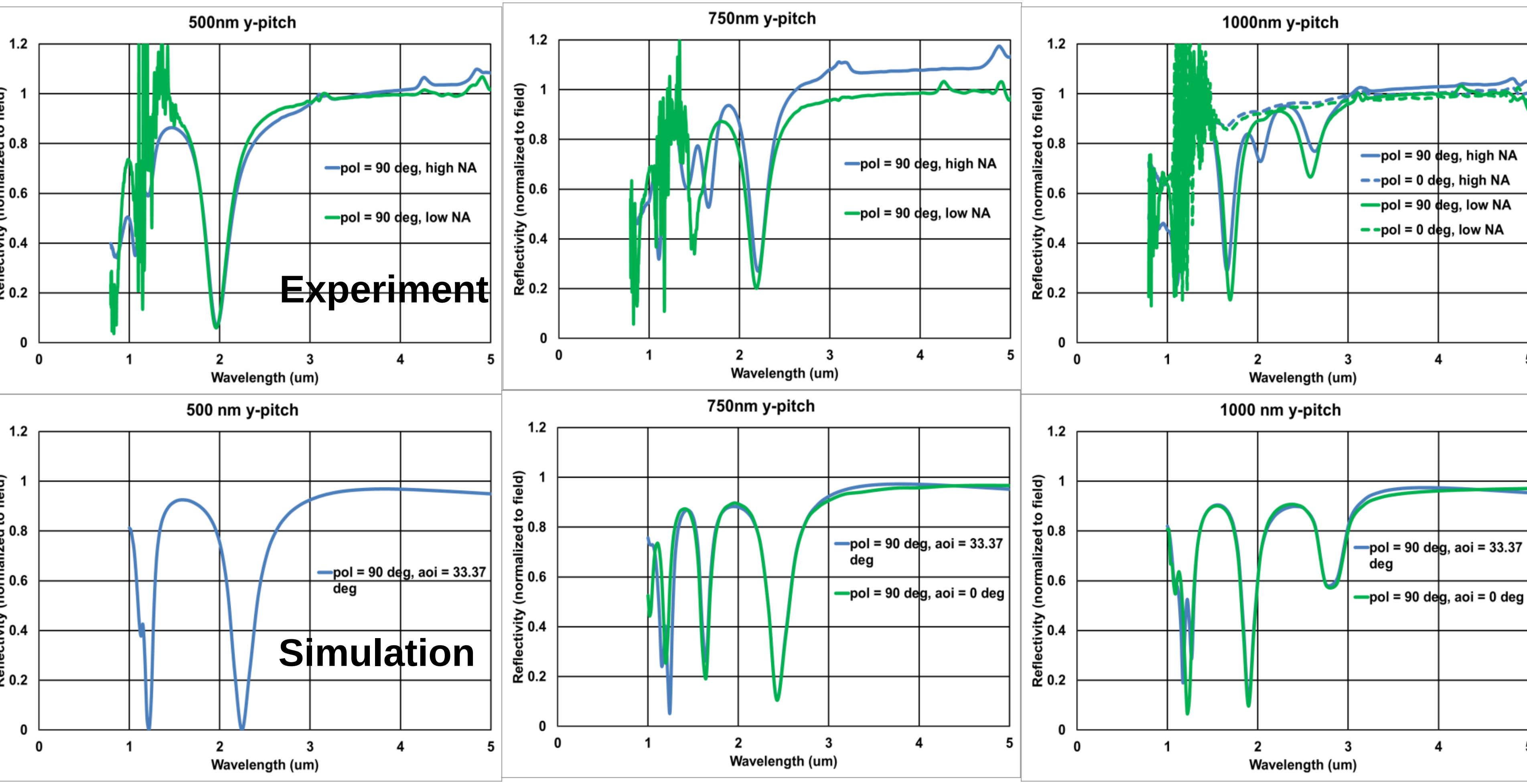


Large asymmetry in E_z needed for rectification



Has very asymmetric E_z, but need stripes to extract current at resonance

Stripe-teeth resonances (Al-Al_2O_3-Al microrectenna arrays)

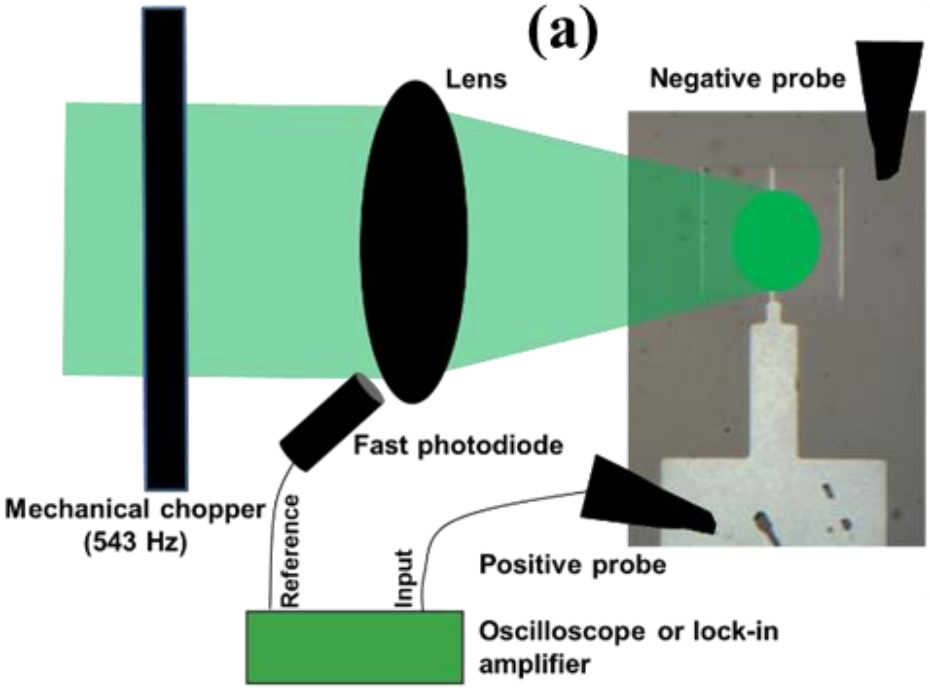


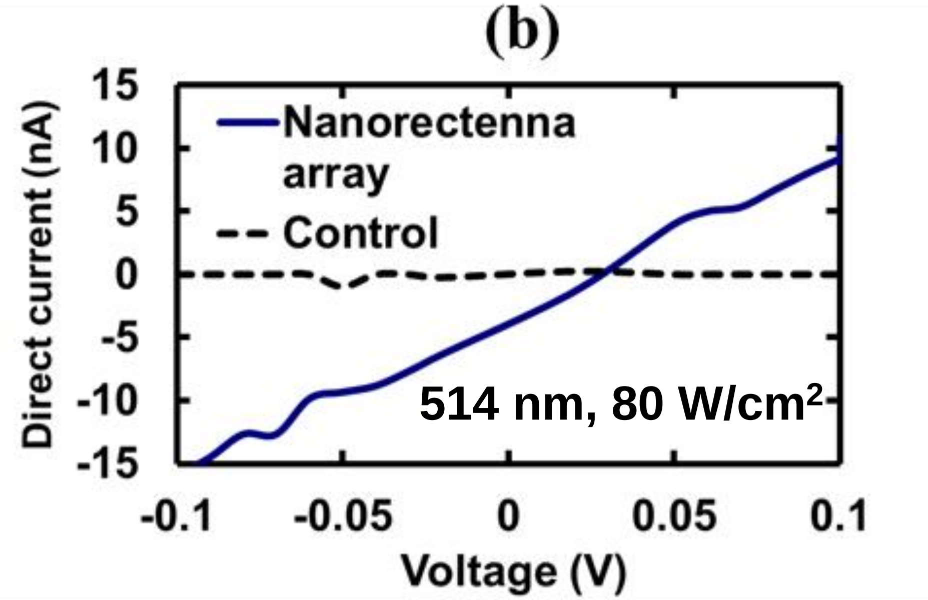
- **Good (not perfect) agreement between FTIR-measured spectra and simulated reflectivity. Insensitive to angle-of-incidence (to > 33°).**

Analysis of horizontal stripe-teeth arrays

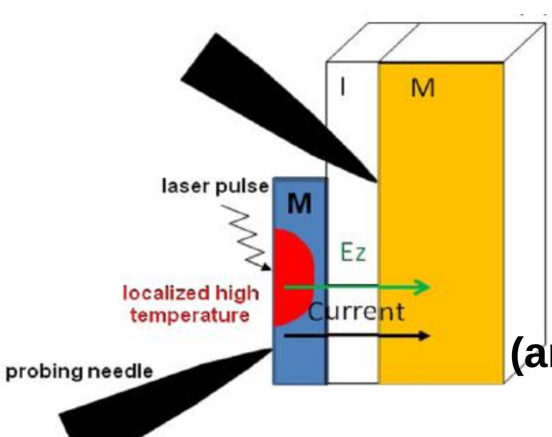
- Designed for maximum asymmetry/non-linearity consistent with stripes to extract current
- Al-Al_2O_3-Al arrays have excellent quality and controlled resonances
  - Make broadband with chirped arrays
  - With “Au wire” responds to cw visible lasers
- Au/Ti-Nb_2O_5-NbO_x-Nb has a lossier ground plane (Nb) and, while an excellent electronic-quality oxide, antenna resonances much broader and weaker
  - However there is an interesting response to cw lasers with small dimensions (“nanorectenna array”)

Nanorectenna array output power from cw laser illumination!





- 5 nA at zero volts - much higher than predicted from rectification responsivity (0.45 A/W maximum)!



NSRDEC measurement, analysis, modeling

Photothermoelectric effect (antenna heated more than the ground plane)?

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Nanowire-based nanorectenna clusters

- Inverted Au/Al_2O_3 (ALD)/Al stack
- Au wire antennas underneath Al electrode
- Regular, high-resolution arrays of lines and dots
- Unique nanopatterning approach

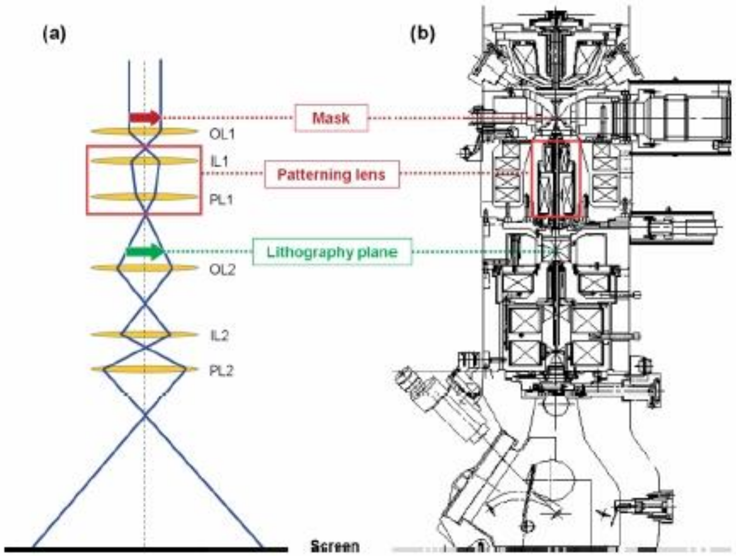
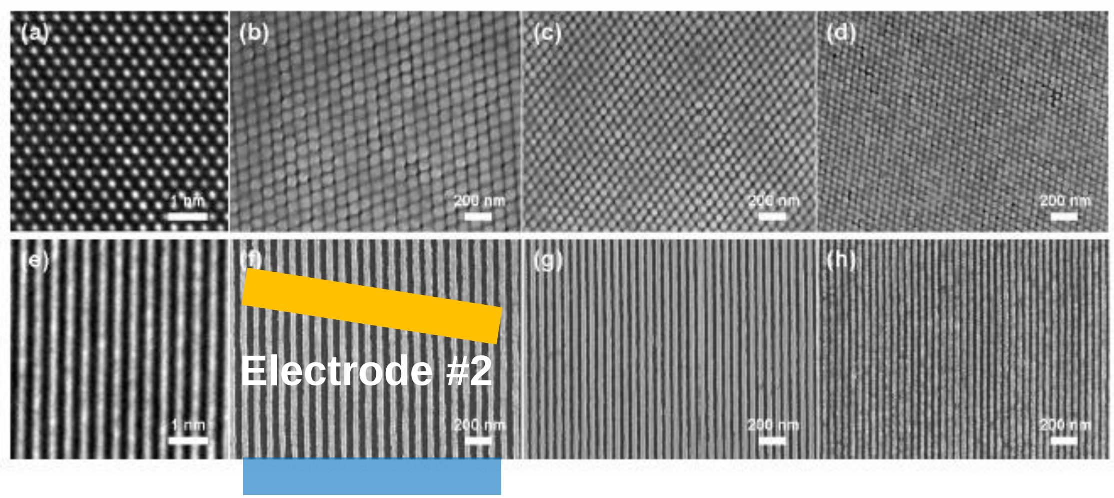


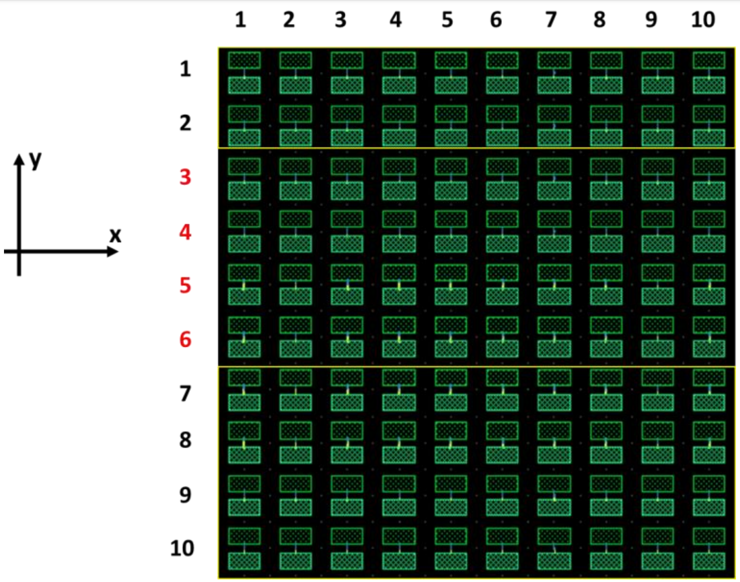
Figure 1. Schematic ray diagram and cross-sectional view of the present lithography system. a) Ray diagram of the basic lens system of image formation, which is composed of two different sets of OL, IL, and PL. The first set magnifies the sample image to the lithography plane with a magnification ranging from 50 to 300 times, while the second set further magnifies this image to the viewing screen. b) The specially designed hardware which was developed based on the modification of a 200 kV TEM equipped with a field emission gun (JEM-2010F, JEOL Ltd.).

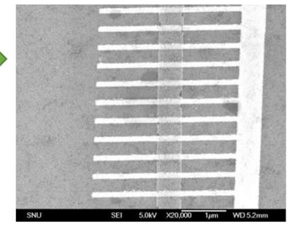


Electrode #1

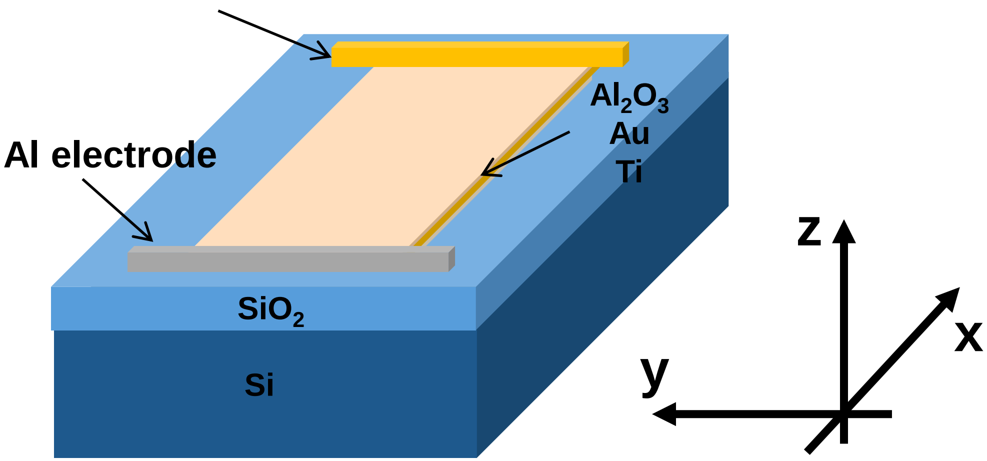
Vertical diode, horizontal antennas

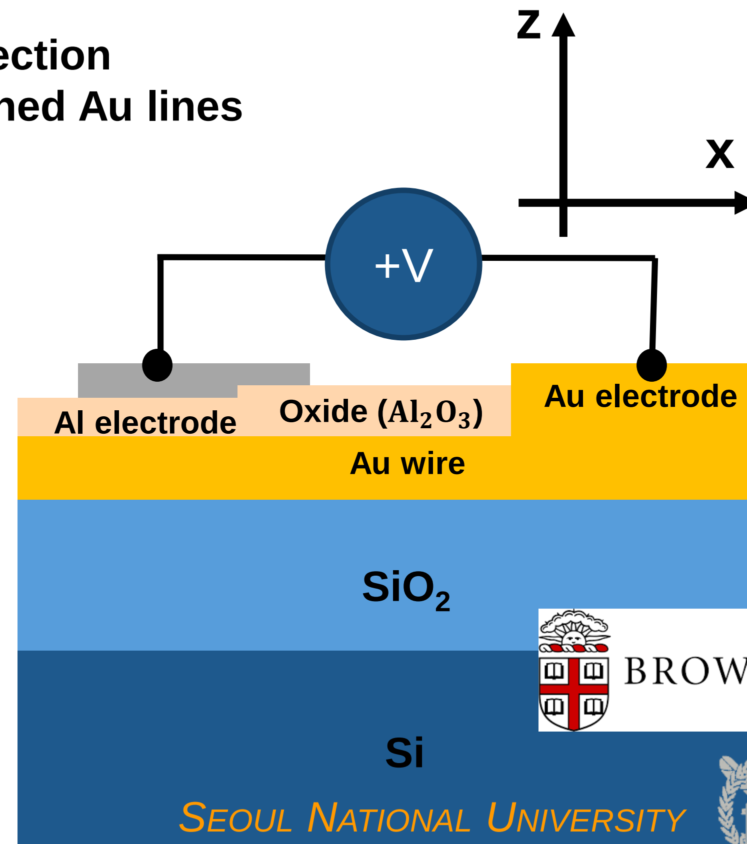
Nanowire-based nanorectenna clusters





Projection nanopatterned Au lines





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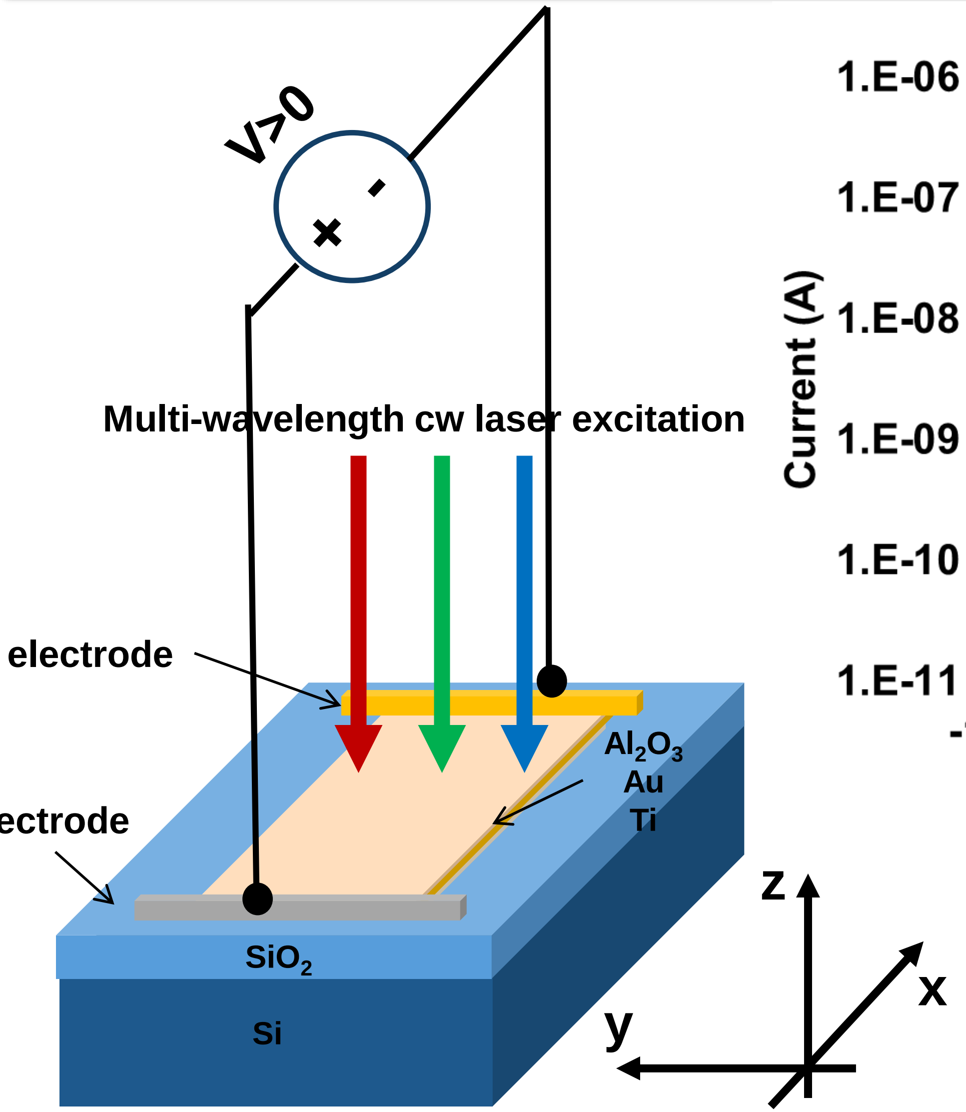
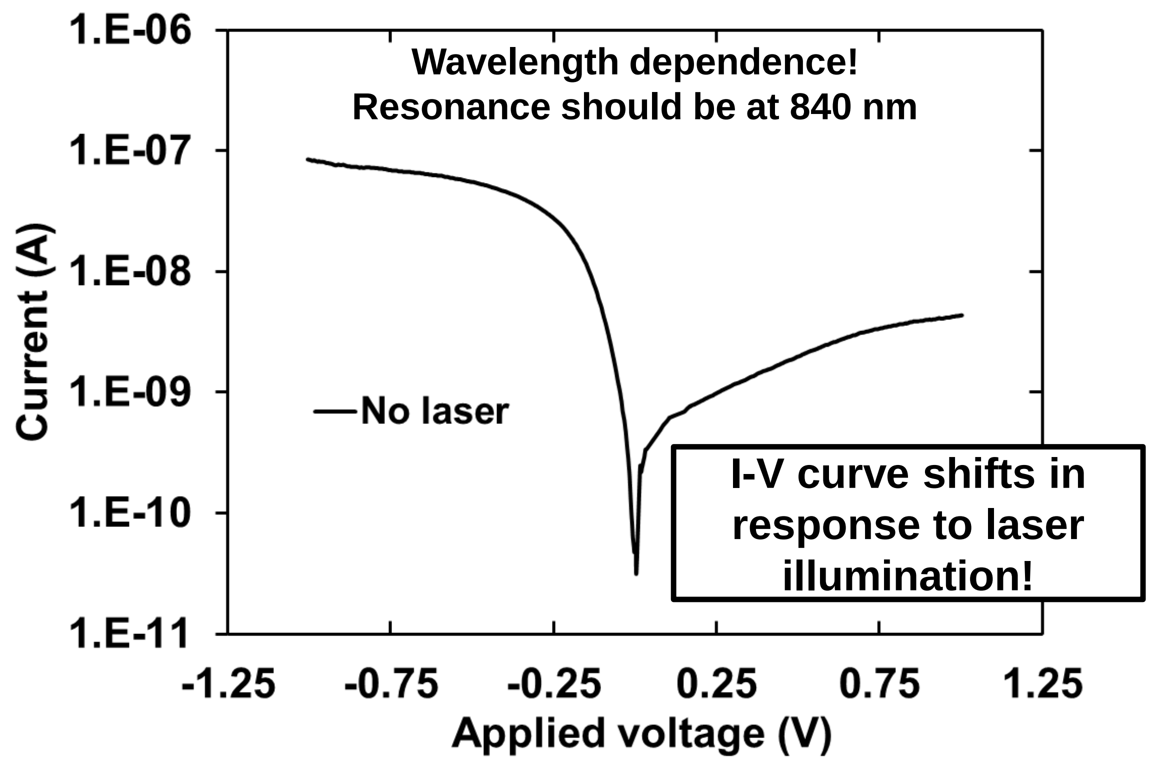
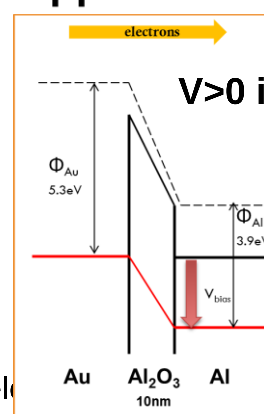
Nanowire-based nanorectenna clusters







V>0 is forward bias ($V_{Al} > 0$)

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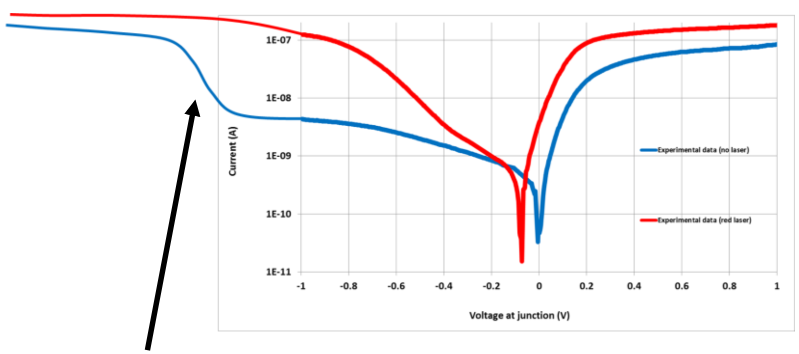
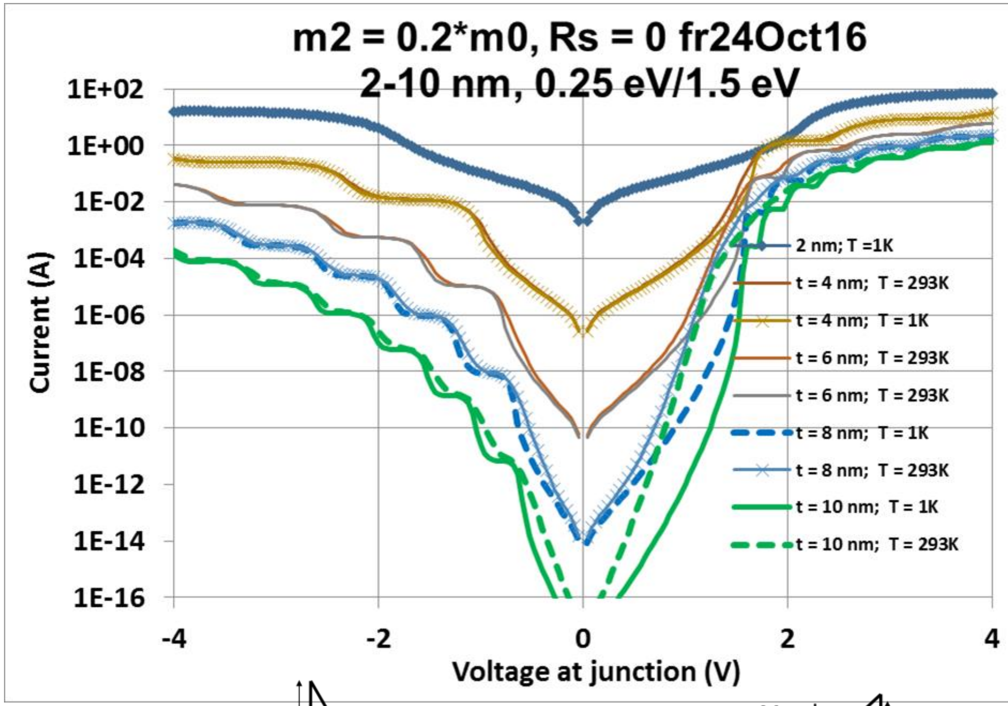
Modeling Al-Al_2O_3-Au nanorectennas to explain data

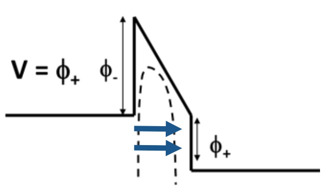
Hypothesis I: steps in I-V curve are due to oscillations in transmission function through barrier layer in MIM diode, which are due to interferences in the transmission through the trapezoidal (image-modified) potential



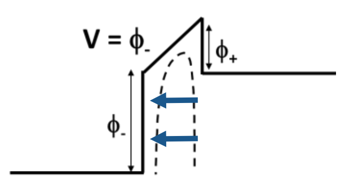
Hypothesized "step" in I-V curve

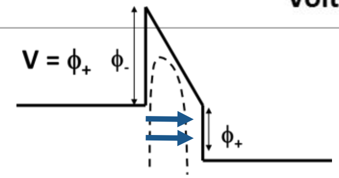


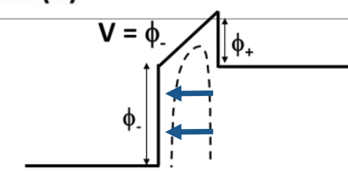
Forward bias



Reverse bias







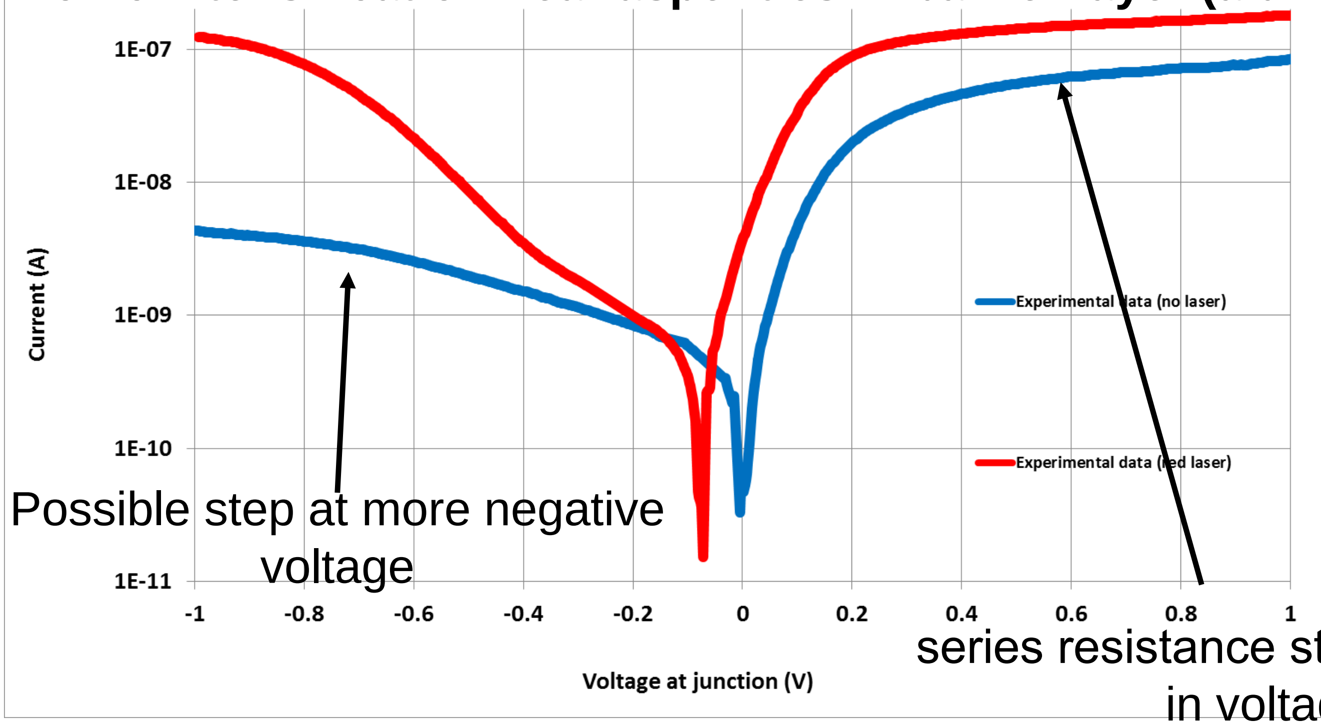
A few states below the Fermi level have tunneling transmission resonances across barrier into empty states (producing steps in the I-V curve at low temperatures), but V must be at least > ϕ_+ (for forward bias) and at least > ϕ_- (for reverse bias)

2-10 nm thick barrier layer, K = 6, Temp = 293 K or 1 K

Note: V > 0 is *reverse bias*

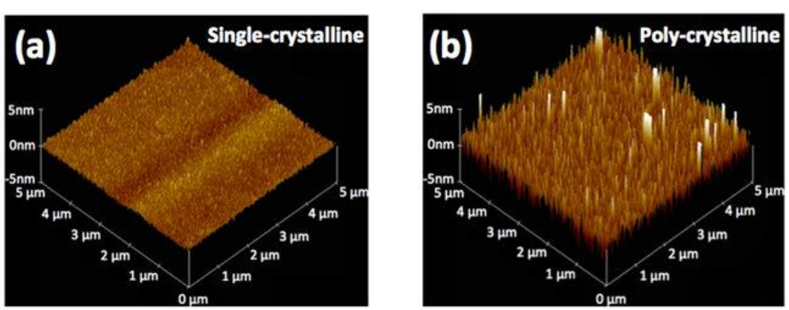
Modeling Al-Al_2O_3-Au nanorectennas to explain data

Hypothesis II: Shift in J-V curve due to laser illumination may be due to field and plasmonic intensification near asperities in barrier layer (aluminum oxide)



Possible step at more negative voltage

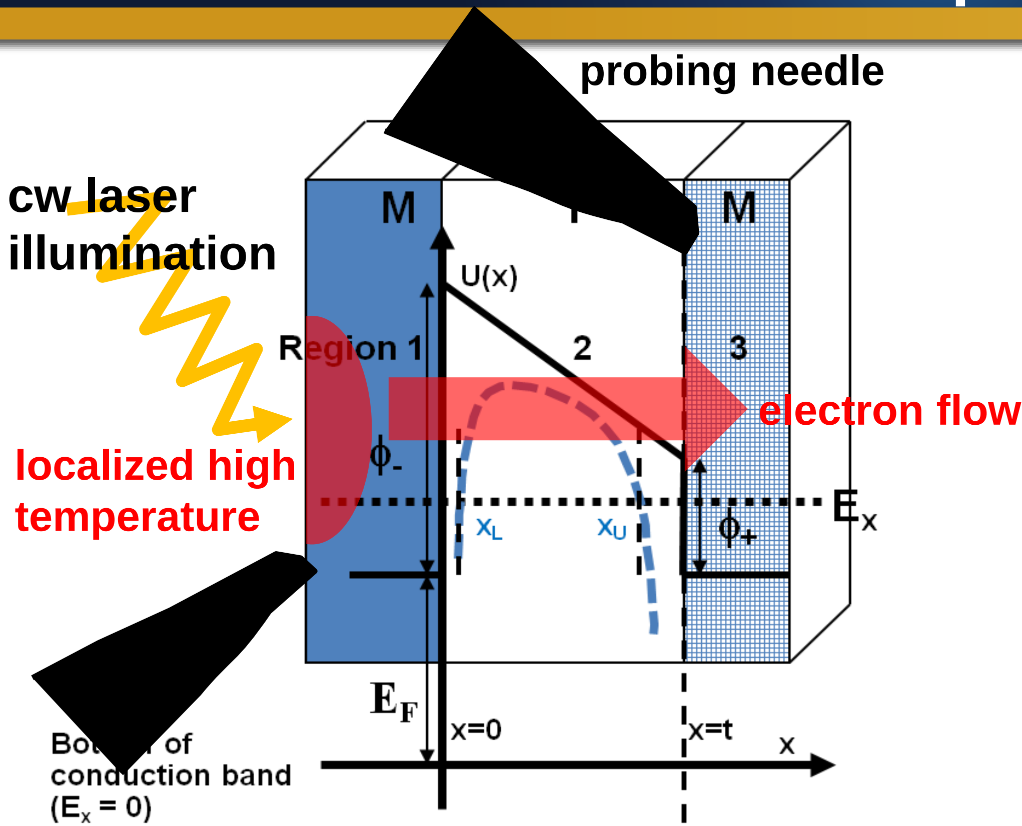
series resistance starts to “stretch” out in voltage here

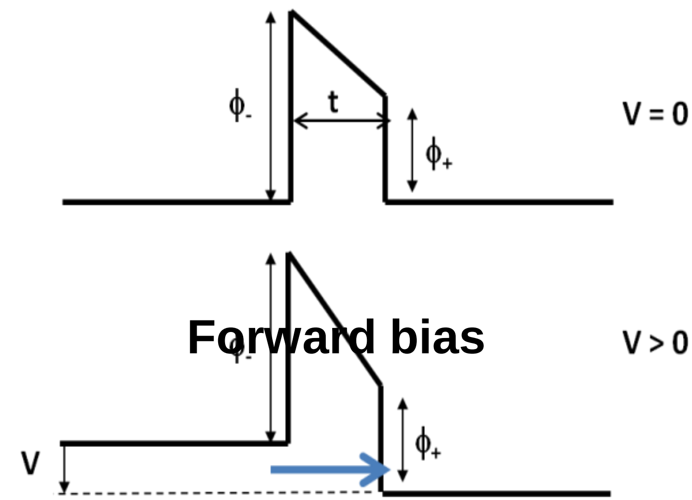


Other possibilities for large response to cw visible laser: rectification, charging

Note: V > 0 is *reverse bias*; opposite from previous notation.

MIM diode model improved to include temperature gradients





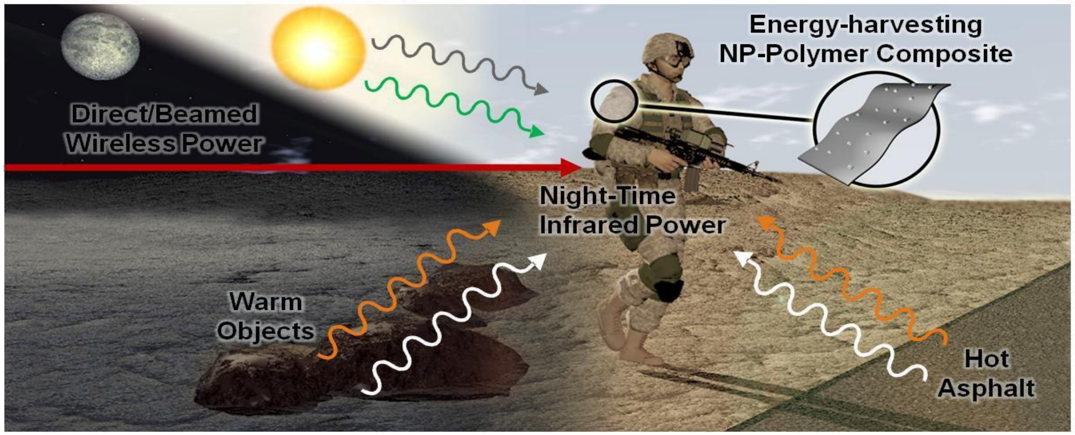
New temperature gradient in NSRDEC MIM diode model; regions 1 and 3 are at different temperatures. Barrier heights: ϕ_- and ϕ_+, where ϕ_- > ϕ_+.

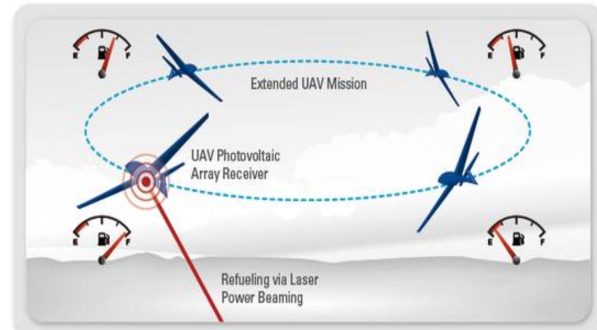
Conclusions

- Nonlinear rectifying metadevices create new opportunities (quantum and nonlinear plasmonics)
- Nb- and Al-based stripe-teeth metamaterial arrays designed and analyzed
  - Both have cross-stripe resonances
  - Au/NbOx/Nb: broad, weak resonances
  - Al/Al_2O_3/Al: well-controlled absorption spectrum
    - Standing wave resonances dependent on y-pitch
    - Angle of incidence has little effect to at least 33 deg.
  - J-V curves for Ag(Ti)/NbOx/Nb show ϕ_-/ϕ_+ = 0.41/0.77 eV
  - J-V curves for Al/Al_2O_3/Au show ϕ_-/ϕ_+ reduced
    - Curves shift with focused laser – due to field enhancement from AlOx roughness, photoemission/charging, and heating effects
    - "Steps" in I-V?
    - Rectification responsivity predicts shift due to laser illumination?
- Large direct current at V = 0 from Ag(Ti)/NbOx/Nb and Al/Al_2O_3/Au microrectenna arrays much larger than predicted by classical and quantum rectification formulas
  - Rectification or photothermoelectric effect?
  - Are steps in MIM diode I-V curves possible?

Potential future concepts

- A new early applied program on narrowband infrared rectenna arrays starting in FY17.
- Proof-of-concept experiments (labscale demonstrations) will be carried out for power and data beaming.





Potential application: Wireless power/data transfer/communications (Warfighter/Soldier/Squad and/or UAS sustainment)

Enhanced thin-film photovoltaics

Potential future application: Solar blankets and/or military shelters