RedWave
ENERGY, INC.

ARPA-E Workshop
Low Grade Waste Heat Harvesting

12/13/16

The Mission

RedWave Energy's mission is to develop disruptive energy harvesting products in the infrared - opening markets in waste heat and using low cost roll-to-roll manufacturing methods.

RedWave Energy, Inc. Proprietary Information

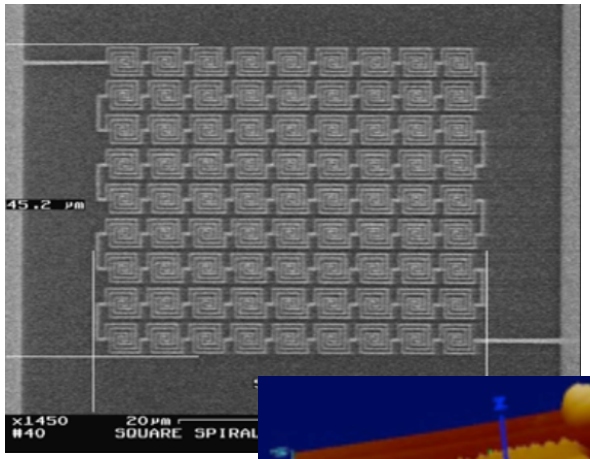
RedWave Energy

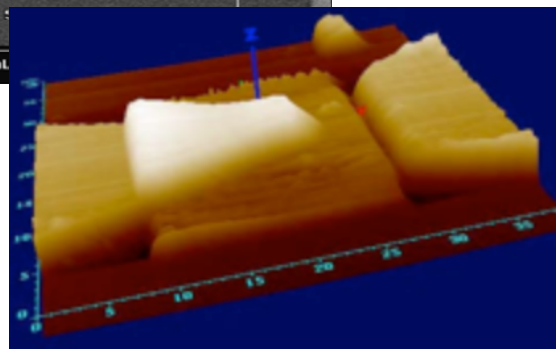
2011 - Formation

Idaho National Labs

Nanoantenna technology

- 30THz FSS
- Roll-to-roll prototype





University of Colorado

Metal Insulator Metal (MIM) Diodes

100GHz+

THz operating potential

Fabrication fit with nanoantenna technology

2012 Funded February - Northwater Capital, Inc

2013 Record setting room temperature THz detector

2016 Series B Funding - Enertech, Prime Coalition

ARPA-E Grant - Year 1: 5% conversion at 100C target

History

Team

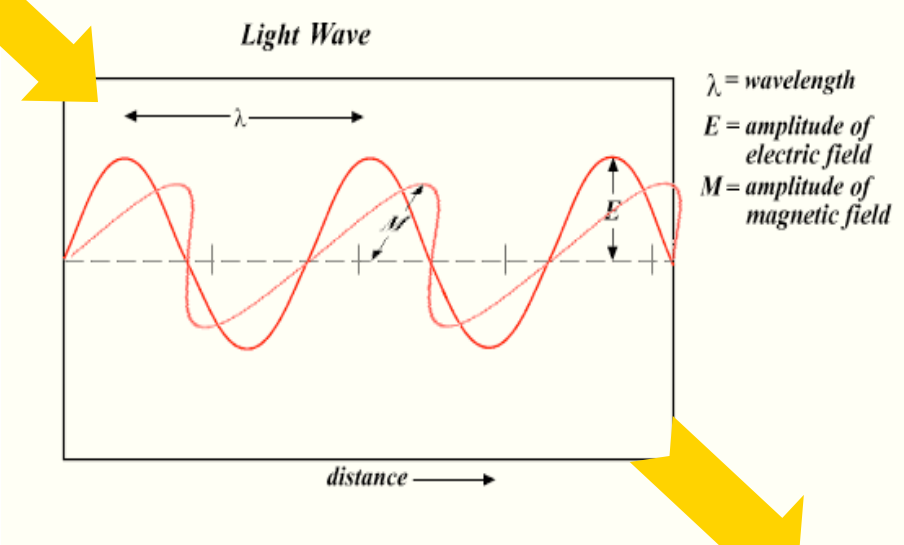
Consortium of Industry and University

- University of Colorado - THz diodes and Metamaterials
  - Dr. Garret Moddel
  - Dr. Won Park
- University of Missouri - Materials Interfaces Expertise
  - Dr. Patrick Pinhero
  - Dr. Zack Thacker
- MicroContinuum, Inc. - Roll-to-Roll Fabrication
  - Dr. Dennis Slafer - Production of ACTfilms
- Redwave Energy, Inc.
  - Jim Nelson - CEO
  - Pat Brady – CTO
  - Dr. Miena Armanious - Antenna Scientist
  - Dr. Pallab Midya – Power Circuit Scientist
- Oregon State University – MIM Diode materials
  - Dr. John Conley

Leadership

Theory of Operation of Rectenna

In coming energy propagate as electromagnetic waves



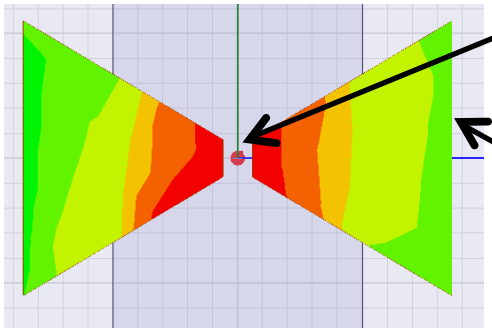
- Captured by a Nanoantenna
- Absorption occurs at antenna resonance

- Induces a cyclic plasma movement of free electrons
- THz current flows toward antenna feedpoint
- Diode is embedded in feedpoint to rectify signal producing DC
- Power is transfer to grid or storage

"Rectenna" = Diode at feedpoint rectifies signal

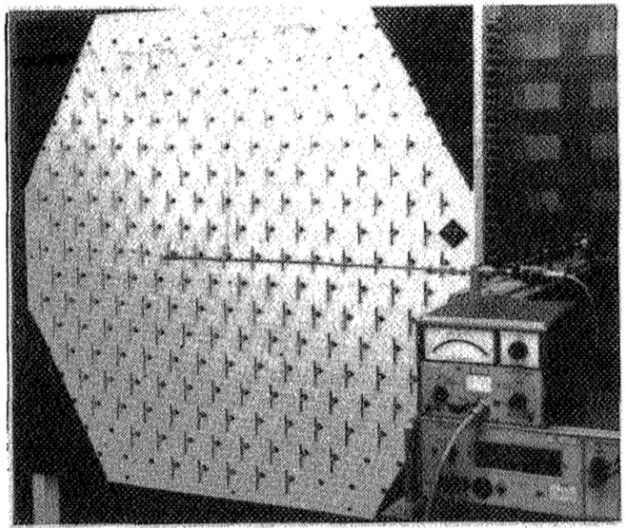
+

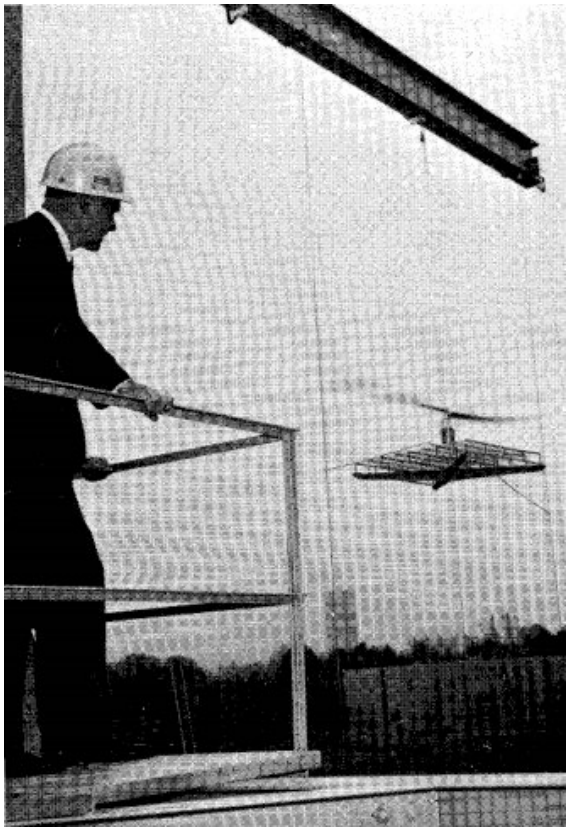
Bowtie antenna



Rectenna history

1963 - Raytheon and Air Force
    Create rectenna to power high altitude atmospheric platform via microwaves
    3.0 GHz system transfers 400kW CW power 70% efficiency
1964 - 200W demonstration of remote power of small helicopter
1968 - NASA
    Interest in using rectenna for power transfer between space vehicles
1970 - Collection efficiency of FSS increased to 93% (MSFC)
1975 - 1.6km power transfer 30kW system 82% efficient
2004 - Estes, Moddel patent Traveling Wave Solar Rectenna
2009 - INL creates 30THz nanoantenna w/R2R
2013 - RedWave builds 1THz detector
2016 - RedWave converts heat to electricity using rectenna





Rectenna technology and waste heat

Rectennas and Solar

- Initially seen as capable of greater efficiency than PV.
- 300 - 750 THz well beyond electronic capabilities
- Very small devices required (wavelength 500nm)
- Metals become lossy

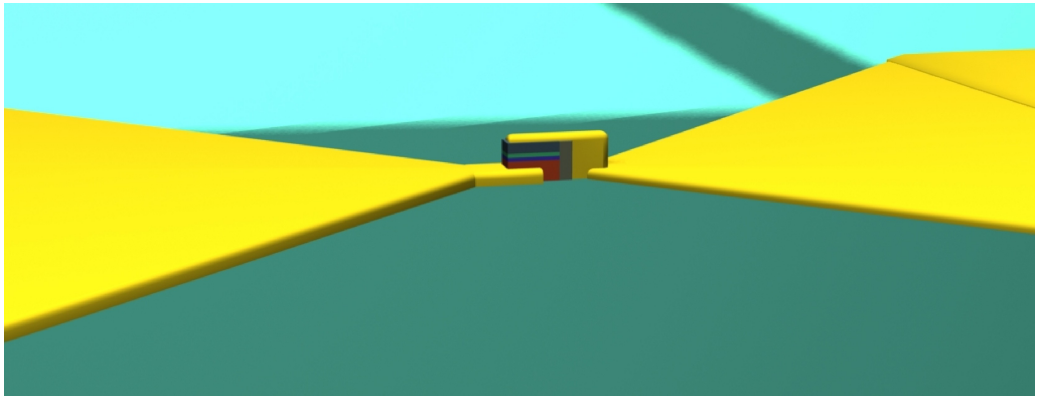
Rectennas and Waste Heat

- Device sizes manageable
- Metal losses manageable
- 30THz - 50THz still beyond semiconductor electronics
- BB radiation
  - Incoherent
  - Very wide band

RedWave Technical direction

Team focus

- Nanoantennas
- MIM diodes



Phase 1

Integrated both technologies into 1THz detector (POC)

Phase 2

Developing two harvesting methods built to adapt MIM diodes to the task

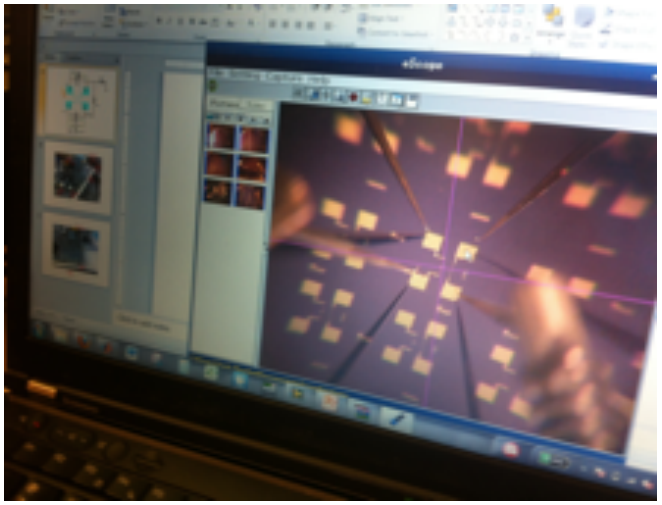
Technology

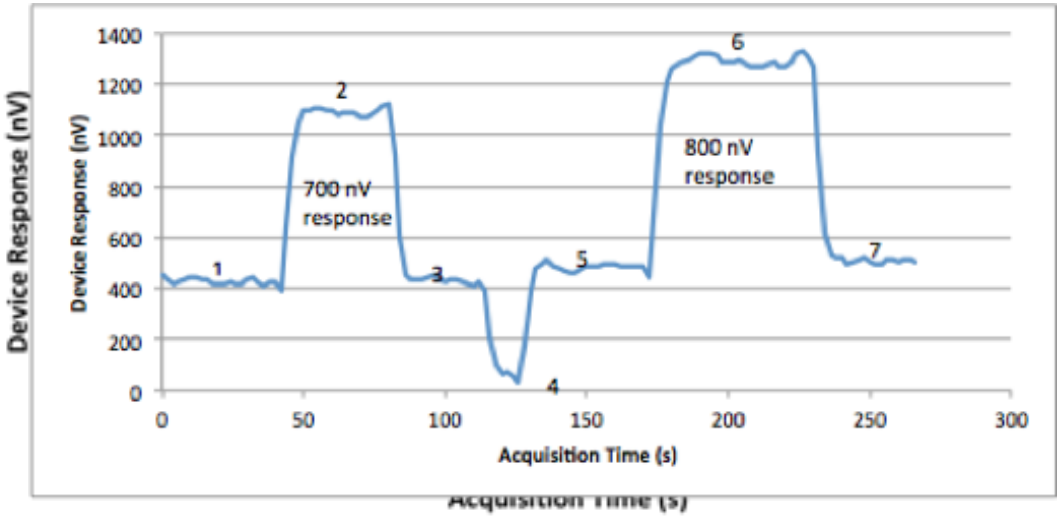
Technical Journey

Phase 1

Completed Device Measurements

Device response:
22% Efficiency



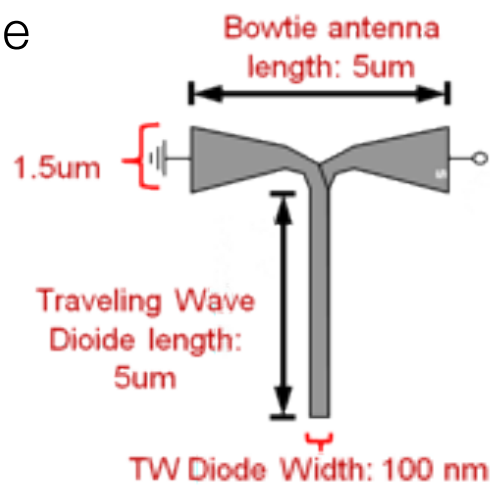


Progress

RedWave Energy Harvesting

Two Harvesting methods

- 28 THz direct harvesting method (traveling wave diode)
  - Antenna delivers plasmon to diode in waveguide form factor.
  - POC complete Jan 2015



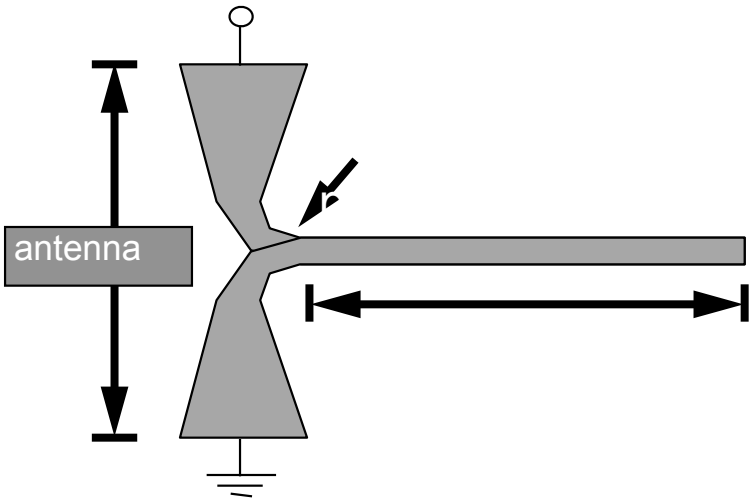
Phase 2

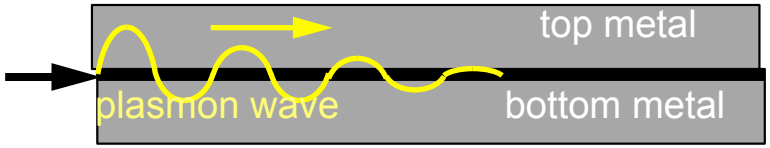
Traveling Wave

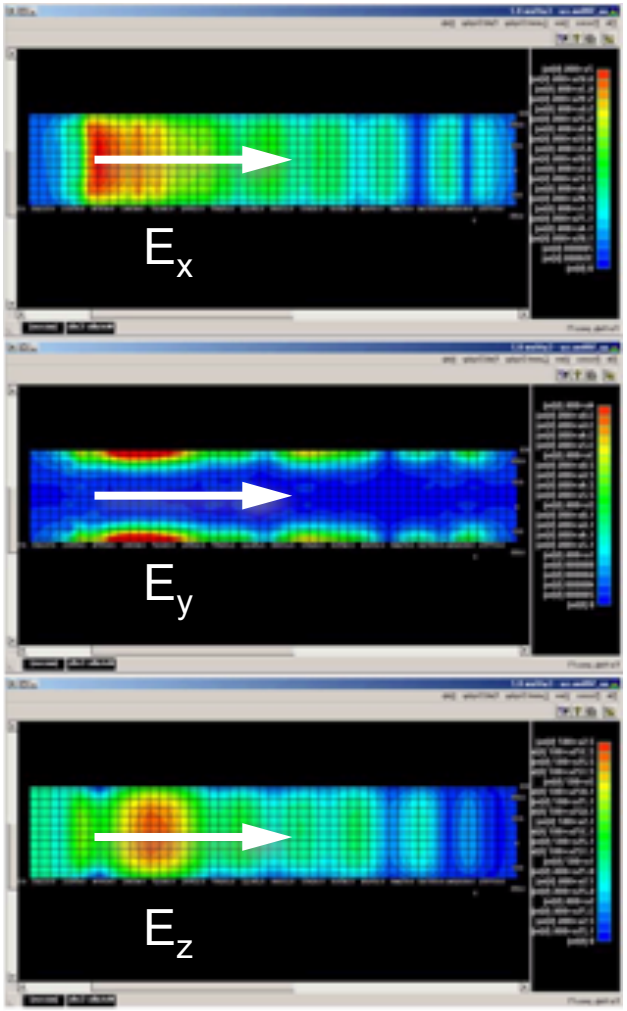
Traveling Wave Device

Improves:

- Efficiency
- Impedance matching to antenna
- RC time constant



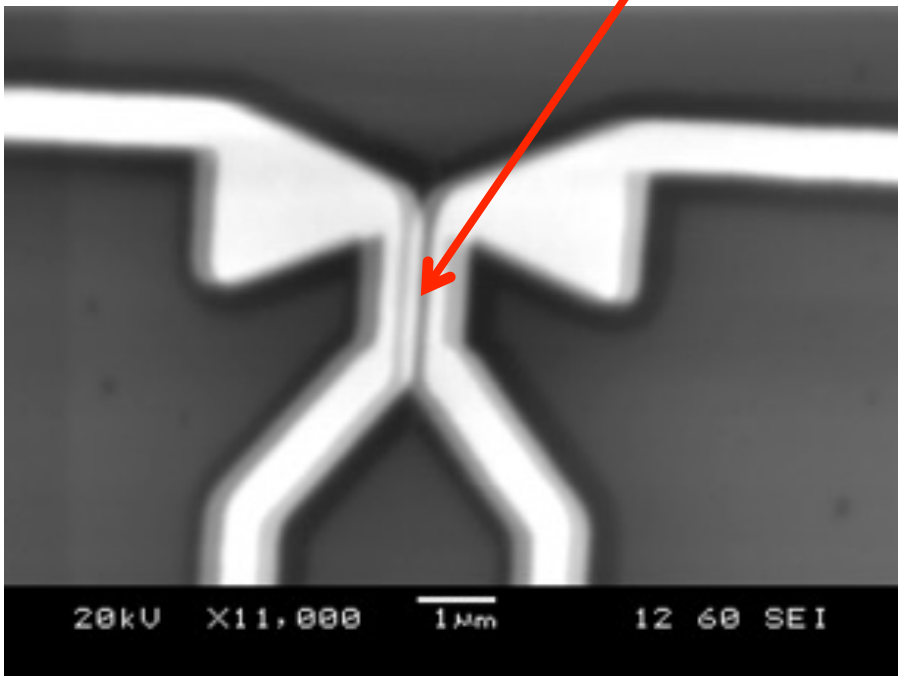




Technology

SEM Image

Traveling Wave Diode Region



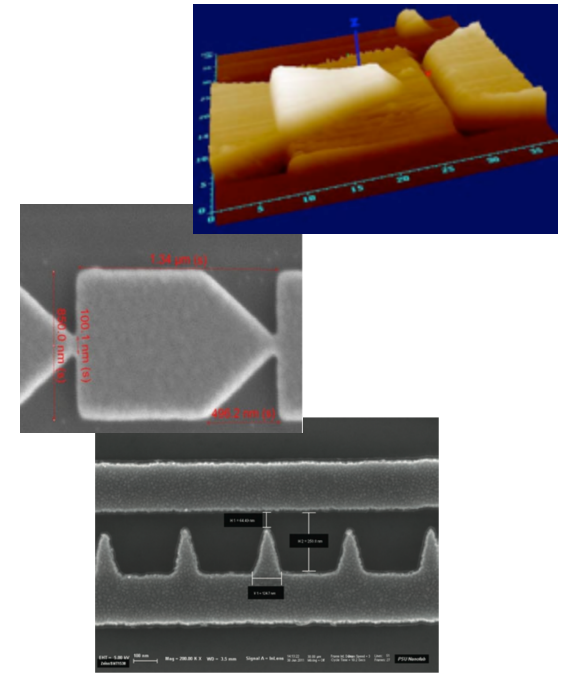
Technology

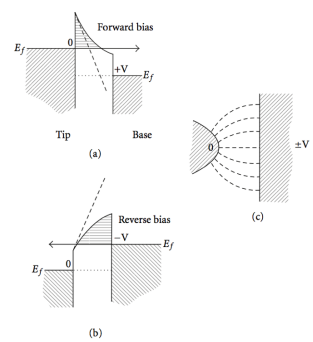
THz Diodes*

Metal Insulator Metal
- tunneling (very fast)
- metals have plenty of charge carriers
- capacitive
- resistance makes impedance match to antenna difficult
- reasonable fabrication

Geometric
- low resistance (good impedance matching)
- requires 10nm structures
- built from graphene

Point Diodes
- THz fast. Speed depends on sharpness of tip
- Small structures required create fabrication issues



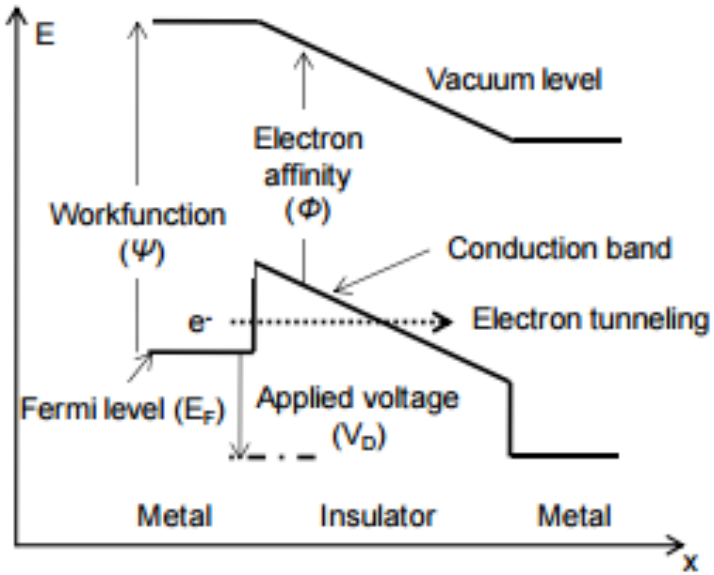


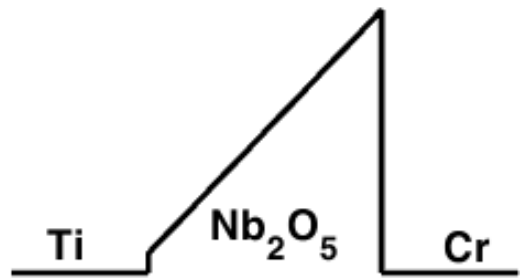
*Note - Semiconductor diodes require charge carrier refresh, making them too slow or THz operation.

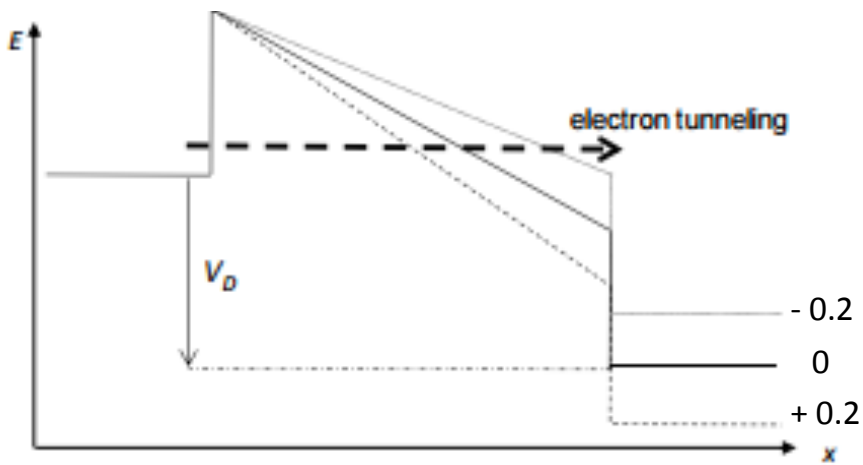
Technology

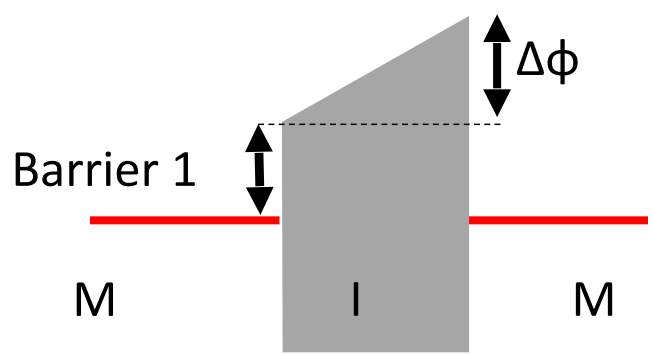
Single Insulator MIM

Energy band diagrams for MIM diodes





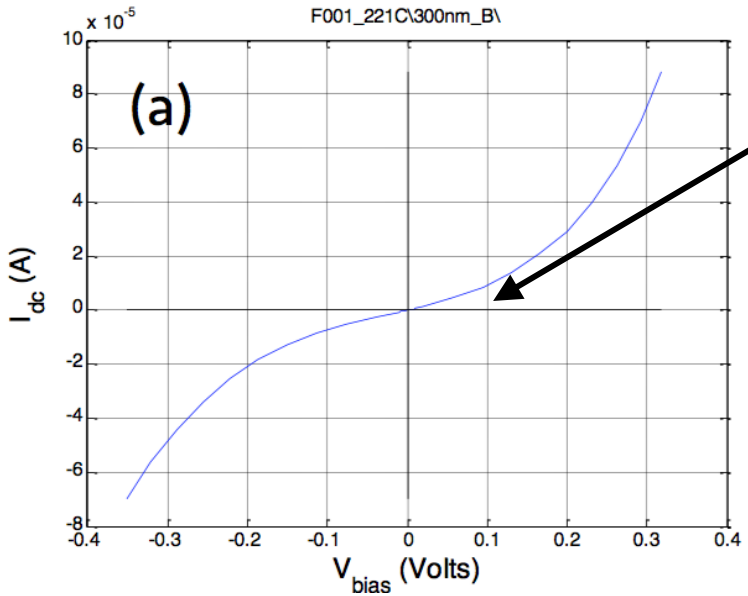




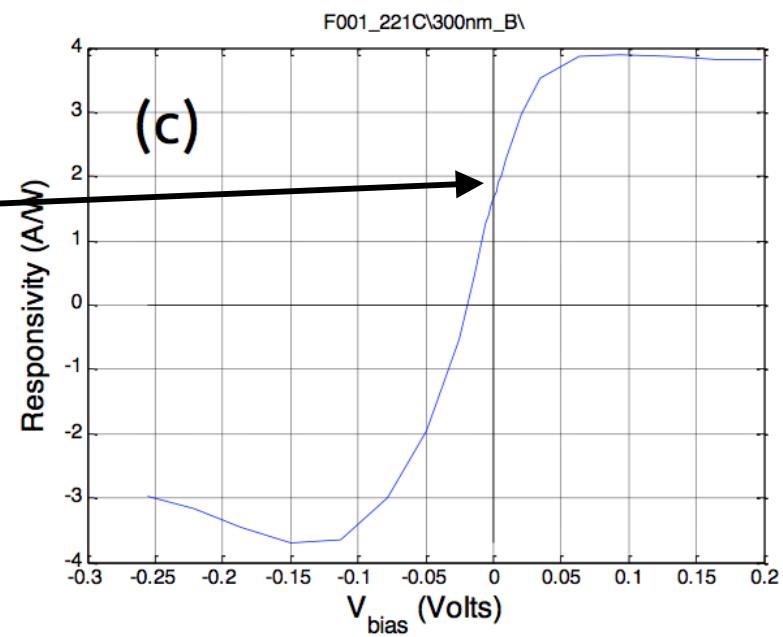
Technology

Diode operating range

MIM diode "turn on" voltage is about 100mV.



Responsivity of diode is near 2 A/W at 0V.



Technology

Diode issues

Required Characteristics

- Low diode turn on voltage
- Low resistance
- Low capacitance
- Low reverse leakage
- High zero bias responsivity

Materials properties and issues

- Need materials with low Electron Affinity and low Relative Permittivity.
- Surface roughness needs to be controlled and better understood.
- Deposition technology (Sputtering/ Evaporation/ALD)

Technology

Diode alternatives

Double insulator MIIM

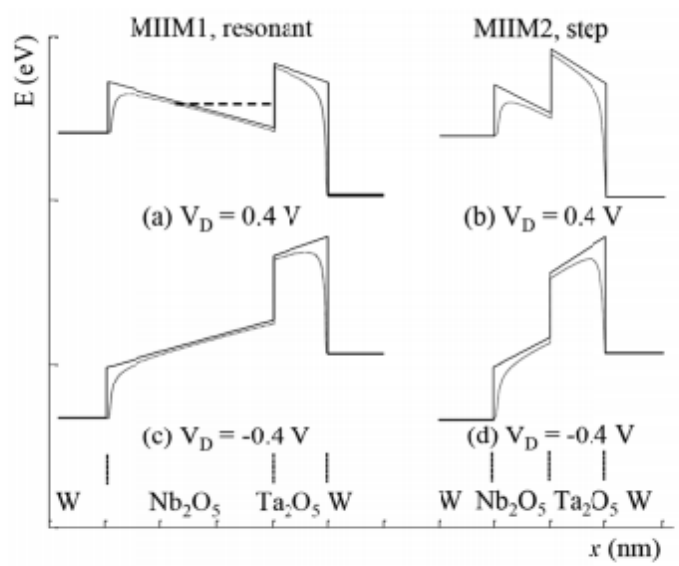


Figure III-1 Energy-band profiles for the resonant and step MIIM diodes. Forward and reverse bias profiles are shown respectively in (a) and (c) for the resonant, and in (b) and (d) for the step diode. The dotted lines show the profiles with barrier lowering. The diode parameters are given in Table I. The thickness of the Nb_2O_5 layer is the only difference between the two diodes.

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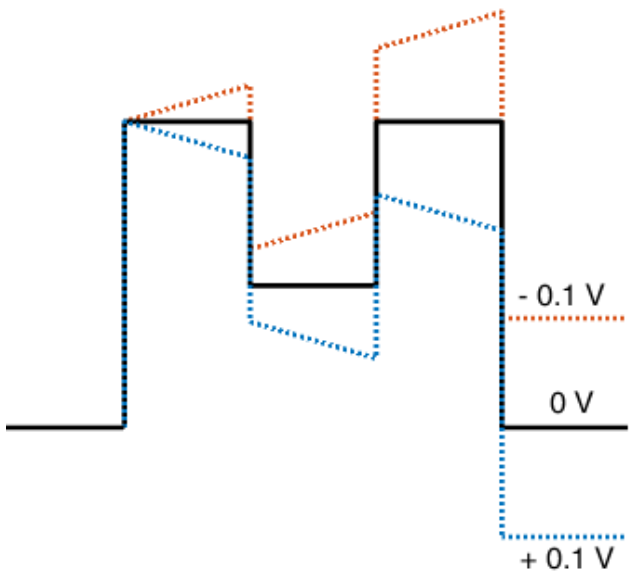
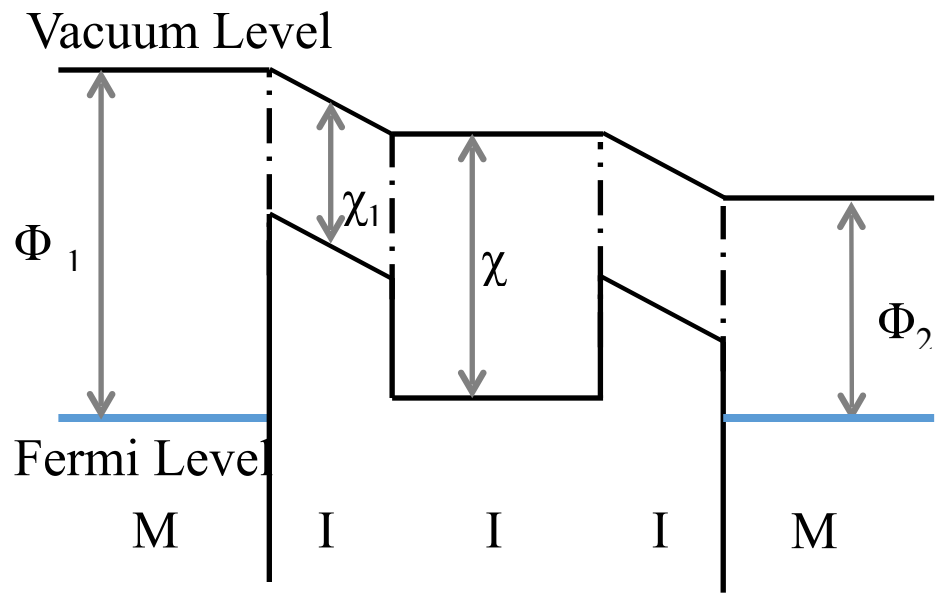
Diode alternatives

Triple insulator MIIM



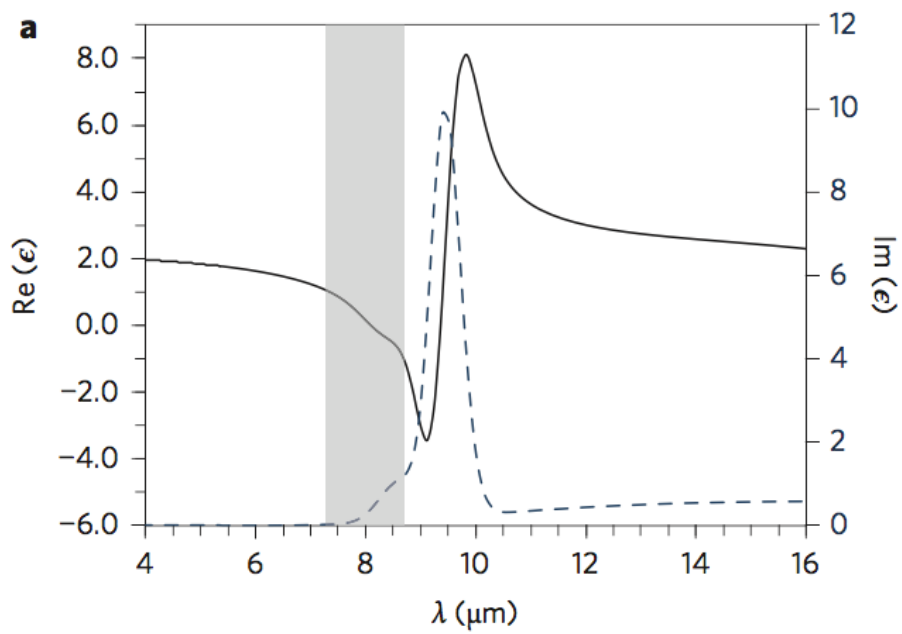
Ideal band diagram of MIIIM with three voltage biases



Technology

Diode alternatives

Exploiting frequency dependence of dielectric properties



Technology

Thank you

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