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Towards Rectennas for Solar Energy Harvesting

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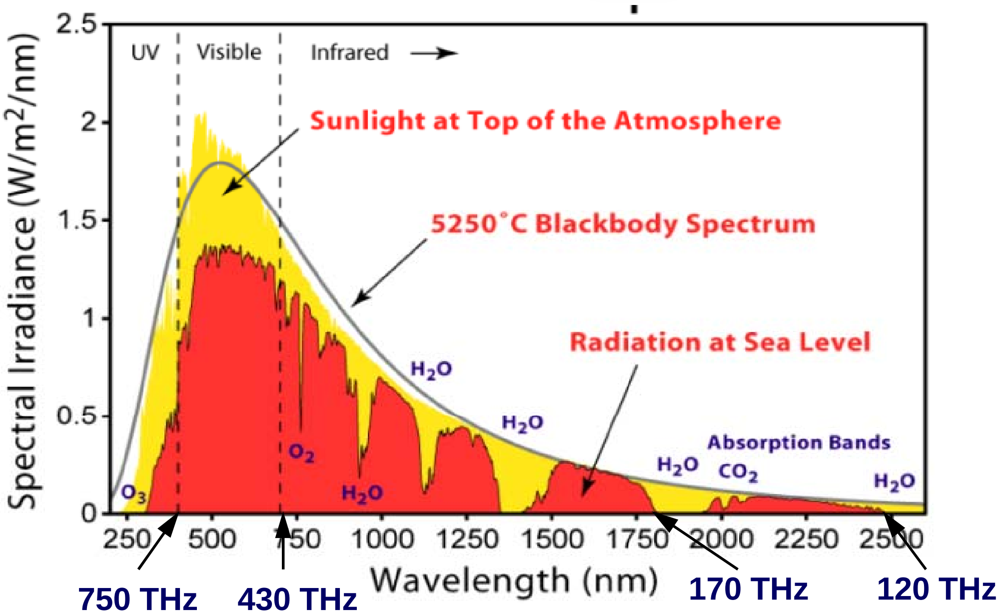
Outline

- **Motivation: Harvesting solar energy by rectennas.**
- **Current status: RF harvesting**
  - **Experimental and simulation results.**
- **Rectification issues.**
- **A design model for resonant tunneling in metal-insulator-insulator-metal (MIIM) rectifiers**
  - **Theory**
  - **Results.**
- **Conclusions.**

Solar Energy



Sun	3.8 times
Geothermal	1 time
Wind	0.5
Biomass	0.4
Hydro	0.15
Tidal/Ocean	0.05

Source: Dr. Joachim Nitsch

- Solar energy has the potential to provide 2850 times the total global needs.
- The potential of all renewable energy resources is 3078 x total global needs.
- *The sun provides enough energy in one day, to accommodate the needs of Earth's inhabitants for over 25 years (or 1 hour for 1 year!)*

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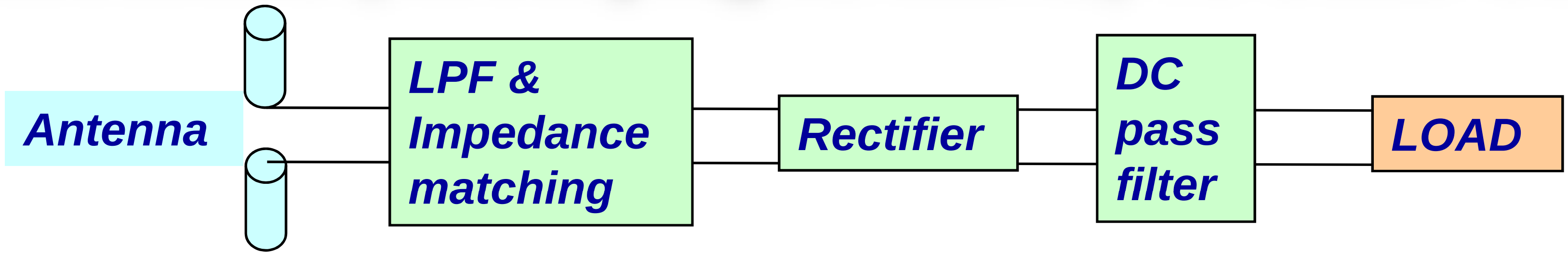
Rectenna (Rectifying Antenna) vs Solar Cells



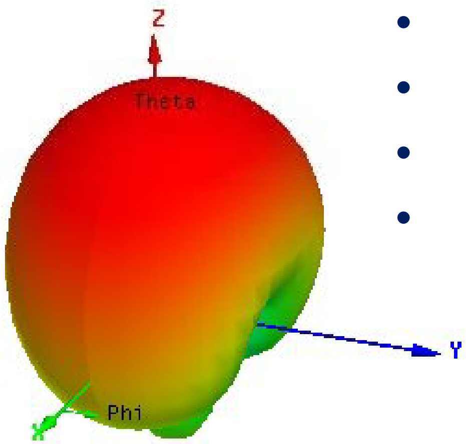
Solar Cell:

- Narrow band.
    - can be improved by multi junction cells.
- Operate in daylight only.
- Expensive.
- Low efficiency:
    - Typical efficiency of commercial arrays: 15-20%.
    - Maximum efficiency in research labs: 50%.
- Low absorption at low frequencies.
- Sensitive to direction of incident light.

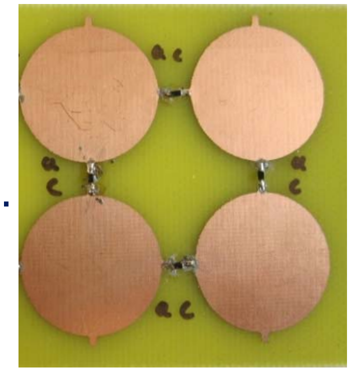
Rectenna:

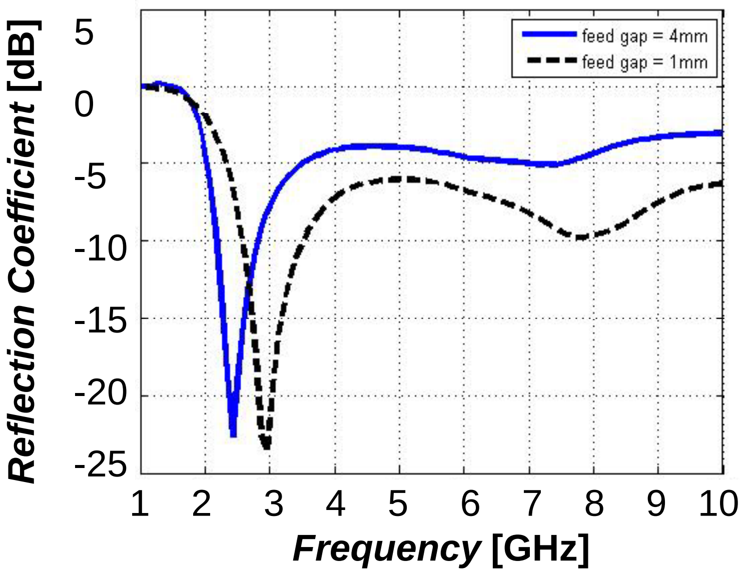
- **Capture the EM waves in broad-band antennas:**
    - **Operates all day and night.**
- **The technology far less expensive than photovoltaics.**
- **Very high efficiencies with full wave rectification (> 80%).**
- **Absorption at all frequencies.**
- **Omnidirectional.**

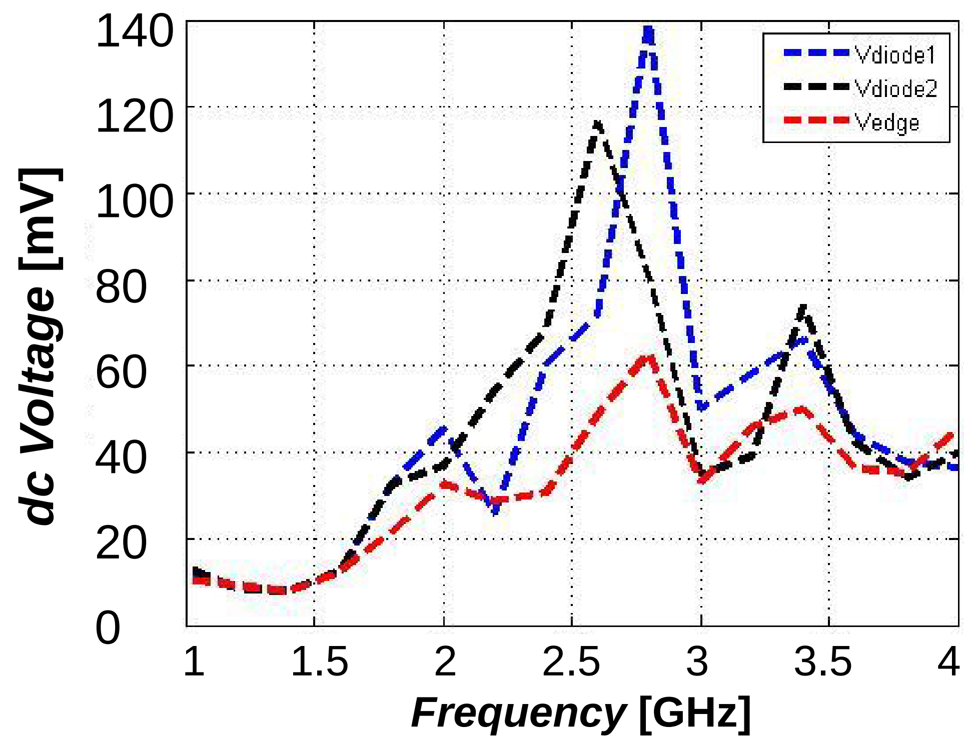
10 GHz Rectenna Results*



- Uniform directional antenna pattern.
- Below - 6 dB reflection threshold with 1 mm feed gap.
- Standard Schottky diode used as rectifier.
- Maximum dc voltage is proportional to number of elements in the array.







*J. Zhang *et al.*, 6th EUCAP, 365, March 2012.

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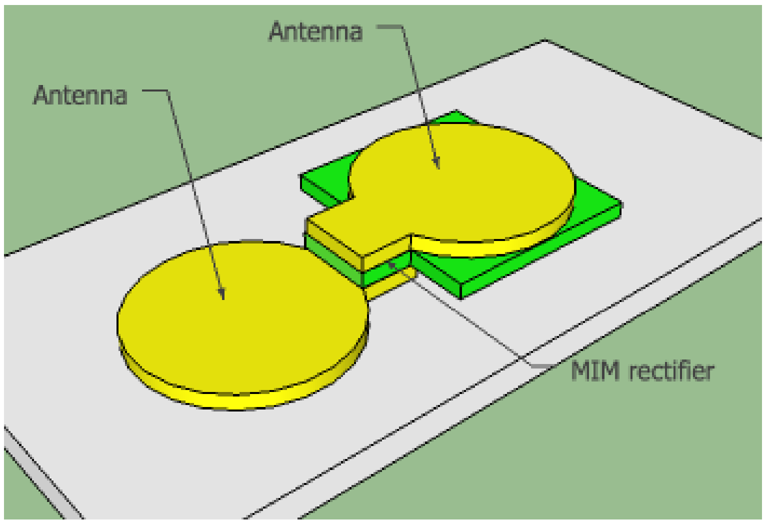
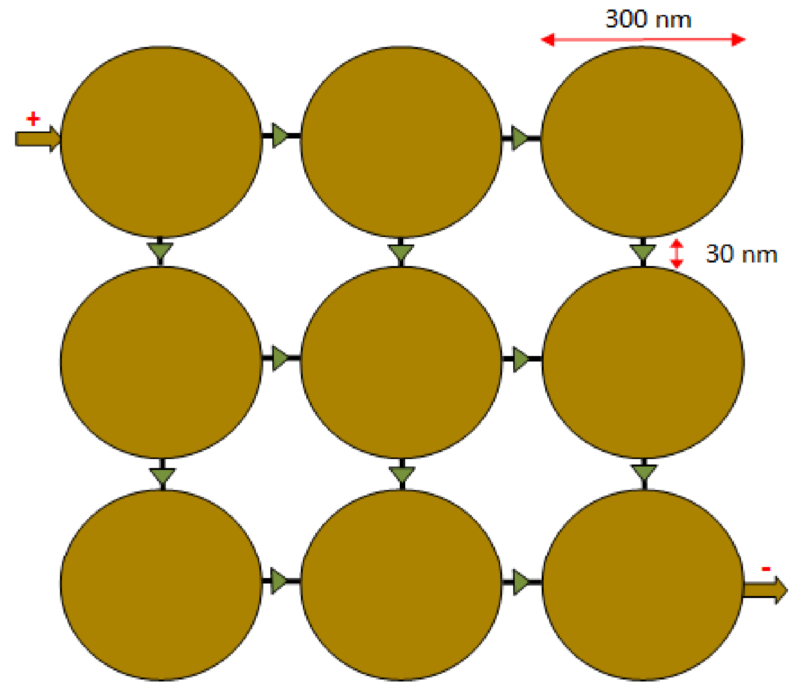
THz Solar Rectenna Design



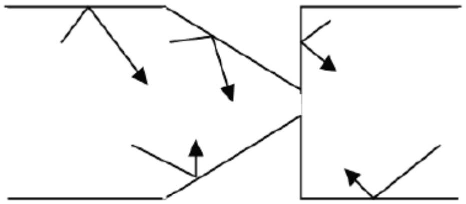


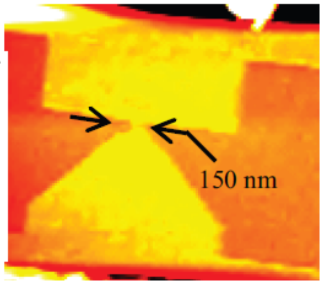
- **Two circular patch antenna.**
- **The MIM or MIIM rectifier between two circles.**
- **Five process steps including two patterning steps.**

PATENT: Y. Huang, S. Hall, Y. Shen; Rectenna 2010, Appl. No. GB1017401.9

Rectifiers: the largest challenge

- ***p-n* junction diodes:**
  - Switching speed is limited by minority carrier charge storage.
  - Maximum frequency: 0.2 THz.
- **Schottky diodes:**
  - Are faster since minority carrier storage is negligible.
  - Switching speed is limited by parasitic capacitance.
  - Maximum frequency: 5 THz.
- **MIM and MIIM diodes:**
  - Transport is limited by tunneling rate.
  - Transit time ~ 1/tunneling probability (circa fs).
  - Maximum frequency: 100 THz (MIM), > 100 THz (MIIM).
- **Geometric diode:**
  - Small diode capacitance.
  - Graphene a promising candidate due to its long electron mean free path.
  - Maximum frequency: 28 THz.





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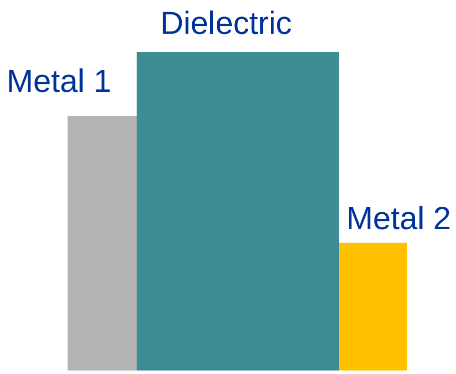
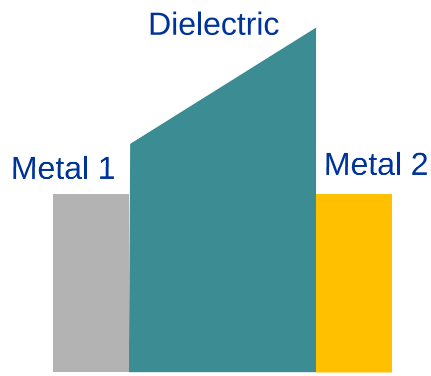
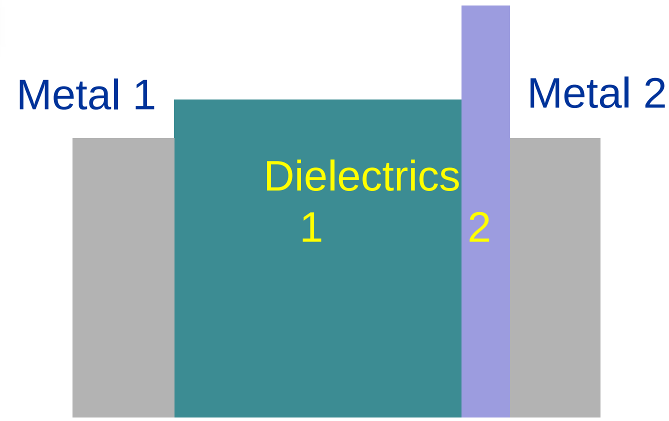
MIM and MIIM Diodes



Asymmetric MIM

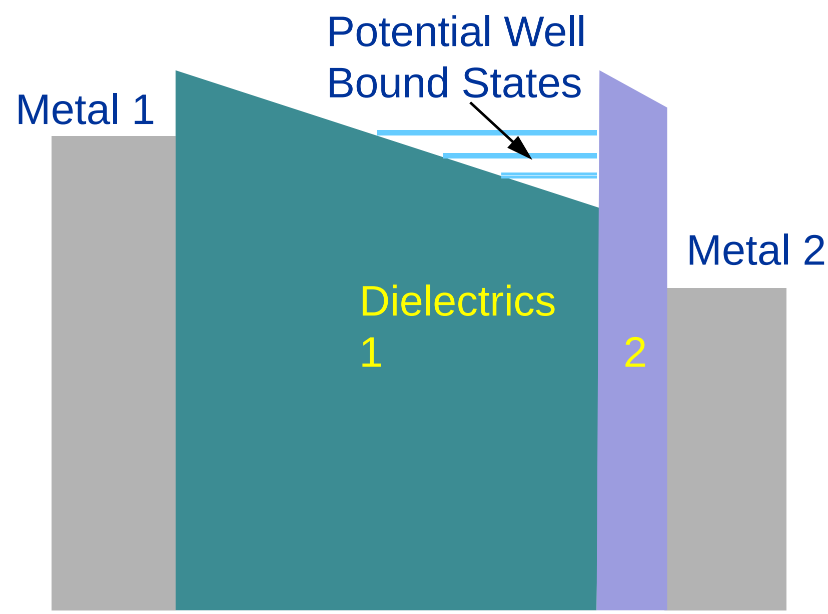


MIM at Zero Bias



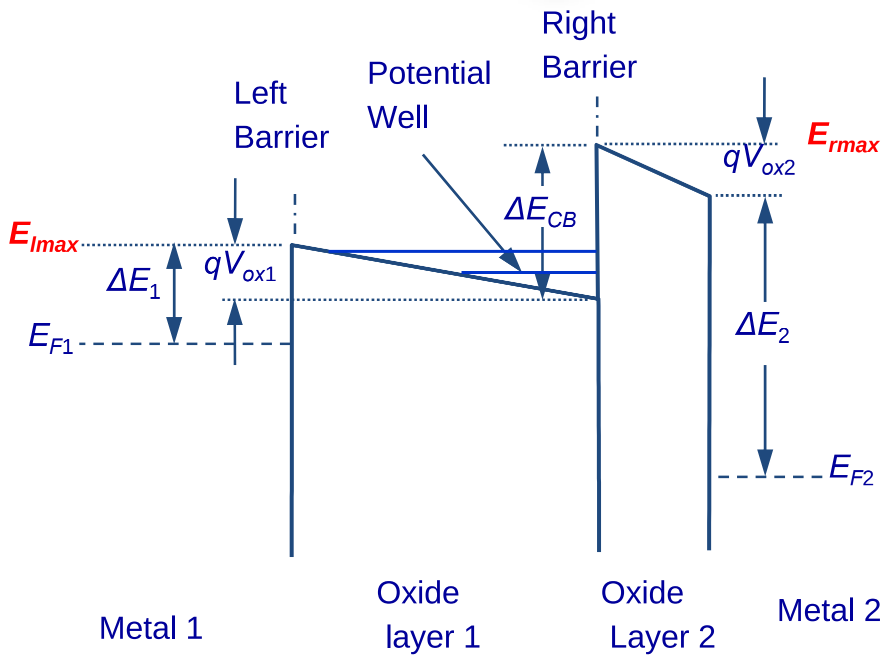
Symmetric MIIM

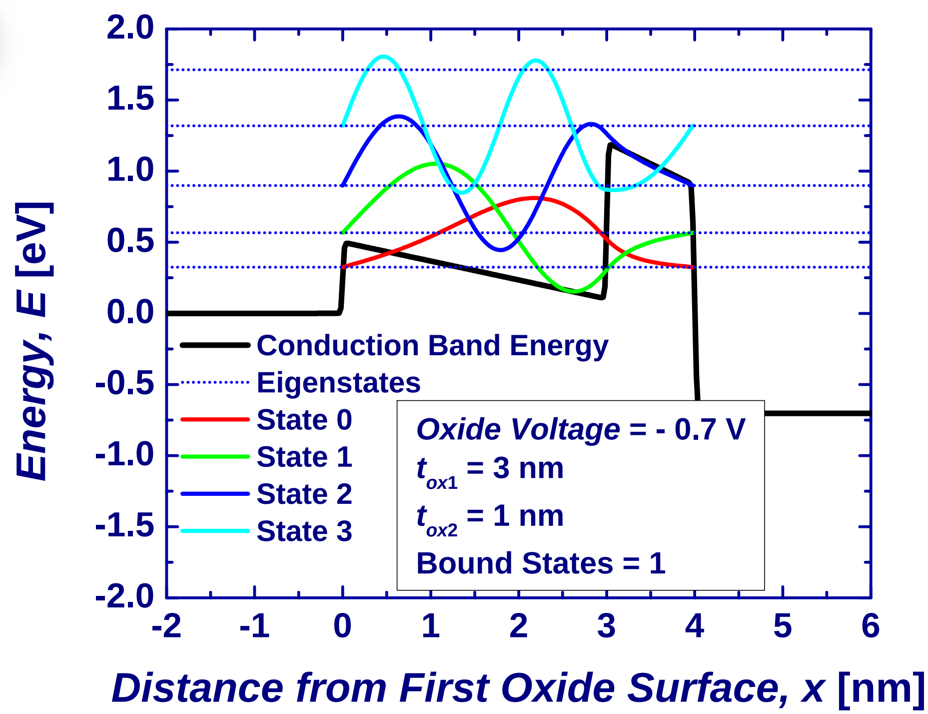
- MIM: current transfer is by direct or FN tunneling.
- MIIM: tunneling probability is increased by bound states in the potential well at positive bias to Metal 2.
- Resonant tunneling through bound states enhances the current and transit speed.



MIIM Positive Bias at Metal 2

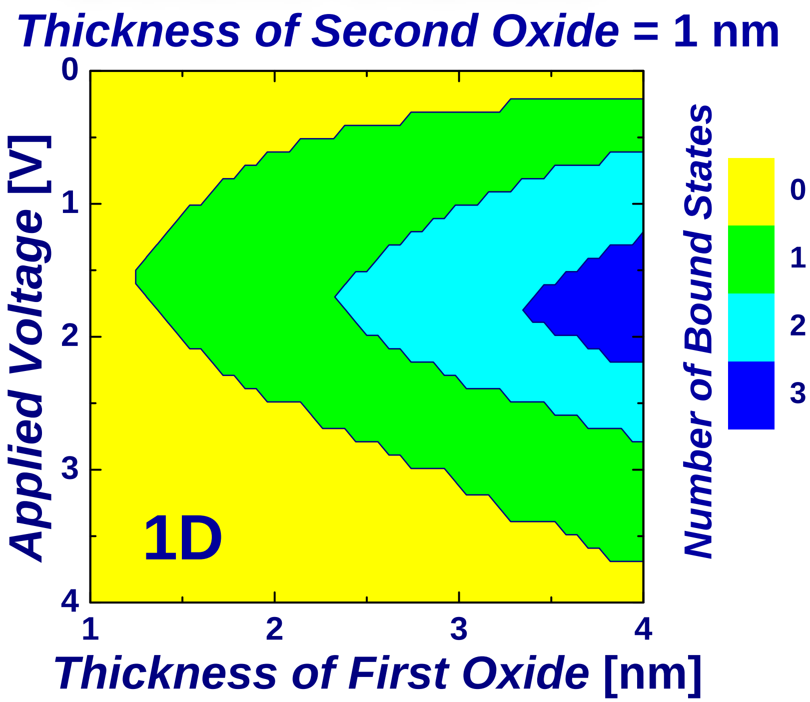
MIIM Design Model

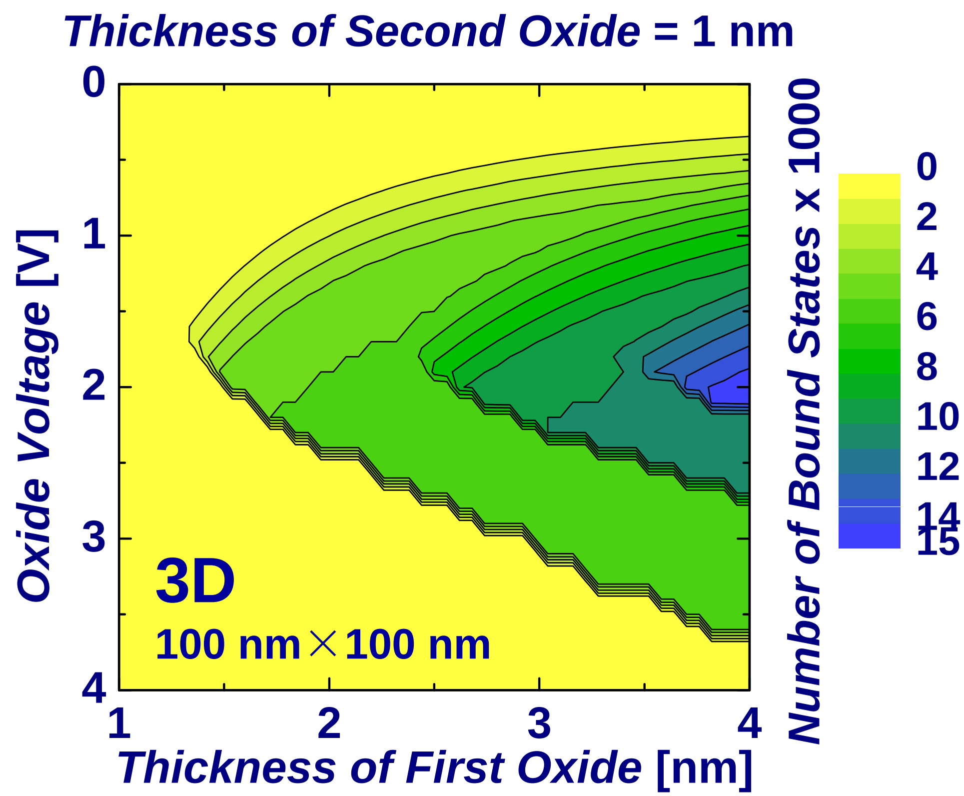




- Hamiltonian matrix is made using a set of localized base states in the stack.
- Eigenstates /energy levels are found by diagonalization or solving time independent Schrödinger equation.
- Only states localized in the potential well (lower than E_{lmax} and E_{rmax}) are considered.
- For each bound state in the 1D well, there are also a set of transverse excitations which generate a band of closely spaced states.

Bound States





- Number of bound states increases with thickness of first oxide.
- The maximum number of states is when the left and right barriers are at the same energy level (circa 2 V on this structure).
- By increasing applied voltage the bound states leak to the right.
- Increasing band offset between two oxides increases the number of bound states.

Current Density Calculation

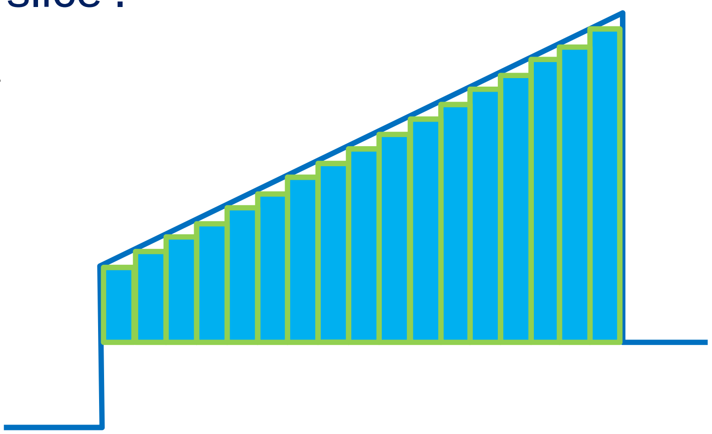
- A modified multi-barrier Tsu-Esaki method* is used:

$$J = J_{L\to R} - J_{R\to L} = \frac{m^* qkT}{2\pi^2\hbar^3}\int_0^\infty T_{coeff}(E_x)\ln\left\{\frac{1+\exp[(E_x - E_{FL})/kT]}{1+\exp[(E_x - E_{FR} - qV_{app})/kT]}\right\}dE_x$$

- **Dielectric stack**: multiple slices of oxide with different barrier heights.
- *J* depends on DoS (*E*) and average occupancy of each state (uses F-D).
- Transmission probability T_{coeff} calculated by transfer matrix (TM) model for tunneling through multiple barriers, containing resonant states.
- Uses WKB for wave-function at each 'slice' through a potential barrier by constructing a piecewise constant TM for each 'slice'.

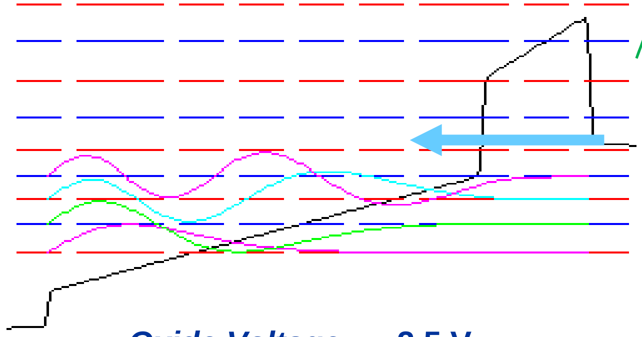
$$P_{Tj} = \exp\left\{-2\left[m^*\left(q\phi_{Bj} - E_{xj}\right)\right]^{1/2} d_j\right\}$$

- T_{coeff}, hence *J* depend on both barrier height and energy, or the area under CB.

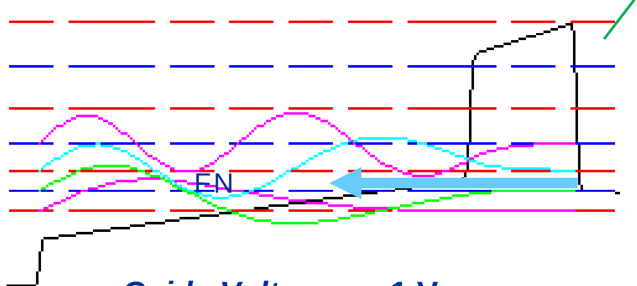


*R. Tsu and L. Esaki, *Appl. Phys. Lett.* **22**, 562 (1973).

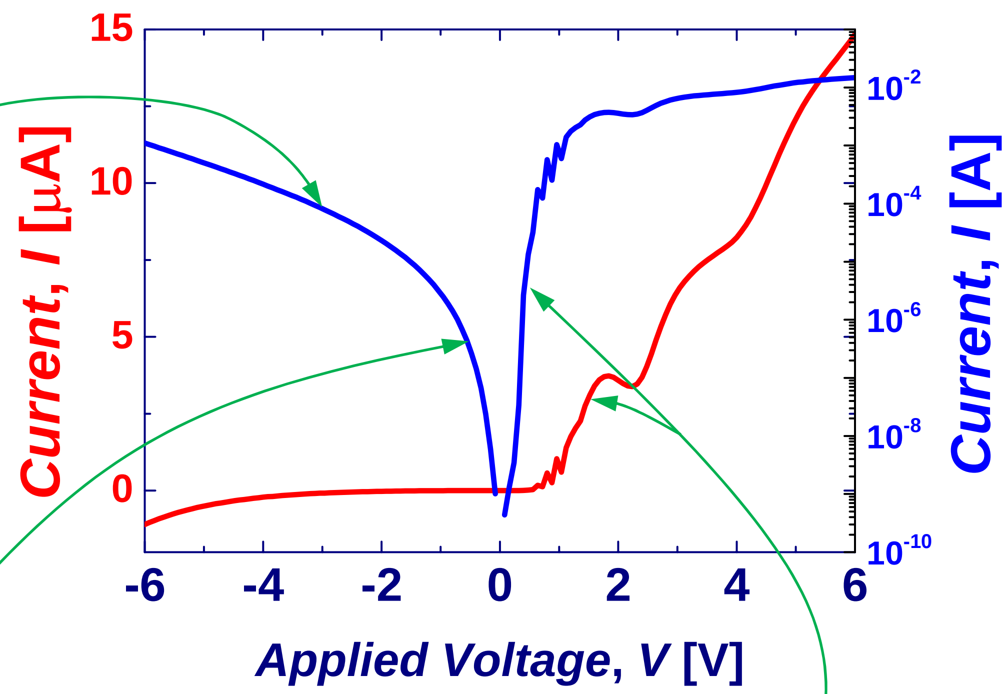
MIIM Current

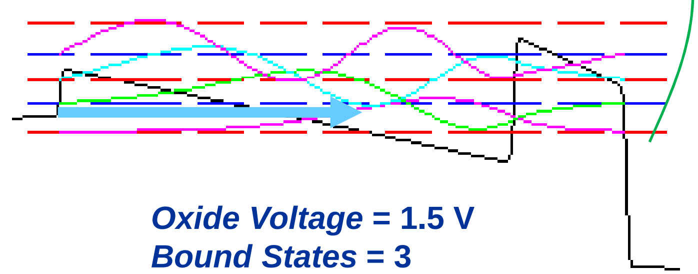


Tunneling is limited only by the large band gap oxide.



Direct tunneling through the right oxide and FN tunneling in the left oxide.





Sharp rise in current due to resonant tunneling into bound states in potential well.

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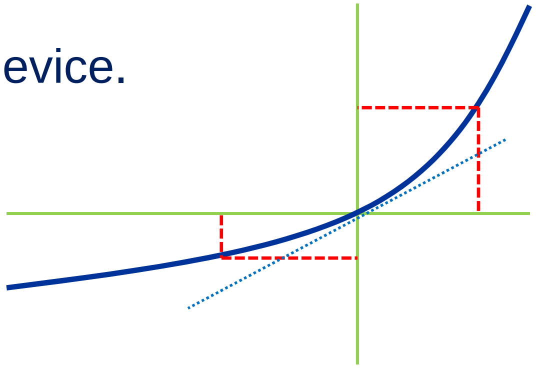
Rectification

- Small signal rectification is realized by nonlinearity of device.
- ***Dynamic resistance***:
  - Low values desirable for impedance matching to antenna and to supply sufficient current to load.

$$r_d = \left.\frac{dV}{dI}\right|_{V_p}$$



- ***Responsivity*** defined as the ratio of rectified dc current to input ac power:

$$Resp = \frac{I_{dc}}{P_{in}} = \left.\frac{1}{2}\frac{I''}{I'}\right|_{V_p} = \frac{1}{2}\frac{dr_d/dV}{r_d}$$

(Square law rectification using the first two terms in Taylor's expansion.)

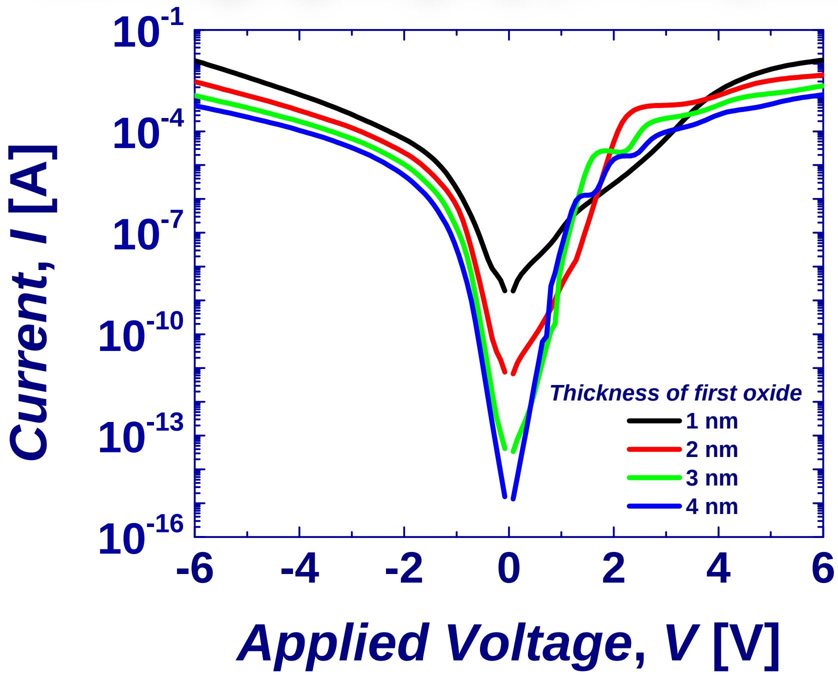
- ***Power efficiency*** defined as rectified dc power to input ac power:

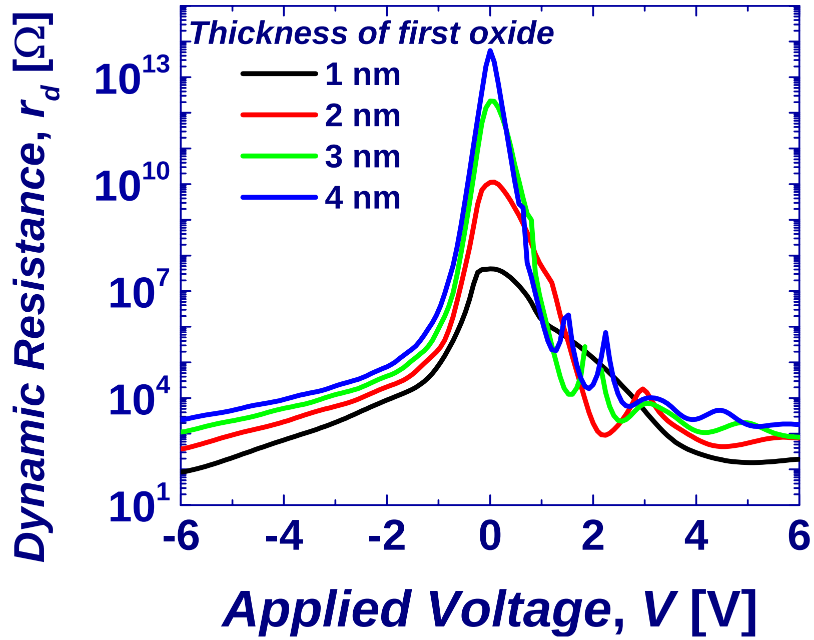
$$\eta = \frac{P_{dc}}{P_{in}} = f\left(Resp, r_d, C_D, R_L, C_L, \omega\right)$$

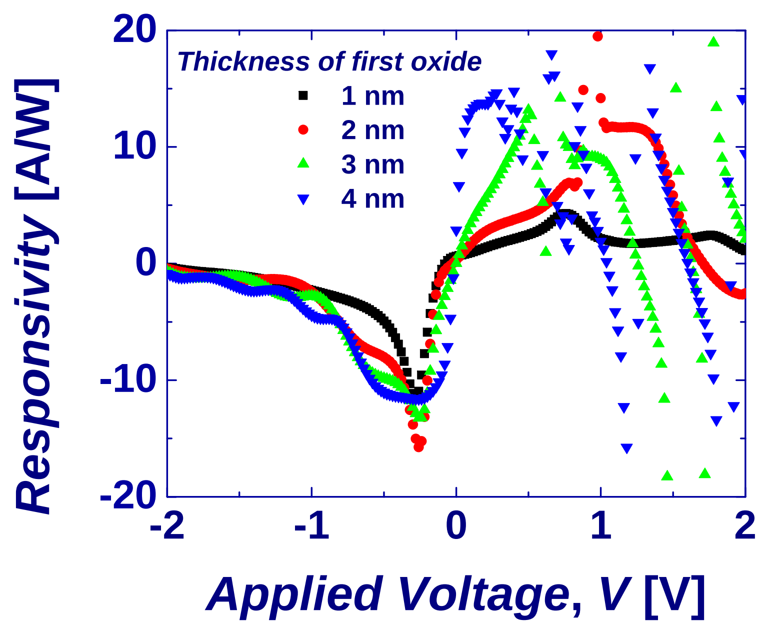
- Main challenge: device area, trade-off between r_d (~ t_{ox}/A) and diode capacitance, C_D (~A/t_{ox}). A possible solution: reduce ε.

MIIM Results

$Al/Ta_2O_5/Al_2O_3$ (1 nm)/Al

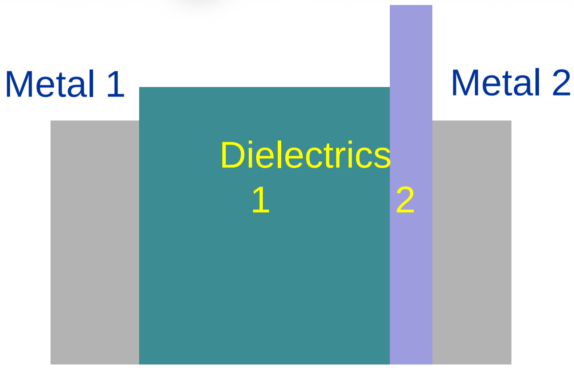


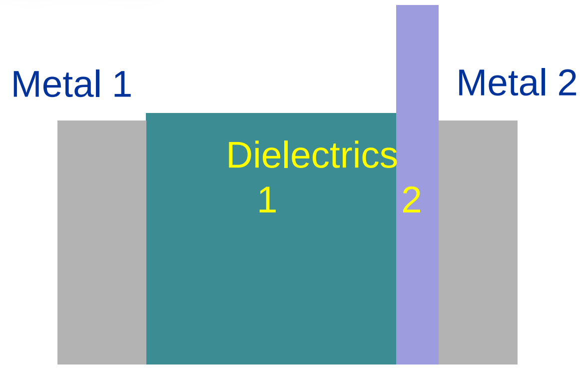




- Most effect of resonant tunneling on device with first oxide thickness of 3 nm (no bound states at 1 nm).
- The fluctuation at positive voltages is due to discrete nature of bound states.

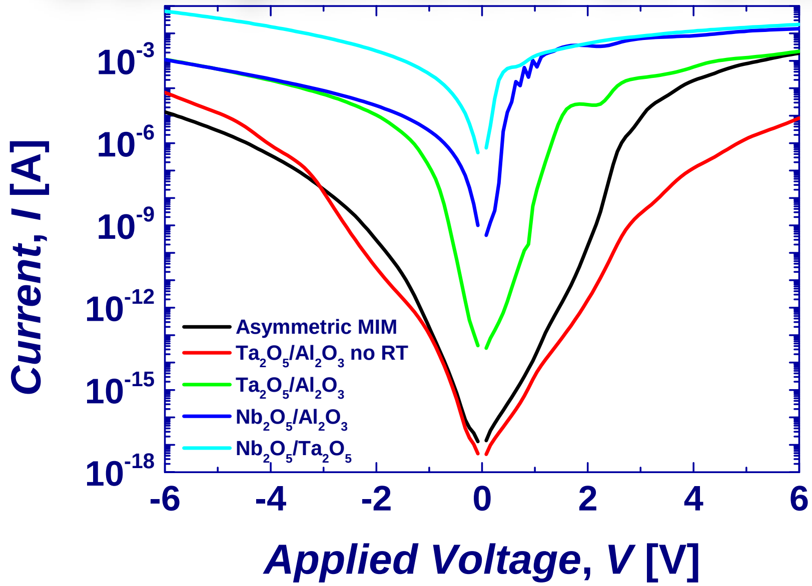
Design Considerations

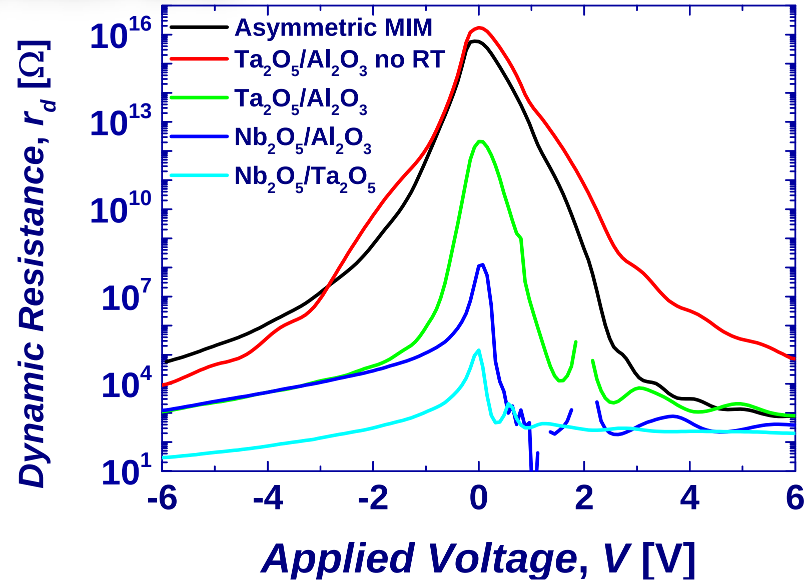




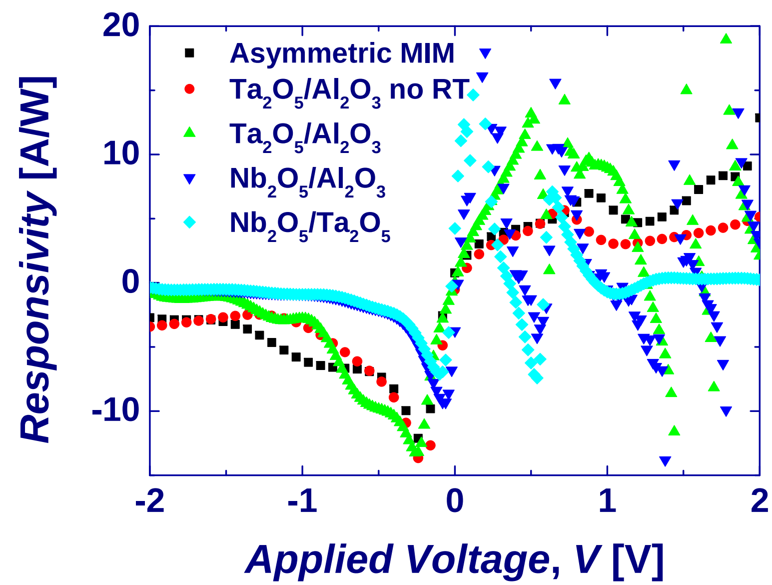
- **Engineering of band offsets and oxide thickness.**
- Optimum thickness of low band-gap dielectric is 3-4 nm with 1 nm of the large band gap dielectric.
- Thicker dielectrics show smaller current and hence larger dynamic resistance.
- The larger the band offset between two dielectrics, more benefit from resonant tunneling.
- Resonant tunneling occurs at lower voltages with lower barrier height between metal contact to left oxide.
- Dielectrics with large electron affinity have larger band offset with large band gap dielectric (Al_2O_3) and lower barrier height to metal contact.

Comparison of Structures





- All devices have the total thickness of 4 nm.
- The rectification on **asymmetrical MIM structure** is by different metal work functions.
- **Device with no bound states** (first oxide thickness of 1 nm) has no advantage over asymmetrical MIM.
- **Nb_2O_5/Al_2O_3** has the highest band offset between oxide layers and lowest barrier to the left metal, hence the largest effect of RT.



Conclusions

- Rectenna has the potential of harvesting solar energy.
- A working RF rectenna for 10 GHz using circular patch antenna is reported and solar energy (THz) rectenna design with MIIM diodes as rectifier is proposed.
- MIIM diodes benefit from resonant tunneling within bound states, increasing the operating frequency to a few 100 THz, in the range of light spectrum.
- The optimum thickness of MIIM oxide layers is 1 nm for large bandgap and 3-4 nm for small bandgap dielectrics.
- Al_2O_3 is the best choice for second oxide because of its low electron affinity (makes the highest barrier with first oxide).
- The best options for metal contacts are low work function metals (Al, Cr, W, …) to benefit from bound states at lower voltages.
- The highest rectification, lowest dynamic resistance, and highest responsivity is from $Al/Nb_2O_5/Al_2O_3/Al$ structure since
  - The largest band offset between Nb_2O_5 and Al_2O_3,
  - Lowest barrier height with left metal.

Acknowledgement

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