WoDiM 2014: 18th Workshop on Dielectrics in Microelectronics
9-11 June 2014, Kinsale, Ireland

Zero Bias Resonant Tunnelling Diode for Use in THz Rectenna

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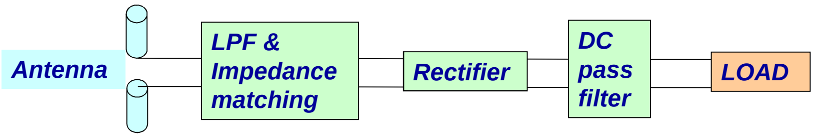
Outline

- **Motivation: Harvesting THz energy by rectennas**
- **Rectifiers needs:**
  - **Small signal rectification with zero bias**
  - **High degree of non-linearity around zero volt**
  - **Small dynamic resistance**
- **A design model for resonant tunneling at zero bias MIIM diodes**
  - **Theory**
  - **Results**
- **Conclusions**

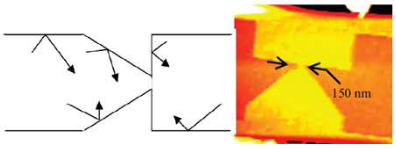
Rectenna (Rectifying Antenna)



- Capture the EM waves in broad-band antennas.
- Can be used for solar energy harvesting (feasible range: IR).
- For solar energy harvesting the technology far less expensive than photovoltaics.
- Very high efficiencies with full wave rectification (> 80%).
- Absorption at all frequencies.
- Omnidirectional.

Rectifiers: the Biggest 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.

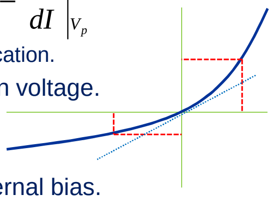


Small Signal Rectification

- In large signal rectification the high forward (on) current usually starts after a turn-on voltage (usually a fraction of a volt in typical diodes).
- Large signal rectification ~ on/off (forward/reverse) current ratio.
- In rectenna signal amplitude captured by antenna: mV and even µV.
  - Large signal rectification out of scope.
- Small signal rectification is realized by nonlinearity of device.
  - (Square law rectification using the first two terms in Taylor's expansion.)
- ***Responsivity*** defined as the ratio of rectified dc current to input ac power:

$$Resp = \frac{I_{dc}}{P_{in}} = \frac{1}{2}\frac{I''}{I'}\bigg|_{V_p} = \frac{1}{2}\frac{dr_d/dV}{r_d} \qquad r_d = \frac{dV}{dI}\bigg|_{V_p}$$

  - A good measure of non-linearity in small signal rectification.
- The highest degree of non-linearity is around turn-on voltage.
- Poor rectification at zero volts
  - Minimum degree of non-linearity.
- Not efficient for THz signal in rectennas without external bias.

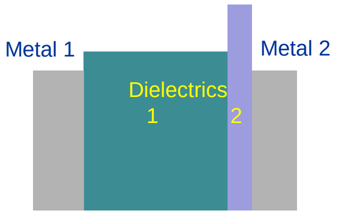


Resonant Tunneling IN MIIM Diodes

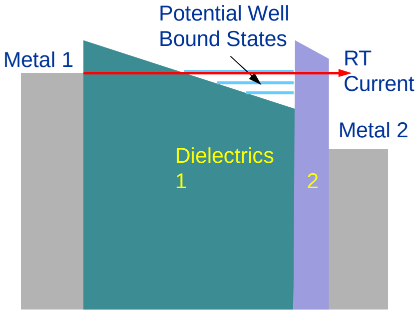
- Tunneling probability is increased by bound states in the potential well at positive bias to Metal 2.
- Resonant tunneling through bound states enhances the current and transit speed.
- No resonant tunneling in reverse bias: Improves large signal rectification.
- Largest responsivity at onset of resonant tunneling.

However:

- **The onset of resonant tunneling is at voltages larger than barrier height of Metal 1 to dielectric (typically > 0.25 V).**
- **Not efficient for signal in rectennas without external bias.**

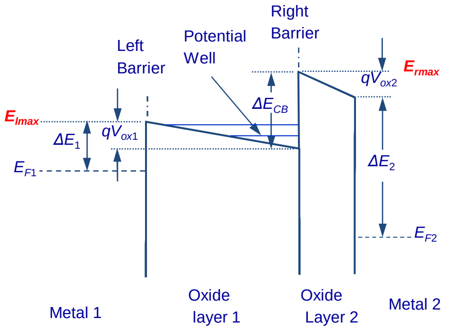


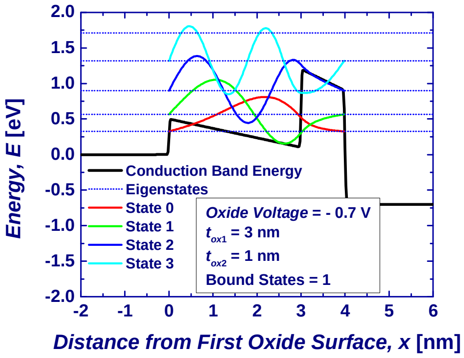
Symmetric MIIM in flat band condition



MIIM positive bias at Metal 2

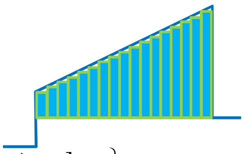
Calculation of Bound States





- 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.

Current Density Calculation



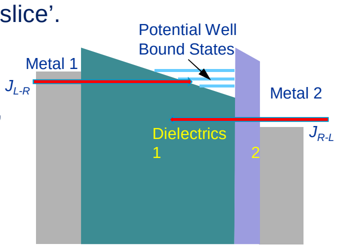
- A modified multi-barrier Tsu-Esaki method* is used.

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

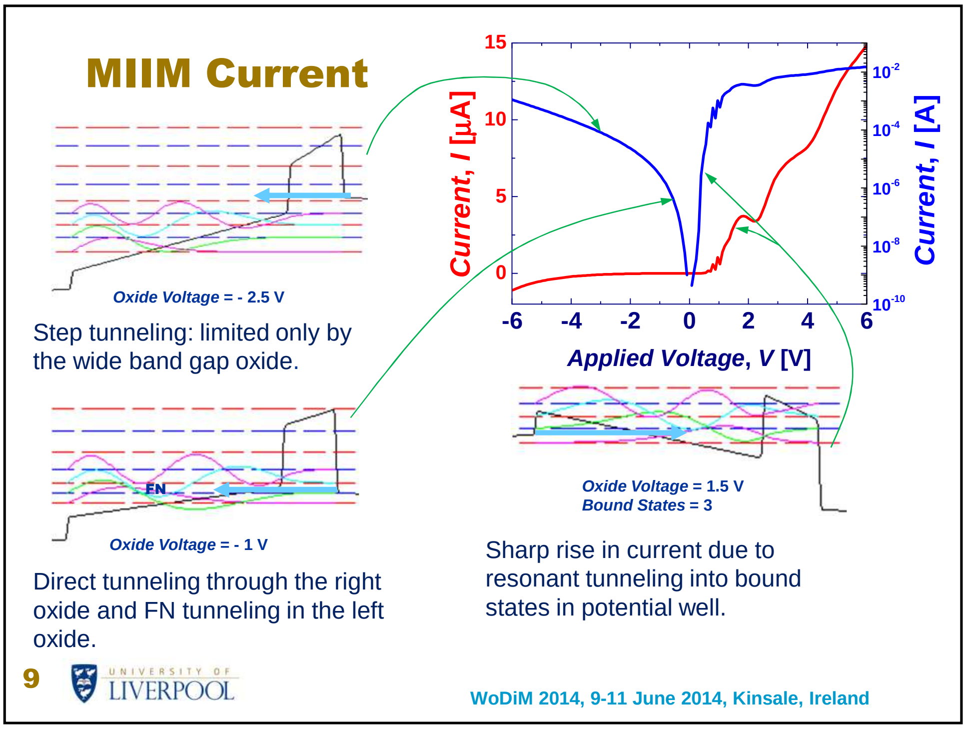
- **Dielectric stack**: multiple slices of oxide with different barrier heights.
- *J* depends on DoS (*E*) and average occupancy of each state (uses F-D).
- Transmission probability T_{coeff} calculated by transfer matrix (TM) model for tunneling through multiple barriers, containing resonant states.
- 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 barrier height, energy, and distance, or the area under CB.



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



MIIM Current

Oxide Voltage = - 2.5 V

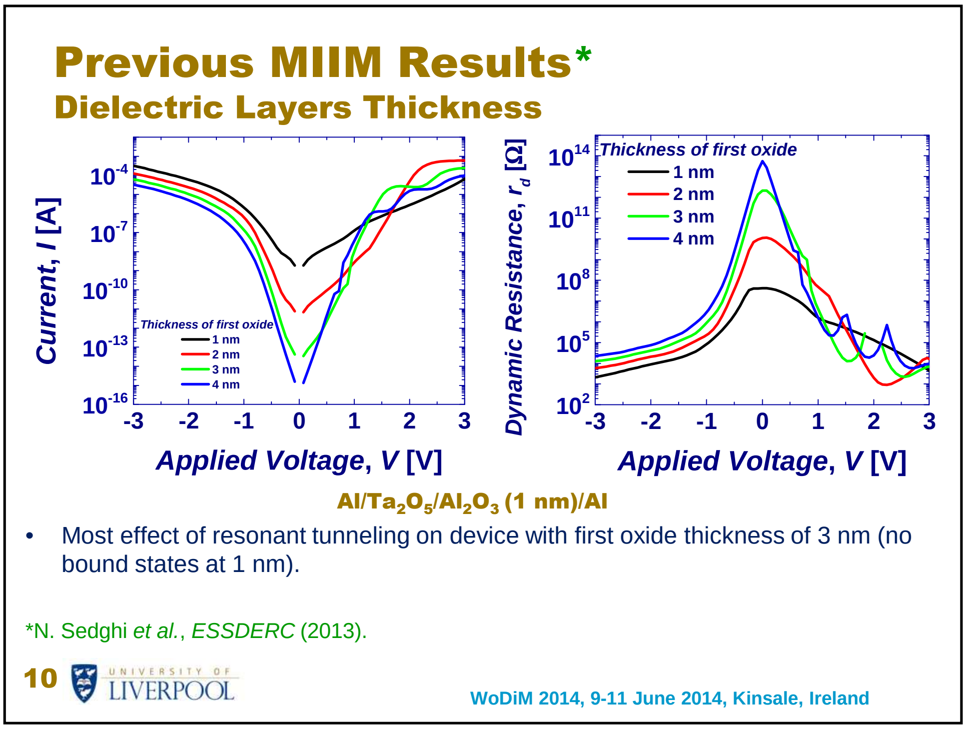
Step tunneling: limited only by the wide band gap oxide.

Oxide Voltage = - 1 V

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

Oxide Voltage = 1.5 V
Bound States = 3

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



Previous MIIM Results*

Dielectric Layers Thickness

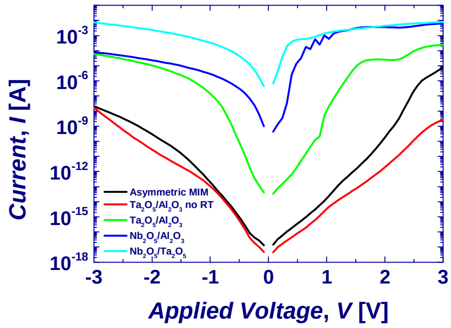
Al/Ta_2O_5/Al_2O_3 (1 nm)/Al

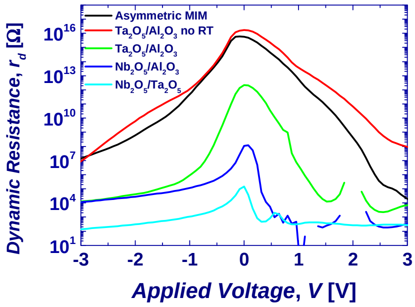
- Most effect of resonant tunneling on device with first oxide thickness of 3 nm (no bound states at 1 nm).

*N. Sedghi *et al.*, *ESSDERC* (2013).

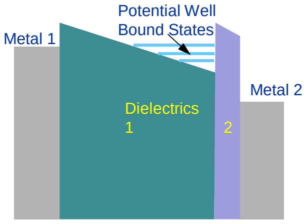
Previous MIIM Results*

Various Structures



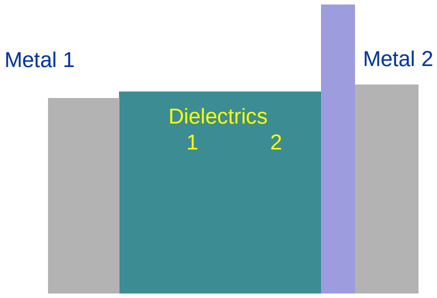


- All devices have the total thickness of 4 nm.
- **Device with no resonant tunneling** has no advantage over asymmetrical MIM.
- **Nb_2O_5/Al_2O_3** has the highest band offset between oxide layers and lowest barrier to the left metal, hence the largest effect of RT.

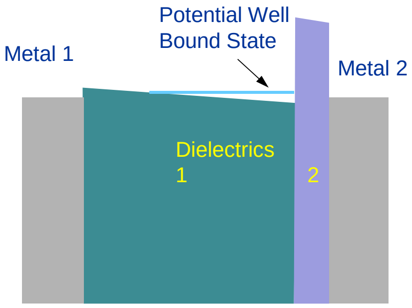


*N. Sedghi *et al.*, *ESSDERC* (2013).

Proposed Structure



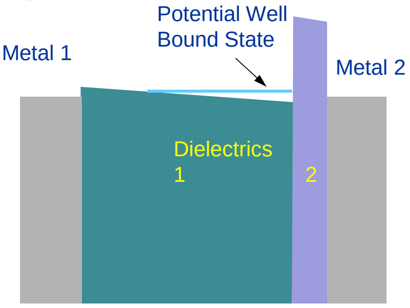
Flat band



Zero Bias

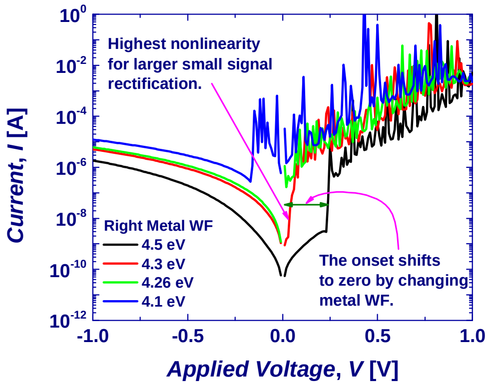
- Work function of Metal 2 slightly lower than Metal 1.
- Bound states exist at zero bias when the band offset between two dielectrics is high enough.
- Even at very small positive voltage at Metal 2 the current is by resonant tunneling.
- At negative voltage to Metal 2 the bound states leak to the left: no resonant tunneling.

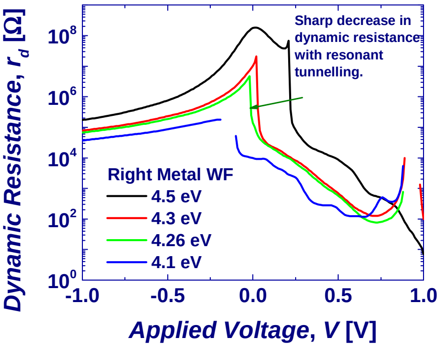
Design Considerations



- Large band offset between two dielectrics increases the number of bound states in the potential well.
- A good choice: Nb_2O_5/Al_2O_3.
- Small barrier height at left:
  - Resonant tunneling at very small positive voltage,
  - Bound states leak to the left at very small negative voltage.
- A good choice: Al/Nb_2O_5.
- Wide choice of metals with close values of work function to fine tune the device: Al, Ti, V, Cr, Fe, Cu, Zn, Mo, Nb, Ag, W, and Ta.
- For more precise work function tuning: alloy of above metals, TaN, or TiN.
- Thickness of dielectric layers can also shift the onset of resonant tunneling.

Simulation Results

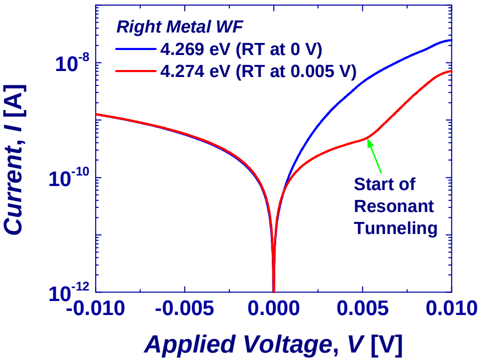


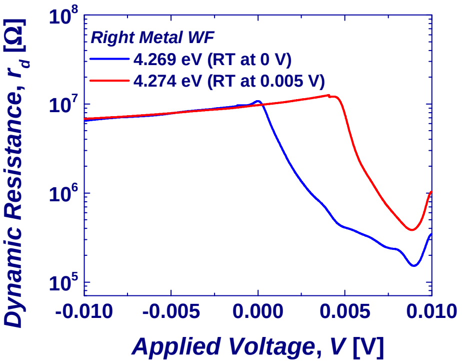


- The work function of left contact is kept at 4.5 eV and the work function of right contact is varied.
- The onset of resonant tunneling on symmetric device is at 0.25 V.
- For right metal contact work function of 4.26 eV the onset of resonant tunneling is at zero volts.

Simulation Results

Low Voltage

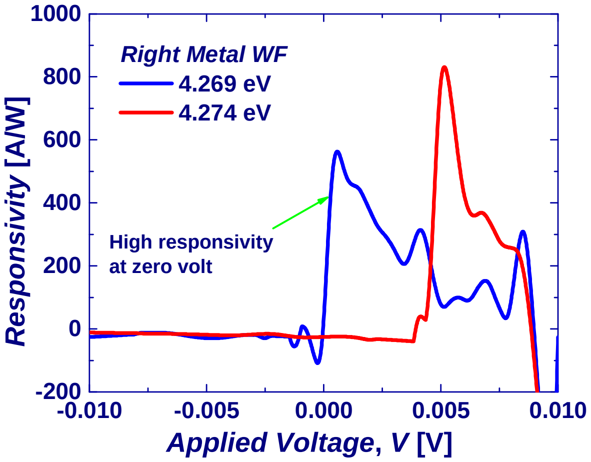




- Simulation at very low voltages (up to 10 mV) with step size of 10 μV.
- Percentile and adjacent average algorithms used to smooth the resonant peaks.
- Sharp rise in current after start of resonant tunneling.

Device Nonlinearity (Responsivity)

- Rectification depends on device nonlinearity.
- Highest degree of nonlinearity (largest responsivity) at start of resonant tunneling.
- The start of resonant tunneling can be brought to zero volts.
- Large rectification for very small amplitude signals (μV) without bias.



Practical Considerations

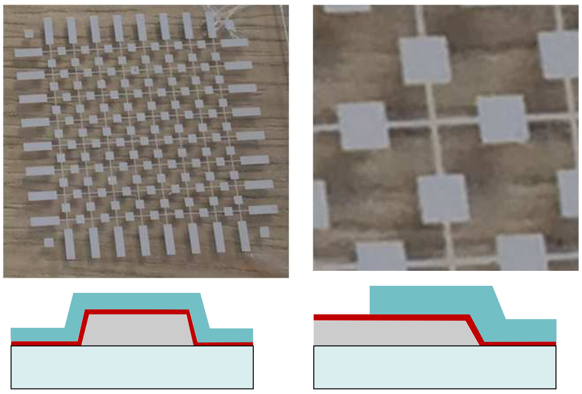
- Selection of right metals and fine tuning the work functions.
  - This is not always straightforward.
- Stored charge at the interface of two dielectrics gives shift to the IV characteristics.
- The right barrier heights might not be achieved due to Fermi pinning.
- Native oxide on the bottom metal electrode is a big issue.
  - Its thickness is close to that of main dielectrics.
- …

Solutions?

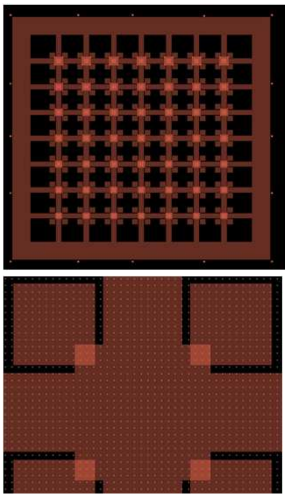
Practical Considerations
Possible Solutions

- The onset of resonant tunneling can be fine tuned practically on trial samples.
  - Metal work functions, oxide layers thicknesses, dielectric type, nitrogen or forming gas annealing.
- The IV characteristics shift due to stored charge is insignificant for low voltage applications.
- Native oxide on metal electrodes can be removed by dry etching prior to oxide deposition.
- Metals with insignificant native oxide thickness can be used.

Fabrication Process



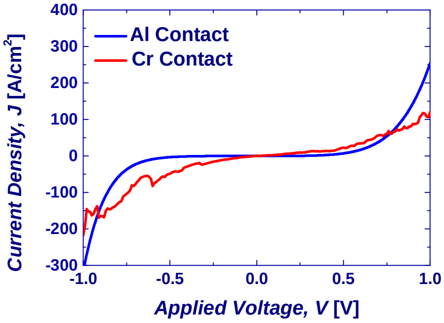
Shadow Mask

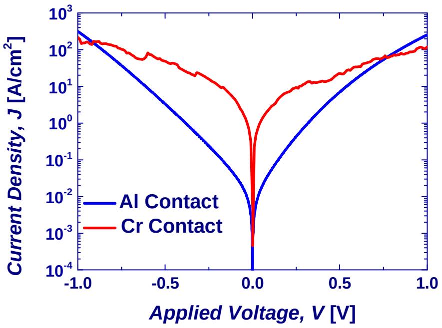


Photolithography

- Cross over structure by shadow mask, overlap structure by lithography.
- Device dimensions: 5-100 µm.
- Single or double dielectric layers deposition by ALD or rf sputtering.

Preliminary Experimental Results*





- MIIM device with Ta_2O_5 as the main dielectric and native oxide as the second dielectric.
- Device with Cr contacts has larger current than one with Al contacts
  - Smaller barrier to Cr_2O_3 than Al_2O_3.
- Responsivity of 8 A/W on sample with Al contacts (close to state-of-the-art values for MIIM with resonant tunneling).

*Don Weerakkody, Electrical Engineering and Rob Treharne, Stephenson's Institute, University of Liverpool are acknowledged for device fabrication.

Conclusions

- Rectenna has the potential of harvesting THz energy.
- MIIM diodes benefit from resonant tunneling within bound states, increasing the operating frequency to a few 100 THz, in the range of light spectrum.
- Signals captured by antenna have very small amplitude and large signal rectification concept is not applicable.
- IN MIIM diodes the highest degree of nonlinearity is at the onset of resonant tunneling (a fraction of volt in conventional symmetric MIIM diodes).
  - Poor rectification around 0 V for small signals.
- An MIIM device configuration is proposed which can bring the onset of resonant tunneling to 0 V.
  - Large degree of nonlinearity for rectification of very small amplitude signals.
- Responsivity values of a few hundreds A/W around 0 V.
  - Typical values without resonant tunneling few tens of A/W.

Acknowledgement

The work was benefited from funding by the Engineering and Physical Sciences Research Council (EPSRC), UK, project no. EP/K018930/1.

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Thank you for your attention.