Detectors at the Intersection of Photons & Electromagnetic Fields
or
Where Einstein Meets Maxwell

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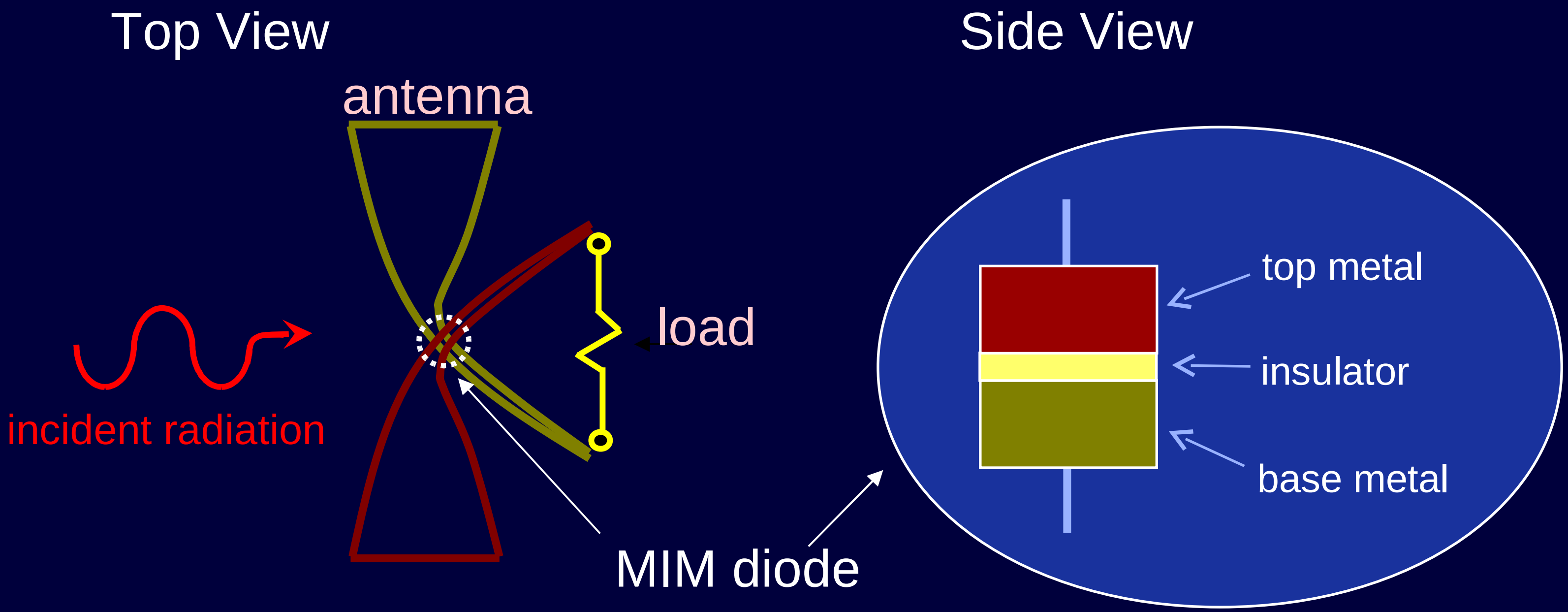
Garret Moddel	University of Colorado & Phiar Corporation

Metal-Insulator Diode Detector



Top View

antenna

load

incident radiation

MIM diode

Side View

top metal

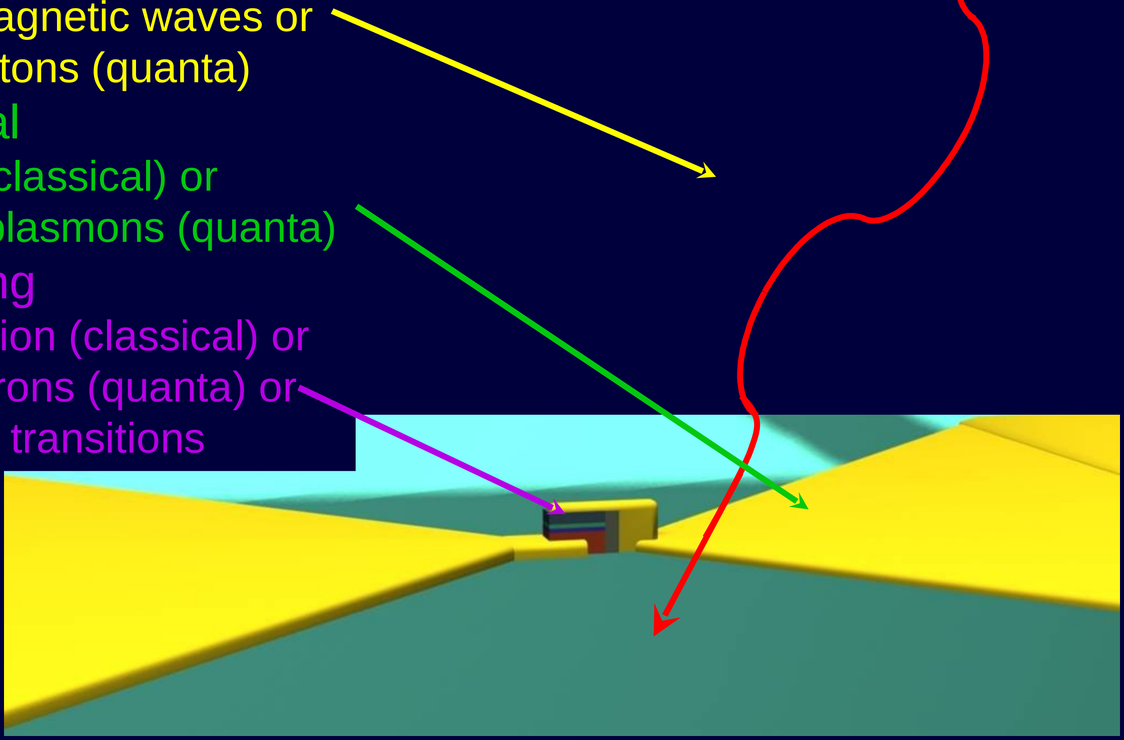
insulator

base metal

a “crystal radio” for
ultra-high frequency electromagnetic waves

Would Maxwell's Equations Suffice?

- Incident radiation
  - Electromagnetic waves or
  - QED photons (quanta)
- Antenna signal
  - Current (classical) or
  - Surface plasmons (quanta)
- Diode tunneling
  - Rectification (classical) or
  - Hot electrons (quanta) or
  - Quantum transitions



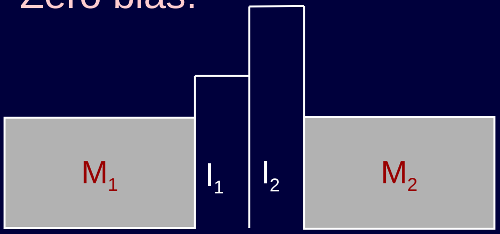
Or do we need help from Einstein?

Outline

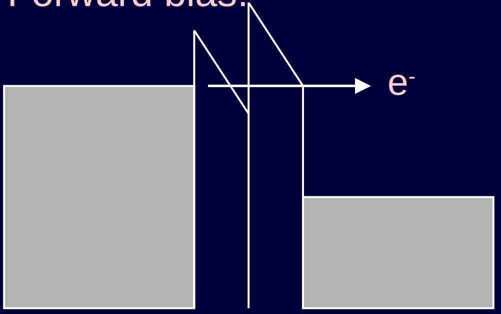
- **Metal-insulator technology**
  - **Diodes & antennas**
  - **Double-insulator diode**
  - Detectors
  - Transistors
- Applications
- Modeling: classical versus quantum
  - Classical versus quantum
  - Ranges

Double-Insulator Tunneling Diode

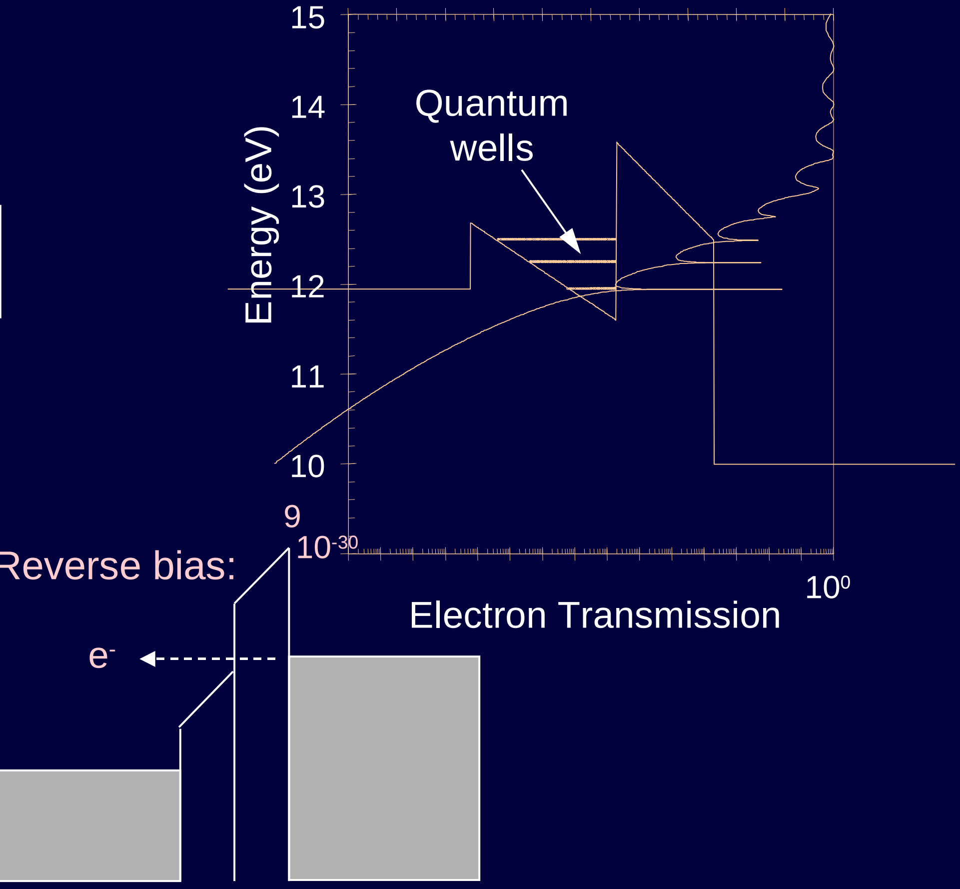
Zero bias:



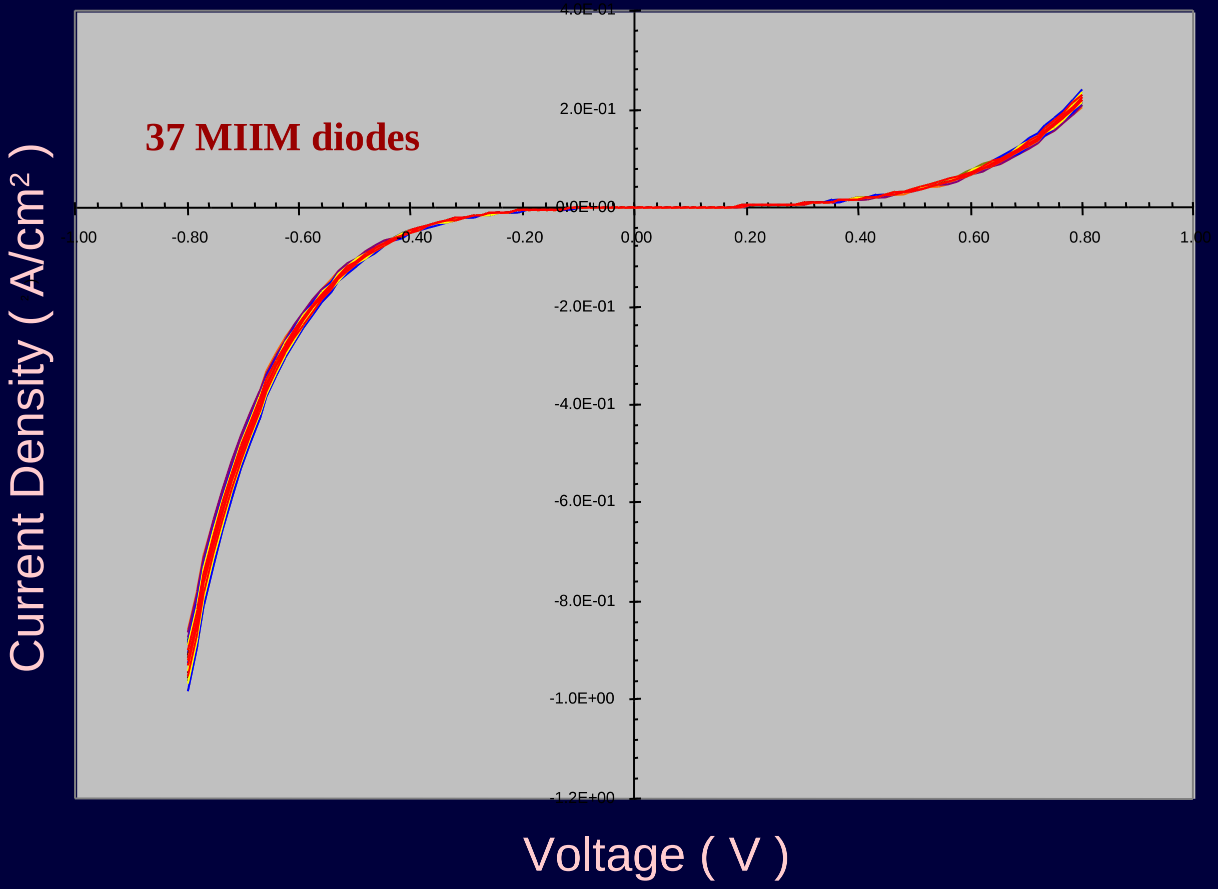
Forward bias:



Reverse bias:



Recently Fabricated Double-Insulator Diodes



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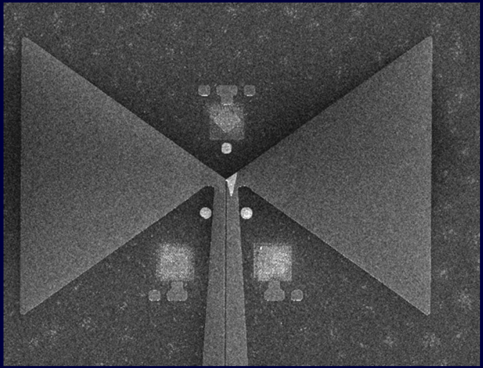
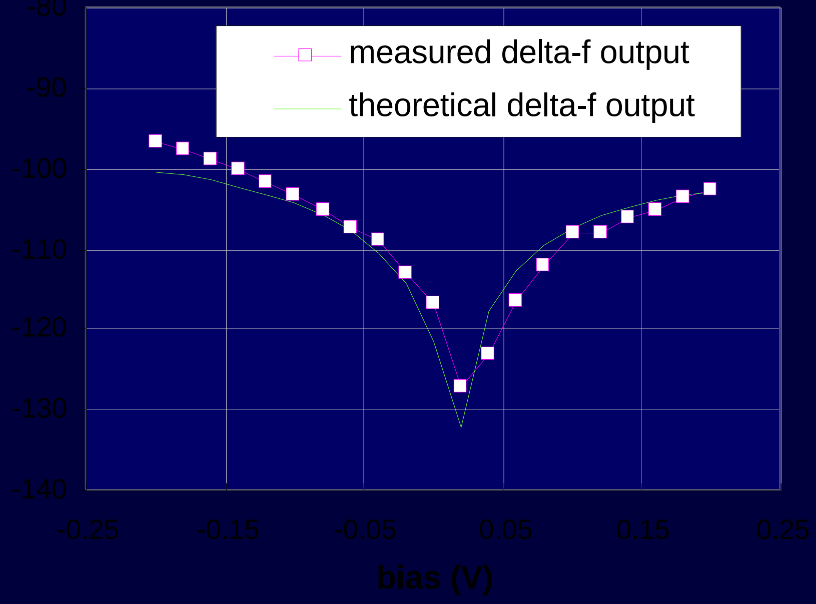
MIM Diode Detector Measurements

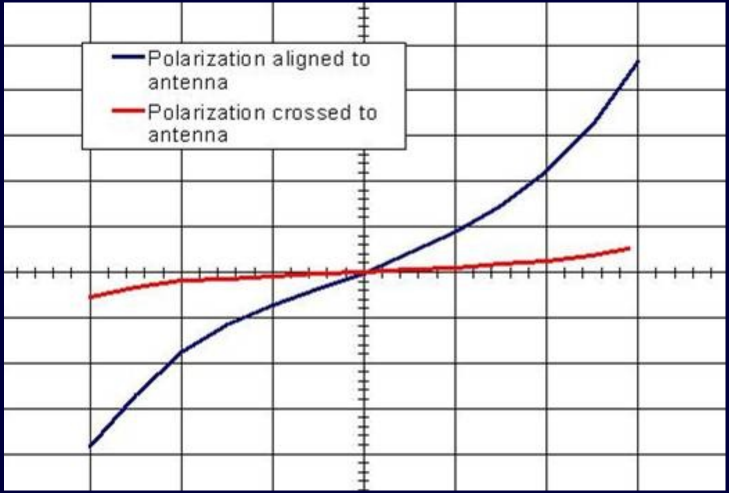
THz detector



200 GHz mixing response



11 µm IR detection (27 THz)



Comparison: THz Detectors

	Zero-Bias MIIM Diode (simulated)	**GaAs Schottky Diode**	**III-Sb Backward Tunnel Diode**	**Microbolometer**
Bias	Zero	Positive	Zero	Positive
Responsivity	8-10 A/W	8 A/W	1-2 A/W	1-10 A/W
NEP	~1×10^{-12} W/Hz$^{1/2}$	1×10^{-11} W/Hz$^{1/2}$	N/A	>1×10^{-12} W/Hz$^{1/2}$
Bandwidth	~10 THz	25 THz	720 GHz	< 1 MHz

- Fast → useful for heterodyne & direct detection
- Sensitive → high responsivity & low noise
- Integratable → thin film deposited at low temp on virtually any substrate (plastic, glass, CMOS, GaAs, etc.)

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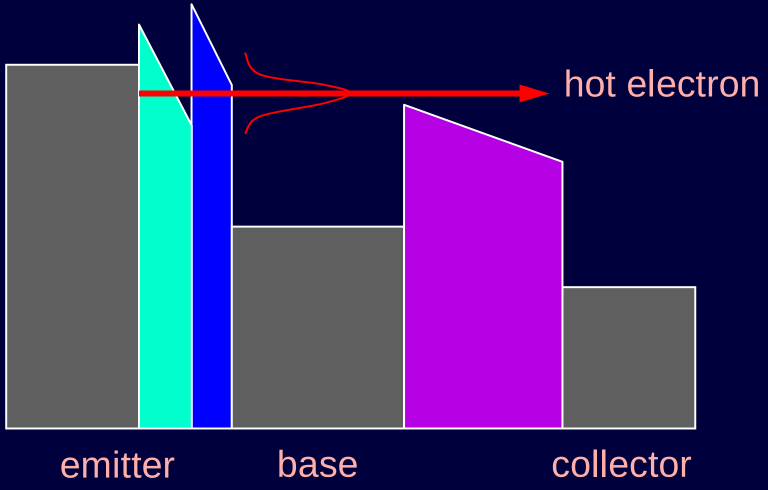
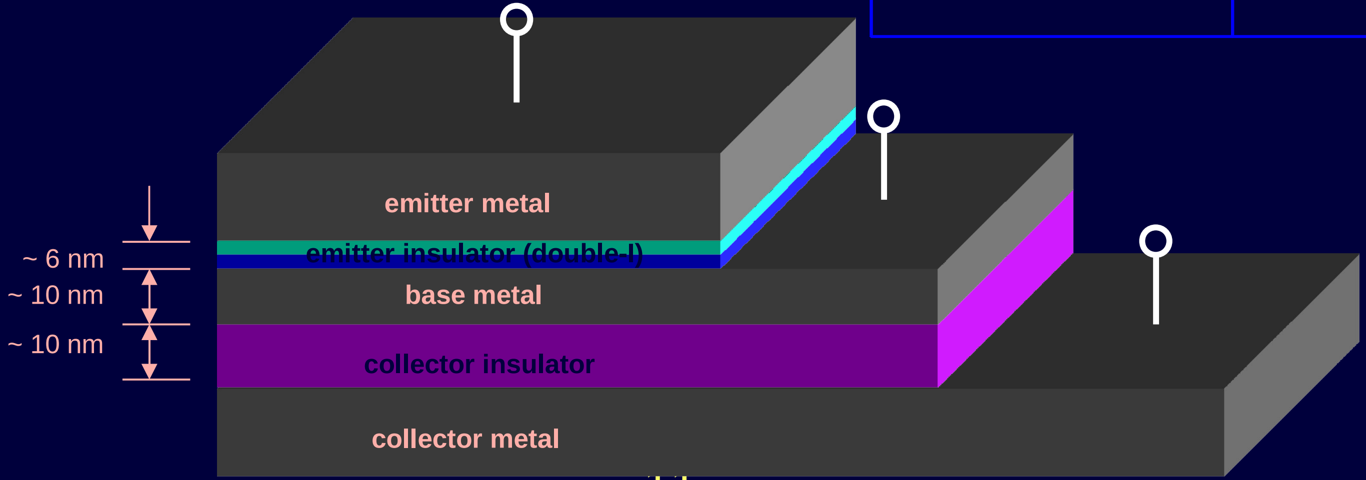
MIIMIM Tunneling Hot Electron Transistor



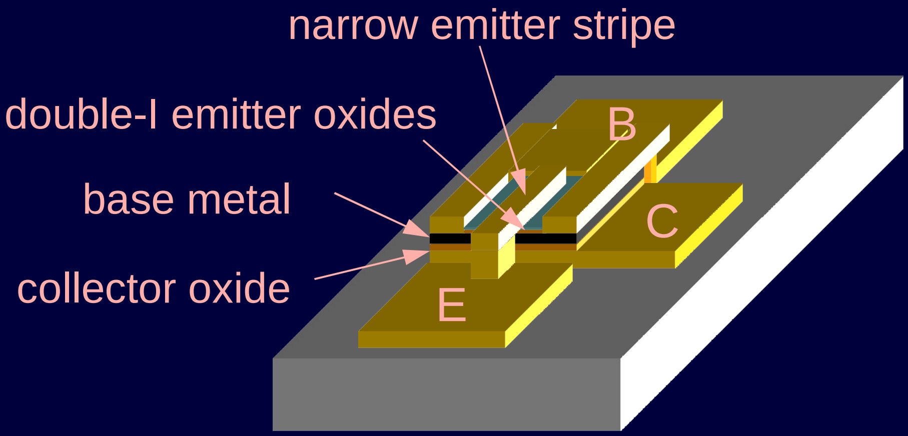
Predicted Performance

Cutoff freq, f_T	1.8 THz
Max osc freq, f_{max}	3.8 THz
Unilateral pwr gain	20 dB
RF output pwr	~1 mW
Power efficiency	> 30%



Features of Transistor

- Ultra-fast metal-insulator nanotechnology transistors
- Thin film: compatible with silicon ICs
- Manufacturable at low cost


narrow emitter stripe

double-I emitter oxides

base metal

collector oxide

Comparison: High-Frequency Transistors

Transistor	Maximum Frequency (GHz)
MIIMIM	**3800 (simulated)**
Silicon	73
Gallium arsenide	133
Silicon-germanium	260+
Indium phosphide	800+

Features of Metal-Insulator Technology

- Ultra-high-speed → THz diodes & transistors
- Thin film → low-cost, large-area, integratable on CMOS, plastic, etc.
- No exotic materials or processes → compatible with CMOS fab
- High efficiency → practical
- Low voltage → compatible with CMOS
- Low cost
- One technology does it all: diodes, transistors, antennas, arrays…

Outline

- Metal-insulator technology
  - Detectors: diodes & antennas
  - Double-insulator diode
- General metal-insulator devices
  - Detectors
  - Transistors
- **Applications**
- Modeling
  - Classical versus quantum
  - Ranges

Applications

- **Broadband communications detectors, transmitters, electronics**
- **Detectors and sources for terahertz imaging**
- Flexible electronics (RF TFTs) for large area radar, communication & security

Terahertz Radiation

- Electromagnetic spectrum between high-frequency radio waves and far infrared light
  - 0.1-10 THz range ⇔ 0.03 - 3 mm wavelength
- Many materials transparent, others exhibit unique absorption signature
- Terahertz imaging applications
  - Security: bombs in packages
  - Medical imaging
  - Pharmaceuticals: drug dosage testing & discovery
  - Non-destructive testing: packaged semiconductors, etc.
  - Gas analysis: pollution monitoring, engine exhaust, astronomy
  - Imaging through obscurants (fog, smoke, etc.)

Phiar CORPORATION

Applications

- Broadband communications detectors, transmitters, electronics
- Detectors and sources for terahertz imaging
- **Flexible electronics (RF TFTs) for large area radar, communication & security**

RF-on-Flex Markets

- Low-cost radar (e.g., automotive)
- Lightweight satellite uplinks/downlinks
- Free-space data links, communications
- RF ID tags and smart tags
- Completely integrated phased arrays on flex
- Very large aperture radar

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  - **Classical versus quantum**
  - **Ranges**

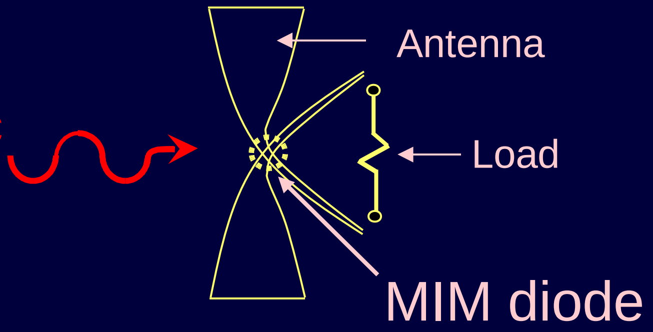
Terminology

Photon energy: $E_{ph}=h\nu$

Diode voltage: $$V_{ph} \cong \sqrt{\frac{2\,n_{ph}\,E_{ph}\,d_{ox}}{Area\,\varepsilon_r\,\varepsilon_o}}$$

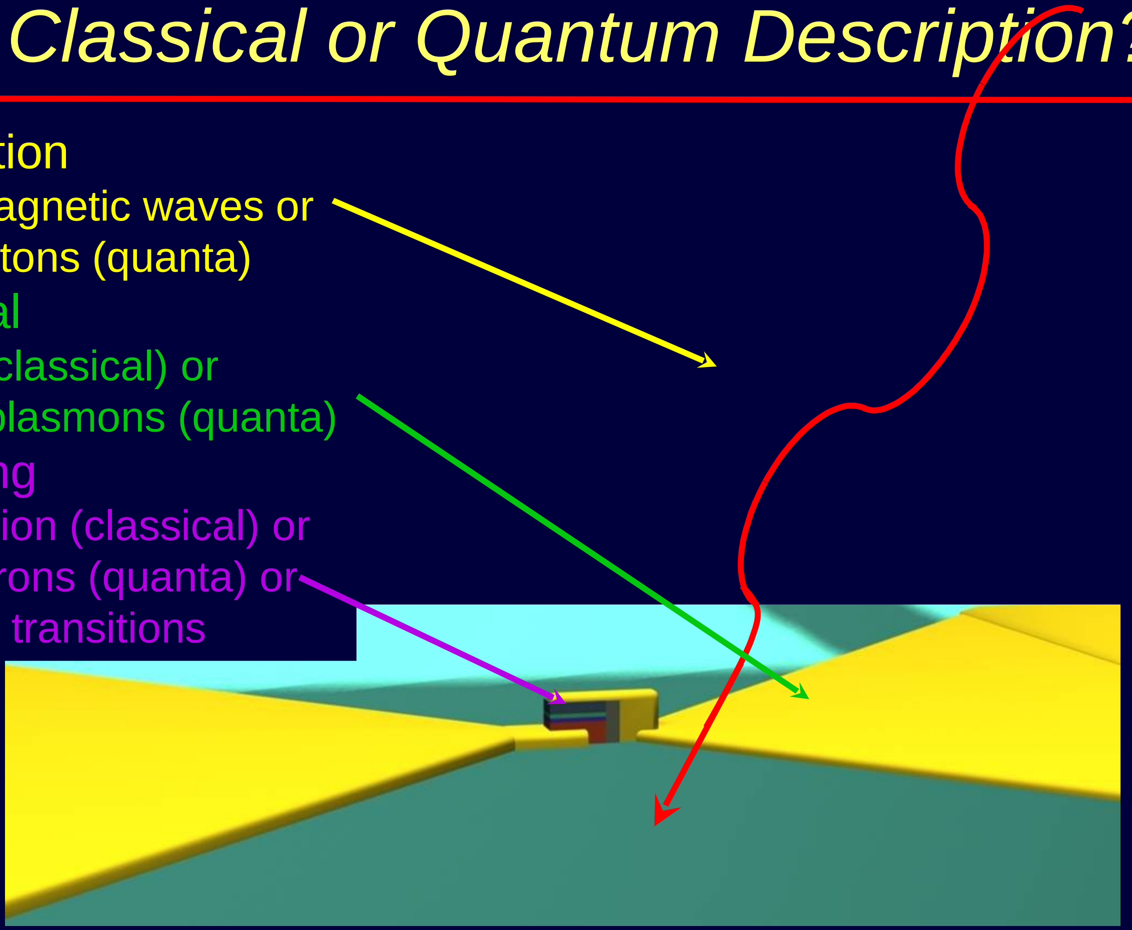
(from confined optical field)

Model depends on V_{ph} & E_{ph}



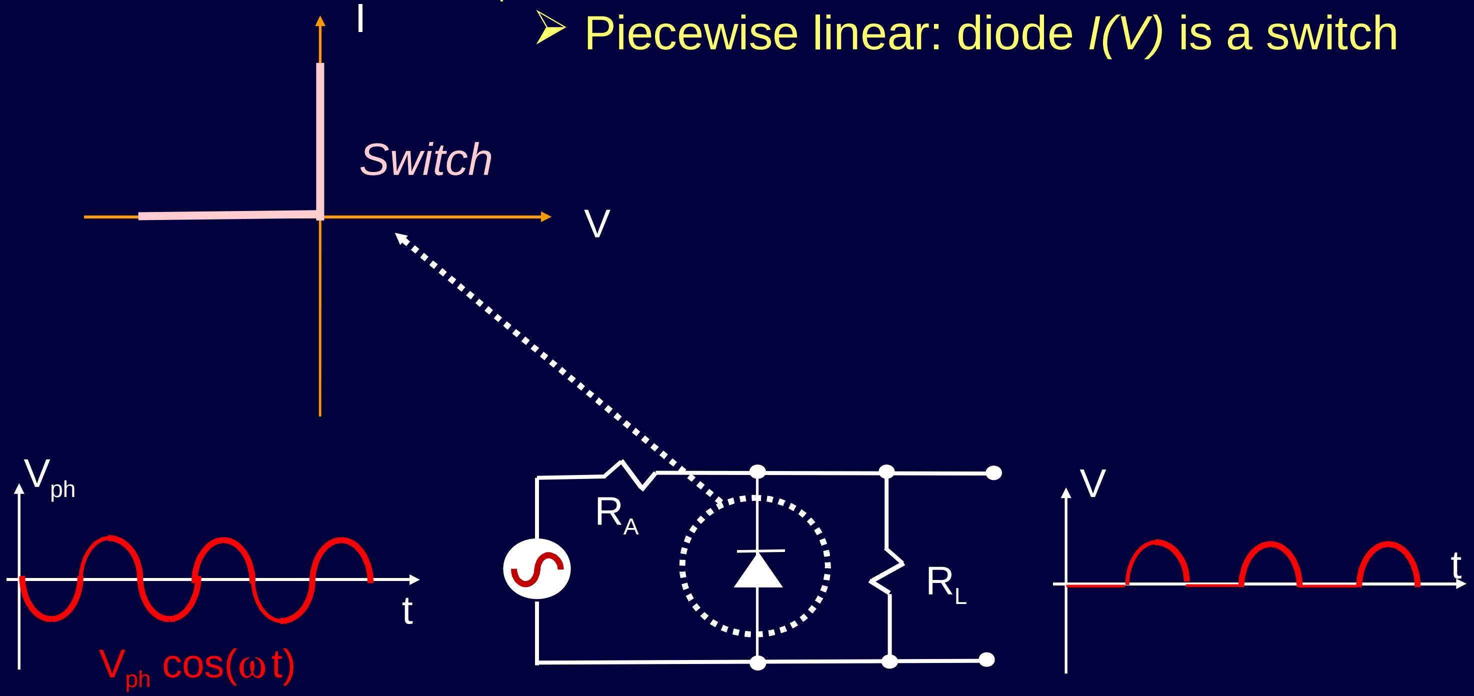
Classical or Quantum Description?

- Incident radiation
  - Electromagnetic waves or
  - QED photons (quanta)
- Antenna signal
  - Current (classical) or
  - Surface plasmons (quanta)
- Diode tunneling
  - Rectification (classical) or
  - Hot electrons (quanta) or
  - Quantum transitions



Classical Large-Signal Rectification

- E_{ph} - small (low frequency)
- V_{ph} - large
  - Piecewise linear: diode *I(V)* is a switch

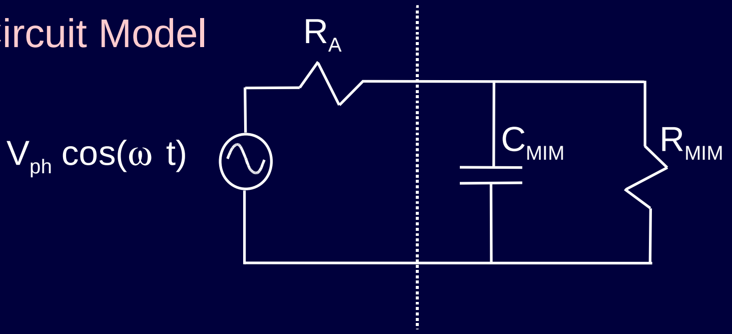


Classical Small-Signal Rectification

- E_{ph} - small (low frequency)
- V_{ph} - small
  - *I(V)* approximated by 2nd order Taylor Series
  - Square-law detection

$$I(\varsigma) = I(0) + \frac{1}{1!}\frac{\partial I}{\partial \varsigma}\varsigma + \frac{1}{2!}\frac{\partial^2 I}{\partial \varsigma^2}\varsigma^2 + \frac{1}{3!}\frac{\partial^3 I}{\partial \varsigma^3}\varsigma^3 + \dots$$

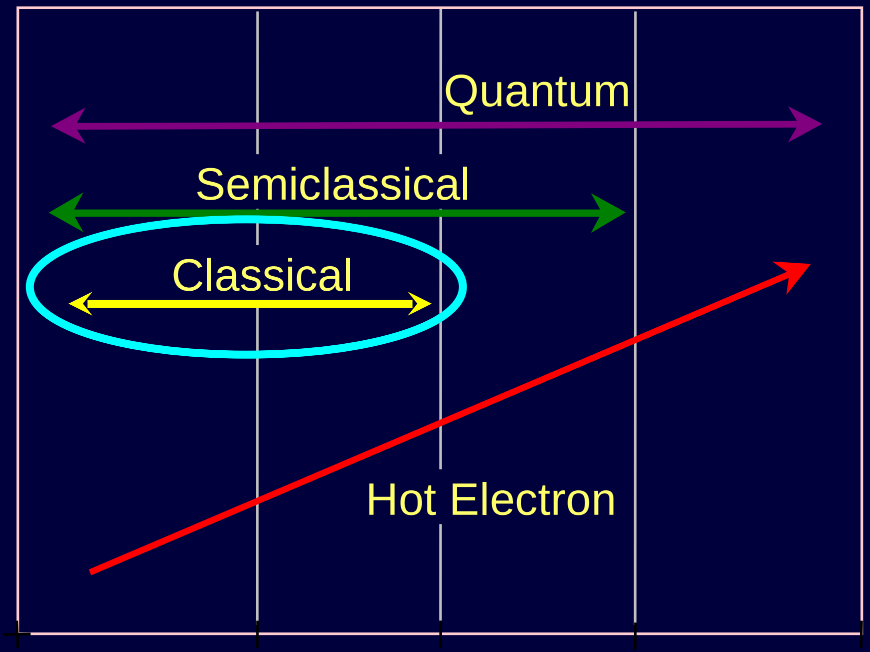
Circuit Model



Diode Responsivity:

$$\Re = \frac{I_{rectified}}{P_{MIM}} = \frac{1}{2}\frac{I''}{I'}$$

Rectification Models



Frequency: Low Low
Photon #: Small Large

Classical

Classical Model Limitations

7.1 GHz ⇔ 0.000029 eV

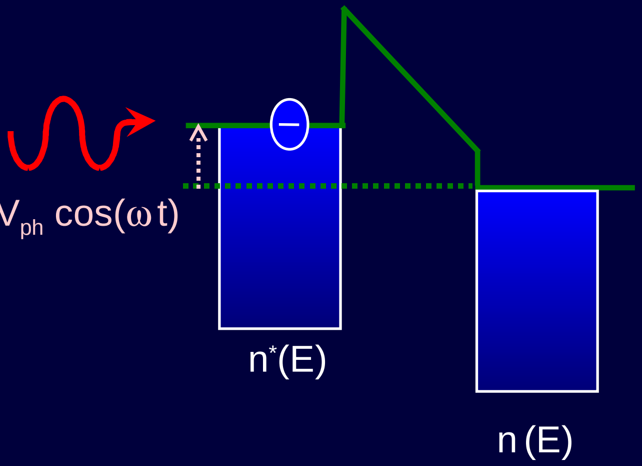
1.0 THz ⇔ 0.0041 eV

10 µm ⇔ 0.12 eV

1.55 µm ⇔ 0.8 eV

500 nm ⇔ 2.48 eV

Semiclassical Model



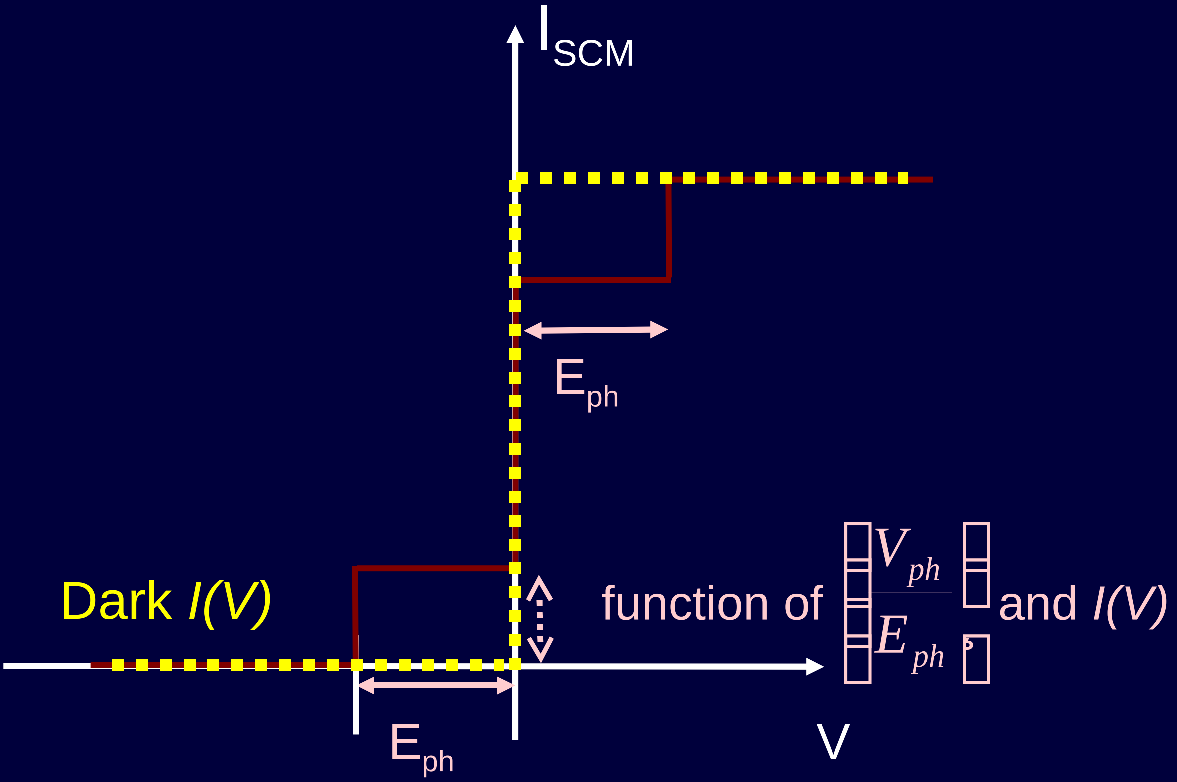
- Modulate (perturb) potential of left-hand metal
- Field not quantized

To find current:

Solve Schrödinger wave equation with perturbation by optical field

$$J_{SCQM}(V_{bias}) = \sum_{n=-\infty}^{n=+\infty} J_n^2\left(\frac{V_{ph}}{E_{ph}}\right) J_{DARK}(V_{bias} + nE_{ph})$$

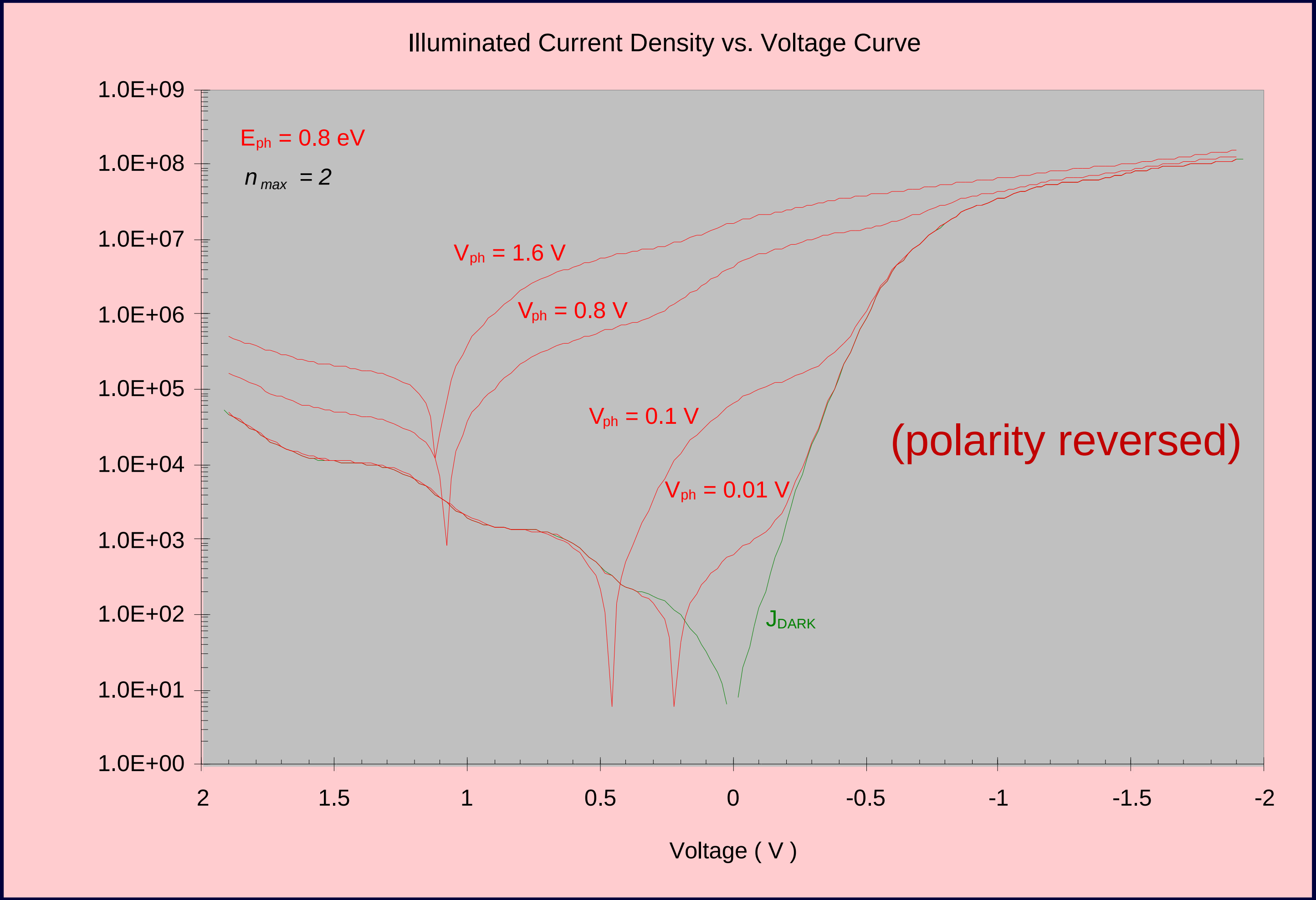
Photon Stepping (Semiclassical Model)



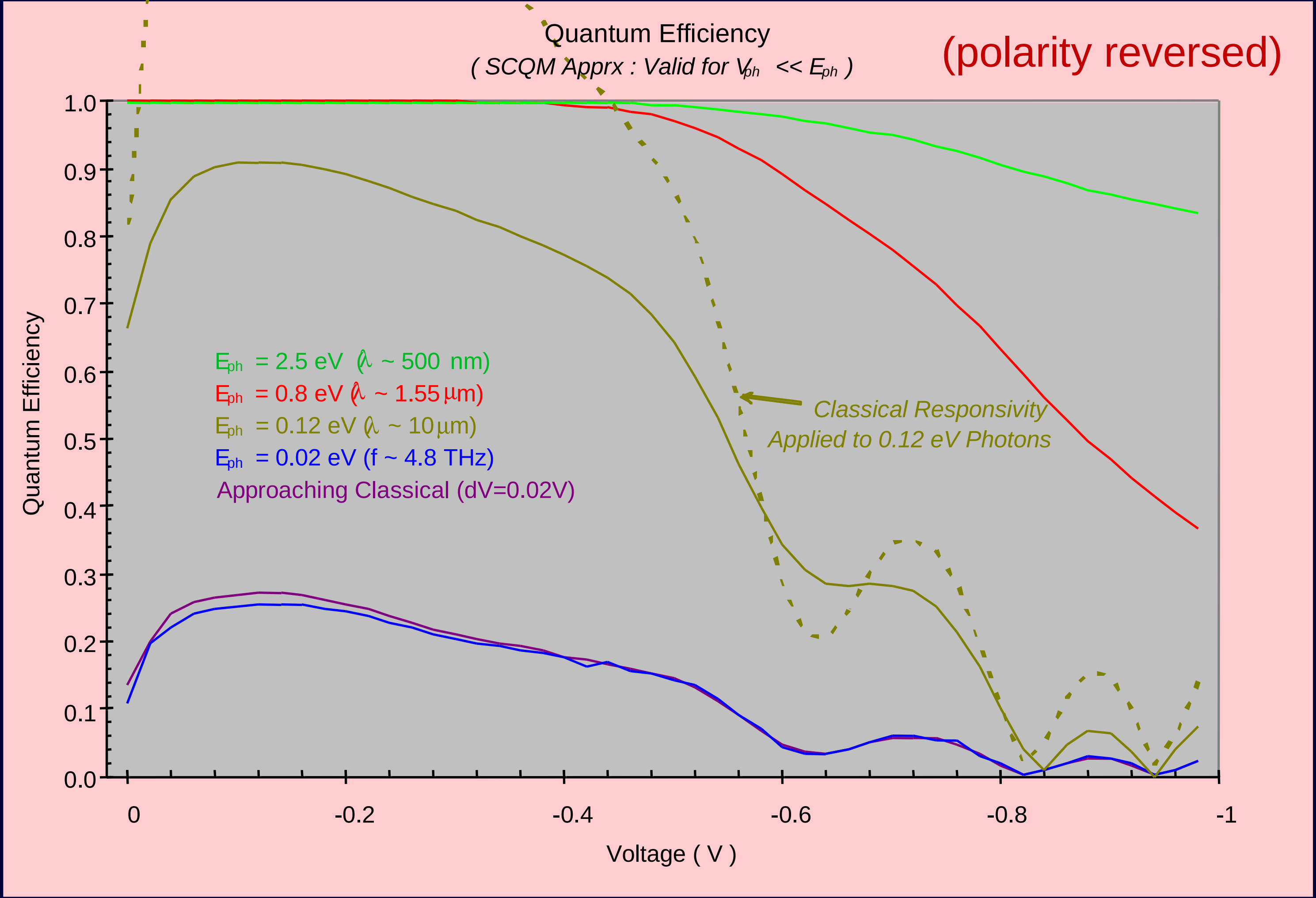
Dark *I(V)*

function of $\left(\frac{V_{ph}}{E_{ph}}\right)$ and *I(V)*

Illuminated MIIM Diode J(V)
(Semiclassical Model)

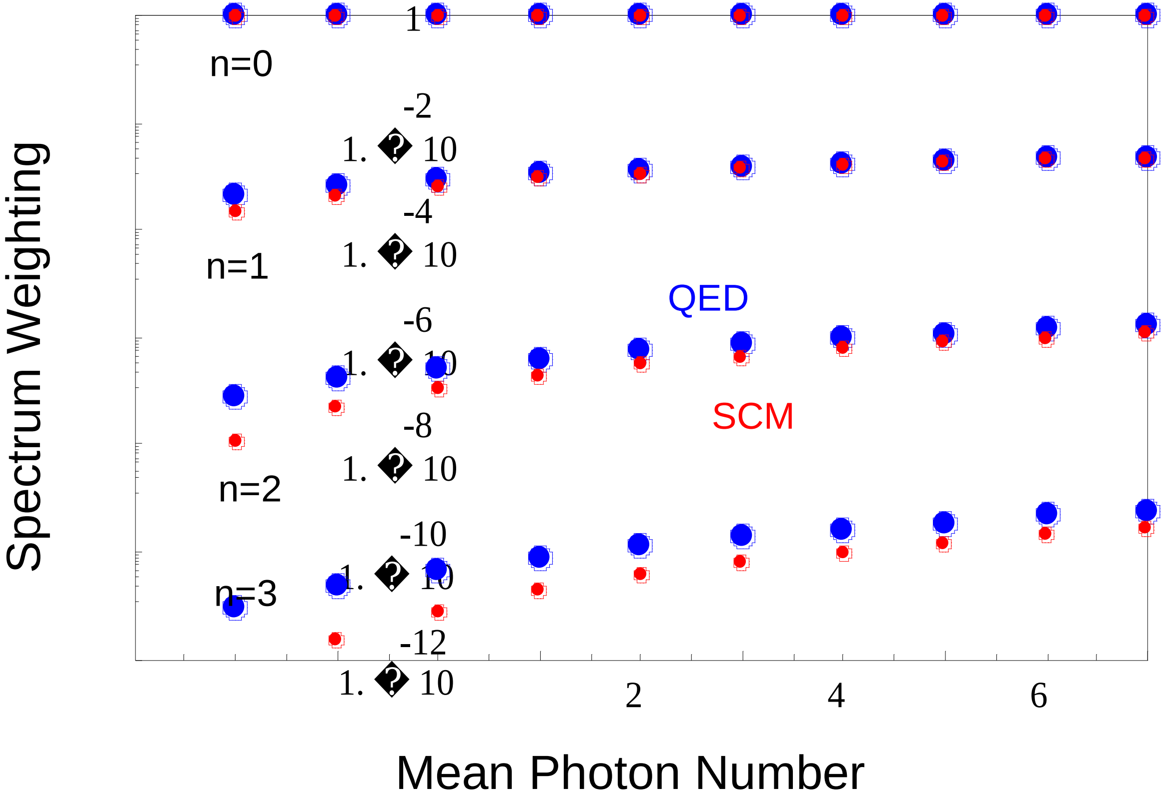


Diode Quantum Efficiency
(Semiclassical Model)



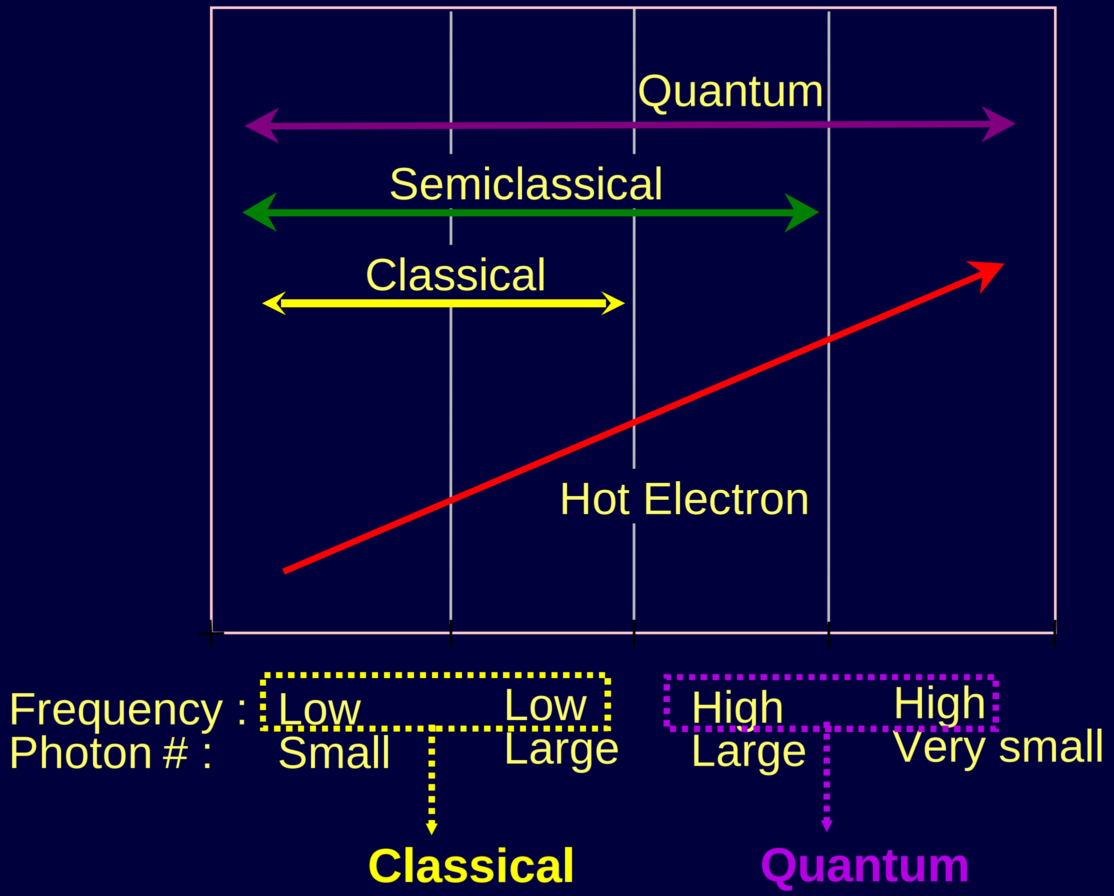
Comparison of Semiclassical Model
) Solution

2.5 eV photons weak coupling



- Agree at high photon number
- Actual photon number >> 10

Rectification Models



Quantum

Semiclassical

Classical

Hot Electron

Frequency : Low Low High High

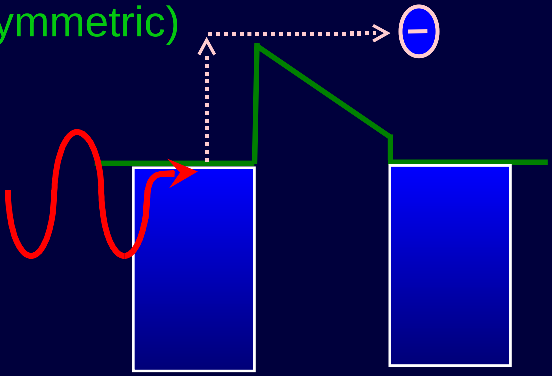
Photon # : Small Large Large Very small

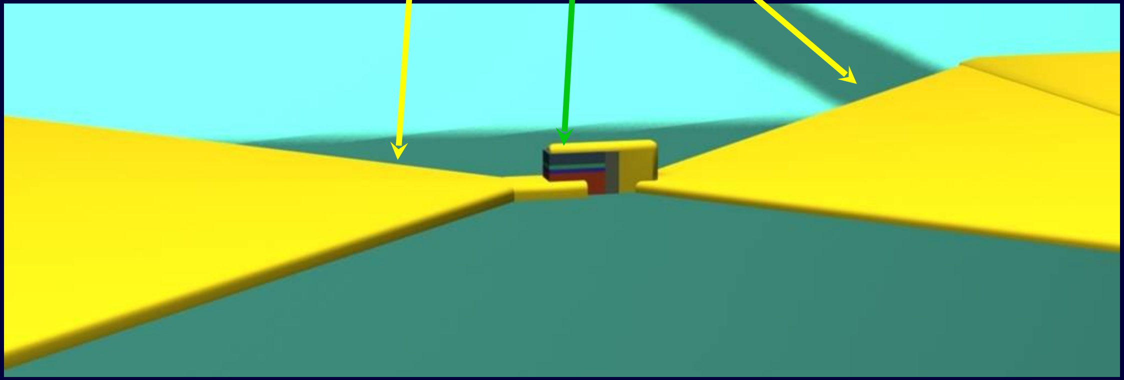
Classical

Quantum

Hot Electrons or Modulation?

- Hot electrons (internal photoelectric effect)
  - Radiation absorbed directly by diode layer (asymmetric)
- Modulate potential across diode
  - Radiation channeled by antenna (symmetric)
  - Modulate electron sea





Conclusions

Metal-insulator device technology

- Double-insulator diode
  - Provides sufficient nonlinearity for practical devices
- Simulated transistors provide gain at ultra-high frequencies
- Technology provides compatibility with silicon CMOS, low cost, high-frequency
- Applications in ultra-high speed electronics, mmW detectors, broadband communications, THz imaging, etc.

Modeling metal-insulator diodes

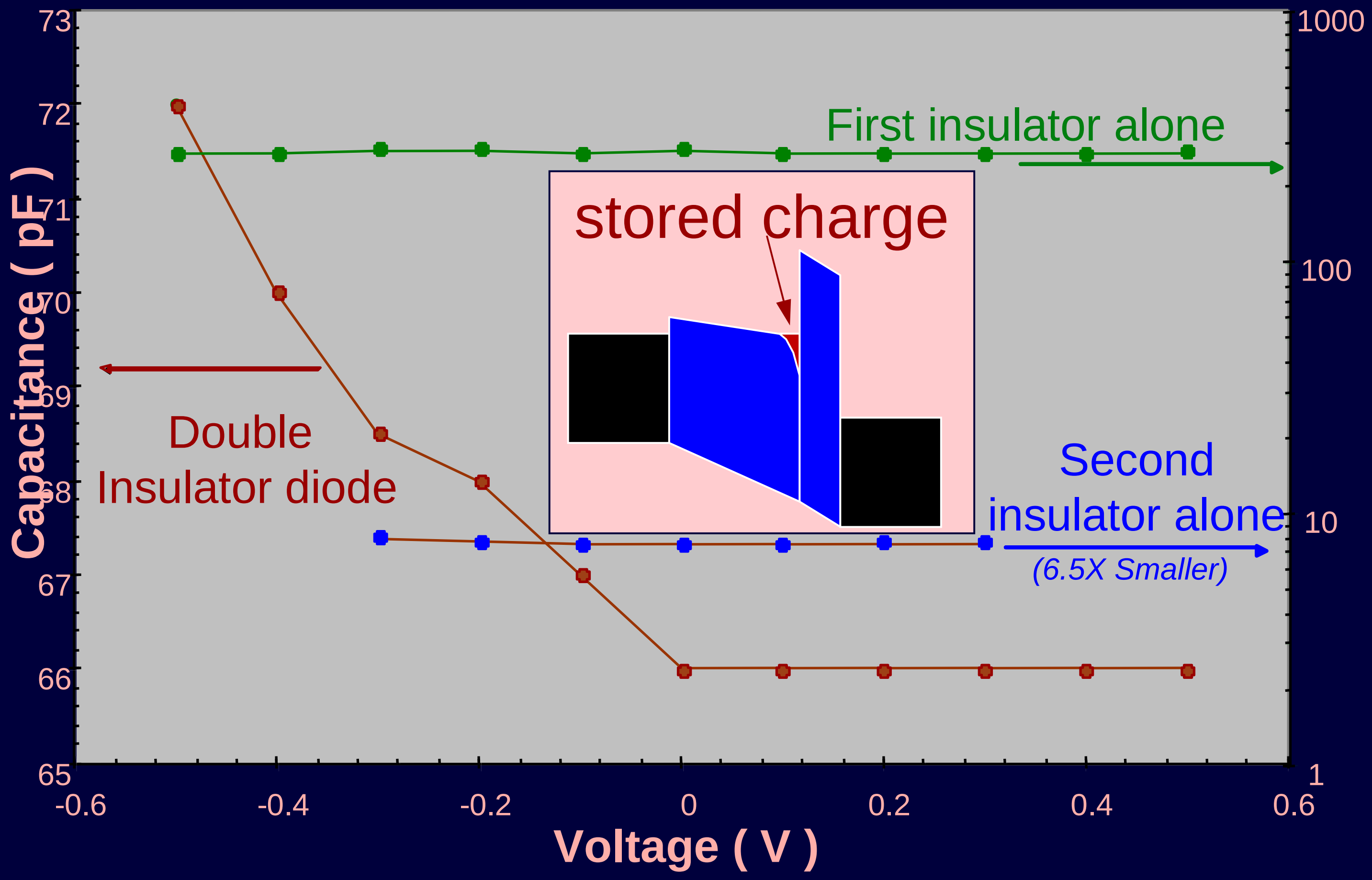
- *Maxwell* Classical model at low photon energies

meets

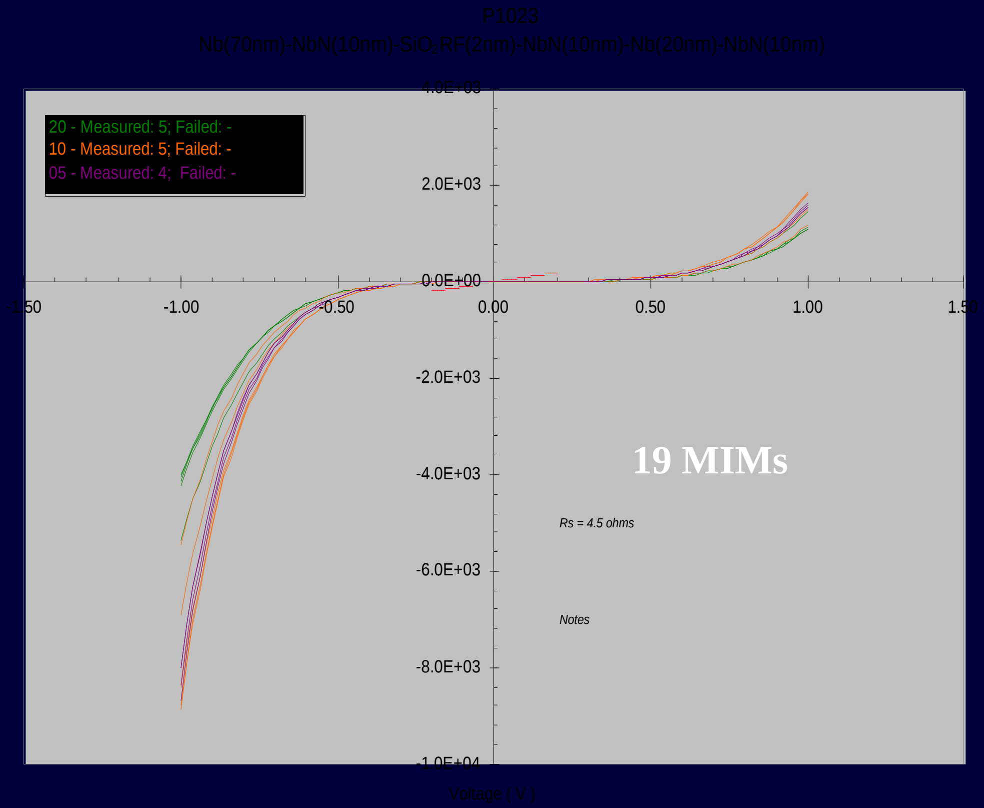
- *Einstein* Semiclassical model accurate for moderate photon energies and moderate to high photon number

Extra Slides

Measured Capacitance Fits Model



RF Sputtered SiO_2 MIM



P1023

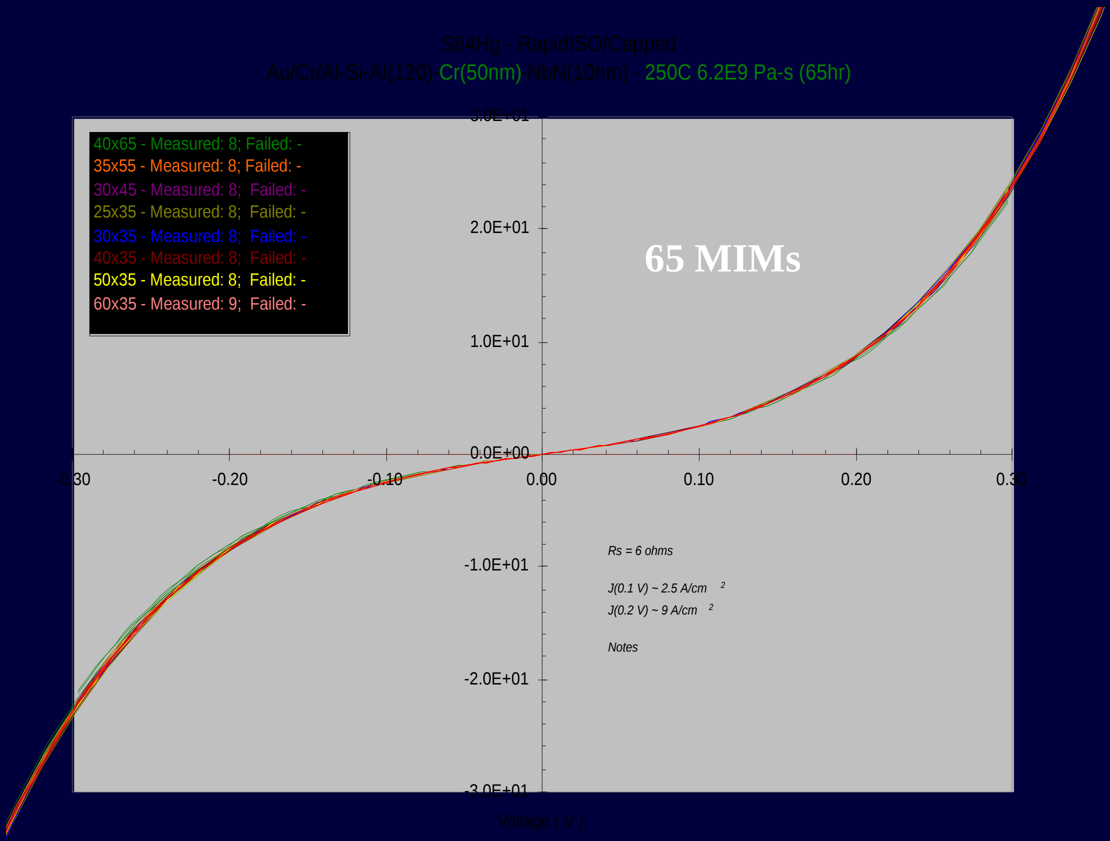
Nb(70nm)-NbN(10nm)-SiO_2RF(2nm)-NbN(10nm)-Nb(20nm)-NbN(10nm)

19 MIMs

Rs = 4.5 ohms

Notes

Thermal Cr_2O_3 MIM



65 MIMs

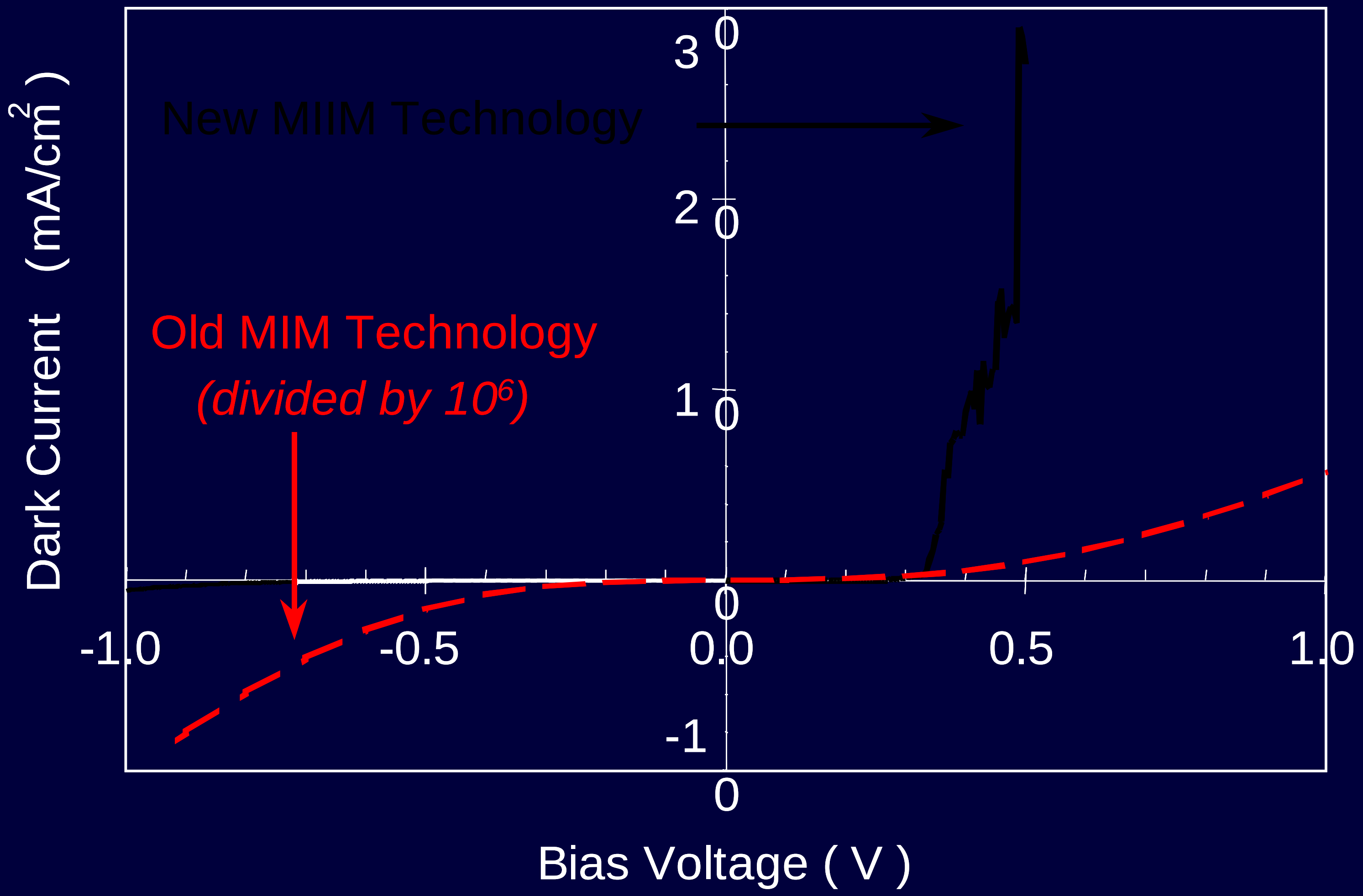
Rs = 6 ohms

J(0.1 V) ~ 2.5 A/cm^2

J(0.2 V) ~ 9 A/cm^2

Notes

Double Insulator



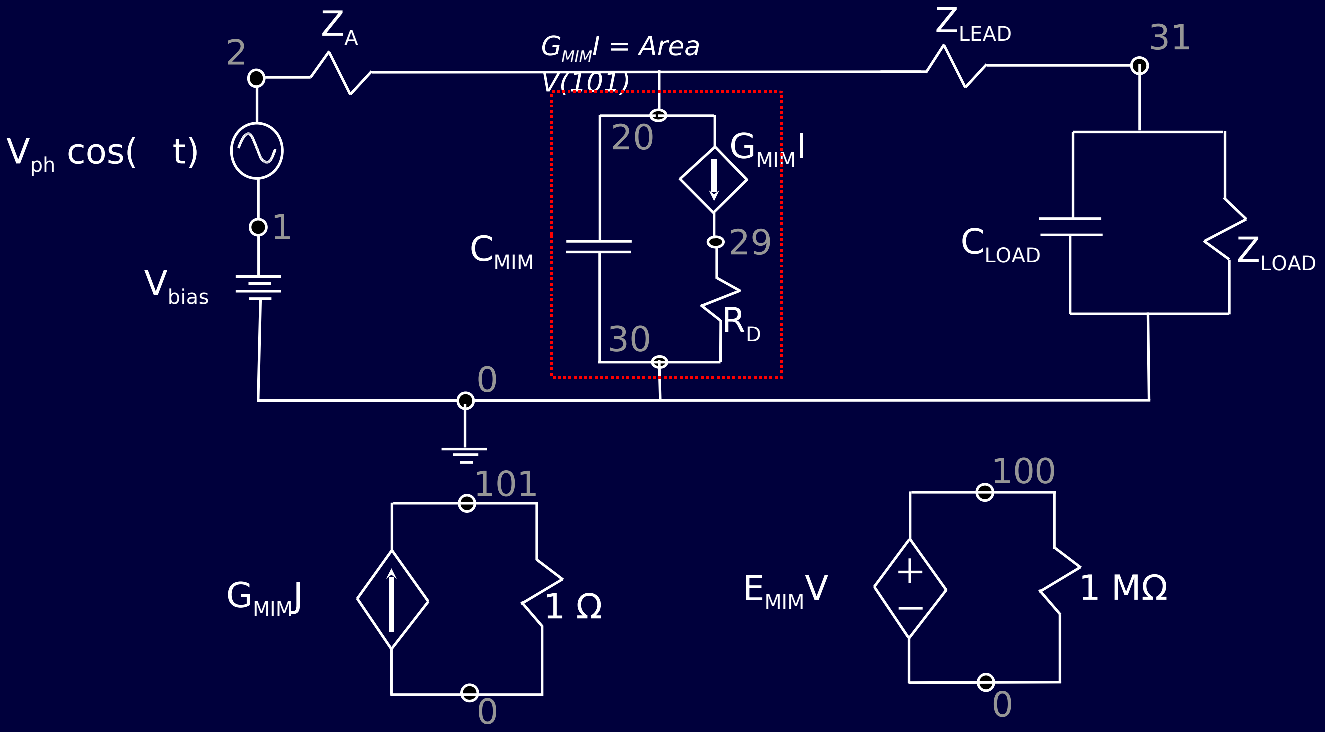
New MIIM Technology

Old MIM Technology

(divided by 10^6)

PSpice Classical Rectification

- V_{ph} - large
- E_{ph} - small (low frequency)



$G_{MIM}J$ = Table {V,J} for V(100)

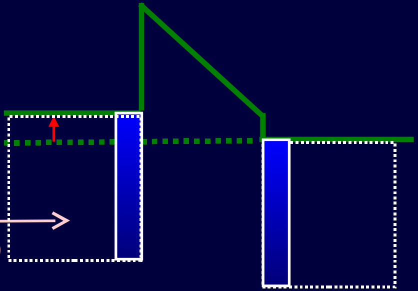
$E_{MIM}V = V(20)-V(30) = V_{MIM}$

Semiclassical Quantum Model – Pictorial View

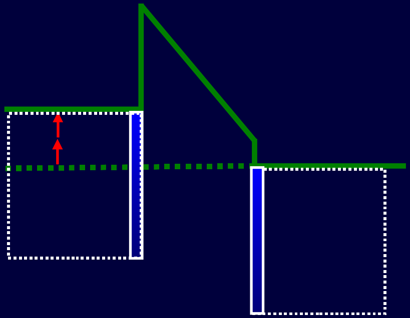
$$J_{SCQM}(V_{bias}) = \sum_{n=-\infty}^{n=+\infty} J_n^2\left(\frac{V_{ph}}{E_{ph}}\right) J_{DARK}(V_{bias}+nE_{ph})$$

$$\sum_{n=-2}^{n=+2}$$

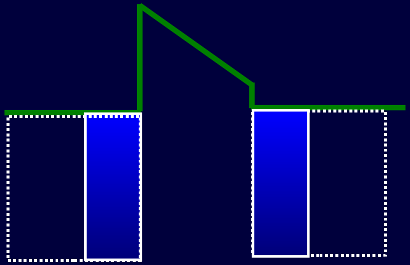
visualized weighted in n(E)



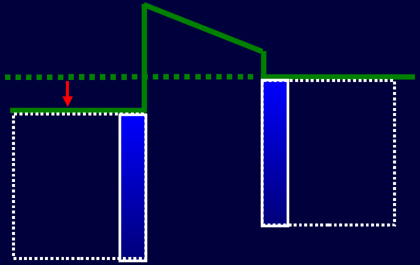
$$J_{-1}^2\left(\frac{qV_{ph}}{E_{ph}}\right) J_{DARK}(V_{bias}-1\cdot E_{ph})$$



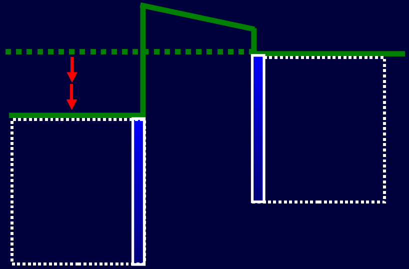
$$J_{-2}^2\left(\frac{qV_{ph}}{E_{ph}}\right) J_{DARK}(V_{bias}-2\cdot E_{ph})$$



$$J_0^2\left(\frac{qV_{ph}}{E_{ph}}\right) J_{DARK}(V_{bias}+0E_{ph})$$

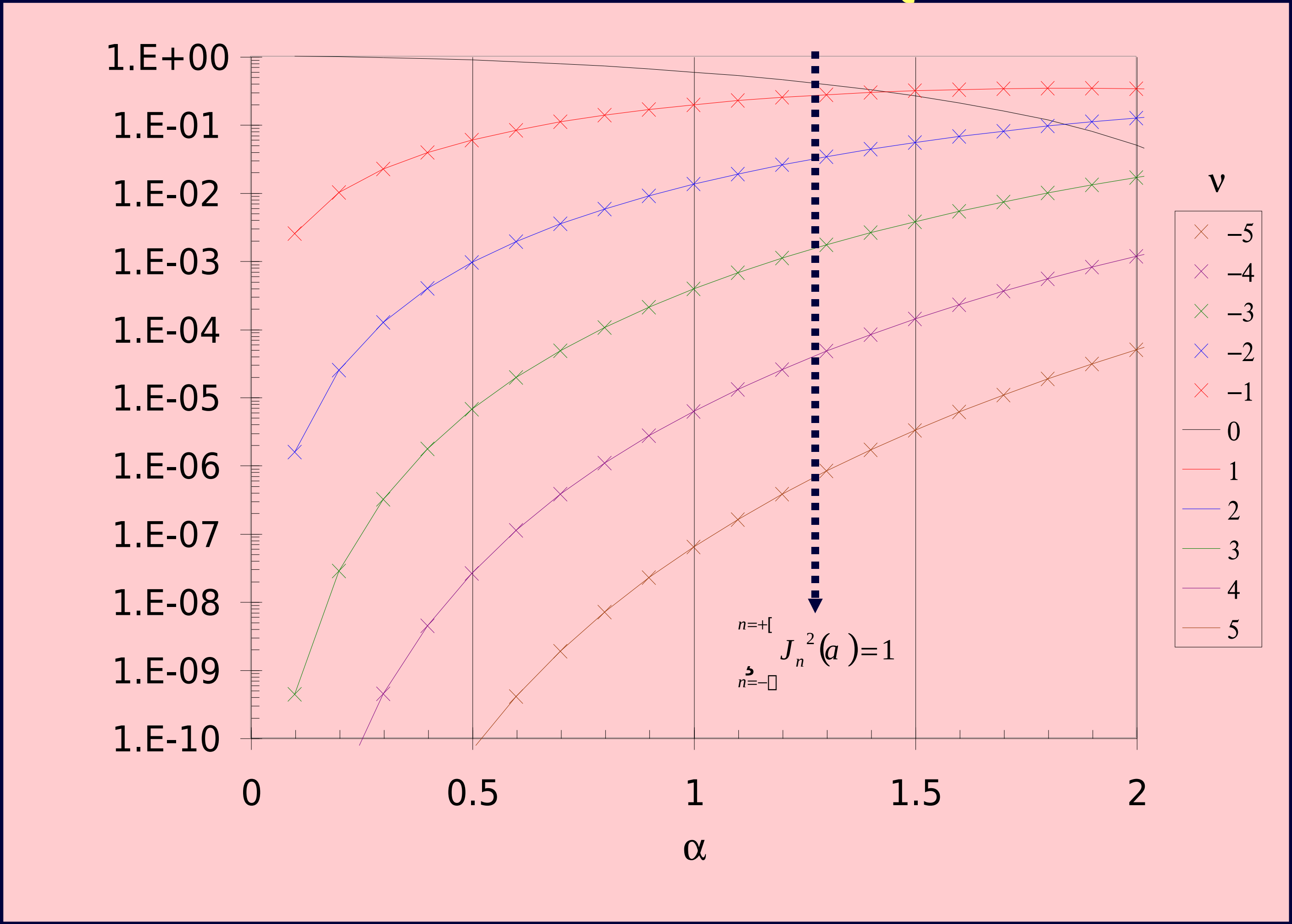


$$J_1^2\left(\frac{qV_{ph}}{E_{ph}}\right) J_{DARK}(V_{bias}+1\cdot E_{ph})$$



$$J_2^2\left(\frac{qV_{ph}}{E_{ph}}\right) J_{DARK}(V_{bias}+2\cdot E_{ph})$$

Bessel Function Terms $J_n^2(\alpha)$ for Semiclassical Quantum Model

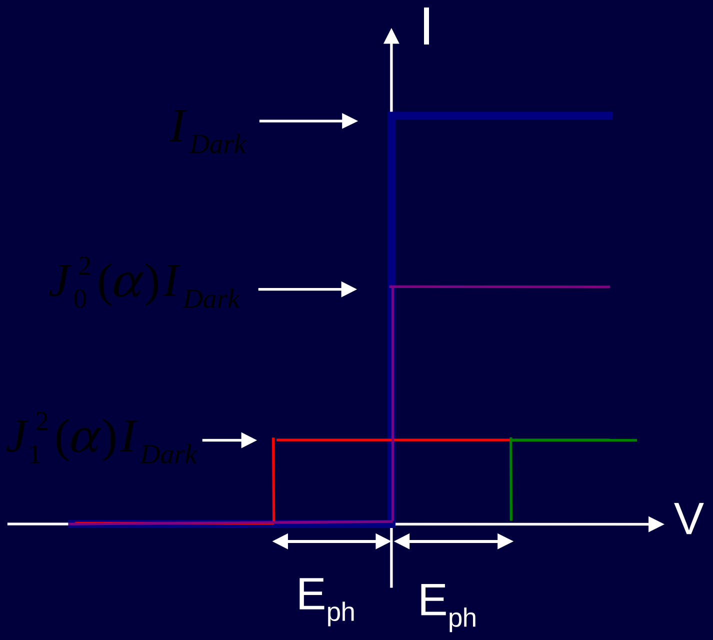


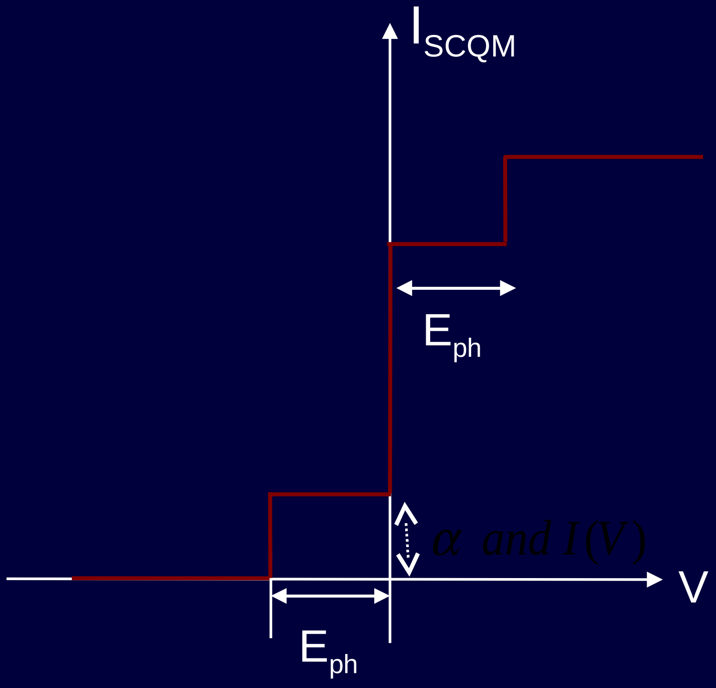
$$\sum_{n=-\infty}^{n=+\infty} J_n^2(\alpha) = 1$$

Photon Stepping

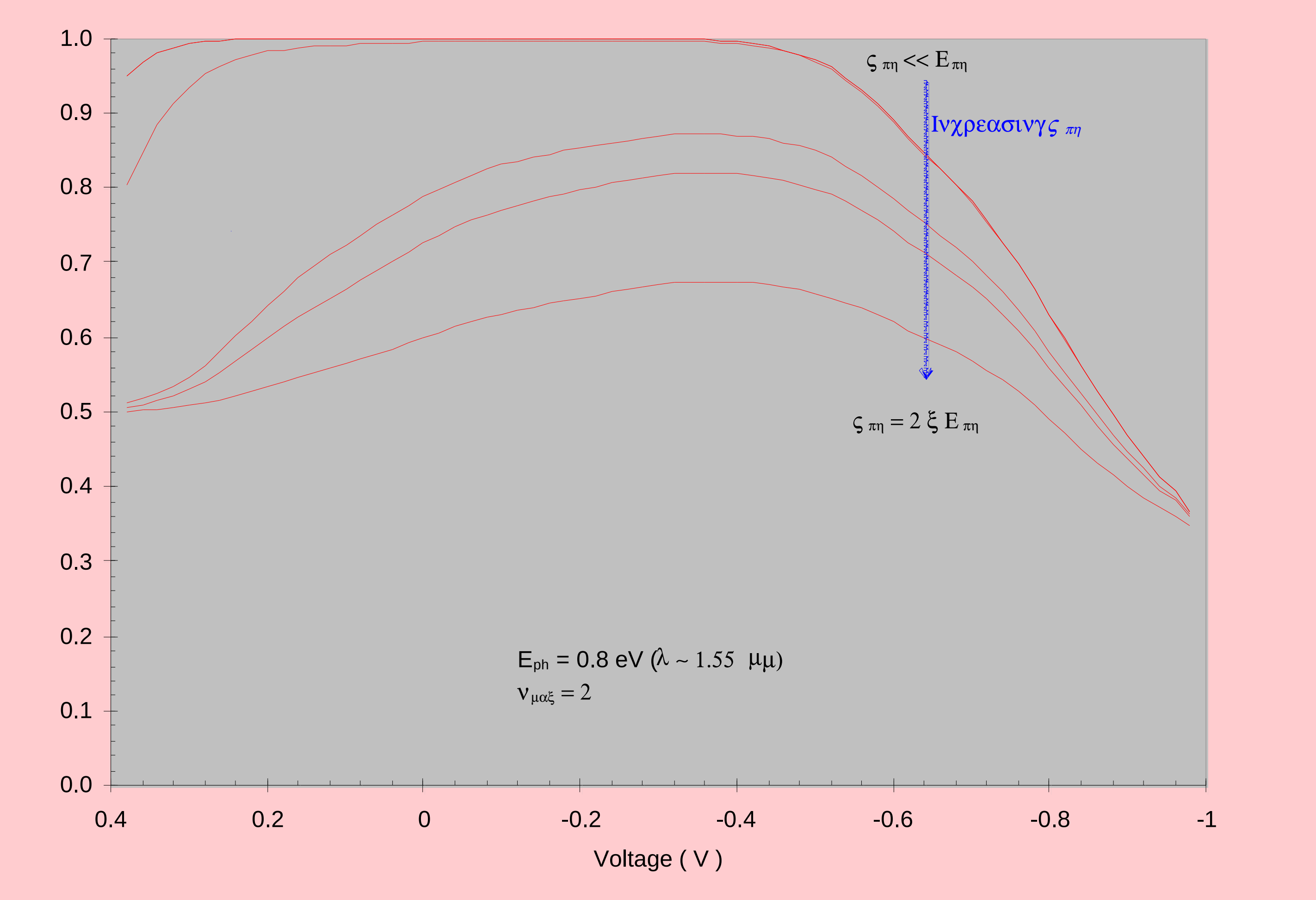
$$
\begin{aligned}
I_{SCQM}(V_{bias}) &= J_{-1}^{2}(\alpha) I_{DARK}(V_{bias} - E_{ph}) \\
&+ J_{0}^{2}(\alpha) I_{DARK}(V_{bias}) \\
&+ J_{1}^{2}(\alpha) I_{DARK}(V_{bias} + E_{ph})
\end{aligned}
$$

$$a = \frac{V_{ph}}{E_{ph}}$$



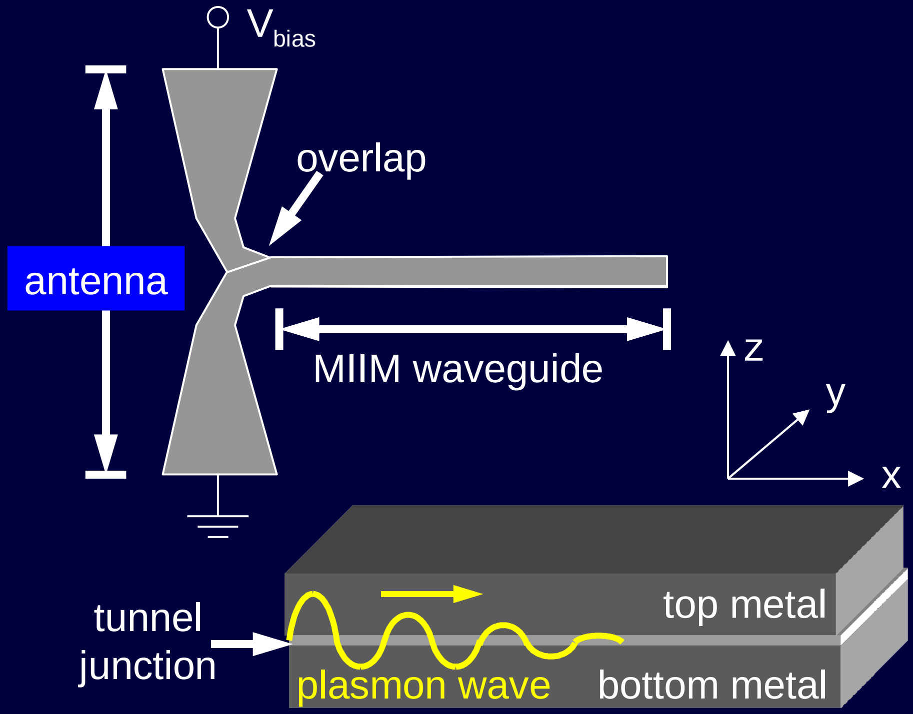


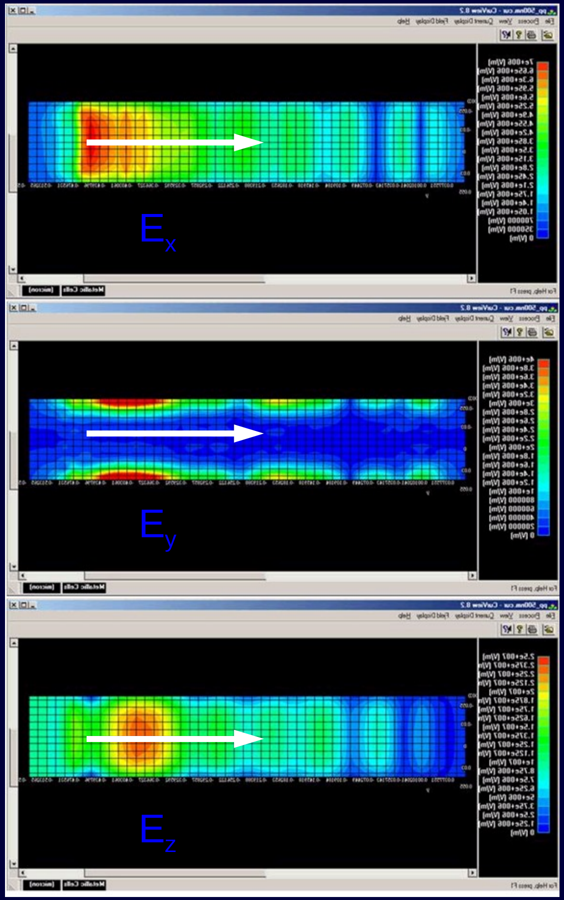
Diode Quantum Efficiency vs V_{ph} (Semiclassical Model)



Traveling Wave Detector

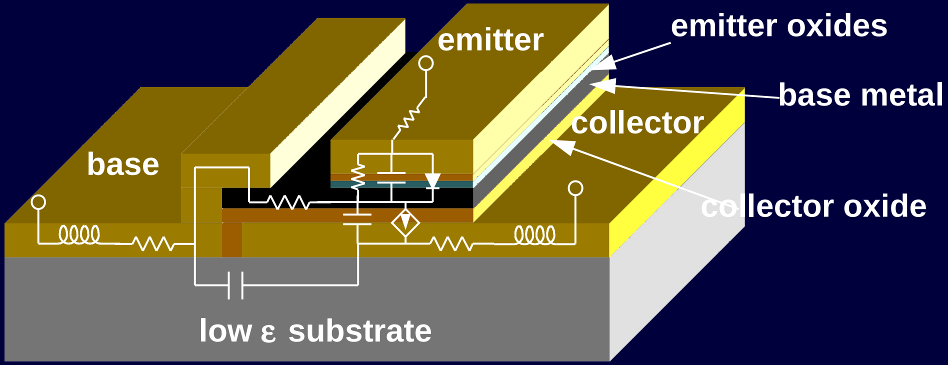
Improves:
- Efficiency
- Impedance matching to antenna
- RC time constant





Transistor: Why It's So Fast

- Short carrier transit time
- Low base resistance
- Low parasitic lead resistance
- Low parasitic substrate capacitance



Advantages over semiconductor transistors:

- Transit time
- Base & lead resistance
- Integratable, etc.

Comparison: THz Sources

Source	Operating Temperature	Cost
Phiar MIIMIM oscillator	**room**	**$1 est.**
Quantum Cascade Laser	requires cooling	$1,000 est.
Microwave Upconverter	low-room	$100s – $1000s est.
Femtosecond Laser	room	$50,000+
Gas Laser	room	$300,000

- Efficient → up to 35% or higher DC-to-THz
- High power → mW output for single device
- Integrated → solid state, thin film