Performance Evaluation in Conventional and Rectenna Solar Cells

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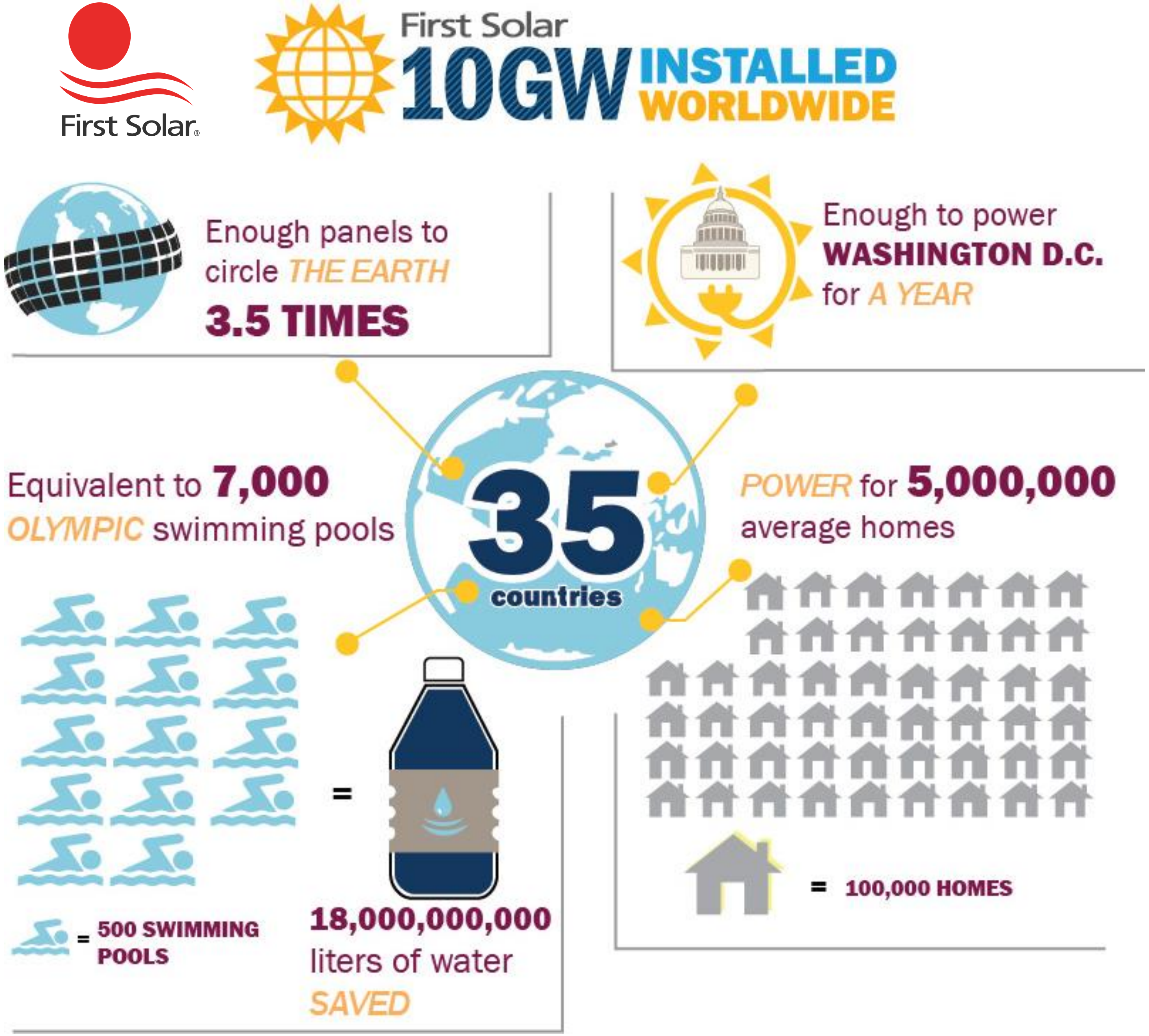
First Solar
2015-present

Scifiniti
2013-2014

NREL
NATIONAL RENEWABLE ENERGY LABORATORY
2011-2013

UNIVERSITY OF COLORADO
1876
2006-2011

First Solar



First Solar 10GW INSTALLED WORLDWIDE

Enough panels to circle *THE EARTH* **3.5 TIMES**

Enough to power **WASHINGTON D.C.** for *A YEAR*

35 countries

Equivalent to **7,000** *OLYMPIC* swimming pools

= **500 SWIMMING POOLS**

=

18,000,000,000 liters of water *SAVED*

POWER for **5,000,000** average homes

= **100,000 HOMES**

San Luis Obispo County, California

Customer: MidAmerican

Size: 550MW (AC)

Construction Time: 2011—2015

Acres: ~7,800 site

Modules: ~9 million

Cars Removed:

73,000

Tons CO_2 Displaced Annually:

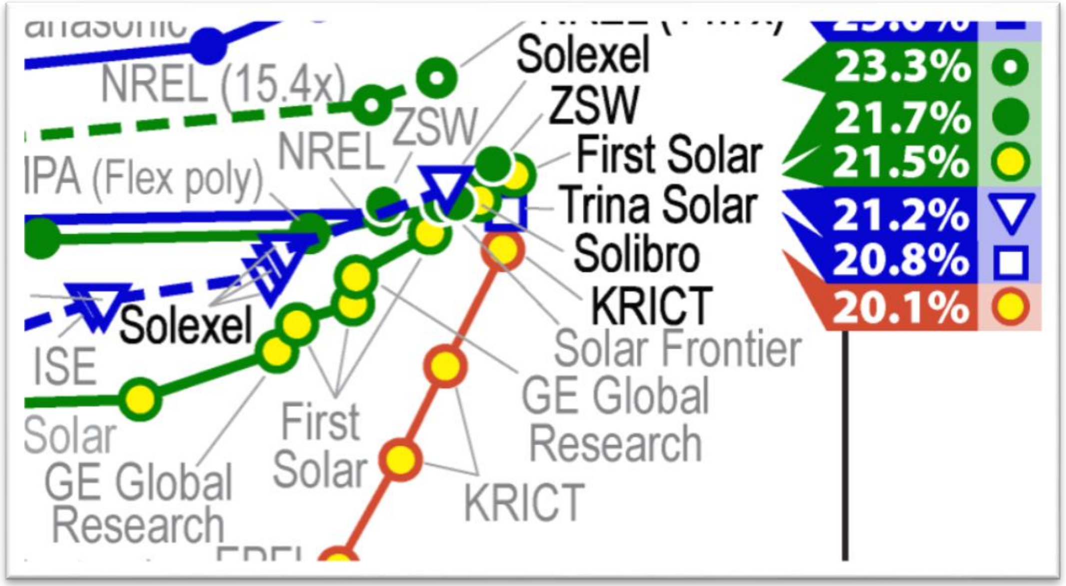
377,000

TOPAZ SOLAR FARM

Record efficiency: 18.6% aperture area efficiency (18.2% full area)

"At one time, we might have been characterized as a low cost, low efficiency technology, but consistent with our technology projections we are now proving that CdTe thin film delivers both industry-leading performance AND sustainable thin-film cost structures.“

-Raffi Garabedian, First Solar CTO

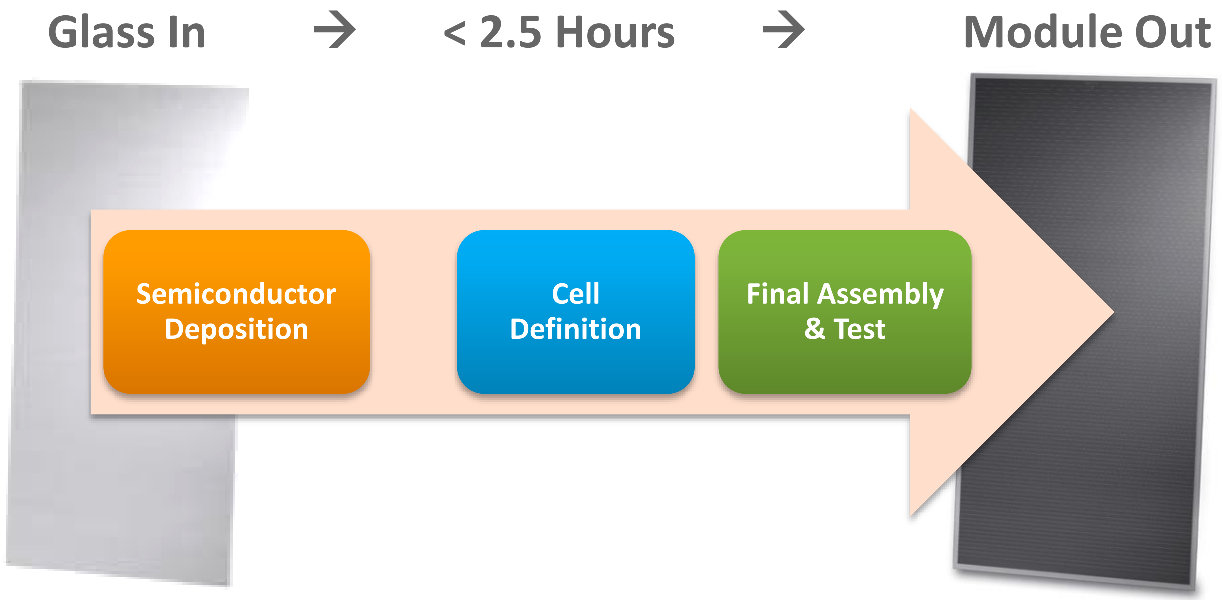


http://investor.firstsolar.com/releasedetail.cfm?ReleaseID=917926

http://www.nrel.gov/ncpv/images/efficiency_chart.jpg

PV Module technology & manufacturing

First Solar Fully Integrated, Automated and Continuous Thin Film (CdTe) Process



Glass In → < 2.5 Hours → Module Out

Semiconductor Deposition

Cell Definition

Final Assembly & Test

- 98-99% reduction in semiconductor material
  - — Direct bandgap material
- Fully integrated, continuous process vs. batch processing
- Large 60 x 120cm (2' x 4') superstrate vs. 6" wafers

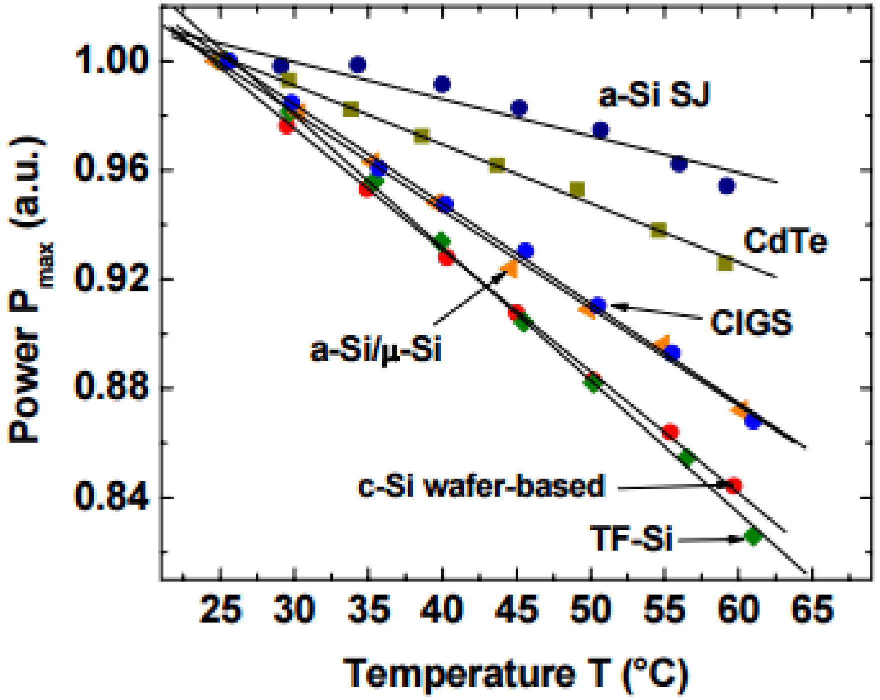
Conventional Crystalline Silicon Batch Technology

Polysilicon → Ingot → Wafer → Solar Cell → Solar Module

Superior Temperature Coefficient of CdTe yields more energy

- Temperate Climate Example:
  - Module Temps often reach 65° C; 40° C above the STC rating
  - The silicon module power output will be reduced by up to 20% at this temperature
  - FSLR output will be reduced by only 10%

- Hot Climate:
  - More hours at higher temps (Module temps can reach 85° C)
  - FS Advantage grows more pronounced



Virtuani, 25th EUPVSEC, 2010

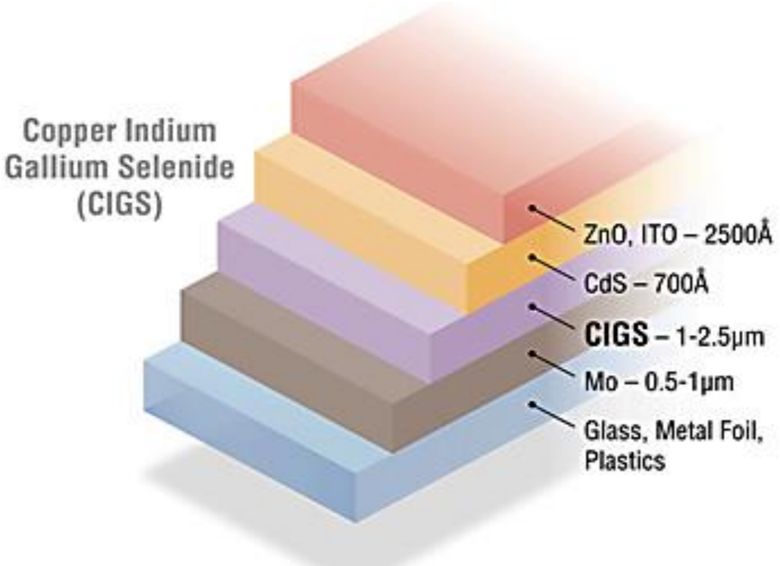
Combining suns-V_{OC} and $V_{OC}(T)$ to quantify recombination in solar cells

Outline

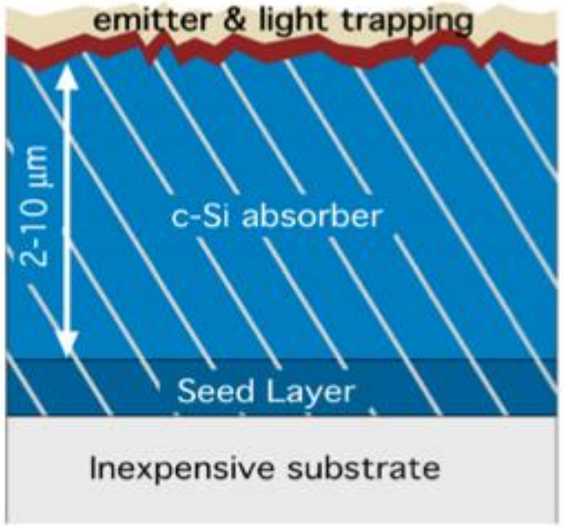
- Derive theoretical dependence of V_{OC} on
  - Light intensity
  - Temperature
  - Strength of recombination channels
- Apply formulation to
  - Quantify recombination in different regions of the cell
  - Extract material and interface quality

Grover et. al., APL, 103, 093502, 2013

Express V_{OC} in terms of SRH recombination in different regions



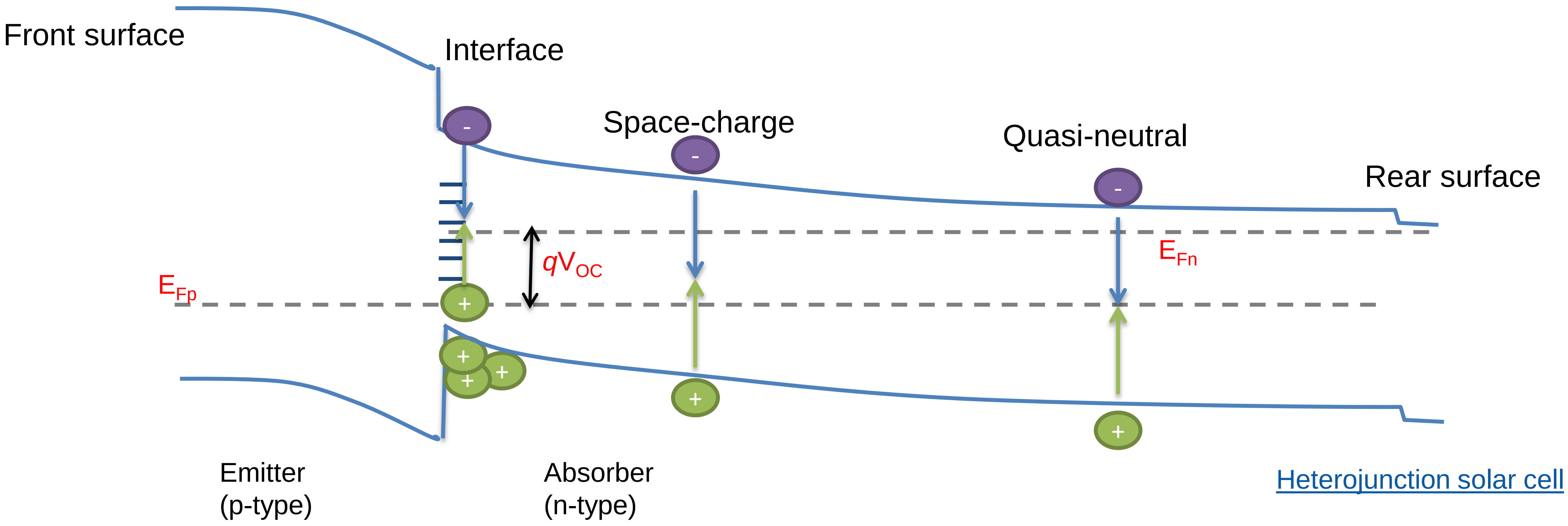
CIGS solar cell
Rau, *Appl. Phys. A* 69, 1999



Epitaxial silicon heterojunction
Branz, *Thin Solid Films*, 519, 2011

Quantitative estimate of (microscopic) recombination from conventional (macroscopic) measurements

Recombination → Quasi-Fermi separation → V_{OC}



$$\underbrace{\hphantom{\text{Absorber region}}}_{\text{Majority of photogenerated carrier recombination at } V_{OC}}$$

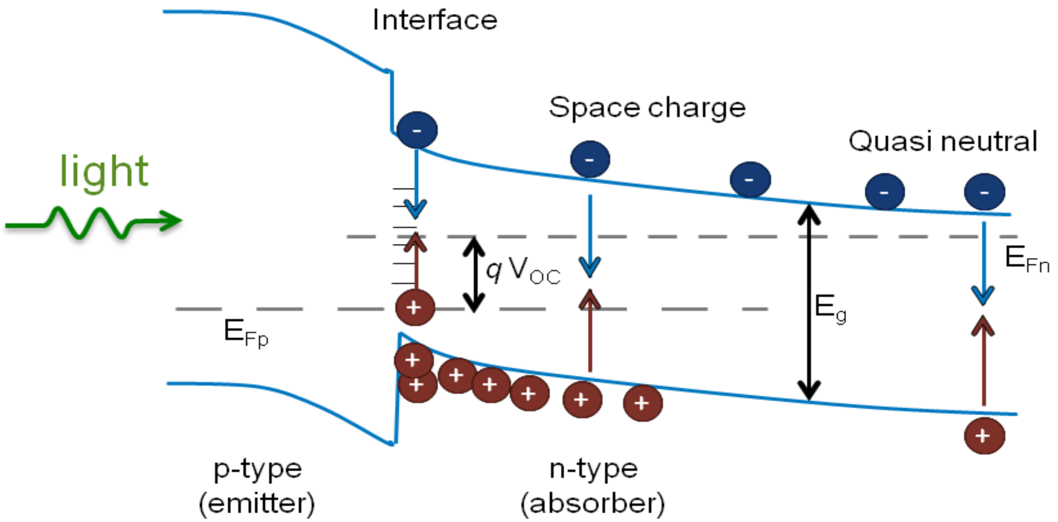
Majority of photogenerated carrier recombination at V_{OC}

$$V_{oc} = \frac{kT}{q}\ln\left(\frac{J_{sc}}{J_{o,total}} + 1\right)$$

Not precise but workable!
Loss of exact dependences on recombination mechanisms

$$J_{o,total} = J_{o,Radiation} + J_{o,Auger} + J_{o,SRH} + J_{o,emitter} + J_{o,rear}$$

Relating V_{OC} to carrier concentrations via β



$$V_{OC} = E_{Fn} - E_{Fp} = \frac{kT}{q}\ln\left(\frac{n_e p_h}{n_i^2}\right) = \frac{kT}{q}\ln(\beta^2)$$

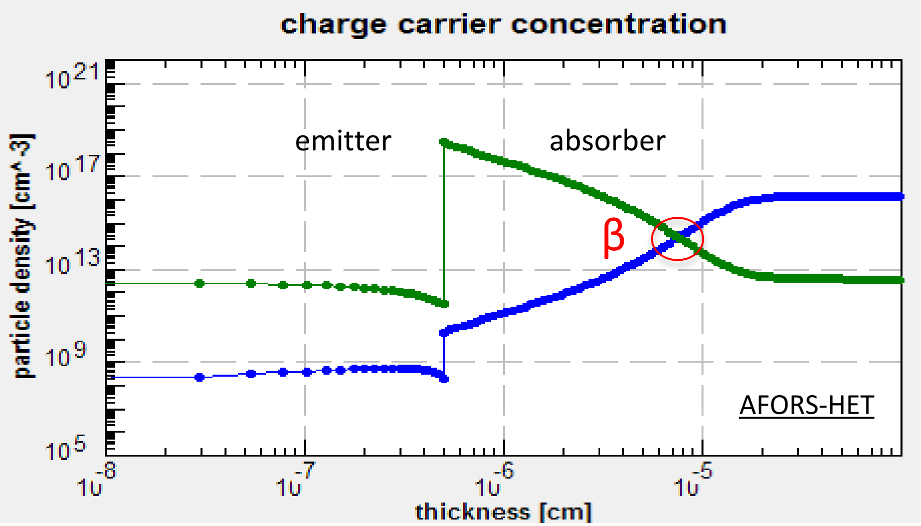
For constant QFL separation, β is constant across cell

$\beta^2 = N_D \Delta p / n_i^2$ in quasi-neutral region

β can similarly be used to relate n_e and p_h at interface

How to think of V_{OC} in this analysis:

- Not a performance metric but a variable
- Depends on light intensity, temperature, and recombination
- Constant or near constant throughout the cell
    - Breaks down for very strong recombination



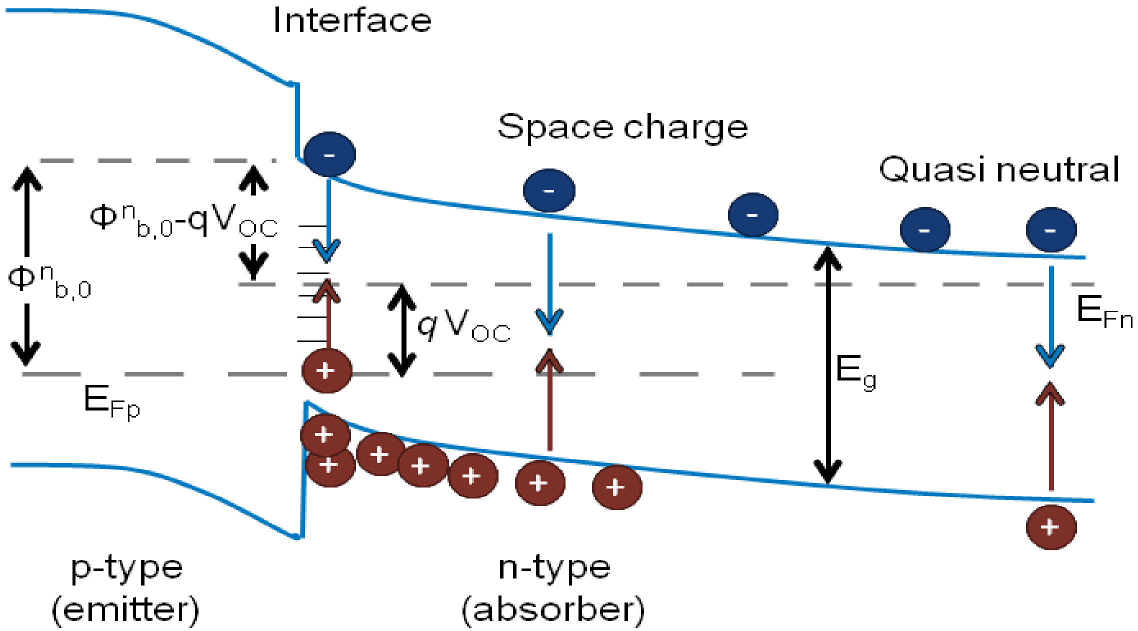
Recombination rate depends on limited availability of carriers

<u>Rate limiting carrier type:</u>

Interface: electrons

Quasi-neutral: holes

Space-charge: both



- Express recombination in terms of β
- Recombination
  - Rate per unit volume: U_{SRH}
  - Rate integrated over thickness: R_{SRH}=U_{SRH}*thickness
- Equate generation and recombination G*W=ΣR_{SRH}
  - G*W=J_{ph}

Defining all recombination with common β

- Simplified SRH equation: $U_{SRH} = \dfrac{np}{\tau_p n + \tau_n p}$

- Quasi-neutral/Bulk (n=1)
  - $N_D >> \Delta p$
  - Activation: E_g

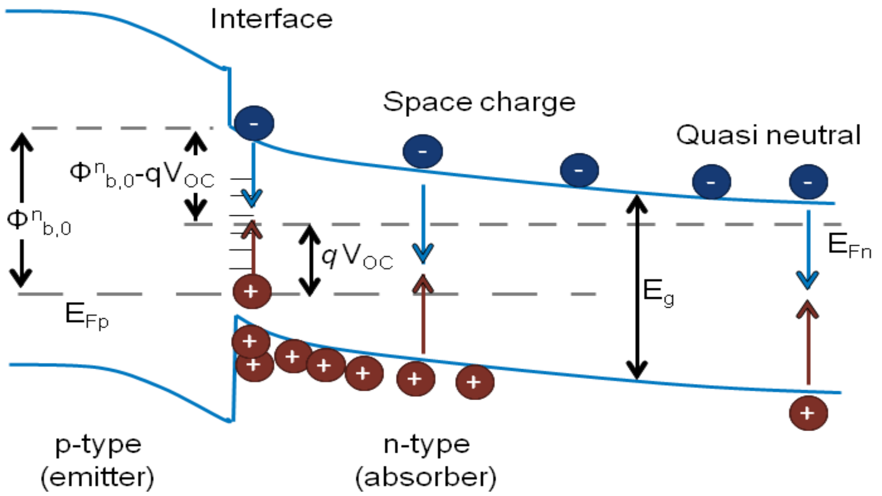
$$R^b = W_b U^b_{SRH} = W_b \frac{\Delta p}{\tau_p} = \left(\frac{W_b n_i^2}{N_D \tau_p}\right)\beta^2 = \boxed{R^b_0 \beta^2}$$

- Interface (n=1)
  - p >> n
  - Activation: $\Phi^n{}_{b,0}$

$$R^I = S_n n_e = S_n N_C \exp\left\{-\frac{\phi^n_{b,0}}{kT}\right\}\beta^2 = \boxed{R^I_0 \beta^2}$$

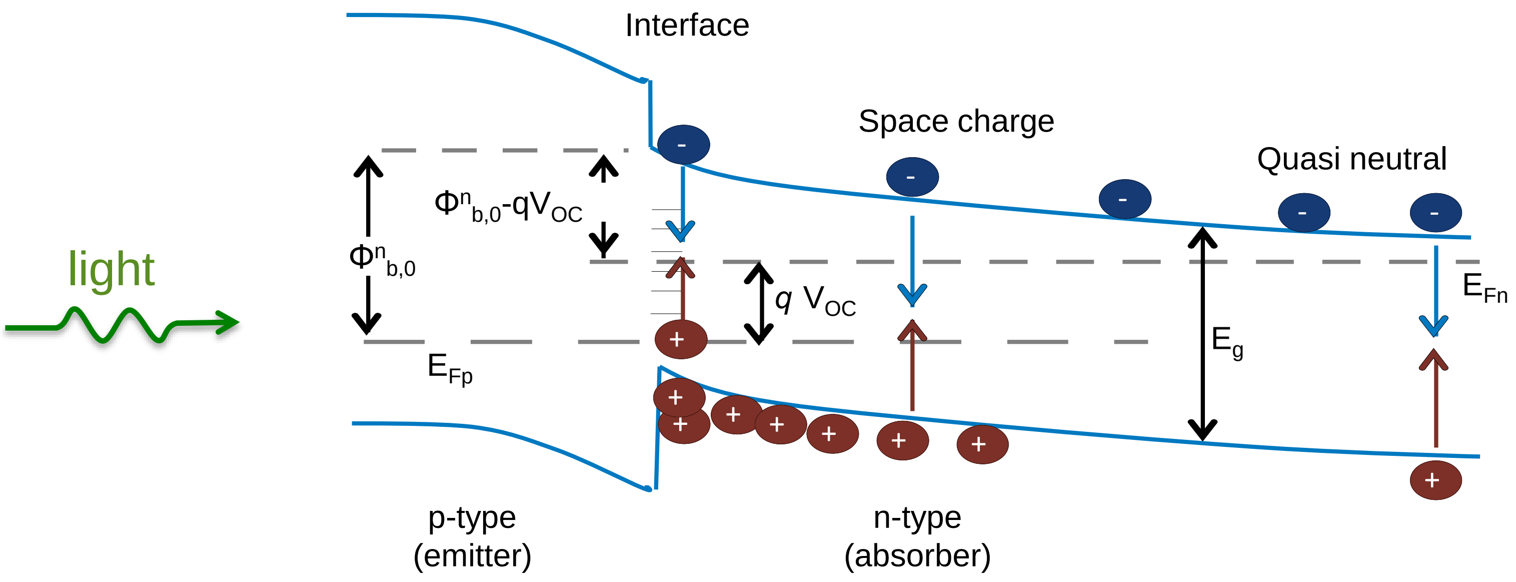
- Space charge (n=2)
  - $p \approx n$
  - Activation: E_g

$$R^d = W_d U^d_{SRH} = \left(\frac{W_d n_i}{\tau_p + \tau_n}\right)\beta = \boxed{R^d_0 \beta}$$



Scheer, JAP, 105, 104505, 2009

Recombination = Generation



$$R^b + R^I + R^d = \int_W G_x dx = G_{avg} W$$

$$R_0^b b^2 + R_0^I b^2 + R_0^d b = \int_W G_x\, dx = G_{avg} W$$

Solve quadratic to obtain β & V_{OC}

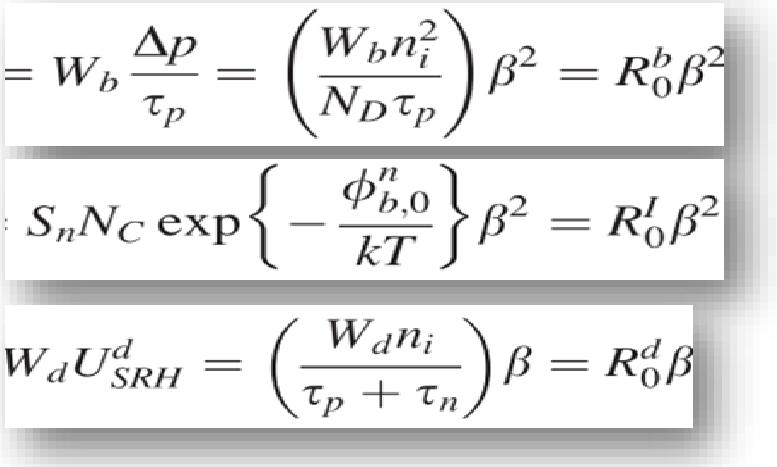
Formula for V_{OC}

$$\boxed{V_{OC} = 2\frac{kT}{q}\ln\left[\frac{k_1\left[\sqrt{1+k_2 G_{avg}} - 1\right]}{n_i}\right]}$$

V_{OC} dependence on:

- Operating conditions: light intensity, temperature
- Strength of SRH recombination in bulk, interface, and depletion

$$k_1 = \frac{R_0^d}{2\left(R_0^I + R_0^b\right)}; \quad k_2 = 4W\frac{\left(R_0^I + R_0^b\right)}{\left(R_0^d\right)^2}.$$

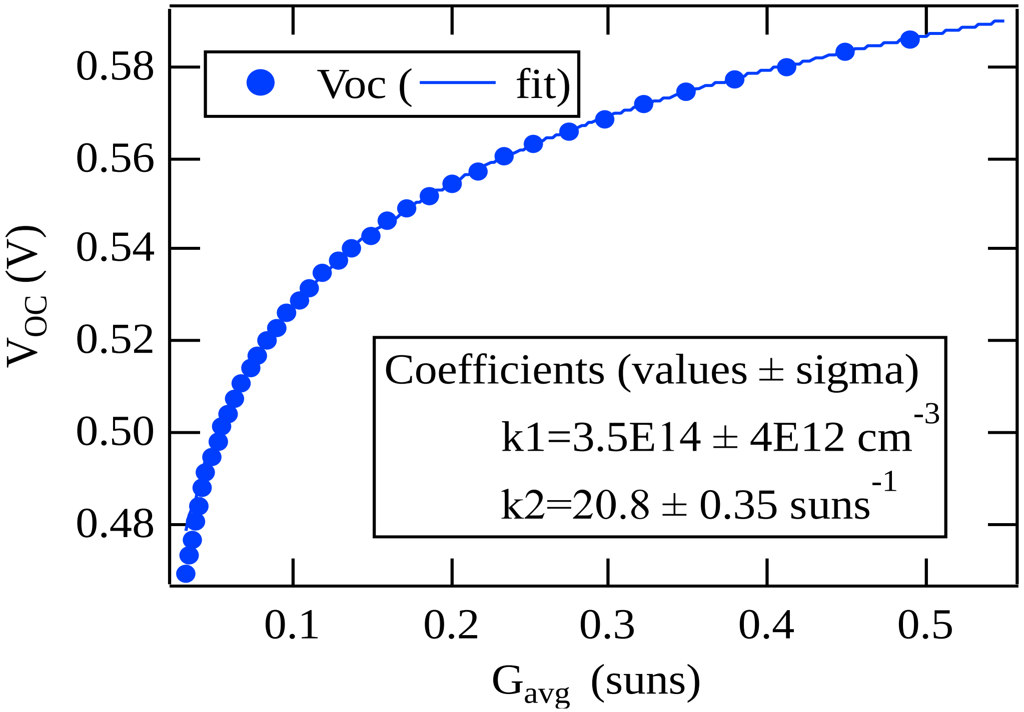


$$= W_b\frac{\Delta p}{\tau_p} = \left(\frac{W_b n_i^2}{N_D \tau_p}\right)\beta^2 = R_0^b \beta^2$$

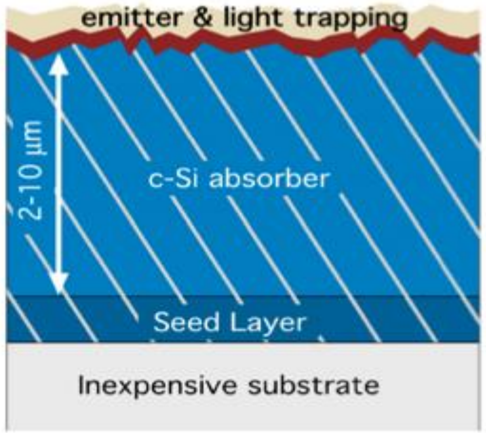
$$S_n N_C \exp\left\{-\frac{\phi_{b,0}^n}{kT}\right\}\beta^2 = R_0^I \beta^2$$

$$W_d U_{SRH}^d = \left(\frac{W_d n_i}{\tau_p + \tau_n}\right)\beta = R_0^d \beta$$

Fitting the light intensity dependence of V_{OC}



Measured light-intensity dependence of V_{OC}



a-Si/c-Si heterojunction solar cell using heteroepitaxial silicon film

Convert light intensity ➔ generation rate

$$V_{OC} = 2\frac{kT}{q}\ln\left[\frac{k_1\left[\sqrt{1+k_2 G_{avg}}\ -1\right]}{n_i}\right].$$

$$k_1 = \frac{R_0^d}{2\left(R_0^I + R_0^b\right)};\quad k_2 = 4W\frac{\left(R_0^I + R_0^b\right)}{\left(R_0^d\right)^2}.$$

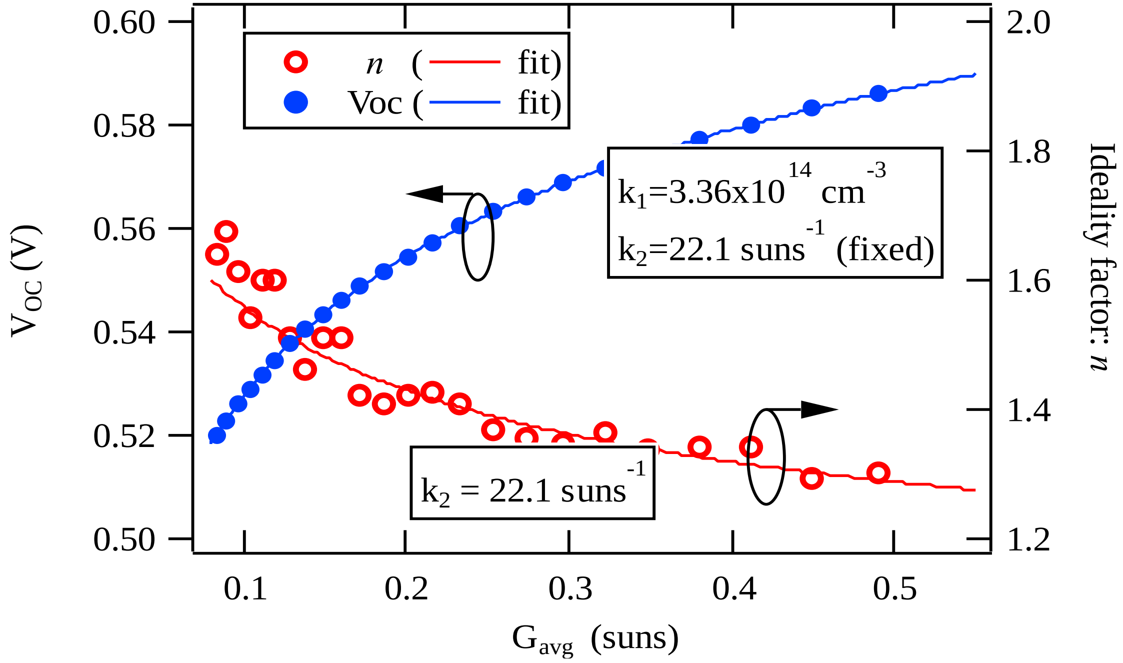
Define and fit ideality factor (n)

$$n = \left[\frac{kT}{q} \frac{d \ln G_{avg}}{dV_{OC}} \right]^{-1}$$

$$n\left(G_{avg}\right) = \frac{k_2 G_{avg}}{\sqrt{1+k_2 G_{avg}}\left[\sqrt{1+k_2 G_{avg}} - 1\right]}$$

$$n\left\{k_2 G_{avg} \rightarrow 0\right\} = 2$$

$$n\left\{k_2 G_{avg} \rightarrow \infty\right\} = 1$$



k_1 & k_2 are sufficient for quantifying recombination in absence of interface

Defining activation energy from V_{OC}(T) extrapolation

Linear extrapolation of V_{OC}(T)

$$V_{OC}\left(T_R\right)=\frac{E_a}{q}+T_R\left.\frac{dV_{OC}}{dT}\right|_{T_R}$$

Substitute explicit dependence of V_{OC} on T

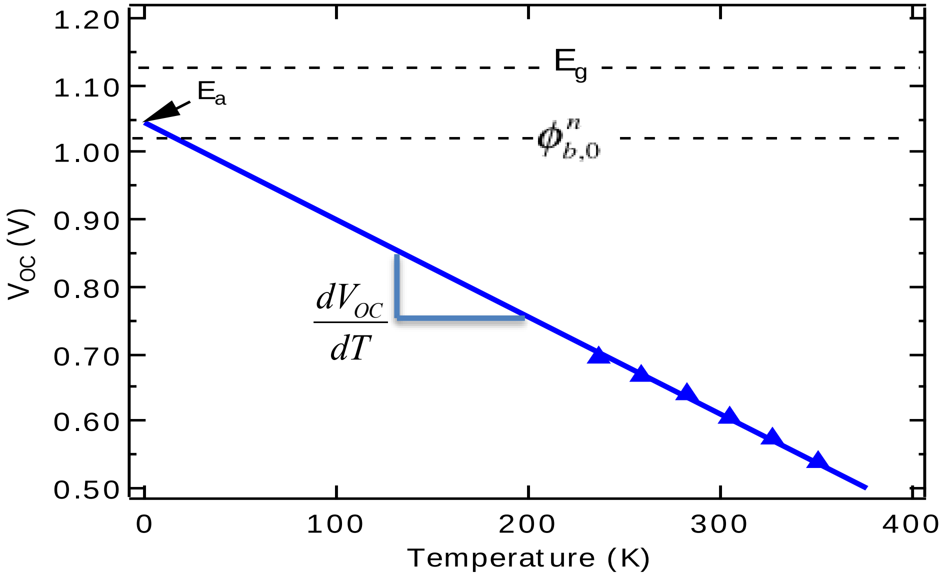
$$V_{OC}=2\frac{kT}{q}\ln\left[\frac{k_1\left[\sqrt{1+k_2G_{avg}}\ -1\right]}{n_i}\right].$$

Assuming k_2G_{avg} >> 1 (negligible SCR, large fwd. bias):

$$\boxed{E_a=\frac{R_0^bE_g\left(T_R\right)+R_0^I\phi_{b,0}^n\left(T_R\right)}{R_0^b+R_0^I}.}$$

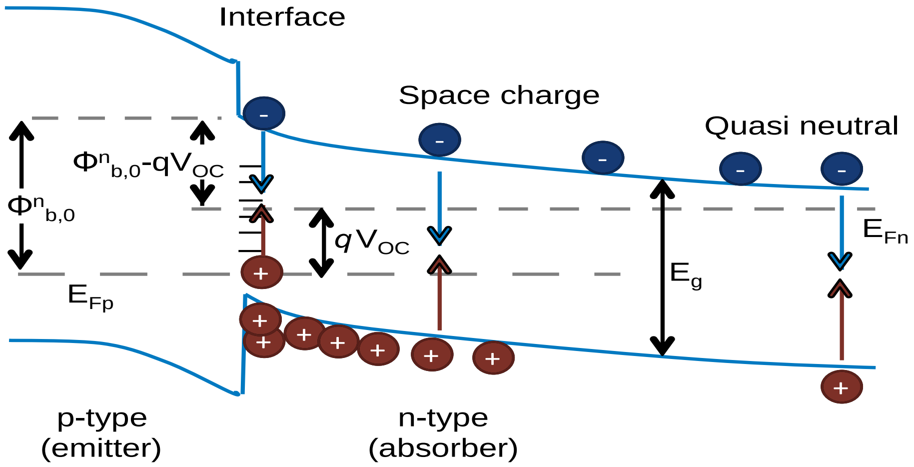
Weighted mean of activation energies

Weights = strength of recombination

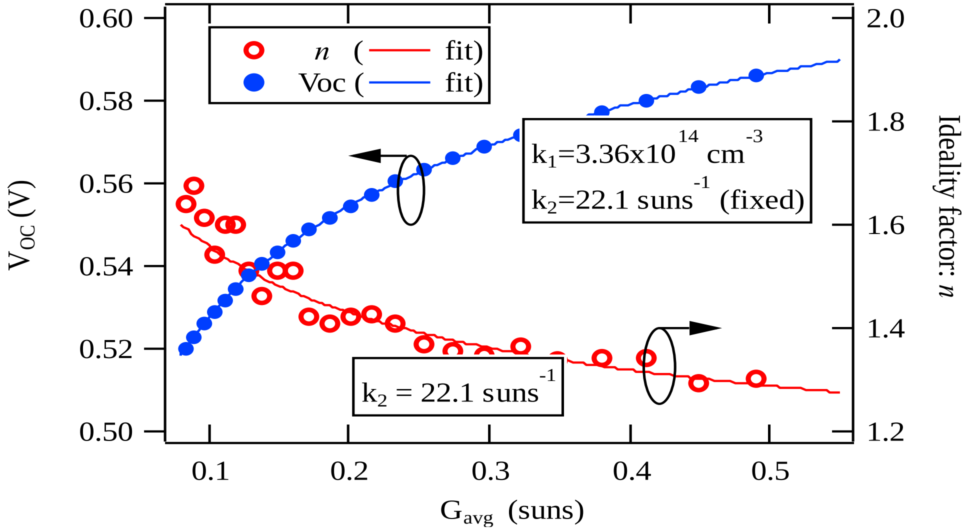


Extrapolated temperature dependence

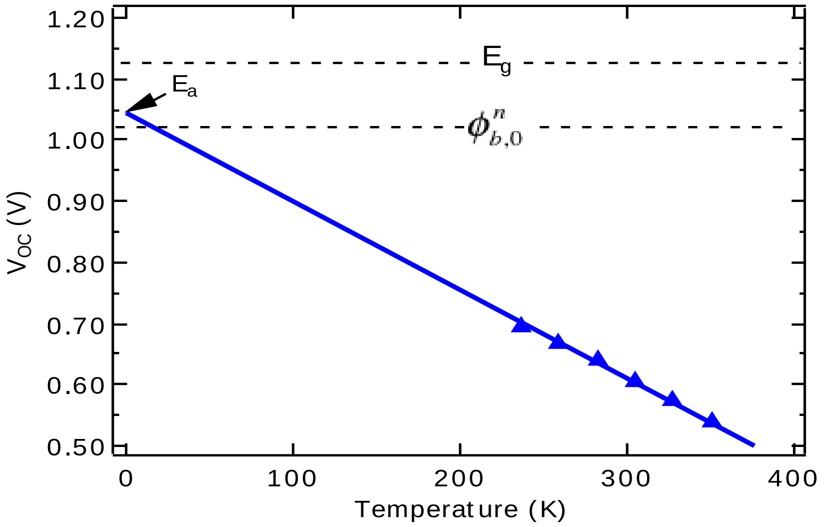
Ea ≠ Eg linked to interface recombination



Quantifying recombination in different regions



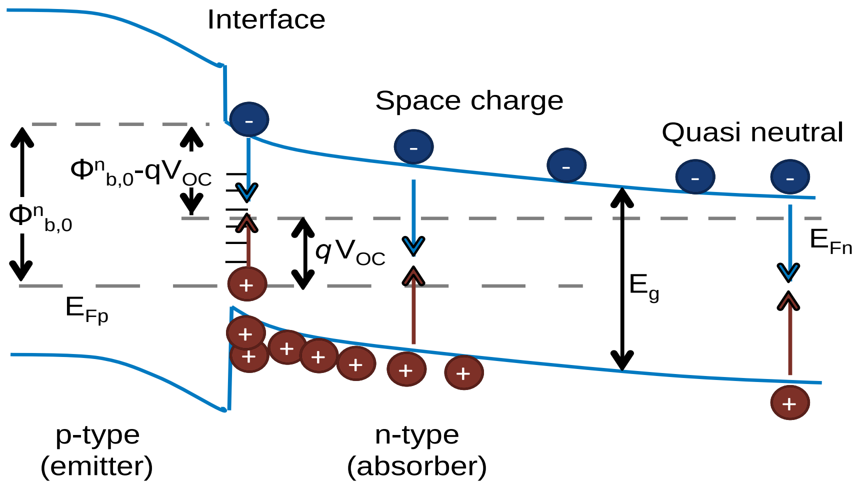
Light-intensity variation



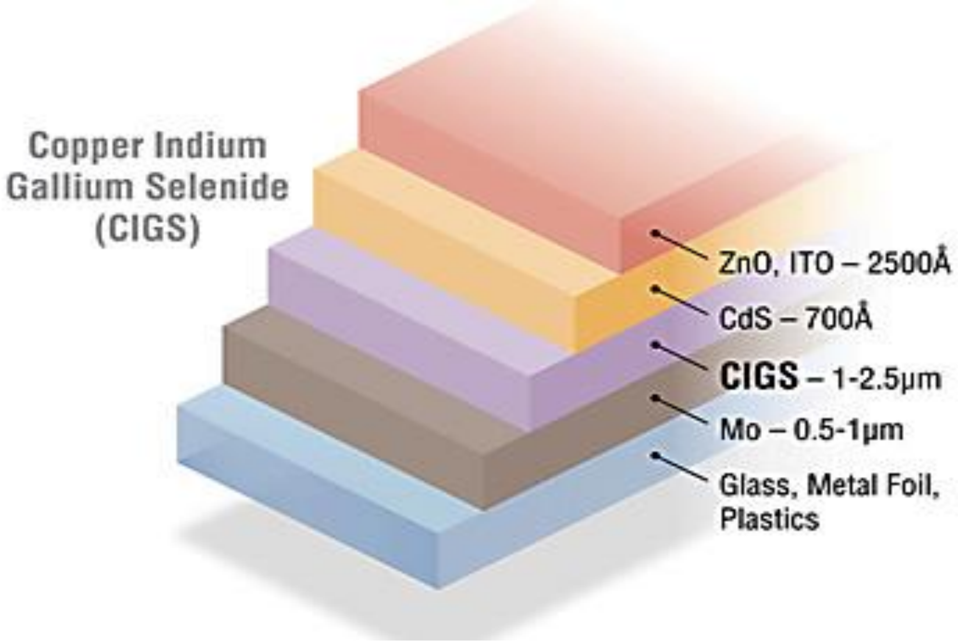
Extrapolated temperature dependence

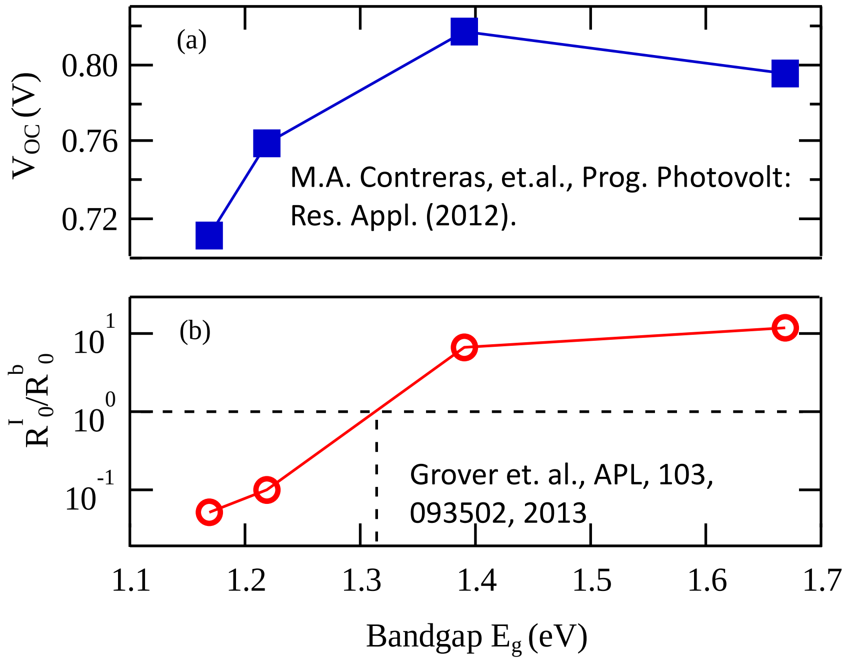
$$\left\{\begin{matrix} k_1 \\ k_2 \\ E_a \end{matrix}\right\} \xrightarrow[C(V)]{V_{OC}(T,G)} \left\{\begin{matrix} R^b = 16\% \\ R^d = 46\% \\ R^I = 38\% \end{matrix}\right\}$$

at 1 sun



Recombination analysis in CIGS cells with varying [Ga]





M.A. Contreras, et.al., Prog. Photovolt: Res. Appl. (2012).

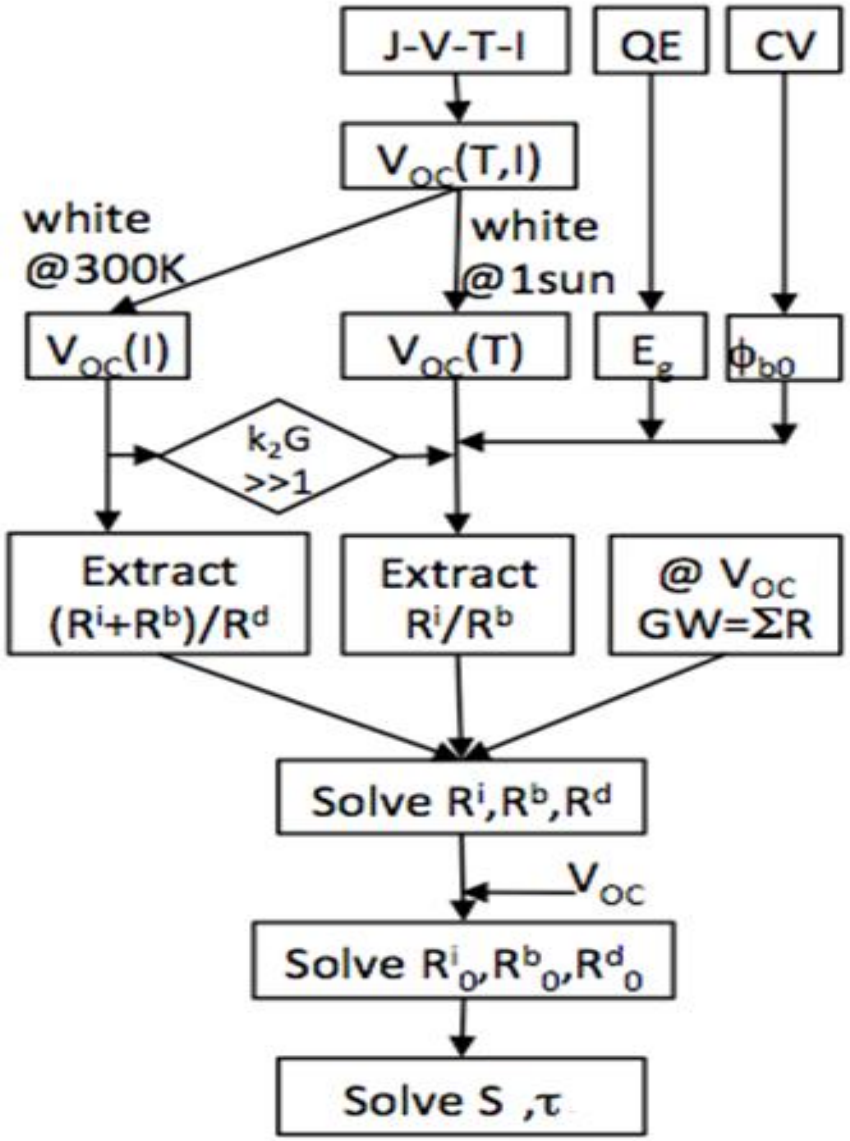
Grover et. al., APL, 103, 093502, 2013

(a): V_{OC} vs. bandgap (E_g) for CIGS solar cells. V_{OC} saturates as E_g increases with increasing Ga content. (b): Ratio of interface (R^I_0) and bulk (R^b_0) recombination strengths increases dramatically for the higher bandgap samples.

- Agreement of lifetime obtained from V_{OC}(T,I) and TRPL
- Successfully tracks nuances of recombination variations based on material properties

Li et.al., A recombination analysis of CIGS solar cells with low and high Ga compositions, *Sol. Energy Mat. and Sol. Cells*, 124 (2014) 143-149

Procedure for calculation of recombination rates



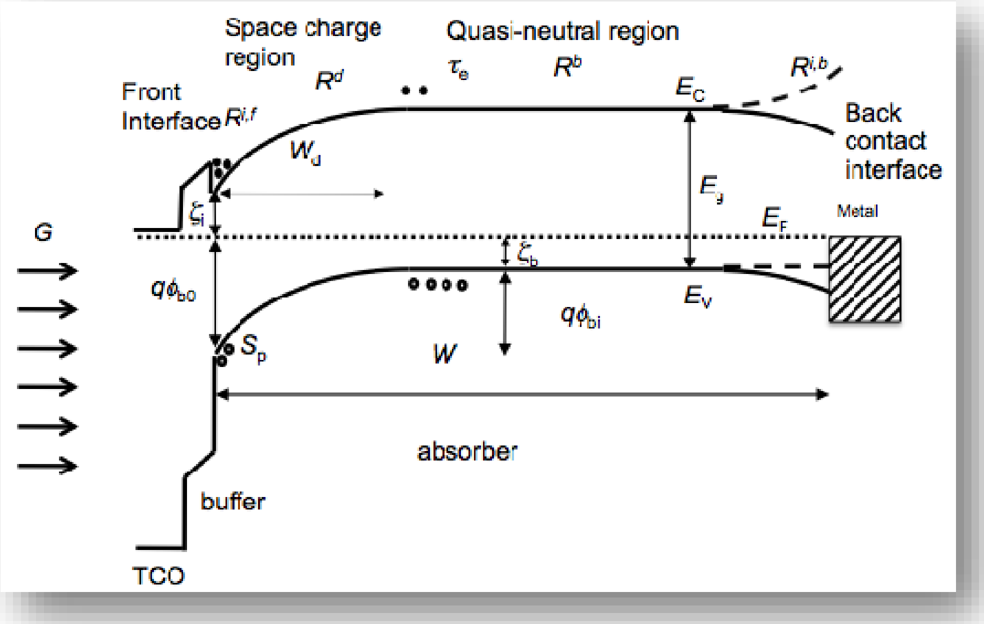
New equation for temperature coefficient of V_{OC}

$$\frac{dV_{OC}}{dT} = -\frac{1}{T}\left[\frac{nE_g}{mq} - V_{OC} + \frac{\gamma nkT}{q}\right]$$

Green, PIP, 11(5), 333–340, 2003

- n – ideality factor; combines all recombination channels
- n/m – experimental fitting parameter

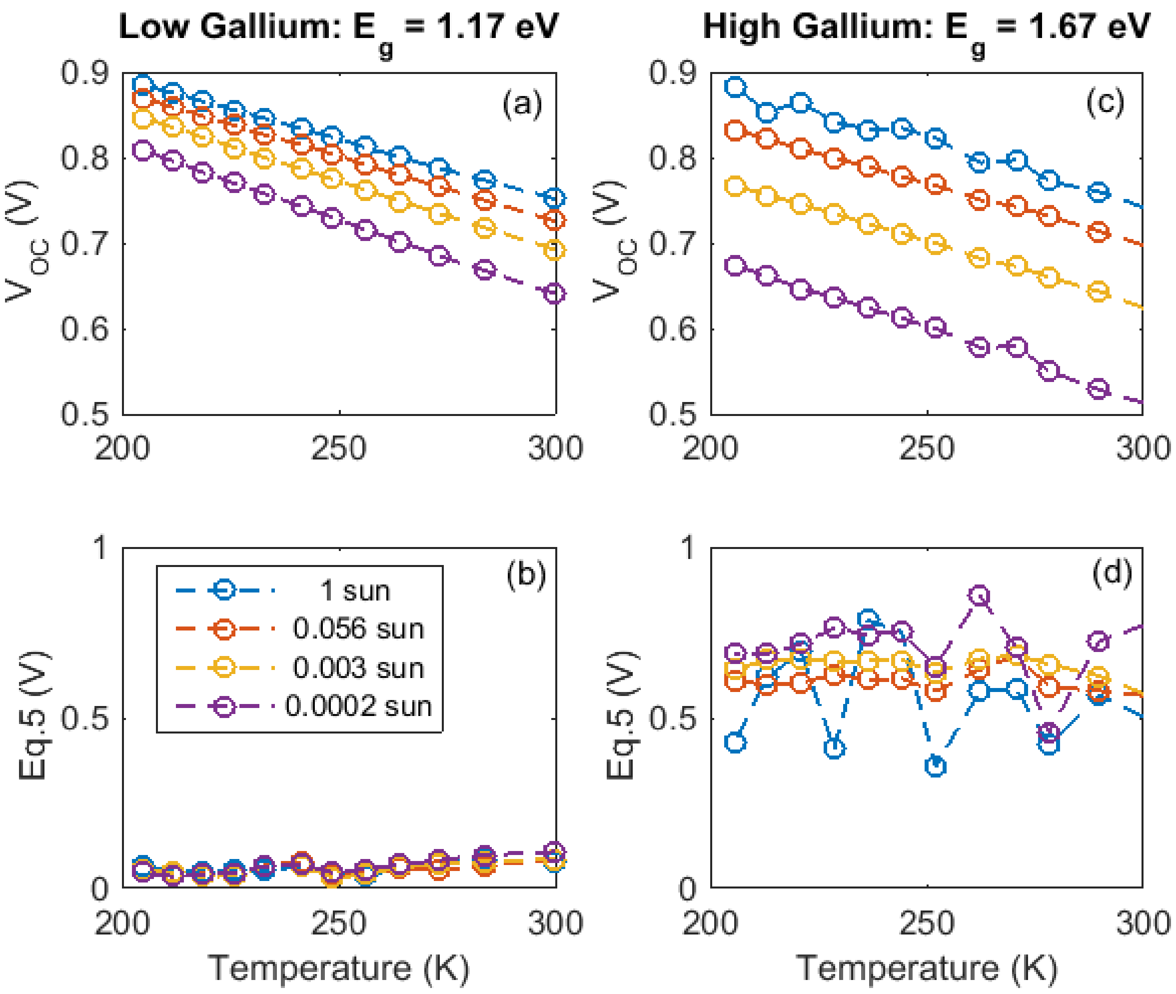
$$\frac{dV_{OC}}{dT} = -\frac{1}{T}\left[\frac{E_g}{q}\left\{1+\frac{\alpha T\left(T+2\beta\right)}{\left(T+\beta\right)^2}\right\} - V_{OC} + \frac{\gamma kT}{q} - \frac{\left(2-n\right)R_0^i}{\left(R_0^i+R_0^b\right)}\frac{\zeta_i}{q}\right]$$

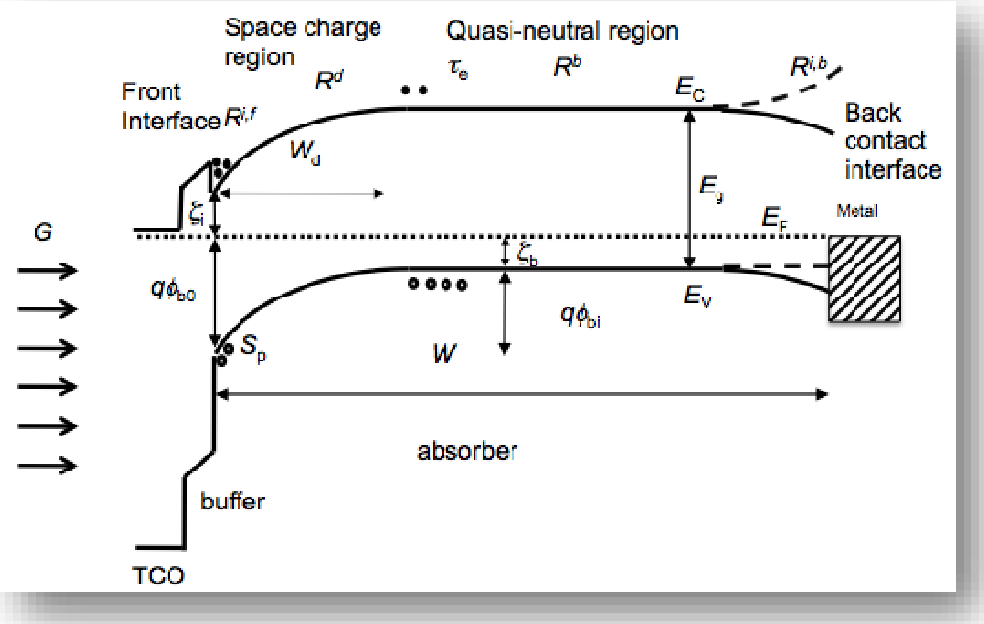


- V_{OC}' depends on interface recombination and Fermi-pinning
- Smaller V_{OC}' for larger interface recombination → not necessarily good

Grover, 42nd PVSC, 2015

High [Ga] CIGS cells are interface limited



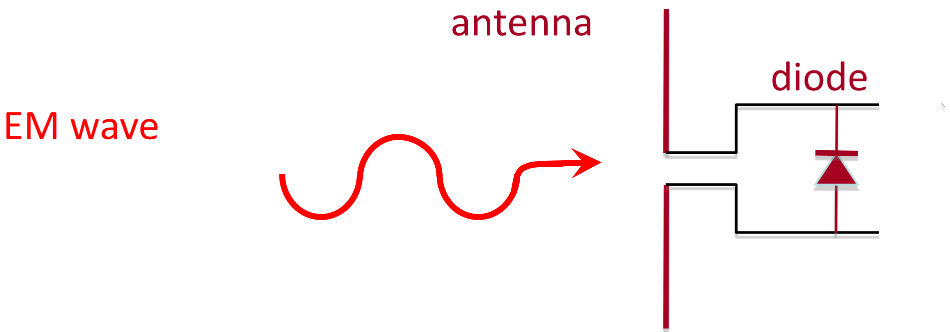


Rearrange terms to calculate interface contribution:

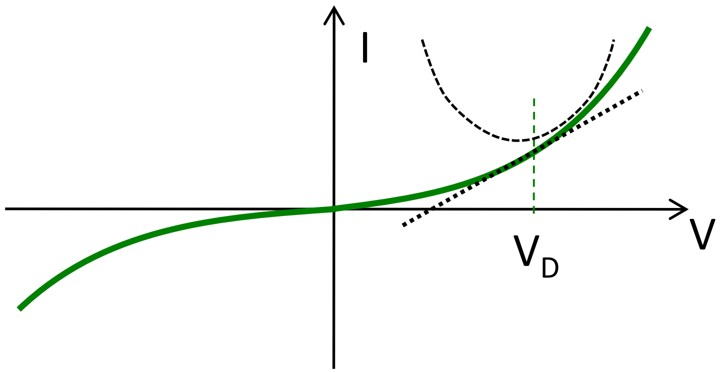
$$\frac{(2-n)R_0^i}{\left(R_0^i+R_0^b\right)}\frac{\zeta_i}{q}=T\frac{dV_{OC}}{dT}+\left[\frac{E_g}{q}-V_{OC}+\frac{\gamma kT}{q}\right]$$

Questions so far?

Operating Principle of Rectennas

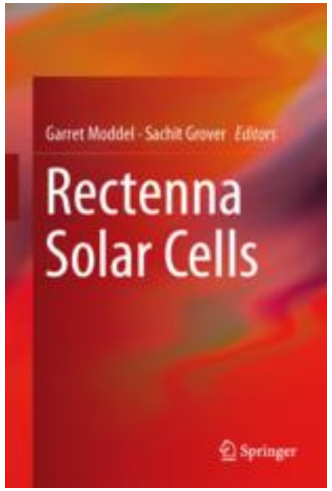


Rectenna



Diode *I*(*V*) curve

- Square-law rectification
  - Signal strength smaller than diode switching voltage
    - 1 mV for 1 sun incident over 1 μm² and 100 Ω antenna
- Key diode parameters
  - Resistance (R_D), responsivity (β_i)



Garret Moddel · Sachit Grover *Editors*

Rectenna
Solar Cells

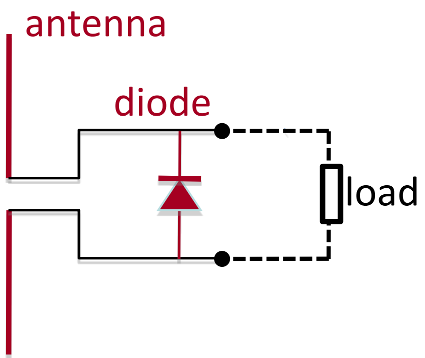
Springer

Operating range and industry impact

- Spectral range and applications

Detection
- Active and passive imager
- Interconnect receiver

Energy harvesting
- Solar
- Thermal



- Potential for high-efficiency low-cost
  - 90% efficient microwave rectennas exist
    - Large-signal: diode operates as switch
- Current state
  - IR detectors demonstrated (Q.E. ~ 0.01% @ 10.6 μm)*
  - Solar cells proposed in 1972, no practical demonstration as yet

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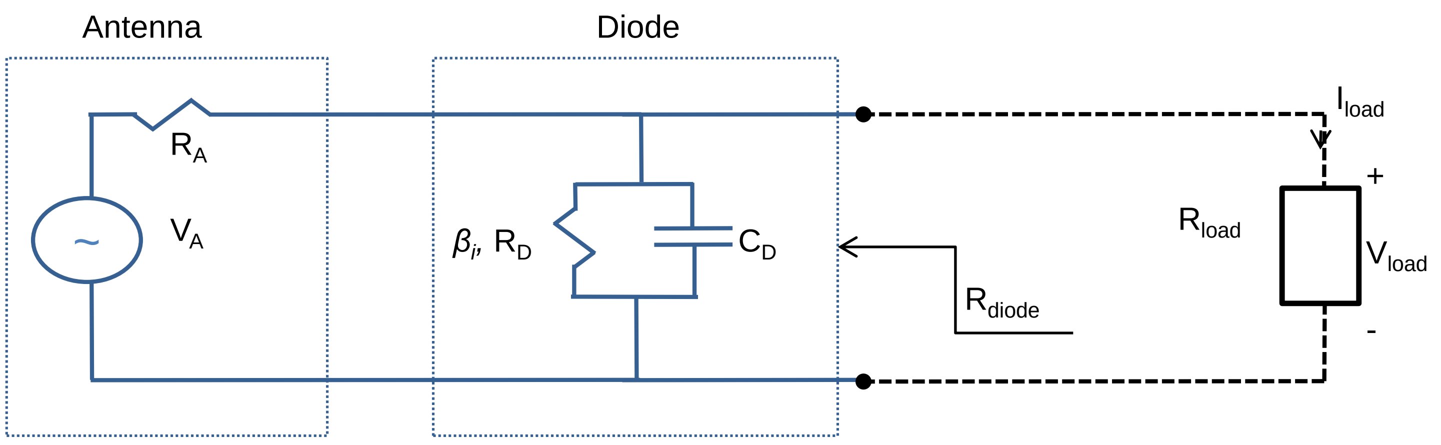
*Phiar Corp., *NRO report* 2002

Requirements for Efficient Rectennas



Small-signal circuit model of rectenna + Load

- Intrinsically fast diode
- Low R_D to match to R_A
- Low C_D to prevent shunting R_D
- High β_i for rectification
- Large V_A for high power-conversion efficiency
- Efficient antennas

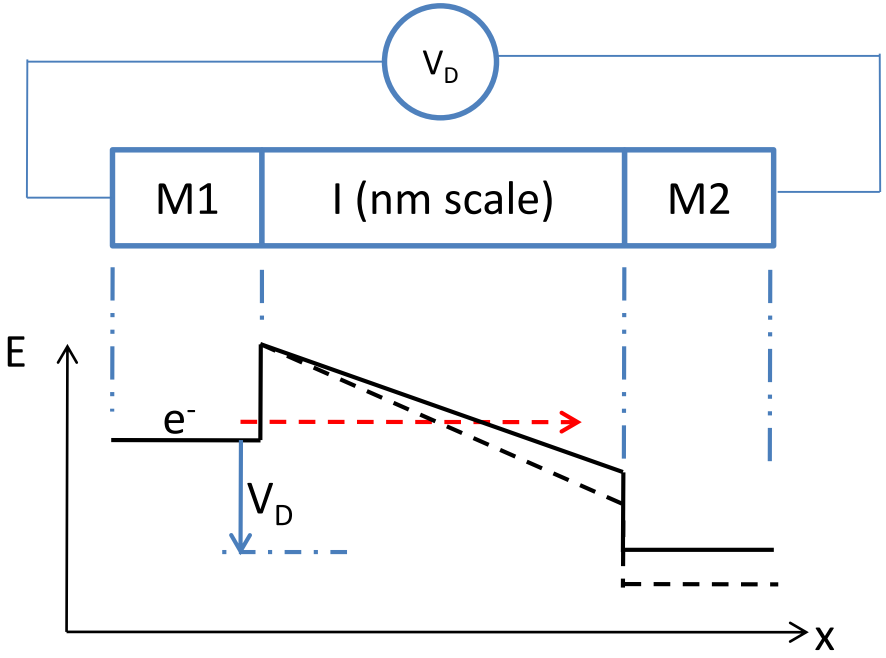
Antenna to diode coupling

Field enhancement

Diode design

Metal/Insulator/Metal Diode

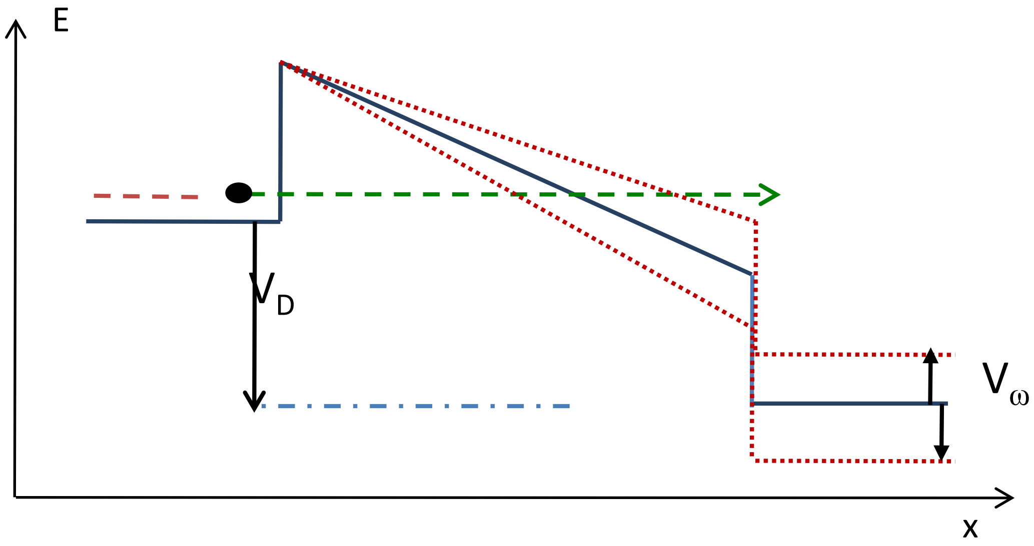
- Mechanism
  - Tunneling across thin insulator
    - Nonlinear $I(V)$
    - Femtosecond fast
- Summary of work done
  - Fabrication
    - Sputtered metals and insulators
  - Simulation
    - Transfer matrix method
  - Modification
    - Field effect transistor
    - Double-insulator (MIIM) barrier design



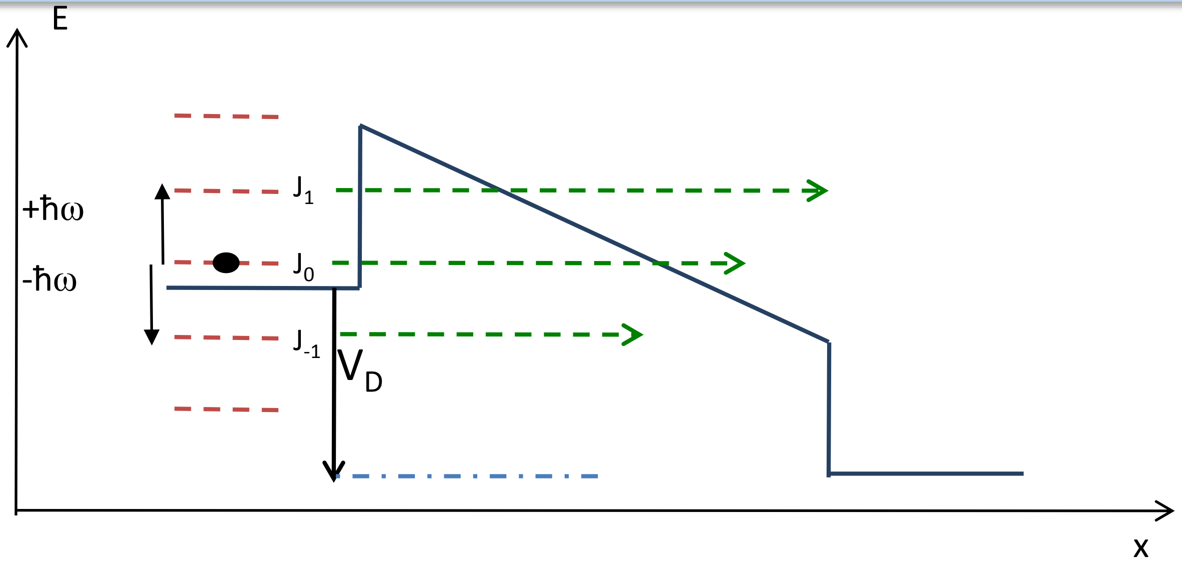
MIM diode energy-band profile

Grover, Ph.D. Thesis, CU Boulder, 2011

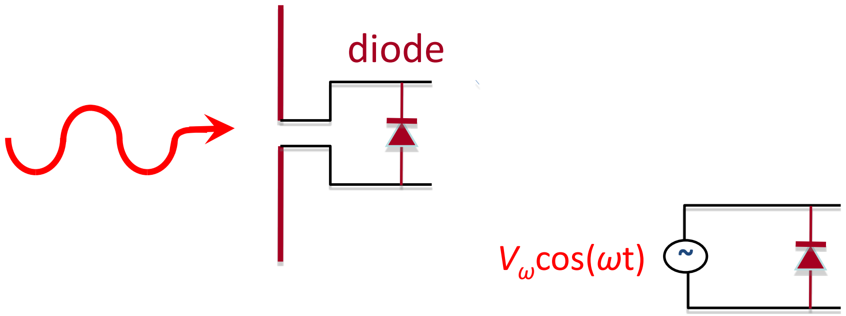
Semiclassical Theory of Rectification in MIM



Classical: low frequency



Semiclassical: high frequency



Photon-assisted transport applies when ħω/e ~ voltage-scale of diode nonlinearity

DC I(V) under illumination:

$$I_{illum}\left(V_D,V_\omega\right)=\sum_{n=-\infty}^{\infty} J_n^2(\alpha) I_{dark}\left(V_D+n\frac{\hbar\omega}{e}\right); \quad \alpha=\frac{eV_\omega}{\hbar\omega}$$

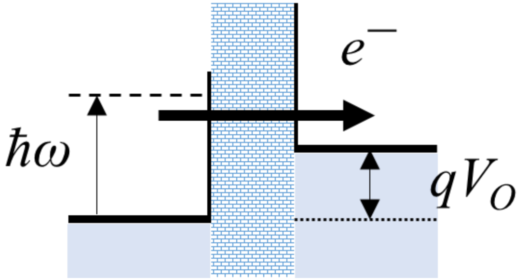
Grover, et.al, J. Phys D., 46 (13), 135106, 2013;
Tien, Gordon, *Phys. Rev.*, 129(2), 1963

Efficiency limit for monochromatic response of rectenna

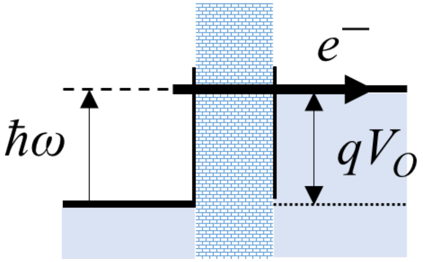
Slide courtesy: Saumil Joshi, UC Boulder

- Assume ideal diode – high fwd/rev asymmetry
- 1 µW input (low intensity regime) – 1 photon process
- $|V_O| < \hbar\omega/q$, 1photon/1electron

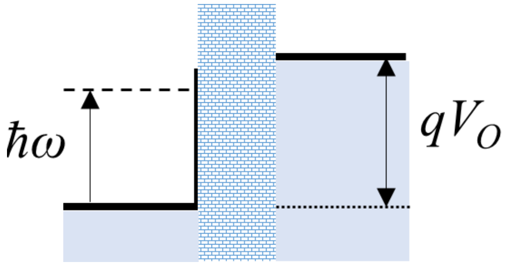
$|V_O| < \hbar\omega/q$

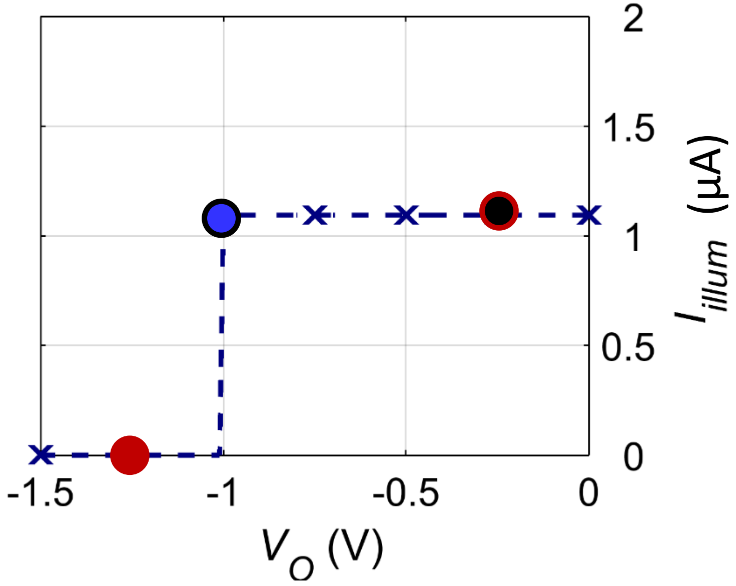


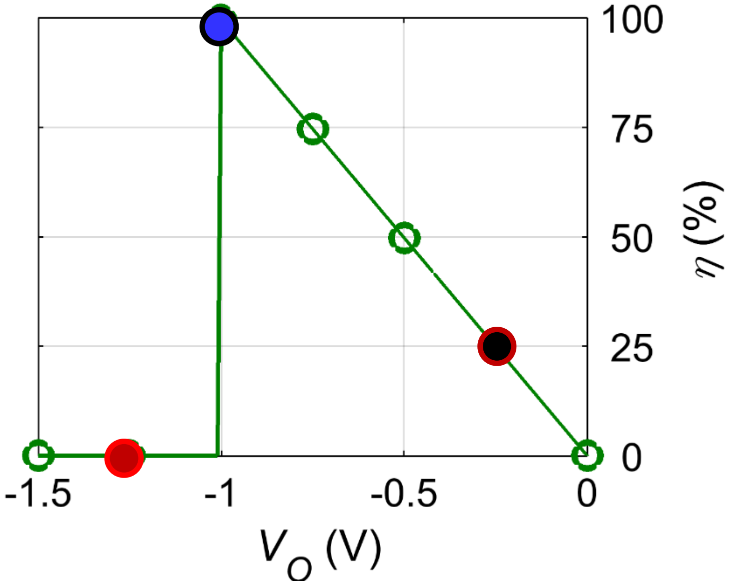
$|V_O| = \hbar\omega/q$



$|V_O| > \hbar\omega/q$

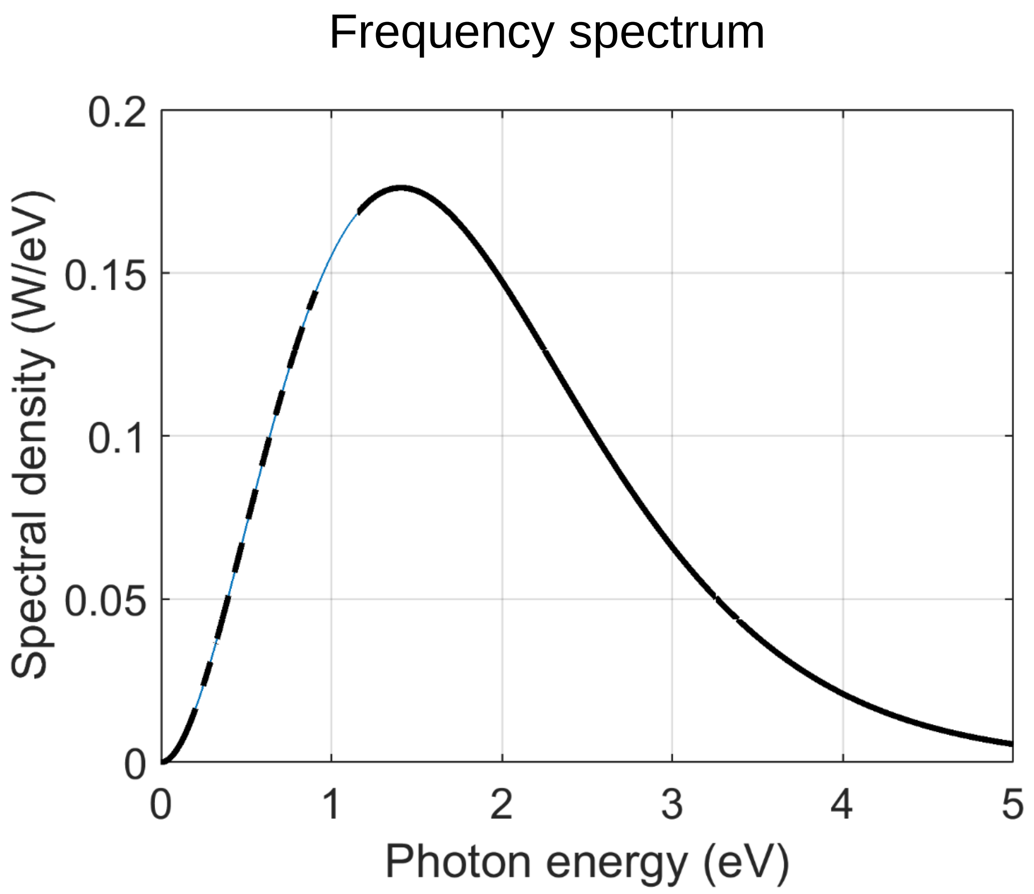


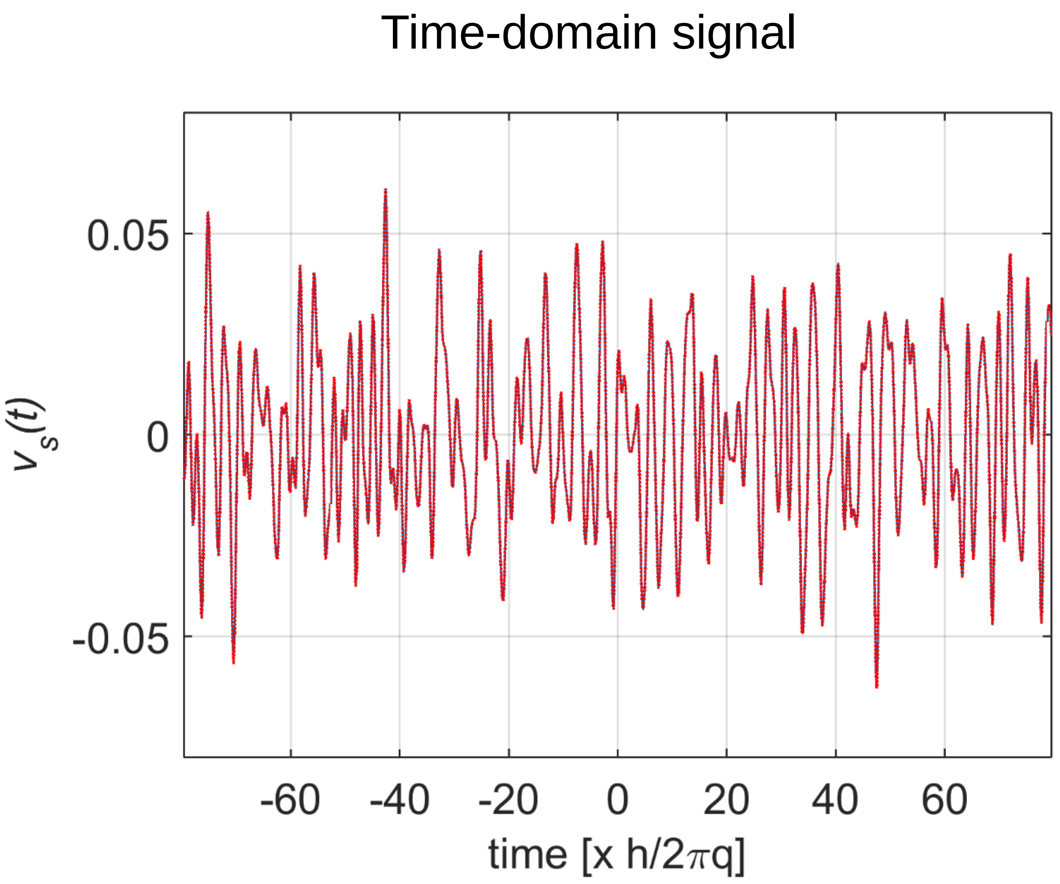




Calculating broadband rectenna response for solar spectrum

Slide courtesy: Saumil Joshi, UC Boulder

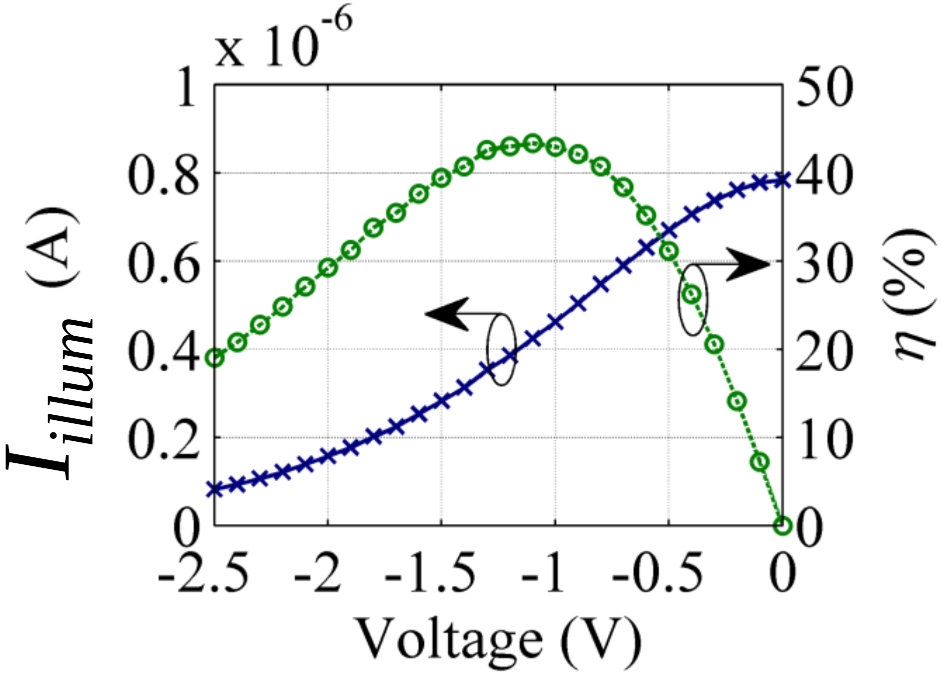

Frequency spectrum


Time-domain signal

Efficiency limit for rectifying solar radiation (quantum regime)

Slide courtesy: Saumil Joshi, UC Boulder

- 5700 K blackbody
- 1000 W/m²
- Spatial coherence area ~19 µm
- Maximum power ~1.1 µW
- Quantum operation
- Peak efficiency ~ 44%
  - Matches Shockley-Queisser's ultimate efficiency limit

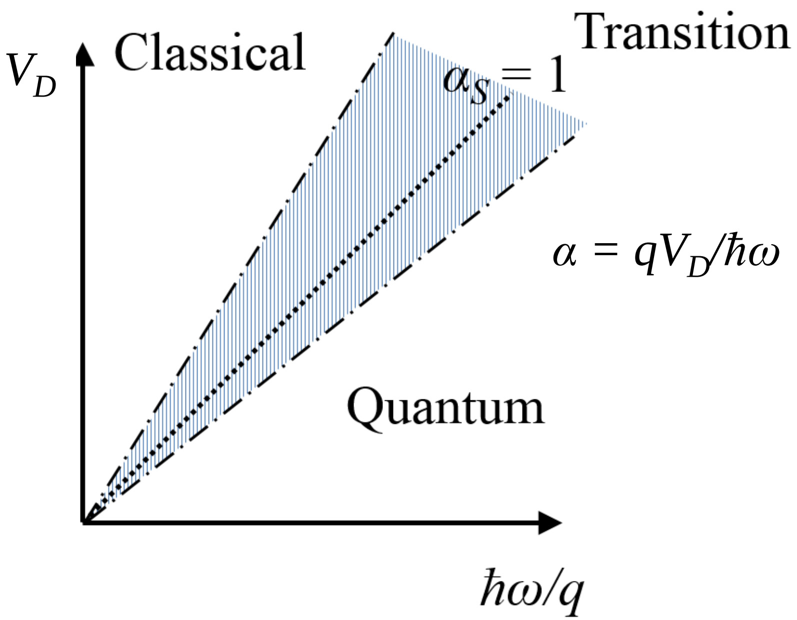


Joshi, Moddel, Appl. Phys. Lett. 102, 083901 (2013)

Can we exceed the 44% limit?

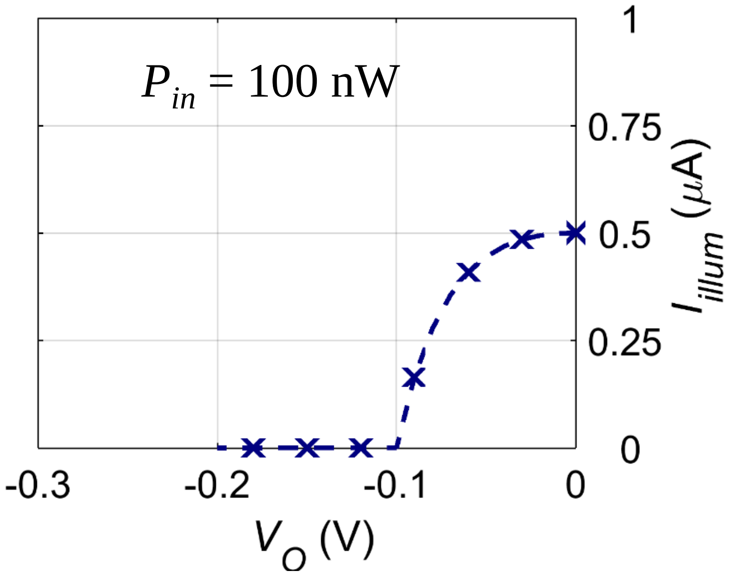
Slide courtesy: Saumil Joshi, UC Boulder

- Microwave rectennas > 70%
- Use low energy photons?
- Three regimes
  - Quantum ($\alpha < 1$)
  - Transition ($\alpha \sim 1$)
  - Classical ($\alpha >> 1$)
- Increase diode voltage, relative to $\hbar\omega/q$
- Two ways to reach classical operating regime
  - High input intensity
  - High radiation resistance

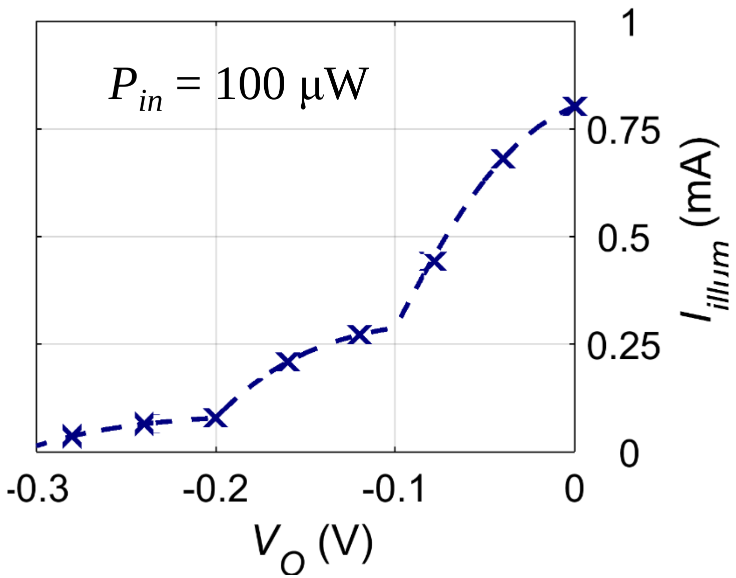


Effect of input intensity on operating regime

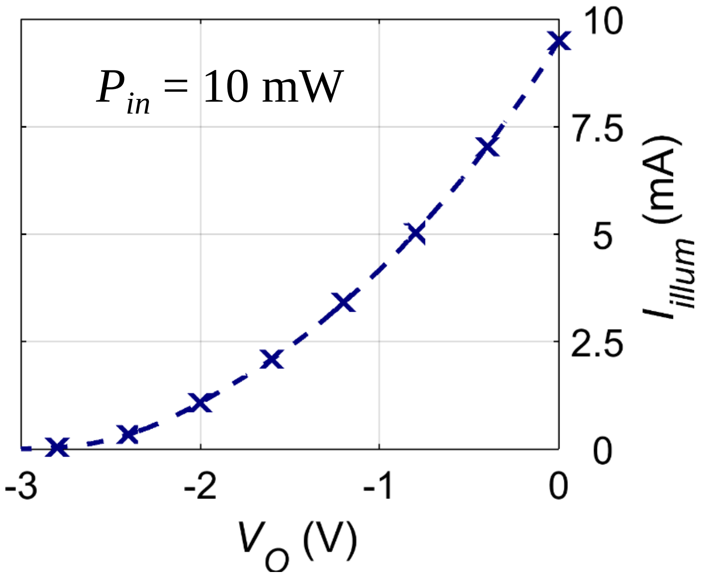
Slide courtesy: Saumil Joshi, UC Boulder



Quantum regime



Transition regime



Classical regime

- Low intensity, high frequency
- Frequency-dependent
- Hump observed

- Higher intensity, multiple photons
- Frequency-dependent
- Multiple steps

- Very high intensity
- Frequency independent
- Large number of photons

Joshi, Ph.D. Thesis, CU Boulder, 2015

Conclusion: efficiency limits of optical rectennas

Slide courtesy: Saumil Joshi, UC Boulder

- Quantum operation
  - Low intensity, high frequency - single photon process
  - Monochromatic efficiency → 100%
  - Broadband efficiency maximum = 44%
  - Split-spectrum > 44%
- (Quantum) classical operation
  - Possible at high frequencies through photon mixing → large voltage operation
  - Broadband efficiency > 44%
- Rectenna solar cell efficiency can exceed Shockley-Queisser limit
  - Through multi-photon process at high intensity
- Challenges
  - Coherence limits power
  - High diode resistance → large *RC* time-constant
  - Diode breakdown

Thank you.

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