Performance Evaluation in Conventional and Rectenna Solar Cells

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First Solar

10GW INSTALLED WORLDWIDE

Enough panels to circle THE EARTH 3.5 TIMES

Enough to power WASHINGTON D.C. for A YEAR

Equivalent to 7,000 OLYMPIC swimming pools

POWER for 5,000,000 average homes

= 500 SWIMMING POOLS

= 18,000,000,000 liters of water SAVED

= 100,000 HOMES

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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 CO₂ 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://www.nrel.gov/ncpv/images/efficiency_chart.jpg
PV Module technology & manufacturing

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

- 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 $65^\circ$ C; $40^\circ$ 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 $85^\circ$ C)
  - FS Advantage grows more pronounced

Virtuani, 25th EUPVSEC, 2010
Combining $V_{OC}$ 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

Quantitative estimate of (microscopic) recombination from conventional (macroscopic) measurements
Recombination $\rightarrow$ Quasi-Fermi separation $\rightarrow$ $V_{OC}$

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

Not precise but workable!

Loss of exact dependences on recombination mechanisms

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

Heterojunction solar cell

Majority of photogenerated carrier recombination at $V_{OC}$
Relating $V_{OC}$ to carrier concentrations via $\beta$

For constant QFL separation, $\beta$ is constant across cell

$$\beta^2 = \frac{N_D \Delta p}{n_i^2} \quad \text{in quasi-neutral region}$$

$\beta$ 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

$$V_{OC} = E_{F_n} - E_{F_p} = \frac{kT}{q} \ln \left( \frac{n_e p_h}{n_i^2} \right) = \frac{kT}{q} \ln(\beta^2)$$
Recombination rate depends on limited availability of carriers

Rate limiting carrier type:

- Interface: electrons
- Quasi-neutral: holes
- Space-charge: both

- Express recombination in terms of $\beta$
- Recombination
  - Rate per unit volume: $U_{SRH}$
  - Rate integrated over thickness: $R_{SRH} = U_{SRH} \times \text{thickness}$
- Equate generation and recombination $G \times W = \Sigma R_{SRH}$
  - $G \times W = J_{ph}$
Defining all recombination with common $\beta$

- Simplified SRH equation:
  \[ U_{SRH} = \frac{np}{\tau_p n + \tau_n p} \]

- Quasi-neutral/Bulk ($n=1$)
  - $N_D >> \Delta p$
  - Activation: $E_g$
    \[ R^b = W_b U_{SRH}^b = W_b \frac{\Delta p}{\tau_p} = \left( \frac{W_b n_i^2}{N_D \tau_p} \right) \beta^2 = R_0^b \beta^2 \]

- Interface ($n=1$)
  - $p >> n$
  - Activation: $\Phi_{n,0}^n$
    \[ R^i = S_n n_e = S_n N_C \exp\left\{ -\frac{\Phi_{n,0}^n}{kT} \right\} \beta^2 = R_0^i \beta^2 \]

- Space charge ($n=2$)
  - $p \approx n$
  - Activation: $E_g$
    \[ R^d = W_d U_{SRH}^d = \left( \frac{W_d n_i}{\tau_p + \tau_n} \right) \beta = R_0^d \beta \]
Recombination = Generation

\[ R^b + R^l + R^d = \int G_x \, dx = G_{avg} W \]

\[ R_0^b \cdot R_0^l \cdot R_0^d = \int G_x \, dx = G_{avg} W \]

Solve quadratic to obtain \( \beta \) & \( V_{OC} \)
Formula for $V_{OC}$

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

$V_{OC}$ dependence on:

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

$$k_1 = \frac{R_0^d}{2 \left( R_0^l + R_0^b \right)}; \quad k_2 = 4W \frac{\left( R_0^l + R_0^b \right)}{(R_0^d)^2}.$$
Fitting the light intensity dependence of $V_{OC}$

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

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

Coefficients (values ± sigma)
- $k_1 = 3.5E14 ± 4E12$ cm$^{-3}$
- $k_2 = 20.8 ± 0.35$ suns$^{-1}$

Measured light-intensity dependence of $V_{OC}$

Convert light intensity ➔ generation rate

a-Si/c-Si heterojunction solar cell using heteroepitaxial silicon film
Define and fit ideality factor ($n$)

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

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

$$ n\{k_2 G_{avg} \to 0\} = 2 $$

$$ n\{k_2 G_{avg} \to \infty\} = 1 $$

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

$k_2 = 22.1 \text{ suns}^{-1}$ (fixed)
Defining activation energy from $V_{OC}(T)$ extrapolation

**Linear extrapolation of $V_{OC}(T)$**

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

Substitute explicit dependence of $V_{OC}$ on T

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

Assuming $k_2 G_{avg} >> 1$ (negligible SCR, large fwd. bias):

$$ E_a = \frac{R_0^b E_g (T_R) + R_0^l n_{b,0} (T_R)}{R_0^b + R_0^l}. $$

**Weighted mean of activation energies**

Weights = strength of recombination

**Extrapolated temperature dependence**

$E_a \neq E_g$ linked to interface recombination

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9/17/2015

Grover @ UNSW
Quantifying recombination in different regions

Light-intensity variation

\[ \begin{align*}
    k_1 & \quad V_{OC}(T,G) \\
    k_2 & \quad C(V) \\
    E_a &
\end{align*} \]

\[ R^b = 16\% \]

\[ R^d = 46\% \]

\[ R^I = 38\% \]

Extrapolated temperature dependence

At 1 sun

\[ \Phi_{n,b,0}^q V_{OC} \]

\[ E_{Fp} \]

\[ E_{Fn} \]

\[ E_g \]

\[ qV_{OC} \]

\[ p\text{-type (emitter)} \]

\[ n\text{-type (absorber)} \]

\[ k_1 = 3.36 \times 10^{14} \text{ cm}^{-3} \]

\[ k_2 = 22.1 \text{ suns}^{-1} \]
Recombination analysis in CIGS cells with varying [Ga]

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

Procedure for calculation of recombination rates
New equation for temperature coefficient of $V_{OC}$

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


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

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

- $V_{OC}'$ 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:

$$\frac{(2-n)R^i_0}{(R^i_0 + R^b_0)} \frac{\xi}{q} = T \frac{dV_{oc}}{dT} + \left[ \frac{E_g}{q} - V_{oc} + \frac{\gamma kT}{q} \right]$$
Questions so far?
Operating Principle of Rectennas

- **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 \( \beta_i \)
Operating range and industry impact

• Spectral range and applications

![Diagram showing spectral range and applications]

- Terahertz
- Infrared
- Visible

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. \( \sim 0.01\% \) @ 10.6 \( \mu \)m)*
  - Solar cells proposed in 1972, no practical demonstration as yet

*Phiar Corp., NRO report 2002
Requirements for Efficient Rectennas

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

Semiclassical Theory of Rectification in MIM

Photon-assisted transport applies when $\hbar \omega / e \sim$ voltage-scale of diode nonlinearity

DC I(V) under illumination:

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

Efficiency limit for monochromatic response of rectenna

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

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

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

$|V_o| > \hbar \omega / q$
Calculating broadband rectenna response for solar spectrum

Slide courtesy: Saumil Joshi, UC Boulder
Efficiency limit for rectifying solar radiation (quantum regime)

- 5700 K blackbody
- 1000 W/m²
- Spatial coherence area \( \sim 19 \, \mu m \)
- Maximum power \( \sim 1.1 \, \mu W \)
- Quantum operation
- Peak efficiency \( \sim 44\% \)
  - Matches Shockley-Queisser’s ultimate efficiency limit

Joshi, Moddel, Appl. Phys. Lett. 102, 083901 (2013)
Can we exceed the 44% limit?

- 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

$$\alpha = qV_D / \hbar \omega$$
Effect of input intensity on operating regime

Slide courtesy: Saumil Joshi, UC Boulder

- **Quantum regime**
  - Low intensity, high frequency
  - Frequency-dependent
  - Hump observed

- **Transition regime**
  - Higher intensity, multiple photons
  - Frequency-dependent
  - Multiple steps

- **Classical regime**
  - Very high intensity
  - Frequency independent
  - Large number of photons

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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