2.626 Fundamentals of Photovoltaics
Fall 2008

Efficiency Loss Mechanisms: Theory and Characterization

Lecture 15 – 2.626

Tonio Buonassisi

Topics of Today's Lecture

- Efficiency loss mechanisms.
- Optical losses, recombination losses, surface recombination velocity, series and parallel resistance (shunts).
- Evaluation of loss mechanisms, common characterization tools.

Short Circuit Current

- Optical Reflection
- Spectral Response
- Minority Carrier Diffusion Length

Optical Reflection

Spectrophotometer: Measures specular and diffuse reflectance, and transmission.

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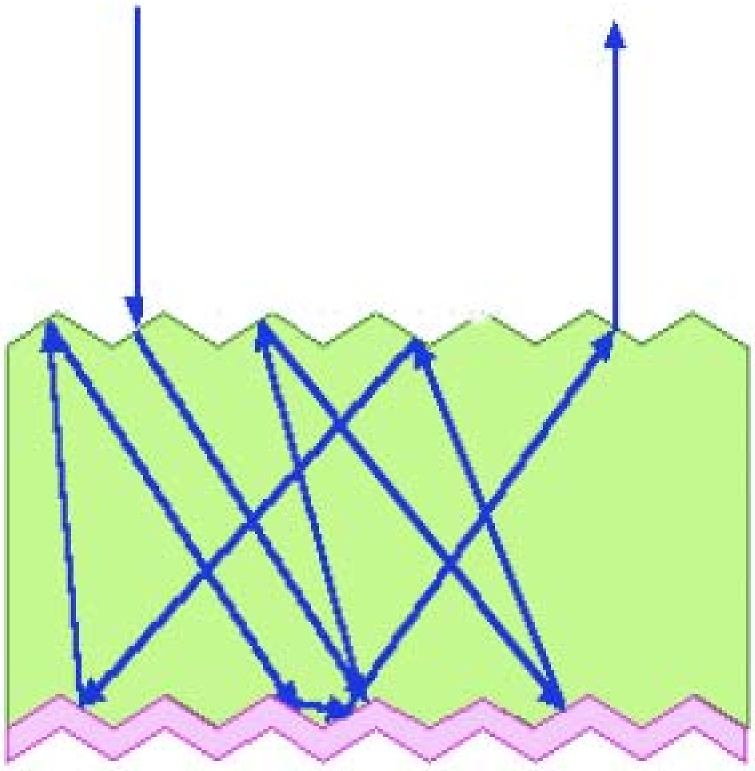
Increasing Absorption

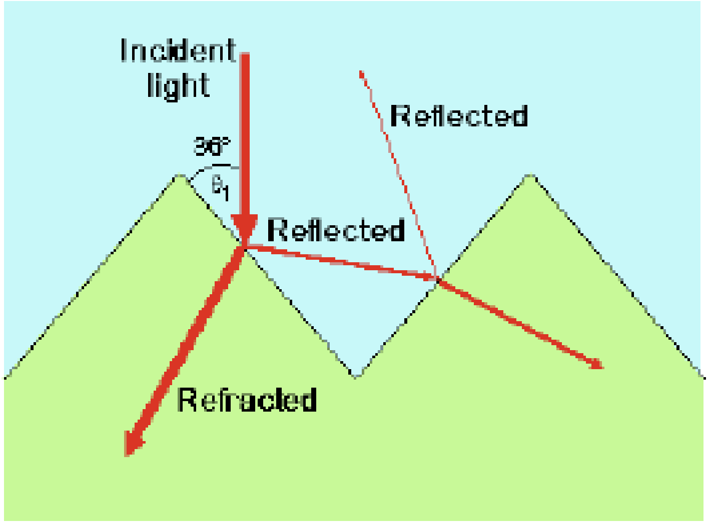
Light trapping increases the “optical thickness” of a material

- Physical thickness can remain low
- Allows carriers to be absorbed close to the junction

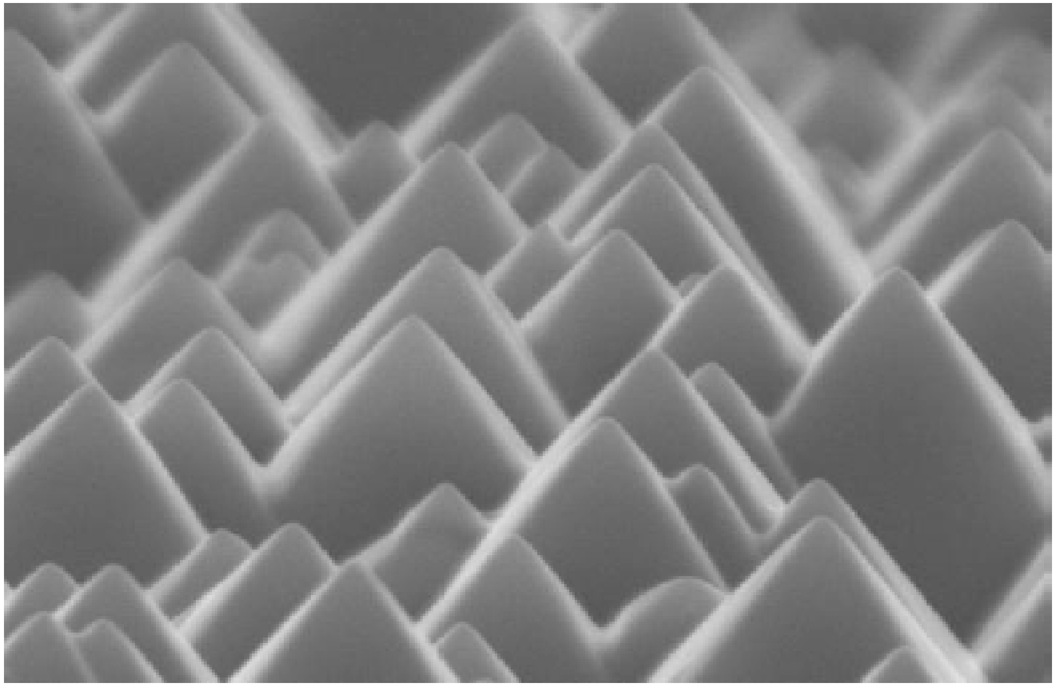


Increasing Absorption

Effect of Textured Surfaces on Light Absorption



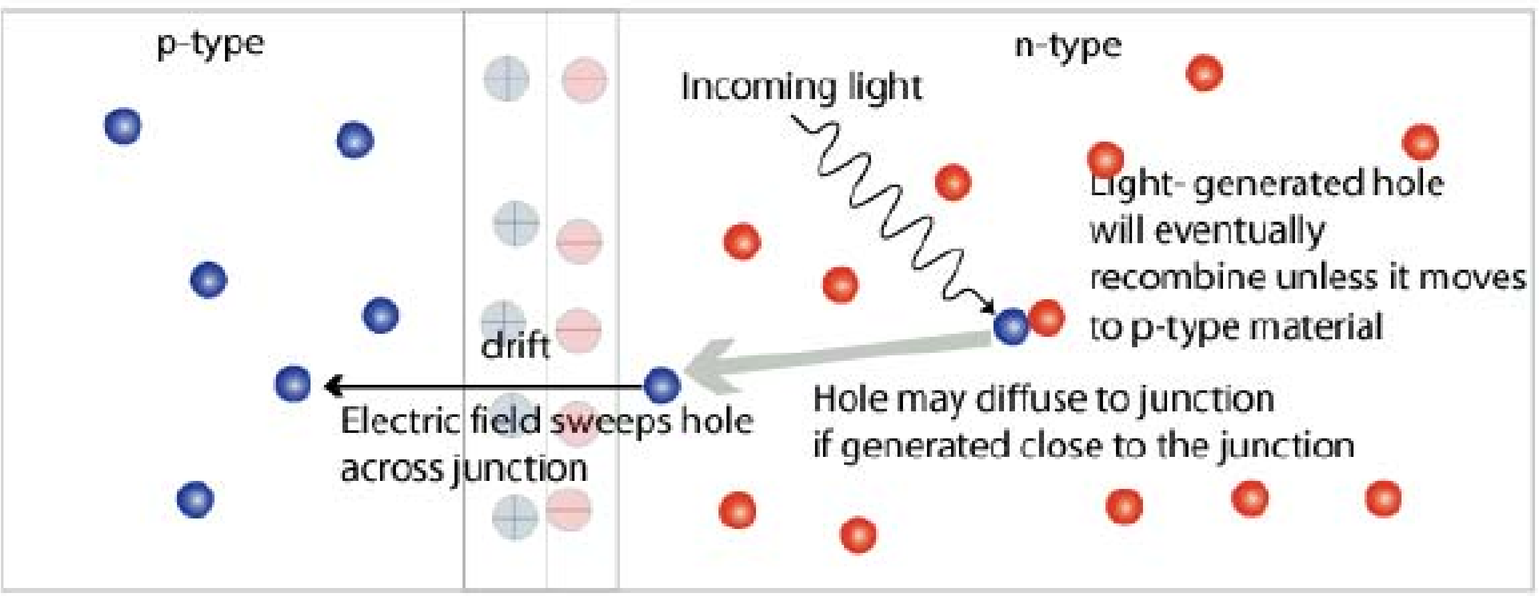
SEM image of textured silicon



Q: What other mechanisms exist to trap light?

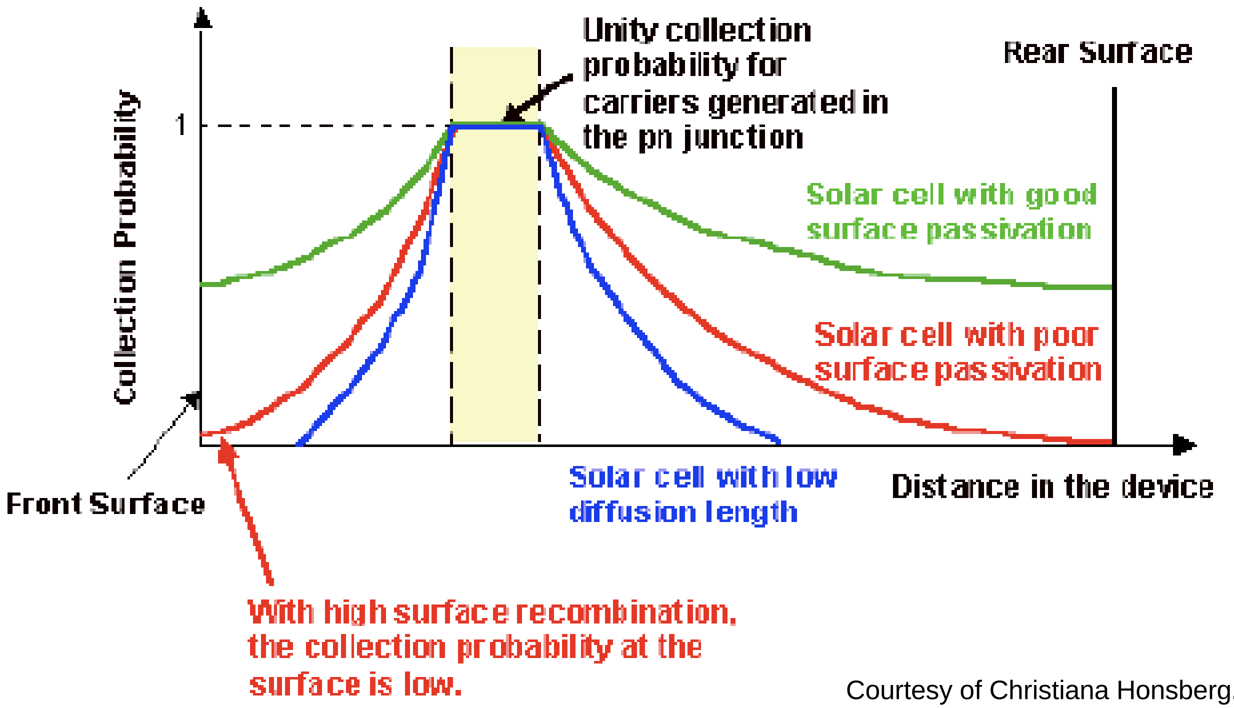
Collection Probability

- A light generated minority carrier can readily recombine.
- If it the carrier reaches the edge of the depletion region, it is swept across the junction and becomes a majority carrier. This process is collection of the light generated carriers.
- Once a carrier is collected, it is very unlikely to recombine.

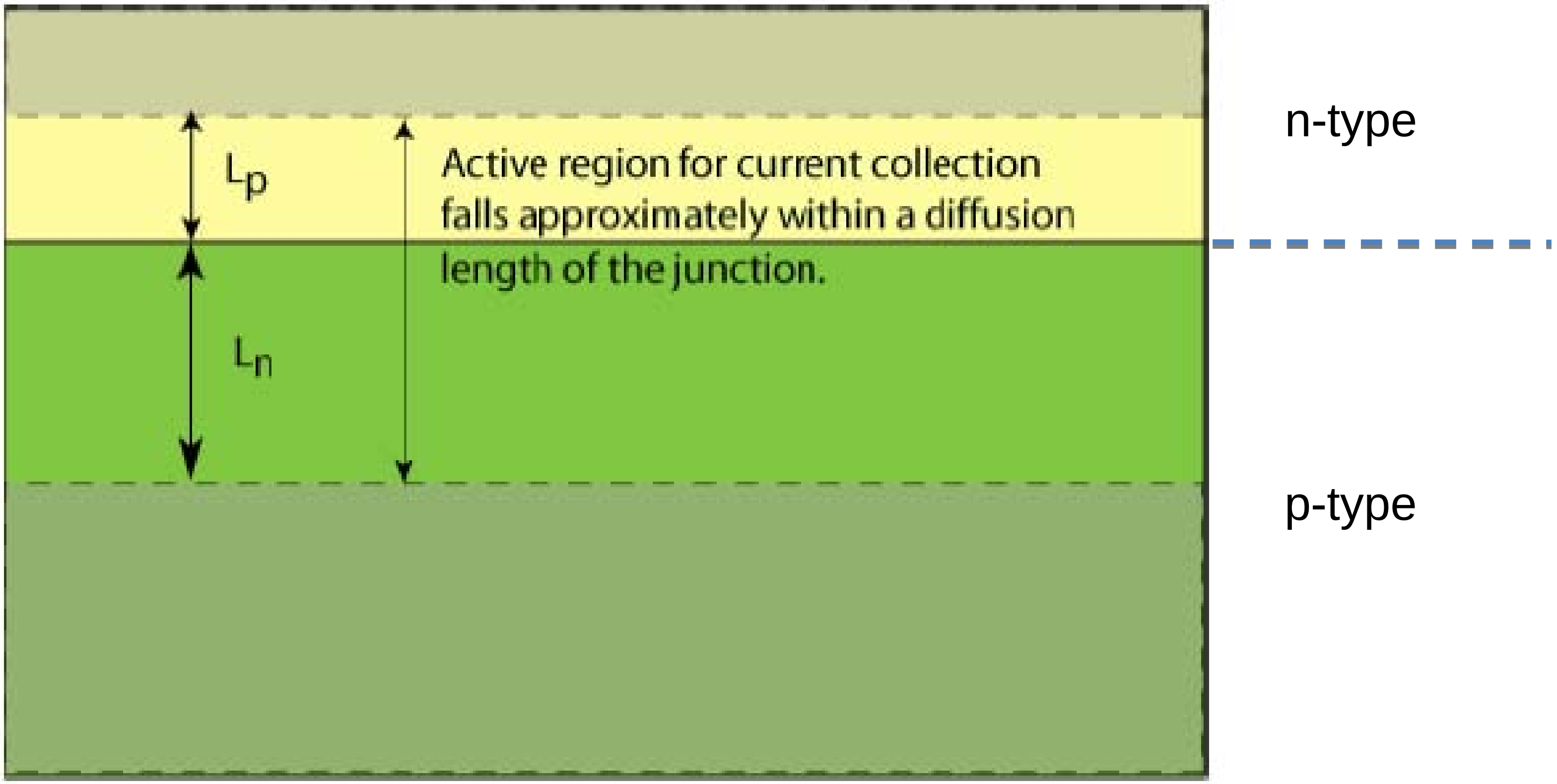


Collection Probability

- Collection probability is the probability that a light generated carrier will reach the depletion region and be collected.
- Depends on where it is generated compared to junction and other recombination mechanisms, and the diffusion length.



Collection Probability



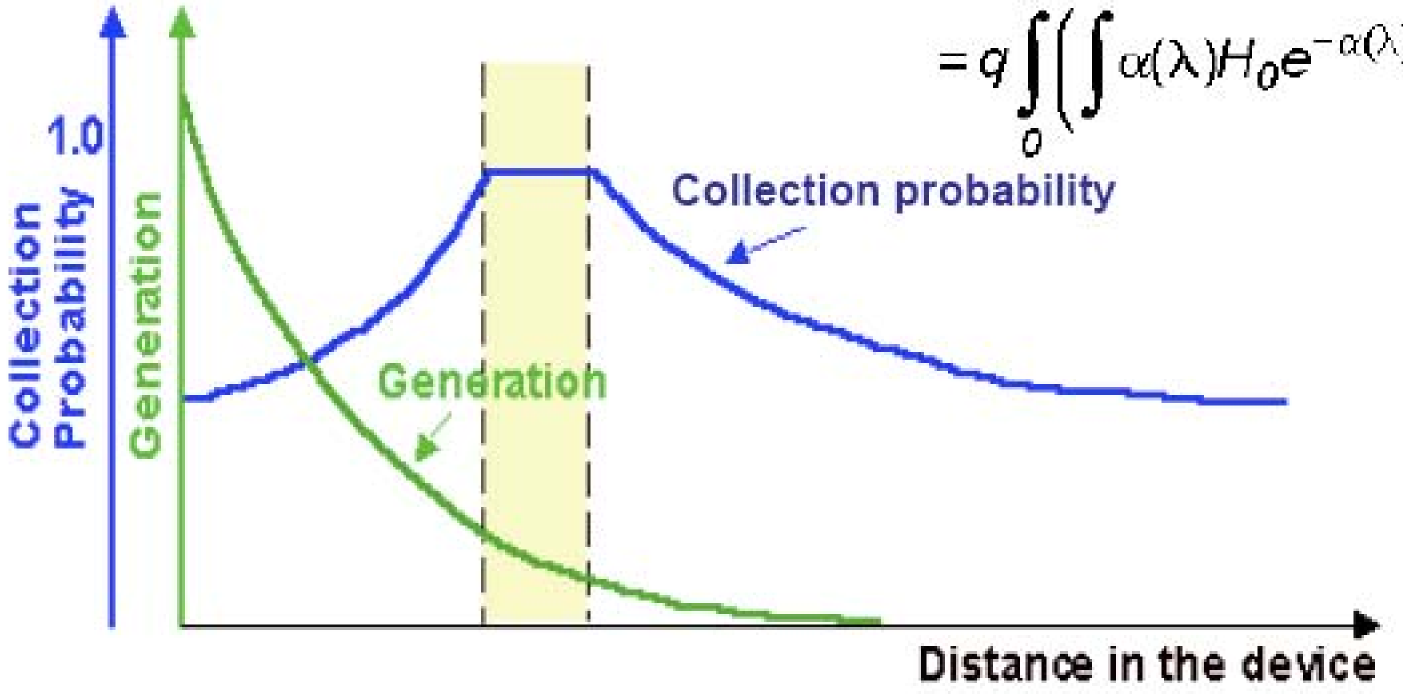
Collection probability is low further than a diffusion length away from junction

Collection Probability

J_{sc} determined by generation rate and collection probability

$$J_L = q\int_0^W G(x)CP(x)dx$$

$$= q\int_0^W \left(\int \alpha(\lambda) H_0 e^{-\alpha(\lambda)x} d\lambda \right) CP(x)dx$$

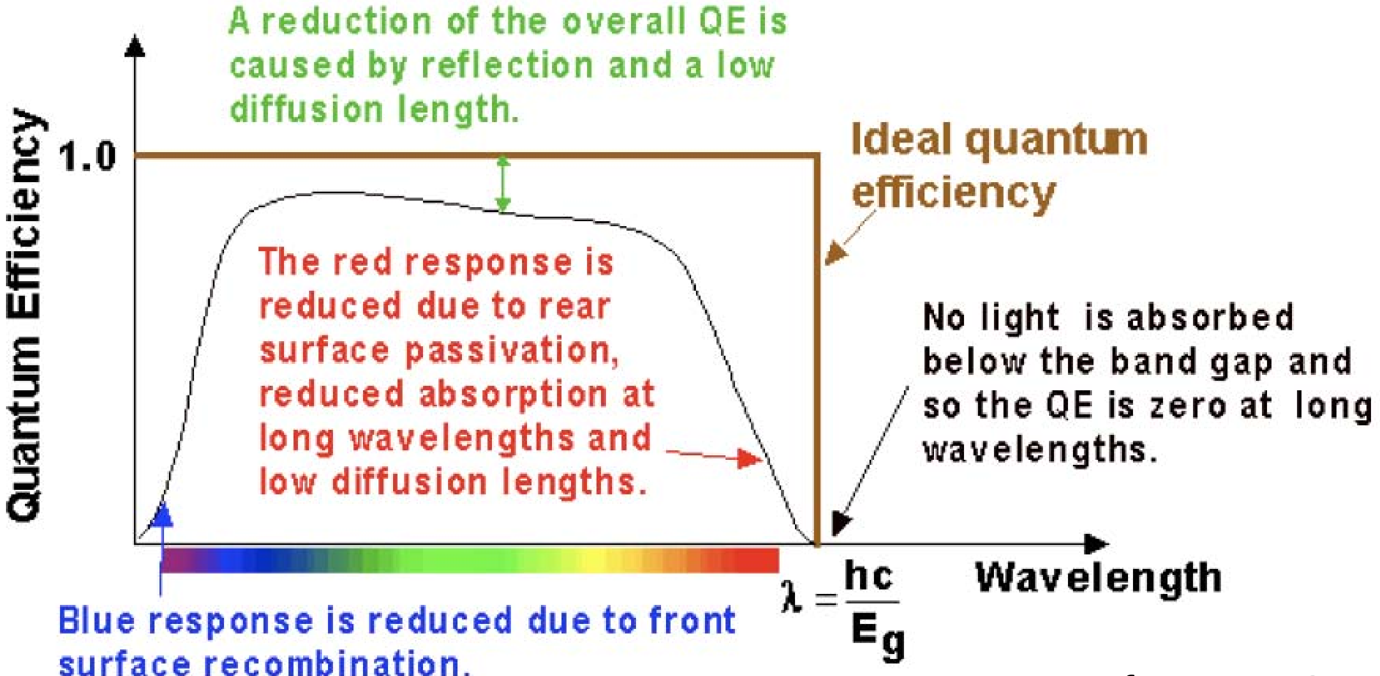


Spectral Response

Diagram of spectral response tool removed due to copyright restrictions.

Newport Spectral Response tool

Spectral Response



from PVCDROM

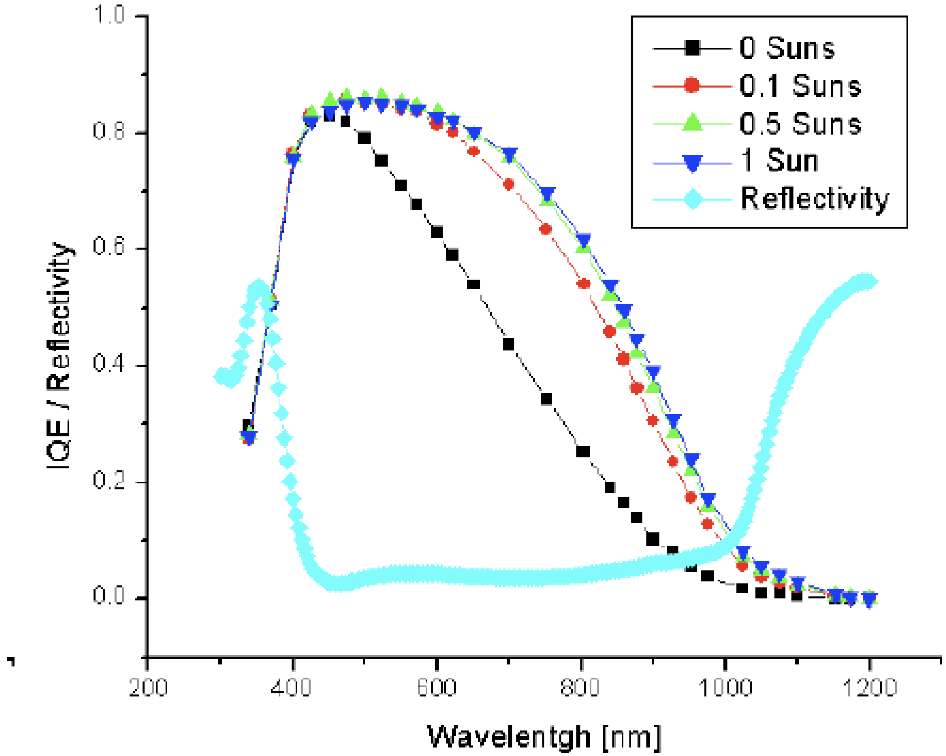
Standards: IEC 60904-3 and 60904-8

External vs. Internal Quantum Efficiency

$$\mathrm{IQE} = \frac{\mathrm{EQE}}{(1-\mathrm{R})} = \frac{\text{Electrons Out}}{(\text{Photons In})\cdot(1-\mathrm{R})}$$

… where R = Reflectivity

Reflectivity and IQE
(measured with different bias illumination)



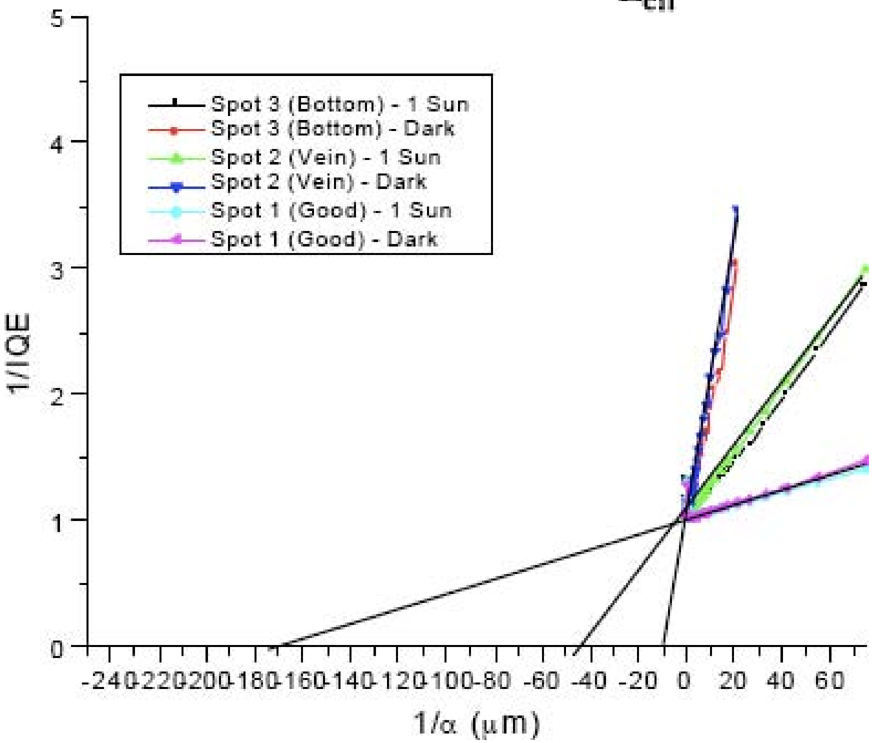
Spectrally-Resolved Laser Beam Induced Current (SR-LBIC)

- 4 or more lasers measure IQE(λ).
- Digital processing of data extracts relevant device parameters.
- XY stage moves sample.
- A 2D map of IQE obtained!
- In advanced versions, all lasers fire simultaneously (as they are pulsed at different frequencies) into a fibre optic cable. FFT of the current signal decouples different wavelengths.

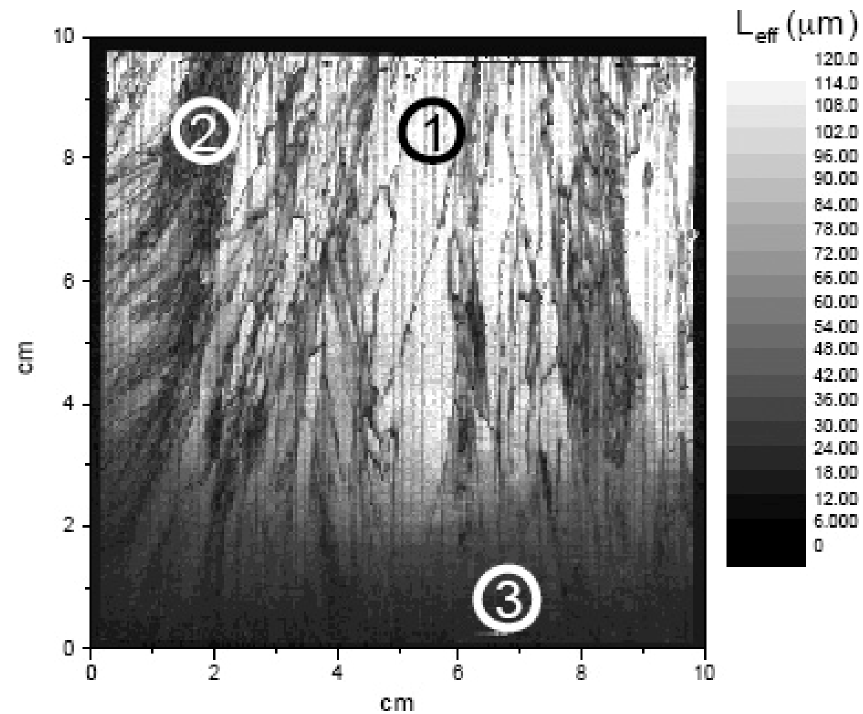
Minority Carrier Diffusion Length

At each point…

$$\mathrm{IQE}^{-1} = 1 + \alpha^{-1}\frac{\cos\,\theta}{L_{\mathrm{eff}}}$$



Mapped over an entire sample…



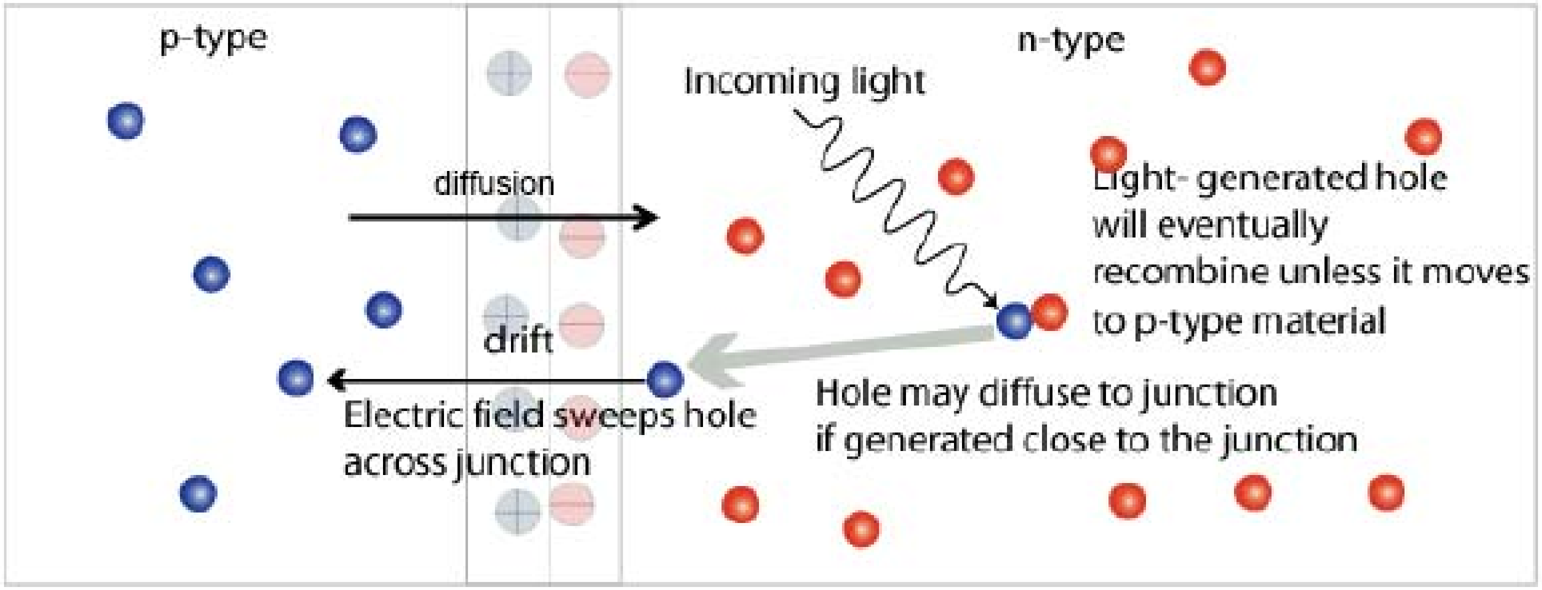
See: P. A. Basore, *IEEE Trans. Electron. Dev*. **37**, 337 (1990).

Voc and Operating Conditions

- IV Curve Measurements
- Series Resistance
  - Contact Resistance
  - Sheet Resistance
- Shunt Resistance
  - Lock-in Thermography
- Electroluminescence

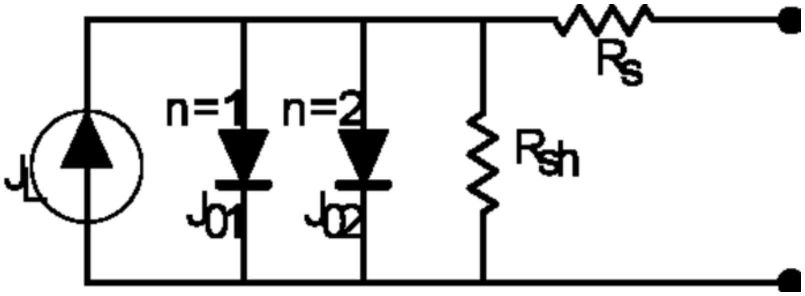
Refresher: Open Circuit Voltage

- If collected light-generated carriers are not extracted from the solar cell but instead remain, then a charge separation exists.
- The charge separation reduces the electric field in the depletion region, reduces the barrier to diffusion current, and causes a diffusion current to flow.



Two Diode Model

Equivalent Circuit Diagram of Solar Cell



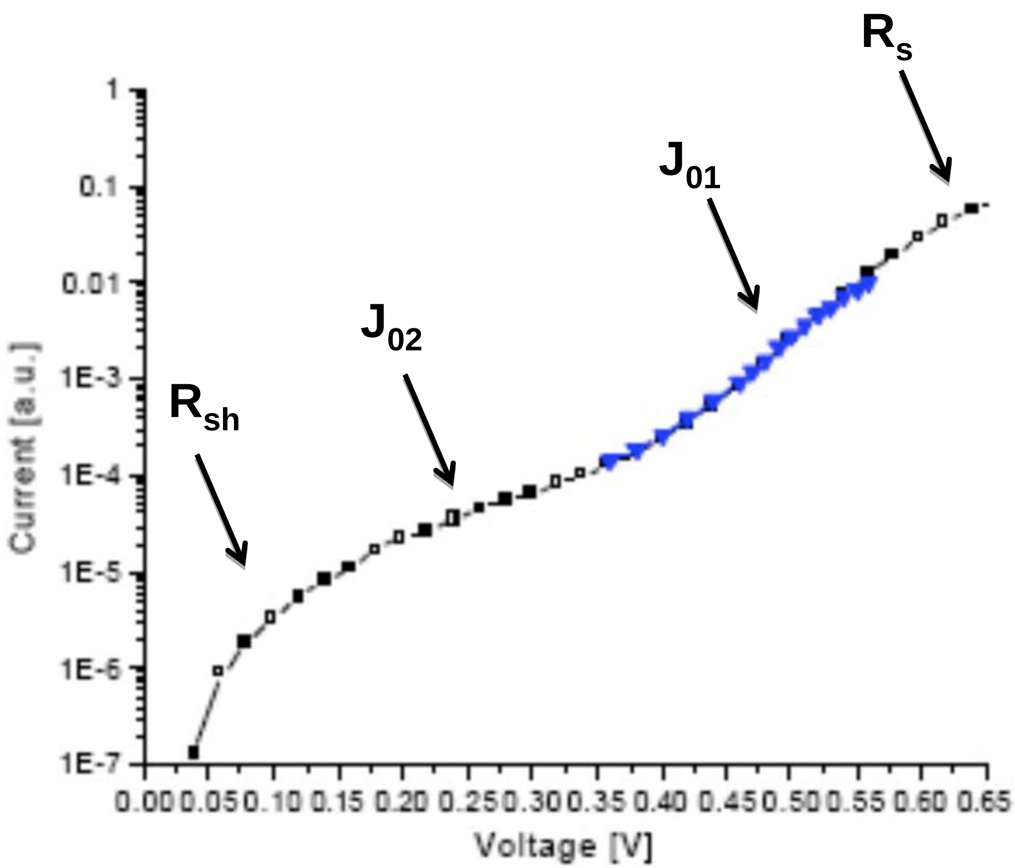
A Prettier Version of the Same

Image removed due to copyright restrictions. Please see Fig. 2.7 in Schumacher, Juergen O., and Wolfram Wettling. "Device Physics of Silicon Solar Cells." Ch. 2 in Archer, Mary D., and Robert Hill. *Clean Electricity from Photovoltaics*. London, England: Imperial College Press, 2001. ISBN: 978-1860941610

$$J = J_L - \underbrace{J_{01}\exp\left(\frac{q(V+JR_s)}{kT}\right)}_{\text{diffusion current}} - \underbrace{J_{02}\exp\left(\frac{q(V+JR_s)}{2kT}\right)}_{\text{recombination current}} - \frac{V+JR_s}{R_{shunt}}$$

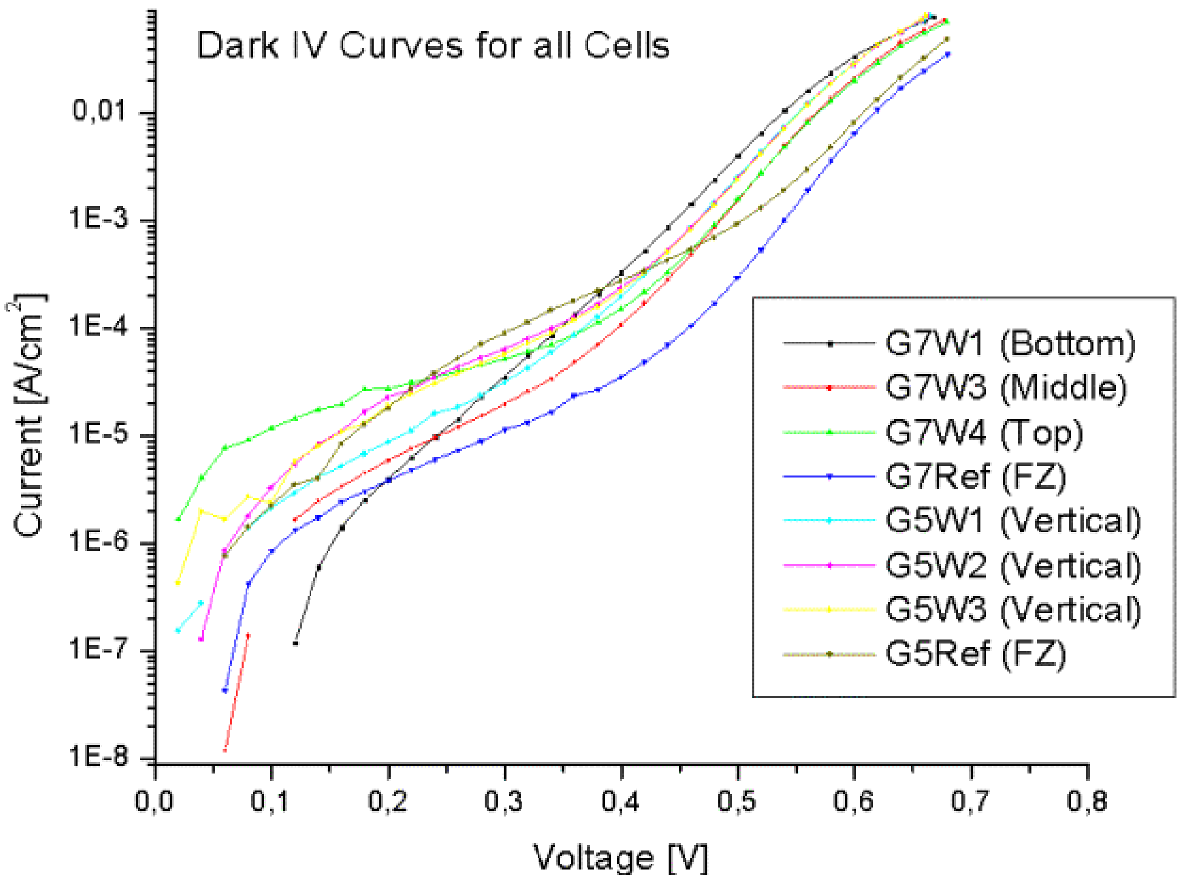
IV Curve Measurements

$$J = J_L - J_{01}\exp\left(\frac{q(V+JR_s)}{kT}\right) - J_{02}\exp\left(\frac{q(V+JR_s)}{2kT}\right) - \frac{V+JR_s}{R_{shunt}}$$



IV Curve Measurements

Several IV curves for real solar cells, illustrating a variety of IV responses!



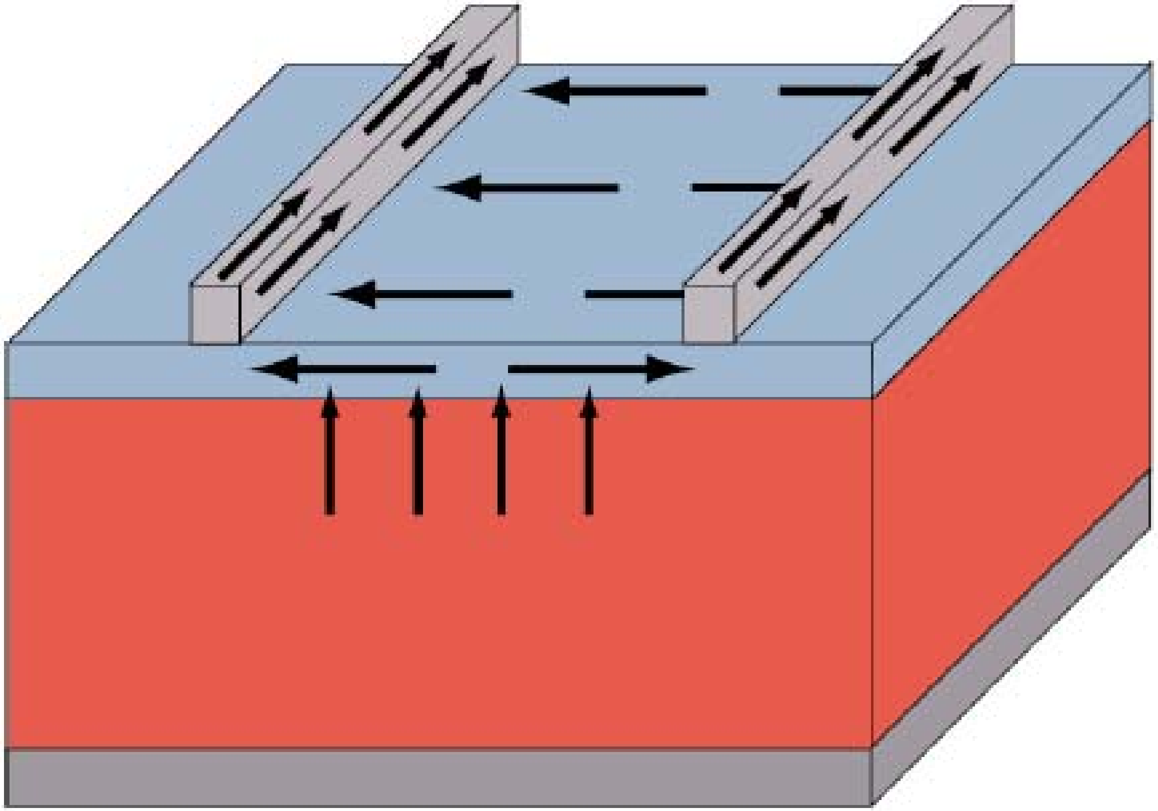
#14
#100
#124
FZ, e.s.r. 79-87 Ω/sq.
#9
#14
#100
FZ, e.s.r. 85-101 Ω/sq.

Physical Causes of Series Resistance

Series resistance composed of emitter and metal grid resistance terms.

Want large cross section area of grid and emitter to reduce resistances.

$$R = \frac{\rho l}{A}$$



Physical Causes of Shunt Resistance

Paths for electrons to flow from the emitter into the base. Can be caused by physical defects (scratches), improper emitter formation, metallization over-firing, or material defects (esp. those that traverse the space-charge region).

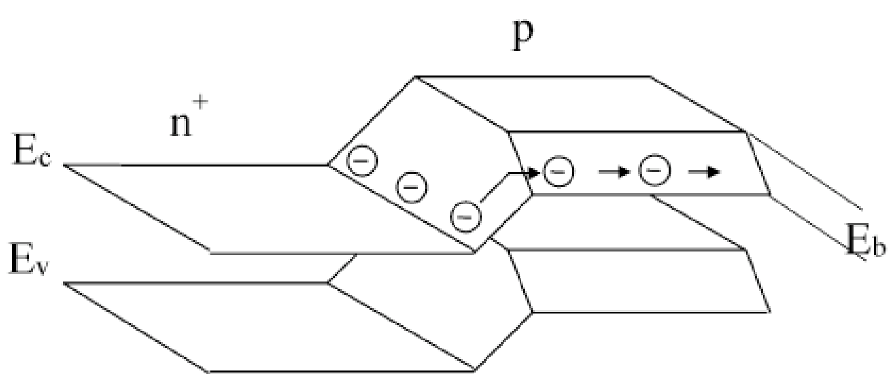
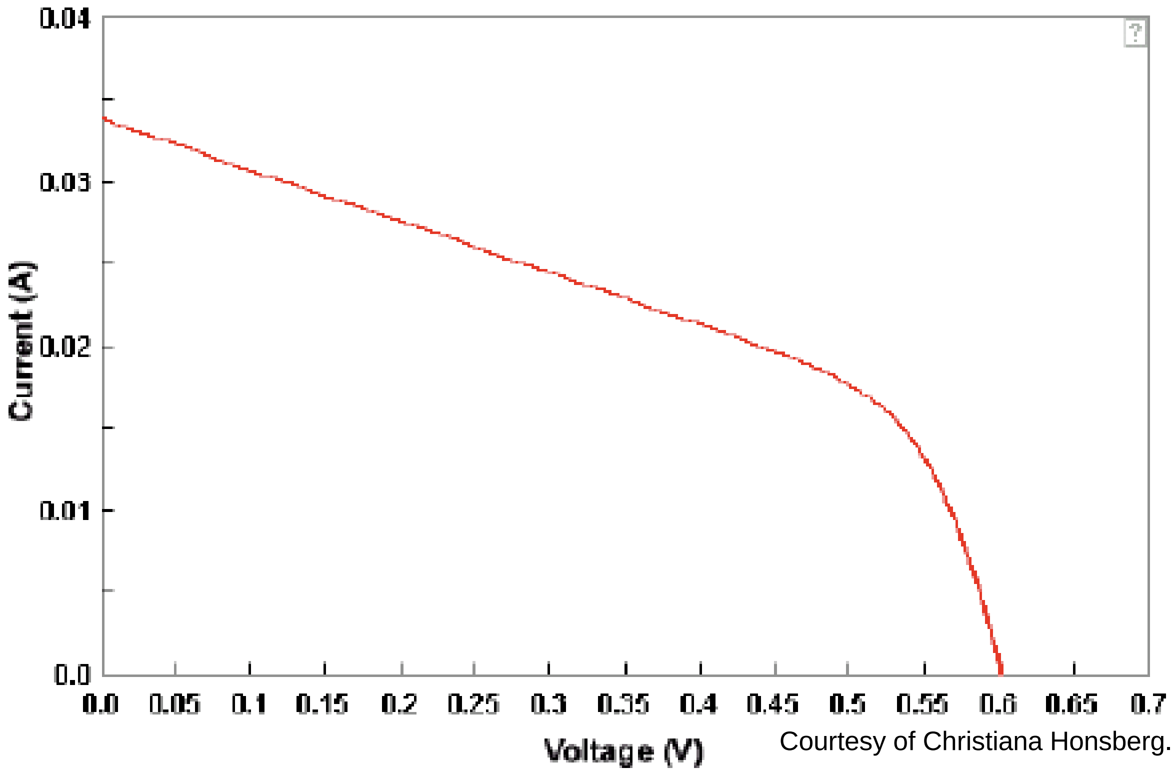


Fig. 6. Schematic 2-dimensional potential distribution on a positively charged surface (in front) crossing an n^+p-junction. E_c: conduction band edge, E_v: valence band edge, E_b: surface potential barrier height.

Effect of R_s and R_{sh}

High series resistance and low shunt resistance degrade primarily FF, but in severe cases Voc and possibly Jsc.



$$J = J_L - J_{01}\exp\left(\frac{q(V+JR_s)}{kT}\right) - J_{02}\exp\left(\frac{q(V+JR_s)}{2kT}\right) - \frac{V+JR_s}{R_{shunt}}$$

Lock-in Thermography

Lock-in Thermography Images Shunts

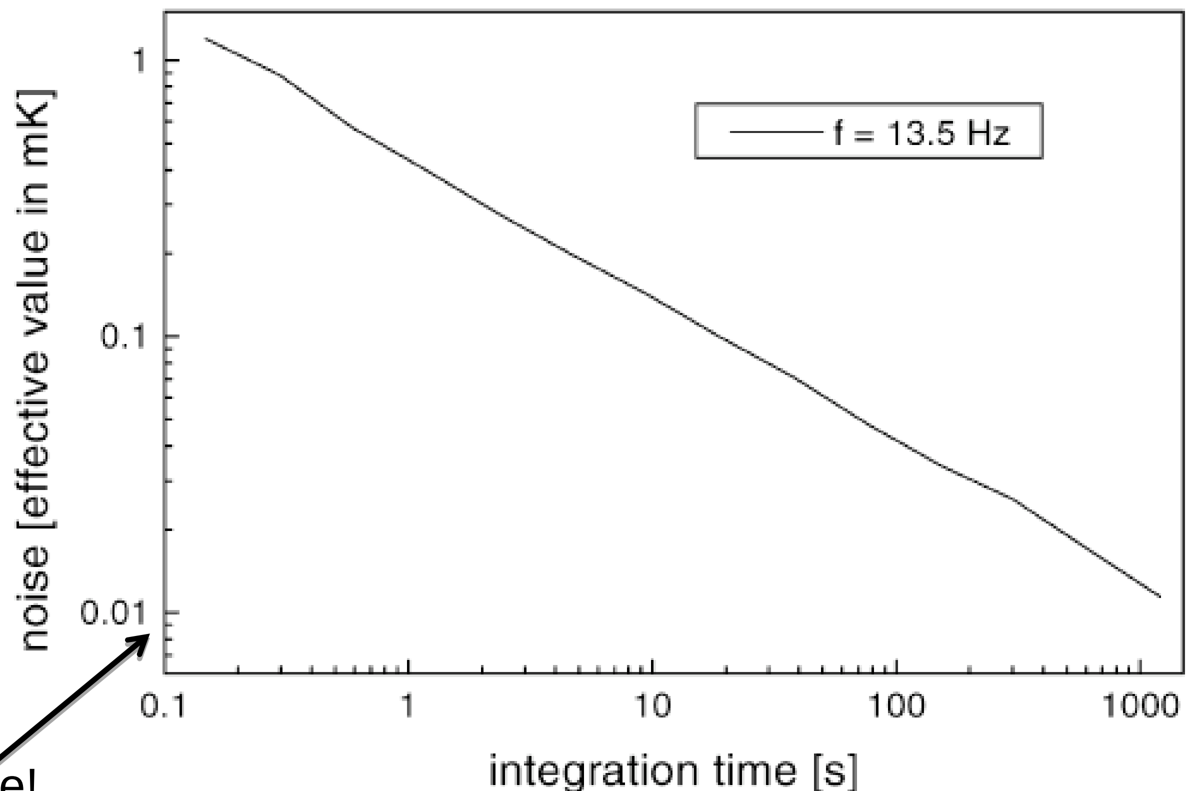
(e.g., Local Increases in
Dark Forward Current)

Lock-in Thermography

Image removed due to copyright restrictions. Please see Fig. 1 in Kaes, M., et al. "Light-modulated Lock-in Thermography for Photosensitive pn-Structures and Solar Cells." *Progress in Photovoltaics: Research and Applications* 12 (2004): 355-363.

M. Kaes et al., *Prog. Photovolt.* **12**, 355 (2004)
J. Isenberg and W. Warta, *Prog. Photovolt*. **12**, 339 (2004)
O Breitenstein et al., *Solar Energy Mater. Solar Cells* **65**, 55 (2001)

Lock-in Thermography - Sensitivity



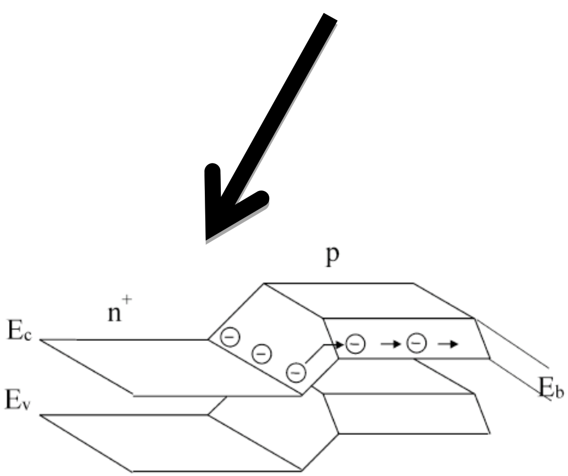
rattlesnake!

Sensitivity is a function of integration time.

Lock-in Thermography – Dark vs. Illuminated

Dark Illuminated

Image removed due to copyright restrictions. Please see Fig. 3 in Kaes, M., et al. "Light-modulated Lock-in Thermography for Photosensitive pn-Structures and Solar Cells." *Progress in Photovoltaics: Research and Applications* 12 (2004): 355-363.



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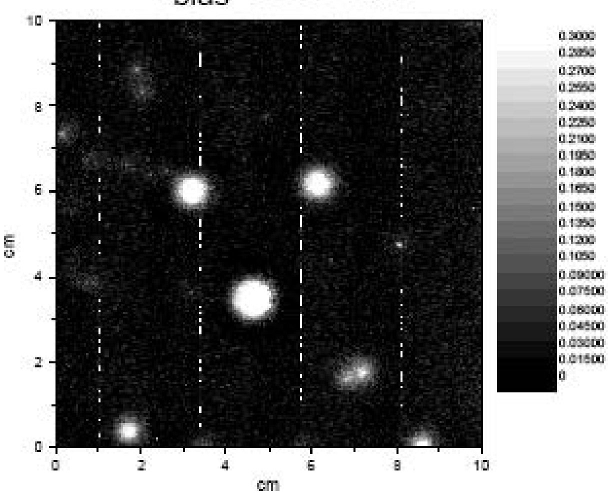
M. Kaes et al., *Prog. Photovolt.* **12**, 355 (2004)
O Breitenstein et al., *Solar Energy Mater. Solar Cells* **65**, 55 (2001)

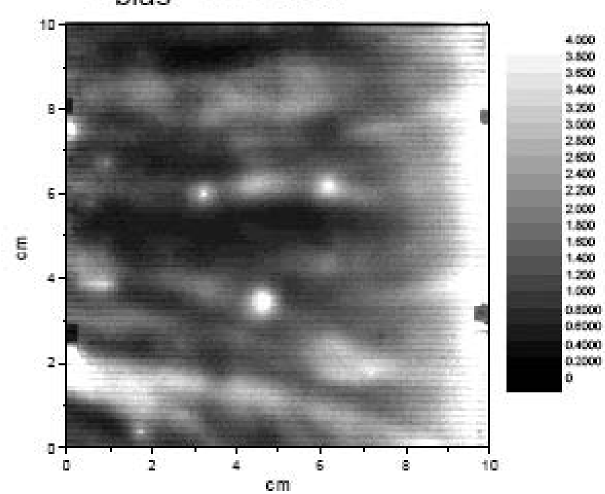
Lock-in Thermography – Imaging Losses

$$J = J_L - J_{01}\exp\left(\frac{q(V+JR_s)}{kT}\right) - J_{02}\exp\left(\frac{q(V+JR_s)}{2kT}\right) - \frac{V+JR_s}{R_{shunt}}$$

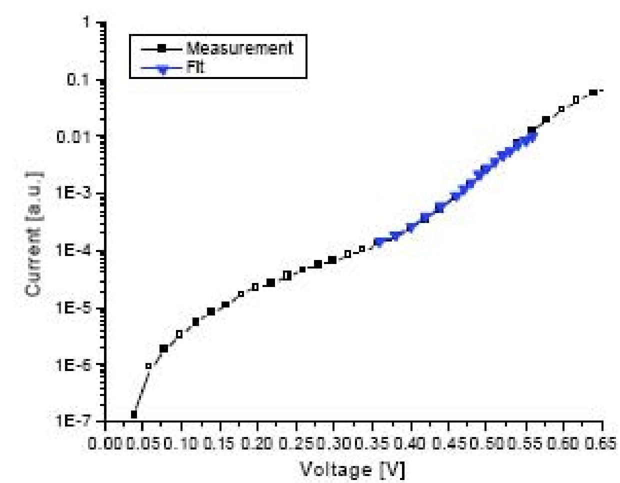
a) Lock in Thermography
V_{bias}=360 mV



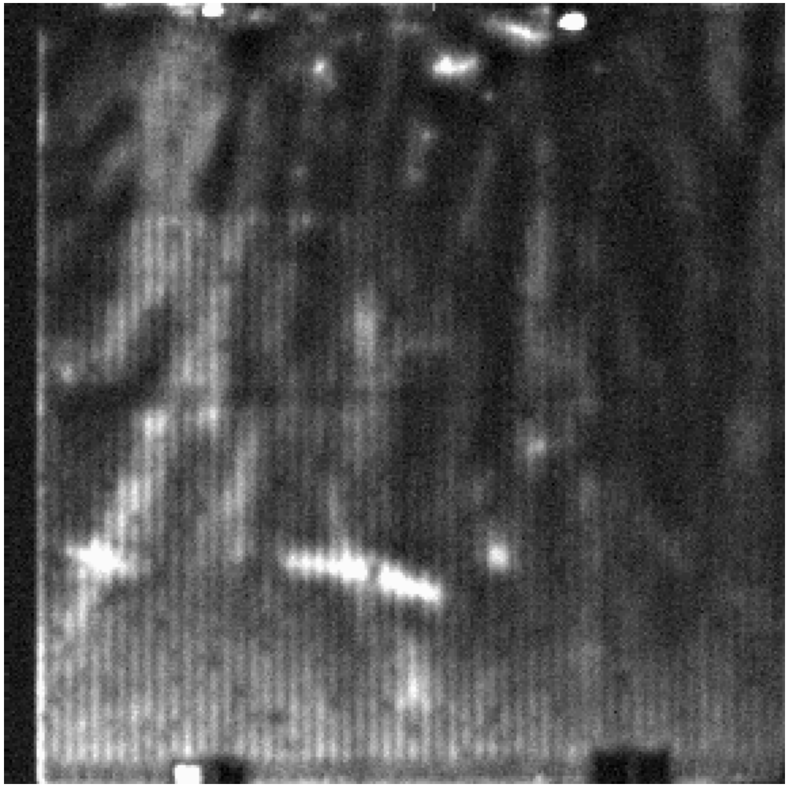
b) Lock in Thermography
V_{bias}=560 mV



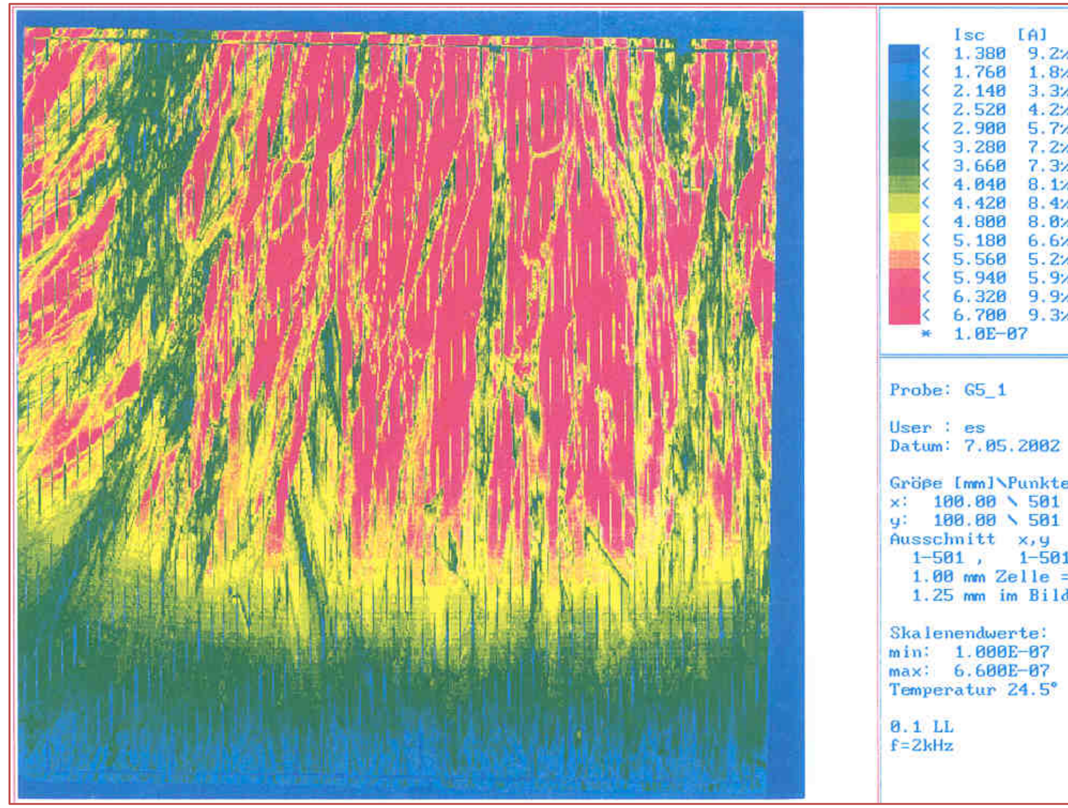
c) Dark IV Curve Fitting



Correlation between Thermography and LBIC



525mV Forward Biased
(V_{oc} = 571mV)
8Hz, 2hour scan, (30000 Frames)



White-light LBIC
(essentially probes the bulk, below the emitter)

Ideal Diode Equation Revisited

$$J = J_0\left(\exp\left(qV/nkT\right) - 1\right) - J_{sc}$$

$$V_{oc} = \frac{nkT}{q}\ln\left(\frac{I_L}{I_0} + 1\right)$$

$$I_0 = A\left(\frac{qD_e n_i^2}{L_e N_A}\cdot\frac{S_h\cosh\left(W_N/L_h\right) + D_h/L_h\sinh\left(W_N/L_h\right)}{D_h/L_h\cosh\left(W_N/L_h\right) + S_h\sinh\left(W_N/L_h\right)} + \frac{qD_h n_i^2}{L_h N_D}\cdot\frac{S_e\cosh\left(W_P/L_e\right) + D_e/L_e\sinh\left(W_P/L_e\right)}{D_e/L_e\cosh\left(W_P/L_e\right) + S_e\sinh\left(W_P/L_e\right)}\right)$$

Note: J is current density A/cm^2, I is current.

Cheaper Methods of Shunt Detection:

Liquid Crystal Thermochromic Sheets

See: “Shunt imaging in solar cells using low cost commercial liquid crystal sheets” C. Ballif *et al*., *Proc. IEEE Photovoltaic Specialists Conference*, 2002, pp. 446-449.

Electroluminescence

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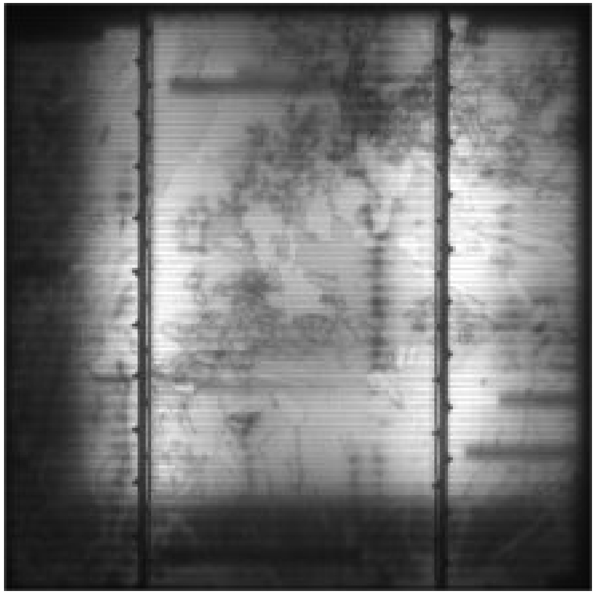
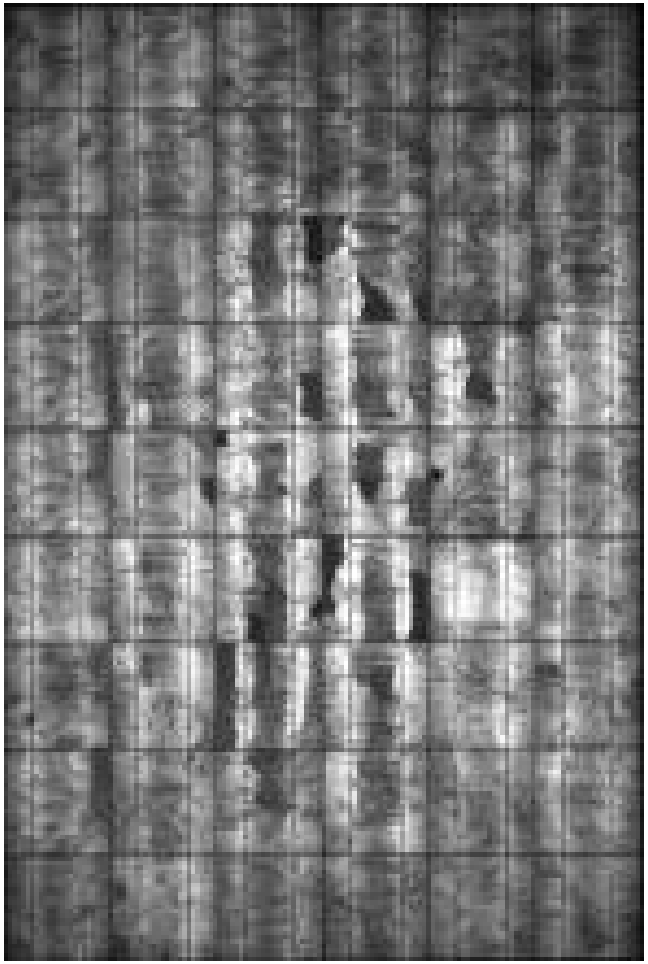
Electroluminescence

Cell



Module



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Evolution of IR Imaging Techniques

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Evolution of IR Imaging Techniques

…and the kitchen sink!