Solar Cell Characterization

Lecture 16 – 11/8/2011

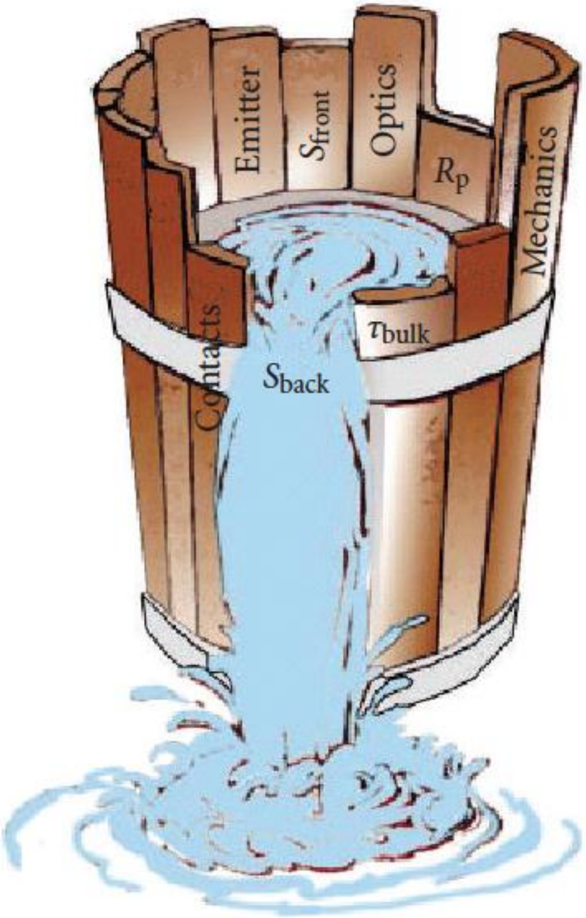
MIT Fundamentals of Photovoltaics
2.626/2.627

Tonio Buonassisi

Learning Objectives: Solar Cell Characterization

1. Describe basic classifications of solar cell characterization methods.
2. Describe function and deliverables of PV characterization techniques measuring J_{sc} losses.
3. Describe function and deliverables of PV characterization techniques measuring FF and V_{oc} losses.

Liebig's Law of the Minimum



S. Glunz, *Advances in Optoelectronics* 97370 (2007)

Image by S. W. Glunz. License: CC-BY. Source: "High-Efficiency Crystalline Silicon Solar Cells." *Advances in OptoElectronics* (2007).

$$\eta_{\text{total}} = \eta_{\text{absorption}} \times \eta_{\text{excitation}} \times \eta_{\text{drift/diffusion}} \times \eta_{\text{separation}} \times \eta_{\text{collection}}$$

Taxonomy of PV Device Characterization Techniques

1. By property tested: Electrical, structural, optical, mechanical...
2. By device performance metric affected: Manufacturing yield, reliability, efficiency (short-circuit current, open-circuit voltage, fill factor)…
3. By location (throughput): In-line (high throughput) vs. off-line (low throughput).

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Short Circuit Current

- Optical Reflection
- Spectral Response
- Minority Carrier Diffusion Length

Optical Reflection

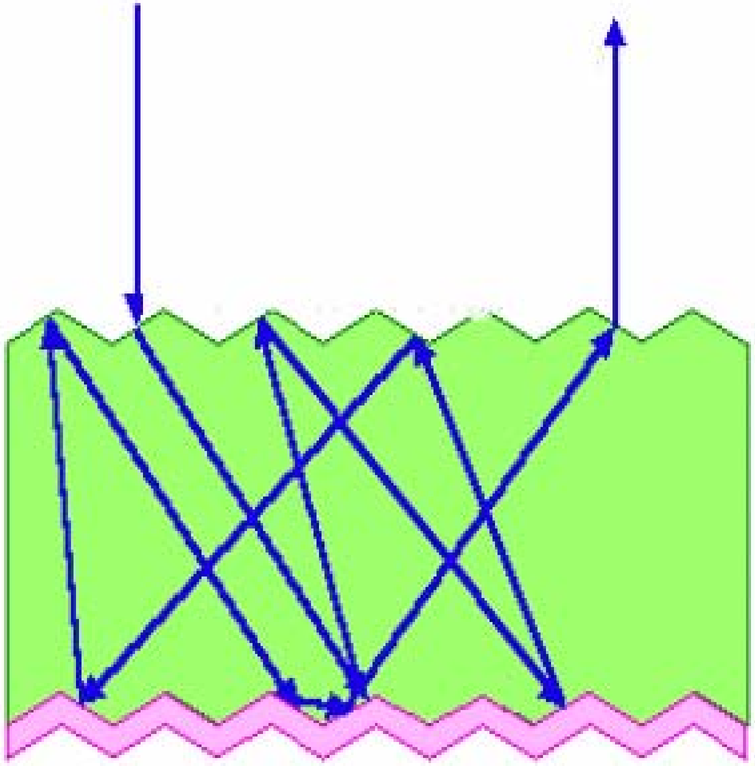
Spectrophotometer: Measures specular and diffuse reflectance, and transmission.

Please see the lecture 16 video to see a photo of a spectrophotometer.

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



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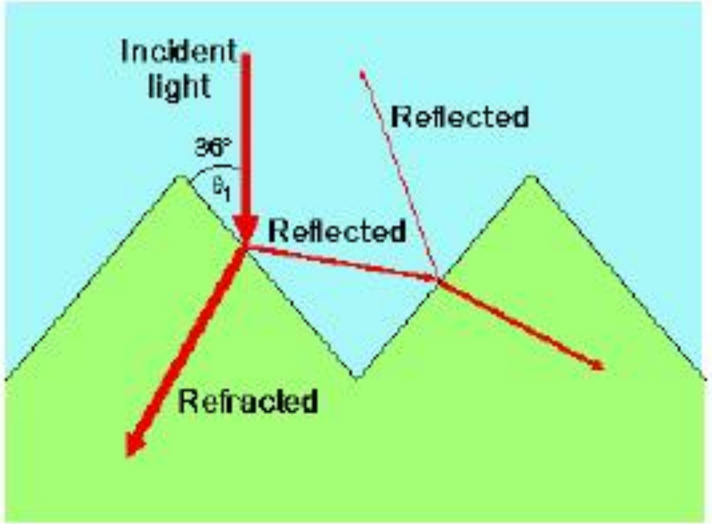
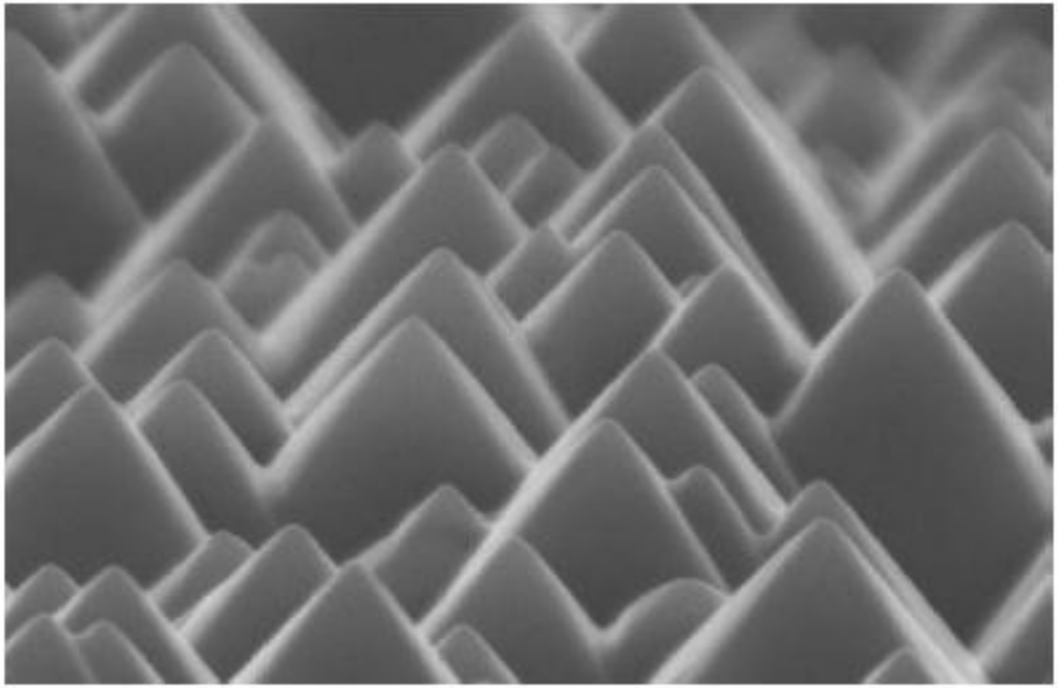
Increasing Absorption

Effect of Textured Surfaces on Light Absorption



SEM image of textured silicon

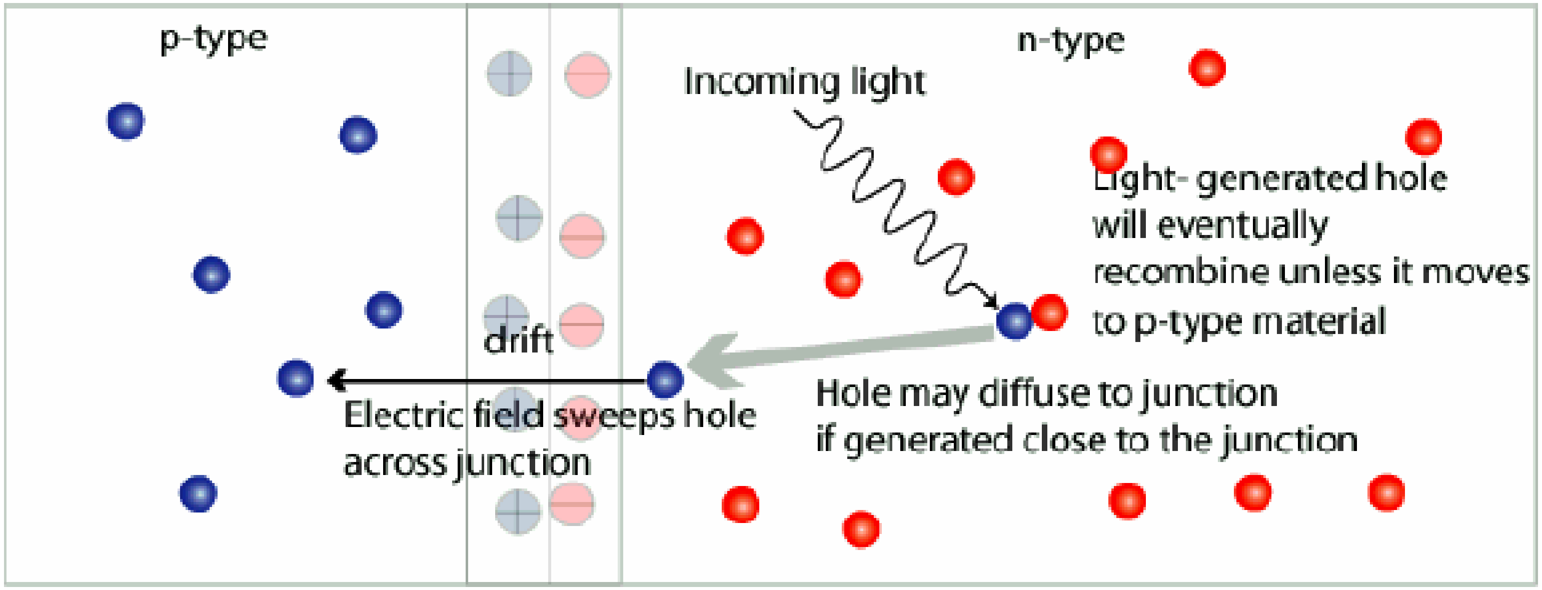


Courtesy of Christiana Honsberg. Used with permission.

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.



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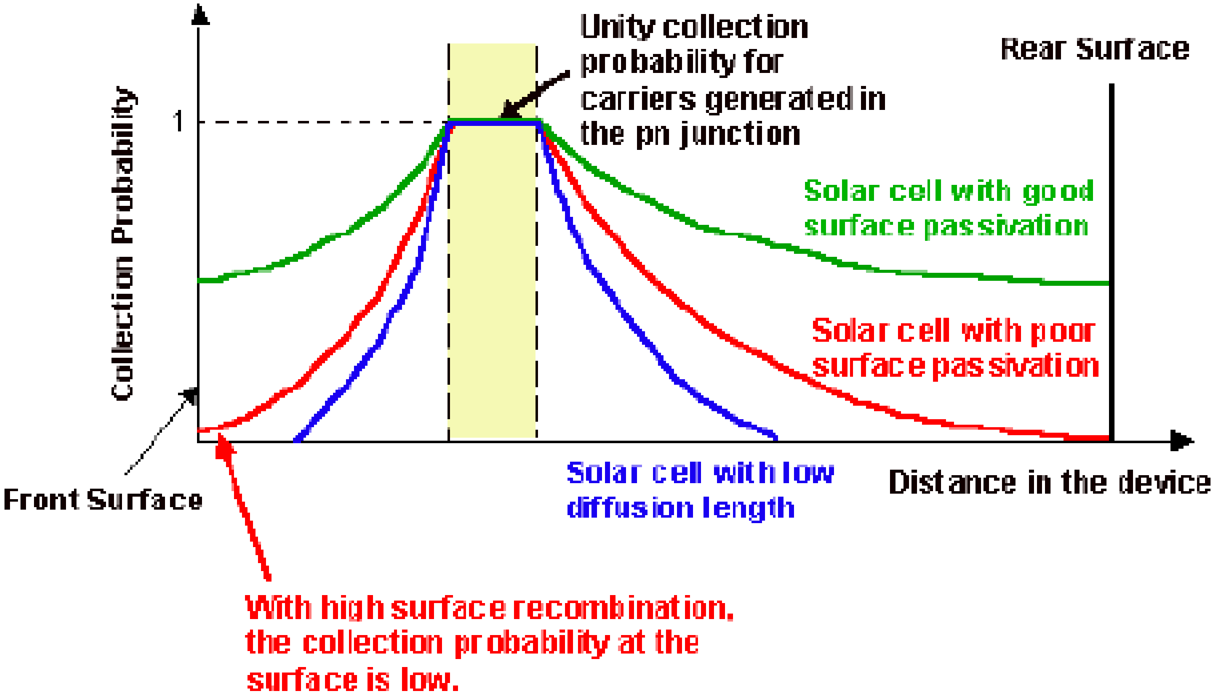
Collection Probability

- 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.



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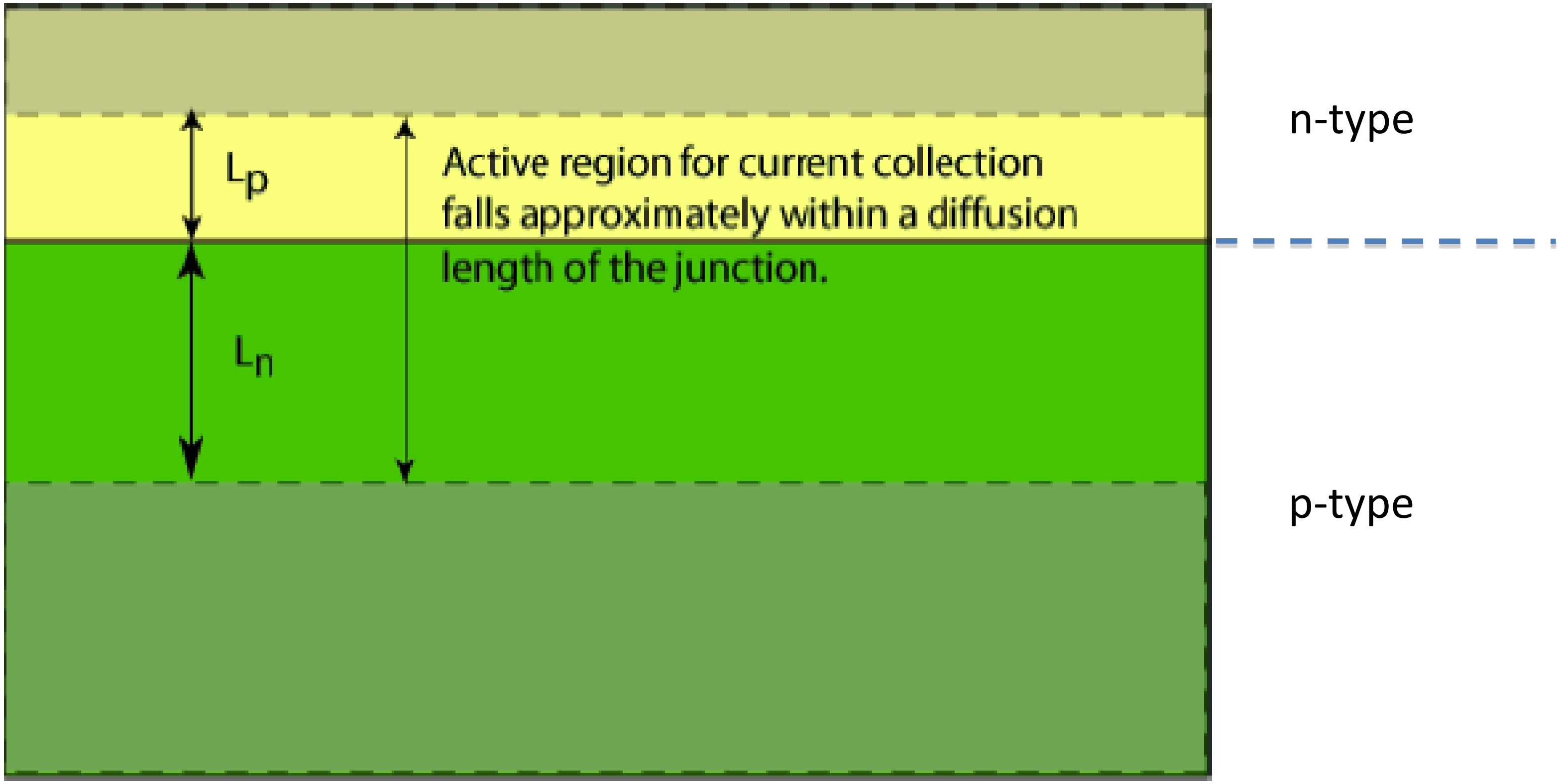
Collection Probability



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

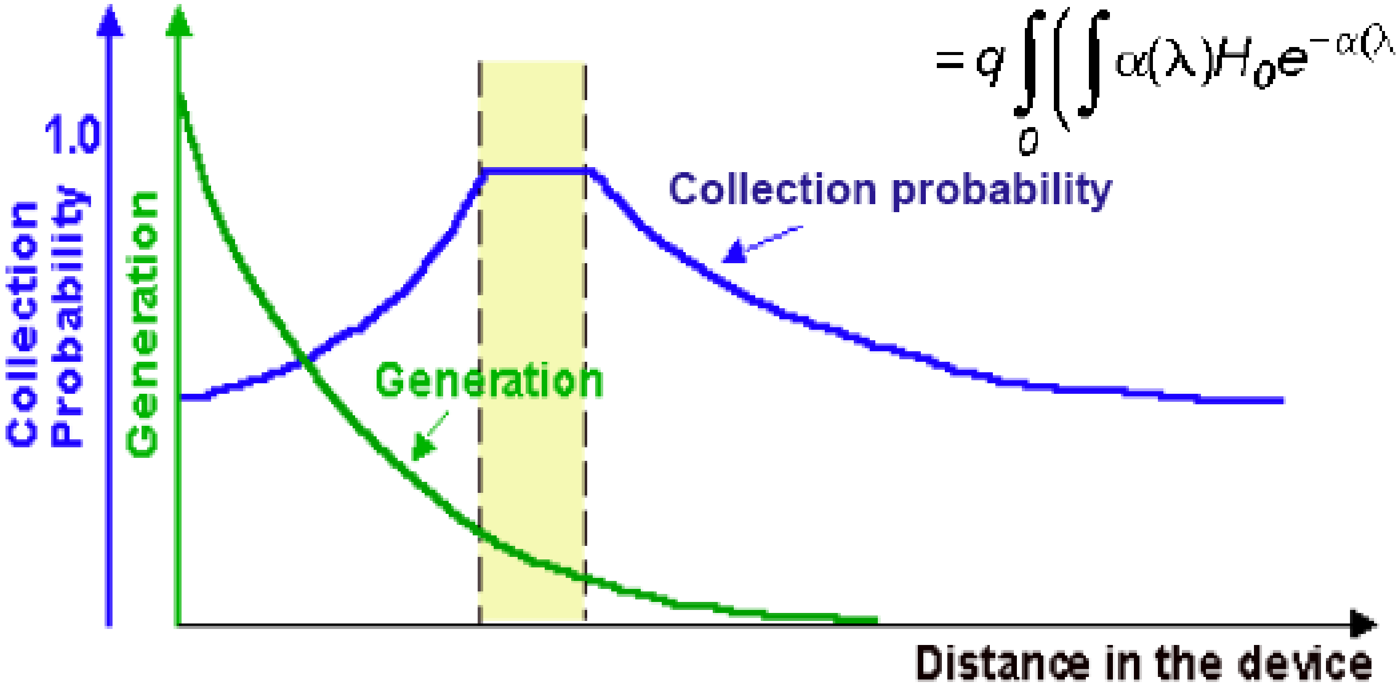
Courtesy of Christiana Honsberg. Used with permission.

Collection Probability

J_{sc} determined by generation rate and collection probability

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

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



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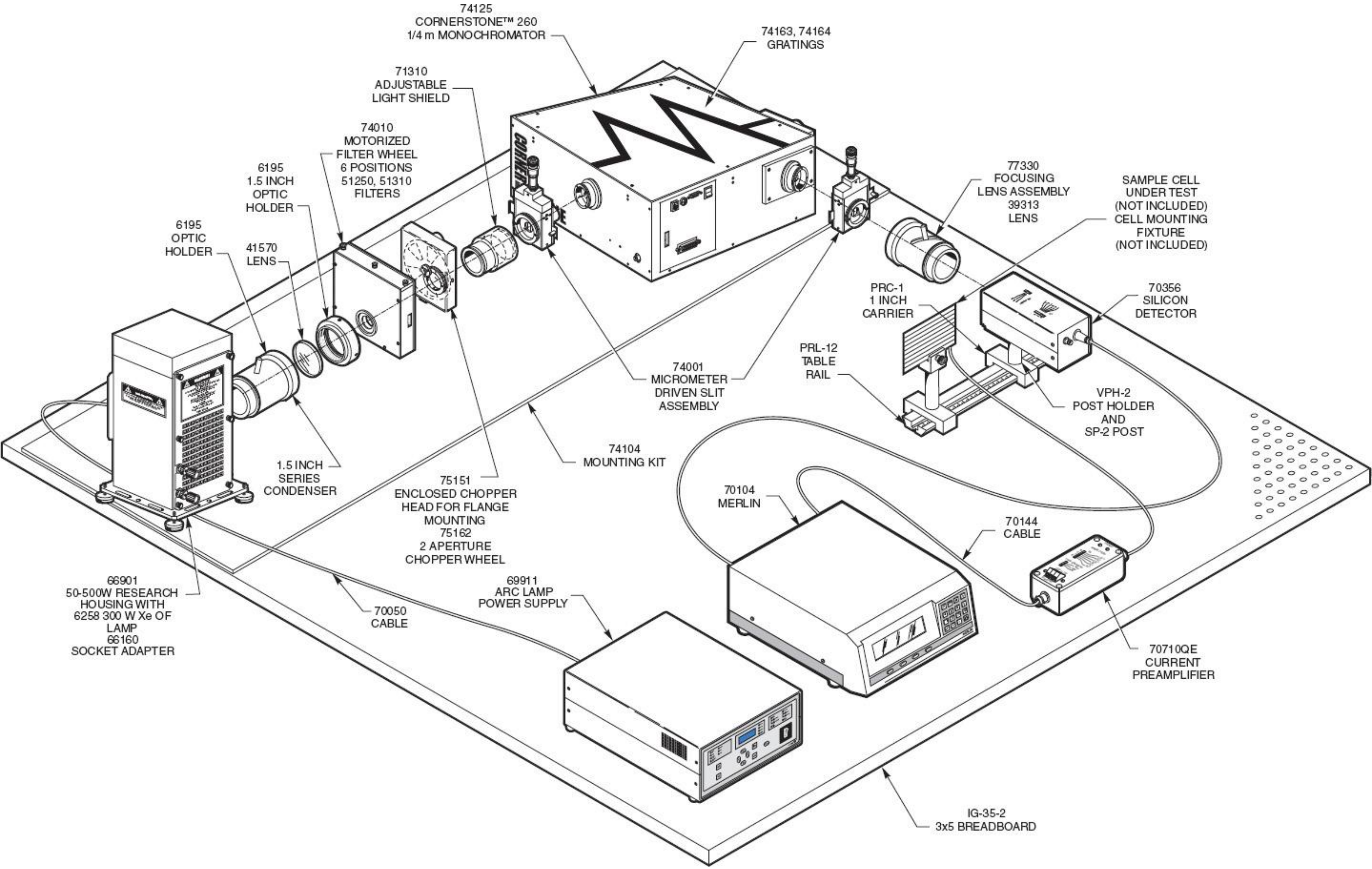
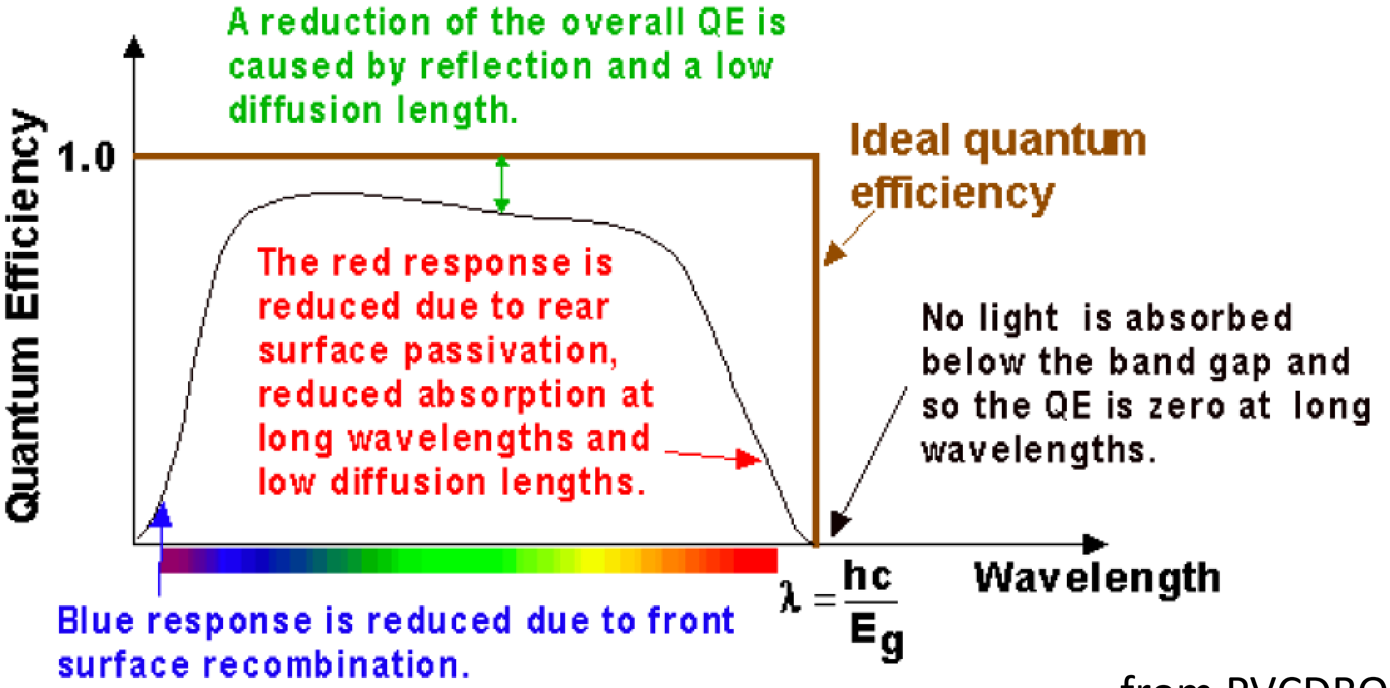
Spectral Response



Newport Spectral Response tool

Spectral Response



A reduction of the overall QE is caused by reflection and a low diffusion length.

Ideal quantum efficiency

The red response is reduced due to rear surface passivation, reduced absorption at long wavelengths and low diffusion lengths.

No light is absorbed below the band gap and so the QE is zero at long wavelengths.

Blue response is reduced due to front surface recombination.

from PVCDROM

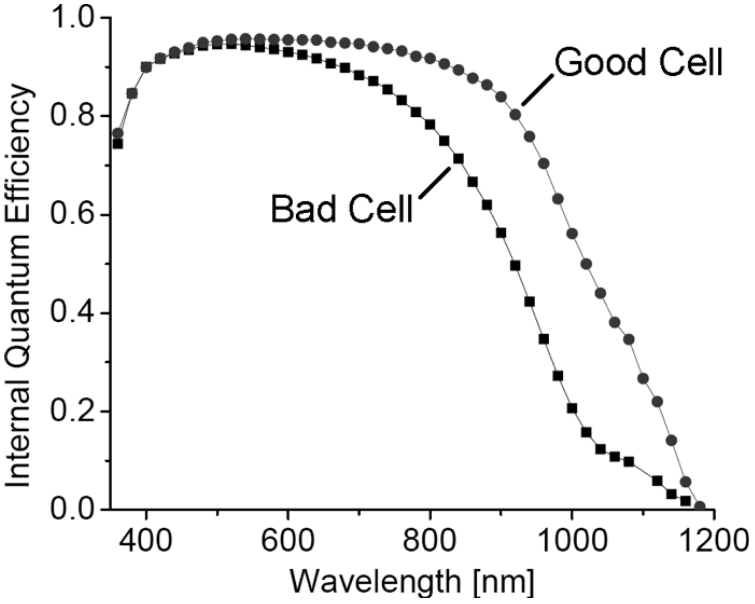
Standards: IEC 60904-3 and 60904-8

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

Internal Quantum Efficiency



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

Please see the lecture 16 video or the link below for a visual of the instrument.

- 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.

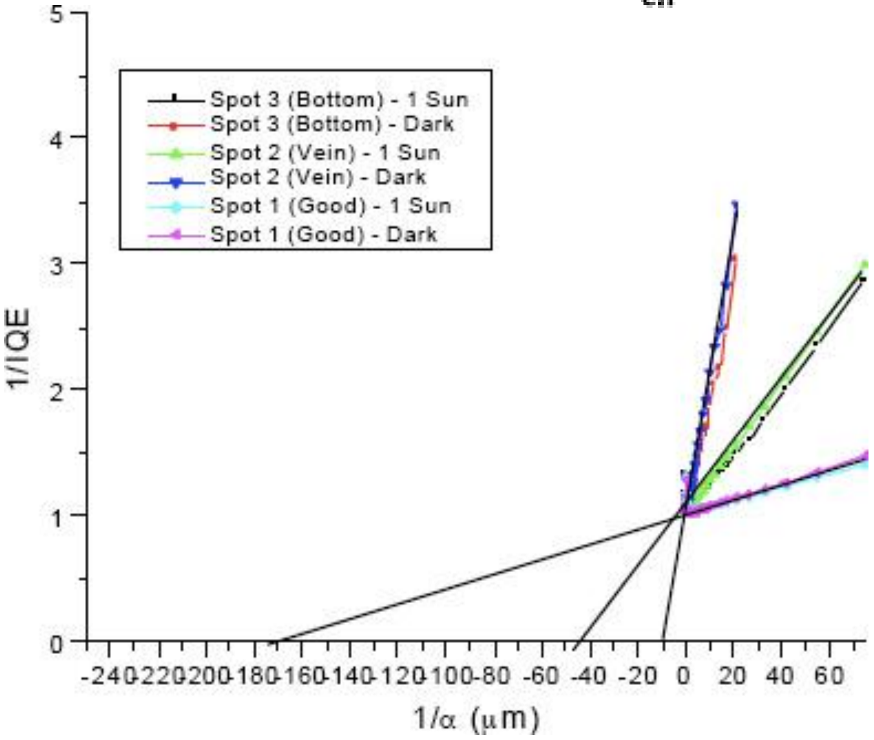
http://www.isfh.de/institut_solarforschung/media/sr_lbic_messplatz_1.jpg

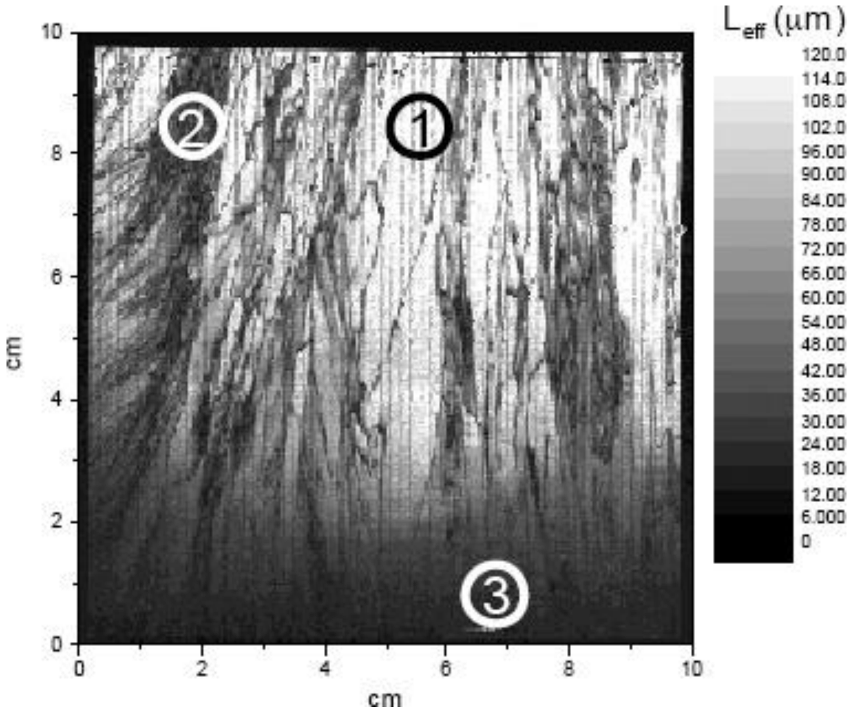
Minority Carrier Diffusion Length

At each point…

Mapped over an entire sample…

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





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

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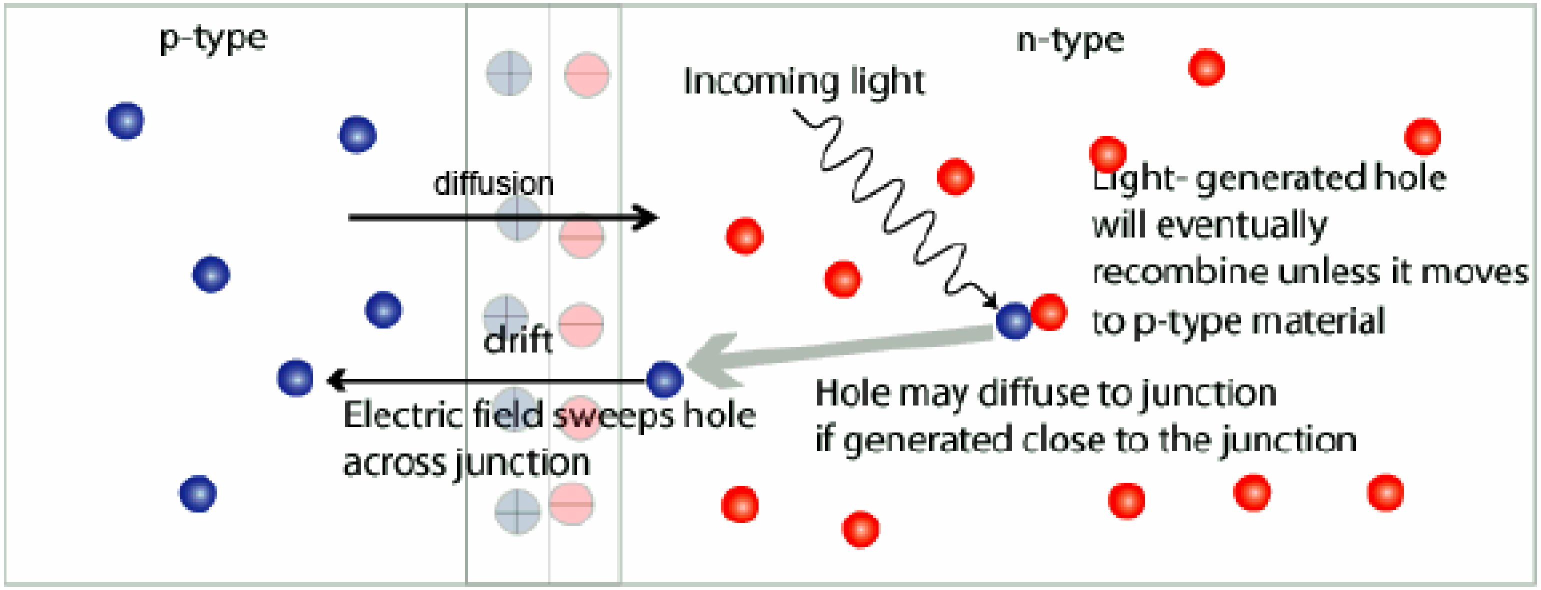
V_{oc} and Operating Conditions

- 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.



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Two Diode Model

Equivalent Circuit Diagram of Solar Cell

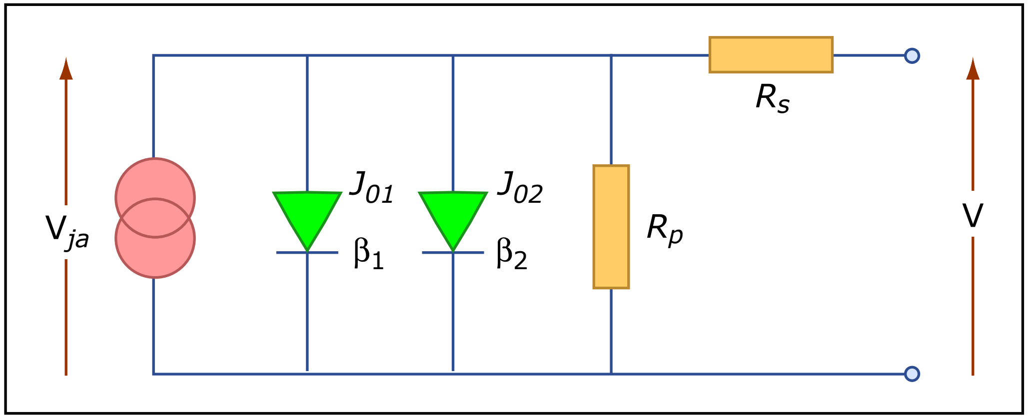


Image by MIT OpenCourseWare.

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

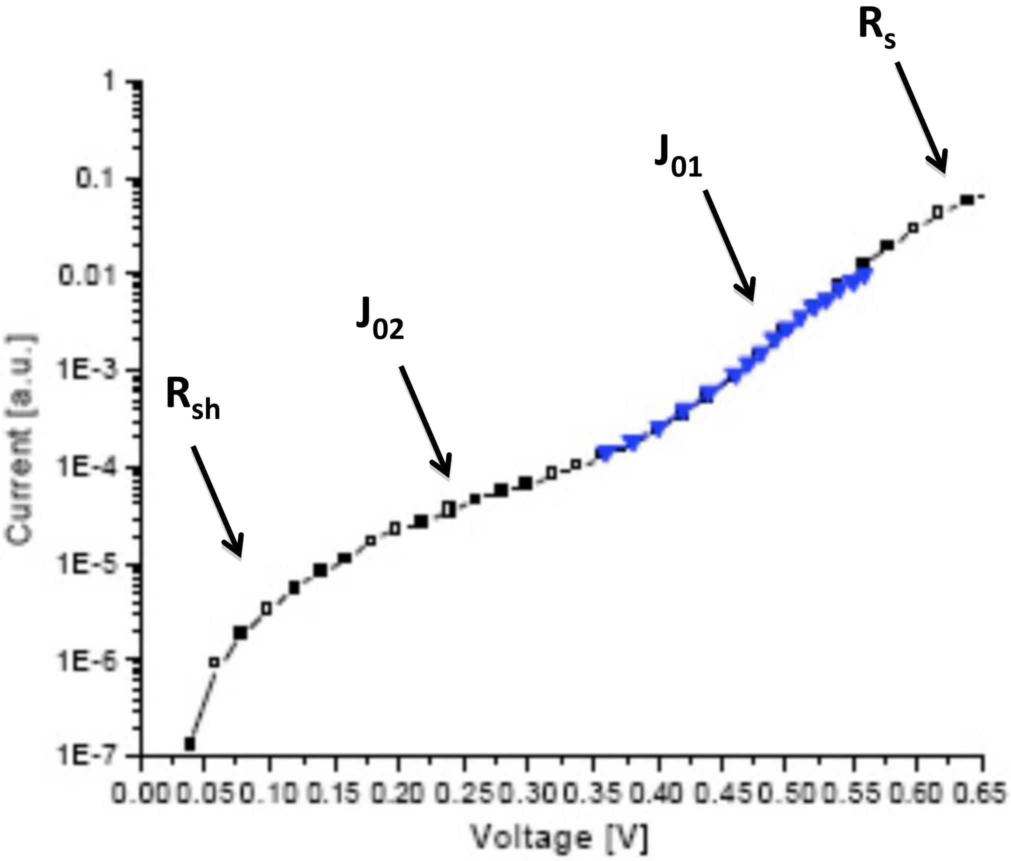
R_s = R_{series}. For good solar cell, this must be <u>small</u>.

R_p = R_{shunt}. For good solar cell, this must be <u>large</u>.

IV Curve Measurements

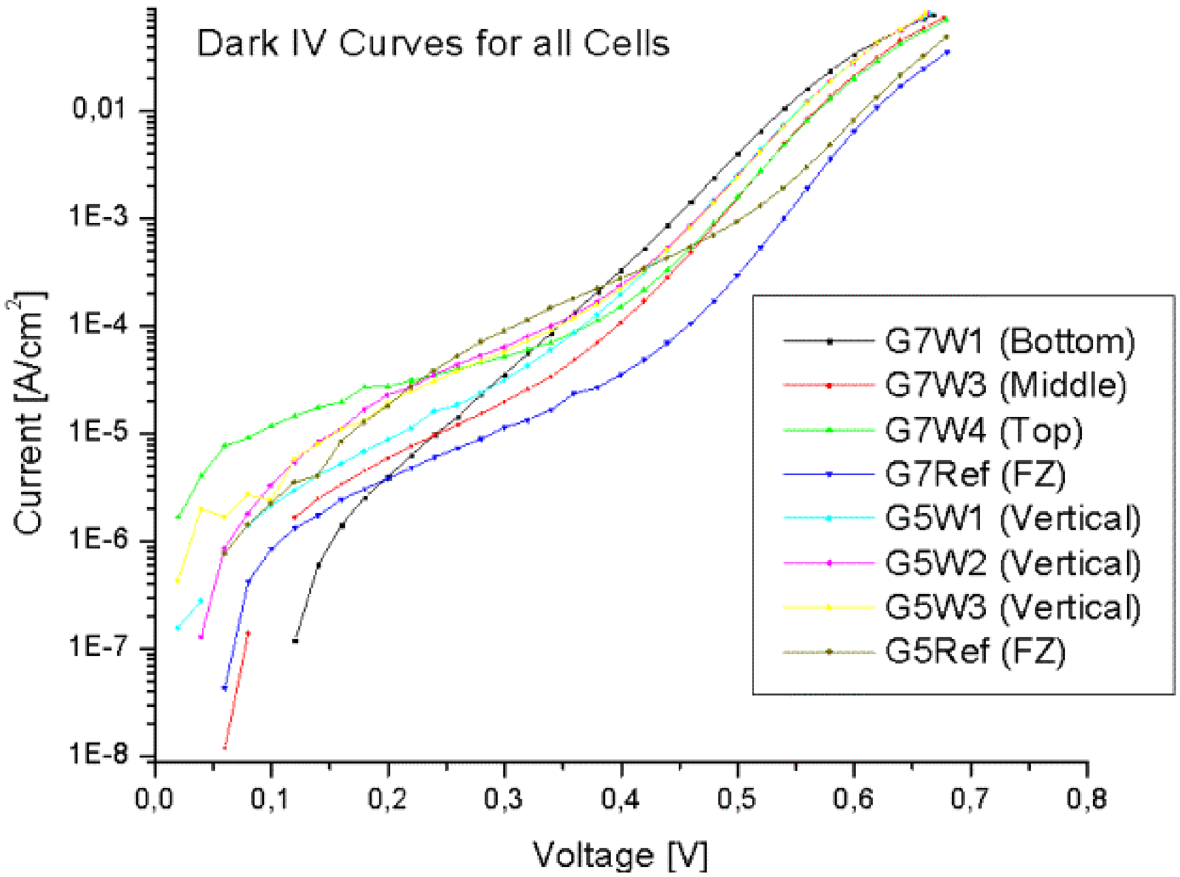
$$J = J_L - J_{01}\exp\left(\frac{q(V+JR_s)}{kT}\right) - J_{02}\exp\left(\frac{q(V+JR_s)}{2kT}\right) - \frac{V+JR_s}{R_{shunt}}$$

Note: You may see this formula with sign of current inverted. Simply multiply each "J" by "-1".



IV Curve Measurements

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

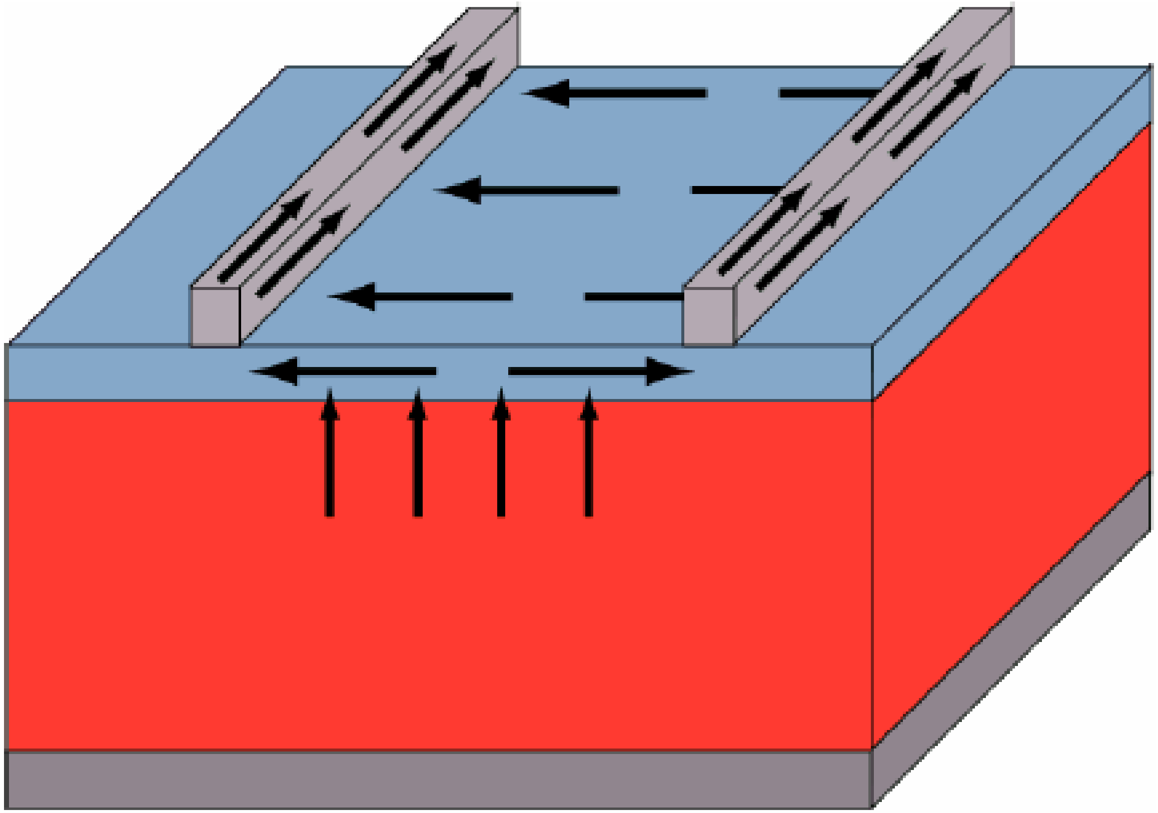


#14
#100
#124
FZ, e.s.r. 79-87 Ω/sq.
#9
#14
#100
FZ, e.s.r. 85-101 Ω/sq.

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.



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

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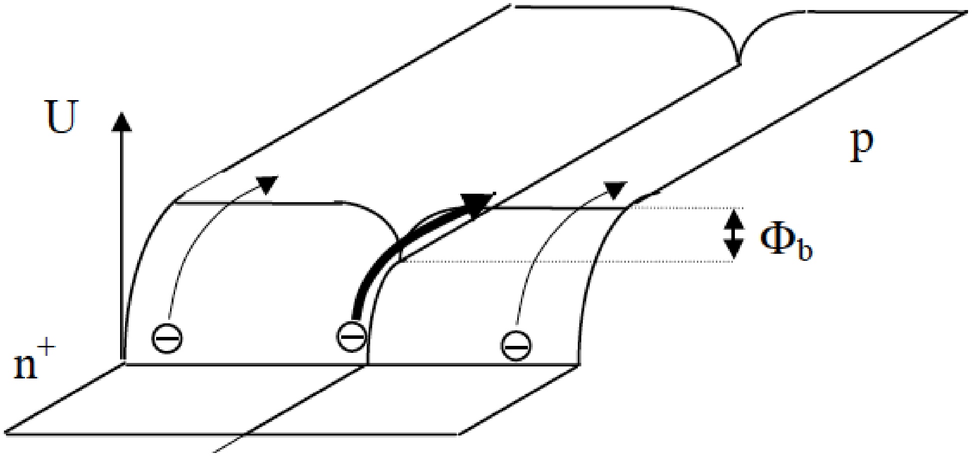
Physical Causes of Shunt Resistance

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).



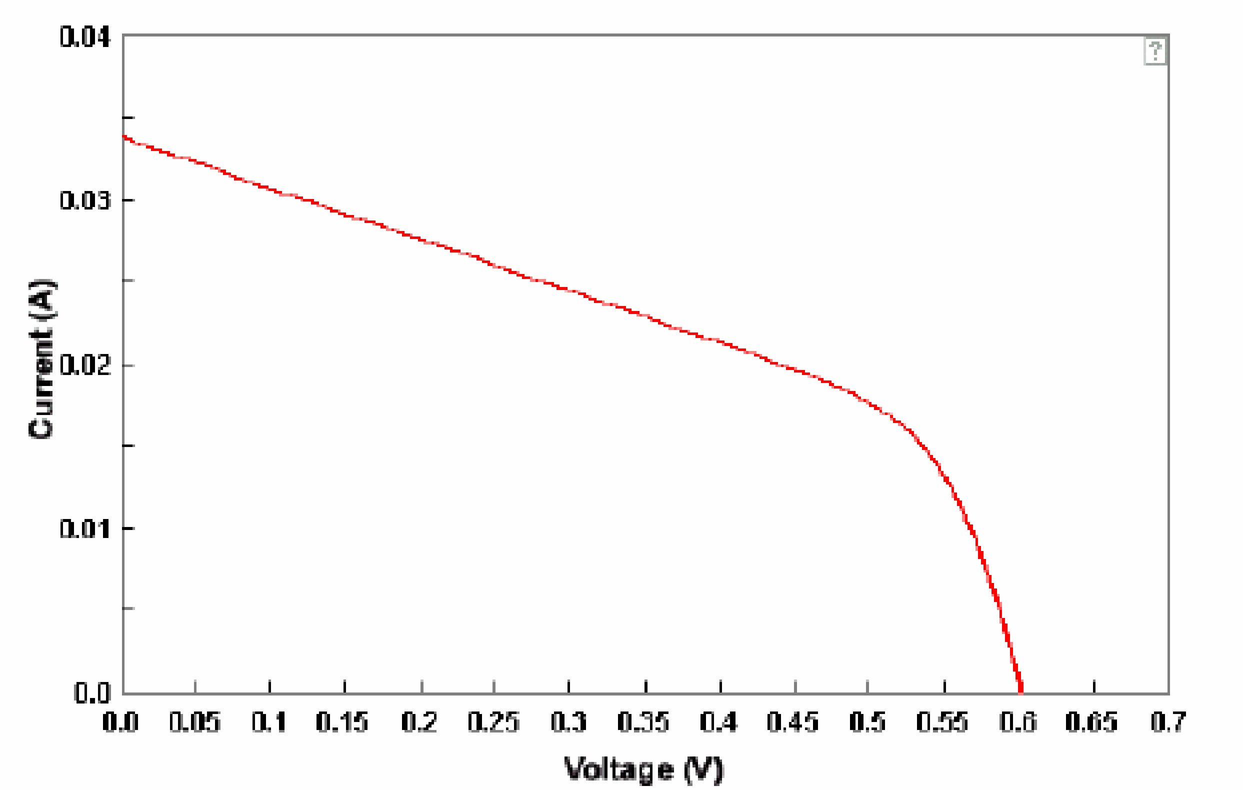
Courtesy of Trans Tech Publications and Otwin Breitenstein. Used with permission.

Potential barrier for electrons at a forward-biased n^+p junction crossed by a charged extended defect.

O. Breitenstein *et al.*, “EBIC investigation of a 3-Dimensional Network of Inversion Channels in Solar Cells on Silicon Ribbons,” *Solid State Phenomena* **78-79**, 29-38 (2001).

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.



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

Lock-in Thermography

Lock-in Thermography Images Shunts

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

See the lecture 16 video for related visuals and explanation.

Lock-in Thermography

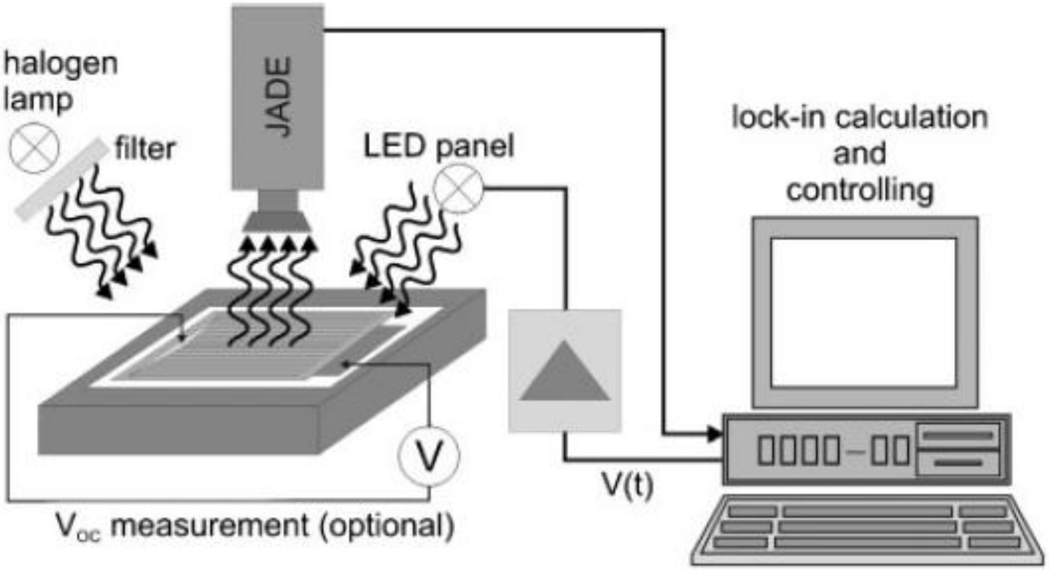
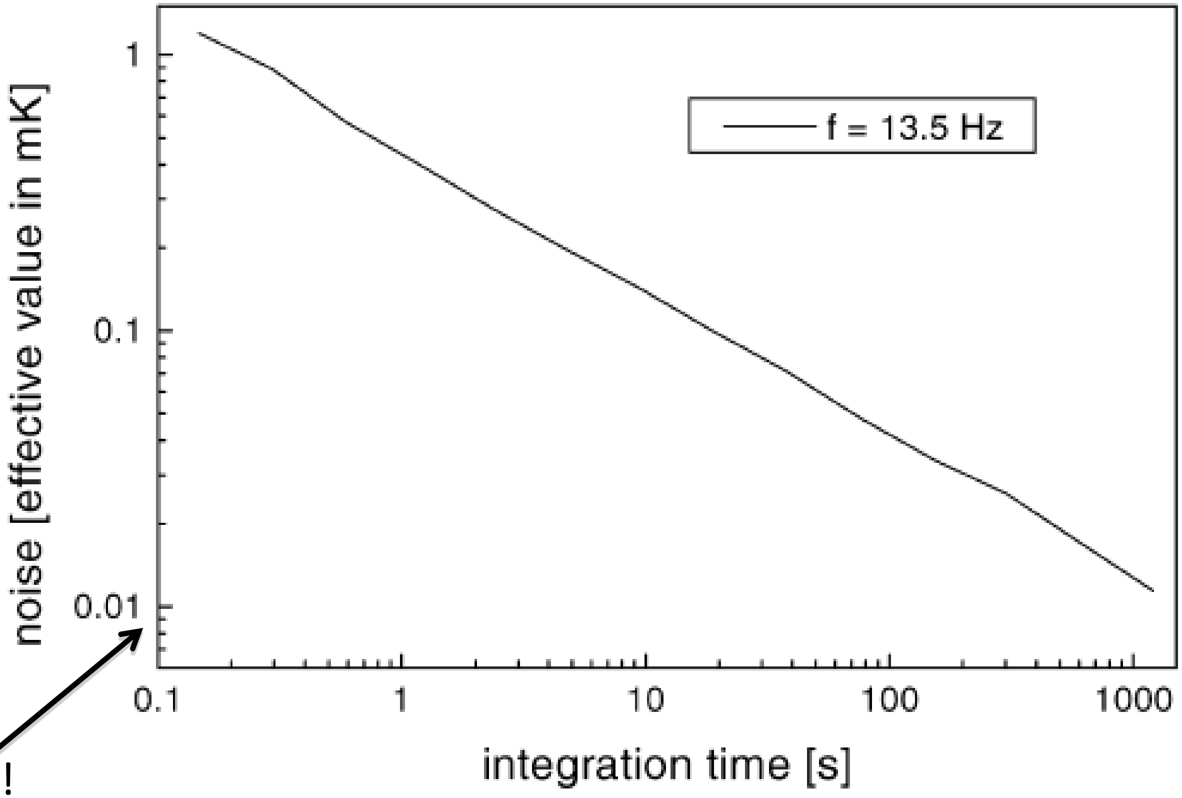


Figure 1. Experimental set-up of the LimoLIT measurement assembly. The wafer with a *pn* junction or the solar cell can be illuminated by a halogen lamp (constant-bias light). The modulated reference signal (pulsed light) is provided by an array of LEDs. Different wavelengths can be used

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



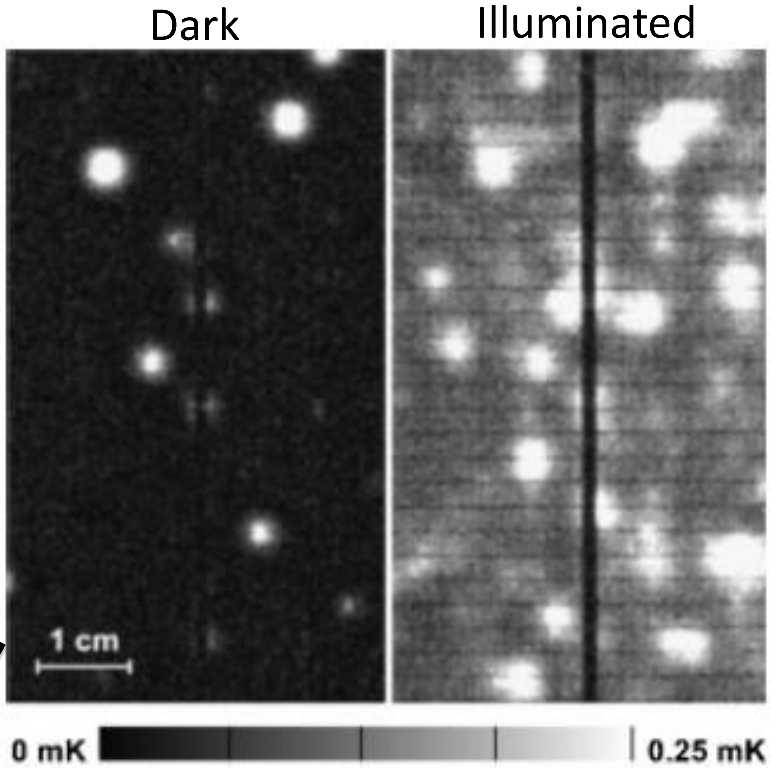
rattlesnake!

Courtesy of Elsevier, Inc., http://www.sciencedirect.com. Used with permission.

Sensitivity is a function of integration time.

O Breitenstein et al., *Solar Energy Mater. Solar Cells* **65**, 55 (2001)

Lock-in Thermography – Dark vs. Illuminated



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

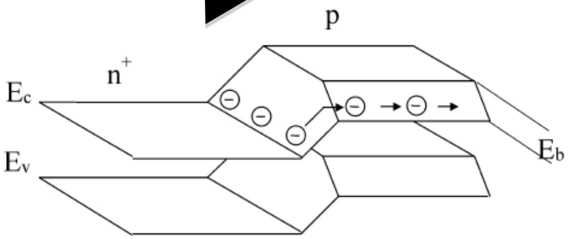


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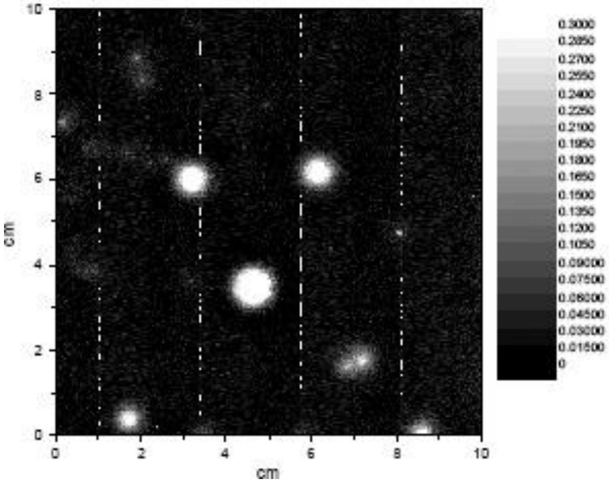
Fig. 6. Schematic 2-dimensional potential distribution on a positively charged surface (in front) crossing an n^+p-junction. E_c: conduction band edge, E_v: valence band edge, E_b: surface potential barrier height.

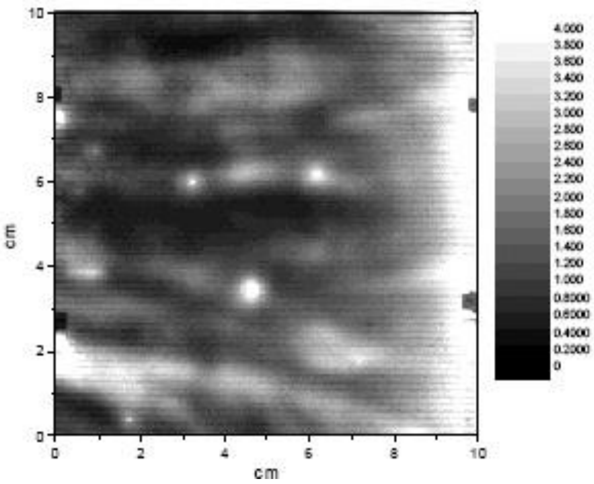
Lock-in Thermography – Imaging Losses

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

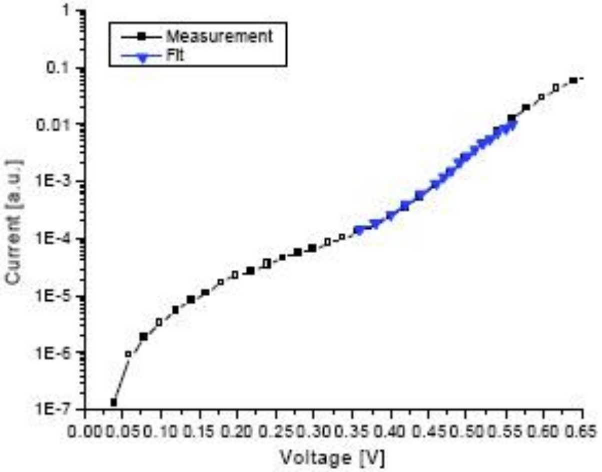
a) Lock in Thermography
V_{bias}=360 mV



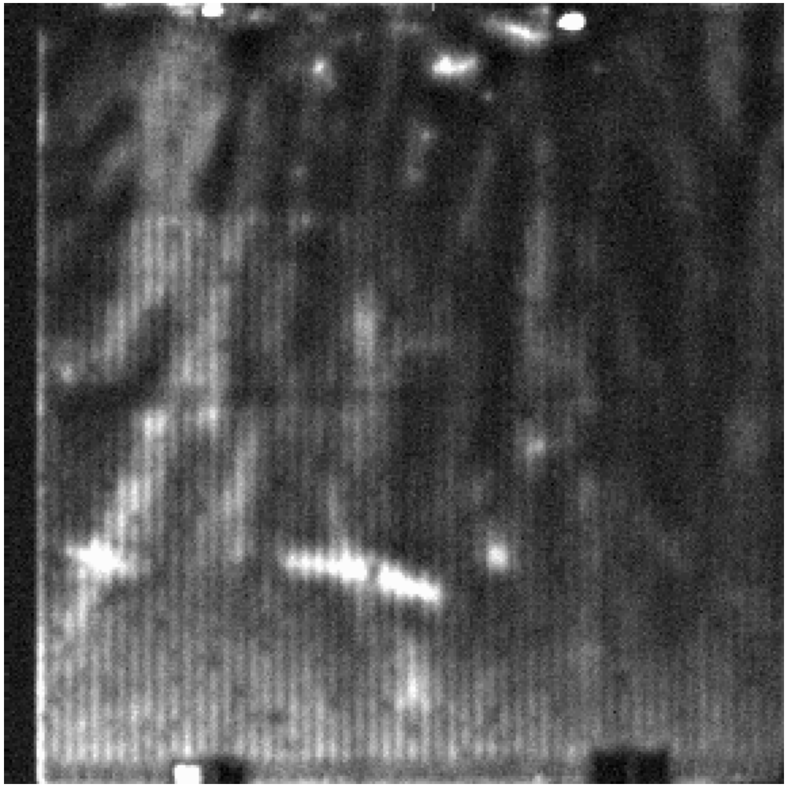
b) Lock in Thermography
V_{bias}=560 mV



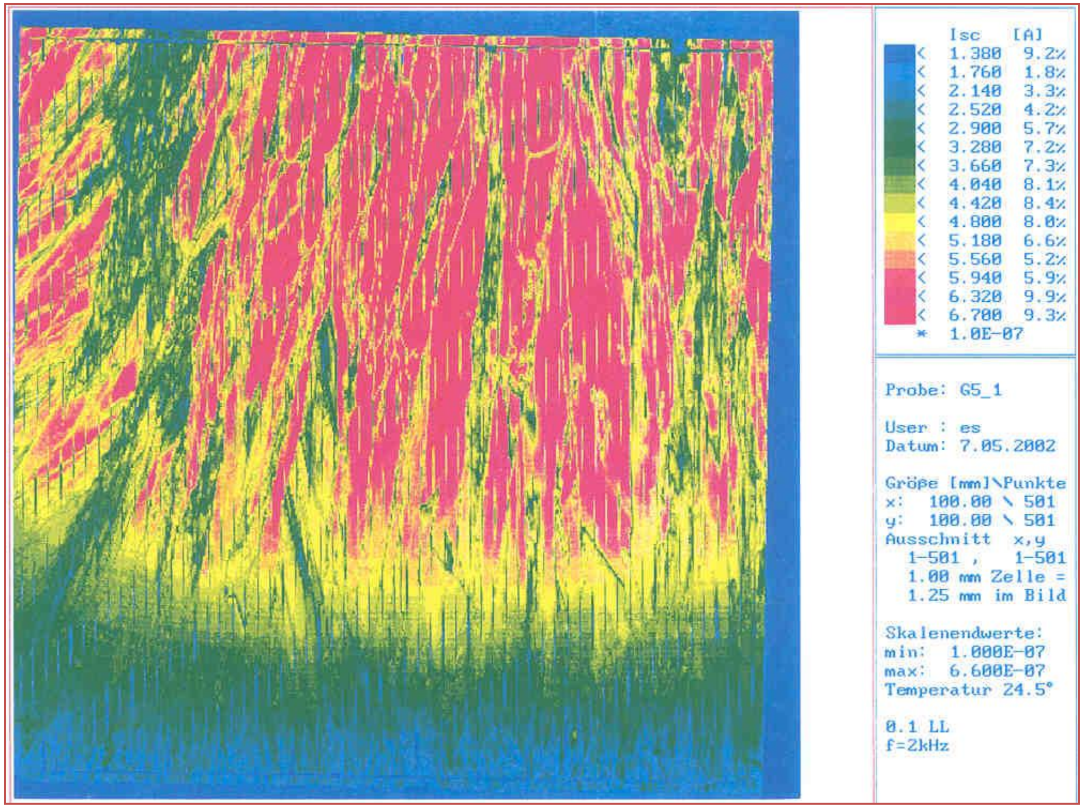
c) Dark IV Curve Fitting



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)

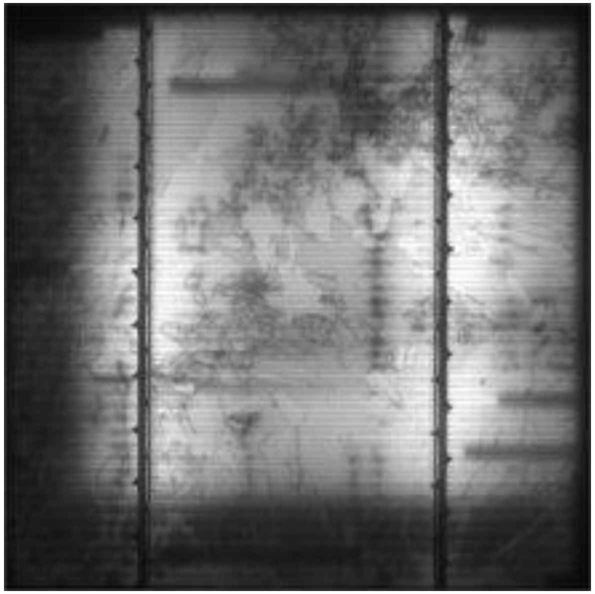
Cheaper Methods of Shunt Detection:

Liquid Crystal Thermochromic Sheets

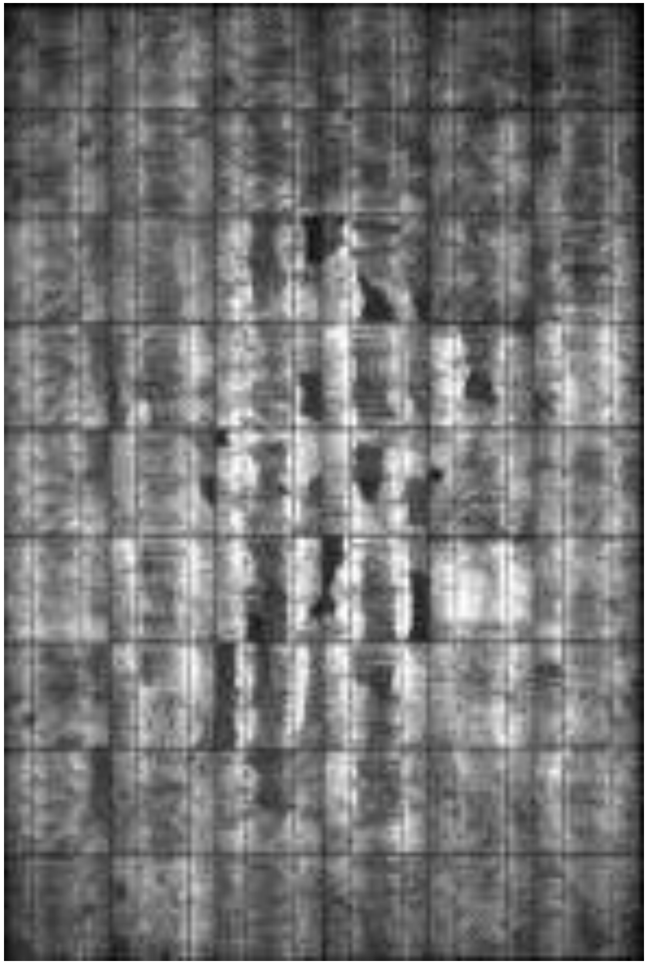
See: “Shunt imaging in solar cells using low cost commercial liquid crystal sheets” C. Ballif *et al.*, *Proc. IEEE Photovoltaic Specialists Conference*, 2002, pp. 446- 449.

Electroluminescence

Cell



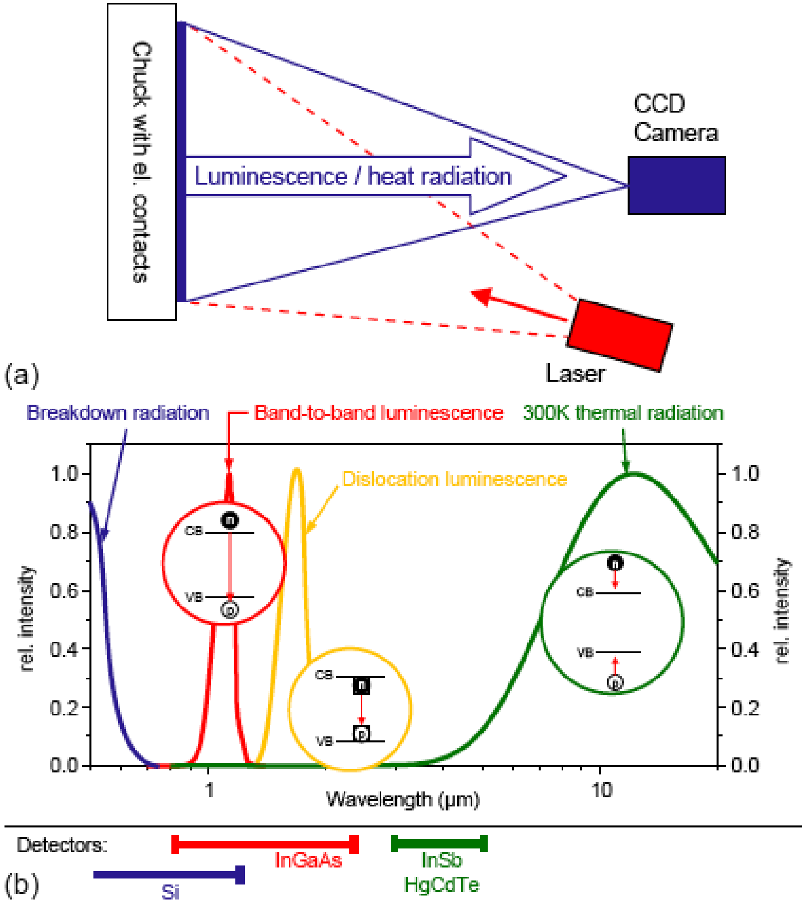
Module



Courtesy of ISFH. Used with permission.

Images courtesy ISFH

Evolution of IR Imaging Techniques



Kasemann, M., et al. “Progress in Silicon Solar Cell Characterization with Infrared Imaging Methods.” Proceedings of the 23rd European Photovoltaic Solar Energy Conference (2008): 965-973.

Suns-Voc

- Measures V_{oc} as a function of illumination condition, with decaying flash lamp.
- Useful for decoupling series resistance losses from other defects.
- Commercialized by Sinton Instruments.

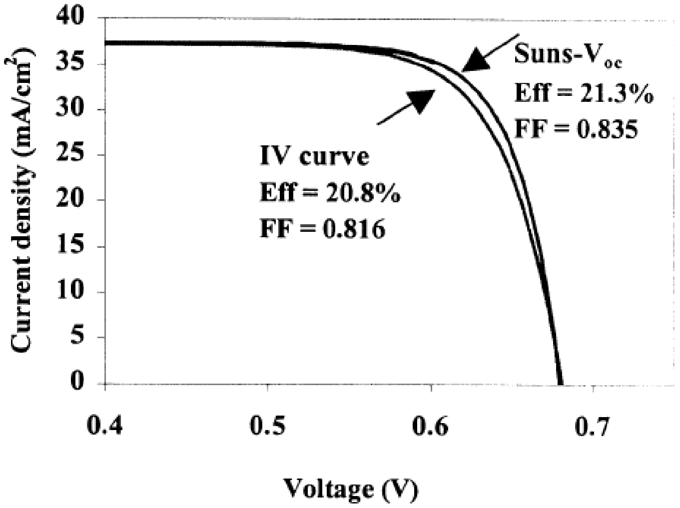


Figure 5. The same Suns-V_{oc} data as in Figure 3, plotted as a photovoltaic IV curve and compared to the IV curve taken on the finished cell.

Sinton and Cuevas, Proc. 16th EU-PVSEC (Glasgow, UK, 2000).

2.627 / 2.626 Fundamentals of Photovoltaics
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