Solar Cell Characterization

Lecture 16 – 11/8/2011
MIT Fundamentals of Photovoltaics
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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

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


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

Q: What other mechanisms exist to trap light?

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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.

With high surface recombination, the collection probability at the surface is low.

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Collection Probability

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

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Collection Probability

\[ J_{sc} \text{ determined by generation rate and collection probability} \]

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

\[ = q \int_0^W \left( \int_0^\infty \alpha(\lambda)H_0e^{-\alpha(\lambda)x}d\lambda \right)CP(x)dx \]

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Spectral Response

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Spectral Response

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

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

Blue response is reduced due to front surface recombination.

Ideal quantum efficiency

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

\[ \lambda = \frac{hc}{E_g} \]

from PVCDROM

Standards: IEC 60904-3 and 60904-8
External vs. Internal Quantum Efficiency

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

...where $R$ = Reflectivity
Spectrally-Resolved Laser Beam Induced Current (SR-LBIC)

- 4 or more lasers measure IQE(\(\lambda\)).
- 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.

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

http://www.isfh.de/institut_solarforschung/media/sr_lbic_messplatz_1.jpg
Minority Carrier Diffusion Length

At each point...

\[ IQE^{-1} = 1 + \alpha^{-1} \cos \theta \]

\[ \frac{1}{\alpha} (\mu m) \]

\[ 1/QE \]

Mapped over an entire sample...

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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

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

- **Diffusion Current**
- **Recombination Current**

\[ R_s = R_{series} \text{ For good solar cell, this must be small.} \]

\[ R_p = R_{shunt} \text{ For good solar cell, this must be large.} \]
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”.

Buonassisi (MIT) 2011
IV Curve Measurements

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

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

**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)

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 \emph{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.

Lock-in Thermography - Sensitivity

Sensitivity is a function of integration time.


Lock-in Thermography – Dark vs. Illuminated


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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  
\( V_{\text{bias}} = 360 \text{ mV} \)

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

c) Dark IV Curve Fitting
Correlation between Thermography and LBIC

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

White-light LBIC 
(essentially probes the bulk, below the emitter)
Cheaper Methods of Shunt Detection:

Liquid Crystal Thermochromic Sheets

Electroluminescence

Cell

Module

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Evolution of IR Imaging Techniques


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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.

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