Electrical Characterization and Measurement of Solar Cells

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Agenda

1. Solar Cell Market and Principle Overview
2. Solar Cell Efficiency
3. I-V Measurement of Efficiency
4. Understanding the Sources of Efficiency Loss
5. Measuring Key Parameters of a Solar Cell
6. Summary and Conclusions
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Solar Power Plant with MPPT of One Axis, US

Source: http://en.wikipedia.org/wiki/Photovoltaics
‘Mega Solar Panels’, 70MW, Southern JP

Source: http://www.renewableenergyfocus.com/
Japan Set to Overtake US and Europe as Leading Solar Market of 2013

Source: http://www.solarsystems-usa.net/
Global Solar Panel Demand to Double in 3 Years

Source: http://www.solarsystems-usa.net/ , 2013
Basic Working Principle of Solar Cell

1. 單晶矽太陽電池 (single crystal Si), Wafer type
2. 多晶矽太陽電池 (poly crystal Si), Wafer type
3. 非晶矽太陽電池 (amorphous Si), Thin film type
4. 化合物半導體太陽電池, Compound semiconductor
5. 其他太陽電池 (Other solar cells)
Schematic of a Typical Single Junction Si Solar Cell: The principle of operation of the solar cell

- A Si pn junction with a very thin and more heavily doped n region
- Finger electrodes and thin antireflection (AR) coating on the surface
- Generation of Electron-Hole Pairs (EHP)

Source: Prof. Wei-I Lee, http://ocw.nctu.edu.tw/
Four and Five Junction Solar Cells

High-Efficiency Multi-junction Photovoltaics

GaP high band gap top cell in multi-junction stack needed to achieve 50% (the DARPA target efficiency)

Source: Purdue University Energy Center
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Key Technical Challenge: Increase Efficiency
Current-Voltage (IV) Load Sweep of a Solar Cell

$I (mA)$

$V$

$I_{ph}$

$V_{oc}$

$I$-V under dark, or dark I-V, shifted by $I_{sc}$ (-$I_{ph}$)

Source: Prof. Wei-I Lee, http://ocw.nctu.edu.tw/
Delivered Power and Fill Factor

- power delivered to the load, \( P_{\text{out}} = I'V' \)

- fill factor \( \text{FF} = \frac{(I_mV_m)}{(I_{sc}V_{oc})} \)
  
  \((I_mV_m)\) : maximized delivered power, i.e. the largest \((I'V')\) rectangular area obtainable (by changing \(R\) or illumination intensity)

- typical \( \text{FF} : 70 \sim 85\% \)

Source: Prof. Wei-I Lee, http://ocw.nctu.edu.tw/
Current-Voltage (IV) Load Sweep of a Solar Cell

- Short Circuit: $I_{sc} = -I_{ph}$

- Driving External Load $R$: $I = I_d - I_{ph}$

- Open Circuit

**Total Current:**

$$I = -I_{ph} + I_o \left[ \exp \left( \frac{eV}{n k_B T} \right) - 1 \right]$$

**Graph:**
- Cell Current (mA) vs. Cell Voltage (V)
- Maximum Power Area: $P_{max} = I_{max} V_{max}$

**Logos:**
- Keithley
- Tektronix
I-V Measurements for Solar Cell Efficiency

Maximum Power Area

\[ P_{\text{max}} = I_{\text{max}} V_{\text{max}} \]

Fill Factor:

\[ FF = \frac{I_{\text{MAX}} V_{\text{MAX}}}{I_{\text{SC}} V_{\text{OC}}} \]

% efficiency vs. an ideal cell
I-V Measurements for Solar Cell Efficiency w/ Keithley ACS (Parameter Extraction)
I-V Measurements for Solar Cell Efficiency

Cell Efficiency ($\eta$):

$$\eta = \frac{P_{\text{MAX}}}{P_{\text{IN}}}$$

*Power output as a ratio of power input to the cell. ($P_{\text{IN}}$ is the power of the light intensity on the cell)*
I-V Measurements for Solar Cell Efficiency

One SMU can be used to set and monitor power into a light source.

Use a light source with a known output power and spectrum.

One SMU conducts the I-V curve on the cell.

Cell Efficiency ($\eta$):

$$\eta = \frac{P_{\text{MAX}}}{P_{\text{IN}}}$$

Power output as a ratio of power input to the cell.

($P_{\text{IN}}$ is the energy of the light on the cell)
I-V Measurements for Solar Cell Efficiency w/ Keithley ACS (Parameter Extraction)
Ideal Electrical Model of a Solar Cell

\[ I = I_L - I_0 \left( \frac{qV}{enkT} - 1 \right) \]
Real World Electrical Model of a Solar Cell

\[ I = I_L - I_0 \left[ \exp \left( \frac{q(V + IR_S)}{nkT} \right) - 1 \right] - \frac{V + IR_S}{R_{SH}} \]
Real World Electrical Model of a Solar Cell, Rs

\[ I = I_L - I_0 \left[ \exp \left( \frac{q(V + IR_S)}{nkT} \right) - 1 \right] - \frac{V + IR_S}{R_{SH}} \]

As Rs increases, cell efficiency decreases
Real World Electrical Model of a Solar Cell, $R_{sh}$

Solar cell

\[ I = I_L - I_0 \left( \exp \left( \frac{q(V + IR_S)}{n k T} \right) - 1 \right) - \frac{V + IR_S}{R_{SH}} \]

As $R_{sh}$ decreases; cell efficiency decreases
Real World Electrical Model of a Solar Cell, T

\[ I = I_L - I_0 \left[ \exp \left( \frac{q(V + IR_S)}{nkT} \right) - 1 \right] - \frac{V + IR_S}{R_{SH}} \]

As T increases; cell efficiency decreases
Measuring Series Resistance (Rs)
Low Rs → Low Parasitic Loss → Better Efficiency

Rs can be roughly approximated from the slope of this portion of the curve, but there are errors!
Measuring Series Resistance (Rs)
Low Rs → Low Parasitic Loss → Better Efficiency

Parameter to be measured: Rs

Rs Measurement with Slope Method
(from a series of forward IV sweeps)

\[ r_s = \frac{\Delta V}{N} \]

This differential method makes the measurement independent of \( n, I_0, \) and \( R_{Sh} \) which are more difficult to accurately measure.
Measuring Series Resistance (Rs)
Low Rs $\rightarrow$ Low Parasitic Loss $\rightarrow$ Better Efficiency
Measuring Shunt Resistance (Rsh)
High Rsh $\rightarrow$ Low Internal Loss $\rightarrow$ Better Efficiency

Rsh can be estimated from slope of a reverse I-V sweep
Measuring Characteristic Resistance: Max Output Efficiency with $R_{CH}$ Matching

Characteristic Resistance: Resistance at Pmax tells you how to connect (set R for load) to avoid external losses

$R_{CH} = \frac{V_{MP}}{I_{MP}}$

It can alternately be given as an approximation where:

$R_{CH} = \frac{V_{OC}}{I_{SC}}$
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### Summary of Electrical Characterization for Solar Cells & Key Parameters

<table>
<thead>
<tr>
<th>I-V Test (Current-Voltage)</th>
<th>DC Instrument Requirements</th>
<th>Available Instruments</th>
</tr>
</thead>
<tbody>
<tr>
<td>open circuit voltage (Voc)</td>
<td>Four Quadrant Operation</td>
<td>![Image of Keithley instruments]</td>
</tr>
<tr>
<td>short circuit current (Isc)</td>
<td>Ability to source and sink current and voltages up to 50A, 40V (dark and illuminated)</td>
<td></td>
</tr>
<tr>
<td>maximum power output (Pmax)</td>
<td>Remote Sense</td>
<td></td>
</tr>
<tr>
<td>Voltage at Pmax (Vmax)</td>
<td>Suitable Keithley Models:</td>
<td></td>
</tr>
<tr>
<td>fill factor (ff)</td>
<td>2430: 2nA-10A, 5μV – 100V</td>
<td></td>
</tr>
<tr>
<td>series resistance (Rs, Ω)</td>
<td>2440: 2nA – 5A, 5μV – 40V</td>
<td></td>
</tr>
<tr>
<td>shunt resistance (Rsh, Ω)</td>
<td>2612A: 1pA – 10A, 5μV – 200V</td>
<td></td>
</tr>
<tr>
<td>conversion efficiency (η)</td>
<td>2651A: 1pA – 50A, 5μV – 40V</td>
<td></td>
</tr>
<tr>
<td>cell resistivity (ρ)</td>
<td>4200-SCS: 1fA – 1A, 1μV – 200V</td>
<td></td>
</tr>
</tbody>
</table>

历史性成就，人类将在2050年达到碳中和。
### Summary of Electrical Characterization for Solar Cells & Key Parameters

<table>
<thead>
<tr>
<th>C-V Test (Capacitance-Voltage)</th>
<th>C-V Instrument Requirements</th>
<th>Available Instruments</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Doping Density (N)</td>
<td>• Variable AC drive</td>
<td></td>
</tr>
<tr>
<td>• Defect Density (defects/unit area)</td>
<td>• Variable DC Bias (up to 30V), must be able to sink current</td>
<td>Tektronix Instruments</td>
</tr>
<tr>
<td></td>
<td>• Multi-frequency</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Wide operating range (pF to μF)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Suitable Keithley Model: 4210-CVU:</td>
<td></td>
</tr>
<tr>
<td></td>
<td>C: 10fF – 10μF</td>
<td></td>
</tr>
<tr>
<td></td>
<td>ACV: 10 mVrms – 100 mVrms</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Frequency: 1kHz – 10MHz</td>
<td></td>
</tr>
</tbody>
</table>
# Summary of Electrical Characterization for Solar Cells & Key Parameters

<table>
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<tr>
<th>Pulsed I-V Test</th>
<th>Pulsed Testing Instrument Requirement</th>
<th>Available Instruments</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Involves measuring photons-input vs. electron-output (across wavelength)</td>
<td>• Large cells require large current output (&gt; 20 A)</td>
<td><img src="image1.png" alt="Pulse Measure Unit" /></td>
</tr>
<tr>
<td>• Minority Carrier Lifetime</td>
<td>• Requires the ability to perform fast current and voltage measurements (carrier lifetimes can be &lt;&lt; 100μs)</td>
<td><img src="image2.png" alt="Pulse Measure Unit" /></td>
</tr>
<tr>
<td>• Pulsed open circuit voltage (Voc)</td>
<td>• Suitable Keithley Instruments:</td>
<td></td>
</tr>
<tr>
<td>• Pulsed short circuit current (Isc)</td>
<td>4225-PMU (high speed pulse-measure unit)</td>
<td></td>
</tr>
<tr>
<td>• Pulsed maximum power output (Pmax)</td>
<td>2651A (high current pulse and high speed acquisition)</td>
<td></td>
</tr>
</tbody>
</table>
Conclusions

1. Solar cell is a good technology of green energy with double digits in 3 Years.

2. Developing processes can be improved with precision I-V measurements of cell parameters (Isc, Voc, Imax, Vmax, Pmax, FF, η, Rs, Rsh, R_{CH}, ...)

3. Solar Cell tests can be done quickly and easily with Keithley single instrument solution.

4. Difficult I-V/C-V measurements of properties of the semiconductor material and doping technologies can be made simple with Keithley measurement system.

5. Right DUT and right tools. Keithley offers different series of SMUs for different requirements of voltage, current, power and accuracy levels.
Q & A

- Thanks for participating in this topic of today’s seminar.

- For more information about electrical characterization of solar cells feel free to visit and view Keithley web site or contact us.

- Any questions
Electrical Characterization and Measurement of Solar Cells

Thanks for your time ~~