Lecture 5
Junction characterisation

Jon Major

October 2018
The PV research cycle

Make cells → Measure cells → Repeat → Data
Key junction characterisation techniques

- Analysis of current voltage (J-V) curves
- External quantum efficiency (EQE) measurements
- Capacitance voltage (C-V) measurements
Parasitic resistances

Perfect p-n junction

Real p-n junction

A good device should have low $R_S$

And high $R_{Sh}$
Causes of high $R_s$ values
- Overly thick absorber layer
- Low conductivity TCO
- Low doping levels
- Low FF

Causes of low $R_{sh}$ values
- Pinholes in layers
- Weak diode regions
- Low $V_{OC}$
J-V analysis (J-V)

CdTe
CdS
ZnO
SnO$_2$:F
To determine $R_{sh}$, fit to straight line portion of JV curve in reverse bias.

$R_s$ can be more difficult to accurately determine. Two common methods:

- **Fit to forward bias region of curve**
- **Measure change as function of light bias**
If a non-ohmic contact is formed this results in the creation of a back contact junction diode.

This back-contact diode opposes the main junction diode and leads to the phenomenon of “roll-over” at high forward bias.
J-V analysis (J-V)

For a p-type semiconductor, we can create an ohmic contact if:

\[ \phi_m \geq \chi_s + E_g \]

- **Metal work function**
- **Electron affinity**
- **Bandgap**

If this condition is not met, we introduce a back contact Schottky barrier:

\[ \Phi \approx \phi_m - (\chi_s + E_g) \]

- **Back contact barrier height**
Influence of barrier height changes as a function of temperature

By measuring J-V curves as a function of temperature we can extract the barrier height
Series resistance varies with temperature via:

\[ R_S = R_{\Omega 0} + \frac{\partial R_{\Omega 0}}{\partial T} T + \frac{C}{T^2} \exp\left(\frac{\Phi_b}{kT}\right) \]

- Ohmic resistance
- Ohmic temperature dependence

Fitting to exponential region allows us to extract a value in eV for the barrier height. Generally anything < 0.3eV is considered a good contact.
Accurate J-V measurement: A cautionary tale

Graphs showing the relationship between etch time (s) and various parameters such as Efficiency (%), $J_{SC}$ (mA/cm$^2$), $V_{oc}$ (V), and Fill factor (%) with error bars.
• High $V_{oc}$ is reliable.

• $J_{sc}$ values are very sensitive to calibration or contact size errors.

• Contacts should be minimum of 0.25cm$^2$

• If it looks too good to be true it usually is!
<table>
<thead>
<tr>
<th>Cells (silicon)</th>
<th>Efficiency (%)</th>
<th>Area (cm²)</th>
<th>Vₜ (V)</th>
<th>Jₛ (mA/cm²)</th>
<th>Fill factor (%)</th>
<th>Test centre (date)</th>
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</tr>
</thead>
<tbody>
<tr>
<td>Si (crystalline)</td>
<td>25.0 ± 0.5</td>
<td>4.00 (da)</td>
<td>0.706</td>
<td>42.7d</td>
<td>82.8</td>
<td>Sandia (3/99)*</td>
<td>UNSW PERL top/rear contacts [44]</td>
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<tr>
<td>Si (large crystalline)</td>
<td>25.0 ± 0.7</td>
<td>120.94 (ap)</td>
<td>0.726</td>
<td>41.5f</td>
<td>82.8</td>
<td>FhG ISE (2/14)</td>
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</tr>
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<td>Si (large multicrystalline)</td>
<td>19.5 ± 0.4</td>
<td>242.7 (t)</td>
<td>0.652</td>
<td>39.0g</td>
<td>76.7</td>
<td>FhG ISE (3/11)</td>
<td>Q-Cells, laser fired contacts [46]</td>
</tr>
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<td>Cells (III–V)</td>
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<tr>
<td>GaInP</td>
<td>20.8 ± 0.6</td>
<td>0.2491 (ap)</td>
<td>1.4550</td>
<td>16.04h</td>
<td>89.3</td>
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<td>0.7963</td>
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### Efficiency tables

#### Jan 2015

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<tr>
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<td>Sharp [7]</td>
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<td>Dye (minimodule)</td>
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<td>26.55 (da)</td>
<td>0.754c</td>
<td>20.19d</td>
<td>69.9</td>
<td>AIST (2/15)</td>
<td>Sharp, seven serial cells [7]</td>
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<tr>
<td>Dye (submodule)</td>
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<td>398.8 (da)</td>
<td>0.697c</td>
<td>18.42d</td>
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<td>Organic thin film</td>
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<td>0.993 (da)</td>
<td>0.793</td>
<td>19.40b</td>
<td>71.4</td>
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<td>Toshiba [8]</td>
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<td>26.14 (da)</td>
<td>0.686c</td>
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<td>Toshiba (eight series cells) [8]</td>
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<tr>
<td>Perovskite</td>
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</tr>
<tr>
<td>Perovskite thin-film</td>
<td>15.0 ± 0.6m</td>
<td>1.017 (ap)</td>
<td>1.090</td>
<td>20.61l</td>
<td>66.8</td>
<td>AIST (2/15)</td>
<td>NIMS [12]</td>
</tr>
</tbody>
</table>
5. Please state the dimensions of the tested solar cells.

6. Please state in the Methods section whether a mask/aperture was used for measurements. If this is the case, please state the size of the used mask/aperture and declare whether the measured short-circuit current density of the devices varies with the mask/aperture area. If a mask/aperture was not used, please explain in the Methods section why it was not used.

7. Have you observed hysteresis or any other unusual behaviour during the characterization of the solar cells? If this is the case, please include a description of the observed behaviour and the related experimental data.
External quantum efficiency (EQE)
External quantum efficiency (EQE)

\[ E(\lambda) = \frac{hc}{\lambda} \]
Define the EQE as the ratio of photons in to current generated

\[ \text{EQE} = \frac{J_{\text{cell}}}{J_{\text{photon}}} \]

A 100% EQE means every photon that strikes the cell generates an electron hole pair which flows through the external circuit.
External quantum efficiency (EQE)

Theoretical case

Area under curve proportional to $J_{SC}$
Most solar cell technologies display same typical “top hat” EQE curve shape.
External quantum efficiency (EQE)

Accelerated Publication

Solar cell efficiency tables (version 44)

Martin A. Green1,*, Keith Emery2, Yoshihiko Hishikawa3, Wilhelm Warta4 and Ewan D. Dunlop5

1 Australian Centre for Advanced Photovoltaics, University of New South Wales, Sydney, 2052, Australia
2 National Renewable Energy Laboratory, 16313 Denver West Parkway, Golden, CO, 80401, USA
3 Research Center for Photovoltaic Technologies (RPVT), National Institute of Advanced Industrial Science and Technology (AIST), 2-1-1, Umezono, Tsukuba, Ibaraki, 305-8568, JAPAN
4 Department of Materials and Technology, Solar Cells, Fraunhofer Institute for Solar Energy Systems, Heidenhofstr. 2; D-76110 Freiburg, Germany
5 Joint Research Centre, Renewable Energy Unit

Abstract

Consolidated tables showing an extensive modules are presented. Guidelines for in 2014 are reviewed. Copyright © 2014 Jo

Table 1: Confirmed terrestrial cell and submodule efficiencies measured under the global AM1.5 spectrum (1000 W/m2) at 25 °C (IEC 60904-3, 2008). ASTM G173-03 (global).

<table>
<thead>
<tr>
<th>Classification</th>
<th>Efficiency</th>
<th>Area^2</th>
<th>Voc</th>
<th>Jsc</th>
<th>Fill factor</th>
<th>Test conditions</th>
<th>Description</th>
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</thead>
<tbody>
<tr>
<td>Si crystalline</td>
<td>25.6 ± 0.5</td>
<td>143.7</td>
<td>0.74</td>
<td>41.0</td>
<td>92.7</td>
<td>JSAC-2 (14)</td>
<td>Panasonic HIT (14)</td>
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<tr>
<td>Si amorphous</td>
<td>19.6 ± 0.3</td>
<td>53.0</td>
<td>0.80</td>
<td>39.0</td>
<td>86.9</td>
<td>JSAC-2 (15)</td>
<td>NREL 600W</td>
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<tr>
<td>CZTSSe (Thin film)</td>
<td>10.5 ± 0.3</td>
<td>19.0</td>
<td>0.88</td>
<td>19.4</td>
<td>73.1</td>
<td>CIGS Solar 200</td>
<td>30 cells (23)</td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>Si-H2 cells</th>
<th>MgF (thin film)</th>
<th>20.8 ± 0.9</th>
<th>0.99</th>
<th>38.0</th>
<th>96.0</th>
<th>JSAC-2 (16)</th>
<th>Alta Devices (34)</th>
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<tbody>
<tr>
<td>InP-InGaN</td>
<td>18.4 ± 0.5</td>
<td>4.01 (11)</td>
<td>0.03</td>
<td>23.2</td>
<td>76.7</td>
<td>JSAC-2 (10)</td>
<td>AFL Solar (24)</td>
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<tr>
<td>HgTe quantum dot</td>
<td>22.1 ± 0.7</td>
<td>4.02 (11)</td>
<td>0.07</td>
<td>29.5</td>
<td>86.7</td>
<td>JSAC-2 (25)</td>
<td>Sapi, epstein (24)</td>
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<tr>
<td>CIGS (thin film)</td>
<td>20.5 ± 0.6</td>
<td>0.99 (222)</td>
<td>0.95</td>
<td>35.7</td>
<td>77.2</td>
<td>JSAC-2 (16)</td>
<td>Solibro, on glass (27)</td>
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<td>18.82 (11)</td>
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<td>76.8</td>
<td>JSAC-2 (16)</td>
<td>GE Global Research (28)</td>
</tr>
<tr>
<td>CuInGSSe (thin film)</td>
<td>19.6 ± 0.4</td>
<td>1.00 (222)</td>
<td>0.86</td>
<td>28.0</td>
<td>80.0</td>
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Wavelength, nm

EQE, %

NREL 23.3% CIGS conc. cell
Snowa Shell 20.9% CIGS cell
Solibro 20.5% CIGS cell
KRIT 17.9% perovskite cell
Advancis 16.6% CIGS module
IBM 12.6% CZTSSe cell
External quantum efficiency (EQE)

Glass
Transparent conductive oxide (e.g. ITO)
Window layer (e.g. CdS)
Absorber layer (e.g. CdTe)

Region 1: $E_{\text{photon}} < E_{\text{Absorber}}$

$E(\lambda) = \frac{hC}{\lambda}$
External quantum efficiency (EQE)
External quantum efficiency (EQE)

Region 2: $E_{\text{photon}} > E_{\text{Absorber}}$

$$E(\lambda) = \frac{hC}{\lambda}$$
External quantum efficiency (EQE)
External quantum efficiency (EQE)

![Graph showing External quantum efficiency (EQE) vs Wavelength (nm)].

Absorber bandgap

\[ E(\lambda) = \frac{hC}{\lambda} \]
External quantum efficiency (EQE)

\[ E(\lambda) = \frac{hc}{\lambda} \]

Region 3: \( E_{\text{photon}} > E_{\text{window}} \)

- Glass
- Transparent conductive oxide (e.g. ITO)
- Window layer (e.g. CdS)
- Absorber layer (e.g. CdTe)
External quantum efficiency (EQE)
External quantum efficiency (EQE)

Window bandgap

\[ E(\lambda) = \frac{hC}{\lambda} \]
Real cells

External quantum efficiency (EQE)

\[
\begin{align*}
\text{QE} &= \text{reflection} + \text{glass absorption} \\
&\quad + \text{TCO absorption} + \text{CdS/CdTe intermixing loss} \\
&\quad + \text{recombination loss}
\end{align*}
\]

[in mA/cm²]

\[
\begin{align*}
\text{J}_{\text{sc}} &= 19.2 \\
\text{Refl. Loss} &= 1.92 \\
\text{Glass Loss} &= 1.83 \\
\text{TCO Loss} &= 1.12 \\
\text{CdS Loss} &= 4.23 \\
\text{Mixing Loss} &= 0.36 \\
\text{Rec. Loss} &= 0.73
\end{align*}
\]
Uniform reduction in EQE signal across wavelength range is an indication of optical losses i.e. reflection loss, optical blockages etc.

Can also be an indication of poor system calibration.
External quantum efficiency (EQE)

**window/ n-type layer losses**

Reduced window layer thickness allows more light transmission to absorber

Higher bandgap n-type layer shifts absorption edge
If absorber layer is thin or depletion width is narrow then longer wavelength photons have an increased probability of not contributing to photocurrent. See a decrease in EQE for longer wavelengths.
In multi component materials such as CZTS can get a broad cut-off region due to changes in the absorber bandgap.

This often signifies the material isn’t single phase and reduces the efficiency.

Can also indicate enhanced recombination close to the back surface.
In certain situations see a complete change in EQE that corresponds to very low performance.

See reasonable EQE response near absorber band-edge but low response at all other wavelengths.
This is a **buried junction response** due to both $p$ and $n$ type regions being present in the absorber layer.
Capacitance-voltage measurements are useful in deriving particular parameters about PV devices.

Depending on the type of solar cell, capacitance-voltage (C-V) measurements can be used to derive parameters such as the doping concentration and the built-in voltage of the junction.

A capacitance-frequency (C-f) sweep can be used to provide information on the existence of traps in the depletion region.
Capacitance Voltage analysis (C-V)

Can treat a p-n junction as a capacitor - depletion region sandwiched between two plates.

Can define the junction capacitance per unit area as

\[ C_j \equiv \frac{dQ}{dV} = \frac{dQ}{W} \frac{dQ}{d\varepsilon_s} = \frac{\varepsilon_s}{W} \]

Where \( W \) is the width of the depletion region and \( \varepsilon_s \) is the semiconductor permittivity.
We generally assume a one sided abrupt junction for calculations. This is due to the higher doping densities in the n-type layer meaning the depletion region lies within the p-type layer.

For a one sided junction, we can determine the depletion width as

\[ W = \sqrt{\frac{2 \varepsilon_s V}{qN_a}} \]

Electron charge \( q \)

Acceptor doping density \( N_a \)

Using previous equation, we get the relation

\[ \frac{1}{C^2} = \frac{2V}{q \varepsilon_s N_a} \]

Hence we can get \( N_a \) from a plot of \( 1/C^2 \) vs \( V \)
Measure the capacitance response of the cell as a function of applied bias.

C-V measurements can be made either forward-biased or reverse biased. However, when the cell is forward-biased, the applied DC voltage must be limited; otherwise non-ohmic back contacts can alter the signal.

**Worked example – CdTe solar cell**

Determine gradient of straight line fit around V=0
Capacitance Voltage analysis (C-V)

p-type doping density is given by

\[ N_a = \frac{2}{q\varepsilon_s A^2 \frac{d\left(\frac{1}{C^2}\right)}{dV}} \]

We have included a contact area term \( A \)

So for a CdTe cell with 5mm diameter square contacts we measured the slope of the \( 1/C^2 \) plot to be \( 2.7 \times 10^{17} \).

\[ \frac{d\left(\frac{1}{C^2}\right)}{dV} = 2.7 \times 10^{17} V^{-1} F^{-2} \]

\[ A = 0.005 \times 0.005 = 0.25 \times 10^{-5} m^2 \]

\[ \varepsilon_s = 10.36\varepsilon_0 = 9.2 \times 10^{-11} Fm^{-1} \]

\[ q = 1.6 \times 10^{-19} C \]

So CdTe doping density is

\[ N_a = 8.1 \times 10^{20} m^{-3} = 8.1 \times 10^{14} cm^{-3} \]
Key junction characterisation techniques

- JV – $R_S$ and $R_{SH}$ → can infer the issue
- J-V-T – Back contact barrier height measurements
- EQE – Layer behaviour and optical losses
- CV - doping density of p-type layer