Advanced Parameter Imaging of Solar Cells

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Solar Cell Characterization

- Need for characterization
  - How they operate
  - Engineering them to be better

- Parameters
  - Open circuit voltage, $V_{OC}$
  - Short circuit density, $J_{SC}$
  - Fill factor, FF
  - Series resistance, $R_S$
  - Dark sat. current density, $J_0$

$$J = J_{pv} - J_{dark} - J_{shunt}$$

$$J = J_{pv} - J_0 \left[ \exp \left( \frac{V + R_S \cdot J}{nKT} \right) - 1 \right] - \frac{V + R_S \cdot J}{R_{shunt}}$$

- Variation of parameters over surface
  - Identify, decouple and quantify losses; better design; quantifying variation and process control

Efficiency

$$\eta = \frac{V_{MPP} \cdot J_{MPP}}{P_{in}} = \frac{V_{OC} \cdot J_{SC} \cdot FF}{P_{in}}$$
Luminescence Imaging

- Key features
  - 808 nm laser
  - 920 nm filter, 1MP CCD camera

- Luminescence measurement
  - PL: optical excitation
  - EL: electrical excitation
  - Biased PL: optical + electrical

- Key equations

\[ V_{xy} = V_T \cdot \log \left( \frac{I_{Hxy} - B_{xy} \cdot I_H}{C_{xy}} \right) \]

\[ B_{xy} = \frac{I_{xy - SC}}{I_{L - SC}} \]

\[ C_{xy} = I_{Lxy} \cdot \exp \left( \frac{V_{OC} - L}{V_T} \right) \]

- B: background, C: calibration constant

Identifying and Quantifying Losses

- Terminal connected diode model
  - Combination of parallel diodes
  - Local parameters are different

\[ V_{\text{term}} - V_{xy} = R_{xy} \left[ J_{0-xy} \exp \left( \frac{V_{xy}}{nV_T} \right) - J_{ph-xy} \right] \]

High Speed Quantum Efficiency Imaging

- **EQE and R measurement (FlashQE)**
  - EQE and Reflectance (R)
  - Point by point scanning
  - Discrete wavelengths
  - 365 nm to 1280 nm
  - Integrated sphere

\[
J_{sc} = e \int_{365 \text{ nm}}^{1280 \text{ nm}} EQE(\lambda)\phi_{in}(\lambda) \, d\lambda \\
IQE(\lambda) = \frac{EQE(\lambda)}{1 - R}
\]

Reflection loss
- a. Front reflection
- b. Escape reflection
Parasitic Absorption & Recombination
- c. Emitter loss
- d. Loss in bulk and rear

High Speed Quantum Efficiency Imaging (Cont...)

- EQE measurement

\[ IQE(\lambda) = \frac{1}{k} \exp \left( -\frac{W_d}{L_a(\lambda)} \right) \frac{1}{1 + \frac{L_a(\lambda)}{L_{eff}}} \]

\[ A_e,l(\lambda) = 1 - IQE(\lambda) \cdot \left( 1 - \frac{L_a(\lambda)}{L_{eff}} \right) \]

\[ A_e,II(\lambda) = 1 - \exp \left( -\frac{W_d}{L_a(\lambda)} \right) \]

- R measurement

\[ t = \frac{\lambda_{min}}{4n} \]

Incorporation of $J_{SC-xy}$ with PL

\[ V_{term} - V_{xy} = R_{xy} \left[ J_{0-xy} \ast \exp \left( \frac{V_{xy}}{nV_T} \right) - J_{ph-xy} \right] \]

- Spatially resolved $J_{SC}$
  - A uniform $J_{SC}$ is normally used in literature
  - Concerns about accuracy with $J_{SC}^{1,2,3}$
- Cell parameters from IV measurement
  - $J_{SC}$: 32.2 mA/cm², $V_{OC}$: 0.612 V
  - $n$: 1.3, $R_S$: 0.2 Ωcm², $J_0$: 3.39x10^{-10} A/cm²

Incorporation of $J_{SC-xy}$ with PL: $R_S$

Cell $R_S=0.2 \ \Omega \text{cm}^2$

- Incorporation of $J_{SC-xy}$ does not change $R_S$ distribution much
  - Using $J_{SC}$ is safe
  - With $n=1.3$, distribution widens, mode being unchanged
Incorporation of $J_{\text{SC-xy}}$ with PL: $J_0$

Cell $J_0 = 3.39 \times 10^{-10} \text{ A/cm}^2$

- Incorporation of $J_{\text{SC-xy}}$ does not change $J_0$ distribution much
  - Using $J_{\text{SC}}$ is safe
  - Recombination shifts to higher value with $n=1.3$ (practical diode)
Incorporation of $J_{SC-xy}$ with PL: Efficiency ($J-V$ curve fitting)

Cell $\eta = 15.4\%$

\[ J_{xy} = J_{sc-xy} - J_0-xy \left[ \exp \left( \frac{V_{xy} + R_{xy} \cdot J_{sc-xy}}{nV_T} \right) - 1 \right] \]

- Incorporation of $J_{SC-xy}$ changes efficiency distribution drastically
  - Using $J_{SC-xy}$ is better
  - $n=1.3$ provides reduced efficiency
Parameter images are important
  • Decoupling losses and finding their root causes
  • Making better performing solar cells

Incorporation of $J_{SC-xy}$ with PL
  • More accurate representation of parameter images
  • Not so much impact on $R_S$ and $J_0$ but big impact on efficiency images
Thank You
Questions?
Solar Cell Structure

AI-BSF

Front side ARC and passivation layer(s)

$n^+$ emitter

Multi $p$-type Si

$p^+$ BSF

Rear contact layer

Front contacts