Advanced inline characterization methods in industrial manufacturing of solar cells and PV-modules

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Company profile

• > 30 years of measurement experience in industrial environment
• Headquarter in Frankfurt, Germany + local office in Suzhou, China
• Expertise in various industrial areas
• Active in PV industry since more than 15 years
• More than 800 systems sold worldwide
• References: Yingli, Trina, Solarworld, FhG ISE, PTB, TÜV, VDE, ...
Product portfolio

IV measurement and sun simulating systems for:

- **Solar cells (production and research)**
  - High speed inline testers up to 4000 cells/hour
  - EL and IR imaging
  - Highly flexible lab systems

- **PV-Modules (production and research)**
  - High throughput sun simulators up to 240 modules/hour
  - Optional EL integration
  - Lab system with high precision temperature control unit

- **PV-Systems**
  - High precision portable outdoor measurement system
Why inline characterization in PV manufacturing?

1. **Quality control**
   - testing and sorting with respect to:
     - product performance
     - product safety
     - product lifetime

2. **Process control**
   - process optimization with respect to:
     - efficiency
     - yield
     - costs
Important PV technology trends

- higher efficiencies
- enhanced blue and IR response
- n-type wafers
- dielectric rear side passivation
- heterojunction cells
- bifacial cell and modules
- busbarless cells

=> simple IV-measurements are not sufficient for quality control and process optimization of these devices
Outline

- IV-measurement of high efficiency cells + modules
- Advanced inline hot spot analysis
- Inline EL imaging with automated defect detection
- Inline spectral response measurement
- IV-measurement of bifacial cells and modules
Hysteresis effect of high efficiency cells + modules

- High efficiency cell measurement
- Steady state curve

<table>
<thead>
<tr>
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<th>Steady State</th>
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<tr>
<td>$V_{OC} [mV]$</td>
<td>730.9</td>
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<td>Eta [%]</td>
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Hysteresis effect of high efficiency cells + modules

- High efficiency cell measurement
- 30 ms sweep ISC → VOC

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Hysteresis effect of high efficiency cells + modules

- High efficiency cell measurement
- 2 x 25 ms h.a.l.m. advanced hysteresis evaluation

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Hysteresis effect of high efficiency cells + modules

Variation of sweep time

Source: Ramspeck et. al., EUPVSEC 2014
IV measurement of high efficiency cells + modules

Advanced hysteresis method allows:

• High precision measurement of cells and modules
• Short sweep times < 2 x 30 ms
• High throughput > 3600 cells per hour
• Low cost of ownership due to enhanced lamp life and no need for device cooling
IR hot spot detection

- Highspeed infrared imaging
- Process and quality control
- Shunt detection and hot spot localization
- Available for high throughput cell testers
IR hot spot detection

Process control:

- localization of hot spot sources
- valuable tool for process optimization

Examples of typical hot spot defects:
Advanced hot spot analysis

Advanced hot spot evaluation for quality control

Implemented thermal model*

$T_{locMod}$
(local module temperature)

* K. Ramspeck et al., Energy Procedia, 2014
Advanced hot spot analysis

IR-image

Temperature on module level
Advanced inline hot spot analysis

Advanced inline hot spot analysis method allows:

• Use of IR- hot spot detection as quality control
• Maximum temperature in module as sorting criteria
• Precision measurement of cells and modules
• Reduction of over kill and under kill in sorting
• Significantly reduce hot spot risk on module level
Inline electroluminescence (EL) imaging
Quality and process control by EL imaging

Key factors:
• high resolution
• automatic error detection
Defects on cell level

Examples of detectable defects

Cracks
Dark areas
Printing defects
Defects on module level

Examples of detectable defects
Inline EL imaging with automated defect detection

Inline EL imaging allows:

• Automated quality control on cell and module level
• Significantly improved process control
• High throughput > 3600 cells per hour
• Low cost of ownership due to integration in flash tester
Inline spectral response measurements

Standard measurement of IV-curve (ISC, VOC, FF, Eta,...)

+ additional measurement of:

\[
\frac{I_{SC-UV}}{I_{SC}}, \quad \frac{I_{SC-IR}}{I_{SC}}
\]

→ Monitoring **front** and **rear** surface losses
Inline spectral response measurement

Inline spectral response measurement allows:

• Improved process control
• discrimination between front and rear surface losses
• identification of deficiencies of different process steps e.g. emitter diffusion, rear surface passivation or metallization
• high throughput > 3600 cells per hour
• Low cost of ownership due to integration in flash tester
IV measurement of bifacial cells + modules

Basic requirements:
• High quality and reproducible illumination from front and rear side
• Independent control of light intensity for front and rear side
• Measurement of light IV-curves within one flash

This allows:
• Independent control of front and rear side performance
• Precise energy yield prediction for various mounting conditions

So far there is no standard for measuring bifacial devices
Schematic of bifacial module flasher
Example illumination profile within one flash

<table>
<thead>
<tr>
<th>Light intensity [W/m²]</th>
<th>Front side</th>
<th>Rear side</th>
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<tr>
<td>1200</td>
<td></td>
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</tr>
<tr>
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<td></td>
<td></td>
</tr>
<tr>
<td>0</td>
<td></td>
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Illumination time [ms]

<table>
<thead>
<tr>
<th>Front side</th>
<th>Rear side</th>
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<tbody>
<tr>
<td>0 sun</td>
<td>1 sun</td>
</tr>
<tr>
<td>1 sun</td>
<td>0.5 sun</td>
</tr>
<tr>
<td>1 sun</td>
<td>1 sun</td>
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## Summary

<table>
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<tr>
<th>Advanced characterization options</th>
<th>Cell production</th>
<th>Module production</th>
<th>Quality control</th>
<th>Process control</th>
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<tr>
<td>Advanced hysteresis</td>
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<tr>
<td>IR hot spot</td>
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<td>Inline EL</td>
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<td>IV test of bifacial devices</td>
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Summary

• Inline characterization required for improved quality control and process control

• PV technology is developing very fast in recent years

• Characterization methods have to adopt to the new technologies (e.g. high efficiency, bifacial, busbarless, ...)

• Advanced characterization methods are a prerequisite for:
  – Improvement of product quality with respect to performance, safety and lifetime
  – Efficient process optimization with respect to efficiency, yield and costs
Thank you for your attention