Novel designs and materials for durable PV modules: applications on the ground, in cities and in the air

Prof. Christophe Ballif
EPFL, Director Photovoltaics and thin film electronics laboratory
CSEM, Director CSEM PV-center

Neuchâtel

IEEE PVSC, Washington 2017
Switzerland:

- Meyer Burger
- Pasan
- Multi-contact
- ABB
- Indeotec
- Megasol
- Oerlikon Solar/Tel
- Flexcell
- ...
- ....

Potential of PV: taken seriously only today!
Politics: important to reach 12-15 GW installed...
Swiss people voting on 21th of Mai 2017 on new energy strategy

-> need for 12 GW of PV by ~2035
Meaning of the survey

Two weeks before the energy vote: 55% for, 45% against
Meaning of the survey!

I ASKED 100 WOMEN
Which shampoo do they prefer?

And the top answer was:
And the top answer was:
- How the hell did you get in here?

L’EPFL donne Hillary Clinton gagnante, pour l’instant
Results vote

• 58% yes and 42% No

Switzerland first country with people voting for
- More energy efficiency
- More renewable
- Less CO2
2000 m² research and piloting… Contracts with over 40 companies along the chain.
Polymer compounding for high reliability: platform for PV packaging materials

- Packaging foil of 0.1 to 2.5 mm thick and width of 20 cm
- Compounder / pelletizer (capacity: 4 Kg/h)
- Flat cast film extrusion / chill roll (capacity: 10kg/h)
Light weight, hail resistant modules
A. Martins, A. Virtuani
Area 8, 2h30 today

Arnaud Walter et al.
16% perovsite single junction modules
Area 6 1630, today

P. Löper,
Passivated contacts,
Area 4, 16 Today

J. Werner
Perovskite/Silicon Tandem Solar Cells
tomorrow 2h45

Stephanie Essig >32.5%
efficient III-V/Si dual-junction solar cells and > 35% triple junction, tomorrow 15h
Power pure : Trends in mainstream crystalline PV

- Diamand Wire sawing for mono
- Thinner mono
- HHP multi

1. AI-BSF → PERC
2. N-PERT, SHJ
3. IBC

- More busbars
- Glass-Glass
- Wires/multi-wires
- Half-cells
- Shingles
- MWT

- Single-axis tracking
- 1500 V
- Bifacial
Commercial products

State of the art p-type PERC Mono (typ 305 W)

666 mV
77.3% FF
18.3% efficient

681 mV
77.9% FF
19.5% efficient

60 cell
LG's new module, NeON™2, adopts Cello technology. Cello technology replaces 3 busbars with 12 thin wires to enhance power output and reliability. NeON™2 demonstrates LG's efforts to increase customer's values beyond efficiency. It features enhanced warranty, durability, performance under real environment, and aesthetic design suitable for roofs.
SHJ
726 mV
78% FF
19.7% efficient

Ultra-agressive warranty

224 mV
79.9% FF
22.2% efficient

GARANTIE DE PERFORMANCE LINEAIRE DUOMAX

Valeur complémentaire issue de la garantie DUOMAX

0.5% de dégradation annuelle sur 30 ans

Trina Solar
Norme de l’industrie
Important

- 2-4% absolute FF points losses between best cells and modules
- 10-15% absolute Efficiency losses between cells and modules (e.g. cells at 21% → module at 18.5% efficiency)
Improving metalisation and interconnection

Minor changes

- Reduced losses in Ag fingers (FF)
- And/or less Ag
- + possible optical gains:
  - White/texture ribbon, round wire → total internal reflection

Challenge:
- Increase cross-section of Cu
- Pack cell closer

Major changes
Exemple: high voltage technology and reduction of

Energy & Environmental Science

The impact of silicon solar cell architecture and cell interconnection on energy yield in hot & sunny climates†

Jan Haschke, a,‡* Johannes P. Seif, a Yannick Riesen, a Andrea Tomasi, a Jean Cattin, a Loïc Tous, b Patrick Choulat, b Monica Aleman, b Emanuele Cornagliotti, b Angel Uruena, b Richard Russell, b Filip Duerinckx, b Jonathan Champliaud, c Jacques Levrat, c Amir A. Abdallah, d Brahim Aïssa, d Nouar Tabet, d Nicolas Wyrsch, a Matthieu Despeisse, c Jozef Szlufcik, b Stefaan De Wolf,‡ a and Christophe Ballif, c

Finding: cells have always a better coefficient of T than modules! Typically 0.05%/°C better for cells than for modules
High voltage technology

- Impact of series resistance on $T_c$ of PMax
- Double Impact of cell voltage:
  - Better intrinsic $T_{coeff}$
  - Less sensitive to Series resistance

10:45 Friday Area 4. J. Haaschke et al.

Haschke et al. EES 2017
Reliability

Up to 10-15% increase in global irradiance
Over the 15 last years in parts of Switzerland/Europe

In place with «lightning of atmosphere» degradation of modules might have been unnoticed

Source.
J. Remund, Meteotest
Tomorrow modules

No Metallization: only wire

- Direct contact between InSn wire coating and TCO from the cell

<table>
<thead>
<tr>
<th>Irradiance</th>
<th>Voc (V)</th>
<th>Jsc (mA.cm⁻²)</th>
<th>Module eff (%)</th>
<th>FF (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>200 W/m²</td>
<td>0.696</td>
<td>7.73</td>
<td>20.6</td>
<td>77.8</td>
</tr>
<tr>
<td>450 W/m²</td>
<td>0.714</td>
<td>17.40</td>
<td>20.7</td>
<td>76.5</td>
</tr>
<tr>
<td>1000 W/m²</td>
<td>0.734</td>
<td>37.30</td>
<td><strong>19.9</strong></td>
<td>74.0</td>
</tr>
</tbody>
</table>

Module without metallization at 19.9 % eff.

SEM image

EL image

IV curves at different irradiances

CSEM acknowledge Choshu Industry Co for cell precursors
Module with Shingle Cell Interconnection: reducing the optical losses

**Tomorrow modules**

No Ribbons nor Wires

- Laser + cleave separations
- Front busbar
- Front finger
- Rear busbar
- 156×156 mm² cell

**Si-HJT**

- Front finger
- Conductive paste
- Small HJT cell (after cutting)
- busbars
- Ribbon

<table>
<thead>
<tr>
<th>CTM losses</th>
<th>Eff da (%)</th>
<th>Power (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>+1.5%</td>
<td>-4.2%</td>
<td>------------</td>
</tr>
</tbody>
</table>

21% module efficiency
Pass 400TC

Source: A. Faes et al.
Smart-wire Motivation

- High module power
  - Light coupling from round wires
  - Increased Cu cross section area
- Silver saving
  - No busbar, no solder pads
  - Fine fingers/Low Rs
- Versatile design
  - Monofacial PERC cell
  - Bifacial PERC, PERT, HJT cell
  - Half-cell
  - Thin wafer compatible
  - GBS, GG
**Improvement in Heterojunction and multi-wire**

**Histogramm Zelleffizienz**

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Anzahl aller Werte</td>
<td>719</td>
</tr>
<tr>
<td>Mittelwert</td>
<td>22.89</td>
</tr>
<tr>
<td>Standardabweich...</td>
<td>0.272</td>
</tr>
<tr>
<td>Minimum</td>
<td>21.16</td>
</tr>
<tr>
<td>Maximum</td>
<td>23.25</td>
</tr>
<tr>
<td>Median</td>
<td>22.94</td>
</tr>
</tbody>
</table>

Pilot line Meyer Burger (D)  
Results 15 days ago on  
719 Cz-wafer, standard wafers  
Black Chuk measurement  
Grid Touch measurement  
22.94% average eff

Average FF, 82%, Voc=735, Current 9.31 A

Courtesy Jun Zaho, MBT
Cell measurement «smart-wire» with grid touch

- Measurement without shading of wire (→ effecting shadowing of 2.25% in module),
- No wire RS loss (→ 3% FF loss in module) 

~ 22% busbar bifacial cells measured on Black chuck with contact at extremity of wires.
**300 mu Indium free**
**SWCT certified @ IEC 2016**

<table>
<thead>
<tr>
<th>TC</th>
<th>Voc</th>
<th>Isc</th>
<th>Pmax</th>
<th>FF [%]</th>
<th>ΔPower (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>43.9</td>
<td>8.84</td>
<td>300.8</td>
<td>77.6</td>
<td>0.0%</td>
</tr>
<tr>
<td>109</td>
<td>44.0</td>
<td>8.86</td>
<td>300.3</td>
<td>77.0</td>
<td>-0.2%</td>
</tr>
<tr>
<td>347</td>
<td>44.0</td>
<td>8.87</td>
<td>299.2</td>
<td>76.6</td>
<td>-0.6%</td>
</tr>
<tr>
<td>DH</td>
<td>43.7</td>
<td>8.8</td>
<td>295.3</td>
<td>76.8</td>
<td></td>
</tr>
<tr>
<td>1000</td>
<td>43.8</td>
<td>8.7</td>
<td>292</td>
<td>76.4</td>
<td>-0.6%</td>
</tr>
<tr>
<td>2000</td>
<td>43.7</td>
<td>8.8</td>
<td>291.9</td>
<td>75.8</td>
<td>-1.3%</td>
</tr>
</tbody>
</table>

*Courtesy T. Söderström, MBT*
8 hours test run at customers

160 MW Line installed in less than 2 months
600 modules produced 8h test after 2 months ramp up
24/7 production running today
Module Line Performance

Power distribution

1000 modules

<table>
<thead>
<tr>
<th>Backsheet Type</th>
<th>P(_{\text{max}}) [W]</th>
<th>V(_{\text{oc}}) [V]</th>
<th>I(_{\text{sc}}) [A]</th>
<th>FF [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>White Backsheet</td>
<td>330.29</td>
<td>44.49</td>
<td>9.46</td>
<td>78.45%</td>
</tr>
<tr>
<td>Black Backsheet</td>
<td>320.42</td>
<td>44.42</td>
<td>9.07</td>
<td>79.52%</td>
</tr>
</tbody>
</table>

1000 module produced power between 300-320W measured with black backsheet
Monitoring in UAE

Example: 21st of April 2017, daily energy production

Measurement at real conditions site with 8 modules bifacial and monofacial.

MB HJT bifacial
Tier 1 PERT bifacial
Tier 1 Monofacial

Courtesy T. Söderström, MBT
Gain of MB technology

- MB modules have a gain of 20% to 25% compared to monofacial
- MB modules have a gain of 9% to 11% compared to bifacial PERT
- HJT technology shows the advantages: bifacial and low temperature coefficient

https://www.meyerburger.com/ch/de/messdaten-weltweit/
Solar Visualised in Europe Award 2016
Trend for BIPV

In Europe: many companies with small volumes
Switzerland, sensitive to acceptance in Rural and Urban Environment

Sensitive to aesthetics
Integrated «Megaslates»
Swiss Solar Award 2015 «renovation category»

Over 10’000 systems installed
Aesthetics in PV
Thermal Insulation
H2O-tightness
Structurally tough
FIRST SMART-WIRE SHJ in roof «BIBV» megaslate configuration
Terra-cotta PV

An example of technological transfer

Thin-film terra-cotta
Mat or shiny finish
Sizes: full size (1100 x 1400) and small size available
Change of strategy: crystalline c-si based terracotta module 115 w/m² together with Issol SA

Simulation, project under realisation
White photovoltaic modules
A new building material

• Better aesthetics
• Easiest integration
• Building façade are becoming active
• Possible over 10% efficiency

➢ A new building material

1st generation product with

Intensive Field testing
Colored photovoltaic modules

Visible

IR

Transmittance (%)

Wavelength (nm)

- PVB Blue
- PVB Dark Green
- PVB Green
- PVB Yellow
- PVB Orange
- PVB Red
Still a simulation
Spatial patterns of solar photovoltaic system adoption: The influence of neighbors and the built environment

Marcello Graziano* and Kenneth Gillingham**.†

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email <kenneth.gillingham@yale.edu>

“Example isn't another way to teach, it is the only way to teach”, A. Einstein
PV Modules Fabrication: Customized PV products

- Development of high-efficient integrated, light and robust PV element for solar plane and boat:
  - 700 g/m² modules 21%, passing 200 cycles from -70°C – 85°C and 1000h in DH (85°C/85% RH)
Solar Stratos... at the edge of space
Solar Stratos... at the edge of space
• To which extent can you color PV?

The Kaleo Project ....
TRUMP WALL
65'

Source: Jigar Shah, LinkedIn
Solar electricity: a bright future with some more work ahead!

You may never know what results come of your actions, but if you do nothing, there will be no results.” *Mahatma Gandhi*

Thanks for your attention!
THANK YOU FOR YOUR ATTENTION!!
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Kaleo team. L. E. Perret-Aebi et al.