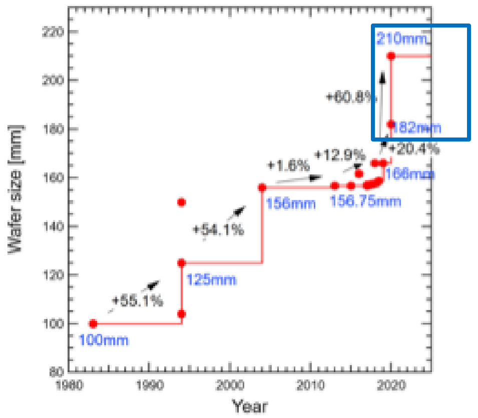
Photo by Josh Bauer, NREL 61725

NREL

Power Rating Industrial Silicon Cells

Nikos Kopidakis
NREL
PV Cell and Module Performance

Bigger cells, less Ag



Chen et al., *Prog. Photovolt. Res. Appl.* 2023;31:1194–1204

Wafer size M10, G12

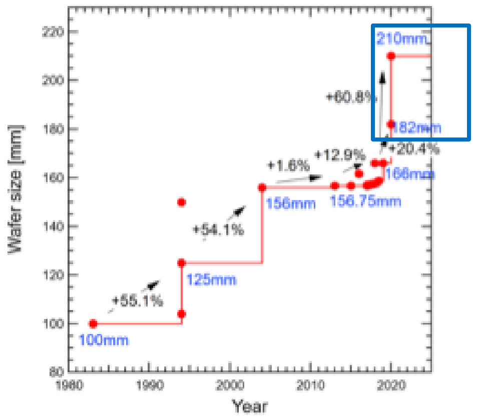
Solar Cell Efficiency Tables, version 66.

TABLE 2 | 'Notable exceptions' for single-junction cells and submodules: 'Top dozen' confirmed results, not class records, measured under the global AM1.5 spectrum (1000 Wm^{-2}) at 25°C (IEC 60904-3:2008 or ASTM G-173-03 global).

Classification	Efficiency (%)	Area (cm^2)	V_{oc} (V)	J_{sc} (mA/cm^2)	Fill Factor (%)	Test centre (date)	Description
Cells (silicon)							
Si (PERC)	25.0 ± 0.5	4.00 (da)	0.706	42.7[a]	82.8	Sandia (3/99)	UNSW, p-type [28]
Si (p-TOPCon)	26.0 ± 0.5[b]	4.015 (da)	0.7323	42.05[c]	84.3	FhG-ISE (11/19)	FhG-ISE, p-type [29]
Si (p-TBC)	26.1 ± 0.3[b]	3.9857 (da)	0.7266	42.62[d]	84.3	ISFH (2/18)	ISFH, p-type [30]
Si (large PERC)	**24.1 ± 0.4[e]**	**441.3 (t)**	**0.6997**	**41.79[f]**	**82.3**	**ISFH (12/24)**	**Trina p-type [31]**
Si (large TOPCon)	**26.4 ± 0.4[g]**	**334.9 (t)**	**0.7412**	**42.38[f]**	**84.0**	**ISFH (5/25)**	**Jinko, n-type [32]**
Si (large TBC)	27.0 ± 0.5[h]	350.0 (t)	0.7447	42.32[i]	85.8	ISFH (8/24)	LONGi, n-type [4]
Si (large HJT)	26.8 ± 0.4[j]	274.4 (t)	0.7514	41.45[k]	86.1	ISFH (10/22)	LONGi, n-type [33]
Si (large p-HJT)	26.6 ± 0.4[j]	274.1 (t)	0.7513	41.30[k]	85.6	ISFH (10/22)	LONGi, p-type [34]

Green et al., *Prog. Photovolt. Res. Appl.*, 2025; 0:1–16

Bigger cells, less Ag



Chen et al., *Prog. Photovolt. Res. Appl.* 2023;31:1194–1204

Wafer size M10, G12

Solar Cell Efficiency Tables, version 66.

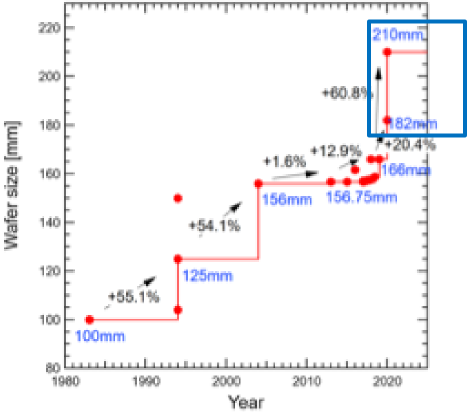
TABLE 2 | 'Notable exceptions' for single-junction cells and submodules: 'Top dozen' confirmed results, not class records, measured under the global AM1.5 spectrum (1000 Wm^{-2}) at 25°C (IEC 60904-3:2008 or ASTM G-173-03 global).

Classification	Efficiency (%)	Area (cm^2)	V_{oc} (V)	J_{sc} (mA/cm^2)	Fill Factor (%)	Test centre (date)	Description
Cells (silicon)							
Si (PERC)	25.0 ± 0.5	4.00 (da)	0.706	42.7[a]	82.8	Sandia (3/99)	UNSW, p-type [28]
Si (p-TOPCon)	26.0 ± 0.5[b]	4.015 (da)	0.7323	42.05[c]	84.3	FhG-ISE (11/19)	FhG-ISE, p-type [29]
Si (p-TBC)	26.1 ± 0.3[b]	3.9857 (da)	0.7266	42.62[d]	84.3	ISFH (2/18)	ISFH, p-type [30]
Si (large PERC)	**24.1 ± 0.4[e]**	**441.3 (t)**	**0.6997**	**41.79[f]**	**82.3**	**ISFH (12/24)**	**Trina p-type [31]**
Si (large TOPCon)	**26.4 ± 0.4[g]**	**334.9 (t)**	**0.7412**	**42.38[f]**	**84.0**	**ISFH (5/25)**	**Jinko, n-type [32]**
Si (large TBC)	27.0 ± 0.5[h]	350.0 (t)				ISFH (8/24)	LONGi, n-type [4]
Si (large HJT)	26.8 ± 0.4[j]	274.4 (t)				ISFH (10/22)	LONGi, n-type [33]
Si (large p-HJT)	26.6 ± 0.4[j]	274.1 (t)	0.7513	41.30[k]	85.6	ISFH (10/22)	LONGi, p-type [34]

M10 16BB/(10+10) BB

Green et al., *Prog. Photovolt. Res. Appl.*, 2025; 0:1–16

Bigger cells, less Ag



Wafer size M10, G12

Chen et al., *Prog. Photovolt. Res. Appl.* 2023;31:1194–1204

Solar Cell Efficiency Tables, version 66.

TABLE 2 | 'Notable exceptions' for single-junction cells and submodules: 'Top dozen' confirmed results, not class records, measured under the global AM1.5 spectrum (1000 Wm^{-2}) at 25°C (IEC 60904-3:2008 or ASTM G-173-03 global).

Classification	Efficiency (%)	Area (cm^2)	V_{oc} (V)	J_{sc} (mA/cm^2)	Fill Factor (%)	Test centre (date)	Description
Cells (silicon)							
Si (PERC)	25.0 ± 0.5	4.00 (da)	0.706	42.7[a]	82.8	Sandia (3/99)	UNSW, p-type [28]
Si (p-TOPCon)	26.0 ± 0.5[b]	4.015 (da)				SE (11/19)	FhG-ISE, p-type [29]
Si (p-TBC)	26.1 ± 0.3[b]	3.9857 (da)				H (2/18)	ISFH, p-type [30]
Si (large PERC)	**24.1 ± 0.4[e]**	**441.3 (t)**	**0.6997**	**41.79[f]**	**82.3**	**ISFH (12/24)**	**Trina p-type [31]**
Si (large TOPCon)	**26.4 ± 0.4[g]**	**334.9 (t)**	**0.7412**	**42.38[f]**	**84.0**	**ISFH (5/25)**	**Jinko, n-type [32]**
Si (large TBC)	27.0 ± 0.5[h]	350.0 (t)	0.7447	42.32[i]	85.8	ISFH (8/24)	LONGi, n-type [4]
Si (large HJT)	26.8 ± 0.4[j]	274.4 (t)	0.7514	41.45[k]	86.1	ISFH (10/22)	LONGi, n-type [33]
Si (large p-HJT)	26.6 ± 0.4[j]	274.1 (t)	0.7513	41.30[k]	85.6	ISFH (10/22)	LONGi, p-type [34]

G12 0BB/16BB, Pmax=10.6W

Green et al., *Prog. Photovolt. Res. Appl.*, 2025; 0:1–16

Summary of this talk

What: challenges of measuring performance of industrial large area silicon cells

Why: not just for efficiency records!
Accurate performance rating at a cell line is critical for

- Quality control
- Comparing production cells against champion lab cells
- Calculating cell to module losses
- Calculating $/W

Measurement Workflow

1. Use Calibration Standard (aka Reference Cell) to set light level
2. Place Cell on temperature-controlled stage
3. 4-wire connection (I-loop and V-sense) to the test cell
4. Sweep IV

Measurement Workflow

1. Use Calibration Standard (aka Reference Cell) to set light level ← At the factory: **same cell as production cells**. Avoids spectral and uniformity corrections (applied at the time of calibration).
2. Place Cell on temperature-controlled stage
3. 4-wire connection (I-loop and V-sense) to the test cell
4. Sweep IV

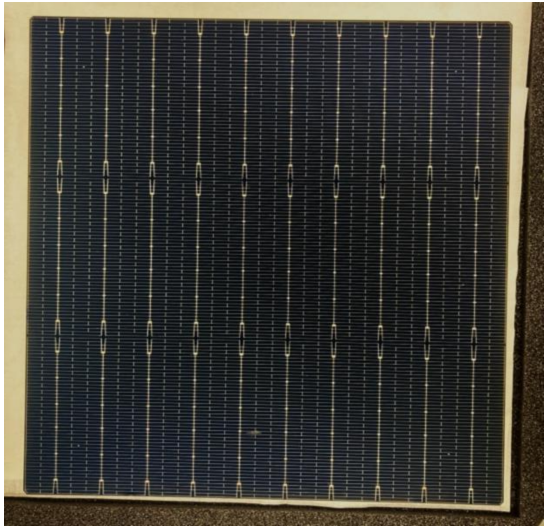
Measurement Workflow

1. Use Calibration Standard (aka Reference Cell) to set light level

2. Place Cell on temperature-controlled stage

3. 4-wire connection (I-loop and V-sense) to the test cell ← Where do you contact a m-BB cell?

4. Sweep IV



Measurement Workflow

1. Use Calibration Standard (aka Reference Cell) to set light level

2. Place Cell on temperature-controlled stage

3. 4-wire connection (I-loop and V-sense) to the test cell ← Where do you contact a m-BB cell? Where do you contact a 0BB cell?

4. Sweep IV

Measurement Workflow

1. Use Calibration Standard (aka Reference Cell) to set light level

2. Place Cell on temperature-controlled stage

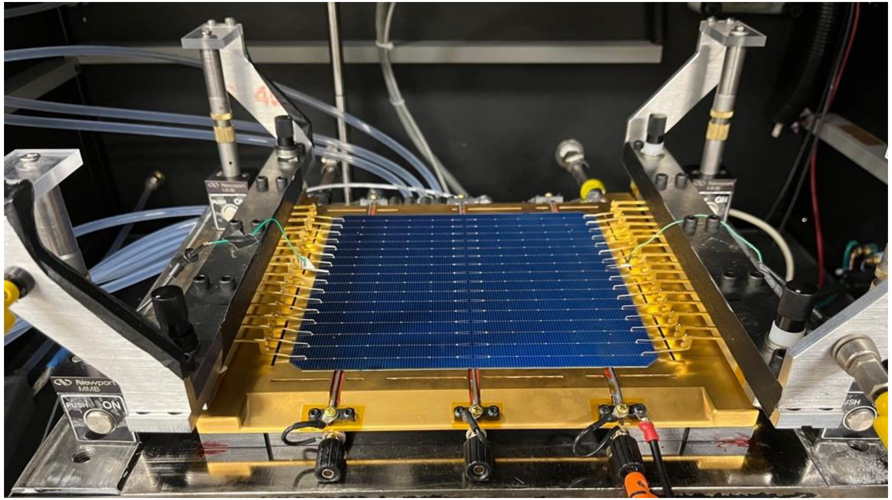
3. 4-wire connection (I-loop and V-sense) to the test cell ←

4. Sweep IV

Where do you contact a m-BB cell?
Where do you contact a 0BB cell?
What about the back side for bifacial cells?

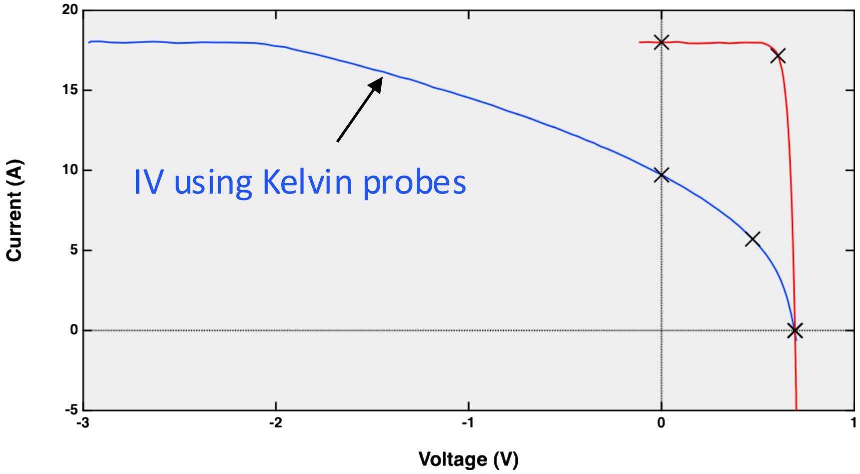
Contacting requirement: must be representative of the cell in the module

Probing Silicon PV Cells: option 1



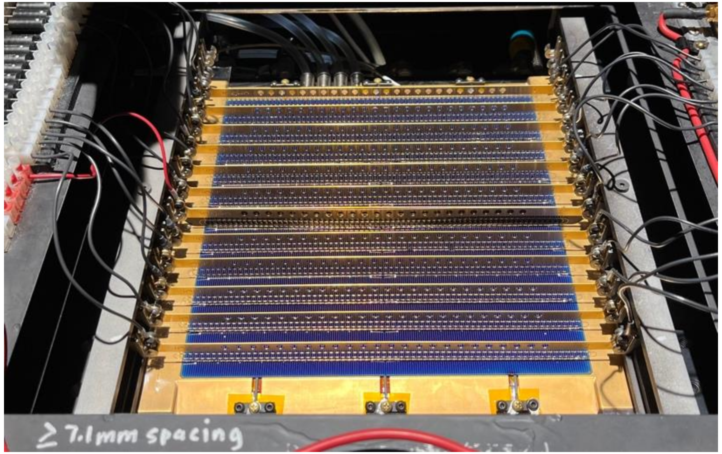
Kelvin probes:

- Minimal shadow on the cell. ✔
- Severe series resistance limitation on FF for narrow BBs. X
- Not applicable to 0BB cells. X



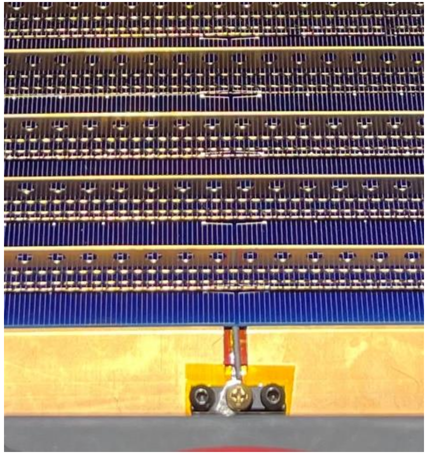
On today's industrial cells Kelvin probing is ***not representative of the cell in a module***

Probing Silicon PV Cells: option 2



Continuous probing bars:

- Busbar Resistance Neglecting (*brn*) –
  Can be representative of the cell in a module. ✔
- Reproducibility of contacting narrow busbars ✔
- Significant shadow on the cell (>5%) X

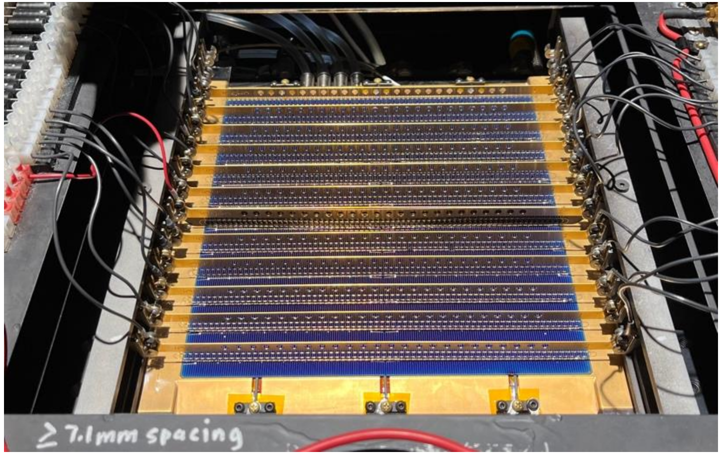


Bothe et al., 37th *EUPVSEC*, 2020

Rauer at al., *Solar Energy Materials and Solar Cells*, 248 (2022) 111988

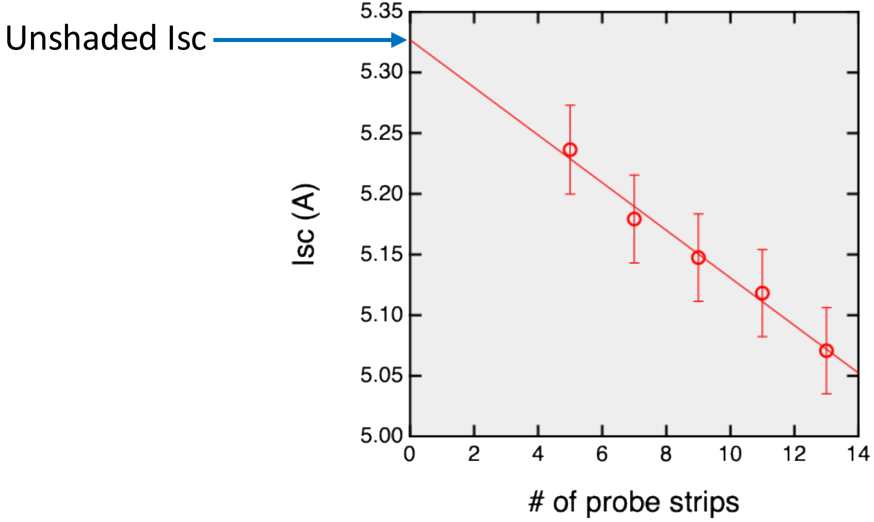
Rauer et al., *Solar RRL,* 2023, 2300873

Probing Silicon PV Cells: option 2

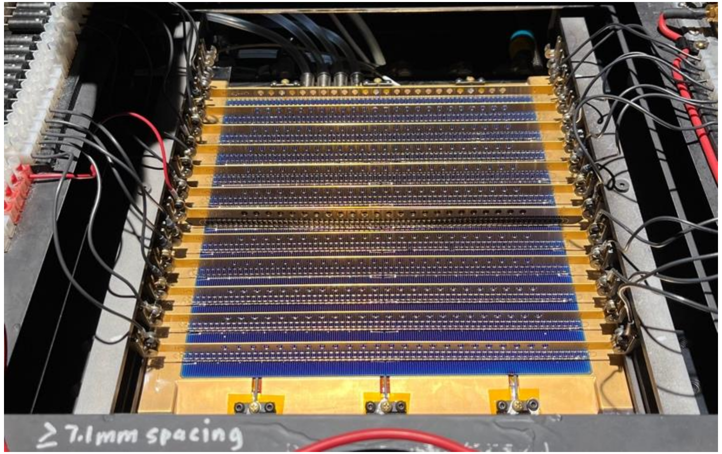


Continuous probing bars:

- Busbar Resistance Neglecting (*brn*) –
  Can be representative of the cell in a module. ✔
- Reproducibility of contacting narrow busbars ✔
- Significant shadow on the cell (>5%) X

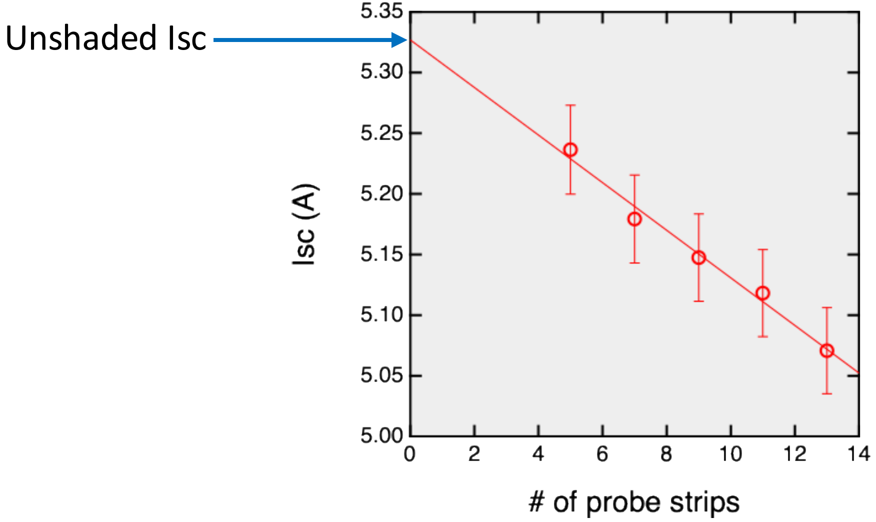


Probing and measurement protocol



Continuous probing bars:

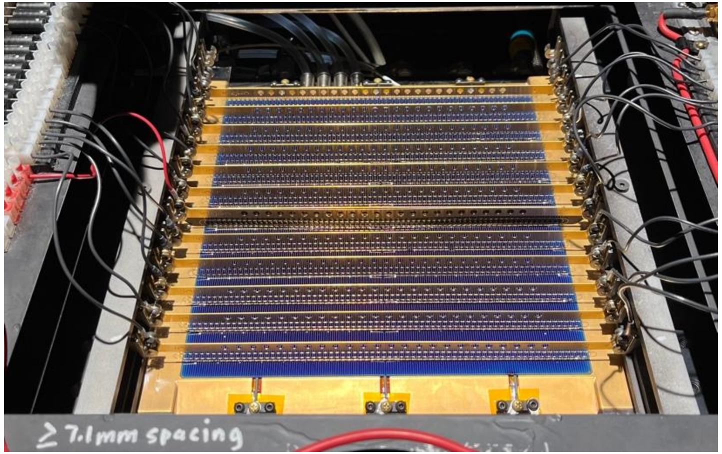
- Busbar Resistance Neglecting (*brn*) – *Can be representative of the cell in a module.* ✓
- Reproducibility of contacting narrow busbars ✓
- Significant shadow on the cell (>5%) **can be corrected** ✓



Measurement sequence:

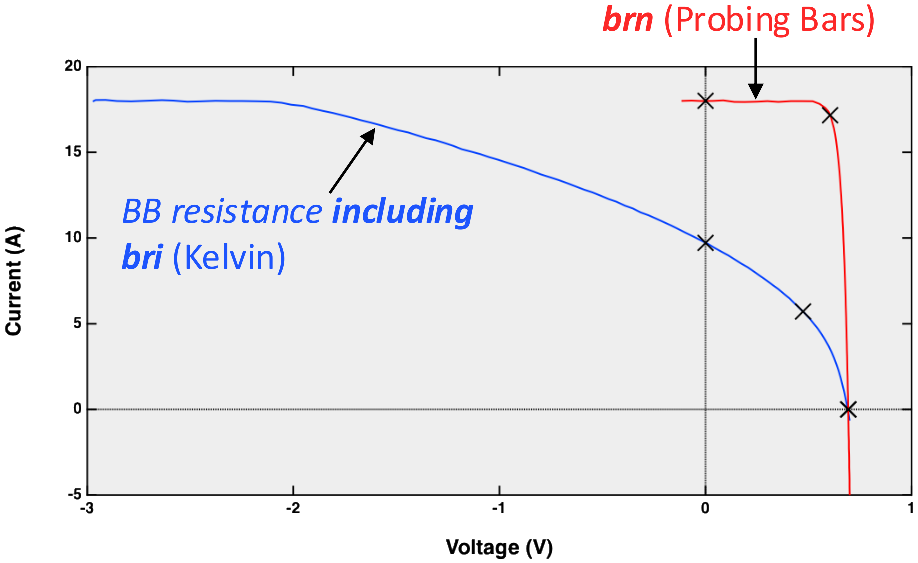
1. Determine shadow-free Isc by extrapolation vs. # of probes (one IV per set-up)
2. Align 1 probe per BB
3. Set light level to achieve Isc from 1
4. Sweep IV – ***brn*** measurement condition

Probing and measurement protocol



Continuous probing bars:

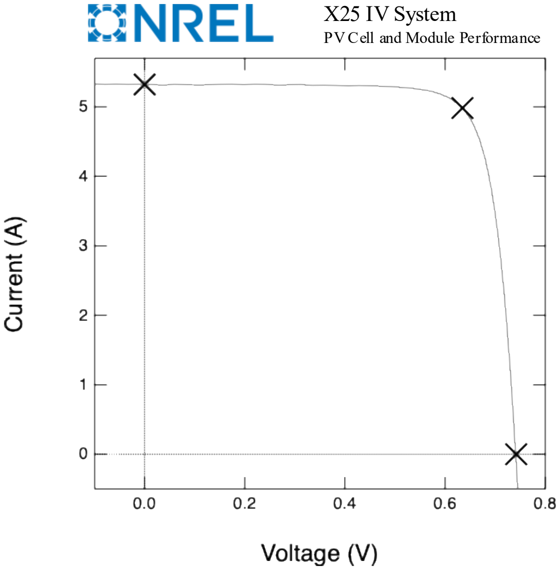
- Busbar Resistance Neglecting (*brn*) – *Can be representative of the cell in a module.* ✔
- Reproducibility of contacting narrow busbars ✔
- Significant shadow on the cell (>5%) **can be corrected** ✔



Measurement sequence:

1. Determine shadow-free Isc by extrapolation vs. # of probes (one IV per set-up)
2. Align 1 probe per BB
3. Set light level to achieve Isc from 1
4. Sweep IV – ***brn*** measurement condition

Probing and measurement protocol



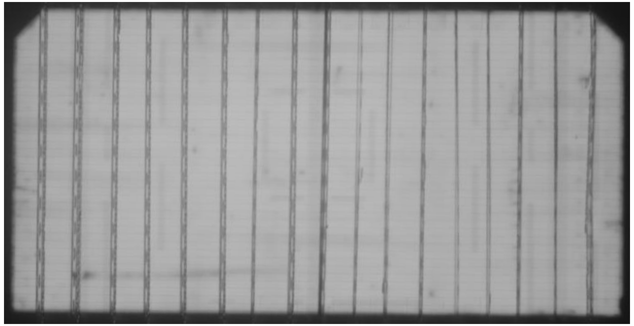
V_{OC} = (0.7420 ± 0.0019) V
I_{SC} = (5.322 ± 0.032) A
J_{SC} = (38.85 ± 0.24) mA/cm^2
Fill Factor = (80.12 ± 0.72) %

I_{max} = (4.986 ± 0.031) A
V_{max} = (0.6347 ± 0.0013) V
P_{max} = (3.164 ± 0.028) W
Efficiency = (23.10 ± 0.14) %

Bothe et al., *37th EUPVSEC*, 2020

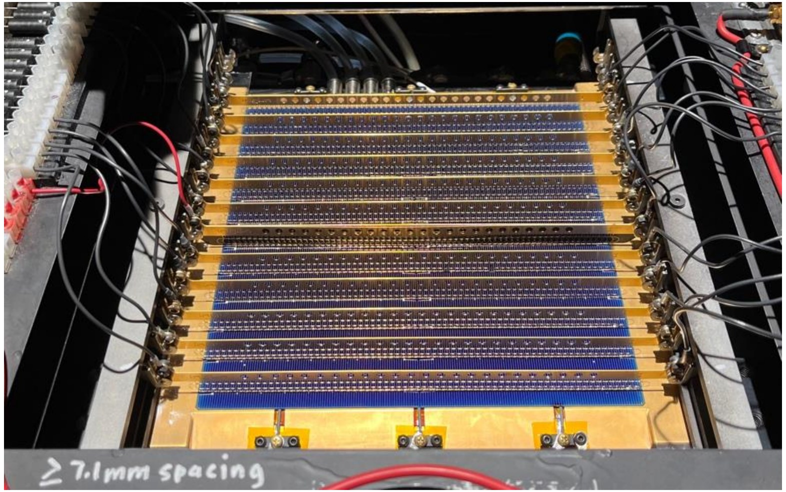
Continuous probing bars:

- Busbar Resistance Neglecting (*brn*) –
  Can be representative of the cell in a module. ✔
- Reproducibility of contacting narrow busbars ✔
- Significant shadow on the cell (>5%) **can be corrected** ✔
- **Applicable to 0BB cells** ✔
  - The probing bars become the BBs
  - Uniform contacting verified by EL
  - Same measurement sequence
  - Weak dependence on probing bar spacing



Summary

- Measurement sequence to obtain shadow-free Isc and "*brn*" FF
  - Calibration-quality IV measurements
  - Reliable input for CTM losses
  - Good agreement in interlaboratory comparison
- Scope:
  - Calibrate production line cells as *reference* (golden) cells for factory tester set-up
  - Performance certification under ISO standards
- *(Back contact cells, such as IBC, is another story, but basic principles still apply)*



NREL's PV Cell and Module Performance Group

- Independent performance testing of PV cells and modules since 1980
- All industrial and emerging PV technologies
- ISO 17025 accredited for reference cell and reference module calibrations
- Available to anyone via a web submission portal
- https://www.nrel.gov/pv/pvdpc/

Acknowledgements

NREL

Chuck Mack
Rafell Williams
Idris Davis
Jeremy Brewer
Tao Song

ISFH

Karsten Bothe
David Hinken

Funding

DOE Solar Energy Technologies Office

nikos.kopidakis@nrel.gov