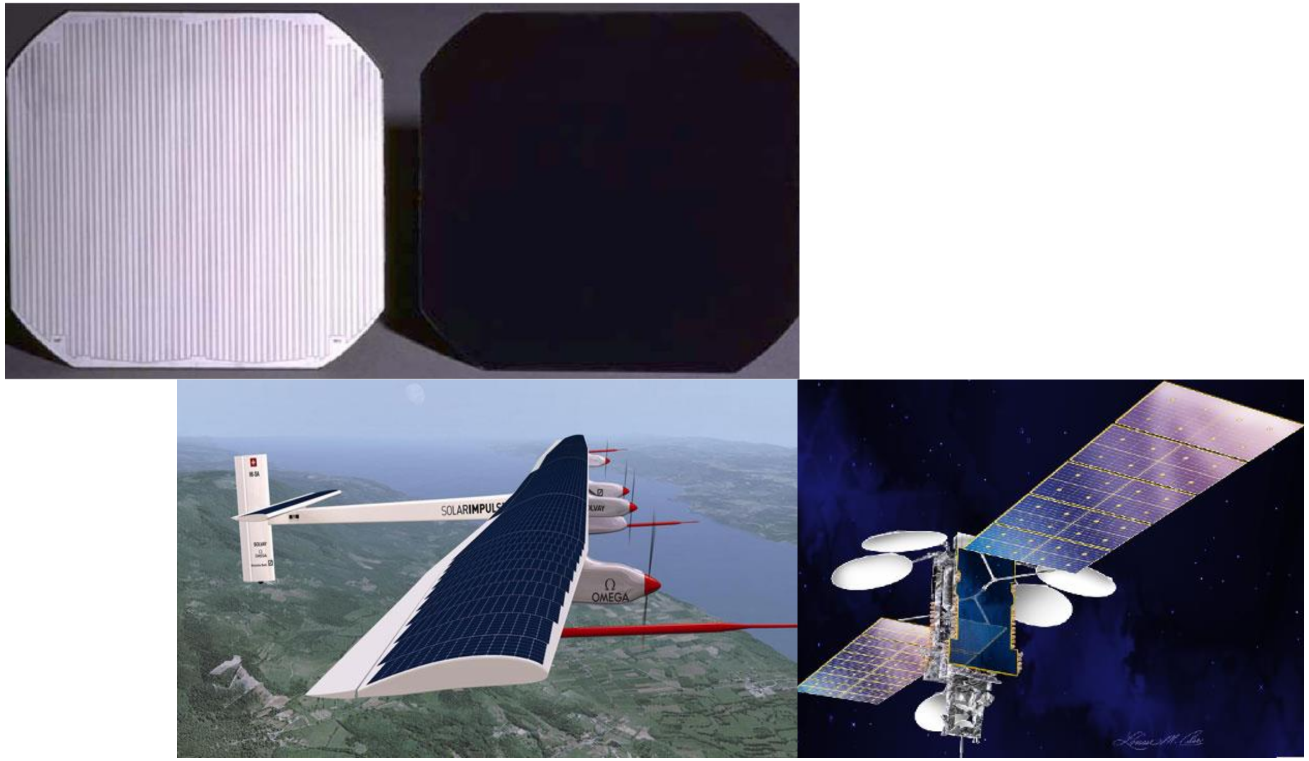
Chapter XI.
High efficiency solar cells: TOPCON, SHJ and IBC



Outline

1. Advantages of high efficiency
2. High temperature passivated contact cells
3. Heterojunction junction solar cells
4. IBC solar cells and use of IBC cells in
5. IBC heterojunction

1. Advantages of higher efficiency

→ require less mounting space

→ lower balance of system costs per installed W

→ higher energy density (if space is expensive or rare)

→ usually better performance at higher temperature and at low illumination

→ Can more advantageously be combined with trackers (1 or 2 axis)

- Single axis tracking systems can bring 25-30% increased energy depending on the location and are becoming mainstream for large parks.
- Can be combined with bifacial with bifacial modules (typ additional 5-20% annual energy yield depending on Albedo)

Higher efficiency cells and modules

Because of their inherent benefits «high efficiency» technologies can be sold at higher price per Watt

For instance in 2020, Sunpower could sell 22.7% module at 0.7$/W in Switzerland (against 0.2-0.3$/W for standard modules) Branding also a factor !

At some point the market is obliged to follow: if everybody sells 22% c-Si, modules, a company will not survive with 17% modules on the long-term

Higher efficiency: Two options

→

Which can be combined

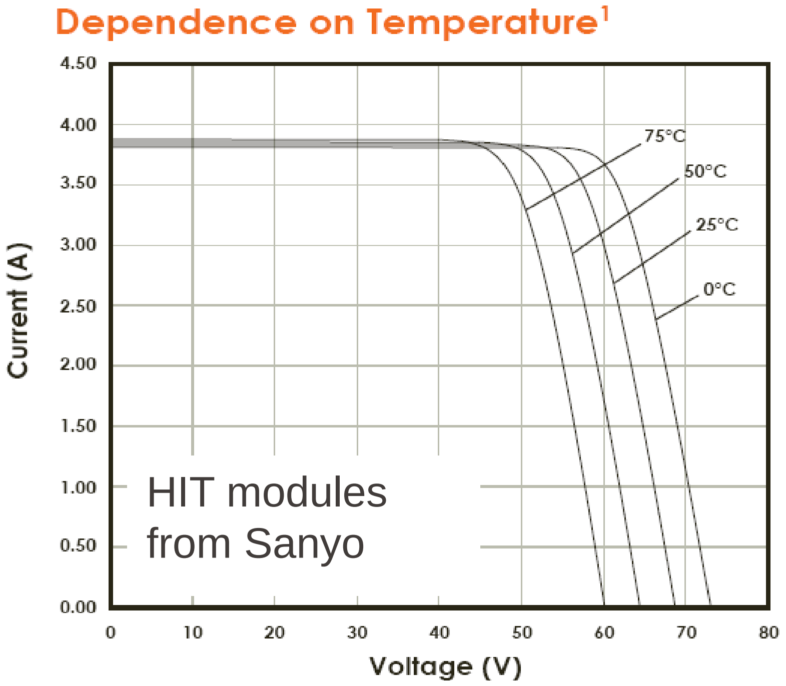
1. Module/cell design
Larger cells and modules (less edges)
½ cells, cells overlap, shingling

2. Improve intrinsically the cell performance, beyond PERC

1. Advantages of high efficiency cells

Coefficient of temperature

Intuitively, when a forward bias is applied on the diode, strong majority carrier currents flow through the junction. If T is increased, the concentration of carriers increases (n_i^2) and the forward "dark" current is increased! This is detrimental to the cell performance (this current adds to the negative photocurrent!)



$$I_0 = qA\frac{Dn_i^2}{LN_D}$$

$$n_i^2 = 4\left(\frac{2\pi kT}{h^2}\right)^3 (m_e^* m_h^*)^{3/2} \exp\left(-\frac{E_{G0}}{kT}\right) = BT^3 \exp\left(-\frac{E_{G0}}{kT}\right)$$

$$\frac{dV_{OC}}{dT} = \text{-2.4 mV/°C for Voc ~600 mV}$$

$$\frac{dV_{OC}}{dT} = \text{-1.64 mV/°C for Voc ~700 mV}$$

In first approximation, by using the diode equation

(11.1) $$\frac{dV_{OC}}{dT} = -\frac{V_{G0} - V_{OC} + \gamma\frac{kT}{q}}{T}$$

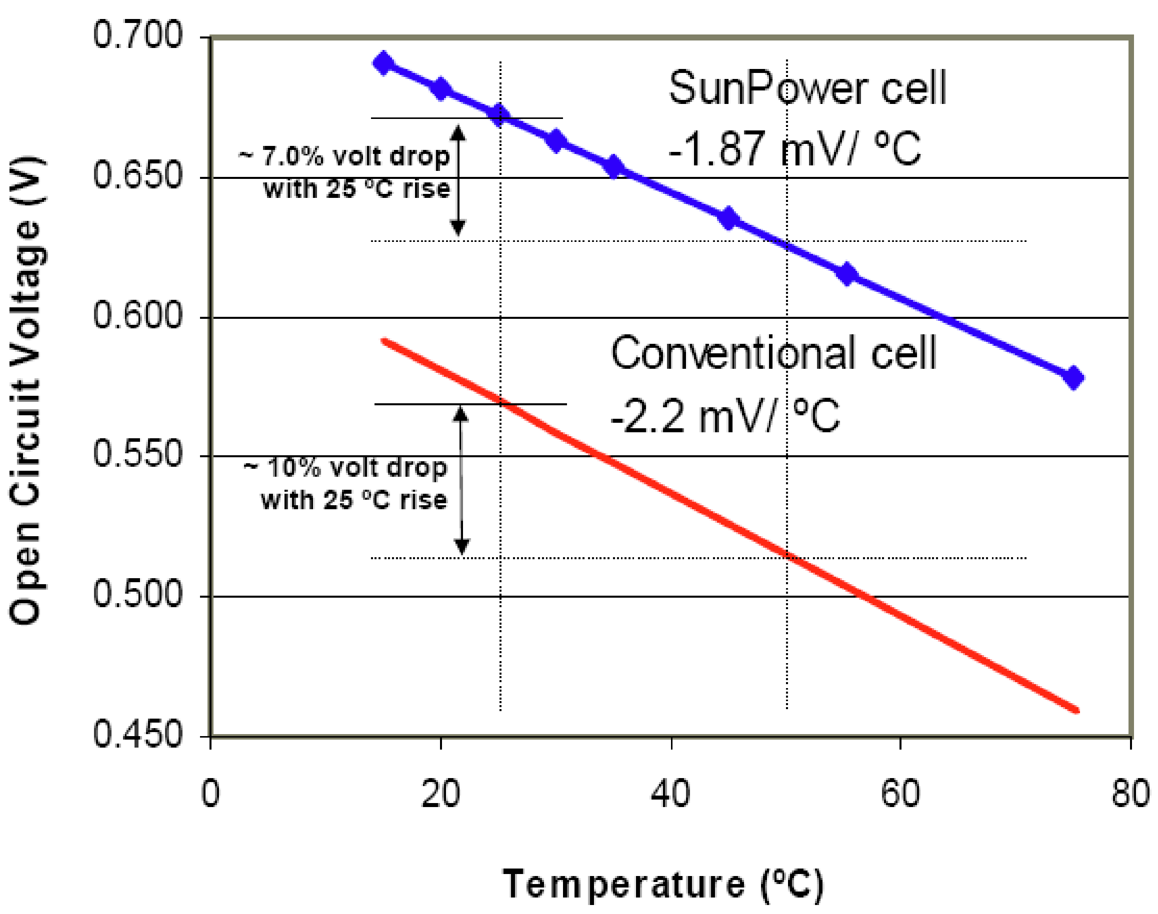
With $E_{go}=eV_{Go}$ ~1.12 eV and γ=3 for Si

- The higher the Voc, the better the temperature dependance of the voltage
- Voc determines esssentially $\boldsymbol{dP_{max}/dT}$: **higher Voc and smaller $\boldsymbol{dV_{oc}/dT}$ → better temperature performance**

- FF also **decreases** similarly with T (unless transport through contacts is thermally activated)
- The current **increases** moderately due to bandgap decrease and more phonon assisted absorption.

1. Advantages of high voltage

Coefficient of temperature



Typically coefficient of temperature (relative decrease) of Pmax, Dpmax/

Al-BSF cells (Voc 640 mV) = 0.45%/°C
PERC cells (Voc 680 mV)= -0.37%/°C
Sunpower cells/Topcon ~(~720 mV) = **-0.30**%/°C
Heterojunction (747 mV) = -0.25%/°C

Example: for an average module temperature of 50°C -0.1% difference in T coefficient means

? more annual energy yield **2.5**%

In addition, High Voc ←→ I_o is small → Improved low light behavior, if no shunts or leakage current
→ 1-2% annual possible extra energy yield

1. High efficiency

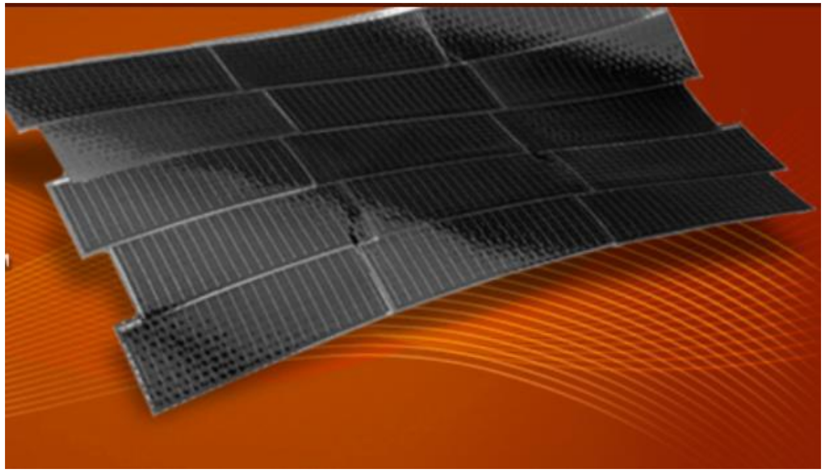
Types of high efficiency cells

- GaAs single junction 29.1% certified record for single junction
- III-V based multi-junction (38.8% five junctions) 39.5% for small devices < 0.25 cm2.

AM1.5 G

See Table of record by M. Green et al. Progress in photovoltaics

Solar cell efficiency tables (Version 63) (wiley.com)
Nov. 2023



Example: Record mini-modules with GaAs from AltaDevice

- Fast epitaxial growth of III-V GaAs
- Lift off-process re-use of substrate
- typical Voc: 1.09 V… remarkable devices

Reminder: niche application, military, drones, space
100-200 €/W

Multi-junction with Silicon

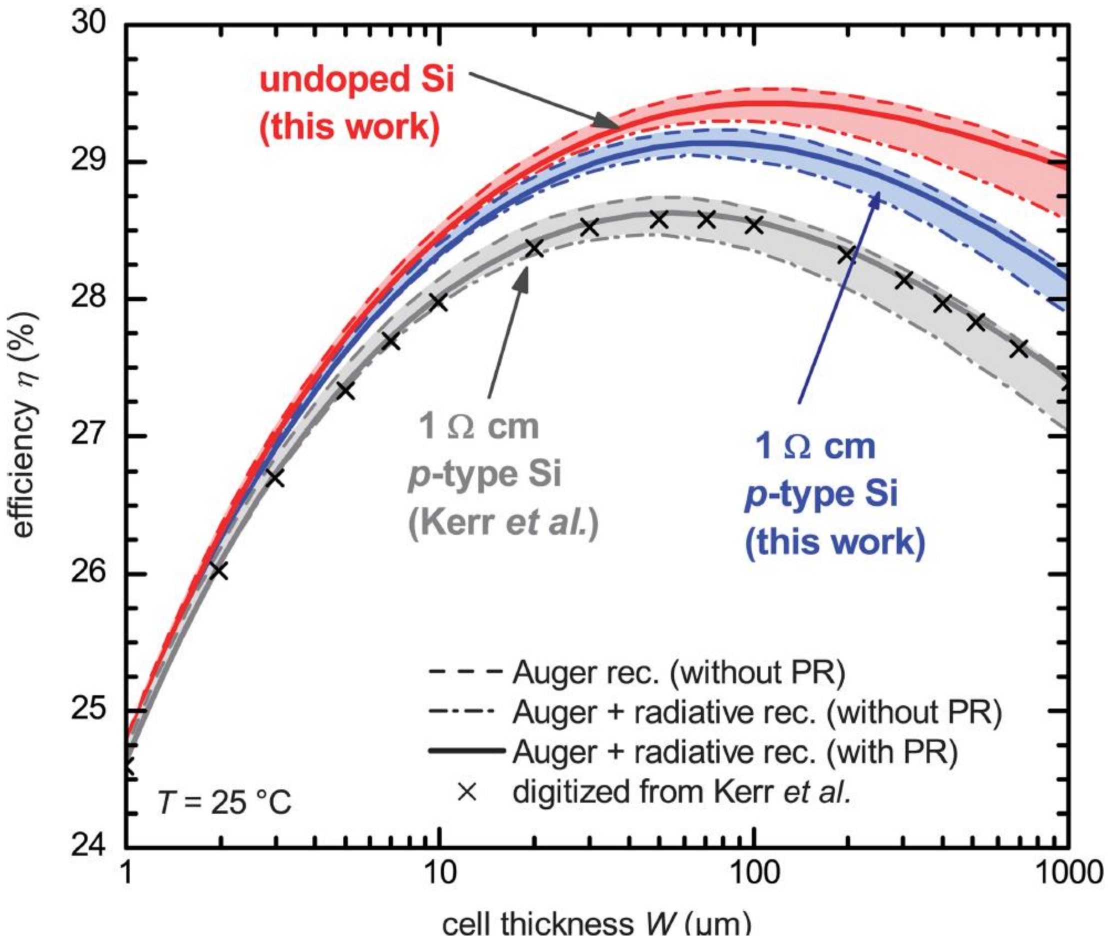
Solar cell efficiency tables (Version 61) (wiley.com)
Nov. 2022

III-V/Si Multijunctions							
GaInP/GaInAsP//Si (bonded)	**36.1 ± 1.3[c]**	**3.987 (ap)**	**3.309**	**12.70[d]**	**86.0**	**FhG-ISE (5/23)**	**FhG-ISE/AMOLF, 2-term.[44]**
GaInP/GaAs/Si (mech. stack)	35.9 ± 0.5[c]	1.002 (da)	2.52/0.681	13.6/11.0	87.5/78.5	NREL (2/17)	NREL/CSEM/EPFL, 4-term.[45]
GaInP/GaAs/Si (monolithic)	25.9 ± 0.9[c]	3.987 (ap)	2.647	12.21[e]	80.2	FhG-ISE (6/20)	Fraunhofer ISE, 2-term.[46]
GaAsP/Si (monolithic)	23.4 ± 0.3	1.026 (ap)	1.732	17.34[f]	77.7	NREL (5/20)	OSU/UNSW/SolAero, 2-term[47]
GaAs/Si (mech. stack)	32.8 ± 0.5[c]	1.003 (da)	1.09/0.683	28.9/11.1[g]	85.0/79.2	NREL (12/16)	NREL/CSEM/EPFL, 4-term.[45]
GaInP/GaInAs/Ge; Si (spectral split minimodule)	34.5 ± 2.0	27.83 (ap)	2.66/0.65	13.1/9.3	85.6/79.0	NREL (4/16)	UNSW/Azur/Trina, 4-term.[48]

But doesn't change the III-V cost problem…..
100-200 €/W → a few $??? Abondance of Ga ??

1. Reminder: limits of Silicon

Basics of efficiency limits in crystalline silicon (beyond Schockley Queisser limit)



- In silicon (contrarily to GaAs), Auger recombination is a limiting factor when coupled with weak absorption: → need thick device to absorb the light, → high carrier concentration at MPP → high Auger recombination at MPP

Hypothesis for simulating Si limiting efficiency based

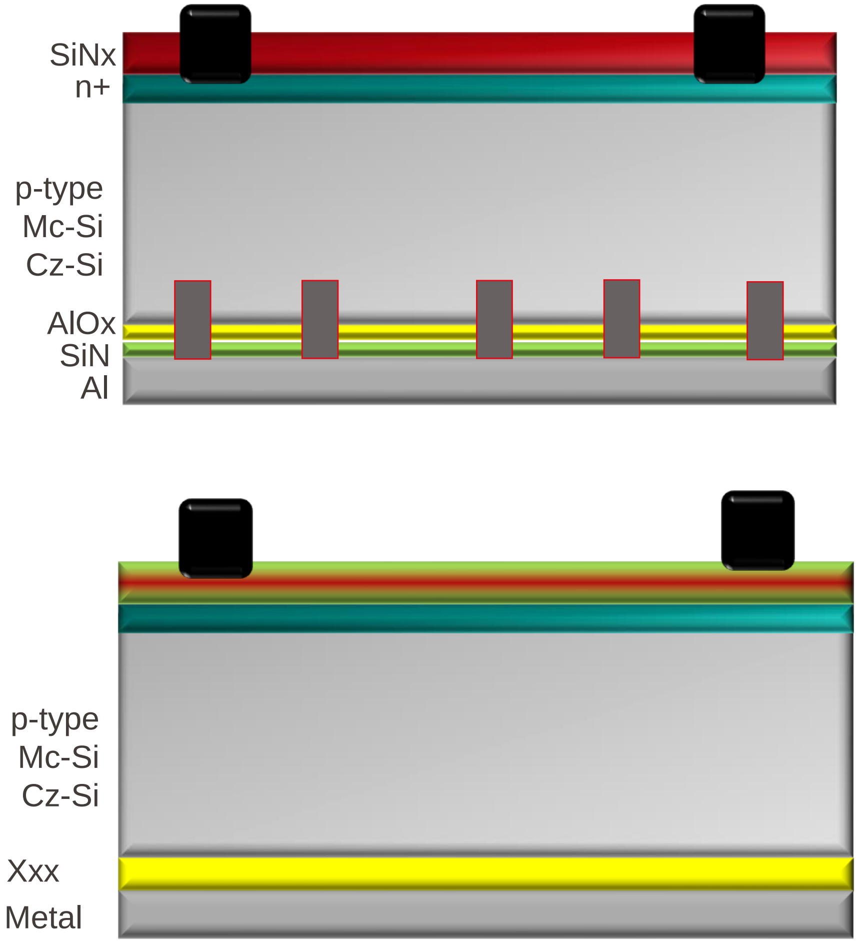
- Perfect material quality
- Perfect surface
- **No recombination at contacts (Passivating contacts)**
- No parasitic absorption
- Quasi ideal light trapping, based on lambertian diffusion

- Maximum efficiency of Silicon at **29.4**%
- Optimum at ~ 80-110 µm
- In STC, no focused light

A. Richter et al. IEEE JPV 2013
F. J. Haug Solmat 2021, for tandem Si/Si

1. How to come closer to the silicon limit

For ultra-high efficiency



Classical c-Si cells (including PERC)
→ Direct c-Si/metal contact
→ Infinite «surface recombination velocity»
Strategies:
- Further minimize metal fraction
- Screen metal with more doping in silicon

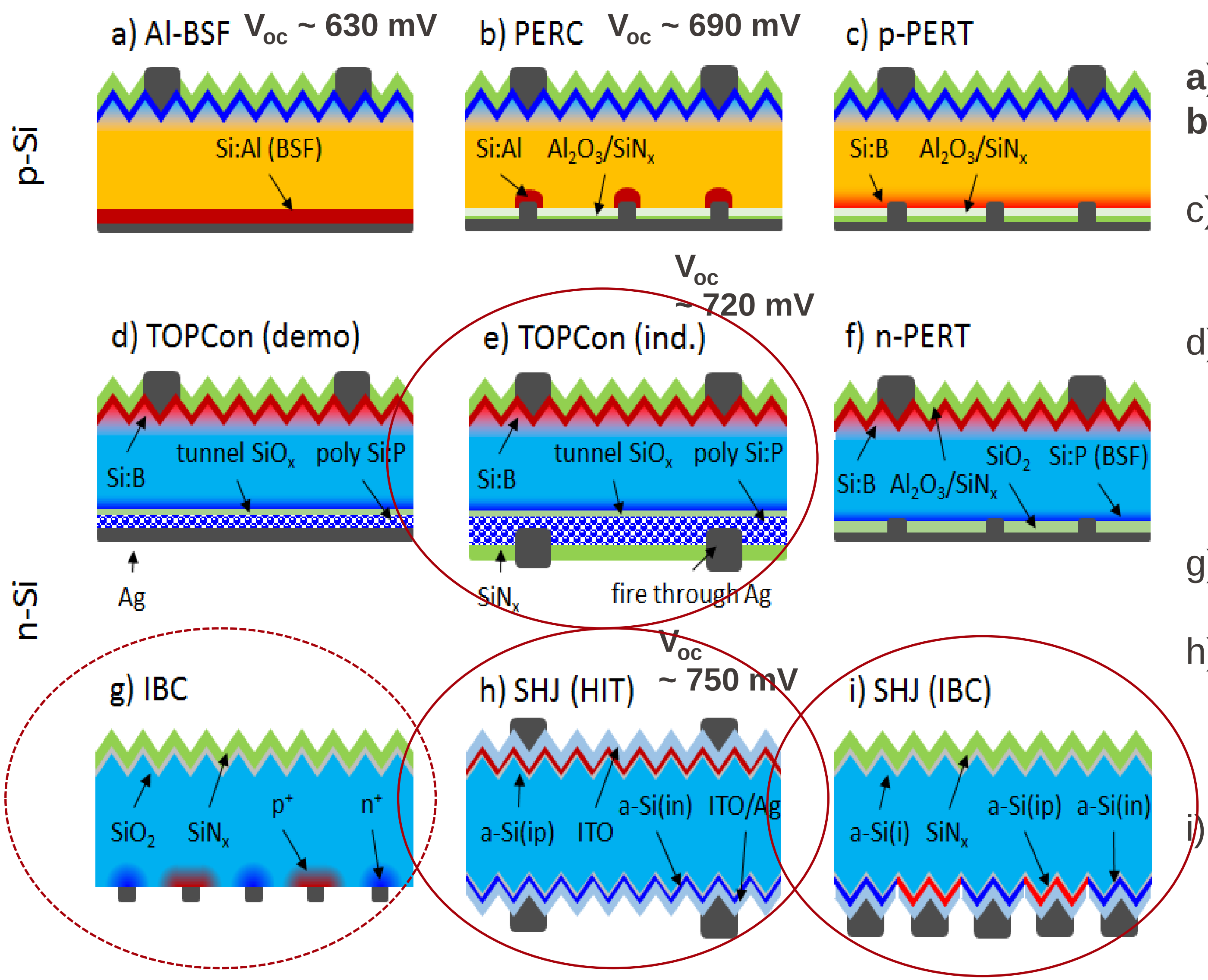
Challenging: PERC already very mature

Passivating contact cells: contact and passivate
→ No direct c-Si/metal contact
→ Ultra-low recombination velocity
Strategies:
- Reduce interface defect density
- Select layers transparent for carriers
- Assist with an electrical field

Back-contacted cells
→ No front shadowing
→ More freedom at the back (with or without passivating contacts)

Typical industrial c-Si solar cell structure

The many different possible structures

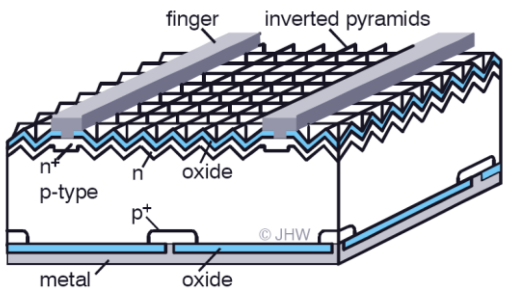


a) **Al-BSF** cell.
b) **PERC** localised rear contacts in the "passivated emitter and rear cell".
c) Local contacts "passivated emitter and rear totally diffused" (PERT), a design that applies to p- as well as n-type wafers.
d) and e) **TOPCon** n-type designs with "tunnel oxide" passivating contact", either with evaporated Ag contact as used in R&D, or with localised fire-through metallisation as becoming mainstream in industry.
g) **IBC** a design with "interdigitated back contacts" ().
h) **SHJ** both-side contacted "Silicon heterojunction" (SHJ) which was first demonstrated on in the "Heterojunction with Intrinsic Thin layer" (HIT). Panel
i) **IBC- SHJ** design.

C. Ballif, F.J. Haug et al. Nature Rev. Mat 2022

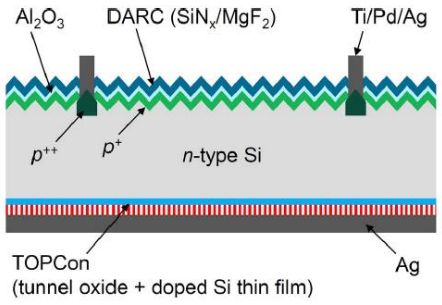
Ultimate possible evolution of c-Si solar cell technologies

Smaller contacts

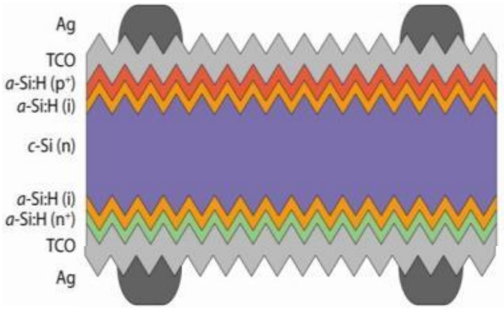


e.g. low cost pholithography

Passivating contacts solar cells

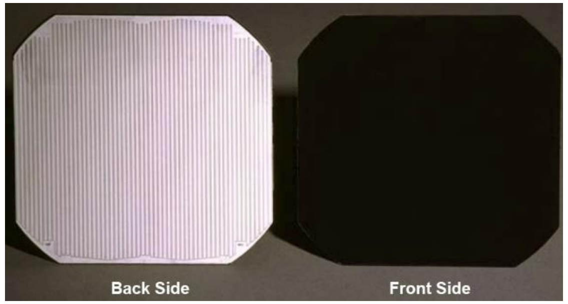


High temperature passivated contacts **«TOPCON»**



Low Temperature passivated contacts «Si heterojunction» **«SHJ» or «HJT» or «HIT»**

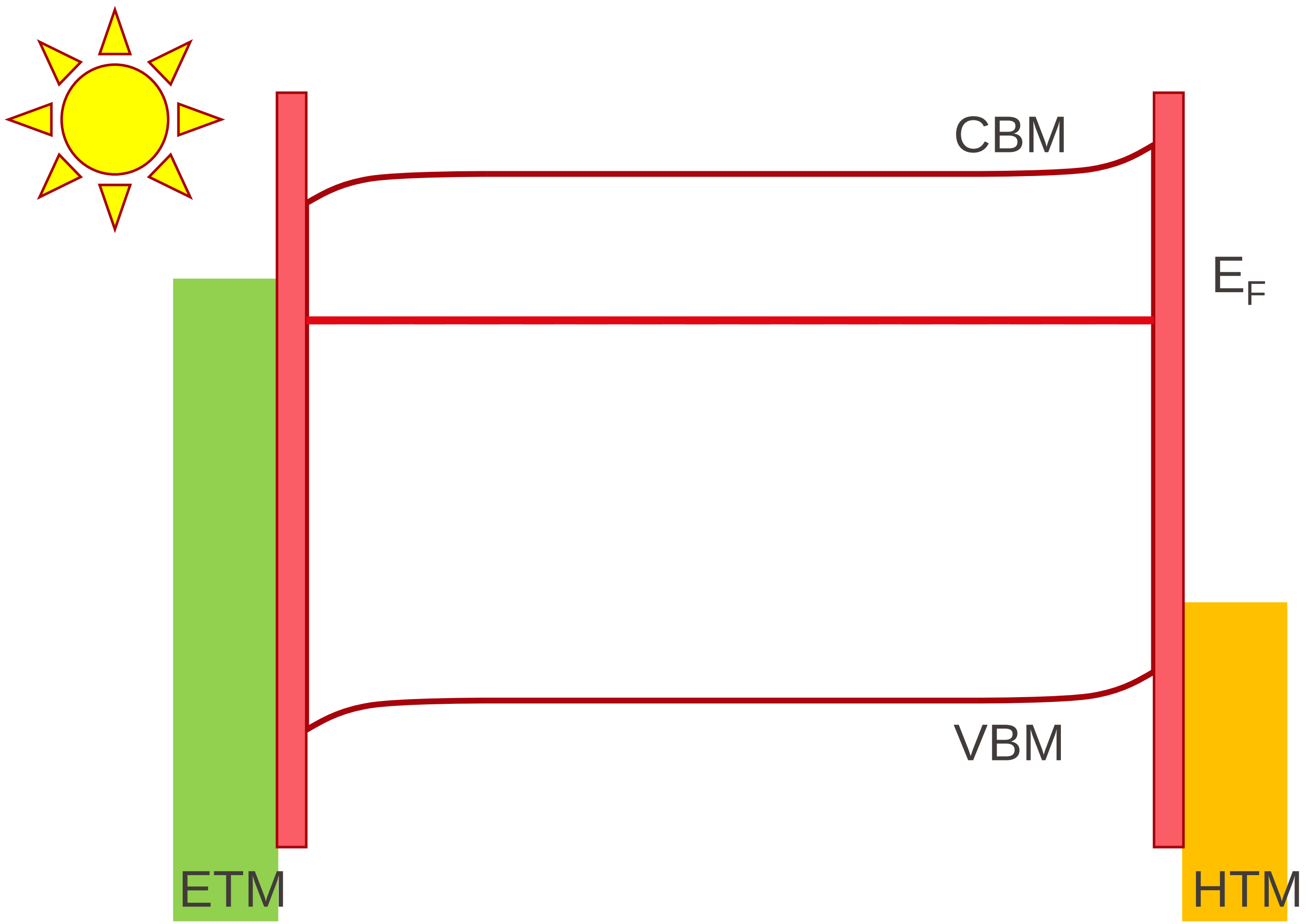
Advanced cell architectures



Interdigitated back-contacted solar cells **«IBC»**

1. Passivating contacts

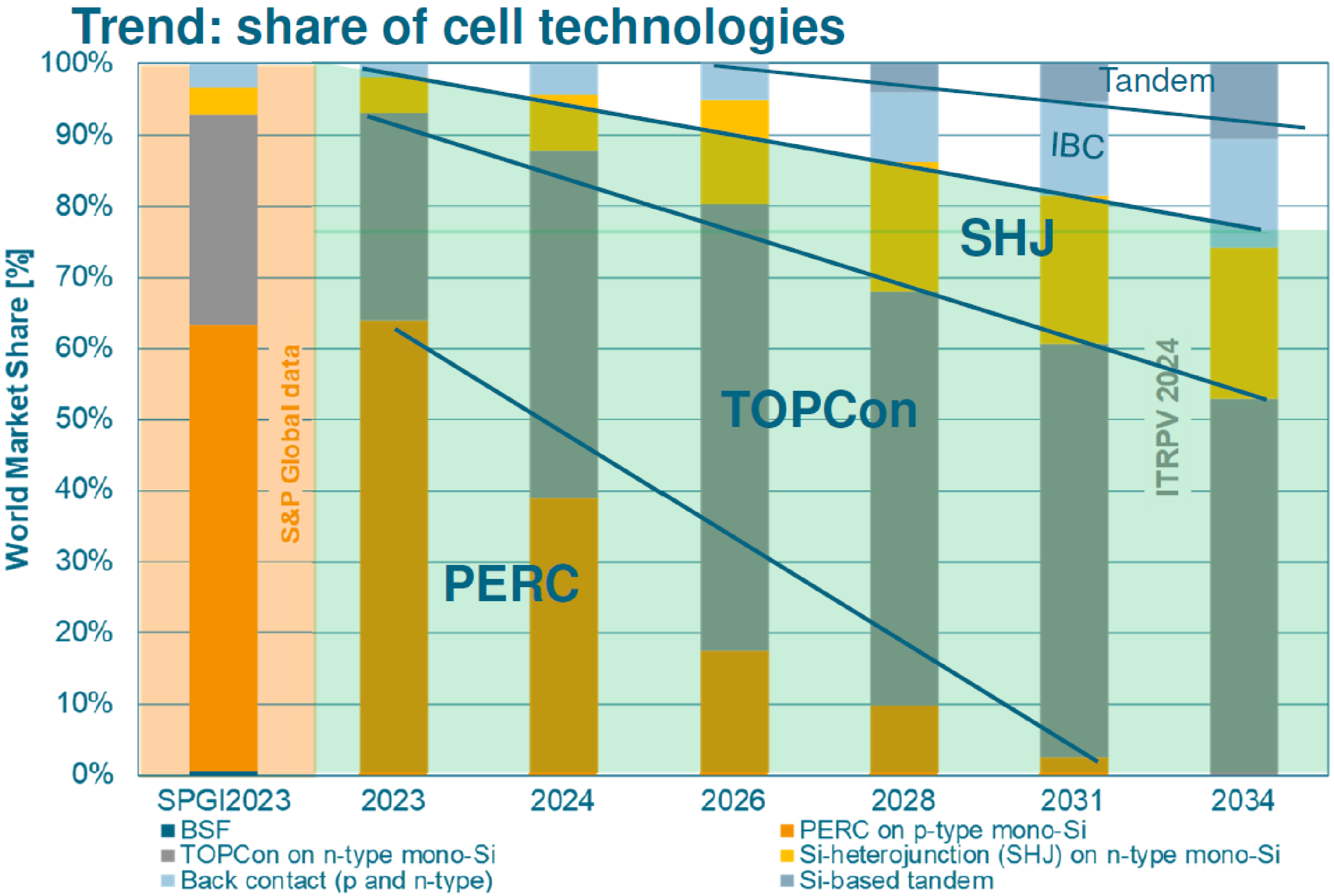
Passivating contacts: reduced interface defect density and get one type of carirrer through



Needs selectivity of one carrier type

Updated industrial view (March 2024)

International Technology Roadmap for Photovoltaic (ITRPV) - vdma.org - VDMA



TOPCON
Heterojunction
Back-contact

And Si based-tandem (Perovskite/Silicon) from 2026

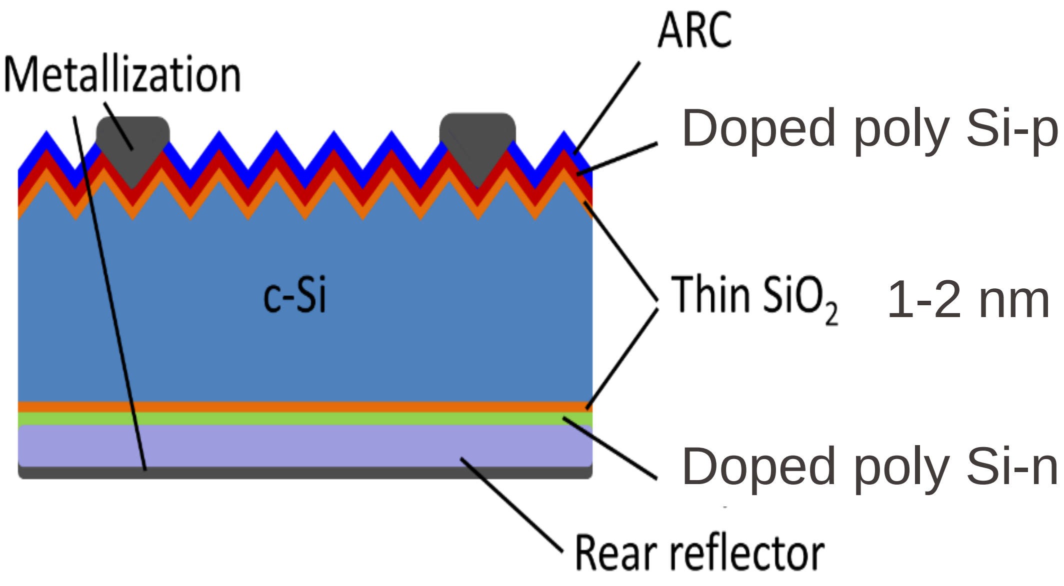
n.b. industry usually predicts wrongly !

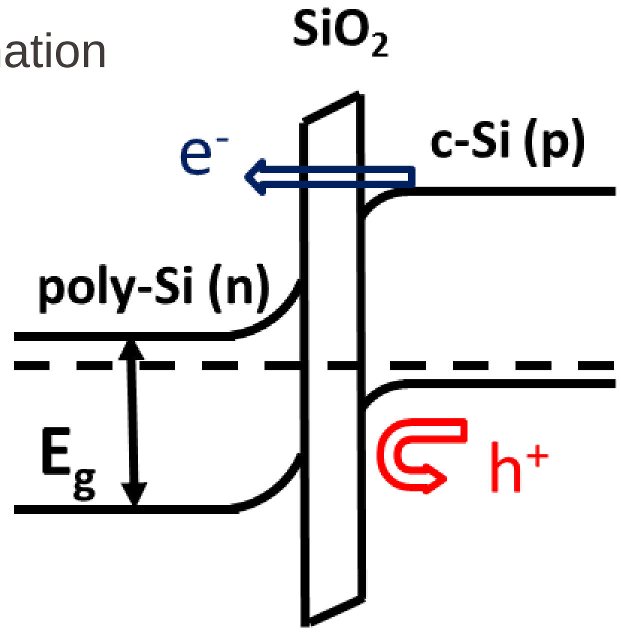
2. High temperature passivating contact (TOPCON*)

- High T process: using **thin «tunnel» oxides (1-2 nm) covered** with doped poly-silicon* (thin crystallised layer of silicon 30-200 nm thick), contact then by a metal.
  TOPCON = tunnel oxide passivated contacts

- The oxide passivates, and the doped polysilcon creates a «field» effect which reduces the need for perfect passivation. Eg. holes can't cross the oxide at a poly-Si(n)- p-Si, whereas electron can

- Contacting the poly-silicon layers with a metal does not introduce recombination





*E. Yablonovitch et al. APL 11 (1985), then introduced by Sunpower as a «secret», then made popular by Fraunhofer ISE in 2014, including for the name Topcon

[1] Feldmannm, F., *et al*., SOLMAT, vol 131, (2014)
[2] Römer, U., SOLMAT, vol 131, (2014)
[3] Young, D. L., Energy Procedia 55, (2014)
[4] Tao, Y., Proceeding 42th IEEE PVSC (2015)
Papers by PV-lab !

IN practice

- Polysilicon at the front is not so convenient (absorption doesn't contribute to current):

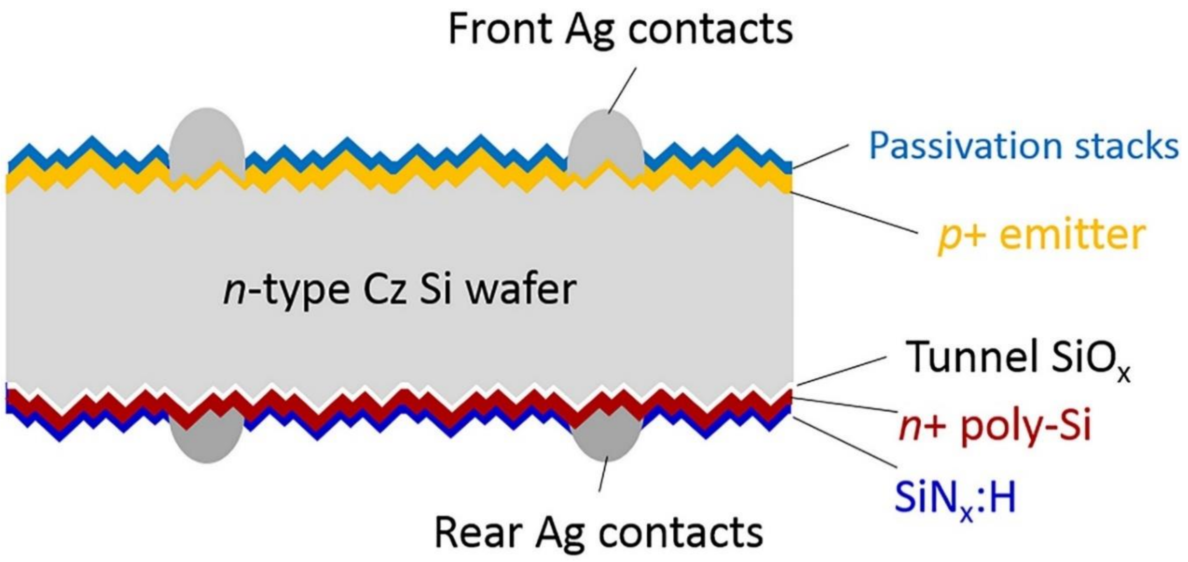
- The industry has selected a route with only a TOPCON contact at the rear, with a front side Boron diffused p-region, with a fire-through contact. The front is limiting the cell but constantly improving!

2. Industrial TOPcon process

PV-lab
IMT NEUCHATEL

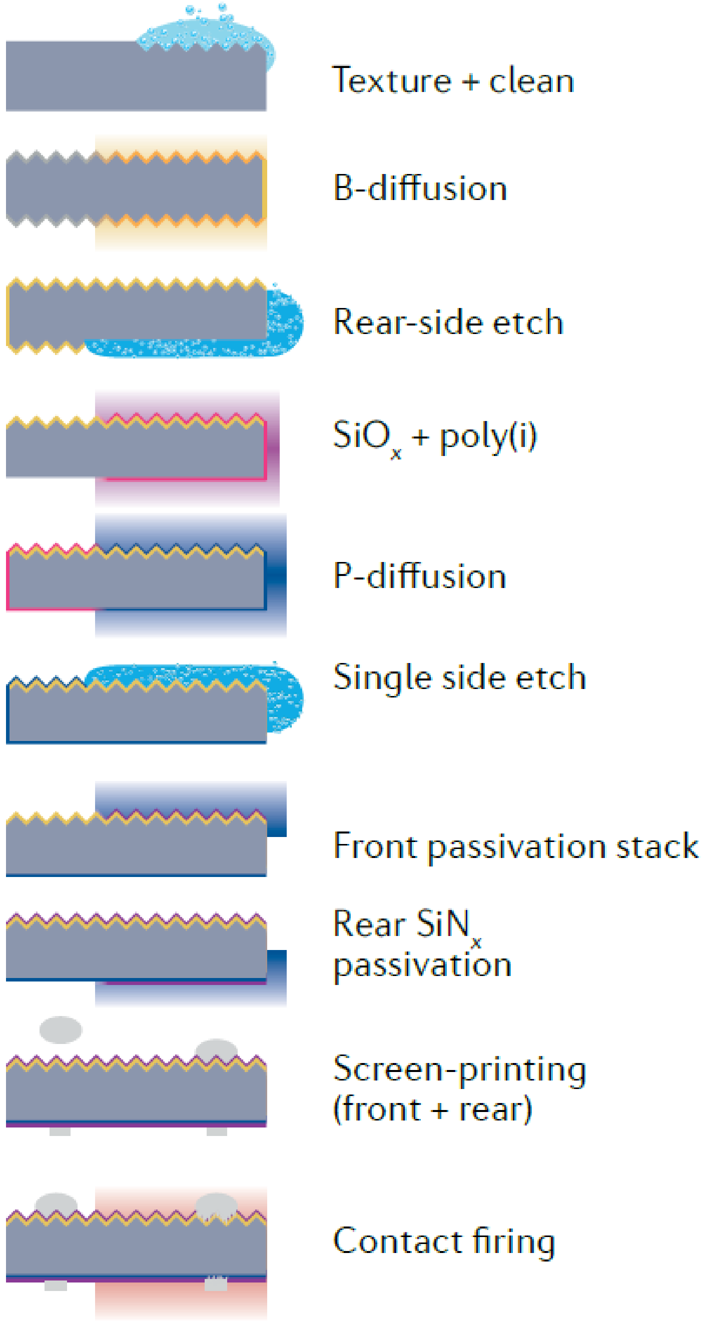
Current mainstream TOPCON (rear contact only)

- Use n-type wafer
- Make high-quality Boron emitter which can be well passivated by Al2O3 at the front
- Make a thin SiOx and a poly contact at the back (various coating techniques possible)
- Passivate front, put dielectric at back, and fire through front and back (without going throught the SiOx layer at the back)



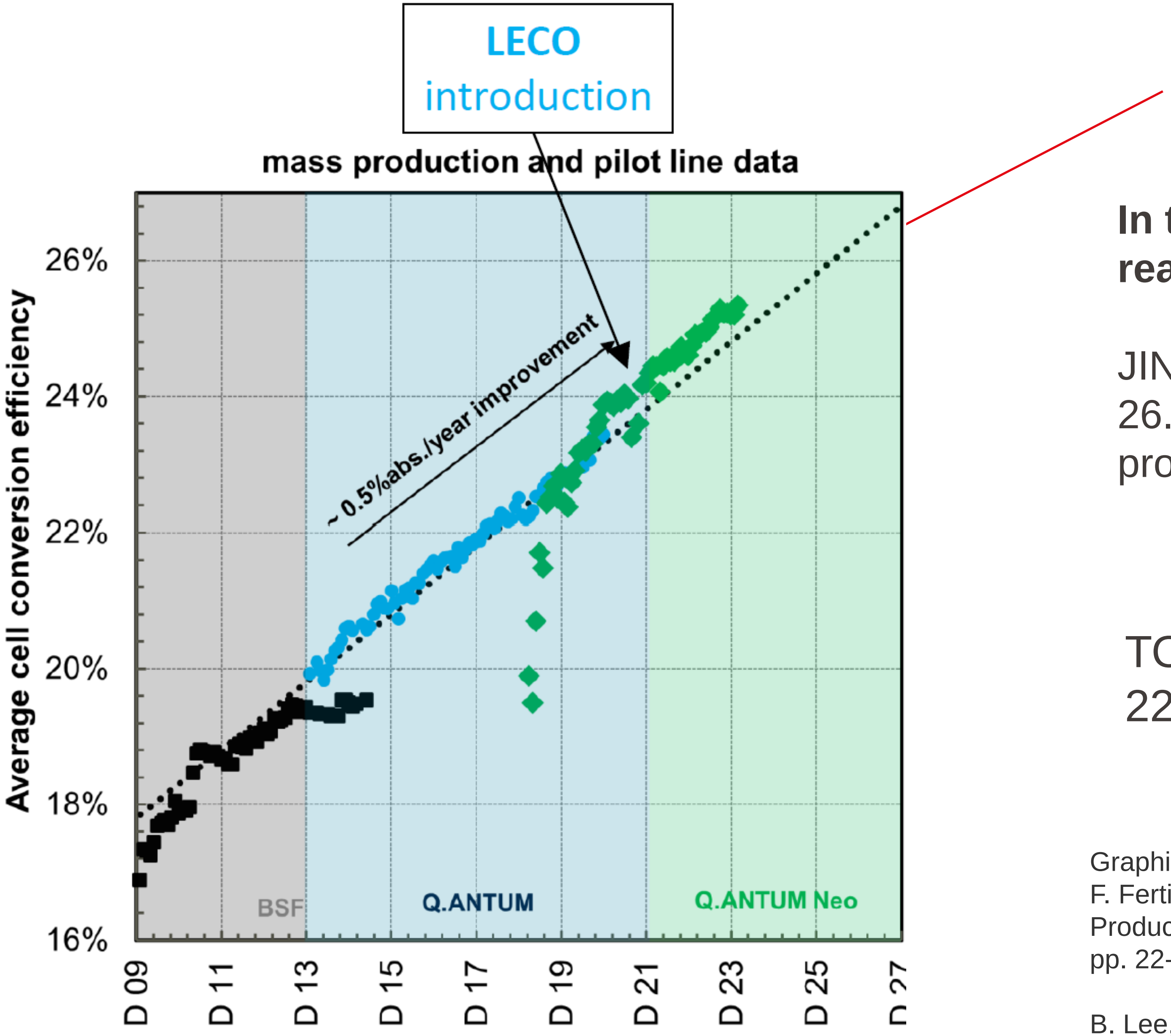
Bifacial structure possible !

Y. Chen, P. Verlinden et al. Photovoltaics Res. Appl. (2019). https://doi.org/10.1002/pip.3180



C. Ballif, F.J. Haug et al. Nat. Review Materials 2022

Continuous improvement of TOPCON (Pass. Contact)



In the best production lines Topcon cells reach ~24.5-25.5 %

JINKO solar certifed a TOPCON cells with 26.89% in 2023 (unknow manufacturing process)

TOPCON modules can reach now 22-23% (large modules)

Graphic: Hansgar Mette, Silicon PV 2024
F. Fertig *et al*., "Q CELLS > 24% Silicon Solar Cells With Mass-Production Processes," in *IEEE Journal of Photovoltaics*, vol. 12, no. 1, pp. 22-25, Jan. 2022, doi: 10.1109/JPHOTOV.2021.3112122.

B. Lee, Q-Cells et al. Proceeding Silicon PV 2023

A magic and quickly evolving »trick » for contacting Silicon

LECO – Laser Enhanced Contact Optimization

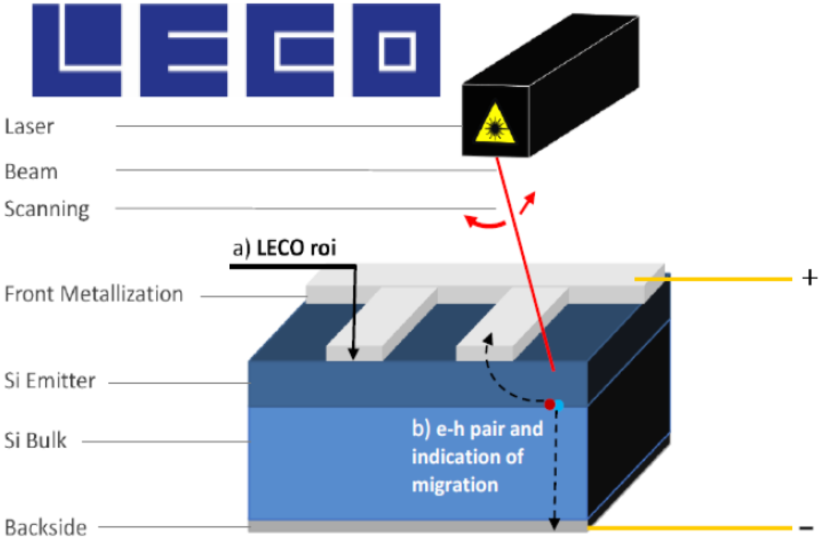
LECO Process

- Laser scans over the cell while a reverse bias is applied
- Free carriers are forced through tiny interface areas between contact and silicon

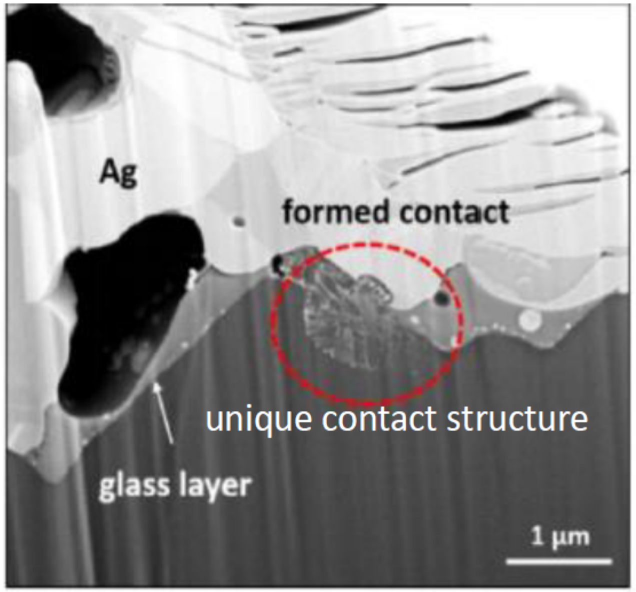
→ A unique contact structure is formed named CFC – Current Fired Contact

Qcells and Cell Engineering joint forces

- LECO was developed by CE (Cell Engineering GmbH) since 2016
- Tool in pilot line at Qcells in 2018, roll out to MP in Q1/2022
- Qcells became 100 % shareholder of CE in October 2022
- IP granted in several countries like EU, China, US, India…
- Qcells and CE are committed to defend its IP to ensure fair and lawful use of LECO



[1] E. Krassowski, WCPEC 2022



[2] S. Großer et. al, doi: 10.1109/JPHOTOV.2021.3129362

Screen-printed front contacts

LECO - Contact properties I

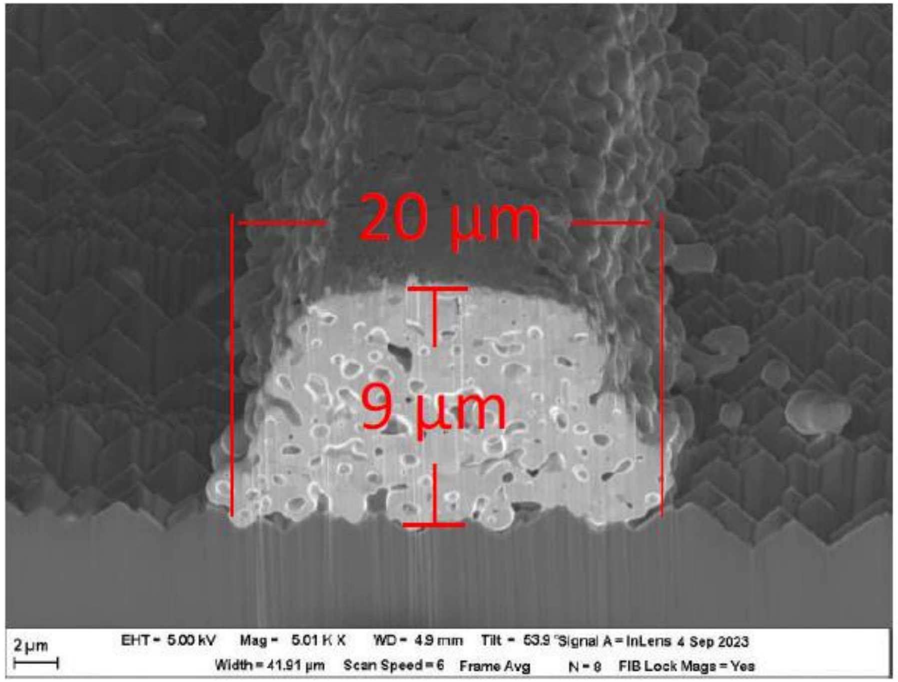
Metallization recombination $j_{0,met}$:

- Solar cells with a metal fraction between 2 % and 20 % have been manufactured
- Extracting of $j_{0,met}$ from these cells

Process	$j_{0,met}$ [fA/cm²]	V_{OC} [mV]
Q4/2021 – no LECO	< 1200	701
Q4/2021 – with LECO	< 400	709
Q1/2024 - Optimised process	< 160	> 730

- Assuming 1.7 % metal shading results in a j_0 fraction for the metallization of < 3 fA/cm²

→ **Low $j_{0,met}$ < 160 fA/cm² for LECO contacts achieved**



Thanks to LECO process, like improved local, while keeping a « partial passivation on less doped emitter*

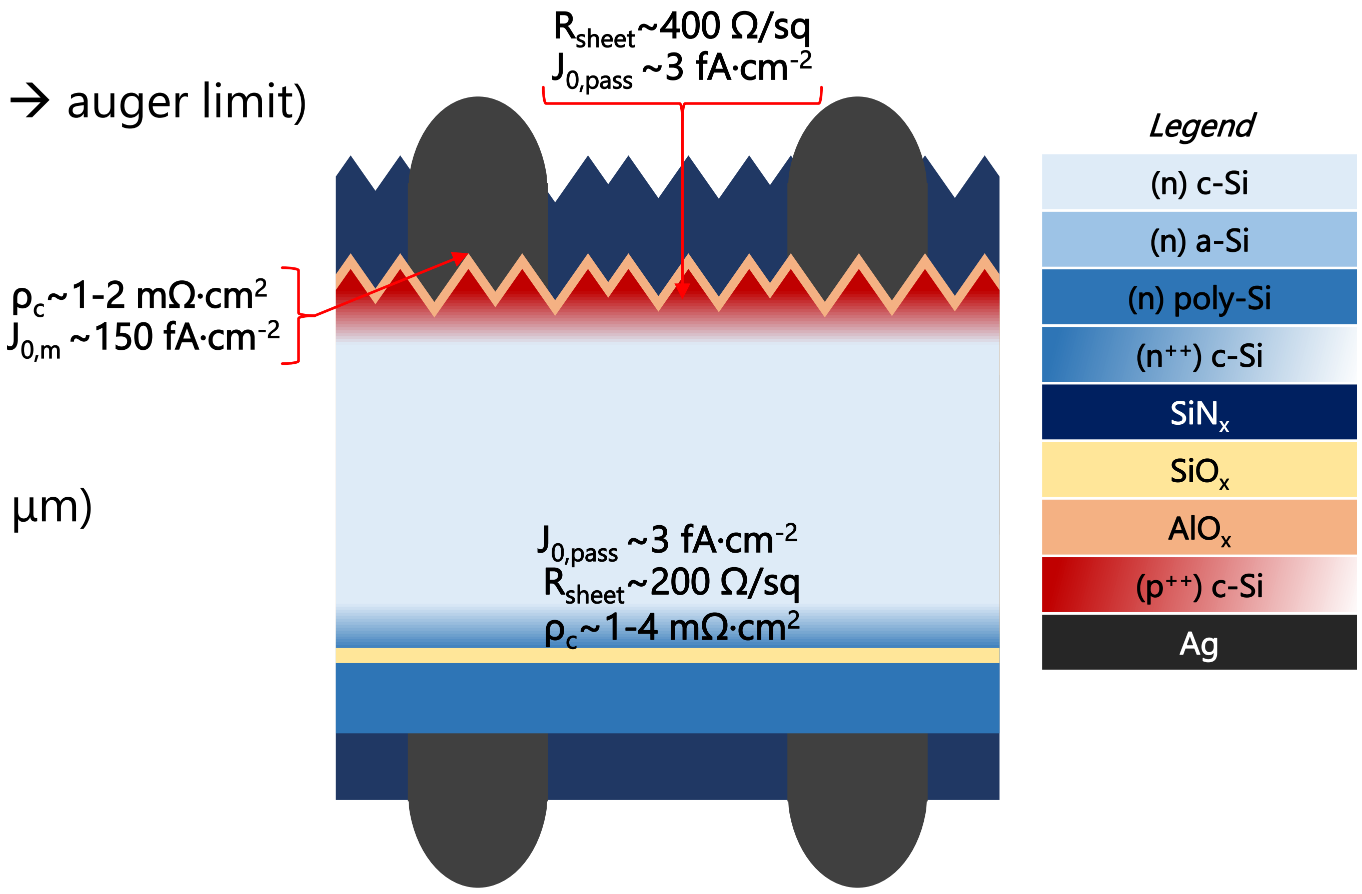
→ Allows low front doping (< $10^{19}/cm^{-3}$)

→ Front sides improves and valorises the quasi perfect backside

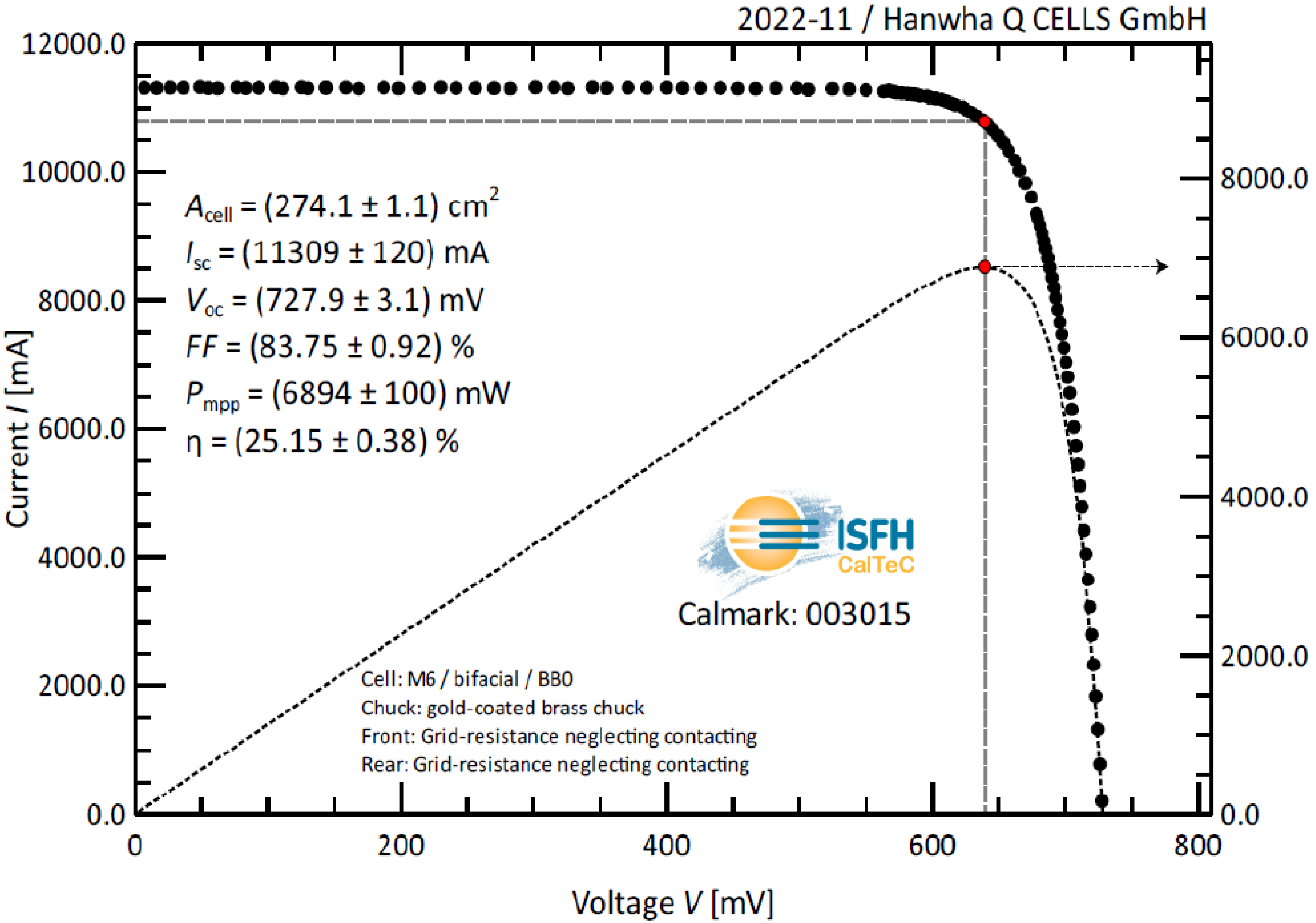
State of the art TOPCon solar cells

CONFIDENTIAL

- State of the art TOPCon solar can reach efficiencies above 26% featuring
  - J_{SC} ~ 41.5 mA·cm^{-2}
  - V_{OC} ~ 738 mV (iV_{OC} reaching 750 mV)
  - FF ~ 86.5% (above (or close to) radiative limit → auger limit)
- To achieve such high efficiency
  - High bulk lifetime (>5 ms)
  - Low surface recombination (<2 fA.cm^{-2})
  - Low metal recombination (<150 fA.cm^{-2})
  - Low contact resistivity (<2 mΩ.cm^{2})
  - High quality metal printing (metal width < 20 µm)



Typical I-V of a very good Topcon 2023



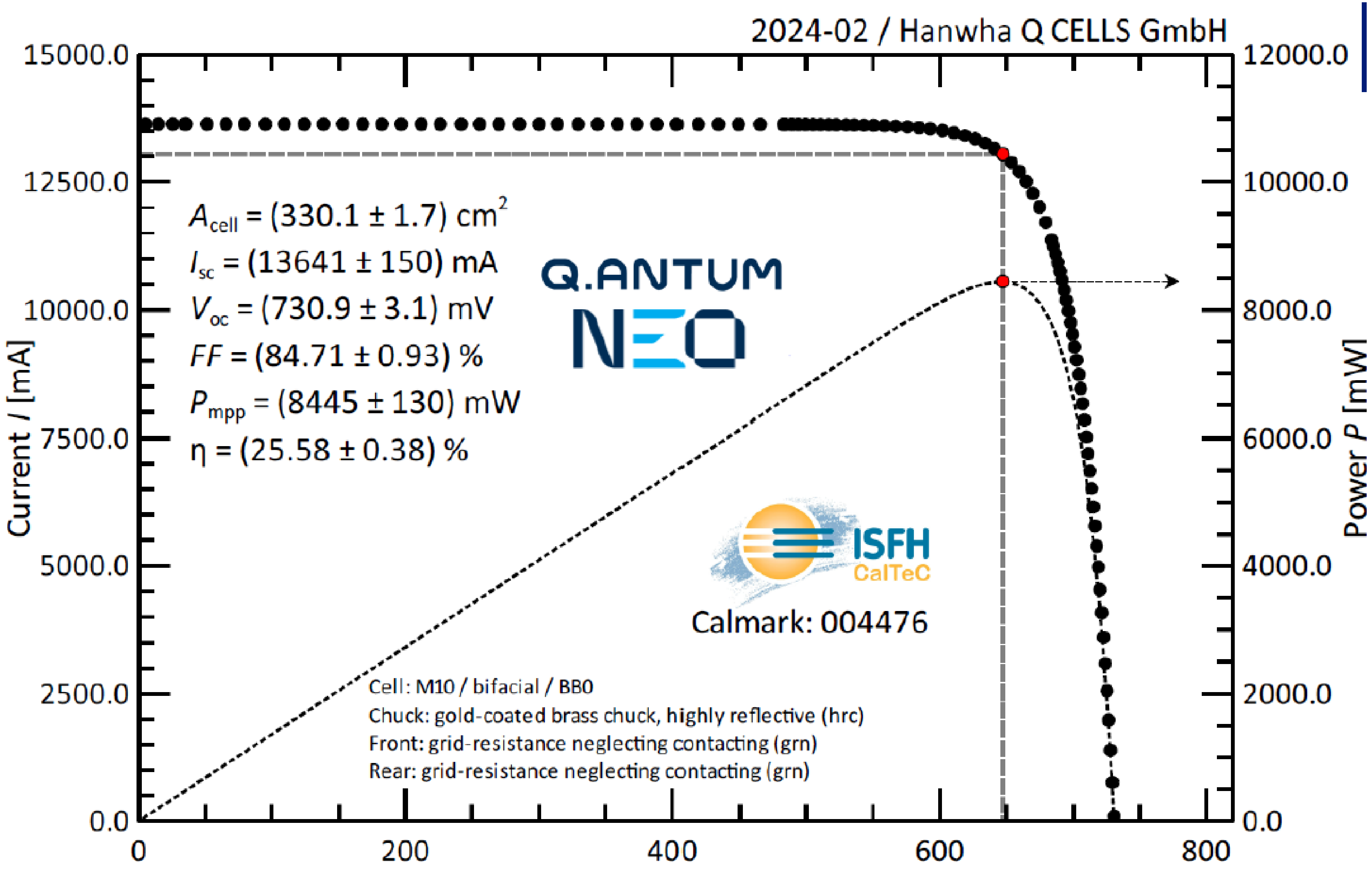
- Similar Jsc to PERC
- 41.25 mA/cm2

- Higher voltage
- 30-40 mV more
- Better FF

no local Al-BSF with possible resisitiv transport losses in wafer

Source: B. Lee
Q-cells, Silicon PV 2023

Typical I-V of a very good Topcon 2024



- 0.05 mA /cm2
- 3 mV more
- 1% FF more

- 0.43% absolute more

In one year

Source: Ansgar Mette
Qcells Silicon PV 2024

From « small » to large Topcon module

Q.TRON M-G2+ SERIES

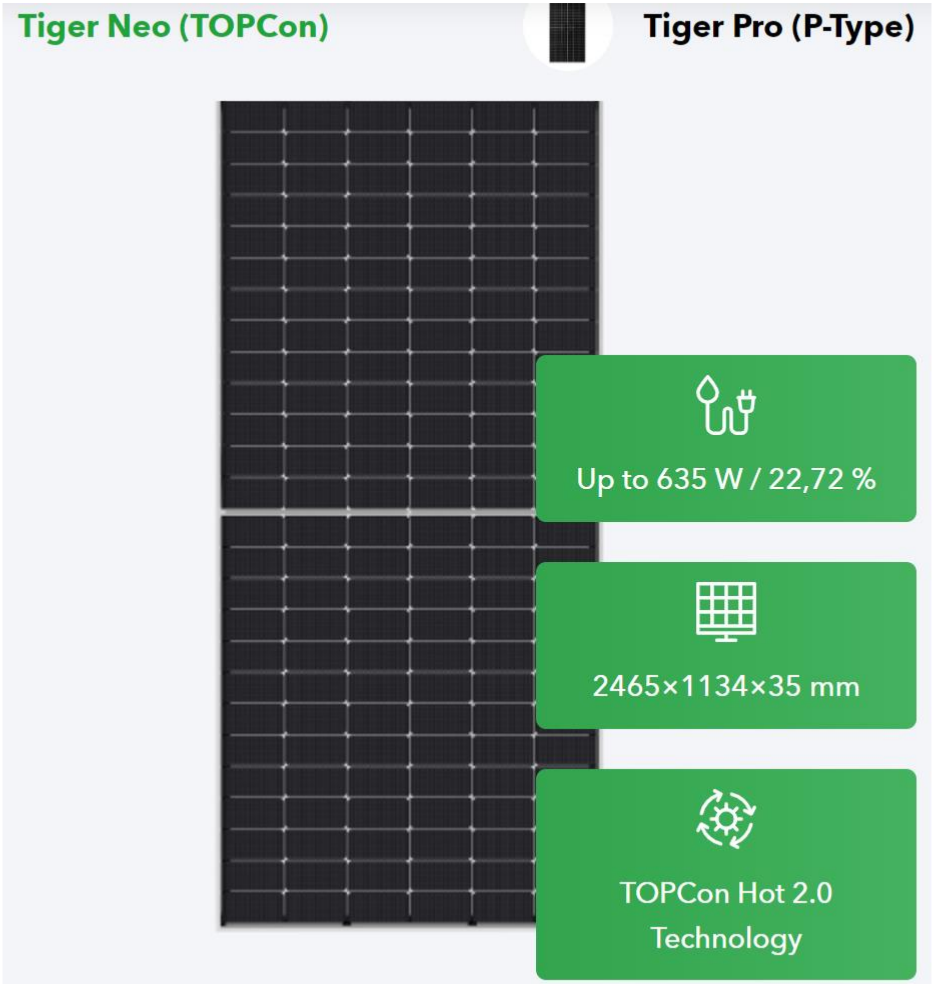
410-435 Wp | 108 Cells
22.3 % Maximum Module Efficiency

MODEL Q.TRON M-G2+
Q.TRON M-G2.4+

Up to 22.3% total area efficiency
Up to 728 mV per cell
Dpmax/T= -0.3%/°K

Note: class from 21 to 22.3%
In practice not always possible to have the best class

JinKO Solar



2. High temperature passivated contact cells

- By adding a tool for deposition of polysilicon + SiOx preparation and with process adaptation (Boron instead of phosphorus diffusion), a gain of ~ 1-1.5% efficiency compared to PERC solar cells can be targeted.

- Most existing industry adopt this technology through massive «new production lines»

(smallest units at 600 MW)

- The current most popular TOPCON process (boron doped front and rear side fully passivated n+ contact) is less and less limited in Voc thanks to improvement of the front contacting process (paste adaptation and LECO process… its now almost like creating tiny quasy perfect contacts with the glass frit somehow passivating the front.

- TOPCon requires 2x the amount of Ag than PERC which could become an issue in the long term

(11-14 mg/W).

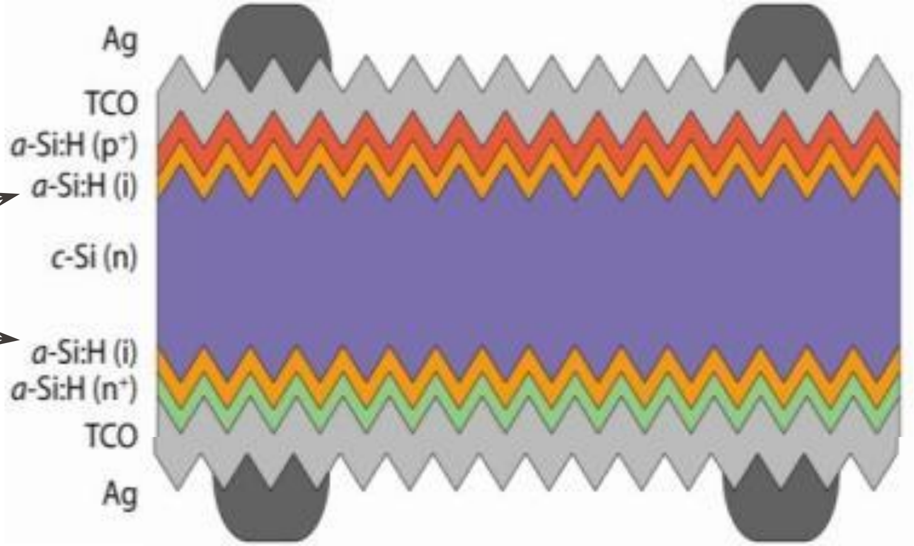
- A logical next step could be local front passivating contacts or even simplified processes (but all come with challenges (see many papers by PV-lab of EPFL)

3. Silicon heterojunction (SHJ) solar cells

Types of high efficiency cells

<u>Heterojunction</u> is the junction between two materials with different bandgaps: here a-Si and c-Si

chemical passivation



- Intrinsic hydrogenated amorphous silicon (a-Si:H) deposited at low temperature (typ 200 ° C) provides excellent passivation of *c*-Si surfaces (with or without field)
- Charges can be extracted through a-Si:H layers, which act as *semi-permeable membranes* or *passivating contacts*
- Contacts to Ag grid is provided by a transparent conductive oxyde (TCO) such as ITO which also support the electron current transport (like the emitter of a p-n junction)

Keypoint of SHJ technology : record V_{oc} values (>750 mV for 150 micron wafers)

S **De Wolf**, A Descoeudres, ZC Holman, C **Ballif**. Green 2 (1), 7, 2012. 944, 2012.
High-efficiency crystalline silicon solar cells: status and perspectives

3. Silicon heterojunction (SHJ) solar cells

Historically

Invented by Sanyo less than 30 years ago

Jpn. J. Appl. Phys. Vol. 31 (1992) pp. 3518–3522
Part 1, No. 11, November 1992

Development of New a-Si/c-Si Heterojunction Solar Cells: ACJ-HIT (Artificially Constructed Junction-Heterojunction with Intrinsic Thin-Layer)

Makoto TANAKA, Mikio TAGUCHI, Takao MATSUYAMA,
Toru SAWADA, Shinya TSUDA, Shoichi NAKANO,
Hiroshi HANAFUSA[1] and Yukinori KUWANO[1]

Functional Materials Research Center, Sanyo Electric Co., Ltd.
1-18-13, Hashiridani, Hirakata, Osaka 573
[1]*R&D Headquarters, Sanyo Electric Co., Ltd., 1-18-13, Hashiridani, Hirakata, Osaka 573*

(Received July 25, 1992; accepted for publication September 19, 1992)

A new type of a-Si/c-Si heterojunction solar cell, called the HIT (Heterojunction with Intrinsic Thin-layer) solar cell, has been developed based on ACJ (Artificially Constructed Junction) technology. A conversion efficiency of more than 18% has been achieved, which is the highest ever value for solar cells in which the junction was fabricated at a low temperature (<200°C).

KEYWORDS: solar cells, heterojunction, crystalline silicon, amorphous silicon, plasma CVD

Commerciallized first under 'HIT' name by leader Panasonic

EPFL PV-lab csem IMT NEUCHATEL

3. Silicon heterojunction (SHJ) solar cells

Neuchâtel : a long history with plasma deposition and SHJ cells shortly after Sanyo

United States Patent [19]

Keppner

[54] **PHOTOVOLTAIC CELL AND METHOD FOR FABRICATION OF SAID CELL**

[75] Inventor: **Herbert Keppner**, Neuchatel, Switzerland

[73] Assignee: **Universite De Neuchatel**, N... Canada

[21] Appl. No.: **446,6...**

[22] PCT Filed: **Sep. 2...**

[86] PCT No.: **PCT/CH...192**

§ 371 Date: **May 31, 1995**

§ 102(e) Date: **May 31, 1995**

[87] PCT Pub. No.: **WO95/10856**

PCT Pub. Date: **Apr. 20, 1995**

[30] **Foreign Application Priority Data**

Oct. 11, 1993 [FR] France 93 12246

...993

ELSEVIER Solar Energy Materials and Solar Cells 34 (1994) 201–209

Solar Energy Materials and Solar Cells

Pa... of amorphous and ... deposited by VHF-GD ...licon solar cells

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Activities stopped in 1995. Swiss governement says to Shah
Thin film silicon is the future. Activities restarted end 2004

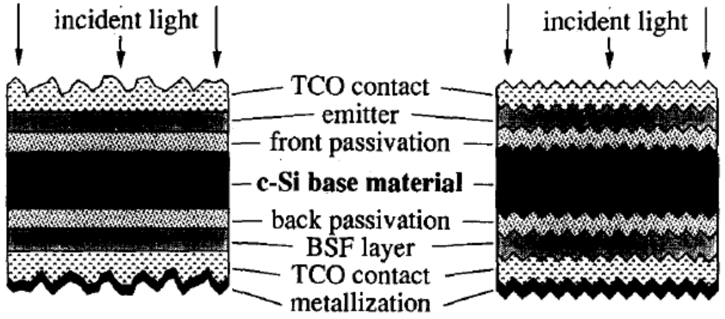


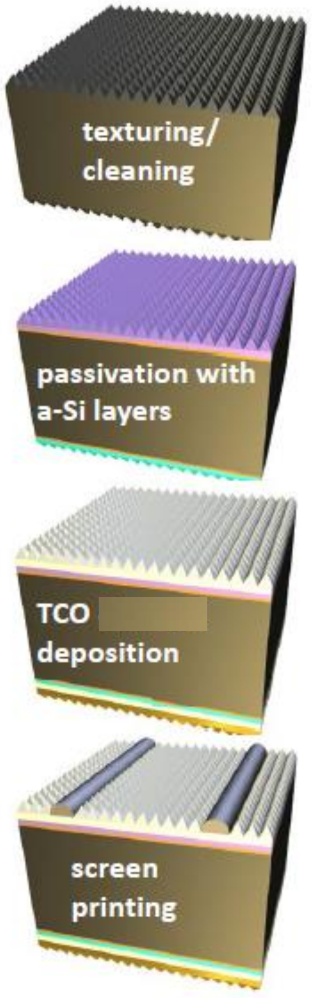
Fig. 5. Light trapping concepts for BAP-cells when thin (100 μm) wafers are used.

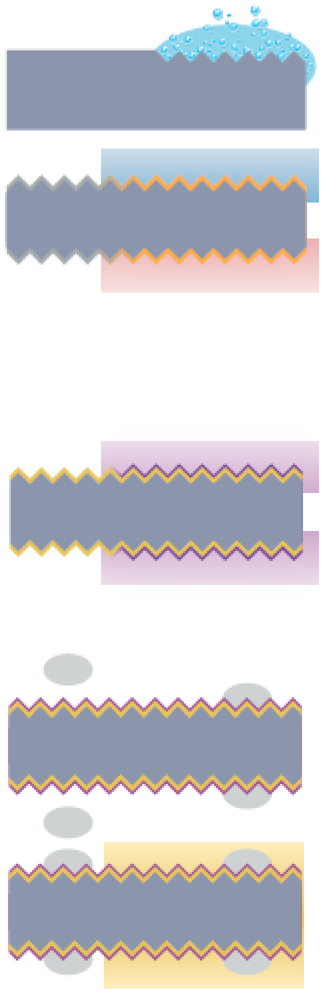
talline silicon [1–3], forming thereby heterojunctions. We present first results of a new structure called ⟨⟨BAP (Both Sides Amorphous Passivated) cell⟩⟩, where the wafer was sandwiched between two intrinsic amorphous silicon layers. These two layers, as well as the μc-Si:H emitter, and the layer forming the BSF (Back Surface Field) were all deposited by

3. Silicon heterojunction (SHJ) solar cells

One of the most simple process flow (developed at IMT, Neuchâtel)

- Saw damage etch / texturing / cleaning
- *i-p* a-Si:H deposition by PECVD (15 nm)
- *i-n* a-Si:H deposition by PECVD (15 nm)
- Front and back ITO DC sputtering (80 nm)
- Screen-printing front and back contact
- Low temperature annealing





8 “process steps” (<200° C)

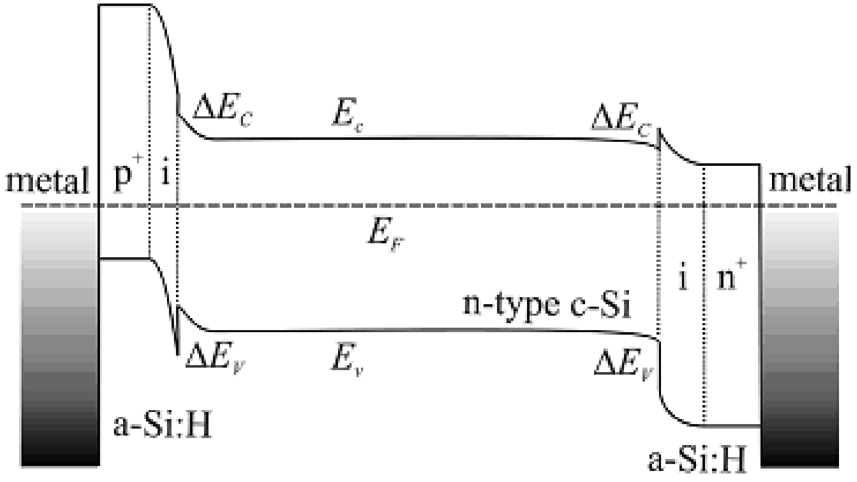
S. Olibet et al. 2006

3. Silicon heterojunction (SHJ) solar cells

Full surface «passivating contacts»

Heterostructure contacts: band structure

⇒ No direct contact between metal and electrically active semiconductor
⇒ Surfaces are passivated (S ~ 1- 15 cm/s for full contacts,) but carrier can still cross the contact



Practically: deposition of hydrogenated amorphous silicon (*a*-Si:H) layers on the surfaces

⇒ Low recombination is mainly thanks to use of thin intrinsic a-Si:H buffer layer
⇒ a-Si:H Films can relatively easily be doped either p- or n-type (allows us to make an "emitter" and "back surface field", or at least to create an asymmetry in carrier collection).

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3. Silicon heterojunction (SHJ) solar cells

Heterostructure contact

The contacts/surfaces are very sensitive (and can be simulated with PC1D) to:

- Mobility in the a-Si:H (low minority carriers mobility → high V_{oc})
- Band offsets that prevent carriers from recombining
- Possible surface or interface defects and charges
- Tunneling and thermionic emission that can affect transport and modify the FF

→ HJT are not trivial to simulate and understand

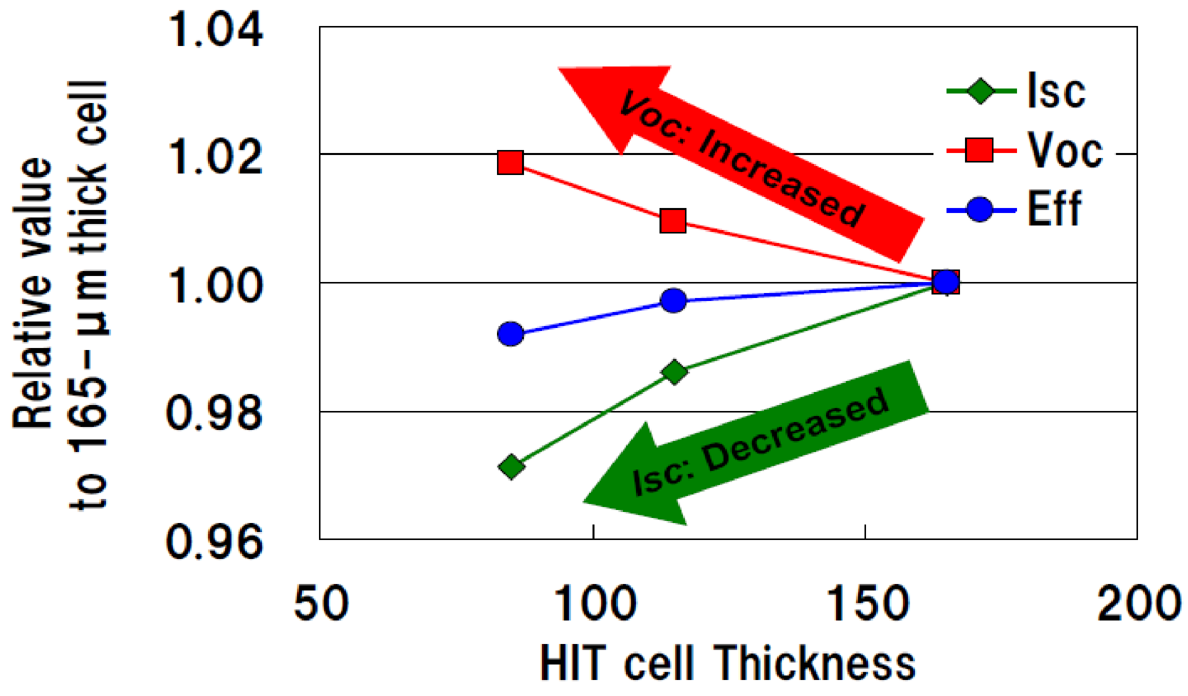
a-Si:H is a disordered semiconductor with properties different than c-Si (bandtails, amphoteric "3 states defects")

3. Silicon heterojunction (SHJ) solar cells

Advantages: towards thin wafers

Almost perfect passivation and low T process allows use of very thin wafers (no warping of substrates etc.)

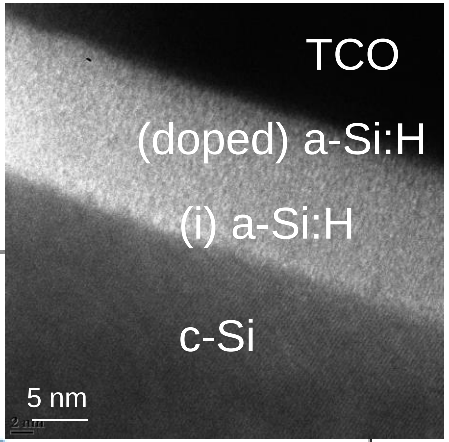
Increased Voc can compensate for the drop in Isc

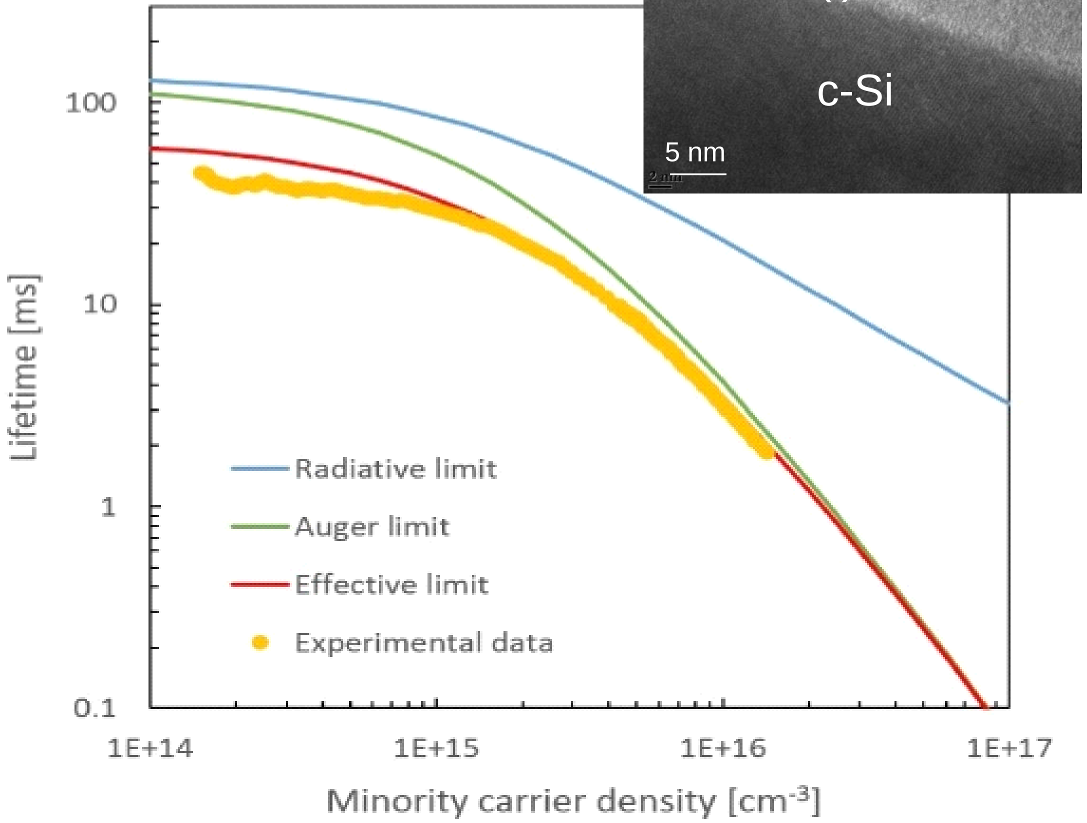


Note: current losses may be avoided by improved optical confinement

3. Silicon heterojunction (SHJ) solar cells

High efficiency Si bottom cell (with lean process)





- Perfect passivation (Seff < 1 cm/s)

Best screen-printed cells so far in EPFL PV-lab

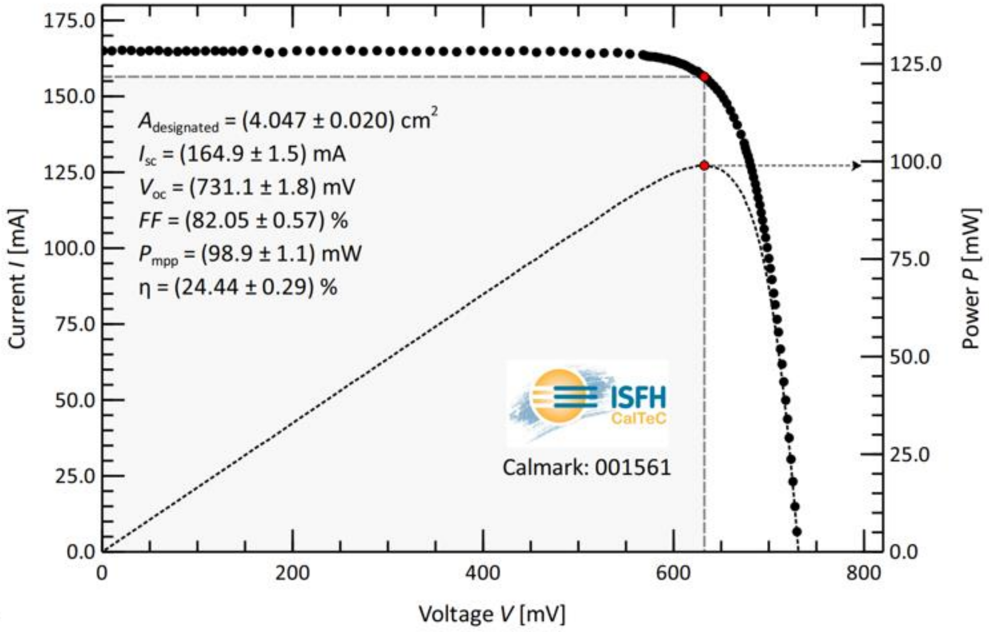
<u>24.42 % (n.b. excellent for 2x 2 cm2 research lab!)</u>

V_{OC} = 731 mV (with thinner wafer → 745 mV)

J_{SC} = 40.7 mA/cm2, (n.b. thick wafer)

FF = 82 %

larger wafers, less edge effects, process tuning → > 26%



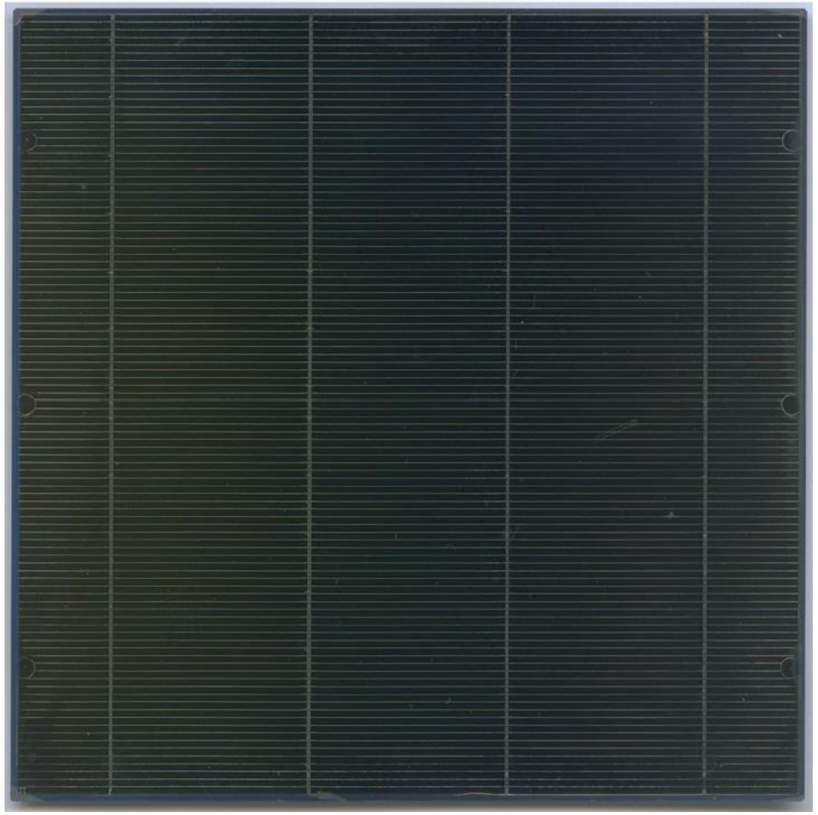
Processes for a-Si:H deposition are key to achieve required opto-electronic properties !

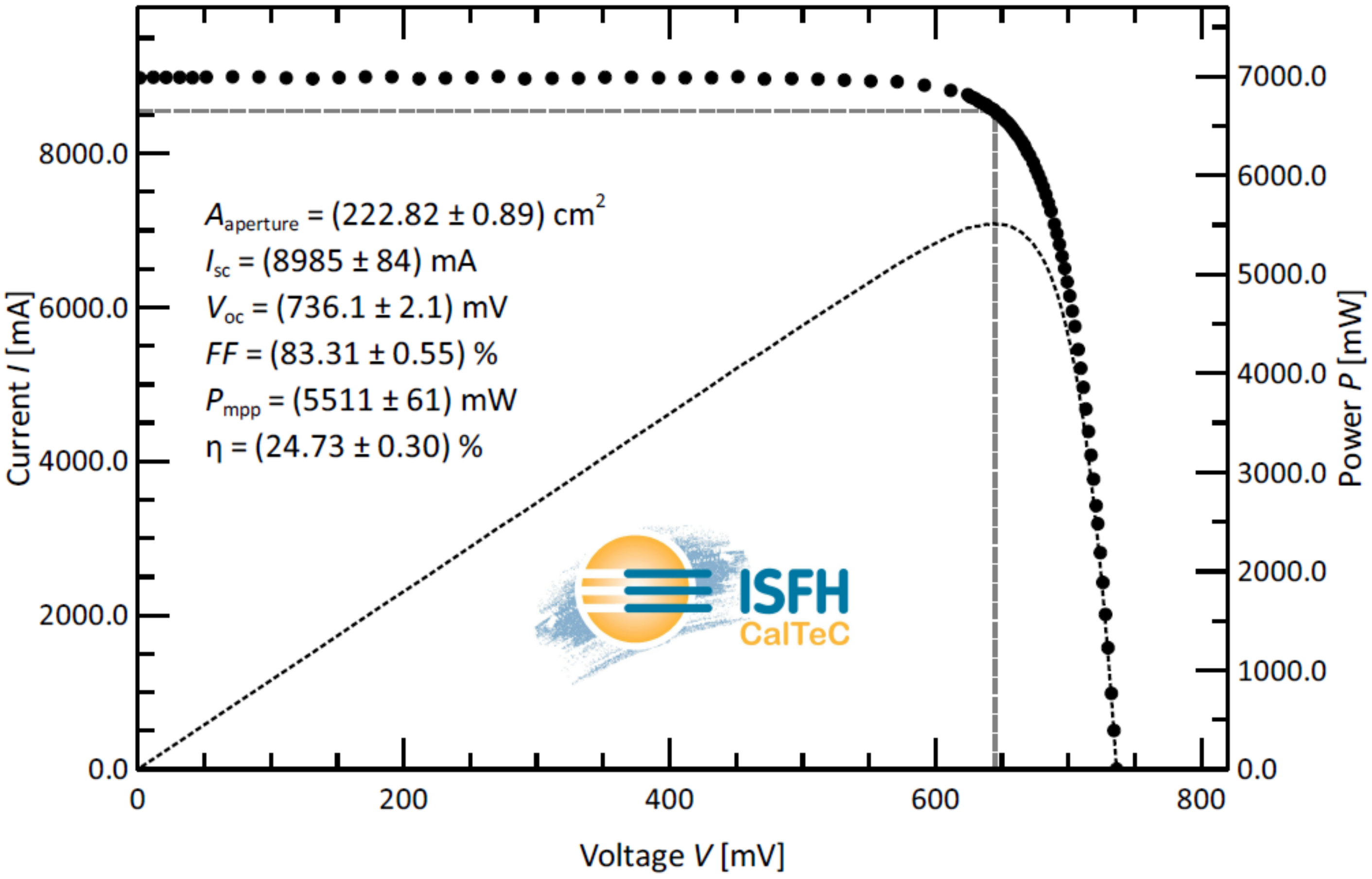
Prof. Christophe Ballif

3. Silicon heterojunction (SHJ) solar cells

Plated heterojunction cells at CSEM: certified efficiency 24.73% on 222 cm^2 (2020)

A. Lachowitz et al. CSEM,
Watabe et al. CIE





3. Silicon heterojunction (SHJ) solar cells

A lean but subtle process: from lab to full production lines

2005

First high efficiency solar cells

Swiss Electric Research award 2007

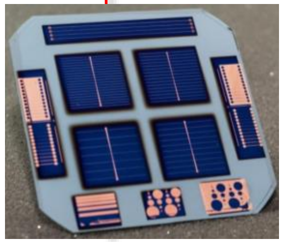
19.2%

2008 2009

Hosting and transfer of technology to Roth&Rau Switzerland

Creation Roth and Rau Switzerland

22-23 %

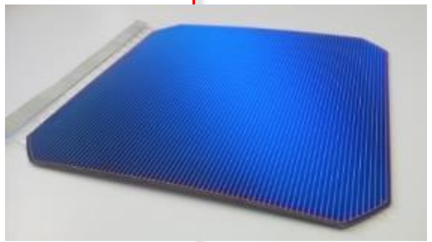


2011

Meyer Burgers Acquires Roth&Rau

MEYER BURGER

22-23 / 24 %



2013

Industri-alisation phase

First Production lines and tools sold

Large scale demonstrator

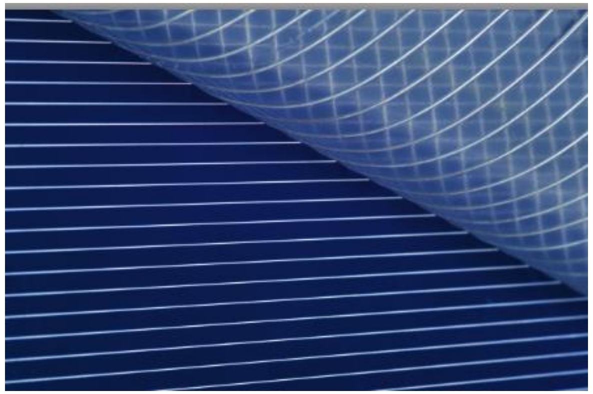
TODAY

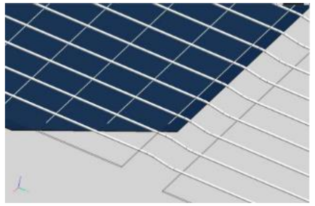
Revival of production in Europe

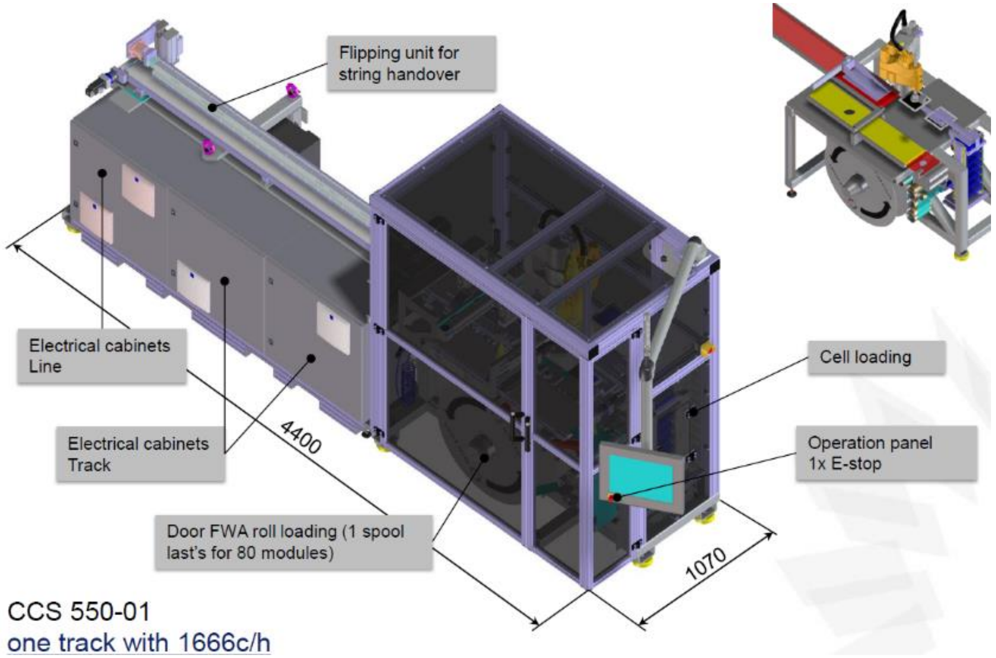
Prof. Christophe Ballif

3. Silicon heterojunction (SHJ) solar cells

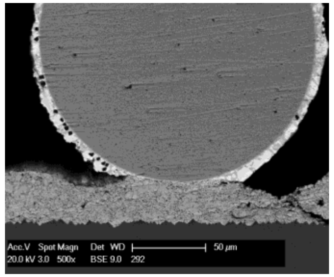
18 "Smart wire" connections : strong reduction of Ag costs







- Thicker wire
- No-more indium
- More transparent polymers
- Much less Ag fingers (or Cu)

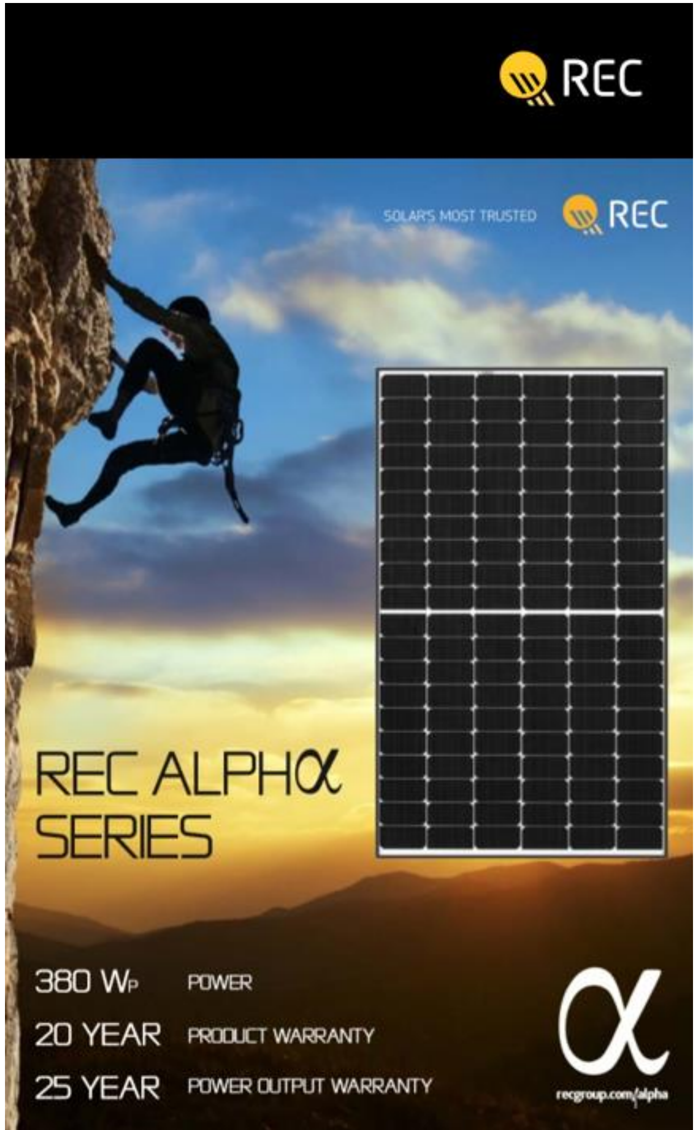


(SWCT™) to play a key role in REC Group's cutting-edge high efficiency solar module technology
02/12/2018

3. Silicon heterojunction (SHJ) solar cells

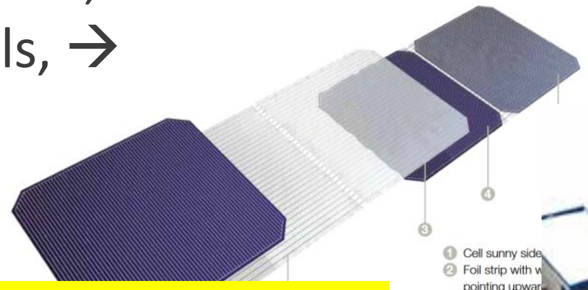
Combining production know-how and equipment

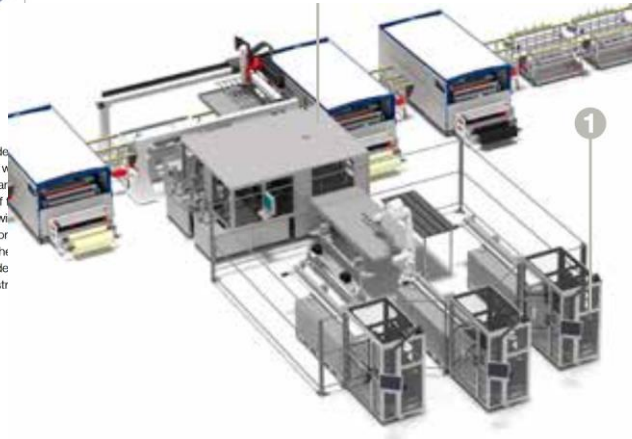
MEYER BURGER



600 MW at REC

Improved production,
smartwire®, ½ cells, →

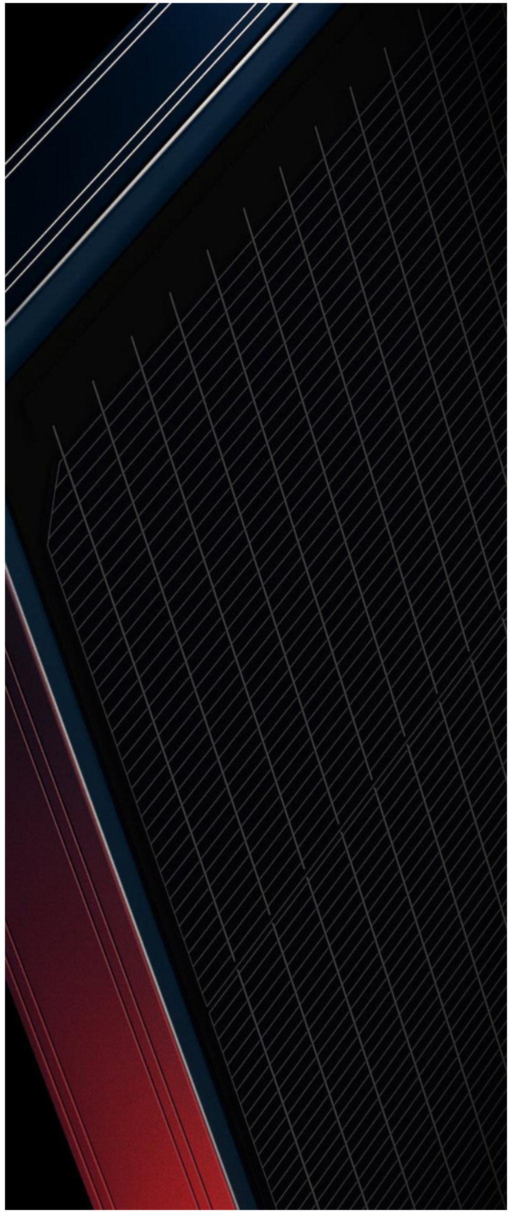




Modules from
20.6% (360 W) to 21.7% (380 W)
With Tcoff Pmax at -0.26%/°C

REC bought by Reliance Groupe (India): they build an integrated (from sand to module) fab of 6 GW SHJ…. Enel going for 3 GW in Europe

3. Silicon heterojunction (SHJ) solar cells



2021: strategy shift of Meyer Burger (equipment makers before) New **Upscaling 1.4 GW**, plan to goes to 5-7 GW by 2026

Reindustrialising cell production in Europe, modules currently up to 21.8% (was 7th best) , new version > 22% !

Strategy: higher price, local, low CO2 product, no issue with labor practice. Targets mostly first private customers ready to pay more !

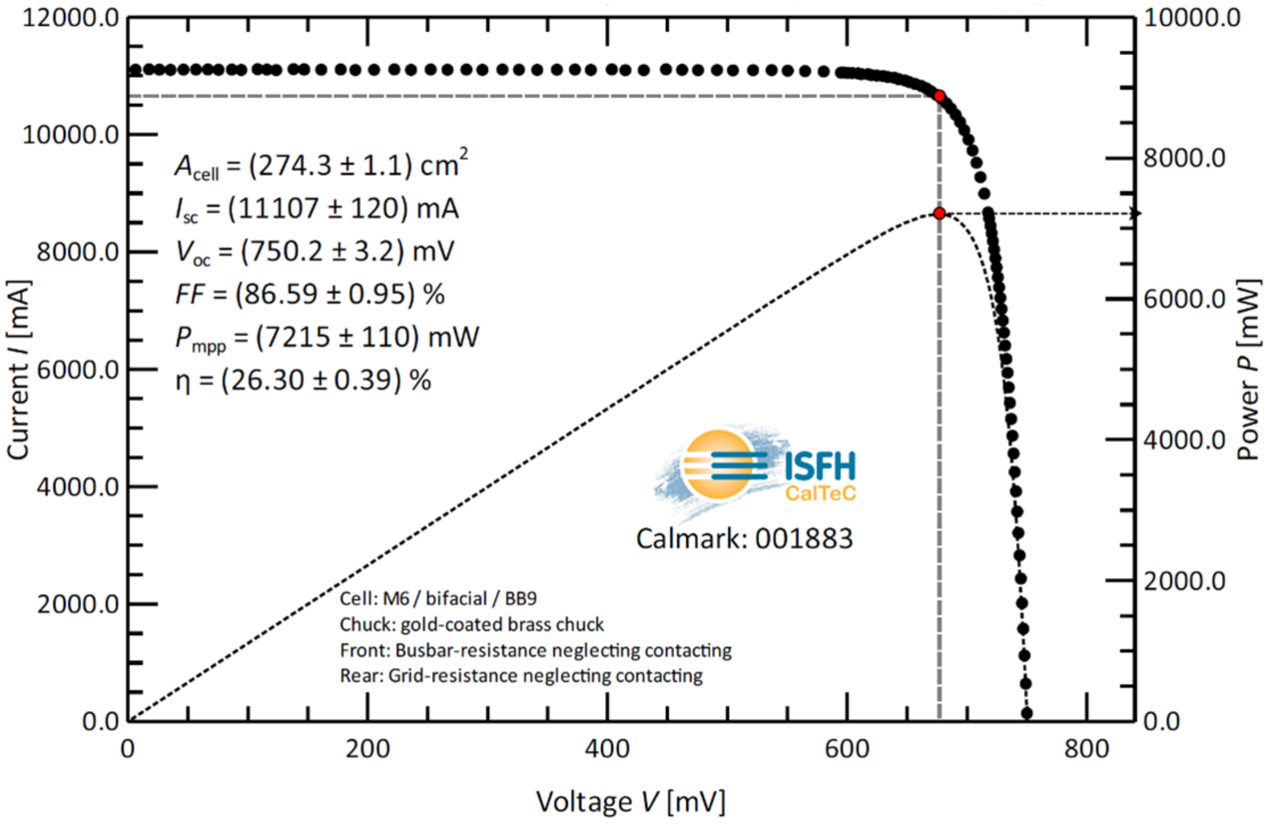
745 mV per cell
in production,
Up to 25% (M6)

Still producing cell in EU but shifting module To USA (IRA)


EPFL
MEYER BURGER
csem
Schweizerische Eidgenossenschaft
Confédération suisse
Confederazione Svizzera
Confederaziun svizra

In the meantime in China

New records for industrial size SHJ from Longi in 2021



Thanks to mass pilot line,
Remarkable by chinese companies

26.3% efficiency by LONGI for SHJ (oct 2021)

Many companies entering SHJ production at GW level. Almost all companies with pilot lines.
Current cell production efficiency ~24.4-26%
Challenge: more Ag usage and In Usage. Technology requires a lot of know-how

Record Si cells in the world with front and rear contact : 26.74 c-Si Heterojunction by Longi

Hao Lin et al. Nature Energy 2023

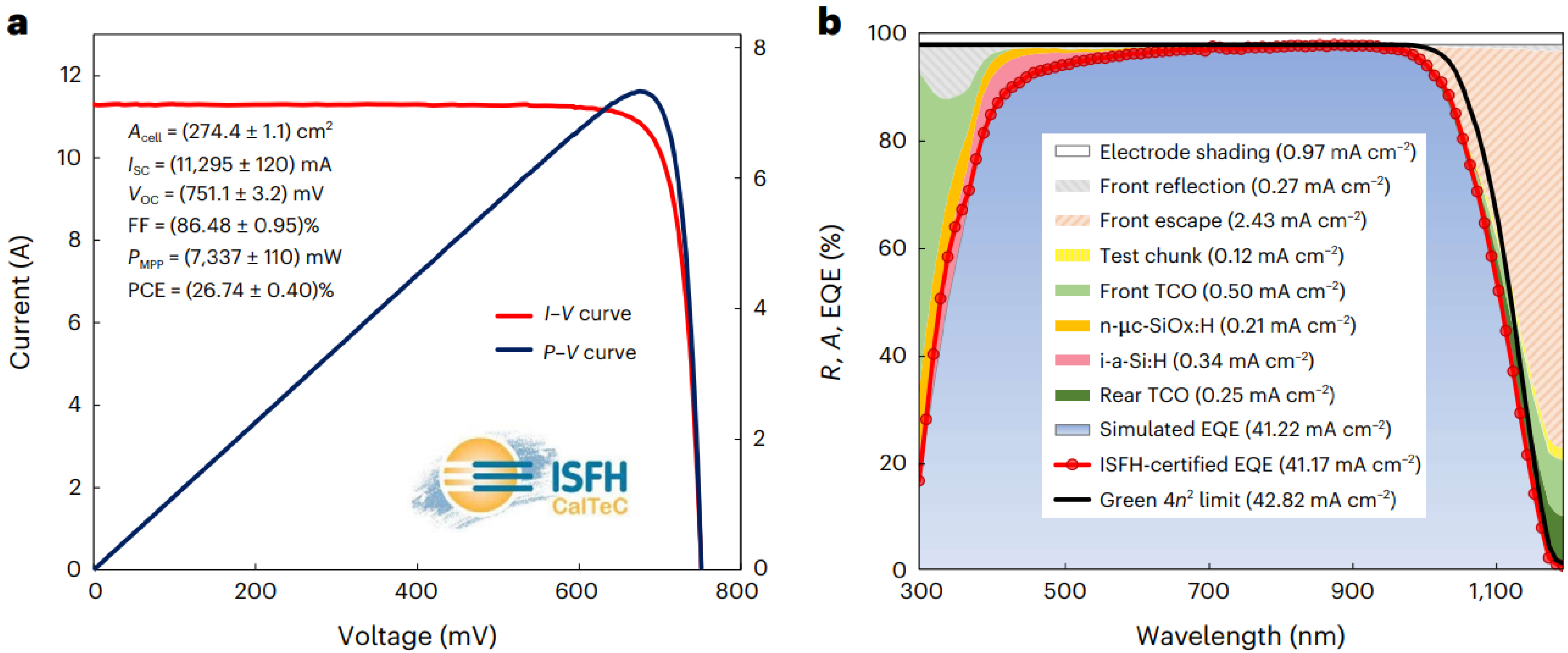


Fig. 5 | Certified SHJ solar cell with a PCE of 26.74%. **a**, Light *I*–*V* and power–voltage (*P*–*V*) curves of the record front–back contact silicon solar cell. **b**, External quantum efficiency (EQE) spectrum and analysis of the optical loss, including reflection (*R*) and absorption (*A*). The maximal EQE (Green $4n^2$ limit[72]) for 130-µm-thick n-Si excluding electrode shading is also reported for comparison.

- Ultra-high FF of 86.48% because **Auger strongly limits Voc**…41.1 mA/cm2 and 751 mV

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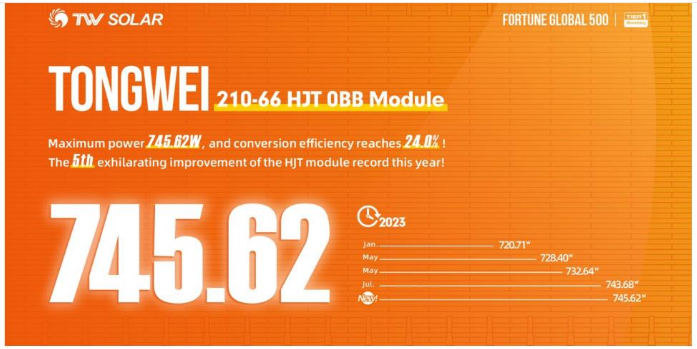
Several chinese companies have started 5-20 GW HJT fab

- Larger cells (1/2 G12)
- Implement a gettering of the wafer
- 110 microns wafer in production
- Cells to 25.5% in production with nc-Si layers (many layers based « partly on our processes developped and refined with Meyer Burger »)



745.62W+24%! Tongwei Solar Achieves Remarkable HJT Module Performance!

TW SOLAR Tongwei Solar
35 359 abonnés
+ Suivre

10 novembre 2023

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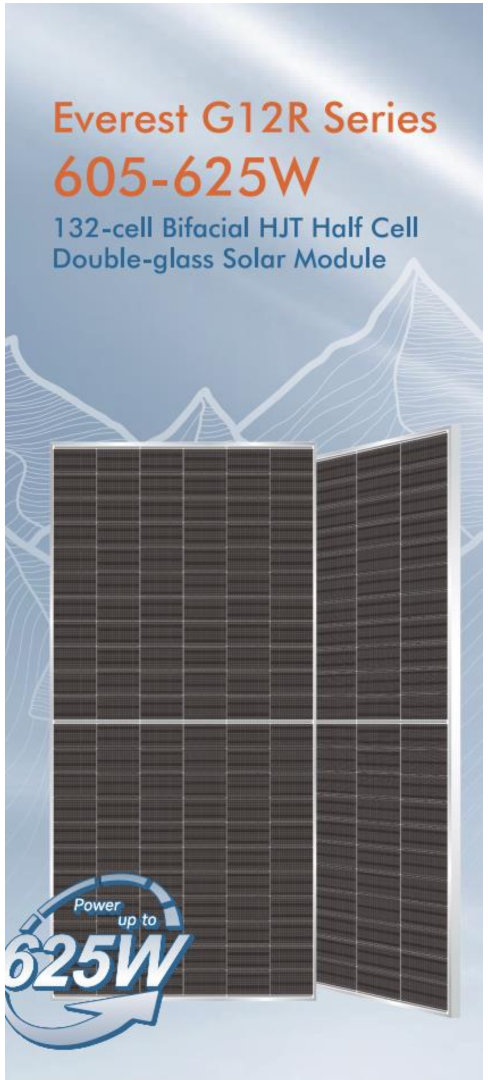
PV-lab
IMT NEUCHATEL

Commercial large SHJ modules with 85% bificiality

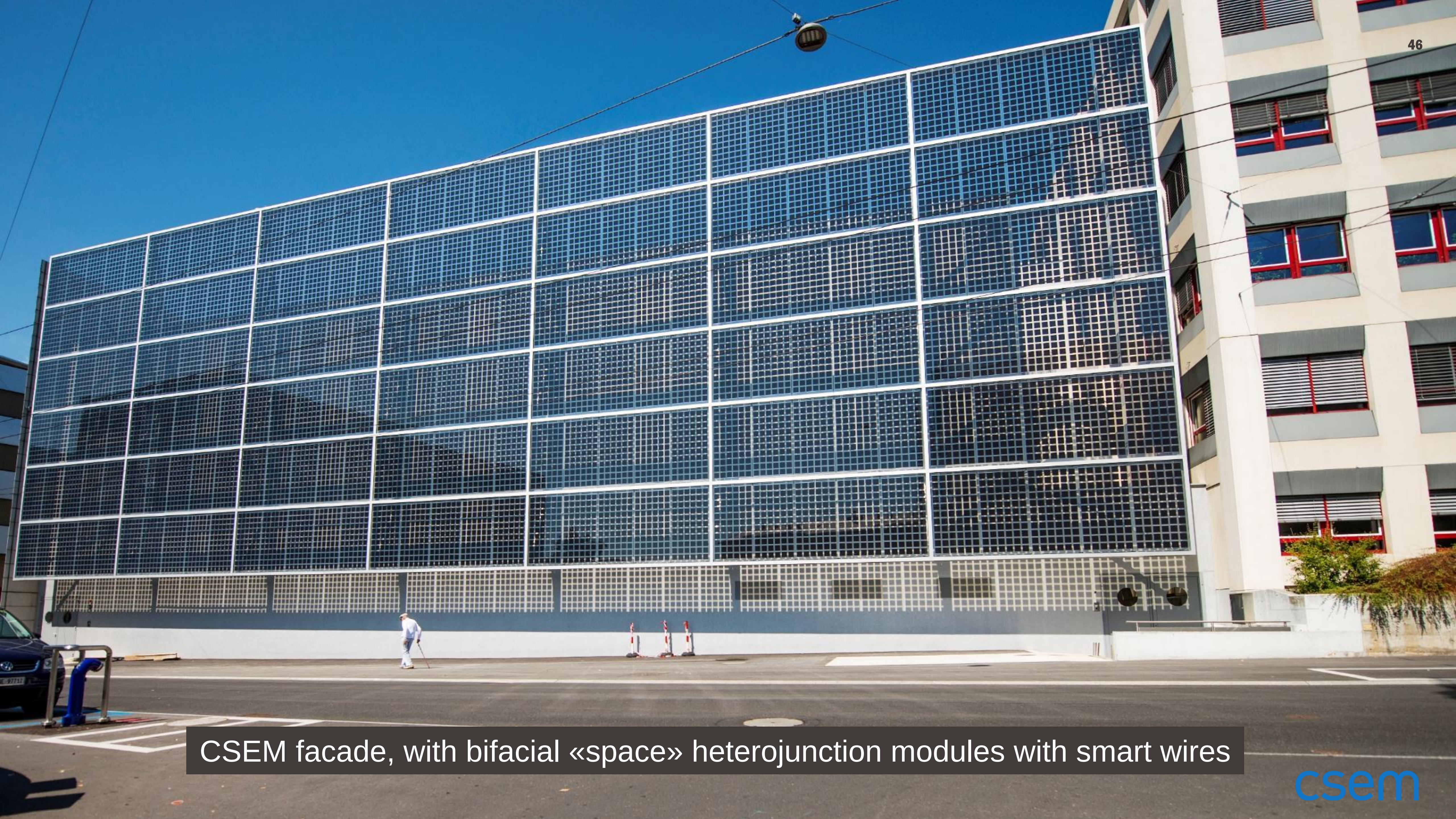


Electrical Characteristics (STC*)

HS-210R-B132	DS605	DS610	DS615	DS620	DS625
Maximum Power (Pmax)	605W	610W	615W	620W	625W
Module Efficiency (%)	22.40%	22.56%	22.77%	22.95%	23.14%
Optimum Operating Voltage (Vmp)	41.82V	42.00V	42.15V	42.30V	42.46V
Optimum Operating Current (Imp)	14.47A	14.53A	14.60A	14.66A	14.72A
Open Circuit Voltage (Voc)	50.57V	50.63V	50.80V	50.98V	51.16V
Short Circuit Current (Isc)	15.27A	15.32A	15.37A	15.42A	15.47A
Operating Module Temperature	-40 to +85°C				
Maximum System Voltage	DC1500V (IEC)				
Maximum Series Fuse	30A				
Power Tolerance	0~+5W				
Bifaciality	85%±5%				

*STC: Irradiance 1000 W/m^2, cell temperature 25°C, AM=1.5. Tolerance of Pmax is within +/- 3%.

But beware: datasheet wrong …. (775 mV per cell)



CSEM facade, with bifacial «space» heterojunction modules with smart wires

csem

3. Silicon heterojunction (SHJ) solar cells

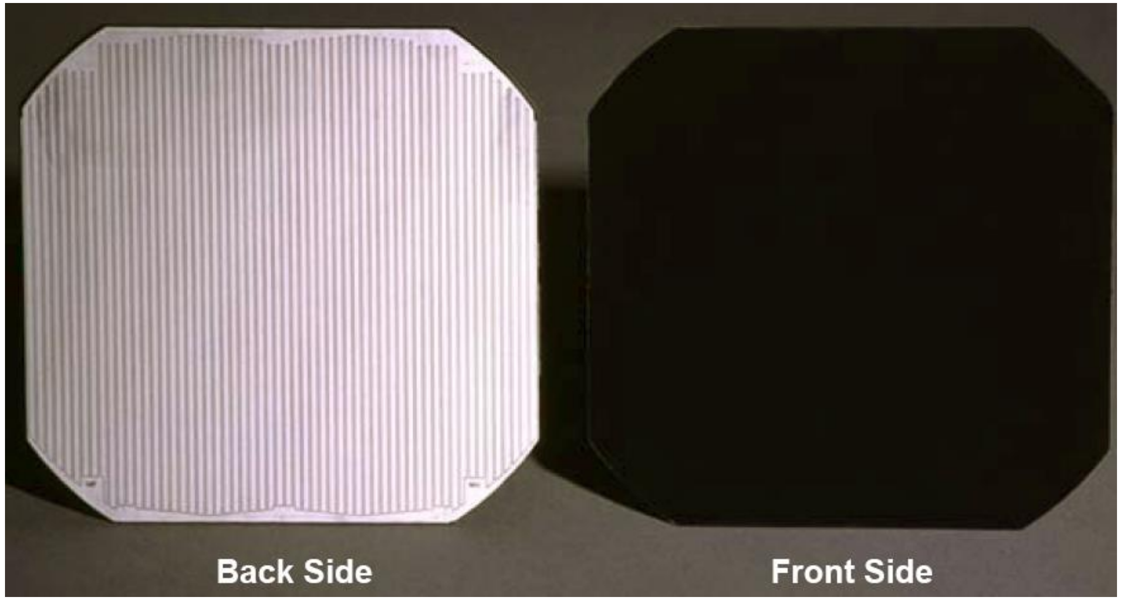
Conclusion

- Attractive and simple process to reach 24.5-25.5% or more in production. Meyer Burger close to 25% in production.
- Excellent bifaciality, potential for ultra-high energy yield thanks to record low T coefficient
- Slightly higher manufacturing costs, in particular because of high Ag consumption (unless using «smart-wire approach») and usage of ITO as front and rear layer
- Higher Voc but lower current than TOPCON because of front side parasitic absorptance, needs very good lifetime wafer (no gettering)

- Many fabs, and pilot lines around the world in development, including Swiss technologies at Meyer Burger, Hevel, REC, ENEL , Huasan, Risen, Tongwei…), now >> 50 GW rapidly growing but suffering from TOPCON fast improvements

- Technology (tools) different than the PERC/TOPCON . Higher capex for the cell line (current 2 to 3x more than PERC at around 5 to 8 millions $/100 MW)

4. Interdigitated back contacted (IBC) solar cells



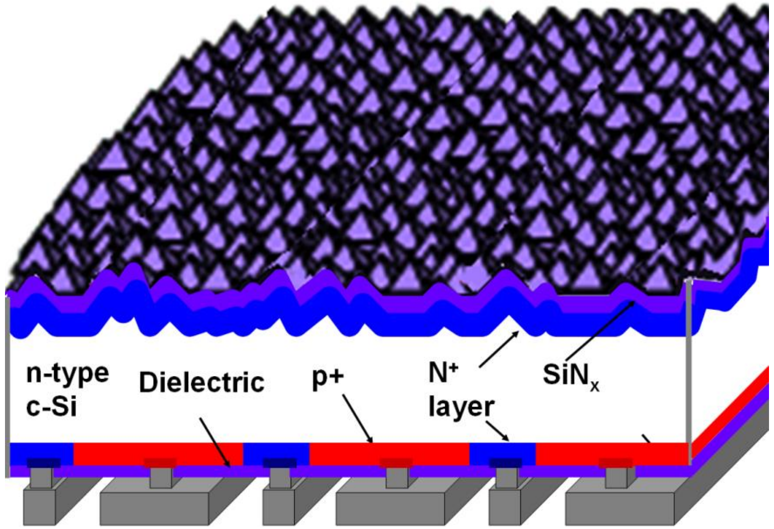
- Not an easy process
- Requires low cost masking/aligning

- Can be combined with standard technology (see e.g. Zebra, from ISC Konstanz, SPIC)
- With TOPCON contacts
- With SHJ (avoids parasitic absorptance)

→ no contact at the front side

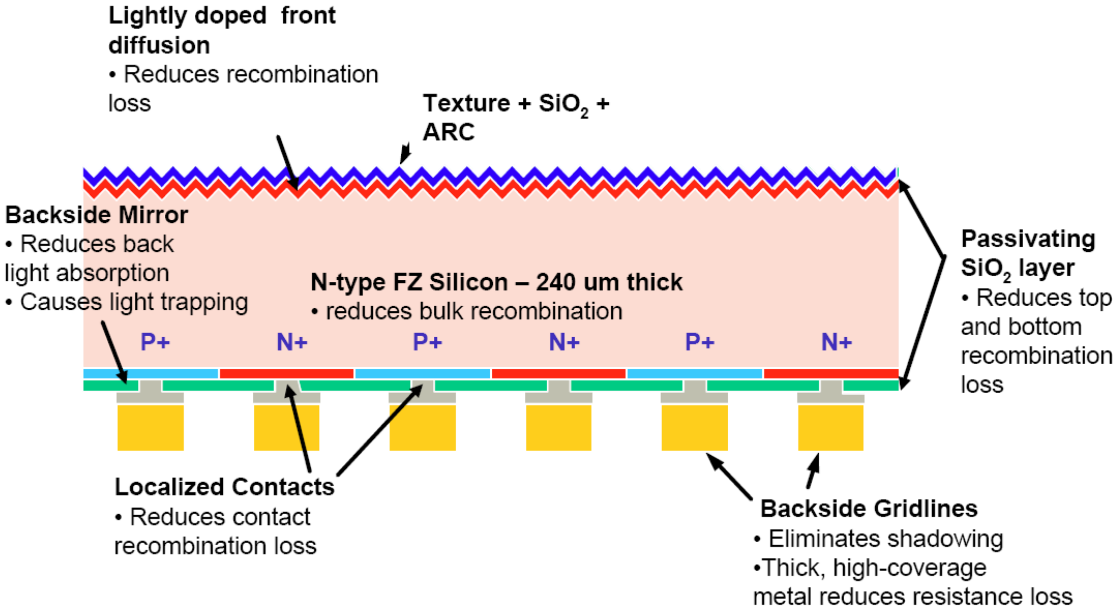
No shadowing losses!
→ high current if **very good lifetime (> 1ms)**
(n-type for avoiding B-O and other defects in p-type)

Easy interconnection in modules
→ closer cell/lower costs

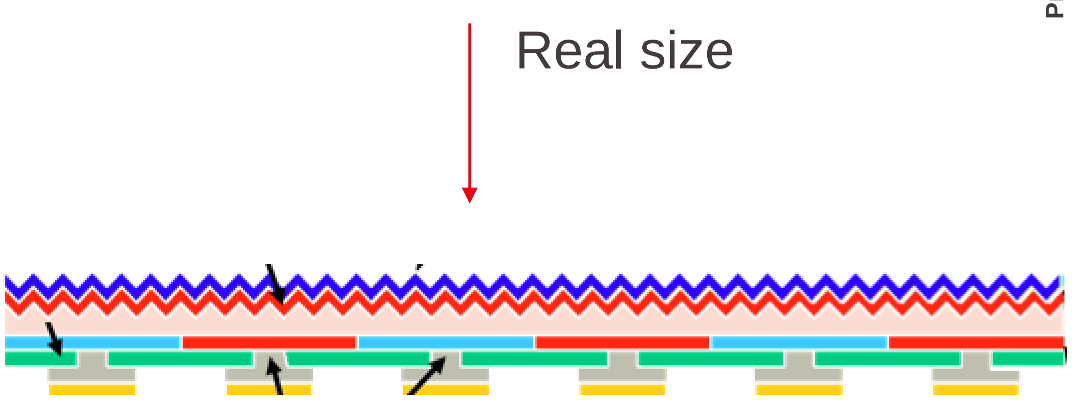


4. Interdigitated back contacted (IBC) solar cells

First approach



Real size



Requirements:

- Perfect front surface passivation (here n+ /SiO_x/SiN) → no recombination
- High diffusion length of holes in n-type wafer(most generation close to the surface) and need to travel along N+ area
- Usually larger area with p+ emitter to collect the minority carriers
- Minimum recombination at the backside (carriers generated above the n+ must diffuse to the p+ parts)
- Resistive losses due to long transport path for majority carriers

4. Interdigitated back contacted (IBC) solar cells

First industrial process : Sunpower, 2004 (now Maxeon)

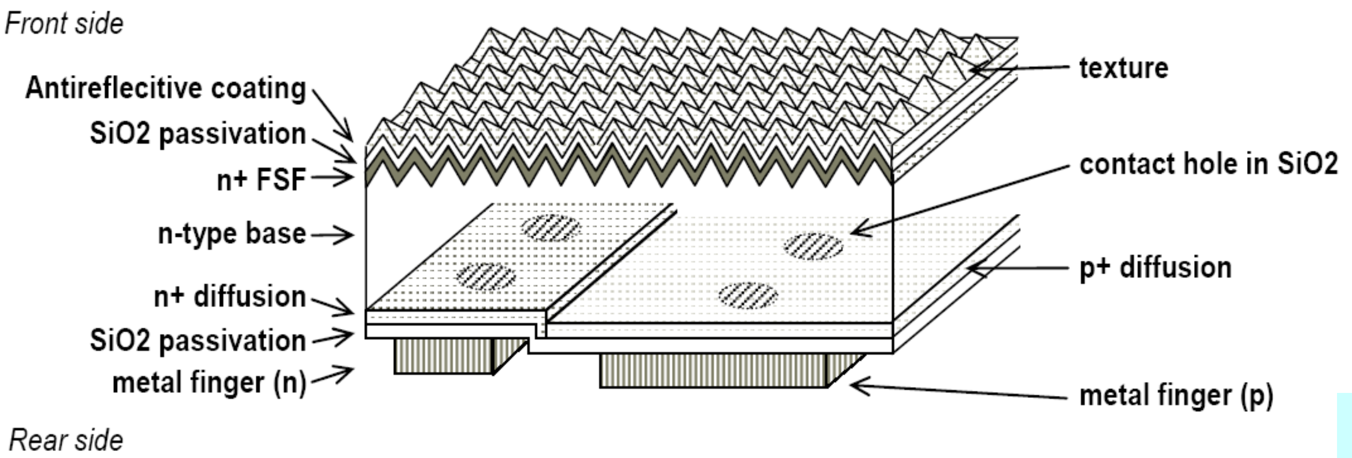


Figure 1: Schematic diagram of SunPower's A-300 solar cell (not to scale).

Table I: NREL-reported parameters of low-cost back-contact solar cell at 100 mW/cm^2, AM1.5g, 25 °C:

Area (cm2)	Silicon	Voc (mV)	Jsc (mA/cm^2)	FF	Efficiency (%)
148.9	PV-FZ	678	39.5	0.803	21.5

Mulligan, et al. "MANUFACTURE OF SOLAR CELLS WITH 21% EFFICIENCY" Proc 19th EUPVSC 2004, Paris

Initially n-type floatzone, Today likely n-type Cz!

Note that 22.7% was demonstrated by the same team for laboratory cells
Verlinden, Sinton et al. Proc. 14th EUPVSC Barcelona 1997

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4. Interdigitated back contacted (IBC) solar cells

Best pre-commercial cells by Sunpower

- 22% efficient Gen 2 technology in production now (integrated in record modules)

Nice R&D results!

- In May 2008 → 23.4%.
- In June 2010 → 24.2% : **introduction of "passivating contacts« cells**

world-record for a large area solar cell (status 2011) !

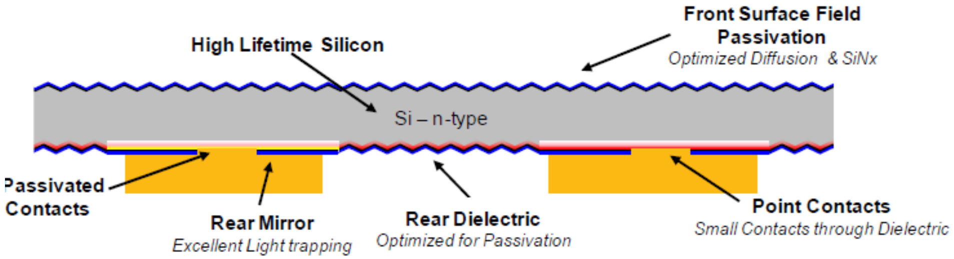

Figure 4. *Schematic of the SunPower Generation 3 Solar cell (not to Scale).*

"passivated contacts"

= optimised same doping for
Contact and oxide at round $10^{18}/cm^{-3}$
With a contact that still works !?

	Wafer Type	Area (cm2)	Voc (mV)	Jsc (mA/cm²)	FF (%)	η (%)
Generation 3 (SunPower)	*CZ(n)*	*155.1*	*721*	*40.46*	*82.9*	*24.2*

Table 1. *Test parameters for the record Generation 3 production cell as measured by NREL testing laboratory.*

Start production in 2012
Under Maxeon® Gen 3

Improved to certified > 25% in 2014 !

P. Cousins et al. Proc. IEEE, 2010
978-1-4244-5892-9

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4. Interdigitated back contacted (IBC) solar cells

One of the best current flat plate commercial modules by Sunpower (now Maxeon) at 24,1 announced

40 years warranty

SunPower Maxeon 7

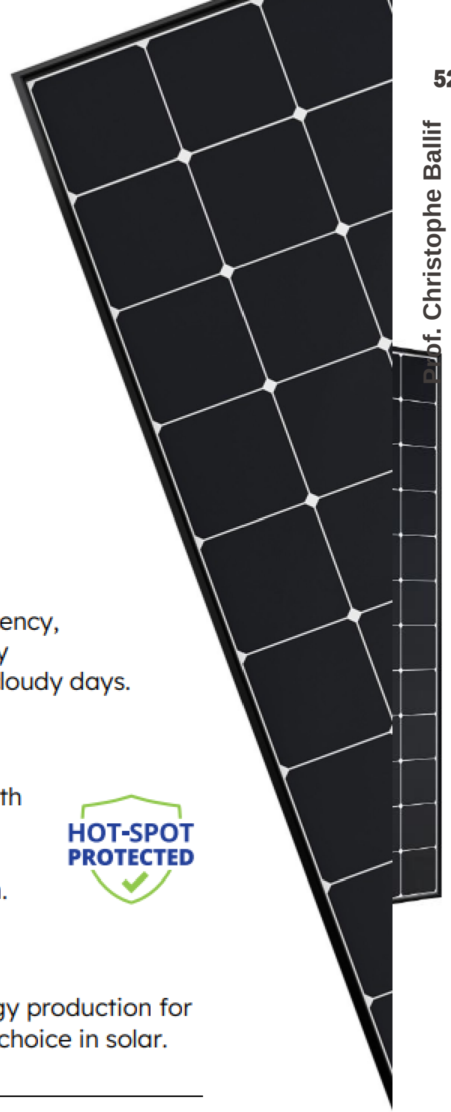
SPR-MAX7-XXX-PT

Home Solar Panel

435–445 W | Up to 24.1% Efficient

Ideal for residential applications

White backsheet, black frame



More Lifetime Energy

Designed to maximise energy generation through leading efficiency, enhanced performance in high temperatures, and higher energy conversion in low-light conditions like mornings, evenings and cloudy days.

Uncompromising Durability

Engineered to power through all types of weather conditions with crack-resistant cells and reinforced connections that protect against fatigue and corrosion, to an electrical architecture that mitigates the impact of shade and prevents hot-spot formation.

HOT-SPOT PROTECTED

Superior Sustainability

Clean ingredients, responsible manufacturing, and lasting energy production for 40 years make SunPower Maxeon panels the most sustainable choice in solar.

40 YEAR WARRANTY Power | Product | Service

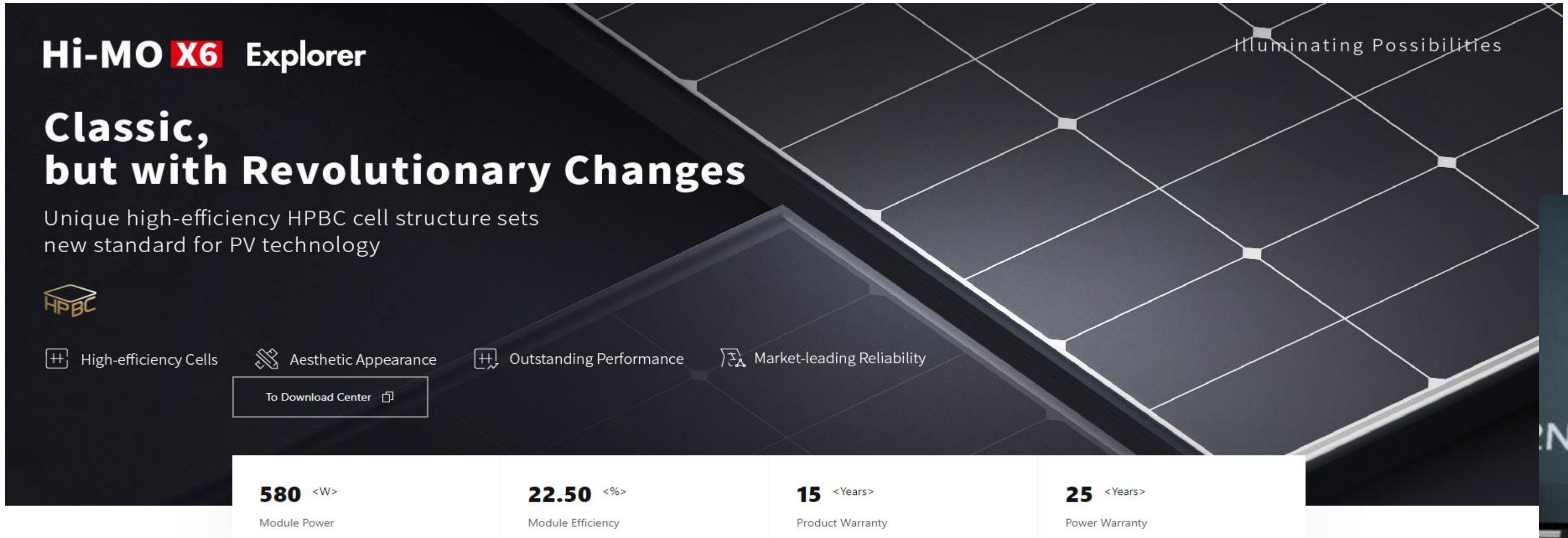
The Industry's Longest Warranty

SunPower Maxeon panels are covered by a 40-year warranty[1] backed by extensive third-party testing and field data from more than 33 million panels deployed worldwide.

Product and power coverage	40 Years
Year 1 minimum warranted output	98.0%
Maximum annual degradation	0.25%

New IBC products on the market

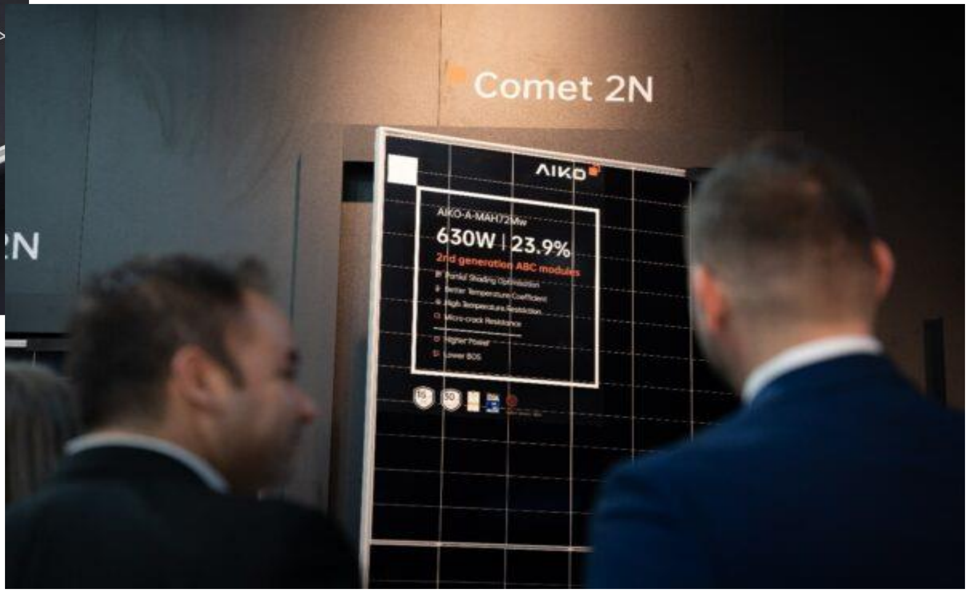
Longi HBPC: likely p-type wafer, 1 PERC contacts + 1 n-type topcon contact at the Back



AIKO ABC

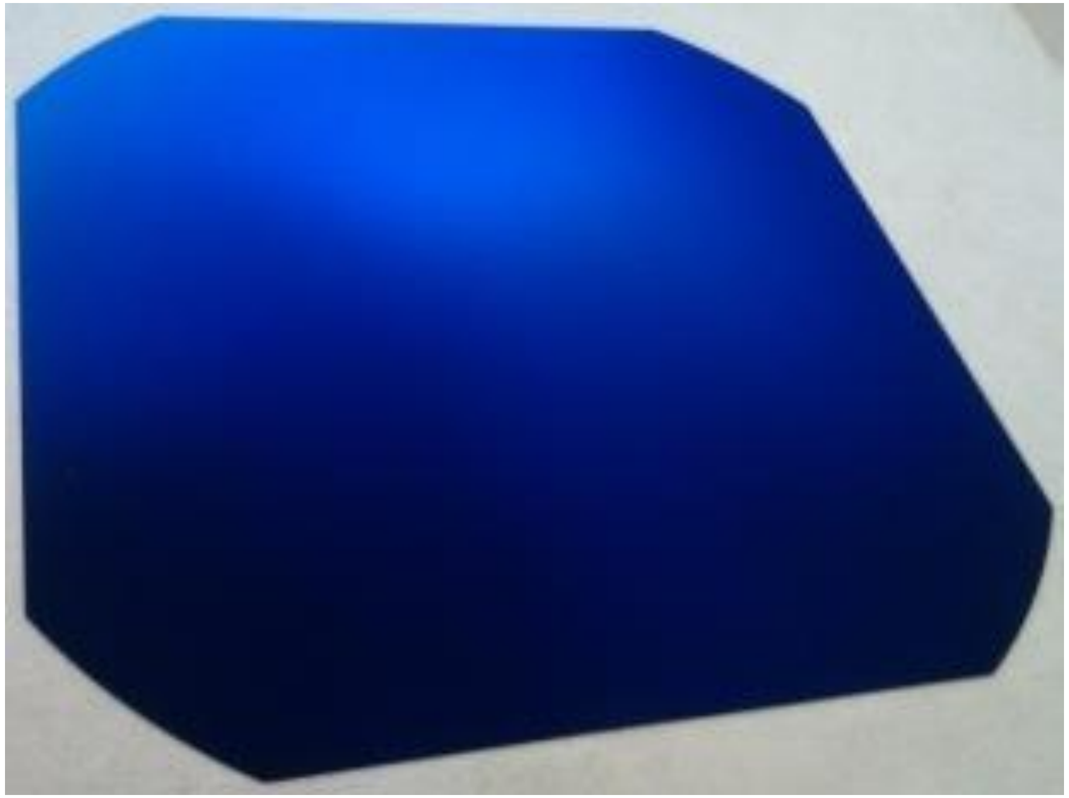
N-type wafer,

Poly-n and poly-p passivated contacts, cells plated with Cupper



And now Maxeon is suing Aiko for infrigement (but Aiko 3x lower price)

5. Interdigitated back-contacted solar cells with heterojunctions (IBC-SHJ)



- In IBC-SHJ, reduced or no parasitic absorption losses at the front
- More flexibility for process at the back !

5. Interdigitated back-contacted solar cells with heterojunctions (IBC-SHJ)

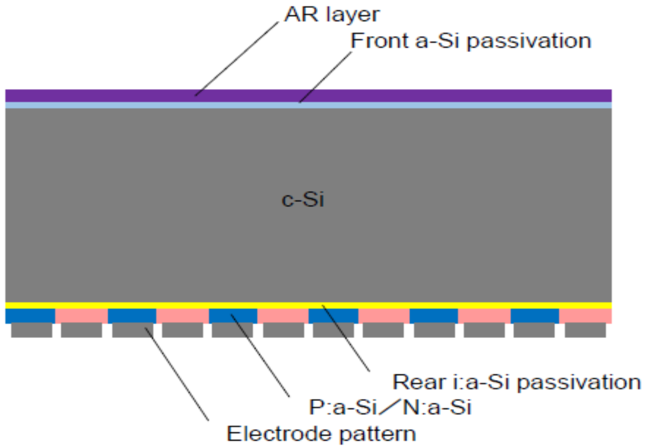
World best IBC c-Si solar cells by Kaneka: IBC-SHJ

7th International Conference on Silicon Photovoltaics, SiliconPV 2017

Exceeding conversion efficiency of 26% by heterojunction interdigitated back contact solar cell with thin film Si technology

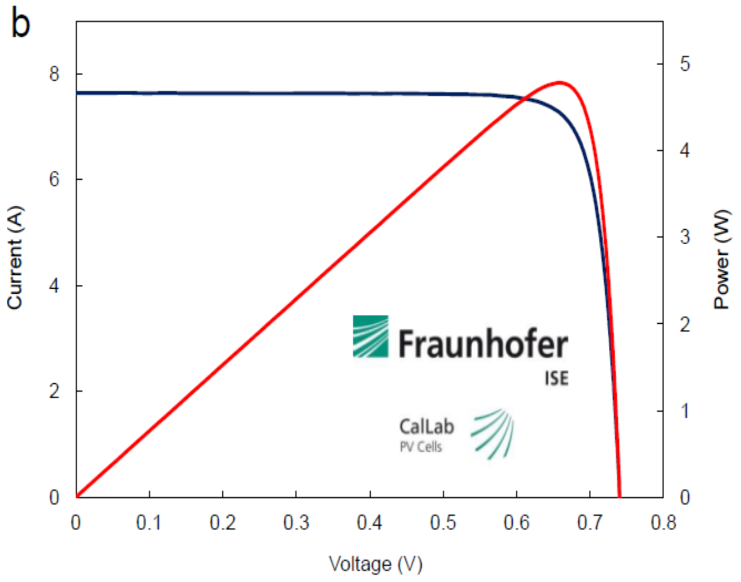
Kunta Yoshikawa, Wataru Yoshida, Toru Irie, Hayato Kawasaki, Katsunori Konishi, Hirotaka Ishibashi, Tsuyoshi Asatani, Daisuke Adachi, Masanori Kanematsu, Hisashi Uzu and Kenji Yamamoto

KANEKA Corporation, 5-1-1 Torikai-Nishi, Settsu, Osaka 566-0072, JAPAN



	V_{OC} [V]	J_{SC} [mA/cm2]	FF%	η%	Cell area [cm^2]	Wafer thickness [μm]	Wafer resistivity [Ohm.cm]
26.3% HJ-IBC [7]	0.744	42.3	83.8%	26.33%	180.4	165	3
26.6% HJ-IBC	0.740	42.5	84.6%	26.63%	179.7	200	7
Relative change%	-0.47%	+0.59%	+1.04%	+1.16%	-	-	-

Table 1. The IV parameters, wafer thickness and wafer resistivity of 26.3% HJ-IBC and 26.6% HJ-IBC.



- **26.7%** long-time world record for c-Si
- 200 micron wafer
- N-type
- 84.6% FF
- 180 cm^2

But photolitography

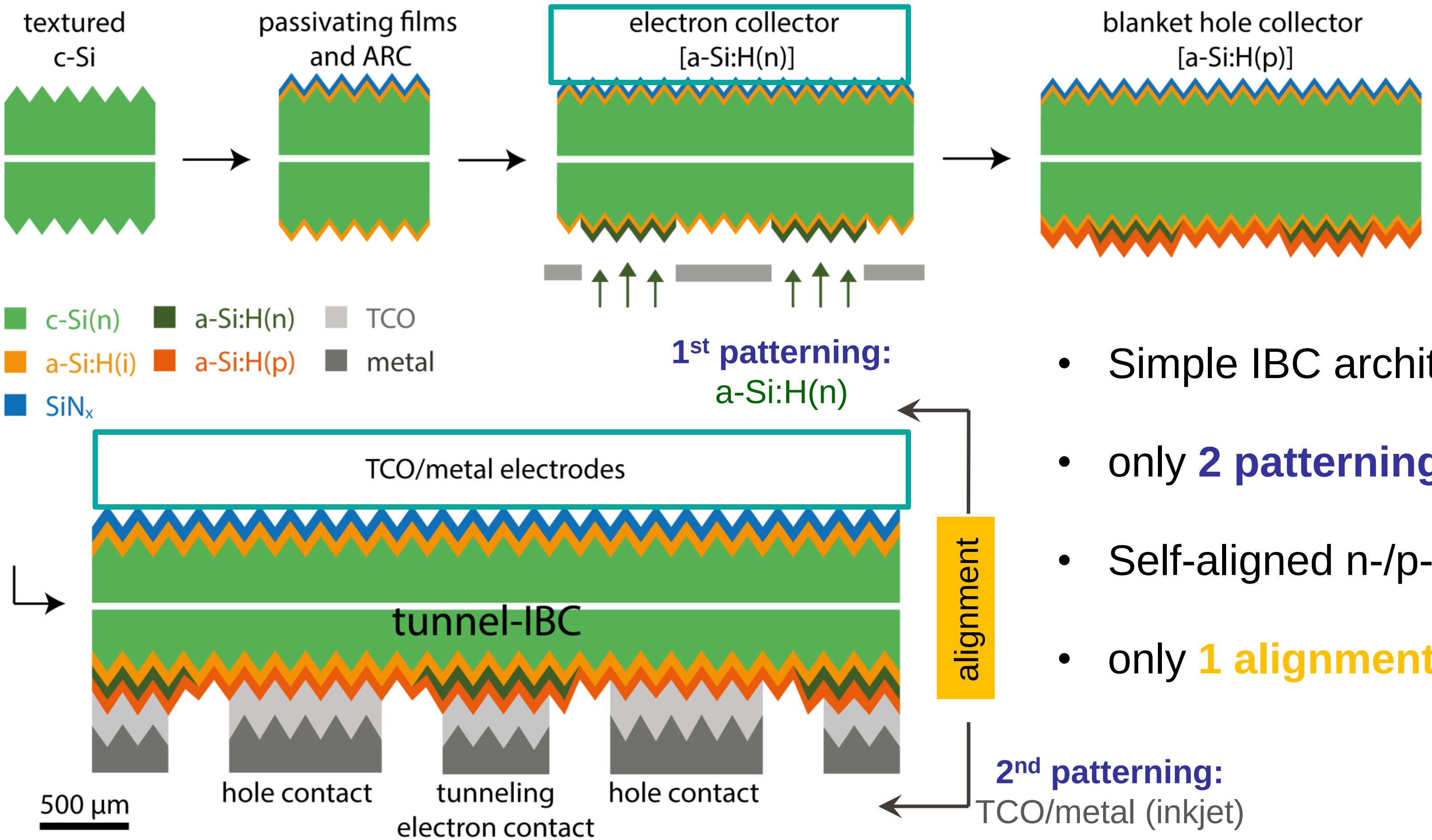
In the mean time record broken by Longi

- 26.9% in 2023
- Mai 2024 27.3%, certified by ISFH

5. Interdigitated back-contacted solar cells with heterojunctions (IBC-SHJ)

Tunnel-IBC: reduce process steps to 7-8?

- Simplified back-contacted SHJ solar cells with passivating contacts



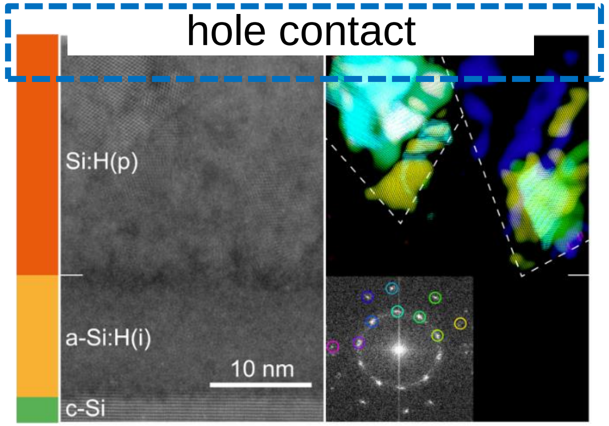
- Simple IBC architecture: tunnel-IBC
- only **2 patterning steps!**
- Self-aligned n-/p-fingers
- only **1 alignment step!**

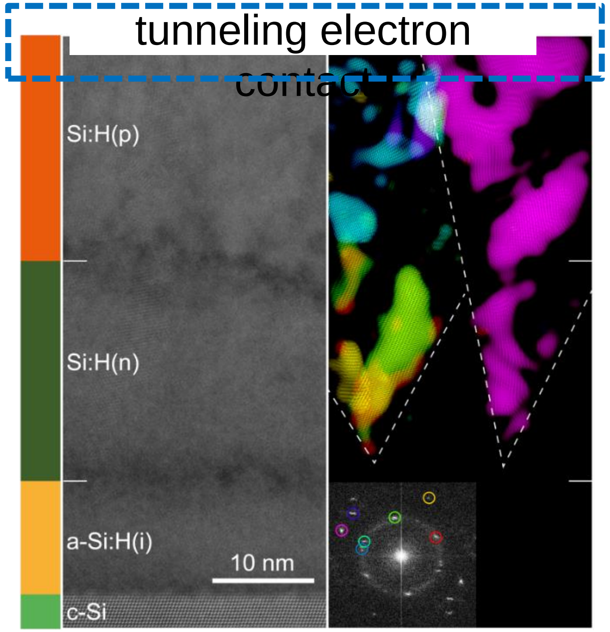
Tomasi *et al.*, *Nature Energy* 2017
DOI: 10.1038/nenergy.2017.62

5. Interdigitated back-contacted solar cells with heterojunctions (IBC-SHJ)

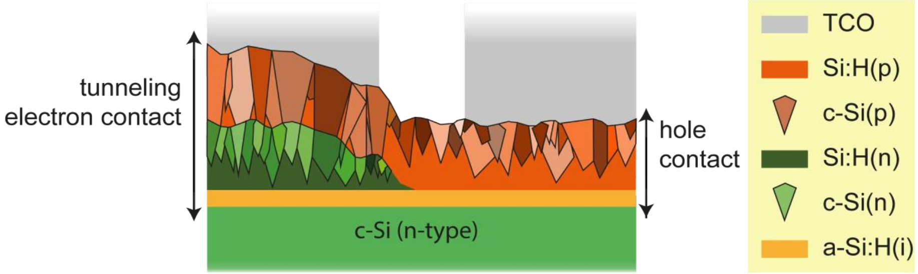
The doped Si:H films

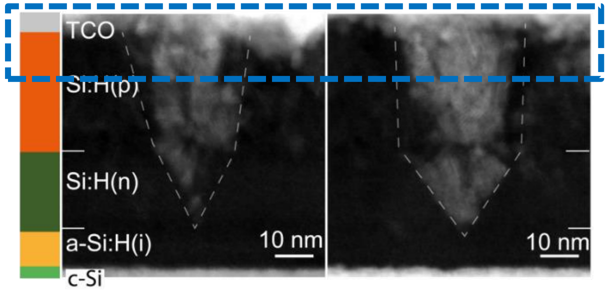
- nc-Si:H growth is strongly substrate-dependent: selective crystalline growth





- Si:H(p) microstructure: high-transverse conductance across the p/n interface and low-lateral conductance



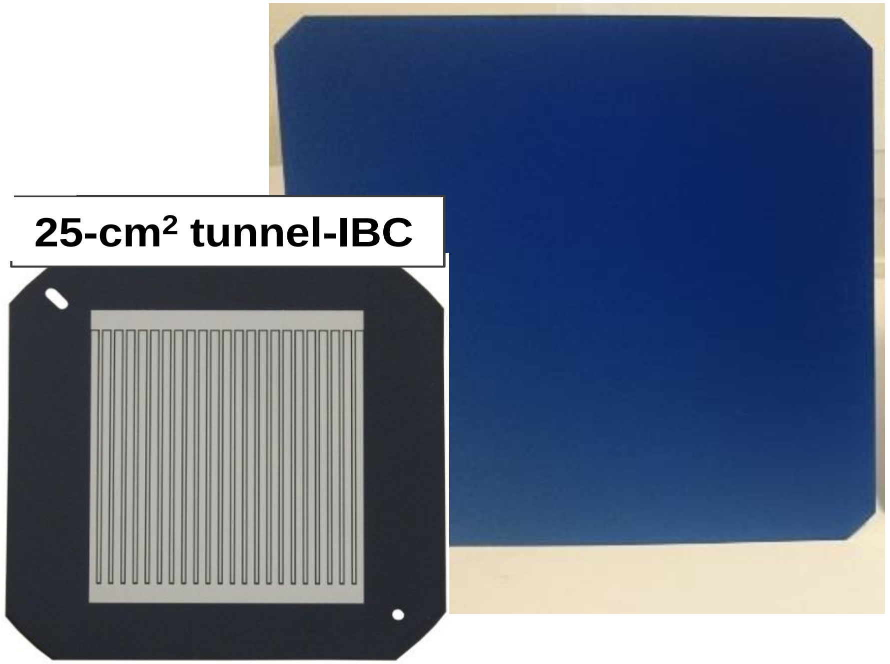


Tomasi *et al.*, *Nature Energy* 2017
DOI: 10.1038/nenergy.2017.62

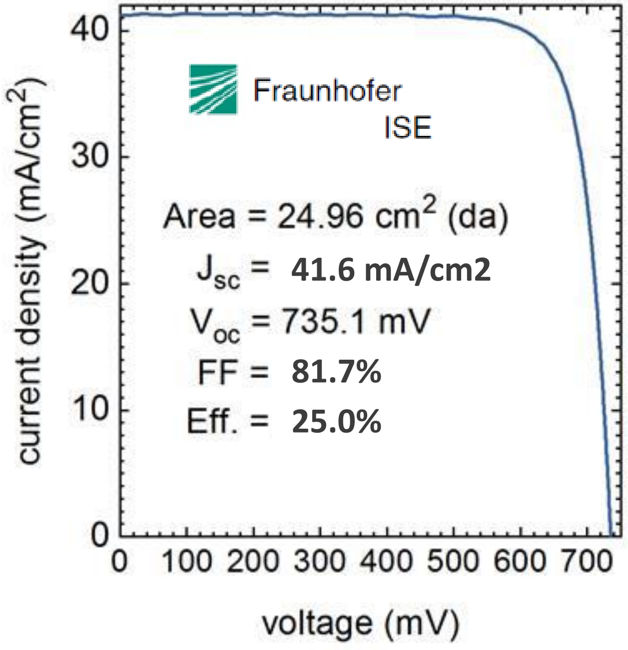
5. Interdigitated back-contacted solar cells with heterojunctions (IBC-SHJ)

Heterojunction: Upgrade scenario to IBC-SHJ

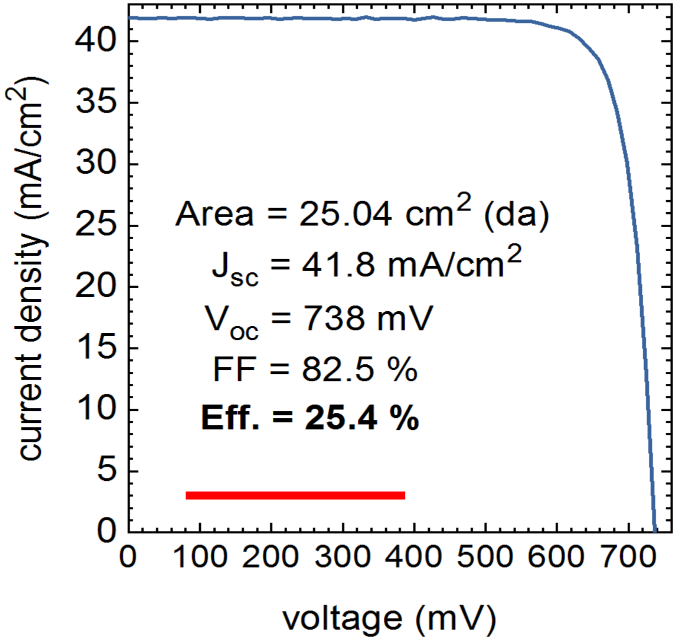
TUNNEL IBC-HJT process of EPFL/CSEM: simple process flow, minimization of materials



Only 9 process steps !!



New cell recently measured in-house



Certified 25% IBC with simplest process on 25 cm^2

Record laminate with IBC cells

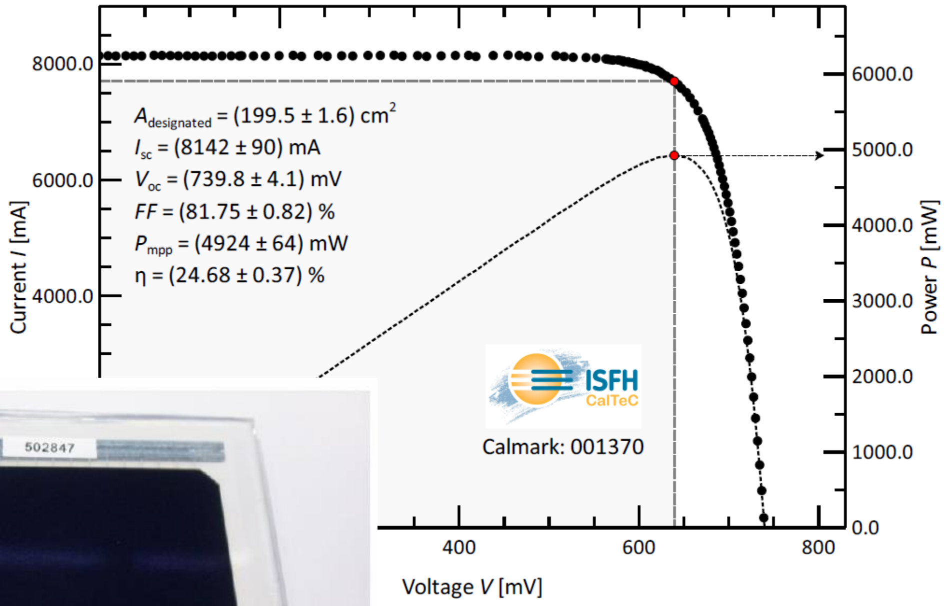
EPFL

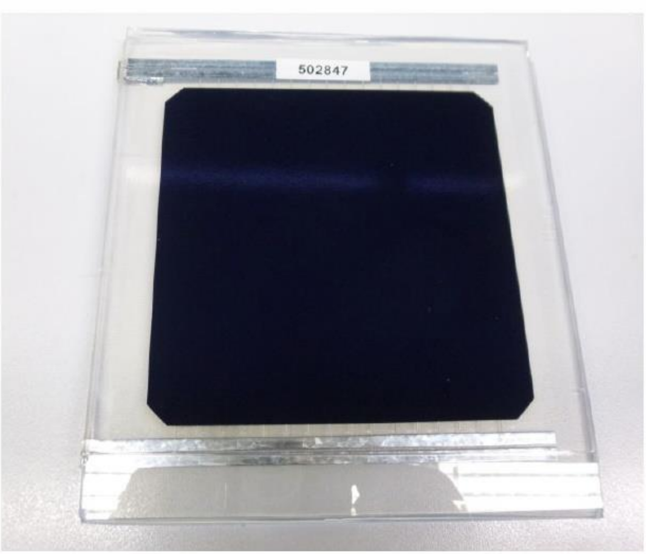
PV-lab IMT NEUCHATEL

Schweizerische Eidgenossenschaft
Confédération suisse
Confederazione Svizzera
Confederaziun svizra

Swiss Federal Office of Energy SFOE

- World record single-cell **laminate** (2022) with tunnel-IBC + SmartWires® :





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csem

These activities are supported by SFOE in the frame of the project "SIRIUS" (2021-2024E)
And EU project PILATUS with EPFL and CSEM

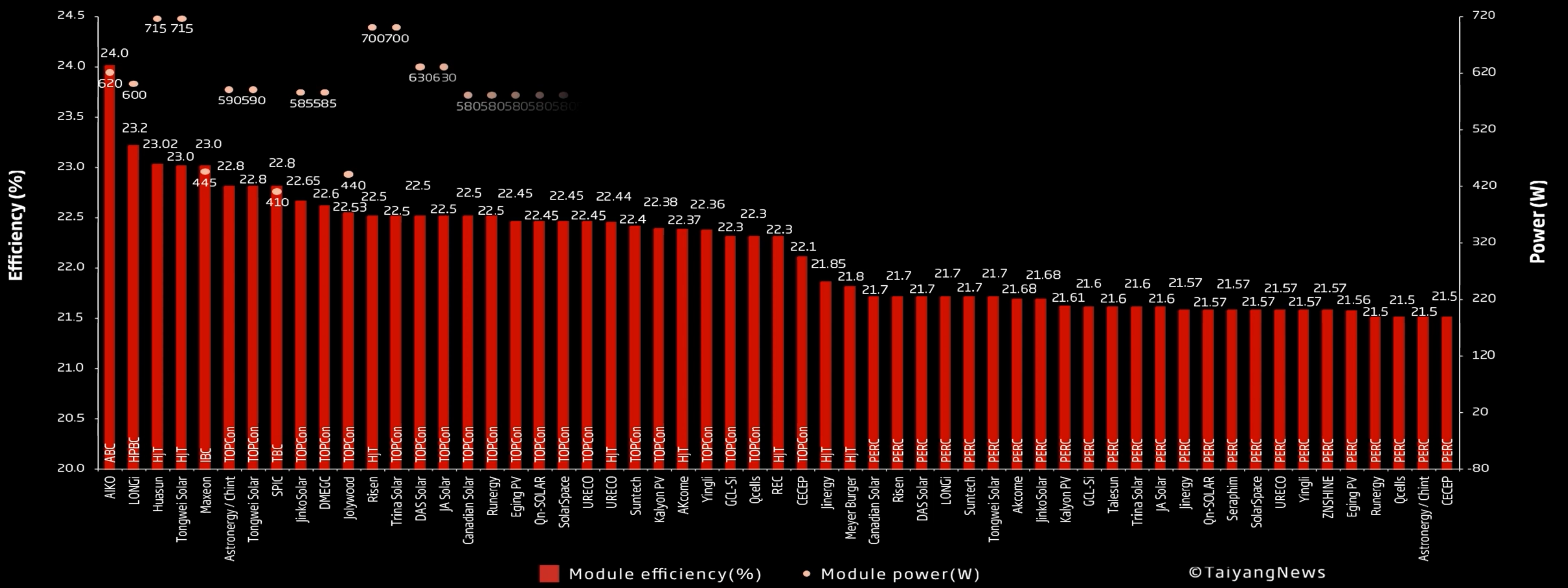
MEYER BURGER

Summary IBC

- Requires higher lifetime for carriers to travel laterally and quasi perfect surface passivations
- Relaxes the constraints (optical) for contacts at the back
- Allows some of the world record c-Si cells efficiency at 27.3% (SHJ)
- Can be combined with various processes
- More and more processes developped an promising simplified routes for making ultimate c-Si cells.
- With improvements in narrow line printing the difference to TOPCON for highest effiicency might decrease (so not clear it makes to large volumen)
- In addition to Maxeon/Sunpower, many companies are coming with IBC products (Aiko, Longi), with or without passivating contacts ! EPFL/CSEM also have some unique technologies

TaiyangNews Top Modules

Highest Efficient Commercial Solar Modules 04-2024



The number of products in our April TOP SOLAR MODULES LISTING remains at 57 from 33 companies

DMEGC's TOPCon module is now listed with an improved efficiency of 22.6%

Suntech's product is now listed with a lower power output of 605 W but with the same efficiency of 22.4%, while GCL has renamed its product series to GCL-LOTUS

6. Key Takeaways

- Know what is a passivating contact (takes selectively and without resistance one of the carrier type)
- Know what is an IBC cell, an SHJ and a Topcon cell and the typical record values
- c-Si highest efficiency cells reach above 24.5-26% in production (Topcon, SHJ, IBC)
- Highest commercial flat plate c-Si modules are above 23% (HJT, IBC)
- TOPCON mainstream 22 to 23% modules
- The best cells have a higher V_{oc} and a better temperature coefficient (you should know why)
- The high density of produced PV electricity and the reduced amount of area related balance of systems costs are a clear advantage of high efficiency PV
- TOPCON will be a leader and some IBC and SHJ companies might keep get some market shares. New manufacturing mass players in Europe (Meyer Burger, ENEL), regular announcement because of the «Green deal», but hard to develop cause no concrete actions.

6. Sunpower cells for special applications: customized PV from water to air (1).

Example 1: Planet Solar

- First PV cruise around the world
- Finished may 4th, 2012

- 60'000 km only on solar, with 95 tons boat

- 537 m^2 of Sunpower modules
- 93 kW peak power,
- Cruising speed 5-8 knots

6. Sunpower cells for special applications: customized PV from water to air (2).

Example 2: Plane for NASA.

Unmanned Helios plane from Aerovironnment

- Reached 30’000 m, but crashed in 2003
- Pegagus cells from Sunpower
- (thinned version of the A300, efficiency > 20%)

6. Sunpower cells for special applications: customized PV from water to air (3).

Example 3: Sunpower cells to equip Solar Impulse

In the last three years, Sunpower:

- Improved efficiency (22%)
- Changed the shape (factor filling from 92 to 96%)
- Reduced the weight (special thickness series)

⇩

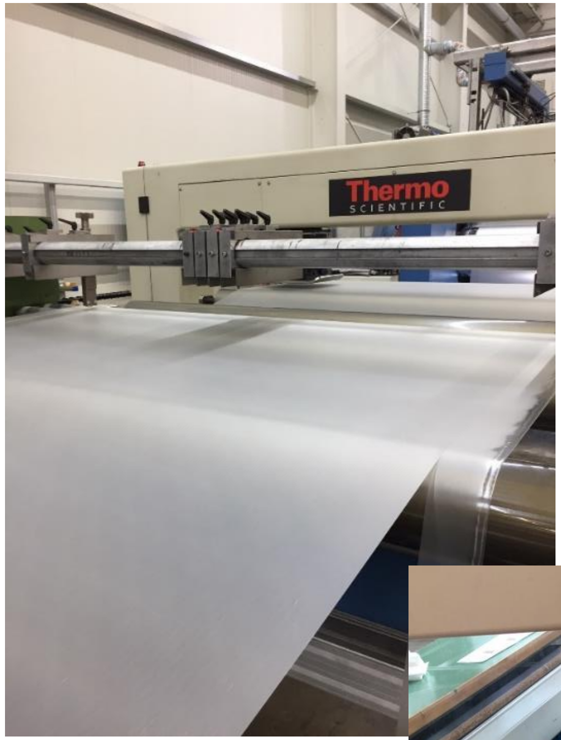
Best compromise weight/efficiency/strength/cost for the 40 kW generator

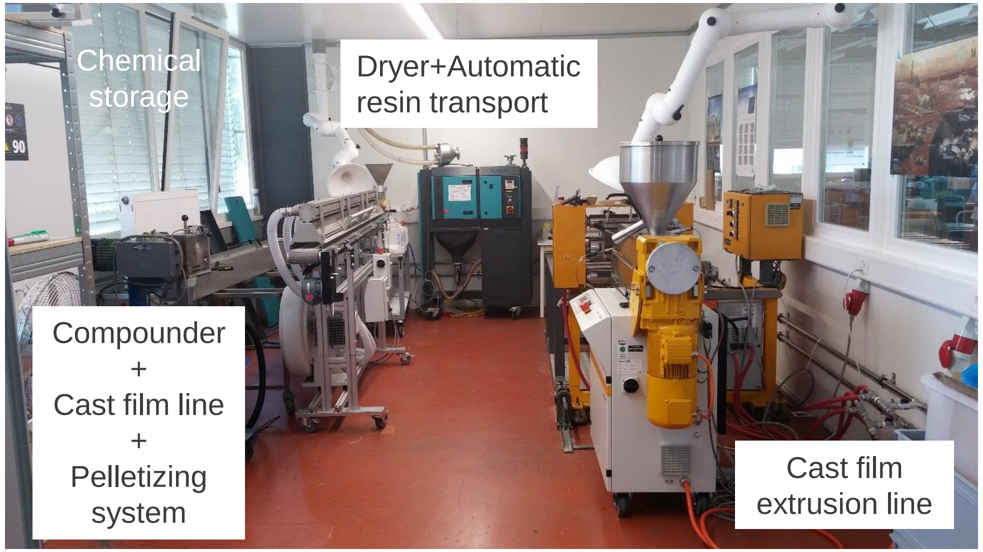
⇩

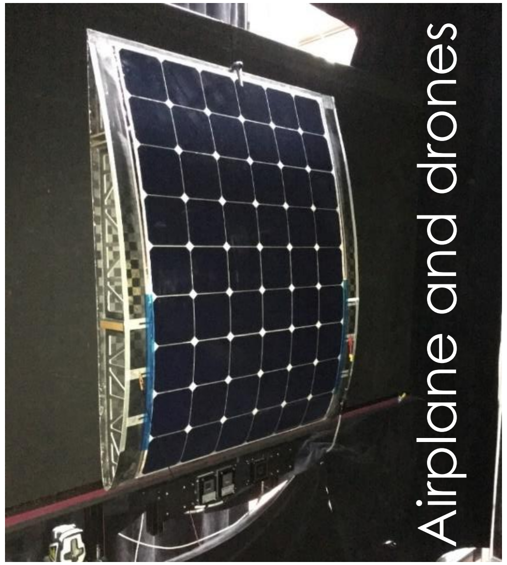
First 24 hours manned solar flight in 2011
(with improved battery level)
→ Full solar flight around the world!

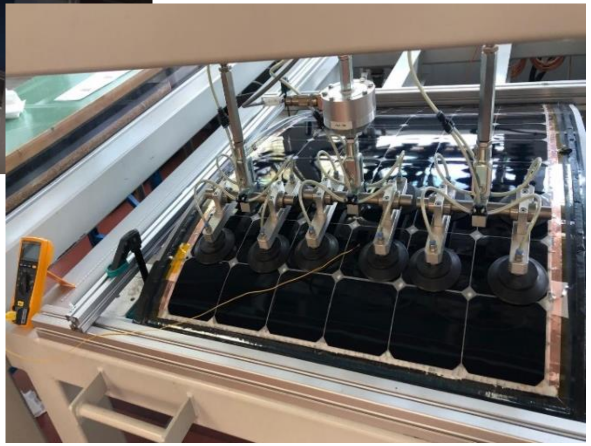
6. Sunpower cells for special applications: customized PV from water to air (4).

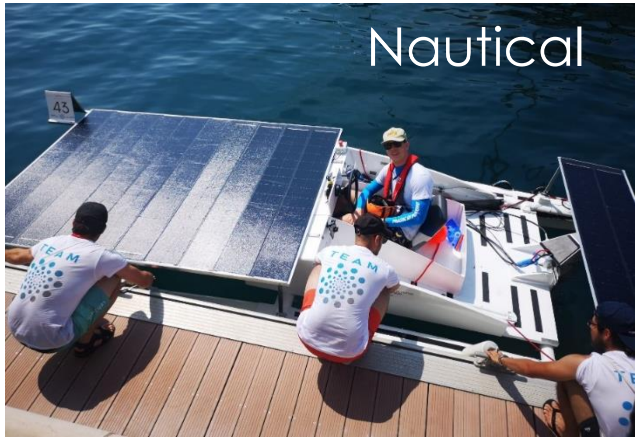
Example 4: Polymers and specialty films for PV: towards ultra-reliable PV.

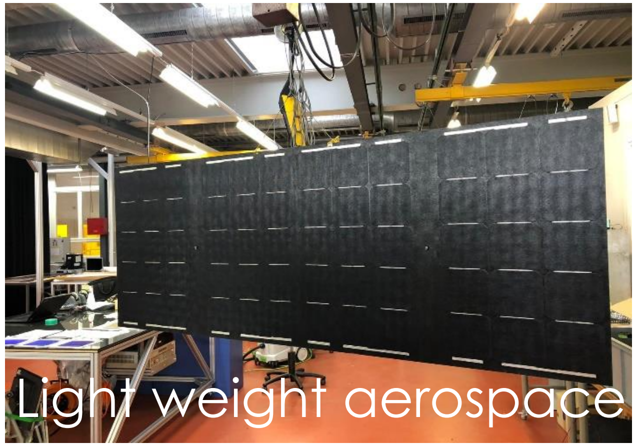












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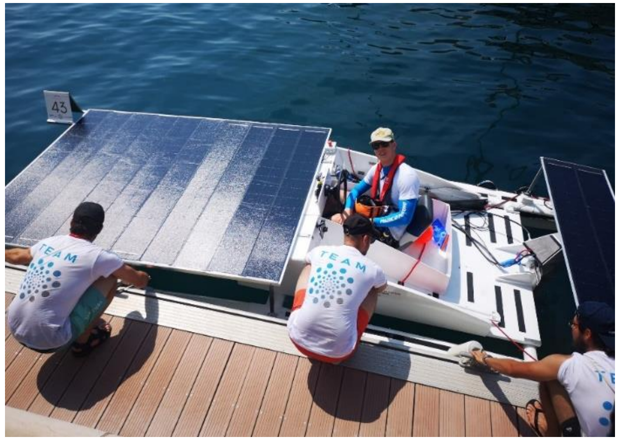
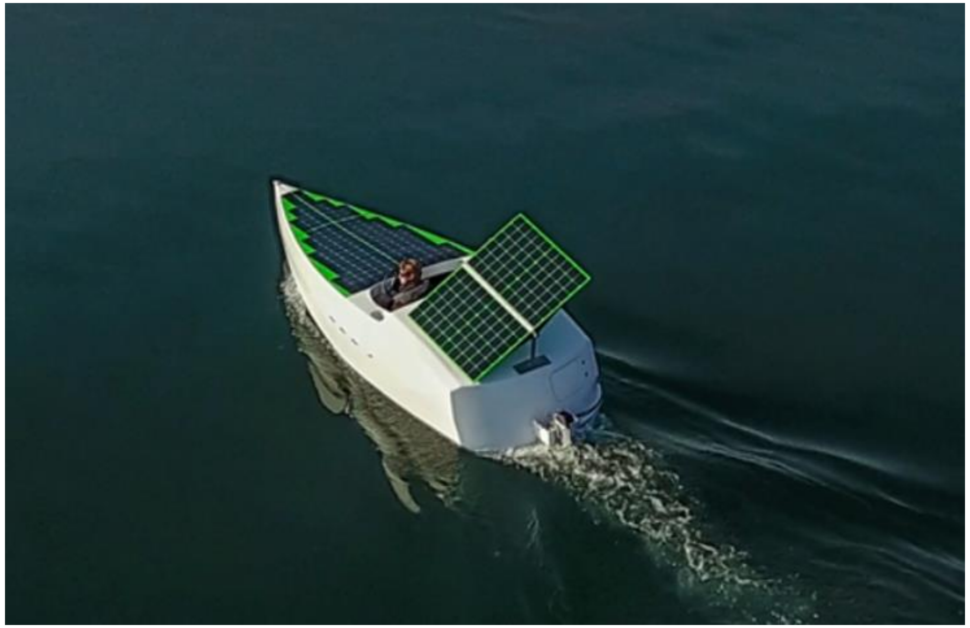
EPFL

Light weight ultra-reliable modules: direct to the applications

PV-lab
IMT NEUCHATEL





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Integrated PV to reach the Stratosphere

SOLARSTRATOS
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Deployable lightweight structures and PV modules qualified in stratosphere !