STRATEGIES FOR ULTIMATE CURRENT GENERATION IN SILICON HETEROJUNCTION SOLAR CELLS

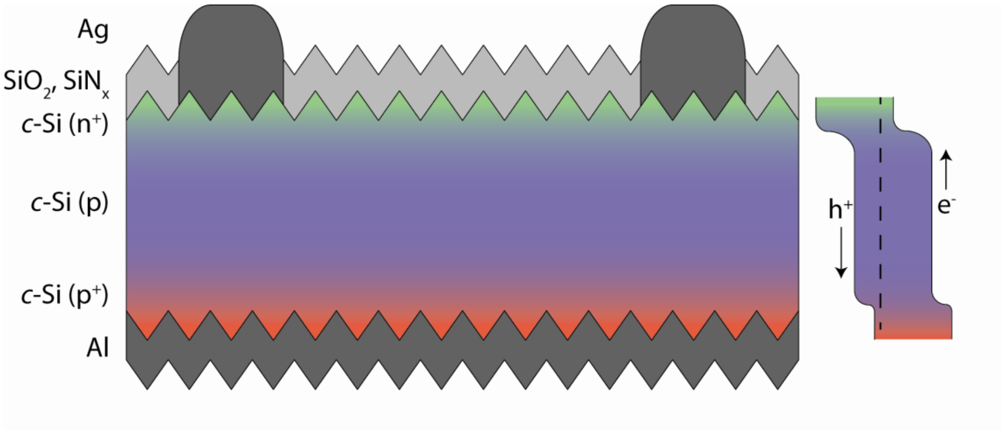
Andrea Tomasi, Bertrand Paviet-Salomon, Jonas Geissbühler, Jérémie Werner, Björn Niesen, Jan Haschke, Silvia Martin de Nicolas, Gizem Nogay, Stephanie Essig, Johannes Seif, Loris Barraud, Antoine Descoeudres, Gabriel Christmann, Damien Lachenal, Benjamin Strahm, Sylvain Nicolay, Matthieu Despeisse, Stefaan De Wolf, Christophe Ballif

andrea.tomasi@epfl.ch

HERCULES Workshop, Berlin, Germany October 2016

Crystalline Si technology

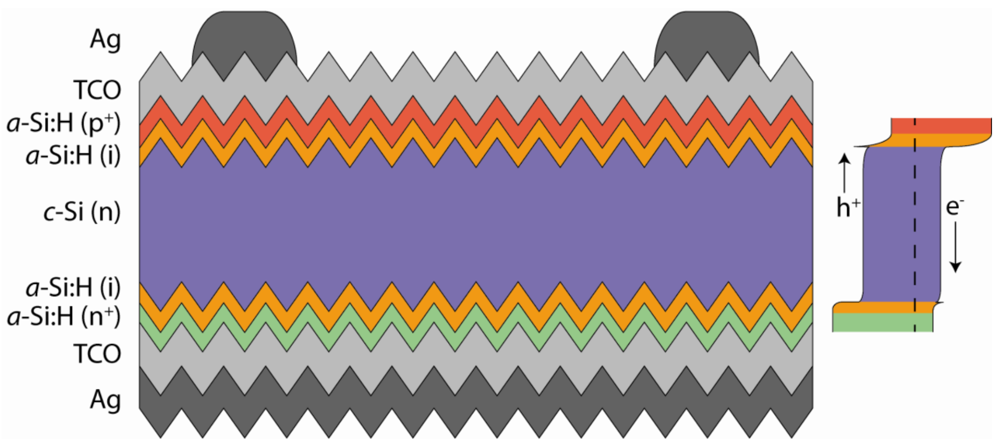
Diffused junction solar cell



Direct contact between absorber and metal
=
Recombinative contact
→ Lower V_{oc}

Efficiency: 18-20 %

Heterojunction solar cell



Thin semiconductor layer (a-Si:H) **between** absorber and metal
=
Carrier-selective passivating contacts
→ Higher V_{oc}, *FF*

Efficiency: 22 – >26 %

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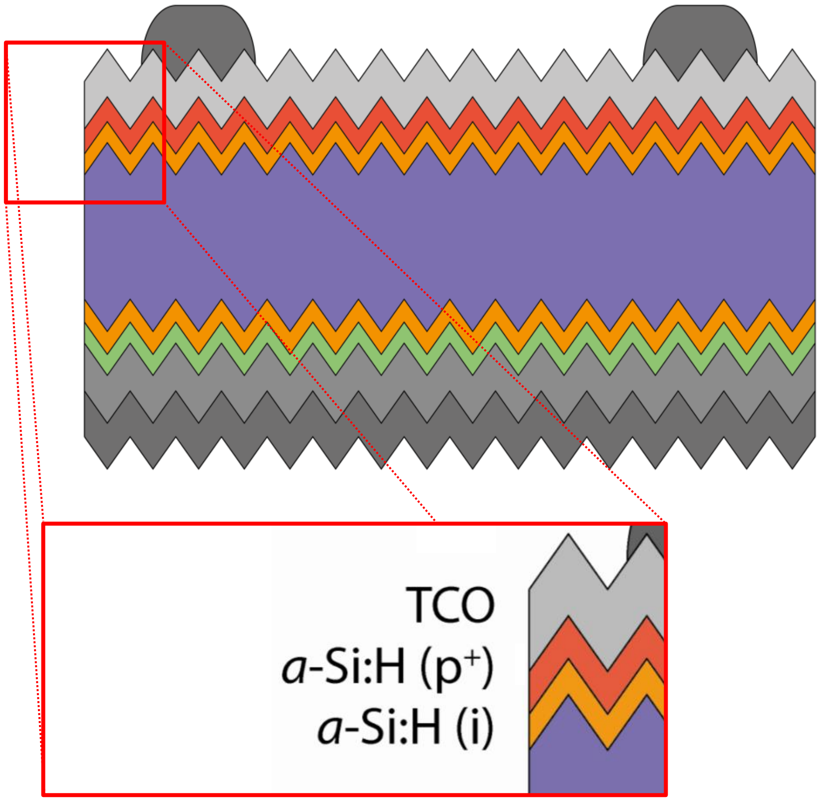
Past research at EPFL (1)

properties
of a-Si:H materials

Heterojunction solar cell



Intrinsic a-Si:H buffer layer

optimum
c-Si surface
passivation

Appl. Phys. Lett. **90**, 042111 (2007)
Appl. Phys. Lett. **93**, 032101 (2008)
Appl. Phys. Lett. **94**, 201501 (2009)
Appl. Phys. Lett. **97**, 183505 (2010)
Appl. Phys. Lett. **99**, 123506 (2011)
Phys. Rev. B **83**, 233301 (2011)
Phys. Rev. B **85**, 113302 (2012)
Appl. Phys. Lett. **102**, 2 ... 4 (2013)
J. Appl. Phys. **116**, 0 ... 014)
Appl. Phys. Lett. 1 ... 014)
J. Appl. Phys. 1 ...
Rev. Sci. Ins ... 15)

→HIGHER V_{oc} and FF!

Doped a... ...icon

optimum
carrier
collector

Ap... 022104 (2006)
A... 1, 112109 (2007)
J. A... 05, 103707 (2009)
IEEE ... 83 (2013)

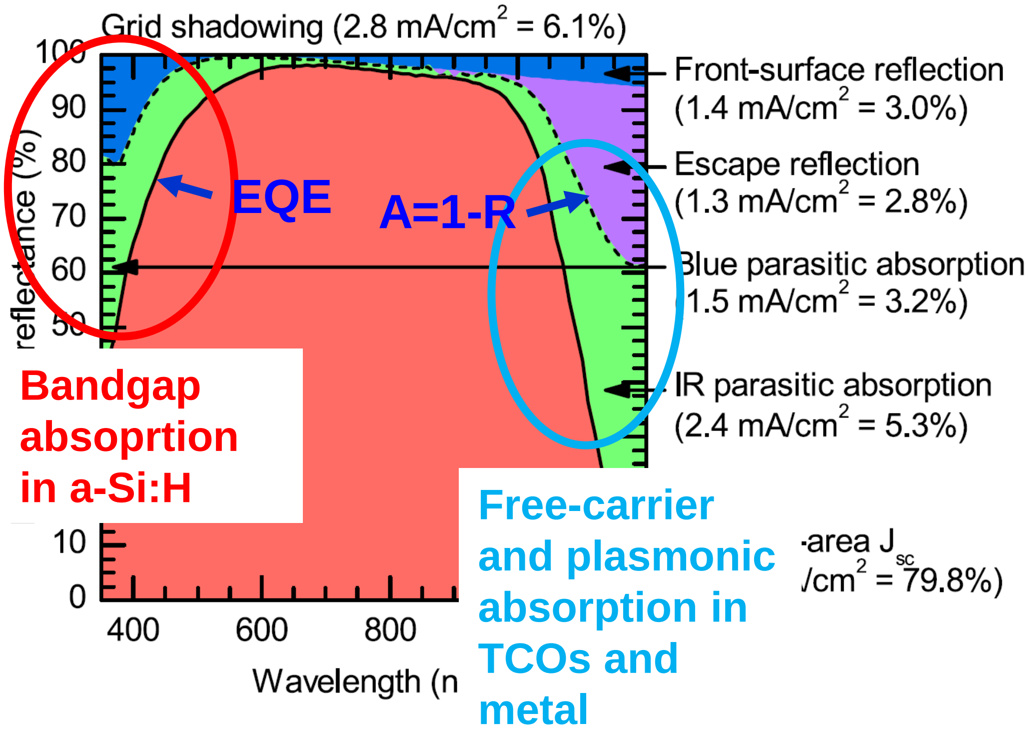
Impact TCO deposition

sputter-damage
and optimum
contact passivation

Appl. Phys. Lett. **101**, 171604 (2012)
IEEE JPV **4**, 1387 (2014)
IEEE JPV **6**, 17 (2016)
APL Materials (2015)

Past research at EPFL (2)

Study of Parasitic Light absorption → moderate J_{sc}



How mitigate these losses?

- High mobility TCOs

  →Improved IR response!

  IO:H vs ITO SOLMAT **115**, 151 (2013)

- Use of advanced rear reflectors

  →Improved ...esponse!

  IR Light managemen...
  Patterned rear M...
  $ZnO:Al+SiO_2$

  ...3, 013107 (2013)
  ...& Applications (2013)
  ...3, 1243 (2013)
  ...ter. Interf. (2015).

- Use of ...ndow layer

  $a\text{-}SiO_x:H(i)$ J.Appl. Phys. 115, 024502 (2014)

  →Improved UV response but transport problems!

→HIGHER J_{sc} !

→Thin amorphous silicon and TCO layers absorb unfortunately some light…

Z. Holman *et al.*, IEEE JPV **2** (7), 2012.

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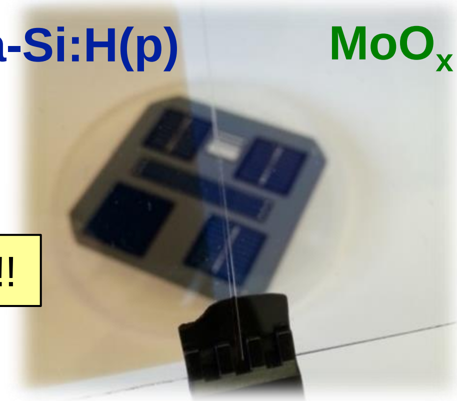
Strategies explored at EPFL-CSEM

Objective: Ultimate current generation in SHJ devices!

1. Two-side-contacted SHJ devices with **metal oxide** materials



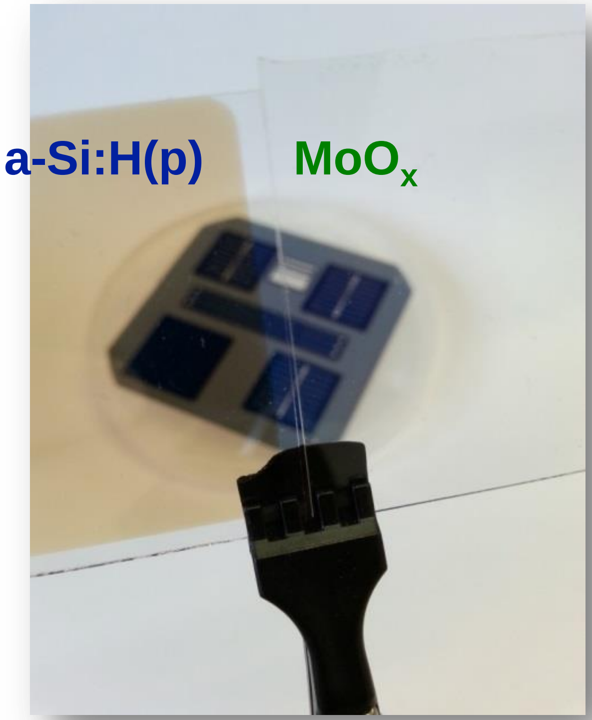
patterning-free!!

2. *Simple* **IBC-SHJ** solar cells

photolithography-free!!

Strategy 1

Patterning-free approach for J_{sc} enhancement



Problem parasitic bandgap absorption of light in doped a-Si:H

Possible solution replacement of doped a-Si:H layers with wide bandgap metal oxides

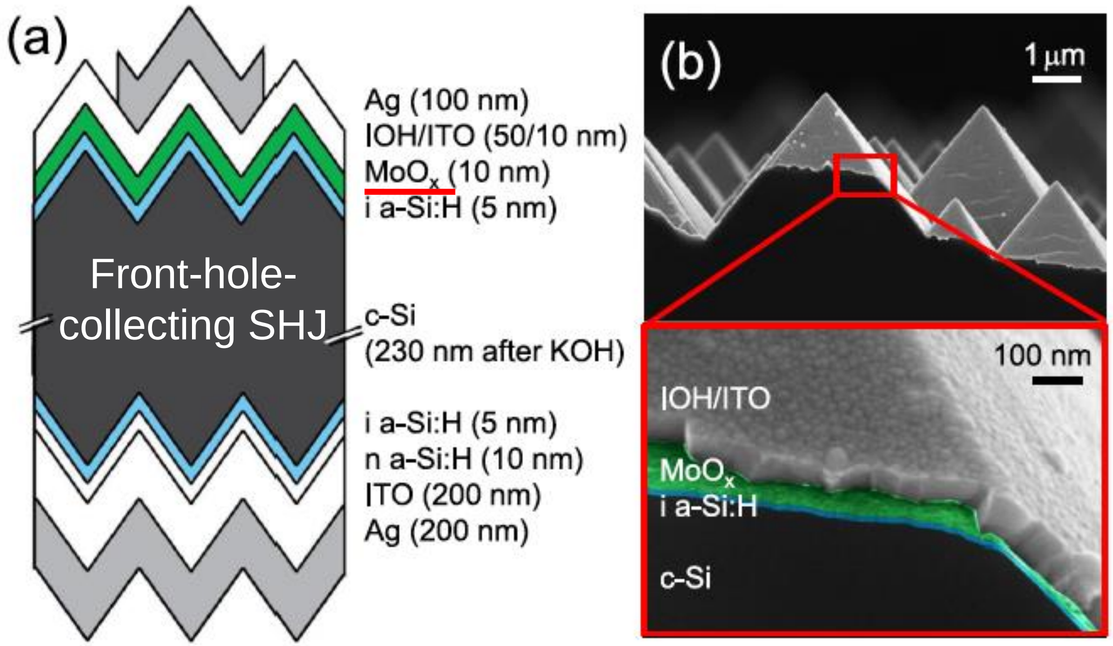
metal oxide with proper work-function	+	passivating layer a-Si:H(i)

passivating contact

Metal-oxide based SHJ

Example: MoOx, high-WF metal oxide to replace p-type a-Si:H

Cross-sectional schematic:



C. Battaglia *et al*., Appl. Phys. Lett. 104, 2014.

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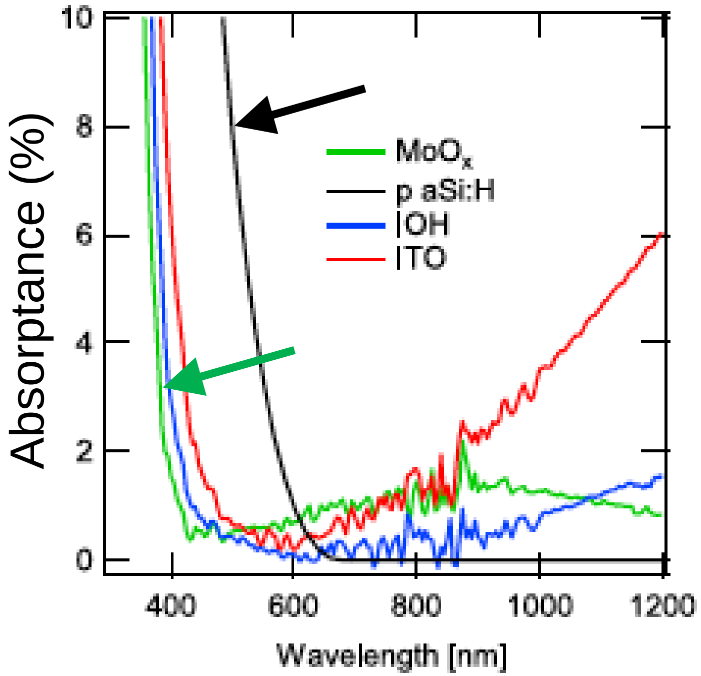
Metal-oxide based SHJ

Example: MoOx, high-WF metal oxide to replace p-type a-Si:H



C. Battaglia *et al*., Appl. Phys. Lett. 104, 2014.

- a-Si:H(p) quite absorbing for λ<600 nm
- MoO_x wide bandgap → higher transparency in short-λ region

→ Clear **potential J_{sc} gain** for MoO_x-based SHJ solar cells

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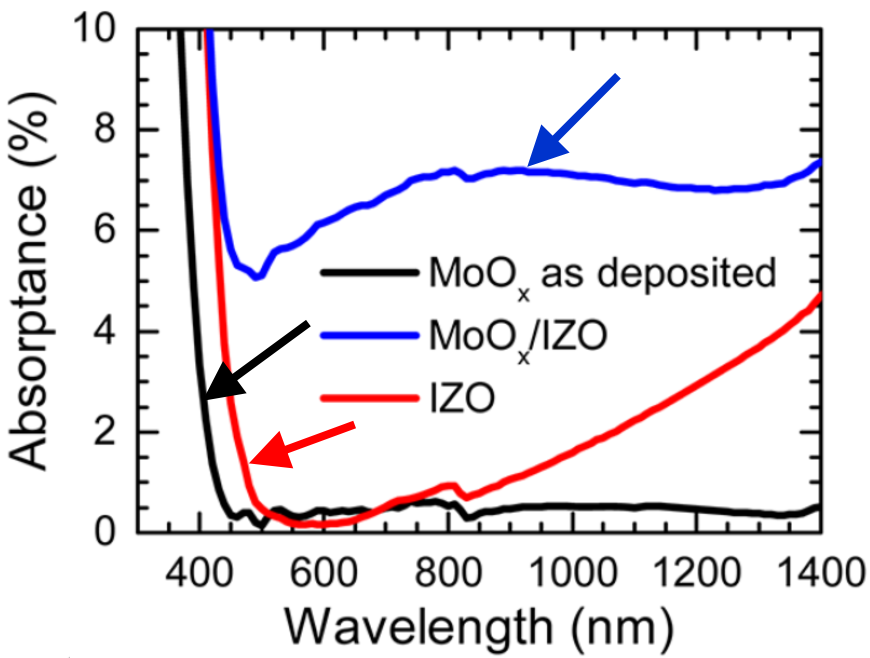
Metal-oxide based SHJ

Problem: Coloration of MoOx after TCO deposition



J. Geissbühler *et al.*, Appl. Phys. Lett. 107, 2015.

J. Werner *et al.*, Appl. Mater. Interfaces 8, 2016.

- MoO$_x$/TCO stack enhanced absorptance (IZO,ITO,ZnO,IO:H as TCOs)
- MoO$_x$ coloration due to TCO sputtering (annealing, ion bombardment, UV light)

→**still better UV-visible response** in MoO$_x$-based cell

but

→the potential J_{sc} gain is **only partially** exploited

Metal-oxide based SHJ

Problem 2: Effect of Annealing on MoO_x

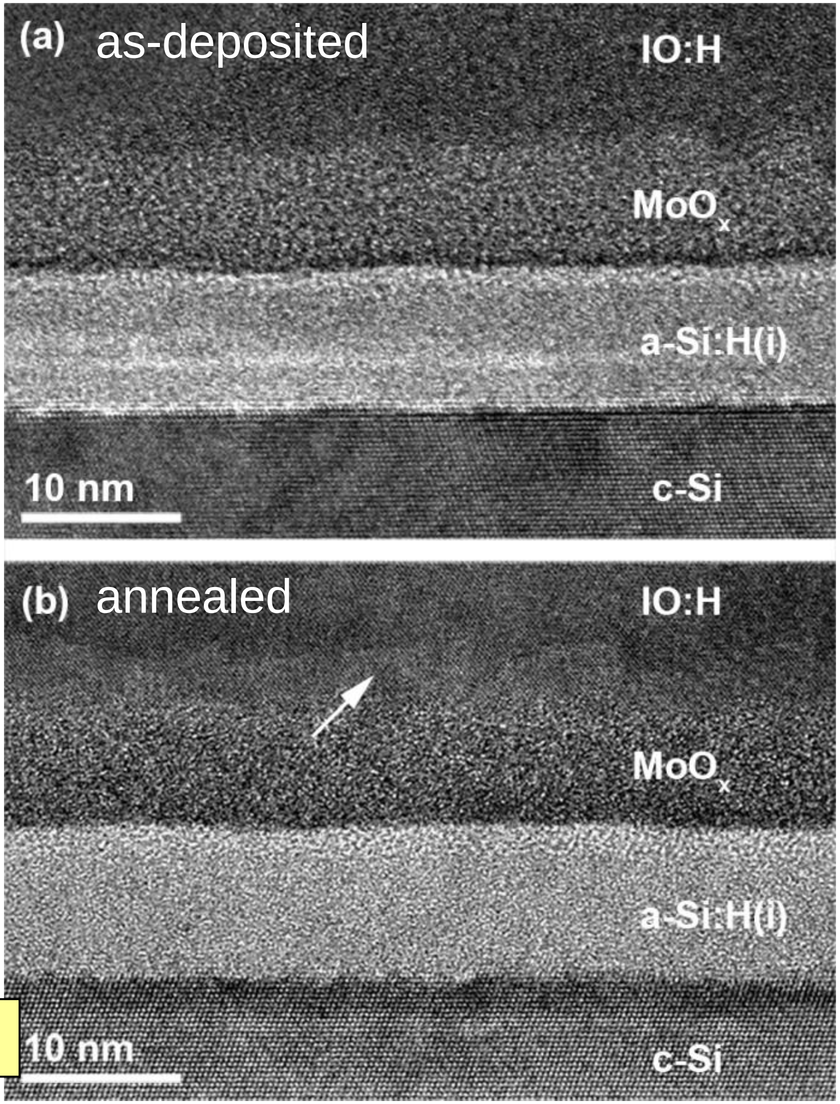
As-deposited:

- *Sharp a-Si:H(i)/MoO_x interface*
- *Well-defined MoO_x/IO:H interface*

After annealing (200°C):

- *Occurence of an inter-layer at the MoO_x/IO:H interface*
- *Seems to cause S-shaped IV curves...*

J. Geisbühler *et al.*, Appl. Phys. Lett. 107, 2015.

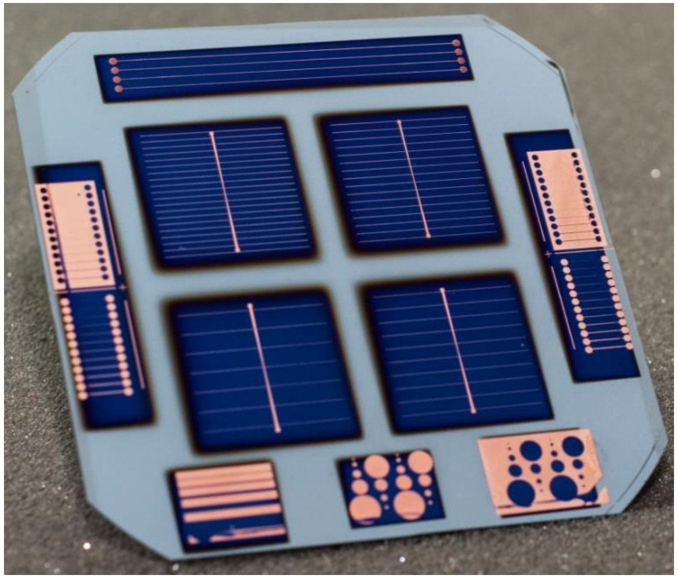


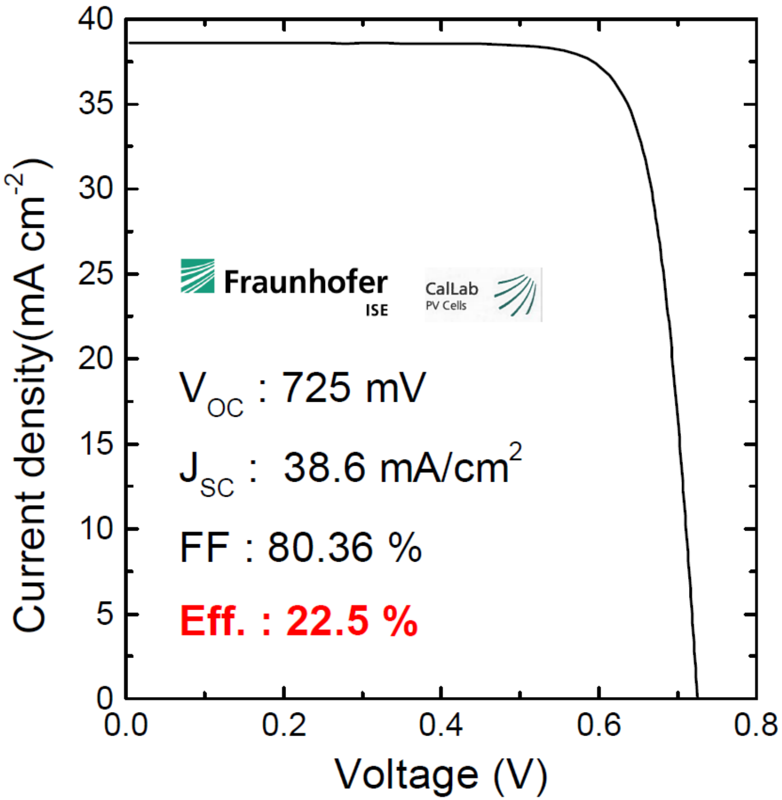
→Need for a **low-temperature** cell process!

Copper-plating + Metal-oxide based SHJ

Cu-plating metallization:

- *Below 130° C*
- *FF above 80%*
- *22.5% certified*





Next step: Fully dopant-free devices?

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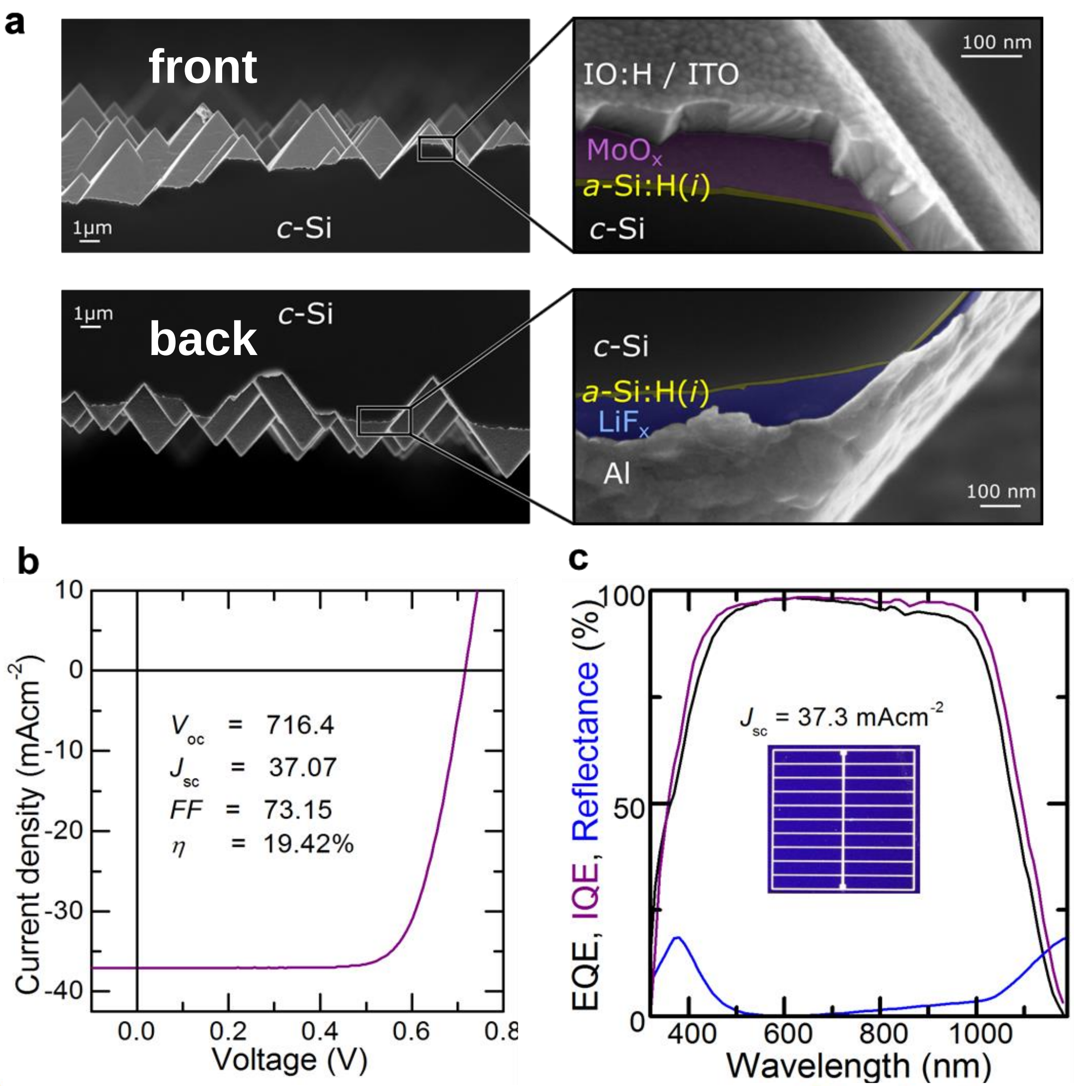
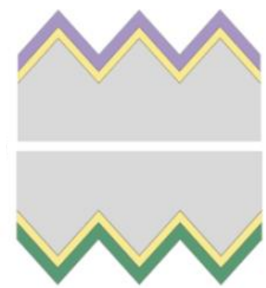
Fully doping-free SHJ



Hole-selective material molybdenum oxide (MoO_x)



Electron-selective material lithium flouride (LiF_x)

J. Bullock *et al.*, Nat. Energy 1 (3), 2016.

nature energy

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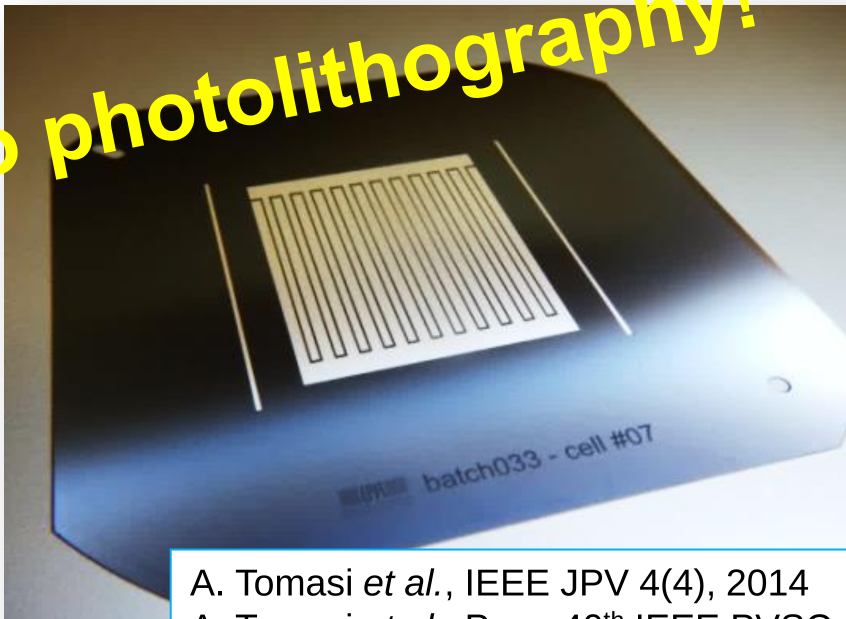
Strategy 2

Simple IBC-SHJ solar cells

No photolithography!



A. Tomasi *et al.*, IEEE JPV 4(4), 2014
A. Tomasi *et al.*, Proc. 40th IEEE PVSC, 2014
B. Paviet-Salomon *et al.*, IEEE JPV 5(5), 2015
A. Tomasi, PhD dissertation, 2016

- No grid electrode at front
- More freedom in engineering of front layers

→World-record efficiency of 26.3%

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IBC-SHJ Fabrication Process

Full-area process | Patterning Step

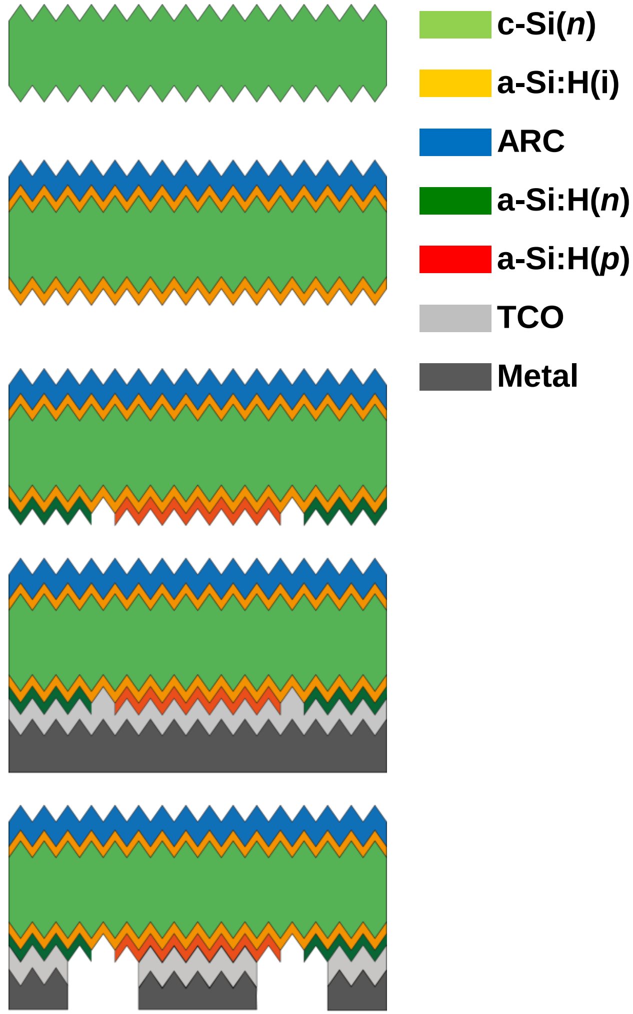
Chemical Baths
Texturing and wafer cleaning

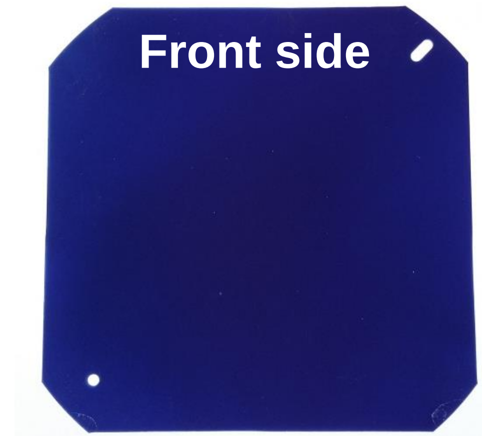
deposition
a-Si:H(i) layers
and ARC

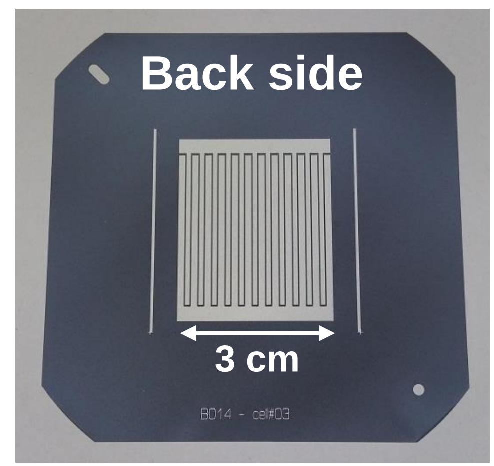
1
***in-situ* masking**
a-Si:H(n/p) doped layers

deposition
TCO/metal layers

2
Inkjet + wet-chemical etching
TCO/metal back-electrodes

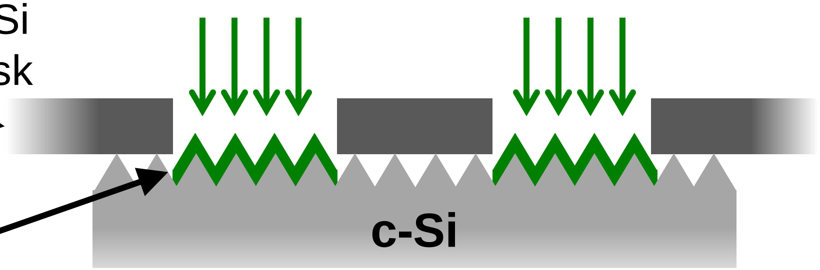


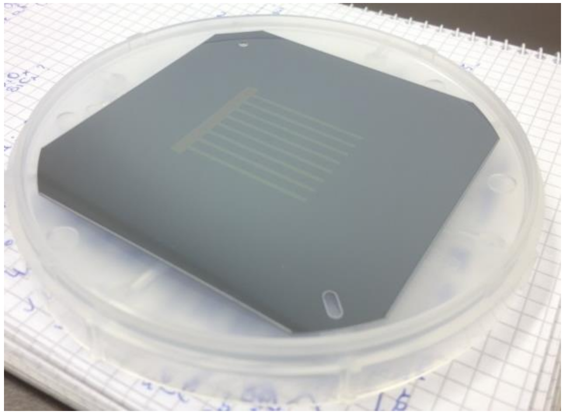




1 Fabrication of the a-Si:H(*n*/*p*) collectors

→ *deposition (PECVD) through laser-cut Si masks:*

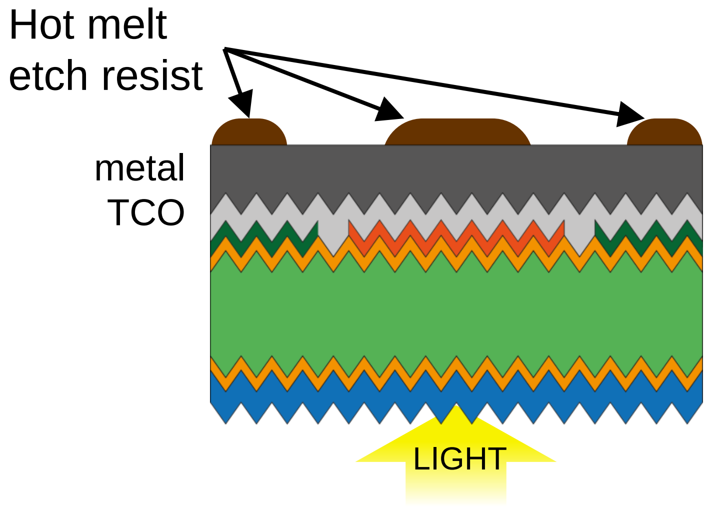




- Simple process
- No photolithography step

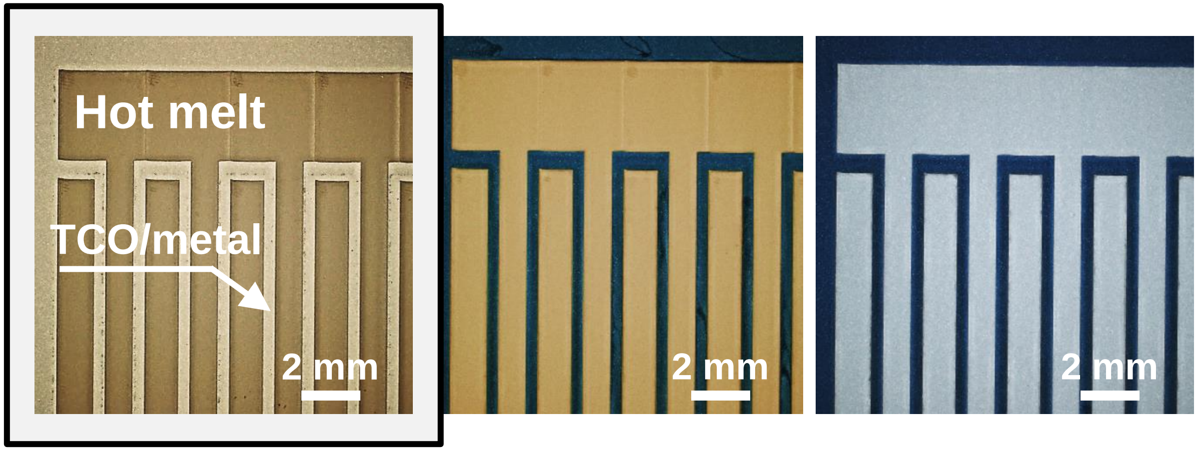
Fabrication of the back contact

2



- **Hot melt inkjet printing**
- Wet-chemical etching
- Hot melt stripping

Optical microscope images:



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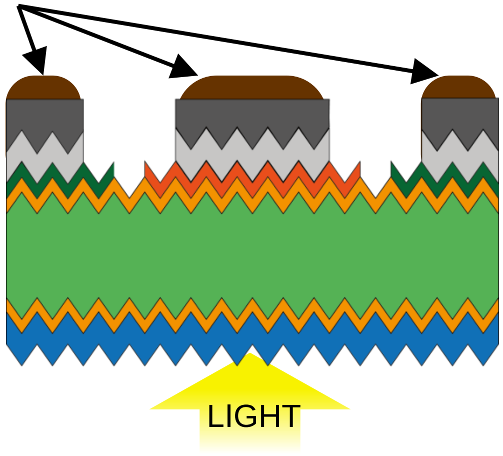
2

Fabrication of the back contact



- Hot melt inkjet printing
- **Wet-chemical etching**
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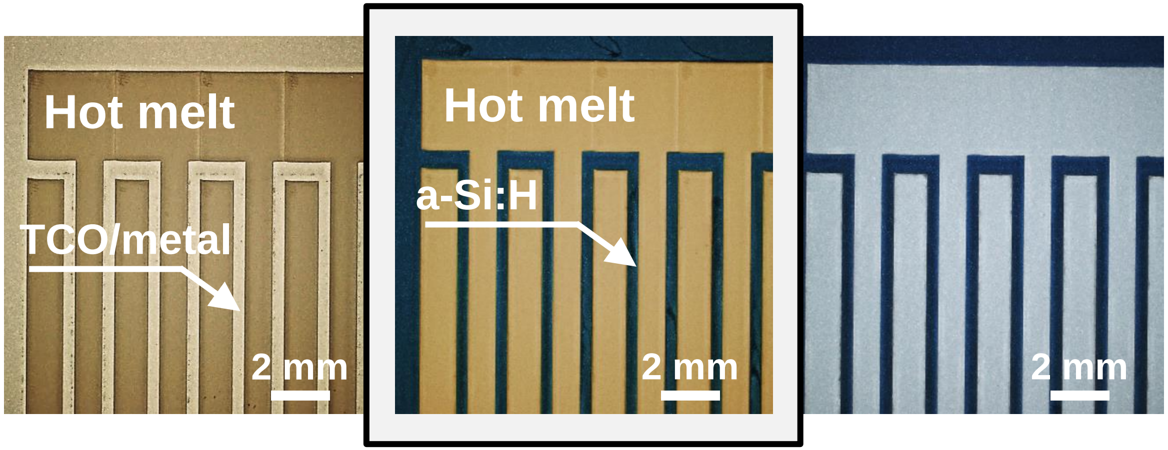
Optical microscope images:



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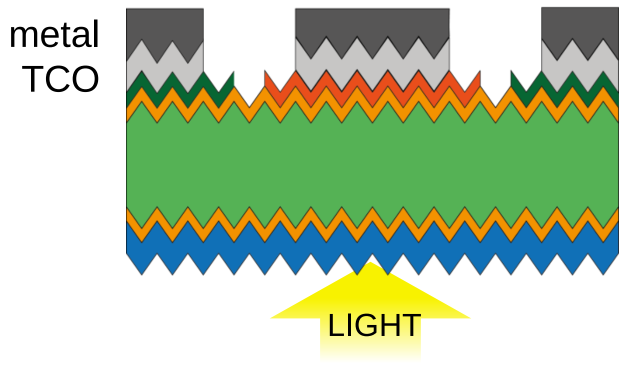
2

Fabrication of the back contact



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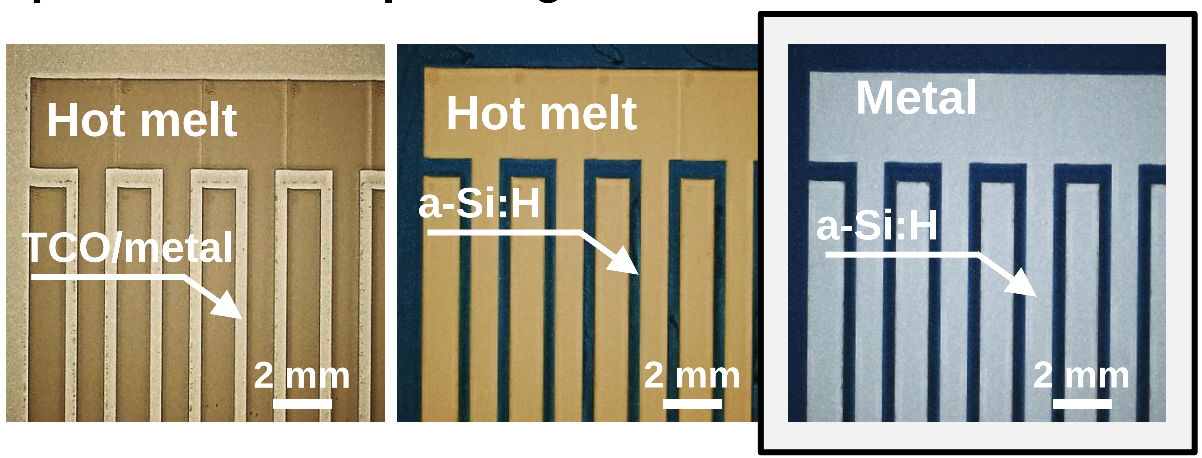

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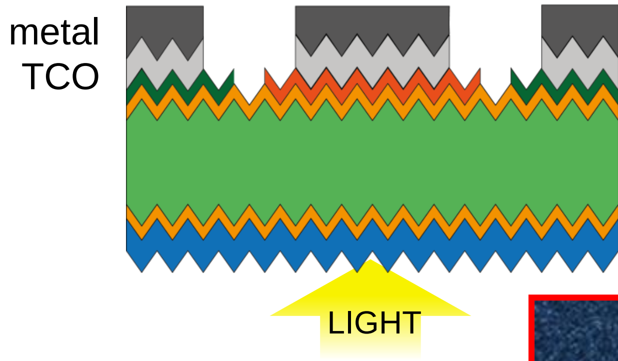
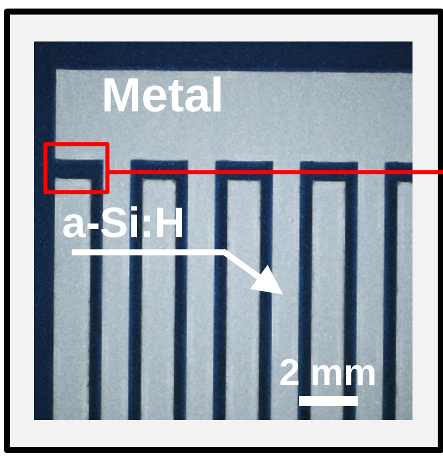
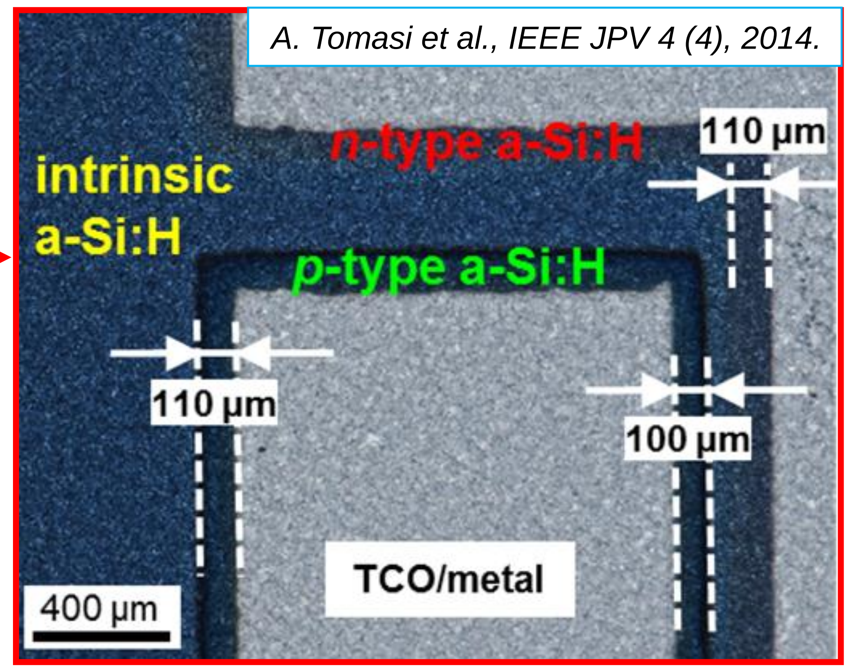
Fabrication of the back contact



- Hot melt inkjet printing
- Wet-chemical etching
- **Hot melt stripping**

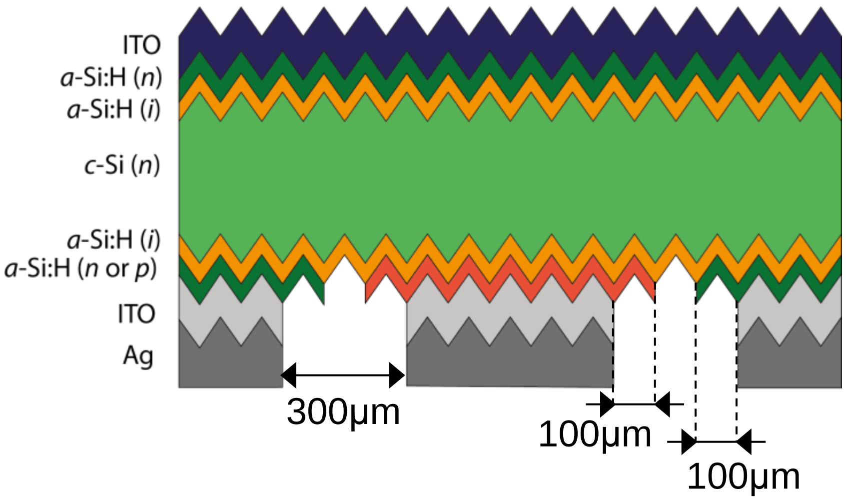




A. Tomasi et al., IEEE JPV 4 (4), 2014.

The Path *towards* Efficient IBC-SHJ Devices

The first IBC-SHJ devices:



Main features:

- a-Si:H(*in*)/ITO front stack
- 100 µm gap a-Si:H(*n*)/(*p*)
- ITO/Ag back electrodes

High efficiency by optimization of:

→Device optics

→Back contact architecture

→Charge-carrier transport

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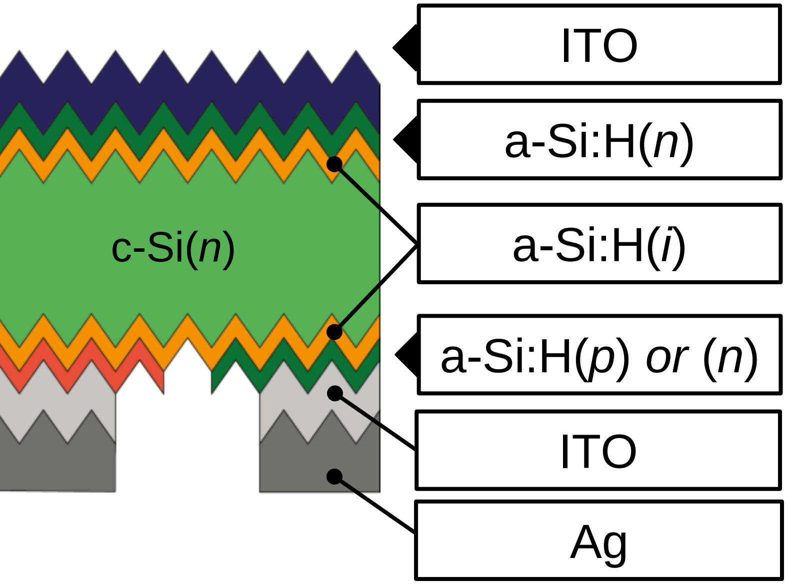
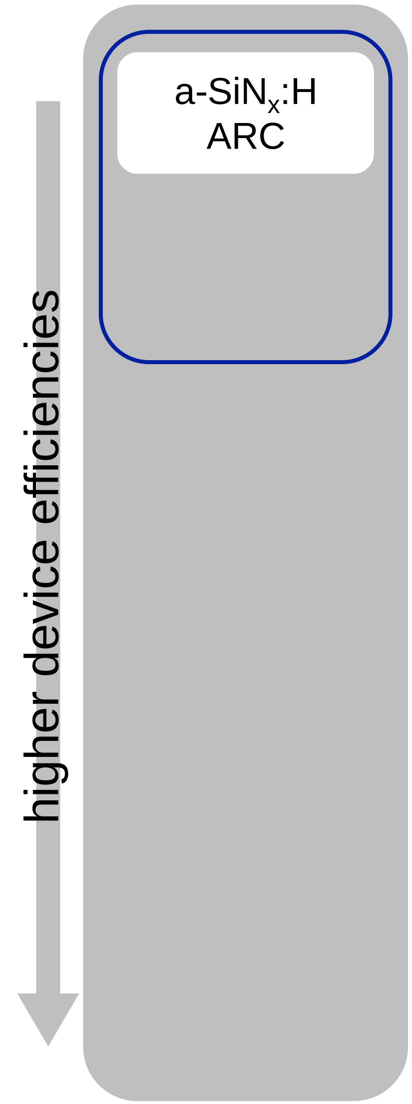
Optical-Loss Mitigation

→Device optics



Problem: free carrier and band gap absorption in front ITO

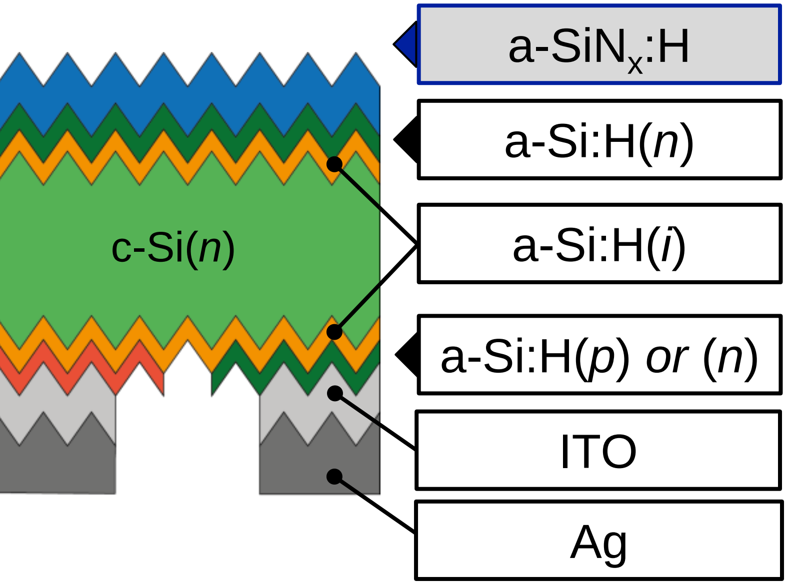


- Development of a low temperature a-SiN_x:H ARC (<200°C)

B. Paviet-Salomon et al., IEEE J-PV 5(5), 2015.

Optical-Loss Mitigation

→Device optics



Problem: band gap absorption in front a-Si:H(*n*)

higher device efficiencies

a-SiN$_x$:H ARC

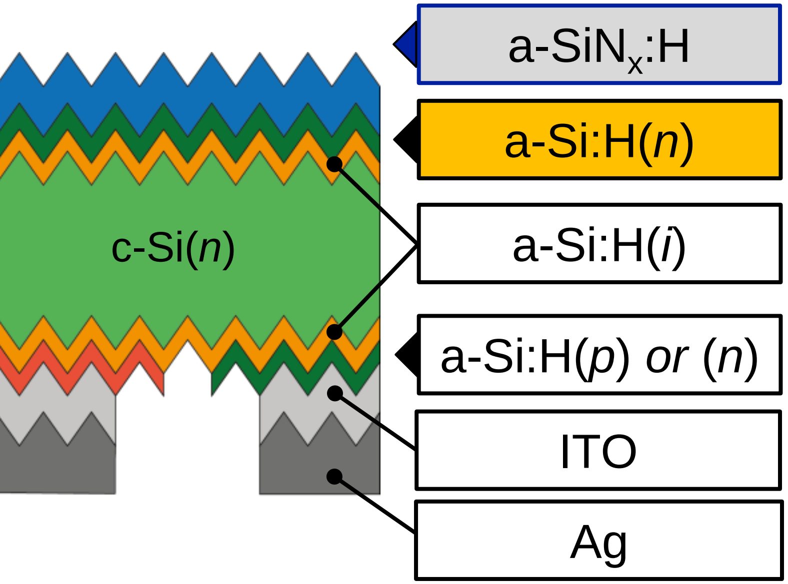
- Development of a low temperature a-SiN$_x$:H ARC (<200°C)

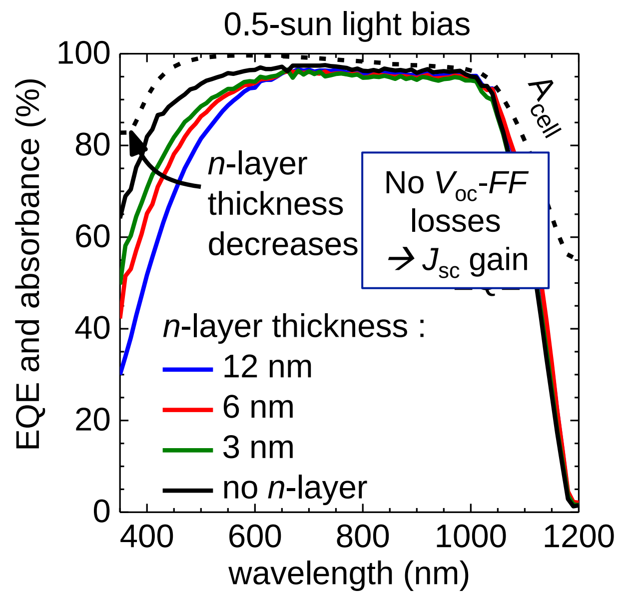
≈0.5 mA/cm^2 J_{sc} gain

B. Paviet-Salomon et al., IEEE J-PV 5(5), 2015.

Optical-Loss Mitigation

→Device optics





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Optical-Loss Mitigation

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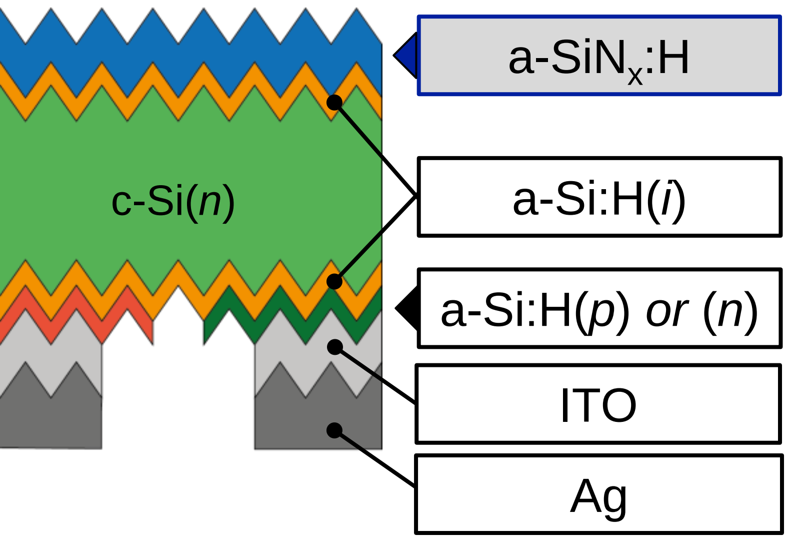

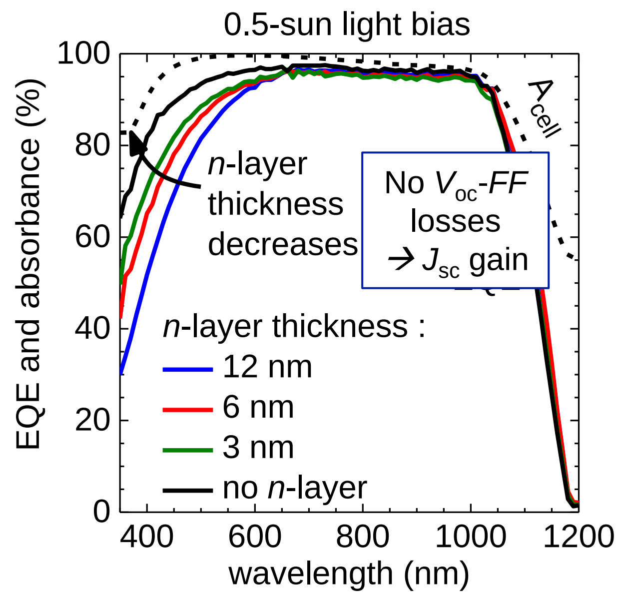

- Development of a low temperature a-SiN_x:H ARC (<200°C)

≈0.5 mA/cm² J_{sc} gain

- No a-Si:H(*n*) in the front stack

≈1 mA/cm² J_{sc} gain

B. Paviet-Salomon et al., IEEE J-PV 5(5), 2015.

+1.5 mA/cm²

J_{sc} >40.5mA/cm²

higher device efficiencies

a-SiN_x:H ARC

No front a-Si:H(*n*)

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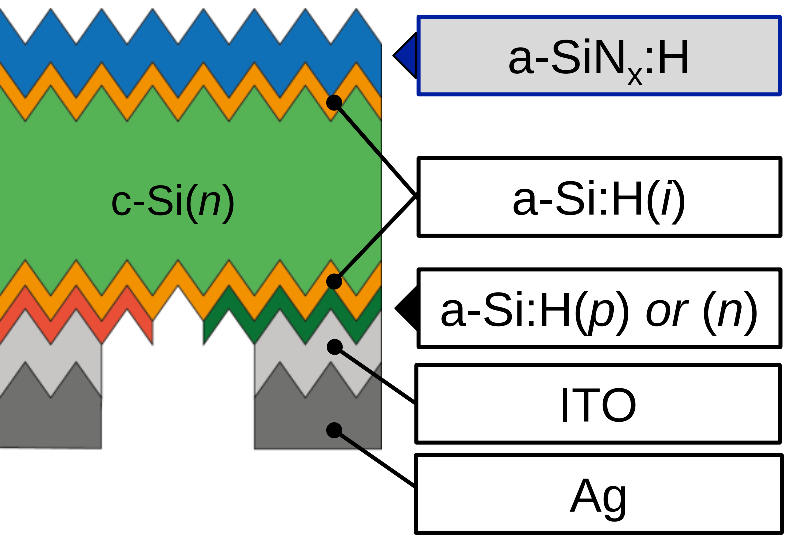
In-situ patterned a-Si:H layers

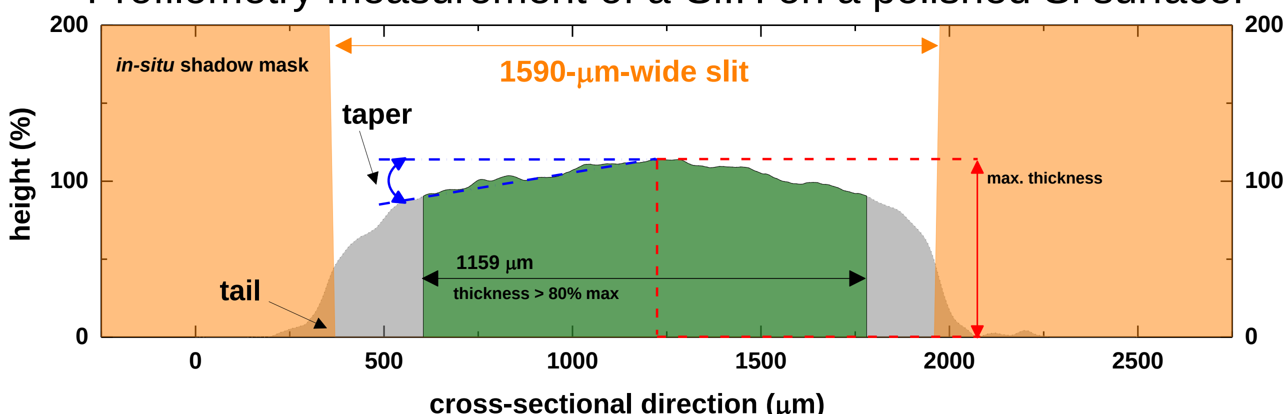
→Back contact architecture

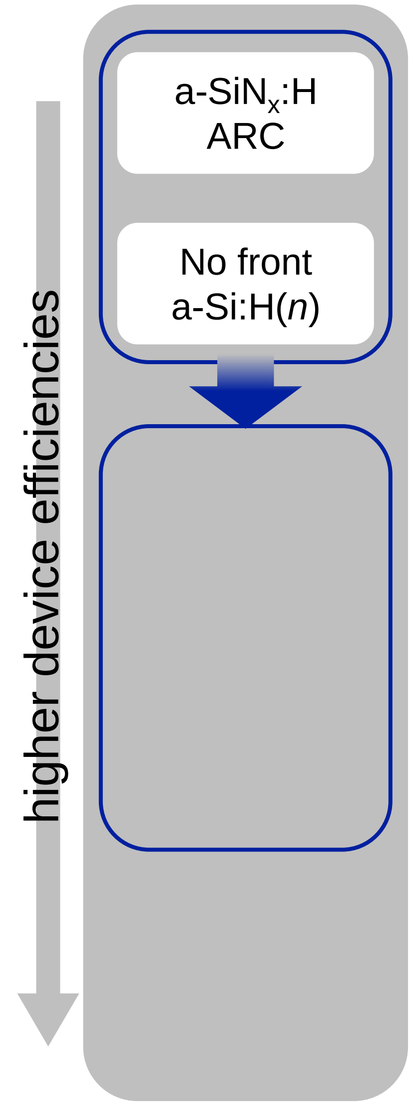


Problem: morphology of doped a-Si:H finger

- Tapering & tailing
- Lower deposition rate for narrower mask slits

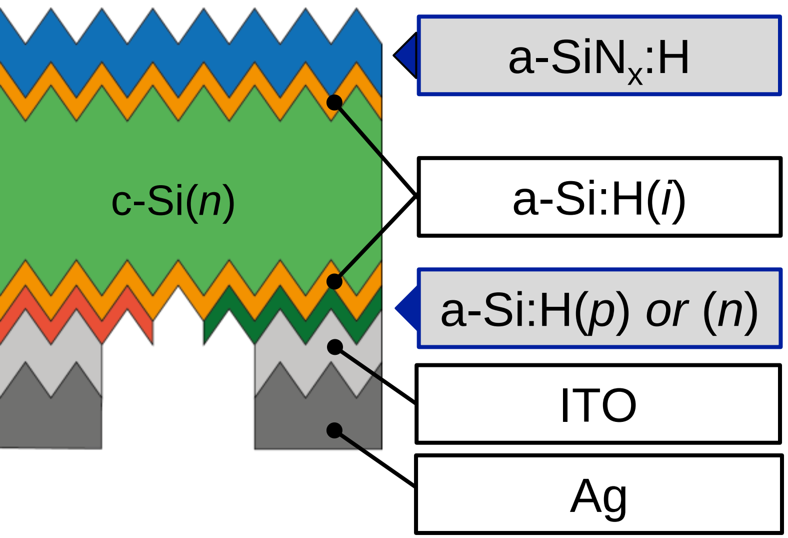
Profilometry measurement of a-Si:H on a polished Si surface:





In-situ patterned a-Si:H layers

→Back contact architecture

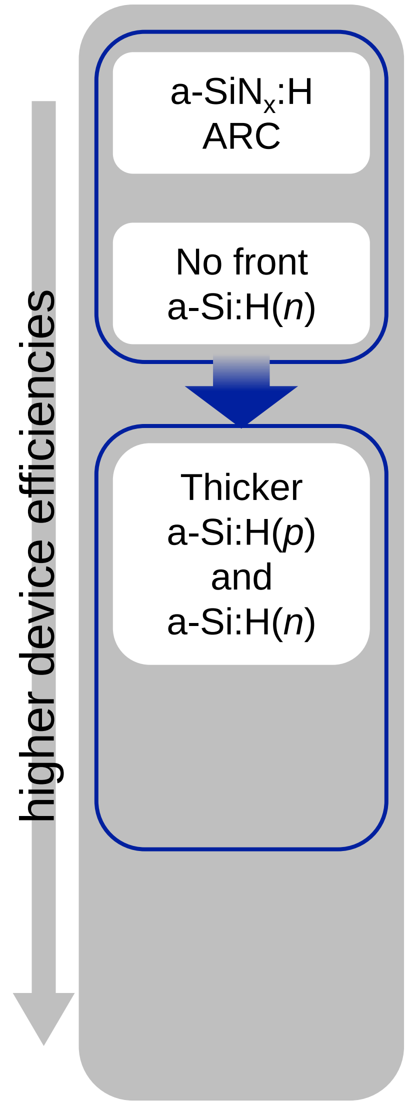


- Thicker doped a-Si:H layers

→*FF* and V_{oc} improvements

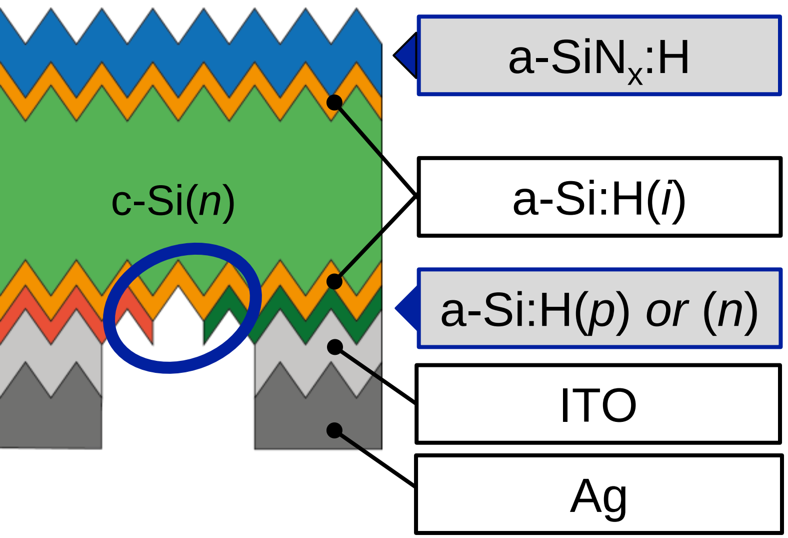
Problem: morphology of doped a-Si:H finger

- **Tapering & tailing**
- Lower deposition rate for narrower mask slits



TCO Sputtering damage

→Back contact architecture

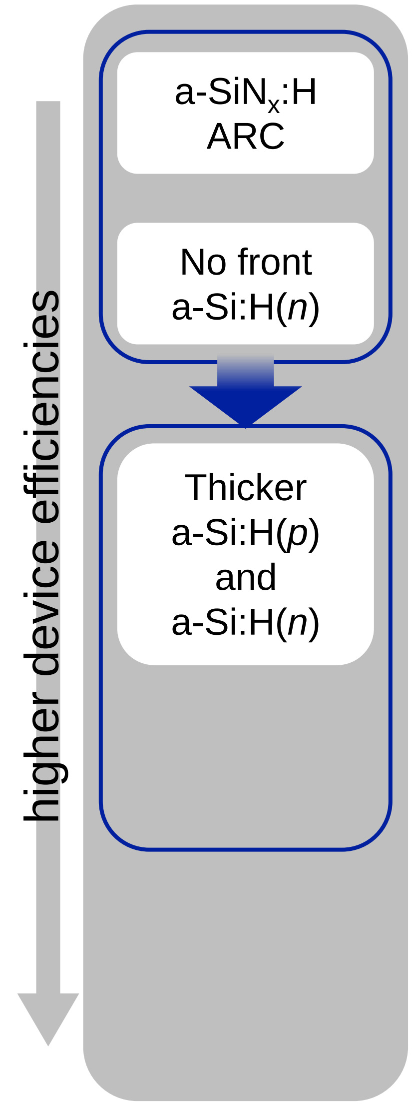


➢ Thicker doped a-Si:H layers

→*FF* and V_{oc} improvements

Problem:
Sputtering damage

- ➢ Heritage of the conventional IBC design
- ➢ ITO sputtering on a-Si:H(*i*) →passivation loss!



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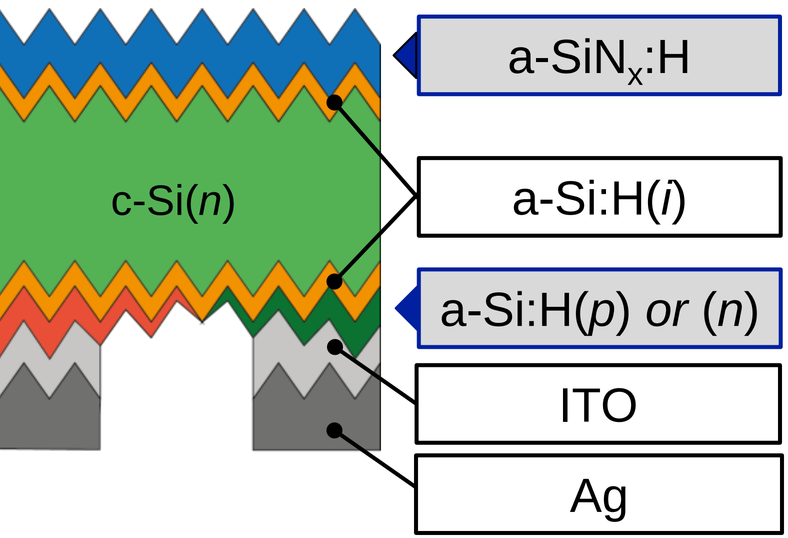
TCO Sputtering damage

→Back contact architecture



Problem:
Sputtering damage

- Heritage of the conventional IBC design
- ITO sputtering on a-Si:H(*i*) →passivation loss!

- Thicker doped a-Si:H layers

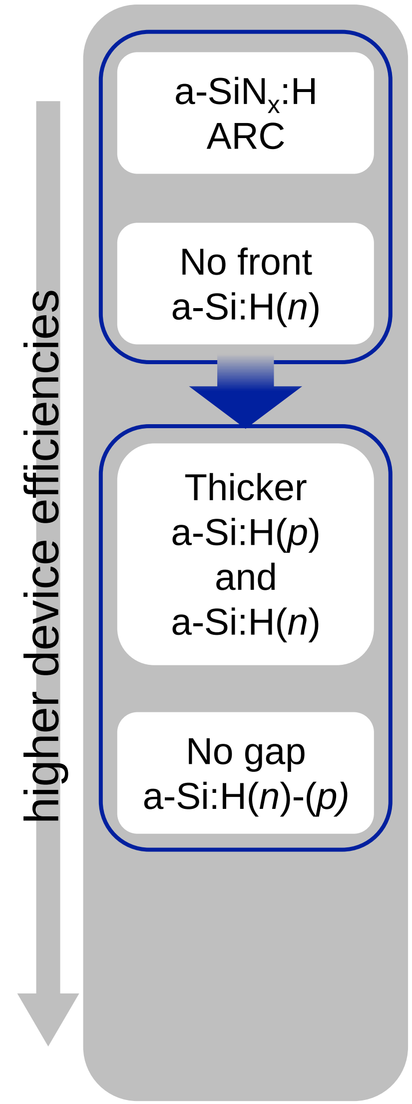
  →*FF* and V_{oc} improvements

- NO GAP between a-Si:H(n)/(p)

  →*FF* and V_{oc} improvements

+*FF*
+V_{oc}

FF >67 % *and* V_{oc} >720 mV



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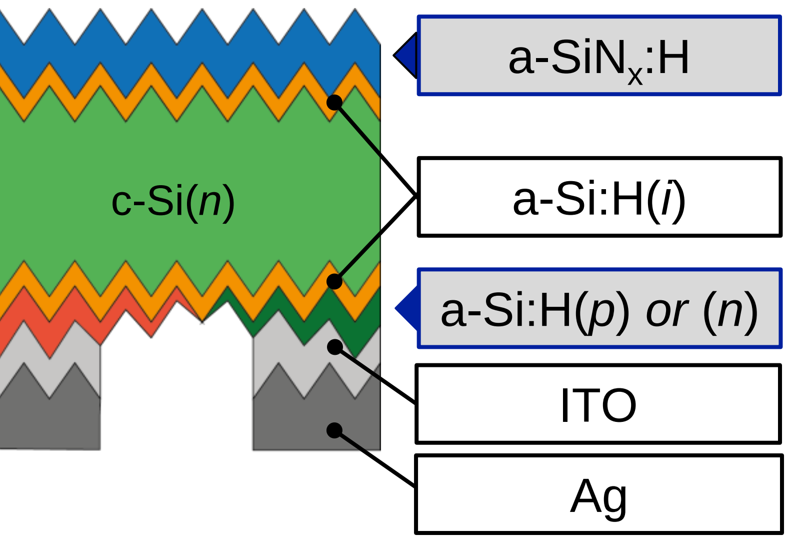
Series Resistance and *heterocontacts*

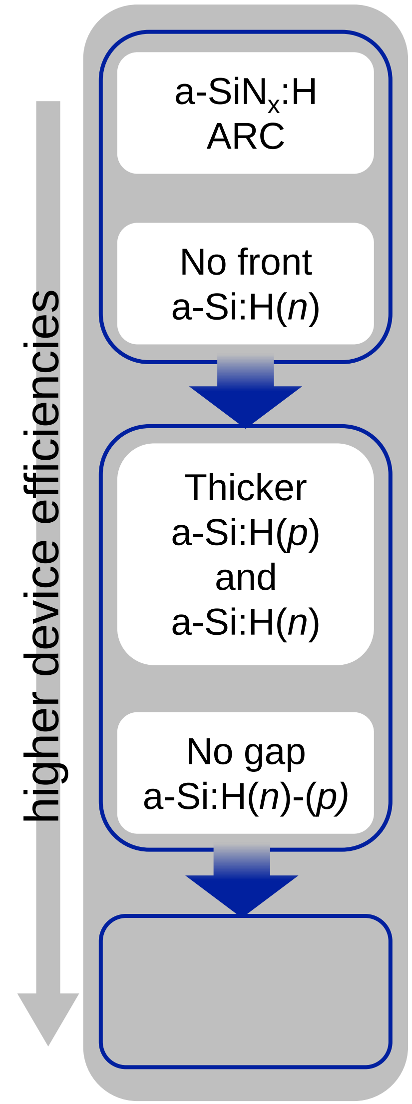
→Charge-carrier transport



Problem:
FF losses due to high R_{series}

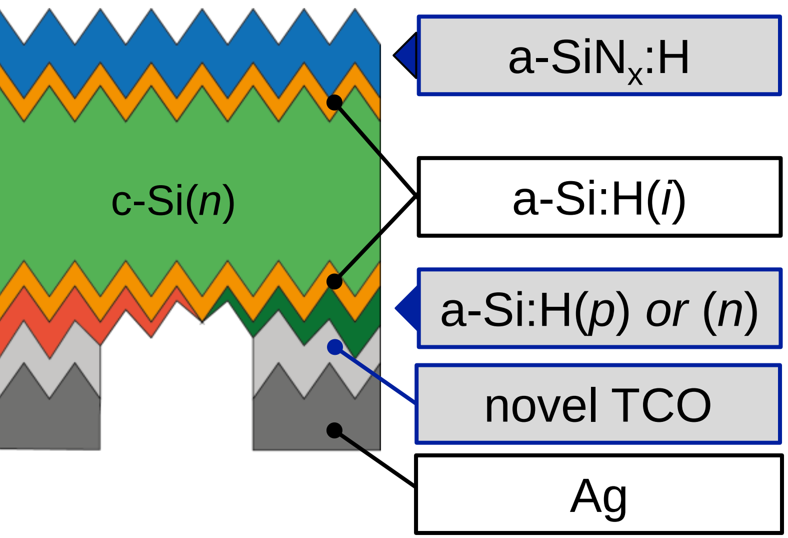
- Experiments
- R_{series} modelling

→High R_{series} is due to low *heterocontact* areas



Series Resistance and *heterocontacts*

→Charge-carrier transport



- Replacement of ITO with novel TCO

→ *FF* gain

- Improved doped a-Si:H layers

→ *FF* gain

Problem:
FF losses due to high R_{series}

- Experiments
- R_{series} modelling

→High R_{series} is due to low *heterocontact areas*

+*FF*

FF >75 %

higher device efficiencies

a-SiN_x:H ARC

No front a-Si:H(*n*)

Thicker a-Si:H(*p*) and a-Si:H(*n*)

No gap a-Si:H(*n*)-(*p*)

Improved contacts

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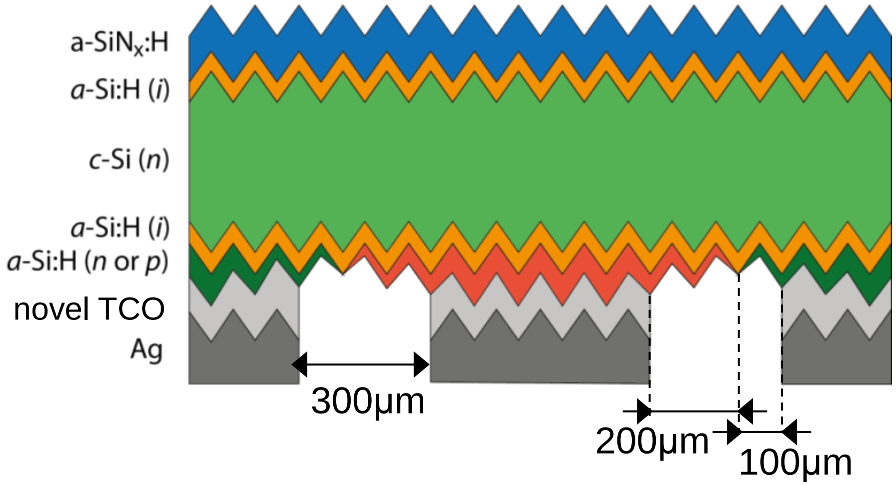
Optimized IBC-SHJ Devices

The best IBC-SHJ devices:



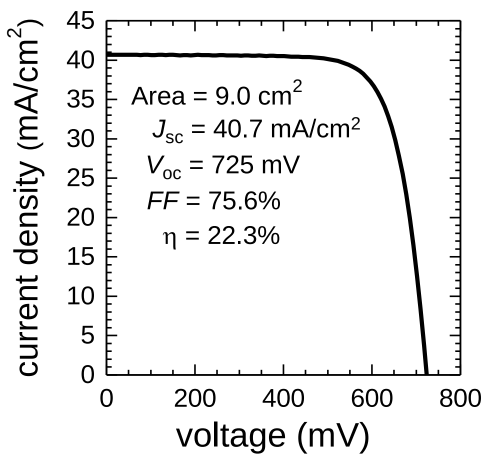
- a-Si:H(*i*)/a-SiN_x:H at front
- NO GAP a-Si:H(*n*)/(*p*)
- Improved *heterocontacts*

J_{sc} >40.5mA/cm^2

FF >75 %

V_{oc} >720 mV

1-sun J-V characteristic



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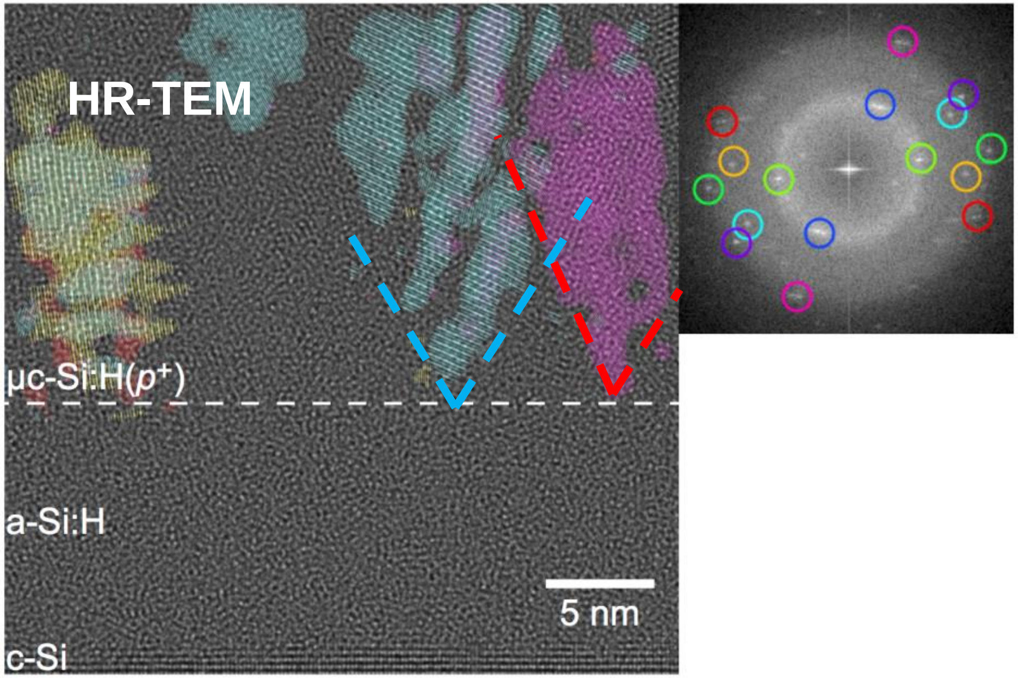
New *heterocontact* materials

→Charge-carrier transport

- New strategies to grow thin doped nc-Si:H films

J. Seif *et al.*, IEEE JPV 6 (5), 2016.

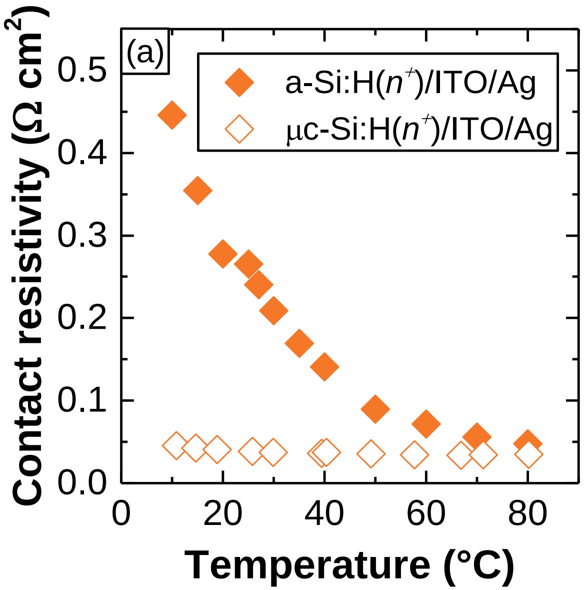
- Fabrication of *heterocontacts* with extremely **low contact resistivity (best ρ_c<10 mΩ*cm^2)**



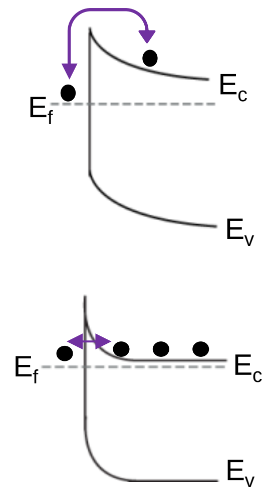
Higher crystallinity →Higher doping **→Improved electrical transport**

Contact Resistivity: *temperature dependence*

Example: the electron contact



…different transport mechanisms?

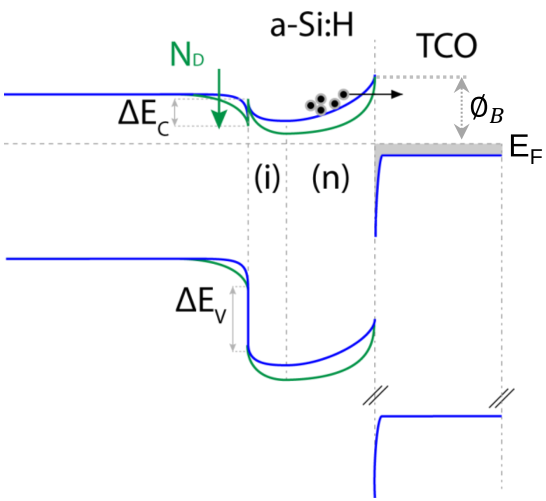


Simplified expression for Thermionic Emission

$$\rho(TE) = \frac{k}{qC_1 T} e^{\frac{q\phi_B}{kT}} \; ; \; \phi_B: \textit{Barrier height}$$

Simplified expression for Field Emission

$$\rho(FE) \sim \exp\left(\frac{C_2}{\sqrt{N}}\right); \; N: \textit{Doping density}$$



- Contact with a-Si stack features a large thermionic component
- Higher the doping, smaller the barrier width at TCO interface → larger field-emission compenent

G. Nogay *et al.*, IEEE JPV *early access.* 2016.

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Best IBC-SHJ Devices

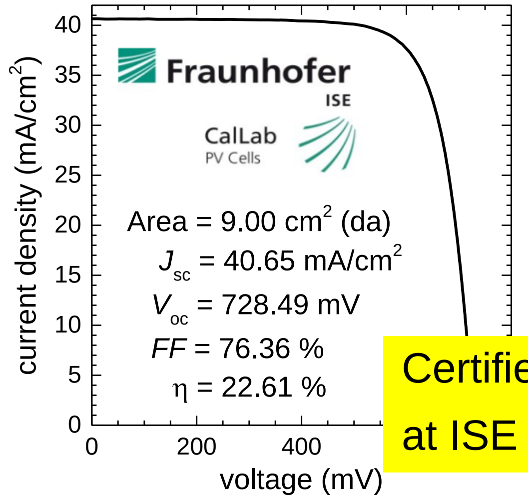
New contact materials!

- new nc-Si:H doped thin film

  implemented in IBC-SHJ devices →

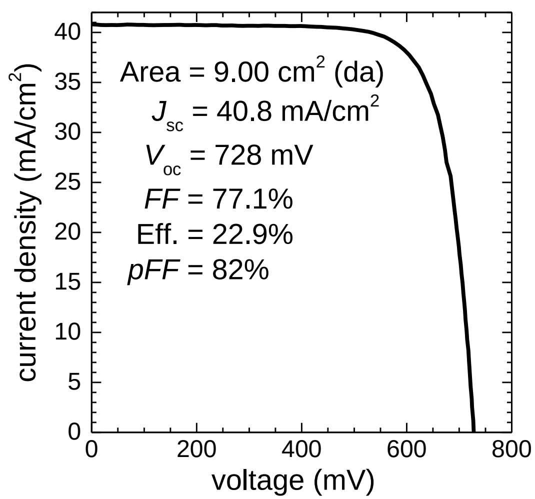
Certified IBC-SHJ

at ISE CalLab:



- I-V characteristic of best IBC-SHJ

  (*in-house measurement*)



A.Tomasi *et al.*, *under submission* , 2016.

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Status IBC-SHJ Devices

Affiliation	Year	Size [cm²]	J_{sc} [mA/cm²]	V_{oc} [mV]	FF [%]	Eff. [%]
Kaneka (JP)	2016	180	?	?	?	26.3
Panasonic (JP)	2014	143.7 (da)	41.8	740	82.7	25.6
Sharp (JP)	2014	3.72 (ap)	41.7	736	81.9	25.1
EPFL-CSEM-MBR (CH)	**2016**	**9.0 (da)**	**40.8**	**728**	**77.1**	**22.9**
IMEC (BE)	2016	3.97	41.6	729	75.3	22.9
CEA-INES (F)	2015	18.1 (da)	40.1	711	72.1	20.6
LG (KR)	2014	221 (ta)	37.5	716	76.4	20.5
HZB-ISFH (DE)	2011	1 (da)	39.7	673	75.7	20.2
University of Delaware (USA)	2015	1 (da)	38.1	697	76.0	20.2

- Three record devices with efficiency >25%!
- Some new results in the 23% range!
- Need for smart fabrication processes to make it industrially feasible!

→IBC-SHJ: Ultimate architecture for c-Si single-junction devices!

Conclusions

Metal-oxide based solar cells

- MoO_x–based contacts provide **better blue response**
- Proven high FF and certified efficiencies of **22.5%**
- Further optical gain by **avoiding MoO_x coloration**

Photolithography free IBC-SHJ cells

- Achievement of **J_{sc} of about 41 mA/cm^2**, higher than in two-side-contacted SHJ
- Efficiency of **22.9%** obtained with new doped Si:H materials

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