Window Layers for Silicon Heterojunction Solar Cells:

Properties and Impact on Device Performance

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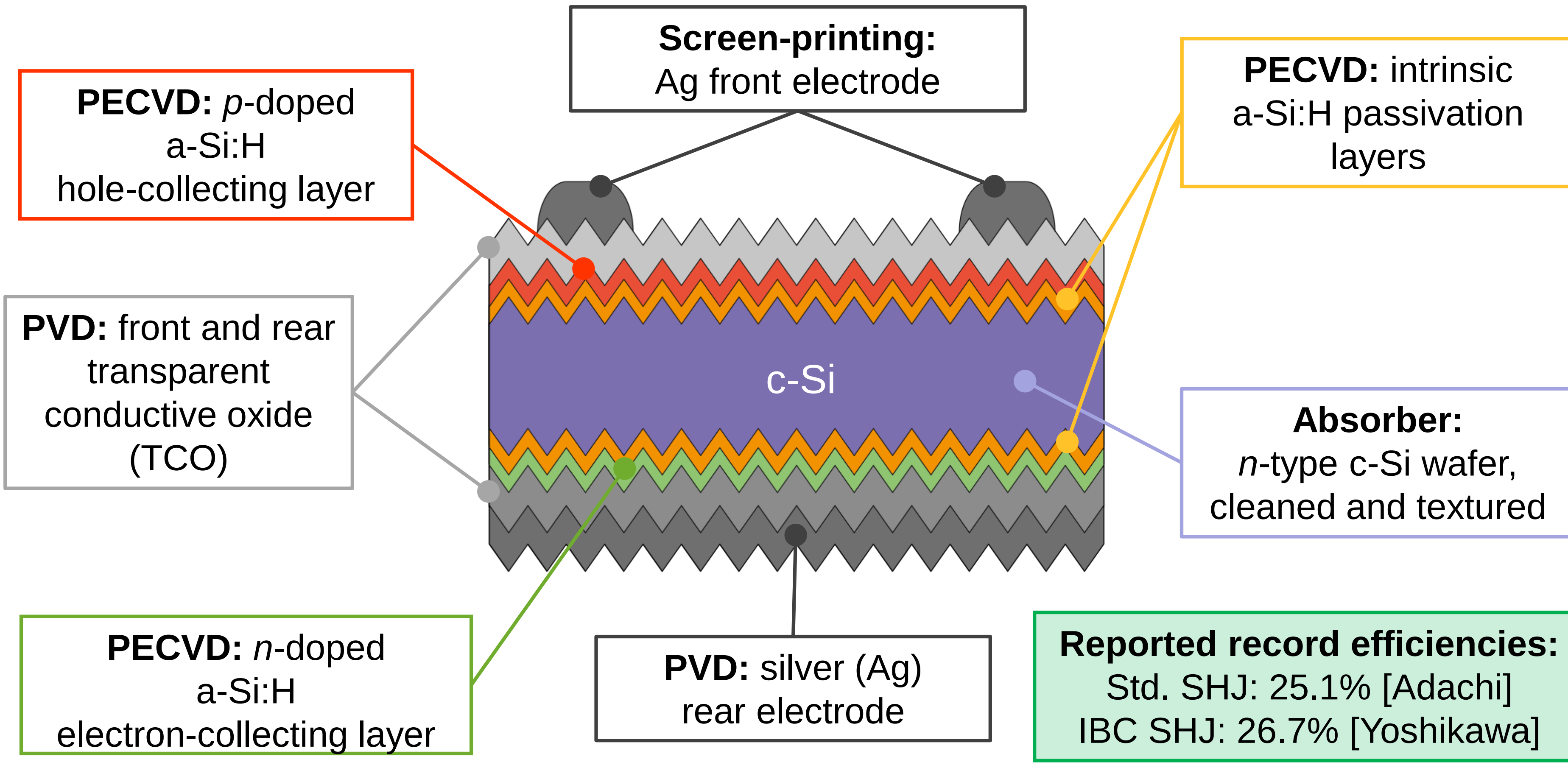
Silicon Heterojunction Solar Cells



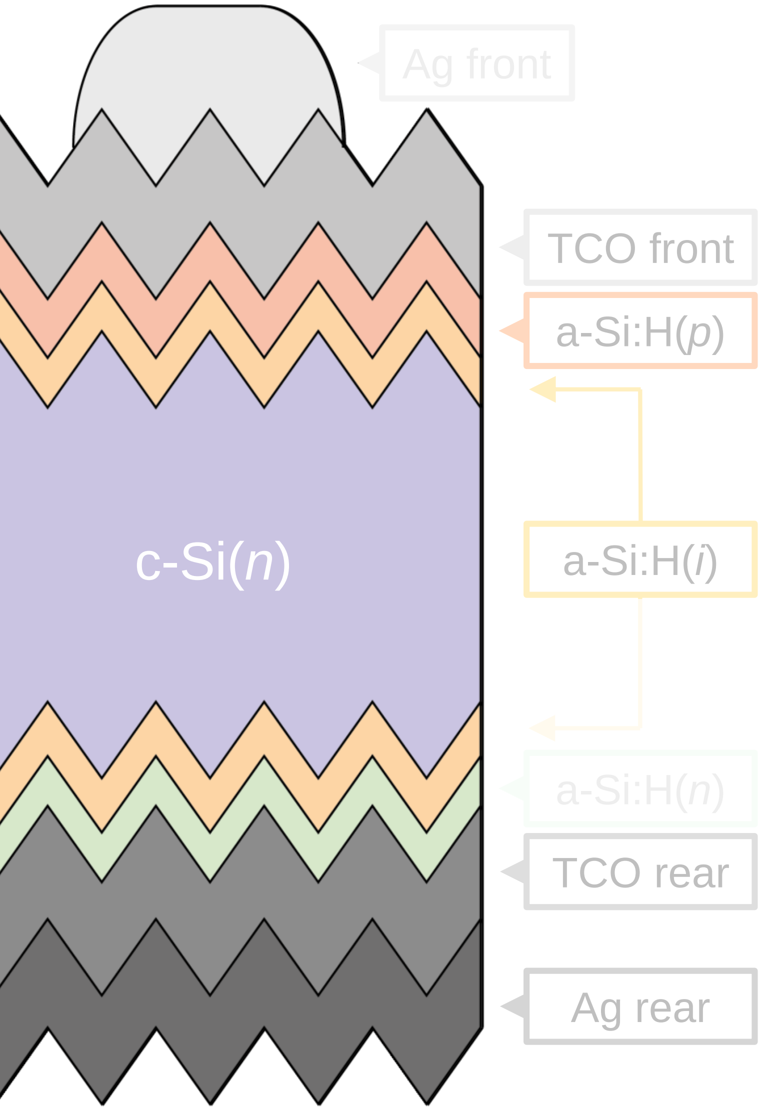
Reported record efficiencies:
Std. SHJ: 25.1% [Adachi]
IBC SHJ: 26.7% [Yoshikawa]

Physical Vapor Deposition / Sputtering (PVD)

Plasma Enhanced Chemical Vapor Deposition (PECVD)

D. Adachi et al., APL, 2015, 107, 233506.
K. Yoshikawa, Nature Energy, 2017, 2(5), 17032.

Challenges: *optical losses*



Parasitic absorption in the front layers: generation of charge carriers that recombine before being collected.

−2.1 mA/cm²

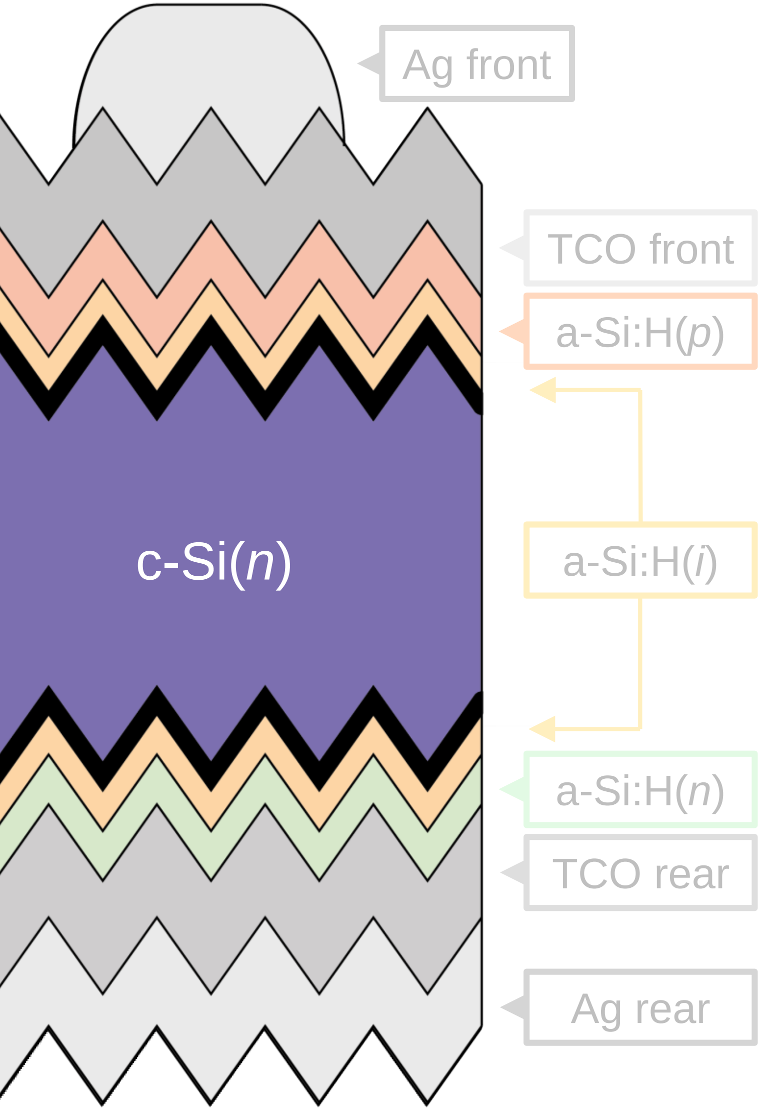
Lower current output of the device, *i.e.* reduced short-circuit current density (J_{sc})

−0.5 mA/cm²

Free-carrier absorption in the highly doped TCO layer **& plasmonic losses** in the metal rear reflector.

Z. C. Holman et al. IEEE J. PV, ***2*** *(1) pp. 7-15, 2012.*

Challenges: *electrical losses*

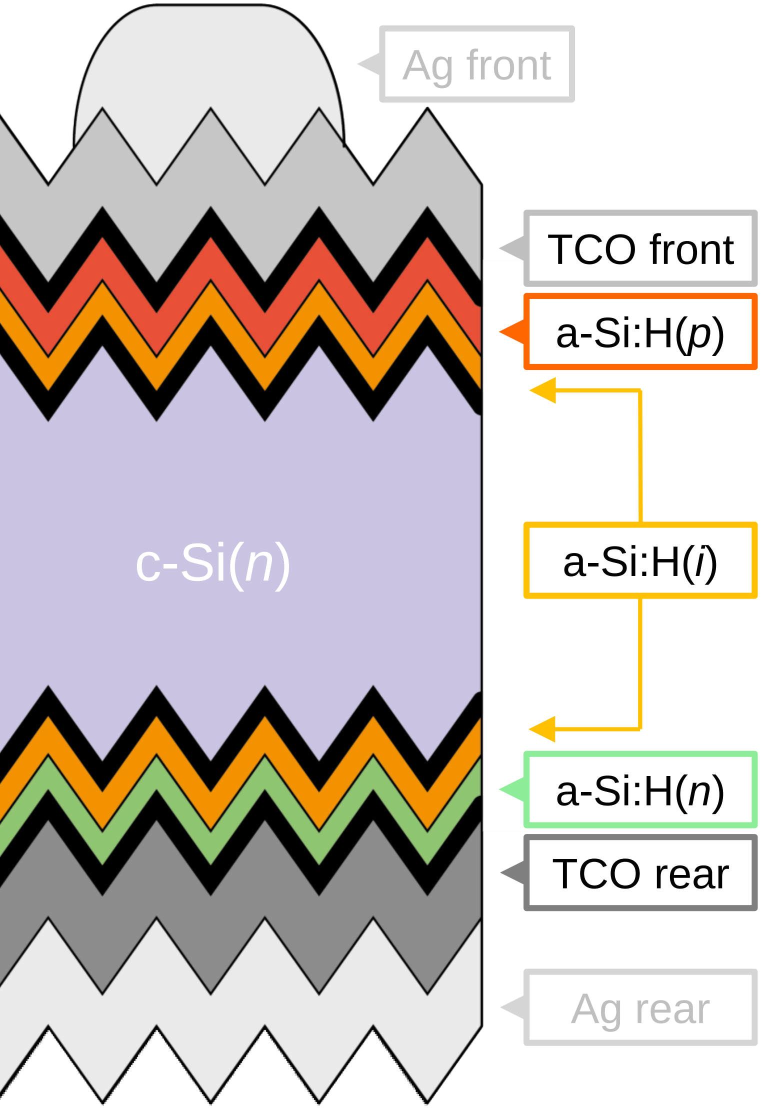


Recombination

- Radiative
- Auger
- Via defect states in the bulk or at the surface

Lowers the maximal attainable voltage, *i.e.* the open-circuit voltage (V_{oc}) and **limits** the voltage at the maximum power point (fill factor, *FF*)

Challenges: *electrical losses*

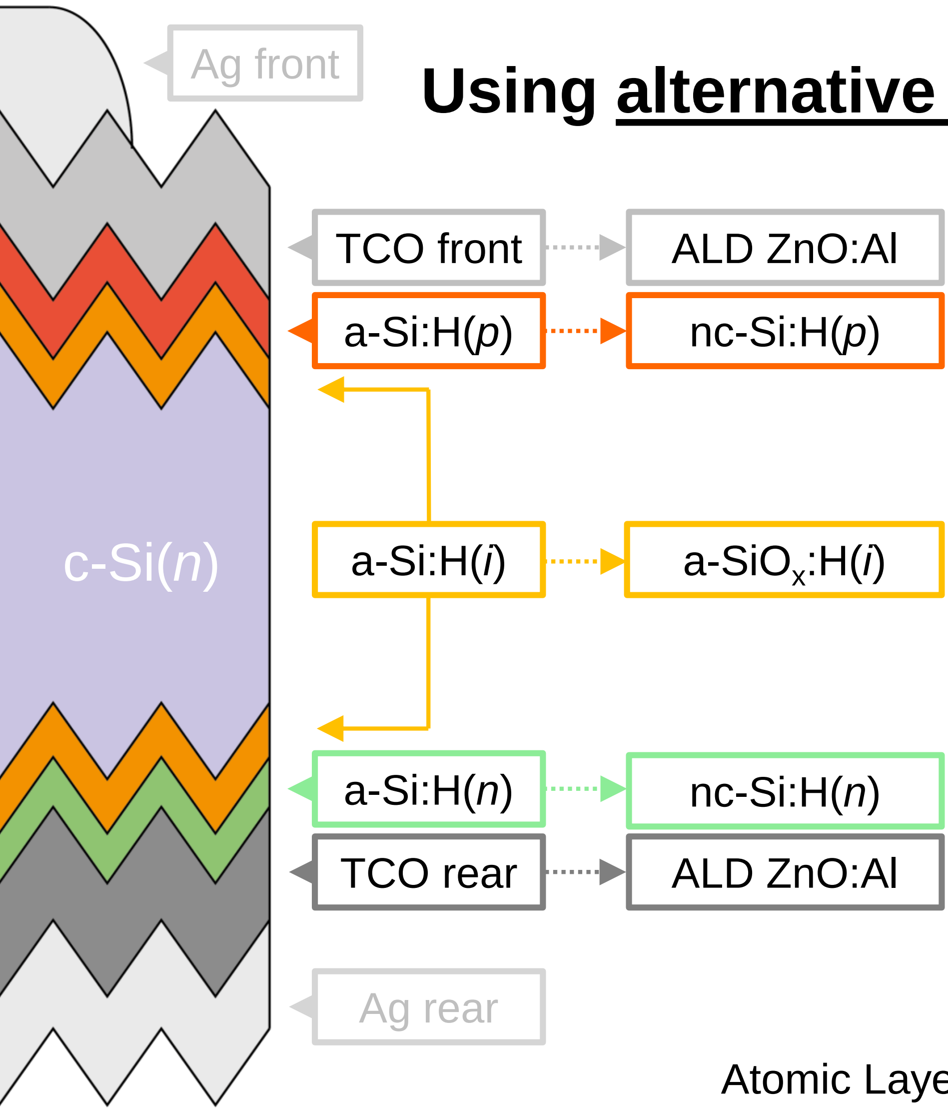


The Transparent Conductive Oxide (TCO) can have an influence on the a-Si:H layers (Schottky barriers) and the a-Si:H/c-Si interface (increased recombination).

Lowers the maximal attainable voltage, *i.e.* the open-circuit voltage (V_{oc}) and **limits** the voltage at the maximum power point (fill factor, *FF*)

Motivation

Using <u>alternative materials</u> to mitigate losses



<u>Goals</u>

- Development of PECVD processes for a-SiO_x:H and nc-Si:H
- Understand their impact (*material properties and processing*) on device performance (J_{sc}, V_{oc}, FF)
- Reduction of optical and electrical losses

Atomic Layer Deposition (ALD)

Outline

Temperature coefficients
Temperature impact
on lifetime and cell performance

Wide-bandgap materials
$a\text{-}SiO_x{:}H$ for passivation
band offsets and transport barriers

Alternative transparent electrodes
atomic-layer-deposited ZnO:Al
as protective layer vs. sputter-damage

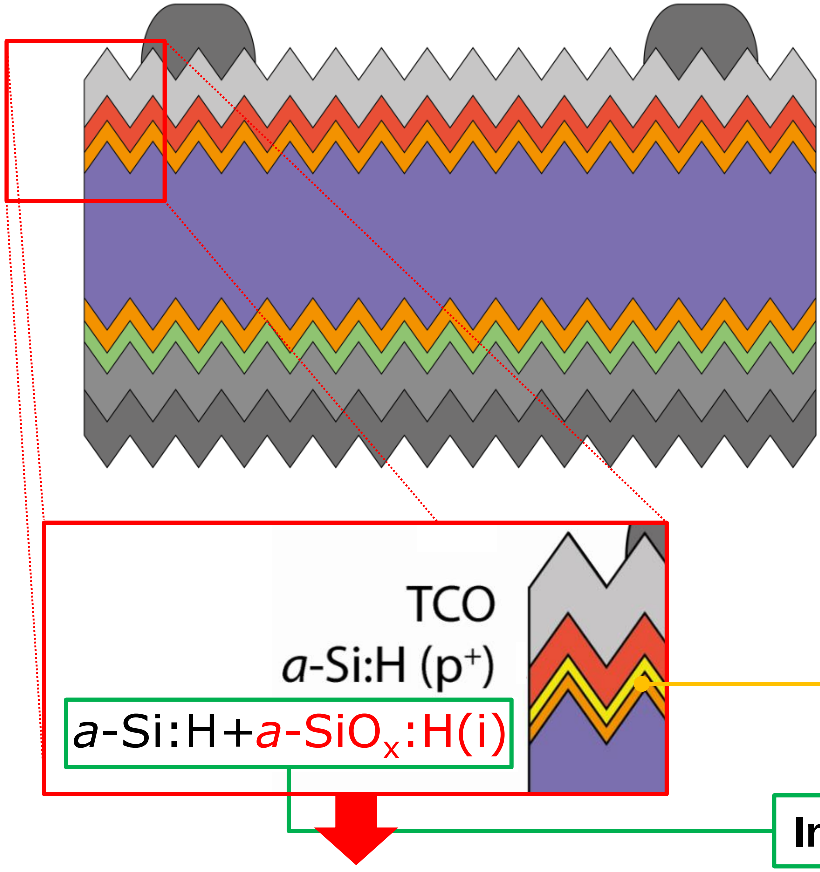
Organic overlayers
spin-coated PVK for work function engineering

Nanocrystalline layers
Deposition strategies &
device performance

Wide-bandgap materials:

a-SiO_x:H – optical gain versus transport

Motivation



Variation of...
i-layer thickness, $[CO_2]/[SiH_4]$ and device structure.

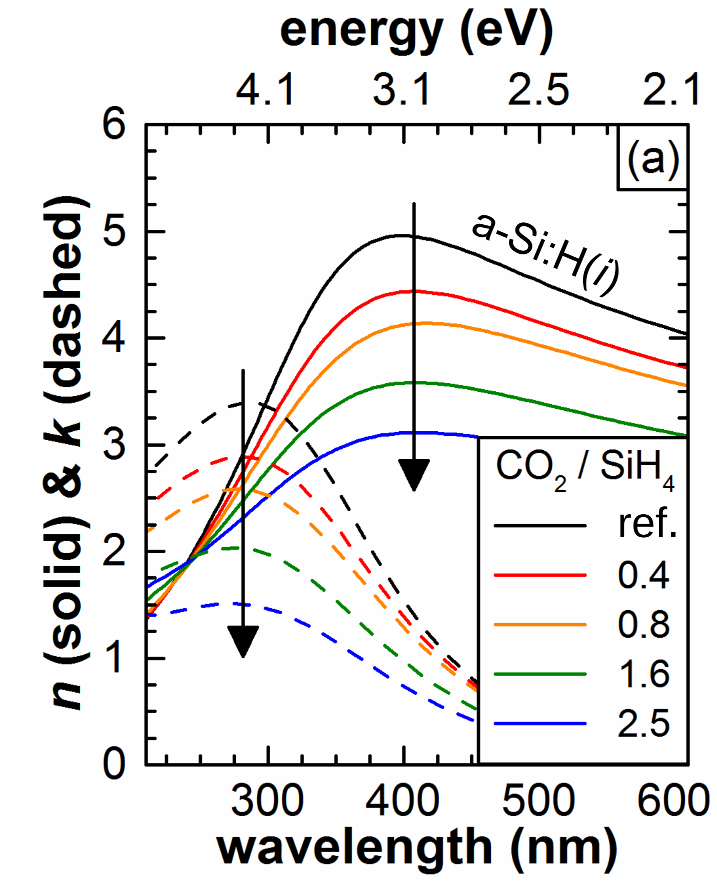
More transparent front side
→ J_{sc} **gain**

In this section: *i*-layer

NOTE: Using a-SiO_x:H only
→ sub-optimal passivation

J. P. Seif et al., JAP, ***115,*** *2014*

a-SiO$_x$:H: *optical properties*



From spectroscopic ellipsometry

Increasing [CO_2]/[SiH_4] ratio leads to a decrease of both:

- **refractive index *n*** and
- **extinction coefficient *k***
- **Bandgap:** + 0.1 eV for [CO_2]/[SiH_4] = 2.5

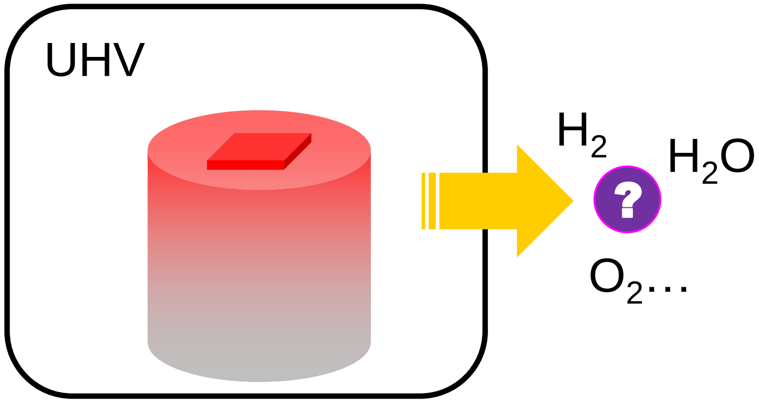
Linked to incorporation of hydrogen* and oxygen

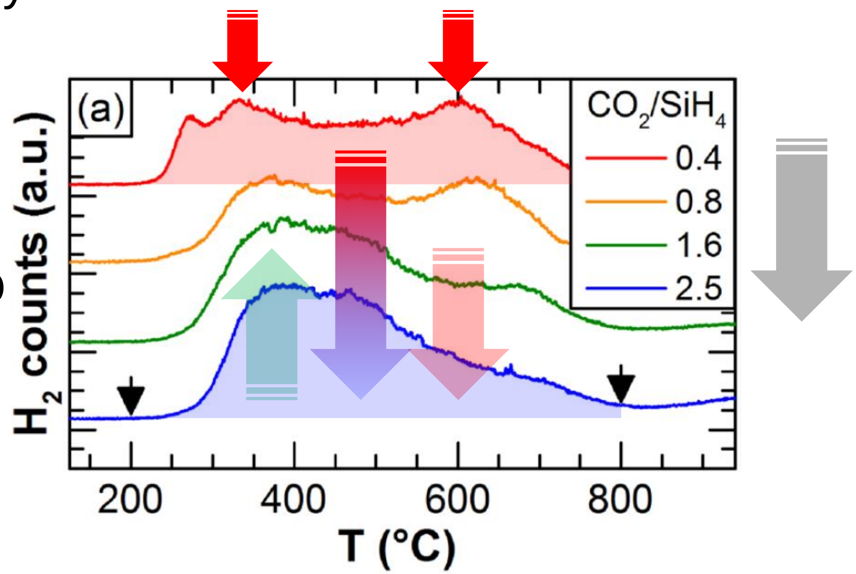
*J. P. Seif et al., JAP, **115,** 2014*

* *T. F. Schulze, L. Korte, F. Ruske, and B. Rech, Physical Review B **83**, 165314 (2011).*

a-SiO$_x$:H: *structural properties*

- Thermal desorption spectroscopy to analyse the layer structure





What we observe:

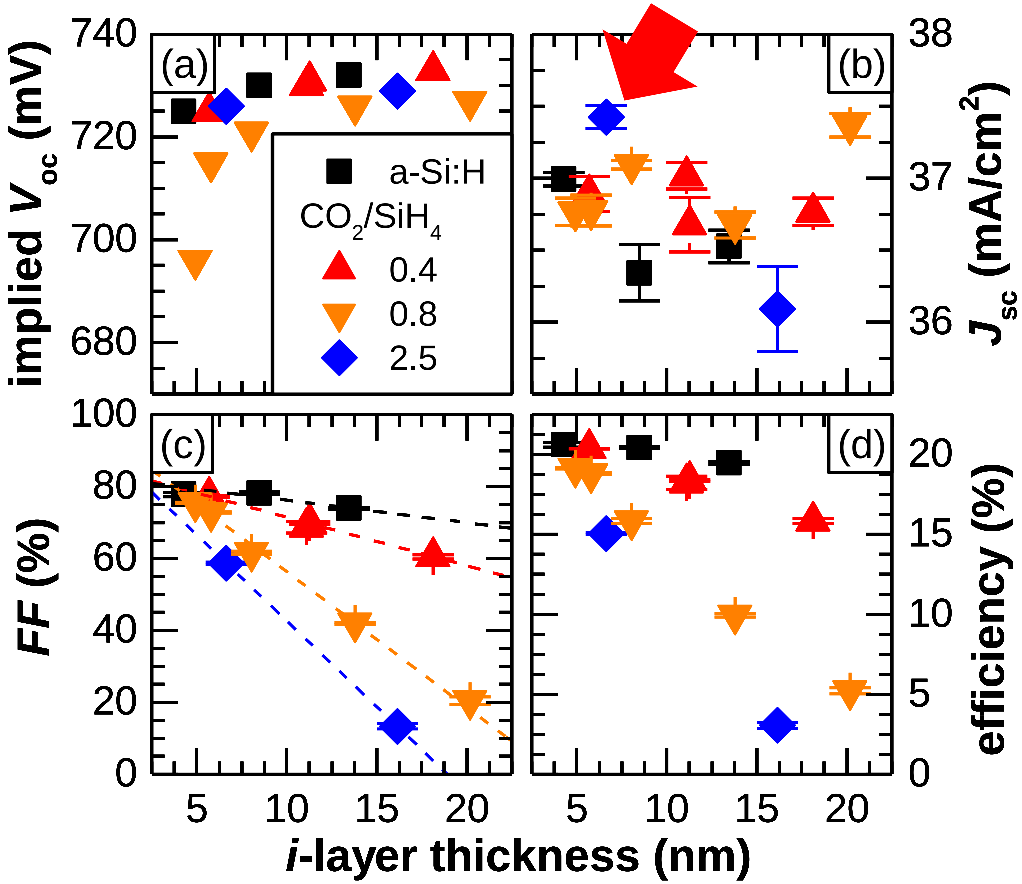
- H$_2$ effusion spectrum varies high-*T* peak decreases, low-*T* peak increases with CO$_2$/SiH$_4$
- The area under the curves increases with CO$_2$/SiH$_4$

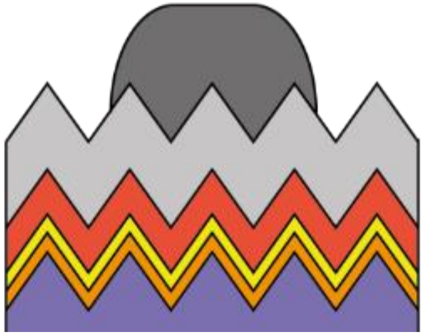
What we learn:

- Structure gets increasingly porous with increasing CO$_2$/SiH$_4$ ratio
- The amount of H$_2$ in the layer increases with CO$_2$/SiH$_4$

a-SiO$_x$:H: *applied to hole contact*

Variation in a-SiO$_x$:H thickness
with various [CO_2]/[SiH_4] ratios





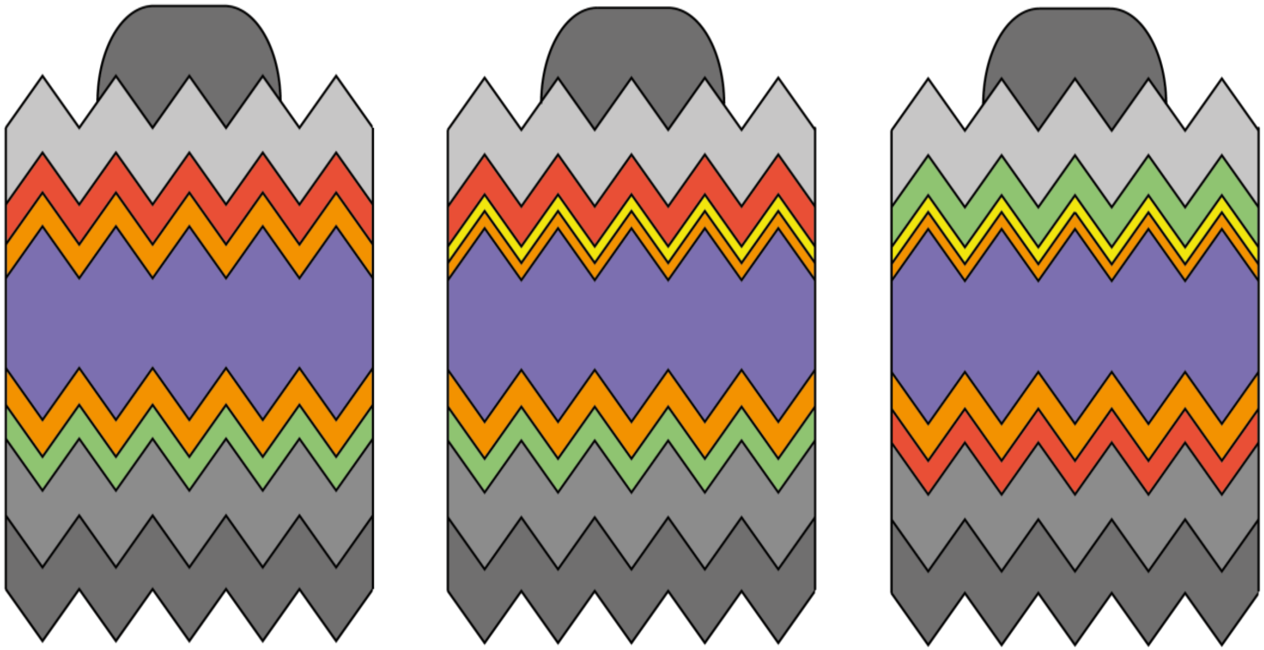
Good passivation:
Implied V_{oc}s between
720–730 mV

Improved current:
by up to **0.4 mA/cm²**
(no clear trend with thickness
due to reduced reflection).*

BUT drop in fill factor:
For a-SiO$_x$:H cells, strongly
influenced by [CO_2]/[SiH_4]
ratio and thickness.

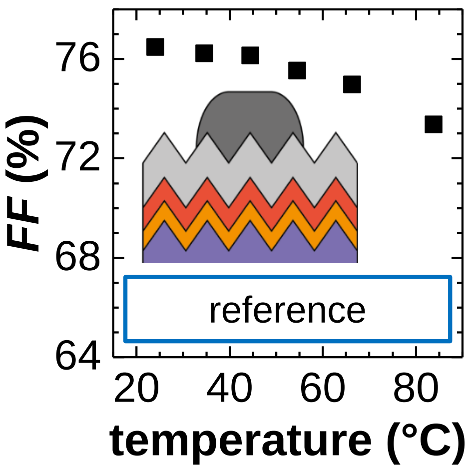
* *Z. C. Holman et al., IEEE JPV, **2(1),** 2012*

a-SiO_x:H permutations

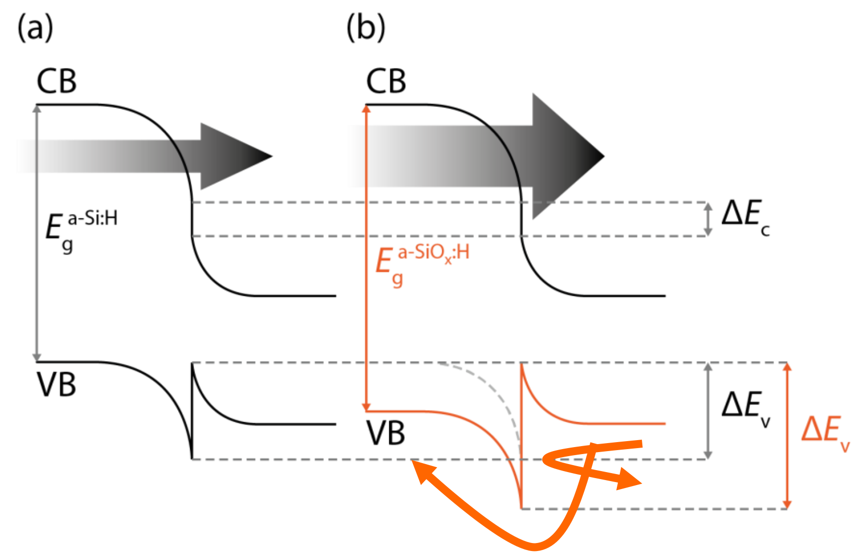


reference | a-SiO_x:H below *p* | a-SiO_x:H below *n*

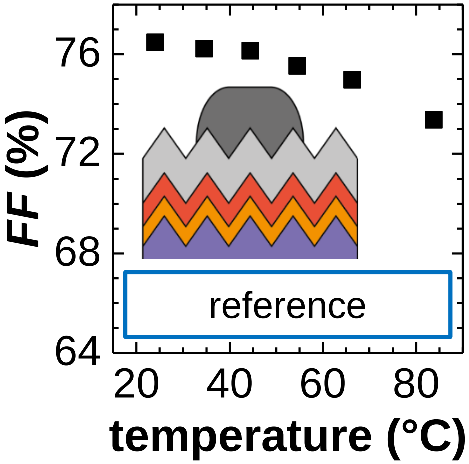
Wide-bandgap a-SiO$_x$:H: *impact on FF*

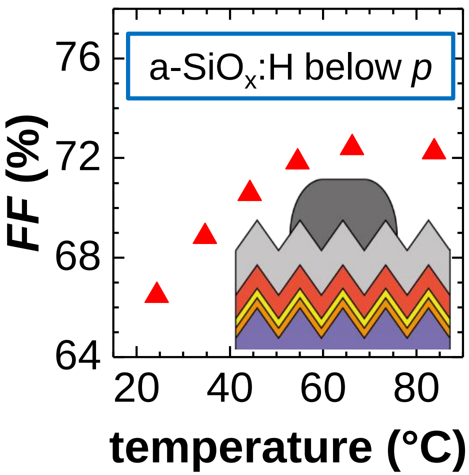


Due to:
Transport problem associated with **increased valence band offset**
(confirmed by simulation)

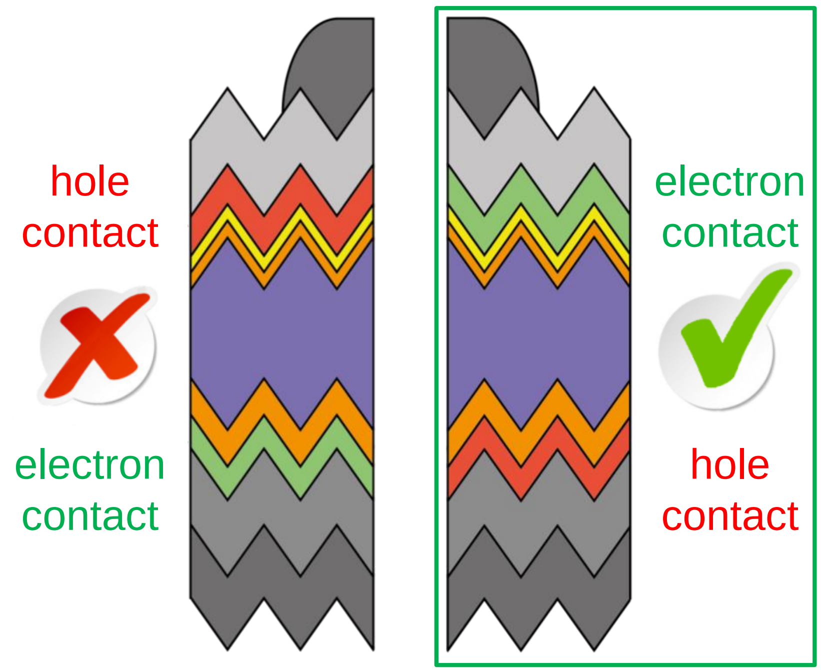


Wide-bandgap a-SiO$_x$:H: *impact on FF*





Confirmation that **holes** are the carriers that **are affected most by the a-SiO$_x$:H(*i*) layer**



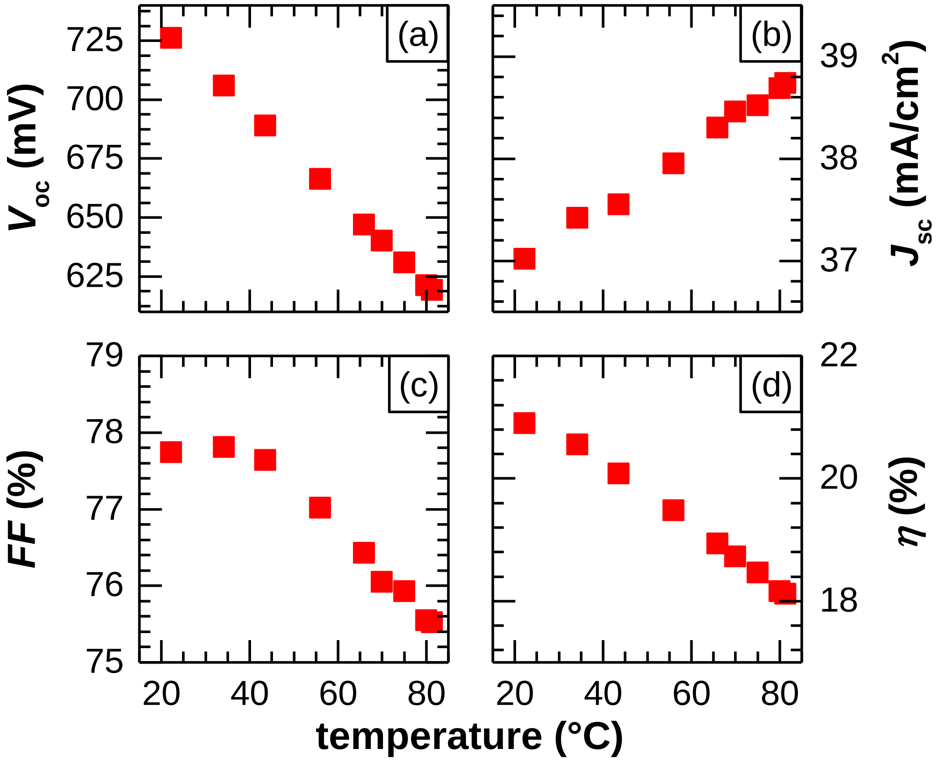
Potential gain in cells with hole collection at the rear

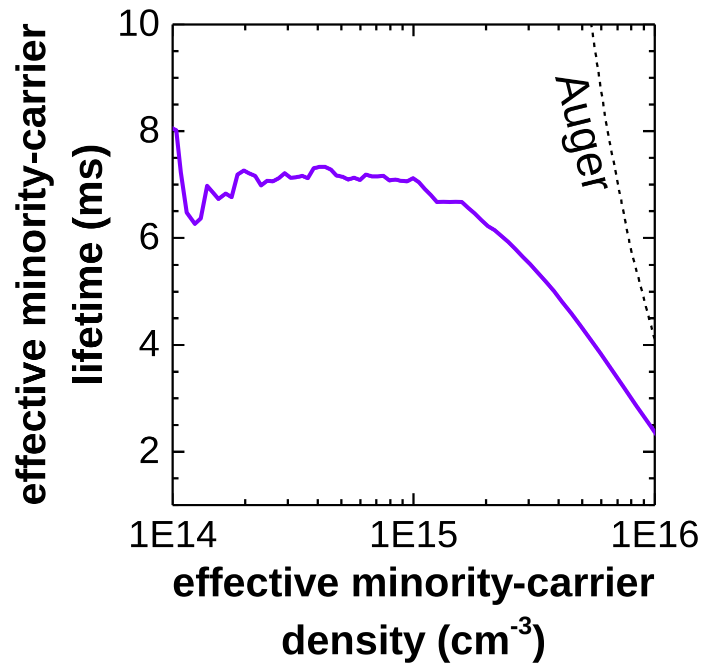
Temperature coefficients:

Ambient-temperature impact on lifetime & performance

Motivation

Typical temperature evolution
of the cell parameters (SHJ solar cell)

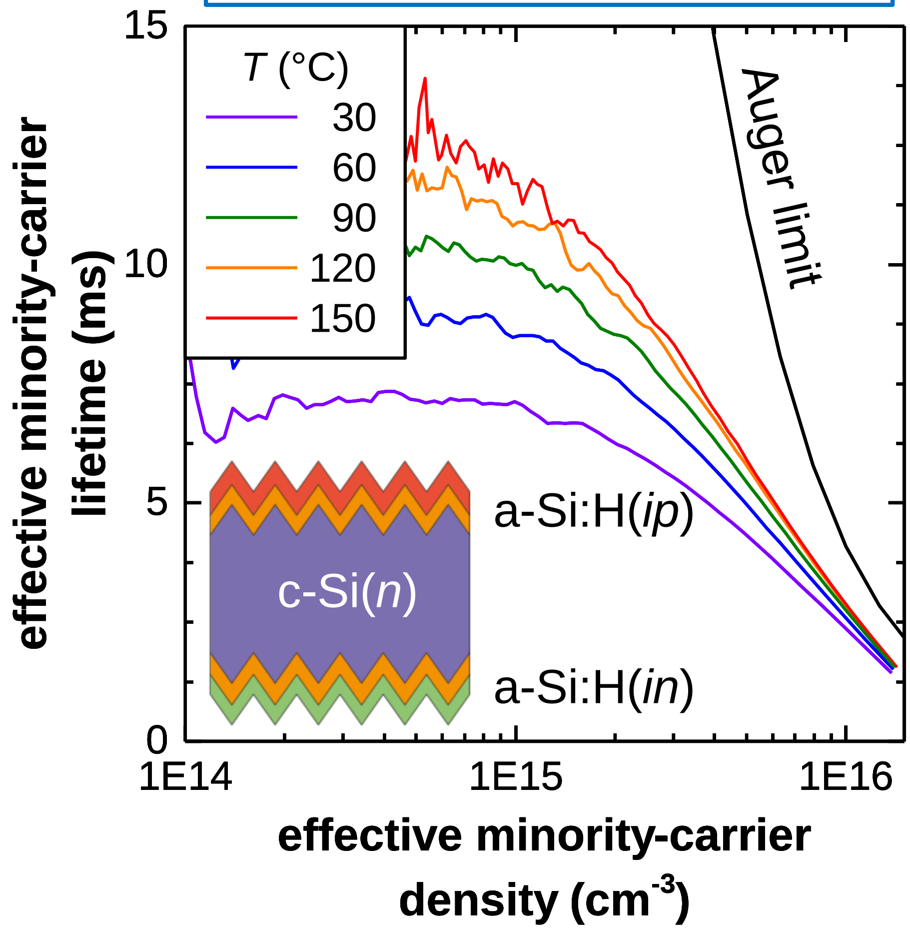




Temperature coefficients (TCs) important for operation in the field: cell *T* up to 90 °C

Lifetime(T) measurements: *passivated wafers*

Typical effective lifetime curve:
Evolution with temperature

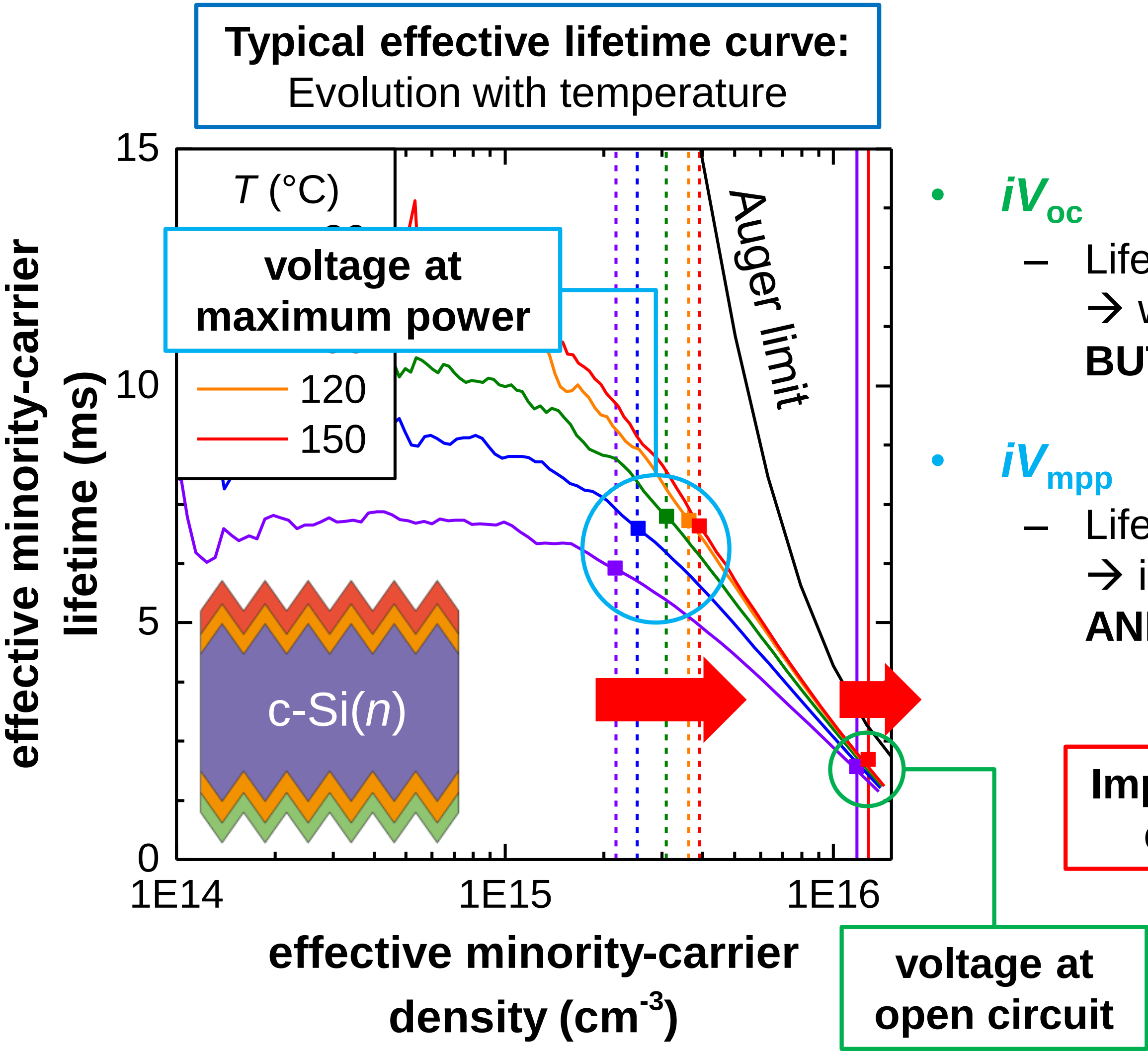


Possibly explained by change in **recombination statistics** / **capture cross-sections** with temperature

D. M. Goldie, American J. Material Science, 2013

cell parameters (J_{sc}, V_{oc}, FF)

Lifetime(*T*) measurements: *passivated wafers*

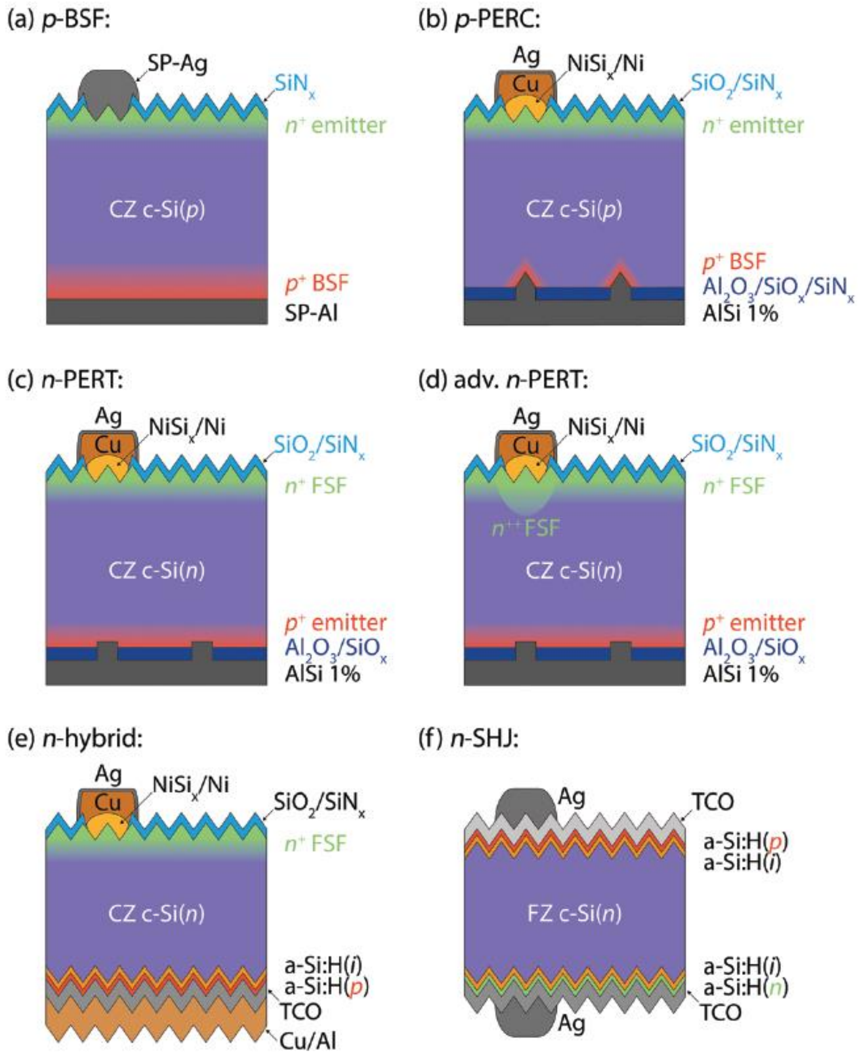


- ***iV*$_{oc}$**
  - Lifetime Auger-limited
    → weak increase of the lifetime with *T*
    BUT shift to higher injection / voltage
- ***iV*$_{mpp}$**
  - Lifetime **NOT** Auger-limited yet
    → increasing the lifetime with *T*
    AND shift to higher injection / voltage

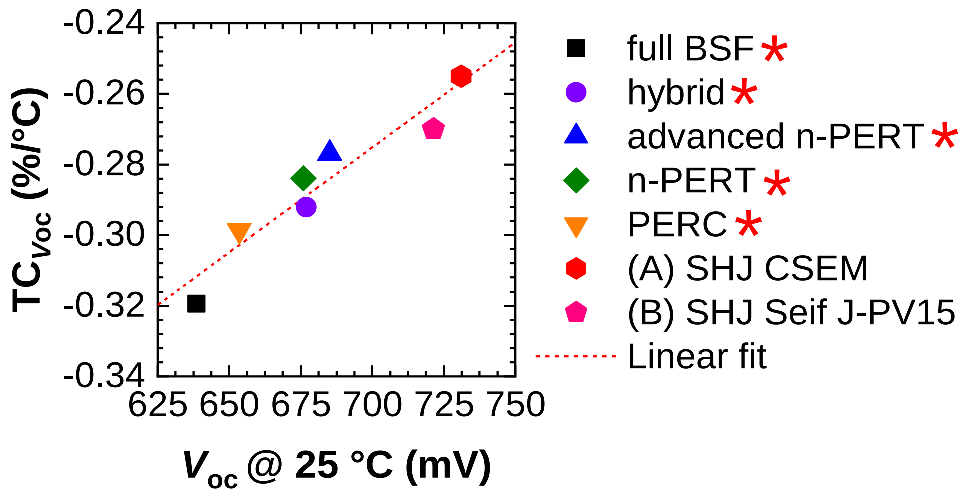
Impact on temperature coefficients of the iV_{mpp} (*i.e. iFF*) and iV_{oc}.

J. P. Seif, et al, IEEE J.PV., 2015.

Temperature coefficients (TC): *impact of V_{oc}*



*Samples from: imec

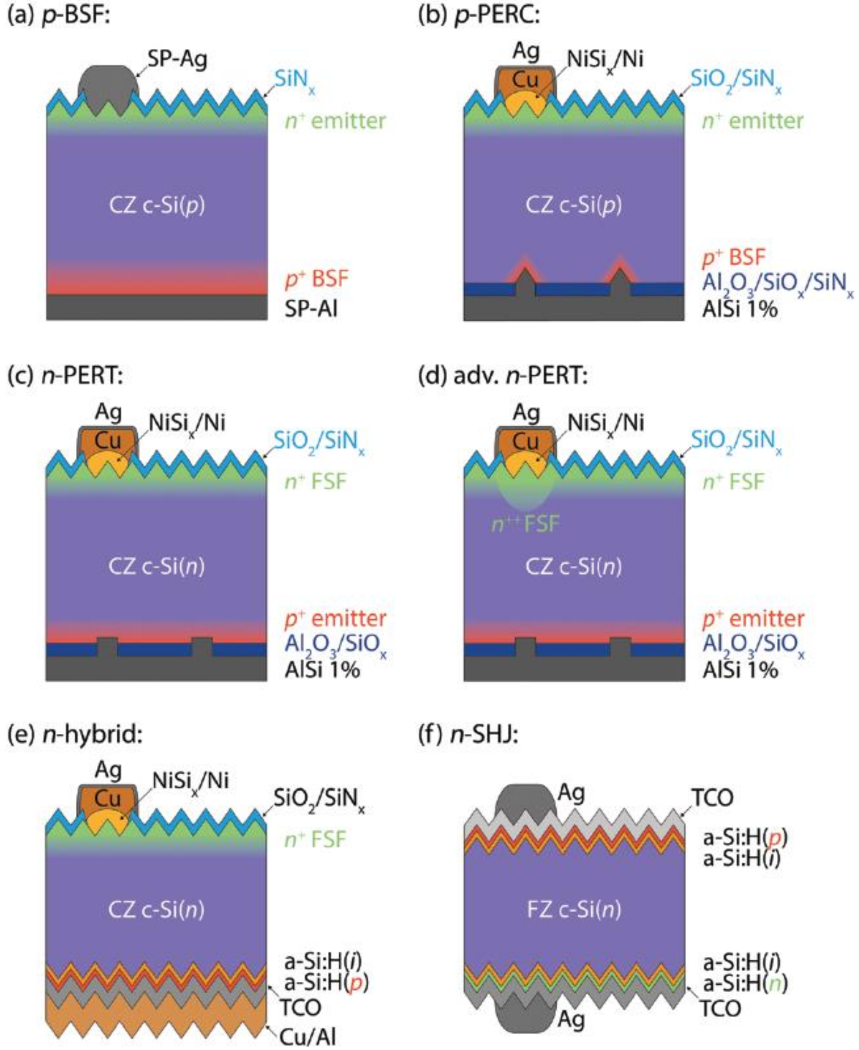


$$\frac{\partial V_{\mathrm{oc}}}{\partial T} = -\frac{(V_{\mathrm{g0}} - V_{\mathrm{oc}} + \gamma kT/q)}{T}$$

M. A. Green, et al., J. Appl. Phys., vol. 58, 1985.

High-quality passivation (high V_{oc})
crucial for good TCs and *FF*!

Temperature coefficients (TC): *Cells vs. Modules*



Study of temperature coefficients (TC) of **different state-of-the-art cells** and **comparison to modules**

- TC_{Voc} and TC_{Jsc} are similar BUT TC_{Vmpp} is worse for modules

Additional series resistance induced by the interconnections between the cells in a module.

High V_{oc} and low-resistive interconnections are essential for hot and sunny climates.

*J. Haschke, et al., Energy & Environmental Science, **10**, 1196-1206, 2017*

Alternative transparent electrodes:

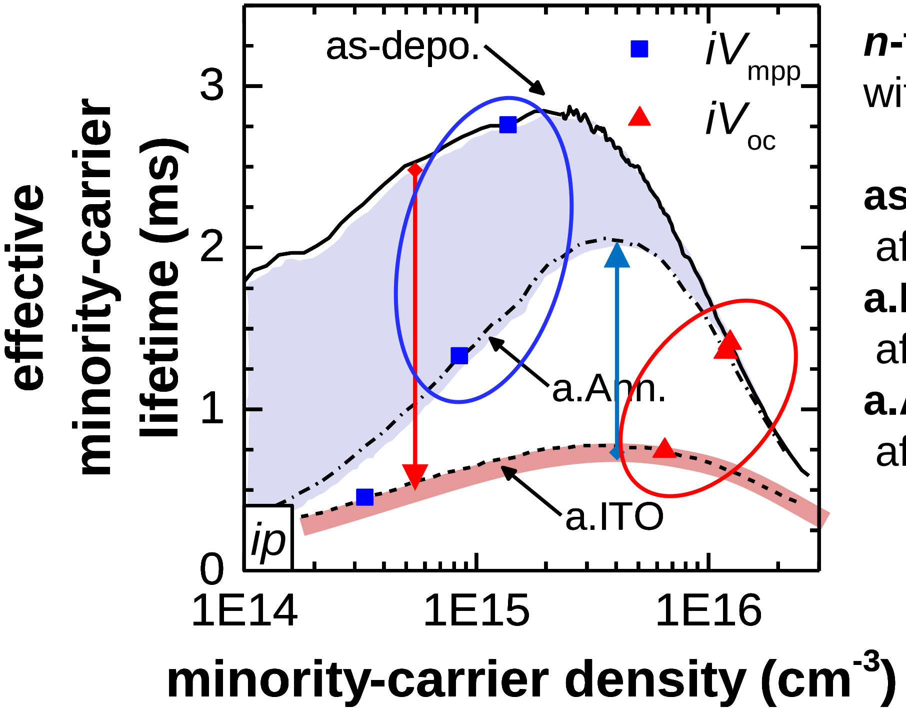
Atomic-layer-deposited ZnO:Al & Organic overlayers

Motivation

Thinner a-Si:H layers at the front → **Higher current output** (increased J_{sc})

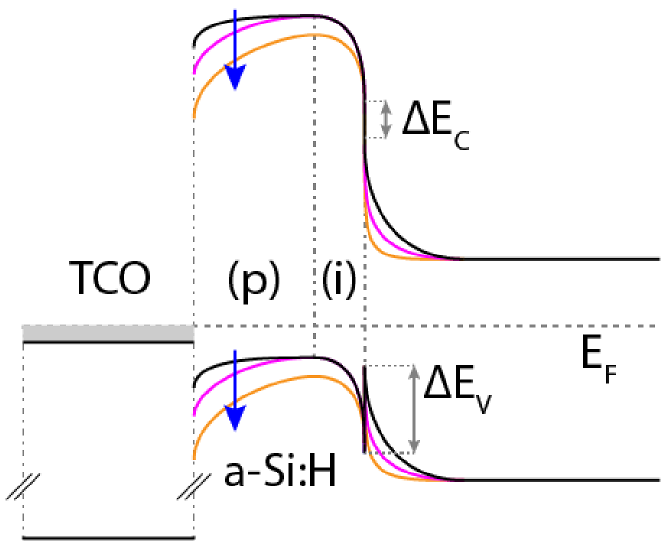
(Permanent) damage associated with sputtering possible

Degradation at lower injection: non-optimal TCO work function / field effect



***n*-type wafer** with *ip/ip*

as-depo.: after PECVD
a.ITO: after sputtering
a.Ann.: after annealing



Solution: Soft deposition technique or protective layer

Solution: TCO with an optimized work function

B. Demaurex, et al. APL 101, 171604, 2012.

M. Bivour, et al. Energy Procedia, 2013. // W. Favre, et al. APL, 2013. // R. Rößler, et al., JAP 2013. // Seif & Demaurex et al. IEEE J-PV, 2015.

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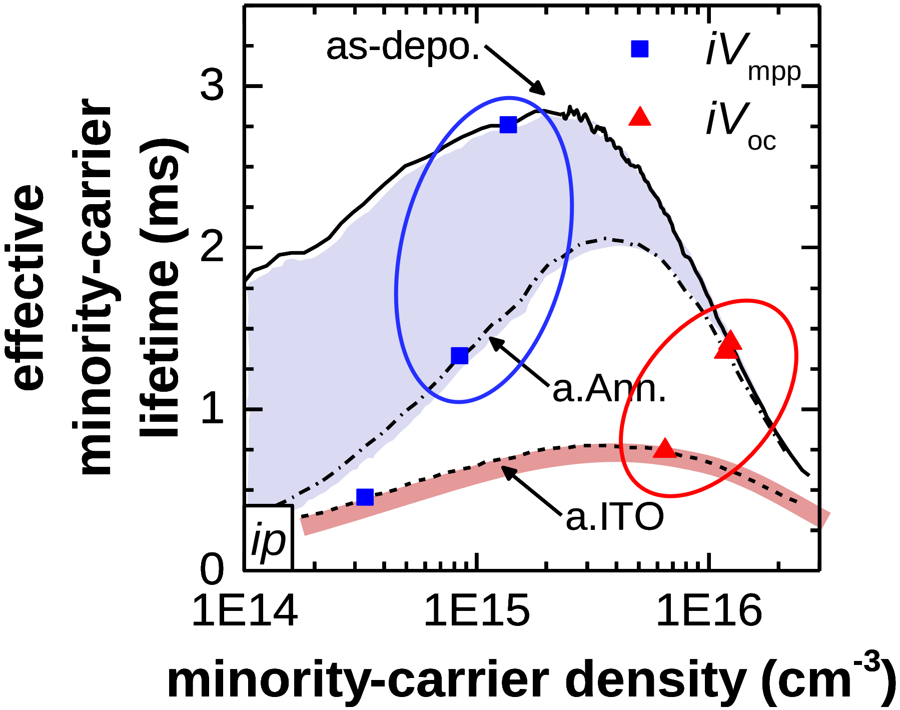
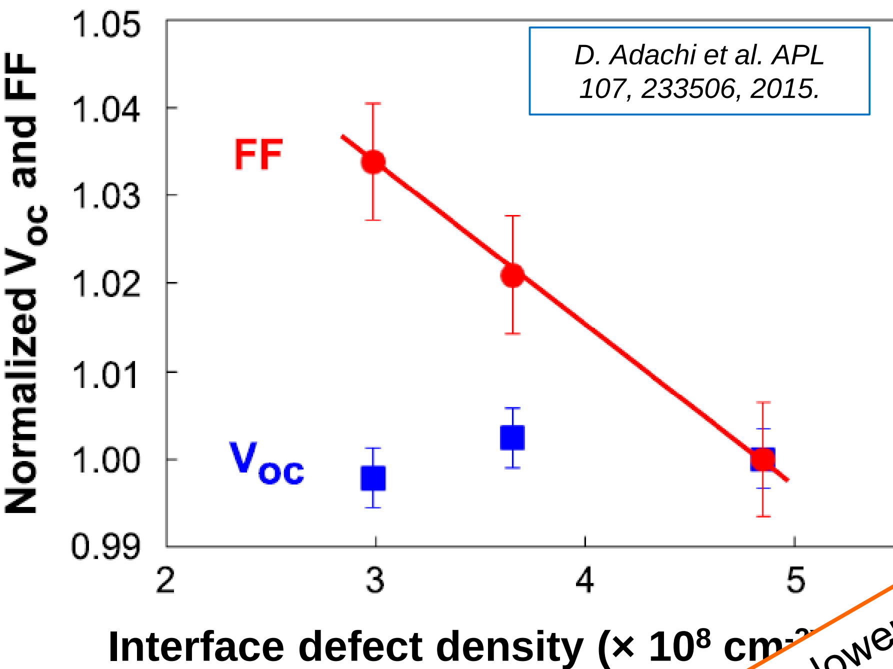




Solution: Soft deposition technique or protective layer

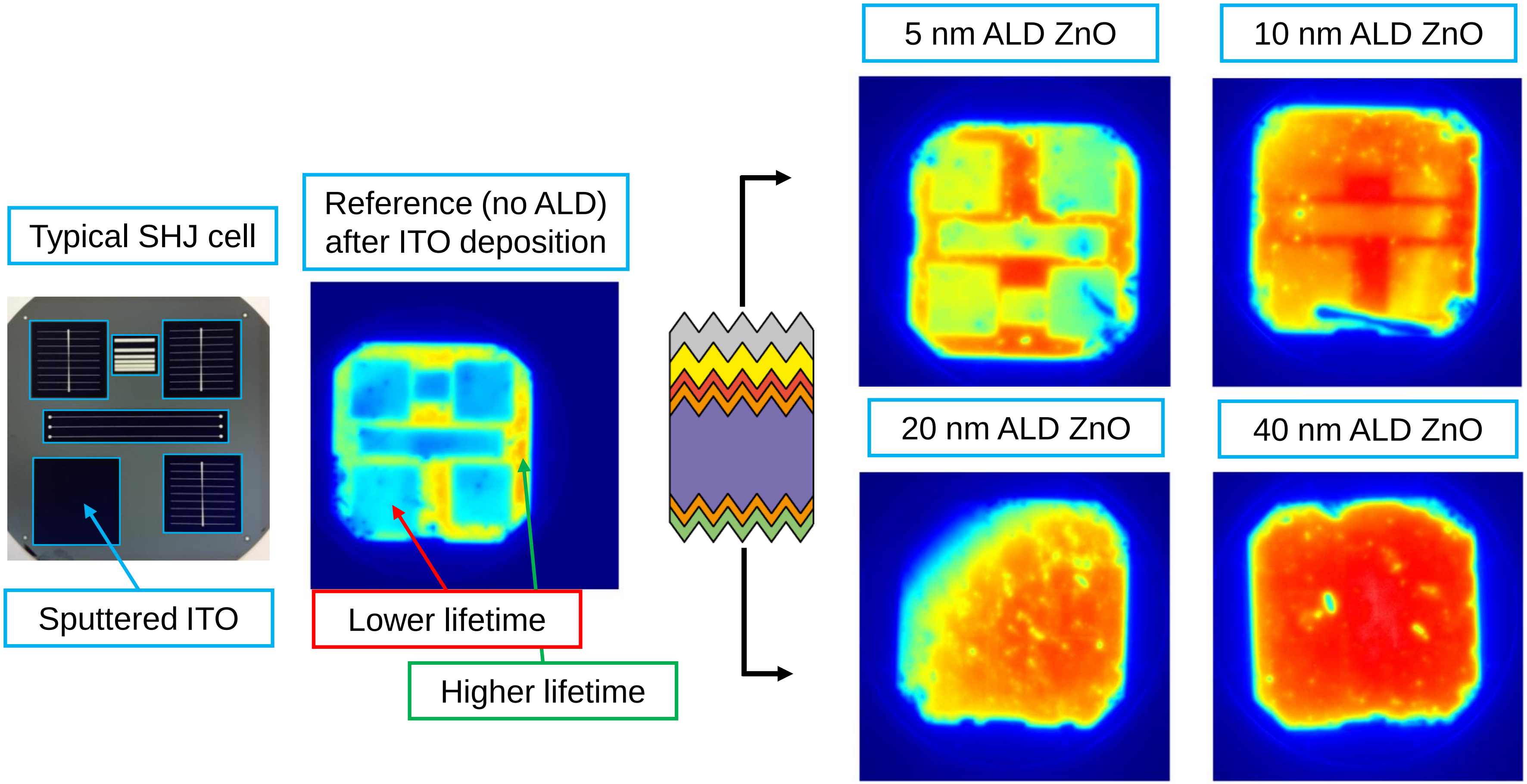
Solution: TCO with an optimized work function

+ lower defect density!

B. Demaurex, et al. APL 101, 171604, 2012.

M. Bivour, et al. Energy Procedia, 2013. // W. Favre, et al. APL, 2013. // R. Rößler, et al., JAP 2013. // Seif & Demaurex et al. IEEE J-PV, 2015.

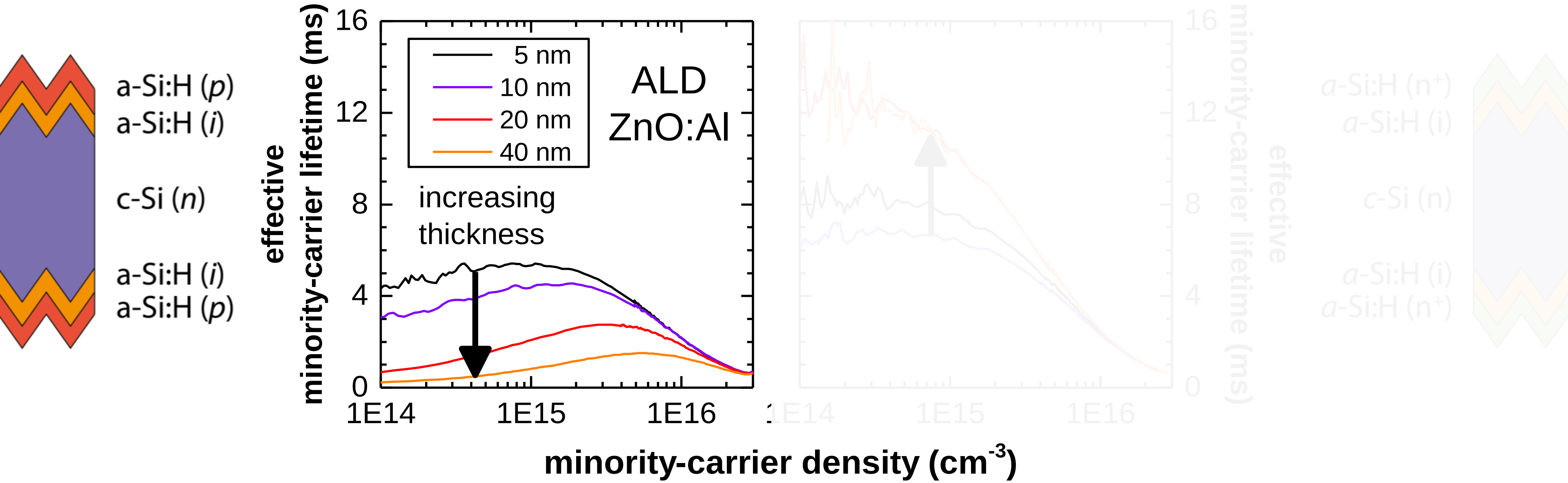
ALD ZnO:Al layer vs. sputter-damage



Effective protection against sputter damage for ZnO layers >10 nm

*Seif & Demaurex et al., IEEE J-PV, **4 (6),** 1387-1396, 2014.*

Lifetime variation: *a workfunction effect*



Negative effect → lower *iFF*

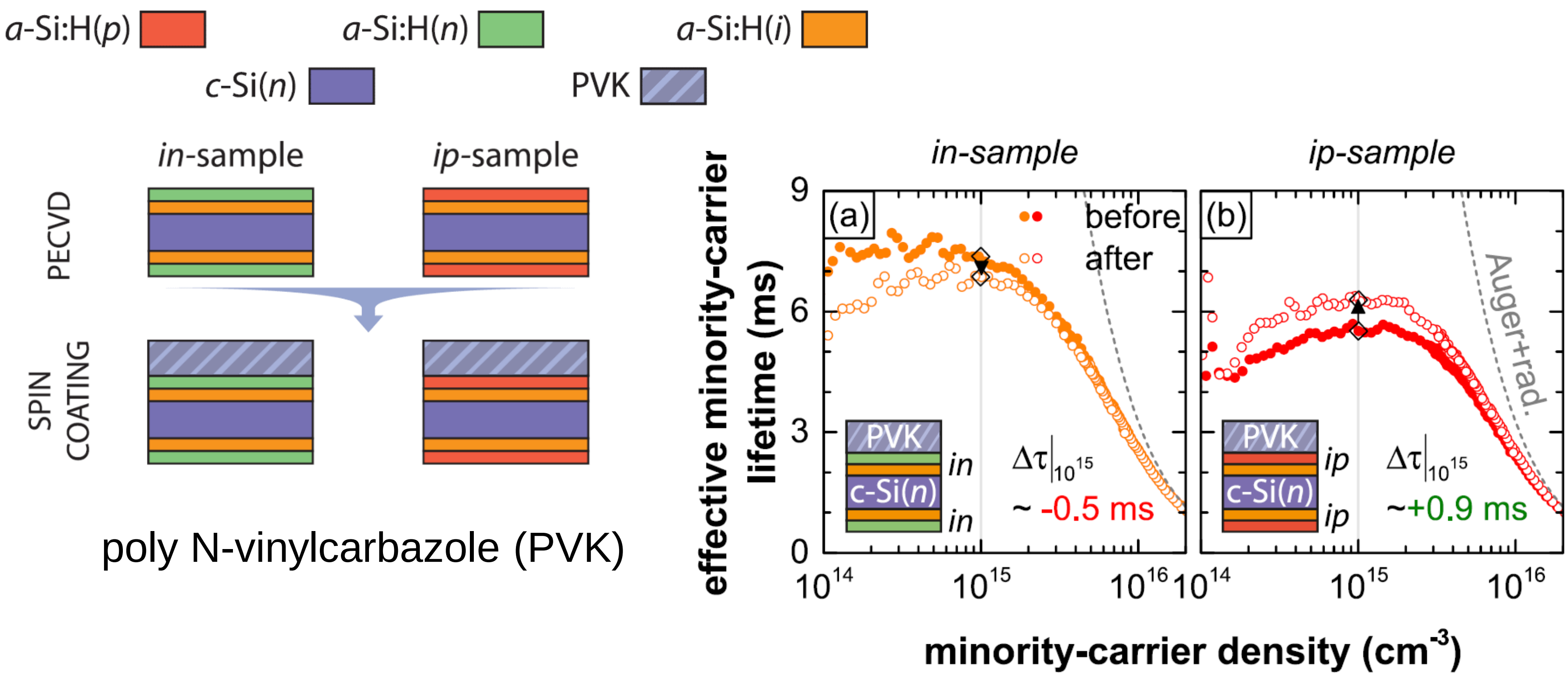
Positive effect → higher *iFF*

Solutions: optimizing ZnO, applying different TCO or organic semiconductors.

Potential application on the electron-collecting side of the device

Work function engineering crucial for high *FF* values.

Alternative materials: *Organic overlayers*



poly N-vinylcarbazole (PVK)

Inverse effect on *in*/*in* (**NEGATIVE**) and *ip*/*ip* (**POSITIVE**) passivated samples.

Work function engineering: Tunable effect with variation of the PVK doping.

Nanocrystalline layers

For silicon heterojunction solar cells

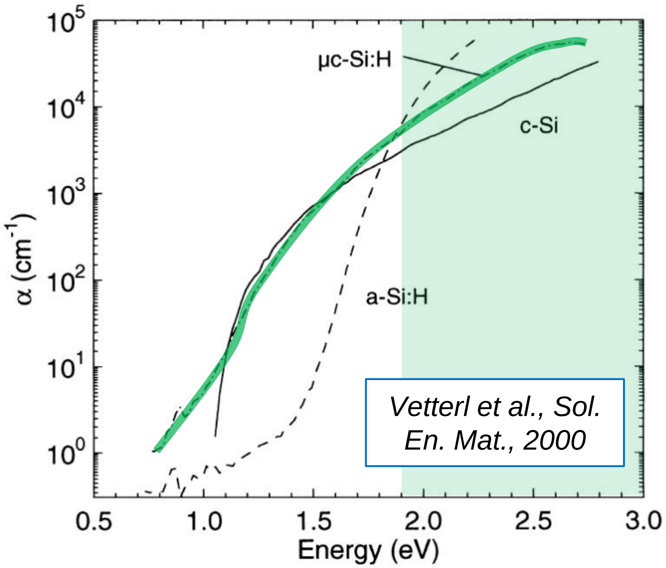
Motivation

Benefits of nanocrystalline materials

- **Optically:** *indirect bandgap of c-Si*
  - better response at short wavelengths
- **Electrically:** *higher doping efficiency and improved transport properties*
  - suppression of Schottky barriers
    → improved contact resistivity

Requirements for PECVD nc-Si layers

1. **Fast nucleation** (thicknesses ~10–20 nm)
2. **Sufficiently high crystallinity**
3. **'*Soft*' deposition for pristine passivation**



Vetterl et al., Sol. En. Mat., 2000

Ghahfarokhi et al., APL, 2014 // Watahiki et al., APExpr., 2015.

Strategies for nanocrystalline layers

method	layer crystallinity/ nucleation speed	application in devices
CO_2 plasma treatments	✓	✗
a-SiO_x:H buffer layers	✓✓	✗✗
SiF_4 nucleation layers	✓✓	✓
$SiH_4 \rightarrow Si_2H_6$	✓	✓
$H_2 \rightarrow D_2$	✓	✓
Temperature	✓✓	✓
✗ Higher deposition frequency (VHF)	✓✓✓	✓
Low frequency and higher pressure	✓✓	✓✓

Non-standard ✗ (SiF_4 nucleation layers, $SiH_4 \rightarrow Si_2H_6$, $H_2 \rightarrow D_2$)

J. P. Seif et al., IEEE JPV, **6 (5),** 1132-1140, 2016

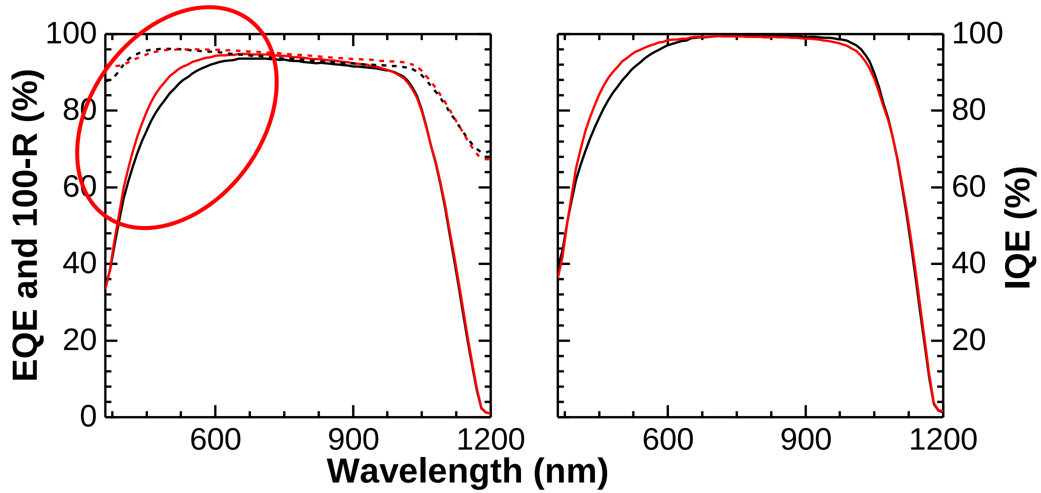
nc-Si:H(*n or p*): *device results*

nc-Si:H(*n*) or nc-Si:H(*p*) layers implemented into SHJ devices

[reference values]

Deposition regime	nc-Si:H(X)	position	V_{oc} (mV)	J_{sc} (mA/cm²)	*FF* (%)	η (%)
81.36 MHz (2 mbar)	*p*	front	717 [719]	37.7 [36.8]	72.6 [72.7]	19.6 [19.2]
13.56 MHz (SiF_4), **40.68 MHz (> 2 mbar)**	i_{SiF4} (nucl.) *p*	front	718 [718]	36.0 [37.1]	78.4 [76.7]	20.3 [20.4]
13.56 MHz (> 2 mbar)	*p* *n*	rear front	720 719	36.5 37.0	79.2 78.7	20.8 20.9

All cells
Textured, 1-5 Ωcm, nominal 240 µm, *n*-type FZ, 2 × 2 cm², with screen-printed Ag front contacts and full Ag contact at the rear.



J. P. Seif et al., IEEE JPV, **6 (5),** 1132-1140, 2016

nc-Si:H(*n or p*): *device results*

Gain in J_{sc}
up to ~ 1 mA/cm^2

Gain in *FF*
up to 2% (abs.)

Stable V_{oc} values
of ~ 720 mV

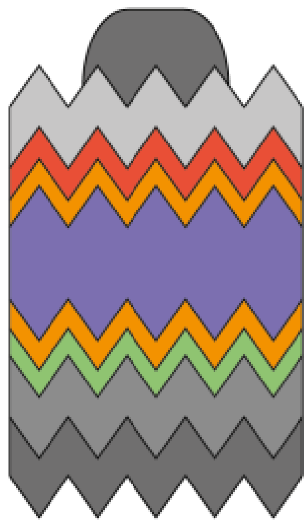
Conversion efficiencies
up to 20.9%

Requirements

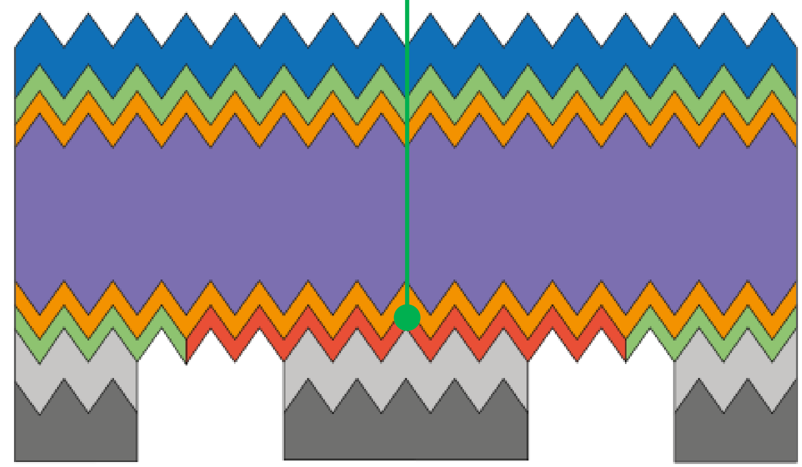
1. **Fast nucleation**
2. **High crystallinity**
3. **‘*Soft*’ deposition**

Achieved with **simple, industry-compatible process** using **standard gases**.

Readily applicable without additional costs.

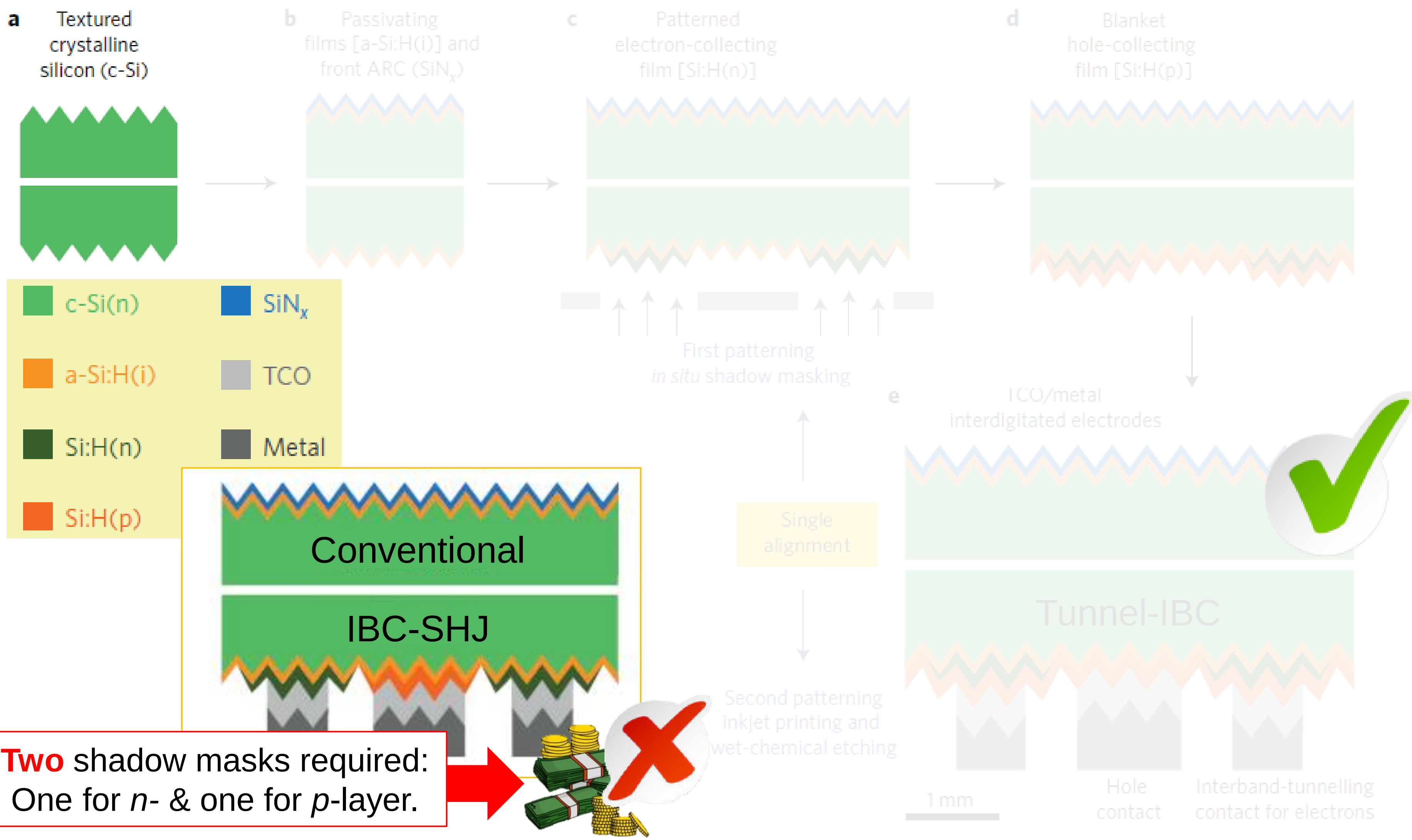


Standard 2-side-contacted SHJ (full area)



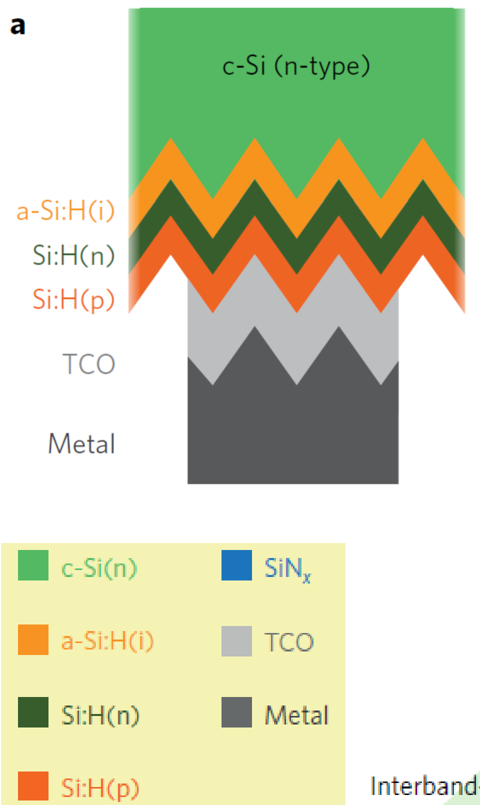
Rear-contacted SHJ (reduced contacting area)

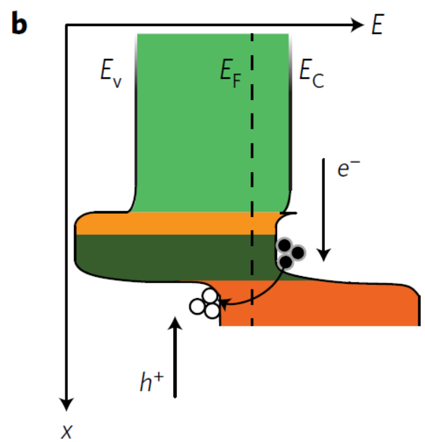
Rear-contacted cells: *nc-Si:H(n and p) inside*



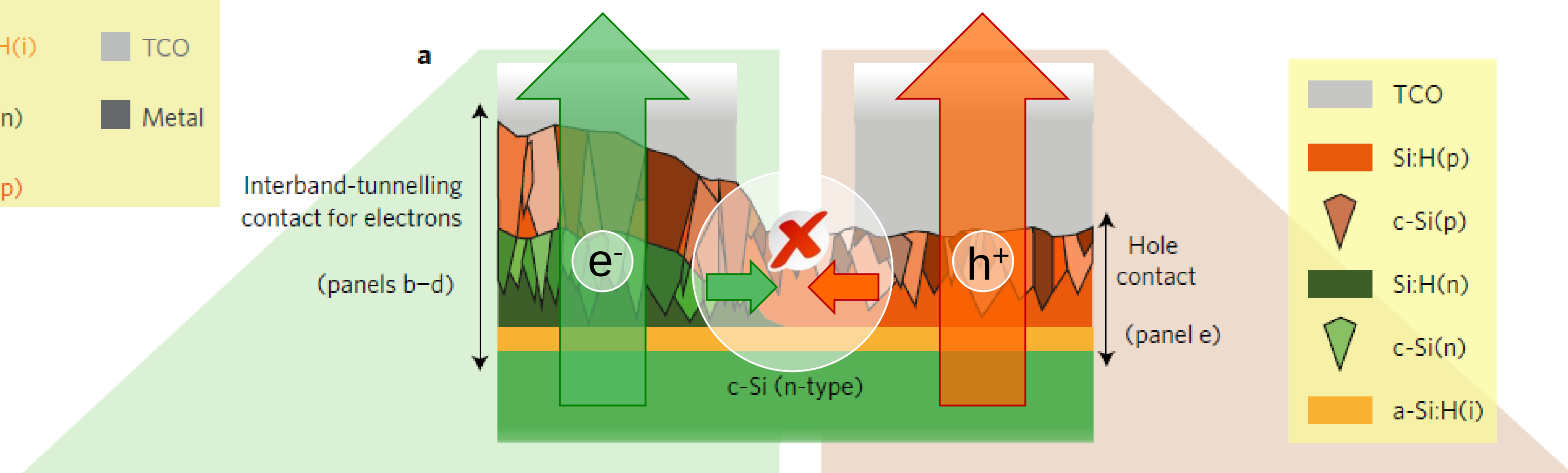
Two shadow masks required:
One for *n*- & one for *p*-layer.

Rear-contacted cells: *nc-Si:H(n and p) inside*

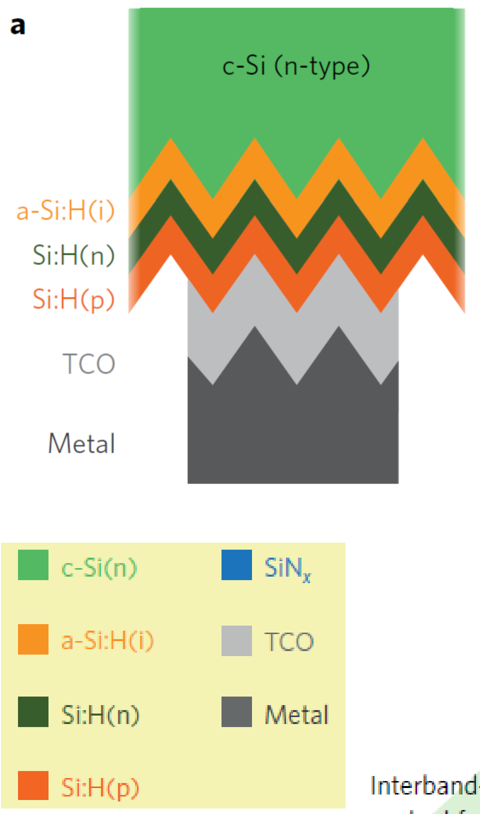


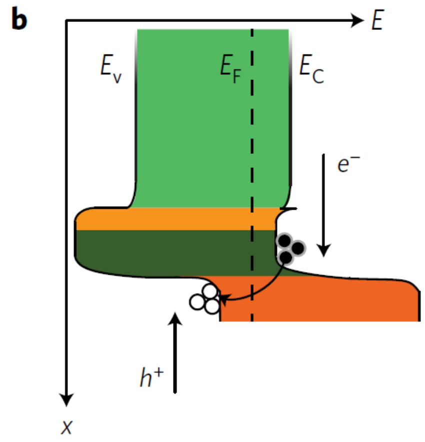


- Efficient interband-tunneling contact for electrons.
- Minimized resistive losses (nc-Si) and optimal carrier selectivity (e^-)
- Low lateral conductance to prevent shunts, thanks to **grain boundaries** and **incubation layer**



Rear-contacted cells: *nc-Si:H(n and p) inside*





Certified efficiency

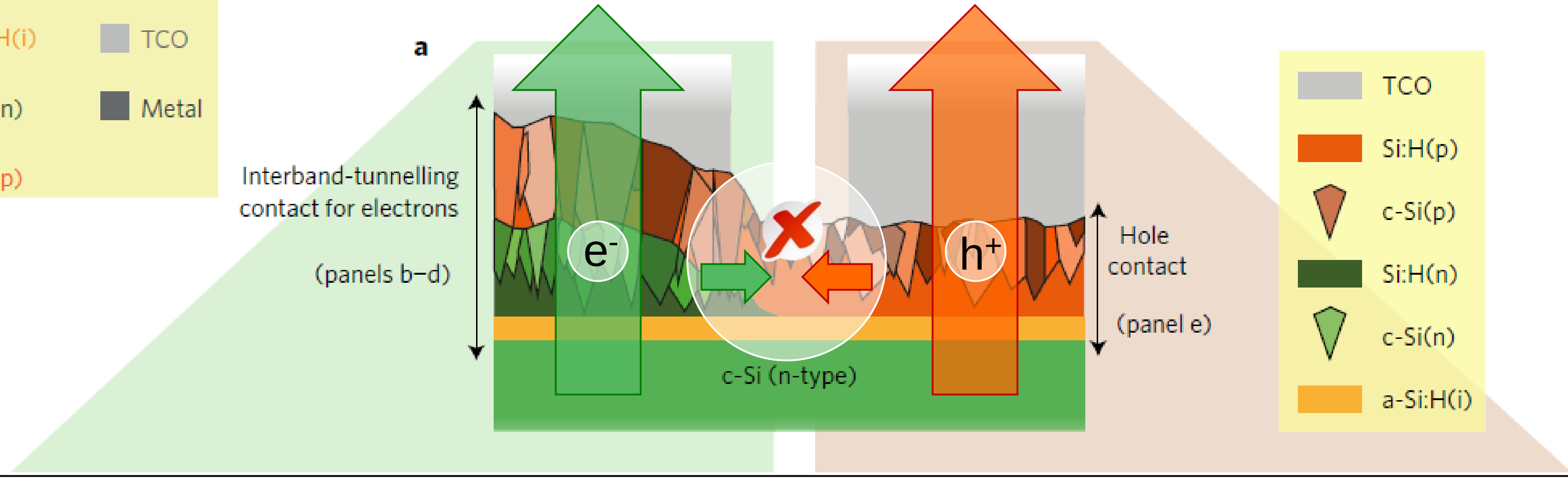
Area = 9.00 cm^2 (da)

J_{sc} = 40.65 mA.cm^{-2}

V_{oc} = 728.49 mV

FF = 76.36%

***η* = 22.61%**



A. Tomasi et al., *Nature Energy*, **2,** 17062, 2017

Conclusions

Ambient-temperature impact

- increasing lifetime with temperature
- TC_{Voc} depends on V_{oc}, device structure and materials
- Modules need high V_{oc}s and low-resistive cell interconnections

Alternative transparent electrodes

Atomic-layer-deposited ZnO:Al

- for effective sputter-damage protection and promising electron-collecting layer

→ **potential gain in J_{sc} and *FF***

Wide-bandgap oxides

Electrons may, but **holes should not** be collected through the window-layer

→ **rear hole collection**

→ **gain in J_{sc} w/o losses in *FF***

+ 0.4 mA/cm² shown

Alternative transparent electrodes

Organic overlayers

- work function engineering for improved contacts

→ **potential gain in *FF***

Nanocrystalline layers can help improve both optical and electrical device performance

→ **gain in J_{sc} and *FF***

+1 mA/cm² and +2% shown


SCIENTIA
MANU ET MENTE
UNSW
SYDNEY
Australia's
Global
University

Passivating contacts
with Transition Metal Oxides (TMO) deposited by **PECVD**

Why TMOs?
- Relatively wide band gaps, yet small conduction and valence band offsets
- Promising materials for electron- (e.g. TiO_x) and hole-collection (e.g. WO_x)
- Fixed charges for passivation

State-of-the-art deposition for TMOs
- Atomic Layer Deposition
- Sputtering

Our approach
PECVD

Why PECVD?
- Common in industry
- High throughput
- Wider parameter space (temperature, pressure, gas ratios,...)
- Possibility to use other precursor gases (vary growth mode and material properties)

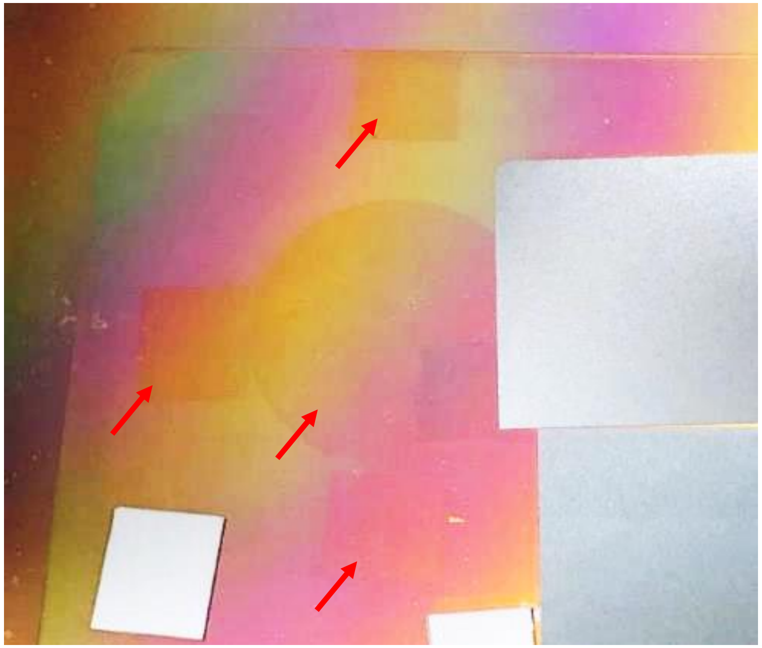
Challenges?
- Uniformity of thin layers
- Thermal stability
- Additional passivation layer needed?

Partners: MEYER BURGER, SUNRISE GLOBAL SOLAR ENERGY

Johannes P. Seif, Anh Le, and Ziv Hameiri

Modifications of the AK-800

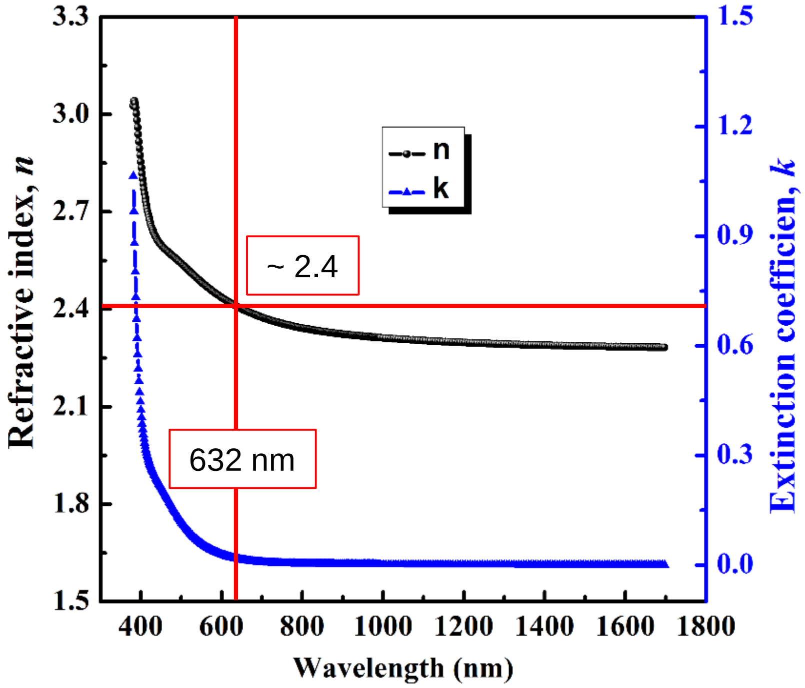
Delivery of new precursors
and first TiO_x depositions



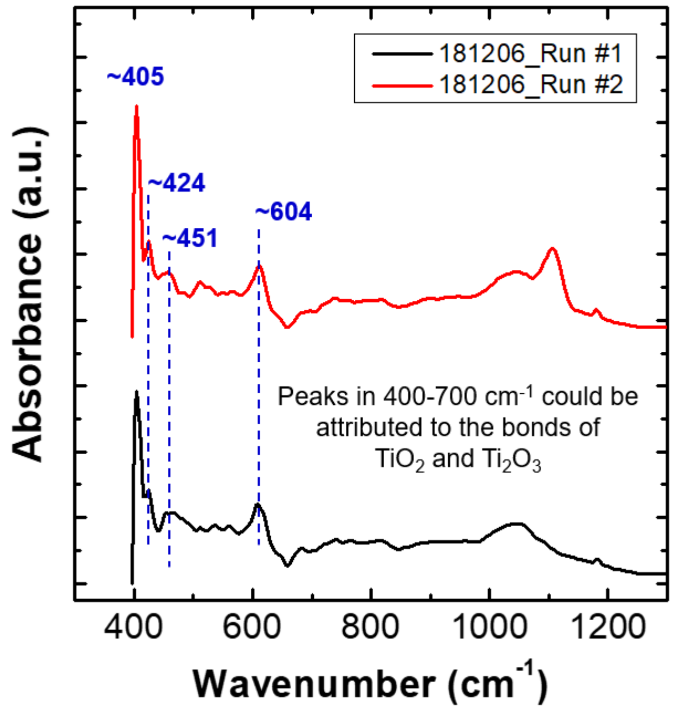
Johannes P. Seif, Anh Le, and Ziv Hameiri

TMO depositions: *First results*

Spectroscopic Ellipsometry



Fourier-Transform Infrared Spectroscopy (FTIR)



Thickness: 7.2 nm
Refractive index: 2.4 @ 632 nm

Other ongoing projects:
With national (incl. UNSW) and international partners

- **Metal work function impact on recombination**
  (ANU and KAUST)
- **Temperature dependence on cell performance**
  (KAUST)
- **Hydrogen migration in c-Si wafers**
  (UNSW, Phill Hamer)
- **Defect parameters of passivated interfaces**
  (UNSW, Michelle Vaqueiro Contreras)
- **Cell perimeter recombination**
  (UNSW)

PV-lab IMT NEUCHATEL

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Thank you for your attention!