Passivating contacts based on thin-film silicon and alloys

Mathieu Boccard

Advancing PV: from passivation to contacts – A passivating contact workshop

Eindhoven, the Netherlands – 31 January 2017

PV-lab
IMT NEUCHATEL

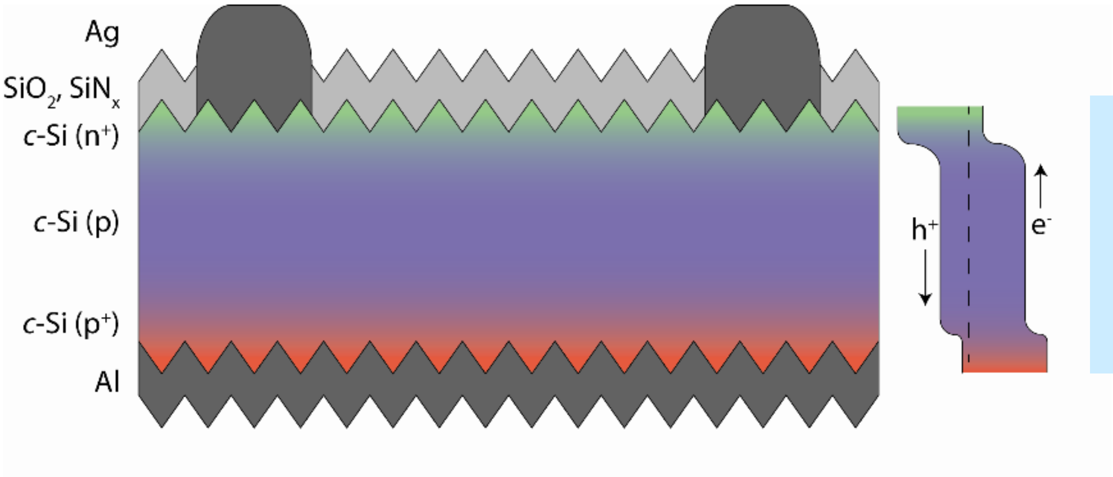
EPFL
ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

Heterojunctions based on a-Si:H

- Quick review of HIT solar cells
- Physics of a-Si:H
- Passivation from i-aSi layers and alloys
- Device properties and limitations
- Specific devices and opportunities

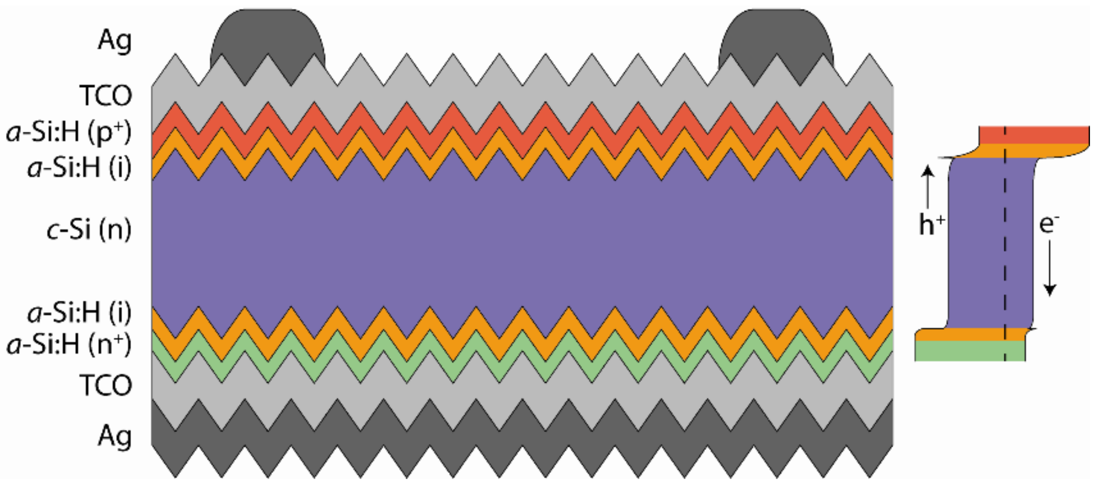
From homo- to heterojunction solar cell

Diffused junction solar cell



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

Heterojunction solar cell



Thin semiconductor layer **between** absorber and metal
=
Passivated contact
→ Higher V_{oc}

Process flow

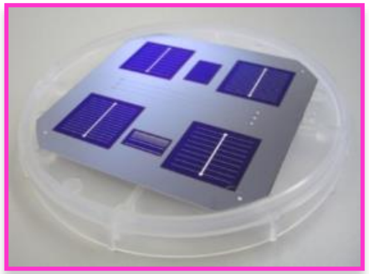
Chemical baths
c-Si surface preparation

PECVD I
Intrinsic film deposition a-Si:H(i)

PECVD II
Doped film deposition a-Si:H(n/p)

PVD
TCO sputtering

Metallization
Screen printing and curing at 200° C



Historically

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)

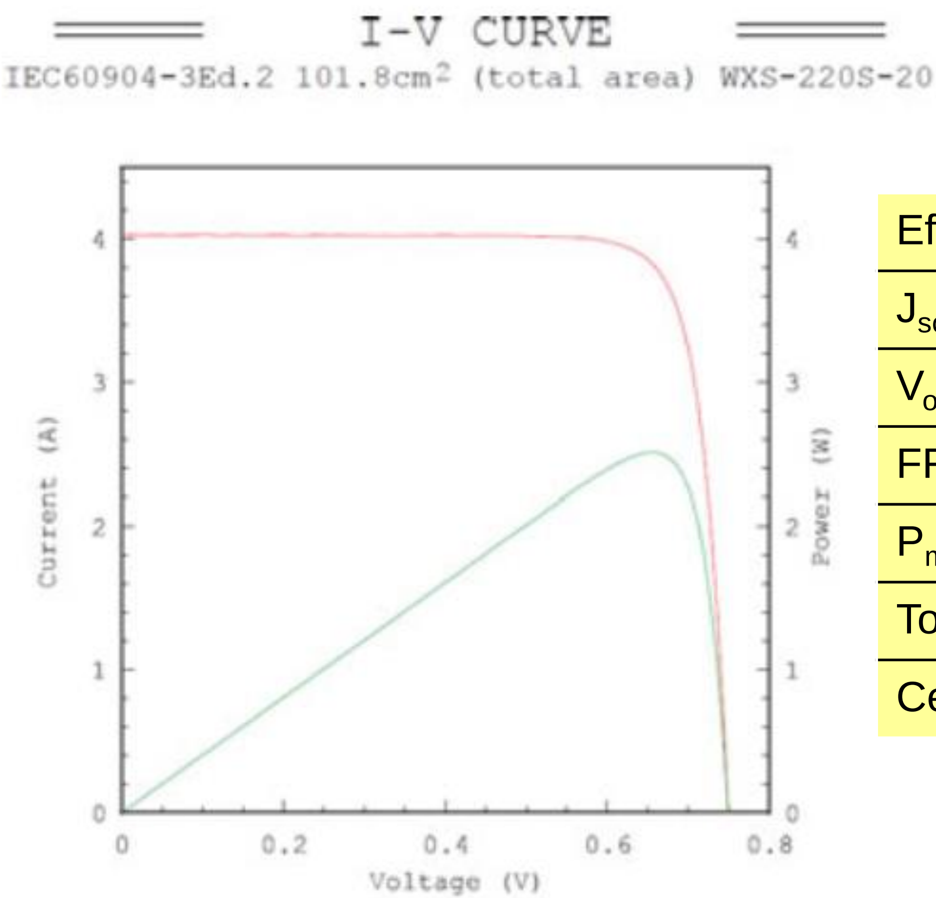
A new type of a-Si/c-Si heterojunction solar cell, called the HIT (Heterojunction with Intrinsic Thin-layer) solar cell, has been developed based on ACJ (Artificially Constructed Junction) technology. A conversion efficiency of more than 18% has been achieved, which is the highest ever value for solar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

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

Invented by Sanyo (now Panasonic), about 25 years ago… → 18% already !

Commerciallized under 'HIT' name shortly after

Heterojunction *c*-Si technology: record



Date : 10 Dec 2012
Data No :
C-11-01
Sample No :
C-11

Efficiency [%]	**24.7**
J_{sc} [mA/cm^2]	39.5
V_{oc} [mV]	**750**
FF [%]	83.2
P_{max} [W]	2.510
Total cell area [cm^2]	101.8
Cell thickness [μm]	**98**

125.83 [mA at100mW/cm2]
Scan Mode
Isc to Voc

M. Taguchi *et al*, IEEE Journal of Photovoltaics 4(1), 2014, 96-99

→ Highest ever measured V_{oc} on any c-Si solar cell!

Becoming a mainstream technology ?

Affiliation	η (%)	V_{oc} (mV)	J_{sc} (mA.cm^{-2})	FF (%)	A (cm^2)	Status	Year
Panasonic,[127] Japan	**24.7**	**750**	**39.5**	**83.2**	**101.8, Cz**	**IC (AIST)**	**2013**
Kaneka,[128] Japan	**23.5**	**737**	**39.97**	**79.77**	**~220, Cz**	**IC (ISE)**	**2012**
CIC,[129] Japan	**22.3**	**733**	**37.28**	**81.8**	**243, Cz**	-	**2013**
CEA-INES,[130] France	**22.2**	**730**	**38.7**	**78.5**	**104**	**IC (ISE)**	**2012**
EPFL,[131] Switzerland	**22.1**	**726**	**38.9**	**78.4**	**4, FZ**	**IC (ISE)**	**2012**
RRR,[116] Switzerland	21.9	735	38.5	77.5	4, Cz	-	2011
AUO,[132] Taiwan	**21.7**				**6inch**		**2013**
Silevo,[133] US	**21.4**	**729**	**37.3**	**78.7**		**IC**	**2012**
Hyundai HI,[134] Korea	21.1	721	36.6	79.9	~220	-	2011
SERIS,[135] Singapore	**21.1**	**702.2**	**38.2**	**78.6**	**1**	-	**2012**
AMAT,[136] US	**>21**	**>720**	**>37**	**>77**	**149, Cz**		**2012**
Titech,[137] Japan	**20.1**						**2012**
Samsung,[138] Korea	**20.14**	**709**	**36.51**	**77.8**	**154.9**	**IC (ISE)**	**2012**
HZB,[139] Germany	19.8	639	39.3	78.9	1, FZ	IC	2006
OM&T,[140] the Netherlands	**19.7**				**1**		**2012**
NTUST,[141] Taiwan	19.6	690	39.1	72.7	1, FZ	PR	2011
ISFH,[142] Germany	**19.4**	**703.7**	**36**	**76.5**	**4**	**PR**	**2012**
Univ. Hagen,[143] Germany	19.3	675	37	77.3	FZ	IC	2009
NREL,[144] USA	**19.24**	**683.2**	**36.2**	**77.7**	**0.9, Cz**	**IC**	**2012**
Delft Univ.,[145] the Netherlands	**19.0**	-	-	-	-	-	**2012**
AU,[146] Taiwan	**18.9**				**5 inch**		**2012**
FhG-ISE,[147] Germany	18.7	~705	~35.0	~75	4, FZ	-	2010
IEC,[69] USA	18.3	694	35.7	74.2	0.55, Cz	IC	2008
LG,[148] Korea	18.2	687	33.3	78.9	1, FZ	-	2010
AIST,[149,#] Japan	17.5	656	35.6	75	0.2	PR	2009
Sungkyunkwan Univ.,[150] Korea	17.4	631	36.3	76.1	Cz	PR	2011
LPICM,[151] France	17.2	701	30.8	79.6	4	-	2011
Utrecht Univ.,[152] the Netherlands	16.7	681	33.5	73.1	1 FZ	-	2011
CNR-IMM,[153] Italy	16.2	573	36.6	77	1, Cz	-	2005
Univ. Toronto,[154] Canada	15.5	679	31.7	72.4	4.2, FZ	-	2011
Kyung Hee Univ.,[155] Korea	14	575	34.4	71	Cz	PR	2011
ECN,[156] the Netherlands	13.2	635	29.1	72	21, FZ	-	2010
KIER,[157] Korea	12.8	< 600			Cz	-	2009
ENEA,[158] Italy	12.4	526	31.9	74	mc	-	2010
UPC,[195] Spain	10.9	525	28.6	72.8	FZ	PR	2006

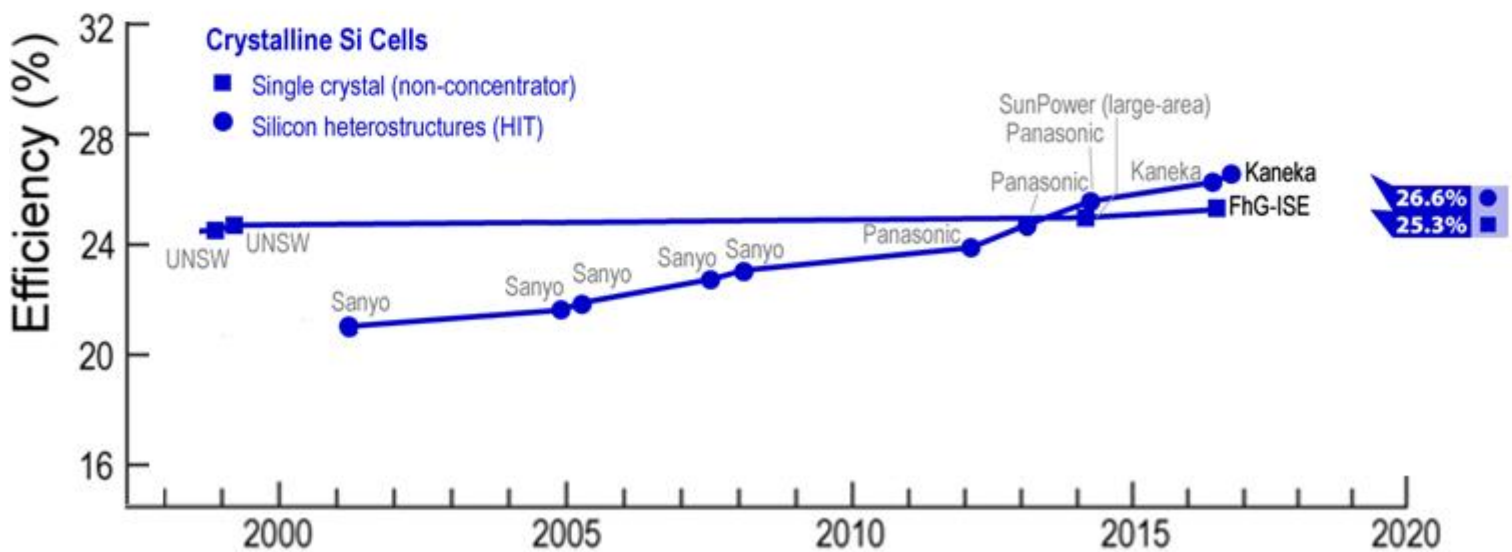
[De Wolf *et al*, Green **2**, 7 (2012).]

Increase R&D activities.

Several groups and industries above 20% with screen-printing or plated contacts (CIC, INES/EDF, Kaneka, R&R, LG, Hyunday,…….)

But industries leaving the field, saturation of progress…

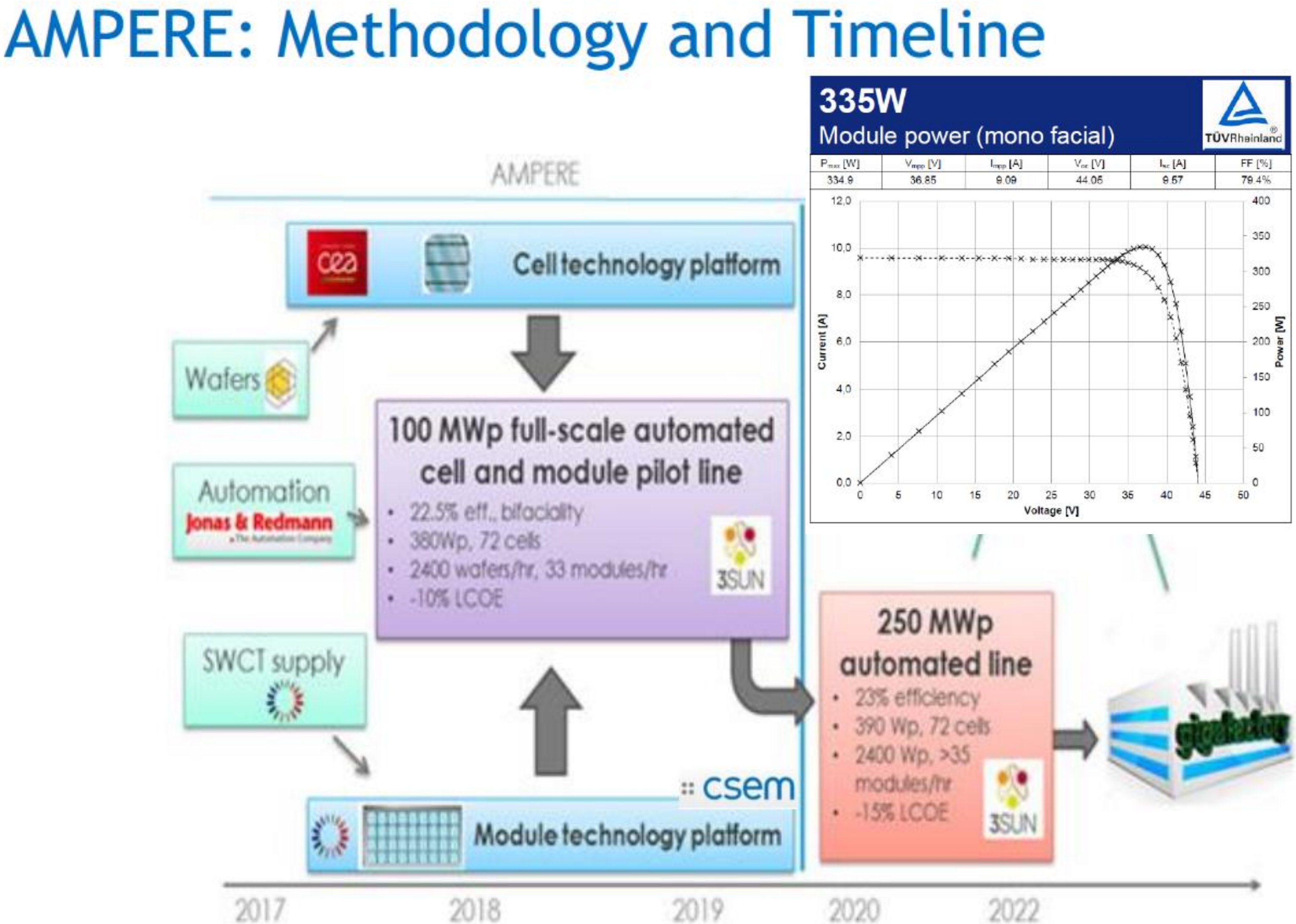
Evolution of efficiency



Adapted from https://www.nrel.gov/pv/assets/images/efficiency-chart.png
This plot is courtesy of the National Renewable Energy Laboratory, Golden, CO.

Impressive steadiness in the efficiency increase
up to the “practical limit” of Si PV technology…

Becoming a mainstream technology ?



MEYER BURGER

SHJ module production in Europe !

PV-lab IMT NEUCHATEL

ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

First demonstration of PECVD a-Si:H (1969)

The Preparation and Properties of Amorphous Silicon

R. C. Chittick, J. H. Alexander, and H. F. Sterling

Standard Telecommunication Laboratories Limited, Harlow, Essex, England

- Resistivity up to 10^{14} Ω.cm
- Large activation energy
- Photoconductivity observed

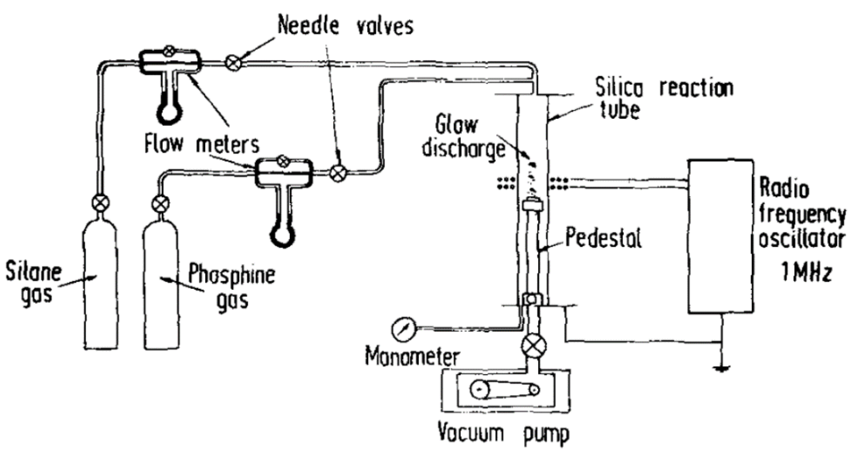


Fig. 1. Glow discharge deposition apparatus

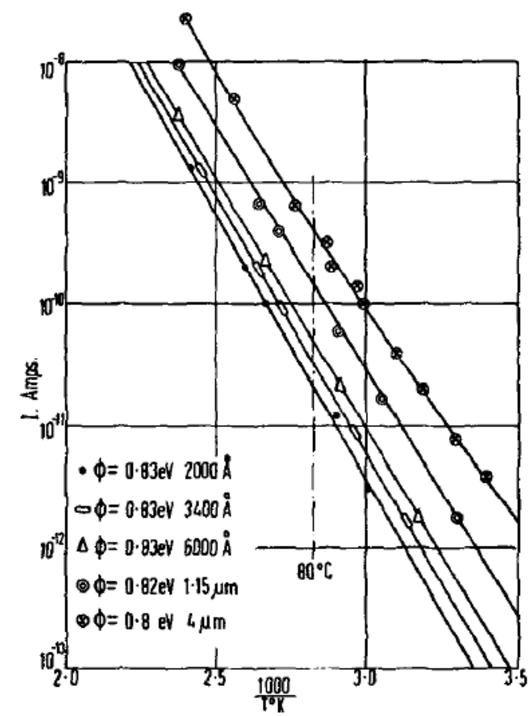
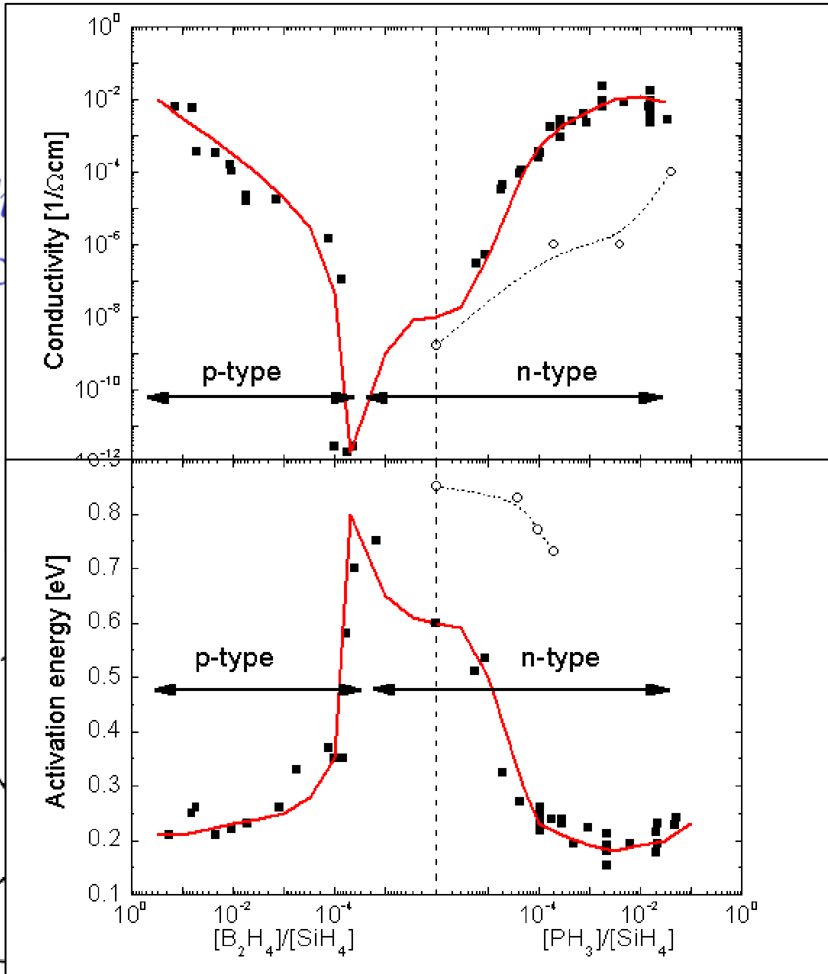
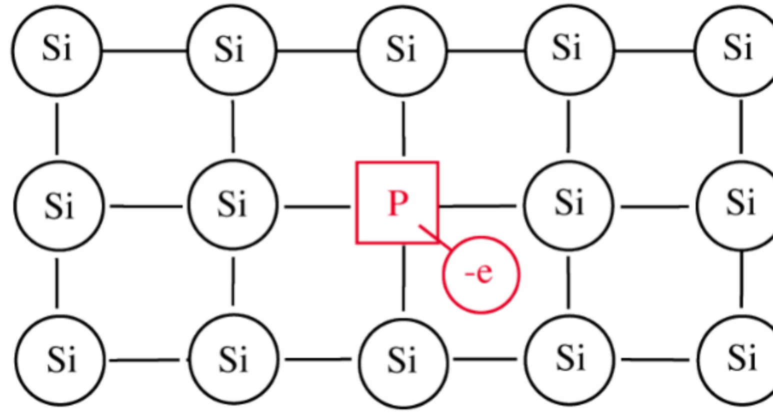


Fig. 2. Deposition temperature 21°C; variation of electrical conduction with temperature for various thicknesses.

Doping in a-Si:H





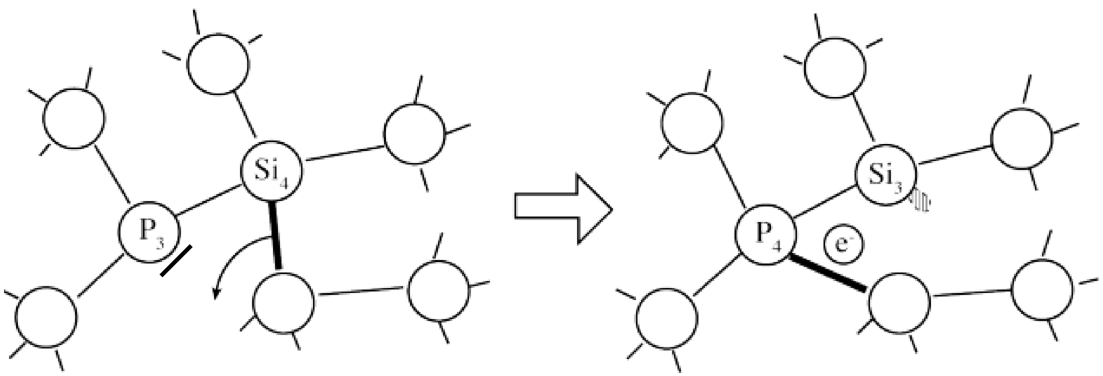
Hydrogenated Amorphous silicon

Doping possible

[9] W. E. Spear and P. G. Lecomber, Substitutional doping of amorphous silicon, *Solid State Communications*, vol. 17, pp. 1193-1196, 1975.

Doping in a-Si:H (1975)

Model of valence transfer :



Transfer of an electron from a weak Si bond on a phosphorous atom will become tetra-coordinated (*donnor effect from the fifth P electron*). This doping effect is correlated with the formation of a *dangling bond* in a neighboring silicon atom.

Substitutional doping and defect creation appears strongly correlated

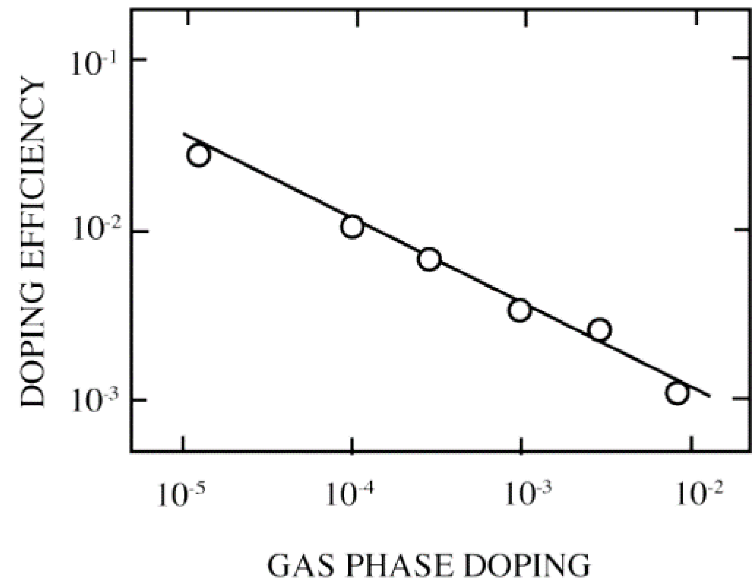
Doping in a-Si:H (1975)

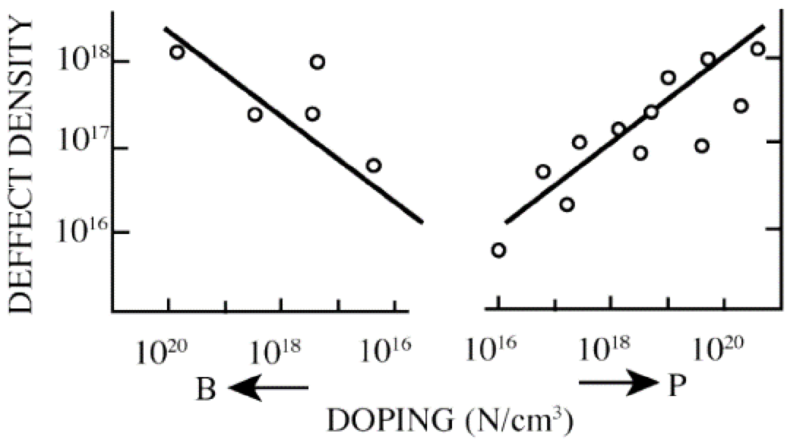
Experimental tests of the autocompensation model of doping

By G. Krötz, J. Wind, H. Stitzl, G. Müller
Messerschmitt-Bölkow-Blohm G.m.b.H., Postfach 80 11 09,
8000 München 80, F.R. Germany

S. Kalbitzer
Max-Planck-Institut für Kernphysik, Postfach 10 39 80,
6900 Heidelberg, F.R. Germany

and H. Mannsperger





Doping possible but at the cost of huge amount of defects… quality too low for p-n solar cells

First cell (1976)

Amorphous silicon solar cell

D. E. Carlson and C. R. Wronski

RCA Laboratories, Princeton, New Jersey 08540

(Received 6 February 1976)

With a p-i-n structure a solar cell can be made

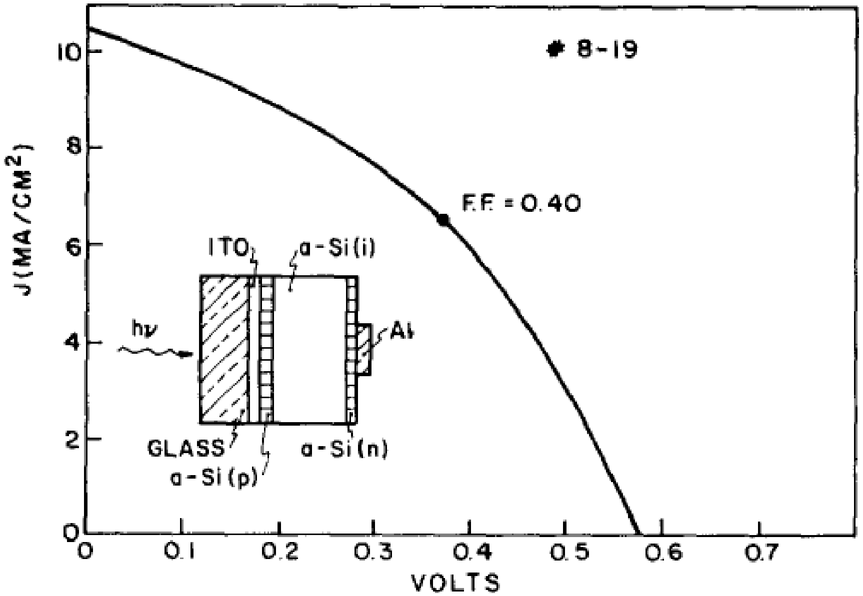


FIG. 1. Current-voltage curve for device #8-19 under illumination comparable to AM-1 sunlight. Also included in the figure is a schematic diagram of a p-i-n structure.

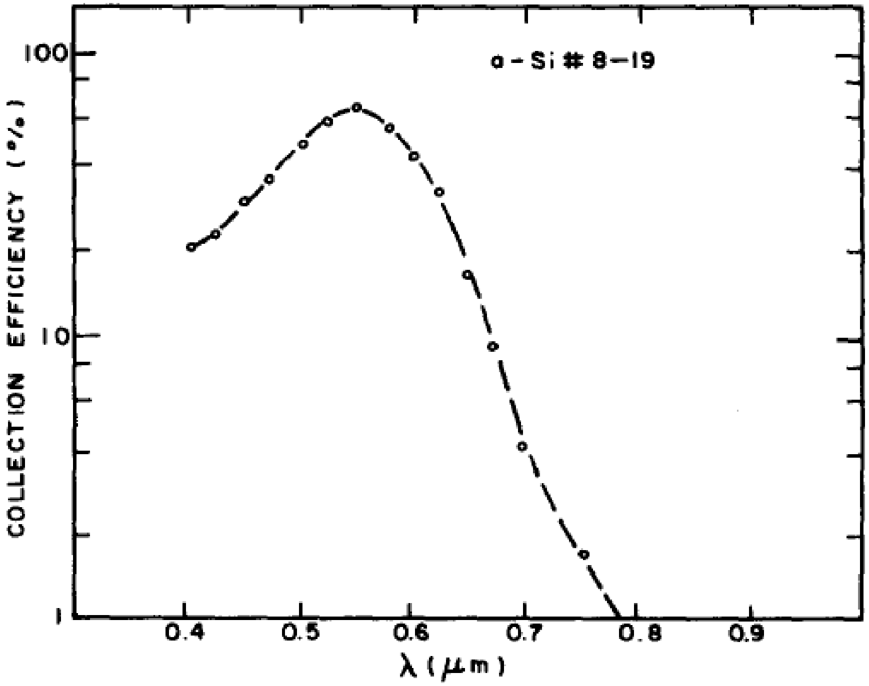


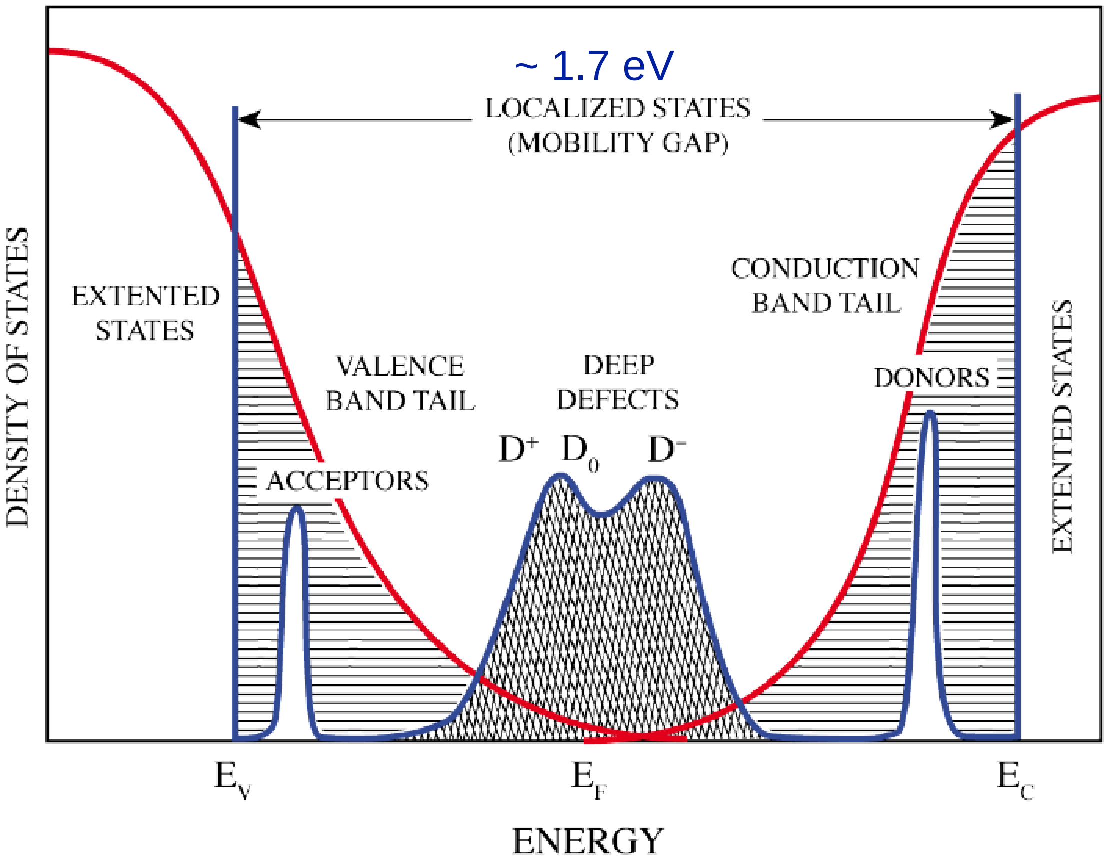
FIG. 2. Collection efficiency as a function of wavelength for device #8-19.

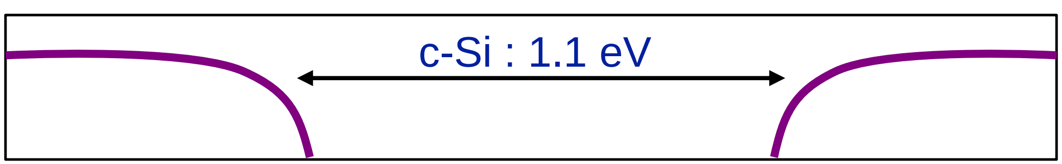
Process fabrication: Si layers

- Millions of square meters of thin-film Si modules,
- TFTs in many displays,

Now mostly consumer electronics…

Typical density of state in a-Si:H





- Band tails (disorder)
- Localized states in the band gap (disorder)
- Increase of deep defect density with doping
- Metastability effects

Material quality limits the efficiency of single-junction a-Si:H cells

Light-induced degradation of a-Si:H (1977)

Reversible conductivity changes in discharge-produced amorphous Si[a)]

D. L. Staebler and C. R. Wronski

RCA Laboratories, Princeton, New Jersey 08540

(Received 9 May 1977; accepted for publication 17 June 1977)

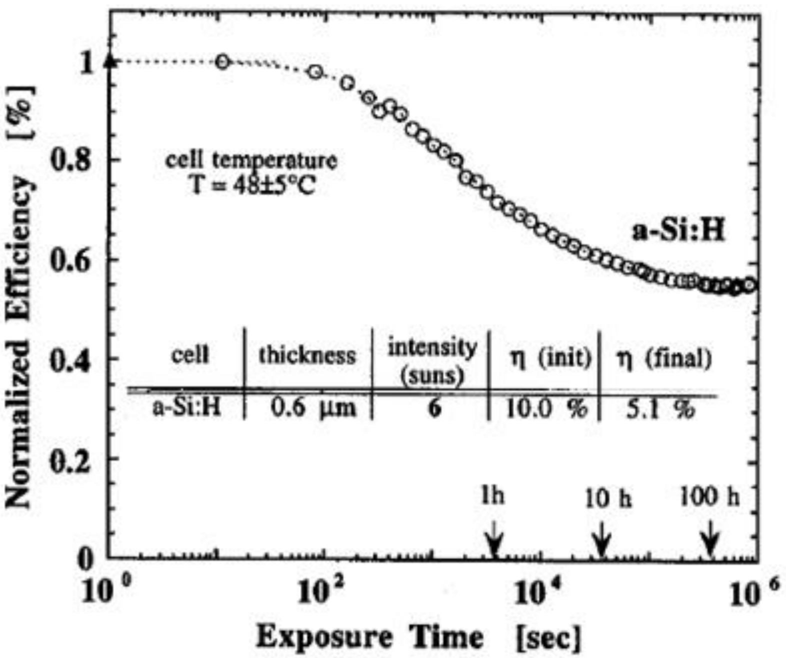


Fig. 15: Normalized cell efficiency of an a-Si:H p-i-n cell

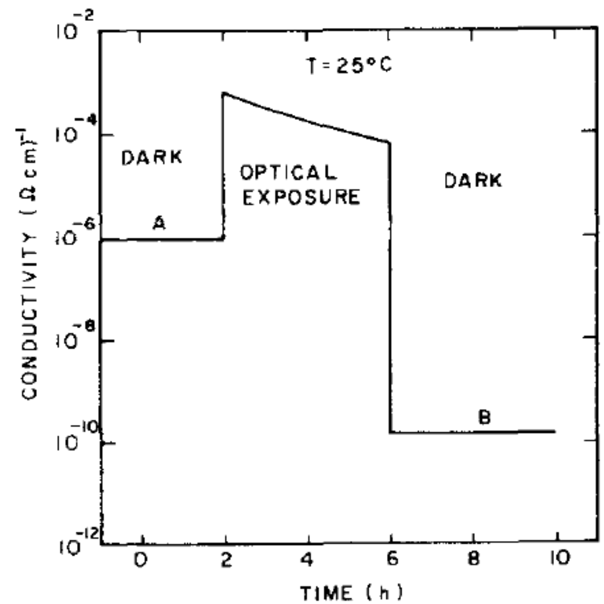


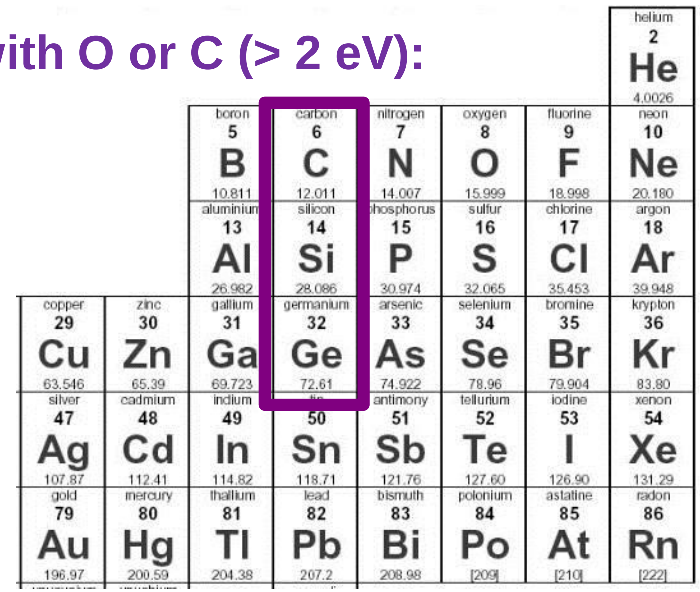
FIG. 1. Conductivity as a function of time before, during, and after exposure to ~ 200 mW/cm² of light in the wavelength range 6000—9000 Å.

- **Light absorption creates metastable defects in a-Si:H.**

→ Inherent to amorphous nature, end of a-Si:H as a PV technology…

Variations around a-Si:H

- **Band gap <u>increase</u> possible through alloying with O or C (> 2 eV):**



Morimoto, T. et al., J. Appl. Phys., 1982.
K. Haga, H. Watanabe, Jpn. J. Appl. Phys., 1990.

- **Band gap <u>decrease</u> possible through alloying with Ge:**

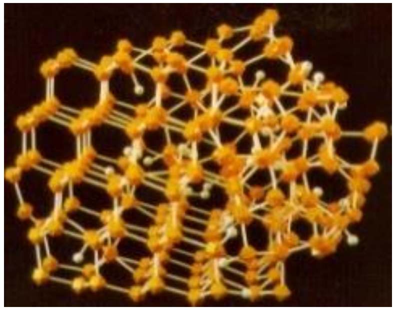
M. Stutzmann et al., J. Appl. Phys., 1989.

Issue: alloying yields more defective material…

- **Microcrystalline material can be grown from H-rich plasma (BG = 1.1 eV)**

J.Meier, et al., *Appl. Phys. Lett.*, 1994.


Amorphous silicon


Microcrystalline silicon

Variations around a-Si:H

C incorporation in a-SiC:H depends on C precursor…

[W. Beyer and H. Mell, in Disordered Semiconductors, edited by Kastner, Thomas, and Ovshinsky (Springer US, 1987)]

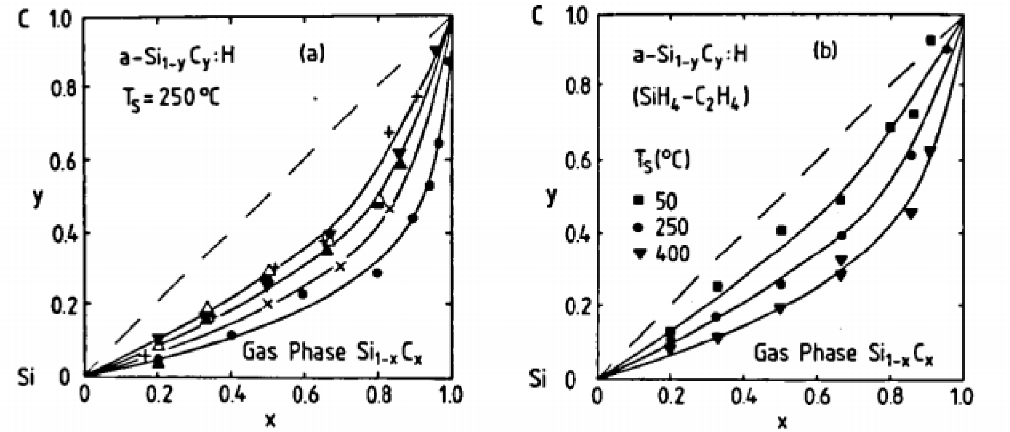
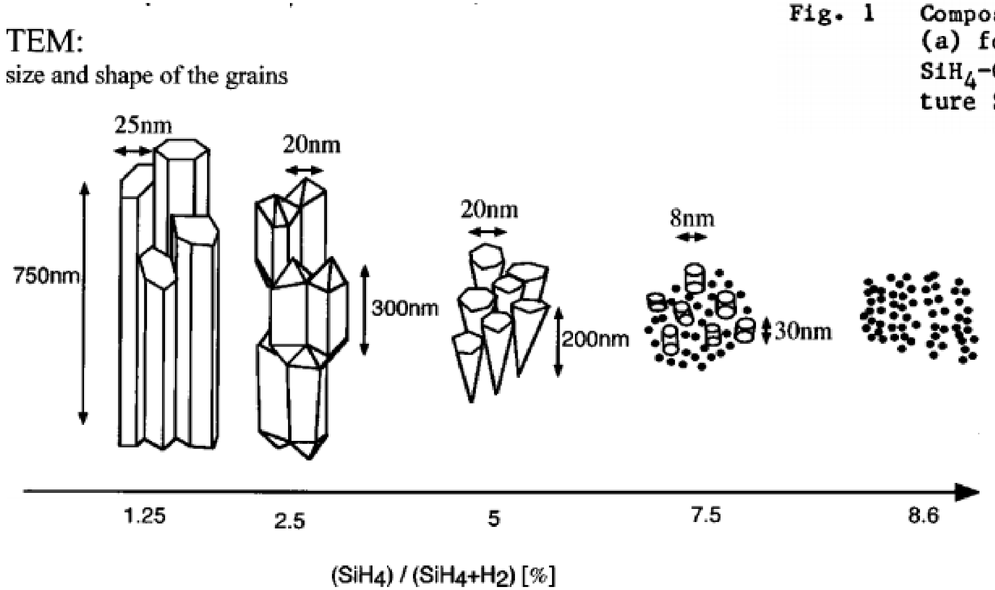


Fig. 1 Composition parameter y versus gas phase mixture parameter x (a) for the mixtures SiH_4-CH_4 (●), SiH_4-C_2H_6 (▲), SiD_4-C_2D_6 (Δ), SiH_4-C_2H_4 (▼), Si_2H_6-CH_4 (×) and Si_2H_6-C_2H_4 (+), (b) for the mixture SiH_4-C_2H_4 deposited at different substrate temperatures.



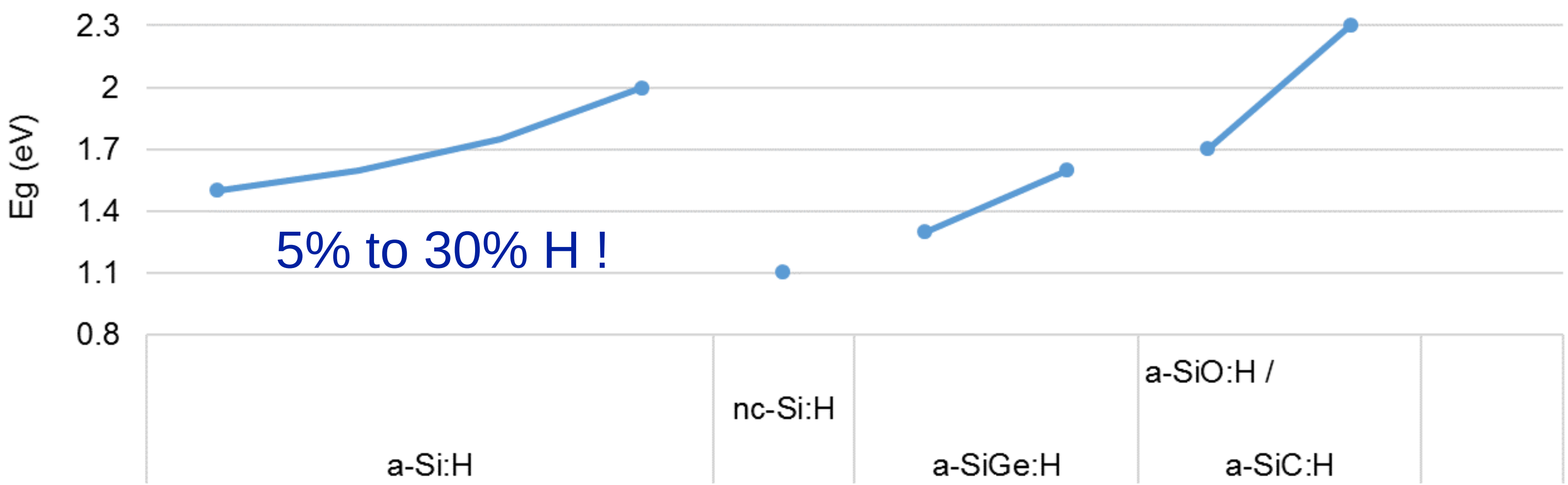
Low SiH_4 / H_2 ratio → crystalline growth

[Vallat Sauvain *et al*, JAP **87**, p3141 (2000)]

Variations around a-Si:H

Lower T°, higher H2 dilution →

Higher C or O content →

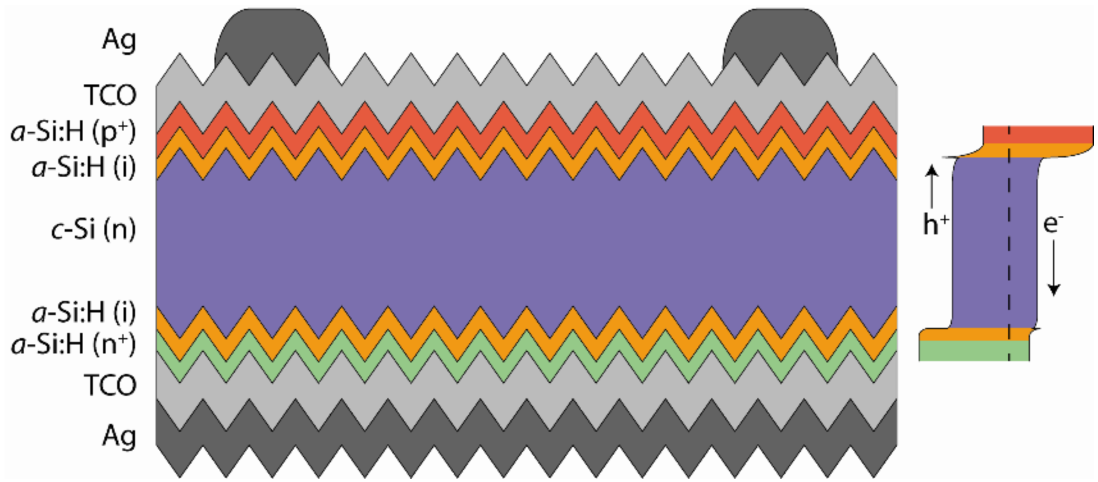


All layers are conducting enough (even undoped) for charge collection unlike SiNx, Al_2O_3, …
→ Passivating contact possibility !

"usable range" for heterojunctions, wider E_G possible

From homo- to heterojunction solar cell

Heterojunction solar cell



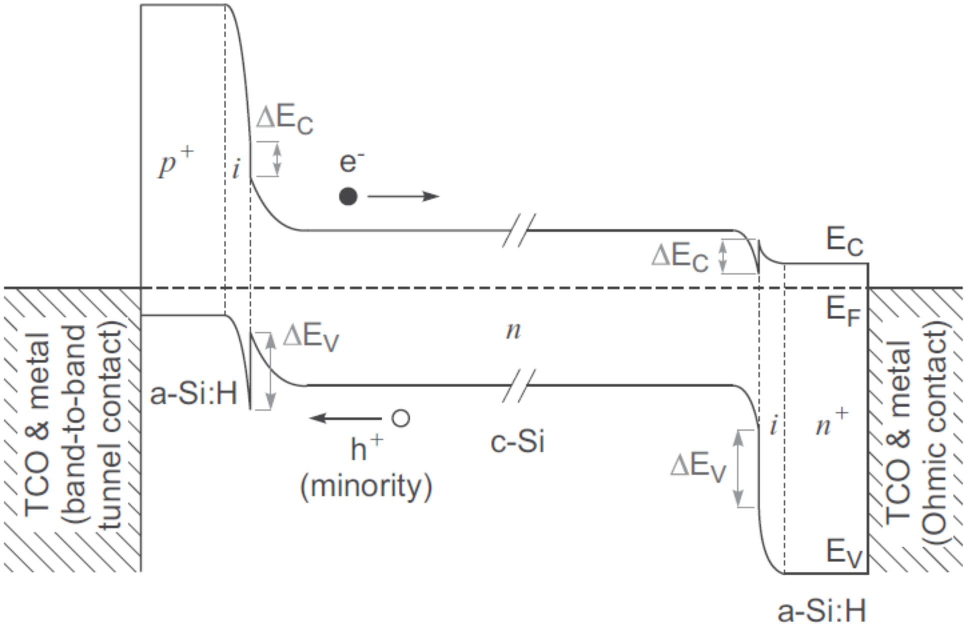
- Si surface passivation from (i)a-Si:H
- Selectivity induced by doped a-Si:H
- Lateral transport provided by TCO (metal on rear)

But…

All layers are interlinked and influence each other !

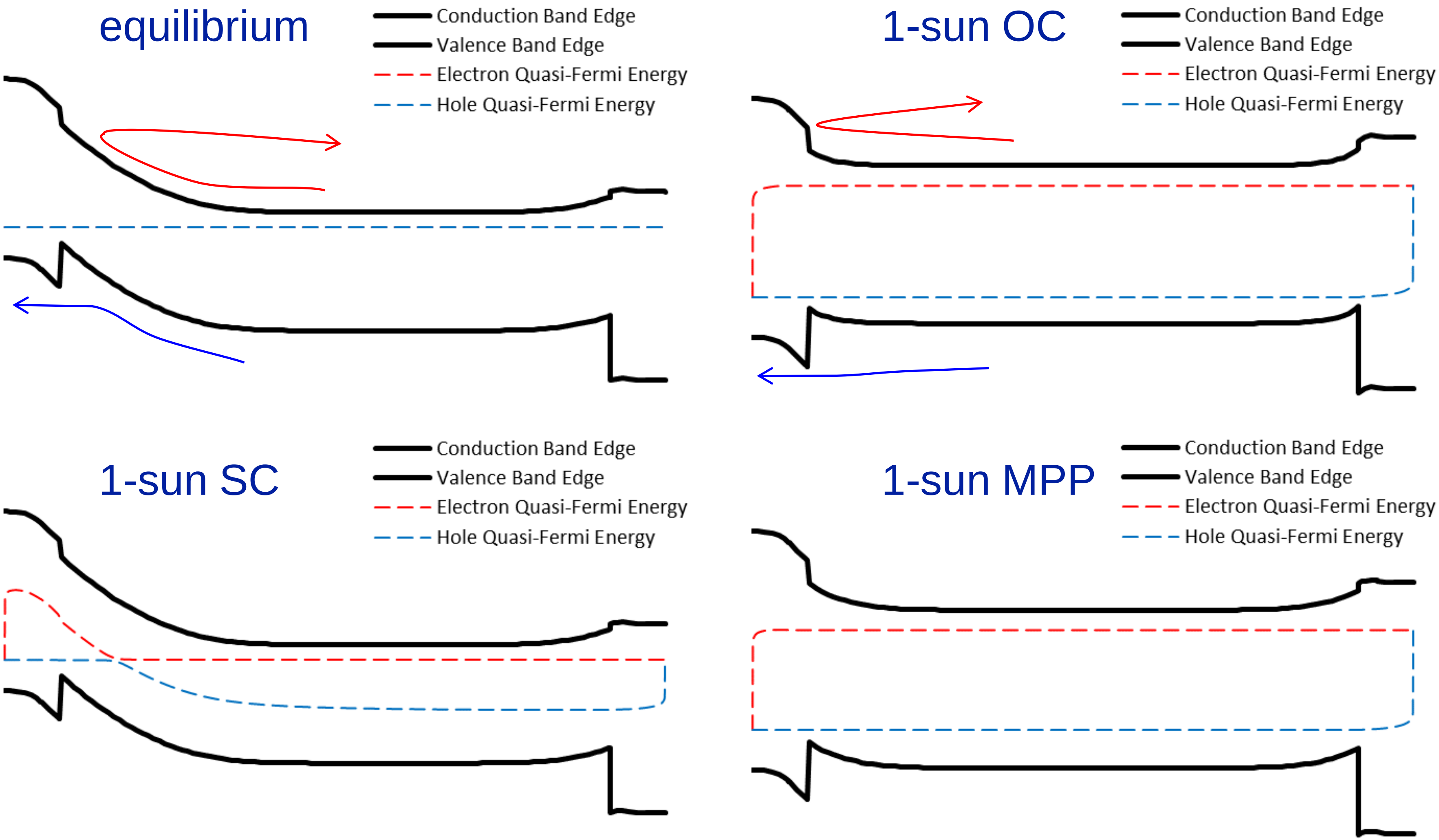
→ Doped layers influence passivation
→ TCO influences passivation
→ TCO influences selectivity
→ …

Heterojunction *c*-Si technology



Band bending, band offsets, surface inversion often represented in equilibrium…

Heterojunction *c*-Si technology



Process flow

Chemical baths

c-Si surface preparation

PECVD I

Intrinsic film deposition a-Si:H(i)

PECVD a-Si:H

Process:
plasma enhanced chemical vapour deposition

Features:
- Process-gas: silane (SiH_4) + hydrogen (H_2)
- Films can be doped by adding dopant gasses

-Deposition-rate: ~1-10 Å/s

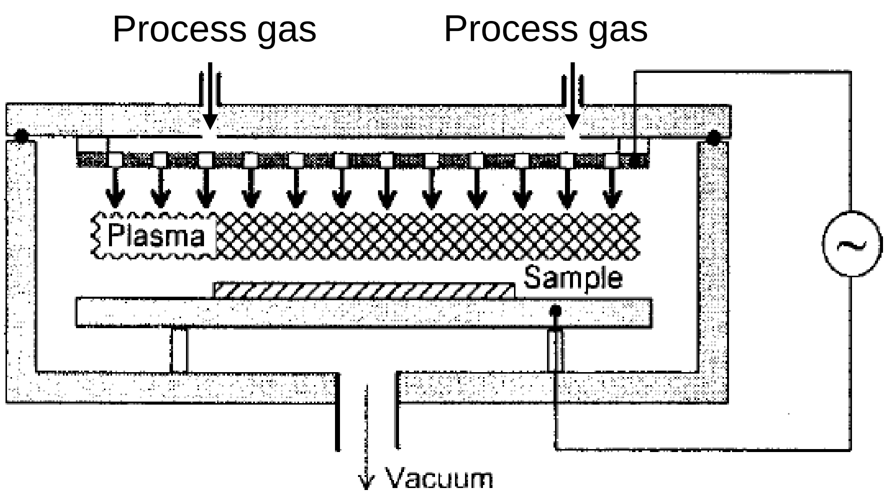
-Deposition-temperature: ~200 degrees C

-Cross-contamination may be an issue, hence use of separate chambers for intrinsic, p-type, and n-type deposition

-employed gasses can be explosive and / or toxic – caution needed !
→ non-ideal safety-wise

Intrinsic films

Amorphous silicon deposition



Taken from Aberle & Hezel, Prog. in Photovolt.: Res. Appl. 5 (1997) 29-50

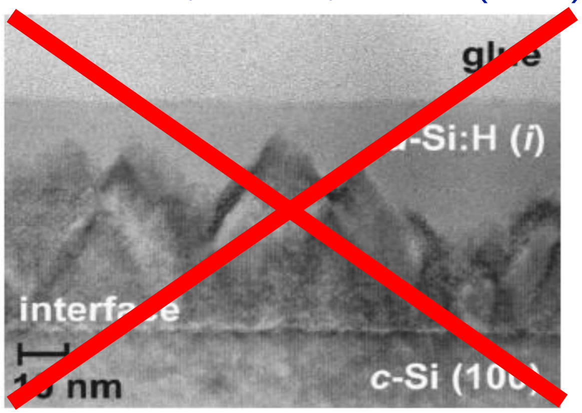
Key points passivation I

Intrinsic films

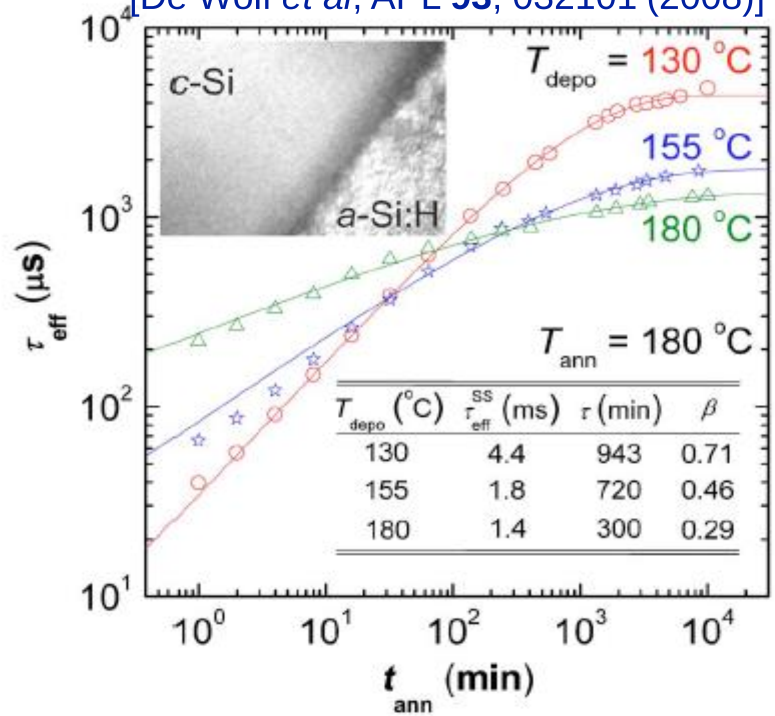
Many in-depth papers from De Wolf

- Epitaxy is detrimental to passivation—only amorphous films passivate c-Si?
- ~200 °C annealing of a-Si:H can yield strong improvements

[De Wolf *et al*, APL **90**, 042111 (2007)]



[De Wolf *et al*, APL **93**, 032101 (2008)]



Key points passivation I

Intrinsic films

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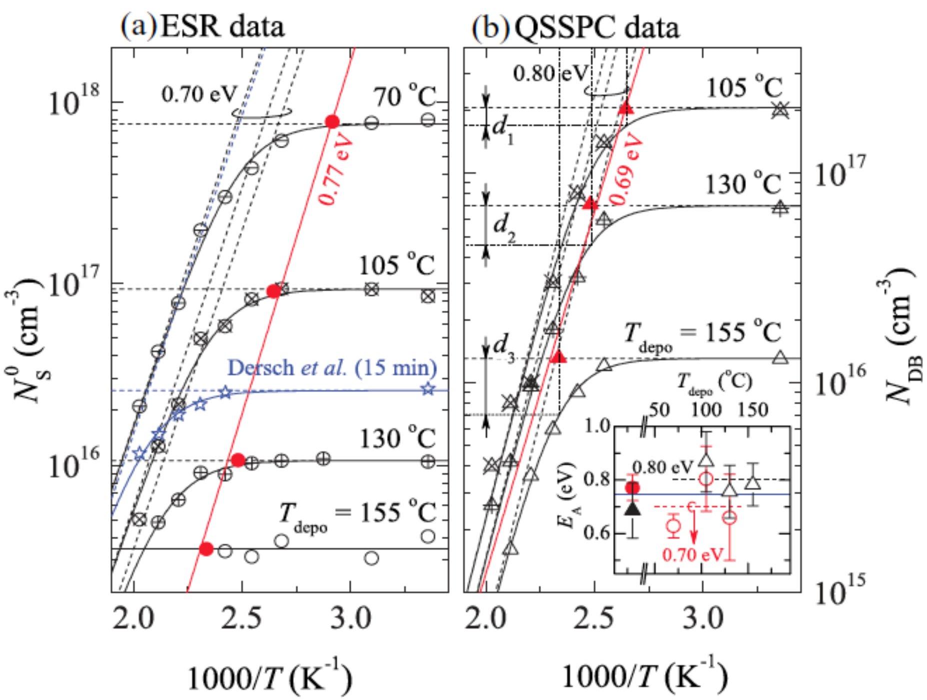


[De Wolf *et al*, PRB **85**, 113302 (2012)]

For *a*-Si:H/*c*-Si interface

Energy barrier of ~0.75 eV,
independent of deposition conditions as well

1) Physical evidence that interface states are dangling bonds as well

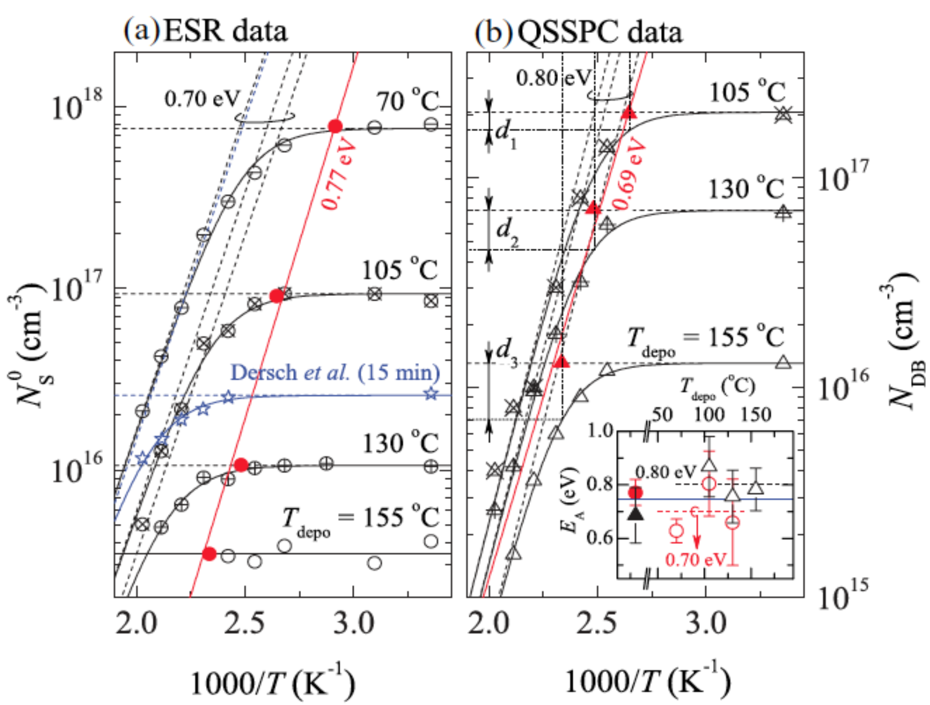
2) Evidence that *a*-Si:H/*c*-Si interface has no unique properties compared to *a*-Si:H bulk

Key points passivation I

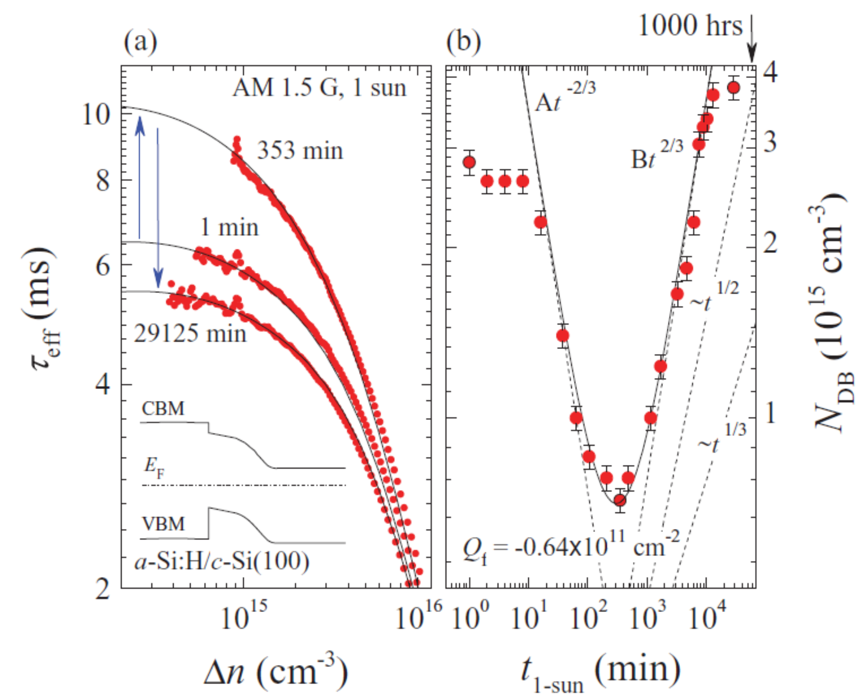
Many in-depth papers from De Wolf

- Epitaxy is detrimental to passivation
- ~200 °C annealing of a-Si:H can yield strong improvements
- Defects at c-Si/a-Si:H interface are similar to bulk a-Si:H defects
- Light-induced degradation also impedes passivation

Lifetime is a very sensitive probe to small changes in defect density !



[De Wolf *et al*, PRB **85**, 113302 (2012)]



[De Wolf *et al*, PRB **83**, 233301 (2011)]

Key points passivation I

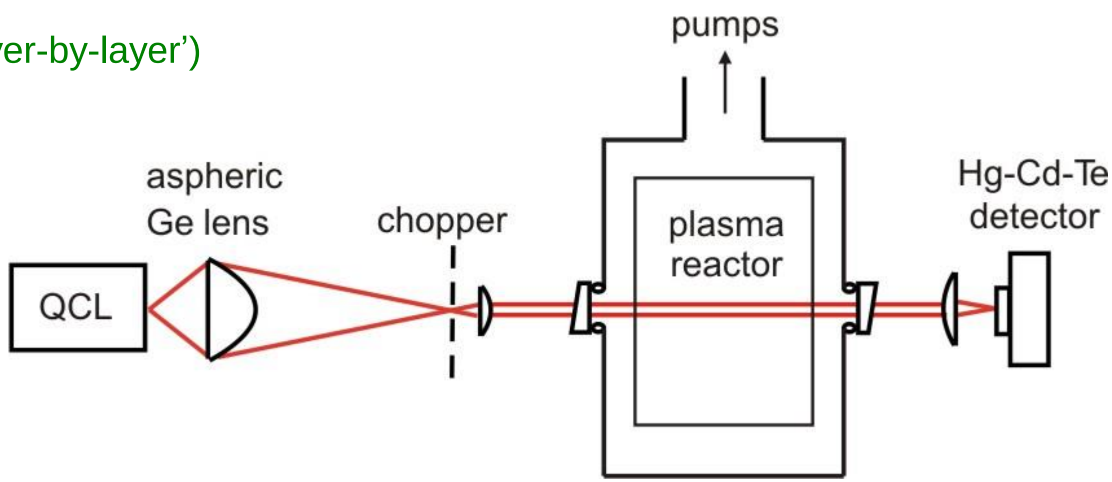
Intrinsic films

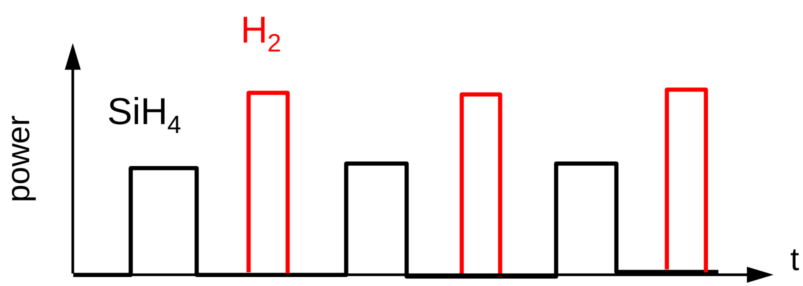
For good devices:

•Go towards the amorphous-to-crystalline transition as much as possible, but NO EPITAXY !

- Use highly depleted silane plasmas
- H_2 plasma during a-Si:H growth ('layer-by-layer')

[Bartlome *et al*, APL **94**, 201501 (2009)]





[Descoeudres *et al.*, APL **97**, 183505 (2010)]

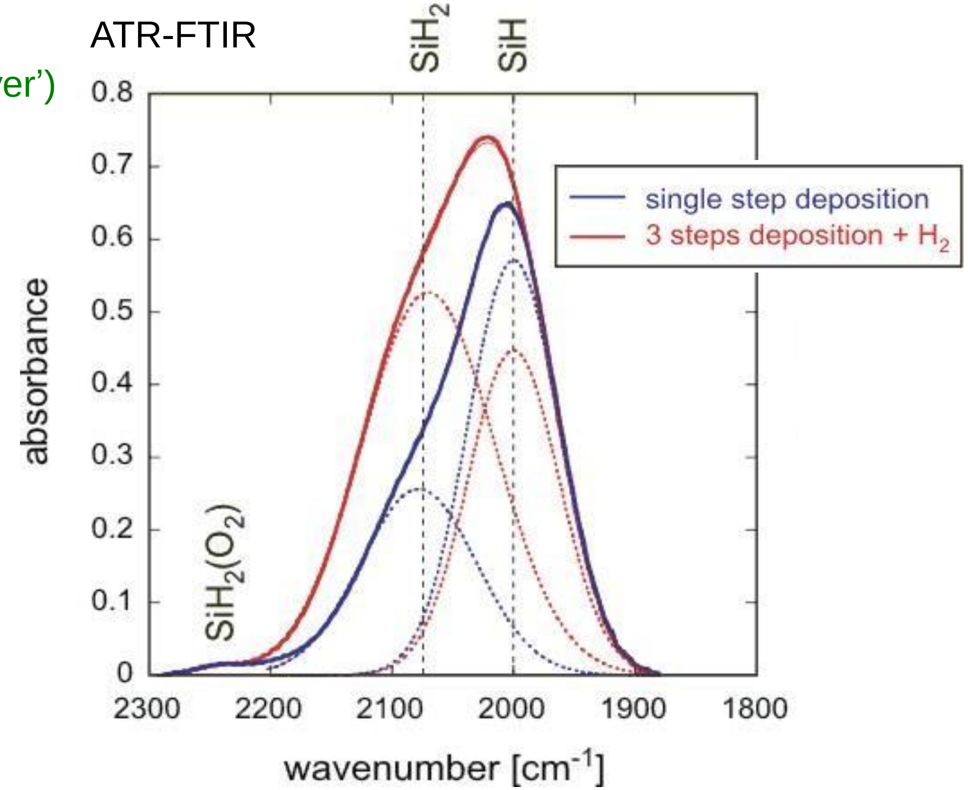
Key points passivation I

Intrinsic films

For good devices:

•Go towards the amorphous-to-crystalline transition as much as possible, but NO EPITAXY !

- ➢ Use highly depleted silane plasmas
- ➢ H_2 plasma during a-Si:H growth ('layer-by-layer')



- Layer properties
  - ➢ Increase in hydrogen content
  - ➢ Increase in band gap
  - ➢ More disordered
  - ➢ Etching effect if H_2 plasma is too long

[Descoeudres *et al*., APL **99**, 123506 (2011)]

Key points passivation I

For good devices:

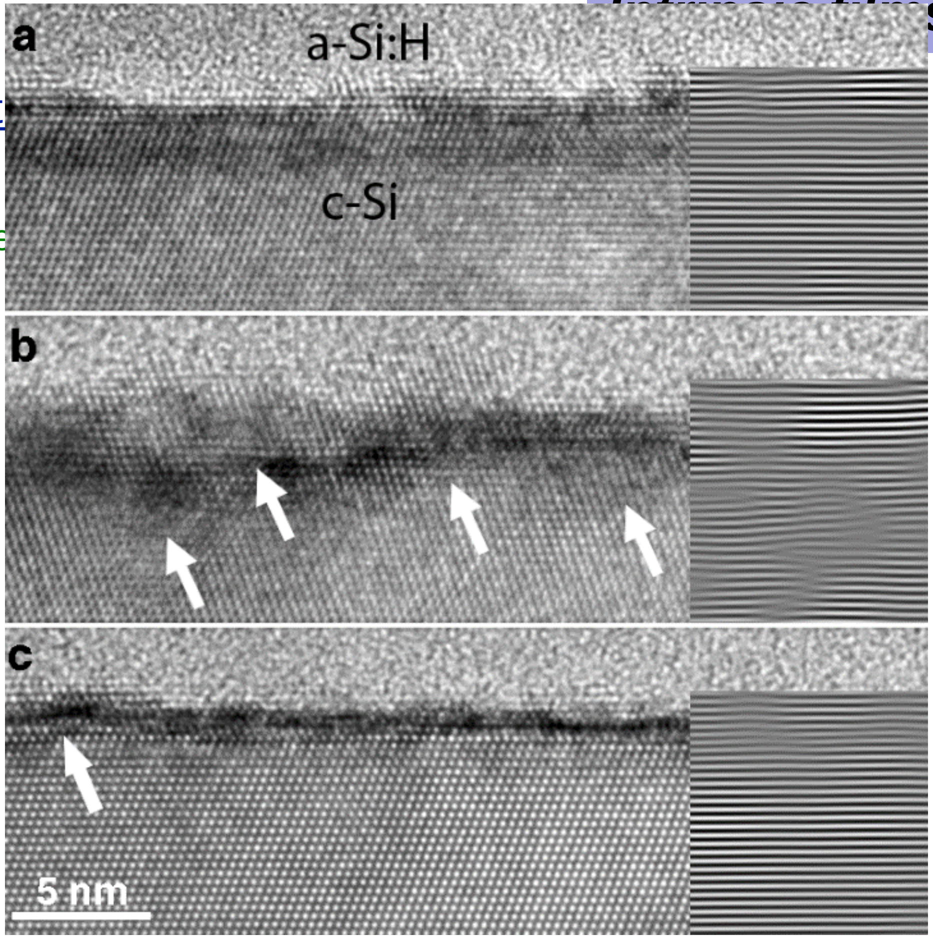
•Go towards the amorphous-to-crystalline transit

- ➢ Use highly depleted silane plasmas
- ➢ H_2 plasma during a-Si:H growth ('layer-by-laye

- Layer properties
  - ➢ Increase in hydrogen content
  - ➢ Increase in band gap
  - ➢ More disordered
  - ➢ Etching effect if H_2 plasma is too long
  - ➢ Minimum buffer layer thickness to be present!

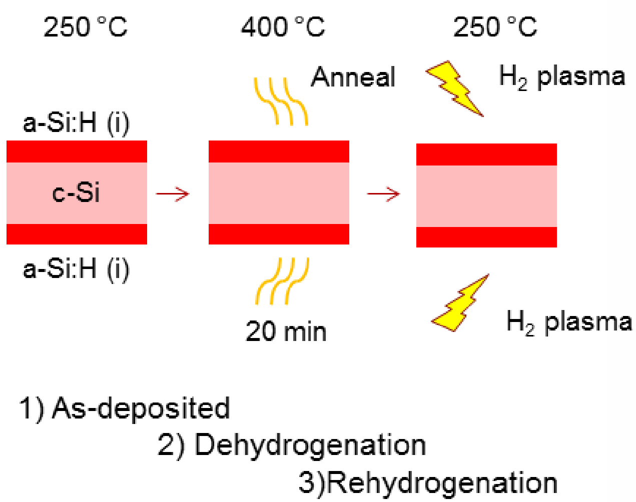
- Globally beneficial for devices

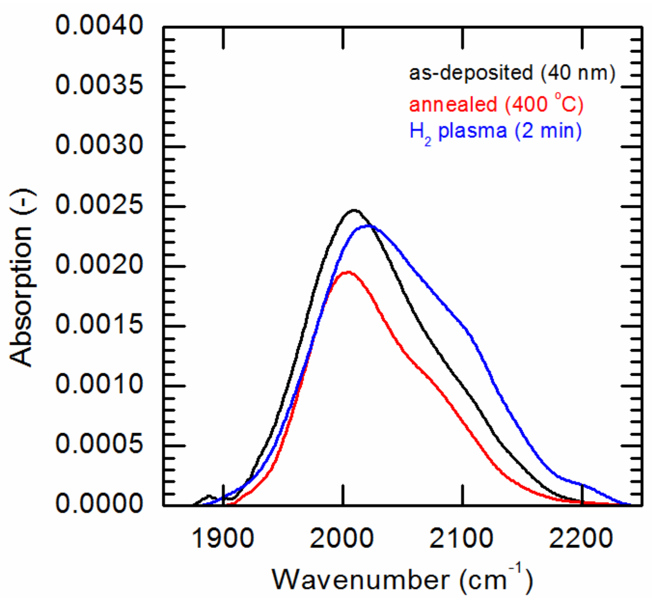
➡ 5-20 mV gain in V_{oc}



[Geissbuehler *et al.*, APL **102**, 231604 (2013)]

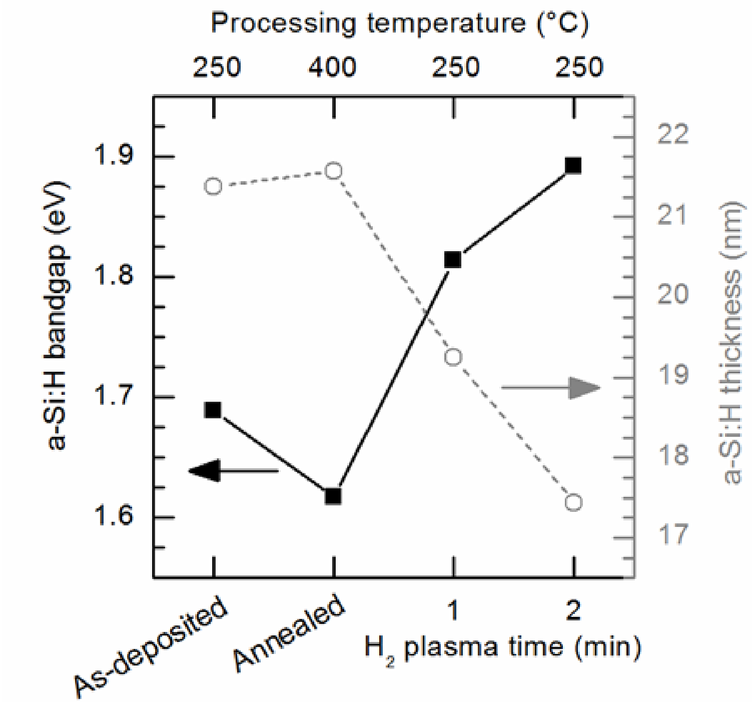
De-hydrogenation and rehydrogenation





J. Shi *et al.*, *Appl. Phys. Lett.* **109**, 031601 (2016)

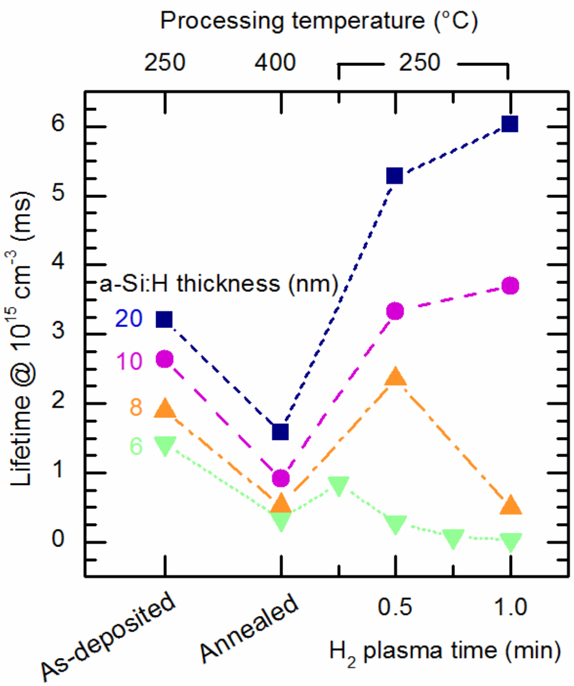
Intrinsic films

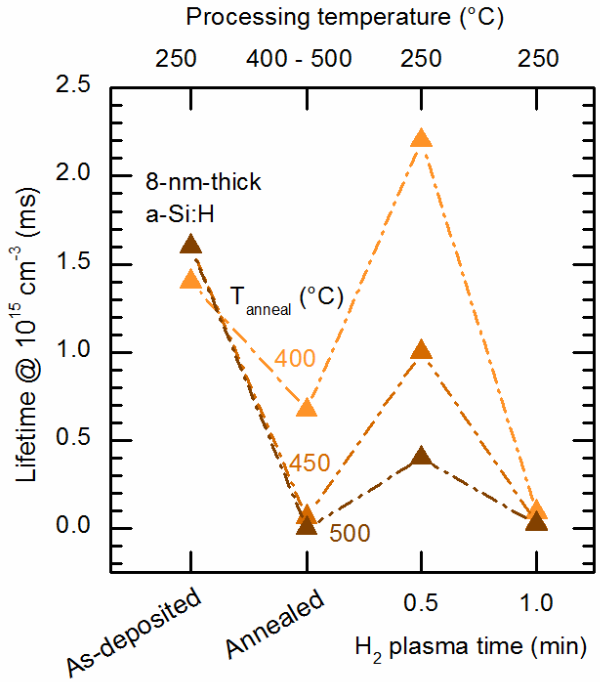


- De-hydrogenation and re-hydrogenation visible through ellipsometry and FTIR
- Very slow etching rate ~2 nm/min

De-hydrogenation and rehydrogenation

J. Shi *et al.*, *Appl. Phys. Lett.* **109**, 031601 (2016)





Intrinsic films

- Re-hydrogenation with H2 plasma allows to recover initial lifetime after high-temperature annealing
  - Only for thick-enough layers
  - Only up to certain temperature (e.g. here 500 °C)
  - Too long plasma is detrimental to passivation **before complete etching**

Process flow

Chemical baths
c-Si surface preparation

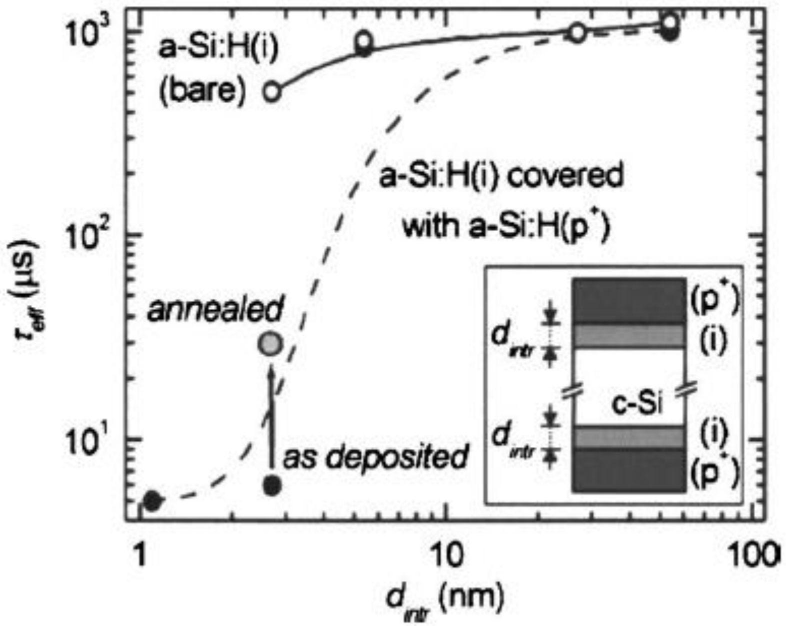
PECVD I
Intrinsic film deposition a-Si:H(i)

PECVD II
Doped film deposition a-Si:H(n/p)

Doped layers effect on passivation

- Doped-layer deposition on thin (i)a-Si:H can yield poor passivation

Doped films

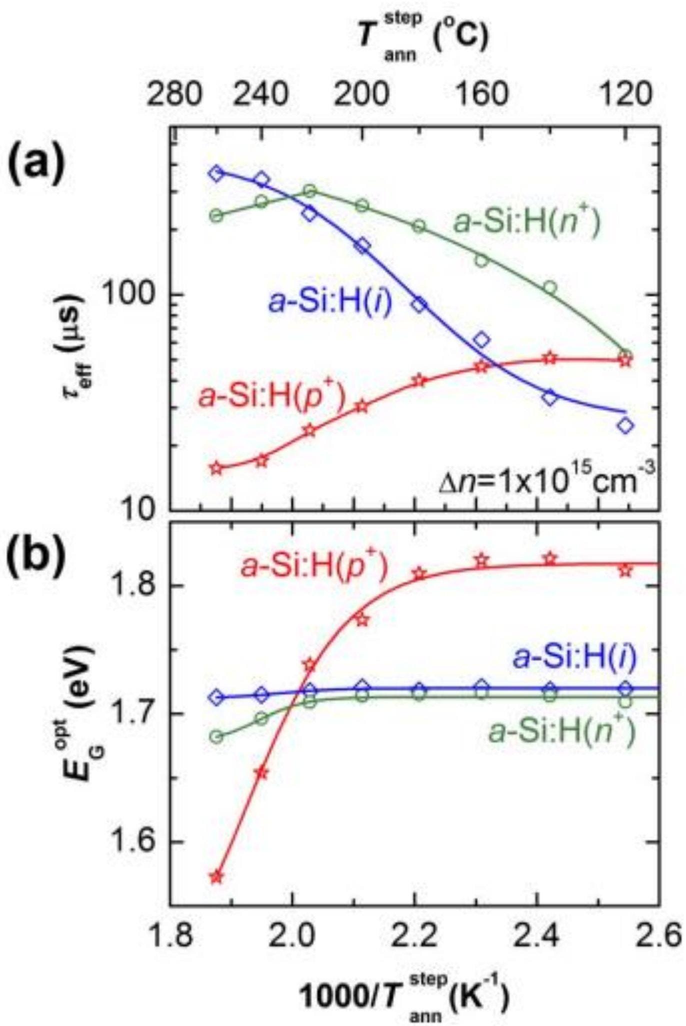


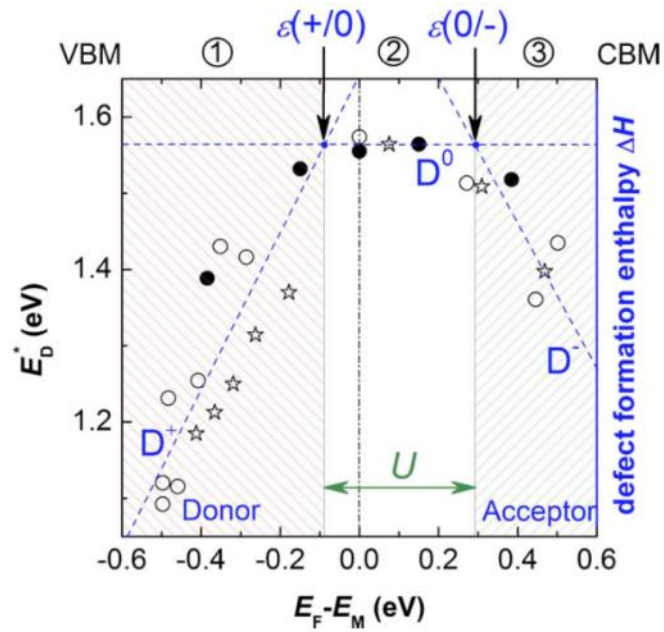
[De Wolf *et al*, APL **88**, 022104 (2006)]

General note:
Doped layers are "easy" to develop, most effort is required for (i)a-Si:H.

Doped layers effect on passivation

S. De Wolf and M. Kondo, *J. Appl. Phys.* **105**, 103707 (2009)



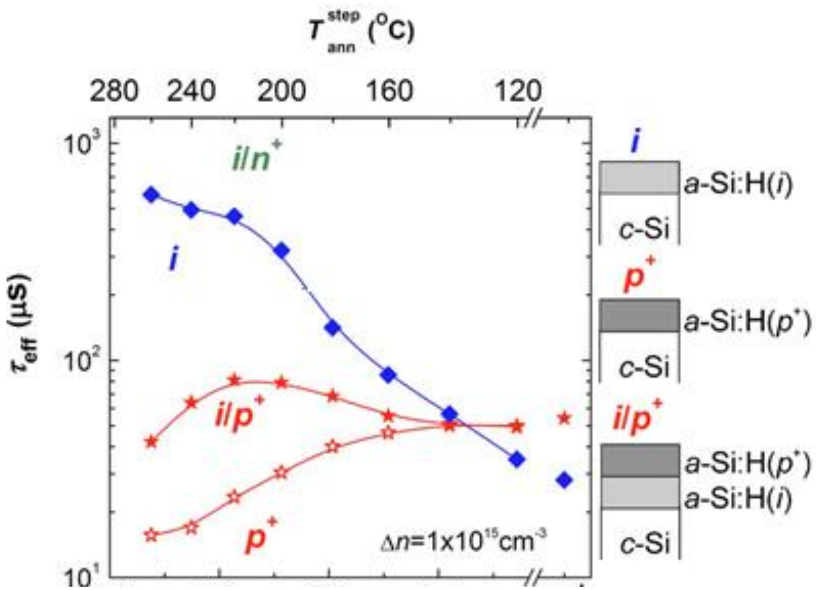


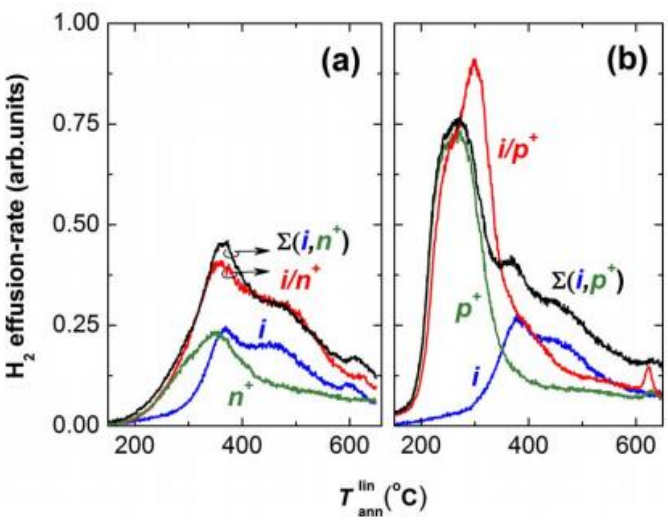
Doped films

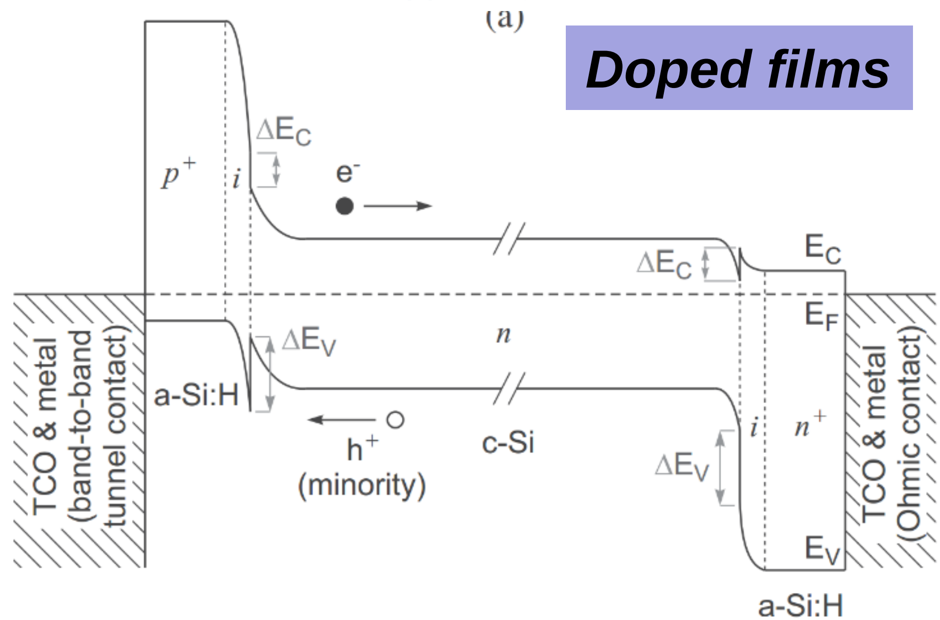
- Passivation from a-Si:H degrades especially for p-type a-Si:H layers upon annealing, with E_G drop
  ➔ Defect formation in a-Si:H requires less energy **if E_F is close to the Valence Band**.

Doped layers effect on passivation

S. De Wolf and M. Kondo, *J. Appl. Phys.* **105**, 103707 (2009)







Doped films

- Passivation from a-Si:H degrades especially for p-type a-Si:H layers upon annealing, with E_G drop
  ➔ Defect formation in a-Si:H requires less energy **if E_F is close to the Valence Band**.
- due to **defect creation from H effusion**, more energetically favorable when E_F is close to the VB.
- Also occurs for the intrinsic layer in i/p a-Si:H stacks

Doped layers effect on passivation

L. Barraud *et al.*, *Silicon PV*, (2016)

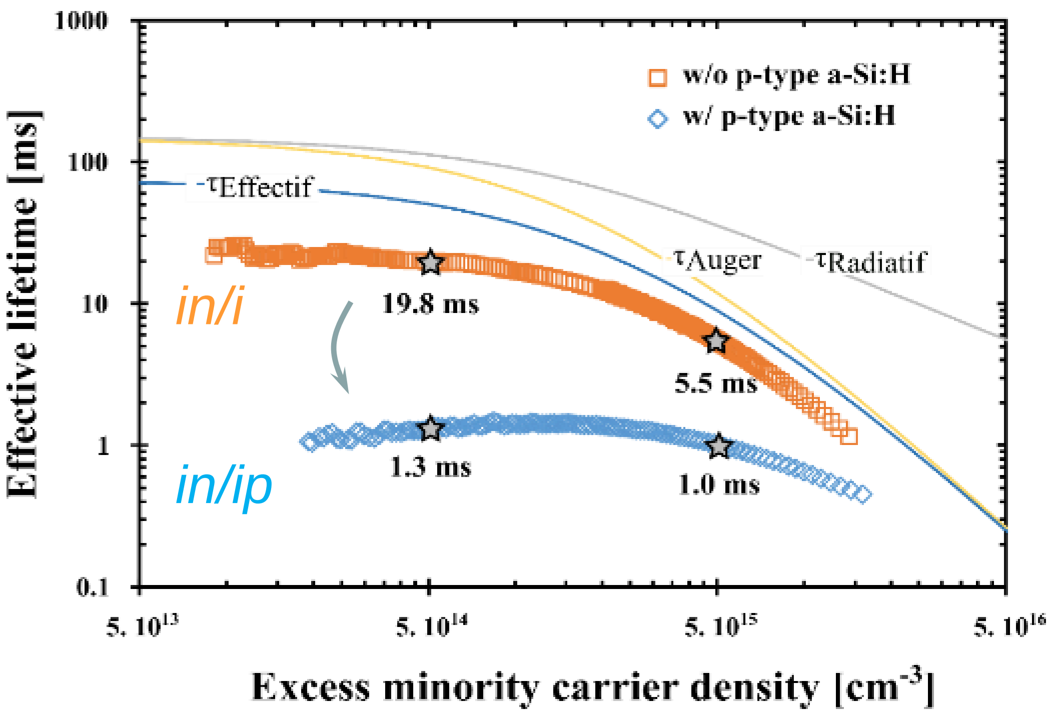
Potential passivation drop after p-layer deposition

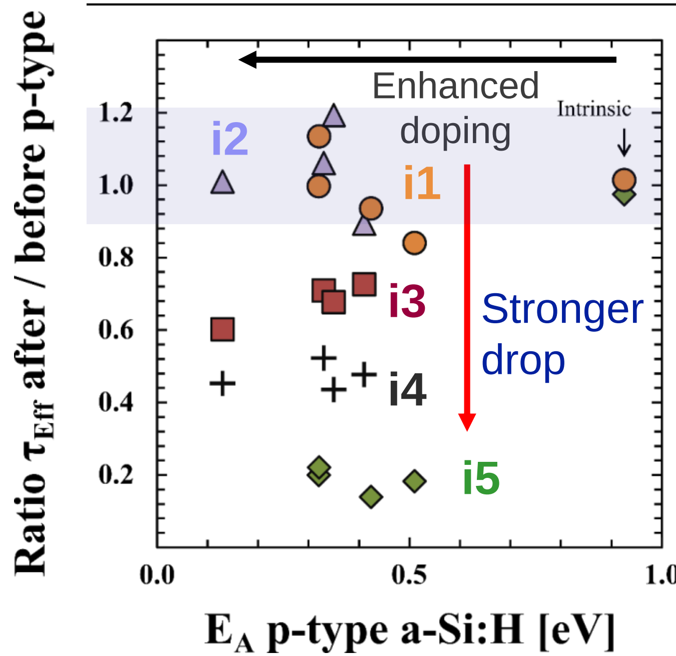
Linked to the

<u>(i) a-Si:H layer properties</u>

Hole-selective passivating contact

		Thickness* [nm]	Band gap [eV]	τ_{Eff} w/o p-type a-Si:H [ms]	τ_{Eff} w/ p-type a-Si:H [ms]
istrong	●	5.9	1.80	6.0	5.1
istrong	▲	7.1	1.83	2.1	2.2
iweak	■	7.4	1.82	4.1	2.8
iweak	+	5.6	1.74	5.3	2.5
iweak	◆	7.2	1.75	5.3	1.3

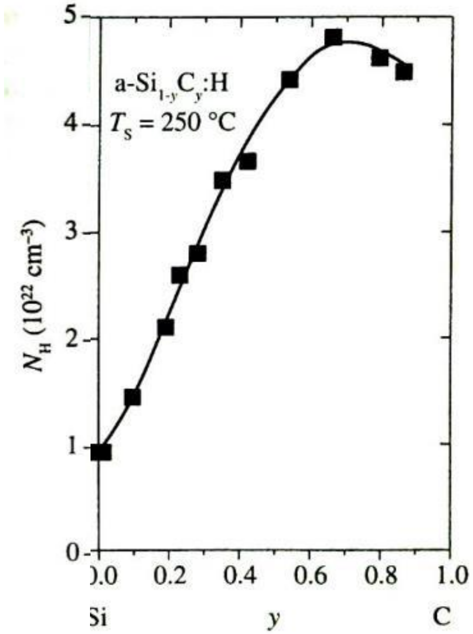


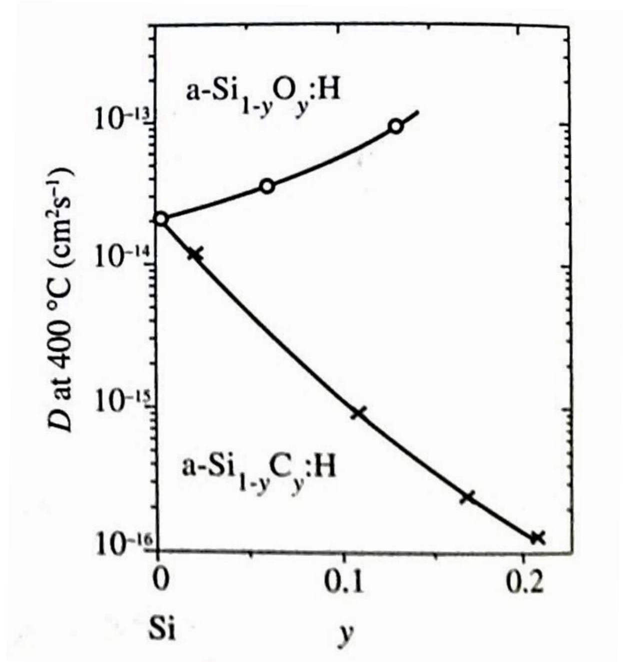


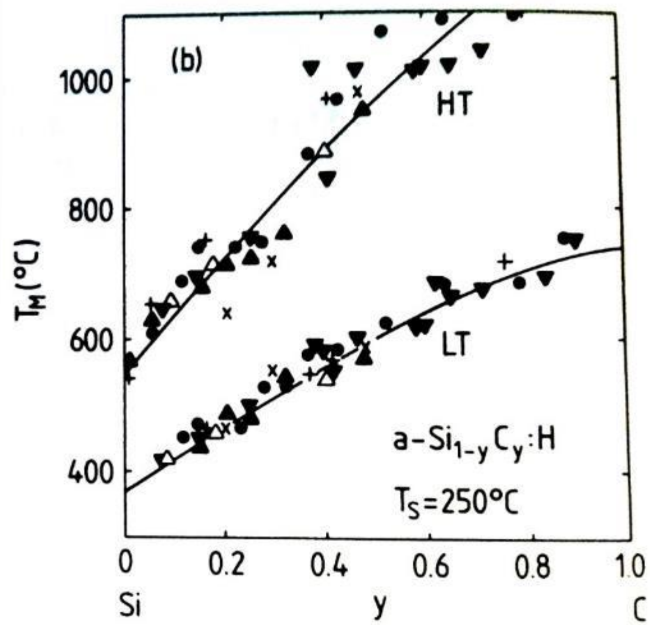
PV-lab IMT NEUCHATEL

ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

Better resilience towards H loss / defect formation





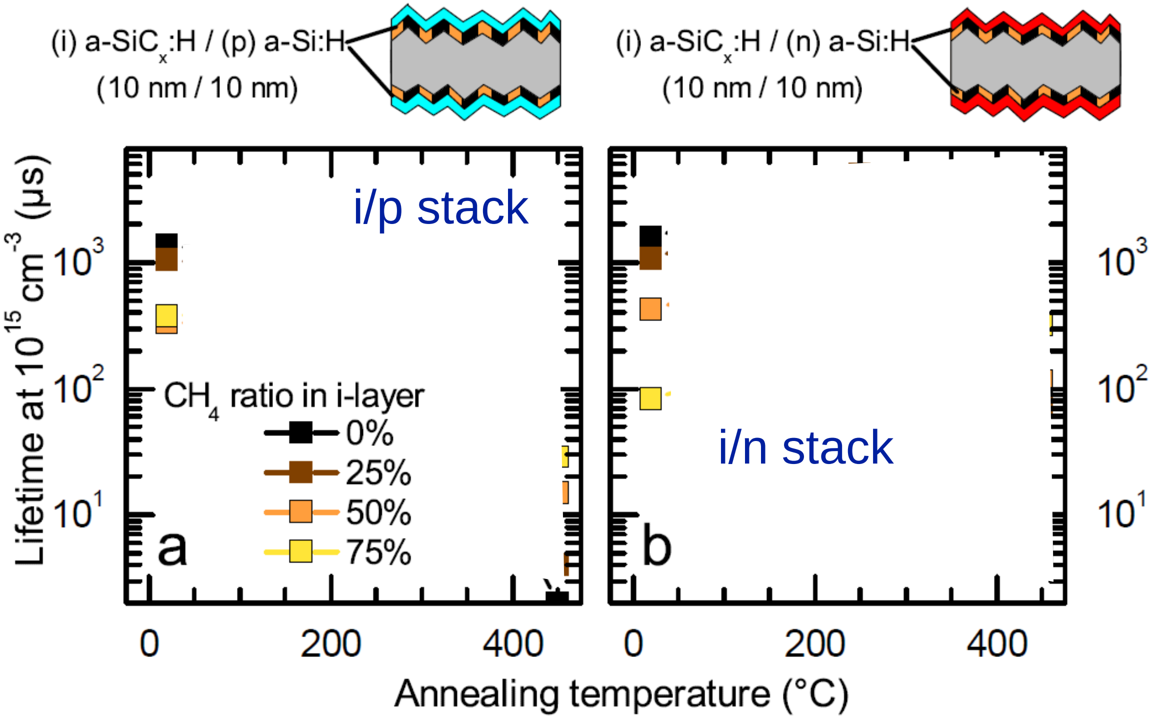


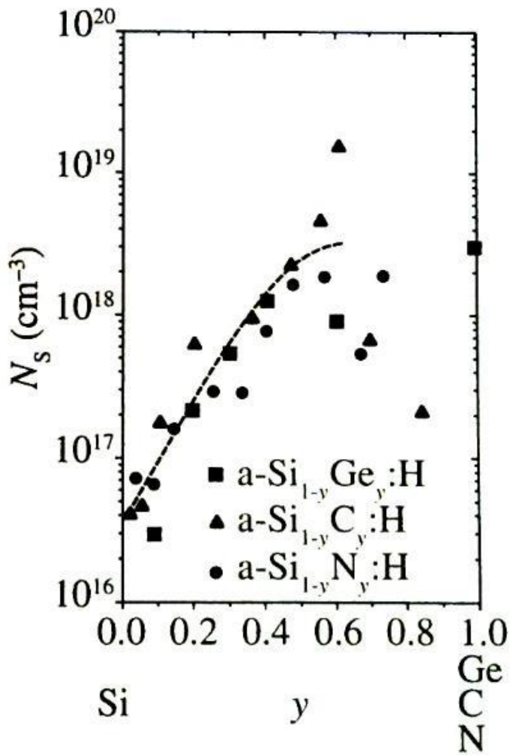
Binding energies:
Si-H : 3.0 eV – 3.2 eV
C-H : 3.4 eV – 3.9 eV

- H incorporation **increases** with C content,
- H diffusion coefficient **decreases** with C content,
- Temperatures of high- and low-temperature H-effusion maxima **increase** with C content.

W. Beyer in *Thin-Film Silicon Solar Cells,* A. Shah, (2010)

Better resilience towards H loss / defect formation



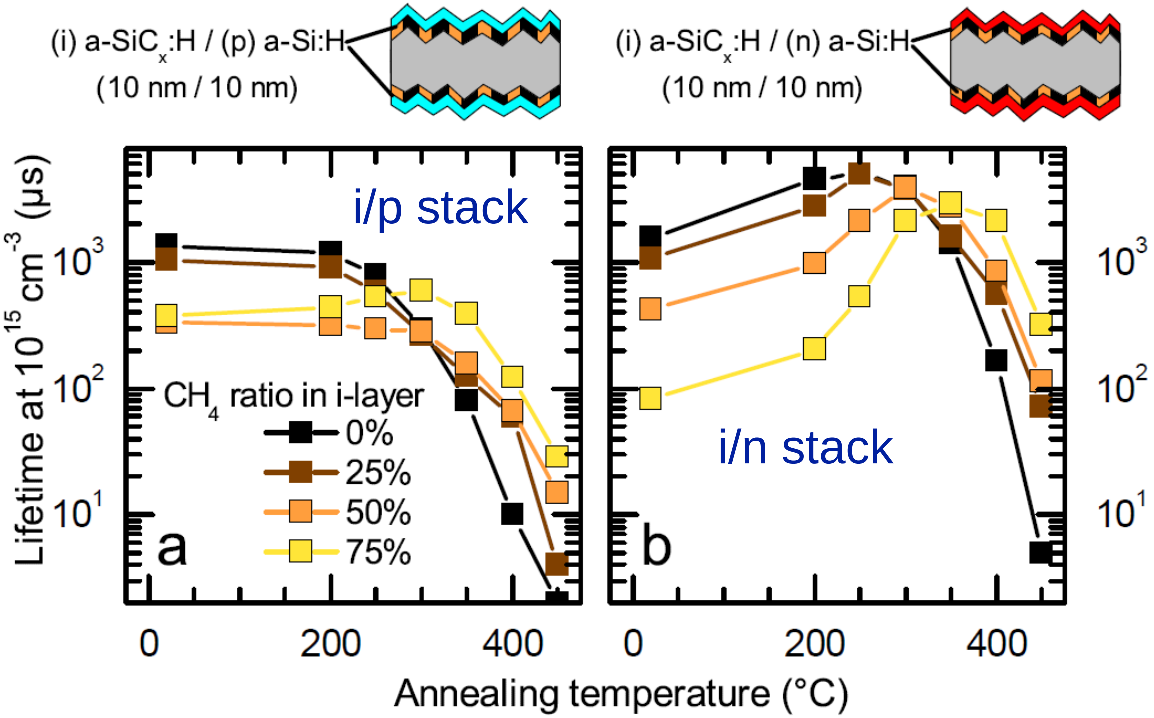


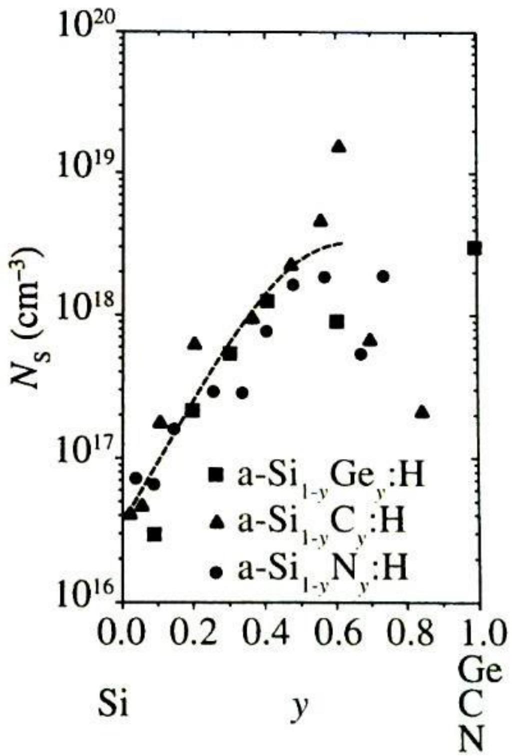
W. Beyer in *Thin-Film Silicon Solar Cells,* A. Shah, (2010)

- passivation scales **down** with CH_4 ratio **initially**,

M. Boccard and Z.C. Holman, *J. Appl. Phys,* **118,** 065704, (2015)

Better resilience towards H loss / defect formation





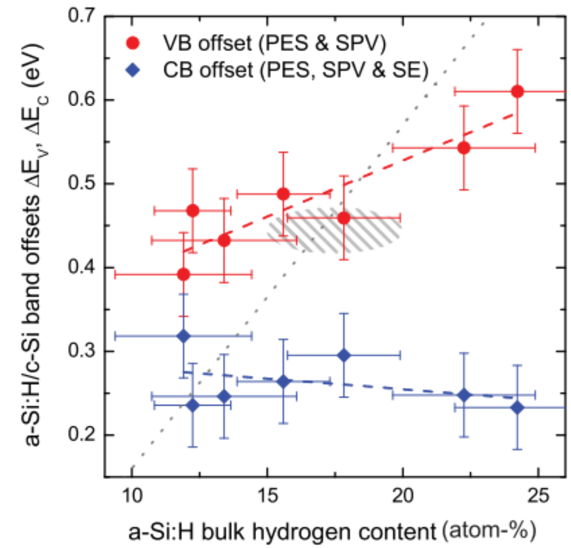
W. Beyer in *Thin-Film Silicon Solar Cells,* A. Shah, (2010)

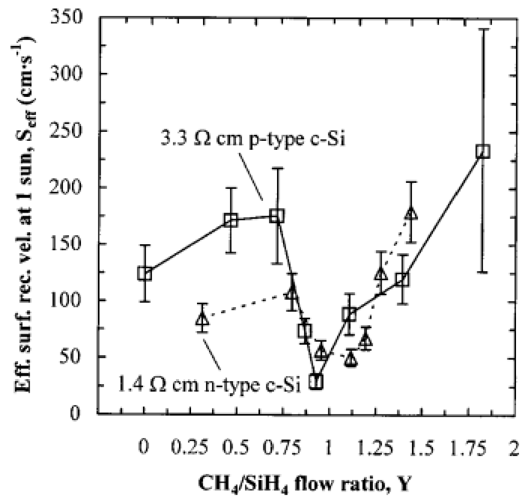
- passivation scales **down** with CH_4 ratio **initially**,
- yet it scales **up** with CH_4 ratio **passed 300 °C**.
- i-p side limits lifetime in all cases.

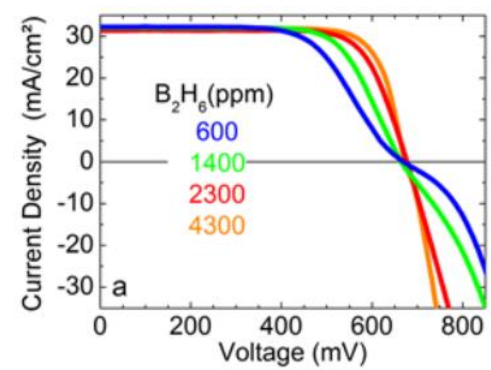
M. Boccard and Z.C. Holman, *J. Appl. Phys,* **118,** 065704, (2015)

Further readings

- Fundamentals of passivation
  - De Wolf *et al.*, many more papers
  - Schultze, T. et al., many papers
- Doped layers influence
  - Reusch et al., Energy Procedia 38 (2013)
  - Bivour et al., Solar Energy Materials & Solar Cells (2012)
  - Barraud et al.
- a-SiC:H / a-SiO:H
  - Martin et al.,
  - Mews et al.,
  - Mazzarella et al.,
  - Seif et al.,
- … many more







Process flow

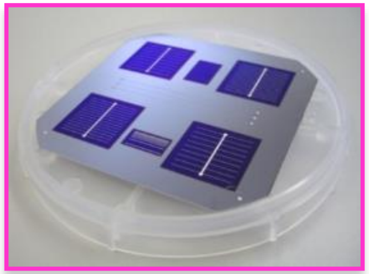
Chemical baths
c-Si surface preparation

PECVD I
Intrinsic film deposition a-Si:H(i)

PECVD II
Doped film deposition a-Si:H(n/p)

PVD
TCO sputtering

Metallization
Screen printing and curing at 200° C



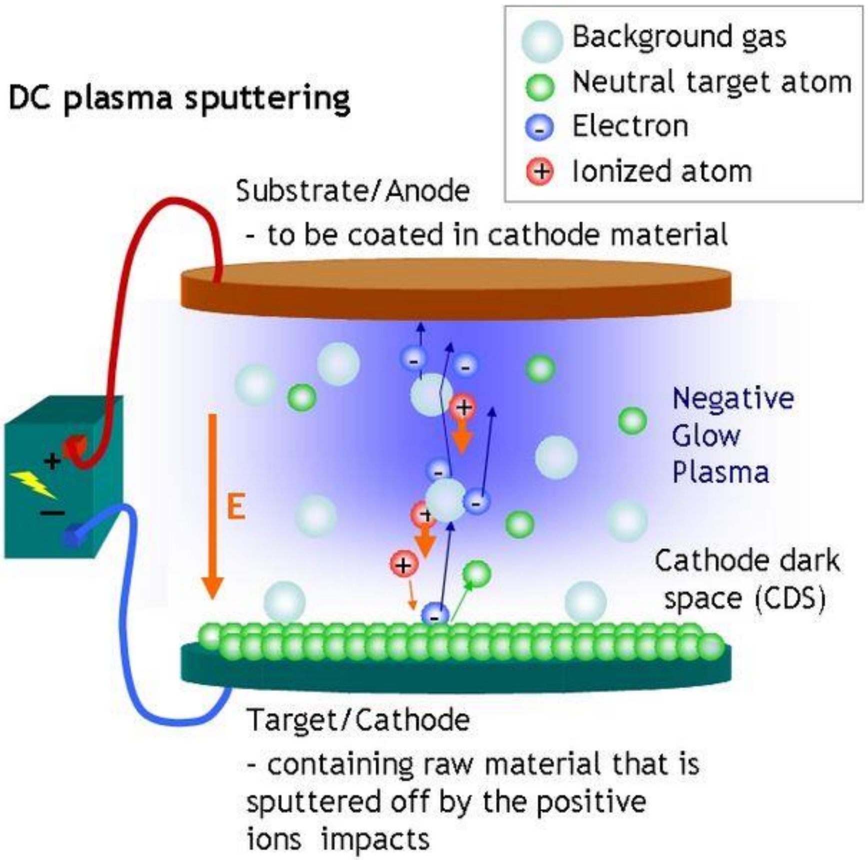
Sputtered TCO

Transparent conductive oxide deposition

Process:
usually done by sputtering
(also known as physical vapour deposition)

Variants include DC and RF-sputtering
(shown example is DC sputtering)

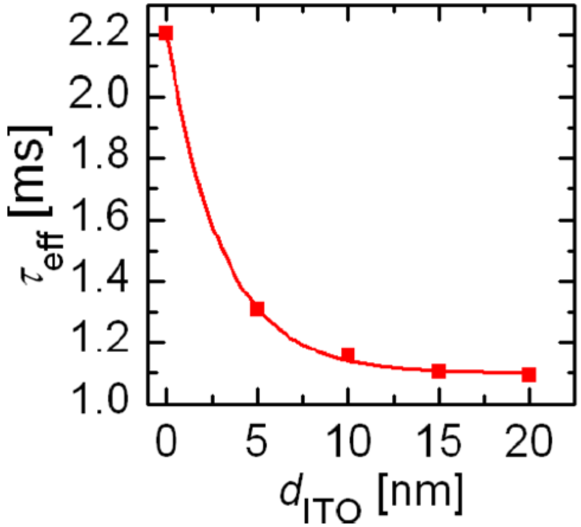
Typical target-material: indium-tin-oxide (ITO)

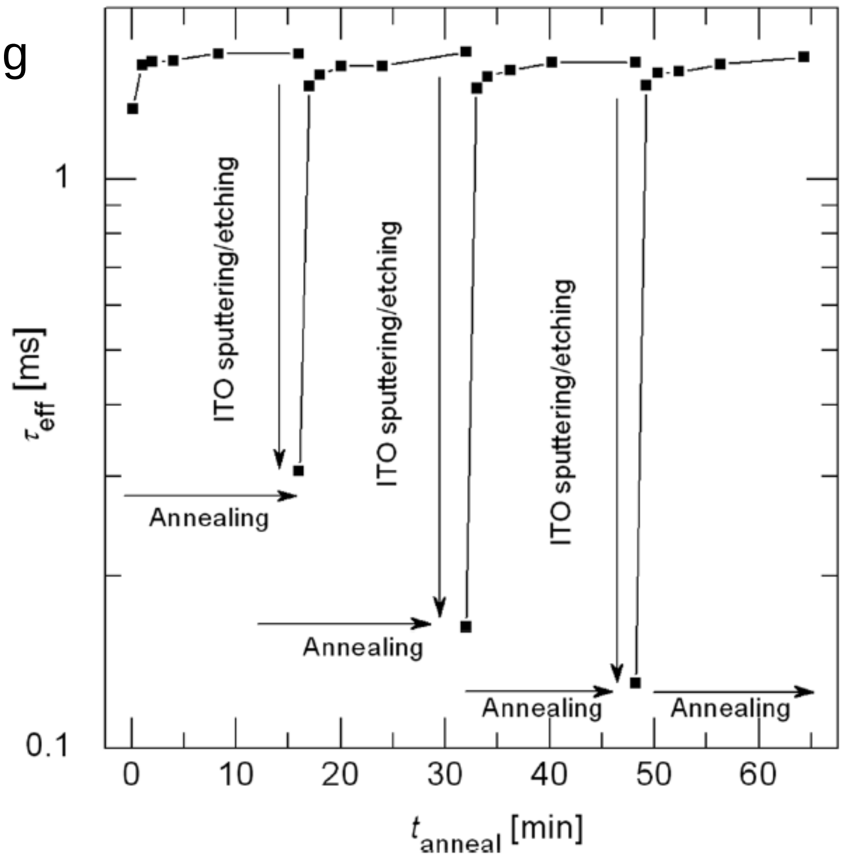


See e.g. M. Ohring, "Materials Science of Thin Films", 2nd Ed., Academic Press (2002)

Sputtered TCO

- Electronic passivation losses by sputtering
- Cause: plasma UV illumination + …
- Curing → passivation restored

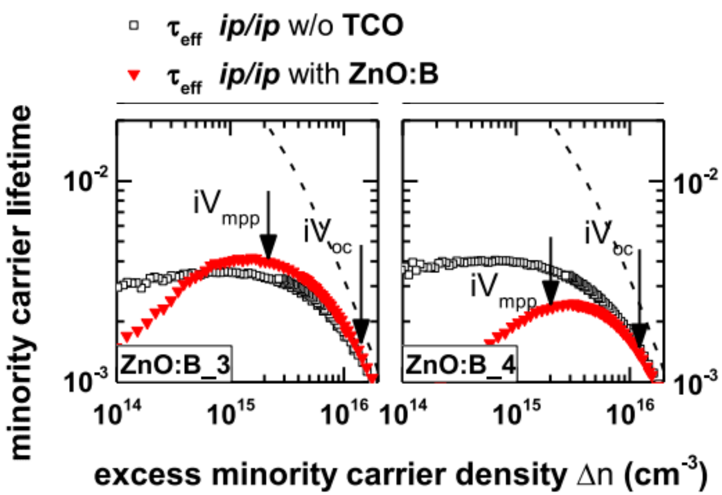




[Demaurex, *et al*. APL **101**, 171604 (2012)]

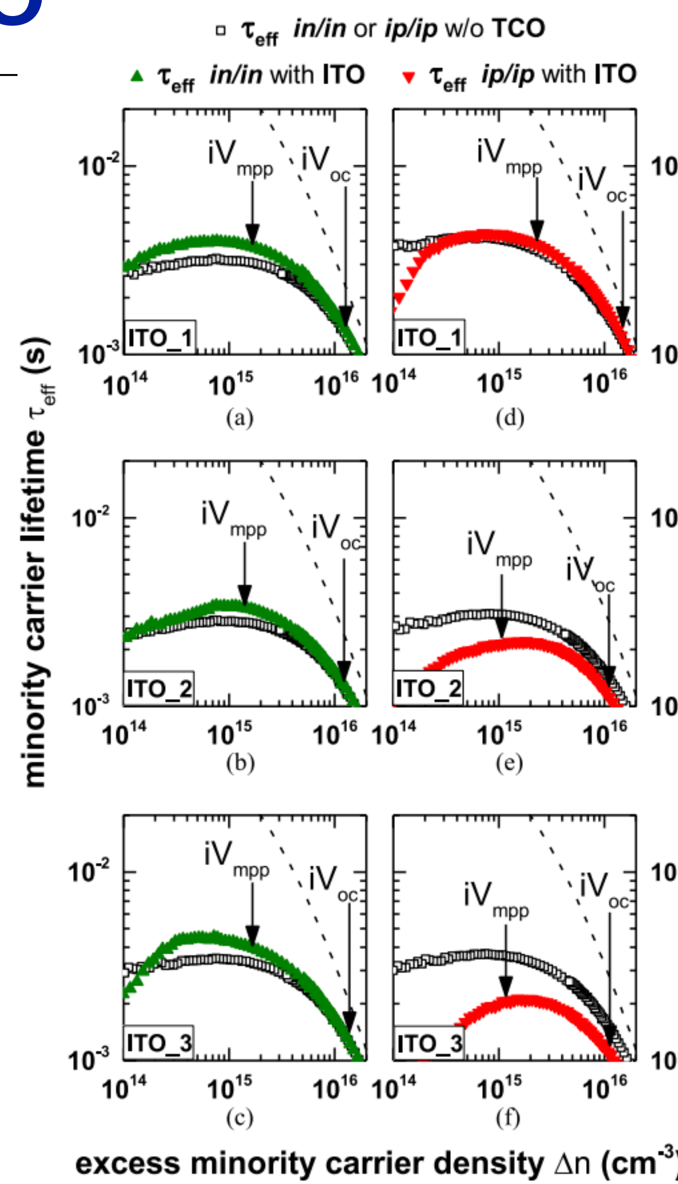
Sputtered TCO

- Electronic passivation losses by sputtering
- Cause: plasma UV illumination + …
- Curing → passivation restored
- …Not always !



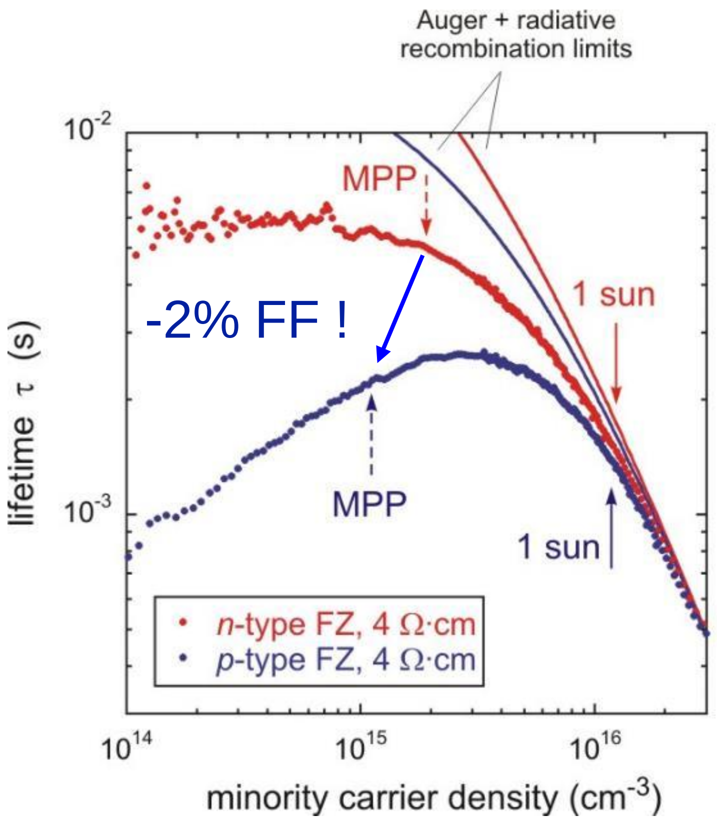
- Also occurring for "soft" deposition

Higher carrier concentration



[Tomasi, *et al*. IEEE JPV, (2016)]

Passivation : impact on FF



$$V^{implied} = \frac{kT}{q}\ln\left(\frac{(n_0 + \Delta n)(p_0 + \Delta p)}{n_0 p_0}\right)$$

- At open circuit → V_{oc}
- At max powerpoint → V_{mpp} → FF

[A. Descoeudres *et al*, IEEE JPV **3**, 83 (2013)]

To obtain high FF : high V_{oc} not sufficient, high lifetime at MPP required as well

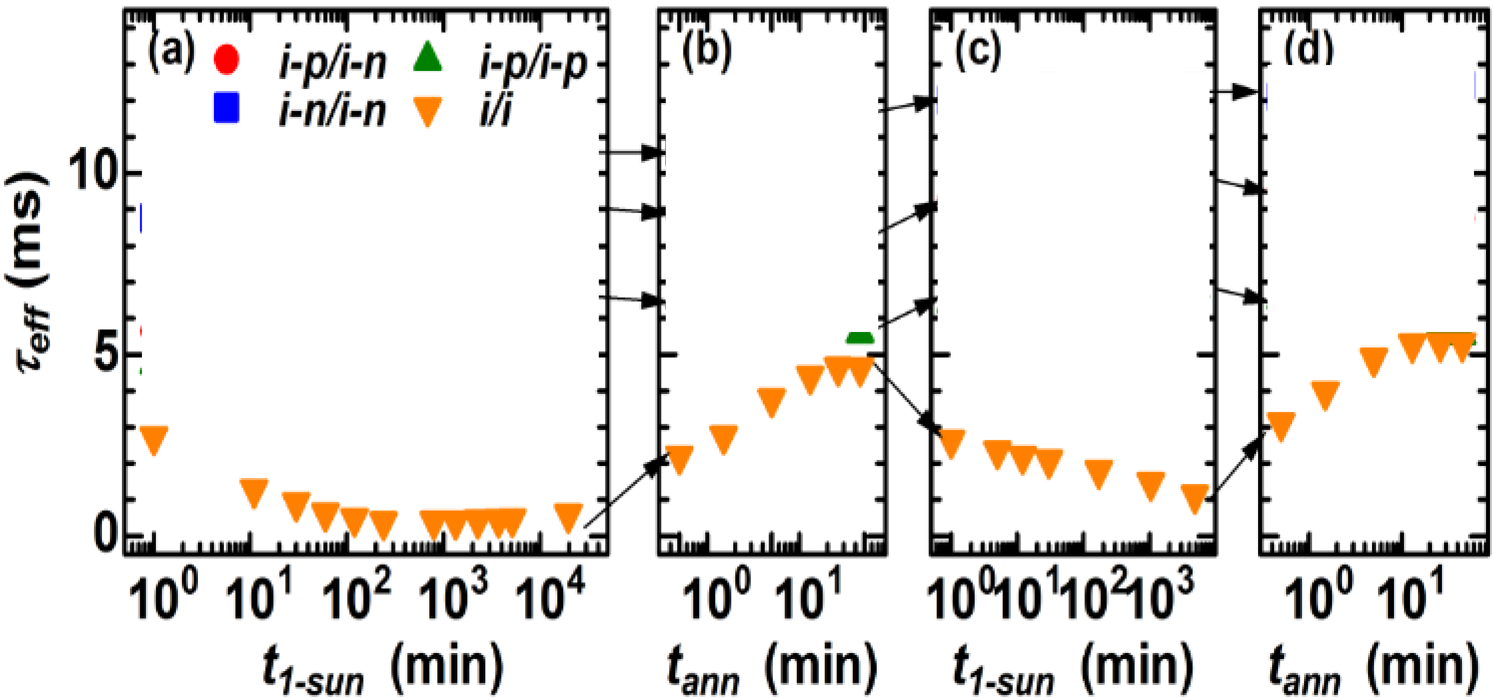
Light annealing effects on SHJ precursors: i-layer

AIP Applied Physics Letters

Kobayashi et al. APL 2016

Light-induced performance increase of silicon heterojunction solar cells

Eiji Kobayashi, Stefaan De Wolf, Jacques Levrat, Gabriel Christmann, Antoine Descoeudres, Sylvain Nicolay, Matthieu Despeisse, Yoshimi Watabe, and Christophe Ballif



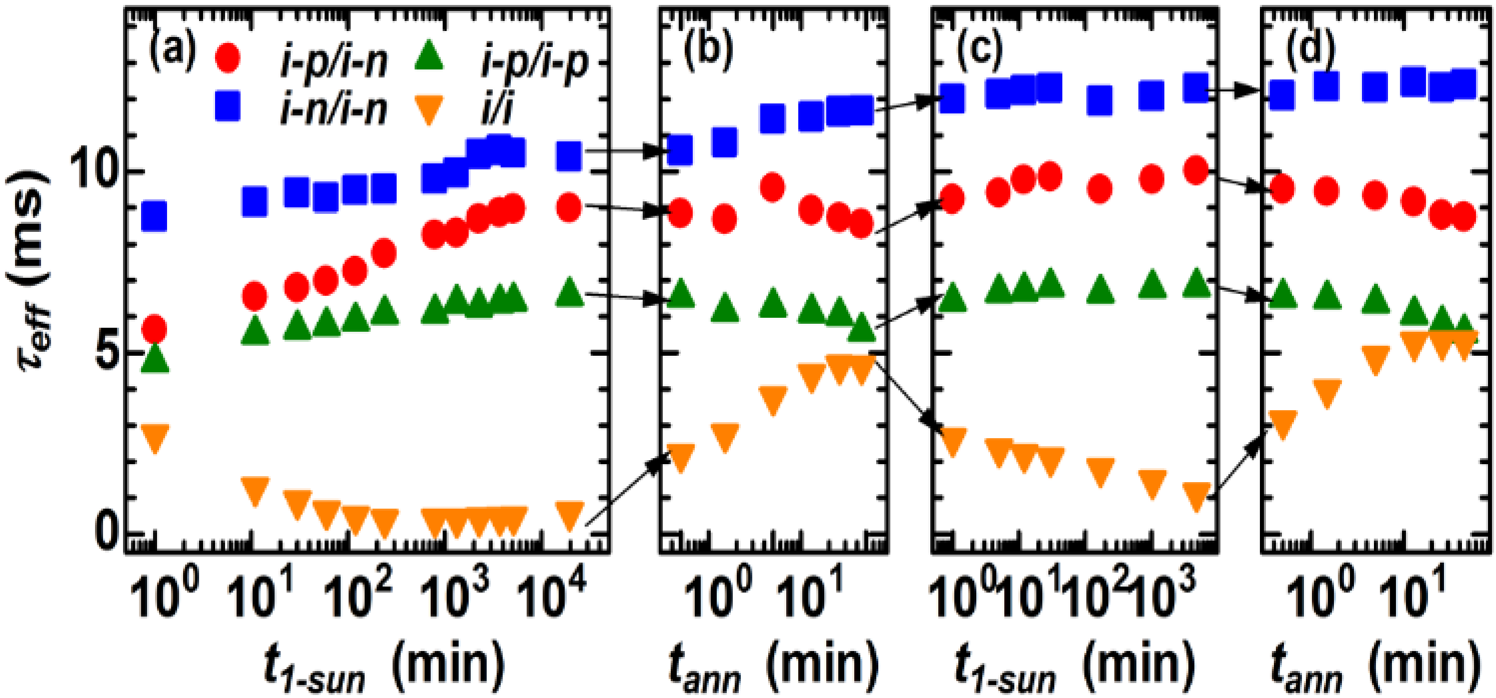
Lifetime **decrease** (= surface passivation decrease)

With intrinsic layers ▼

See also. **De wolf et al. 2006-2015**

Light annealing effects on SHJ: change with doped layers

Kobayashi et al. APL 2016



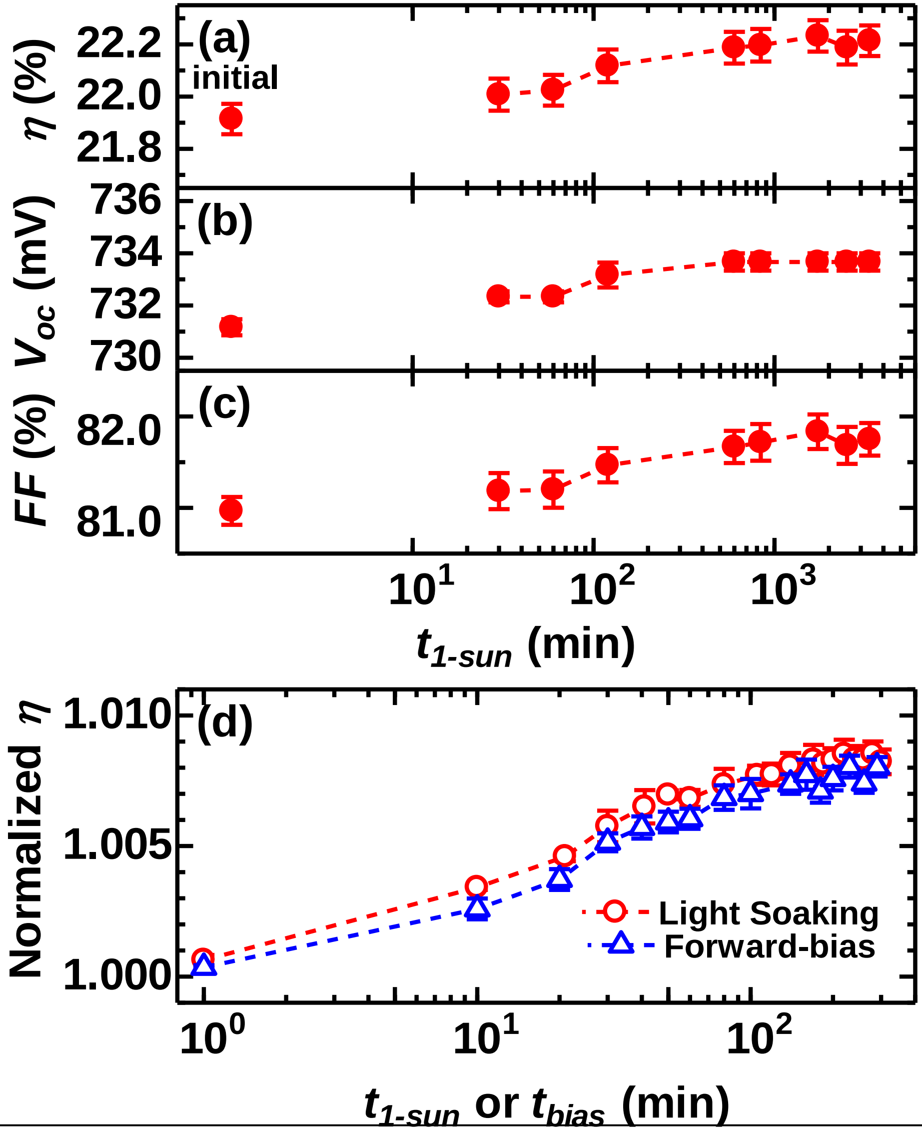
Lifetime increase with doped layers n and p layer !

Efficiency increase under light soaking

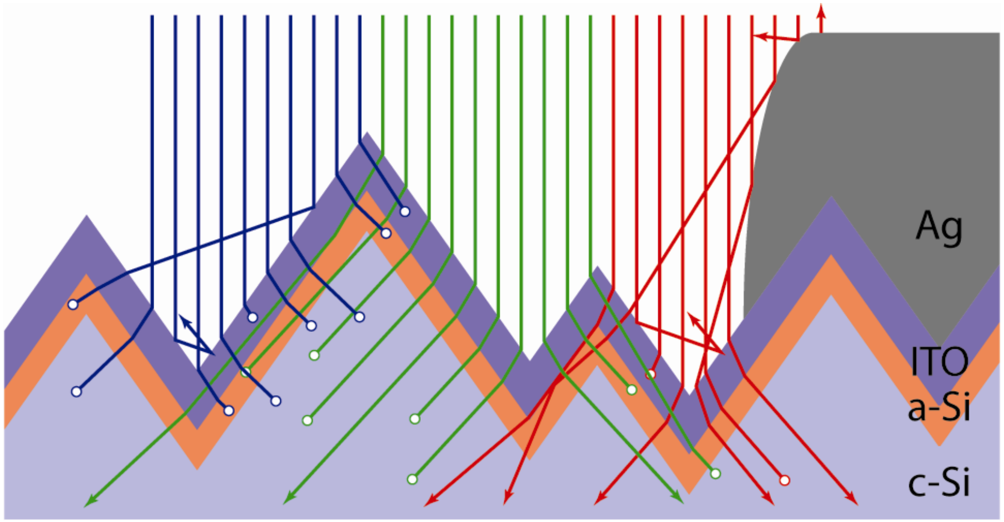
- **SHJ efficiency increase under**
- **light soaking or**
- **recombination current**

- **Typically 1-1.5% relative increase !**

- **Still not fully understood…**

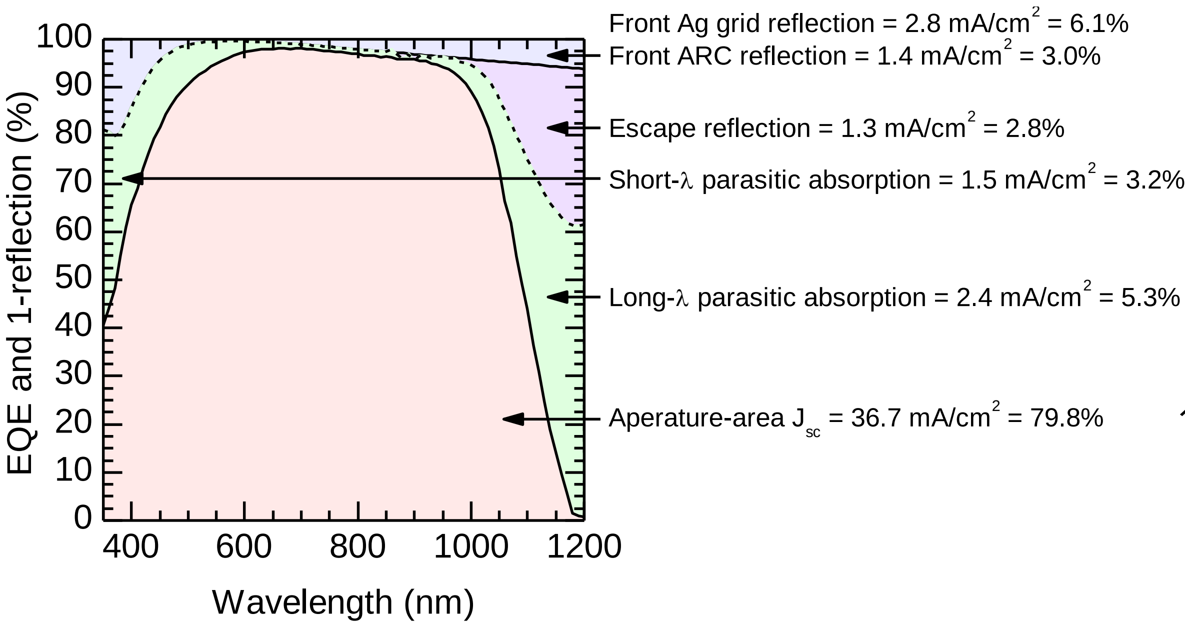


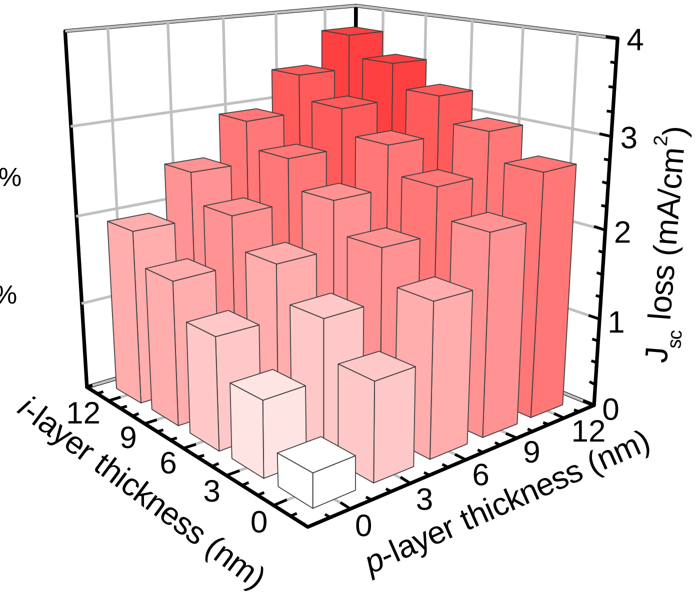
Light management



- Reflection from Ag grid and TCO anti-reflection coating
- UV and blue parasitic absorption in front *a*-Si layers
- UV and IR parasitic absorption in front TCO; IR parasitic absorption in rear TCO
- Incomplete trapping of IR light

Current losses at the front





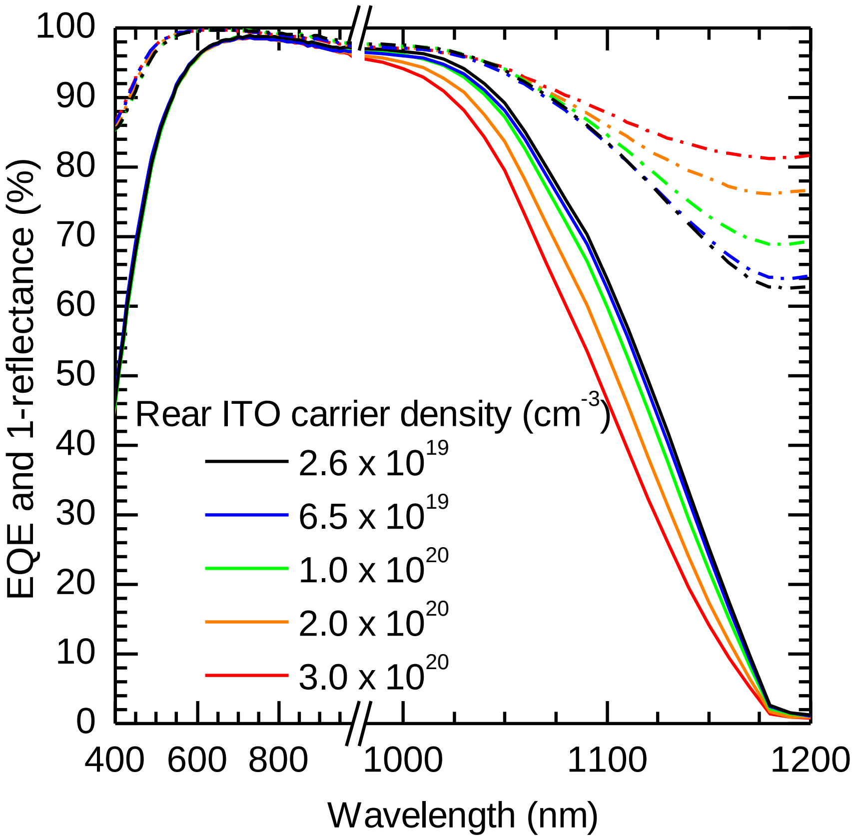
- Over 2 mA/cm^2 is lost in an optimized heterojunction cell

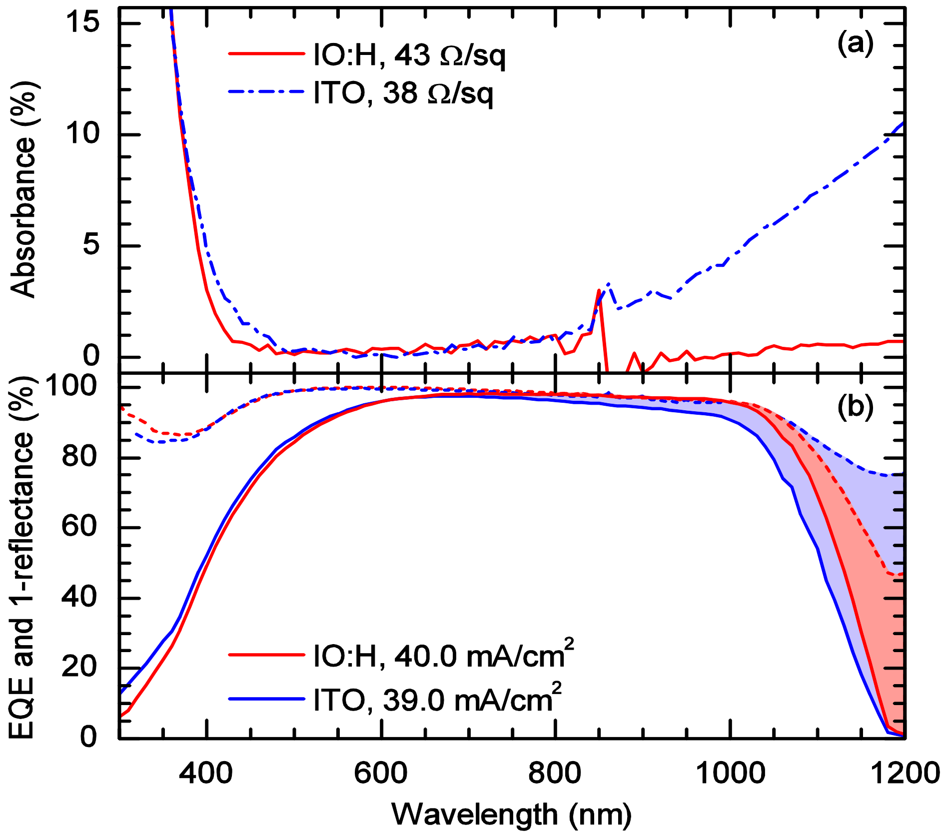
    → due to parasitic absorption in the front layers

- All light absorbed in ITO and *p*-layer is lost, ~70% of light in *i*-layer is lost
- Model allows us to predict UV/blue current loss for arbitrary layers, provided optical constants are known

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

Current losses at the front





- Free-carrier absorption erodes J_{sc}
- Replace ITO with IO:H or other high mobilty TCO

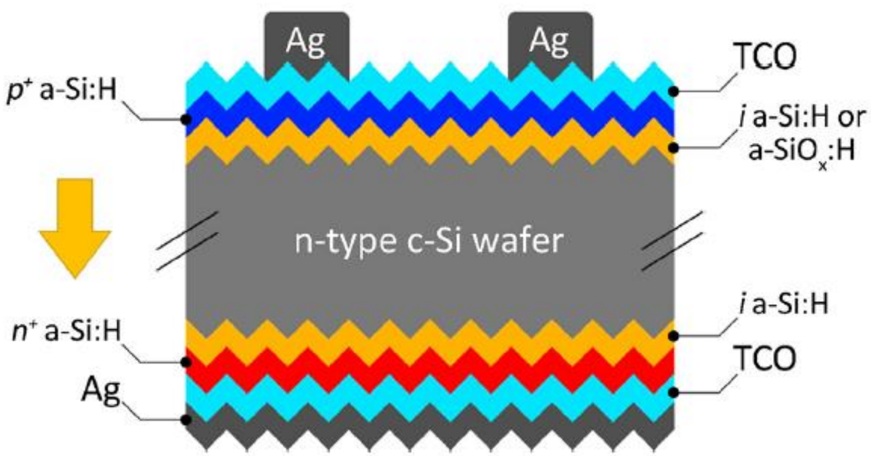
[T. Koida *et al*, JJAP (2008);

L. Barraud *et al.*, SOLMAT (2013).]

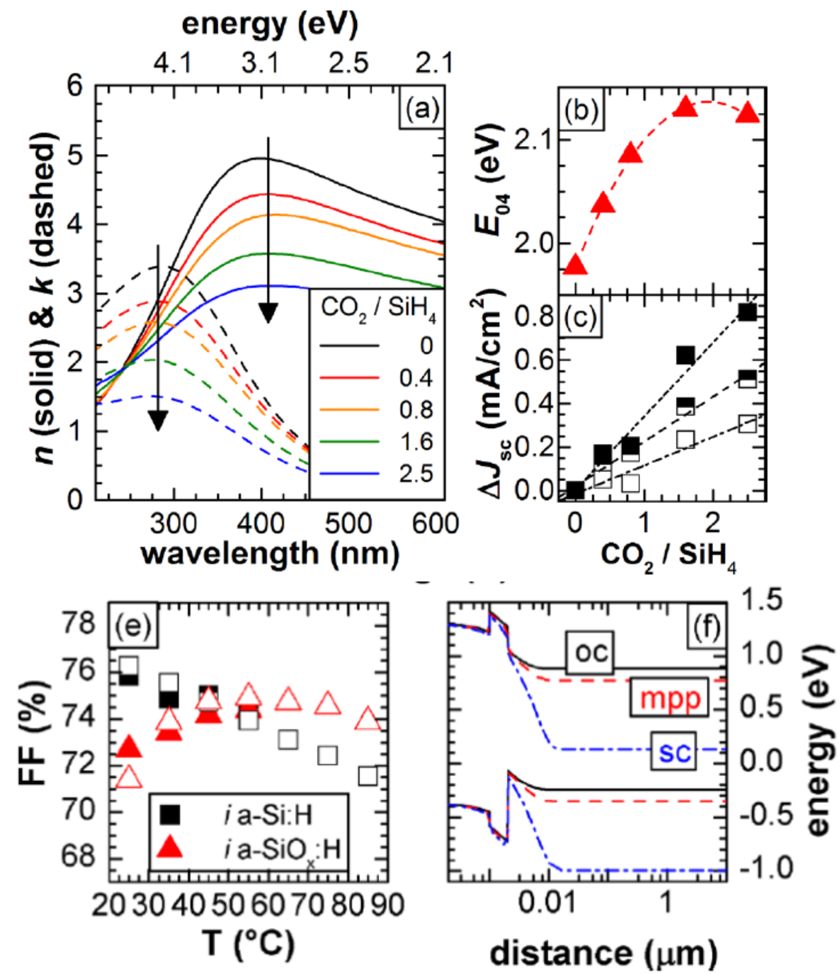
Current losses at the front

Reduction of parasitic absorption through single-, mixed-phase and alloyed materials: **microstructure and band gap variation**

- (i)a-SiO:H



- Doped μc-Si:H
- Doped and intrinsic μc-SiO_x:H and a-SiO_x:H
- Doped a-SiC:H

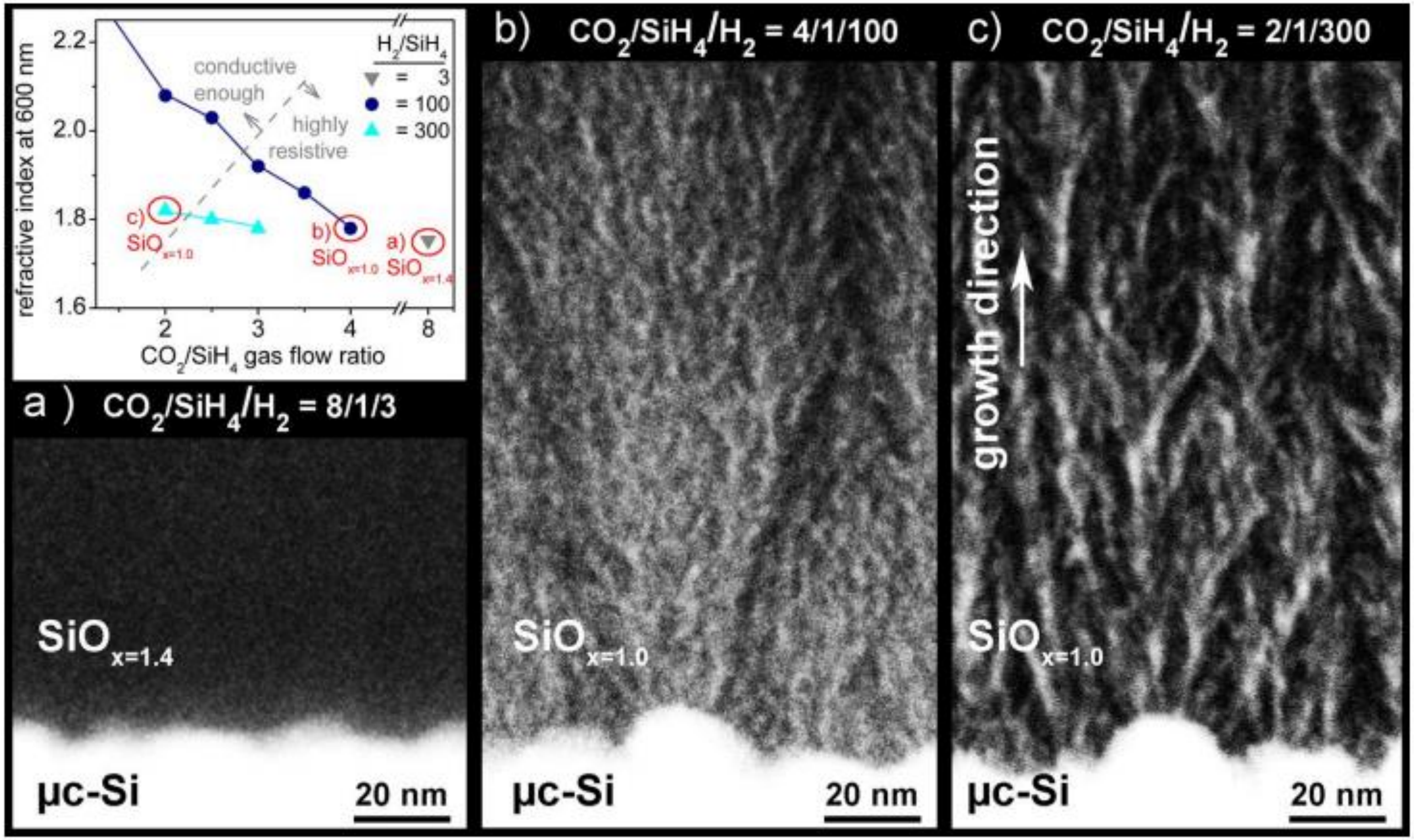


[Seif et al., Mazzarella et al., Van Cleef et al.…]

[J.P. Seif *et al.*, JAP **115**, 024502 (2014).]

Current losses at the front

Nano-crystalline SiO layers

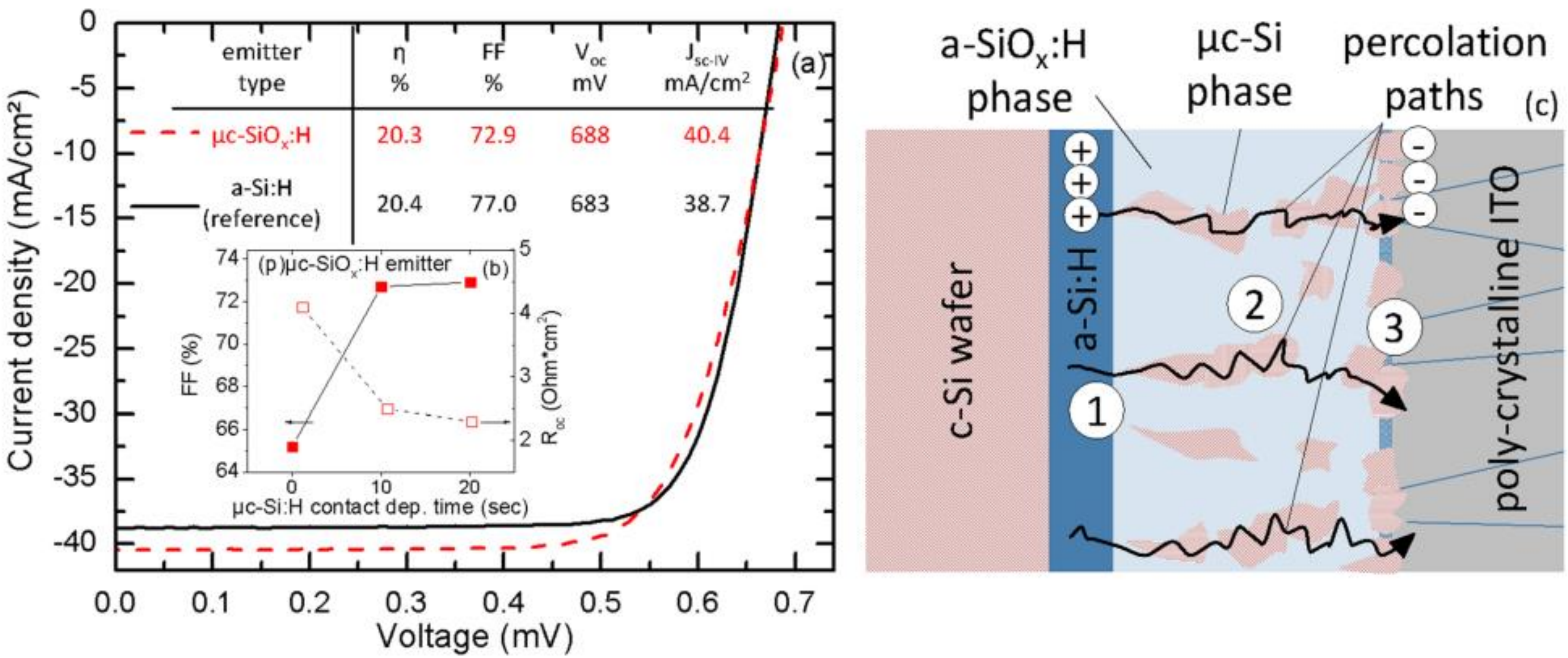


[Kaneka patent !]

[P. Cuony, PhD thesis, EPFL, 2010]

Current losses at the front

Nano-crystalline SiO layers

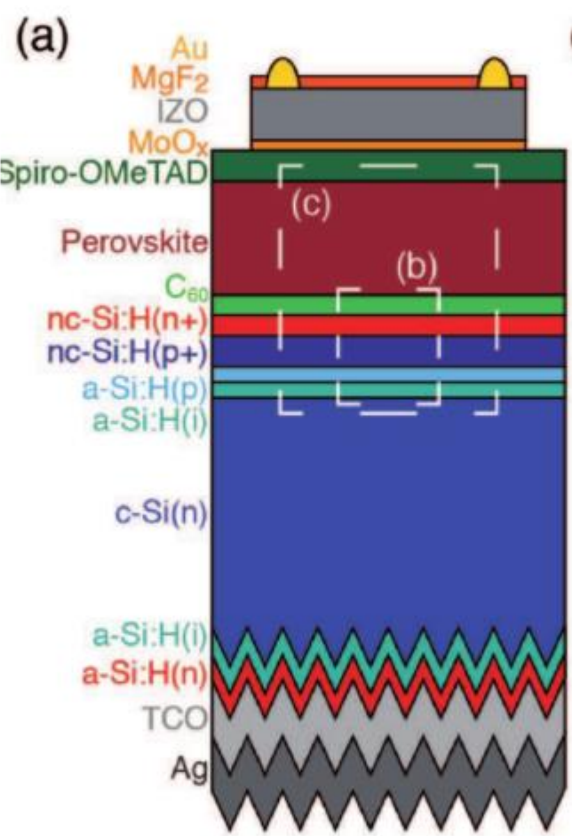


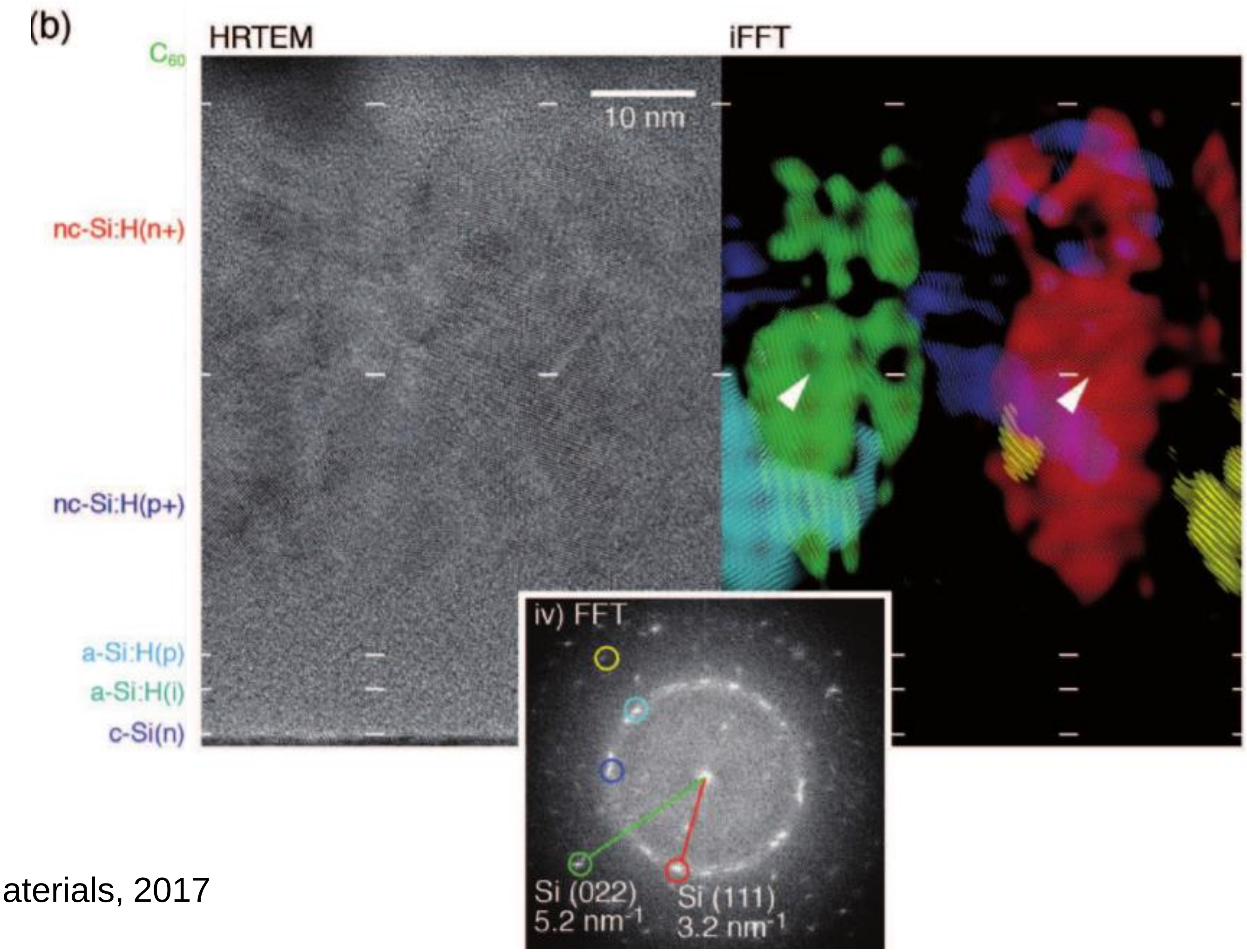
Jsc gain but FF drop…

[L. Mazzarella, APL106, 023902 (2015)]

Current losses at the front

- Preventing the need for transparent window contact: Tandems!

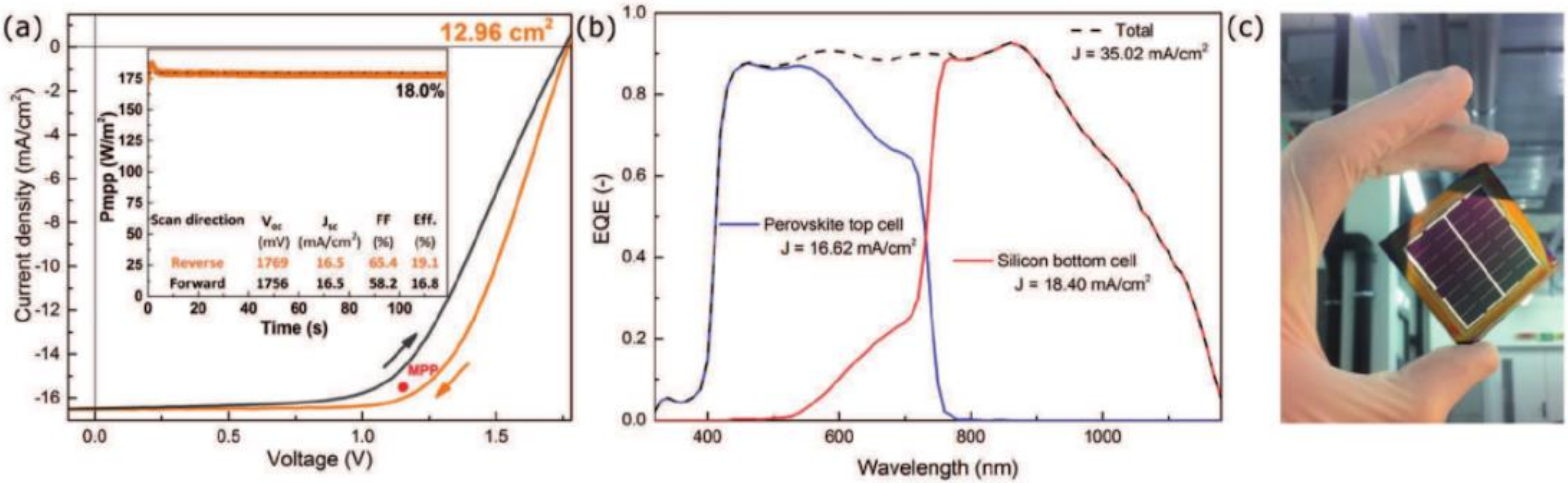




F. Sahli *et al.* Adv. Ener. Materials, 2017

Current losses at the front

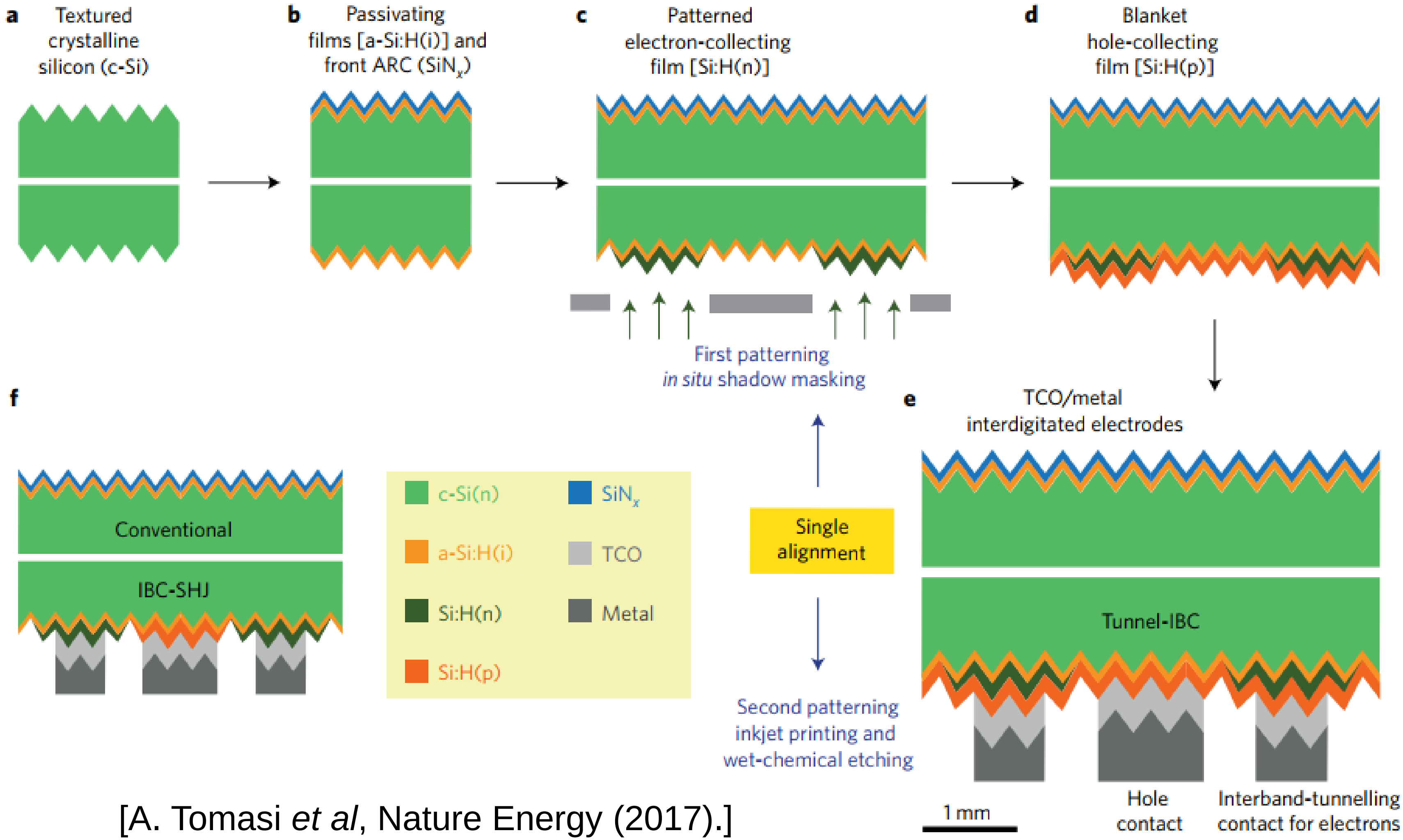
- Preventing the need for transparent window contact: Tandems!
  - Lower shunting → easier large-area integration
  - better optical coupling → higher photocurrents



F. Sahli *et al.* Adv. Ener. Materials, 2017

Current losses at the front

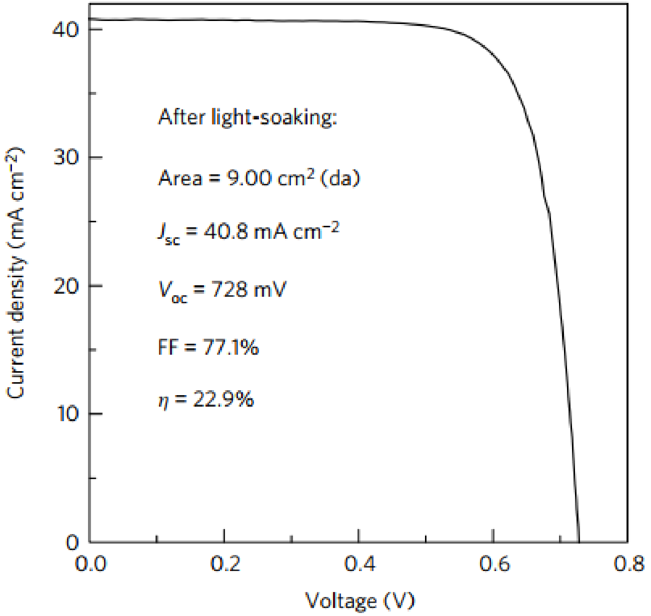
- Preventing the need for transparent window contact: IBC !

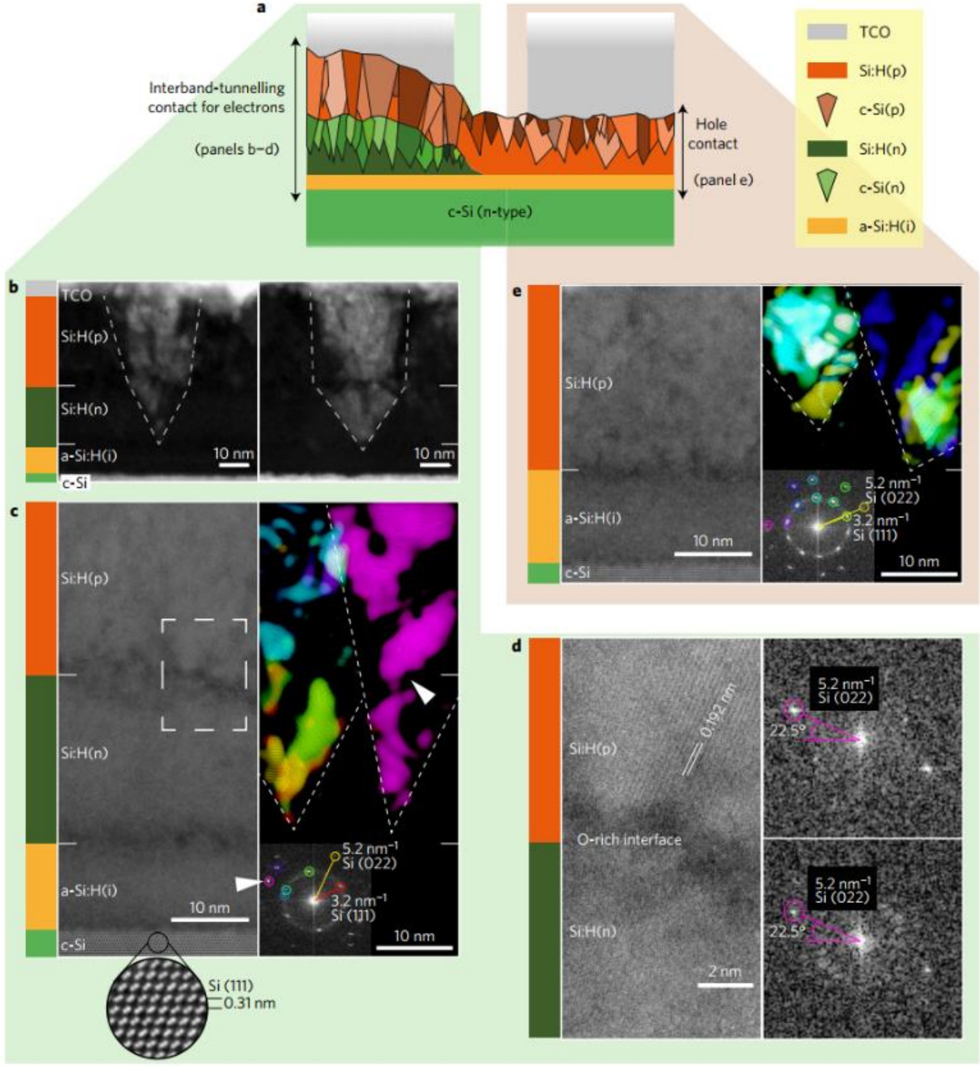


[A. Tomasi *et al*, Nature Energy (2017).]

Current losses at the front

Fully back contacted solar cells

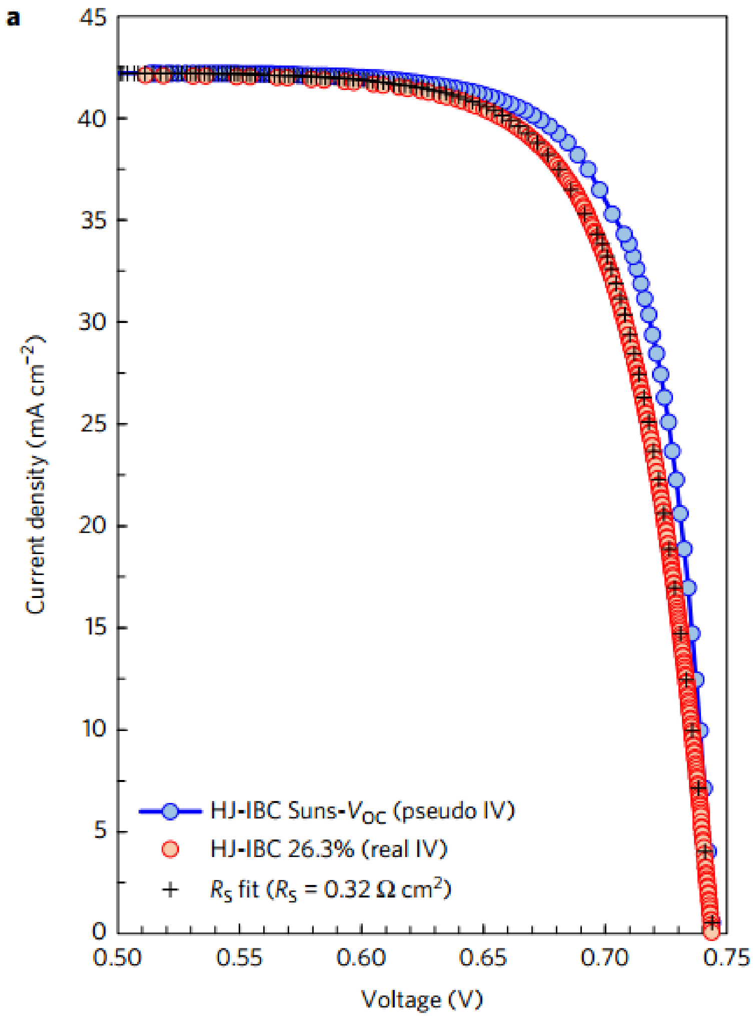


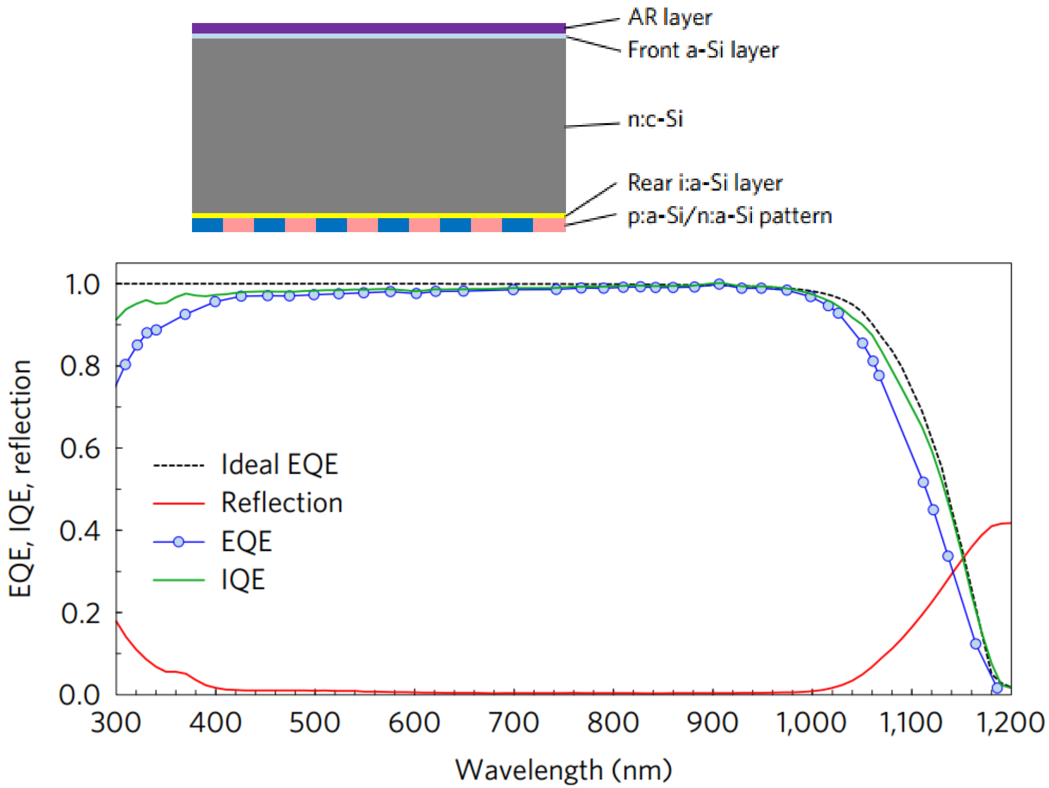


[A. Tomasi *et al*, Nature Energy (2017).]

Current losses at the front

Rear-contacted SHJ





Optimized process
→ Ultra-low Rs and optical losses

[Yoshikawa *et al*, Nature Energy (2017).]

Conclusion and perspective

Old / New technology
- 25 years from invention to large-area world record / module efficiency world record
- Tremendous TF-Si knowledge as background
- Good perspectives for large-scale production ?

Delicate process
- “Secret” to high FF mastered by a couple of (Japanese) companies…
- Good passivation for thin layers requires lots of know-how
- Still many open questions on the physics of passivation

Opportunities
- Lots of knowledge on contacts to gather for all PV technologies
- There **must be** better alternative contacts to a-Si:H

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