Technische Universiteit Eindhoven University of Technology

Solar cell innovations by nanolayers

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www.tue.nl/pmp

Where innovation starts

Presentation prelude

- In the Netherlands, we have a rich tradition and a strong position in the field of thin film materials
  - Also for the field of solar energy
  - Both academically and industrially
- Many technological innovations driven by advances in "materials"
  - Also true for solar cells
  - Currently strong focus on nanoscale materials
- In this presentation: discuss how solar cell innovations have been enabled by nanolayers and will continue doing so!
- Will do so from a personal perspective and by taking big leaps

TU/e Technische Universiteit Eindhoven University of Technology

Outline – trends to be discussed

#1 From Al-BSF to PERC cells

#2 PECVD and ALD Al_2O_3 passivation layers

#3 Towards *n*-type silicon cells

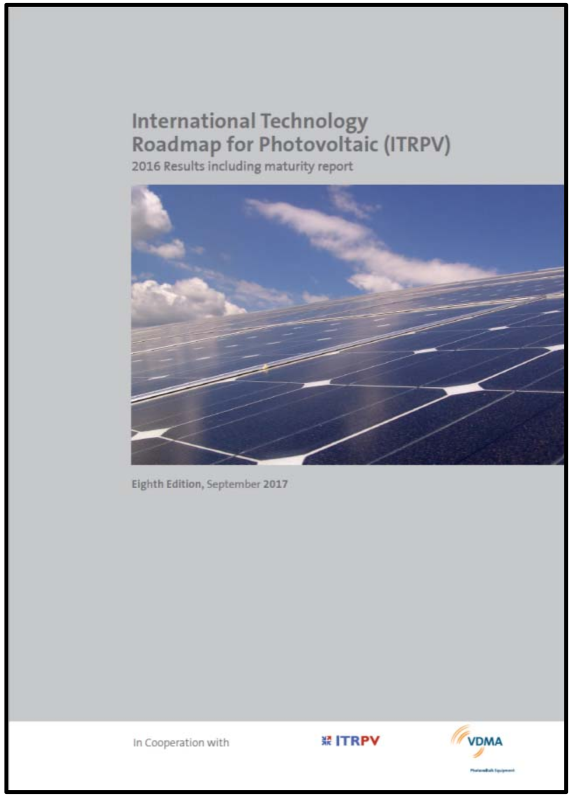
#4 Towards silicon heterojunction cells

#5 Towards interdigitated back-contact cells

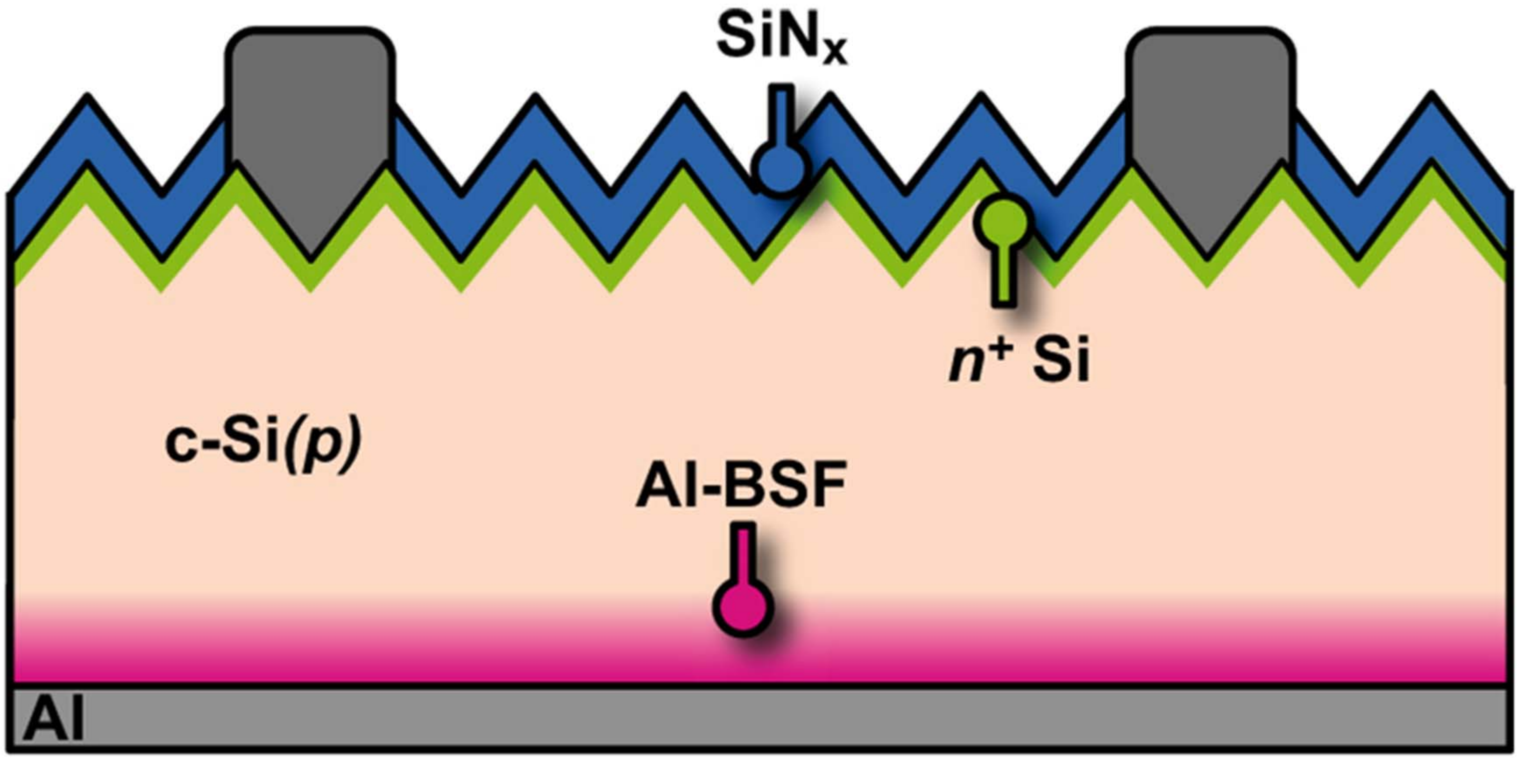
#6 Towards silicon based tandem cells

#7 Towards perovskite solar cells

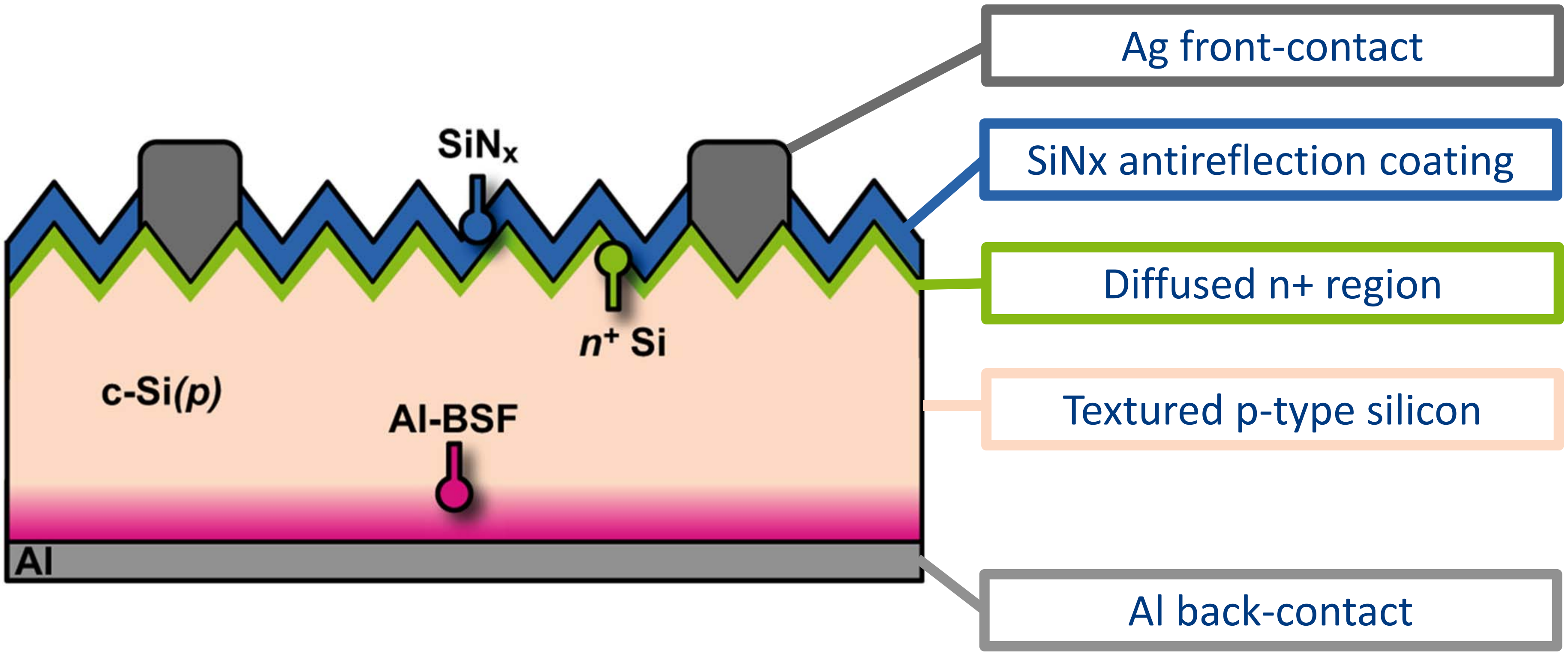
ITRPV
International Technology Roadmap for Photovoltaic



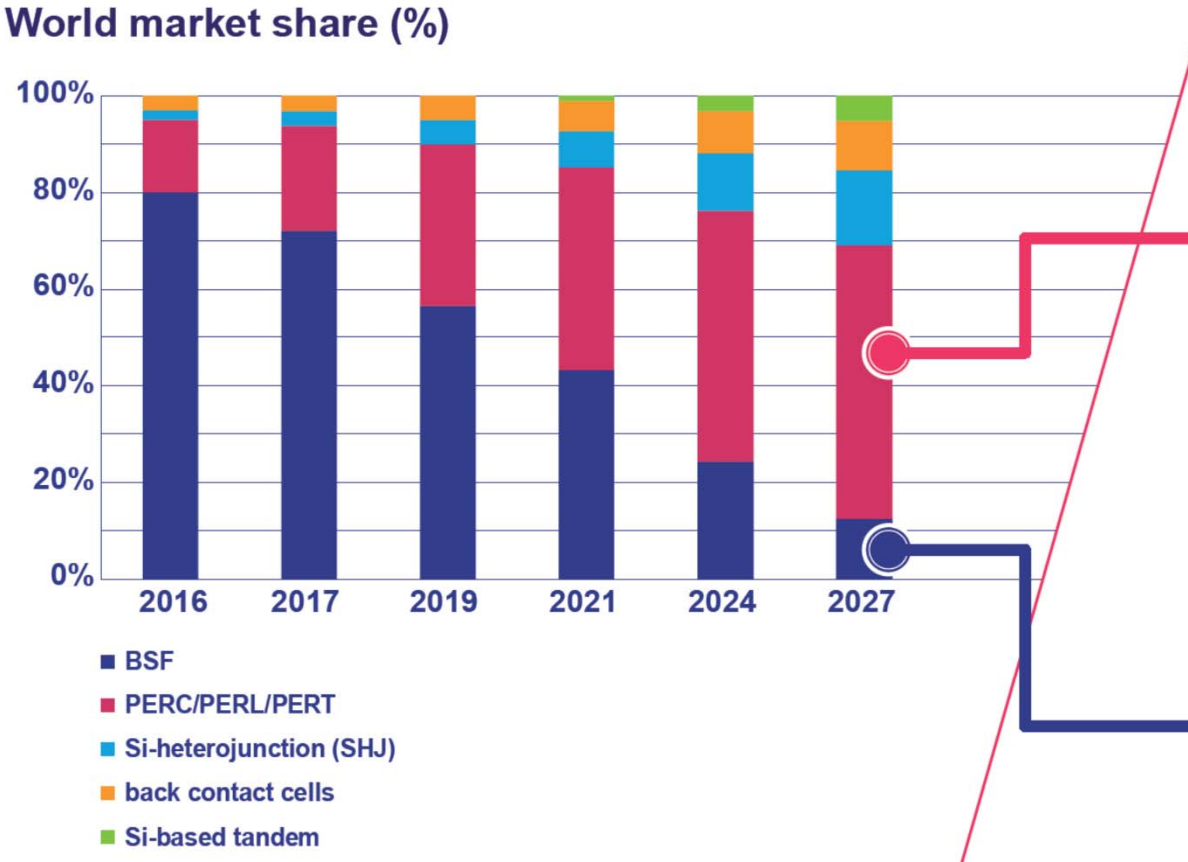
The Al-back-surface-field (Al-BSF) solar cell

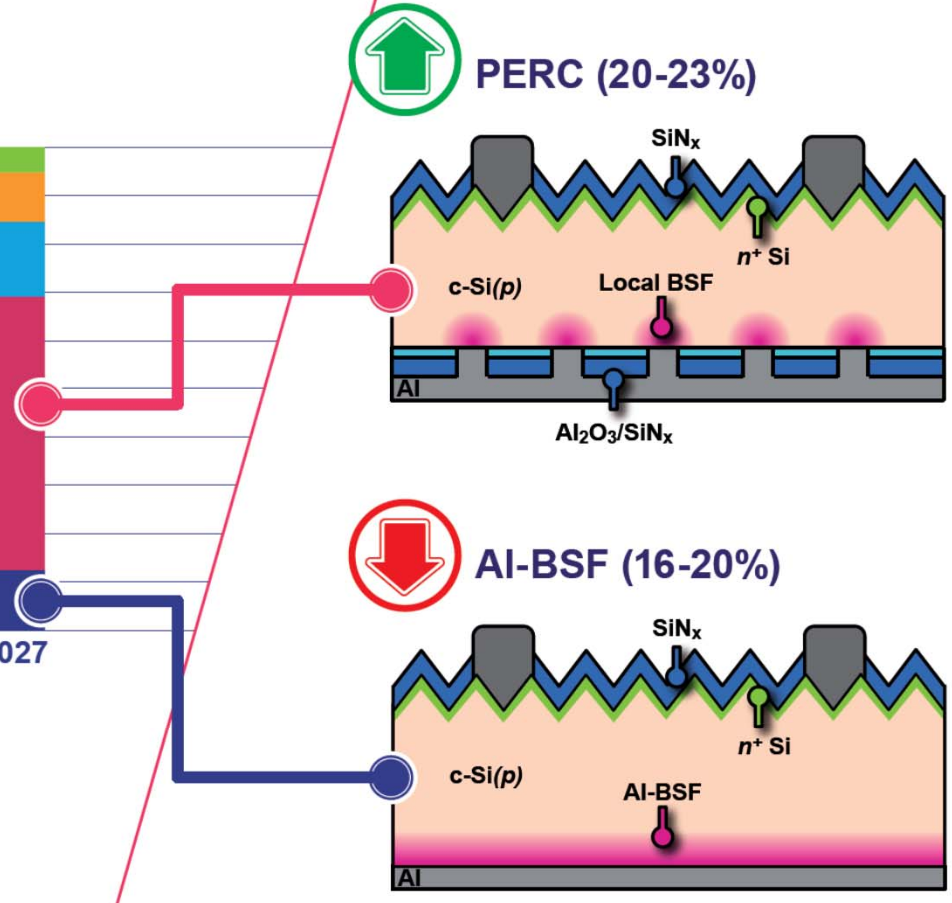


The Al-back-surface-field (Al-BSF) solar cell



Trend #1: From Al-BSF to PERC





Source: ITRPV - 8th Edition, September 2017

PERC enabled by passivating Al_2O_3 nanolayers

APPLIED PHYSICS LETTERS **89**, 042112 (2006)

Ultralow surface recombination of *c*-Si substrates passivated by plasma-assisted atomic layer deposited Al_2O_3

B. Hoex, S. B. S. Heil, E. Langereis, M. C. M. van de Sanden, and W. M. M. Kessels[a)]
Department of Applied Physics, Eindhoven University of Technology, P.O. Box 513, 5600 MB Eindhoven, The Netherlands

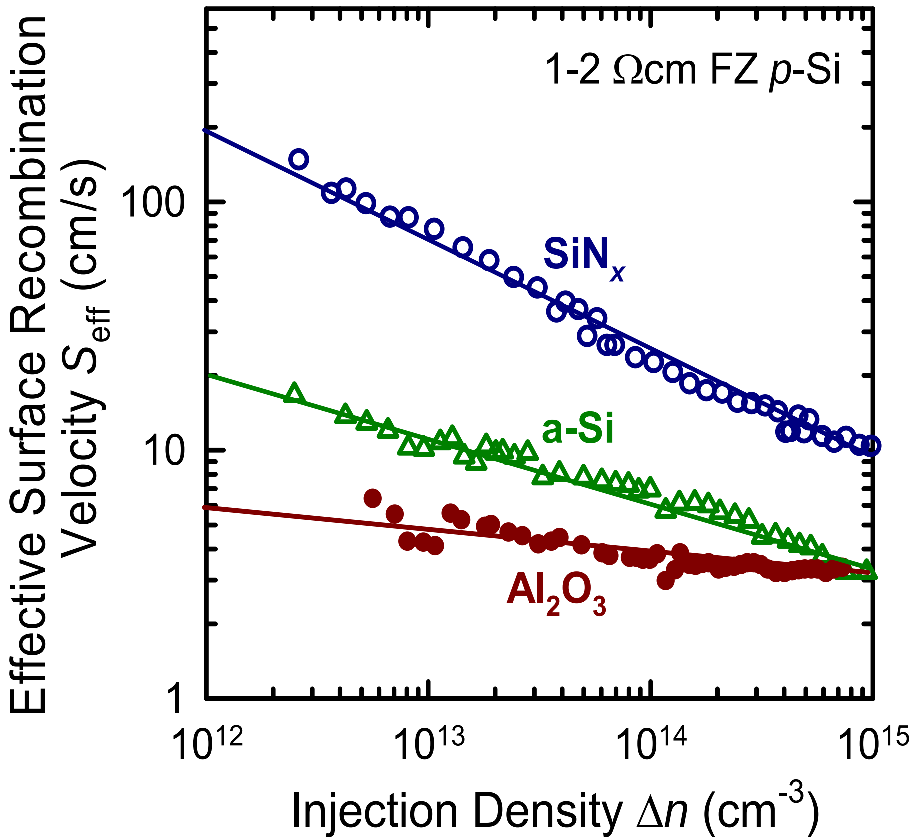
(Received 19 April 2006; accepted 9 June 2006; published online 27 July 2006)

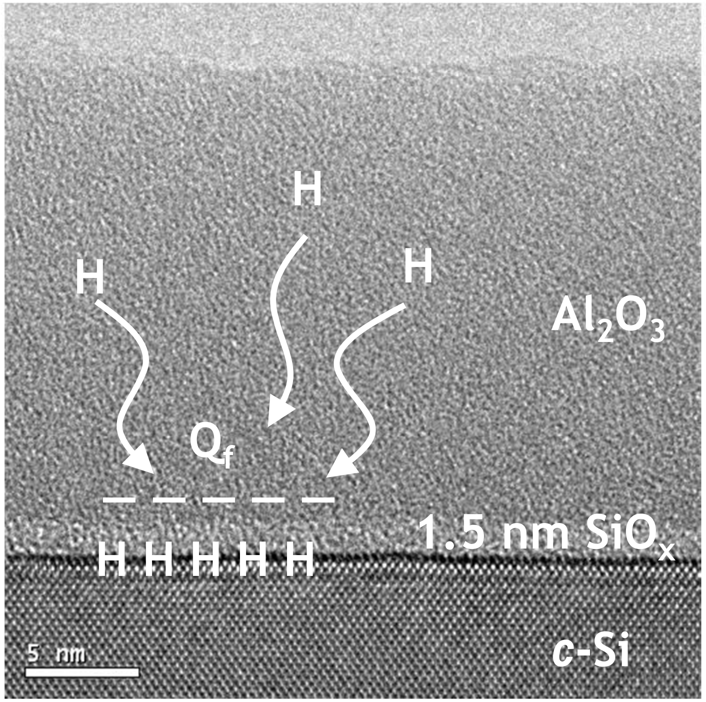
Excellent surface passivation of *c*-Si has been achieved by Al_2O_3 films prepared by plasma-assisted atomic layer deposition, yielding effective surface recombination velocities of 2 and 13 cm/s on low resistivity *n*- and *p*-type *c*-Si, respectively. These results obtained for ~30 nm thick Al_2O_3 films are comparable to state-of-the-art results when employing thermal oxide as used in record-efficiency *c*-Si solar cells. A 7 nm thin Al_2O_3 film still yields an effective surface recombination velocity of 5 cm/s on *n*-type silicon. © *2006 American Institute of Physics*.

Bram Hoex
Junior Einstein Award
2008

Hoex *et al*., Appl. Phys. Lett. 89, 042112 (2006).
Review paper: Dingemans *et al*., J. Vac. Sci. Technol. A 30, 040802 (2012).

Excellent passivation: breakthrough by ALD Al_2O_3





Al_2O_3 nanolayers (**~5 nm**) lead to excellent passivation of silicon surfaces

Due to: **1)** passivation of Si defects by H; **2)** shielding of electrons by fixed charge

Hoex *et al.*, Appl. Phys. Lett. 89, 042112 (2006).
Dingemans *et al.*, J. Vac. Sci. Technol. A 30, 040802 (2012).

Atomic layer deposition of Al_2O_3

Technische Universiteit **Eindhoven** University of Technology

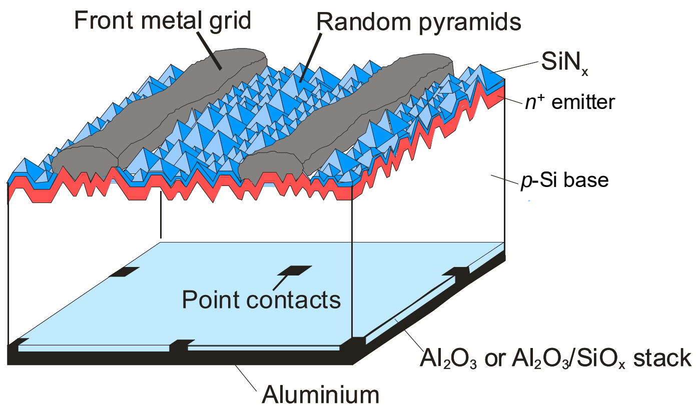
First PERC cells with Al_2O_3 nanolayers

PROGRESS IN PHOTOVOLTAICS: RESEARCH AND APPLICATIONS
Prog. Photovolt: Res. Appl. (2008)
Published online in Wiley InterScience (www.interscience.wiley.com) DOI: 10.1002/pip.823

Research

Surface Passivation of High-efficiency Silicon Solar Cells by Atomic-layer-deposited Al_2O_3

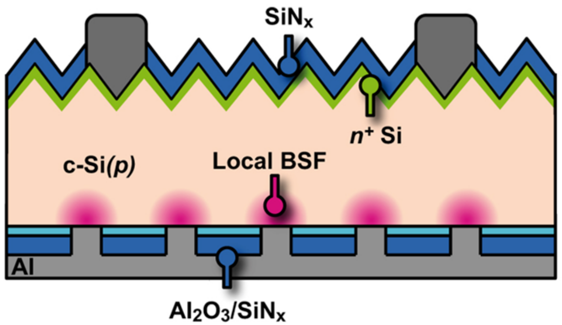
J. Schmidt[1*,†], A. Merkle[1], R. Brendel[1], B. Hoex[2], M. C. M. van de Sanden[2] and W. M. M. Kessels[2]
[1]*Institut für Solarenergieforschung Hameln/Emmerthal (ISFH), Am Ohrberg 1, D-31860 Emmerthal, Germany*
[2]*Department of Applied Physics, Eindhoven University of Technology, P.O. Box 513, 5600 MB Eindhoven, The Netherlands*



Atomic-layer-deposited aluminium oxide (Al_2O_3) is applied as rear-surface-passivating dielectric layer to passivated emitter and rear cell (PERC)-type crystalline silicon (c-Si) solar cells. The excellent passivation of low-resistivity p-type silicon by the negative-charge-dielectric Al_2O_3 is confirmed on the device level by an independently confirmed energy conversion efficiency of 20·6%. The best results are obtained for a stack consisting of a 30 nm Al_2O_3 film covered by a 200 nm plasma-enhanced-chemical-vapour-deposited silicon oxide (SiO_x) layer, resulting in a rear surface recombination velocity (SRV) of 70 cm/s. Comparable results are obtained for a 130 nm single-layer of Al_2O_3, resulting in a rear SRV of 90 cm/s.

Schmidt *et al.*, Prog. Photovolt. Res. Appl. 16, 461 (2008).

Worldwide PERC capacity 2017



PERC (Passivated emitter rear cell)

Courtesy of Morgan Ku (March 2, 2017)

Hanwha Q Cells
Global Operation for R&D and Production

Germany
- Global R&D Center (>210)
- Global QM

Korea
- Capacity (2016YE):

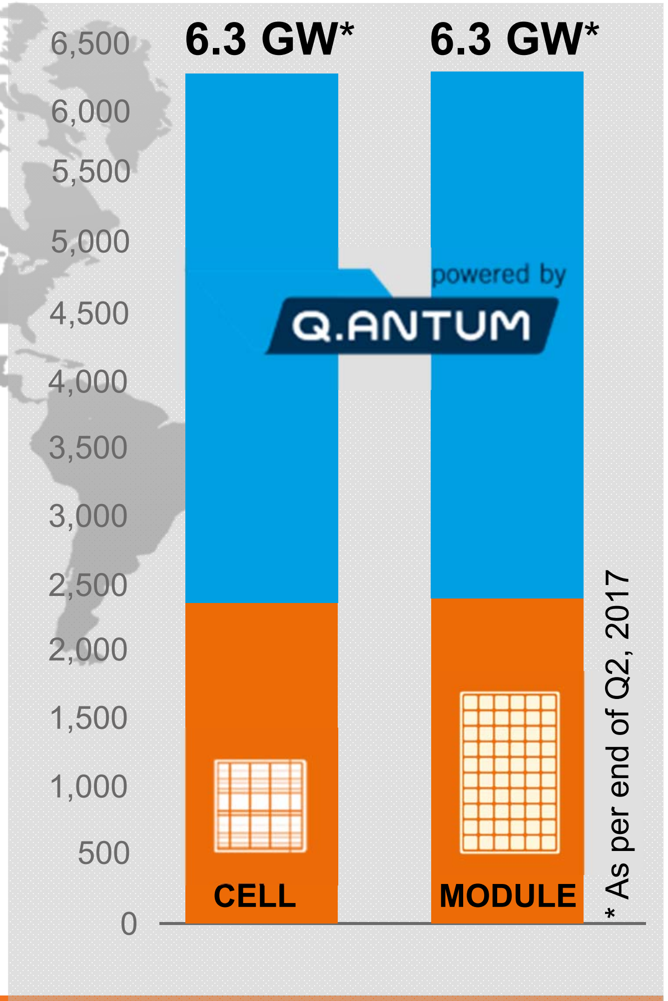
Gijs Dingemans
Winner Solar Thesis Award 2012

Mal
- Ca

Eng
- Co

Wafer 900 MW

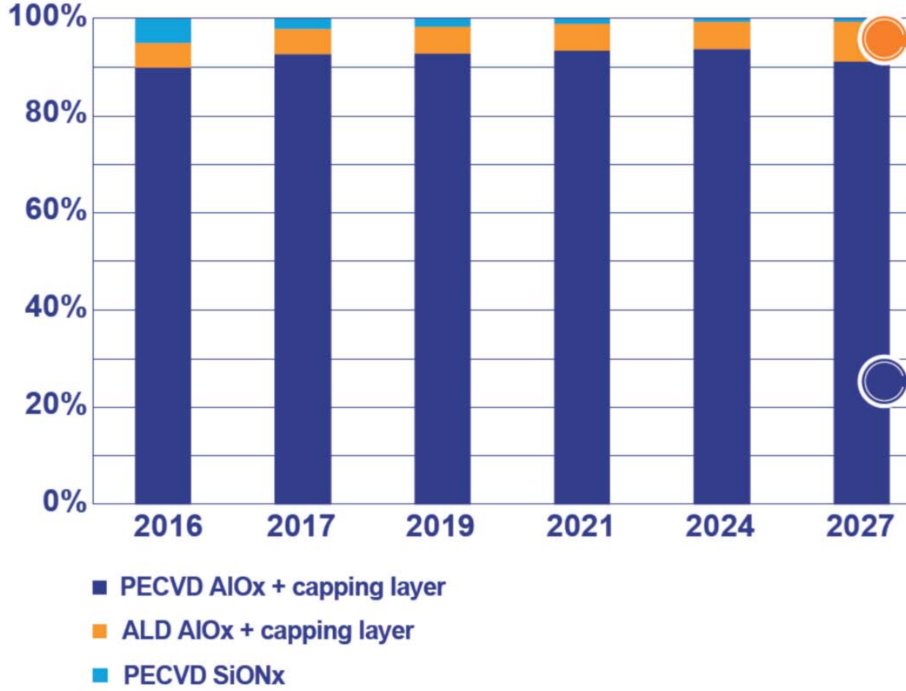
Engineering
- Crystallization
- Continuous improvement



*Capacity in South Korea belongs to affiliated and non-listed company Hanwha Q CELLS Korea Corporation

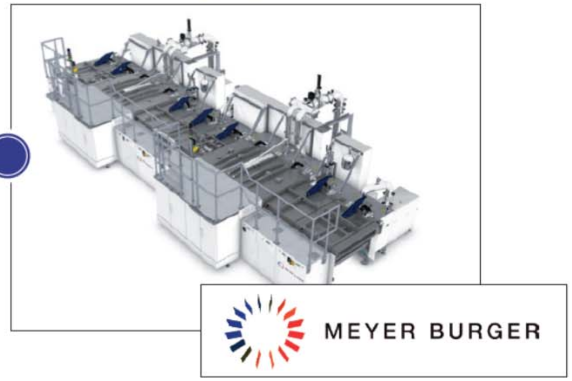
Trend #2: PECVD and ALD Al_2O_3

World market share (%)



ALD Al_2O_3

PECVD Al_2O_3



Source: ITRPV - 8th Edition, September 2017

Spatial ALD for Al_2O_3 - SolayTec

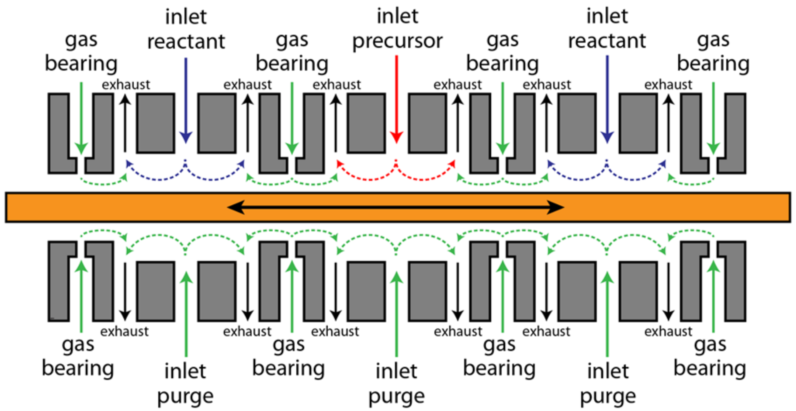
Spin-off from TNO (2010)
Now part of the Amtech group

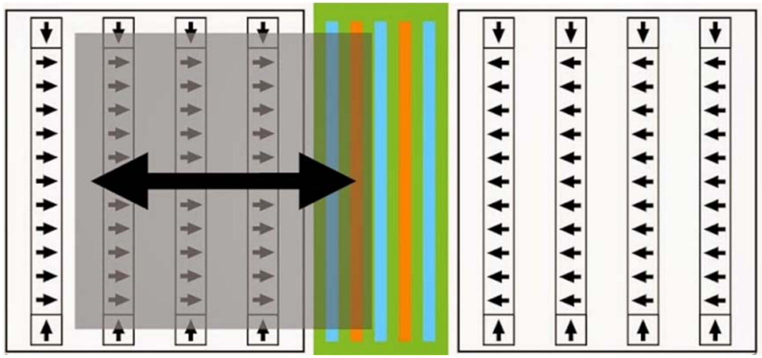
System throughput:
Up to 4800 wafers/hr

Side view

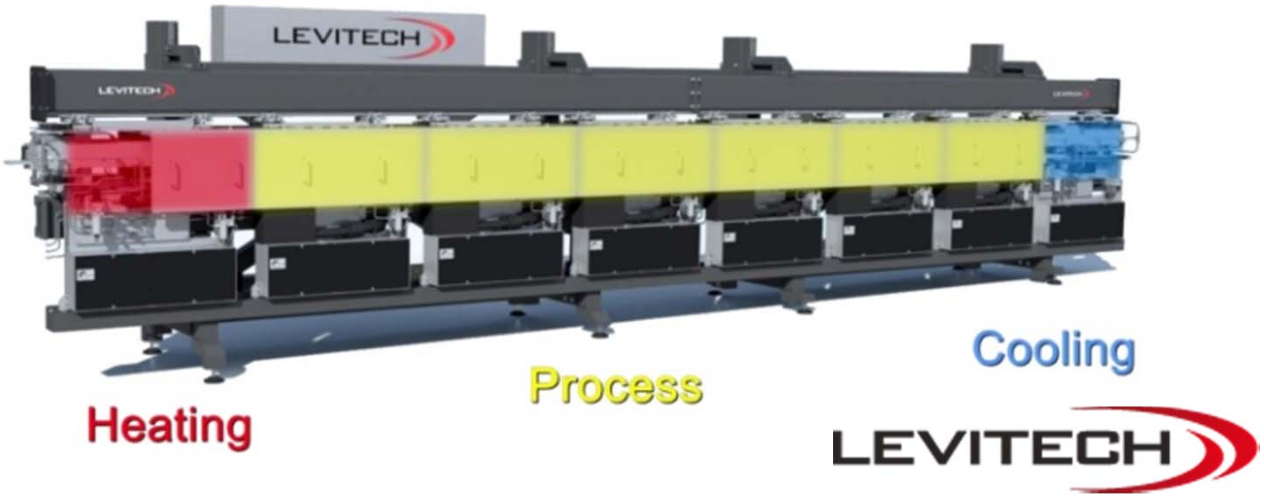
Wafer moves hence and forth

Top view





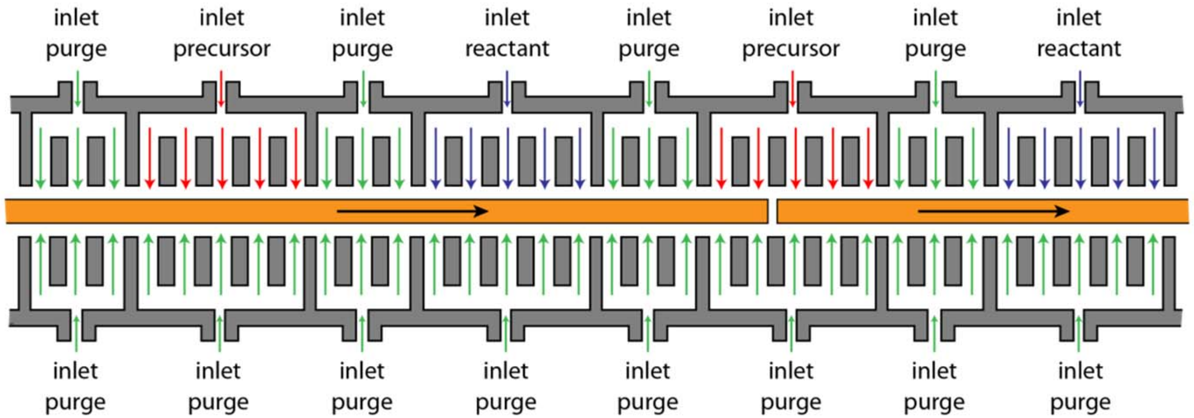
Spatial ALD for Al_2O_3 - Levitech

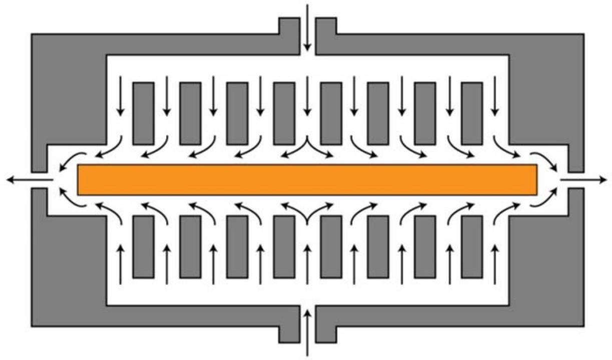


Spin-off from
ASM International (2009)

System throughput:
Up to 6000 wafers/hr

Side view | Wafer from one side to the other | Cross-sectional view

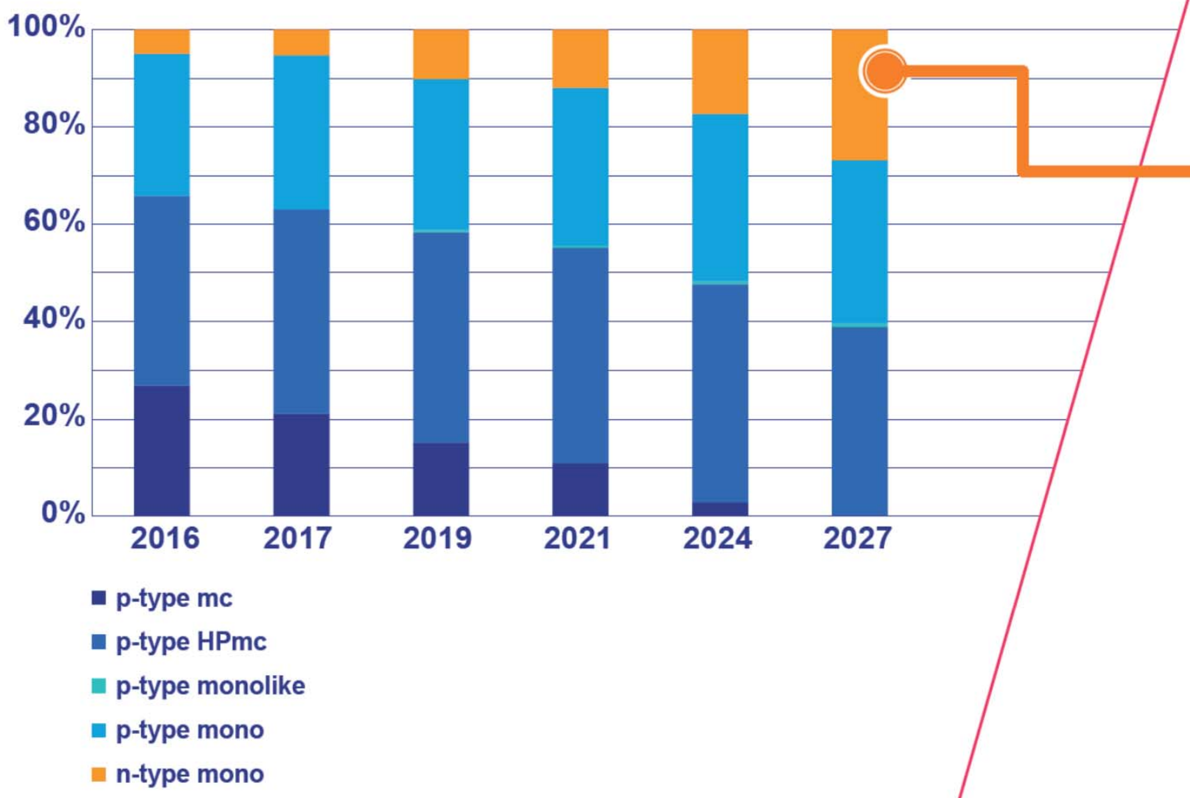




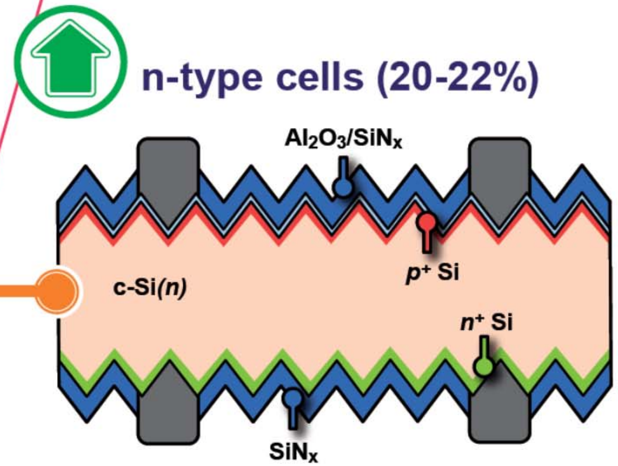
Levitech B.V. - www.levitech.nl

Trend #3: Towards *n*-type silicon

World market share (%)



n-type cells (20-22%)



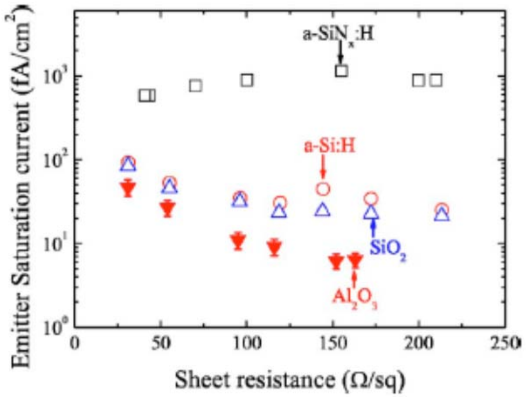
Source: ITRPV - 8th Edition, September 2017

First cell with p^+-emitter passivated by ALD Al_2O_3

APPLIED PHYSICS LETTERS **91**, 112107 (2007)

Excellent passivation of highly doped *p*-type Si surfaces by the negative-charge-dielectric Al_2O_3

B. Hoex[a)]
Department of Applied Physics, Eindhoven University of Technology, P.O. Box 513, 5600 MB Eindhoven, The Netherlands
J. Schmidt and R. Bock
Institute for Solar Energy Research Hameln (ISFH), Am Ohrberg 1, D-31860 Emmerthal, Germany

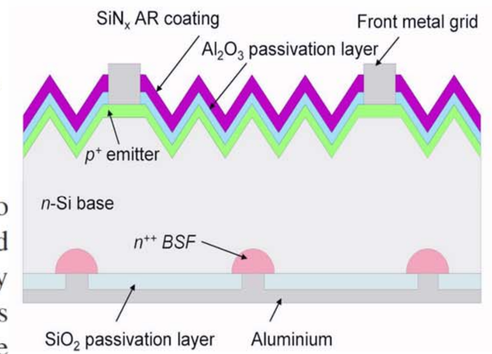


APPLIED PHYSICS LETTERS **92**, 253504 (2008)

High efficiency *n*-type Si solar cells on Al_2O_3-passivated boron emitters

Jan Benick,[1,a)] Bram Hoex,[2] M. C. M. van de Sanden,[2] W. M. M. Kessels,[2] Oliver Schultz,[1] and Stefan W. Glunz[1]
[1]*Fraunhofer Institute for Solar Energy Systems (ISE), Heidenhofstrasse 2, D-79110 Freiburg, Germany*
[2]*Department of Applied Physics, Eindhoven University of Technology, P.O. Box 513, 5600 MB Eindhoven, The Netherlands*

(Received 1 May 2008; accepted 9 May 2008; published online 25 June 2008)



In order to utilize the full potential of solar cells fabricated on *n*-type silicon, it is necessary to achieve an excellent passivation on B-doped emitters. Experimental studies on test structures and theoretical considerations have shown that a negatively charged dielectric layer would be ideally suited for this purpose. Thus, in this work the negative-charge dielectric Al_2O_3 was applied as surface passivation layer on high-efficiency *n*-type silicon solar cells. With this front surface passivation layer, a confirmed conversion efficiency of 23.2% was achieved. For the open-circuit voltage V_{oc} of 703.6 mV, the upper limit for the emitter saturation current density J_{0e}, including the metalized area, has been evaluated to be 29 fA/cm^2. This clearly shows that an excellent passivation of highly doped *p*-type *c*-Si can be obtained at the device level by applying Al_2O_3. © *2008 American Institute of Physics*. [DOI: 10.1063/1.2945287]

Hoex *et al.*, Appl. Phys. Lett. 91, 112107 (2007).
Benick *et al.*, Appl. Phys. Lett. 92, 253504 (2008).

TU/e Technische Universiteit Eindhoven University of Technology

Article in newspaper *NRC Handelsblad*

Zonnecel met laagje aluminiumoxide is zeer efficiënt

Wetenschappers van de TU Eindhoven en het Duitse Fraunhofer Instituut hebben een zonnecel gemaakt die heel efficiënt is, omdat hij aan de bovenkant voorzien is van een flinterdun laagje aluminiumoxide. Het laagje voorkomt dat elektronen en corresponderende positieve ladingen (gaten) die door zonlicht ontstaan zijn, *recombineren* voordat ze stroom hebben opgewekt.

Bram Hoex, vorige week aan de TU Eindhoven gepromoveerd, heeft de zonnecel met een rendement van 23,2 procent afgelopen woensdag gepresenteerd op een conferentie in San Diego. De technologie is in potentie fantastisch, aldus zonnecelspecialist Wim Sinke van Energieonderzoek Centrum Nederland, nadat hij in San Diego voor commentaar is wakker gebeld. Sinke was niet direct bij het onderzoek betrokken.

Op termijn is het misschien mogelijk om met de Eindhovense technologie het wereldrecord te breken van 24,7 procent voor een silicium zonnecel, maar Sinke noemt dat totaal oninteressant. Voor hem telt niet het lab, maar de mogelijkheid om met de nieuwe technologie efficiëntere zonnecellen te maken in de fabriek.

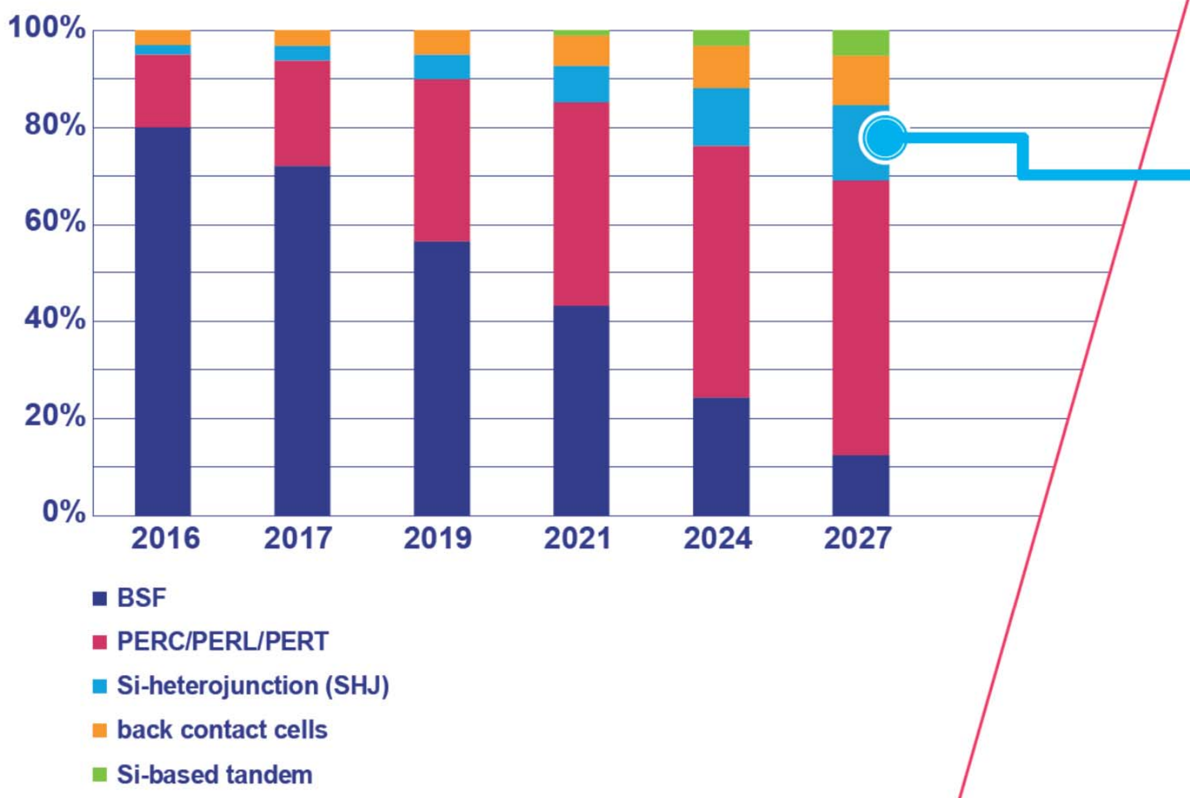
Conventionele zonnecellen bestaan uit een plak silicium die is opgedeeld in twee delen die beide opzettelijk zijn vervuild ('gedoteerd') met andere atomen. Onderop ligt een dikke laag p-type silicium dat wordt gedoteerd met bijvoorbeeld borium, een element dat in de buitenste atoomschil makkelijk een elektron opneemt. Erbovenop ligt een dunne laag n-type silicium, gedoteerd met bijvoorbeeld fosfor dat in de buitenste atoomschil makkelijk een elektron loslaat. Als zonlicht de dikke, positief gedoteerde laag bereikt, dan worden elektronen (negatief) en gaten (positief) vrijgemaakt en vervolgens van elkaar gescheiden. Ze kunnen dan de overgang maken naar de elektrische contacten aan weerzijden van de cel. Op conventionele zonnecellen voorkomt een positief geladen laag siliciumnitride dat de gaten en de elektronen aan het oppervlak van de zonnecel weer snel recombineren, waardoor ze geen stroom kunnen leveren. De cel van Hoex werkt precies andersom, aldus medeonderzoeker Erwin Kessels, wegens een gebroken sleutelbeen niet aanwezig in San Diego. De dikke laag is in dit geval gemaakt van n-type silicium met een dunne laag silicium van het p-type daarbovenop. Recombinatie aan het oppervlak wordt voorkomen met een sterk *negatief* geladen laagje aluminiumoxide. Het opbrengen van deze laag van 30 nanometer gebeurt door atoomlaagdepositie met behulp van een plasma – Eindhovense expertise. Het verruilen van n-type en p-type silicium maakt de zonnecel volgens Kessels minder gevoelig voor verontreinigingen door bijvoorbeeld ijzer en dat is voor een robuuste productie een groot voordeel. ***Michiel van Nieuwstadt***

FOTO BLOOMBERG NEWS

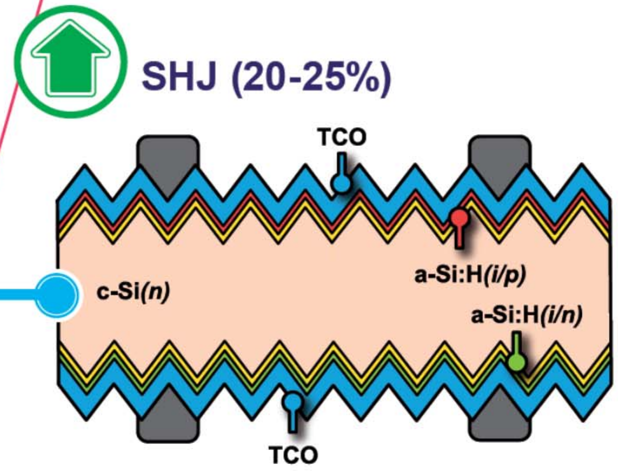
• ***Zonnepanelen op een appartementenblok in Londen dat geen koolstof uitstoot bij zijn energievoorziening.***

Trend #4: Towards silicon heterojunctions

World market share (%)



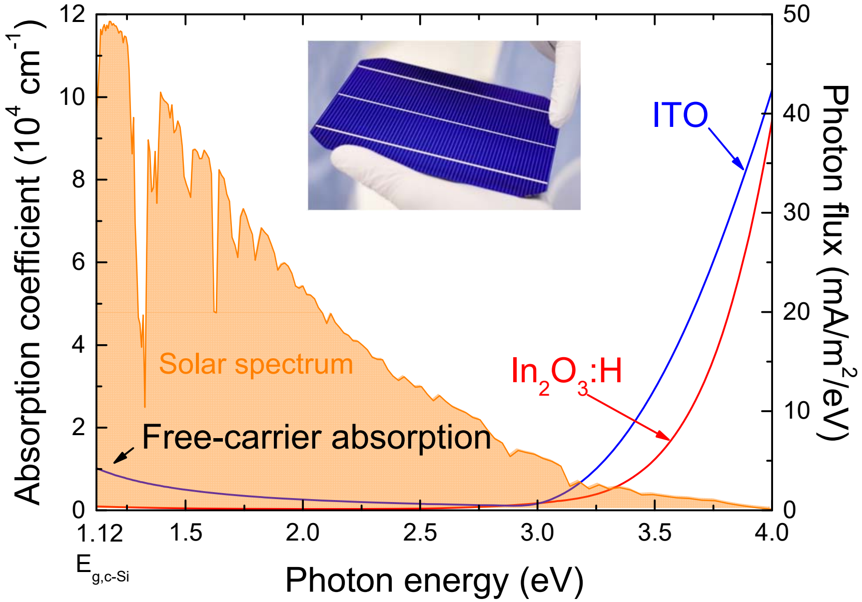
SHJ (20-25%)

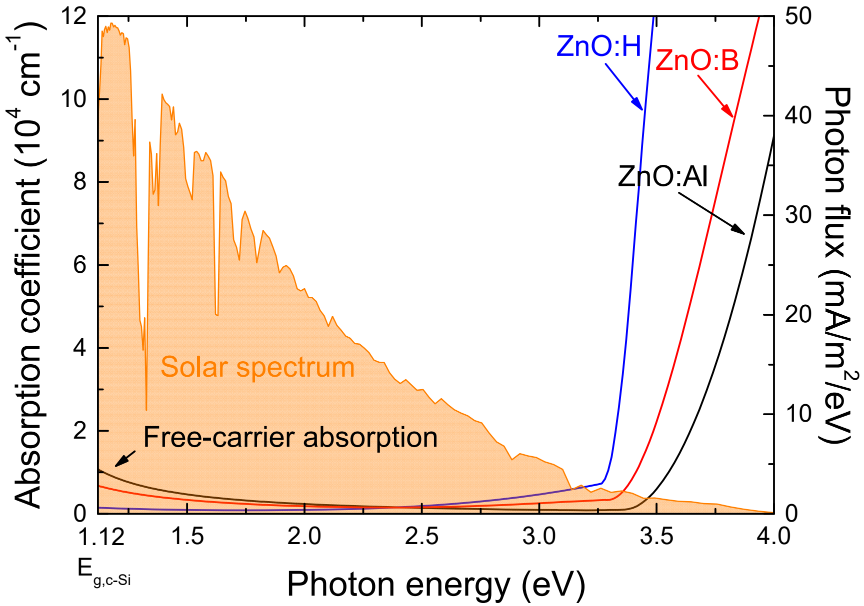


Source: ITRPV - 8th Edition, September 2017

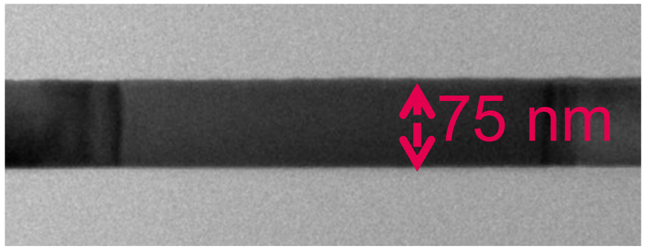
STW perspectief project: Flash

ALD of high-mobility transparent conductive oxides (TCOs)

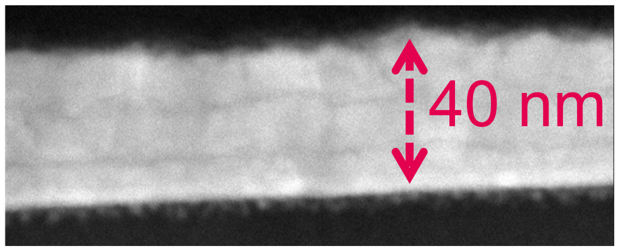




ALD In_2O_3:H



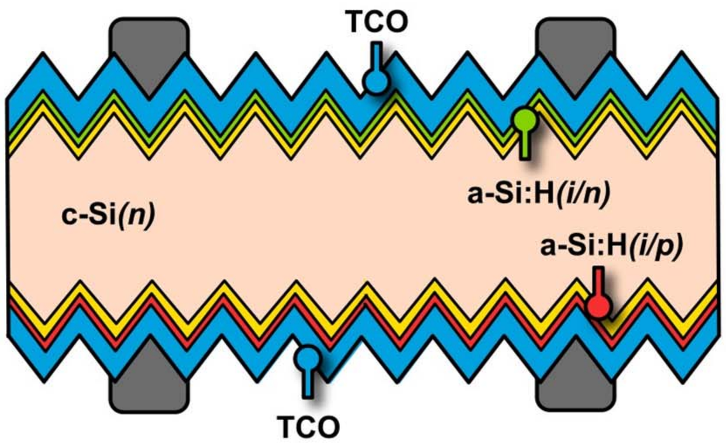
ALD ZnO:Al



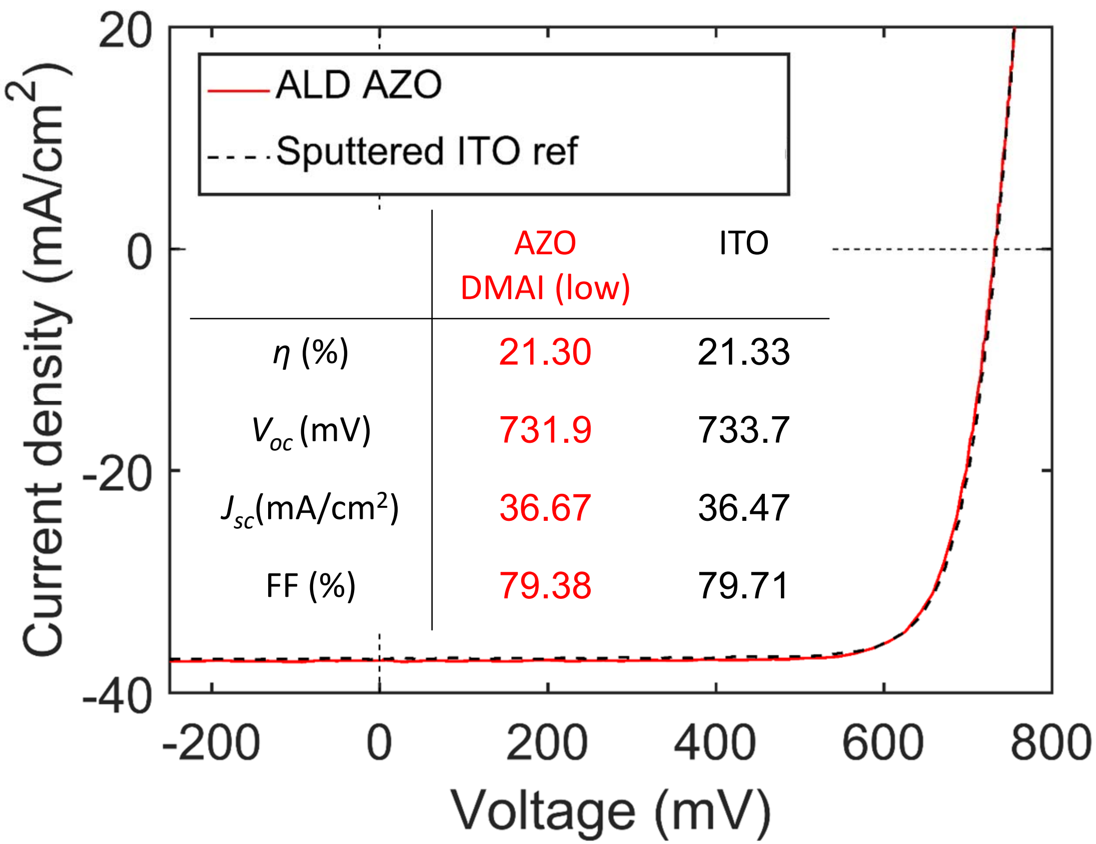
Macco *et al*., Phys. Status Solidi RRL 8, 987 (2014).
Macco *et al*., Semicond. Sci. Technol. 29, 122001 (2014).

Application of ALD ZnO:Al at rear side SHJ cell

Si heterojunction cell
with **ZnO:Al at the rear**



Abundant ZnO:Al as good as
more expensive ITO
(but not yet at the front)



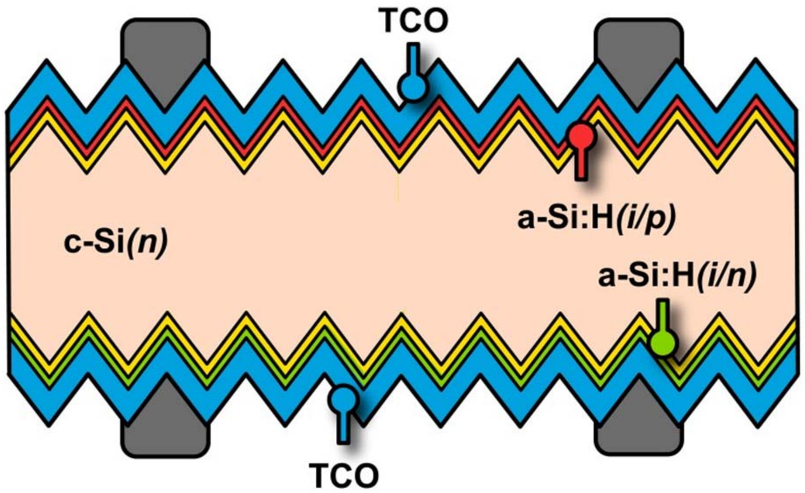
	AZO DMAI (low)	ITO
η (%)	21.30	21.33
V_{oc} (mV)	731.9	733.7
J_{sc} (mA/cm^2)	36.67	36.47
FF (%)	79.38	79.71

csem INREP Towards Indium free TCOs

Niemelä *et al.*, to be published (2018).

Passivating contact cells

Cells with metal contacts separated from silicon through passivation layer



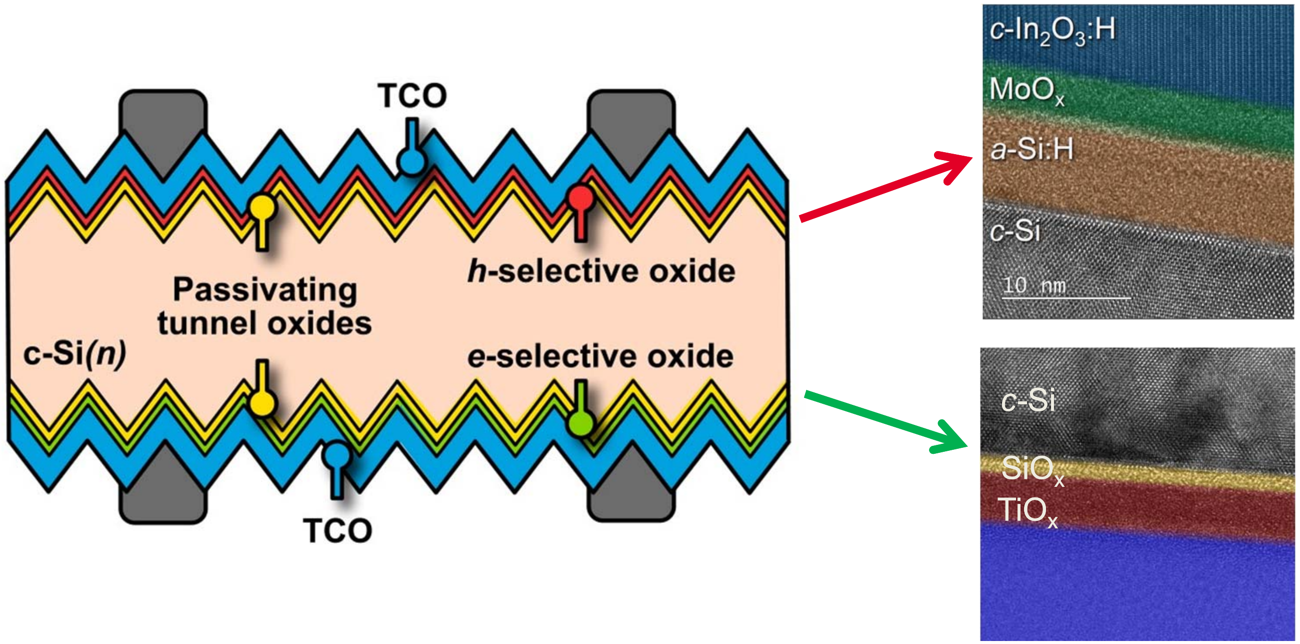
A simple concept: *"Just depositing stacks of thin films on silicon"*

Passivating contact cells

TKI URBAN ENERGY
Topsector Energie

Cells with metal contacts separated from silicon through passivation layer

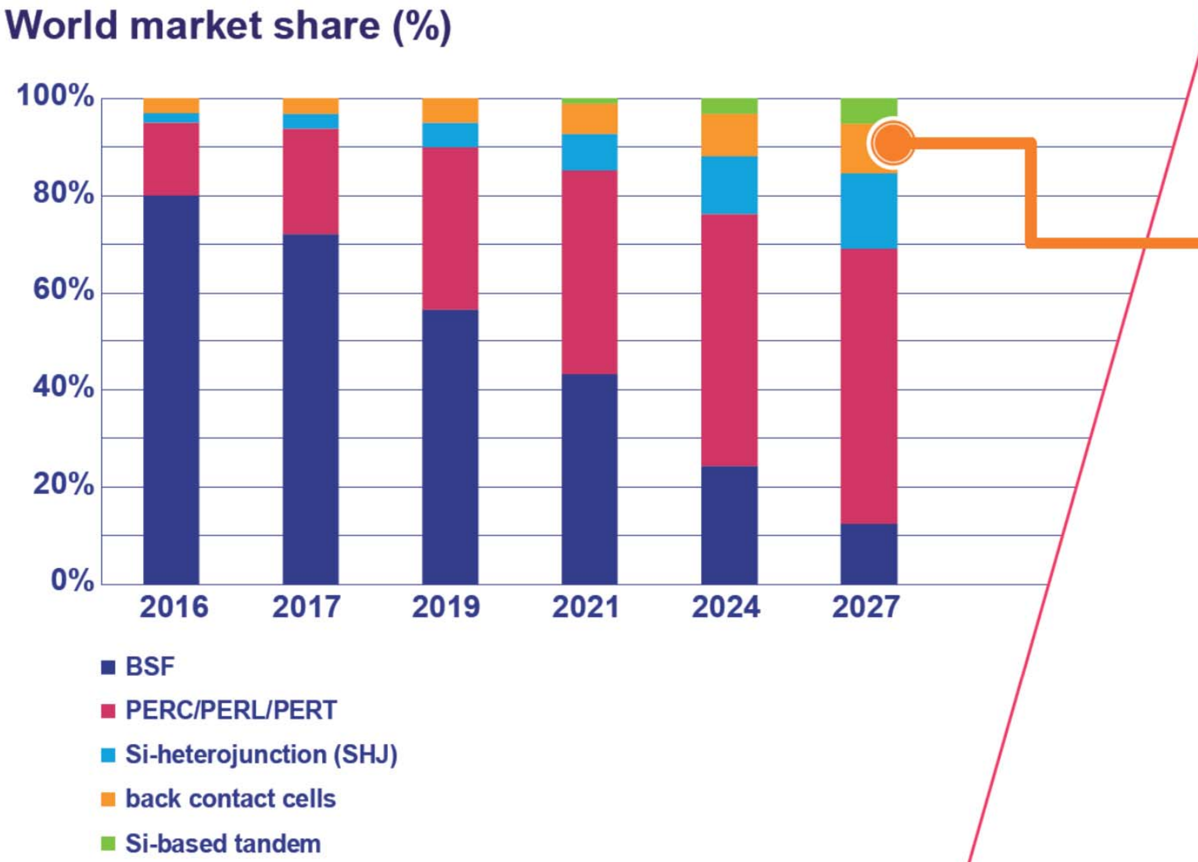
Preferably with highly transparant and stable nanolayers!

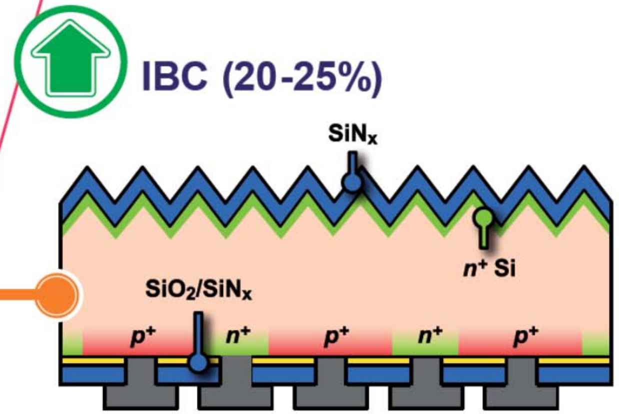


A simple concept: *"Just depositing stacks of thin films on silicon"*

Many new materials: doped poly-Si, metal fluoriudes, metal oxides, …

Trend #5: Towards interdigitated back-contacts





Source: ITRPV - 8th Edition, September 2017

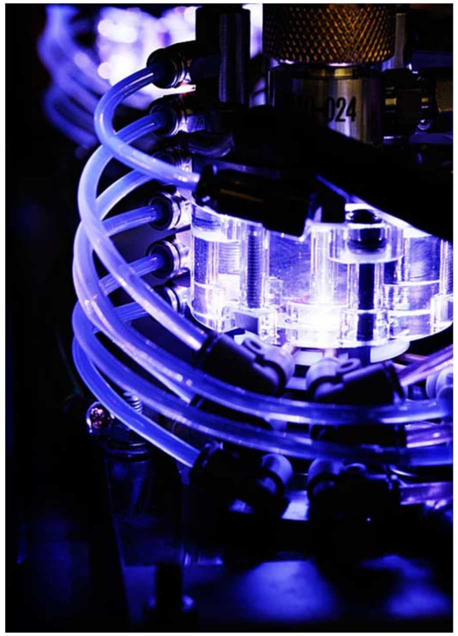
TU/e solar family car “Stella Vie”

BRIDGESTONE WORLD SOLAR CHALLENGE

Rank	Team	Location	Charges	P-km	External energy	Efficiency (P-km/kWh)	Efficiency score
1	40. Solar Team Eindhoven Stella Vie **Pace:** 69 km/h, 118 mins ahead	Adelaide	6	10197	45.7 kWh	223.2	80

SiN_x antireflection coatings prepared by the DEPx

DEPx fast deposition system with **expanding thermal plasma** source (developed at TU/e)

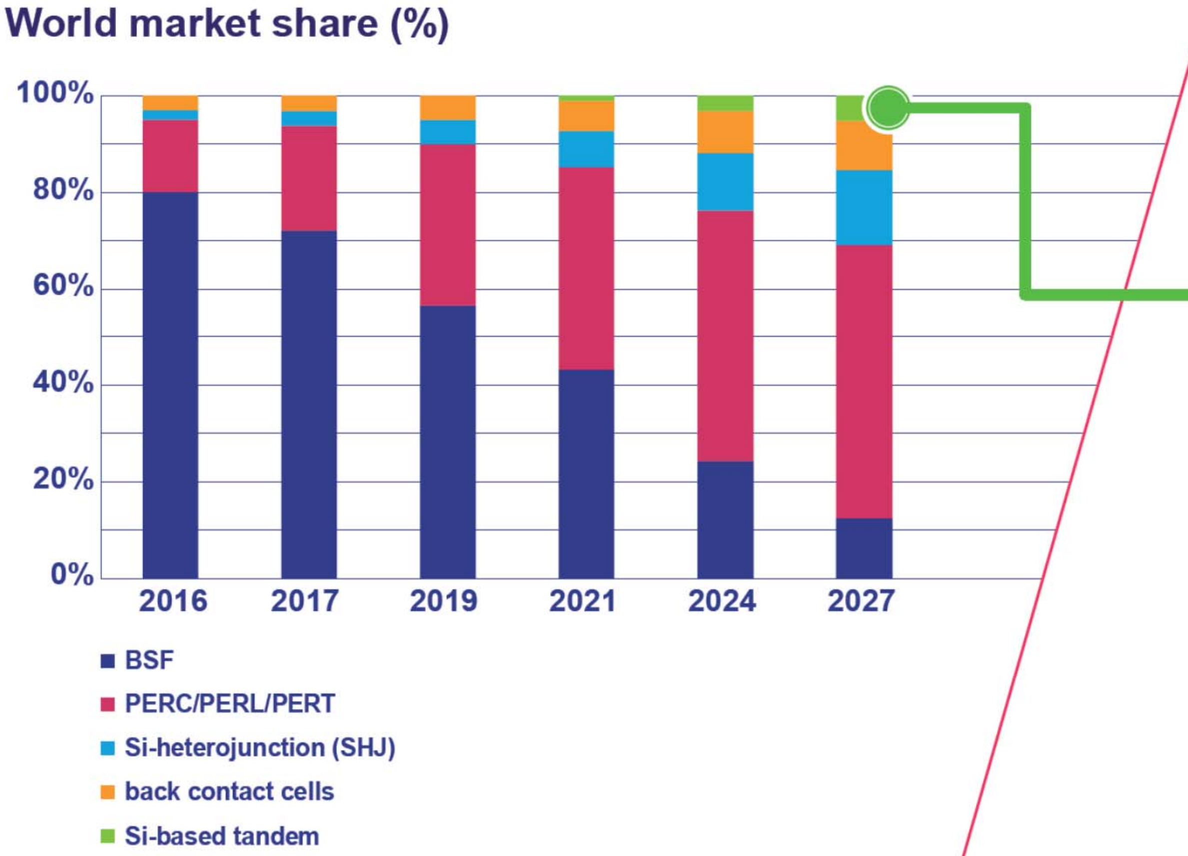


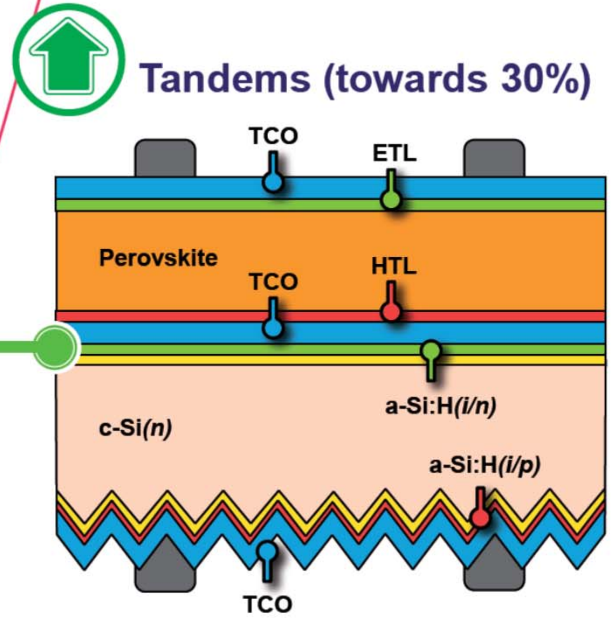
2010 **2011**

OTB Solar B.V. → Roth & Rau B.V. → Meyer-Burger B.V.

(known from SiNA & MAiA)

Trend #6:
Towards Si-based tandems

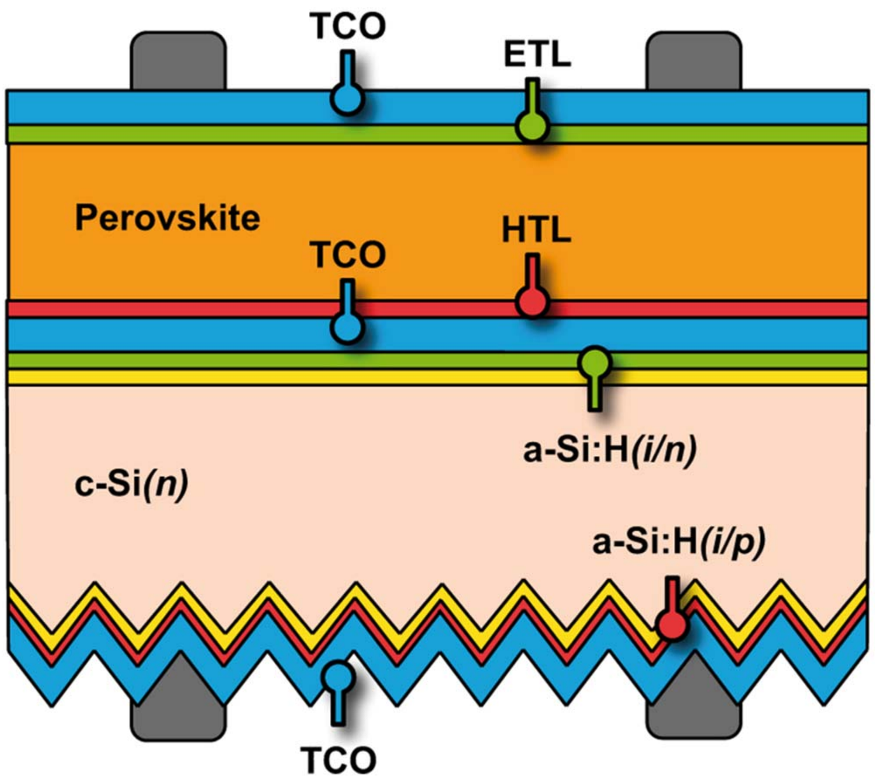




Source: ITRPV - 8th Edition, September 2017

Joint Solar Programme III

New project on high-efficiency hybrid tandem solar cells started in September 2017



Metallization & light management

FOM Institute AMOLF

Organic and inorganic perovskites

Universiteit van Amsterdam TU/e

Nanolayers & passivation

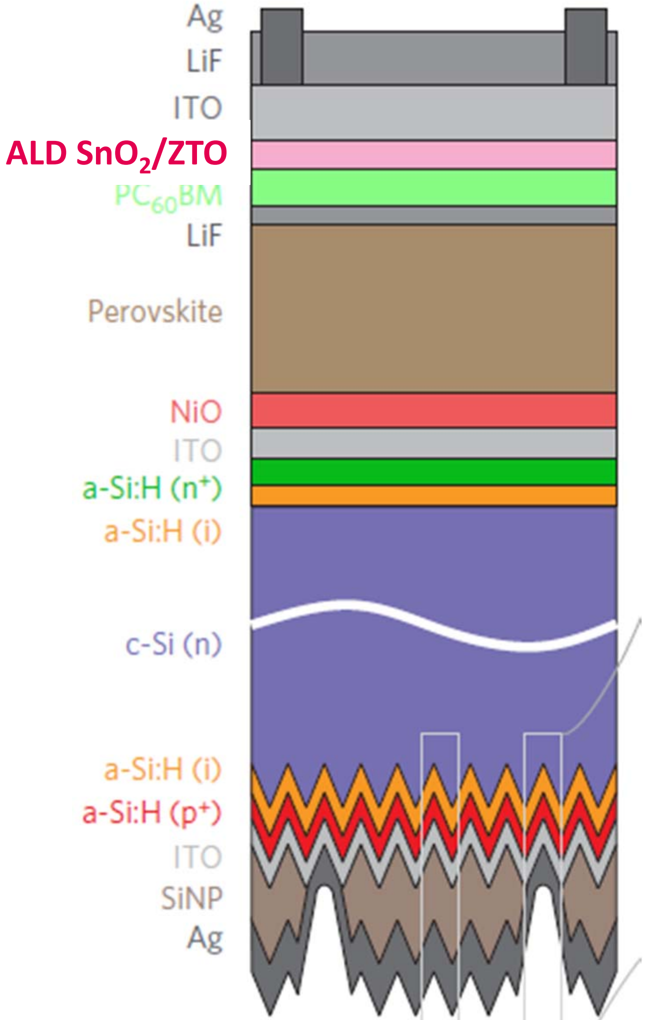
TU/e

Tandem architecture & silicon cell

TU Delft

Note: project focuses on 4-terminal cell with IBC silicon bottom cell

Silicon-perovskite tandem cells with ALD



Stanford-ASU-MIT-etc.

2-terminal device with ALD SnO_2:

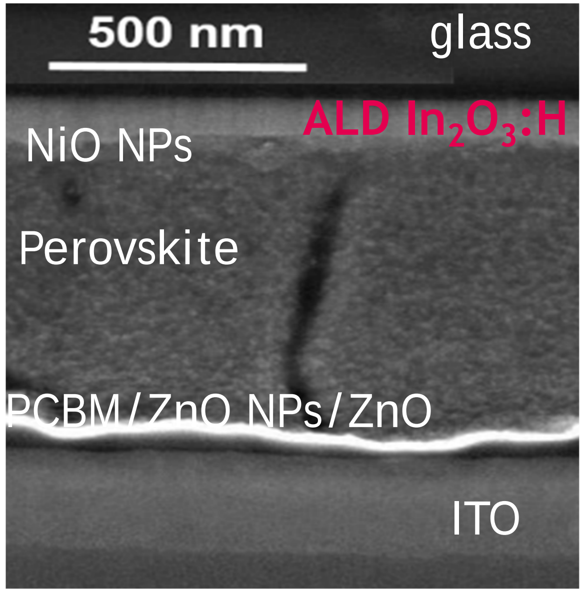
23.6% efficiency (certified)

SOLAR RESEARCH SOLLIANCE

4-terminal device with **ALD In_2O_3:H**

22.6% efficiency

Top cell:
- Triple cation perovskite -

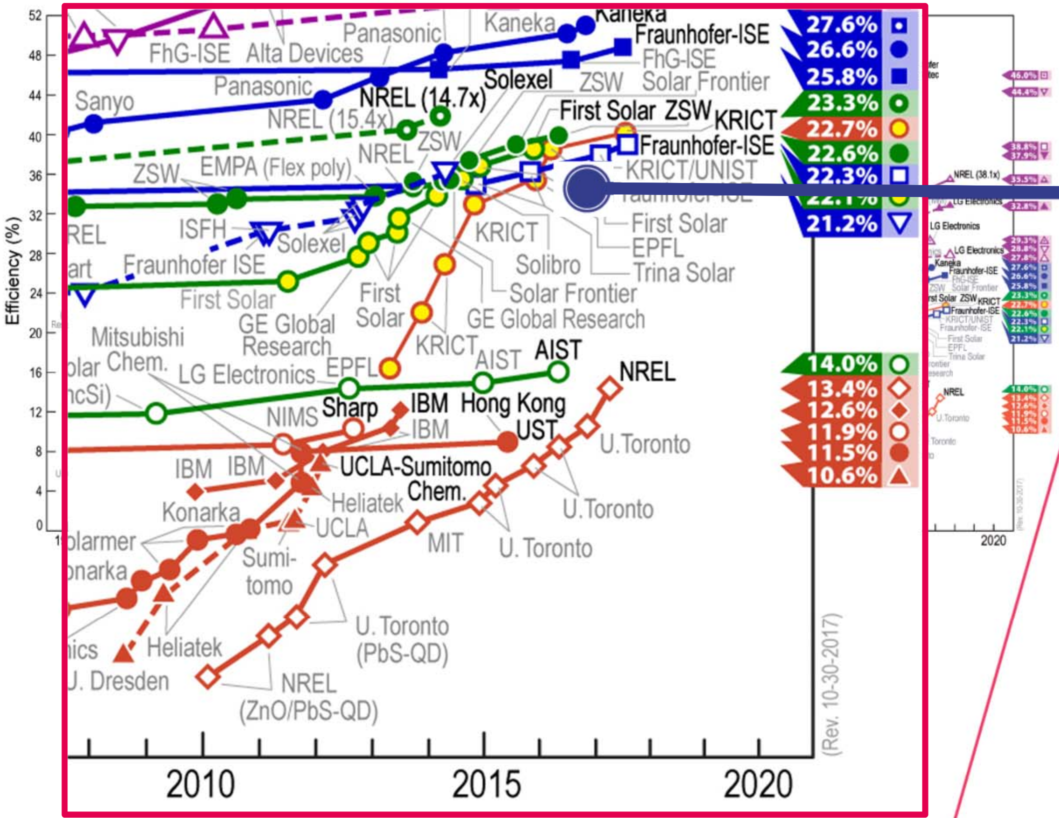


Bottom cell:
- Metal-wrap-through c-Si(n) cell -

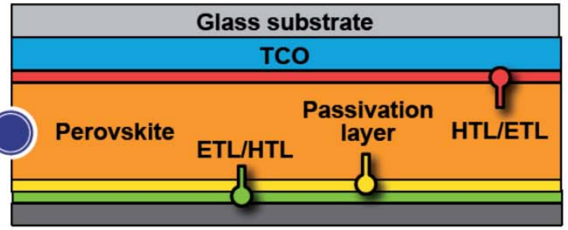
Bush *et al.*, Nature Energy 2, 17009 (2017).
Koushik *et al.*, to be published (2018).

Trend #7: Towards perovskite solar cells

Best research-cell efficiencies

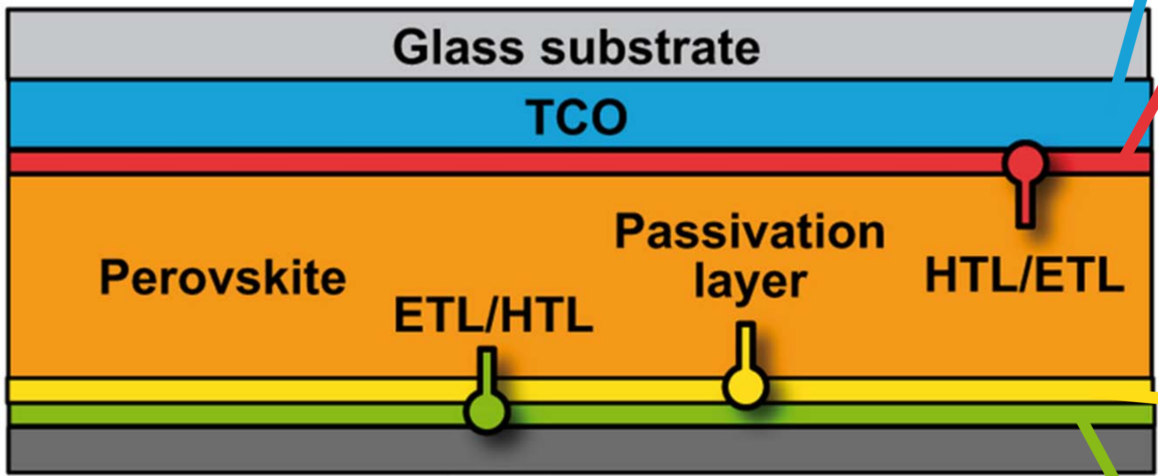


Perovskites (towards 25%)



Source: ITRPV - 8th Edition, September 2017

Perovskite cells with nanolayers



TCO

In_2O_3, ZnO:Al, ZnO:B, …

Electron transport layer

TiO_x, SnO_x, …

Passsivation layers

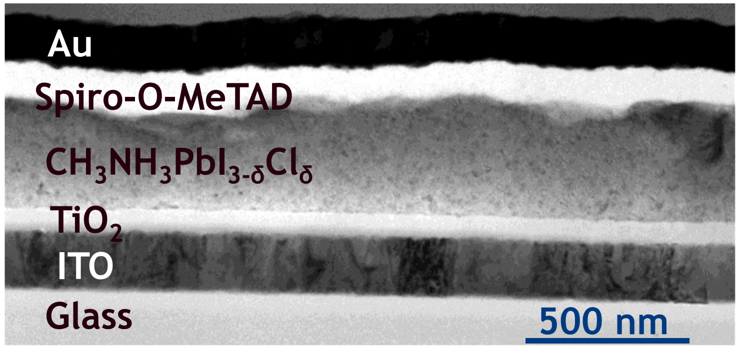
Al_2O_3, …

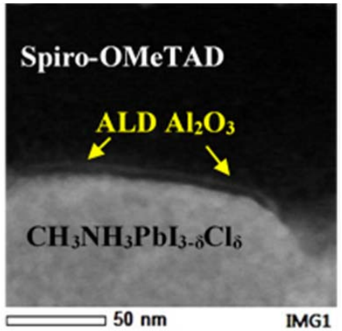
Hole transport layer

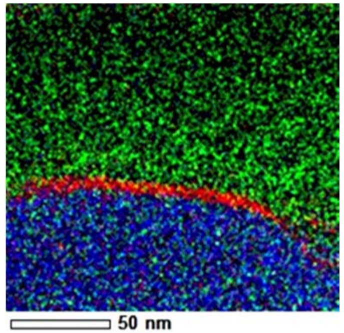
NiO_x, CuO_x, MoO_x, WO_x, …

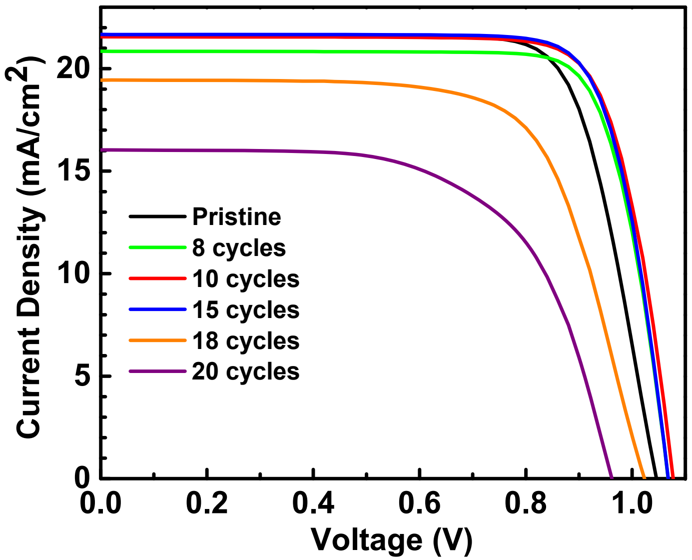
Zardetto *et al.*, Sust. Energy Fuels 1, 30 (2017).

Perovskite with ALD Al_2O_3 nanolayer







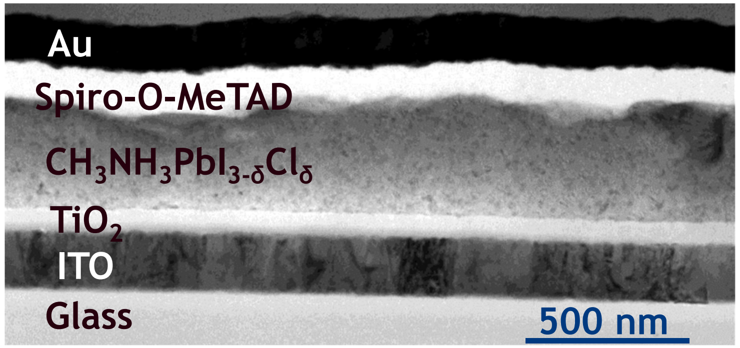


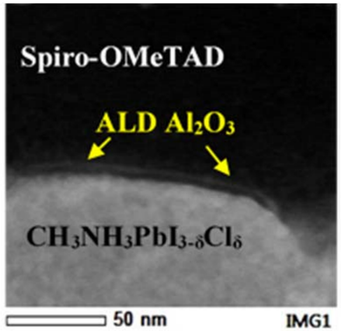
No. of cycles	V_{oc} (V)	J_{sc} (mA/cm²)	FF	PCE (%)
0	1.03	21.3	0.69	15.1
8	1.07	20.8	0.78	17.4
10	1.08	21.7	0.77	18.0
15	1.07	21.7	0.77	17.9
18	1.02	19.5	0.69	13.7
20	0.96	16.0	0.63	9.7

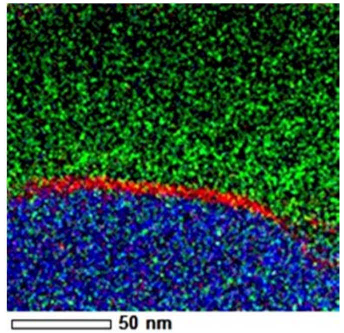
3% absolute increase in efficiency with **10-15 cycles Al_2O_3**

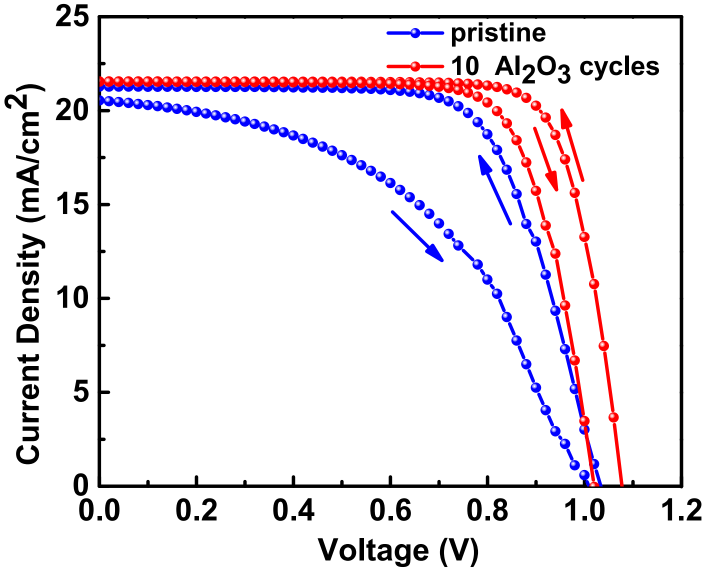
Koushik *et al*., Energy & Envir.Science, 10, 91-100 (2017).
Koushik *et al*, Advanced Mat. Interfaces 1700043 (2017).

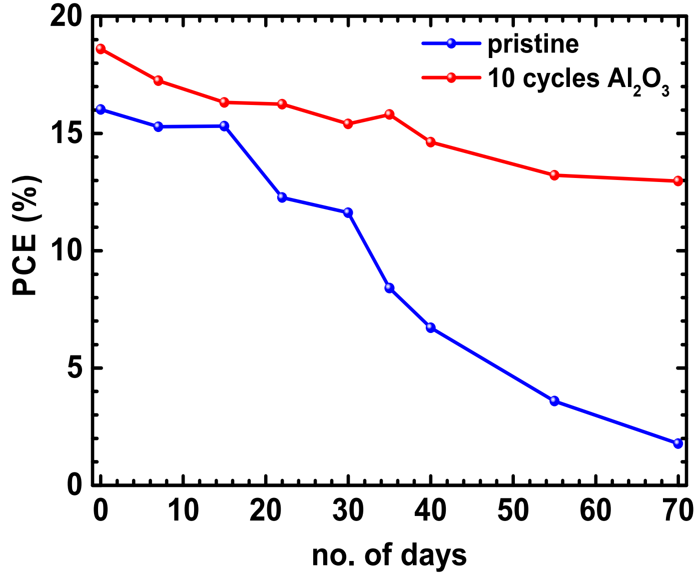
Perovskite with ALD Al_2O_3 nanolayer







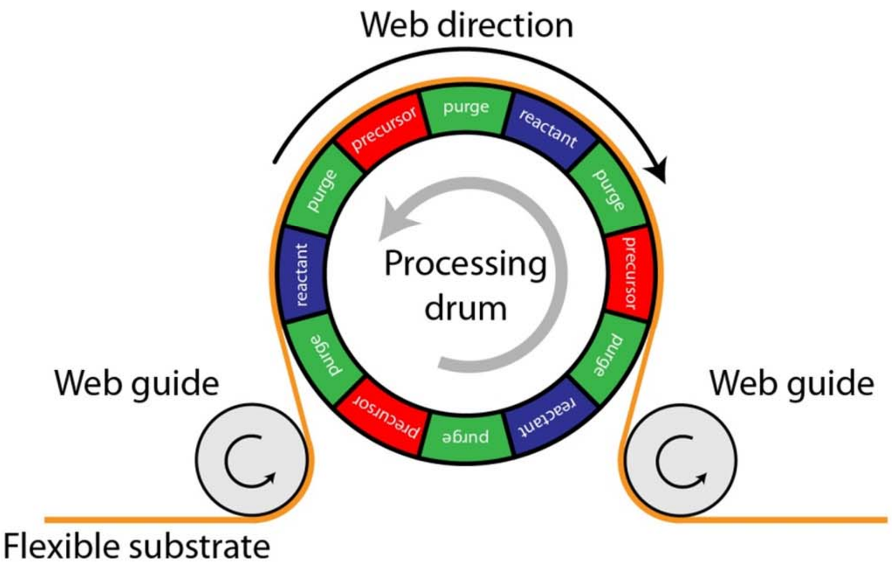




Ageing studies: **Al_2O_3 significantly delays cell degradation**

Koushik *et al.*, Energy & Envir.Science, 10, 91-100 (2017).
Koushik *et al*, Advanced Mat. Interfaces 1700043 (2017).

Roll-to-roll ALD

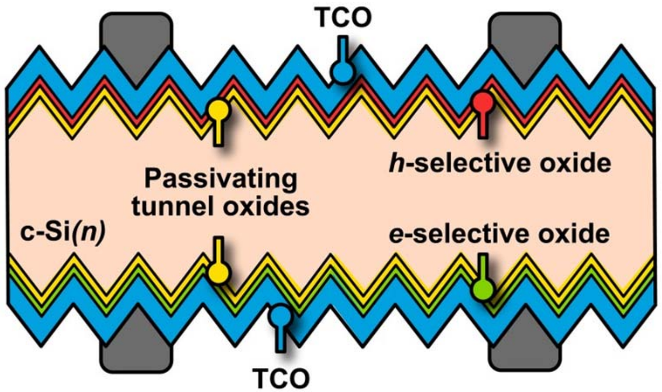


Poodt *et al.*, J. Vac. Sci. Technol. A 30, 01A142 (2012)
Meyer-Burger B.V. - www.meyerburger.com

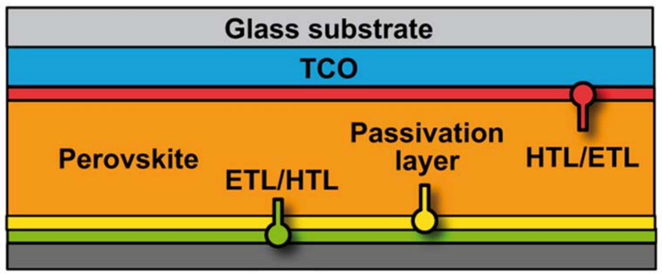
Summary

- Nanolayers have enabled important innovations in the field of crystalline silicon photovoltaics → most prominently: **Al_2O_3**!
- Many more opportunities exist for (ALD) nanolayers:
  - Crystalline silicon (e.g. passivated contacts)
  - Perovskites
  - Tandem solar cells
  - …

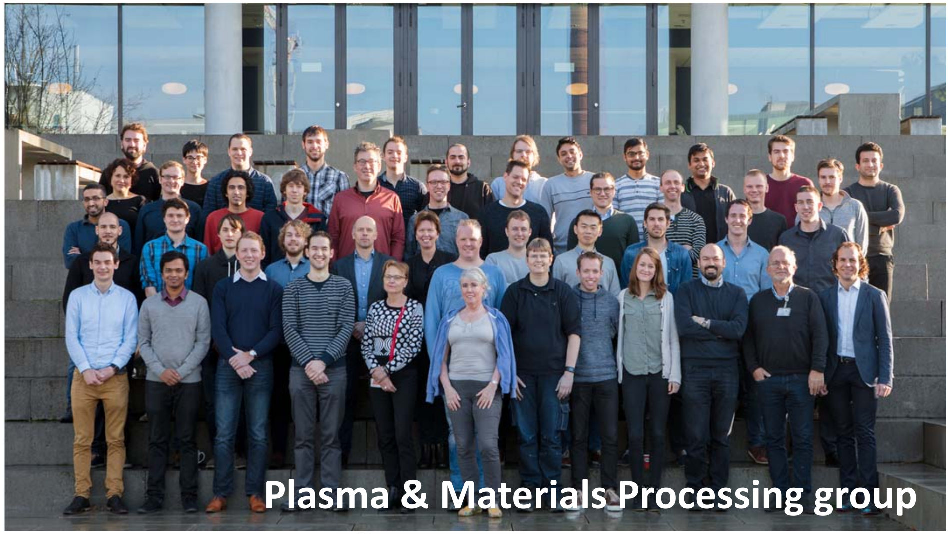
Passivated contacts solar cell



Perovkite solar cell



Acknowledgments



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