UPPSALA UNIVERSITET

imec
aspire invent achieve

KATHOLIEKE UNIVERSITEIT LEUVEN

FWO VLAANDEREN
Fonds Wetenschappelijk Onderzoek
Research Foundation - Flanders

SEVENTH FRAMEWORK PROGRAMME

MARIE CURIE ACTIONS

Vetenskapsrådet

Passivation of Si and CIGS surfaces

- Part I: Al_2O_3 passivation for Si PERx
- Part II: PERC meets CIGS - PercIGS

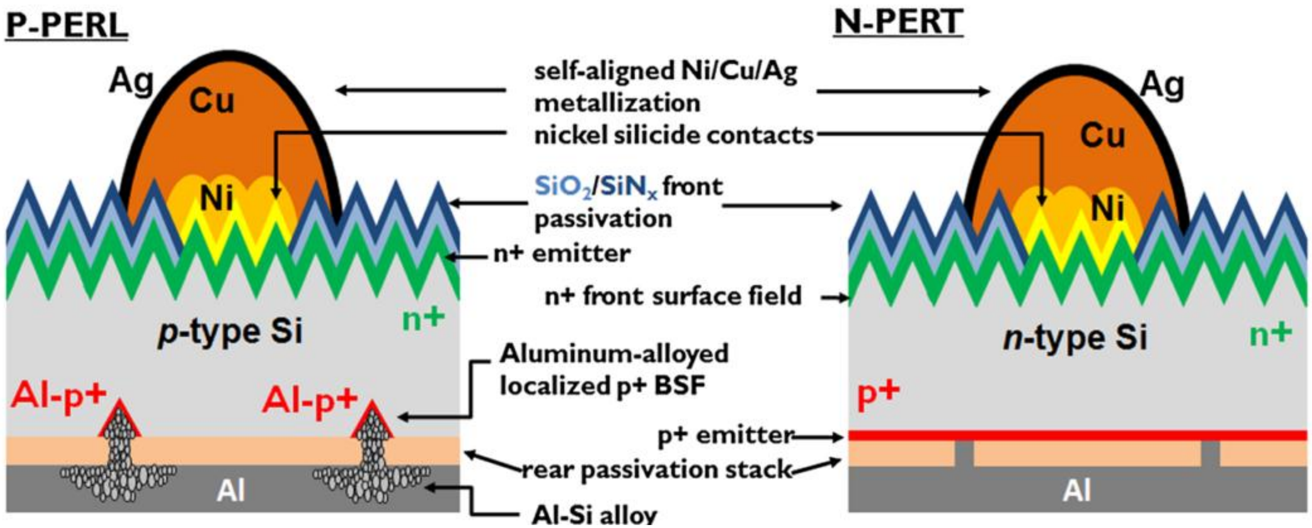
Bart Vermang et al.

Part I: Al_2O_3 passivation for Si PERx

- p-type PERL ≥ 20.5 %
- n-type PERT ≥ 21.5 %
- Rear passivation stack = ALD Al_2O_3 (+ capping)

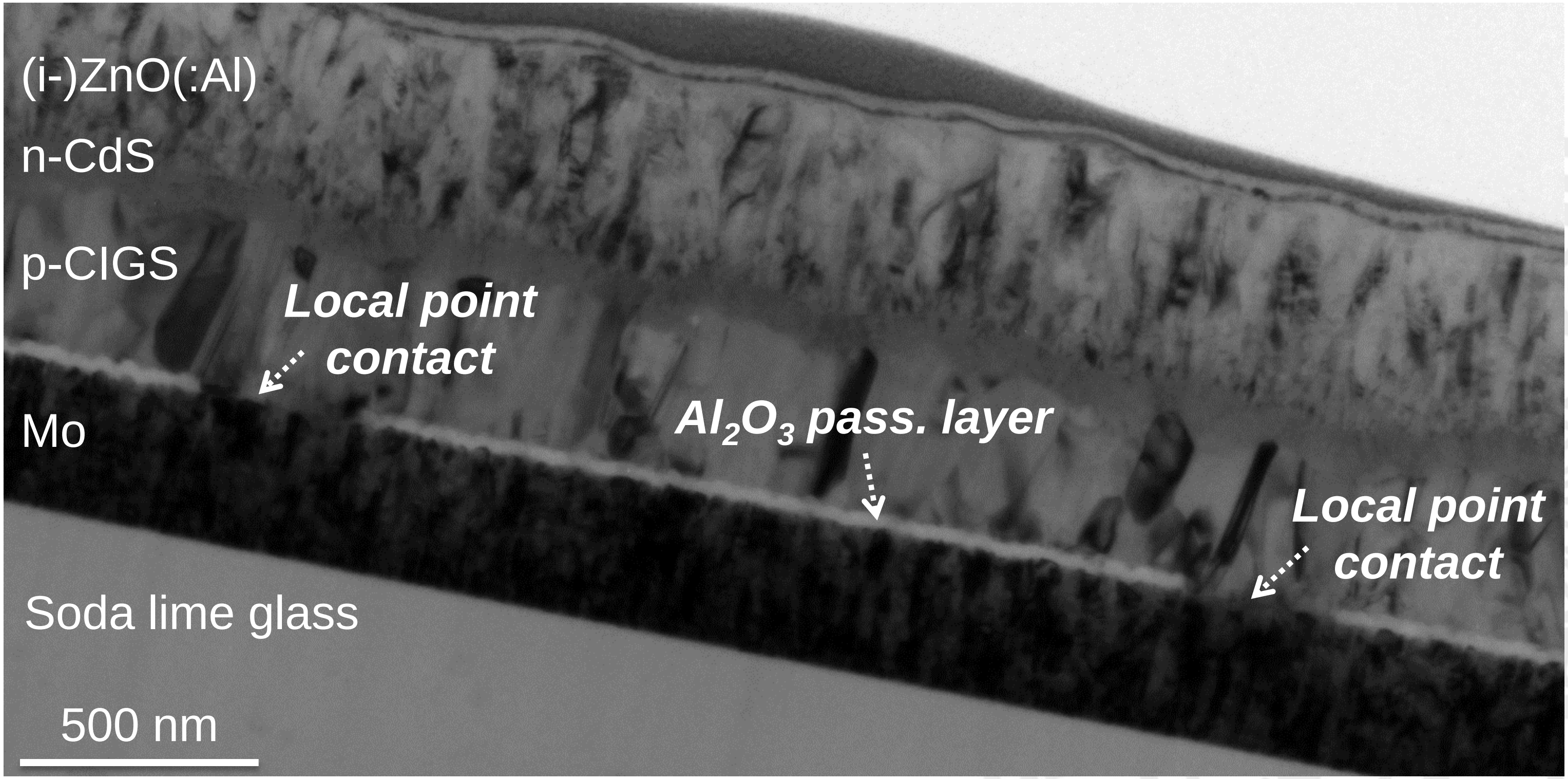
Fraunhofer ISE

CalLab PV Cells



L. Tous et al., Prog. Photovolt: Res. Appl. (2014) DOI: 10.1002/pip.2478

Part II: PERC meets CIGS - PercIGS

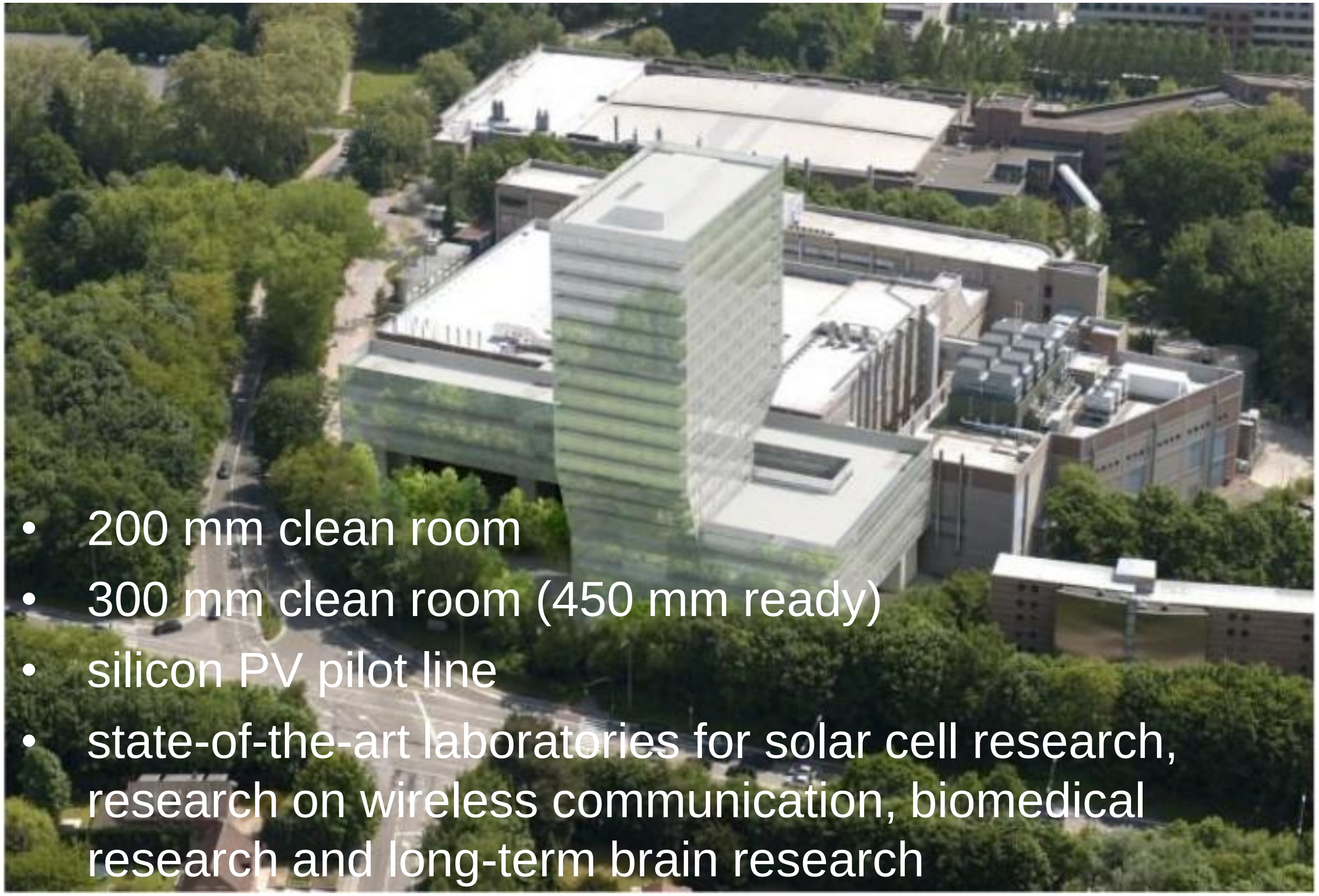


B. Vermang et al., IEEE J. Photovoltaics (2014) in press

Leuven, Belgium

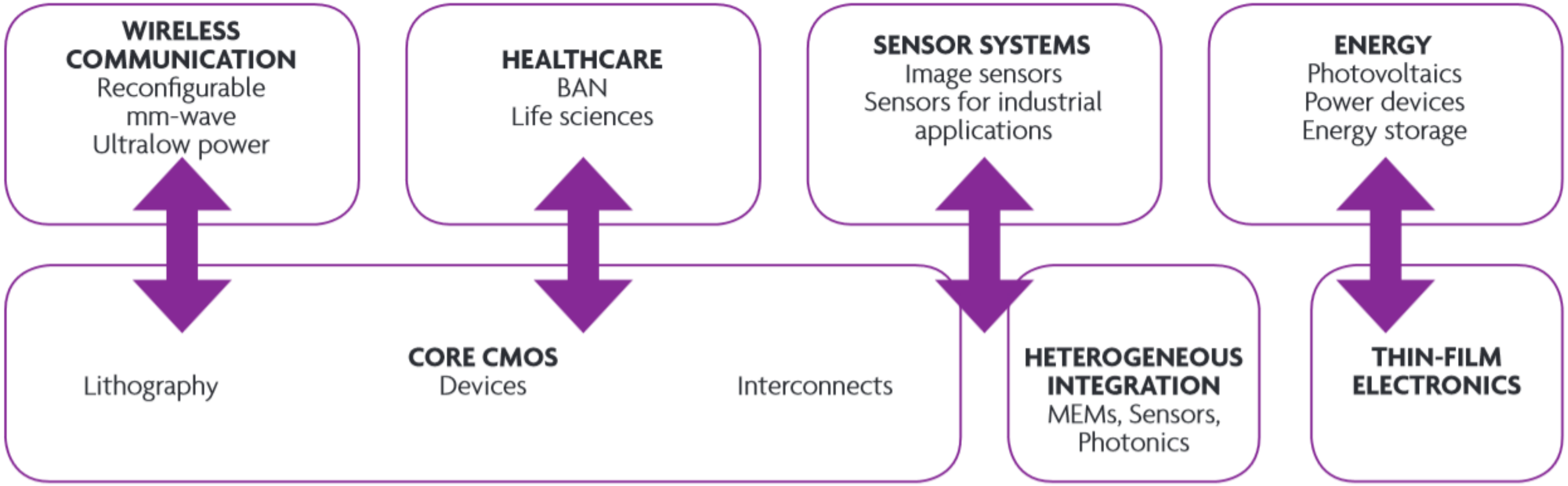
Interuniversity Micro-Electronics Centre (imec), Leuven, Belgium

24,400 m² of office space, laboratories, training facilities, and technical support rooms



- 200 mm clean room
- 300 mm clean room (450 mm ready)
- silicon PV pilot line
- state-of-the-art laboratories for solar cell research, research on wireless communication, biomedical research and long-term brain research

Imec’s research structure



WIRELESS COMMUNICATION
Reconfigurable
mm-wave
Ultralow power

HEALTHCARE
BAN
Life sciences

SENSOR SYSTEMS
Image sensors
Sensors for industrial applications

ENERGY
Photovoltaics
Power devices
Energy storage

Lithography

CORE CMOS
Devices

Interconnects

HETEROGENEOUS INTEGRATION
MEMs, Sensors, Photonics

THIN-FILM ELECTRONICS

- Si PV, OPV, TF PV (CZTS, a-Si), Perovskites, multi-junctions ...

Part I - outline

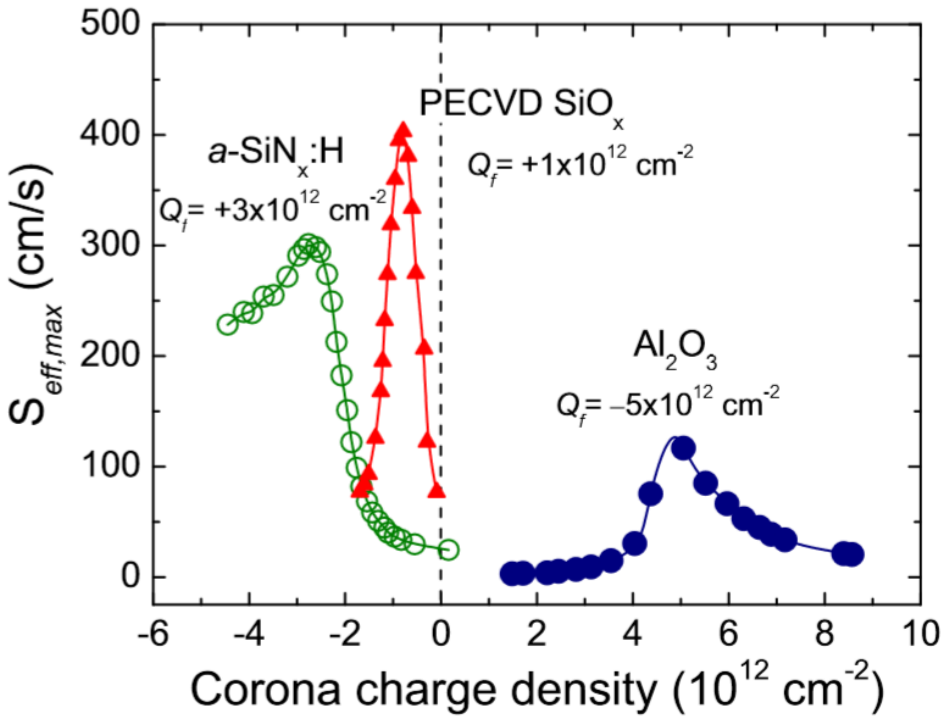
- Why Al_2O_3?
- Spatial atomic layer deposition (ALD) of Al_2O_3
- Thermal stability
- p-type PERL
- Illumination independency
- n-type PERT and Al_2O_3 contact passivation / doping

J. Vac. Sci. Technol. A (2012) DOI: 10.1116/1.4728205
Prog. Photovolt: Res. Appl. (2011) DOI: 10.1002/pip.1092
38th IEEE PVSC (2012) DOI: 10.1109/PVSC.2012.6317802
Sol. Energy Mater. Sol. Cells (2012) DOI: 10.1016/j.solmat.2012.01.032
Prog. Photovolt: Res. Appl. (2012) DOI: 10.1002/pip.2196
Phys. Status Solidi RRL (2012) DOI: 10.1002/pssr.201206154
Prog. Photovolt: Res. Appl. (2014) DOI: 10.1002/pip.2478
Energy Procedia (2014) DOI: 10.1016/j.egypro.2014.08.041
Phys. Status Solidi (a) (2013) DOI: 10.1002/pssa.201329058

Why Al_2O_3?

- Chemical passivation - Low D_{it}
- Field effect passivation - $Q_f < 0$

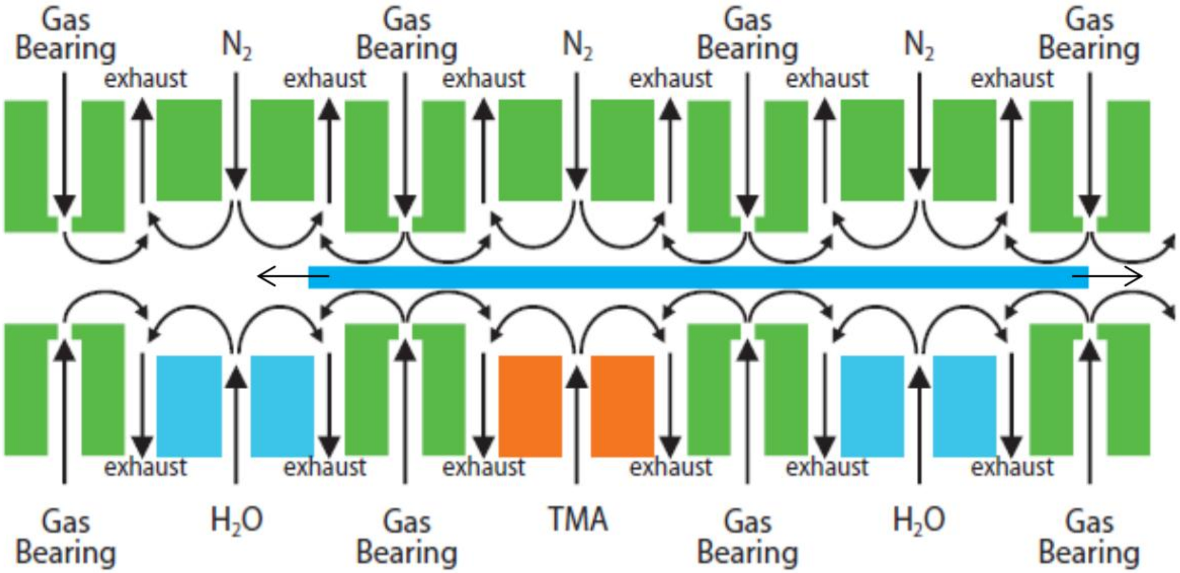
$$U_{surface} = \int_{E_V}^{E_C} \frac{v_{th}(n_s p_s - n_i^2)}{\frac{n_s + n_1(E_{it})}{\sigma_p(E_{it})} + \frac{p_s + p_1(E_{it})}{\sigma_n(E_{it})}} D_{it}(E_{it}) \mathrm{d}E_{it}$$



G. Dingemans et al., J. Vac. Sci. Technol. A (2012) DOI: 10.1116/1.4728205

Spatial ALD Al_2O_3

- Atmospheric pressure
- Increased throughput and TMA efficiency compared to standard "temporal" ALD



In-line
1-side depo
> 1 nm/s

SoLayTec

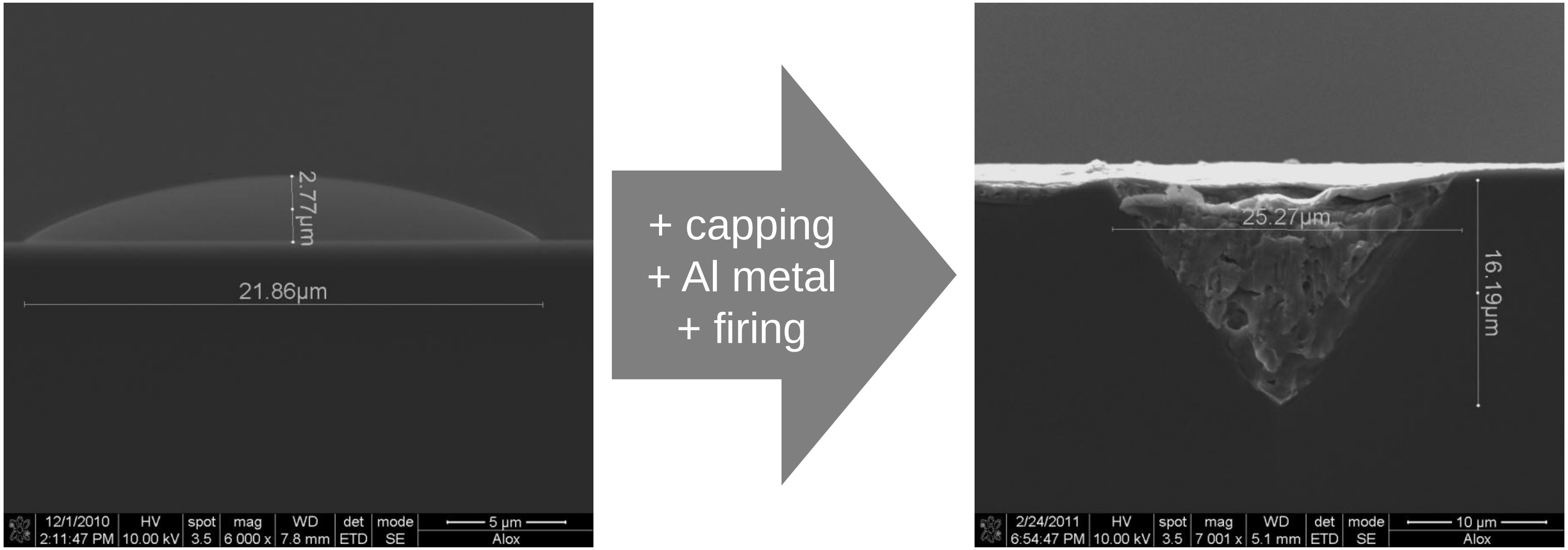
LEVITECH

B. Vermang et al., Prog. Photovolt: Res. Appl. (2011) DOI: 10.1002/pip.1092

EP 2 482 328, TW 2012 50839, US 2012 192943, JP 2012 160732

Thermal stability (blistering)

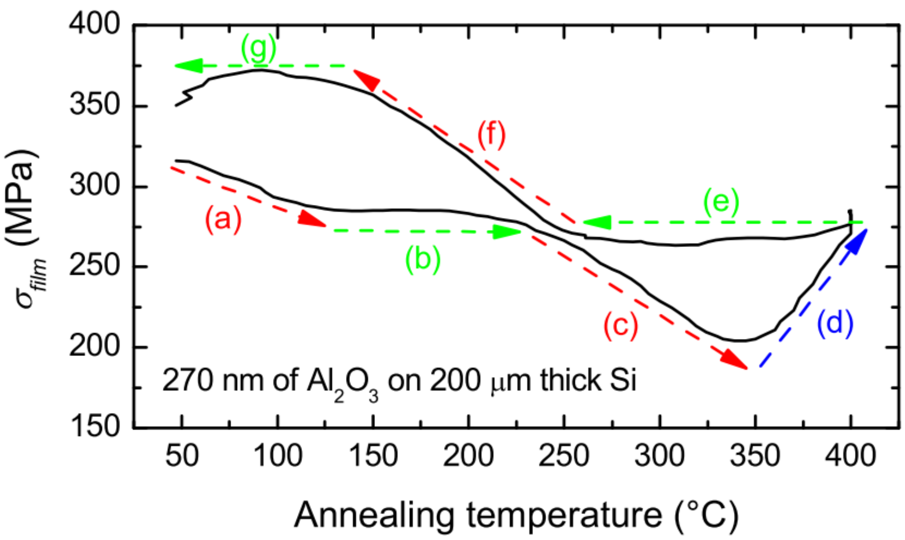
- Thick or capped (ALD) Al_2O_3 films blister upon annealing
- Blisters lead to additional point contacts

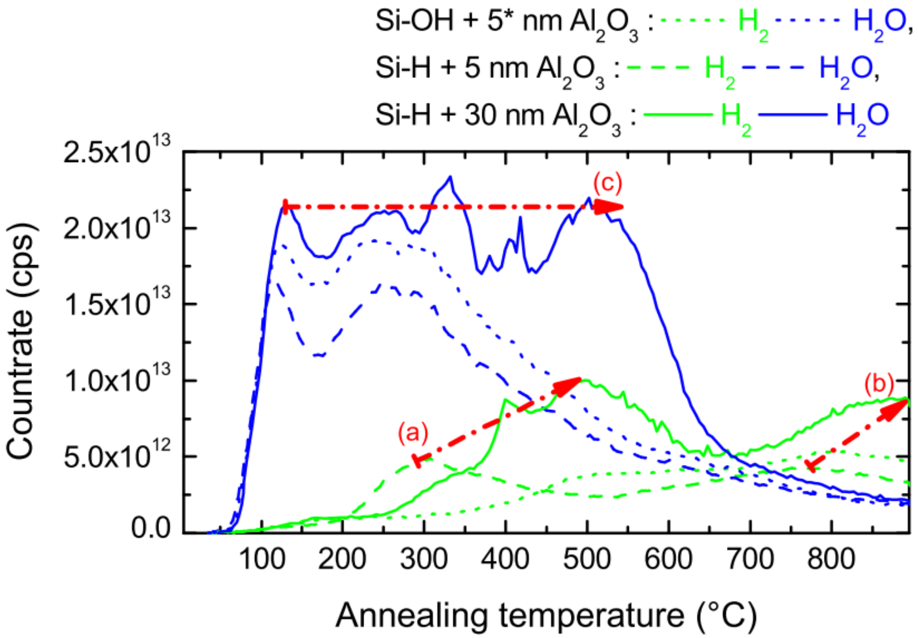


B. Vermang et al., 38th IEEE PVSC (2012) DOI: 10.1109/PVSC.2012.6317802
B. Vermang et al., Sol. Energy Mater. Sol. Cells (2012) DOI: 10.1016/j.solmat.2012.01.032

Thermal stability (blistering)

- Combination of (tensile) stress and outgassing (effusion of H_2, H_2O)
- Solution: thin ALD films and annealing before capping



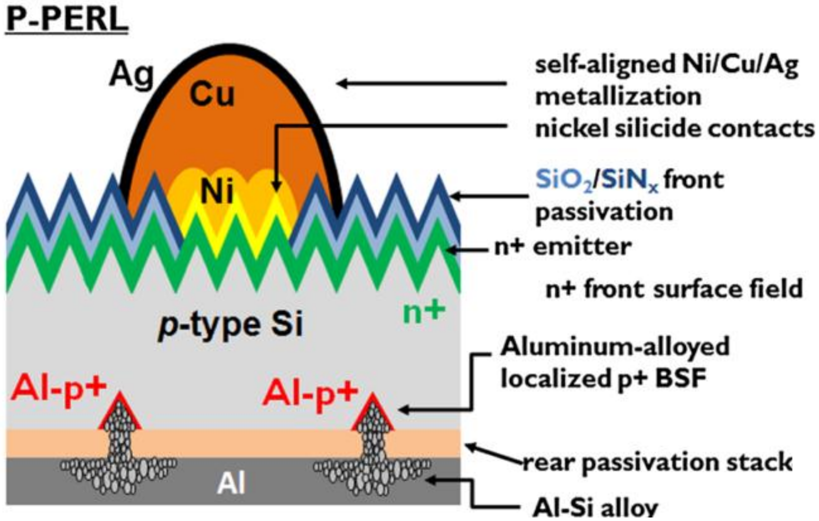


B. Vermang et al., 38th IEEE PVSC (2012) DOI: 10.1109/PVSC.2012.6317802
B. Vermang et al., Sol. Energy Mater. Sol. Cells (2012) DOI: 10.1016/j.solmat.2012.01.032

EP 2 398 044, TW 2012 06857, US 2011 0308603, JP 2012 039088
EP 2 533 305, TW 2013 20188, US 2012 0306058, JP 2012 253356

p-type PERL

- Rear pass. stack = spatial ALD Al_2O_3 (≤ 10 nm) + annealing + SiN_x
- Best cell 20.5 %
  - V_{OC} = 665 mV; J_{SC} = 38.6 mA/cm^2; FF = 79.9 %
- Imec’s Si PV focus moved to n-type

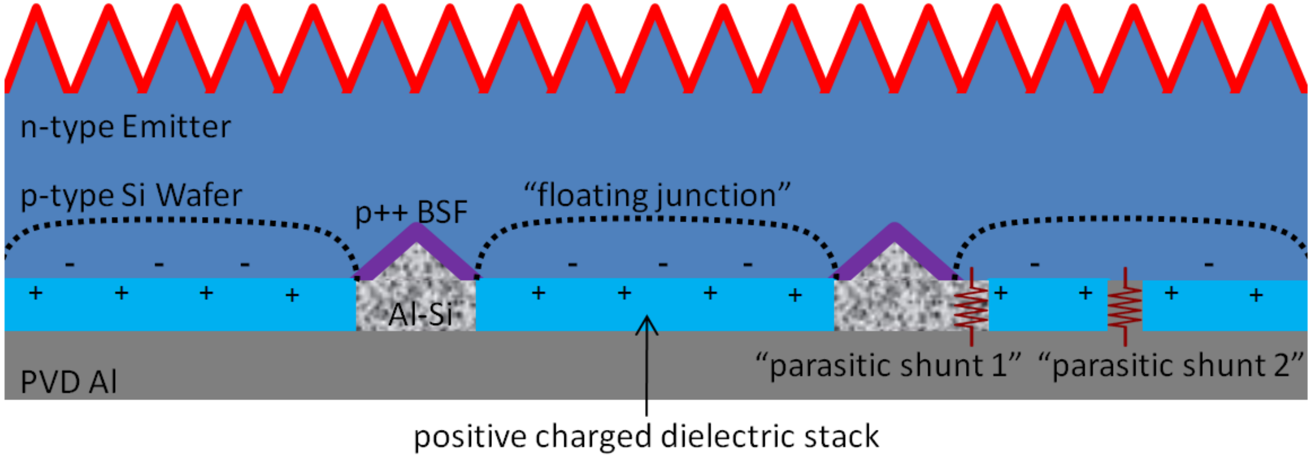


Similar technologies:
Trina Solar
Suntech
Canadian Solar
Ja Solar
Hanwha Solar
...

B. Vermang et al., Prog. Photovolt: Res. Appl. (2012) DOI: 10.1002/pip.2196
L. Tous et al., Prog. Photovolt: Res. Appl. (2014) DOI: 10.1002/pip.2478

Illumination independency

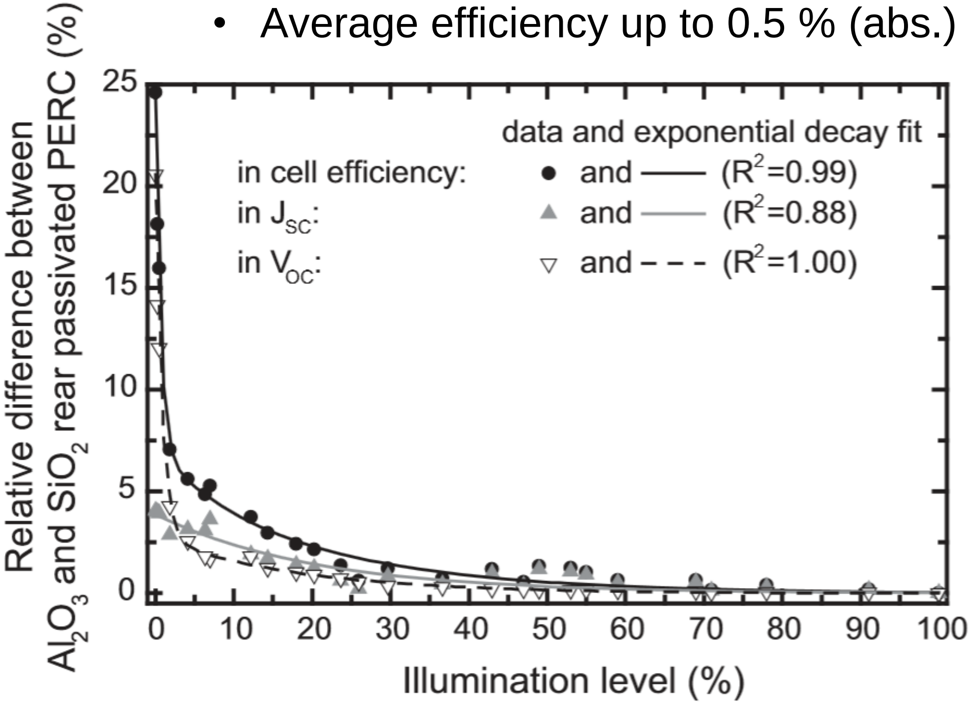
- V_{OC} → pos./neg. charged surf. pass. (S_{eff}, S.R.H.)
- J_{SC} → parasitic shunting
  - Rear passivation of p-type Si PERC =
    - Pos. charged dielectric → inversion = floating junction, constant loss of photo-generated e^- from the inverted region via the shunt
    - Neg. charged dielectric → accumulation



B. Vermang et al., Phys. Status Solidi RRL (2012) DOI: 10.1002/pssr.201206154

Illumination independency

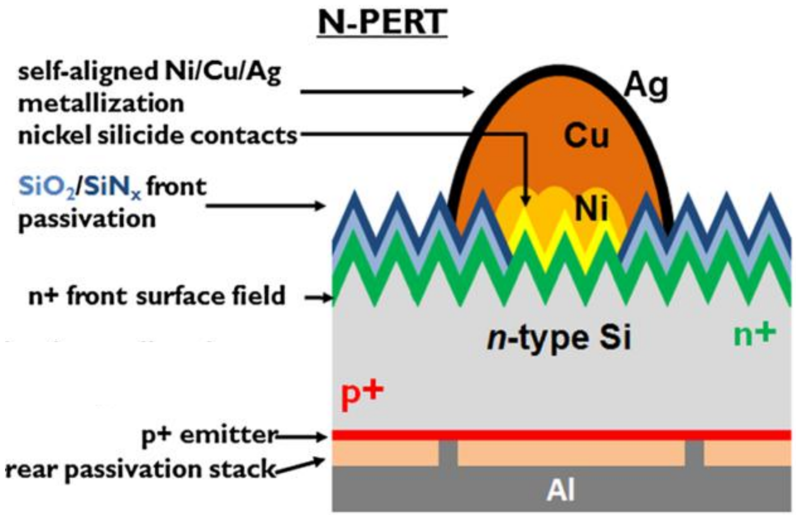
- SiO_2 compared to Al_2O_3 rear passivated p-type Si PERC
    - Filters are used to reduce the light intensity < 100 %
- SiO_2 rear pass. p-Si PERC
    - Average efficiency up to 0.5 % (abs.) lower in low solar irradiation regions



B. Vermang et al., Phys. Status Solidi RRL (2012) DOI: 10.1002/pssr.201206154

n-type PERT
and contact pass. + doping

- Rear pass. stack = spatial ALD Al_2O_3 (≤ 10 nm) (+ ann.) + SiN_x
- Best cell 21.5 %
  - V_{OC} = 677 mV; J_{SC} = 39.1 mA/cm^2; FF = 81.3 %
- Contact pass. of n^+-Si & p^+-doping by laser ablation of Al_2O_3/SiN_x



L. Tous et al., Prog. Photovolt: Res. Appl. (2014) DOI: 10.1002/pip.2478
J. Deckers et al., Energy Procedia (2014) DOI: 10.1016/j.egypro.2014.08.041
N.-P. Harder, Phys. Status Solidi (a) (2013) DOI: 10.1002/pssa.201329058

All of this is teamwork!

My promoter Jef Poortmans and all imec colleagues

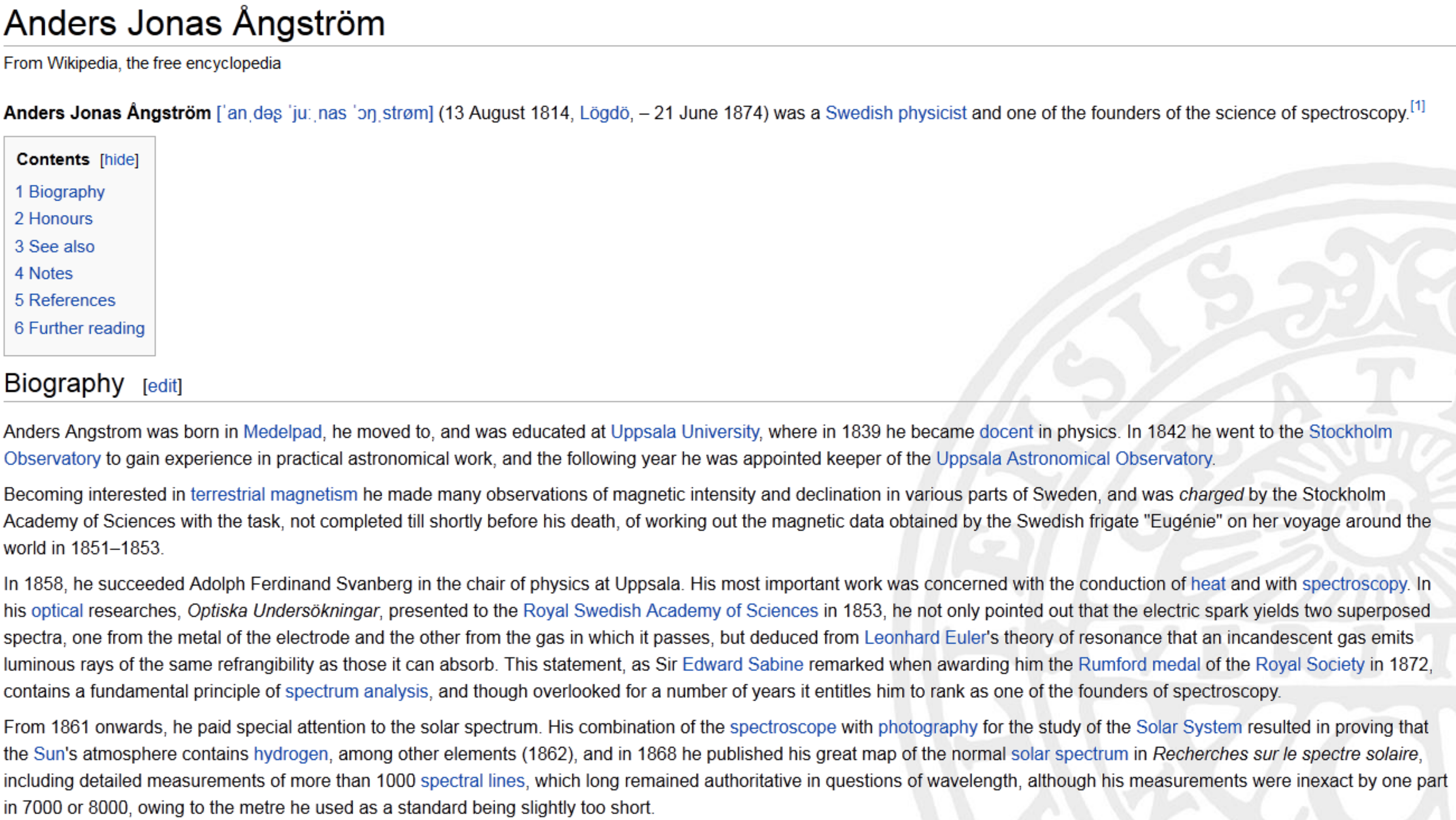
Uppsala, Sweden

Ångström Solar Center, University of Uppsala

Ångström laboratiet / laboratory

- Group
  - Tunnfilmssolceller / Thin Film Solar Cells
- Department
  - Fasta Tillståndets Elektronik / Solid State Electronics

1 Ångström = 1 Å = 0.1 nm



Anders Jonas Ångström

From Wikipedia, the free encyclopedia

Anders Jonas Ångström [ˈanˌdəʂ ˈjuːˌnas ˈɔŋˌstrøm] (13 August 1814, Lögdö, – 21 June 1874) was a Swedish physicist and one of the founders of the science of spectroscopy.[1]

Contents [hide]

Biography [edit]

Anders Angstrom was born in Medelpad, he moved to, and was educated at Uppsala University, where in 1839 he became docent in physics. In 1842 he went to the Stockholm Observatory to gain experience in practical astronomical work, and the following year he was appointed keeper of the Uppsala Astronomical Observatory.

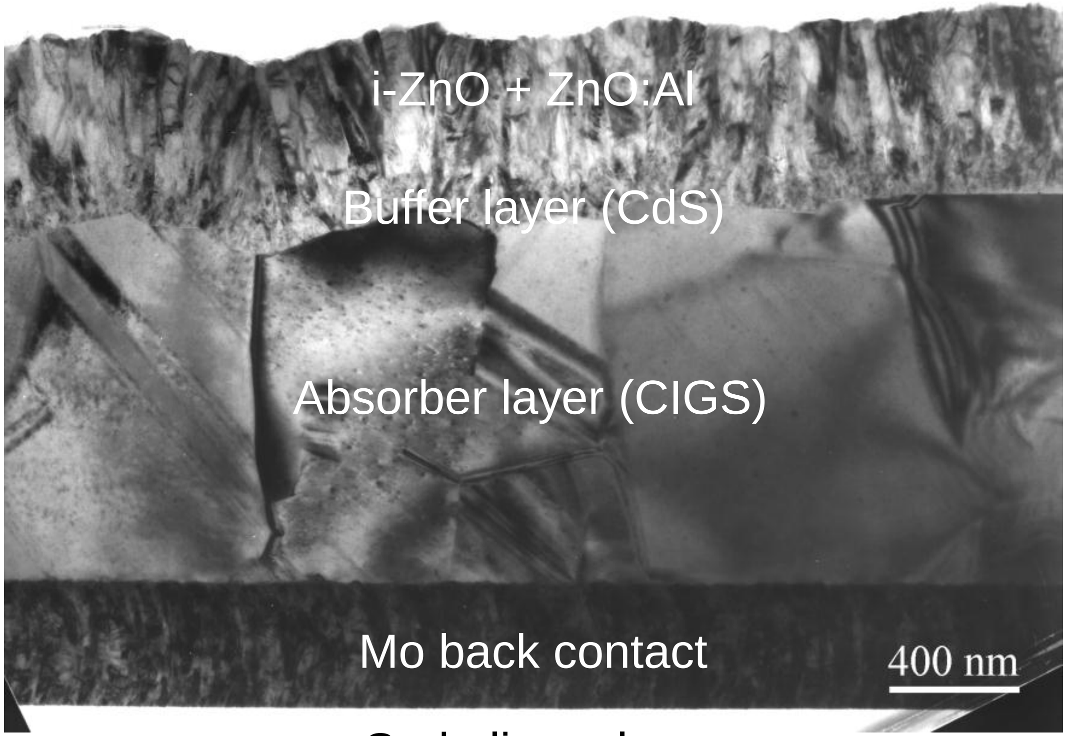
Becoming interested in terrestrial magnetism he made many observations of magnetic intensity and declination in various parts of Sweden, and was *charged* by the Stockholm Academy of Sciences with the task, not completed till shortly before his death, of working out the magnetic data obtained by the Swedish frigate "Eugénie" on her voyage around the world in 1851–1853.

In 1858, he succeeded Adolph Ferdinand Svanberg in the chair of physics at Uppsala. His most important work was concerned with the conduction of heat and with spectroscopy. In his optical researches, *Optiska Undersökningar*, presented to the Royal Swedish Academy of Sciences in 1853, he not only pointed out that the electric spark yields two superposed spectra, one from the metal of the electrode and the other from the gas in which it passes, but deduced from Leonhard Euler's theory of resonance that an incandescent gas emits luminous rays of the same refrangibility as those it can absorb. This statement, as Sir Edward Sabine remarked when awarding him the Rumford medal of the Royal Society in 1872, contains a fundamental principle of spectrum analysis, and though overlooked for a number of years it entitles him to rank as one of the founders of spectroscopy.

From 1861 onwards, he paid special attention to the solar spectrum. His combination of the spectroscope with photography for the study of the Solar System resulted in proving that the Sun's atmosphere contains hydrogen, among other elements (1862), and in 1868 he published his great map of the normal solar spectrum in *Recherches sur le spectre solaire*, including detailed measurements of more than 1000 spectral lines, which long remained authoritative in questions of wavelength, although his measurements were inexact by one part in 7000 or 8000, owing to the metre he used as a standard being slightly too short.

Ångström Solar Center - Lab

Cell and module fabrication
Electrical and material characterization



Scribing / lamination

ARC MgF_2
EG evaporation Al/Ni/Al

(i-)ZnO(:Al) sputtering

CBD CdS
ALD (Cd-free)

CIGS co-evaporation
- Inline
- 2 x Batch (+ MS control)

CIGS sputtering
CZTS sputtering

NaF evaporation

Mo sputtering

Ångström Solar Center - Goals

- CIGS solar cell ≥ 22 % efficiency (1-stage!)
  - Cd-free alternative buffers ≥ 20 %
- CZTS solar cell ≥ 12 % efficiency

- Back contact passivation
- Electrical modeling
- Absorber layer formation
- Module energy yield modeling
  - Focus: northern climate

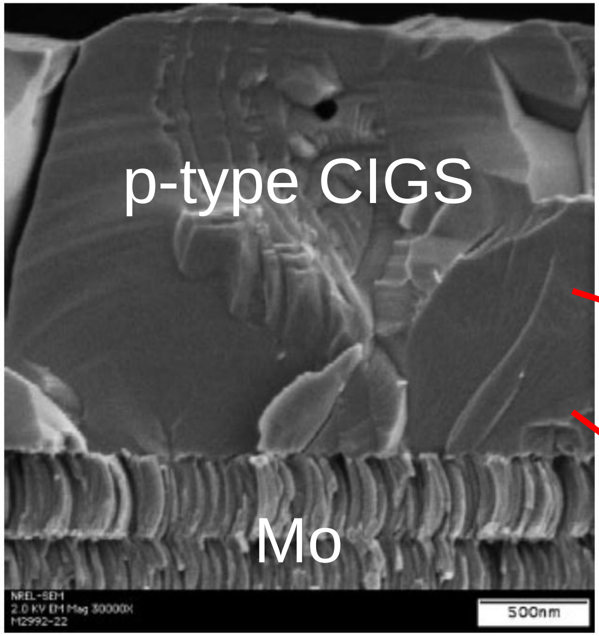
Part II - outline

- Standard CIGS solar cells
- PercIGS = PERC meets CIGS
- Al_2O_3 as CIGS surface passivation
- Al_2O_3 rear passivated CIGS solar cells
- Contacting approaches (3)
- Na optimization in rear passivated CIGS solar cells

Appl. Phys. Lett. (2012) DOI: 10.1063/1.3675849
Sol. Energy Mater. Sol. Cells (2013) DOI: 10.1016/j.solmat.2013.07.025
IEEE J. Photovoltaics (2013) DOI: 10.1109/JPHOTOV.2013.2287769
Prog. Photovolt: Res. Appl. (2014) DOI: 10.1002/pip.2527
Uppsala University MSc. Thesis (2014) ISSN: 1650-8300, UPTEC ES14 030
Phys. Status Solidi RRL (2014) DOI: 10.1002/pssr.201409387
IEEE J. Photovoltaics (2014) in press
Thin Solid Films (2014) under review

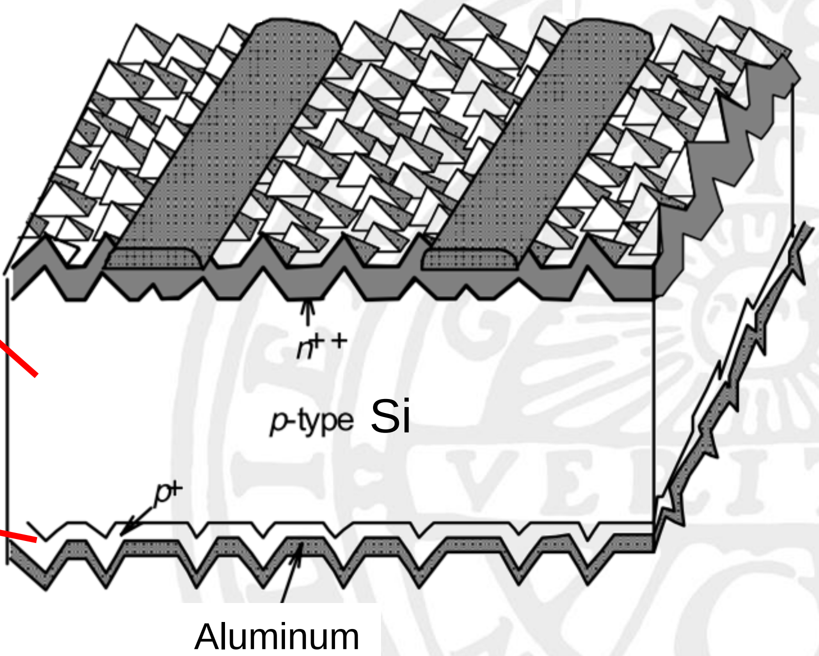
Standard CIGS solar cells

- Back surface field (BSF) to passivate Mo/CIGS rear interface
  - Highly recombinative ($1\text{x}10^4$ cm/s ≤ S_b ≤ $1\text{x}10^6$ cm/s) and lowly reflective (R_b < 60 %)
  - Very comparable to Al BSF in standard Si solar cells



Thick absorber layer

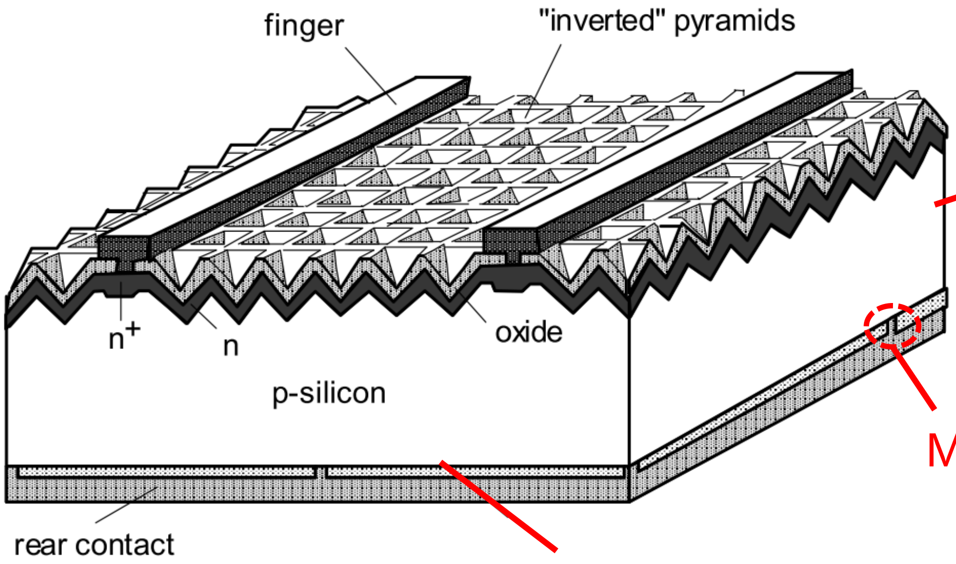
BSF



B. Vermang et al., Sol. Energy Mater. Sol. Cells (2013) DOI: 10.1016/j.solmat.2013.07.025

PercIGS = PERC meets CIGS

- Rear of Si PERC = a combination of an adequate rear surface passivation layer and micron-sized local point contacts



Ever thinner wafer thickness

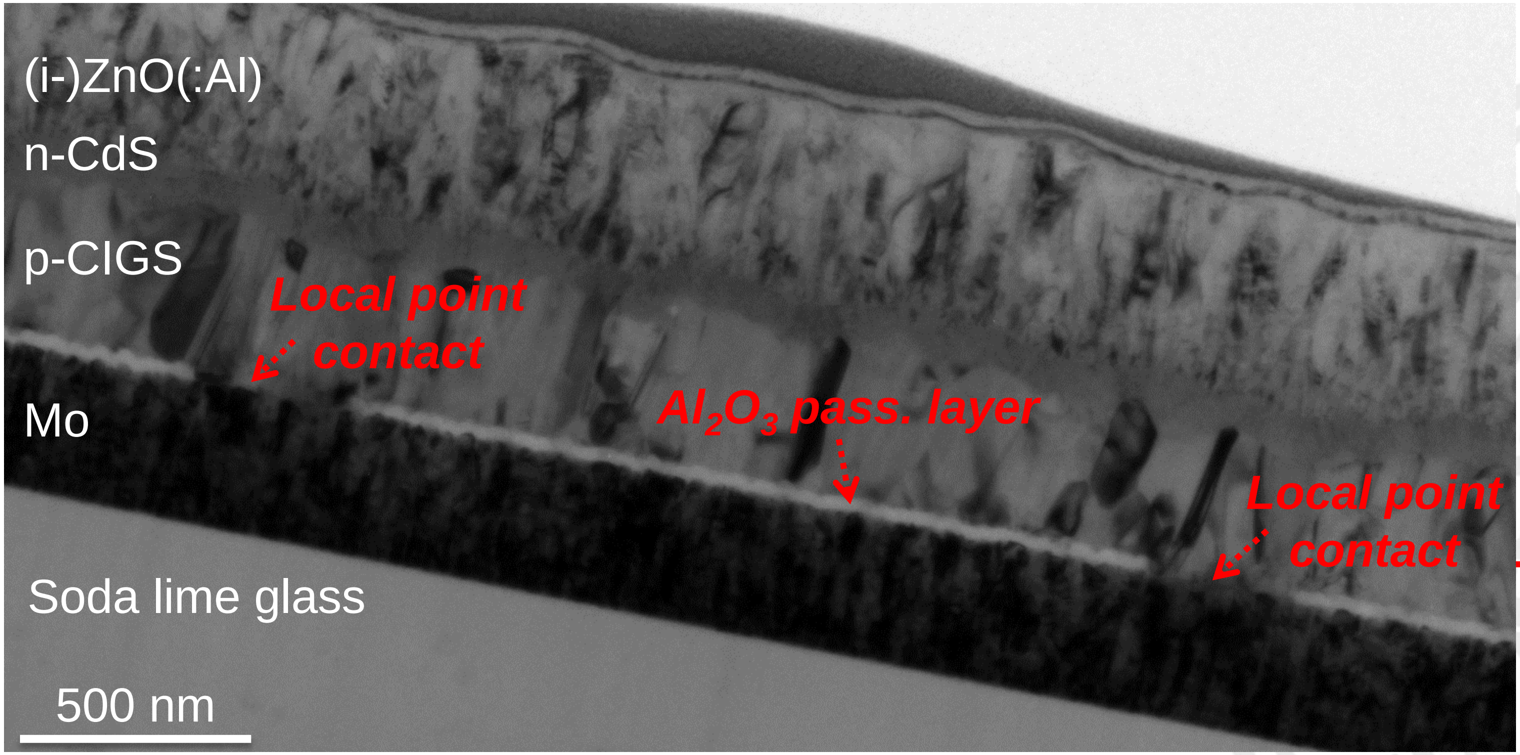
Micron-sized local point contact

Passivation layer

B. Vermang et al., Sol. Energy Mater. Sol. Cells (2013) DOI: 10.1016/j.solmat.2013.07.025

PercIGS = PERC meets CIGS

- PercIGS = a combination of an adequate rear surface passivation layer and nano-sized local point contacts

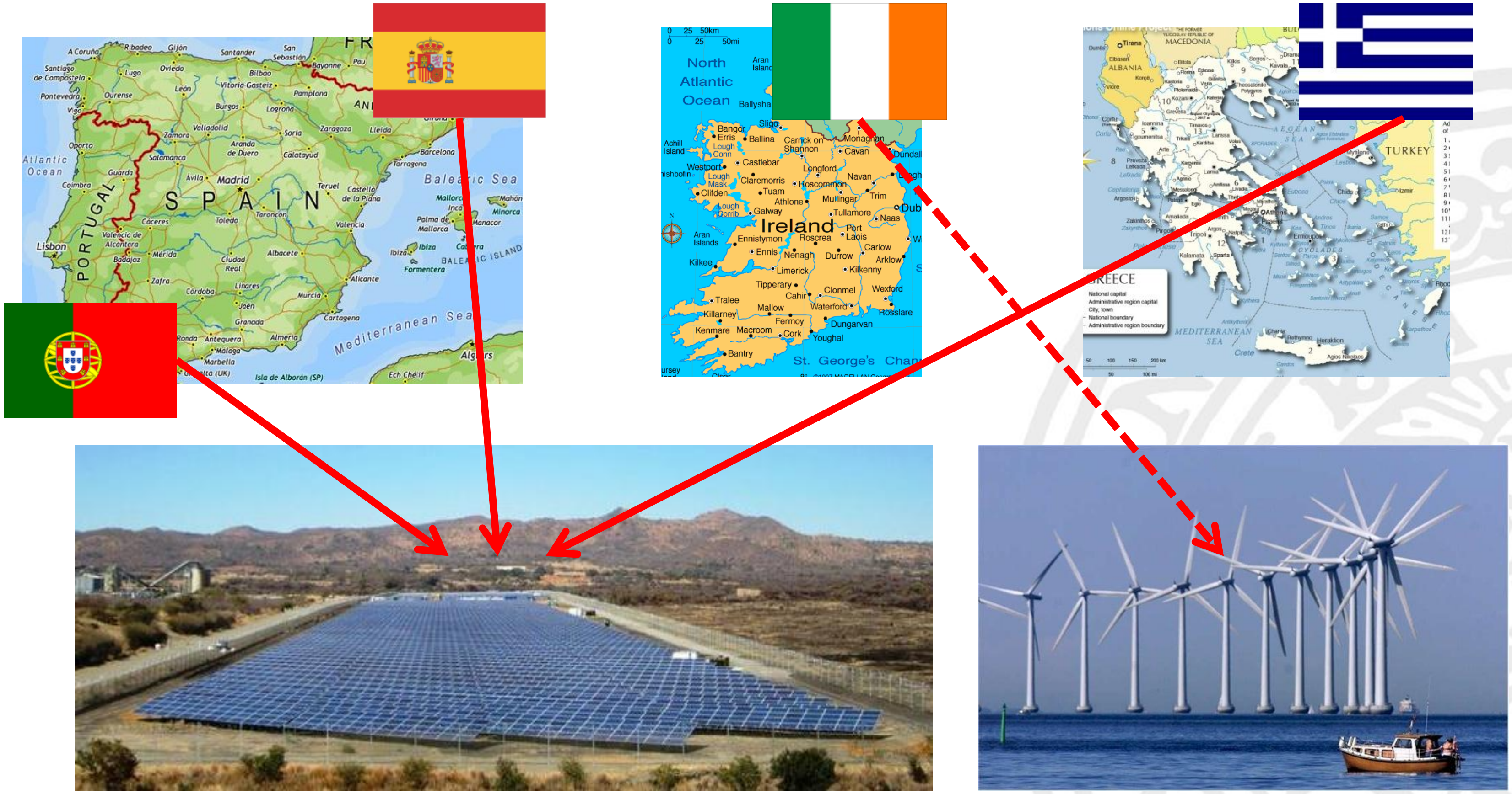


Ever thinner absorber layer

B. Vermang et al., Sol. Energy Mater. Sol. Cells (2013) DOI: 10.1016/j.solmat.2013.07.025

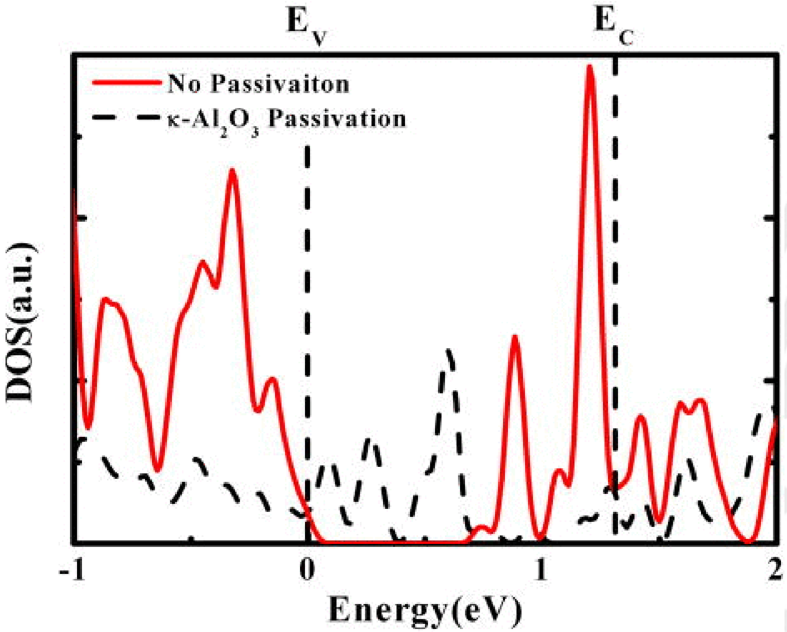
PercIGS

- European project



Al_2O_3 as CIGS surface passivation

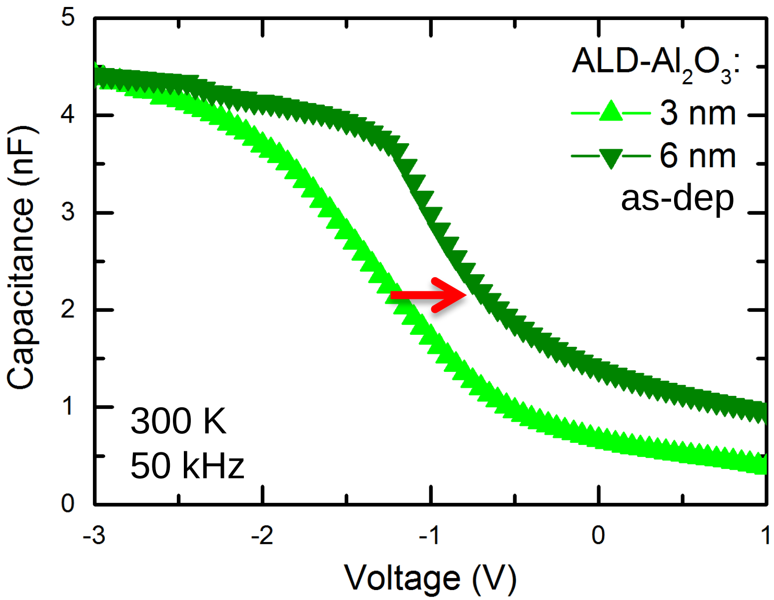
- Chemical passivation - Low D_{it}
  - First principle calculations: 35 % reduction in D_{it} as compared to unpassivated CIGS surface

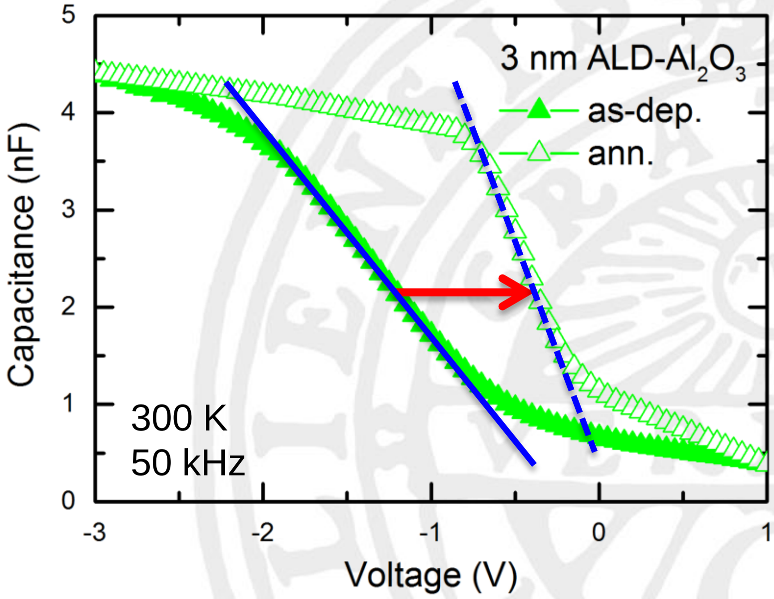


W.-W. Hsu, Appl. Phys. Lett. (2012) DOI: 10.1063/1.3675849

Al_2O_3 as CIGS surface passivation

- Field effect passivation - $Q_f < 0$
  - $Q_f < 0$ – positive shift in flat-band voltage (V_{FB}) a.f.o. Al_2O_3 thickness
  - $\Delta Q_f < 0$ – positive shift in V_{FB} after annealing
  - Reduction in D_{it} – steeper CV slope after annealing

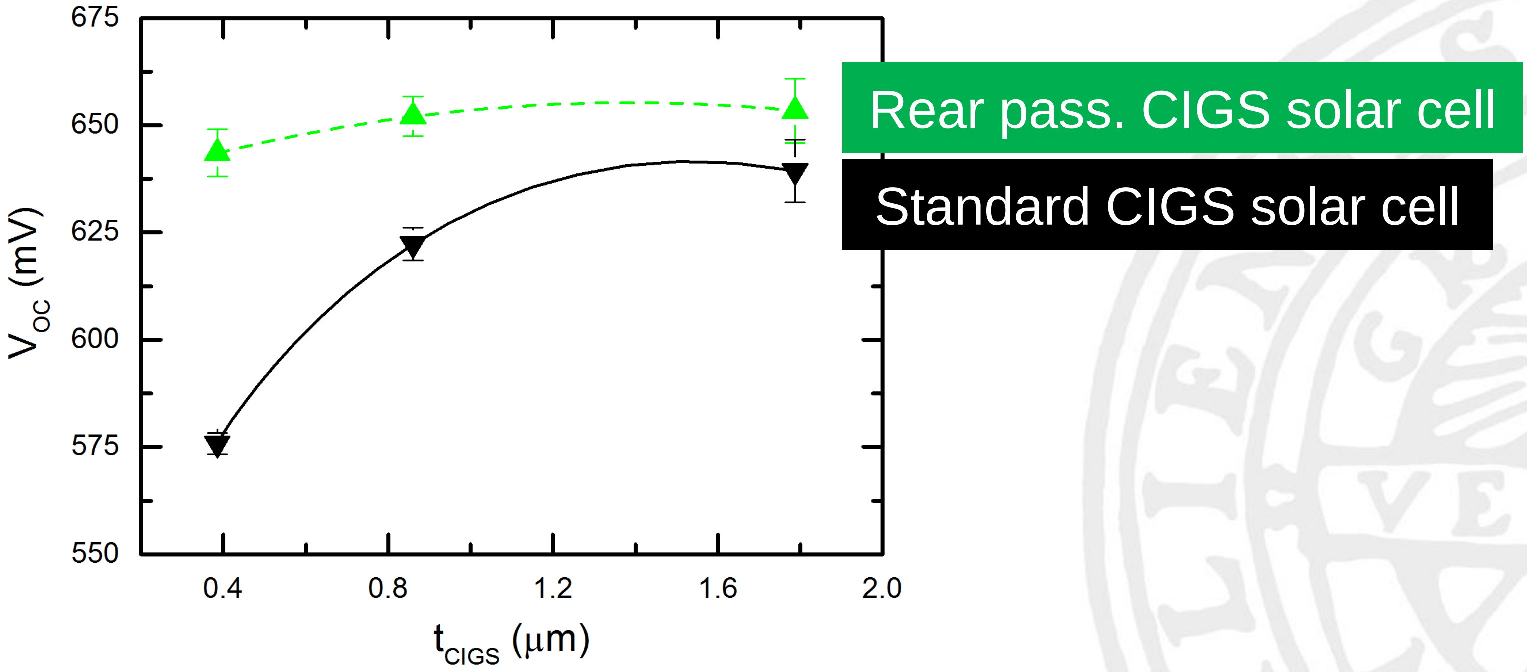




J. Joel, Uppsala University MSc. Thesis (2014) ISSN: 1650-8300, UPTEC ES14 030

Al_2O_3 rear passivated CIGS solar cells

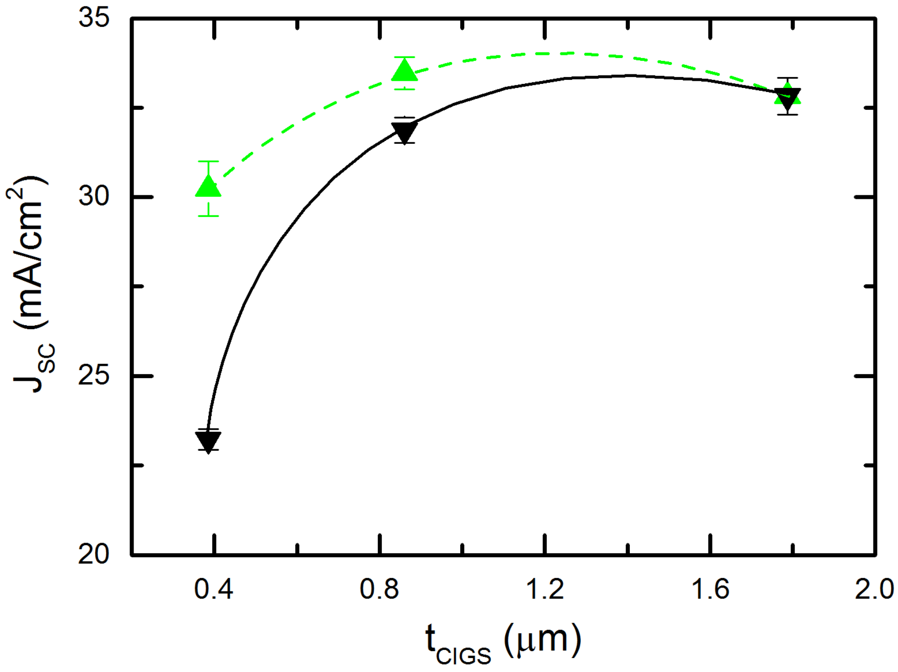
- Always increase in V_{OC} compared to unpassivated standard cells
- More obvious for ever thinner t_{CIGS}
- Rear surf. pass. - very comparable as “PERC ↔ std. Si solar cell”

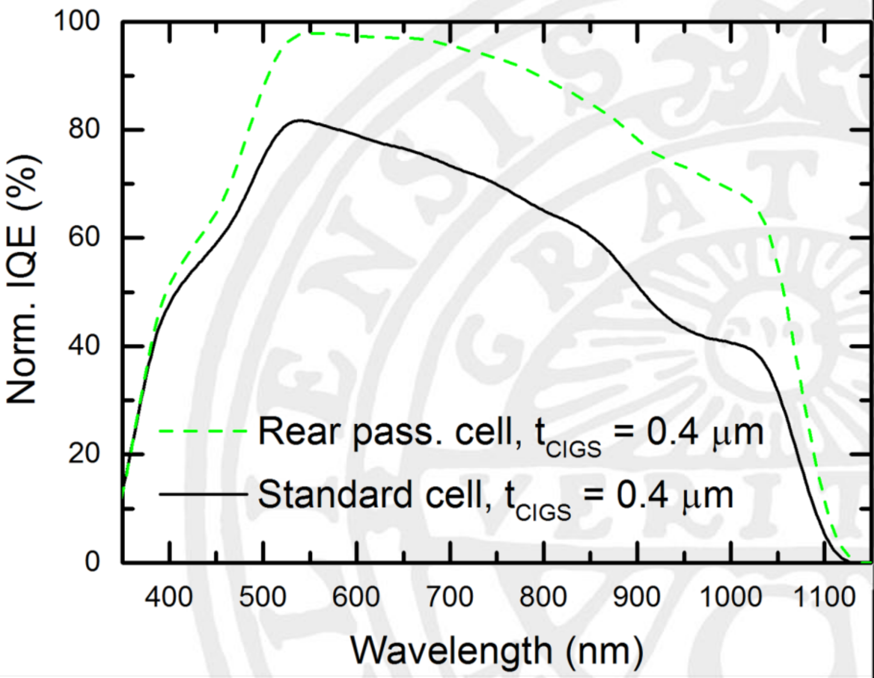


B. Vermang et al., Prog. Photovolt: Res. Appl. (2014) DOI: 10.1002/pip.2527

Al_2O_3 rear passivated CIGS solar cells

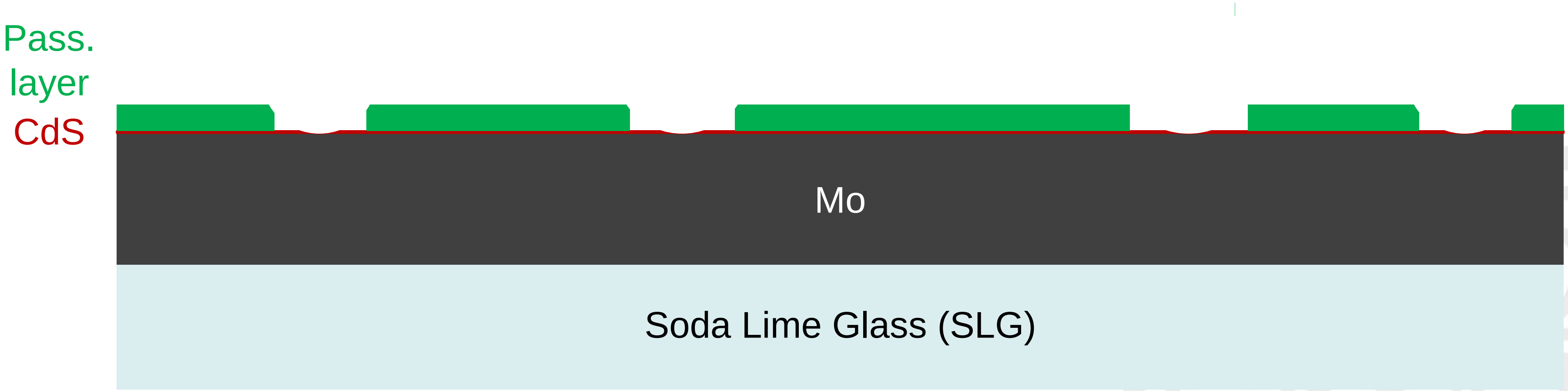
- Only increase in J_{SC} for ever thinner t_{CIGS}
- Still a loss in J_{SC} compared to thick standard CIGS solar cells
- Rear int. refl. & surf. pass. - comparable as “PERC ↔ std. Si cell”





B. Vermang et al., Prog. Photovolt: Res. Appl. (2014) DOI: 10.1002/pip.2527

Contacting approach 1: CdS nano-particles + removal

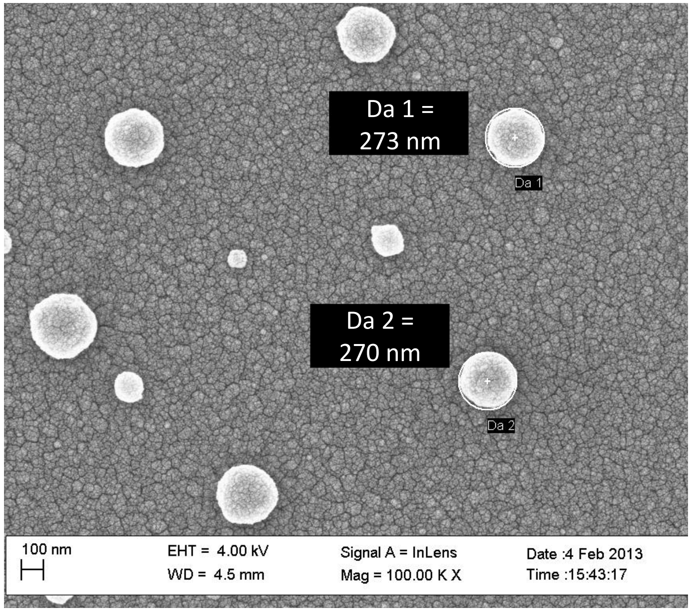


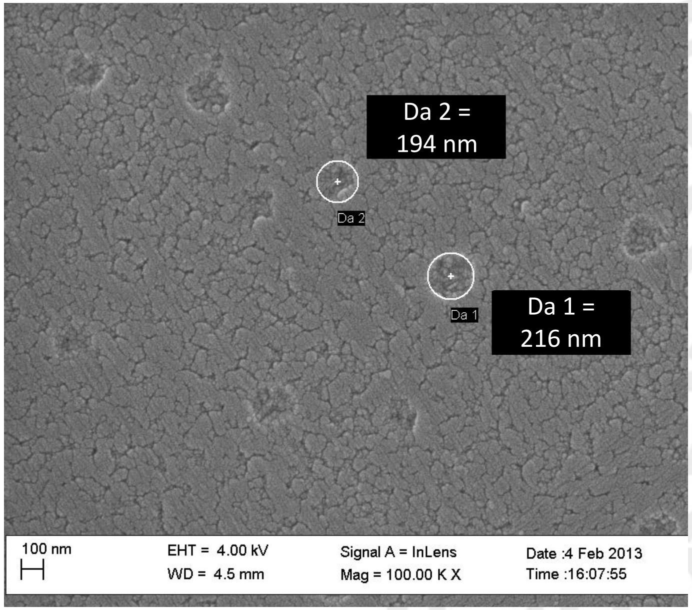
1. Deposit (chemical bath deposition = CBD) a particle-rich CdS layer on the Mo back contact
2. Deposit the surface passivation layer
    - DC-sputt. Al_2O_3 or evap. MgF_2/ALD-Al_2O_3
3. Remove the CdS nano-particles

B. Vermang et al., Sol. Energy Mater. Sol. Cells (2013) DOI: 10.1016/j.solmat.2013.07.025
B. Vermang et al., IEEE J. Photovoltaics (2013) DOI: 10.1109/JPHOTOV.2013.2287769
B. Vermang et al., Prog. Photovolt: Res. Appl. (2014) DOI: 10.1002/pip.2527

Contacting approach 1:
CdS nano-particles + removal

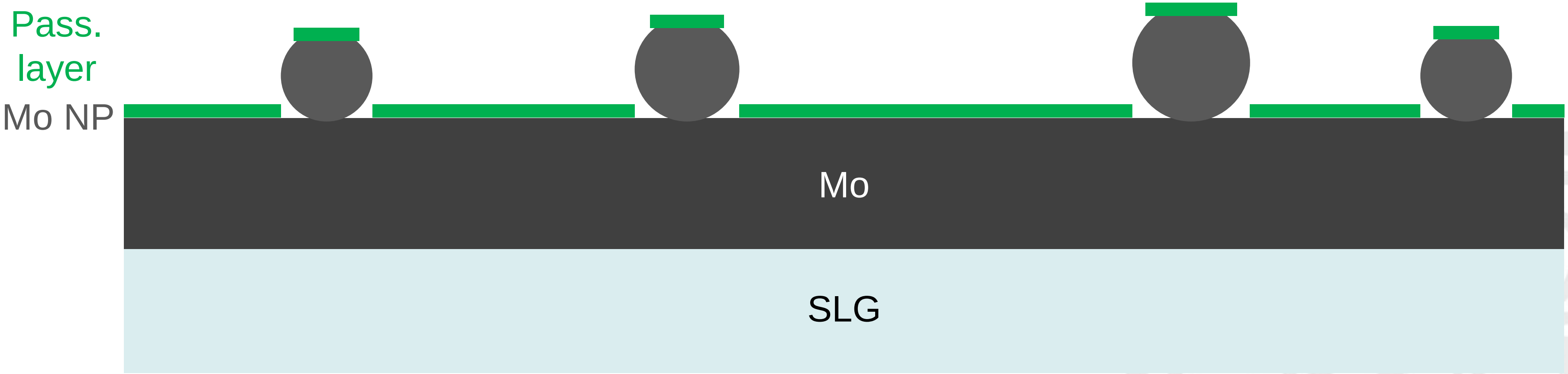
- Particle diameter = 285 ± 30 nm
- Point opening diameter = 220 ± 25 nm
- High R_S, as the point contacting grids are only sub-optimized





B. Vermang et al., Sol. Energy Mater. Sol. Cells (2013) DOI: 10.1016/j.solmat.2013.07.025
B. Vermang et al., IEEE J. Photovoltaics (2013) DOI: 10.1109/JPHOTOV.2013.2287769
B. Vermang et al., Prog. Photovolt: Res. Appl. (2014) DOI: 10.1002/pip.2527

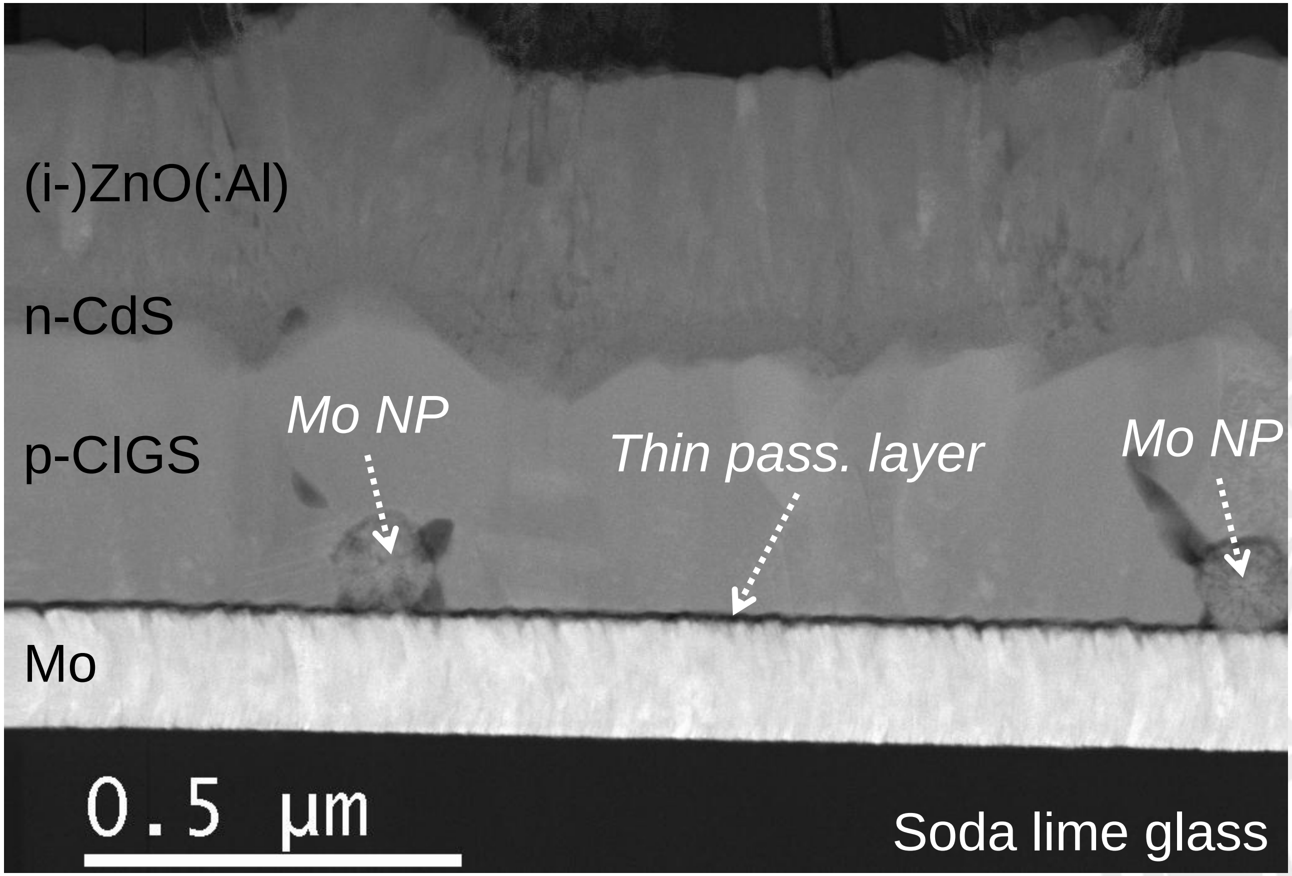
Contacting approach 2: Mo nano-particles



1. Deposit Mo NP (formed by a plasma process) on the Mo back contact
2. Deposit the surface passivation layer
    - DC-sputt. Al_2O_3 (< 25 nm)

B. Vermang et al., Thin Solid Films (2014) under review

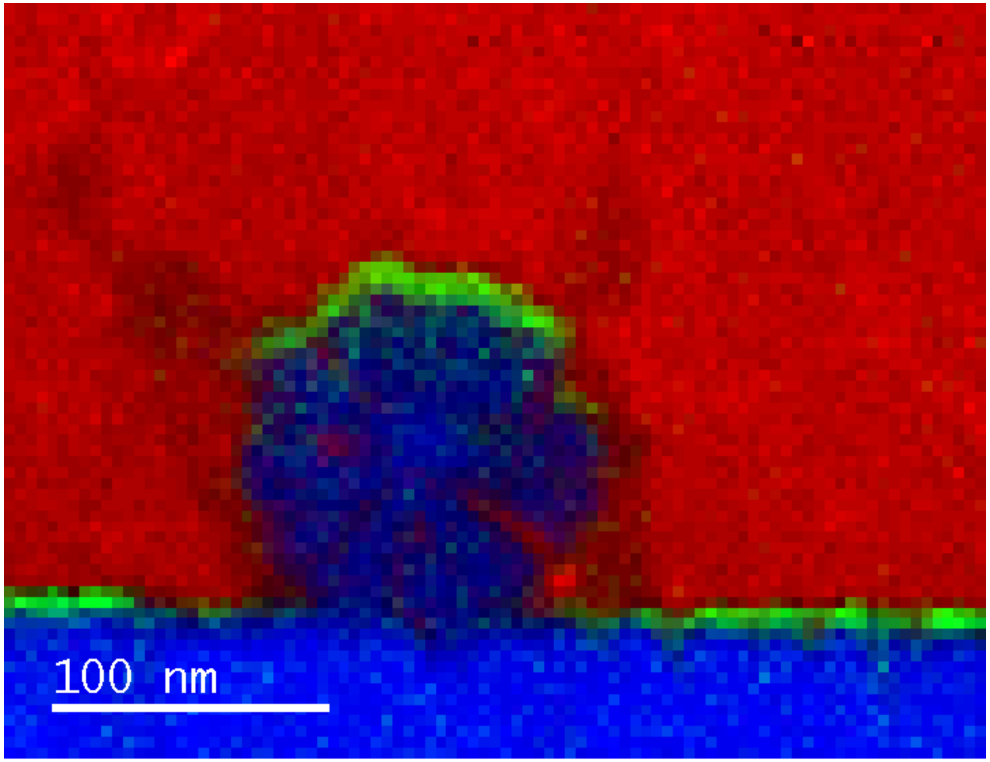
Contacting approach 2: Mo nano-particles



B. Vermang et al., Thin Solid Films (2014) under review

Contacting approach 2:
Mo nano-particles

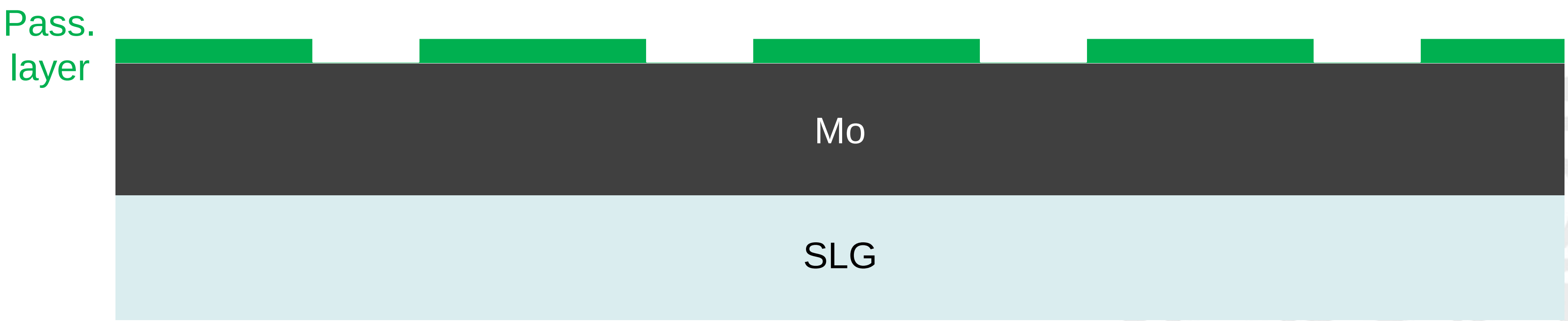
- STEM-EDX picture of a finished solar cell



Cu
Al
Mo

B. Vermang et al., Thin Solid Films (2014) under review

Contacting approach 3: Electron beam lithography

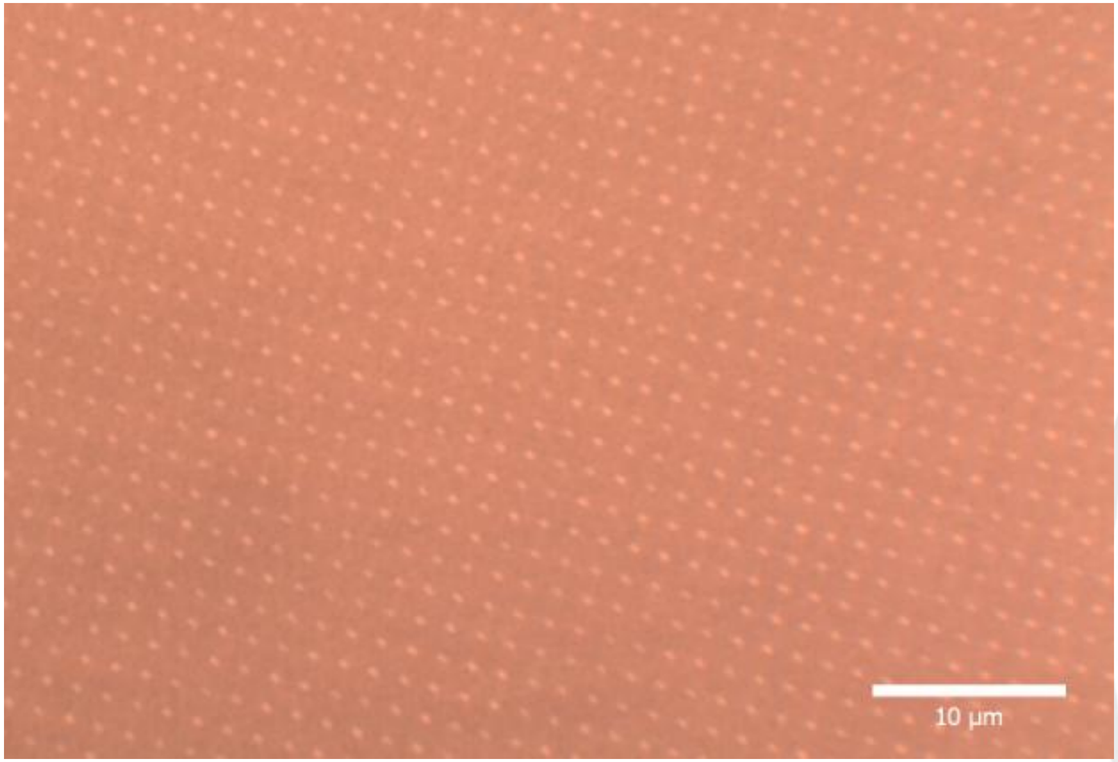


1. Deposit the surface passivation layer
    - Sputt. Al_2O_3 or ALD-Al_2O_3 (thick layers!)
2. Deposit the resist
3. Open the resist by e-beam litho
4. Etch the passivation layer
5. Remove the resist

B. Vermang et al., IEEE J. Photovoltaics (2014) in press

Contacting approach 3: Electron beam lithography

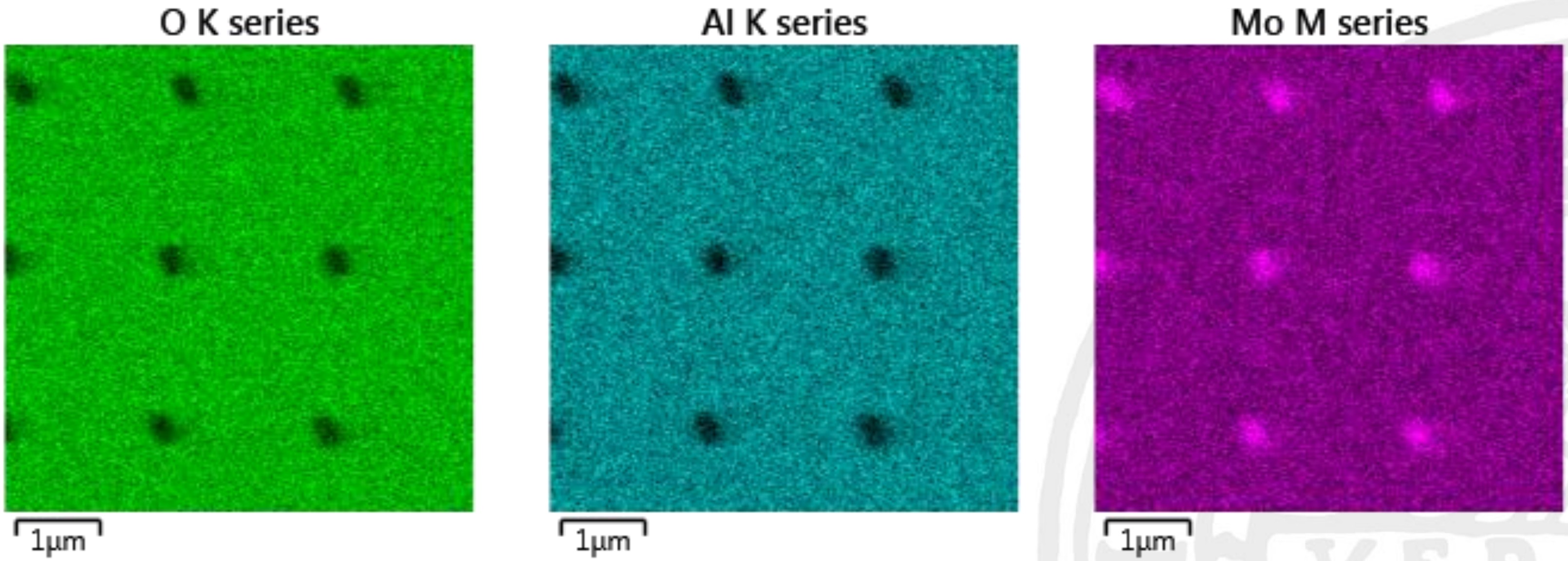
- Optical microscopy top-view picture of an opened passivation layer
  - Well-structured grid



B. Vermang et al., IEEE J. Photovoltaics (2014) in press

Contacting approach 3: Electron beam lithography

- SEM-EDX top-view picture of an opened passivation layer
  - Al_2O_3 etching is satisfactory

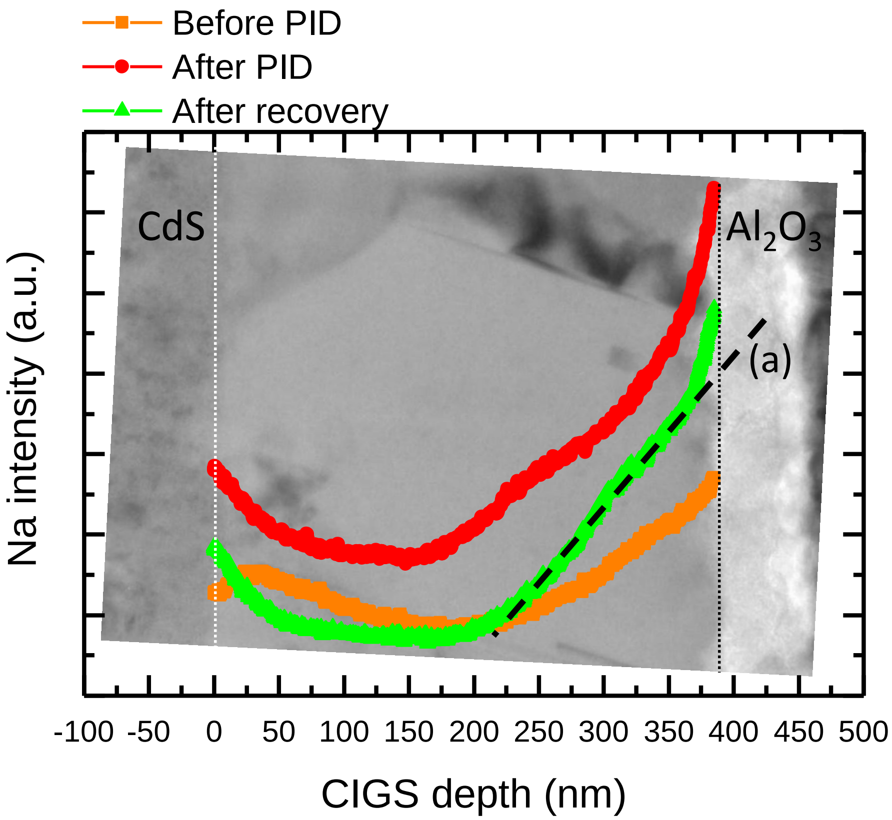


- High FF and V_{OC}
  - Low R_S

B. Vermang et al., IEEE J. Photovoltaics (2014) in press

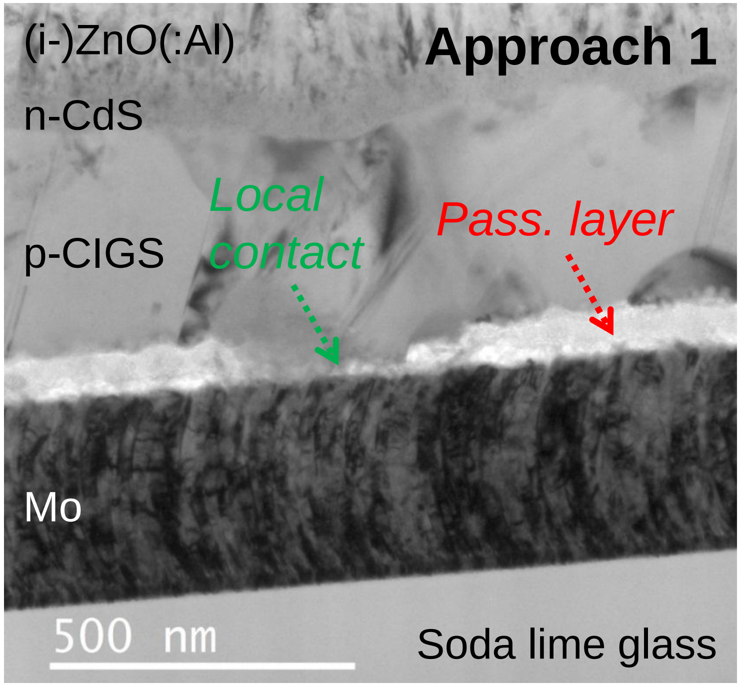
Optimization of Na in rear passivated CIGS solar cells

- “Curing” Na-deficient cells by applying electrical fields



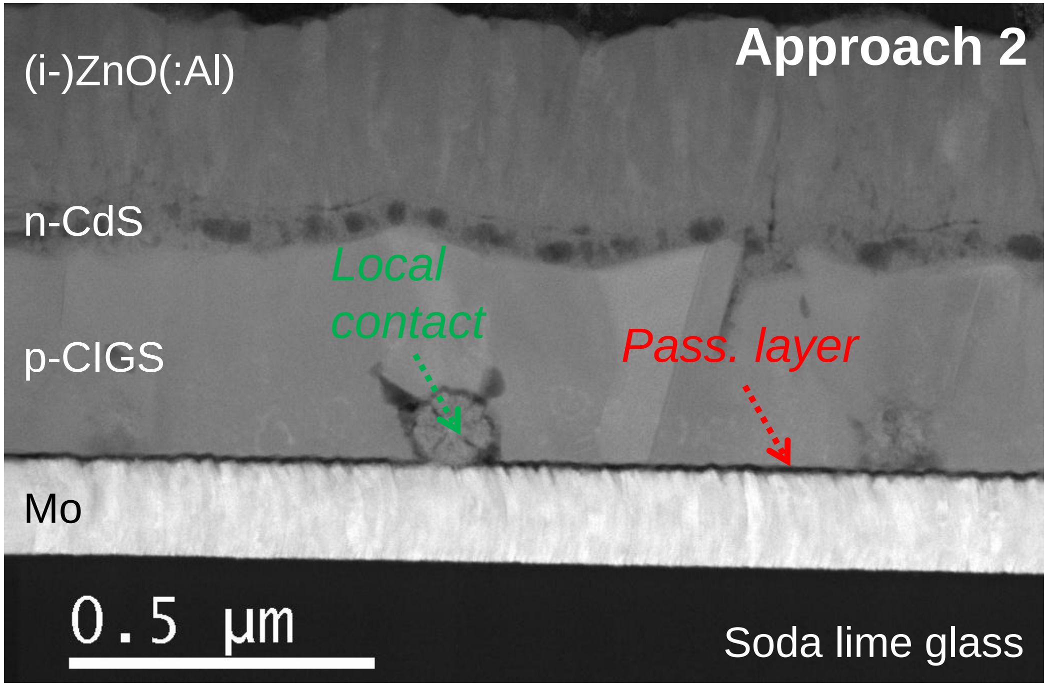
B. Vermang et al., Phys. Status Solidi RRL (2014) DOI: 10.1002/pssr.201409387

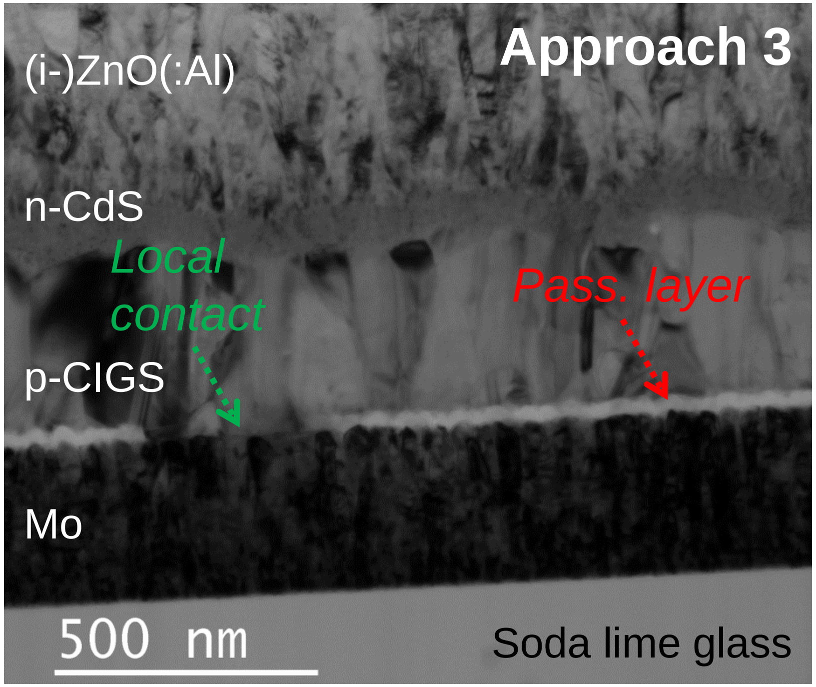
PERC meets CIGS: PercIGS



Introduction of a rear surface passivation layer and nano-sized local contacts

Increase in V_{OC}, J_{SC} and FF for rear surface passivated ultra-thin CIGS solar cells compared to (unpassivated) standard ultra-thin CIGS solar cells





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Thank you for your attention!

SEVENTH FRAMEWORK PROGRAMME

MARIE CURIE ACTIONS

Vetenskapsrådet