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What measures can be taken to enhance the efficiency of future solar cells?

Marika Edoff

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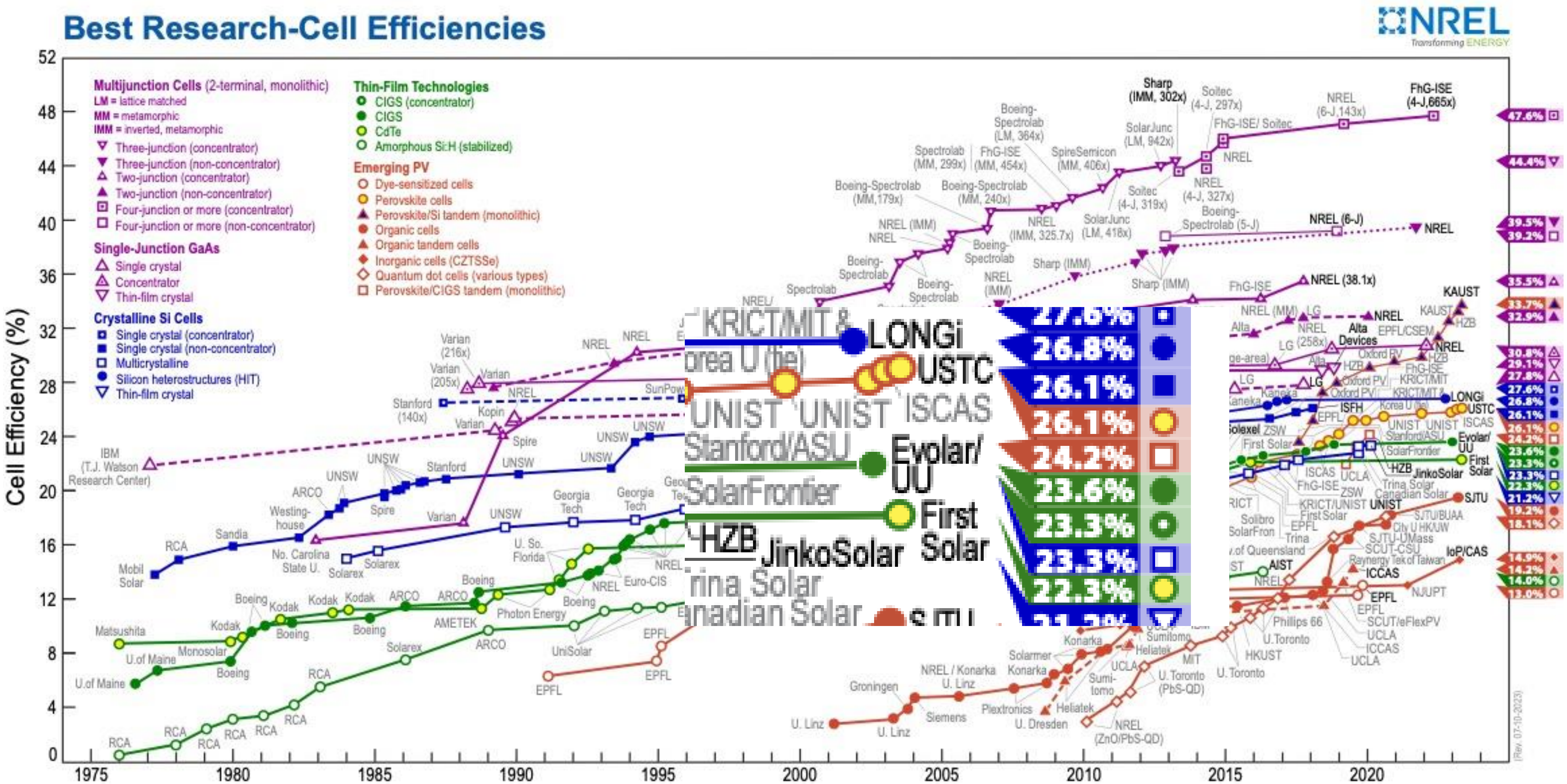
The NREL chart of solar cell records



Important assets for low cost renewables

- Low cost production of components
- Low cost (and fast) installation
- Reliable operation (long term stable)
- Safe to use (low risk of accidents)
- Low carbon footprint (lower CO_2 taxes)
- Low end-of-life costs

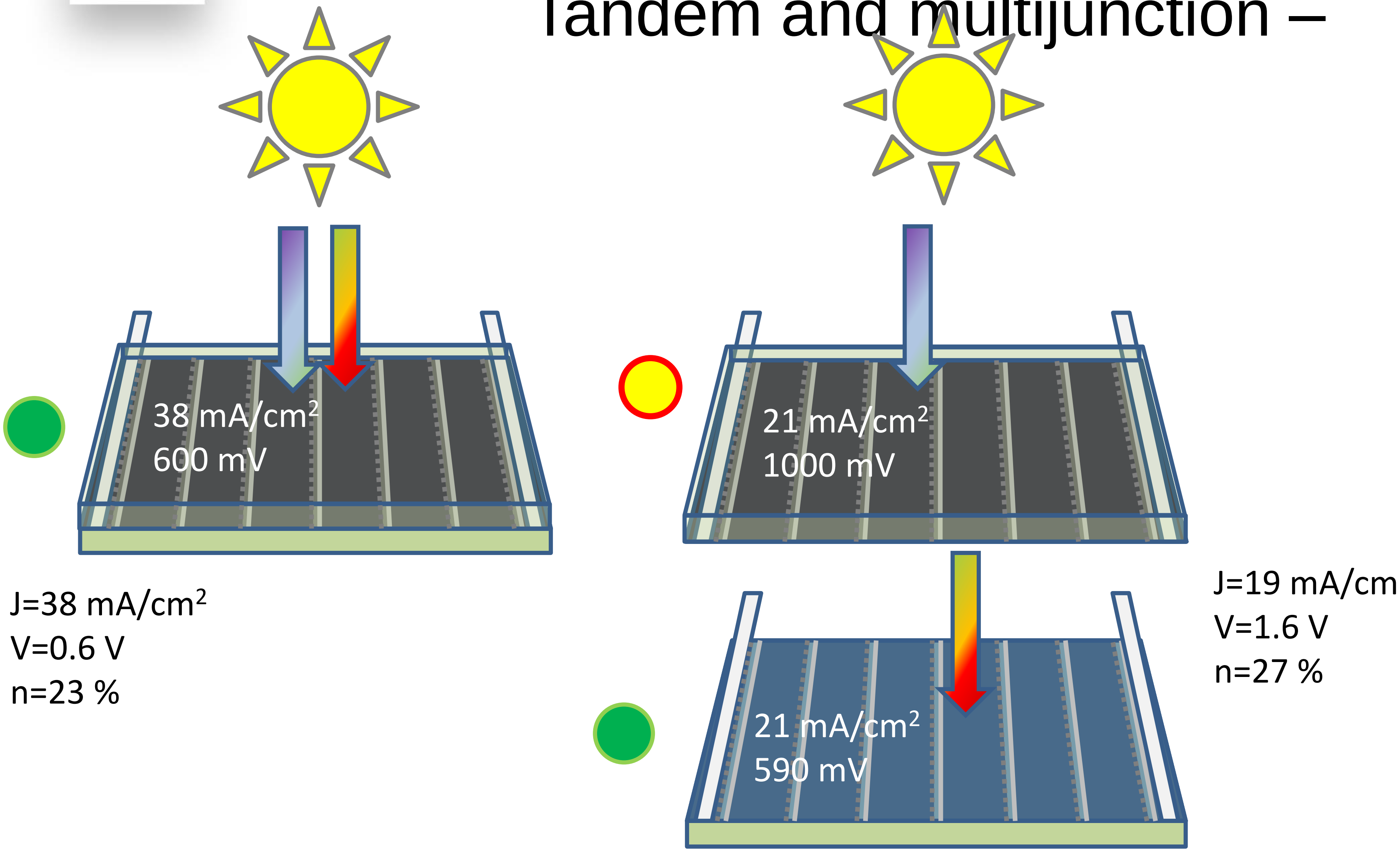
Solar cells tick all the boxes!

The trends:
Solar cell technology champions

Crystalline Si		Thin Film						III-V
23.3%	26.8%	14.0%	22.3%	23.6%	14.9%	26.1%	19.2%	29.1%
Multi-X Si	Mono-X Si	a-Si	CdTe	CIGS	CZTS	Perovsk	Organic	GaAs

The solar cell test site at the Ångström roof

Challenging the limits: Tandem and multijunction –



New tandem strategies:

Crystalline Si		Thin Film						III-V
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Multi-X Si	Mono-X Si	a-Si	CdTe	CIGS	CZTS	Perovsk	Organic	GaAs

33.7% (28.6 full area commercial)

- Perovsk
- Mono-X Si

24.2%

- Perovsk
- CIGS

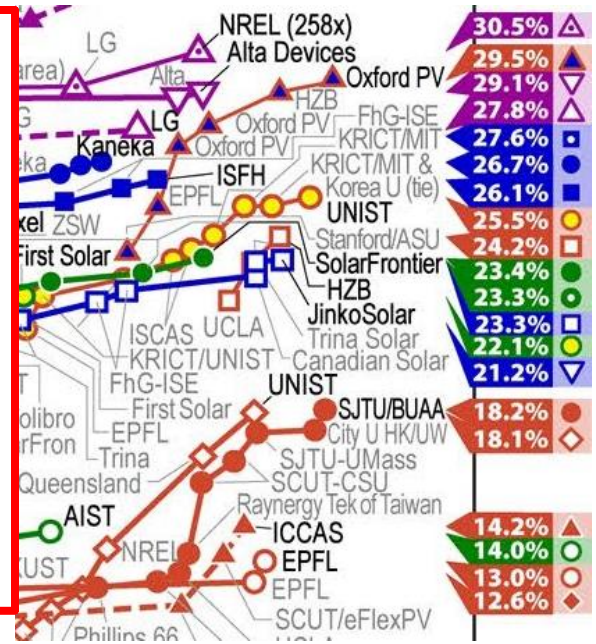
Hi-BITS

32.9%

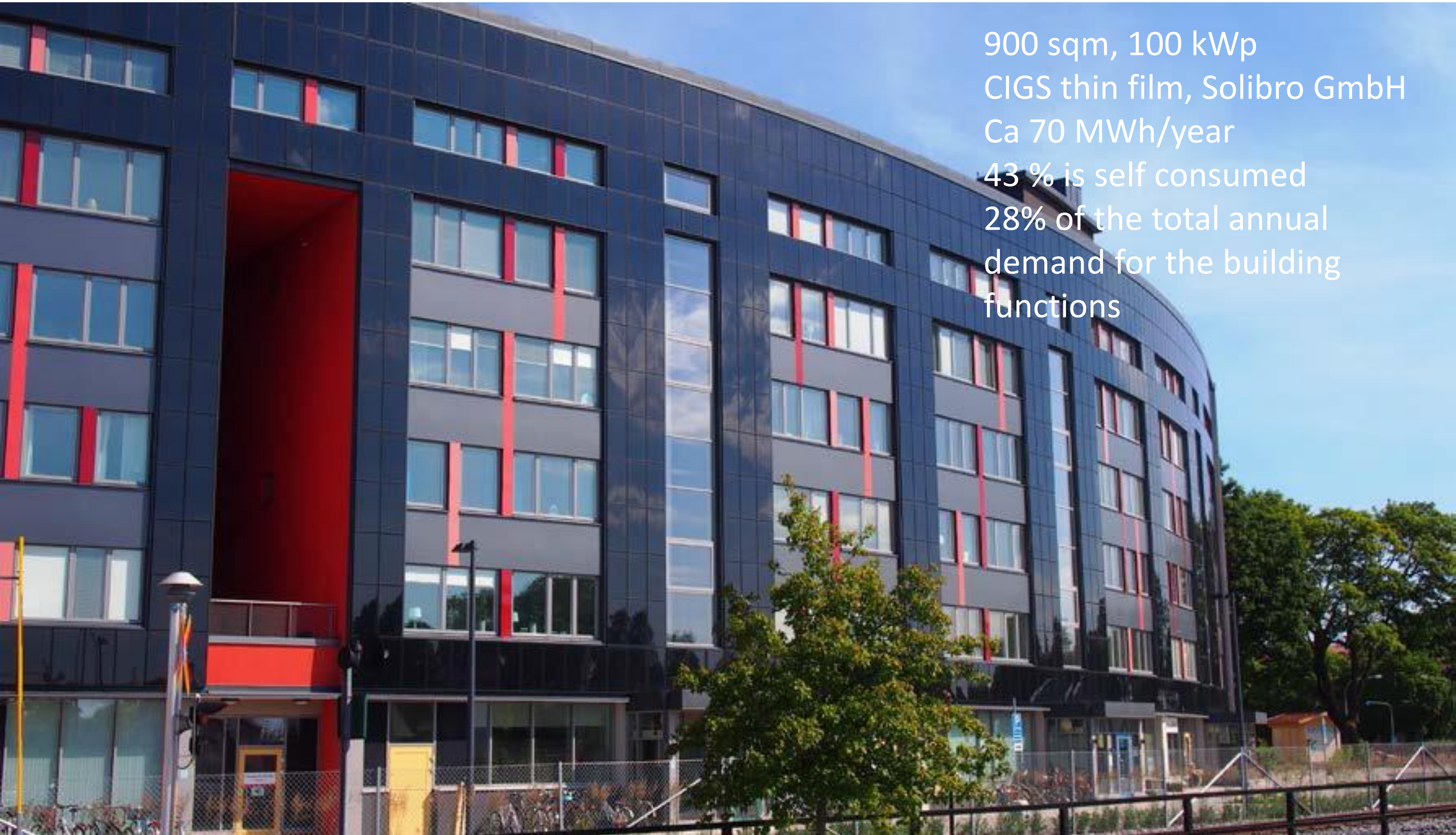
- III-V
- III-V

SITA
Stable Inorganic Tandem Solar cells

- ACIGS
- CIGS
- ACIGSe CIGSu
- Mono-X Si

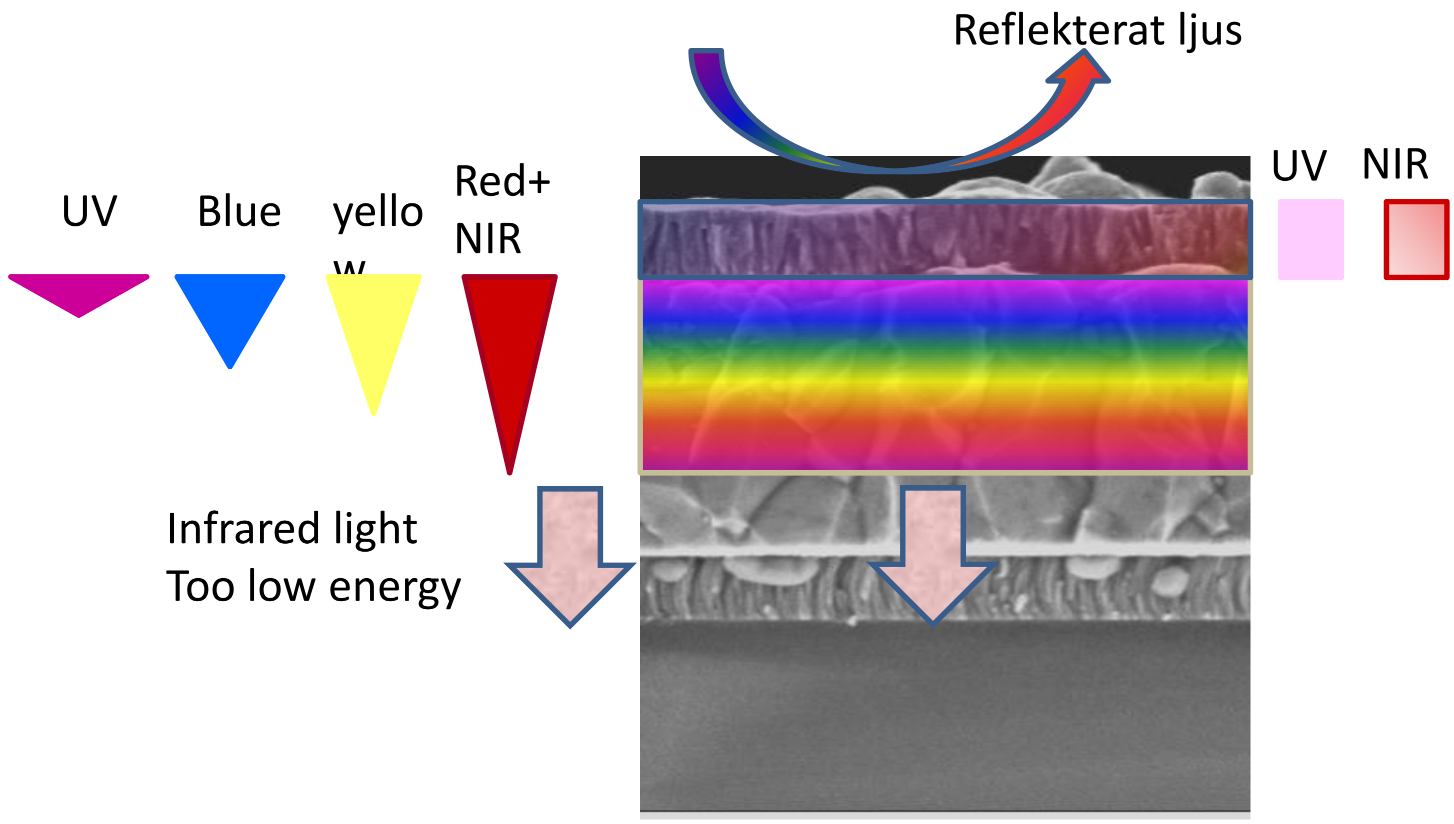


Frodeparken, Uppsala, CIGS



900 sqm, 100 kWp
CIGS thin film, Solibro GmbH
Ca 70 MWh/year
43 % is self consumed
28% of the total annual demand for the building functions

Absorption of light in a solar cell



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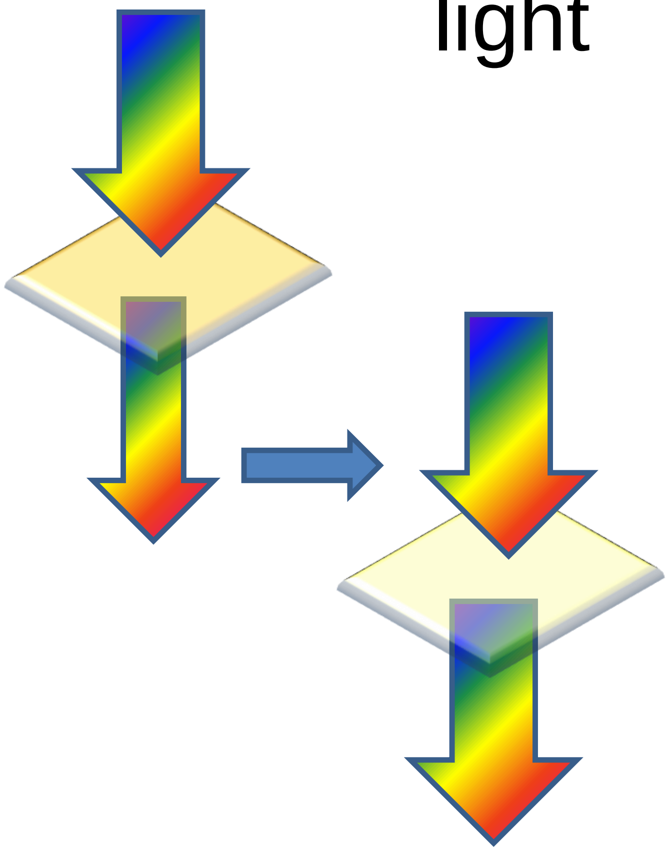
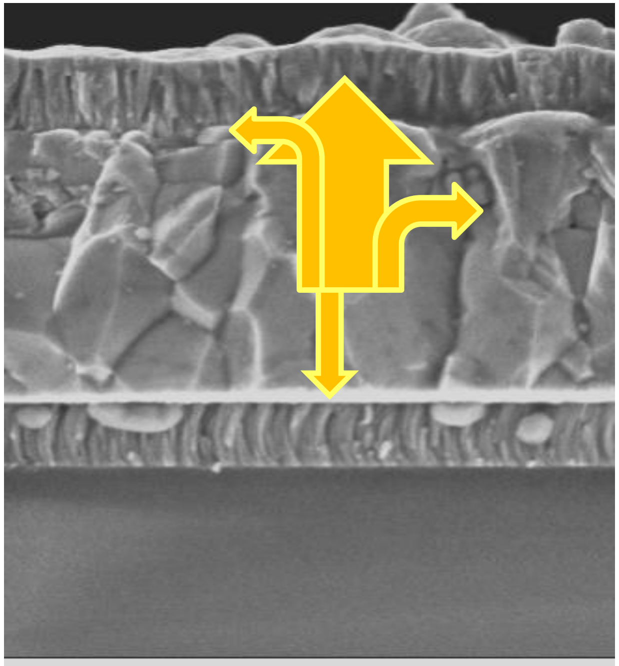
Research aiming to increase use of light

- Reduce front contact absorption
  - Improve material quality
  - New material with inherent higher mobility for electrons
- Reduce absorption in interfaces
  - Use interface materials with high bandgap
- (Reduce reflectance)
  - Antireflective stacks or coatings

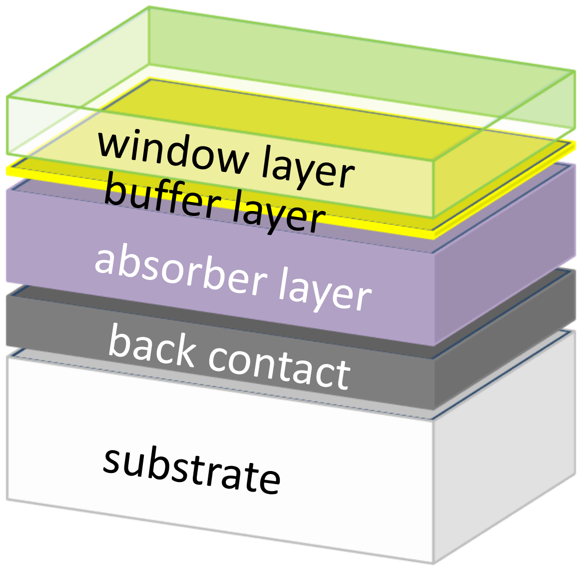


All electrons out of the solar cell!

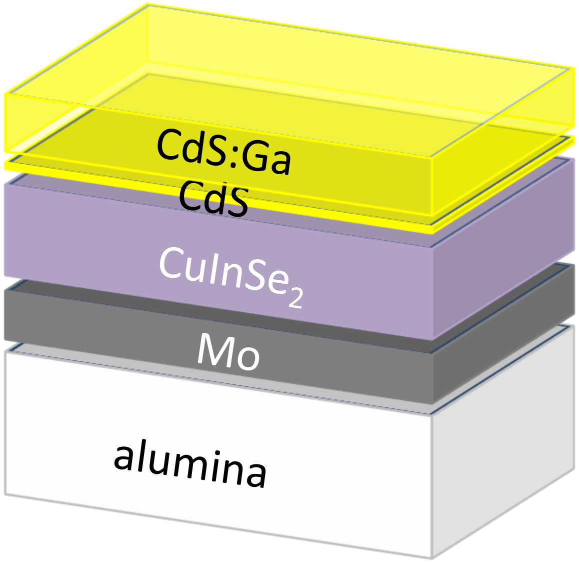
- Reduce recombination
  - Materials with long electron lifetime
  - Benign back contact
  - No defects and barriers at front contact



A story of fighting bottlenecks in CIGS technology



The Thin Film CIGS solar cell
”La Grand-Mère”

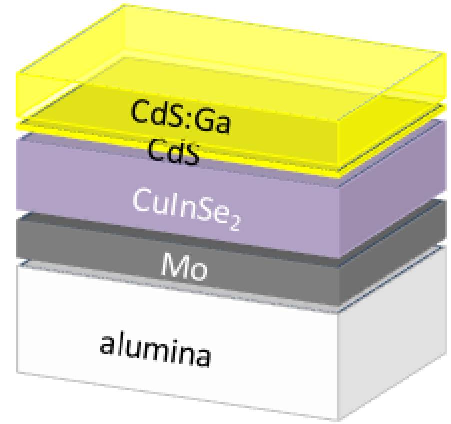


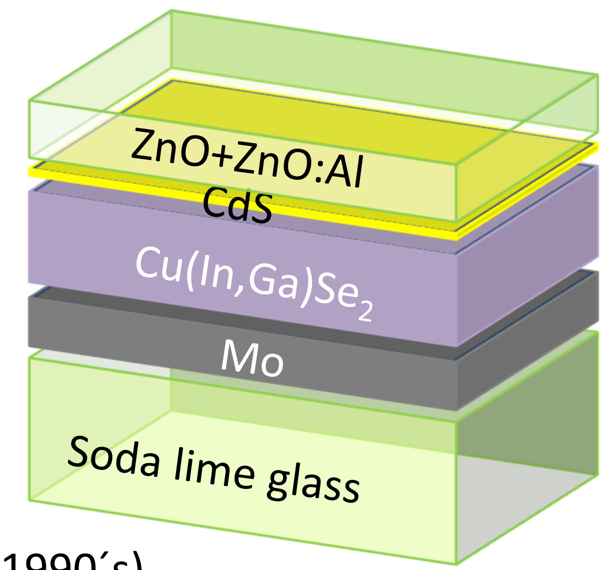
10% efficiency (1980´s)

A story of fighting bottlenecks in CIGS technology

- Three important improvements
  - Glass substrate
    - In-diffusion of Na
  - Introduction of Ga
    - Improved material quality
    - Possibility for bandgap grading
    - Better adjustment to solar spectrum
  - CdS by chemical bath deposition
    - Much improved interface properties (ARCO and ENSCP)
  - Sputtered ZnO+ZnO:Al window layer
    - Replacement of CdS:Ga with a high bandgap material with low parasitic absorption
    - Protective layer for reducing effects of defect related shorts

10% efficiency





15-17% efficiency (1990´s)

A story of fighting bottlenecks in CIGS technology

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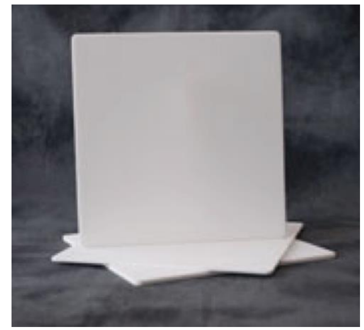

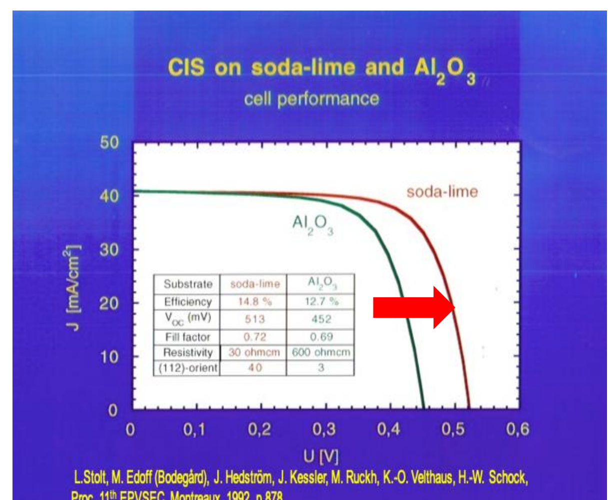

Substrate	soda-lime	Al_2O_3
Efficiency	14.8 %	12.7 %
V_{OC} (mV)	513	452
Fill factor	0.72	0.69
Resistivity	30 ohmcm	600 ohmcm
(112)-orient	40	3

A story of fighting bottlenecks in CIGS technology

- Important improvements
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    - In-diffusion of Na
  - **Introduction of Ga (Boeing)**
    - **Improved material quality**
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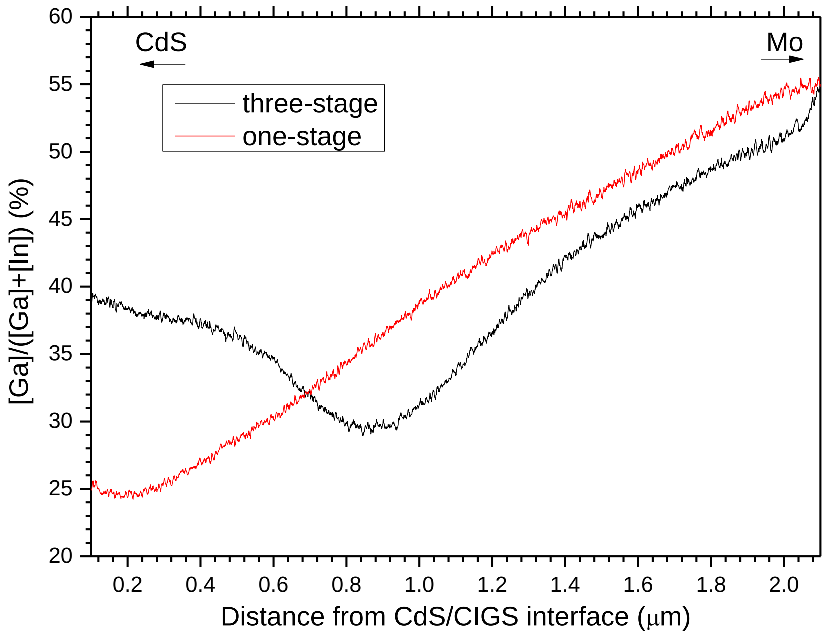

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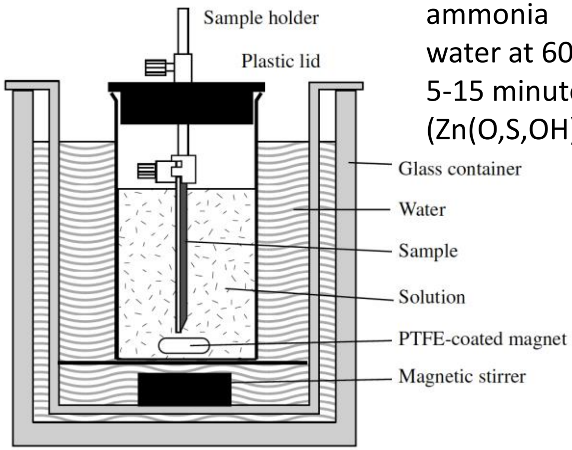
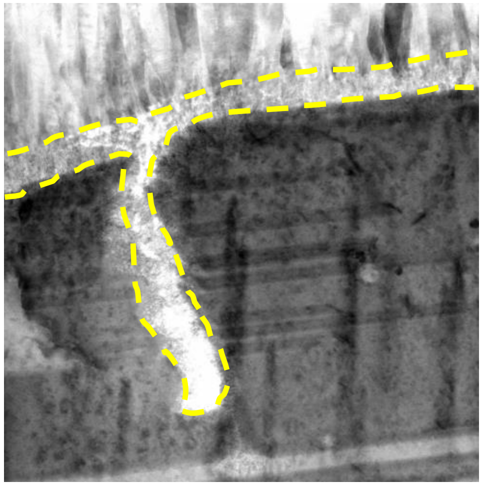
Thiourea, Cd salt and ammonia
water at 60 °C
5-15 minutes
(Zn(O,S,OH), ZnCdS..)





TEM: L. Riekehr

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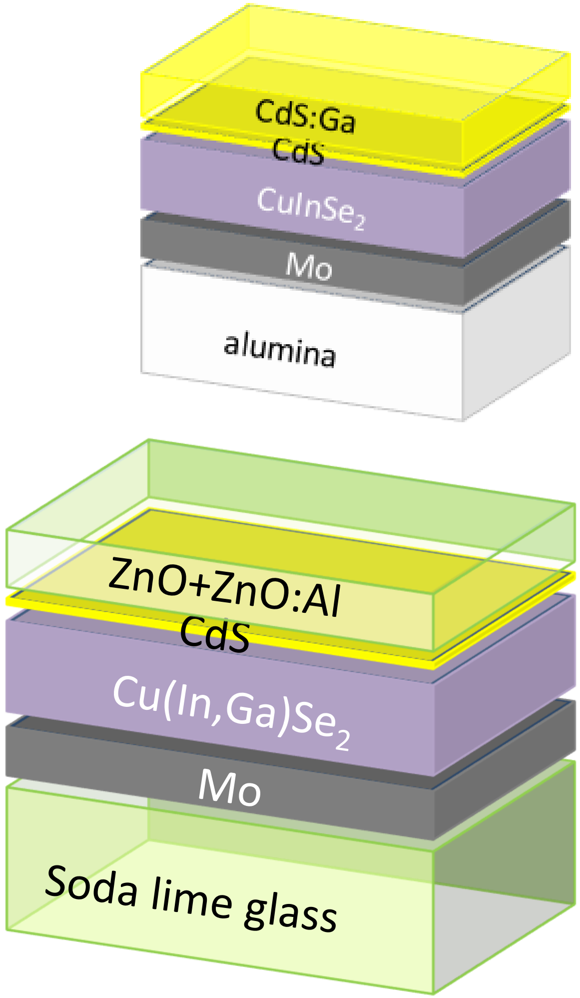

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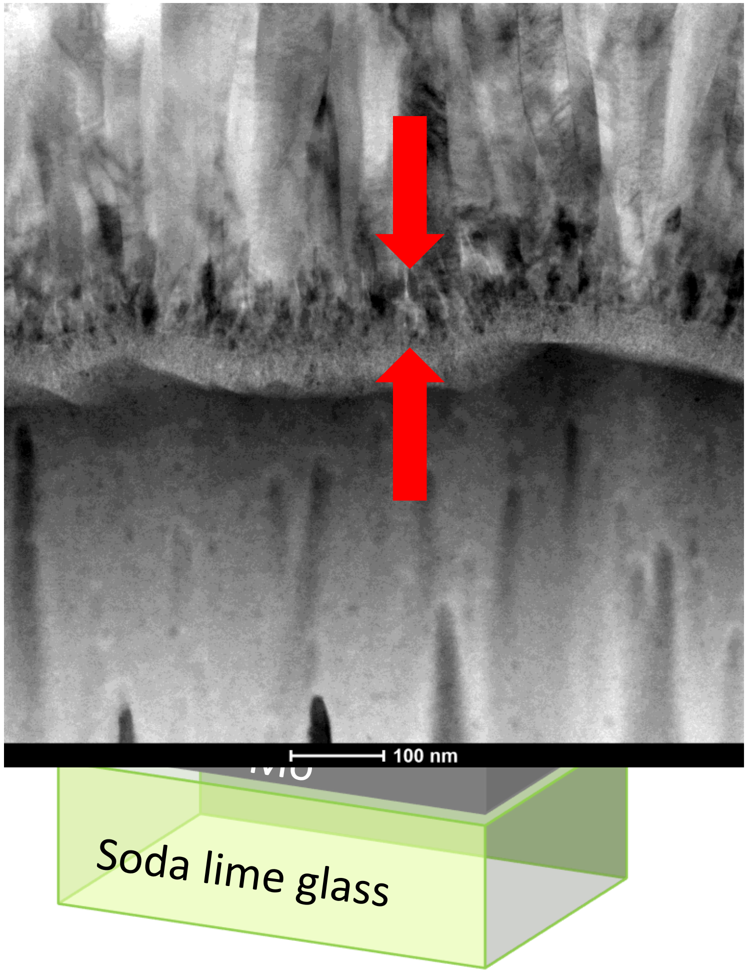


More recent development leading to efficiency improvements

- The alkali post deposition treatment (empa)
  - Alkali fluoride treatment after CIGS deposition
  - Ultrathin CdS reduces parasitic absorption
  - Increased voltage
  - Formation of alkali-In-Se(S) surface layer

nature materials LETTERS
PUBLISHED ONLINE: 3 NOVEMBER 2013 | DOI: 10.1038/NMAT3789

Potassium-induced surface modification of $Cu(In,Ga)Se_2$ thin films for high-efficiency solar cells

Adrian Chirilă[1*†], Patrick Reinhard[1†], Fabian Pianezzi[1], Patrick Bloesch[1], Alexander R. Uhl[1], Carolin Fella[1], Lukas Kranz[1], Debora Keller[1], Christina Gretener[1], Harald Hagendorfer[1], Dominik Jaeger[2], Rolf Erni[3], Shiro Nishiwaki[1], Stephan Buecheler[1] and Ayodhya N. Tiwari[1]

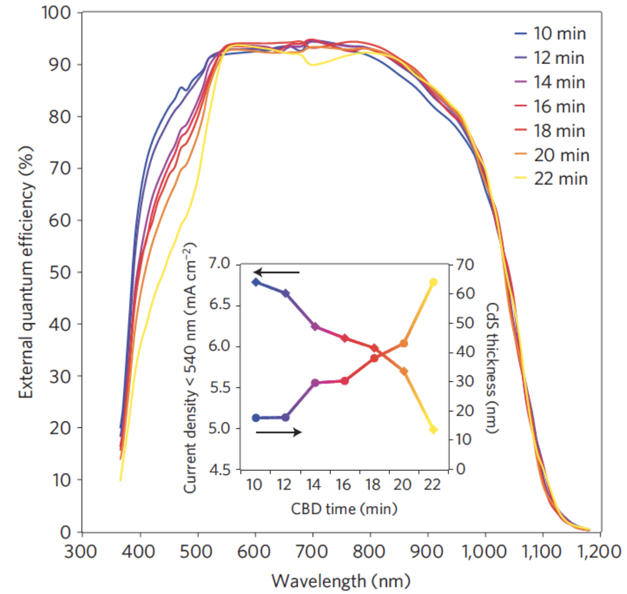
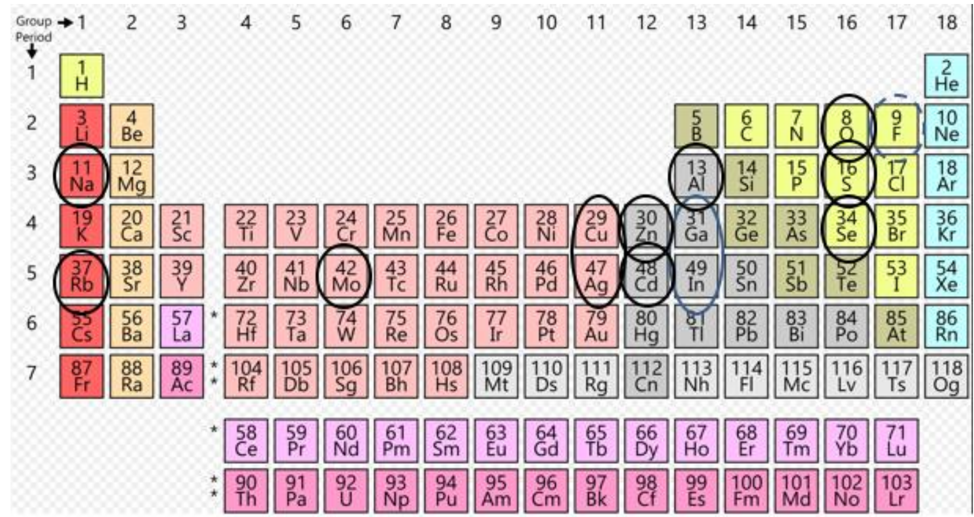
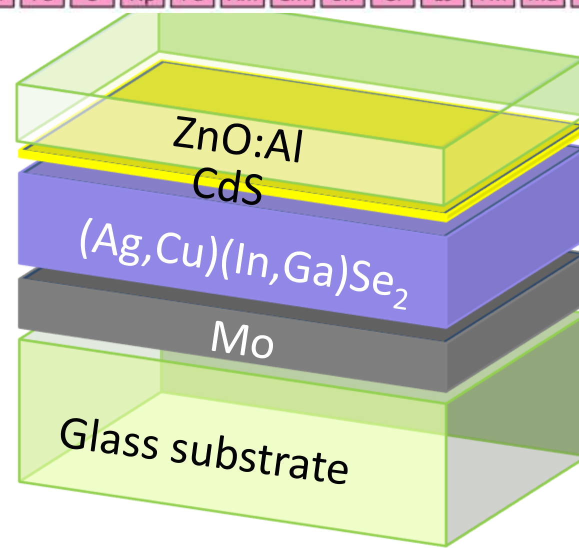


Figure 3 | Variation of CdS film thickness. EQE measurements from devices grown with various CBD deposition durations of 10 min (blue) up to 22 min (yellow). The inset figure shows the related contribution to J_{SC} from photons with wavelength below 540 nm together with corresponding CdS layer thickness as determined with ICPMS.

The 23.6 % efficient solar cell by Evolar (former Solibro) in collaboration with UU

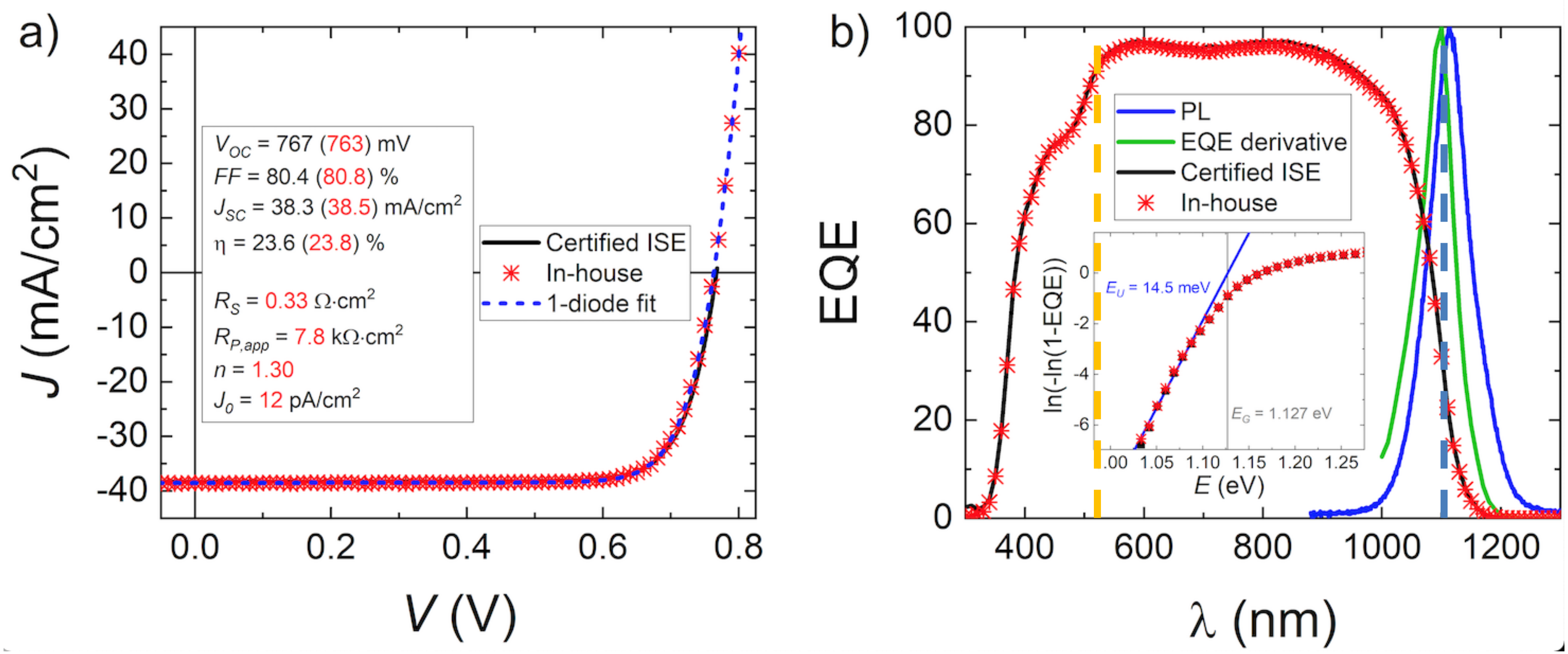


RbF post deposition treatment



Lundberg, IWCIGSTech, 2019

Record JV


a)
V_{OC} = 767 (763) mV
FF = 80.4 (80.8) %
J_{SC} = 38.3 (38.5) mA/cm^2
η = 23.6 (23.8) %
R_S = 0.33 Ω·cm^2
$R_{P,app}$ = 7.8 kΩ·cm^2
n = 1.30
J_0 = 12 pA/cm^2
Certified ISE
In-house
1-diode fit
J (mA/cm^2)
V (V)
b)
PL
EQE derivative
Certified ISE
In-house
E_U = 14.5 meV
E_G = 1.127 eV
ln(-ln(1-EQE))
E (eV)
EQE
λ (nm)

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New developments

- Optimize for tandem:
  - Low bandgap bottom cell
  - Bifacial solar cells
  - High bandgap top cell optimized for the low bandgap bottom cell
  - **Leave no electron behind!**
  - **Take good care of every photon!**

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