Modern photovoltaic technologies
PHYS-609

Part 1.3 Thin-film solar cells*

- CIGS solar cells
- CdTe solar cells

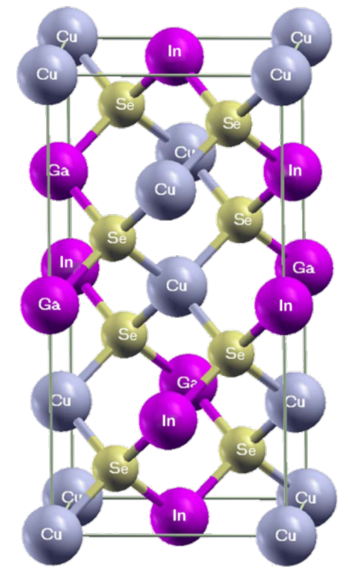
* Amorphous Si and perovskite cells are also thin-film technologies and will be covered on Day 2 & 3

Dr. Yaroslav Romanyuk
Laboratory for Thin films and Photovoltaics
Empa – Swiss Federal Laboratories for Materials Science and Technology
yaroslav.romanyuk@empa.ch

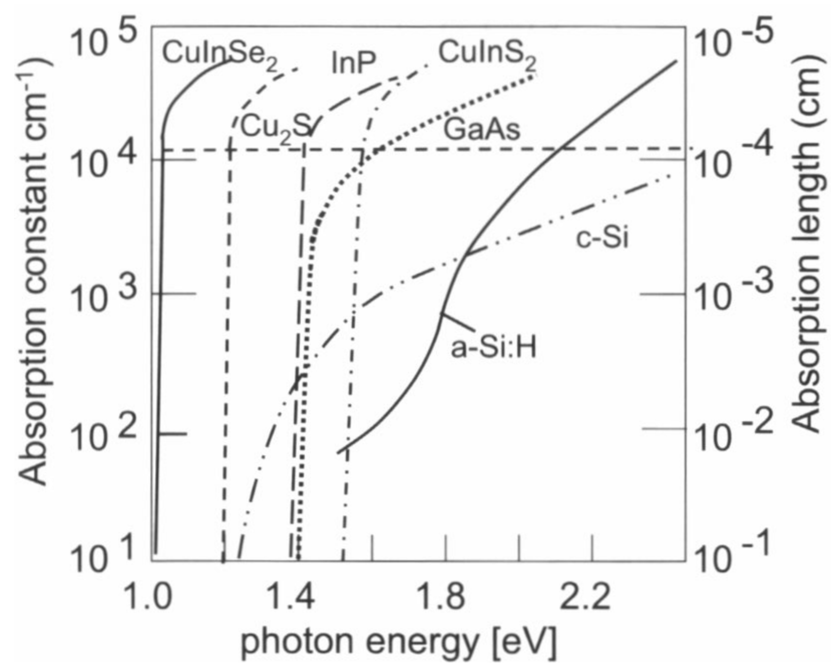
Empa
Materials Science and Technology

$Cu(In,Ga)Se_2$ (CIGS) solar cells

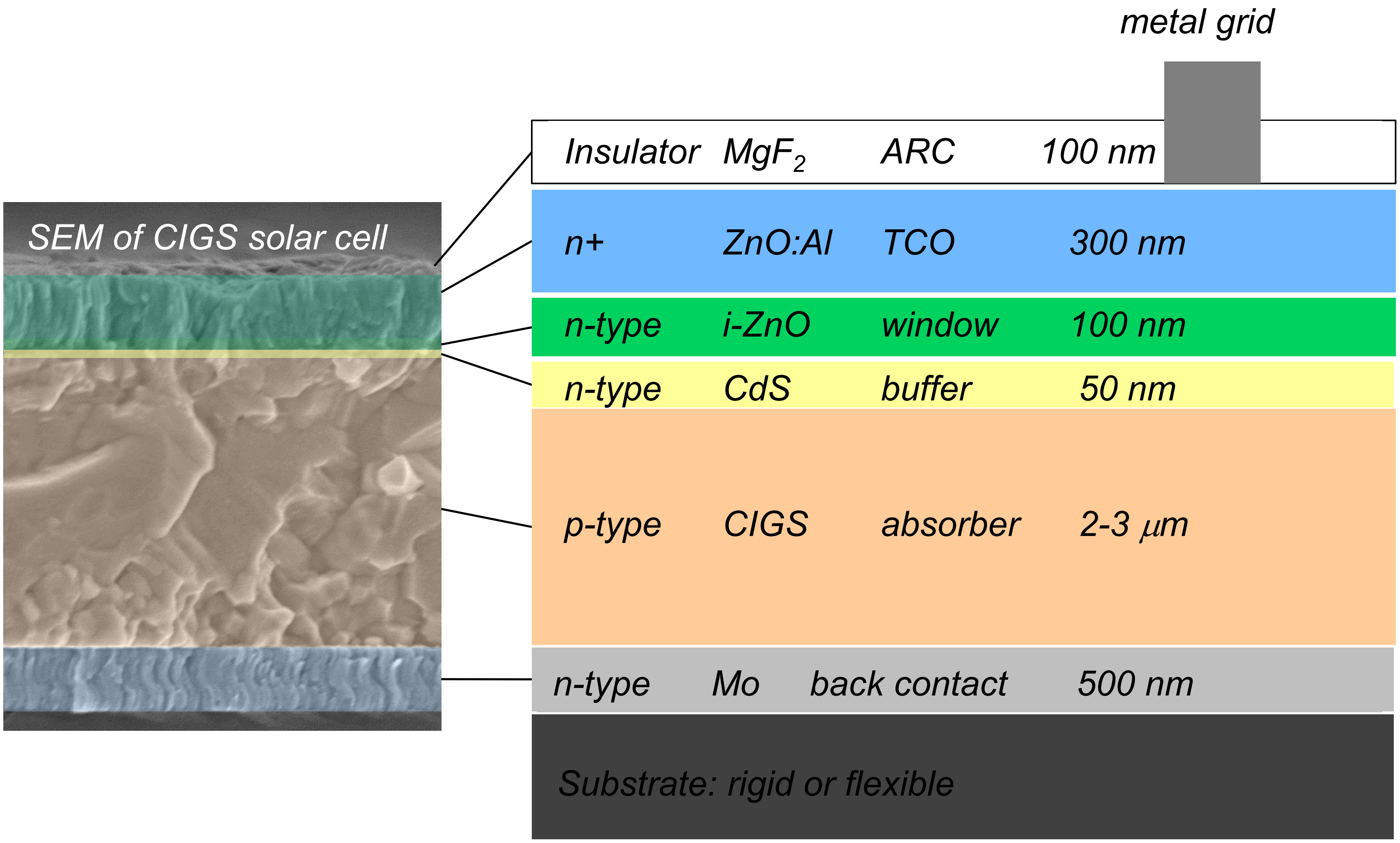
$CuInSe_2$ = CIS



- crystal structure:
  - tetragonal chalcopyrite ($CuFeS_2$) structure derived from cubic ZnSe
- direct gap semiconductor
  - band gap 1.04eV – 1.68eV (adding Ga)
  - absorption coefficient > 10^4 cm^{-1}
  - =>thickness of <1µm is enough to absorb light
- p-type conductivity
  - Cu vacancies -> intrinsic p-doping
  - electrically inactive grain boundaries
  - polycrystalline material
    => robustness, flexible substrates



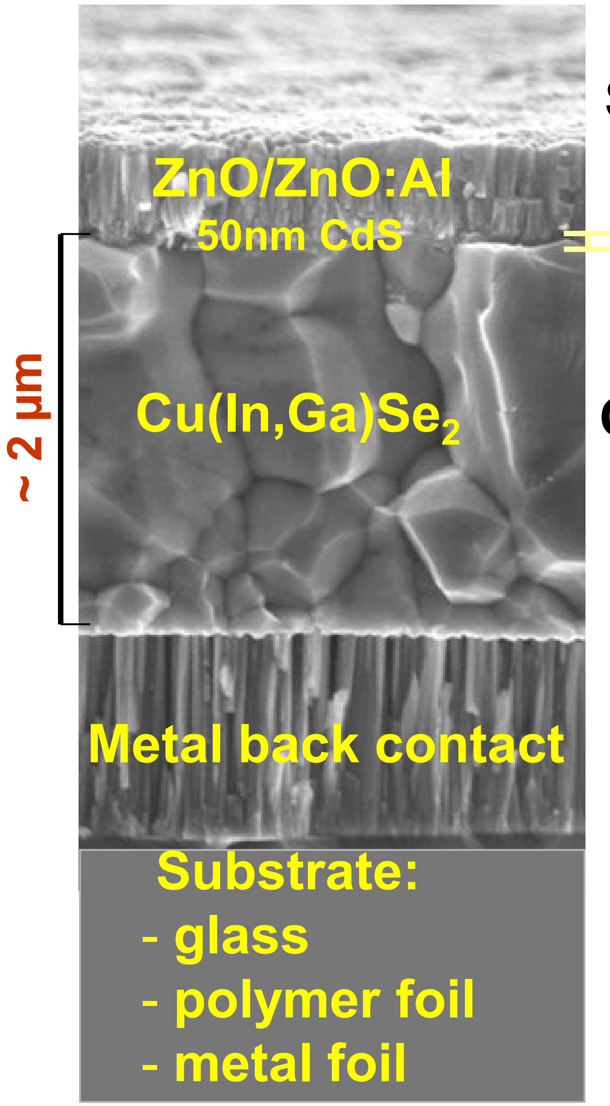
Structure of CIGS cell



Resistivity (Ω cm):

ZnO:Al (~10^{-3}), i-ZnO (~10^{5}), CdS (~10^{5}), CIGS (~10^{2}), Mo (~10^{-6})

Fabrication of CIGS solar cells

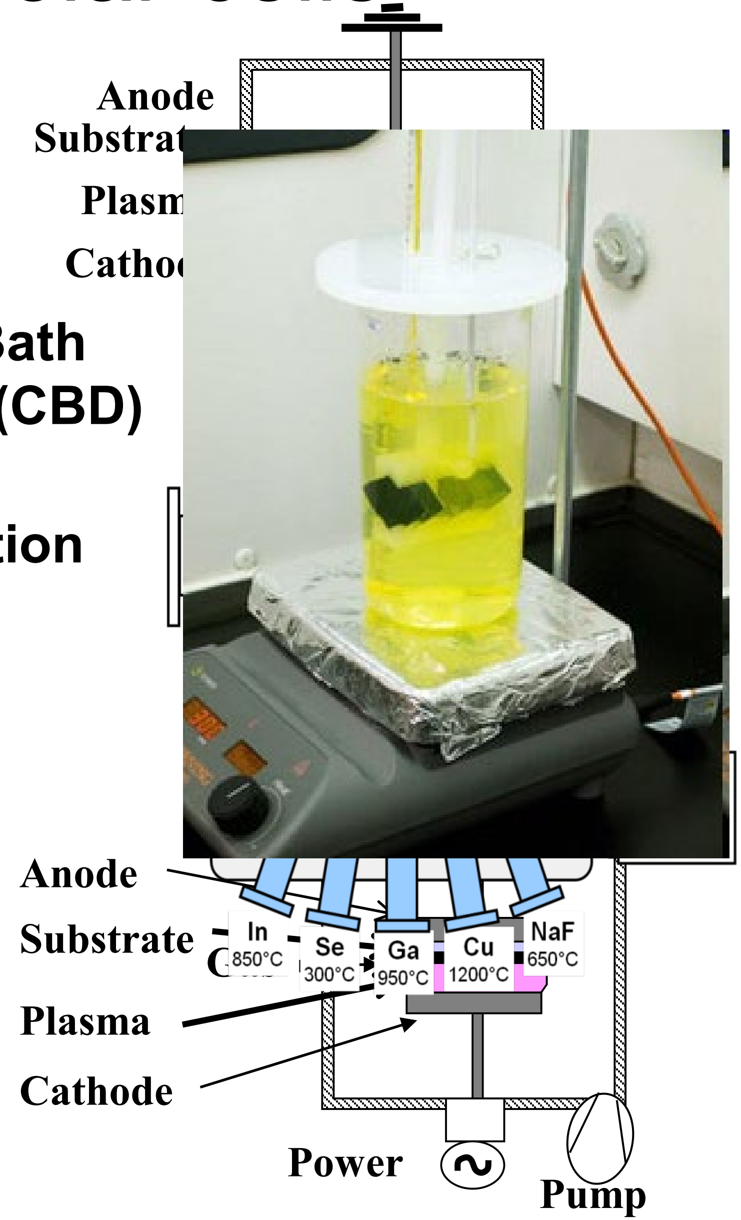


Sputtering

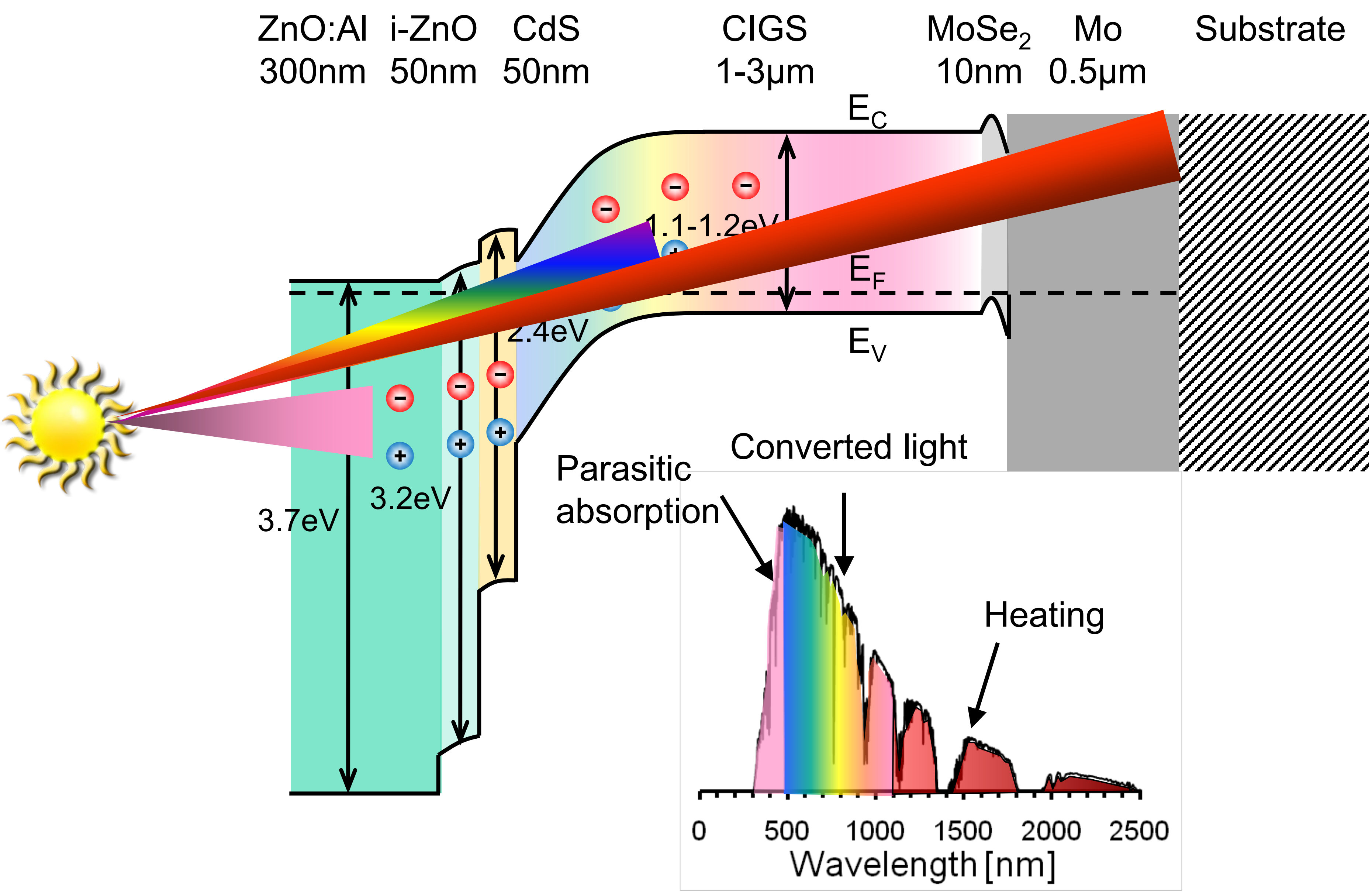
Chemical Bath Deposition (CBD)

Co-evaporation

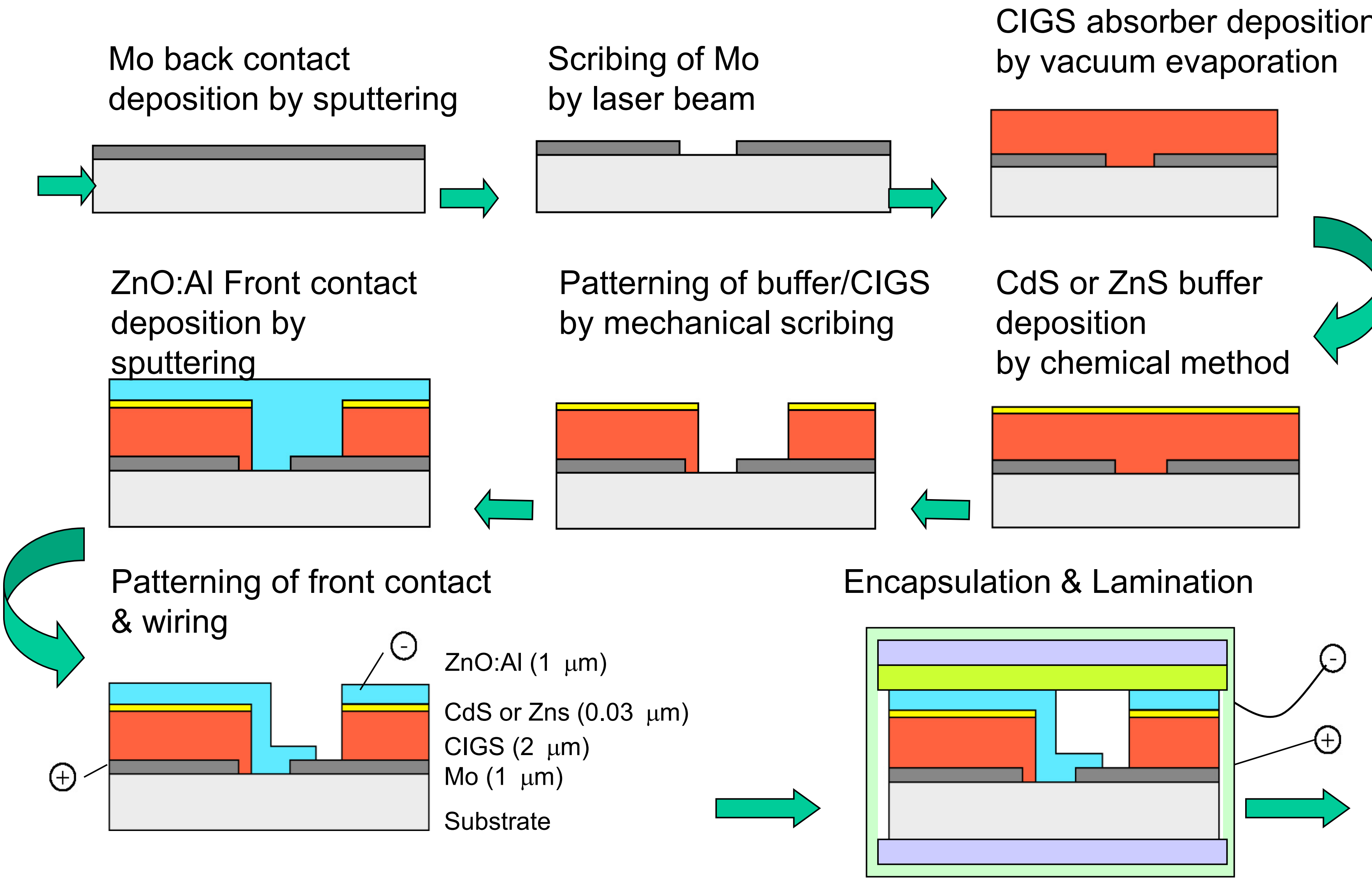
Sputtering



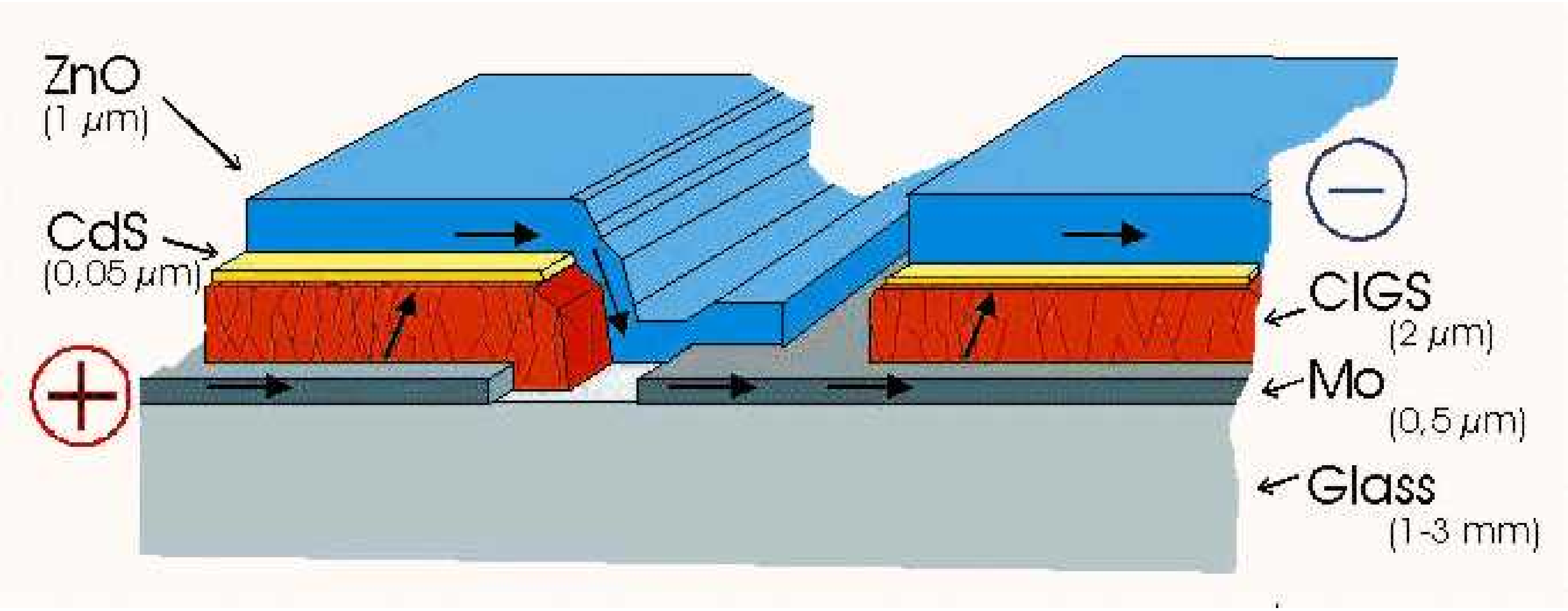
Operation of CIGS solar cell



CIGS solar module fabrication



Monolithic interconnection in modules



- Connections between cells are made between deposition of individual layers (in contrast to wiring of individual silicon cells solar)
- Lasers and/or sharp needles are used for scribing

CIGS solar modules on glass

Solar Frontier (Japan), NICE Solar (Manz Solar) (Germany), Avancis (Germany), Honda (Japan), TSMC (Taiwan), …

60 cm X 120 cm

WÜRTH SOLAR

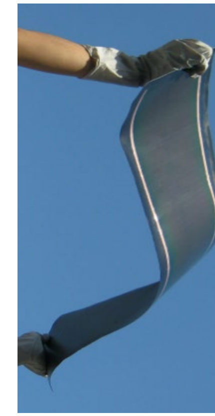
WÜRTH SOLAR

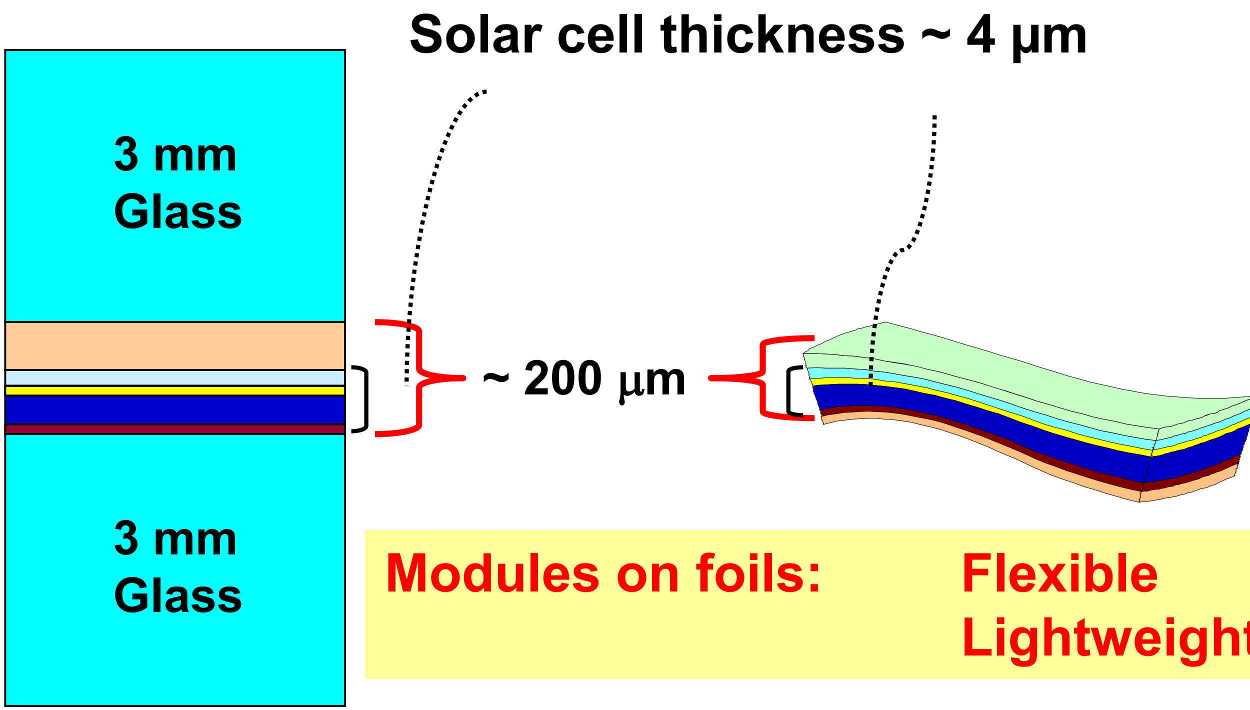
Solar Frontier

Flexible thin film solar modules

Mature technology

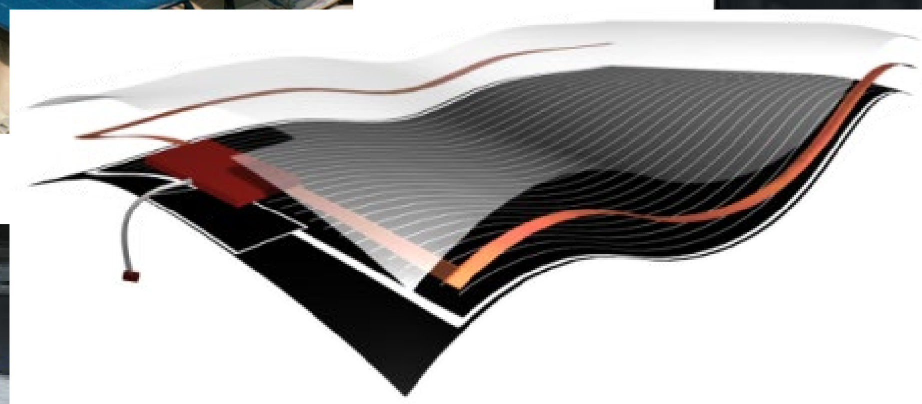
Emerging technology

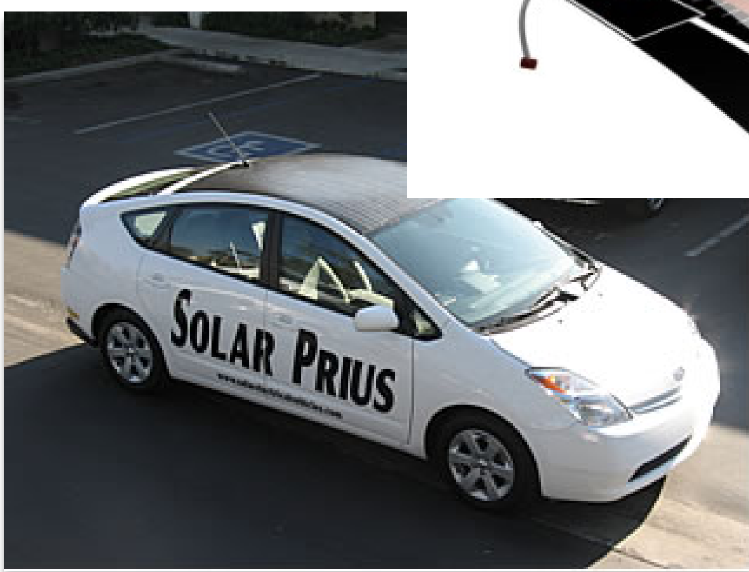


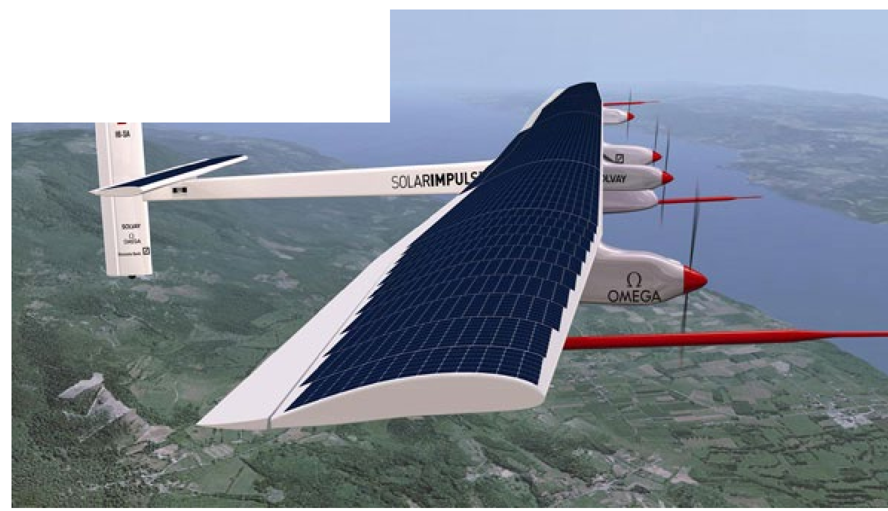


Modules on foils: Flexible
Lightweight

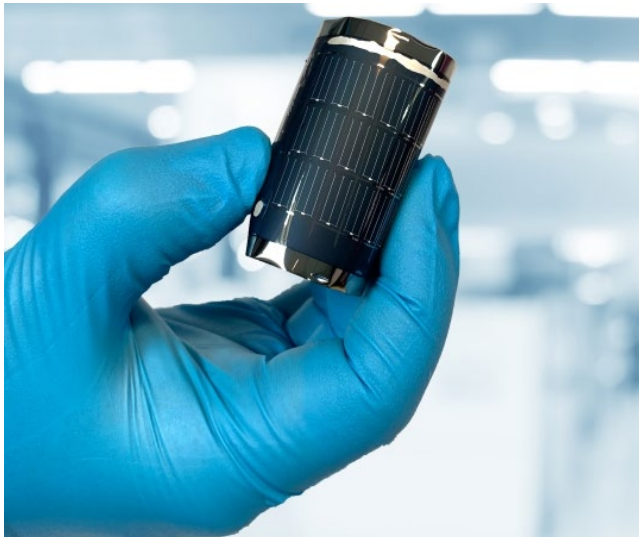
Targeted applications for flexible solar cells





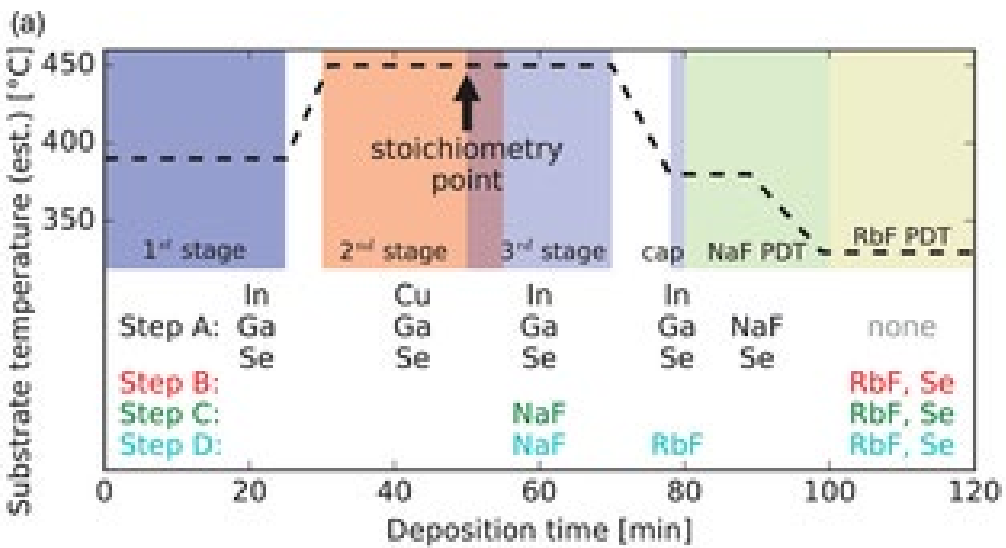


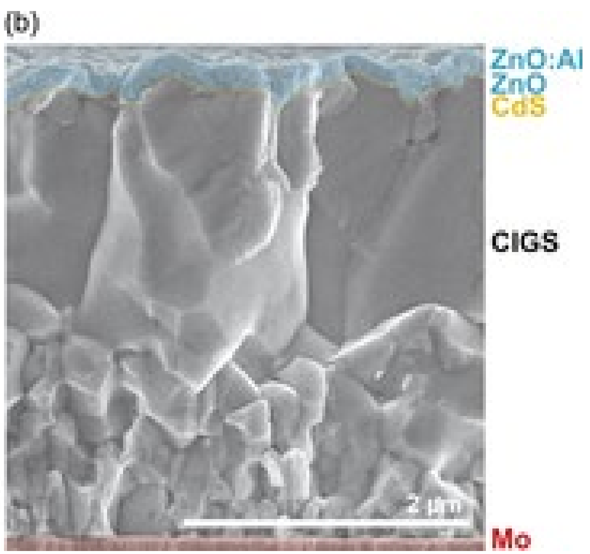
CIGS on flexible polymer substrate



World record 20.8% flexible CIGS cell on polyimide substrate (Empa 2019)

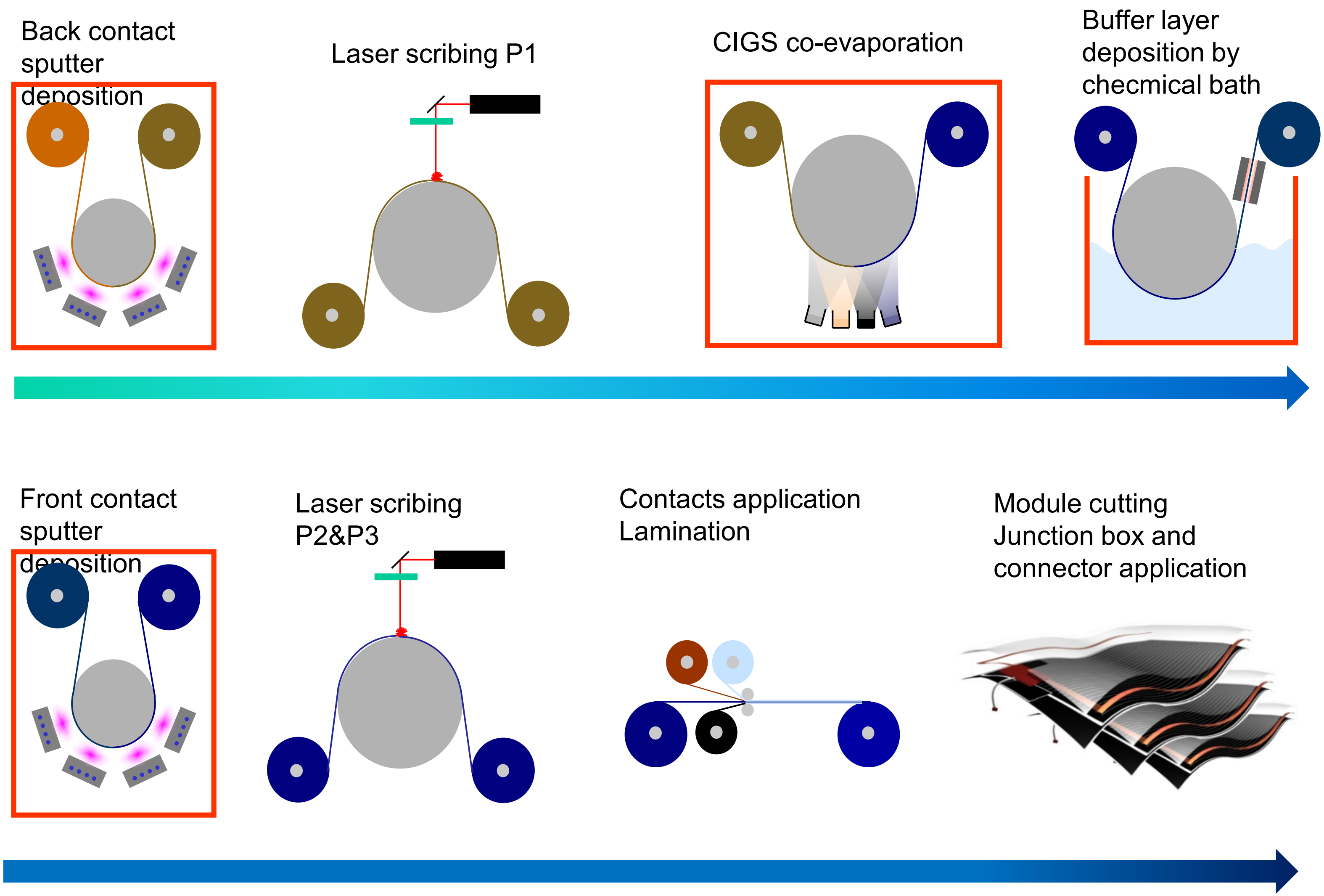
- Complex 3-stage evaporation process at 450°C together with NaF & RbF co-doping





Adv. Energy Mater. 9 (2019) 1900408

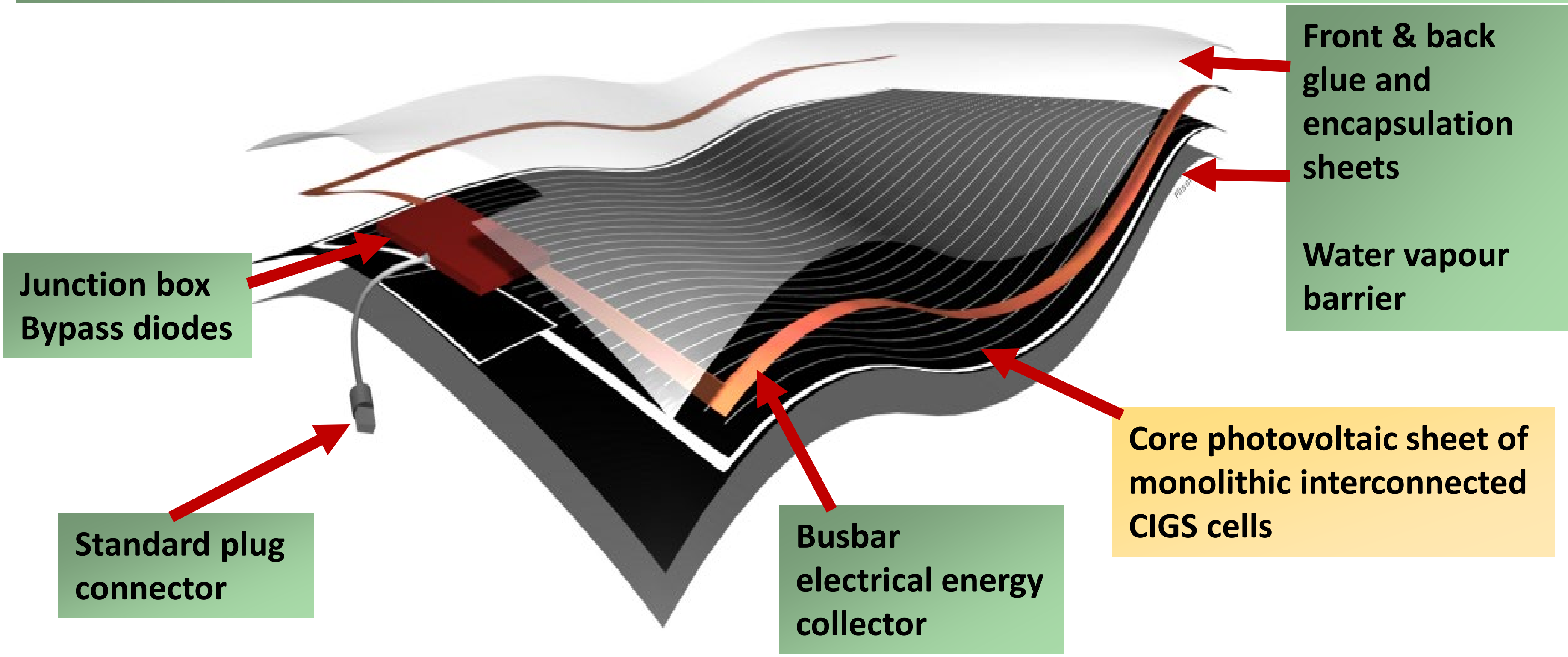
Roll-to-roll manufacturing



Flexible CIGS solar module

Front-end processing: Active layers & metal grid coatings on Substrate material

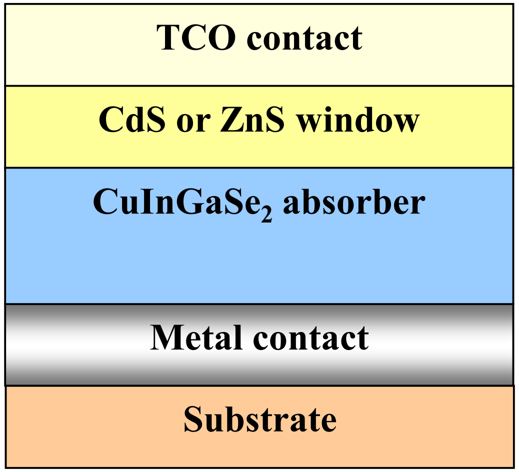
Back-end processing: Contacts, Encapsulation foils, Lamination, Junction Box



- **High material costs in back-end processing**
- **Sophisticated automatization availible**
- **Production area intensive**

Flisom
Flexible Solar Modules

Summary CIGS thin film technology

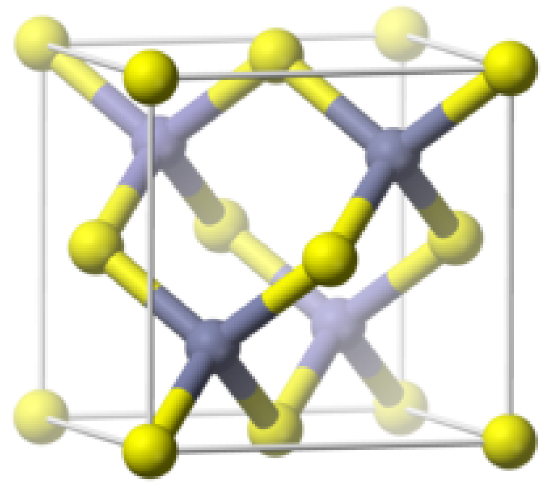


- High efficiency on various substrates:
  - 23.4% on glass (SolarFrontier, 2019)
  - 20.8% on flexible polymer foil (Empa, 2019)
  - 17.6% module efficiency (NICE Solar, 2019)
- Suited for BIPV and mobile applications
- Little environmental and health hazards (with Cd-free buffers)

CdTe solar cells

CdTe material

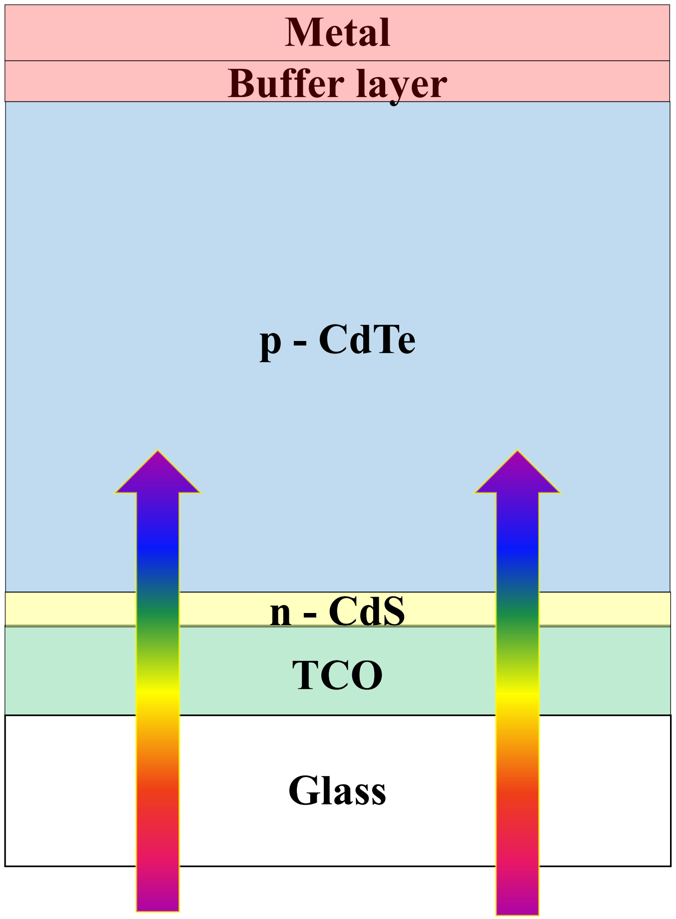
- Almost ideal energy band gap of 1.45 eV at room temp
- High absorption coefficient (1 µm CdTe absorbs >92% of the photons with energy above band gap)
- Simple growth of CdTe
- Chemically and thermally robust



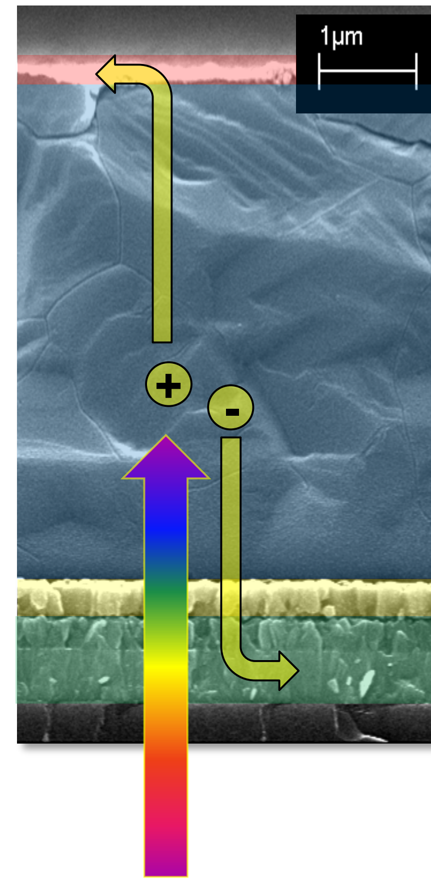
www.wikipedia.com

Structure of CdTe solar cells

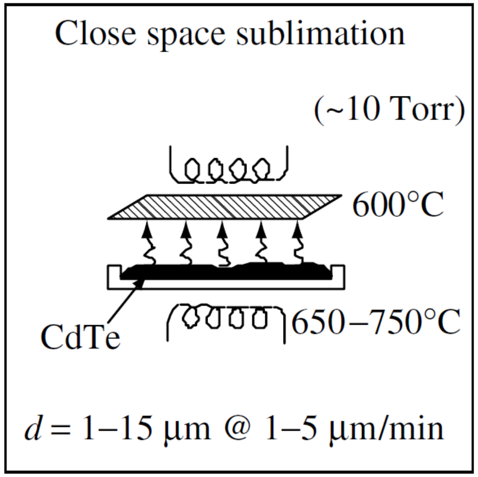
- Superstrate configuration is used for high efficiency CdTe cells:
- Substrate must be transparent (glass)

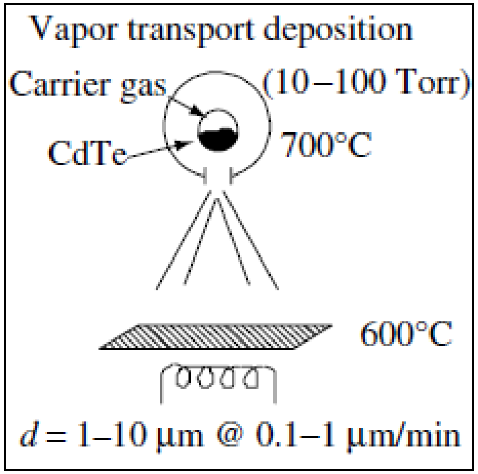


Back contact	**50 - 2000 nm**
Absorber	**2 - 10 µm**
Window	**30 - 500 nm**
Front contact	**0.5 - 1 µm**
Substrate	**1 - 3 mm**

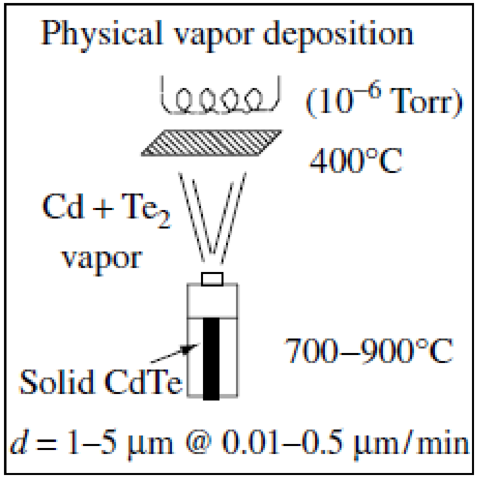


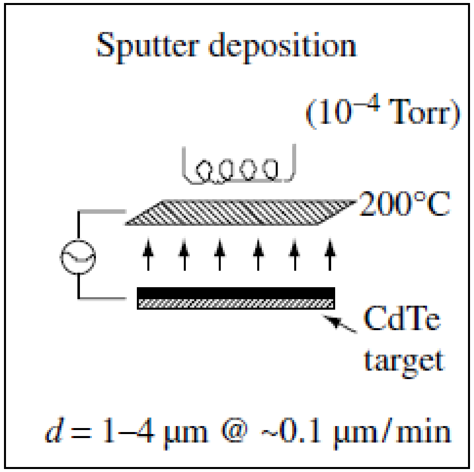
Deposition methods for CdTe





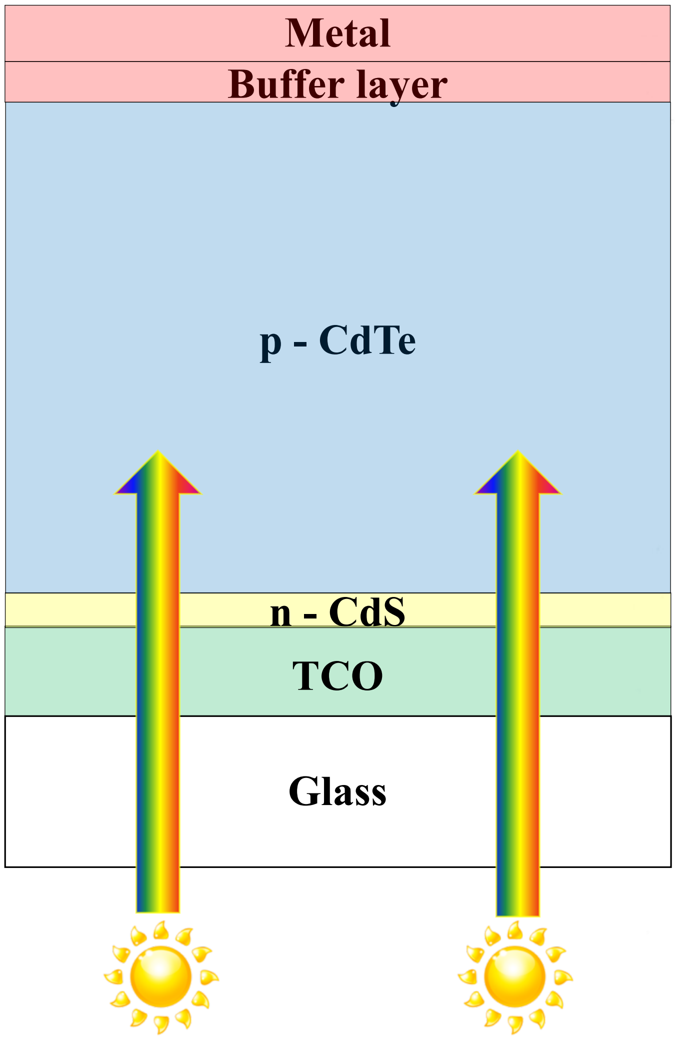
Vacuum techniques

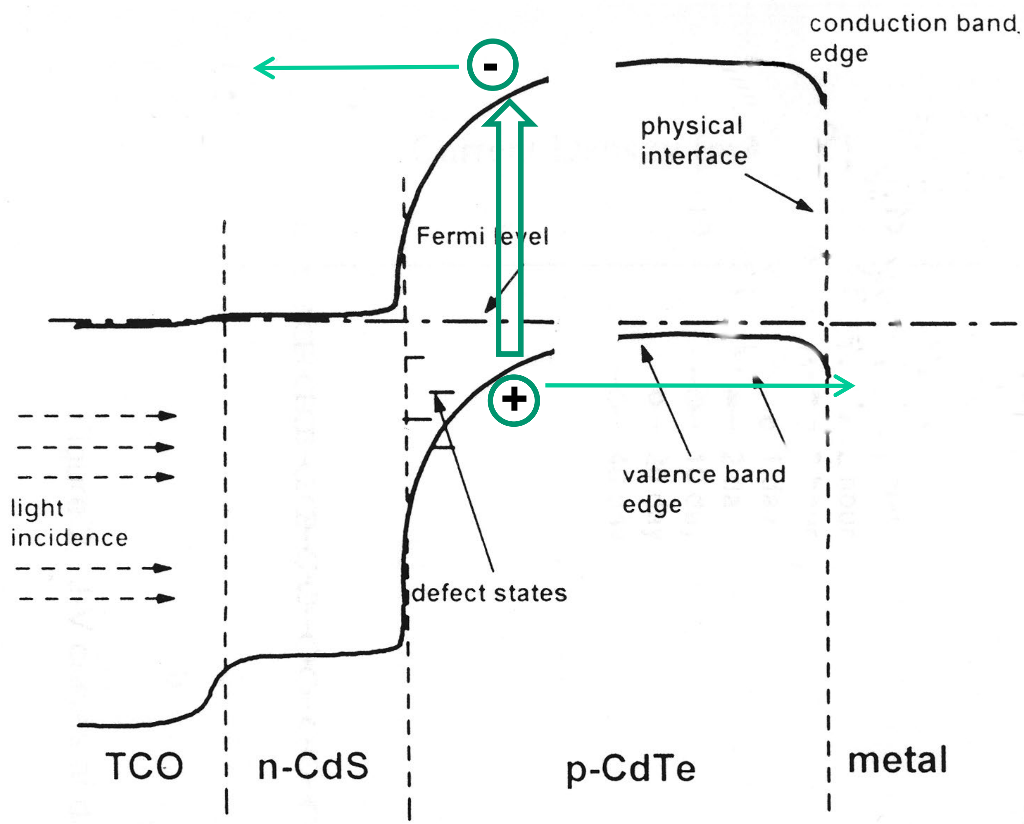




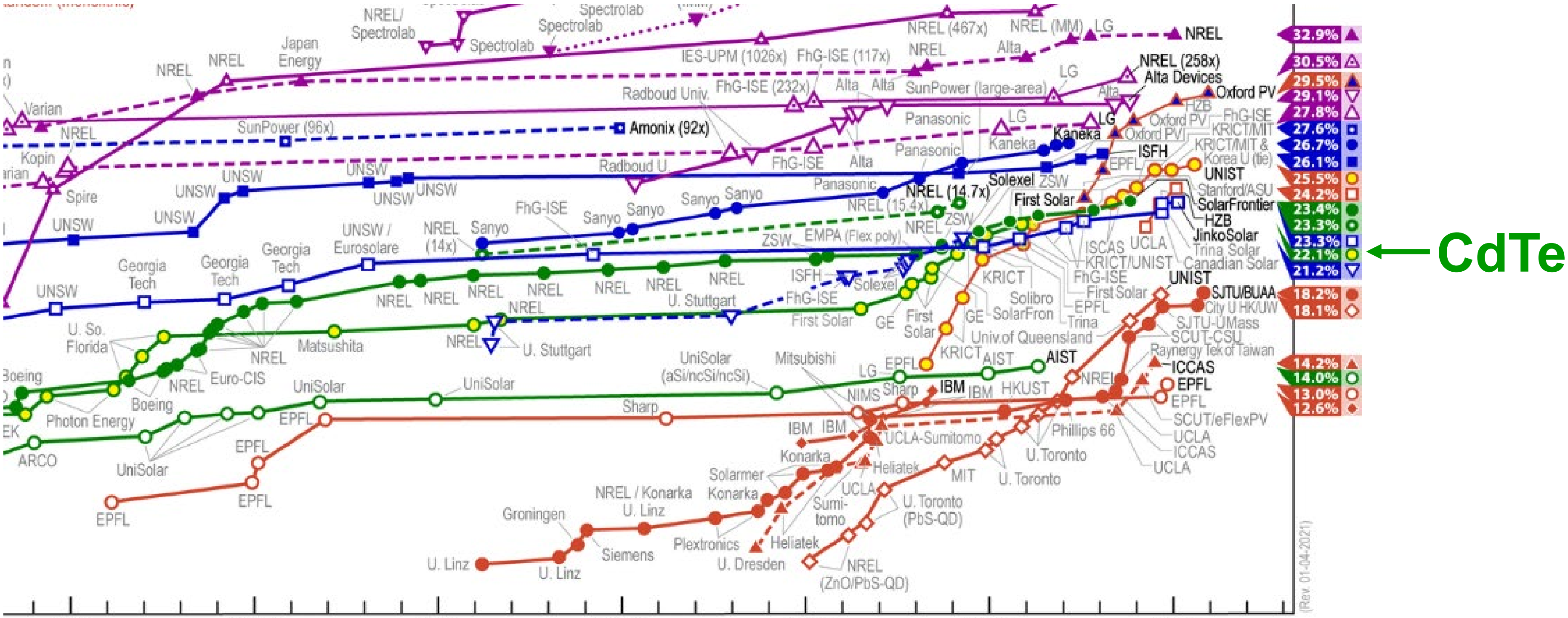
Handbook of Photovoltaic Science and Enginnering, 2011

Operation


Metal
Buffer layer
p - CdTe
n - CdS
TCO
Glass


conduction band edge
physical interface
Fermi level
light incidence
defect states
valence band edge
TCO
n-CdS
p-CdTe
metal

Efficiency of CdTe solar cells



- Significant efficiency improvement from 16.7% to 22.1% within 6 years thanks to industrial research at FirstSolar and GE Global Research

First Solar – the only CdTe company

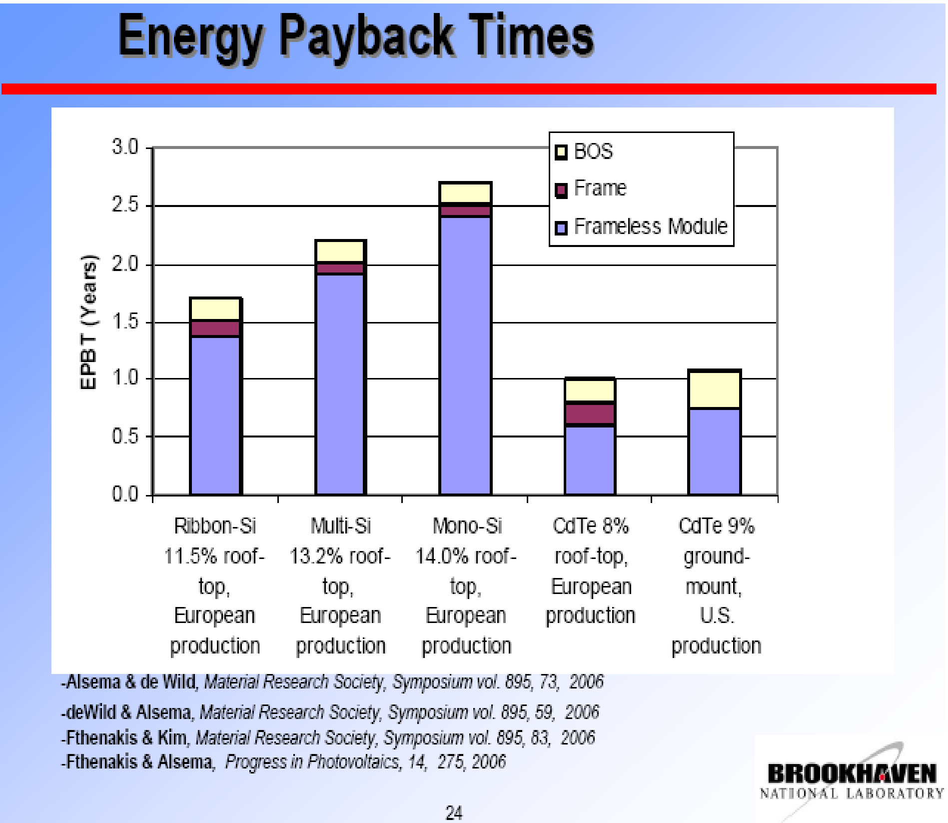
- More than 10 GW installed worldwide
- 30 manufacturing lines worldwide w/ 2.7 GW of annual manufacturing capacity
- Research lab solar cell efficiency 22.1% (2017)

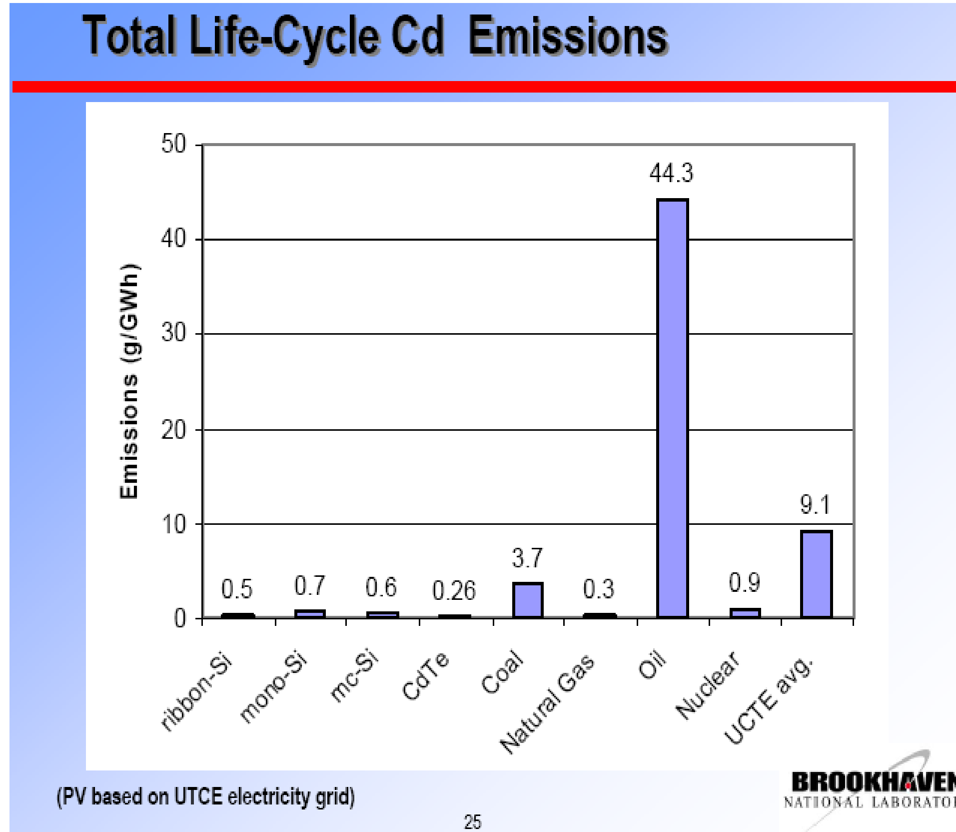
18.6% module efficiency (2017)

Company sells large-scale utility plants (not modules)

Source: http://www.firstsolar.com/
https://www.youtube.com/watch?v=DksYJqtNcX8

Environmental aspects of Cd





- CdTe has one of the lowest energy pay-back times

- CdTe is a stable compound
- No Cd emission during normal operation
- CdTe modules have the lowest total life-cycle Cd emission

V. Fthenakis, EMRS-2006 Spring meeting

Summary CdTe technology

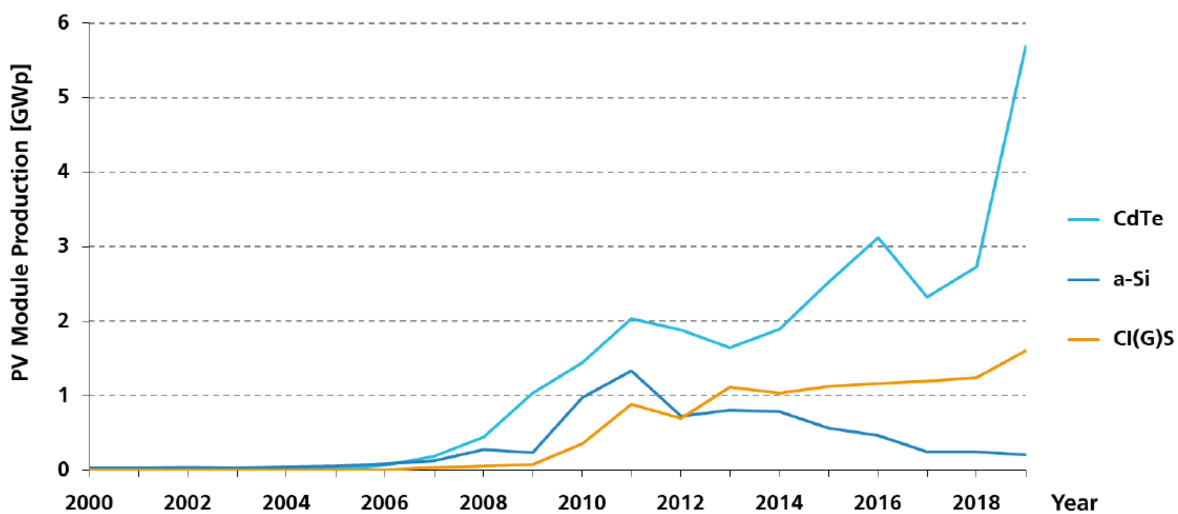
- CdTe solar cells are fabricated in **superstrate configuration**

- Maximum efficiency:

  22.1 % on glass (First Solar)

  18.6 % modules (First Solar)

- Highest market share among thin-film technologies



Photovoltaics Report, Fraunhofer ISE (Sept 2020)