Modern photovoltaic technologies
PHYS-609

Part 1.3 Thin-film solar cells*

- CdTe solar cells
- CIGS solar cells

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

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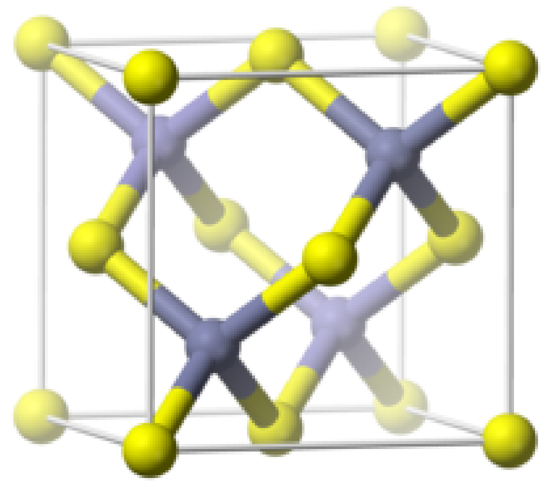
Empa
Materials Science and Technology

CdTe solar cells

CdTe material

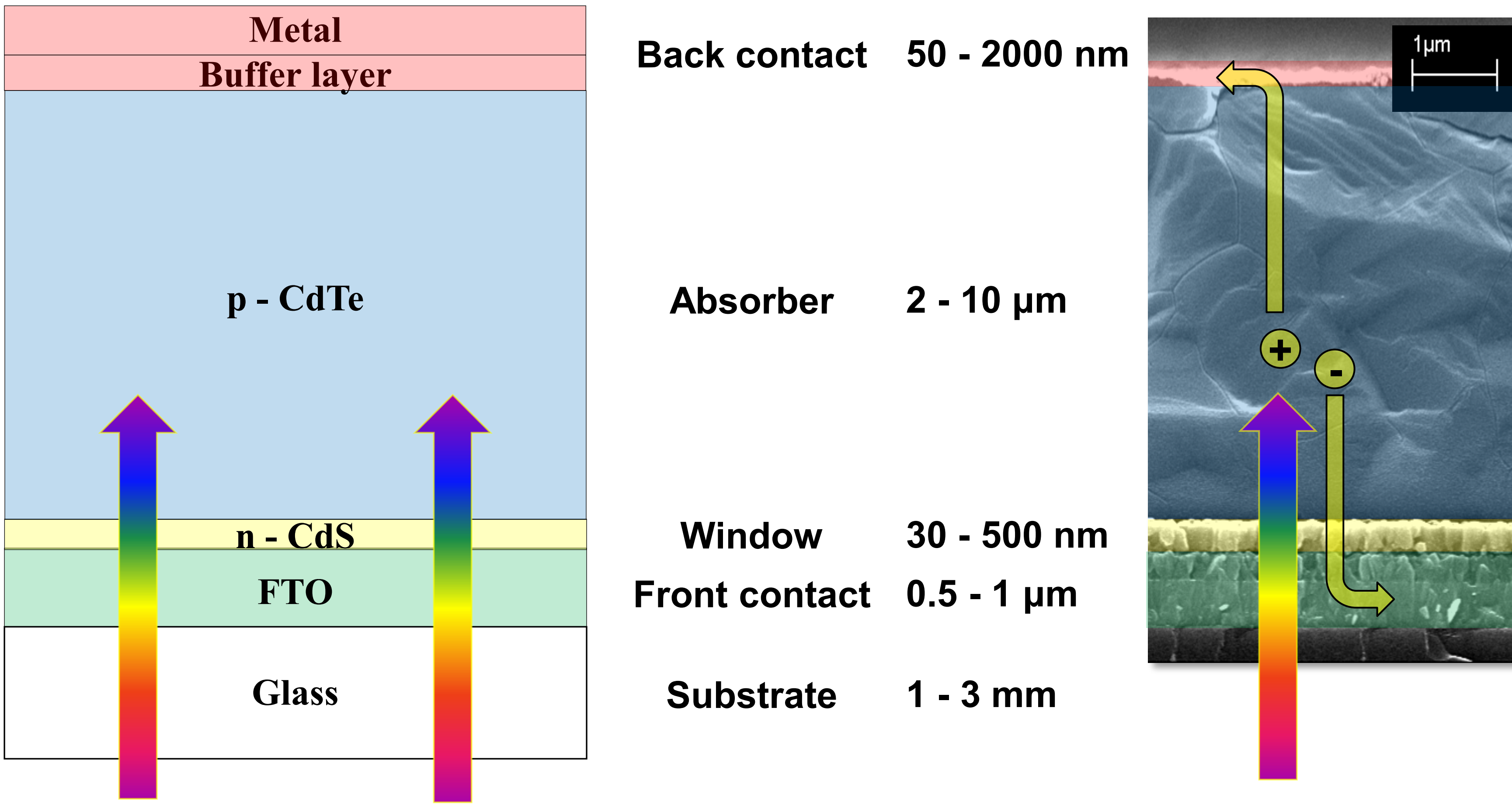
- Almost ideal energy band gap of 1.45 eV at room temp
- High absorption coefficient (1 µm CdTe absorbs >92% of the photons with energy above band gap)
- Simple growth of CdTe
- Chemically and thermally robust



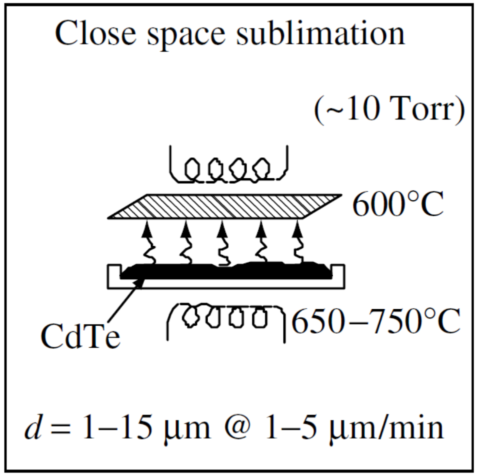
www.wikipedia.com

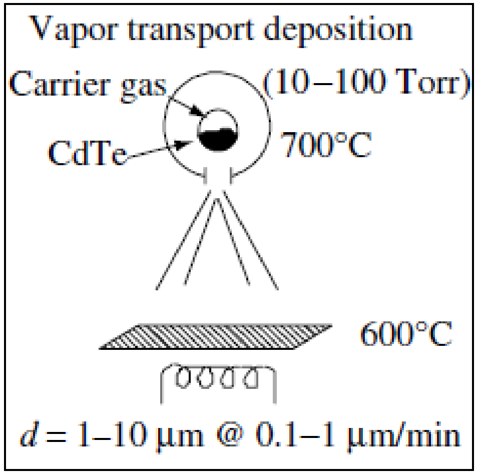
Structure of CdTe solar cells

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

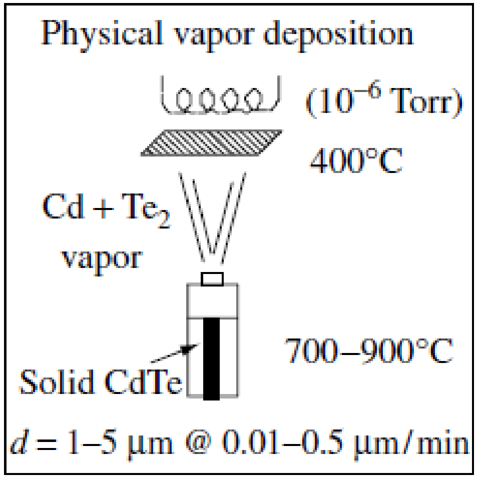


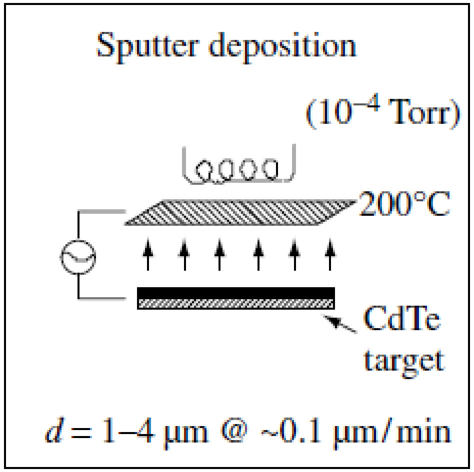
Deposition methods for CdTe





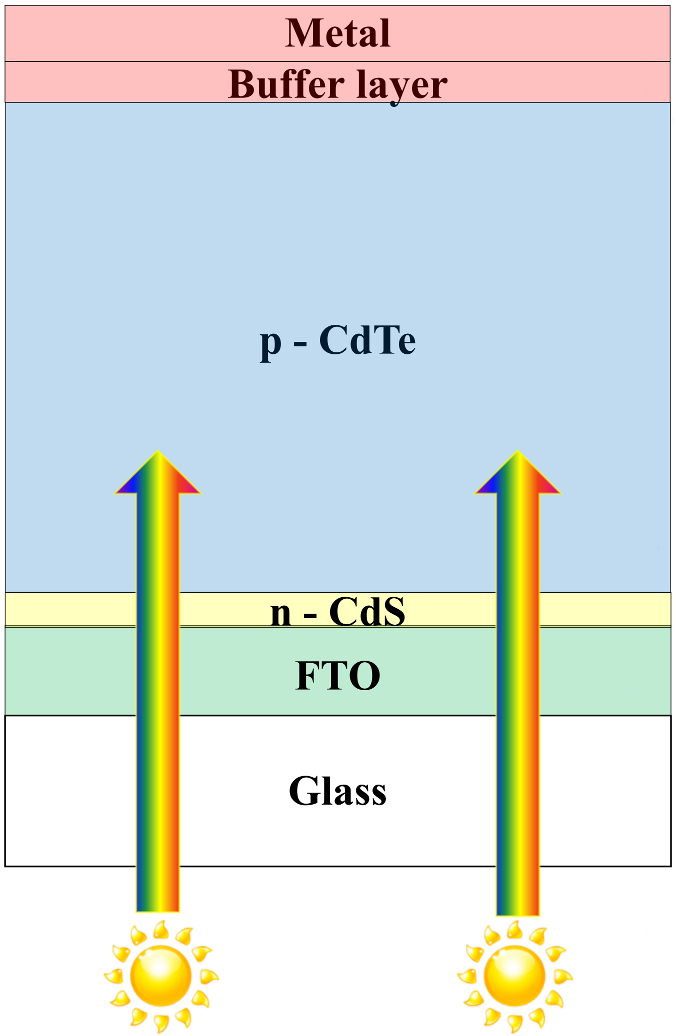
Vacuum
techniques



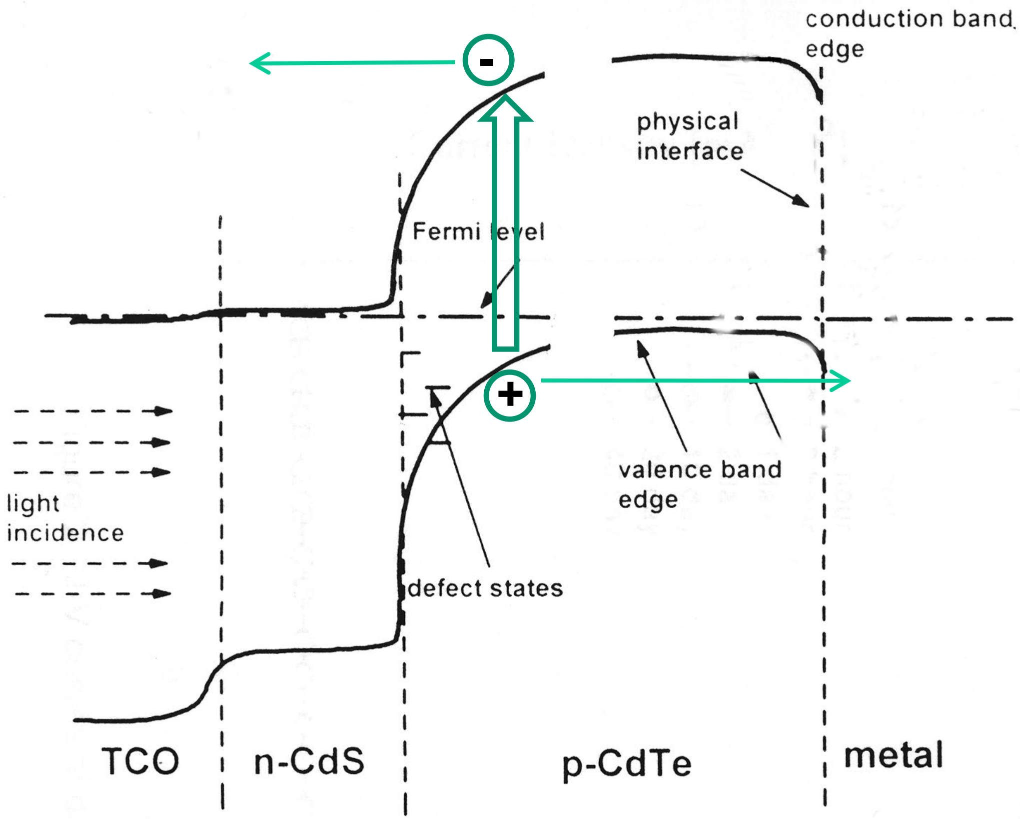


Handbook of Photovoltaic Science and Enginnering, 2011

Operation

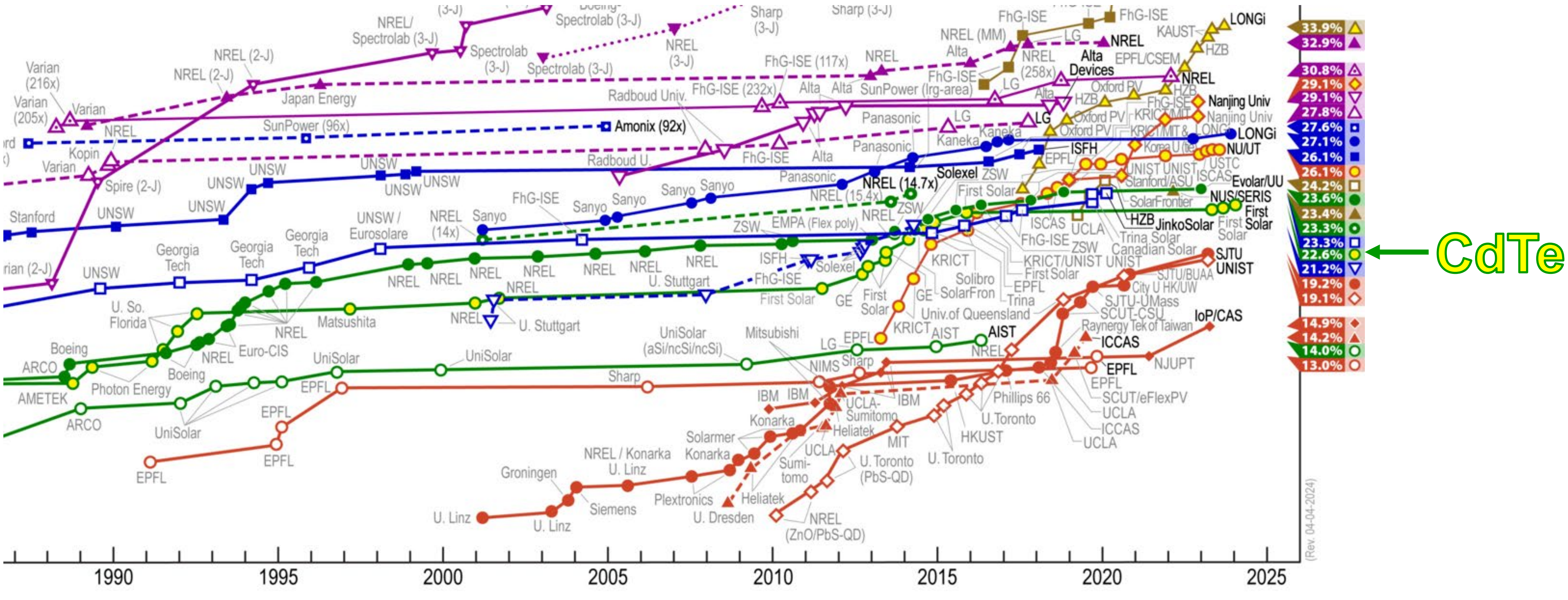


Metal
Buffer layer
p - CdTe
n - CdS
FTO
Glass



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

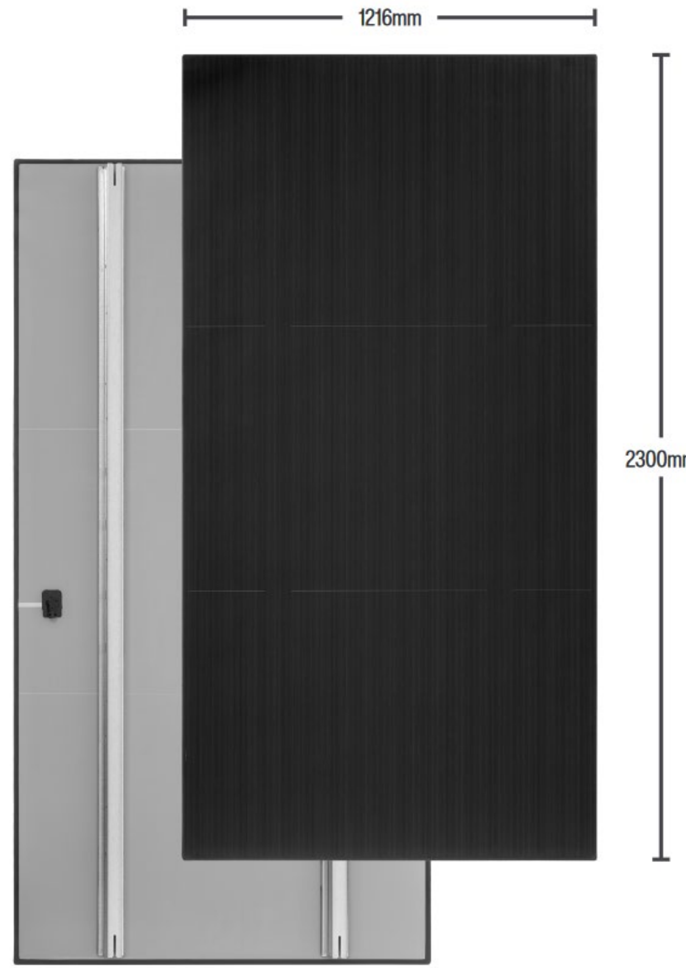


- Significant efficiency improvement from 16.7% to > 22.6% within 6 years thanks to competitive industrial research at FirstSolar and GE Global Research

First Solar – the only CdTe company

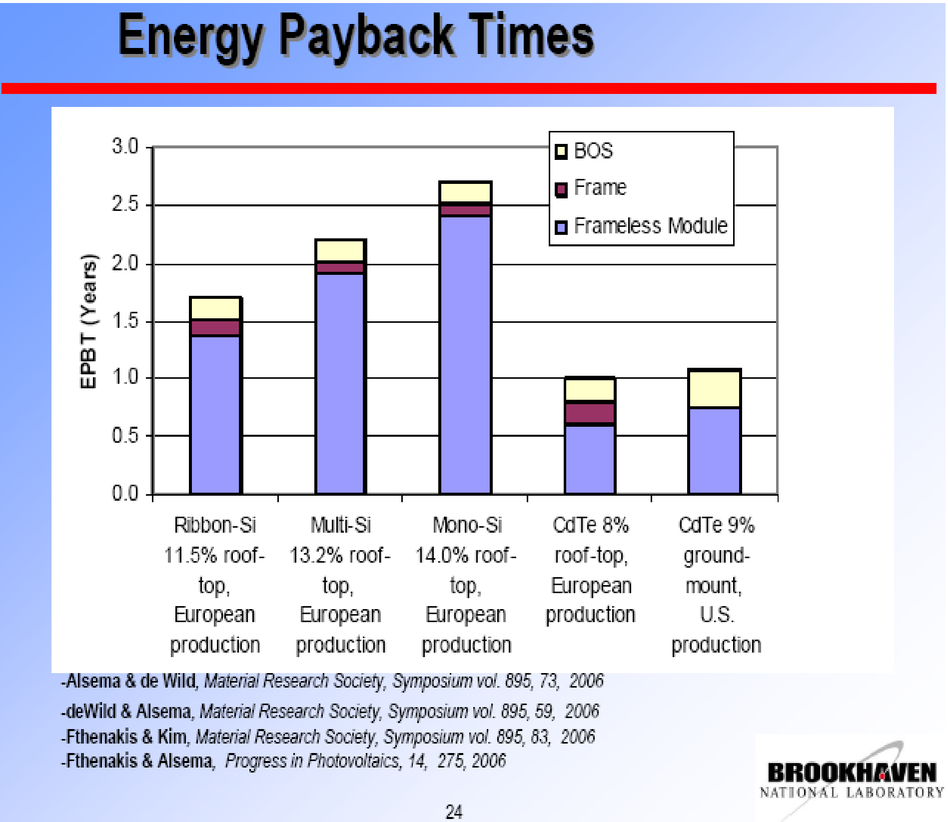
- More than 10 GW installed worldwide
- 30 manufacturing lines worldwide
w/ > 5 GW of annual manufacturing capacity
- 19.7% module efficiency (Series 7 modules)

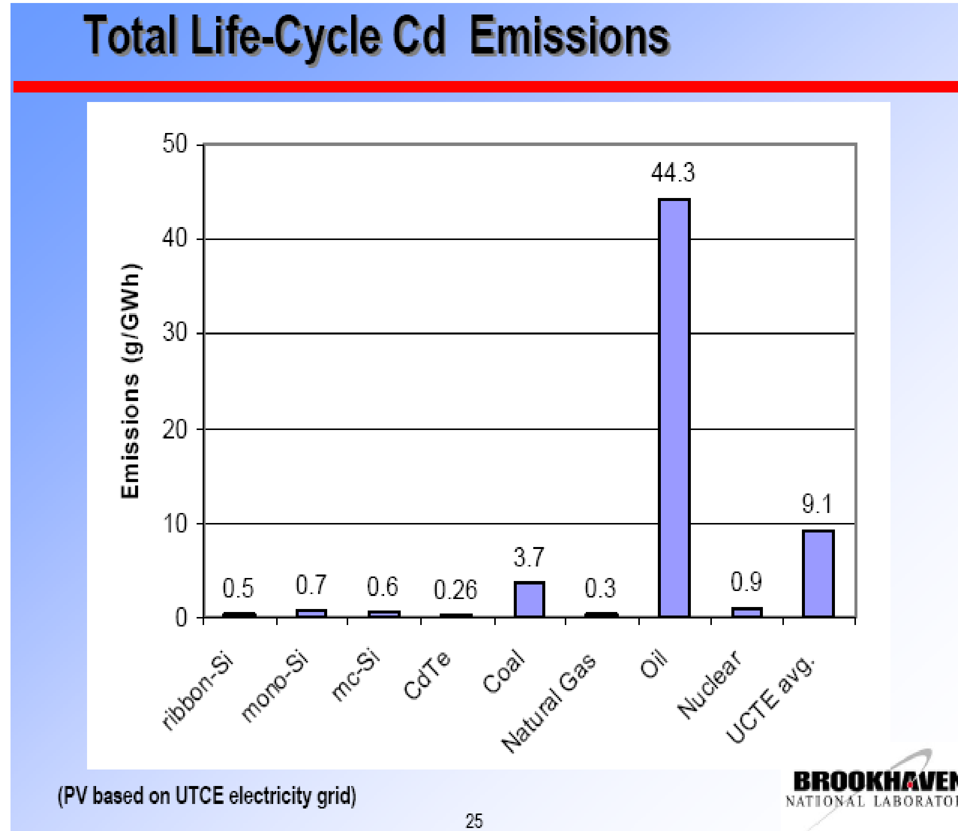
FirstSolar sells large-scale utility plants



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

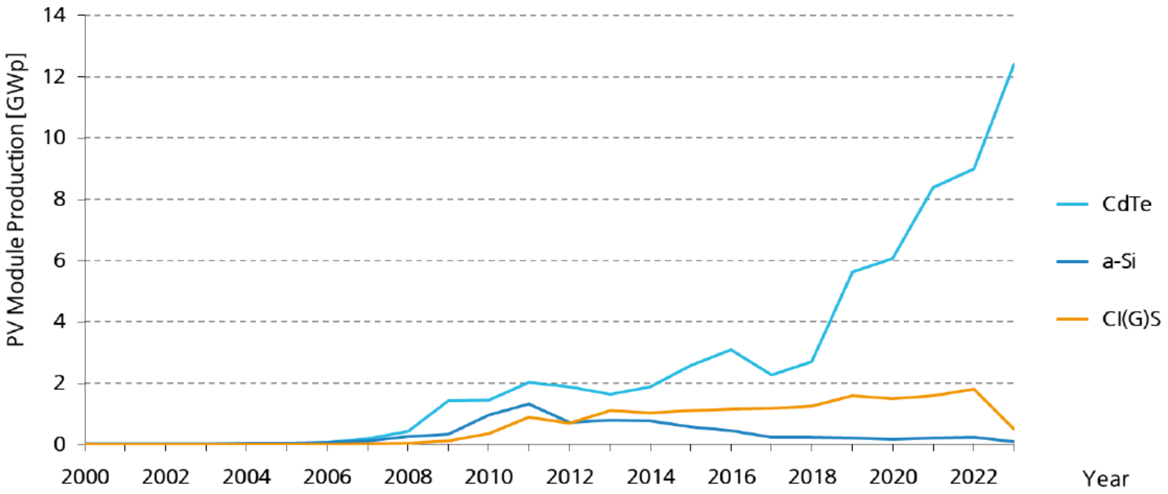
- CdTe solar cells are fabricated in **superstrate configuration**

- Maximum efficiency:

  22.6 % on glass (First Solar)

  19.7 % modules (First Solar)

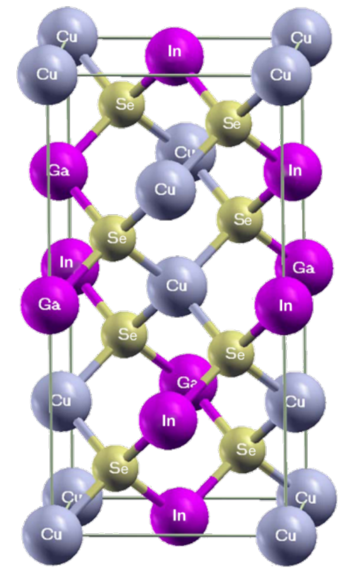
- Highest market share among thin-film technologies



Photovoltaics Report, Fraunhofer ISE (May 2024)

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

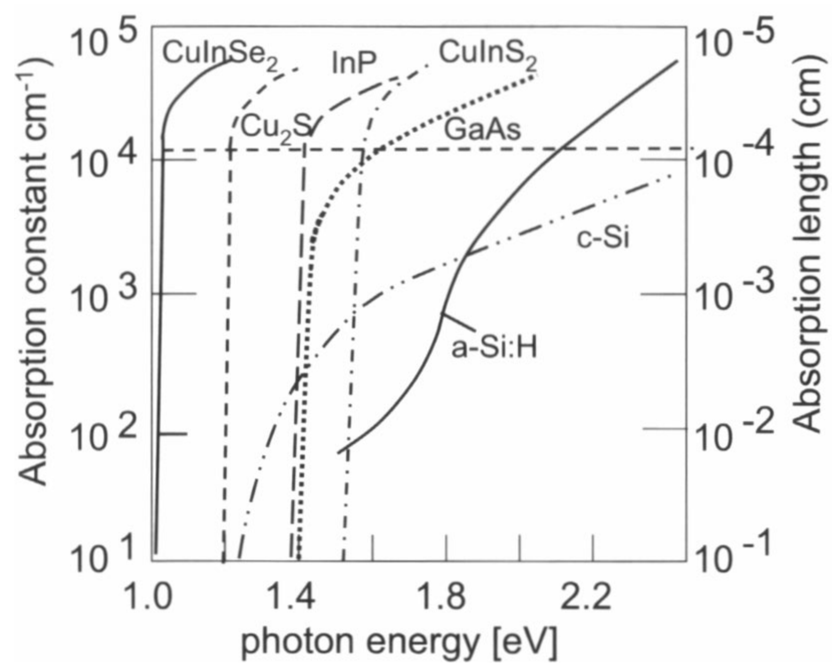
$CuInSe_2$ = CIS



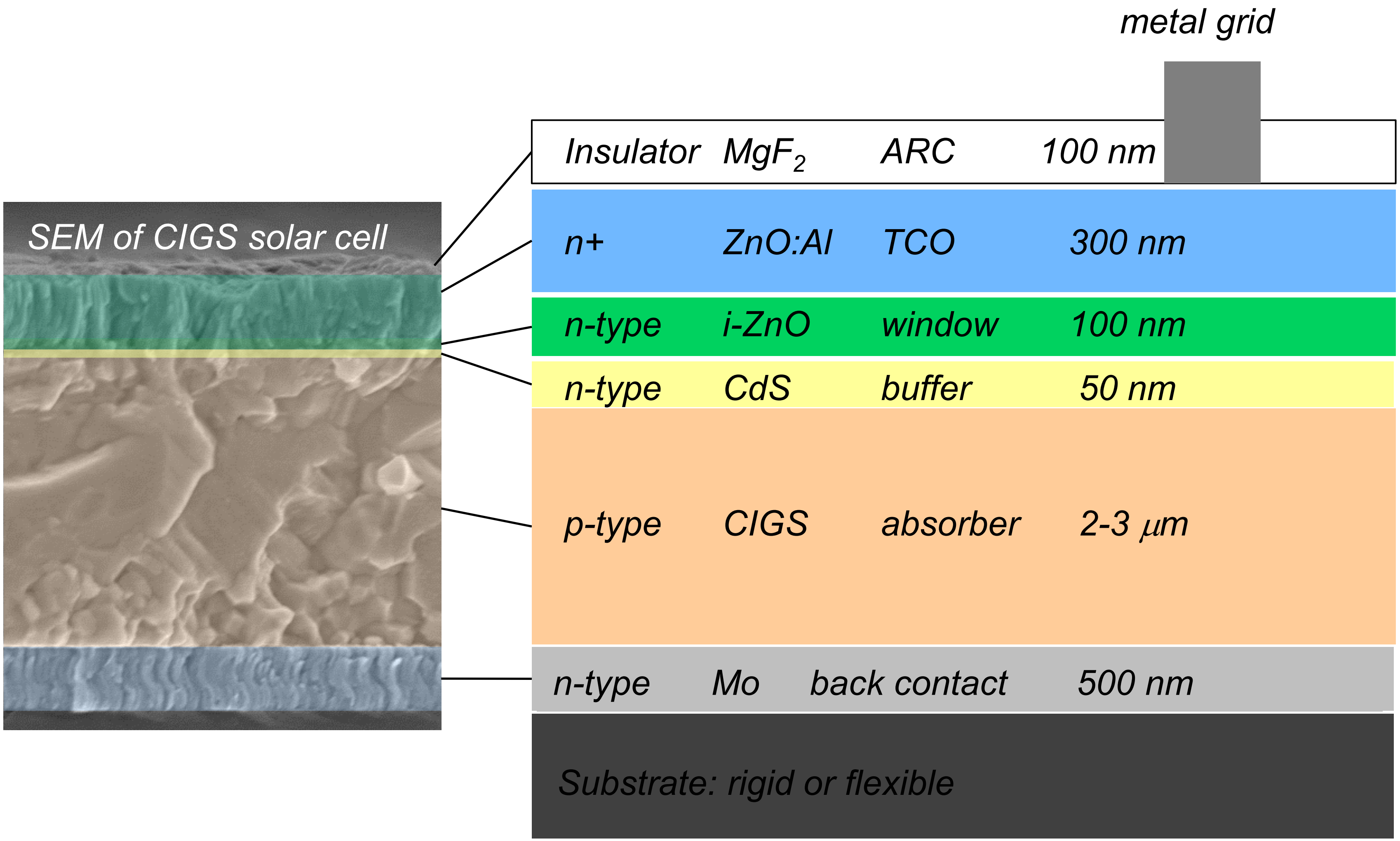
- crystal structure:
  - tetragonal chalcopyrite ($CuFeS_2$) structure derived from cubic ZnSe
- direct gap semiconductor
  - band gap 1.04eV – 1.68eV (adding Ga)
  - absorption coefficient > 10^4 cm^{-1}

  =>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



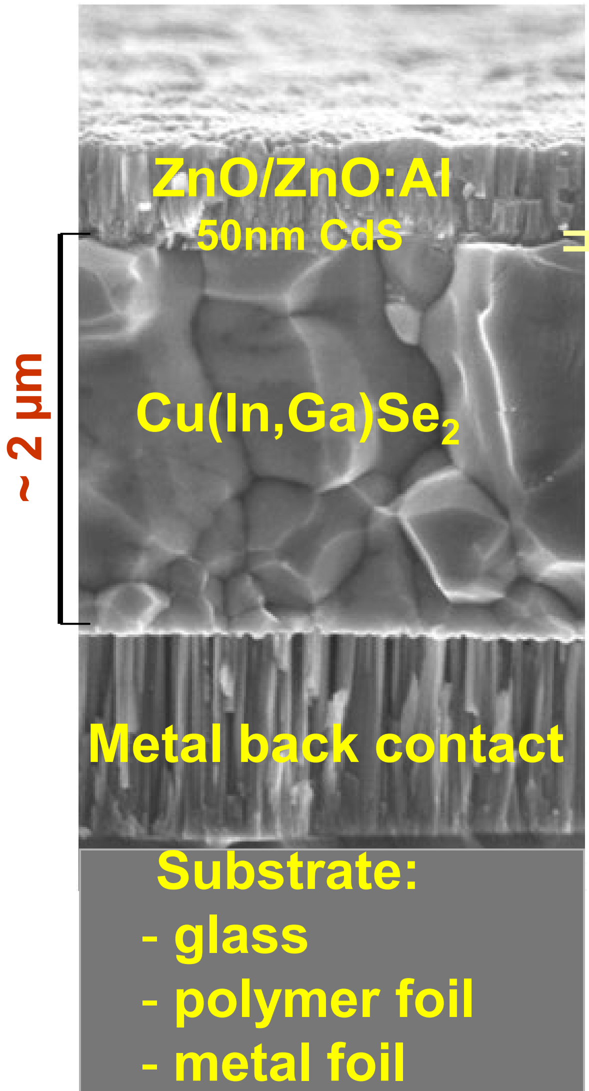
Structure of CIGS cell



Resistivity (Ω cm):

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

Fabrication of CIGS solar cells

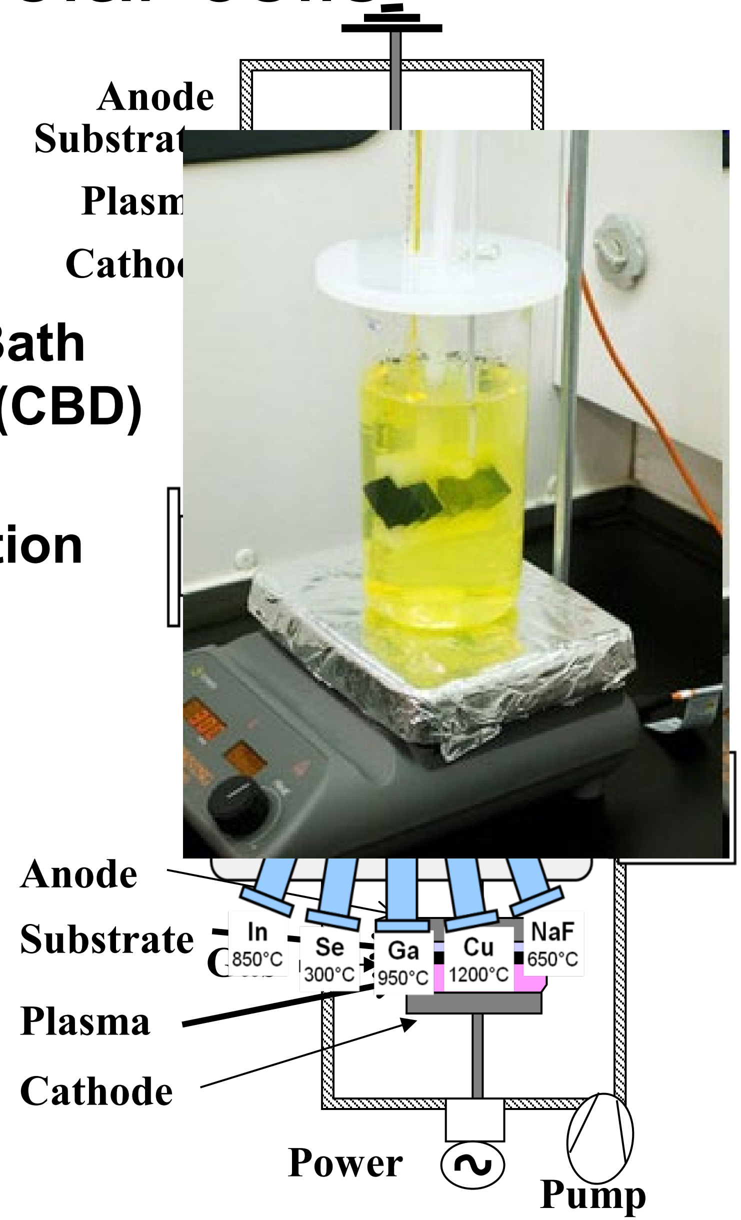


Sputtering

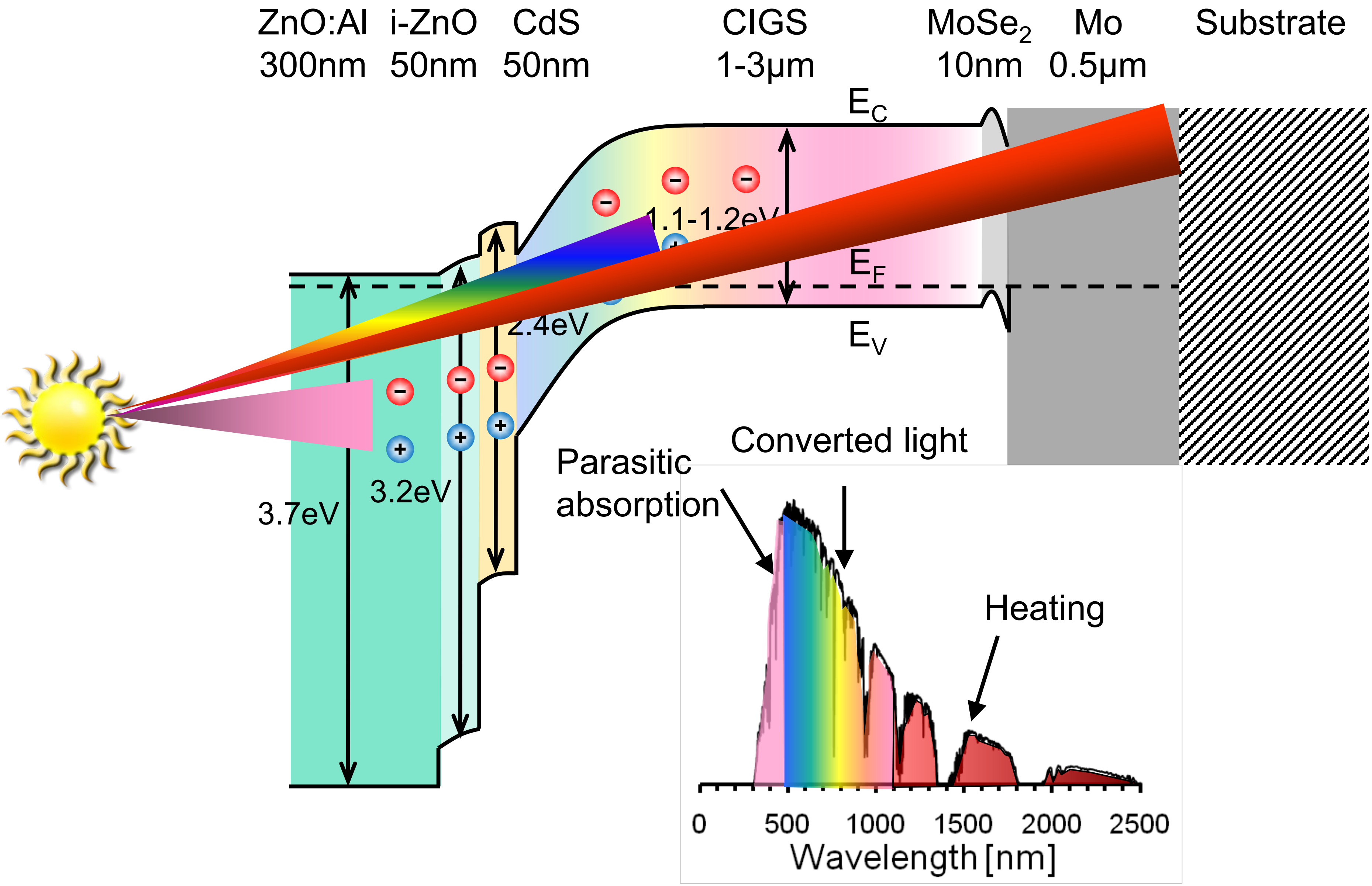
Chemical Bath Deposition (CBD)

Co-evaporation

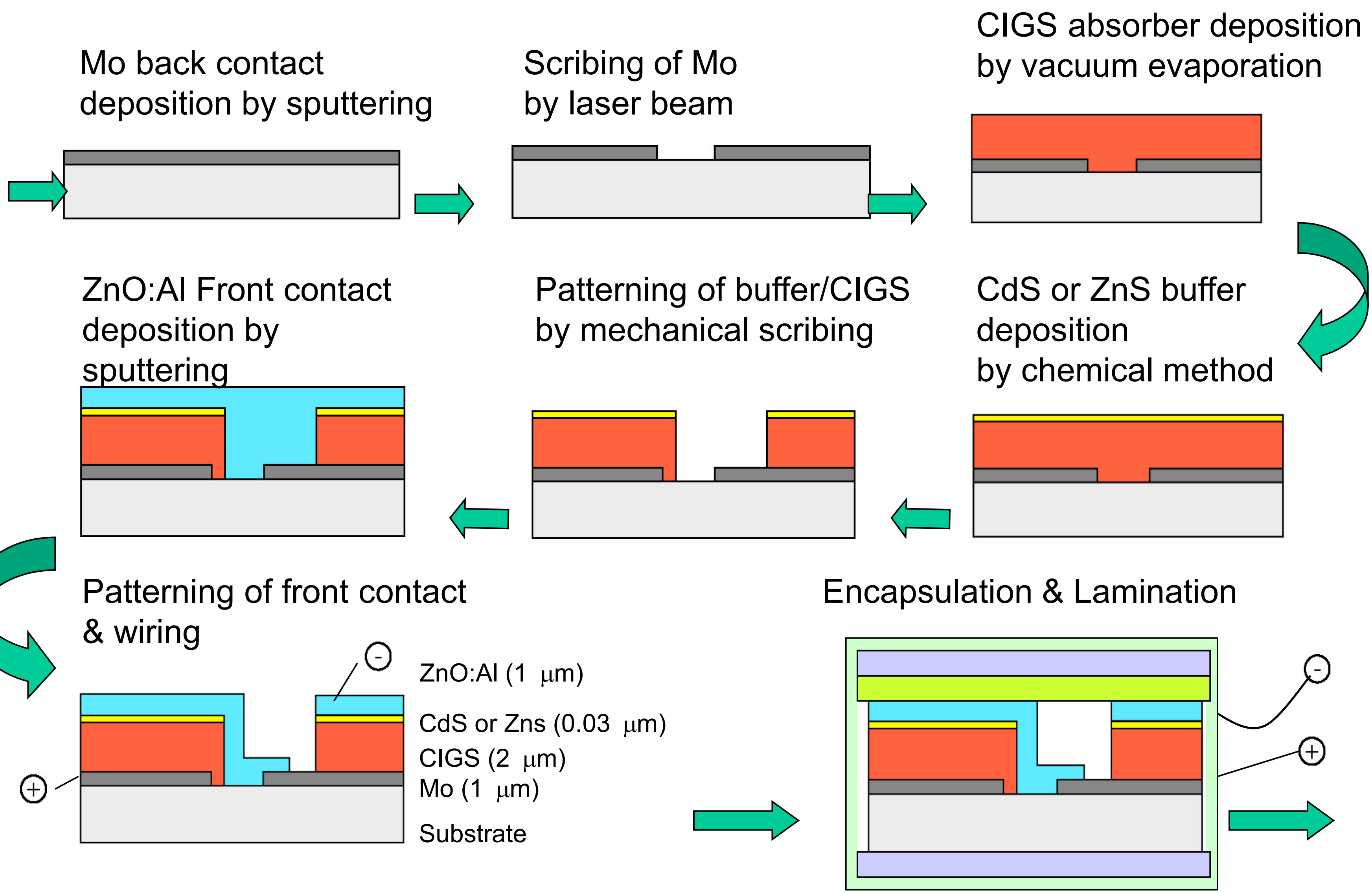
Sputtering



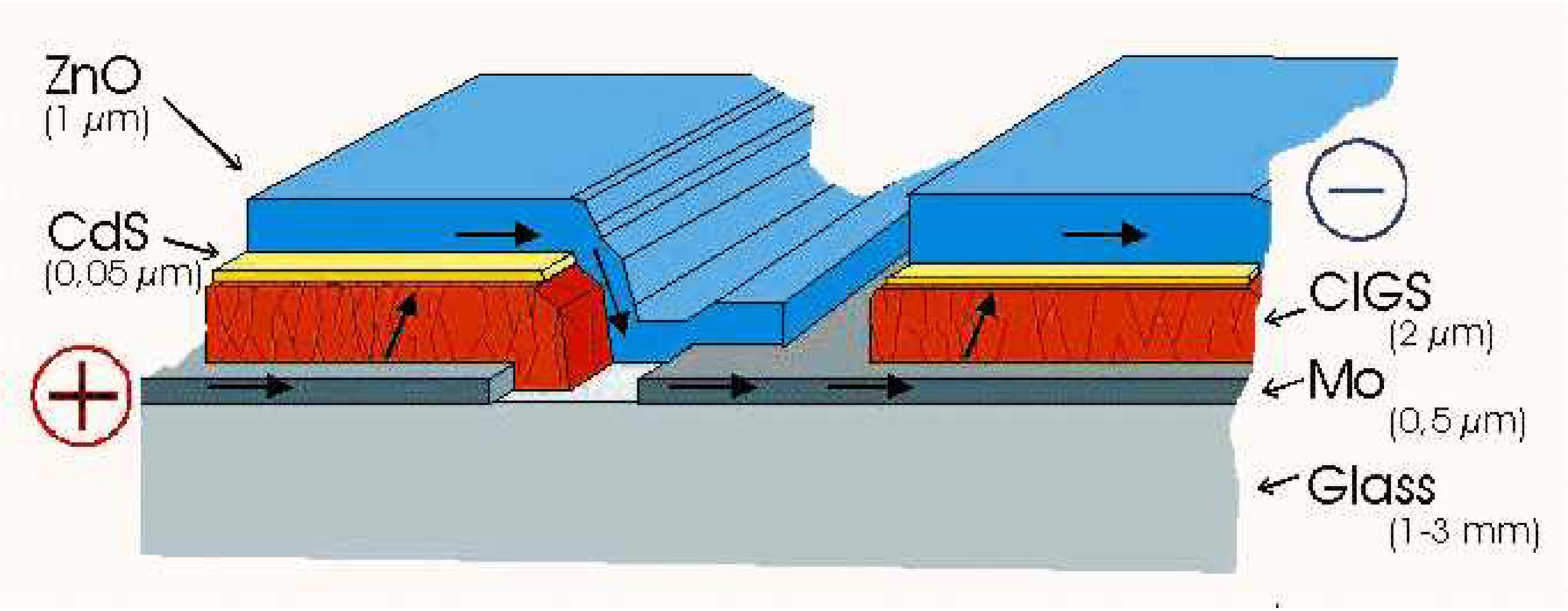
Operation of CIGS solar cell



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

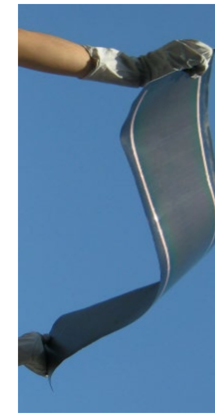
WÜRTH SOLAR

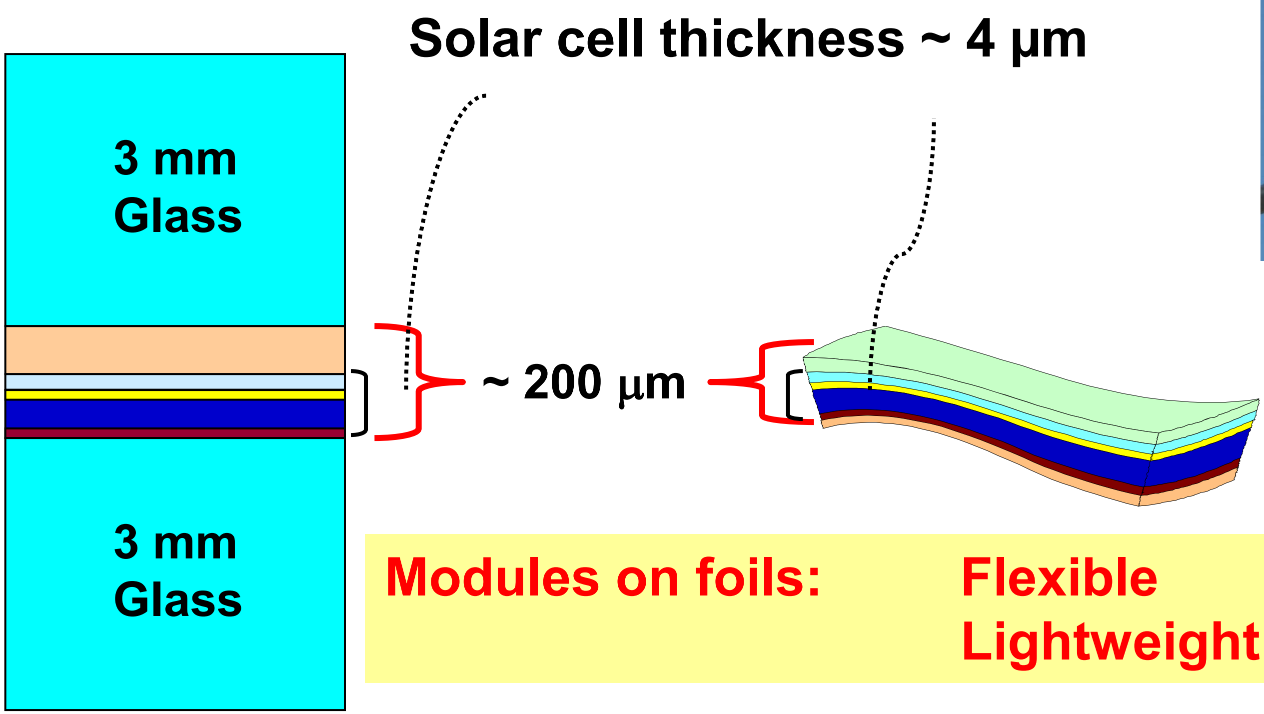
Solar Frontier

Flexible thin film solar modules

Mature technology

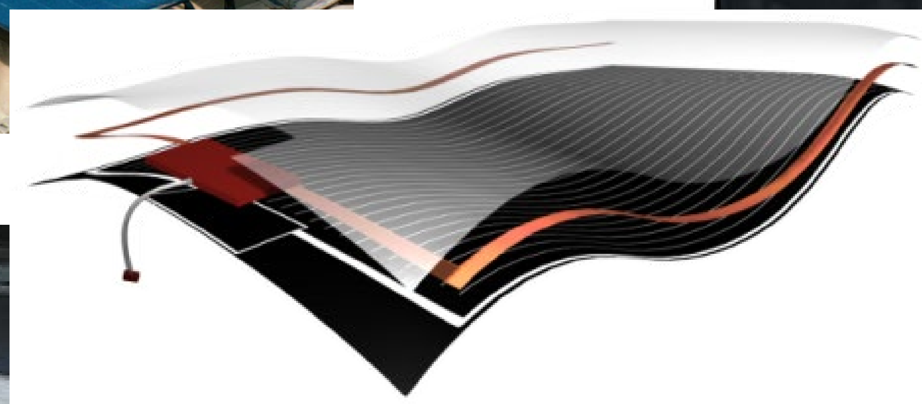
Emerging technology

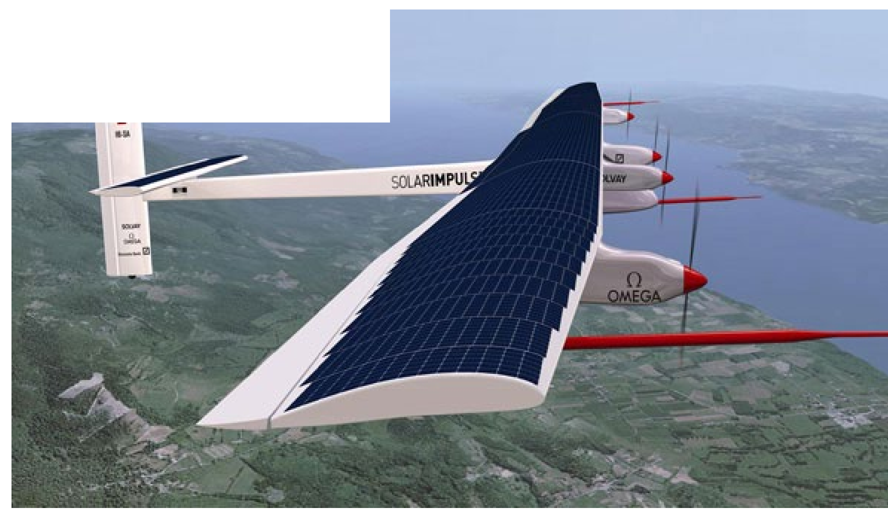




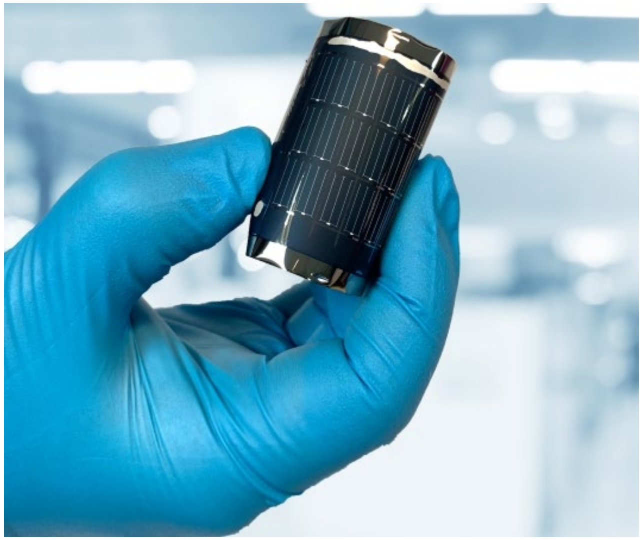
Modules on foils: **Flexible**
Lightweight

Targeted applications for flexible solar cells



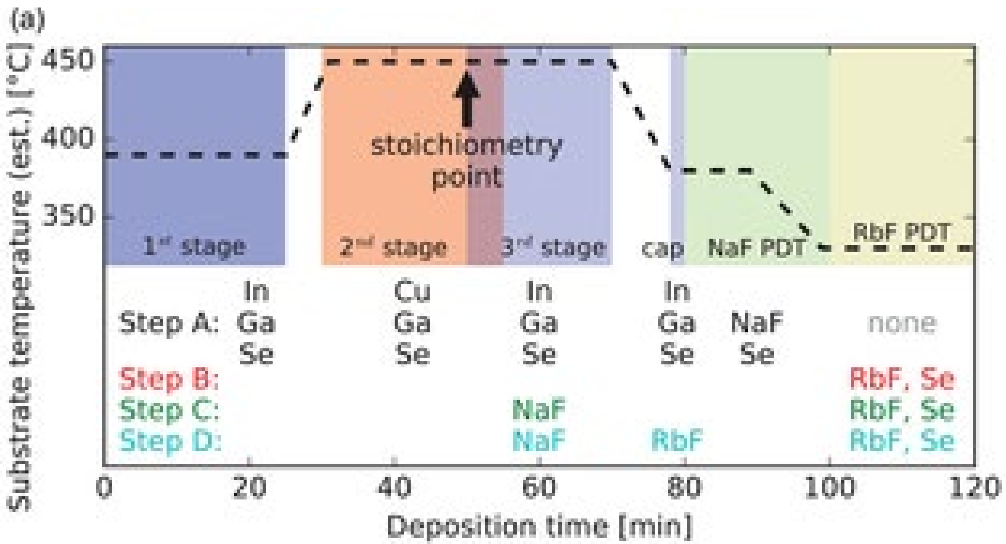


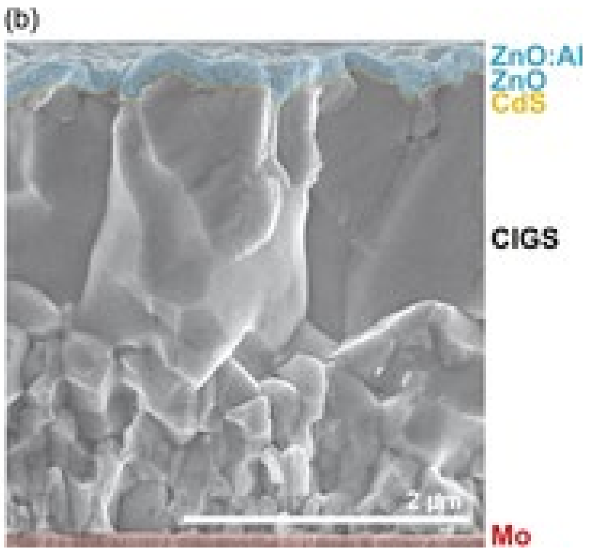
CIGS on flexible polymer substrate



World record 21.4% flexible CIGS cell on polyimide substrate (Empa, 2021)

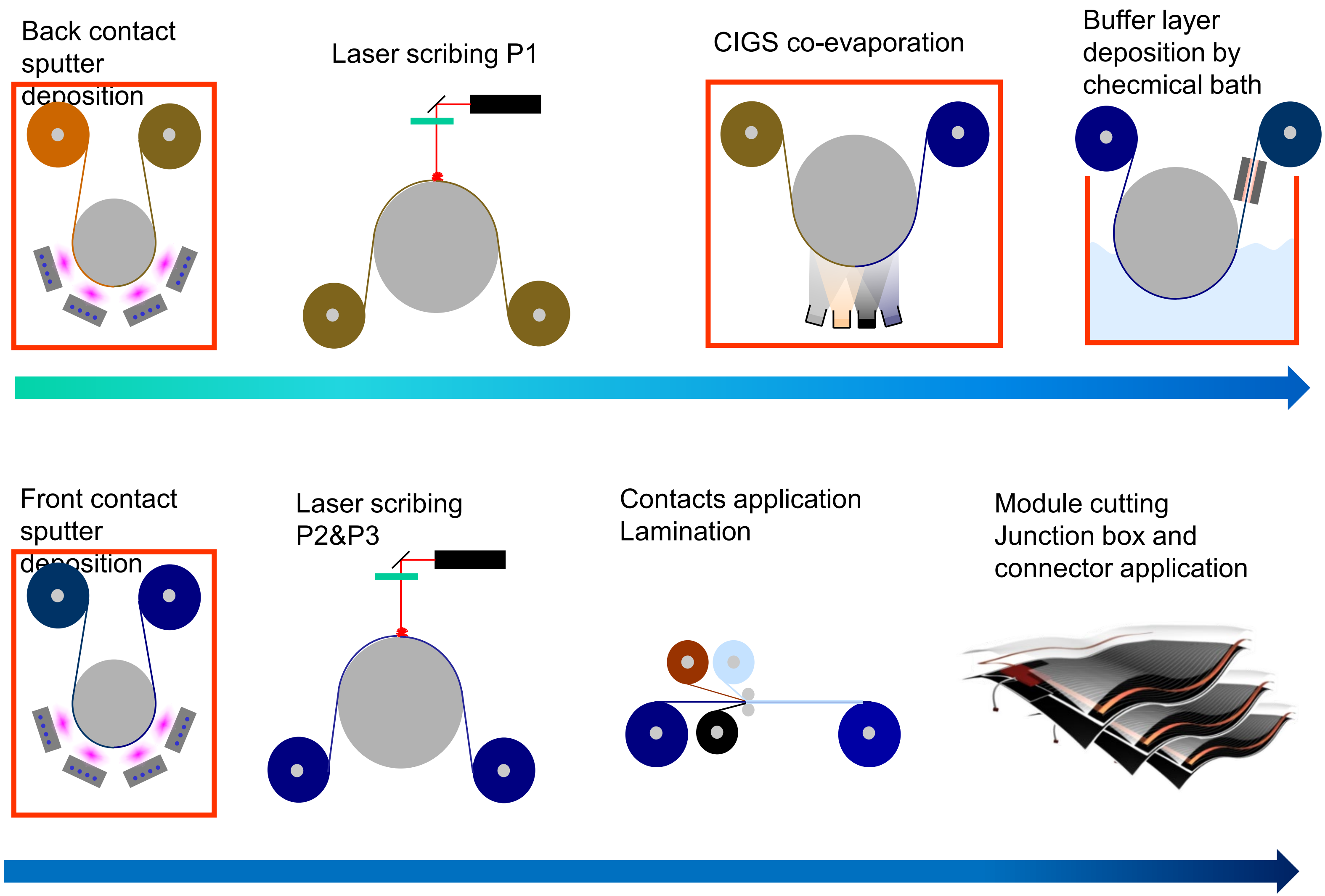
- Complex 3-stage evaporation process at 450°C together with NaF & RbF co-doping





Adv. Energy Mater. 9 (2019) 1900408

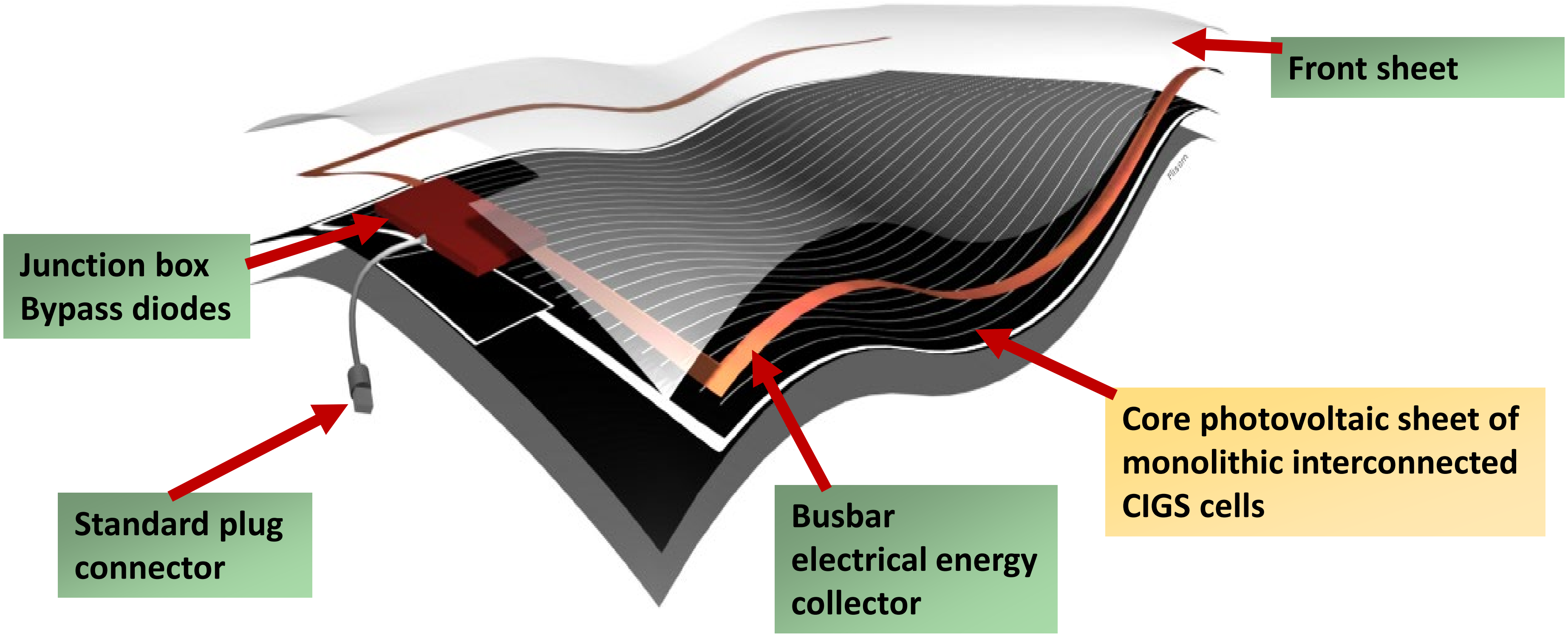
Roll-to-roll manufacturing



Flexible CIGS solar modules

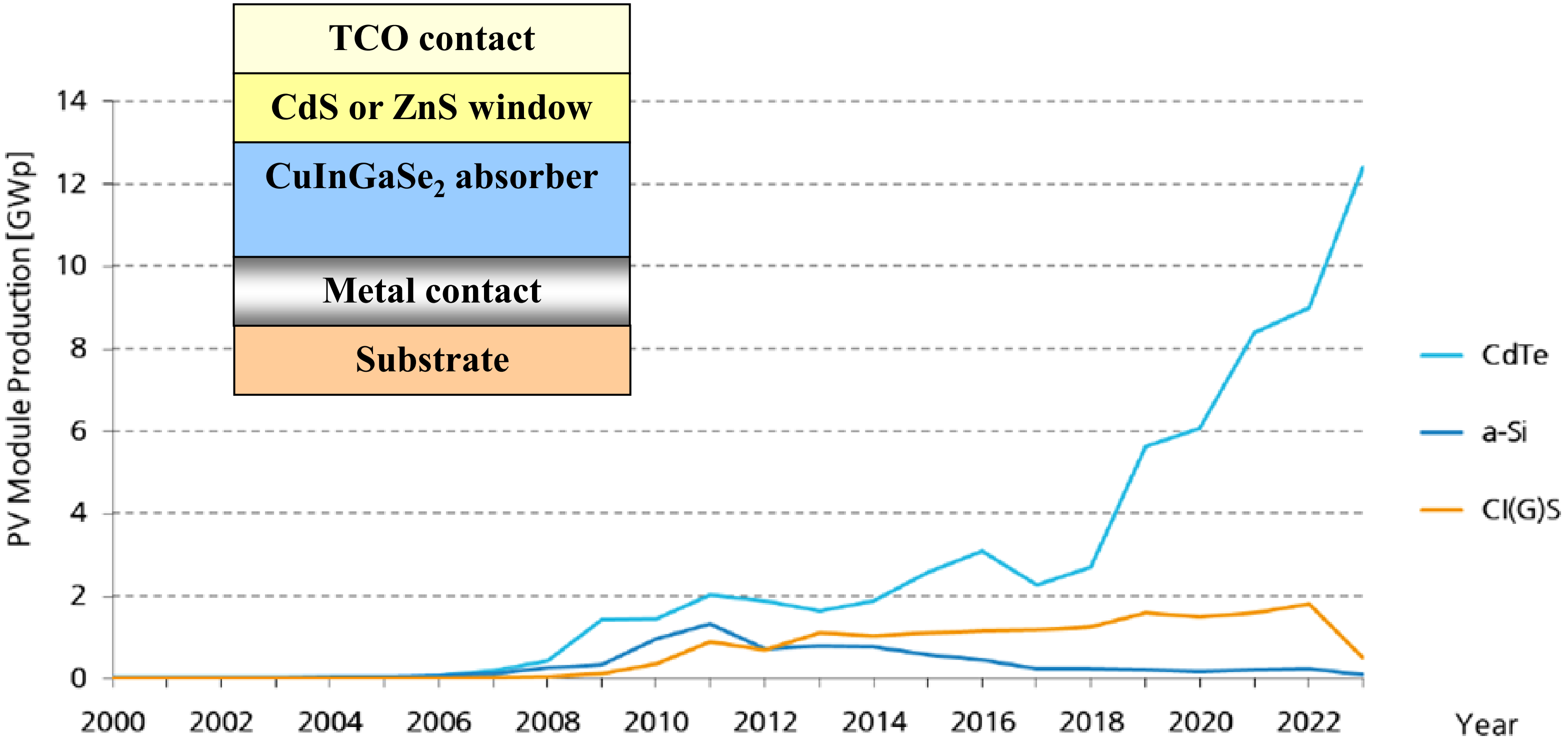
Front-end processing: Active layers & metal grid coatings on Substrate material

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



(was acquired by Ascent Solar Technologies (US) in April 2023
in liquidation since Sept 2023)

Summary CIGS thin film technology



Efficiency on various substrates:

- 23.4% on glass (SolarFrontier, 2019)
- 22.2% on flexible polymer foil (Empa, 2022)
- 17.6% module efficiency (NICE Solar, 2019)

BUT: many CIGS companies went out of business (SolarFrontier, NICE solar, Solibro, Flisom,…)

only a few remaining: AVANCIS (DE), Midsummer (Sweden)