Modern photovoltaic technologies
PHYS-609

Part 1.3 Thin-film solar cells*

- CIGS solar cells
- CdTe solar cells

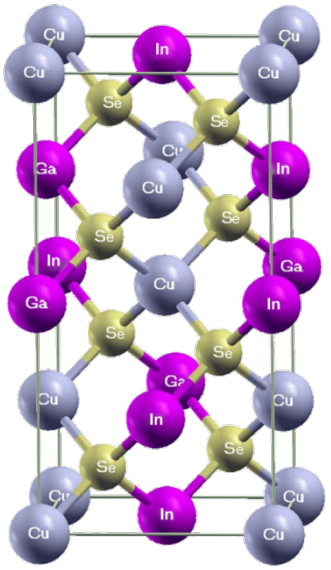
* Amorphous Si and perovskite cells are also thin-film technologies and will be covered on Day 2 & 3

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



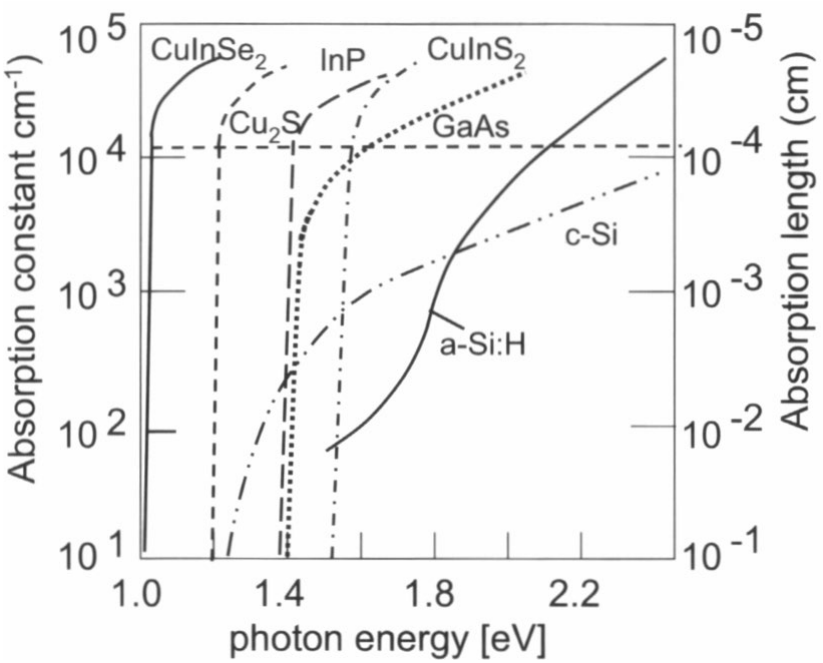
- crystal structure:
  - tetragonal chalcopyrite ($CuFeS_2$) structure derived from cubic ZnSe

- direct gap semiconductor
  - band gap 1.04eV – 1.68eV (adding Ga)
  - absorption coefficient > 10^4 cm^{-1}

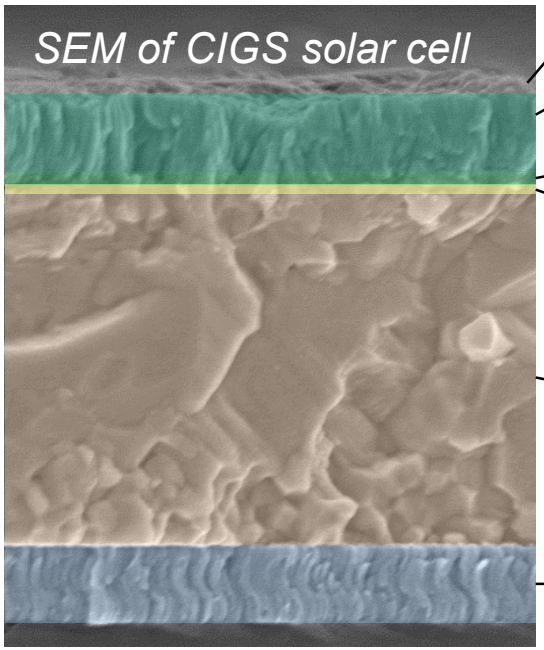
  =>thickness of <1µm is enough to absorb light

- p-type conductivity
  - Cu vacancies -> intrinsic p-doping
  - electrically inactive grain boundaries
  - polycrystalline material

    => robustness, flexible substrates



Structure of CIGS cell



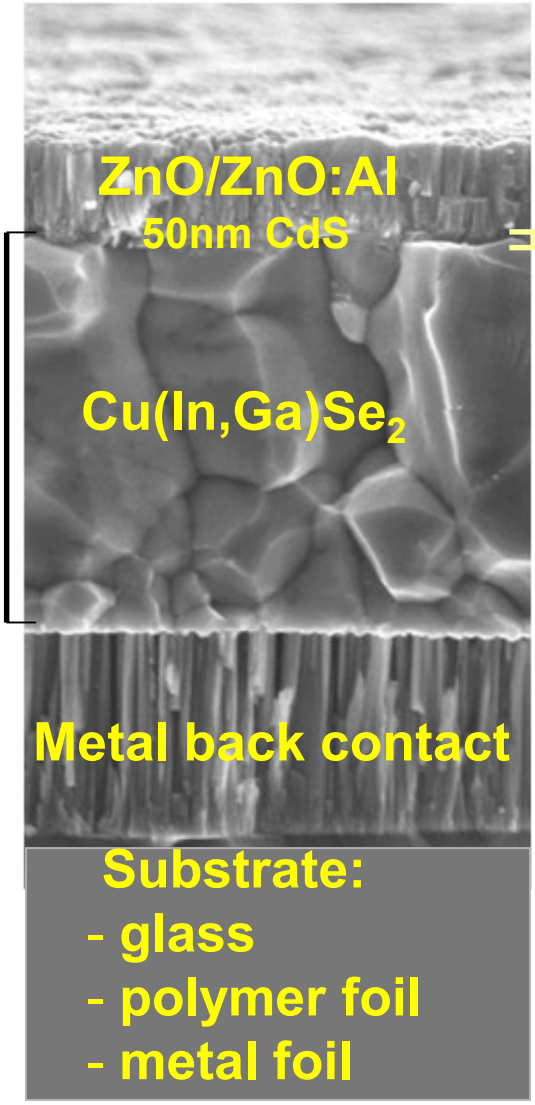
metal grid

Insulator	MgF_2	ARC	100 nm
n+	ZnO:Al	TCO	300 nm
n-type	i-ZnO	window	100 nm
n-type	CdS	buffer	50 nm
p-type	CIGS	absorber	2-3 μm
n-type	Mo	back contact	500 nm
Substrate: rigid or flexible			

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

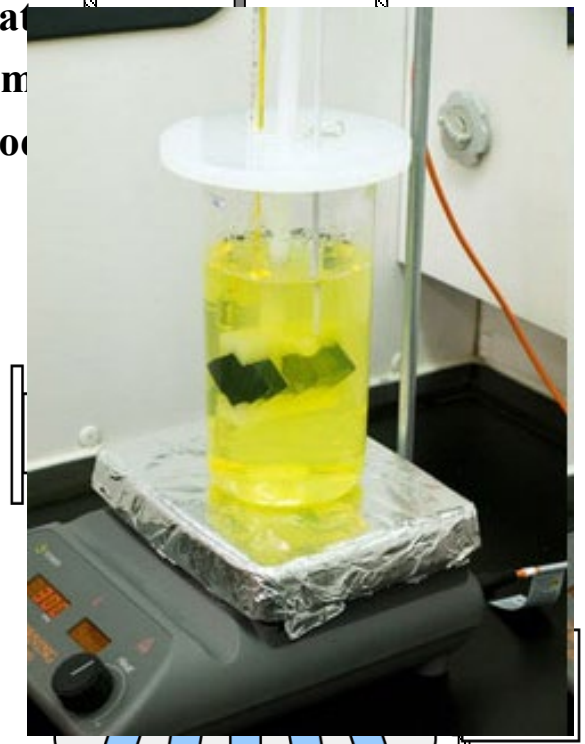


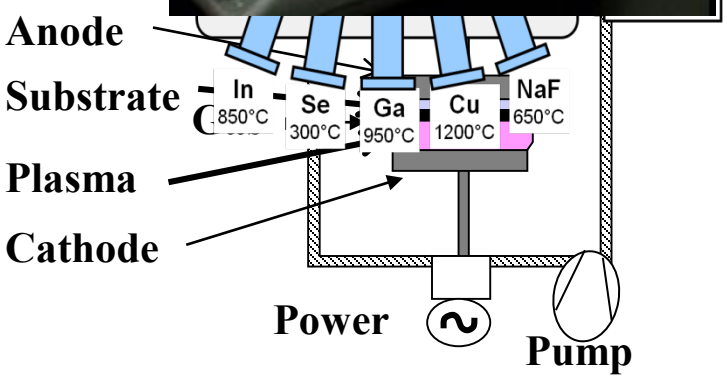
Sputtering

Chemical Bath Deposition (CBD)

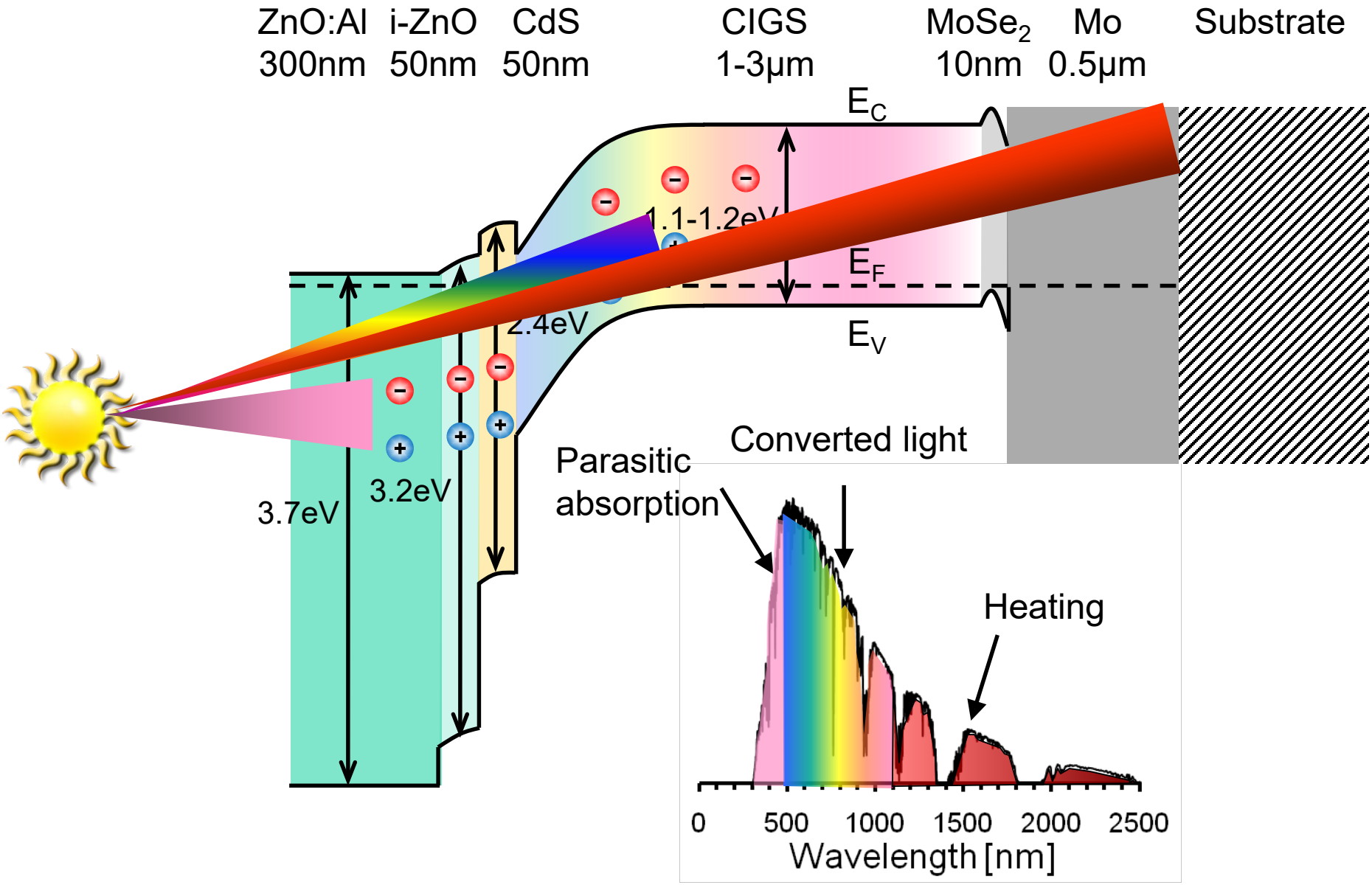
Co-evaporation

Sputtering

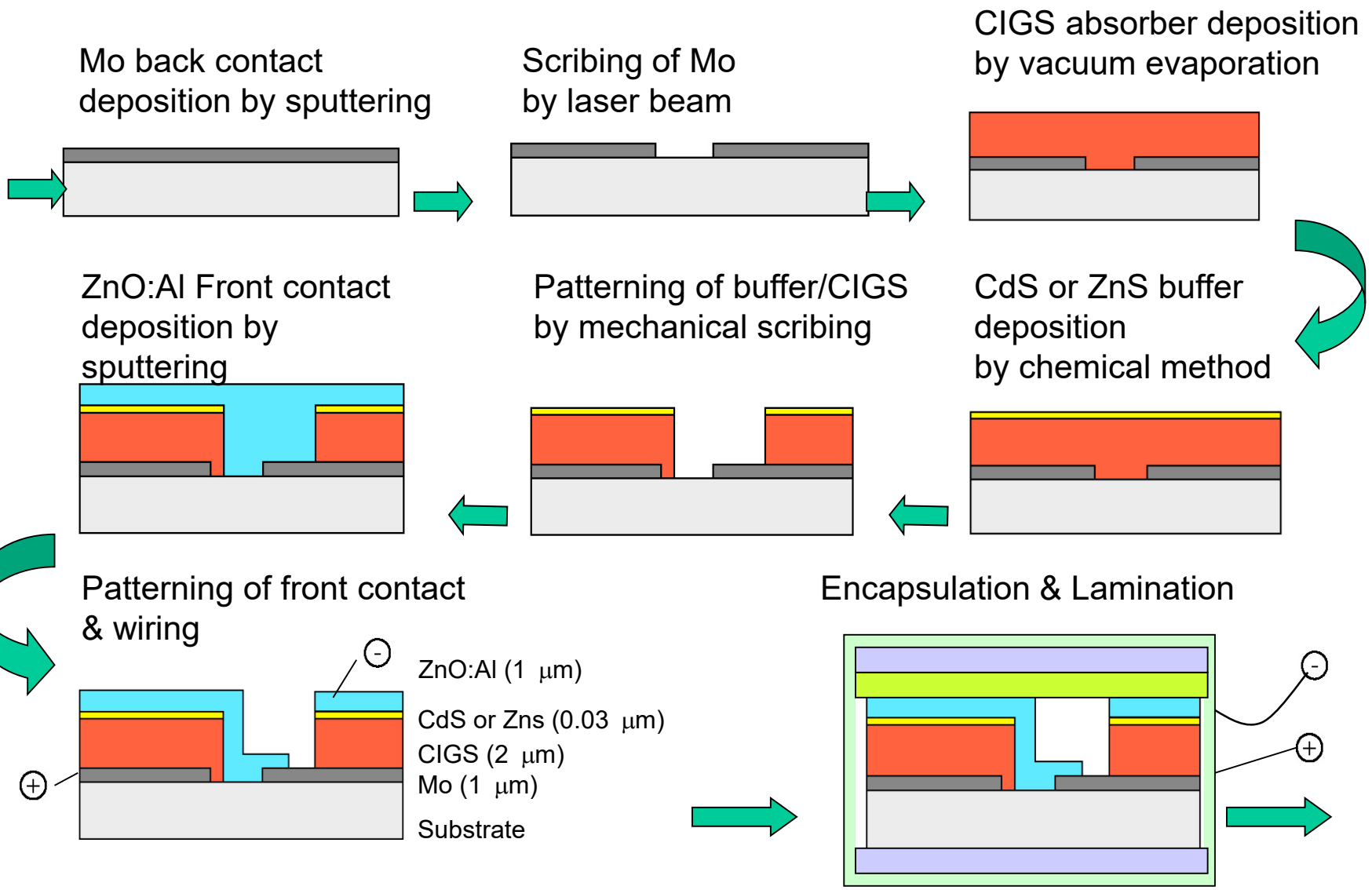




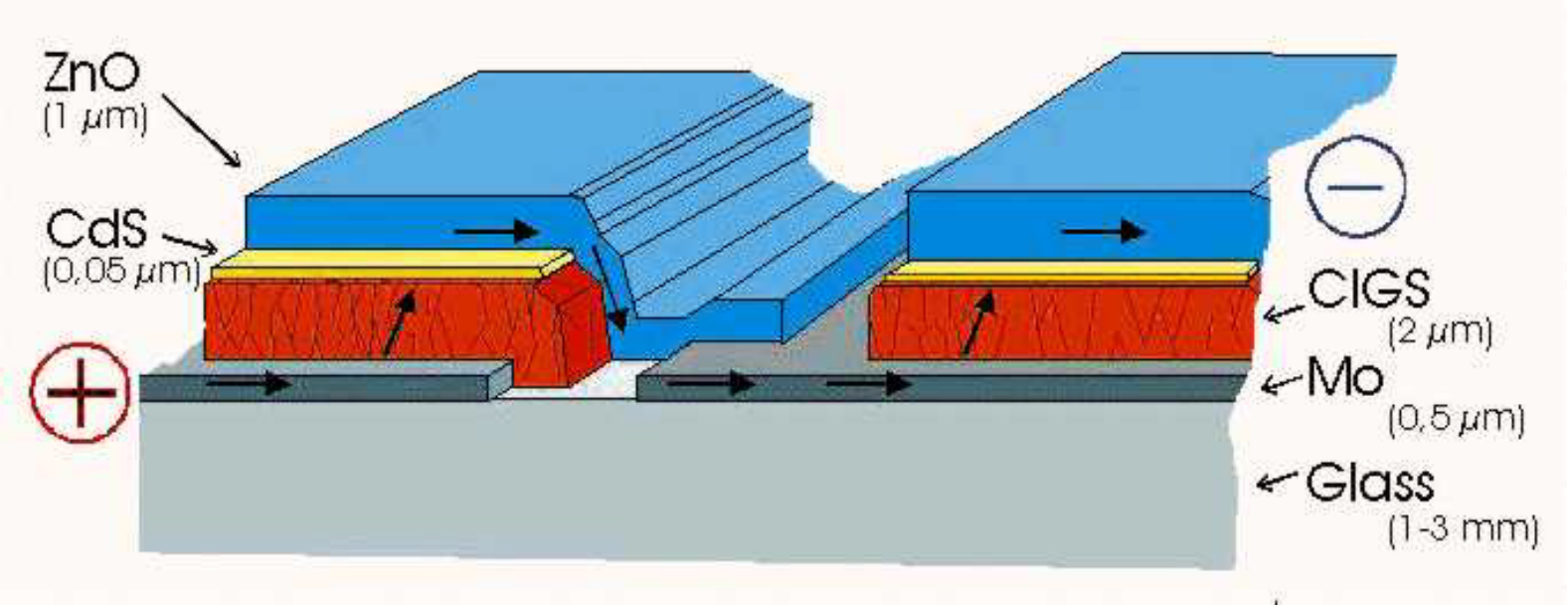
Operation of CIGS solar cell



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

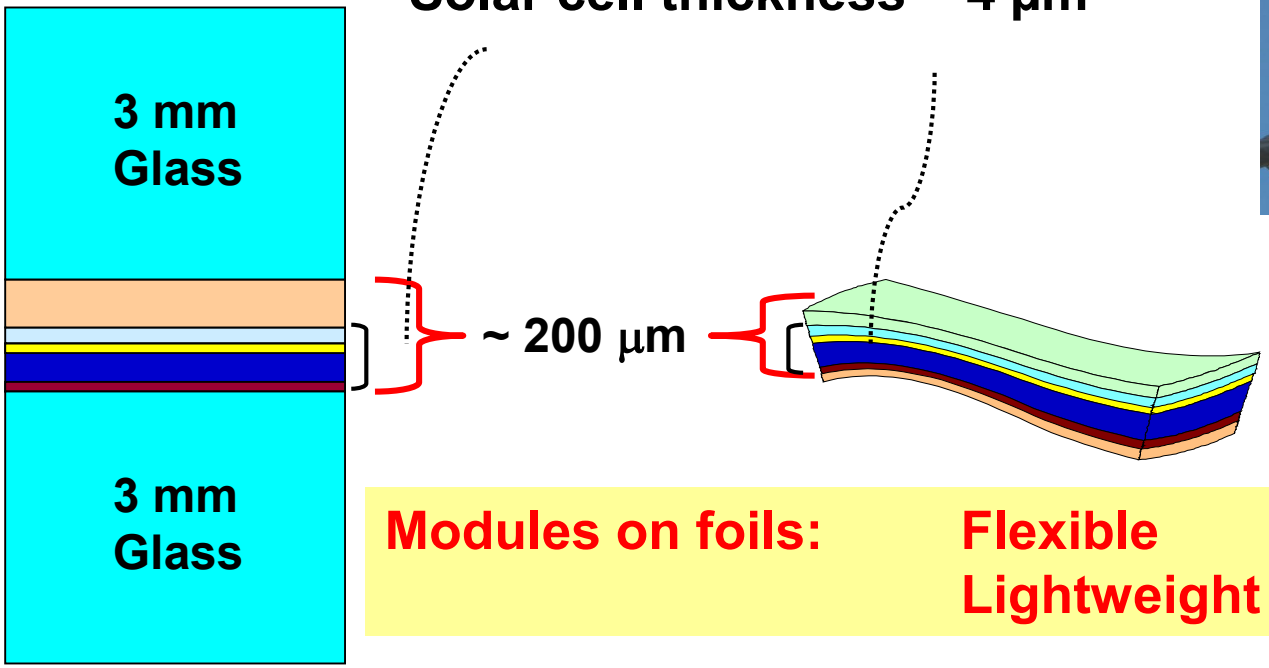
Solar Frontier

Flexible thin film solar modules

Mature technology

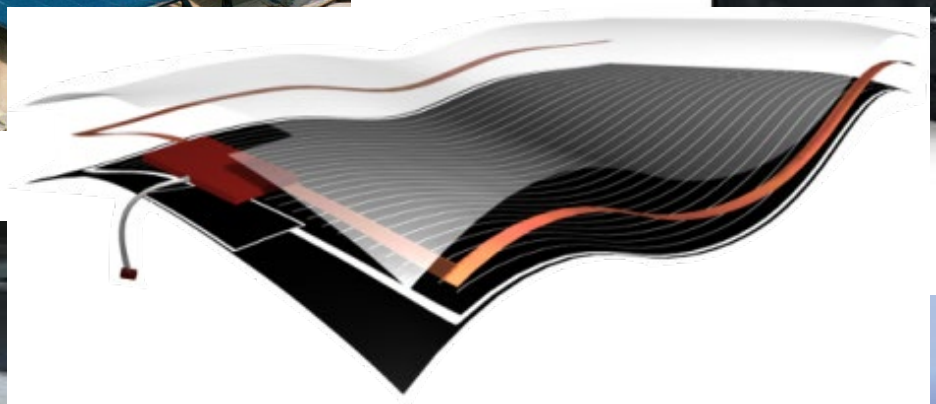
Emerging technology

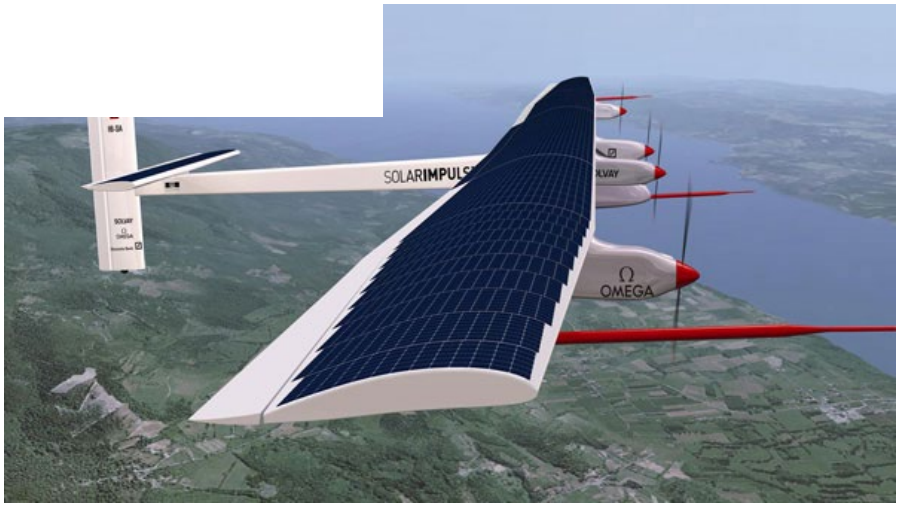
Solar cell thickness ~ 4 µm



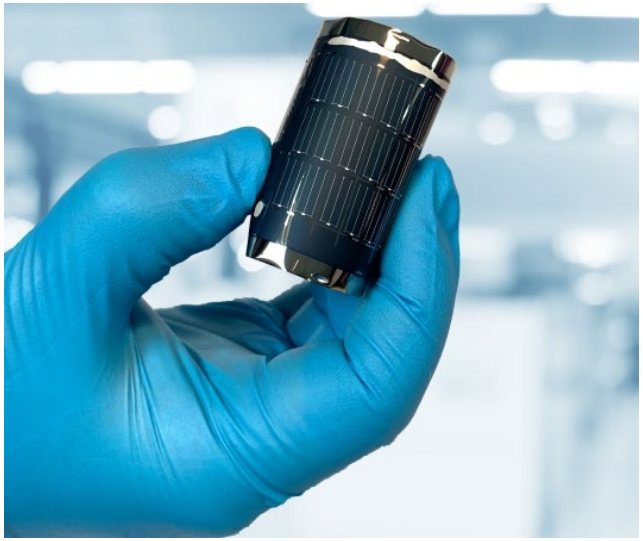
Modules on foils: **Flexible**
Lightweight

Targeted applications for flexible solar cells



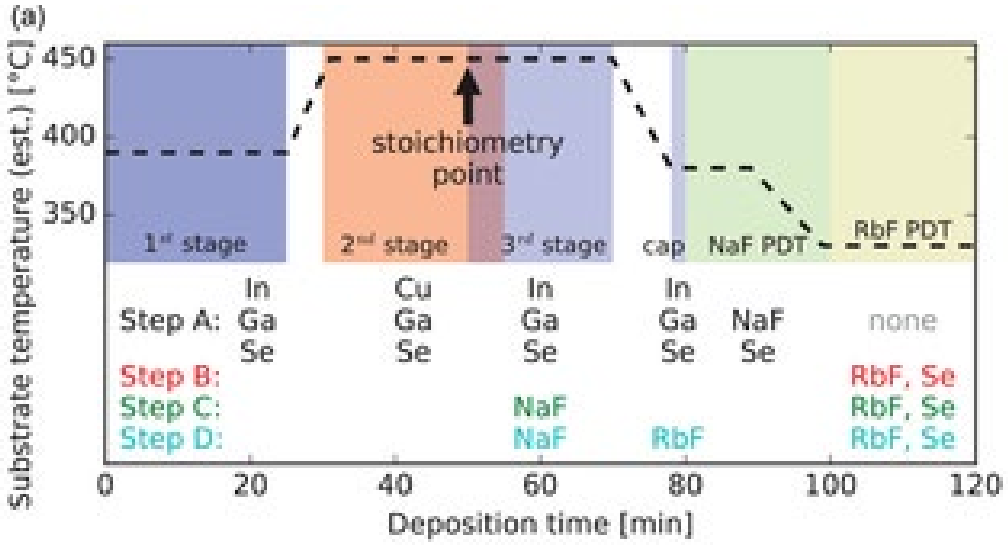


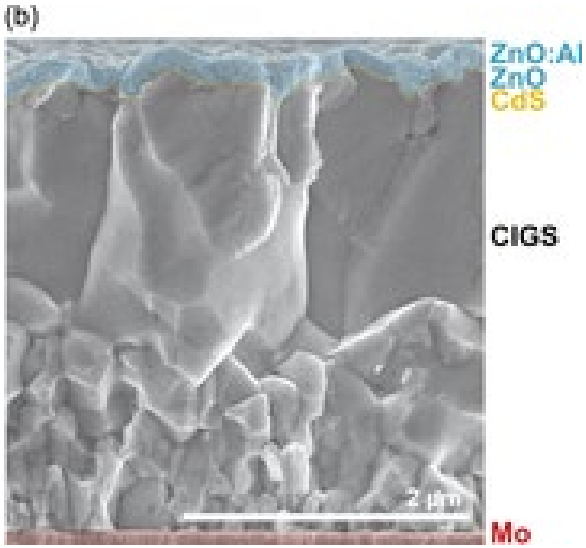
CIGS on flexible polymer substrate



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



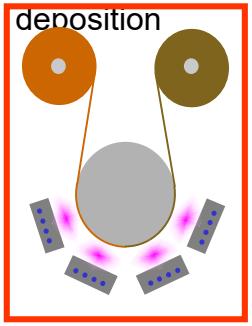


Adv. Energy Mater. 9 (2019) 1900408

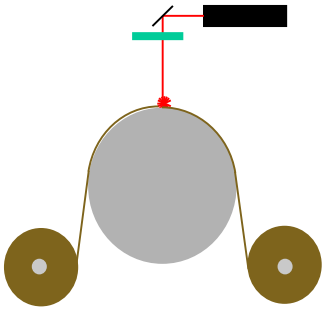
Roll-to-roll manufacturing

Flisom
Flexible Solar Modules

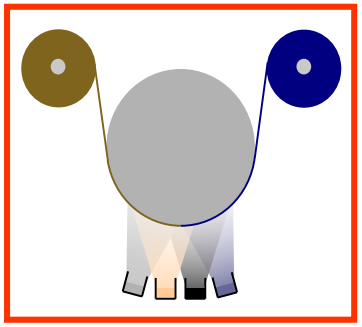
Back contact sputter deposition



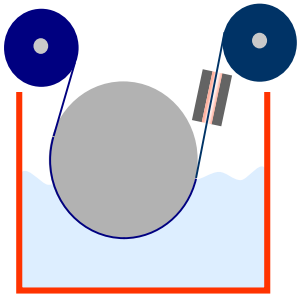
Laser scribing P1



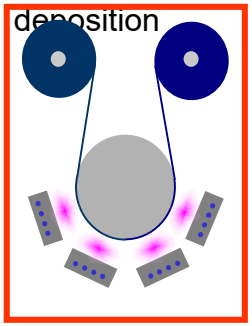
CIGS co-evaporation



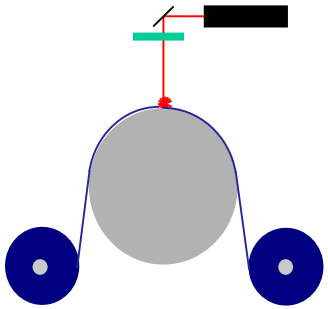
Buffer layer deposition by checmical bath



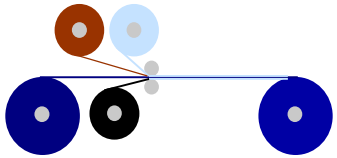
Front contact sputter deposition



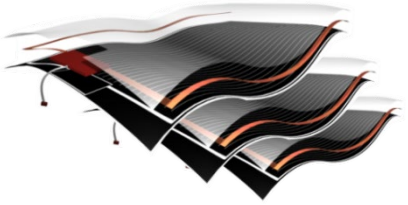
Laser scribing P2&P3



Contacts application Lamination



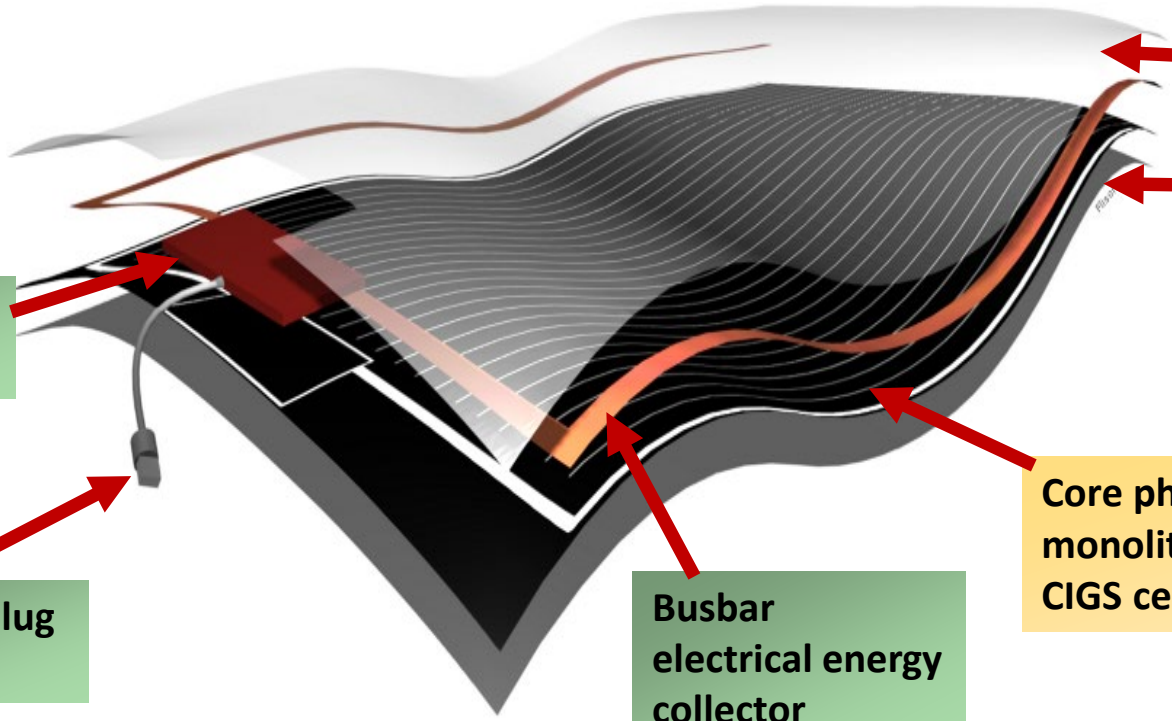
Module cutting Junction box and connector application



Flexible CIGS solar modules

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

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



Front & back glue and encapsulation sheets

Water vapour barrier

Junction box Bypass diodes

Standard plug connector

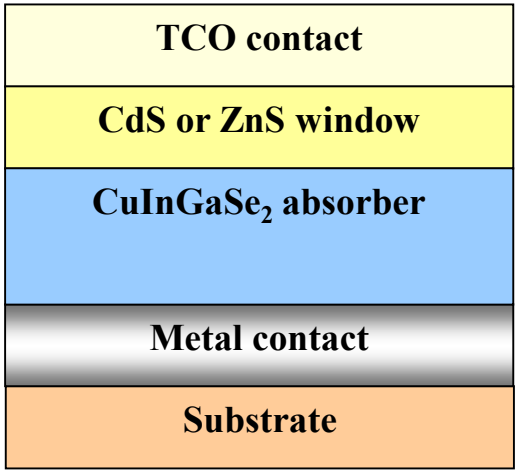
Busbar electrical energy collector

Core photovoltaic sheet of monolithic interconnected CIGS cells

Flisom
Flexible Solar Modules

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

Summary CIGS thin film technology

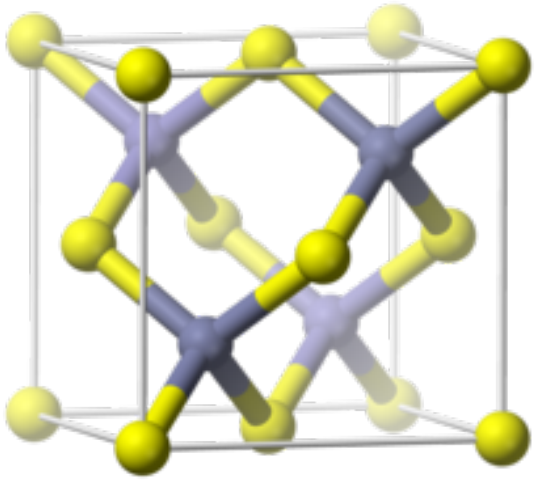


- Efficiency on various substrates:
  - 23.4% on glass (SolarFrontier, 2019)
  - 22.2% on flexible polymer foil (Empa, 2022)
  - 17.6% module efficiency (NICE Solar, 2019)
- Suited for BIPV and mobile applications

CdTe solar cells

CdTe material

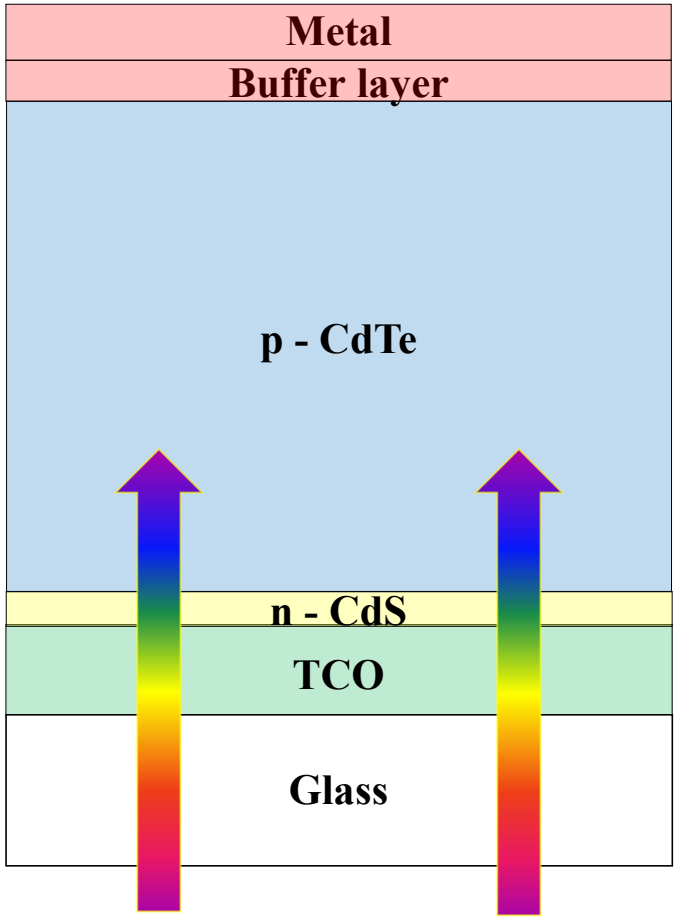
- Almost ideal energy band gap of 1.45 eV at room temp
- High absorption coefficient (1 μm CdTe absorbs >92% of the photons with energy above band gap)
- Simple growth of CdTe
- Chemically and thermally robust



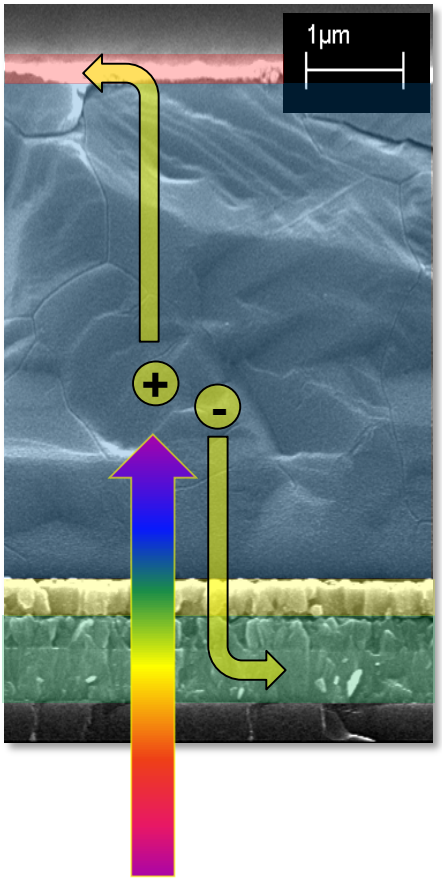
www.wikipedia.com

Structure of CdTe solar cells

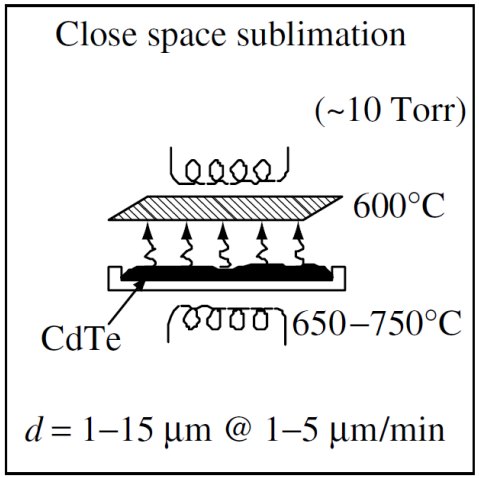
- Superstrate configuration is used for high efficiency CdTe cells:
- Substrate must be transparent (glass)

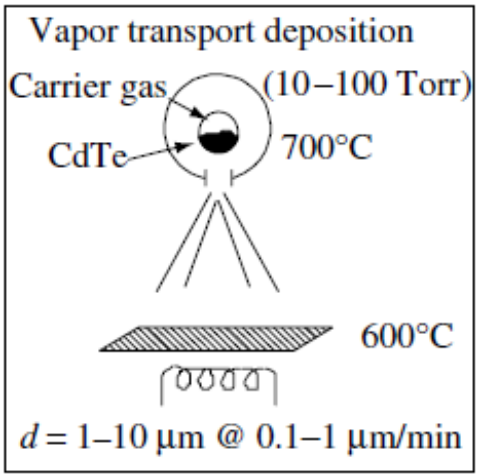


Back contact	**50 - 2000 nm**
Absorber	**2 - 10 µm**
Window	**30 - 500 nm**
Front contact	**0.5 - 1 µm**
Substrate	**1 - 3 mm**

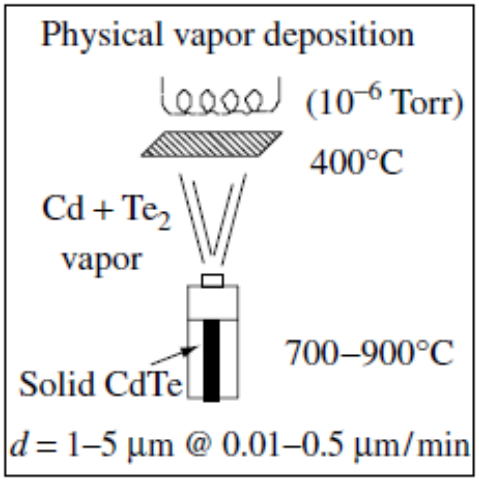


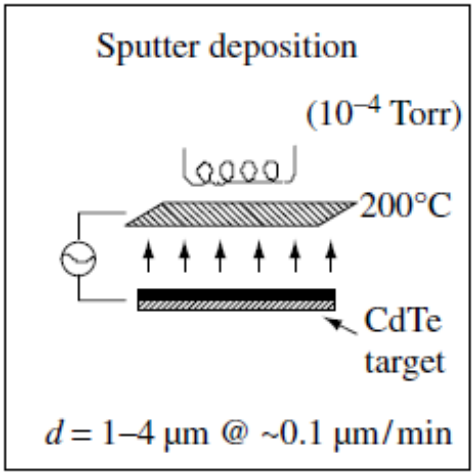
Deposition methods for CdTe





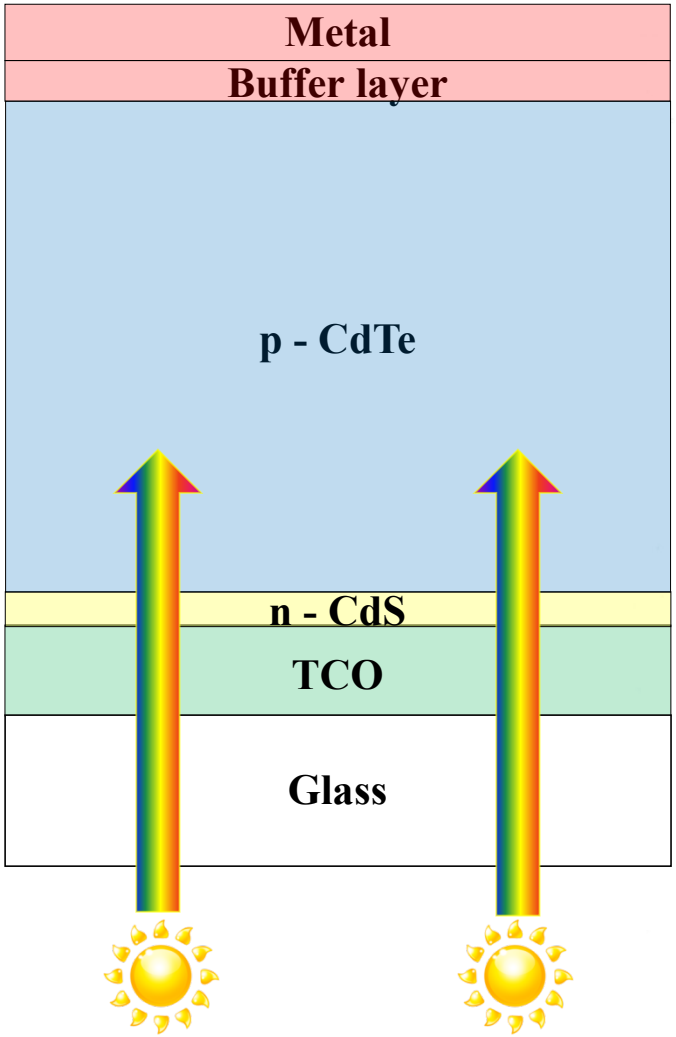
Vacuum techniques

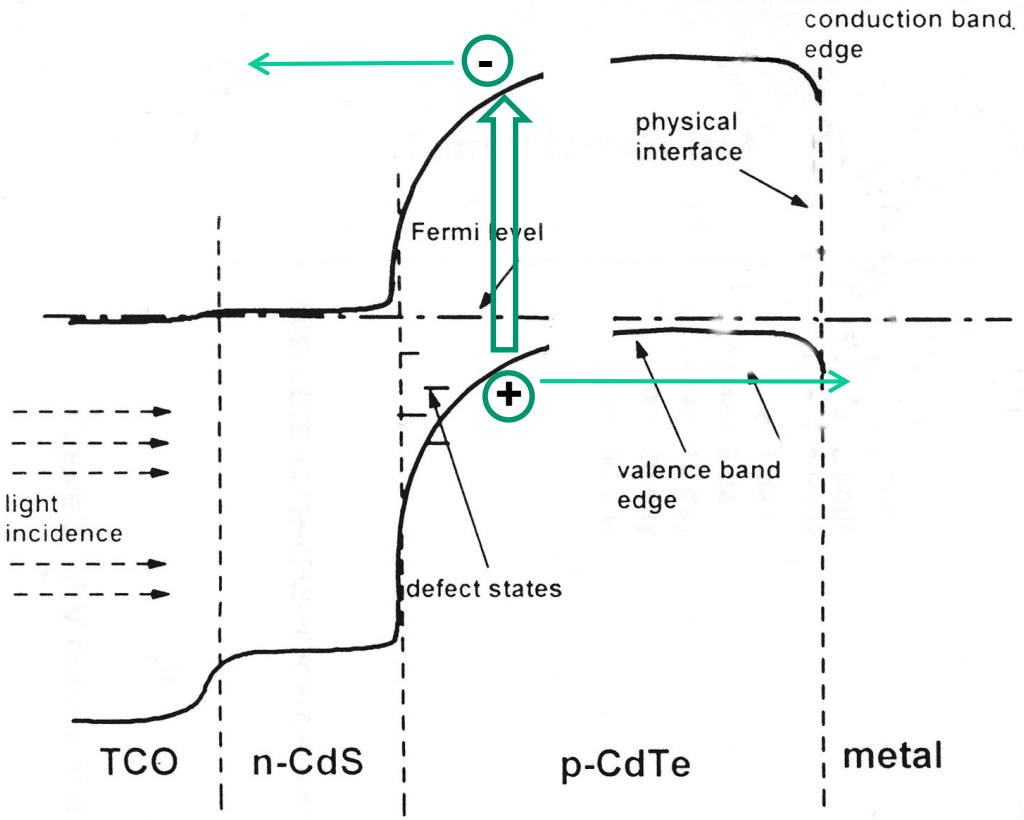




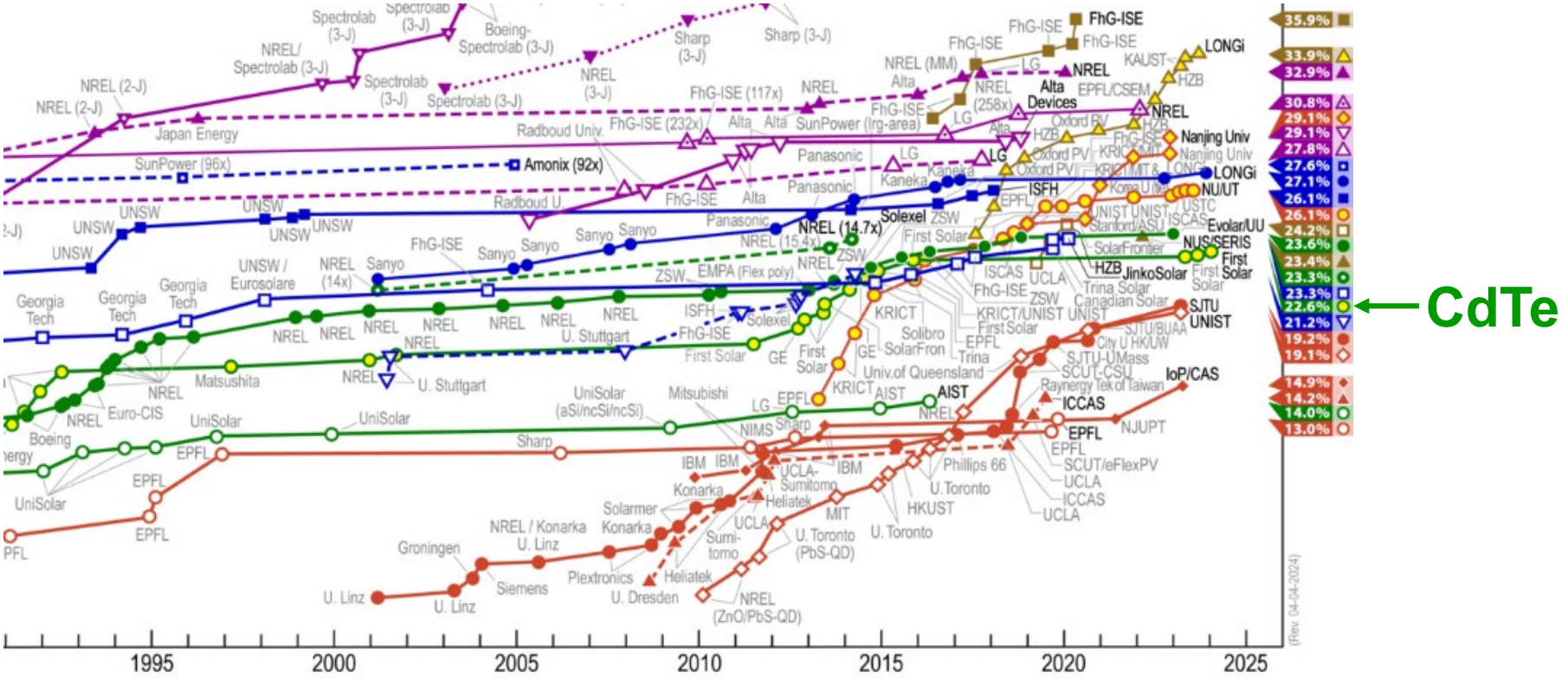
Handbook of Photovoltaic Science and Enginnering, 2011

Operation


Metal
Buffer layer
p - CdTe
n - CdS
TCO
Glass


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

Efficiency of CdTe solar cells



- Significant efficiency improvement from 16.7% to > 22 within 6 years thanks to competitive industrial research at FirstSolar and GE Global Research

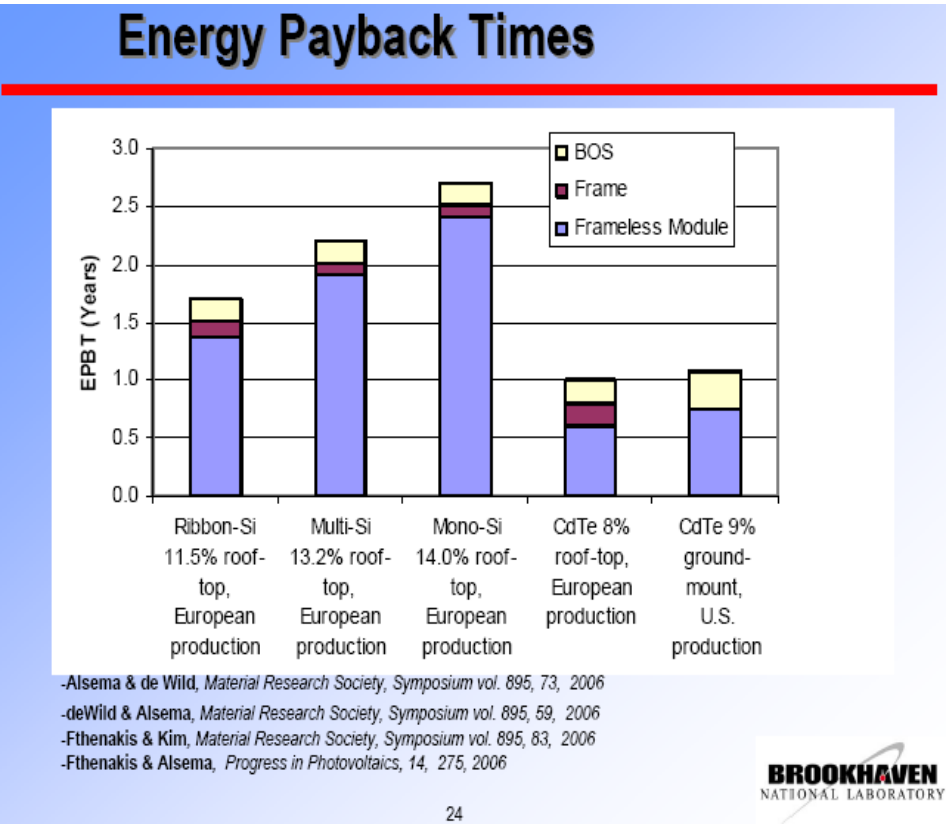
First Solar – the only CdTe company

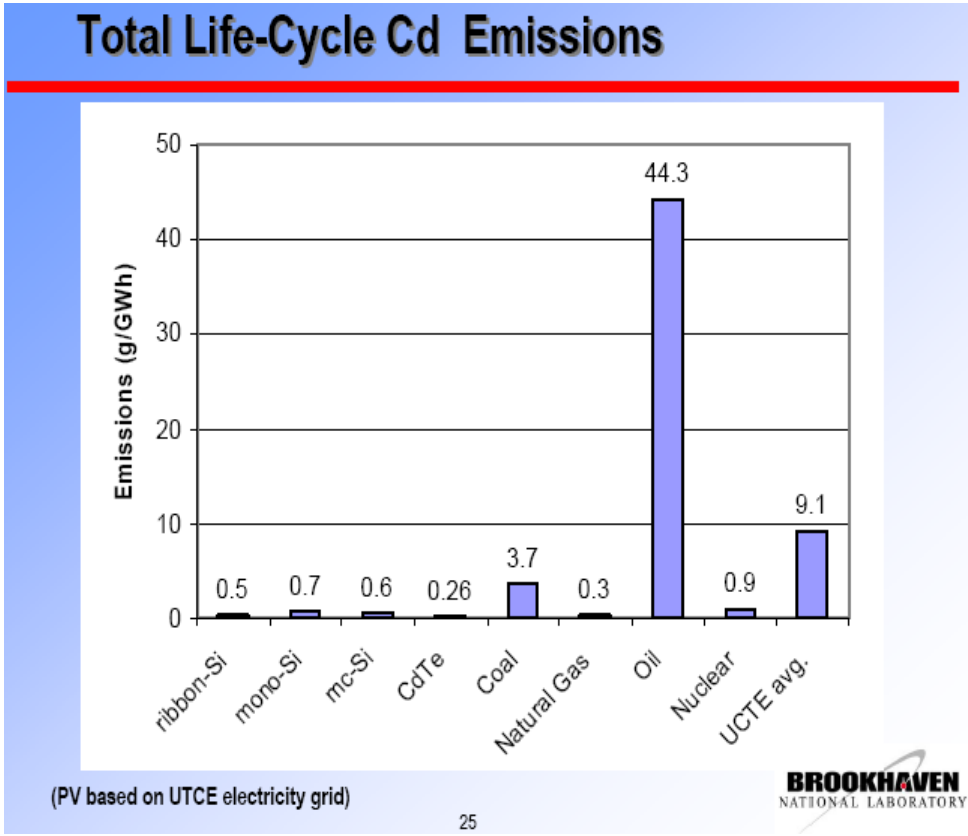
- More than 10 GW installed worldwide
- 30 manufacturing lines worldwide
w/ > 5 GW of annual manufacturing capacity
- 19.7% module efficiency (Series 7 modules)

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

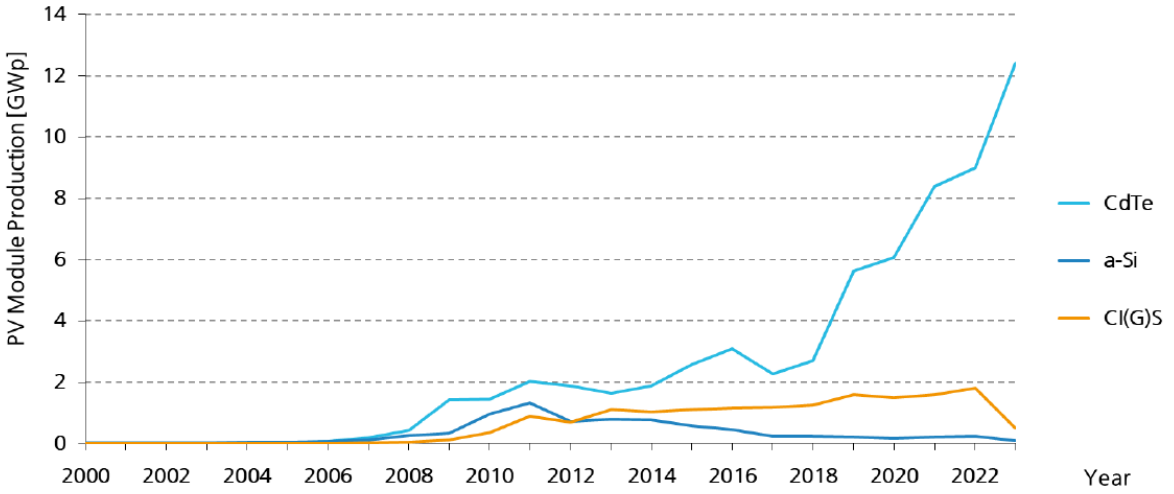
- CdTe solar cells are fabricated in **superstrate configuration**

- Maximum efficiency:

  22.1 % on glass (First Solar)

  18.6 % modules (First Solar)

- Highest market share among thin-film technologies



Photovoltaics Report, Fraunhofer ISE (May 2024)