"Solar Energy" WS 2021/2022

PV Technology:

Lecture 8: Inorganic Thin-film Solar Cells

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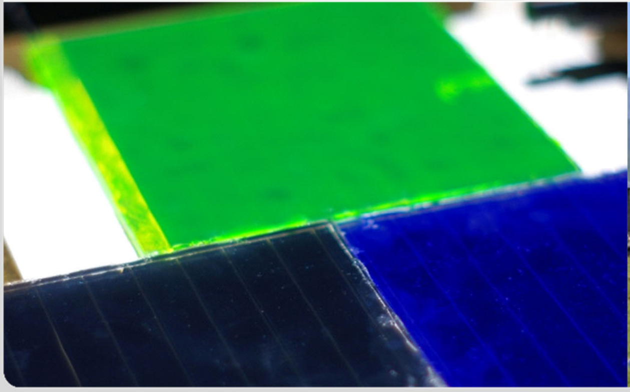


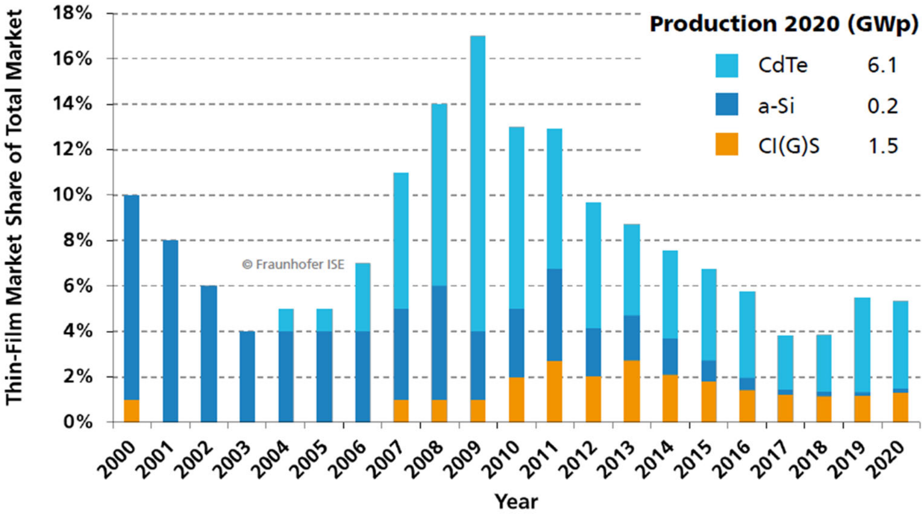
Thin Film PV

General motivation for thin-film PV:

- Technical:
  - Significant losses during wafering process
  - Solar cells end up inside a sheet of glass anyway, so why not use the glass as a substrate to deposit onto?
  - With good light trapping ⇒ don't need 200 μm of Si, 2 μm of semiconductor enough (even with Si)
  - Potentially higher throughput
- Marketing: More uniform product appearance
- Economic:
  - Very energy-intensive process growing MG-Si, and then either Cz c-Si or mc-Si ingots
  - Thus, can possibly have a cost advantage

PV Market Today

- Thin-film PV represents ~5% of global annual production
- Had largest market share in 2009 ± 2 years ⇒ years when there was a Si shortage
- Cadmium telluride (CdTe) clearly has largest share
- Copper indium gallium diselenide (CIGS) second
- Amorphous silicon (a-Si) PV market share shrinking



Source: *https://www.ise.fraunhofer.de/en/downloads-englisch/pdf-files-englisch/photovoltaics-report-slides.pdf*

Comparing Thin Film PV Modules

Photo: Manz

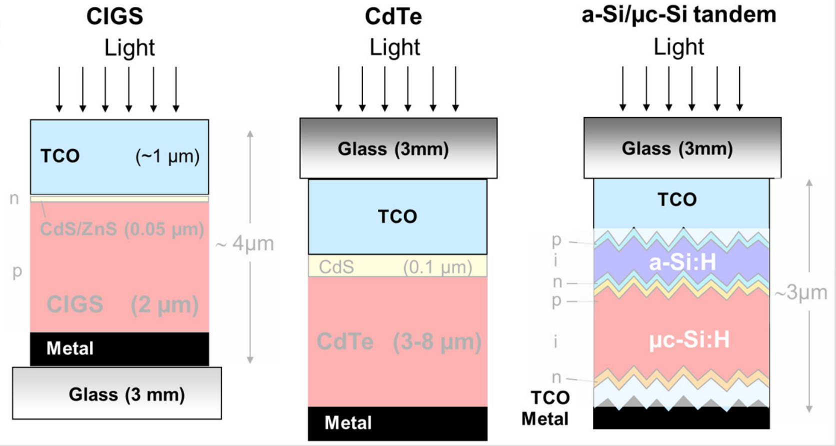
Photo: First Solar

Photo: Schott Solar

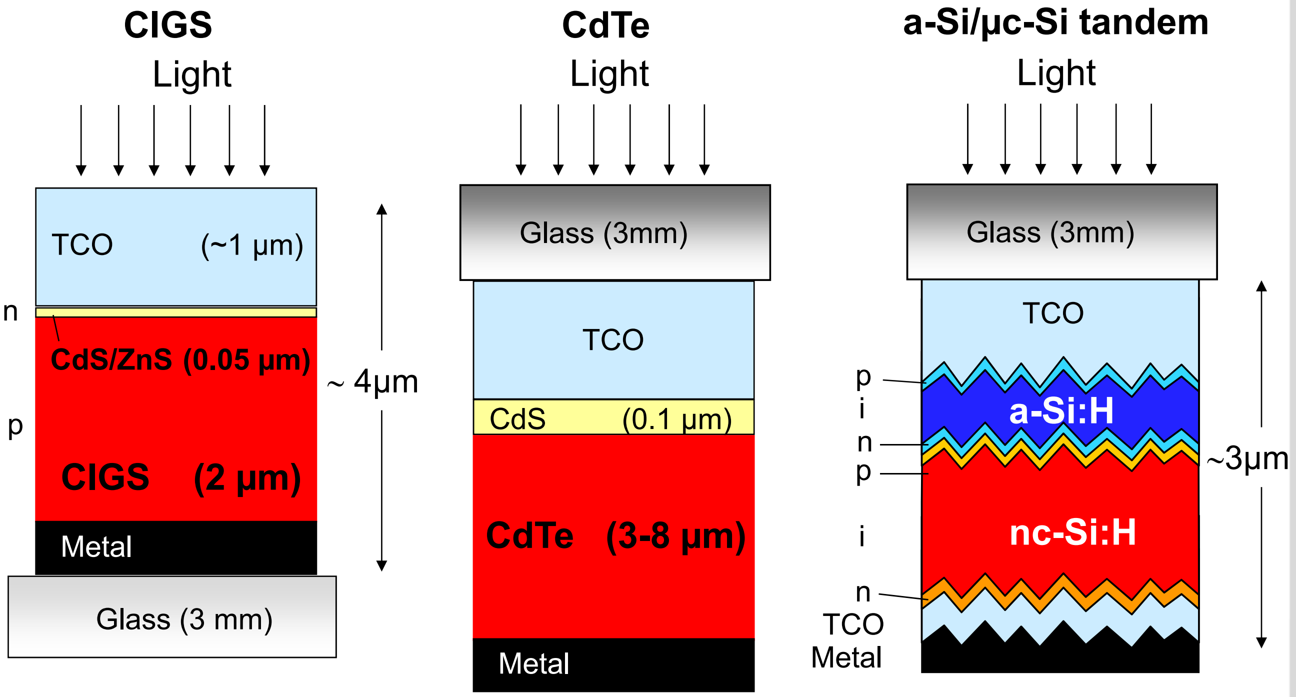
Comparing Thin Film Solar Cells

What do all thin-film PV devices have in common?

- Glass substrate (e.g. CIGS) or superstrate (e.g. CdTe, a-Si) – other materials also used, e.g. stainless steel, polymer foil
- Transparent conducting oxide (TCO) to extract current from the top-side of the device
- Thin absorber layers: 100nm – 5µm
- *pn* or *pin* junction
- Rear metal contact



Comparing Thin Film Solar Cells



$Cu(In_{1-x}Ga_x)(Se_{1-y}S_y)$

CdTe

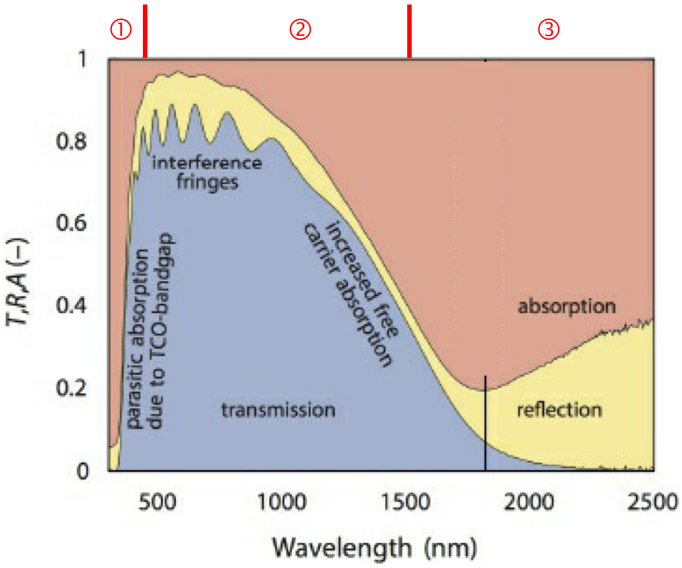
a-Si, a-Si/a-SiGe$_x$, a-Si/nc-Si

Transparent Conducting Oxides

- TCO layer has two roles:
  i) acts as electric front contact of solar cell
  ii) guides incident light to the active layers
- Thus, TCO needs to be both i) highly conductive and ii) highly transparent in the active wavelength range
- Typical TCO layers are made from:
  - fluorine-doped tin oxide (FTO, or SnO_2:F),
  - aluminium-doped zinc oxide (AZO, or ZnO:Al),
  - indium tin oxide (ITO) – mixture ~90% indium oxide (In_2O_3) and ~10% tin oxide (SnO_2)
  - hydrogen-doped (hydrogenated) indium oxide (In_2O_3:H)
- Films are deposited using such as sputtering (AZO, ITO), or chemical vapour deposition based techniques (others)

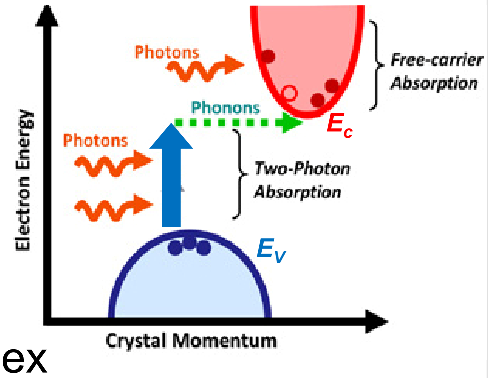
Transparent Conducting Oxides

- Typical transmission (*T*), reflection (*R*) and absorption (*A*) spectra of ZnO:Al layer – divided into three regions:
- ① at short λ, *T* is very low due to high absorption of light (energy greater than bandgap of TCO material)
- ② in this region, *T* is high ⇒ interference fringes can be used to estimate film thickness
- ③ in the NIR region *A* increases again ⇒ “free carrier absorption” (FCA)



Source: textbook

Transparent Conducting Oxides



- FCA: a material absorbs a photon and a carrier (e^- or h^+) is excited from an already-excited state to another unoccupied state in same band
- This intraband absorption is parasitic – not useful like interband absorption
- Material properties link to refractive index *n* and extinction coefficient *k* of TCO material
- With more metallic-like properties ⇒ *k* will increase ⇒ material exhibits both higher reflection and absorption
- TCO should be highly transparent in active region of absorber, but electrical properties of TCO improve when free carrier density is greatest

  ⇒ Trade-off between optical and electrical properties

Source: https://www.osa-opn.org/home/articles/volume_20/issue_6/features/green_silicon_photonics/

Transparent Conducting Oxides

- Of all commercial-scale TCOs, best performer is ITO
- However, indium is a rare element with a very low abundance of 0.05 ppm in Earth’s crust (similar to silver)
- Thus, less preferable for TW-scale PV
- Motivation to use other TCO materials, e.g. abundance of elements much better in AZO and FTO: aluminium 7.96%, zinc 65 ppm, fluorine 525 ppm, tin 2.3 ppm

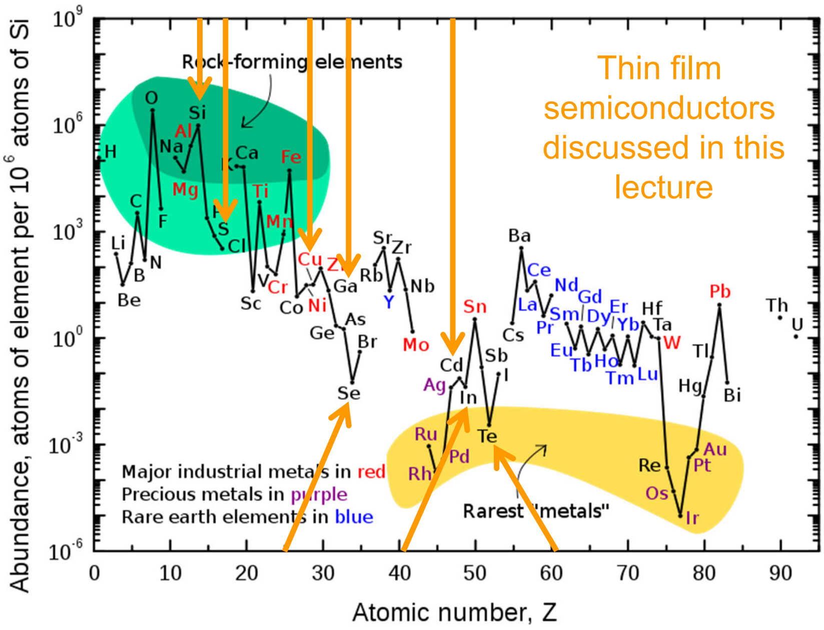
Materials Abundance

Many different semiconductors are used for thin-film solar cells

Some semiconductors require very rare elements, e.g. indium (In), selenium (Se), or tellurium (Te)

To realise TW-scale PV, solar cells should ideally be based on abundant elements

Also, ideally elements thatare potentially toxic (e.g. Cd) should also be avoided



Source: http://en.wikipedia.org/wiki/Abundance_of_the_chemical_elements

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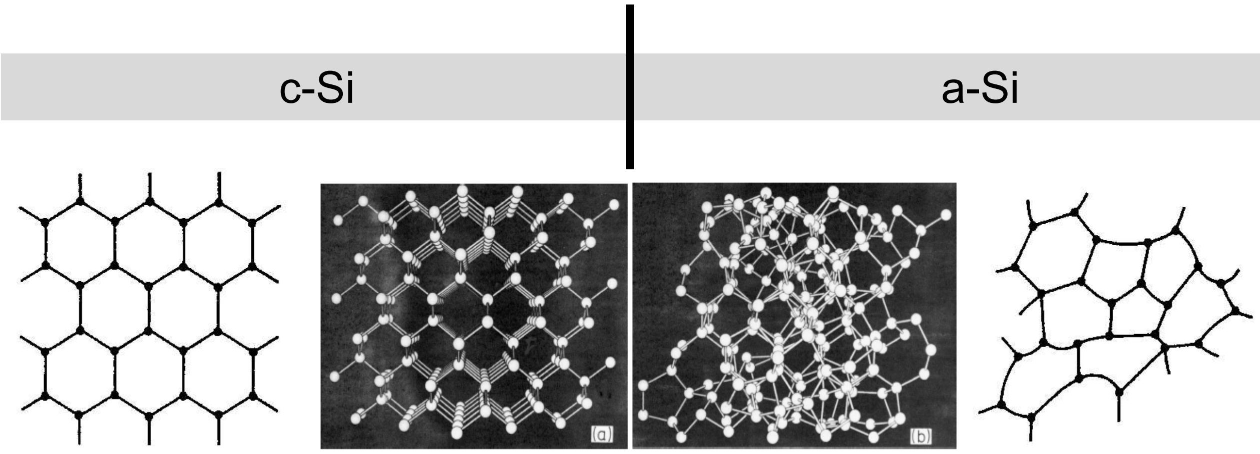
Amorphous vs Crystalline Silicon

“Amorphous” commonly refers to non-crystalline materials:

- chemical bonding of atoms nearly unchanged from crystals, e.g. Si still bonded to Si
- But small, disorderly variations in the angles between the bonds ⇒ eliminates regular lattice structure



a-Si:H Solar Cells

- First thin films of amorphous silicon (a-Si) layers deposited in 1965 using a silane (SiH_4) gas as precursor
- But took another 10 years to discover that a-Si actually had semiconducting properties
- Not recognized immediately that hydrogen plays very important role and that this is this actually an alloy of silicon and ~10% hydrogen
- Thus, electronic grade material is called **hydrogenated amorphous silicon (a-Si:H)**
- First successful a-Si:H solar cell with $\eta = 2.4\%$ was reported in 1976

a-Si:H Solar Cells

Back then, seemed promising technology due to:

i) a-Si:H has a direct bandgap
   ⇒ high absorption coefficient (α) in visible spectrum
   ⇒ 1 μm-thick a-Si:H layer can absorb 90% of above-bandgap solar energy

ii) PECVD technique allowed for production of a-Si:H films over >1m² area and at low-T (100–250°C)

   ⇒ low T enables use of low cost substrates, e.g. glass, metal or polymer foils

   ⇒ also opened up possibility of flexible PV modules

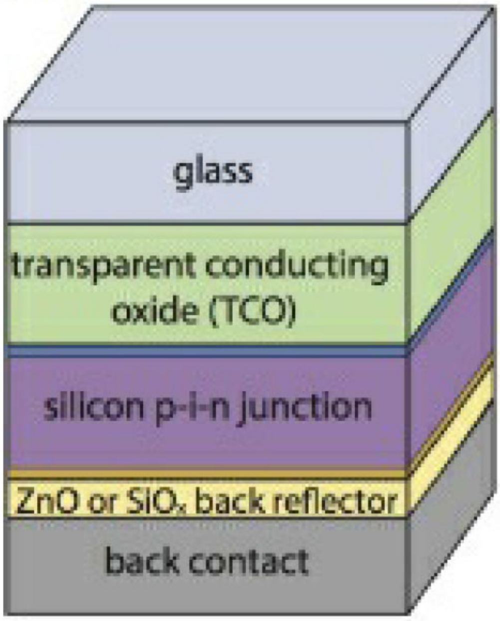
iii) Possibility of "bandgap engineering"

a-Si:H Solar Cells

- Compared to c-Si, a-Si:H films have a high amount of defects (~$10^{16}/\text{cm}^{3}$, c.f. below detection limit for c-Si)
- Due to the disordered structure, not all electrons able to bond with the neighbouring Si atoms ⇒ dangling bonds act as defects that limit the lifetime of the excited charge carriers
- SRH recombination ⇒ reduces diffusion length, L
- Due to high defect density, L in a-Si:H is only ~100nm (and even 2-3 orders of magnitude lower when *n*- or *p*-doped)
- Thus, cannot rely on diffusion for transport of charge carriers in thick a-Si:H absorber
- Therefore, a-Si:H devices are not based on a *p-n* junction like wafer-based c-Si solar cells

a-Si:H Solar Cells

- Instead, a-Si:H cells based on a *p-i-n* junction ⇒ thicker intrinsic *i* layer (undoped) sandwiched between very thin *p*- and *n*-doped layers
- Thicknesses:
  i-layer ~300nm thick, while *p*- and *n*-doped layers are only ~10 nm thick
- Between highly-doped *p*- and *n*-doped layers ⇒ built-in electric field across *i*-layer (absorber) created



Source: textbook

a-Si:H Solar Cells

- Remember: diffusion length, L_D:

$$L_D = \sqrt{D\tau} = \sqrt{\frac{\mu\tau k_B T}{q}}$$

(noting that both lifetime τ and mobilities μ are 50-1000x lower in a-Si:H compared to c-Si)

- Instead: drift length, $L_E \equiv$ average distance a carrier can travel with its drift velocity in an electric field E before it recombines

$$L_E = v_E\tau = \mu\tau\left|\vec{E}\right|$$

= 1μm assuming that we have a voltage drop of 1V over a 1μm absorber thickness (roughly what we have in a-Si:H solar cell), indicating that $\left|\vec{E}\right|=10^4$ V/cm

- In such a device, where electronic drift due to electric field is the dominant transport mechanism $\Rightarrow$ called a drift device

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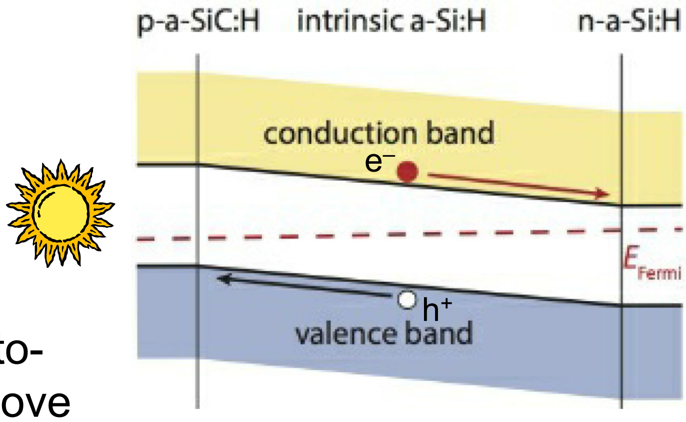
a-Si:H Solar Cells

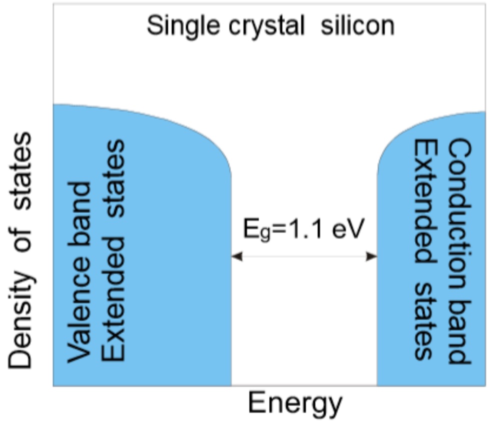


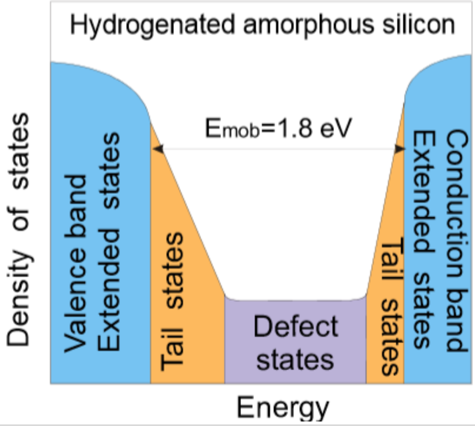
- Electronic band diagram : the slope in the intrinsic film reflects the built-in electric field
- Due to the electric field, photo-generated charge carriers move through the intrinsic layer
- h$^+$ move up slope in the valence band towards *p*-type layer, e$^-$ move down slope in conduction band towards the *n*-layer
- In *p*-layer, the h$^+$ are majority charge carriers $\Rightarrow$ dominant transport mechanism is diffusion (similarly for e$^-$ in *n*-layer) $\Rightarrow$ but due to short diffusion lengths, both *p*- and *n*-layers must be very thin

Source: textbook

a-Si:H Solar Cells

- a-Si:H has <u>direct</u> bandgap
  ⇒ thus high absorption ~10^5 cm^{-1}
- But bands are "smeared" due to band tails and defect states
  ⇒ no clear bandgap ⇒ thus often refer to “optical bandgap” vs. “electrical bandgap” (i.e. there might be absorption at longer λ but is it useful?)





Source: <u>http://ocw.tudelft.nl/fileadmin/ocw/courses/SolarCells/res00030/CH7_Thin_film_Si_solar_cells.pdf</u>

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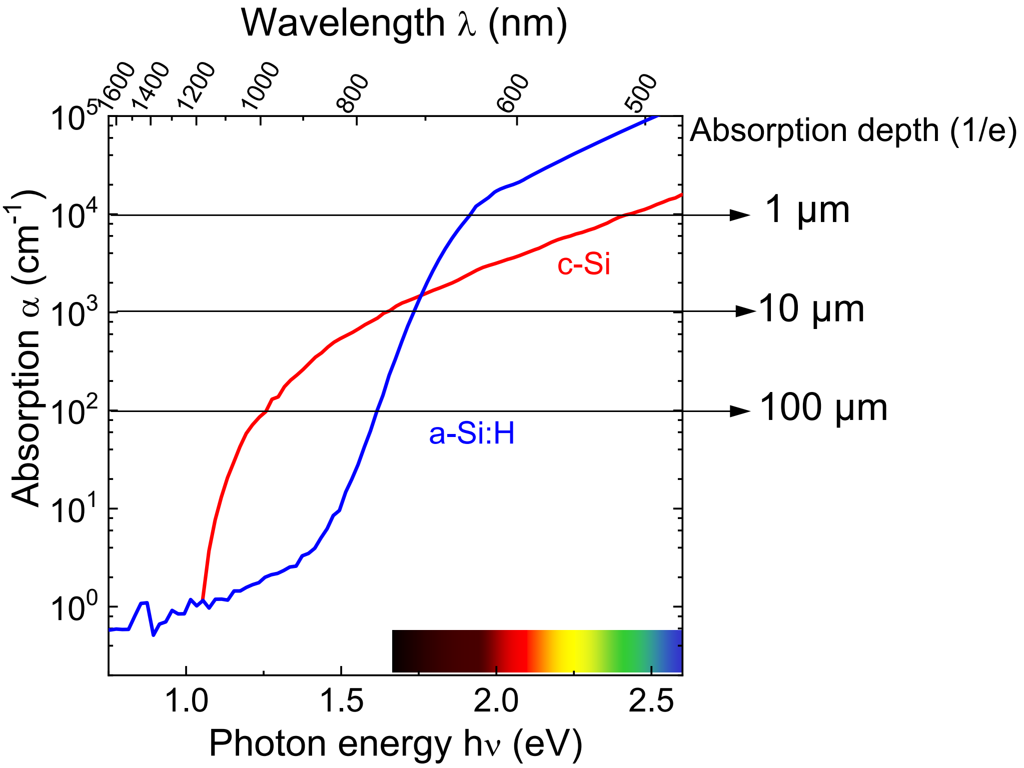
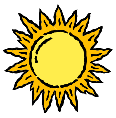
a-Si:H Solar Cells

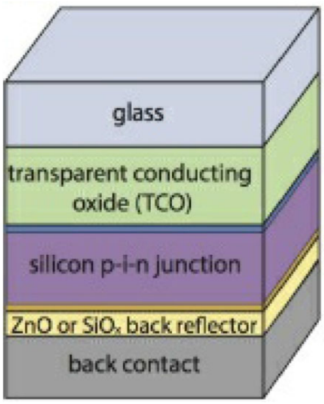


Source: Courtesy of FZJ – IEF 5

a-Si:H Solar Cells

- Cell deposited in <u>superstrate</u> configuration
- Means that light encounters the layers in order that they were deposited in production process
- When we talk about a “p-i-n device”, this also indicates the order of depositions
- Glass is typically used as superstrate because it:
  - i) is highly transparent;
  - ii) can handle the conditions during cell deposition;
  - iii) can be supplied pre-coated with a TCO;
  - iv) is cheap; and
  - v) serves as excellent mechanical and environmental protection of the solar cell.





Source: textbook

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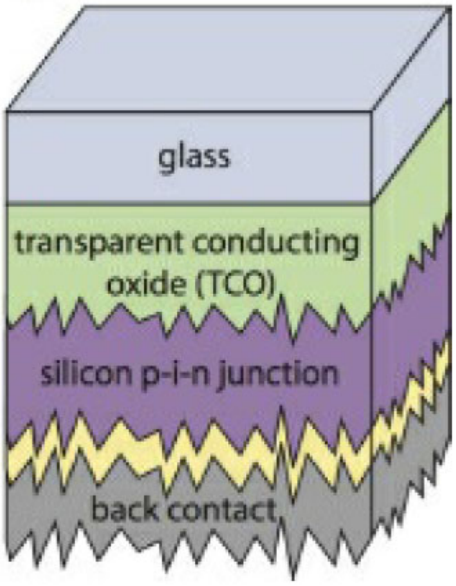
a-Si:H Solar Cells

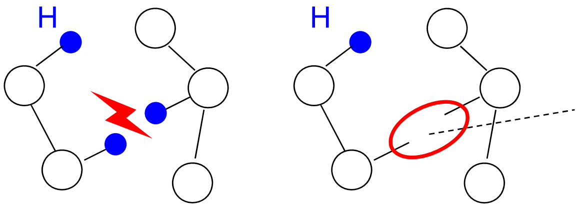


- Typically, a-Si:H solar cells are not planar devices $\Rightarrow$ instead are deposited on nanotextured TCO
- Textured TCO scatters incident light $\Rightarrow$ helps increase average pathlength of photons $\Rightarrow$ increase amount of light absorbed without increasing the thickness of absorber layer $\Rightarrow$ higher $J_{sc} \Rightarrow$ higher η (N.B. similar motivation for pyramid texture in c-Si)
- E_g of a-Si:H is ~ 1.75 eV $\Rightarrow$ V_{oc}’s ~1.0V $\Rightarrow$ limited by high levels of SRH recombination
- Only absorbs λ < 700 nm $\Rightarrow$ highest J_{sc}’s achieved in single-junction a-Si:H device ~ 17–18 mA/cm^2 at average EQE ~75%

Source: textbook

a-Si:H Solar Cells

- Light-induced degradation (Staebler–Wronski effect, SWE) ⇒ biggest challenges for a-Si:H thin-film solar cells
- Mechanism: recombination of light-excited charge carriers uses energy to break weaker bonds and creates metastable defects in absorber layer ⇒ forms dangling bonds, that lie within the bandgap ⇒ increased defect density leads to increased recombination ⇒ lower η



2 non-passivated or “dangling” bonds result

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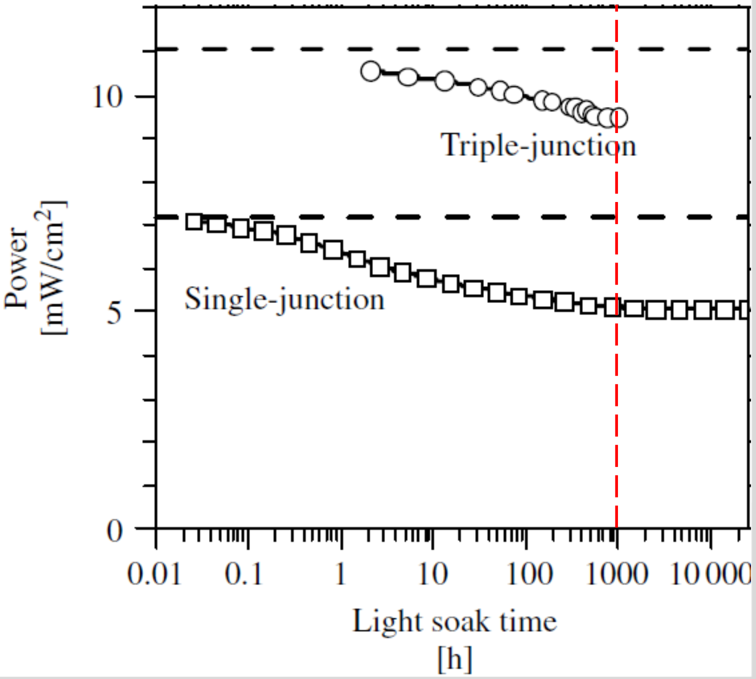
a-Si:H Solar Cells

- SWE: after ~1000 hours of illumination, η stabilizes at 80–85% of initial η value and then remains stable
- Effects can be somewhat minimized but never avoided completely
- Highest <u>stabilized</u> single-junction lab-scale solar cell η = 10.1% (Oerlikon Solar, Switzerland)
- a-Si:H modules η more typically 3 – 4%



Source: “Amorphous Silicon-based Solar Cells” by Deng and Schiff (2002), in *Handbook of Photovoltaic Science and Engineering*, edited by A. Luque and S. Hegedus

a-Si:H Solar Cells

Bandgap Engineering:

- Alloying of Si with elements, such as Ge and C, can be realised during thin film deposition
- Inclusion of C in a-Si:H increases E_g (~2.0 eV for a-SiC:H)
- Inclusion of Ge in a-Si:H decreases E_g (~1.0eV for a-Ge:H)
- Resulting alloys have wide range of bandgaps

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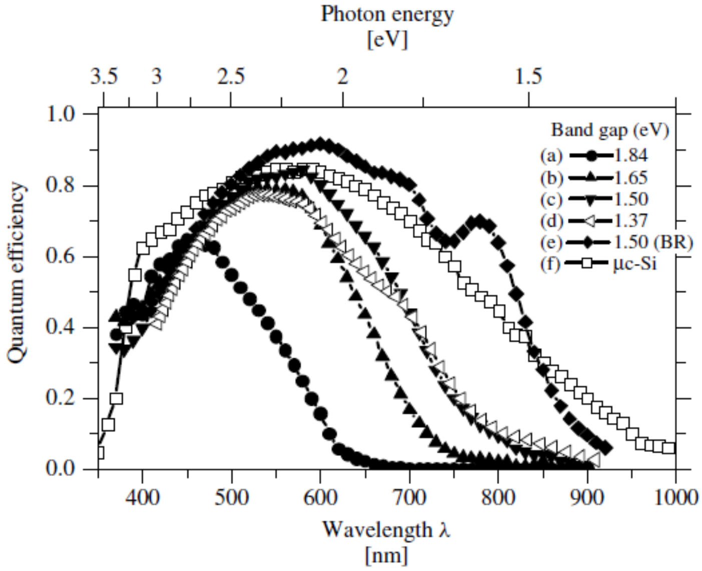
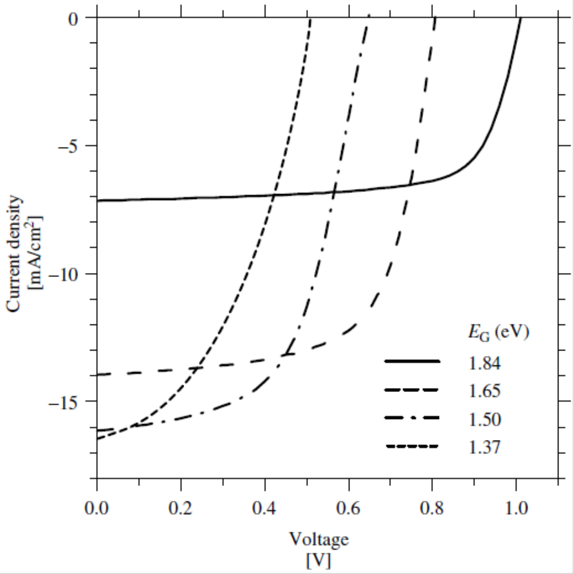
a-Si:H Solar Cells

- E.g. a-Si:H (1.84 eV) vs devices made from a-SiGe:H mixtures
- Increased Ge content ⇒ lower E_g ⇒ longer EQE response ⇒ higher currents ⇒ lower voltages

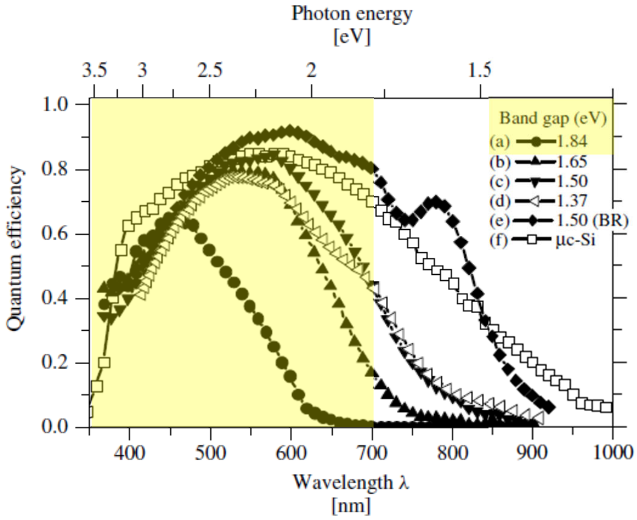


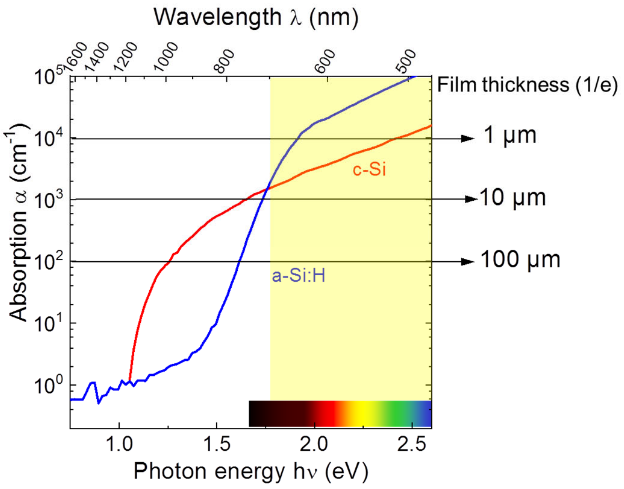


Source: "Amorphous Silicon-based Solar Cells" by Deng and Schiff (2002), in *Handbook of Photovoltaic Science and Engineering*, edited by A. Luque and S. Hegedus

a-Si:H Solar Cells

- Reminder: not all absorption is useful
- e.g. optical absorption data of a-Si:H looks like it should respond to 1100nm light, but electrically the solar cell does not respond to light with λ > 700nm





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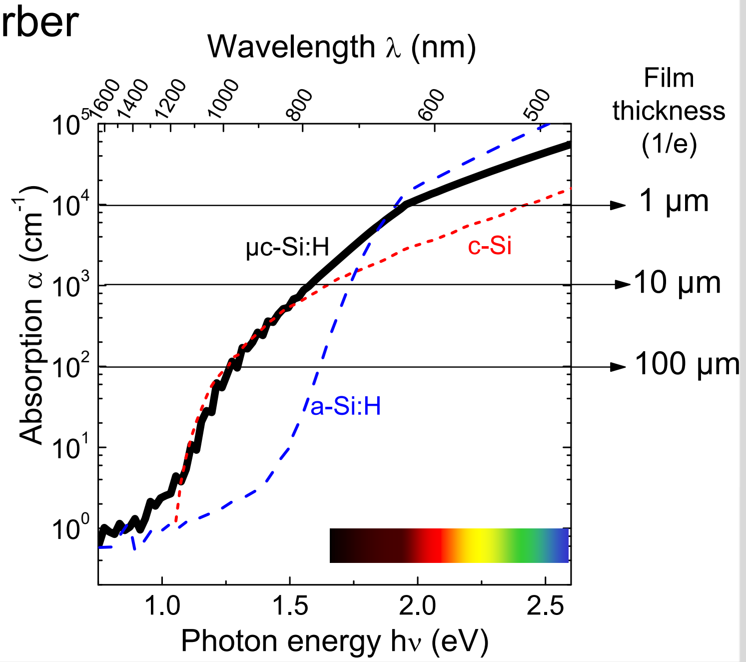
a-Si:H Solar Cells

Bandgap Engineering:

- Also, hydrogenated micro- (μc-Si:H) and nanocrystalline silicon (nc-Si:H) as possible absorber
- Also suffers less from SWE
- Bandgap similar to c-Si and also indirect
- But to harvest >700nm range (where a-Si:H responds poorly), thicker films (1 – 3 μm) and light-trapping required



Source: Courtesy of FZJ – IEF 5

a-Si:H Solar Cells

Multijunction (also called tandem) solar cells:

- Multijunction solar cell approach allows for absorbing a wider range of photons ⇒ stack higher bandgap a-Si:H solar cell on top of lower bandgap a-SiGe:H or nc-Si:H
- Solar cell with the highest bandgap is used as a top cell that converts the most energetic photons into electricity, while the lower bandgap material is used for the bottom cell and converts the lower energetic photons
- Add voltages of the two solar cells together
- The current is determined by the minimum current flowing in each device ⇒ thus tandem solar cells require "current matching" *(discussed in more detail in tandems lecture)*

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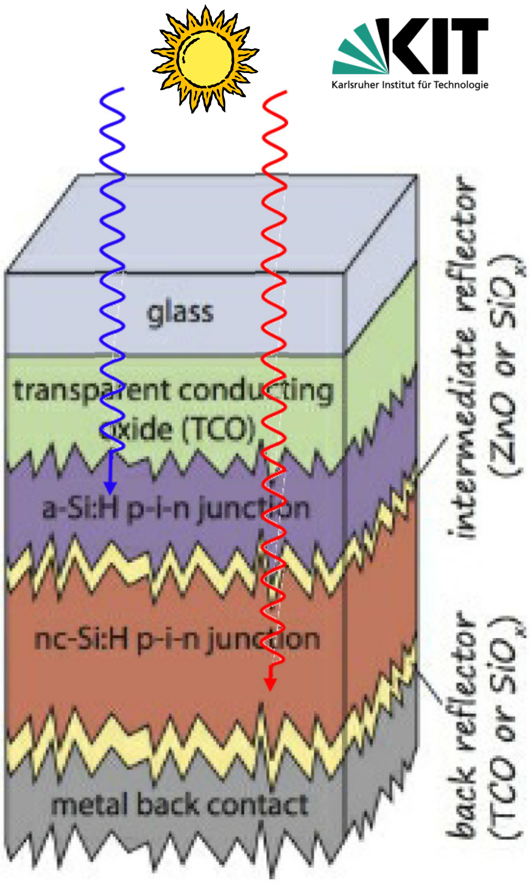
a-Si:H Solar Cells

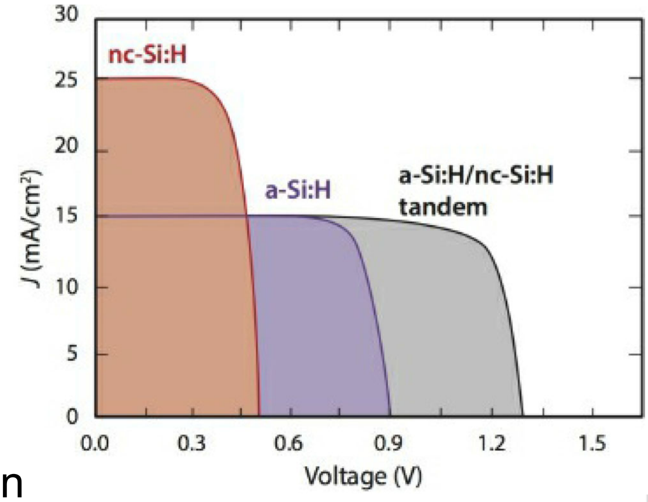
- With a-Si:H can have double- and triple-junction devices
- Common device was "micromorph" solar cell ⇒ with a-Si:H top cell and nc-Si:H bottom cell
- Blue and green short-λ light is absorbed in top cell, generating e^--h^+ pairs, while longer-λ (red and NIR) light is absorbed in bottom cell, also generating e^--h^+ pairs



Source: adapted from textbook

a-Si:H Solar Cells

- Total current density = that of junction with the lowest current density ⇒ optimized multijunction cell
  ⇒ current densities in each subcell have to be matched
- a-Si:H: V_{oc} = 0.9 V
  J_{sc} = 15 mA/cm^2
- nc-Si:H: V_{oc} = 0.5 V
  J_{sc} = 25 mA/cm^2
- a-Si:H/nc-Si:H tandem:
  J_{sc} ~ 15 mA/cm^2
  V_{oc} of bottom cell will be slightly lower than for each single junction cell as $V_{oc} \propto \ln(J_{ph}/J_0)$



Current record double-junction has η = 12.3% (Kaneka)

Source: textbook

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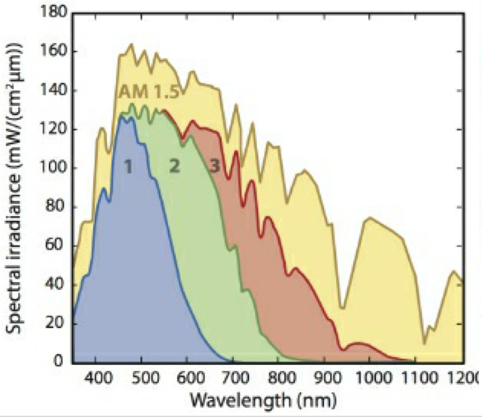
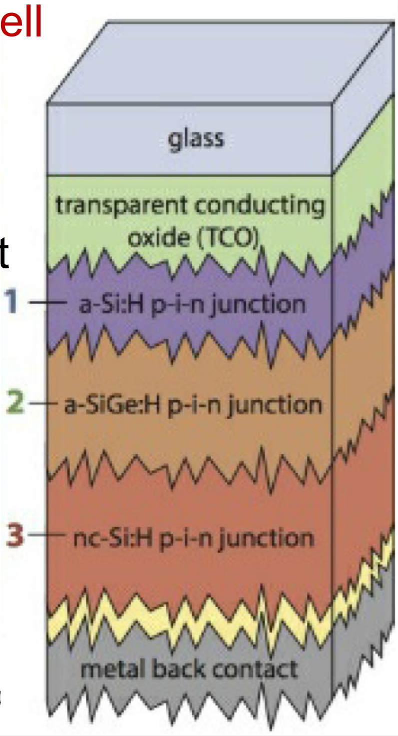
a-Si:H Solar Cells

- United Solar Ovonic triple-junction devices: **1**) a-Si:H top cell; **2**) a-SiGe:H middle cell; **3**) nc-Si:H bottom cell
- Significant overlaps between EQE spectra ⇒ optimising thin-film multijunction solar cells ⇒ complex interplay between various absorber thicknesses and light management concepts
- Optimise under AM1.5G standard spectrum…?

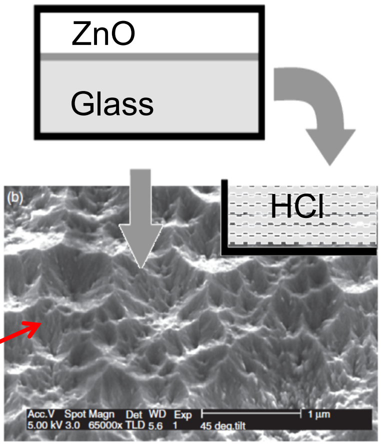
Highest initial cell $\eta = 16.3\%$ (η ~12% stabilized, η ~7% module)





Source: textbook

a-Si:H Solar Cells



Fabrication steps for single-junction *pin* a-Si:H superstrate technology:

1. Glass cleaning (abrasive + washing)
2. Front contact:
   - sputtering of 50nm SiO_2 (as Na diffusion barrier)
   - deposition ~600nm TCO (can be ITO, FTO, **AZO** - last two can be textured)
3. Structuring of front contact (laser patterning and wet chemical cleaning)
4. 10-20 nm *p*-type a-Si:H
   300-500 nm *i*-type a-Si:H
   10-20 nm *n*-type a-Si:H

   pin junction deposited using PECVD with SiH_4 + H_2 gases, along with diborane (B_2H_6) for *p*-doping and phosphine (PH_3) for *n*-doping
5. Sputtering of back Al contact (or evaporation)
6. Laser welding of contact strips
7. Testing

N.B. This describes fabrication of a solar cell, but thin-film PV usually deposited as a module directly ⇒ covered in PV module lecture

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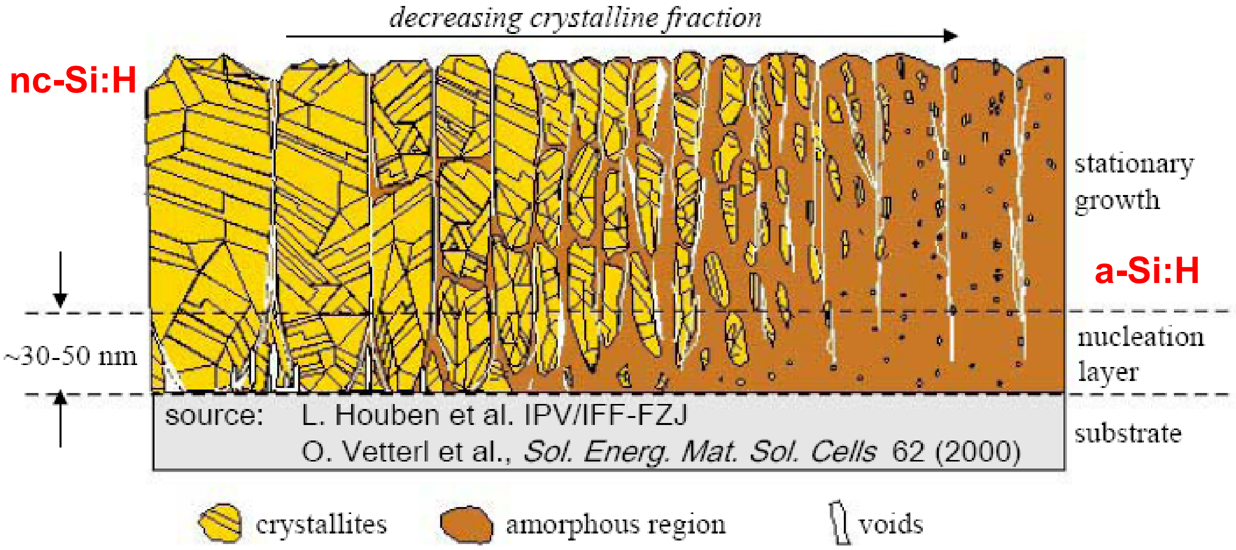
a-Si:H Solar Cells

- PECVD used for deposition of both a-Si:H and nc-Si:H – just vary deposition parameters (temperature and H_2 ratio)

influence of deposition parameters: silane concentration, power, frequency, temperature, ...



source: L. Houben et al. IPV/IFF-FZJ
O. Vetterl et al., *Sol. Energ. Mat. Sol. Cells* 62 (2000)

Thin-Film Crystalline Si Solar Cells

Why not use crystalline silicon for thin-film PV?

- Non-toxic and earth abundant material (unlike In, Cd, Te, etc)
- Doesn’t degrade like hydrogenated amorphous silicon (a-Si:H)
- Thin films made of very small-grained material, called microcystalline silicon (μc-Si) – but no hydrogen
- Still indirect bandgap material ⇒ light absorption challenging
- Complex device processing, high-T processes needed
- Never achieved $\eta > 10\%$ for full-size (~$1 m^2$) modules

Source: http://www.pressebox.de/pressemitteilung/csg-solar-ag/Dr-Ottmar-Koeder-wird-neues-Vorstandsmitglied-fuer-den-Bereich-Produktion-der-CSG-Solar-AG/boxid/186646

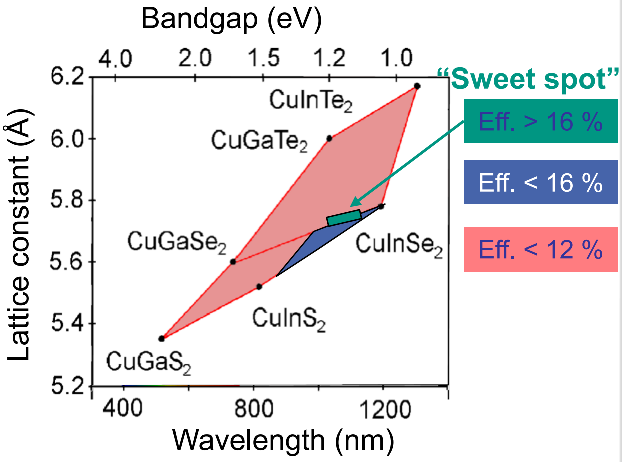
CIGS solar cells

- Chalcogenides include semiconductors containing elements S, Se or Te
  - Copper indium gallium selenide (CIGS)
  - Cadmium telluride (CdTe)

$$\begin{pmatrix} Cu \\ Ag \\ Au \end{pmatrix} \begin{pmatrix} Al \\ Ga \\ In \end{pmatrix} \begin{pmatrix} S \\ Se \\ Te \end{pmatrix}$$

- Change In:Ga ratio x and Se:S ratio y ⇒ tune bandgap of CI(G)S from 1.0 – 1.7 eV: $Cu(In_x Ga_{1-x})(Se_y S_{1-y})_2$

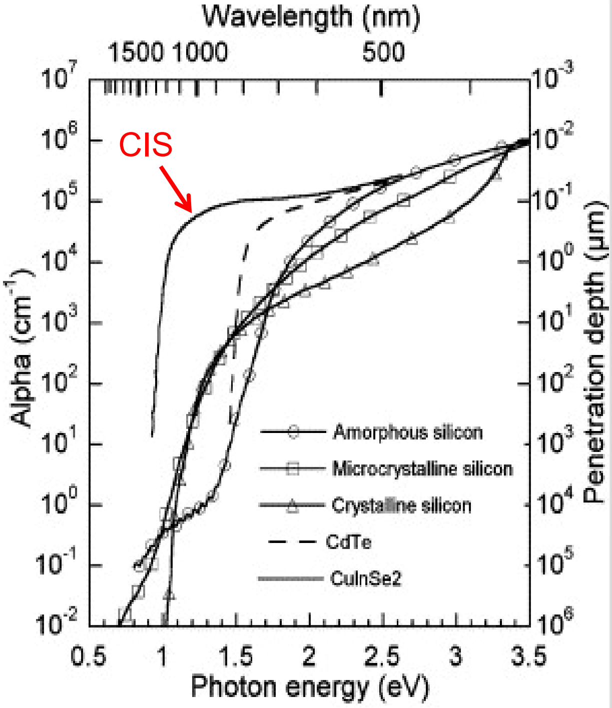
e.g. $CuInSe_2$ has E_g = 1.0 eV, while $CuInS_2$ has E_g = 1.5 eV, and $CuGaSe_2$ has E_g = 1.7 eV



Source: textbook
Powalla (ZSW)

CIGS solar cells

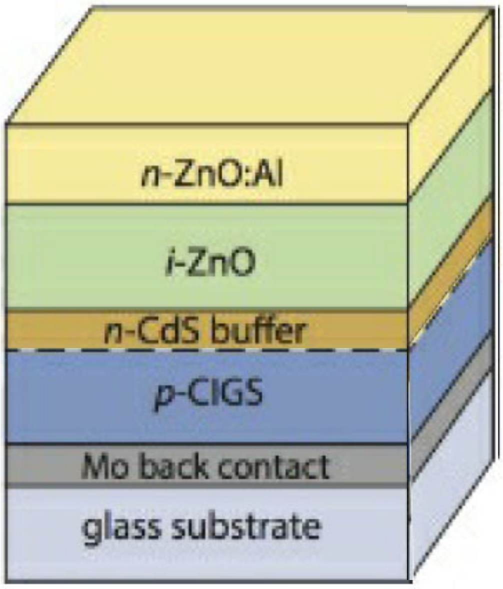
- CIGS is a direct bandgap semiconductor material
- High absorption coefficient over broad wavelength range
- Absorber thickness of 1–2 µm sufficient to absorb a large fraction of above-bandgap light
- Typical diffusion length is about few µm
- CIGS is *p*-type ⇒ resulting from intrinsic defects in material (Cu deficiencies)



Source: Powalla (ZSW)

CIGS solar cells

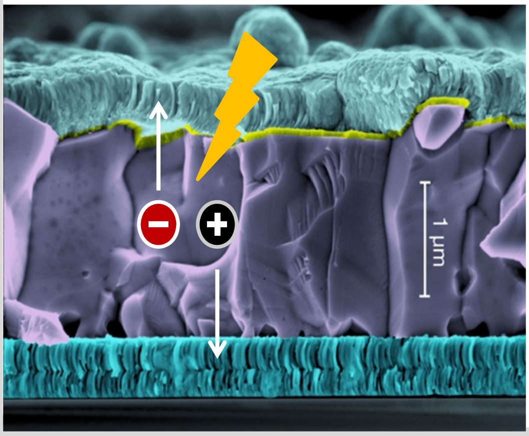
- Typical CIGS solar cell deposited on glass substrate
- Molybdenum (Mo) layer ~500 nm thick deposited as rear contact
- *p*-type CIGS absorber layer deposited (up to 2 µm thick)
- *p*-*n* junction formed by depositing thin (~50 nm thick) cadmium sulphide (CdS) buffer
- Then intrinsic zinc oxide (*i*-ZnO) layer deposited (role not fully understood), followed by TCO based on Al-doped ZnO

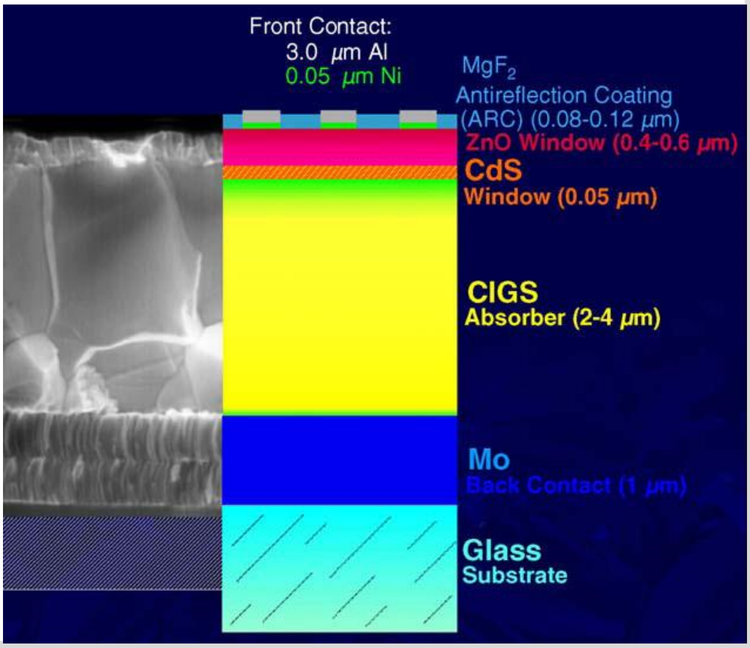


Source: adapted from textbook

CIGS solar cells

- Grain boundaries largely run vertically through the absorber ⇒ less damaging that horizontal grain boundaries;
- CIGS solar cells are (roughly) planar devices ⇒ no texturing needed for high light absorption

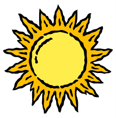


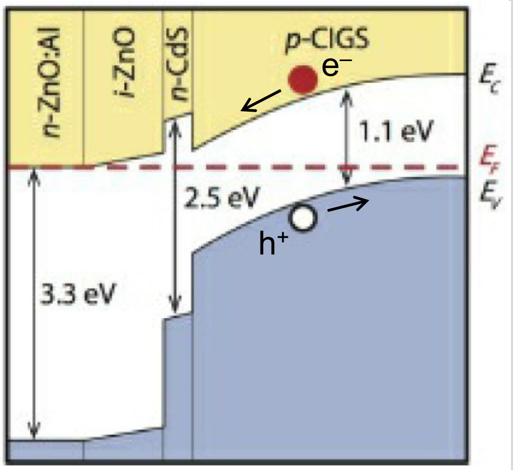


Source: https://en.wikipedia.org/wiki/Copper_indium_gallium_selenide_solar_cells
ZSW Annual Report 2008

CIGS solar cells

- Light enters cell from left, via the ZnO ⇒ high bandgap of E_g = 3.3 eV minimizes parasitic absorption losses
- *n*-type CdS buffer layer has E_g = 2.5 eV
- Commercial *p*-type CIGS absorber layer E_g = 1.1 eV, achieved using $Cu(In_xGa_{1-x})Se_2$ with $x \approx 0.3$
- Bandgaps of *n*- and *p*-type materials are different ⇒ CIGS considered as heterojunctions (c.f. Si homojunction)
- Role of sodium (Na) ⇒ reduces recombination at grain boundaries in CIGS (like H^+ in Si) ⇒ Na-source in soda-lime glass (window glass)





Source: textbook

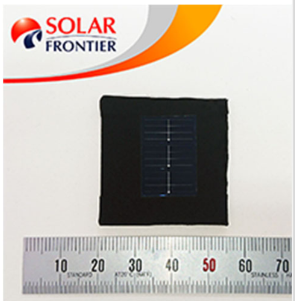
CIGS solar cells

- Fabrication of CIGS solar cells – many different approaches:
  - i) <u>co-evaporation</u> under vacuum conditions via crucibles of copper, gallium, indium and selenium onto heated substrate
  - ii) <u>sputtering</u> onto a non-heated substrate, then thermally annealed in presence of selenium vapour
- Variety and complexity of reactions taking place during the ‘selenization’ process ⇒ CIGS properties difficult to control
  - iii) Non-vacuum techniques based on depositing nanoparticles of the precursor materials onto substrate then sintering the film ⇒ plus then followed by selenization step

Source: textbook

CIGS solar cells

- CIGS solar cells have achieved one of the highest conversion efficiencies for thin-film PV
- Previous solar cell efficiency record held Centre for Solar Energy and Hydrogen Research (ZSW, Stuttgart) with η = 22.6% for CIGS ⇒ working with Manz AG for commercialisation
- Overtaken by Solar Frontier (Japan) with η = 23.3% (1cm^2 device with V_{oc} = 734 mV, J_{sc} = 39.58 mA/cm^2, FF = 80.4%) ⇒ notably for a Cd-free CIS device

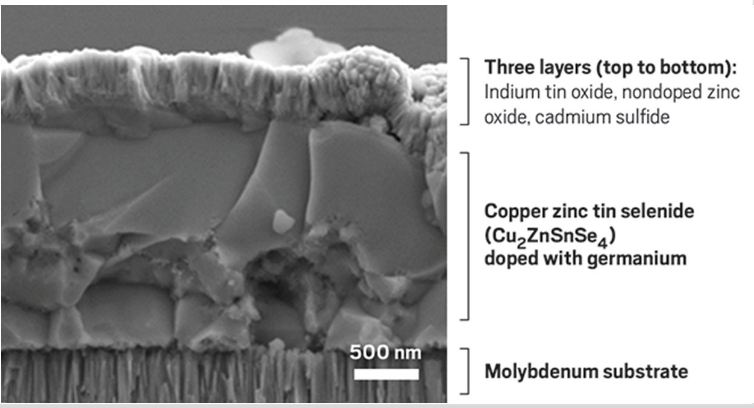


- Despite the very high η, CIGS technology faces challenges: i) complex deposition process; ii) achieving uniform large-area depositions with iii) a high production yield

Source: http://www.solar-frontier.com/eng/news/2019/0117_press.html

Kesterite solar cells

- Indium is a very rare element, but crucial to CIGS solar cells ⇒ scarcity may prevent upscaling of CIGS PV to TW scale
- Also, current thin-film display industry depends on In as well, with ITO is integrated in many display screens.
- Cadmium is toxic but efforts underway to replace Cd with Zn
- Kesterite $Cu_2ZnSn(S,Se)_4$ is based on abundantly available and non-toxic elements
- Record efficiency was η = 12.6% (IBM, 2013)
- Challenge controlling defects and presence of unwanted phases



Source: https://cen.acs.org/articles/96/i7/Kesterite-solar-cells-ready-shine.html

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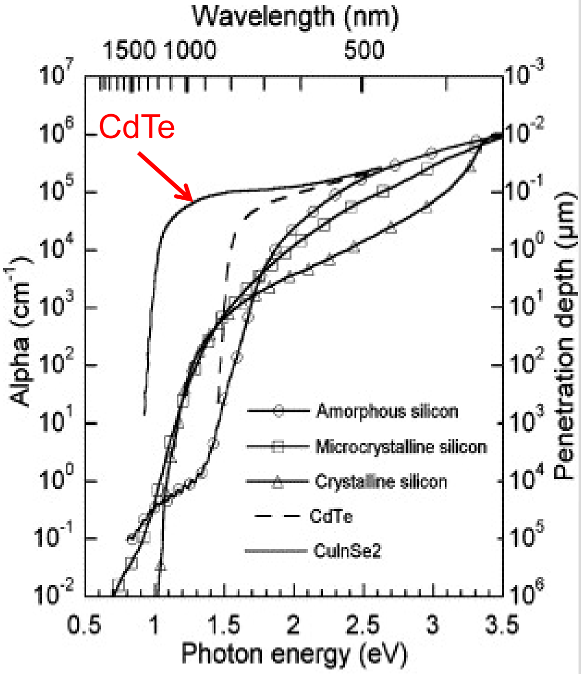
CdTe solar cells

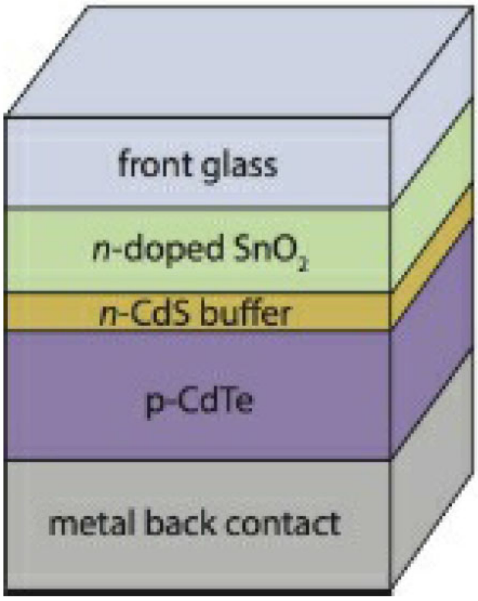
- Cadmium telluride (CdTe) PV – the thin-film technology with currently lowest demonstrated cost per Wp
- CdTe: *p*-doped semiconductor with E_g = 1.44 eV ⇒ close to ideal for single-junction device
- CdTe is a direct bandgap material ⇒ only few µm of CdTe required to absorb all above-bandgap photons
- History: first suggested for PV in 1956, followed by first solar cells being made in the 1960s, with η = 5% devices made in 1972



Source: Powalla (ZSW)

CdTe solar cells

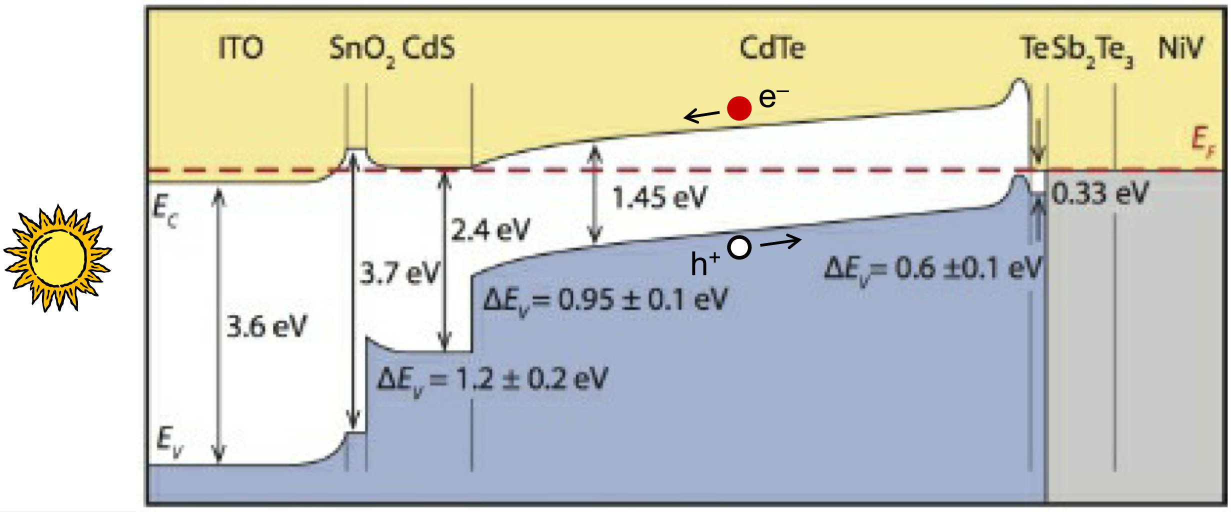
- First, TCO front deposited onto glass superstrate (ITO with tin oxide layer)
- *n*-type layer is CdS
  (same as for CIGS but thicker)
- Then, *p*-type CdTe absorber layer (few μm thick) is deposited
- Making a good back contact on CdTe is challenging due to limited choice of acceptable metals
- Thus, often another semiconductor material is added to improve the contact, e.g. antimony telluride layers in combination with molybdenum rear metal contact *(not discussed in detail here)*



Source: textbook

CdTe solar cells

- CdS/CdTe is a heterojunction (like for CIGS)
- Light-excited minority electrons in the *p*-layer are separated at the heterojunction and collected at the TCO-based front contact. The holes are collected at the back contact.



Source: textbook

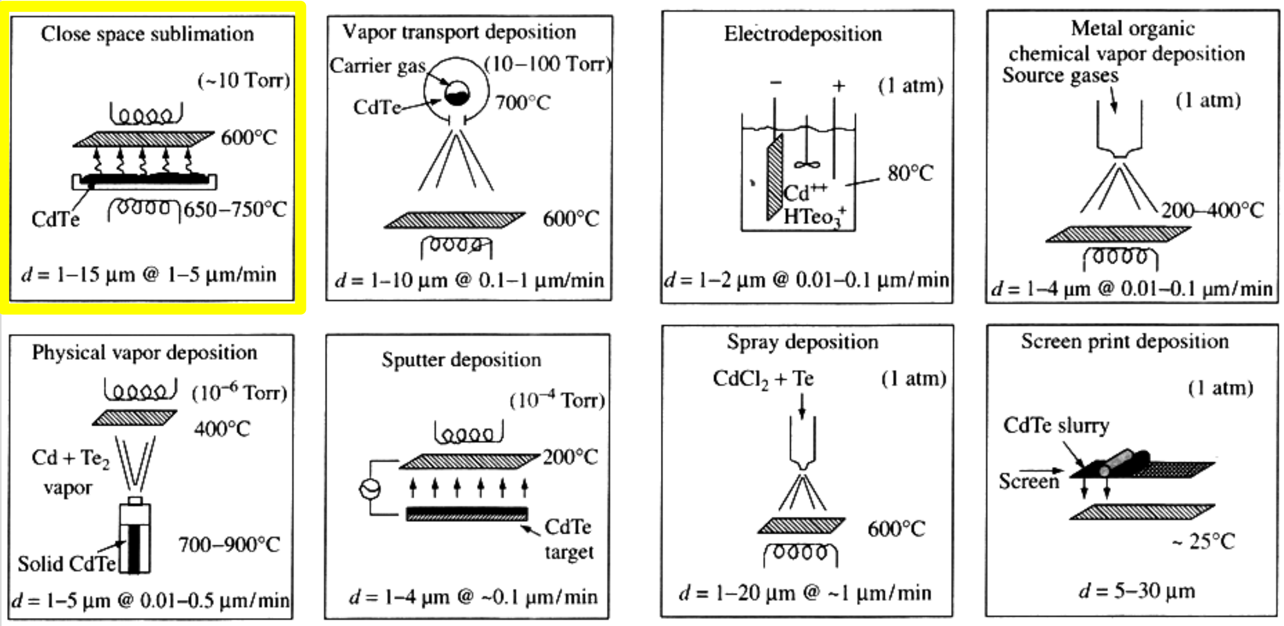
CdTe solar cells

- CdS/CdTe layers are processed using the closed-space sublimation (CSS) method
- *Sublimation ≡ transition of substance directly from solid to gas phase, without passing through intermediate liquid phase*
- Source consists of granules/powders of CdTe
- Source material and substrate are placed close together (mm – cm) under vacuum conditions
- Both source and substrate are heated ⇒ source is at higher temperature than substrate ⇒ temperature difference is the driving force for thin film deposition on substrate
- Glass limits temperatures that can be used

Source: textbook

CdTe solar cells

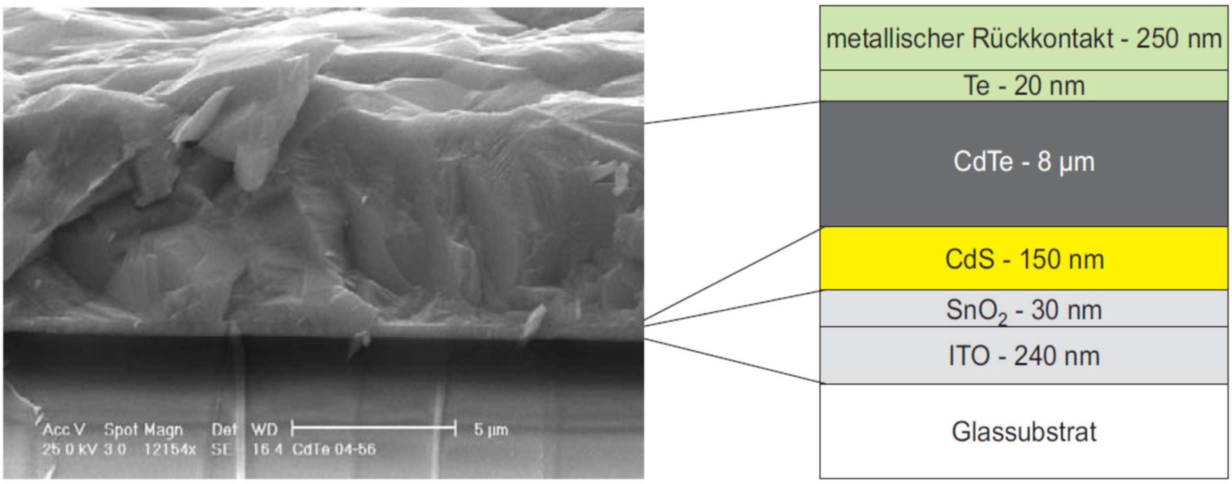
- At least eight different ways of depositing CdTe layers:



Source: Luque, Handbook of PV

CdTe Solar Cells

- Cross-sectional image via scanning electron microscopy (SEM) of device from Antec Solar (Germany)
- Note, very rough surfaces



metallischer Rückkontakt - 250 nm

Te - 20 nm

CdTe - 8 µm

CdS - 150 nm

SnO_2 - 30 nm

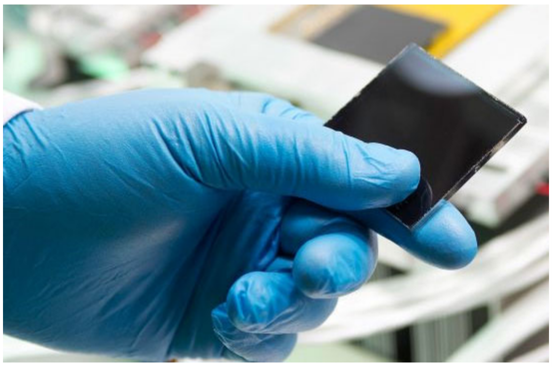
ITO - 240 nm

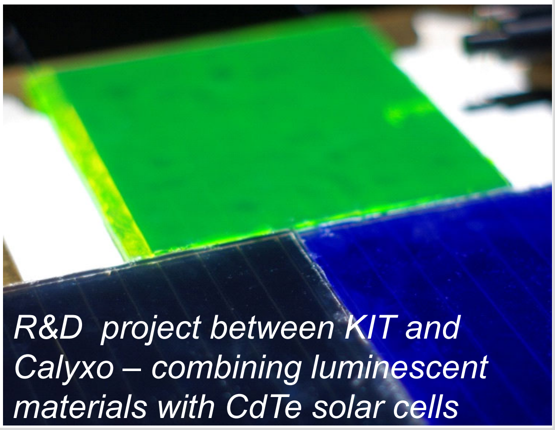
Glassubstrat

Source: Diss. Fritsche, TU Darmstadt 2003

CdTe Solar Cells

- First Solar (USA) – leading CdTe PV module producer and current world record solar cell efficiency
- η = 22.1% for 0.5 cm^2 device with V_{oc} = 887 mV, J_{sc} = 31.69 mA/cm^2, FF = 78.5%
- Three German CdTe PV producers (“second solars”):
  - Antec Solar
  - Calyxo
  - CTF-Solar (German R&D, manufactured in China)





R&D project between KIT and Calyxo – combining luminescent materials with CdTe solar cells

Sources: https://www.greentechmedia.com/articles/read/first-solar-hits-record-22-1-conversion-efficiency-for-cdte-solar-cell
Ross *et al.*, Solar Energy Materials and Solar Cells 103 (2012): 11-16.

CdTe Solar Cells

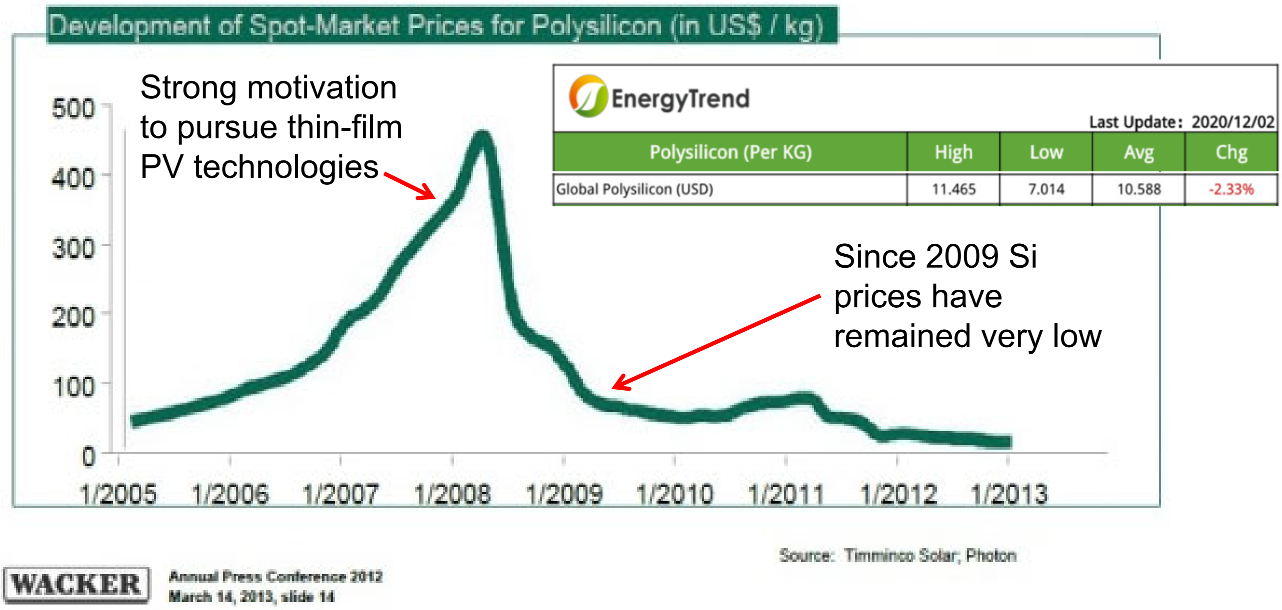
- Although Cd is toxic, insoluble compounds like CdTe and CdS are much less toxic than elementary Cd
- Still very important to prevent Cd from entering into ecosystem
- First Solar producing ~5.6 GWp/year
  ⇒ ~5% of total Cd consumption
- Recycling schemes established have been set up for installed CdTe solar modules ⇒ fund where \$0.05/Wp of purchase price set aside to cover cost of recycling at end-of-module lifetime
- Another challenge is supply of Te ⇒ one of rarest elements (abundance similar to Pt)
- Also Te not used for many other applications, hence dedicated Te mining not explored (currently by-product of Cu mining – 1000 tonnes Cu ⇒ 1kg of Te)

Sources: https://www.greentechmedia.com/articles/read/first-solar-hits-record-22-1-conversion-efficiency-for-cdte-solar-cell
Ross *et al.*, Solar Energy Materials and Solar Cells 103 (2012): 11-16.

Silicon vs Thin-film PV

AVERAGE PRICE OF SOLAR-GRADE SILICON FELL BY HALF IN PAST YEAR

Development of Spot-Market Prices for Polysilicon (in US\$ / kg)



Strong motivation to pursue thin-film PV technologies

Since 2009 Si prices have remained very low

Last Update: 2020/12/02

Polysilicon (Per KG)	High	Low	Avg	Chg
Global Polysilicon (USD)	11.465	7.014	10.588	-2.33%

Source: Timminco Solar; Photon

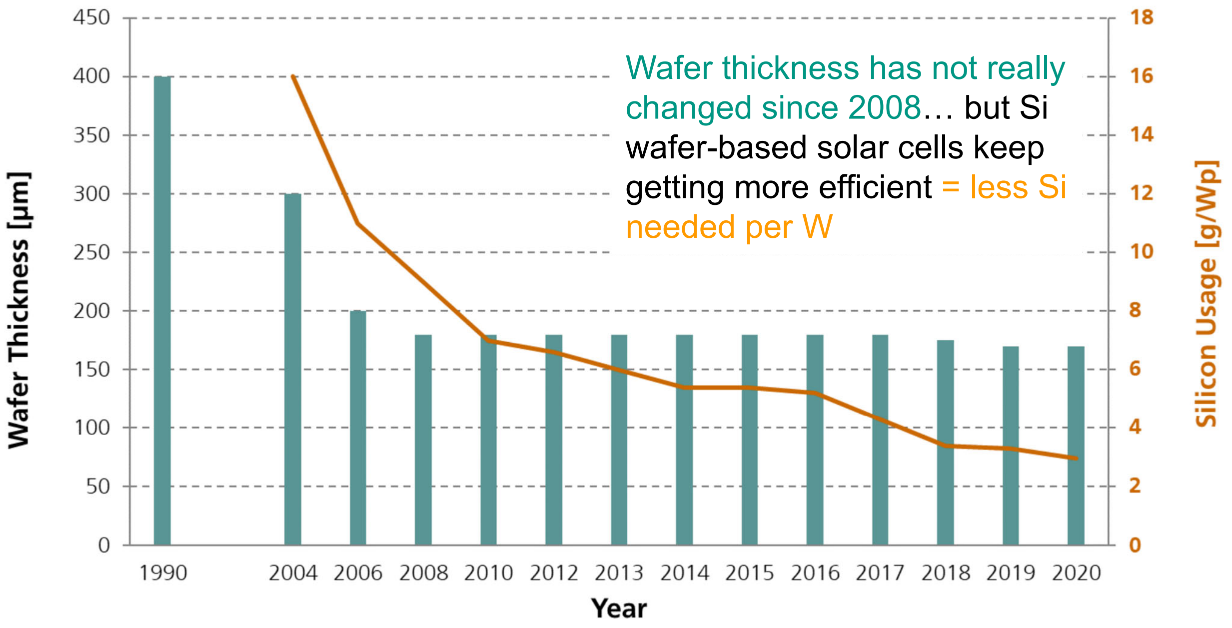
Annual Press Conference 2012
March 14, 2013, slide 14

Source: http://www.pv-tech.org/news/polysilicon_prices_at_wacker_fell_50_in_2012

Silicon vs Thin-film PV

- Huge demand for PV in mid-2000’s ⇒ over-demand & under-supply of Si ⇒ Si prices sky-rocketed ⇒ two responses:
  1) huge investment in thin-film PV technologies to move away from wafer-based Si;
  2) but at same time, massive plants for poly-Si manufacturing were being built
- Global recession started in 2008 ⇒ investors have no money ⇒ massively reduced demand ⇒ made worse by massive over supply of poly-Si ⇒ bottom dropped out of wafer-based silicon solar market ⇒ Si PV manufacturers forced to cut costs to stay in business and take loans from government (e.g. China) ⇒ many EU Si PV companies go bankrupt ⇒ thin-film PV technologies largely still developing and cannot compete ⇒ many go bankrupt between 2010 – 2012

Silicon vs Thin-film PV

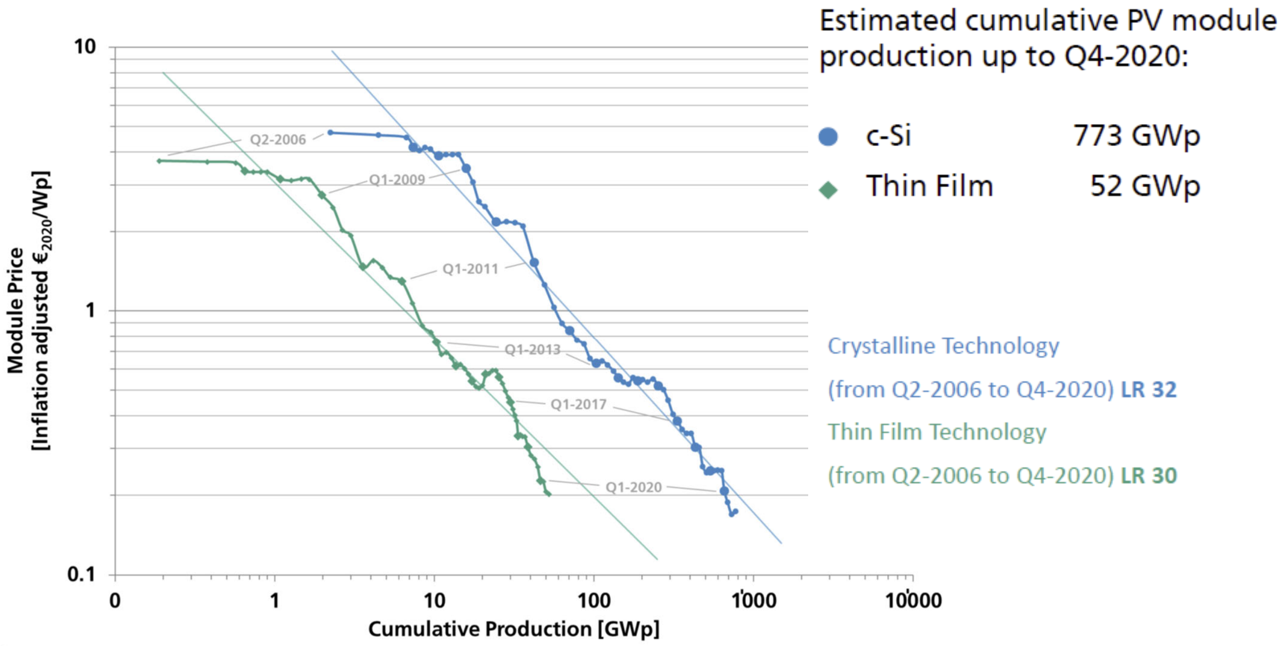


Wafer thickness has not really changed since 2008… but Si wafer-based solar cells keep getting more efficient = less Si needed per W

Source: https://www.ise.fraunhofer.de/en/downloads-englisch/pdf-files-englisch/photovoltaics-report-slides.pdf

Silicon vs Thin-film PV

- Learning rate (LR) for thin-film PV slower than for c-Si PV



Source: https://www.ise.fraunhofer.de/en/downloads-englisch/pdf-files-englisch/photovoltaics-report-slides.pdf

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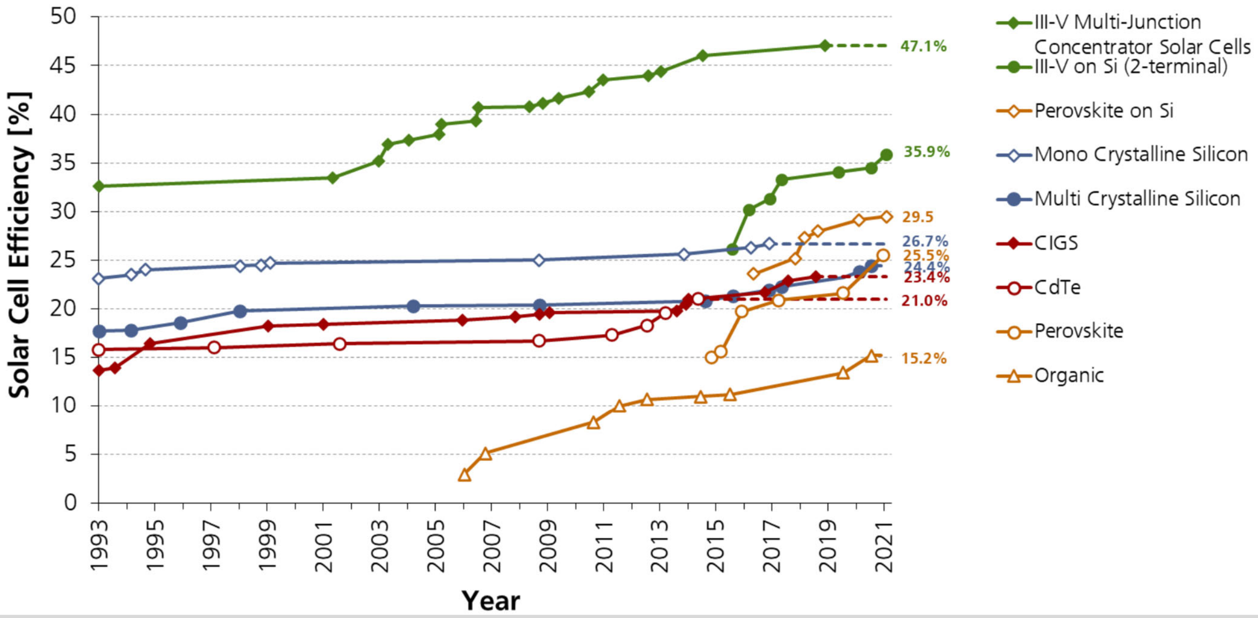
Silicon vs Thin-film PV

- c-Si and mc-Si solar cell efficiencies hardly increasing (approaching η ~ 30% theoretical efficiency limit) – CdTe and CIGS also no recent progress
- Most rapidly increasing efficiency is for perovskite solar cells (and tandems of perovskite on Si)



Source: https://www.ise.fraunhofer.de/en/downloads-englisch/pdf-files-englisch/photovoltaics-report-slides.pdf

Comparing Thin Film PV Modules

CIGS

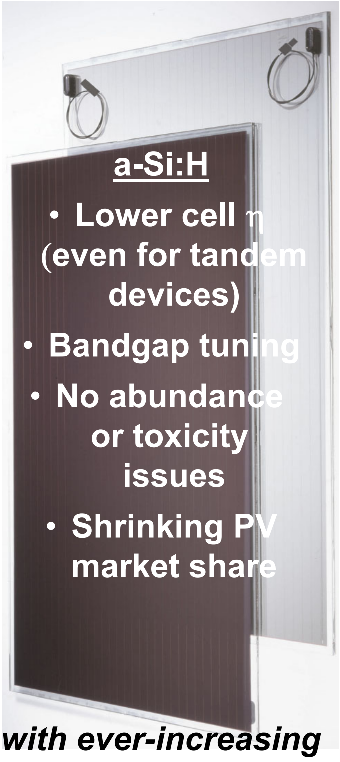
- High cell η
- Bandgap tuning
- Abundance of In?
- Possibility of Cd-free?
- Significant commercial production

Photo: Manz

CdTe

- High cell η
- Toxicity of Cd?
- Abundance of Te?
- Significant commercial production
- Lowest cost inorganic thin-film PV technology

Photo: First Solar



a-Si:H

- Lower cell η (even for tandem devices)
- Bandgap tuning
- No abundance or toxicity issues
- Shrinking PV market share

Photo: Schott Solar

All thin-film PV technologies finding it tough to compete with ever-increasing efficiencies and ever-reducing costs of c-Si wafer-based solar cells

Thin-Film PV Summary

- Range of materials can be used for thin-film solar cells:
  i) a-Si:H (incl. a-Si:H/nc-Si:H tandems) and thin-film c-Si
  ii) CIGS
  iii) CdTe
- Main goal was to move away from energy intensive process of making c-Si, but ultimately thin-film struggles on cost
- a-Si and thin-film Si never achieved η > 10-11% large-area ⇒ cannot ignore "balance-of-systems" (BoS) costs
- CIGS and CdTe exhibit higher efficiencies but issues with abundance and toxicity remain ⇒ compatible with TW-scale?
- c-Si fabrication processes are simple and robust ⇒ plus c-Si also very stable ⇒ hard for a new technology to beat
- Thin-film PV market not growing ⇒ main hope lies in the perovskites (and their tandems with c-Si)?

Homework: a-Si:H solar cells

- What role does H play in a-Si:H?
- Why is it necessary to make a *pin*-junction out of a-Si:H material? (or why won't a *pn*-junction made from a-Si:H work very well?)
- How does the Stäbler-Wronski Effect (SWE) affect the performance of a-Si:H-based devices?
- Describe one way of introducing light-trapping into a a-Si:H solar cell.
- With two elements can Si be alloyed to tune the bandgap of a-Si:H solar cells up and down?
- What is the critical issue to consider when fabricating a tandem/multijunction solar cell? State why.

Homework: a-Si:H solar cells

- Reading Chapter 13 textbook