Thin film solar cells

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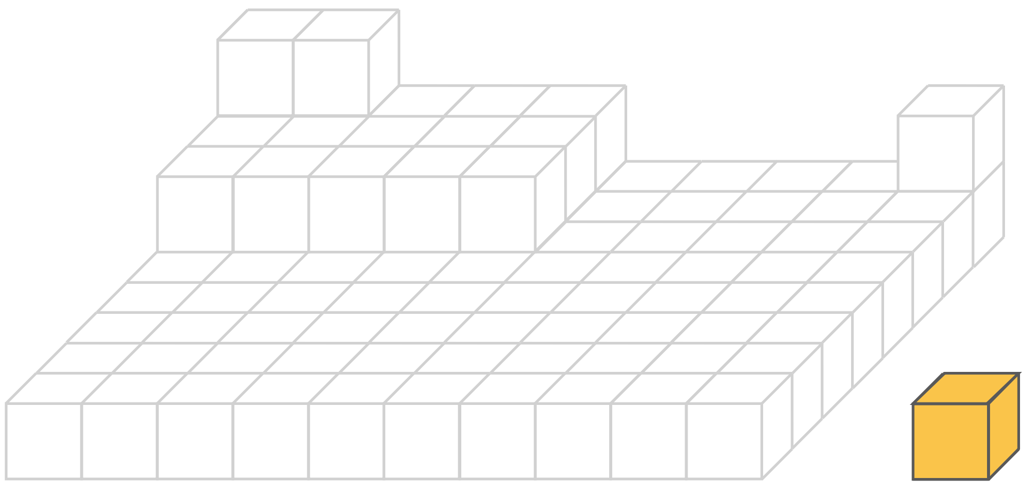


10.11.2017

UNIK 4450/9450 – Schedule

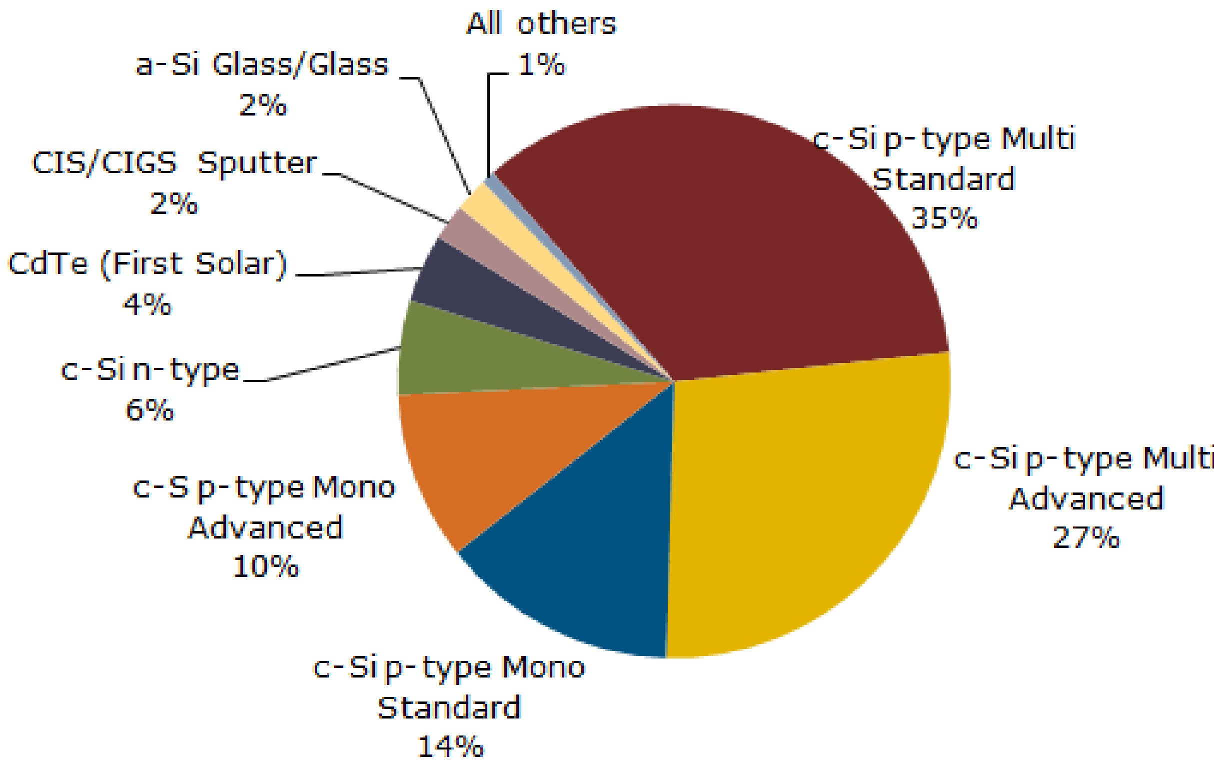
- 30/8 Solar cell fundamentals
- 6/9 Solar cell efficiency
- 13/9 Semiconductor theory
- 20/9 Generation
- 27/9 Recombination and lifetime
- 4/10 Silicon
- 11/10 Junctions
- 18/10 Solar cells
- 25/10 Silicon solar cells I (@IFE)
- 1/11 Silicon solar cells II
- 8/11 Light management
- 15/11 Alternative solar cells
- 29/11 Solar modules & systems
- 6/12 Q&A

- Oral exam December 12th

Overview

- Thin film deposition
- The effect of microstructure
- Silicon-based thin film solar cells
- Alternative thin film solar cells
  - CIGS and it's relatives
  - CdTe
  - Recent developments

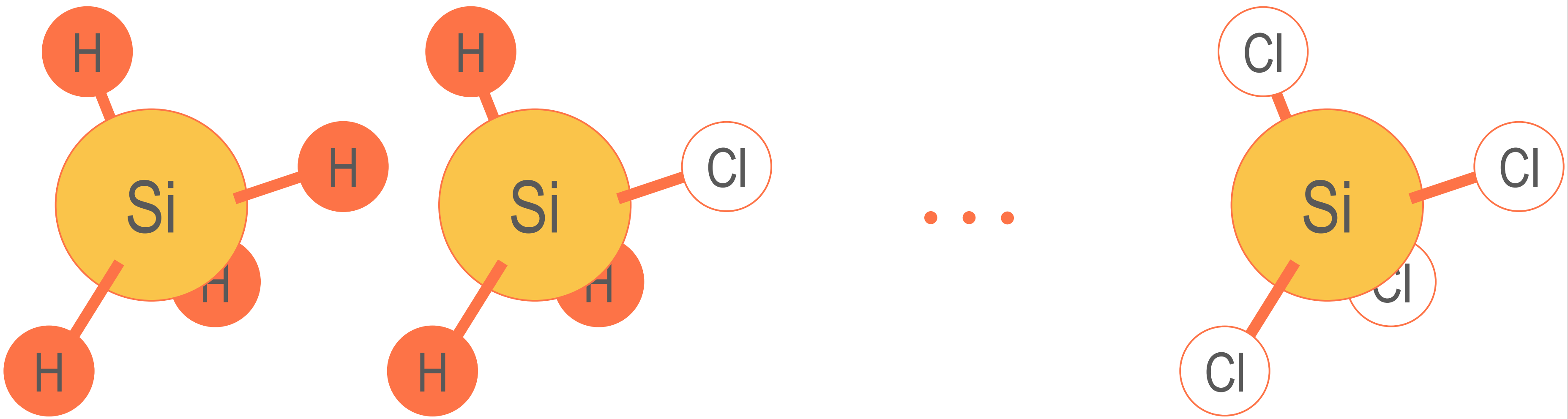
Solar cells anno 2014



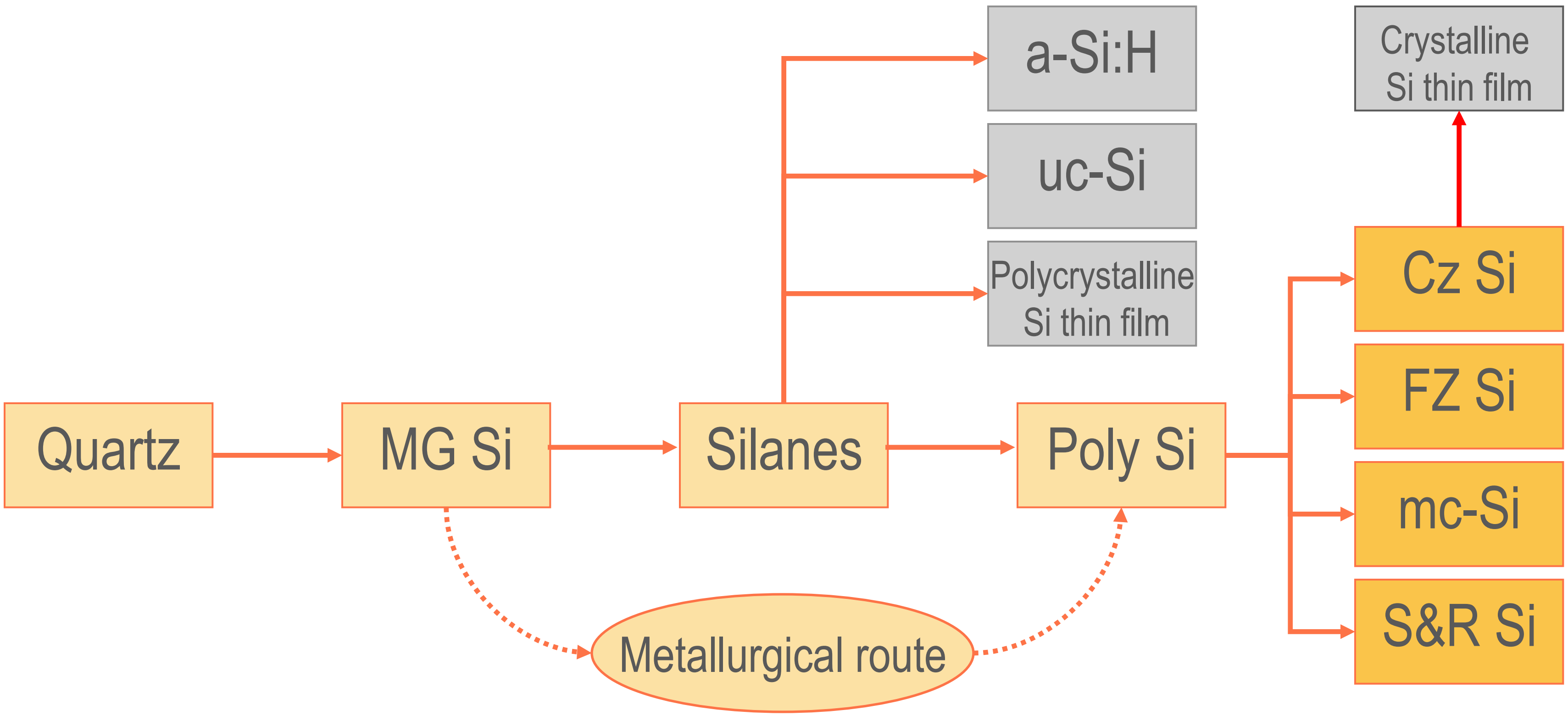
- NPD Solarbuzz forecast for 2014

Silicon-based solar cells

Silanes



Silicon-based solar cells



Thin film deposition

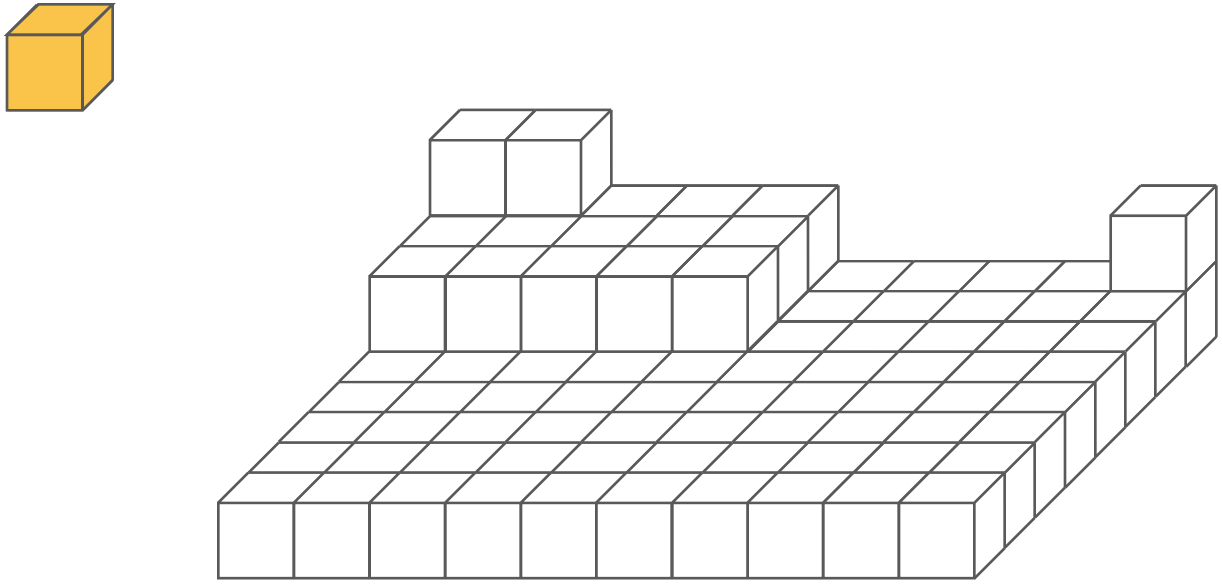
Thin film deposition

Source	Solid, liquid, vapour, gas
↓	
Transport	Vacuum, fluid, plasma
↓	
Deposition	Substrate condition, reactivity, energy input
↓	
Annealing	
↓	
Analysis	Structure, composition, properties

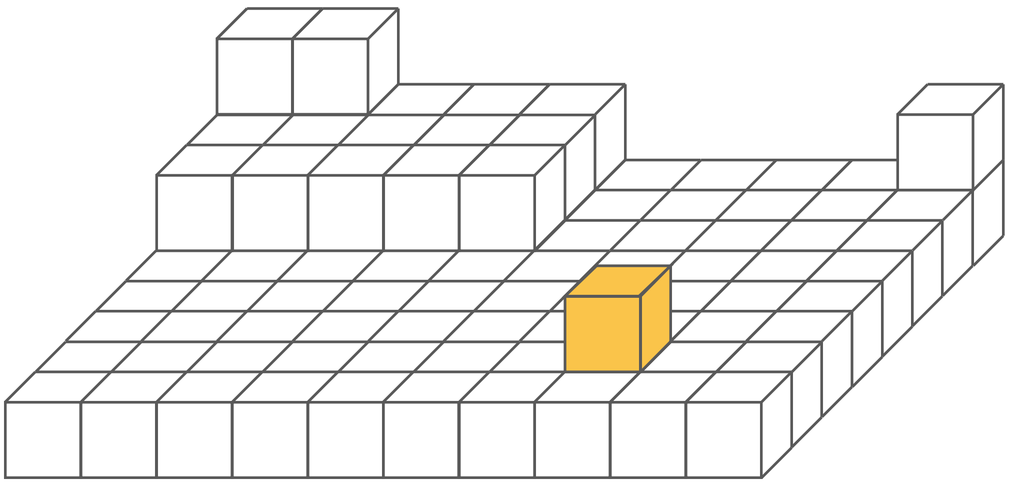
Deposition methods

- Evaporation
  - Thermal evaporation
  - E-beam evaporation
- Sputtering
  - Reactive sputtering
- Pulsed laser deposition
- Chemical vapour deposition (CVD)
  - Plasma-enhanced CVD (PECVD)
  - Metal-organic CVD (MOCVD)
- Molecular beam epitaxy
- Atomic layer deposition/epitaxy
- Printing
  - Screen printing
  - Ink-based printing
- …

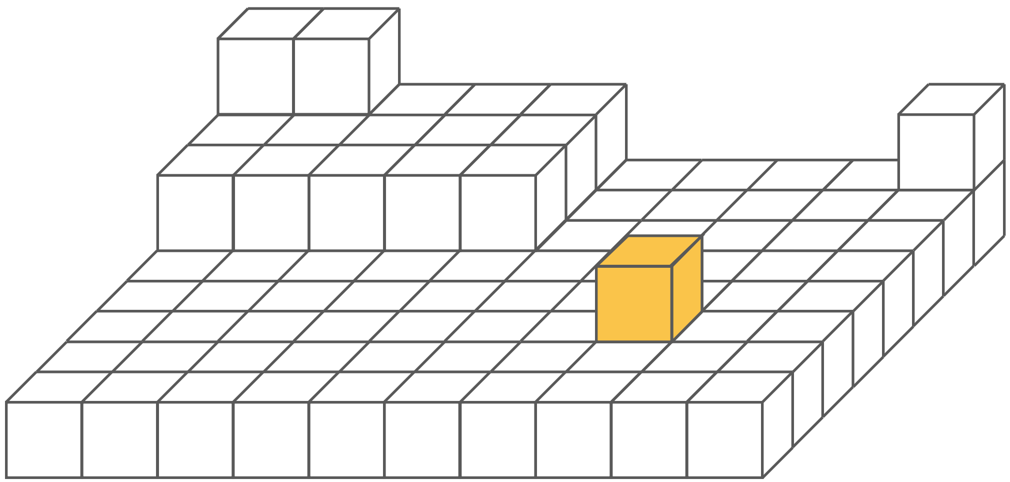
Thin film deposition



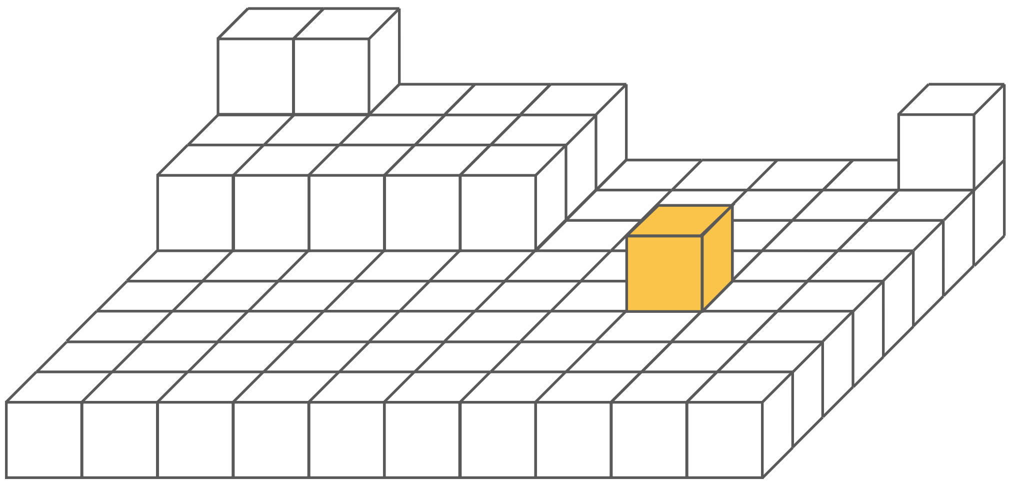
Thin film deposition



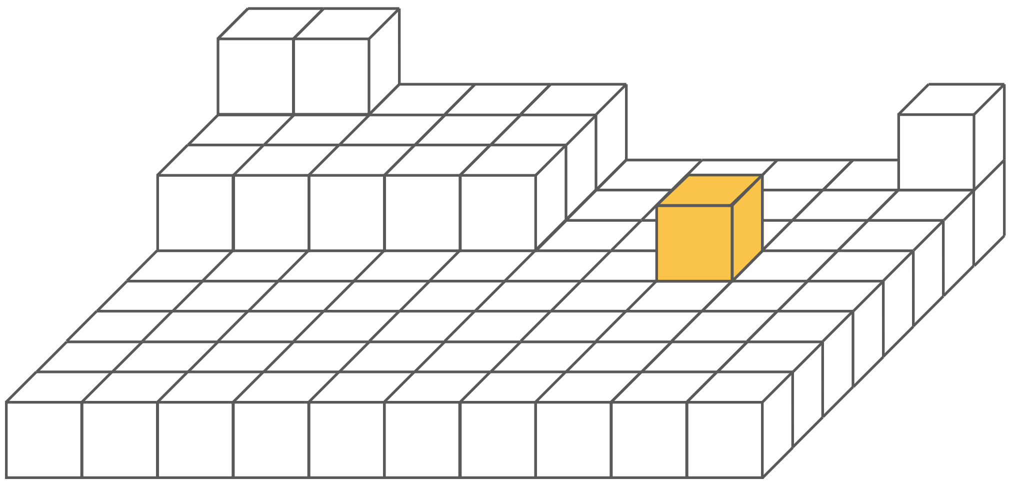
Thin film deposition



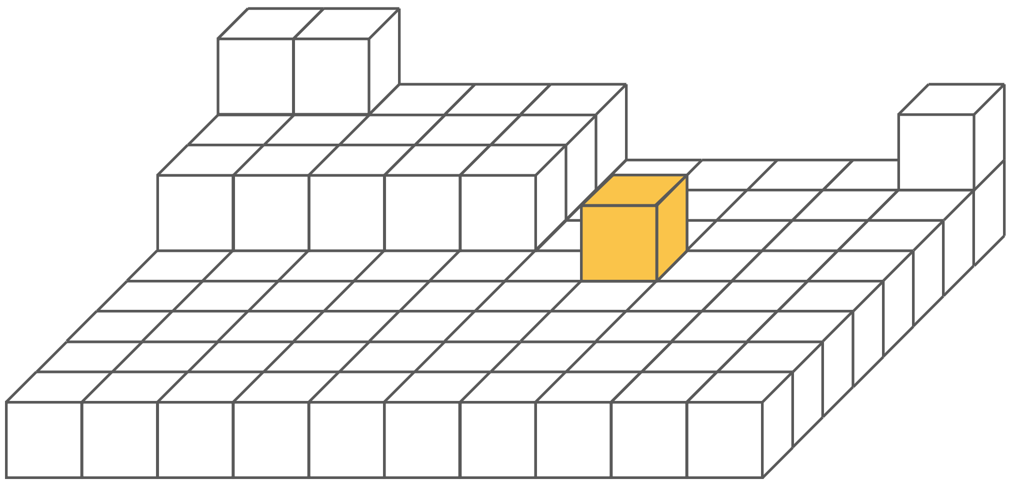
Thin film deposition



Thin film deposition



Thin film deposition



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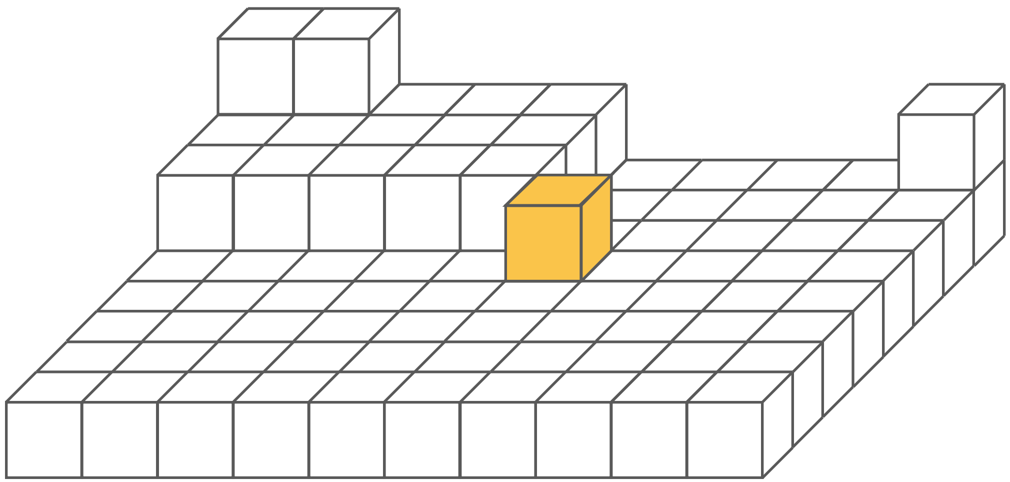
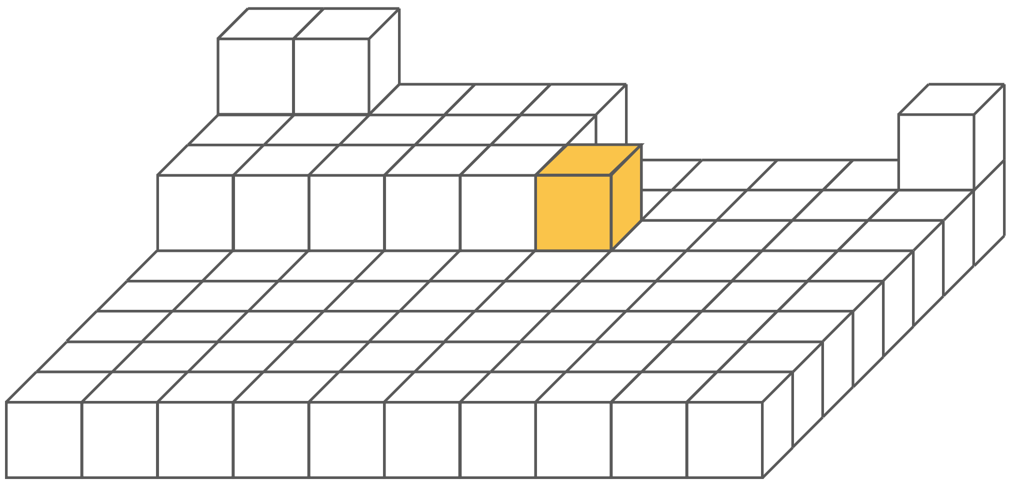
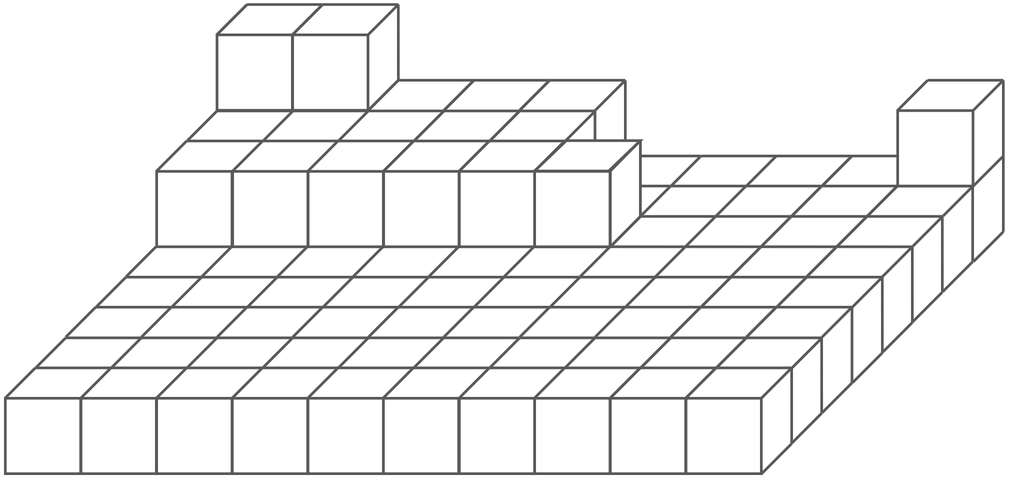


Thin film deposition



Thin film deposition



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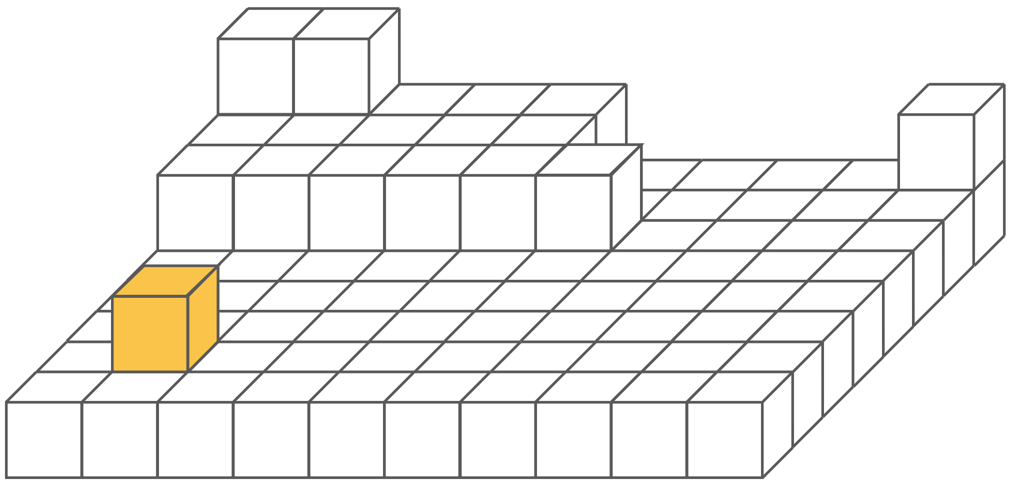

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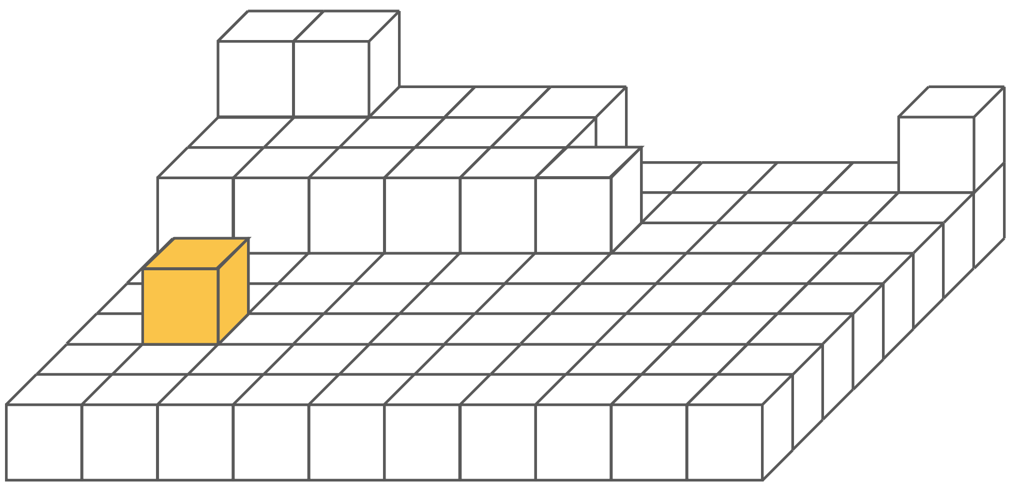
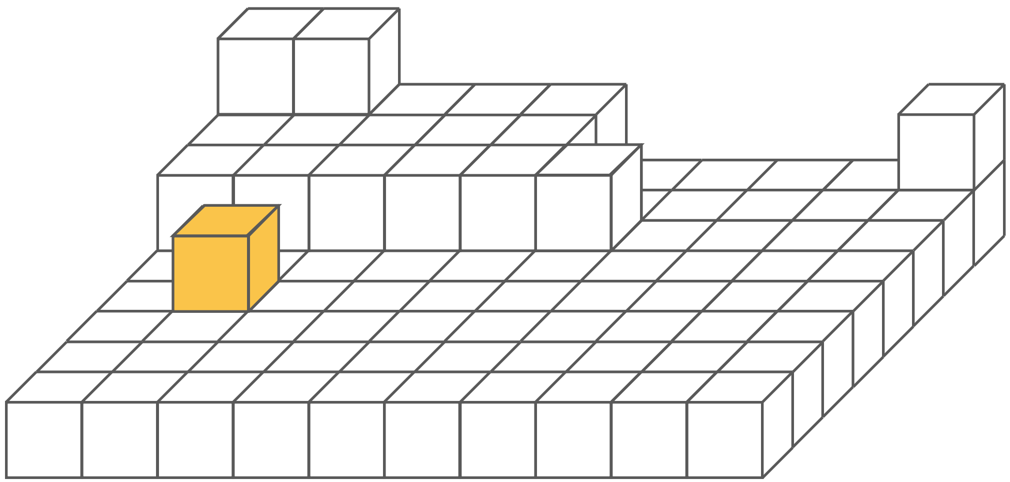
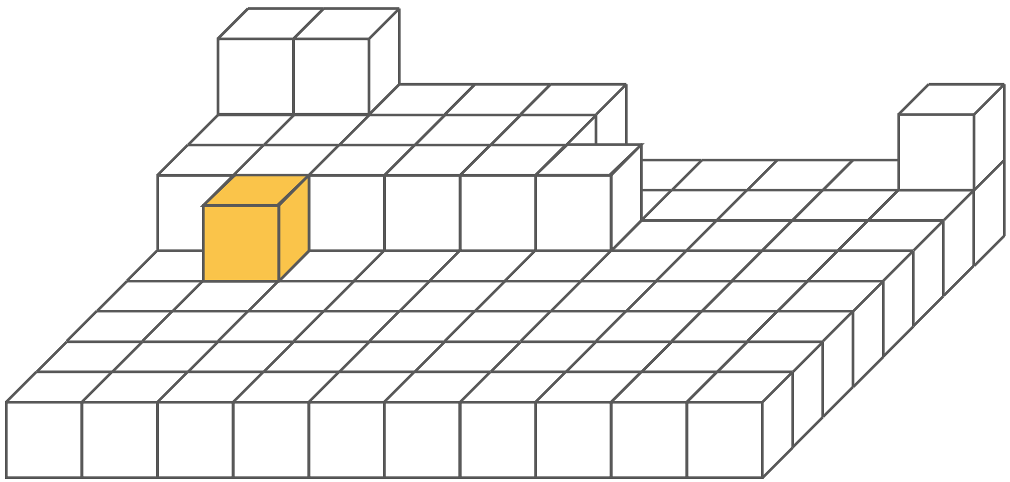


Thin film deposition



Thin film deposition



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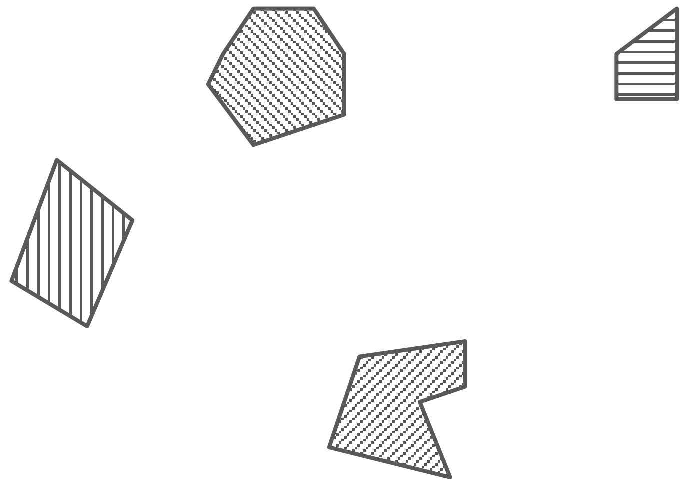
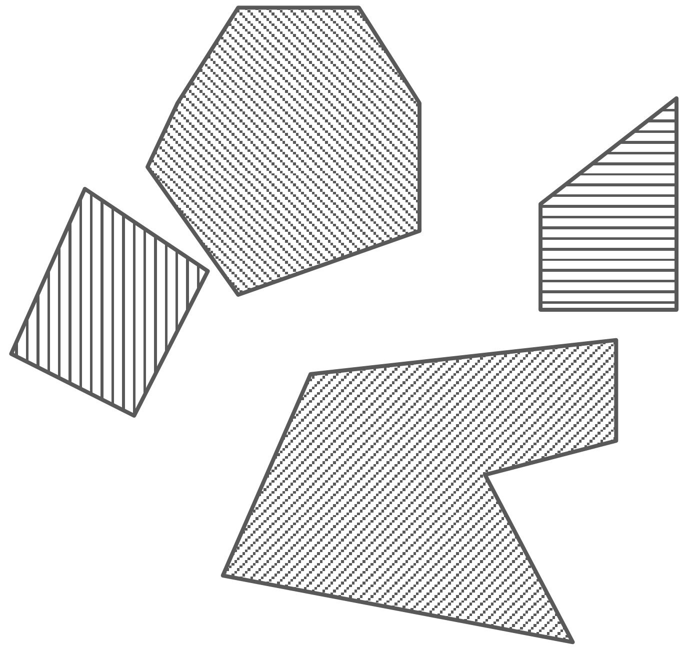
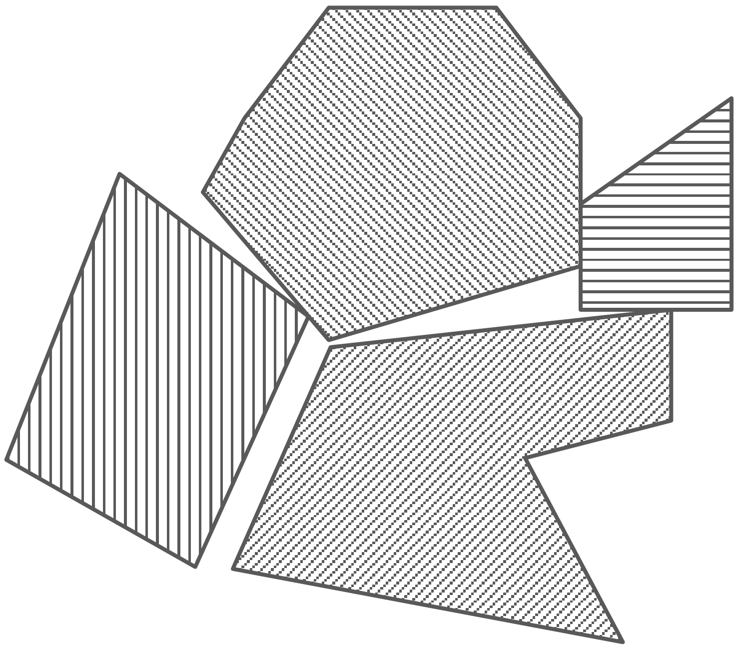


Thin film deposition



Thin film deposition



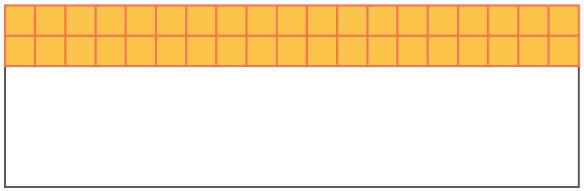
Microstructure

- The microstructure of a thin film material is ***strongly*** dependent of the deposition conditions!
- Phenomena:
  - Transport
  - Adhesion, bonding, binding
  - Desorption
  - Nucleation
  - …
- Parameters:
  - Concentrations of precursors/source gases
  - Temperature
  - Total gas flow rates
  - Reactant gas flow rates
  - RF power
  - …

…first you take a substrate

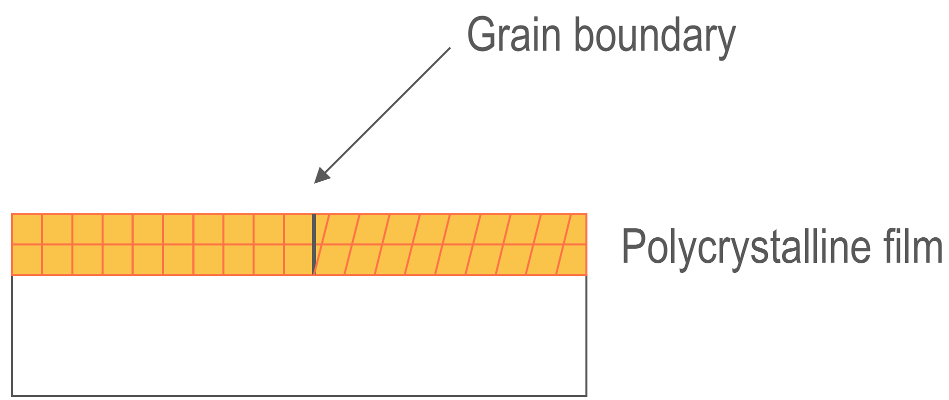
Substrate

Epitaxial/crystalline thin films



Crystalline film

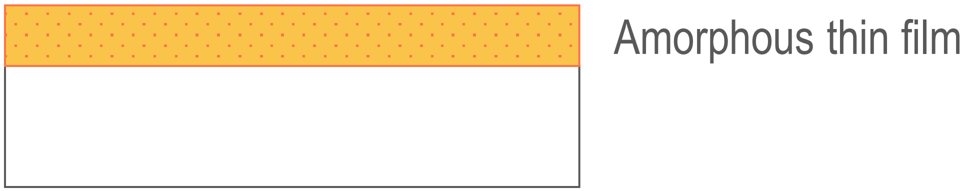
Polycrystalline thin films



Columnar growth/polycrystalline films

Polycrystalline film

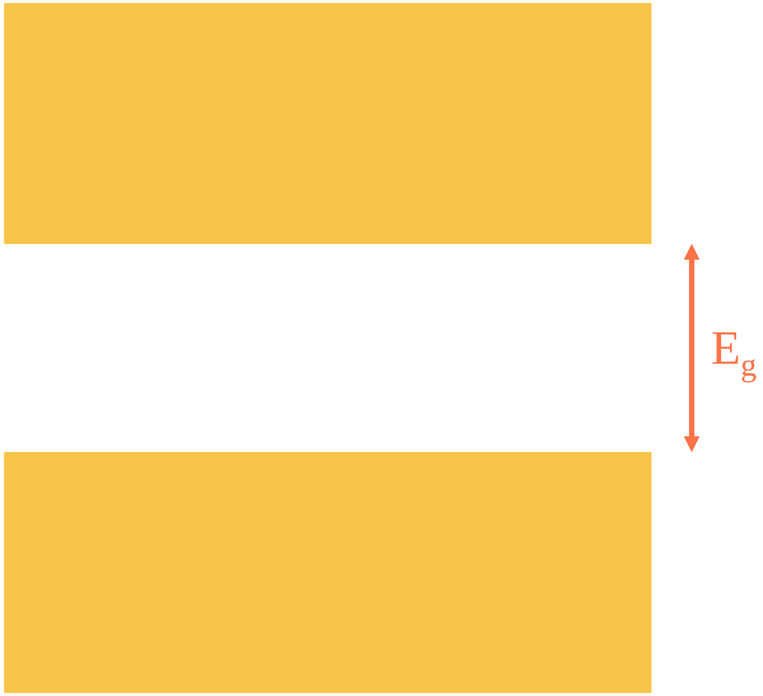
Amorphous thin films



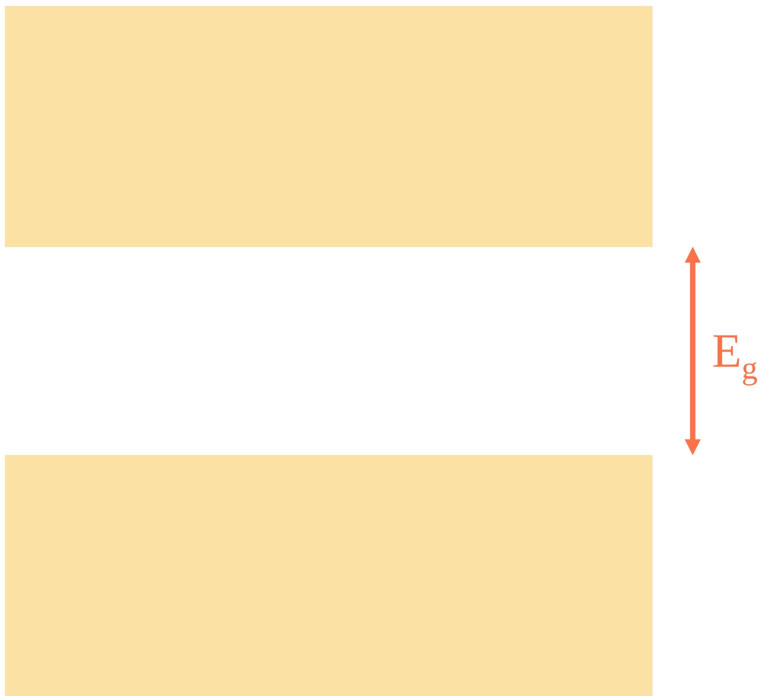
Microstructure

- Textbook semiconductor physics in its simplest form assumes perfect (i.e. crystalline) semiconductors
- Microstructure effects can include
  - Complete change of overall material properties (a-Si ≠ c-Si)
  - Changed charge carrier mobilities
  - Changed recombination rates
  - Grain boundary effects on transport and recombination
  - Staebler-Wronskij degradation
  - …

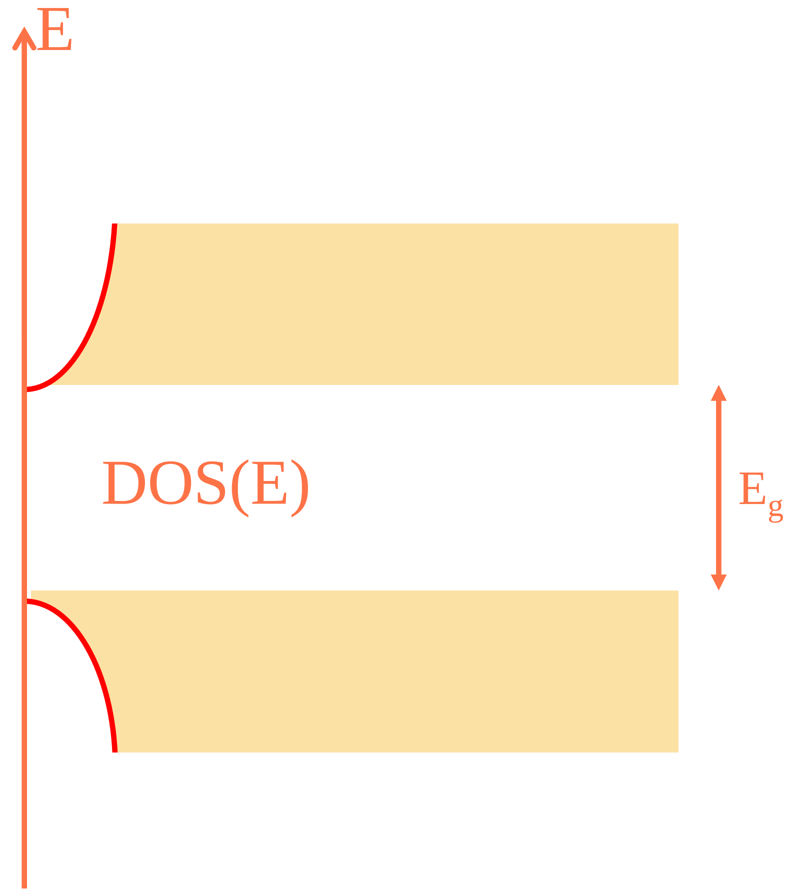
Microstructure



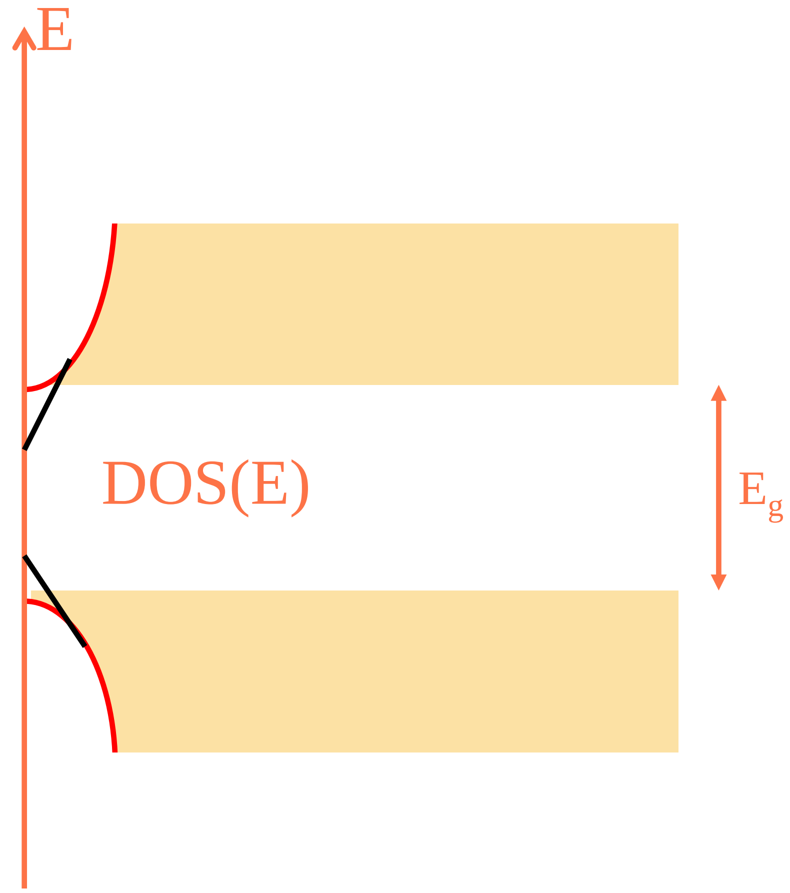
Microstructure



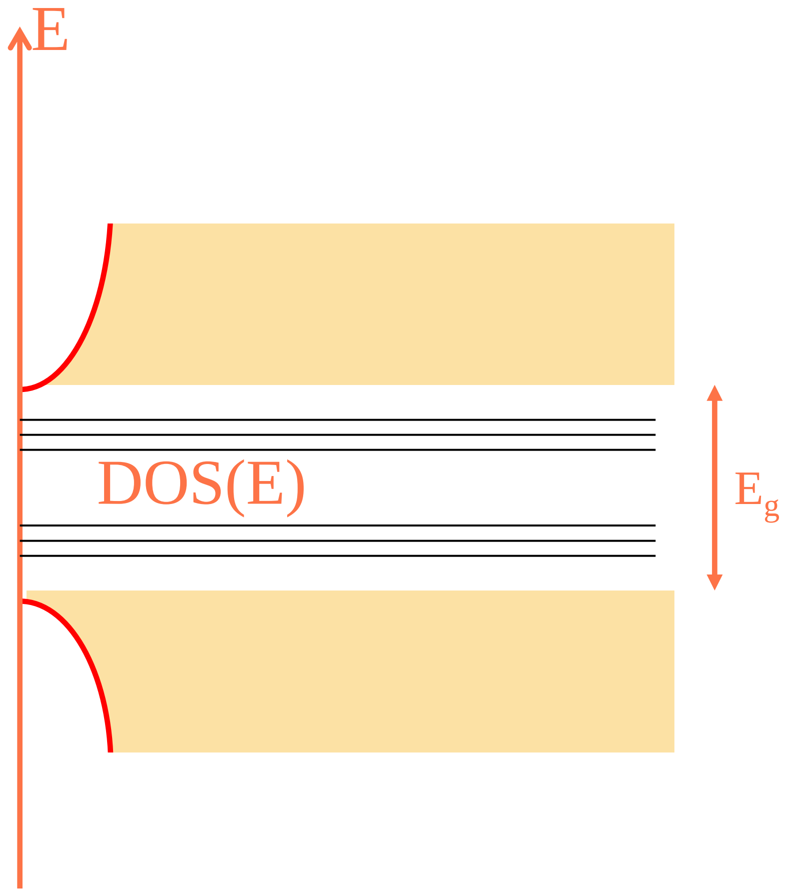
Microstructure



Urbach tails

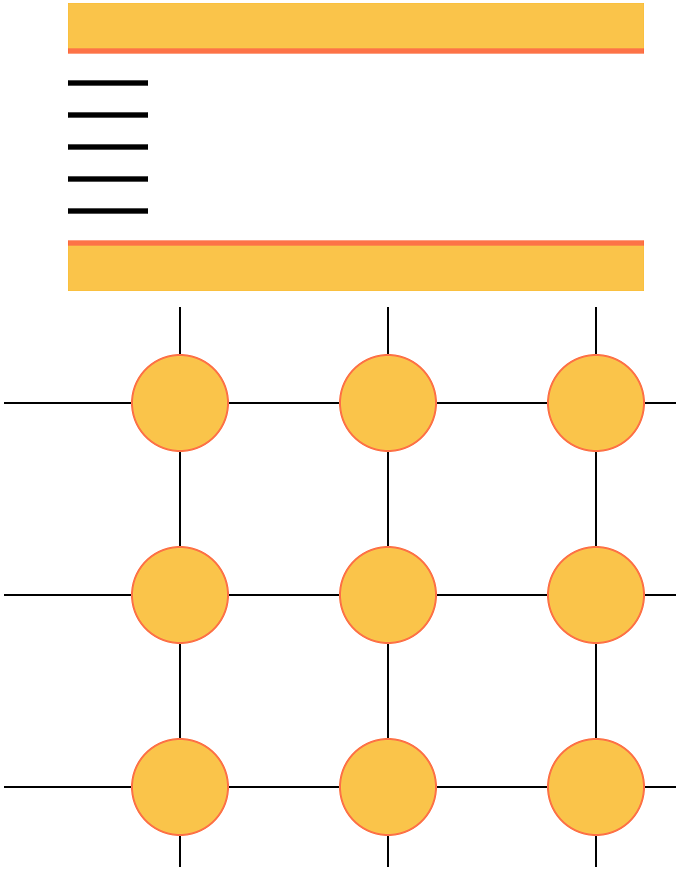


Defect bands



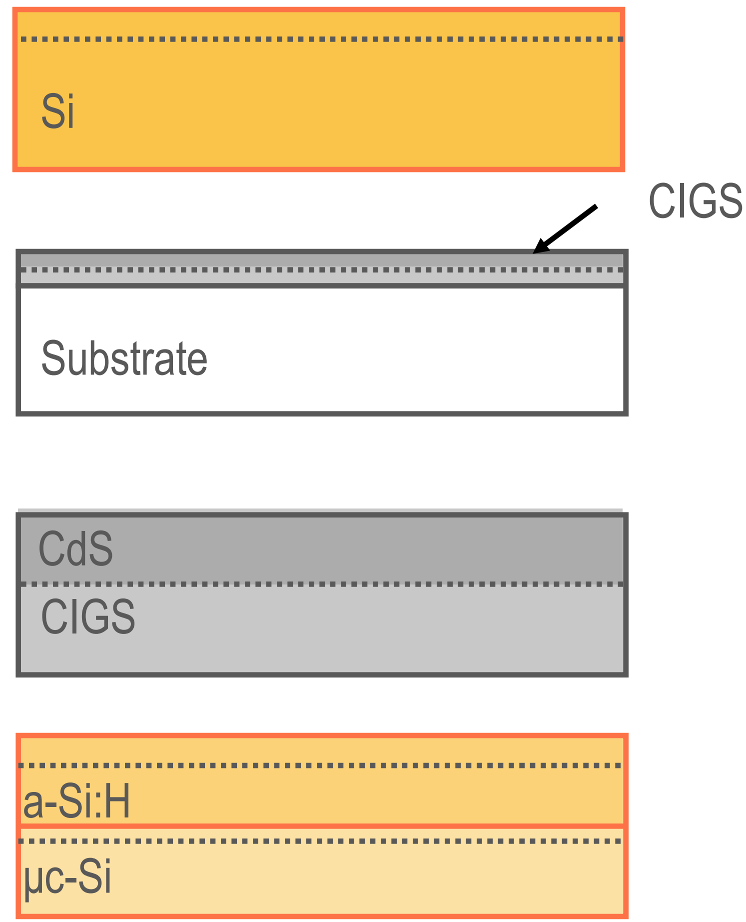
Surfaces and interfaces

- Surfaces and interfaces are likely to contain defects
  - Intrinsic defects: defects due to an interrupted crystal structure
  - Extrinsic defects: e.g. Impurities adsorbed at the interface
- These defects often introduce states in the band gap
- These defects are localized at the interface and can trap charge
  - Will influence potential distribution across interface
  - Will affect band bending across interface



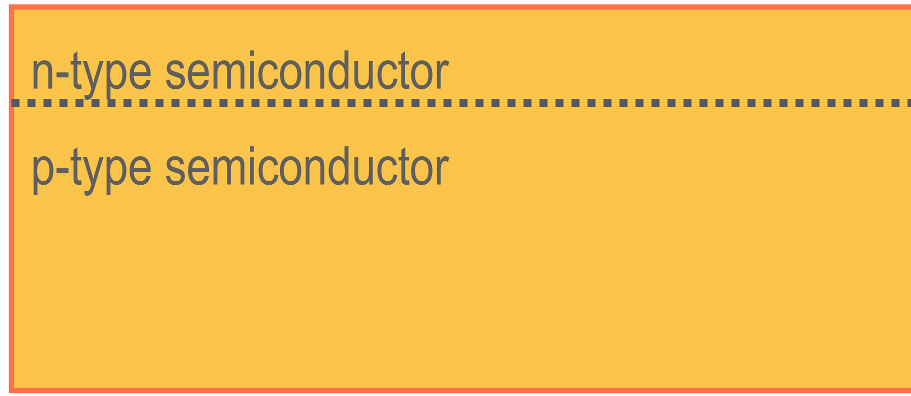
Solar cell technologies

- Homojunction solar cells
  - Crystalline silicon
- Thin film cells
  - Amorphous Si (a-Si:H)
  - Composite semiconductors
    - $Cu(In,Ga)Se_2$ (CIGS)
    - CdTe
- Heterojunction solar cells
- 3rd generation solar cells
  - Tandem solar cells



Homojunctions

- Materials
  - Silicon
  - Compound semiconductors
- Advantages
  - Efficient
  - Relatively cost-efficient
  - Mature technology
- Disadvantage
  - Material consumption

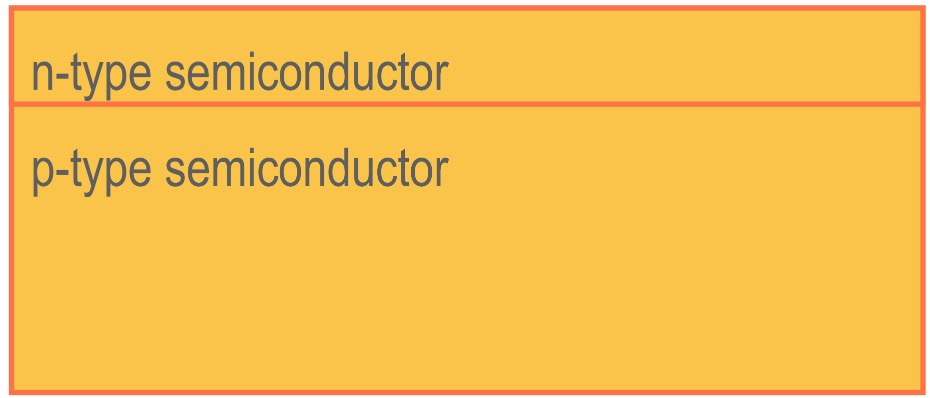



sc-Si


mc-Si

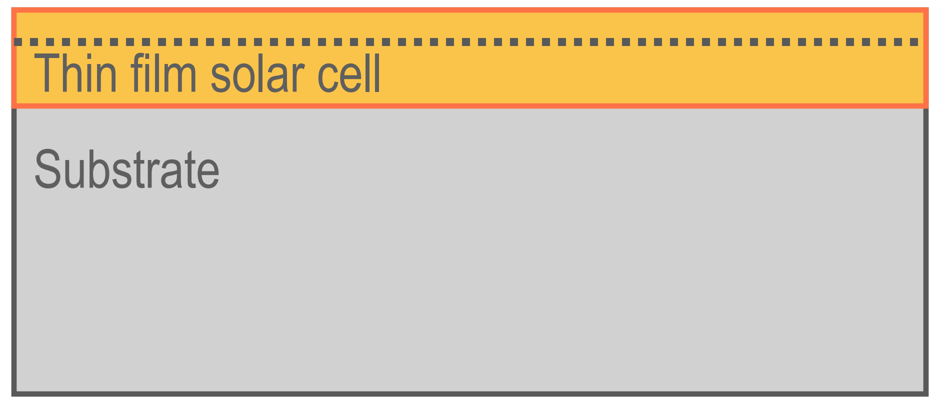
Heterojunctions

- Materials
  - a-Si on Si
  - Most thin film solar cells
    - CdS on CdTe or CIGS
- Advantages
  - Potentially very efficient
- Disadvantages
  - Metallurgical interface



Thin film solar cells

- Materials
  - Si (a-Si, sc-Si)
  - CdTe
  - CIS/CIGS ($Cu(In,Ga)Se_2$)
- Advantages
  - Low material consumption
  - Potentially cost-effective



- Disadvantages
  - Material quality
  - Material issues (In, Cd)
  - Somewhat immature technology

Clever student question:

If deposited materials often are of low quality, why bother with thin film solar cells?

Motivation

- The **big** challenge for the photovoltaic industry is to make solar electricity cost-competitive
- Currently, substrate-based solar cells made from crystalline silicon dominate the solar cell
  - “First generation solar cells”
  - Strengths: infrastructure, performance, material availability
  - Weaknesses: high material consumption (“thick” substrates, kerf losses), relatively expensive materials, high energy consumption
- Thin film solar cells might reduce costs and energy expenditure due to a significantly lower consumption of expensive materials

… so what is all the fuzz about?

- Dagens næringsliv 27/12 2006:
  - Lars Stolt, Solibro: ”Skal sette REC i skyggen” DN 27/12 2006
  - “Current REC solar cells will be out of the competition in 15 years”
  - Technology now in production under Q-modules
- Flexible CIGS submodule reaches 15.9% efficiency
  - April 2010

- Is the silicon era coming to an end?

Worried about the competition?

Q.CELLS

Core Business	New Technologies
- World's second largest cell producer - Forecast 2006: Production 255 MW_p Sales EUR 525 million - Strategy: Growth and cost reduction - Strong focus on R&D/new technologies - New cell concepts and thin film modules	**EverQ GmbH** - String Ribbon technology - Q-Cells share: 33% **CSG Solar AG** - Thin-film technology: Crystalline Silicon on Glass - Q-Cells share: 23% **Brilliant 234. GmbH** - Micromorph silicon thin-film technology - Q-Cells share: 100% **VHF-Technologies SA** - a-Si roll-to-roll on film ("flexcell") - Q-Cells share: 15 to 51% **Calyxo GmbH** - Thin-film technology - Q-Cells share: 100% **NewCo GmbH** - Thin-film technology under consideration

Q-Cells

The benefits of thin film solar cells

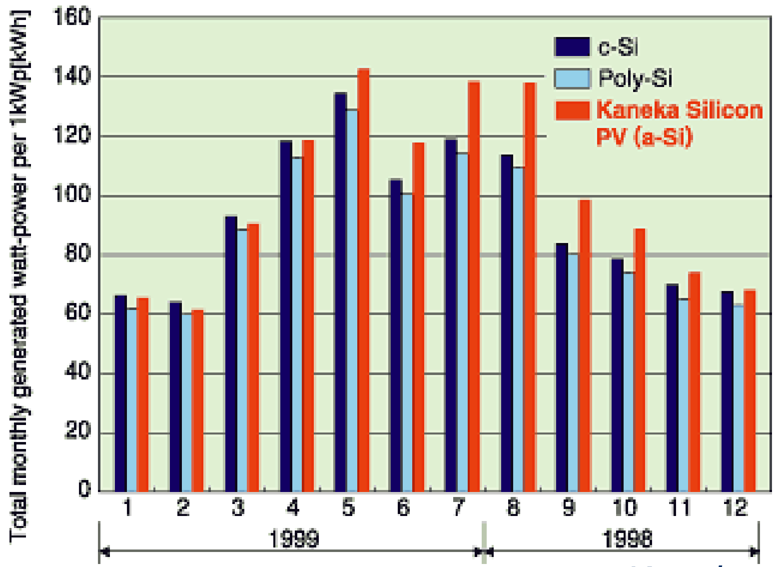
- Potential for drastic cost reductions for solar electricity
  - Less consumption of expensive materials (~1 µm cell vs ~250 µm cell)
  - Solar cell efficiencies are still increasing both in laboratories and production
  - Integrated production of solar cell modules

Silicon production	Wafering	Solar cell processing	Module fabrication
Solar cell deposition and module fabrication			

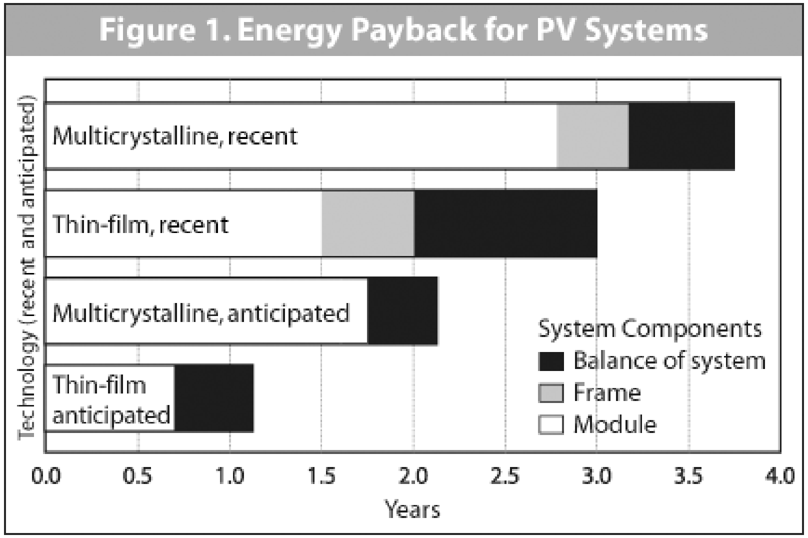
  - Scribing and creative use of interconnections allow for flexibility in module voltages
  - Many available substrates

The benefits of thin film solar cells

- Lower energy payback times
- Good field performance when compared with nominal output



Kaneka



NREL

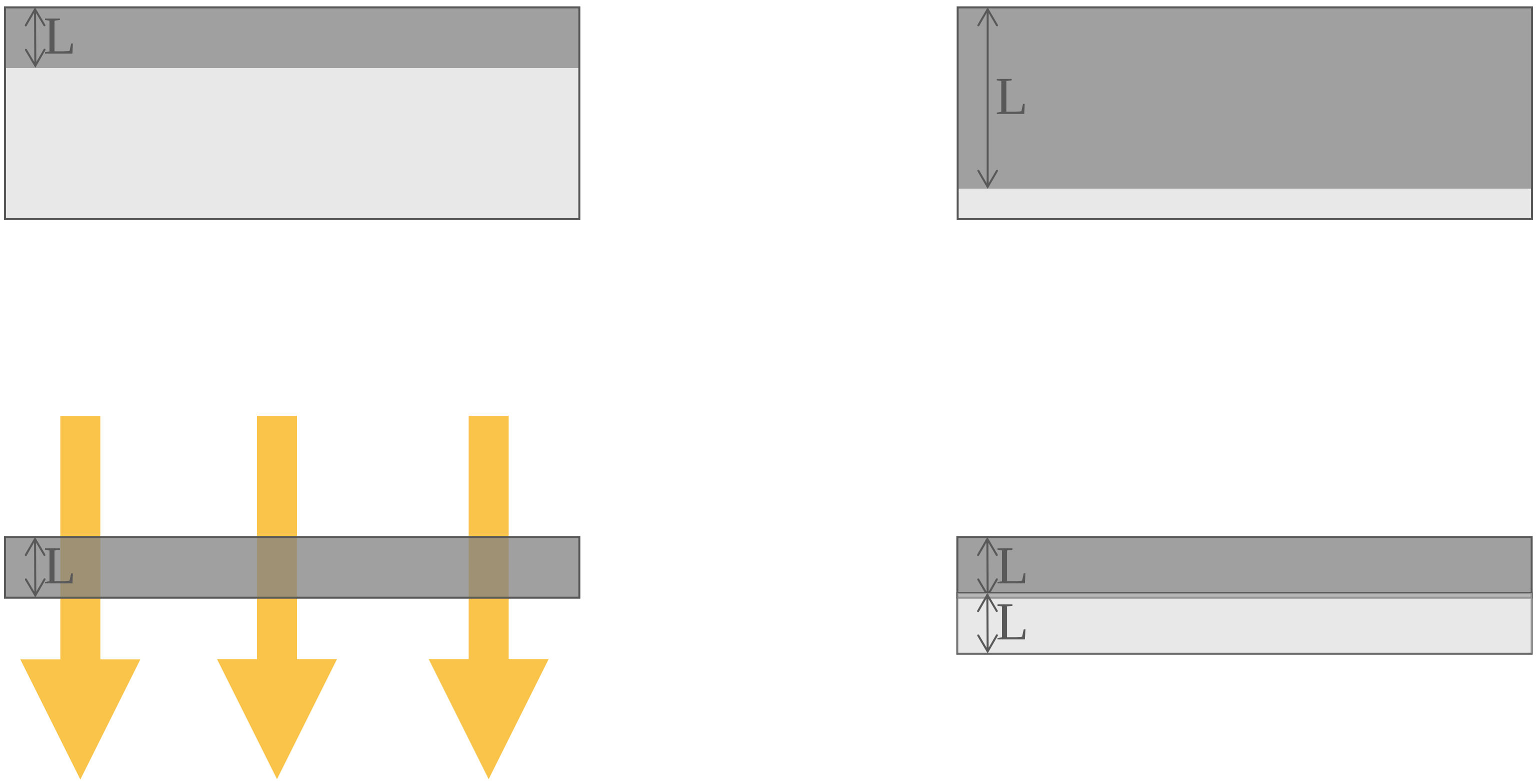
The challenges of thin film solar cells

- All of the technologies to be presented is faced with one or more of the following challenges:
  - Immature technologies
  - Throughput / deposition rates
  - Short module lifetimes
  - Low availability of esoteric materials
    - In, Ga …
  - Cadmium usage
  - Typically low ***module*** efficiencies compared with Si
    - mc-Si: 15 – 18%
    - sc-Si: 17 – 20%
    - ”high-end” sc-Si: 20 – 23%

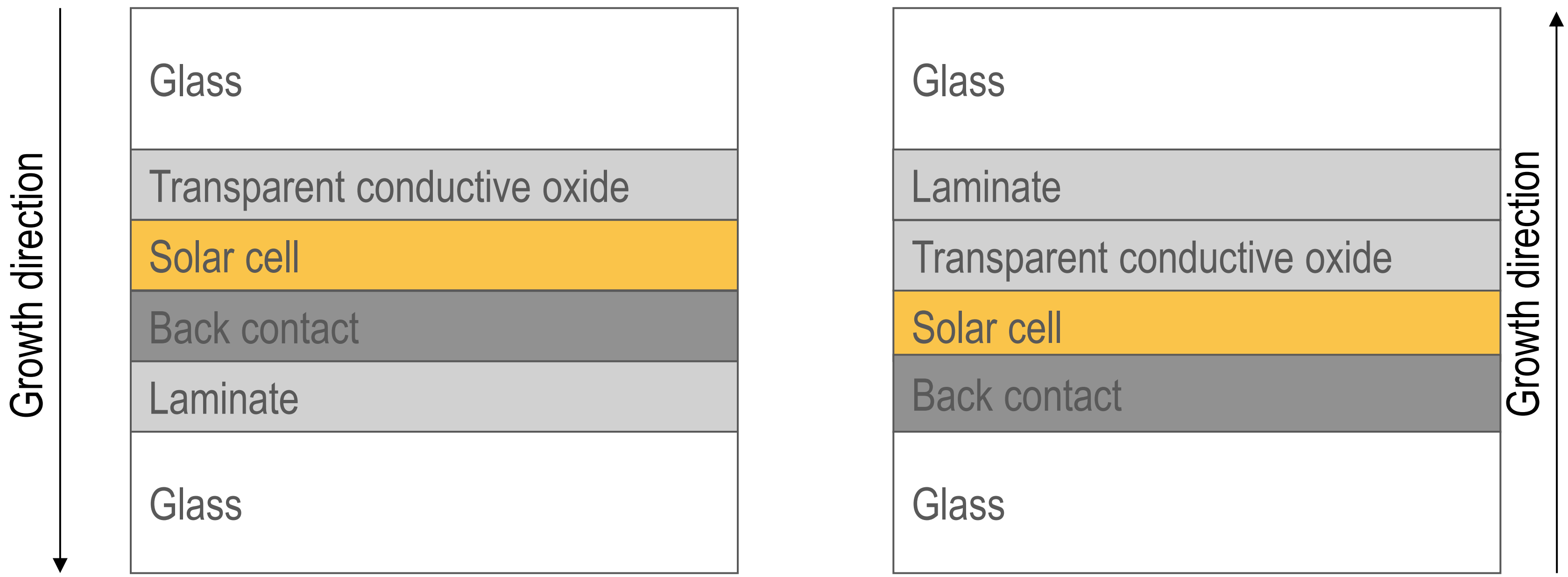
Material requirements for thin film solar cells

- Strong absorption vital
- Diffusion lengths can be shorter
- Surface passivation can be important
- Interface recombination must be low

Material requirements for thin film solar cells



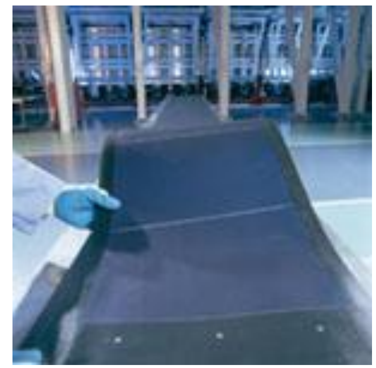
Substrates/superstrates



Silicon-based thin film solar cells

Amorphous silicon thin film

- The most developed of the thin film technologies
- Thin films of a-Si are produced using CVD of silane
  - Usually PECVD or ”hot wire” CVD
- Wide selection of substrates
  - Glass, metal sheets, plastics…
- High H content required in order to passivate defects
- Solar cell efficiency is severely degraded during illumination
  - Staebler-Wronski effect



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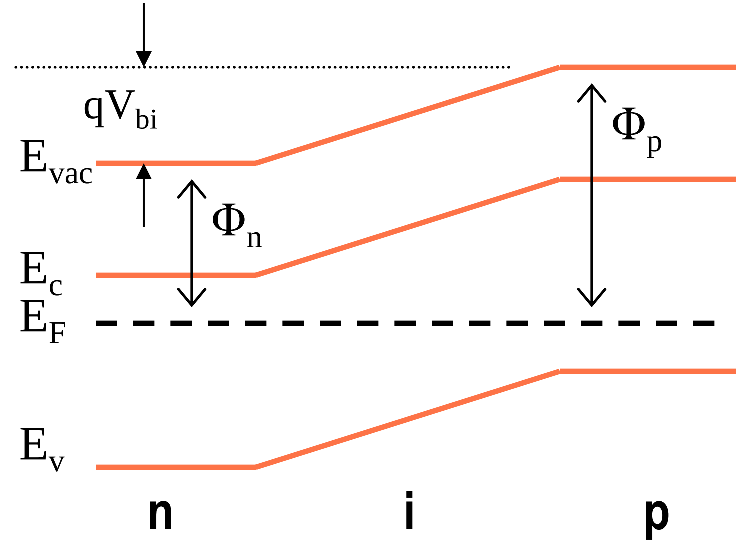
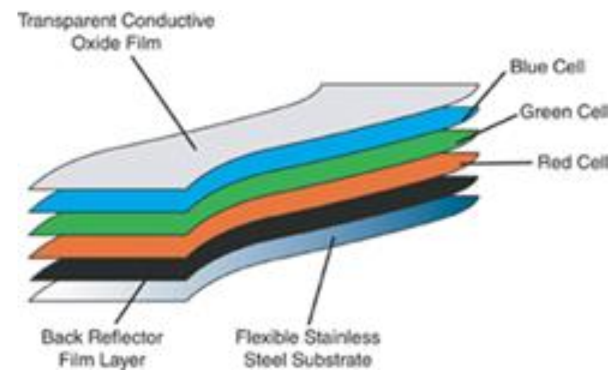
Amorphous silicon thin film

- Cell design challenges
  - Doping a-Si gives large recombination losses
  - Cells must have a certain thickness in order for sufficient absorption to occur
  - Conventional p-n homojunction structures not suitable
- Good solar cell performance is made by using p-i-n structures or tandem solar cells
  - a-Si and µc-Si or a-SiGe
  - More complex cell fabrication!





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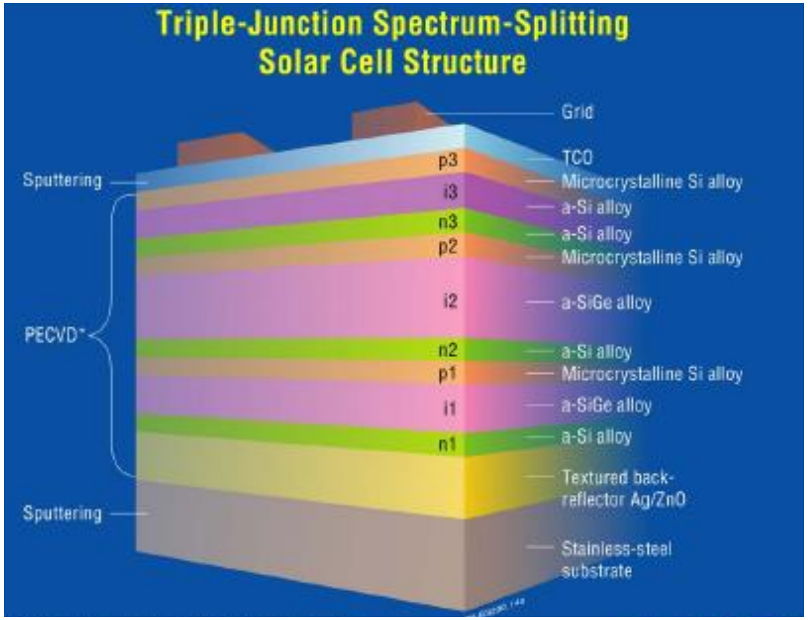
Amorphous silicon thin film

- Typical module efficiency
  - ~ 6 – 8 %
- Record efficiency: 10.2 % (AIST)



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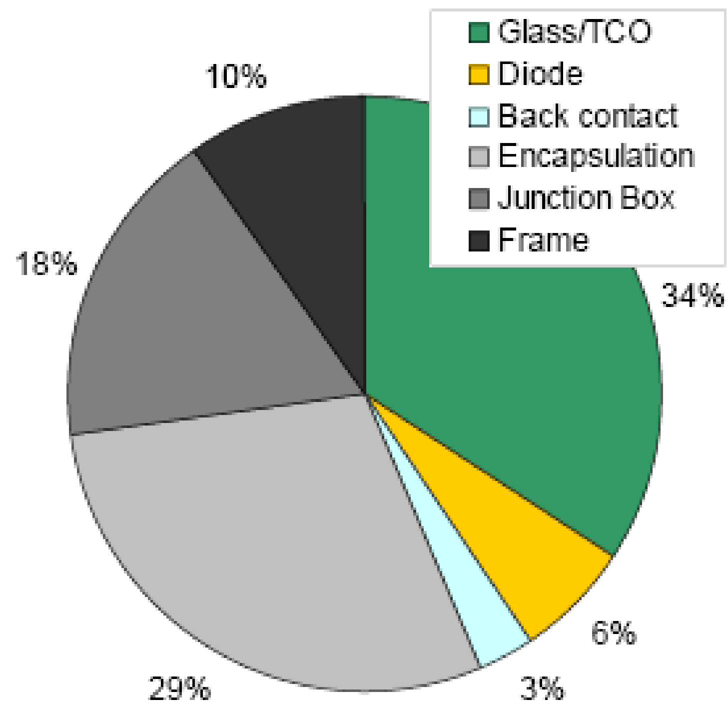
Microcrystalline silicon thin film

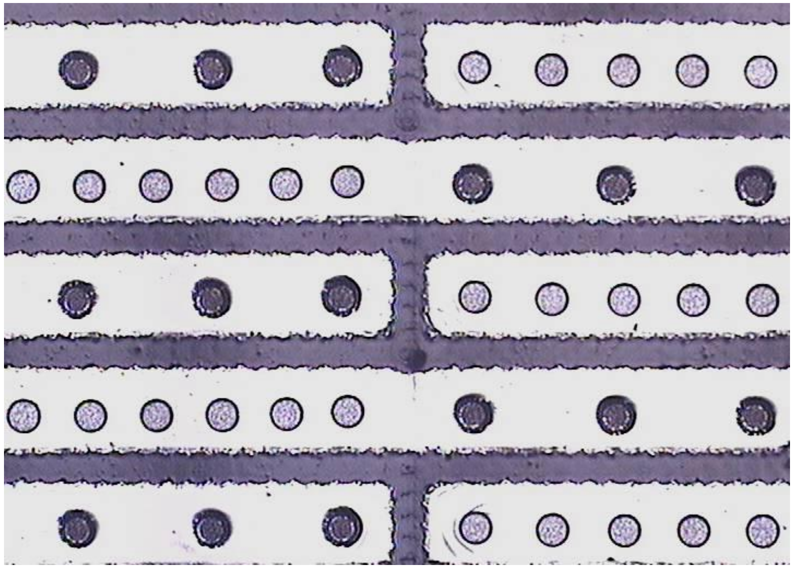
- Builds on experience with a-Si solar cells
- Main idea: to combine a-Si advantages with the stability and performance of crystalline Si
  - Best efficiencies
    - µc-Si: 10%
    - a-Si/uc-Si: 14%
- µc-Si can also replace a-SiGe in a-Si tandem solar cells
  - Use of expensive germane is avoided
  - Must have thick uc-Si and thinner a-Si due to absorption and stability, hence deposition rates are an issue
- Efficiency record: 11.9% (AIST)



Brilliant234/Q-cells

Polycrystalline silicon thin film

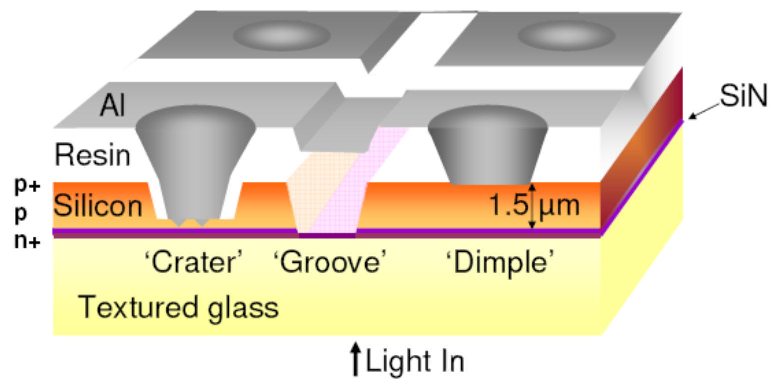
- A further improvement in Si material quality
  - Larger Si grains than in µc-Si
- Module efficiencies:
  - Approaching 10 %
- Research groups
  - IMEC, UNSW



CSG Solar

Polycrystalline silicon thin film

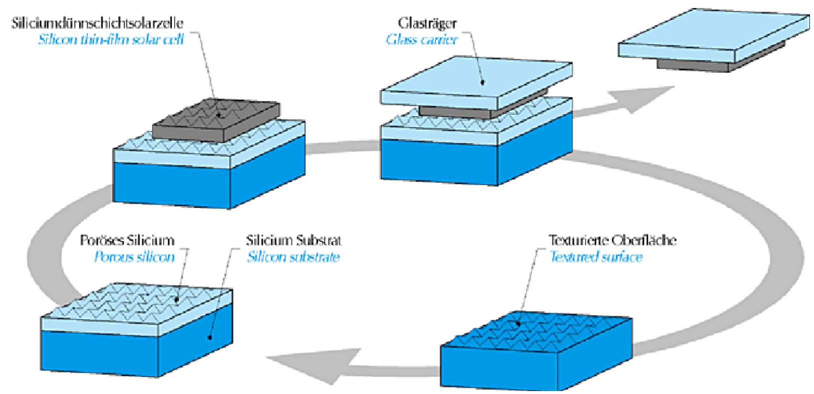
- Example process: CSG Solar
  1. Use a textured borosilicate glass substrate
  2. Deposit SiN with PECVD
  3. Deposit n+/p/p+ Si structure with PECVD
  4. Crystallise Si
  5. Anneal defects
  6. Hydrogen passivation
  7. Laser scribing (cell separation)
  8. Resin coating
  9. Opening of resin and selective etching of Si (two steps: front and rear contact)
  10. Deposit Al contacts
  11. Laser pattering of contacts



CSG Solar

Monocrystalline silicon thin film

- A thin film solar cell that maintains all benefits of sc-Si
- Based on lift-off techniques
  1. A porous silicon double layer is formed on a silicon substrate
  2. Silicon is epitaxially grown atop the porous film
  3. The silicon film thus grown is lifted off the silicon (carrier) substrate
- Related companies
  - Crystal solar, solexel
- Also relevant
  - ELTRAN process (Canon)



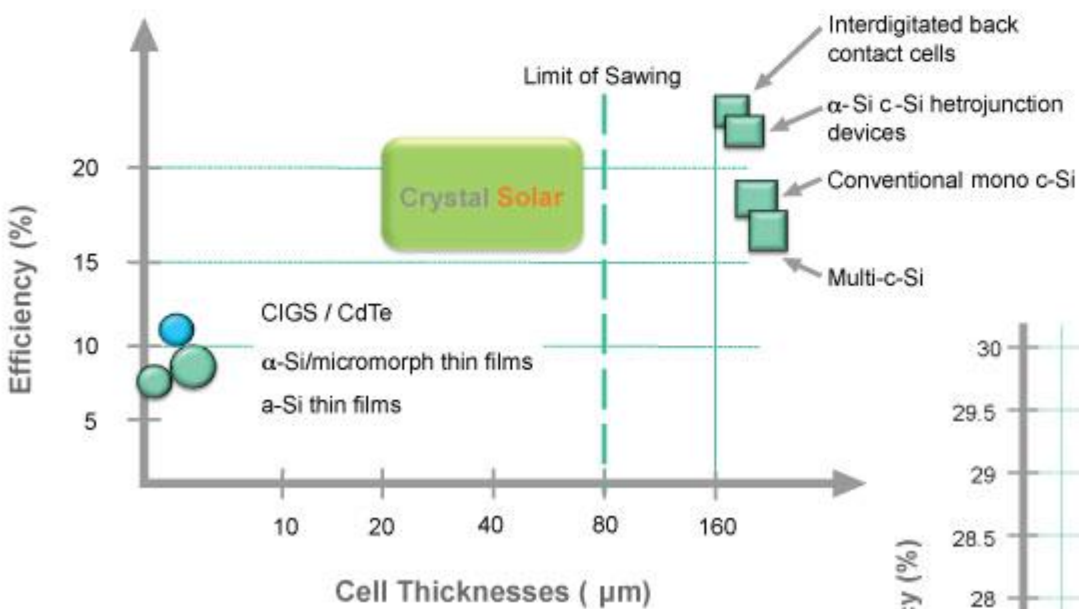
ISFH

Example module

SOLEXEL®

Example module

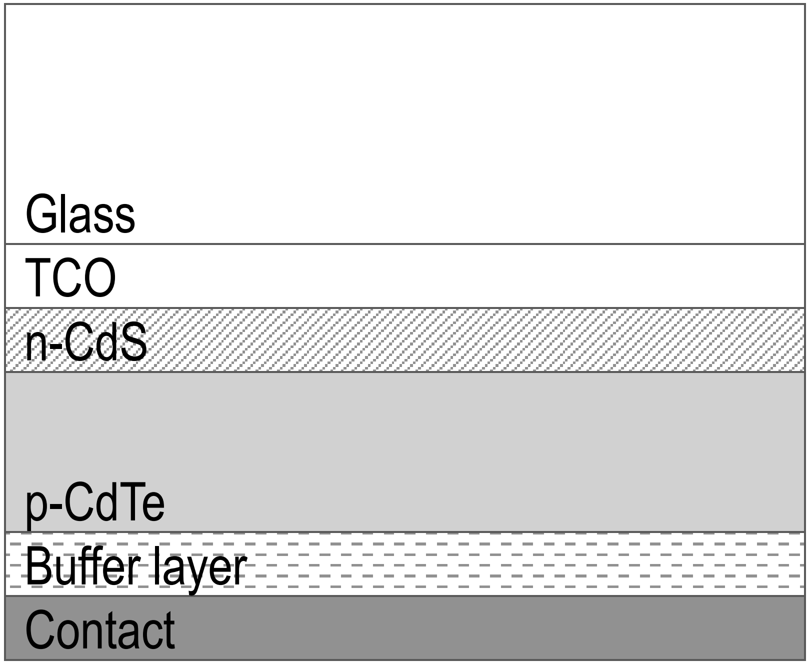
Example module



Alternative thin film solar cells

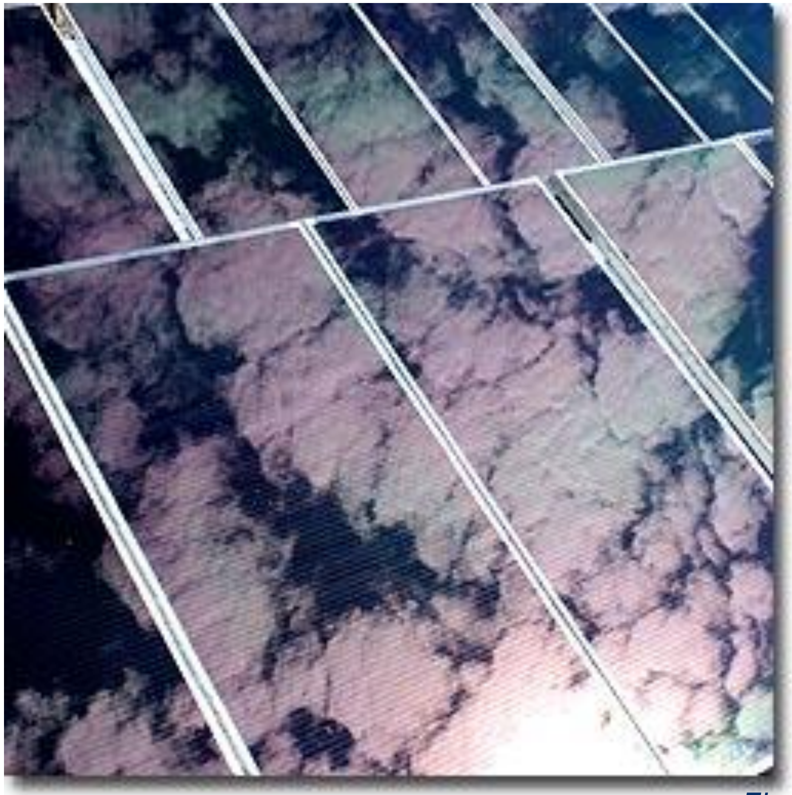
CdTe solar cells

- Heterojunction solar cell
  - n-type CdTe is hard to make
    - Best p-n CdTe homojunction cell: ~ 13% efficiency
    - CdTe/CdS heterojunction: 21.0%
- Solar cell structure
  - CdS buffer / window layer
  - CdTe absorber layer
- Band gap energies
  - CdTe: 1.45 eV
  - CdS: 2.4 eV



CdTe solar cells

- Fabrication techniques
  - Close spaced sublimation (CSS) used in the industry for CdTe formation
  - Chemical bath deposition typically used for depositing CdS
  - CVD, screen-printing, electrodeposition, spray pyrolysis and sputtering other candidates
- Company
  - First Solar



First Solar

CdTe solar cells

- Cadmium is **not** the greenest of elements
  - Toxic
  - Environmentally risky
  - Politically unpopular
- However, very little Cd is actually used for each module, and only in a bound state
- One serious challenge: response to fires

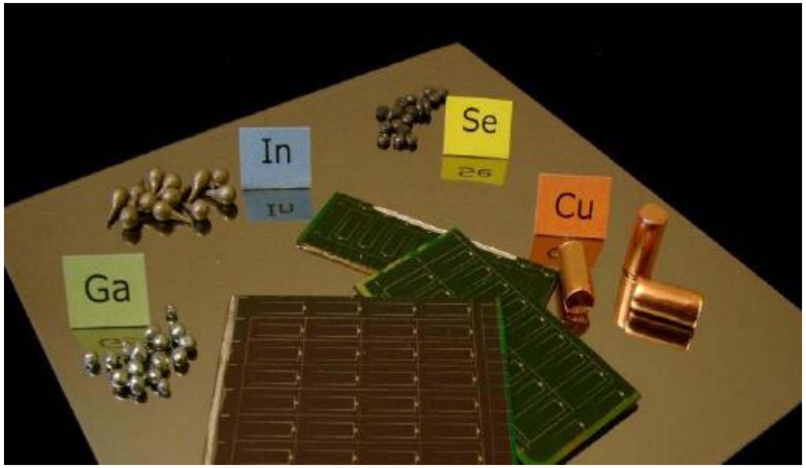
www.wikipedia.org

CIS/CIGS

- What is CIS and CIGS?
  - CIGS = $CuIn_{,x}Ga_{1-x}Se_2$
  - CIS = $CuInS_2$
- Exhibit a chalcopyrite material structure
- Band gap energies
  - CIS: 1.5 eV
  - CIGS: ~1.0 – 1.25 eV
- Tunable band gap energy

$$E_g\ [eV] = 1.02 + 0.67x + bx(x-1)$$
$$x = Ga/(In+Ga),\ b \sim 0.1 - 0.2$$

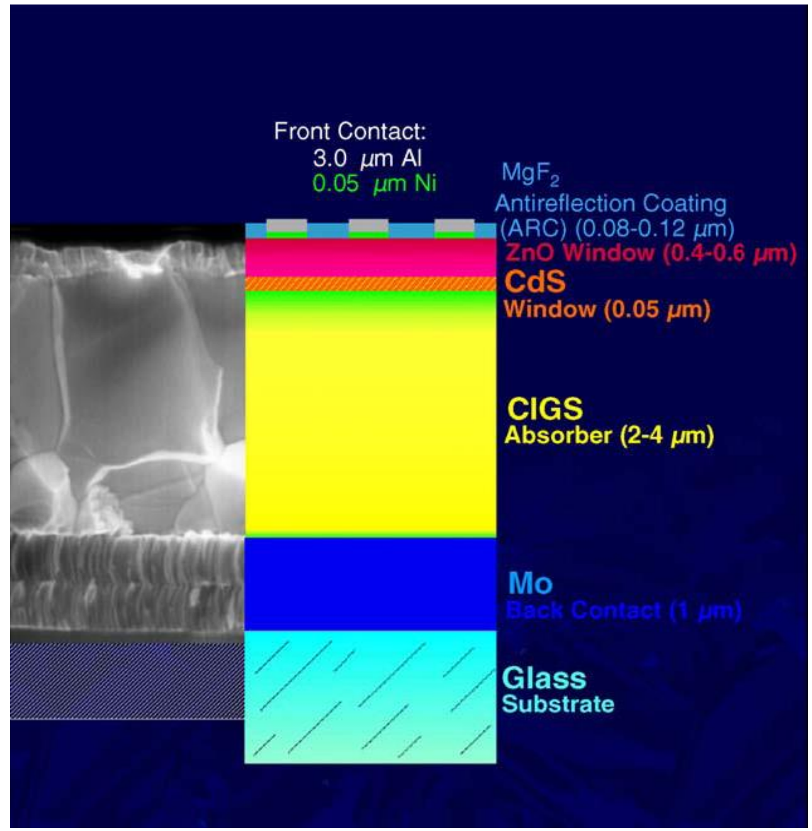
- 1.25 eV seems to be the maximum usable value before resistive losses caused by Ga become dominant



M. Edoff – ÅSC

CIS/CIGS

- Heterojunction solar cells perform better than homojunctions
- Record efficiency: 21.7% (Solar Frontier)



L. Kazmersky – NREL

Challenges

- Moisture is harmful for CIGS cells
- CdS should be replaced by other compounds
  - E.g. ZnO, [Zn,Mg]O, In_2S, ZnS
  - Work at ÅSC has shown that ZnO deposited by ALD gives improved blue response when compared with CdS
- Little In available
- Poor red response
- Recombination at heterojunction

«Kesterites»

- CZTS, a substitutional alloy
- Record efficiency 10.0% (UNSW)

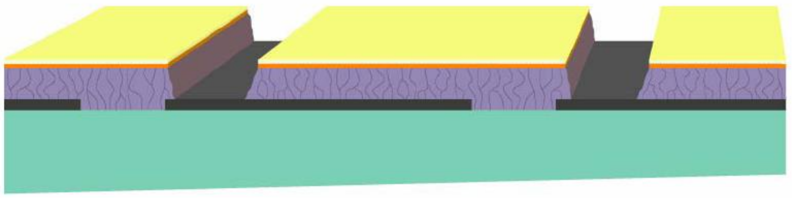
Making CIGS modules

1. The float glass substrate is washed
2. Deposition of Mo back contact by sputtering
3. Patterning of the back contact by laser scribing

L. Stolt – ÅSC/Solibro AB

Making CIGS modules

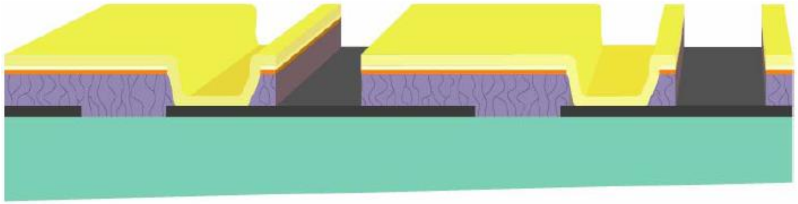
4. The CIGS-layer (Cu(InGa)Se2) is deposited by co-evaporation
5. Coating of ultra-thin buffer layers (50 nm) of CdS and ZnO
6. These semiconductor layers are patterned using a mechanical stylus



L. Stolt – ÅSC/Solibro AB

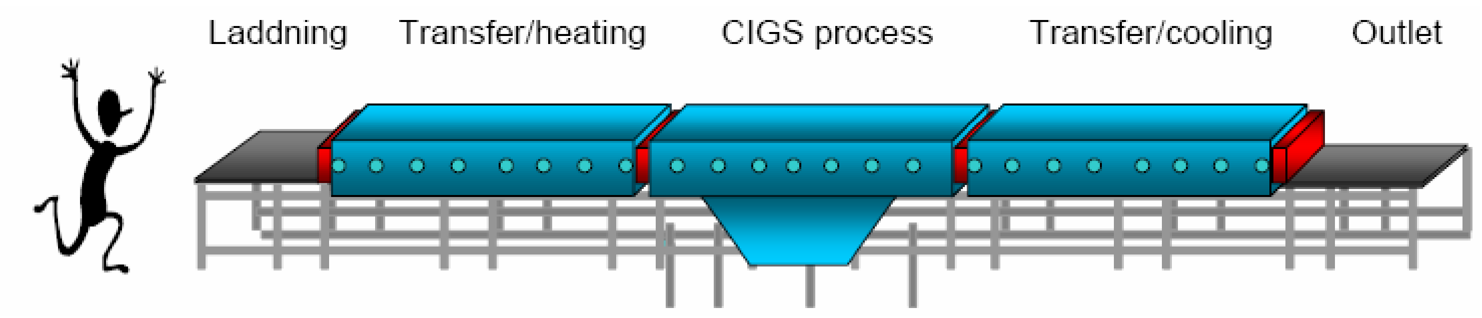
Making CIGS modules

7. A front contact of Al-doped ZnO is sputter-deposited
8. The front contact is patterned using a mechanical stylus



L. Stolt – ÅSC/Solibro AB

Making CIGS modules



L. Stolt – ÅSC/Solibro AB

Making CIGS modules

9. Edge deletion
10. Edge tabbing
11. Lamination
12. Framing
13. Junction box

Perovskites?

nature photonics

ARTICLES

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Efficient inorganic–organic hybrid heterojunction solar cells containing perovskite compound and polymeric hole conductors

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Efficiency

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ACCELERATED PUBLICATION

Solar cell efficiency tables (version 50)

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TABLE 1 Confirmed single-junction terrestrial cell and submodule efficiencies measured under the global AM1.5 spectrum (1000 W/m^2) at 25°C (IEC 60904-3: 2008, ASTM G-173-03 global). New entries in bold type

Classification	Efficiency (%)	Area (cm^2)	V_{oc} (V)	J_{sc} (mA/cm^2)	Fill Factor (%)	Test Centre (date)	Description
Silicon							
Si (crystalline cell)	**26.7 ± 0.5**	**79.0 (da)**	**0.738**	**42.65[a]**	**84.9**	**AIST (3/17)**	**Kaneka, n-type rear IBC[5]**
Si (multicrystalline cell)	**21.9 ± 0.4[b]**	**4.0003 (t)**	**0.6726**	**40.76[a]**	**79.7**	**FhG-ISE (2/17)**	**FhG-ISE, n-type[6]**
Si (thin transfer submodule)	21.2 ± 0.4	239.7 (ap)	0.687[c]	38.50[c,d]	80.3	NREL (4/14)	Solexel (35 μm thick)[7]
Si (thin film minimodule)	10.5 ± 0.3	94.0 (ap)	0.492[c]	29.7[c]	72.1	FhG-ISE (8/07)[e]	CSG Solar (<2 μm on glass)[8]
III-V cells							
GaAs (thin film cell)	28.8 ± 0.9	0.9927 (ap)	1.122	29.68[f]	86.5	NREL (5/12)	Alta Devices[9]
GaAs (multicrystalline)	18.4 ± 0.5	4.011 (t)	0.994	23.2	79.7	NREL (11/95)	RTI, Ge substrate[10]
InP (crystalline cell)	**24.2 ± 0.5[b]**	**1.008 (ap)**	**0.939**	**31.15[a]**	**82.6**	**NREL (9/12)**	**NREL[11]**
Thin film chalcogenide							
CIGS (cell)	**21.7 ± 0.5**	**1.044 (da)**	**0.718**	**40.70[a]**	**74.3**	**AIST (1/17)**	**Solar Frontier[12]**
CdTe (cell)	21.0 ± 0.4	1.0623 (ap)	0.8759	30.25[d]	79.4	Newport (8/14)	First Solar, on glass[13]
CZTS (cell)	**10.0 ± 0.2**	**1.113 (da)**	**0.7083**	**21.77[a]**	**65.1**	**NREL (3/17)**	**UNSW[14]**
Amorphous/microcrystalline							
Si (amorphous cell)	10.2 ± 0.3[g,b]	1.001 (da)	0.896	16.36[d]	69.8	AIST (7/14)	AIST[15]
Si (microcrystalline cell)	**11.9 ± 0.3[b]**	**1.044 (da)**	**0.550**	**28.72[a]**	**75.0**	**AIST (2/17)**	**AIST[16]**
Perovskite							
Perovskite (cell)	19.7 ± 0.6[g,h]	0.9917 (da)	1.104	24.67[i]	72.3	Newport (3/16)	KRICT/UNIST[17]
Perovskite (minimodule)	**16.0 ± 0.4[g,h]**	**16.29 (ap)**	**1.029[c]**	**19.51[c,a]**	**76.1**	**Newport (4/17)**	**Microquanta, 6 serial cells[18]**
Dye sensitised							
Dye (cell)	11.9 ± 0.4[j]	1.005 (da)	0.744	22.47[k]	71.2	AIST (9/12)	Sharp[19]
Dye (minimodule)	10.7 ± 0.4[j]	26.55 (da)	0.754[c]	20.19[c,l]	69.9	AIST (2/15)	Sharp, 7 serial cells[19]
Dye (submodule)	8.8 ± 0.3[j]	398.8 (da)	0.697[c]	18.42[c,m]	68.7	AIST (9/12)	Sharp, 26 serial cells[20]
Organic							
Organic (cell)	11.2 ± 0.3[n]	0.992 (da)	0.780	19.30[d]	74.2	AIST (10/15)	Toshiba[21]
Organic (minimodule)	9.7 ± 0.3[n]	26.14 (da)	0.806	16.47[c,l]	73.2	AIST (2/15)	Toshiba (8 series cells)[22]

TABLE 2 Confirmed multiple-junction terrestrial cell and submodule efficiencies measured under the global AM1.5 spectrum (1000 W/m^2) at 25°C (IEC 60904-3: 2008, ASTM G-173-03 global). New entries in bold type

Classification	Efficiency (%)	Area (cm^2)	Voc (V)	Jsc (mA/cm^2)	Fill Factor (%)	Test Centre (date)	Description
III-V Multijunctions							
5 junction cell (bonded)	38.8 ± 1.2	1.021 (ap)	4.767	9.564	85.2	NREL (7/13)	Spectrolab, 2-terminal[23]
(2.17/1.68/1.40/1.06/0.73 eV)							
InGaP/GaAs/InGaAs	37.9 ± 1.2	1.047 (ap)	3.065	14.27[a]	86.7	AIST (2/13)	Sharp, 2 term.[24]
GaInP/GaAs(monolithic)	31.6 ± 1.5	0.999 (ap)	2.538	14.18[b]	87.7	NREL (1/16)	Alta Devices, 2 term.[25]
Multijunctions with c-Si							
GaInP/GaAs/Si (mech. stack)	**35.9 ± 0.5[c]**	**1.002 (da)**	**2.52/0.681**	**13.6/11.0**	**87.5/78.5**	**NREL (2/17)**	**NREL/CSEM/EPFL, 4-term.[26]**
GaInP/GaAs/Si (wafer bonded)	**31.3 ± 1.1[c]**	**3.981 (ap)**	**3.046**	**11.7[d]**	**87.5**	**FhG-ISE (3/17)**	**Fraunhofer ISE, 2-term.[27]**
GaInP/GaAs/Si (monolithic)	19.7 ± 0.7[c]	3.943 (ap)	2.323	10.0[e]	84.3	FhG-ISE (8/16)	Fraunhofer ISE[28]
GaAs/Si (mech. stack)	**32.8 ± 0.5[c]**	**1.003 (da)**	**1.09/0.683**	**28.9/11.1**	**85.0/79.2**	**NREL (12/16)**	**NREL/CSEM/EPFL, 4-term.[26]**
Perovskite/Si (monolithic)	23.6 ± 0.6[f]	0.990 (ap)	1.651	18.09[e]	79.0	NREL (8/16)	Stanford/ASU[29]
GaInP/GaInAs/Ge; Si(spectral split minimodule)	34.5 ± 2.0	27.83 (ap)	2.66/0.65	13.1/9.3	85.6/79.0	NREL (4/16)	UNSW/Azur/Trina, 4-term.[30]
a-Si/nc-Si Multijunctions							
a-Si/nc-Si/nc-Si (thin-film)	14.0 ± 0.4[g,c]	1.045 (da)	1.922	9.94[e]	73.4	AIST (5/16)	AIST[31]
a-Si/nc-Si (thin-film cell)	12.7 ± 0.4%[g,c]	1.000(da)	1.342	13.45[h]	70.2	AIST (10/14)	AIST[15,32]

TABLE 3 Confirmed terrestrial module efficiencies measured under the global AM1.5 spectrum (1000 W/m^2) at a cell temperature of 25°C (IEC 60904-3: 2008, ASTM G-173-03 global). New entries in bold type

Classification	Effic. (%)	Area (cm^2)	V_{oc} (V)	I_{sc} (A)	FF (%)	Test Centre (date)	Description
Si (crystalline)	24.4 ± 0.5	13177 (da)	79.5	5.04[a]	80.1	AIST (9/16)	Kaneka (108 cells)[5]
Si (multicrystalline)	19.9 ± 0.4	15143 (ap)	78.87	4.795[a]	79.5	FhG-ISE (10/16)	Trina Solar (120 cells)[33]
GaAs (thin film)	**24.8 ± 0.5**	**865.3 (ap)**	**11.07**	**2.288[b]**	**84.7**	**NREL (11/16)**	**Alta Devices[34]**
CIGS (Cd free)	**19.2 ± 0.5**	**841 (da)**	**48.0**	**0.456[b]**	**73.7**	**AIST (1/17)**	**Solar Frontier (70 cells)[35]**
CIGS (large)	15.7 ± 0.5	9703 (ap)	28.24	7.254[c]	72.5	NREL (11/10)	Miasole[36]
CdTe (thin-film)	18.6 ± 0.6	7038.8 (ap)	110.6	1.533[d]	74.2	NREL (4/15)	First Solar, monolithic[37]
a-Si/nc-Si (tandem)	12.3 ± 0.3[e]	14322 (t)	280.1	0.902[f]	69.9	ESTI (9/14)	TEL Solar, Trubbach Labs[38]
Organic	8.7 ± 0.3[g]	802 (da)	17.47	0.569[h]	70.4	AIST (5/14)	Toshiba[22]
Multijunction							
InGaP/GaAs/InGaAs	31.2 ± 1.2	968 (da)	23.95	1.506	83.6	AIST (2/16)	Sharp (32 cells)[39]

TABLE 4 "Notable exceptions": "Top dozen" confirmed cell and module results, not class records measured under the global AM1.5 spectrum ($1000\ Wm^{-2}$) at 25°C (IEC 60904-3: 2008, ASTM G-173-03 global). New entries in bold type

Classification	Efficiency (%)	Area (cm^2)	V_{oc} (V)	J_{sc} (mA/cm^2)	Fill Factor (%)	Test Centre (date)	Description
Cells (silicon)							
Si (crystalline)	25.0 ± 0.5	4.00 (da)	0.706	42.7[a]	82.8	Sandia (3/99)[b]	UNSW p-type PERC top/rear contacts[40]
Si (crystalline)	**25.7 ± 0.5[c]**	**4.017 (da)**	**0.7249**	**42.54[d]**	**83.3**	**FhG-ISE (3/17)**	**FhG-ISE, n-type top/rear contacts[41]**
Si (large)	**26.6 ± 0.5**	**179.74 (da)**	**0.7403**	**42.5[d]**	**84.7**	**FhG-ISE (11/16)**	**Kaneka, n-type rear IBC[5]**
Si (multicrystalline)	21.3 ± 0.4	242.74 (t)	0.6678	39.80[e]	80.0	FhG-ISE (11/15)	Trina Solar, large p-type[42]
Cells (III-V)							
GaInP	21.4 ± 0.3	0.2504 (ap)	1.4932	16.31[f]	87.7	NREL (9/16)	LG Electronics, high bandgap[43]
Cells (chalcogenide)							
CIGS (thin-film)	22.6 ± 0.5	0.4092 (da)	0.7411	37.76[f]	80.6	FhG-ISE (2/16)	ZSW on glass[44]
CIGSS (Cd free)	**22.0 ± 0.5**	**0.512 (da)**	**0.7170**	**39.45[f]**	**77.9**	**FhG-ISE (2/16)**	**Solar Frontier on glass[12]**
CdTe (thin-film)	22.1 ± 0.5	0.4798 (da)	0.8872	31.69[g]	78.5	Newport (11/15)	First Solar on glass[45]
CZTSS (thin-film)	12.6 ± 0.3	0.4209 (ap)	0.5134	35.21[h]	69.8	Newport (7/13)	IBM solution grown[46]
CZTS (thin-film)	**11.0 ± 0.2**	**0.2339(da)**	**0.7306**	**21.74[d]**	**69.3**	**NREL (3/17)**	**UNSW on glass[14]**
Cells (other)							
Perovskite (thin-film)	22.1 ± 0.7[i]	0.0946 (ap)	1.105	24.97[j]	80.3	Newport (3/16)	KRICT/UNIST[17]
Organic (thin-film)	**12.1 ± 0.3[k]**	**0.0407 (ap)**	**0.8150**	**20.27[d]**	**73.5**	**Newport (2/17)**	**Phillips 66**

Abbreviations: CIGSS, CuInGaSSe; CZTSS, $Cu_2ZnSnS_{4-y}Se_y$; CZTS, Cu_2ZnSnS_4; (ap), aperture area; (t), total area; (da), designated illumination area; AIST, Japanese National Institute of Advanced Industrial Science and Technology; NREL, National Renewable Energy Laboratory; FhG-ISE, Fraunhofer-Institut für Solare Energiesysteme.

TABLE 5 "Direct beam" terrestrial concentrator cell and module efficiencies measured under the ASTM G-173-03 direct AM1.5 spectrum at a cell temperature of 25°C. New entries in bold type

Classification	Effic. (%)	Area (cm^2)	Intensity[a] (suns)	Test Centre (date)	Description
Single cells					
GaAs	29.3 ± 0.7[b]	0.09359 (da)	49.9	NREL (10/16)	LG Electronics
Si	27.6 ± 1.2[c]	1.00 (da)	92	FhG-ISE (11/04)	Amonix back-contact[48]
CIGS (thin-film)	23.3 ± 1.2[d,e]	0.09902 (ap)	15	NREL (3/14)	NREL[49]
Multijunction cells					
GaInP/GaAs; GaInAsP/GaInAs	46.0 ± 2.2[f]	0.0520 (da)	508	AIST (10/14)	Soitec/CEA/FhG-ISE 4j bonded[50]
GaInP/GaAs/GaInAs/GaInAs	45.7 ± 2.3[d,g]	0.09709 (da)	234	NREL (9/14)	NREL, 4j monolithic[51]
InGaP/GaAs/InGaAs	44.4 ± 2.6[h]	0.1652 (da)	302	FhG-ISE (4/13)	Sharp, 3j inverted metamorphic[52]
GaInP/GaInAs	**35.1 ± 1.1 [d,i]**	**0.05376 (da)**	**407**	**FhG-ISE (3/17)**	**Fraunhofer ISE 2j[53]**
Minimodule					
GaInP/GaAs; GaInAsP/GaInAs (wafer bonded)	43.4 ± 2.4[d,j]	18.2 (ap)	340[k]	FhG-ISE (7/15)	Fraunhofer ISE 4j (lens/cell)[54]
Submodule					
GaInP/GaInAs/Ge; Si	40.6 ± 2.0[m]	287 (ap)	365	NREL (4/16)	UNSW 4j split spectrum[55]
Modules					
Si	20.5 ± 0.8[d]	1875 (ap)	79	Sandia (4/89)[k]	Sandia/UNSW/ENTECH (12 cells)[56]
Three junction (3j)	35.9 ± 1.8[m]	1092 (ap)	N/A	NREL (8/13)	Amonix[57]
Four junction (4j)	38.9 ± 2.5[n]	812.3 (ap)	333	FhG-ISE (4/15)	Soitec[58]
"Notable Exceptions"					
Si (large-area cell)	21.7 ± 0.7	20.0 (da)	11	Sandia (9/90)[k]	UNSW laser grooved[59]
Luminescent minimodule	7.1 ± 0.2	25(ap)	2.5[k]	ESTI (9/08)	ECN Petten, GaAs cells[60]

Concluding remarks

- Many alternatives to crystalline silicon solar cells have been proposed
- Several thin film technologies, as well as some electrochemical solar cells have been industrialized
- What impact these technologies will have on the overall solar cell market both in the short and long run is uncertain
- Main challenges:
  - Scale-up in size and production volume
  - Increases in module efficiency
  - Stability
  - Material properties and, for very large production volumes, avaliability