MIT 3.071
Amorphous Materials

12: Amorphous Silicon Macroelectronics

Juejun (JJ) Hu

Electron's travels: from Lilliput to Brobdingnag

Microelectronics

"Smaller is smarter"

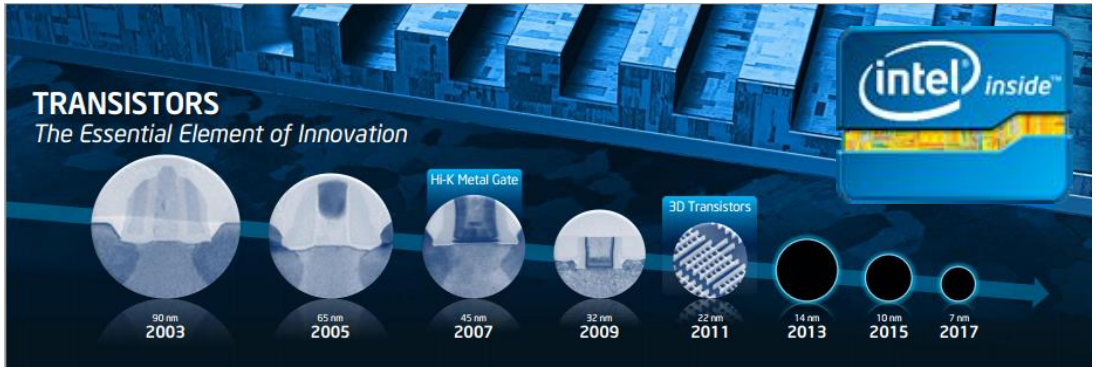


Image © Intel. All rights reserved. This content is excluded from our Creative Commons license. For more information, see http://ocw.mit.edu/help/faq-fair-use/.

Macroelectronics

"Bigger is better"



Courtesy of Springinging on Wikimedia Commons. License: CC BYSA. This content is excluded from our Creative Commons license. For more information, see http://ocw.mit.edu/help/faq-fair-use/.

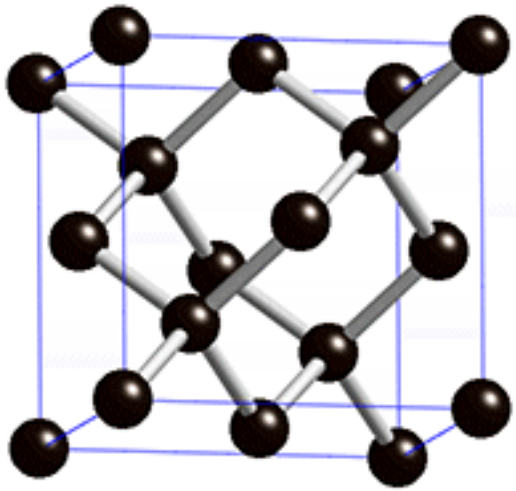
Why amorphous silicon?

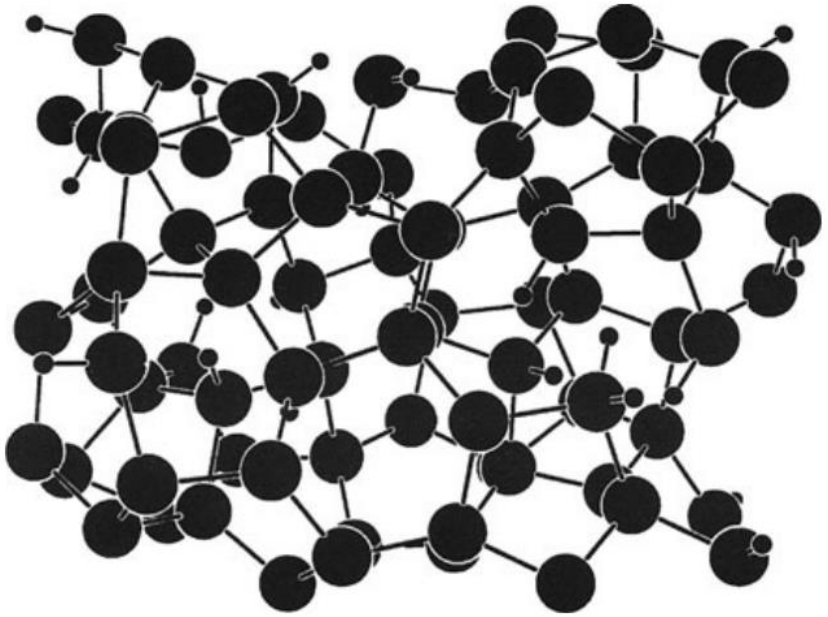
- Large-area, low-temperature, monolithic deposition
  - Low-cost, mature plasma-enhanced CVD (PECVD) process
  - Dielectrics and passivation layers can be formed using the same process
- Doping capacity
  - Effective passivation of defects (hydrogenation)
- CMOS compatibility
  - Leveraging existing infrastructure and knowledge base from the microelectronics industry

"The essence of being human is that one does not seek perfection."

-- George Orwell

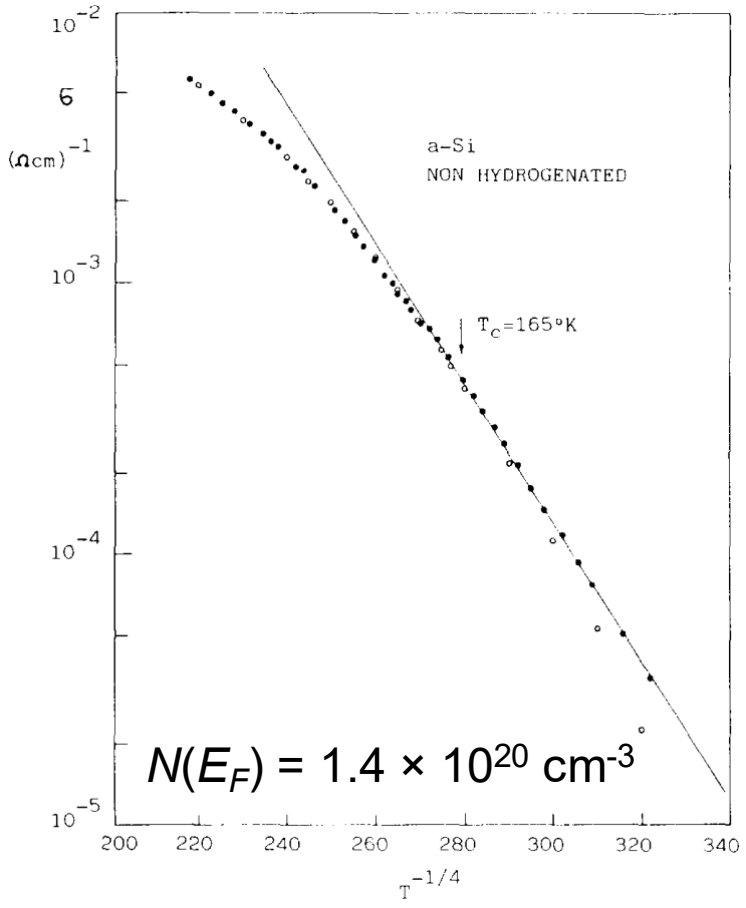
Structure of amorphous silicon





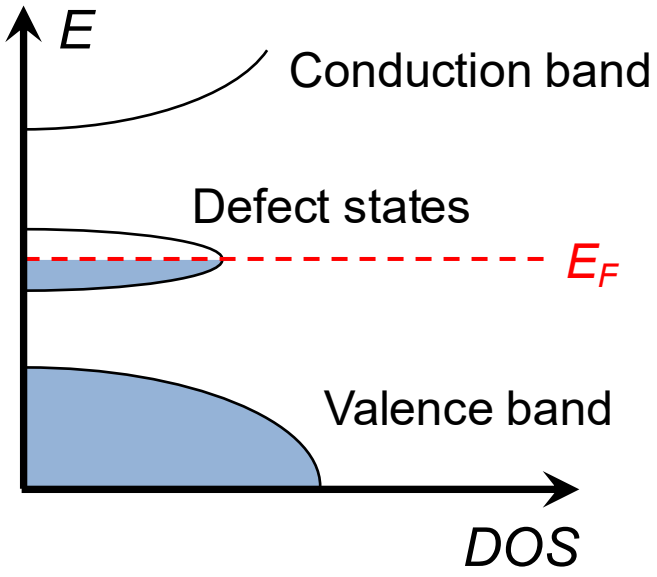
- c-Si: diamond structure consisting of 6-member rings formed by 4-fold coordinated Si atoms
- a-Si: continuous random network consisting of rings of varying sizes formed by mostly 4-fold coordinated Si atoms

Hydrogen passivation (hydrogenation)



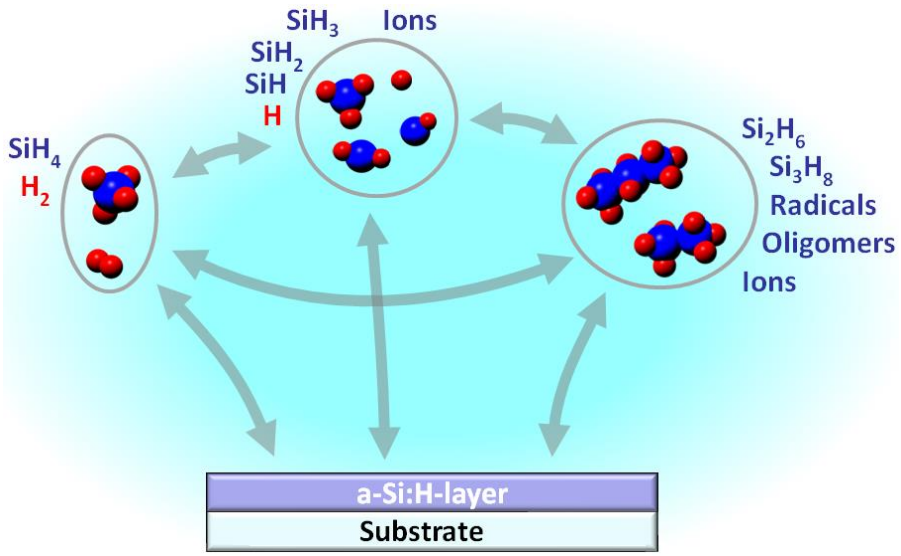
Solid-State Electron. **28**, 837 (1985)

- Pure a-Si has large deep level defect density
  - Unpassivated dangling bonds: recombination centers
  - Fermi level pinning

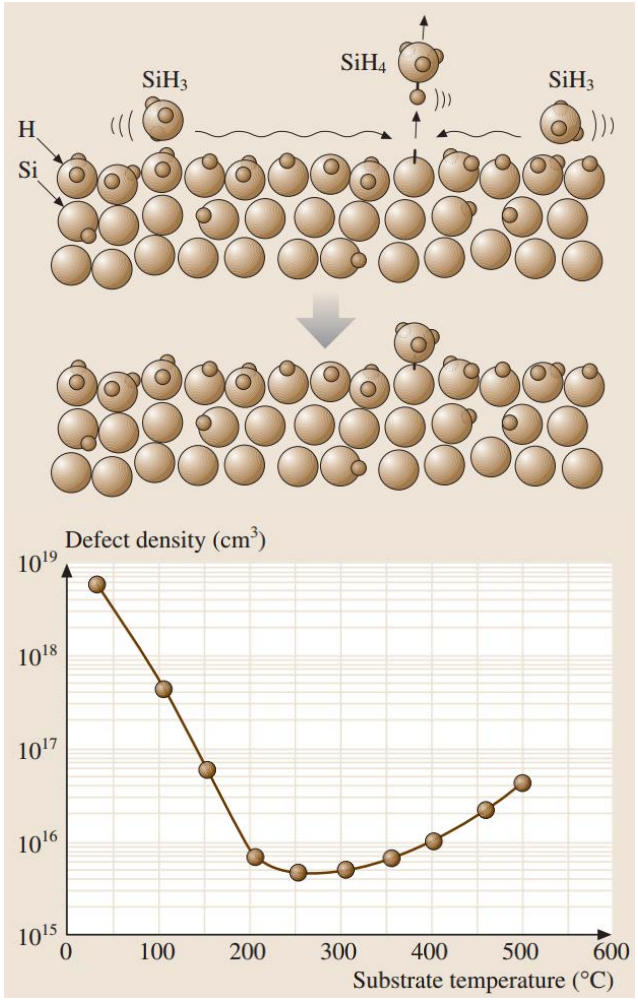


Courtesy of Elsevier, Inc., http://www.sciencedirect.com. Used with permission.
Source: D'Amico, A. and G. Fortunato. "Conductivity and Noise in Thin Films of Nonhydrogenated Amorphous Silicon in the Hopping Regime." Solid-state Electronics 28, no. 8 (1985): 837-844.

Hydrogen passivation (hydrogenation)



- $SiH_4 \rightarrow$ a-Si:H + H_2
- Dangling bond formation on a-Si:H surface due to H removal by adsorbed SiH_3 radicals



Springer Handbook of Electronic and Photonic Materials, Ch. 26

© Springer. All rights reserved. This content is excluded from our Creative Commons license. For more information, see https://ocw.mit.edu/help/faq-fair-use/

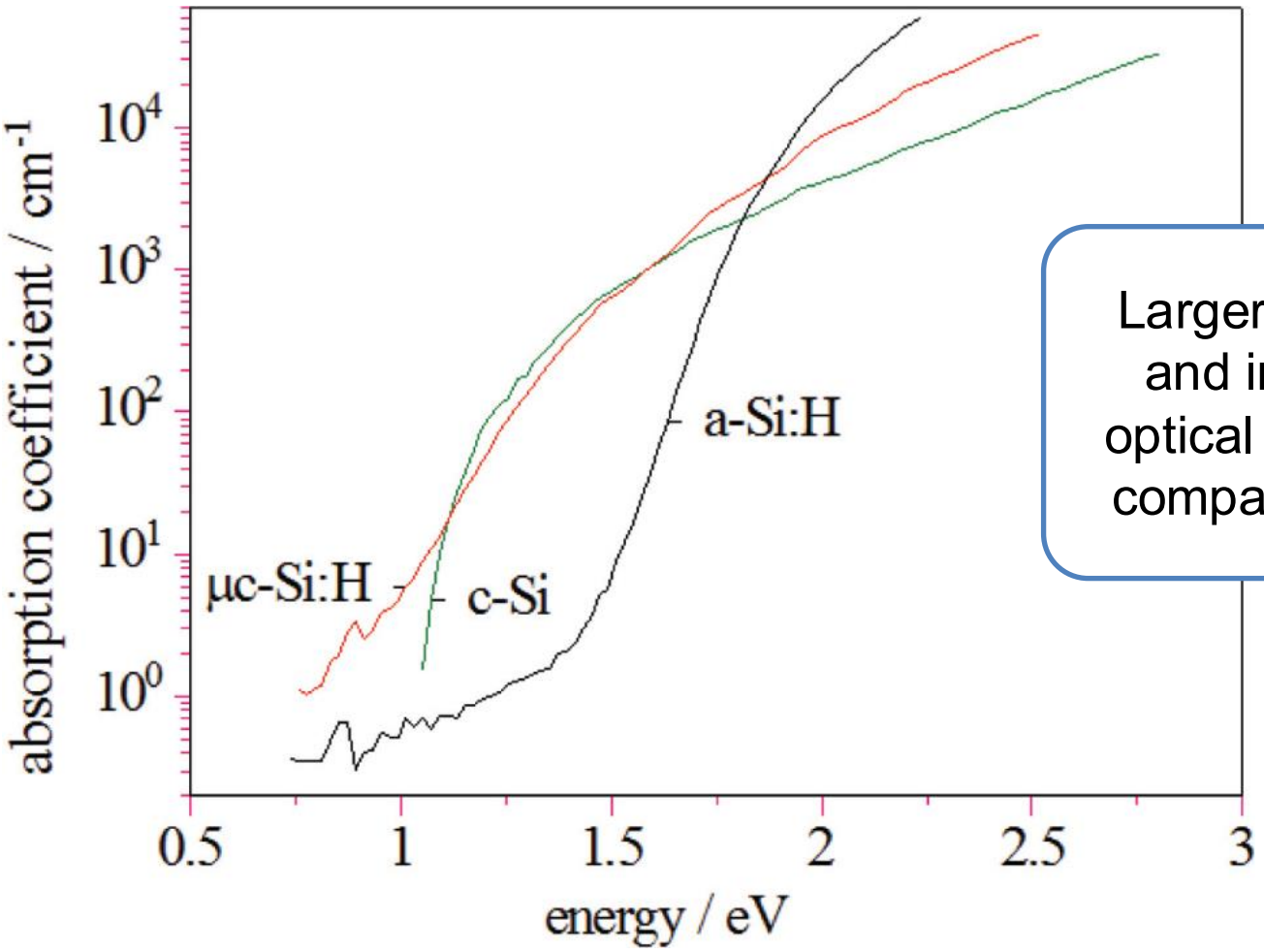
Electronic properties of a-Si:H

	c-Si (bulk, intrinsic)	a-Si:H (film)
Electron drift mobility	1400 $cm^2\ V^{-1}\ s^{-1}$	1 $cm^2\ V^{-1}\ s^{-1}$
Hole drift mobility	450 $cm^2\ V^{-1}s^{-1}$	0.003 $cm^2\ V^{-1}s^{-1}$
Carrier diffusion length	> 10 cm	0.3 μm
Undoped conductivity	< $10^{-5}\ \Omega^{-1}\ cm^{-1}$	$10^{-11}\ \Omega^{-1}\ cm^{-1}$
Doped conductivity	> $10^{4}\ \Omega^{-1}\ cm^{-1}$	Up to $10^{-2}\ \Omega^{-1}\ cm^{-1}$
Optical band gap	1.1 eV	1.7 eV

- Low carrier mobility: carrier trapping and scattering
- Substitutional doping by PH_3 (n-type) or B_2H_6 (p-type)
- High optical absorption: loss of crystal momentum conservation

Data from R. Street, *Technology and Applications of Amorphous Silicon* and http://www.ioffe.rssi.ru/SVA/NSM/Semicond/Si/electric.html

Optical absorption in a-Si:H



Larger band gap and increased optical absorption compared to c-Si

Z. Phys. Chem. **234**, 1055 (2020)

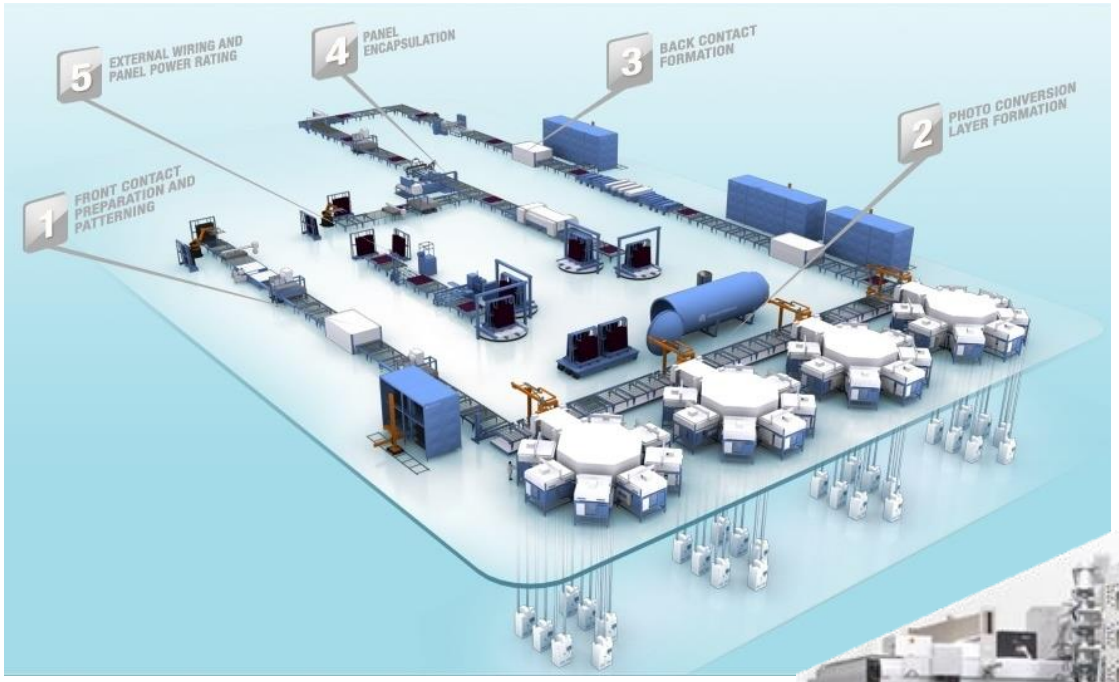
Courtesy of Finger, F, Welter, K, Urbain, F, Smirnov, V, Kaiser, B and Jaegermann, W. Used with permission. License: CC-BY.

Large-area PECVD a-Si:H deposition



© Applied Materials. All rights reserved. This content is excluded from our Creative Commons license. For more information, see https://ocw.mit.edu/help/faq-fair-use/

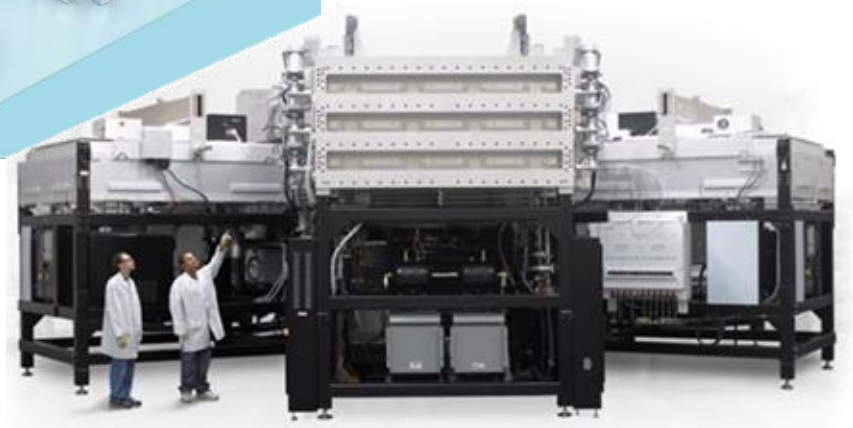
Large-area PECVD a-Si:H deposition



APPLIED MATERIALS®

Applied SunFab
Thin Film Line

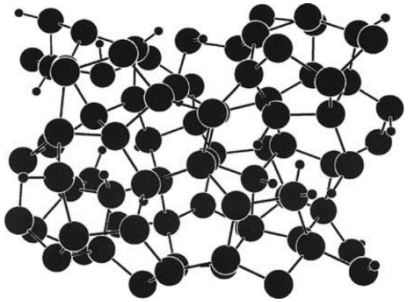
Glass substrate size: 5.7 m^2



Images © Applied Materials. All rights reserved. This content is excluded from our Creative Commons license. For more information, see http://ocw.mit.edu/help/faq-fair-use/.



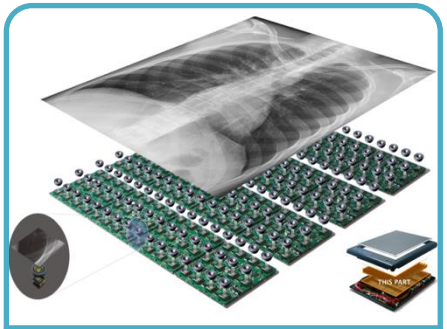
Active matrix display



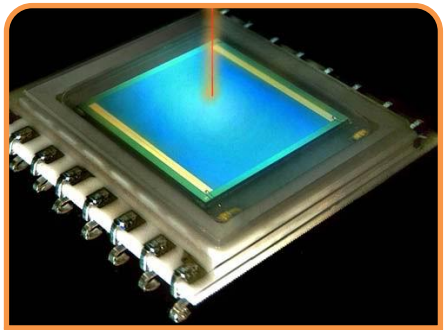
Amorphous silicon macroelectronics



Solar cell



X-ray imager



Position sensitive detector

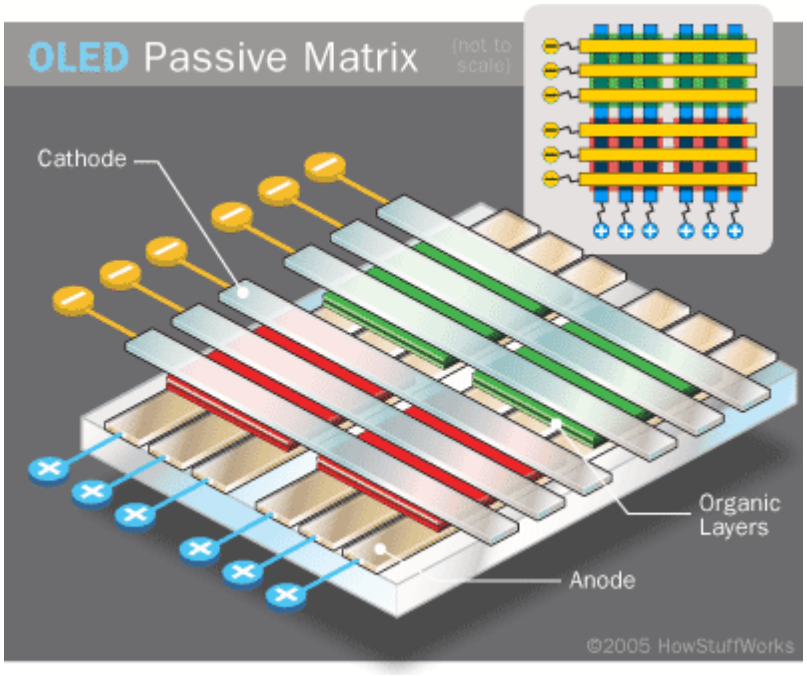


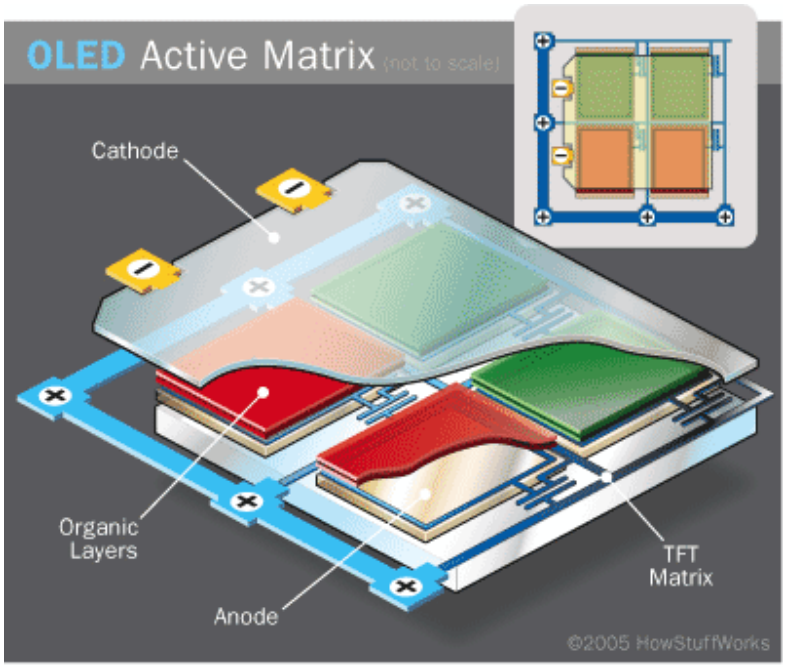
IR bolometer

Various commercial images © unknown. All rights reserved. This content is excluded from our Creative Commons license. For more information, see http://ocw.mit.edu/help/faq-fair-use/

Passive matrix vs. active matrix (AM) display

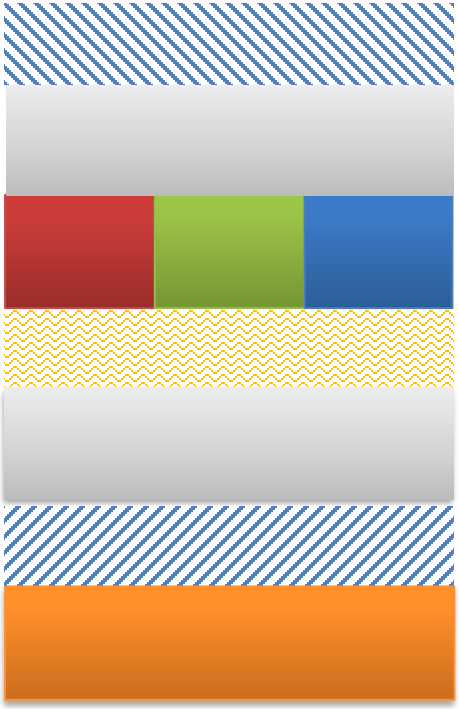
- Passive matrix: $m + n$ control signals address an $m \times n$ display
- Active matrix: each pixel is individually addressed by a transistor
  - High refresh rate
  - Low cross-talk and superior image resolution





© HowStuffWorks, a System1 Property. All rights reserved. This content is excluded from our Creative Commons license. For more information, see https://ocw.mit.edu/help/faq-fair-use/

Active Matrix Liquid Crystal Display (AMLCD)



Polarizer

Cover glass

Color filter

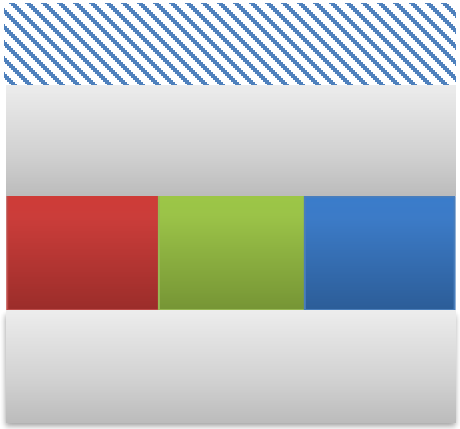
Liquid crystal

TFT backplane

Polarizer

Back light

Active Matrix Organic Light Emitting Diode (AMOLED)



Polarizer

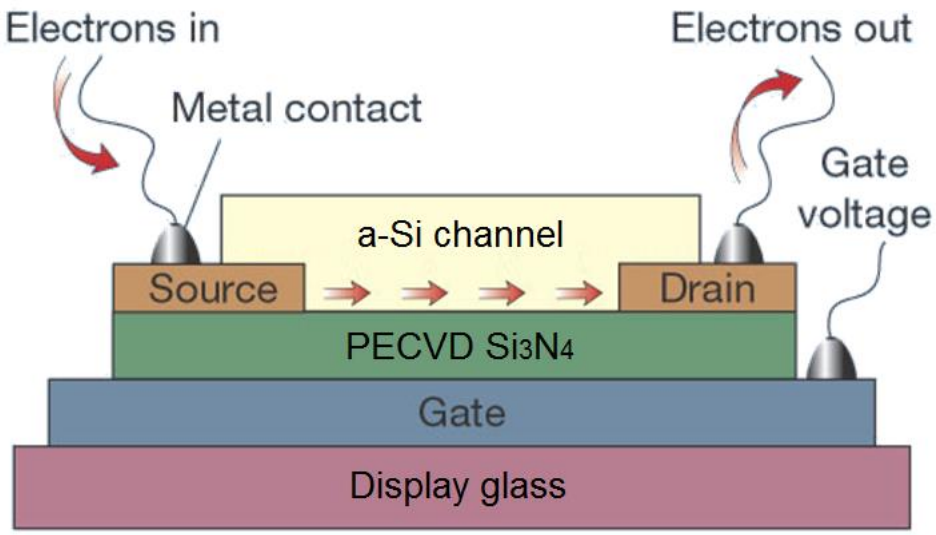
Cover glass

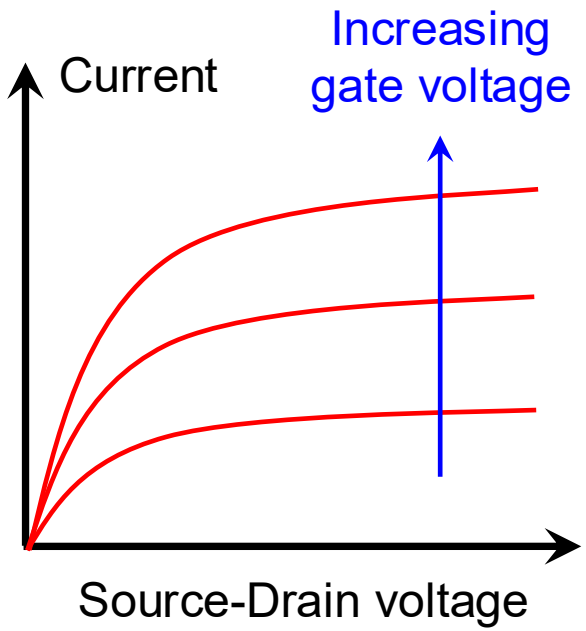
OLEDs

TFT backplane

Thin film transistors (TFTs) are made of a-Si or low-temperature poly-silicon (LTPS)

a-Si / LTPS thin film transistors





Courtesy of Macmillan Publishers Limited. Used with permission. Source: Kanatzidis, M.G. "Semiconductor Physics: Quick-set Thin Films." Nature 428 (2004): 269-271.

- Applied gate voltage modulates a-Si / LTPS channel conductance and the TFT on/off state
- Si_3N_4 and a-Si can be deposited using the same PECVD system
- Display glass: flat glass produced by down-draw fusion process

Images from Wikimedia Commons, *Nature* **428**, 269 (2004)

LTPS vs. a-Si

Characteristic	a-Si	LTPS (low-temperature poly-silicon)	
Mobility ($cm^2/V/s$)	~ 1	~ 100	
Preparation Method	PECVD	Post-deposition annealing of a-Si	Excimer laser annealing (ELA) of a-Si
Processing Temperature	350 °C	600 °C	> 1500 °C
Resolution	Low	> 500 ppi	
Cost	Low	Relatively high	

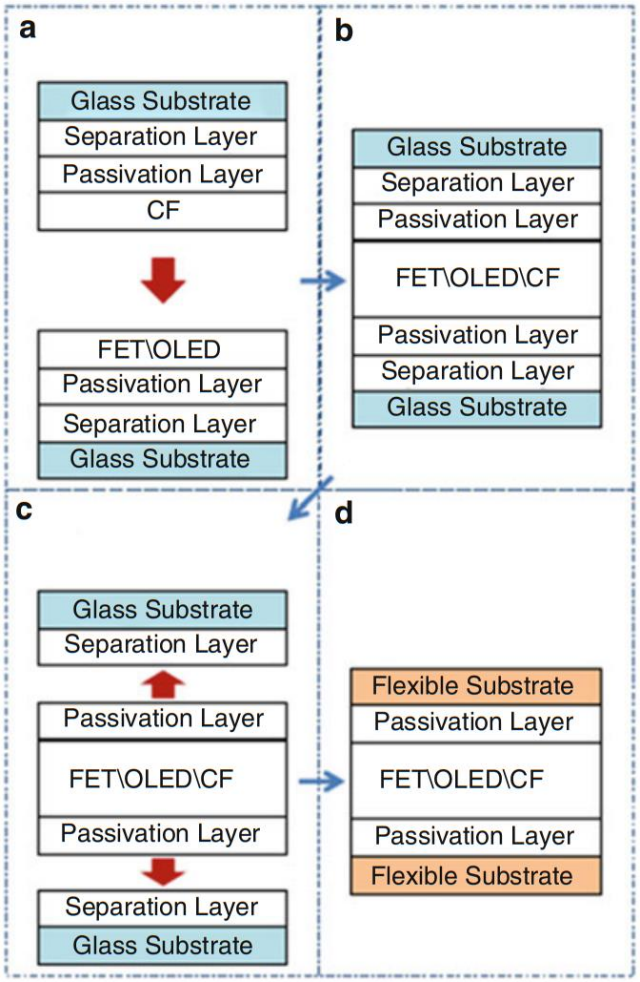
Low-temperature poly-silicon (LTPS) exhibits improved electronic properties compared to a-Si:H

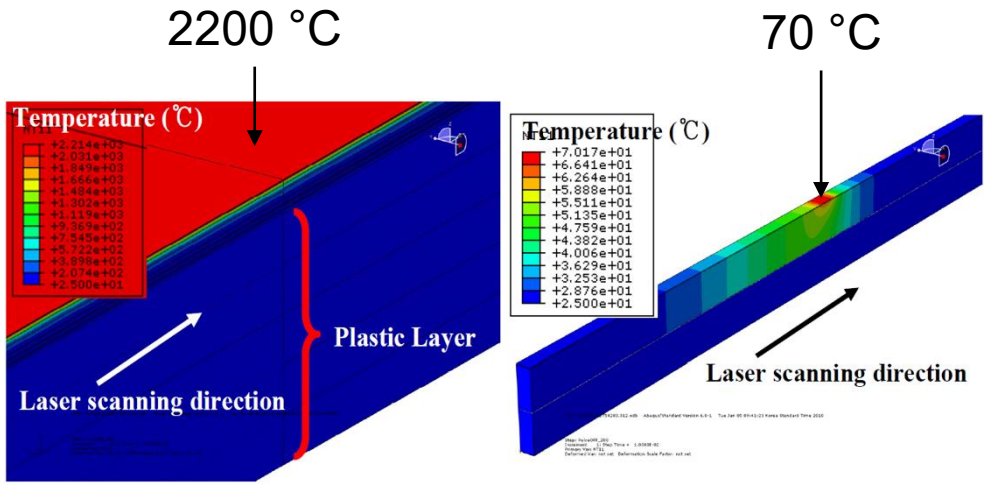
Flexible AMOLED display



© Royole Corporation. All rights reserved. This content is excluded from our Creative Commons license. For more information, seehttps://ocw.mit.edu/help/faq-fair-use/

LTPS-TFT process for flexible display





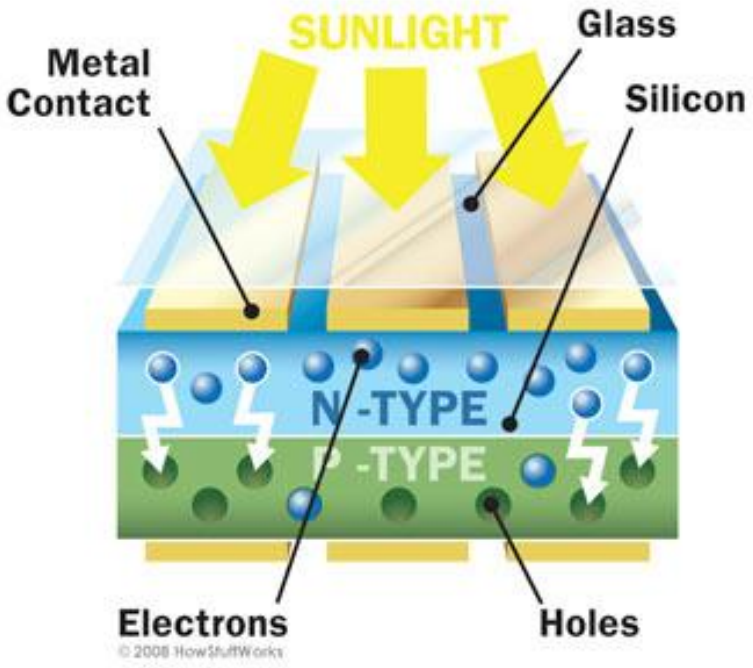
Highly localized heating during ELA prevents damage to plastic substrates

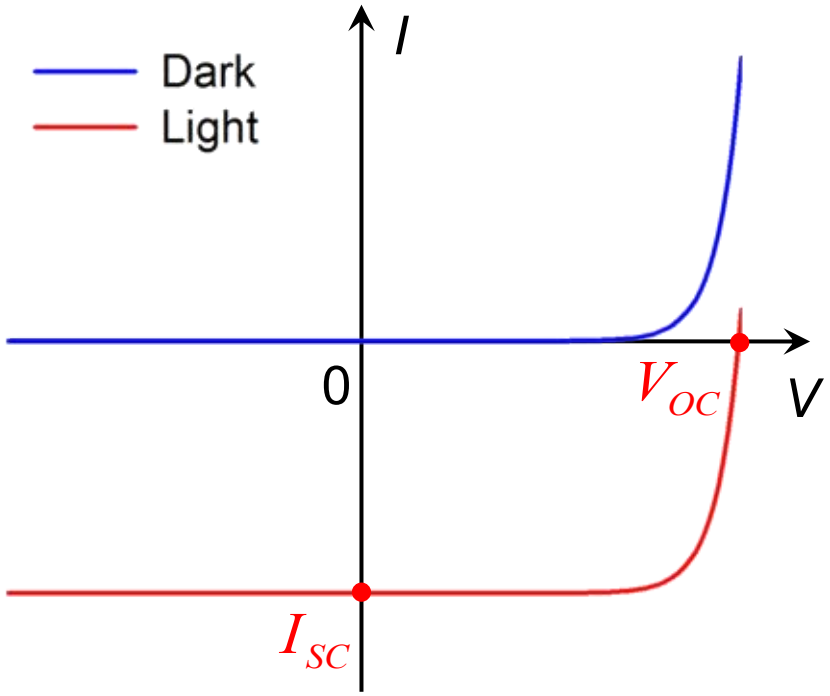
M. Kim *et al.*, "16.2: World-Best Performance LTPS TFTs with Robust Bending Properties on AMOLED Displays." *SID* **42**, 194-197 (2011)

Y. Jimbo *et al.*, "25.1: Tri-Fold Flexible AMOLED with High Barrier Passivation Layers," *SID* **45**, 322-325 (2014)

© John Wiley & Sons, Inc. All rights reserved. This content is excluded from our Creative Commons license. For more information, see https://ocw.mit.edu/help/faq-fair-use/

Basic solar cell structure





$$I = I_s \cdot \left[\exp\left(\frac{eV}{k_B T} \right) - 1 \right] - I_{SC}$$

I_{SC} : short circuit current

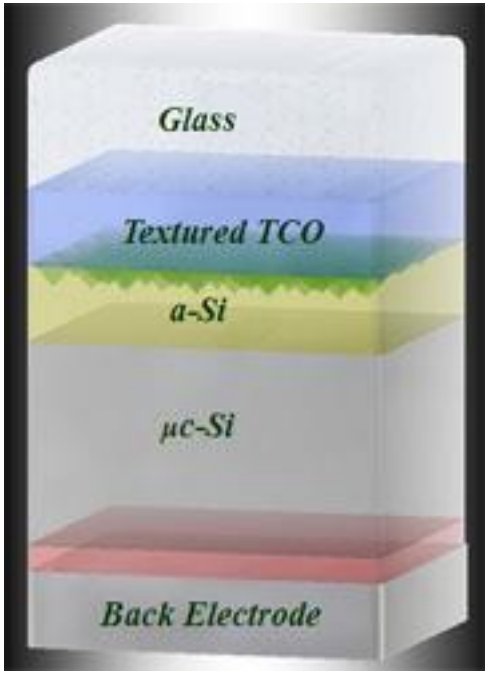
I_s : diode saturation current

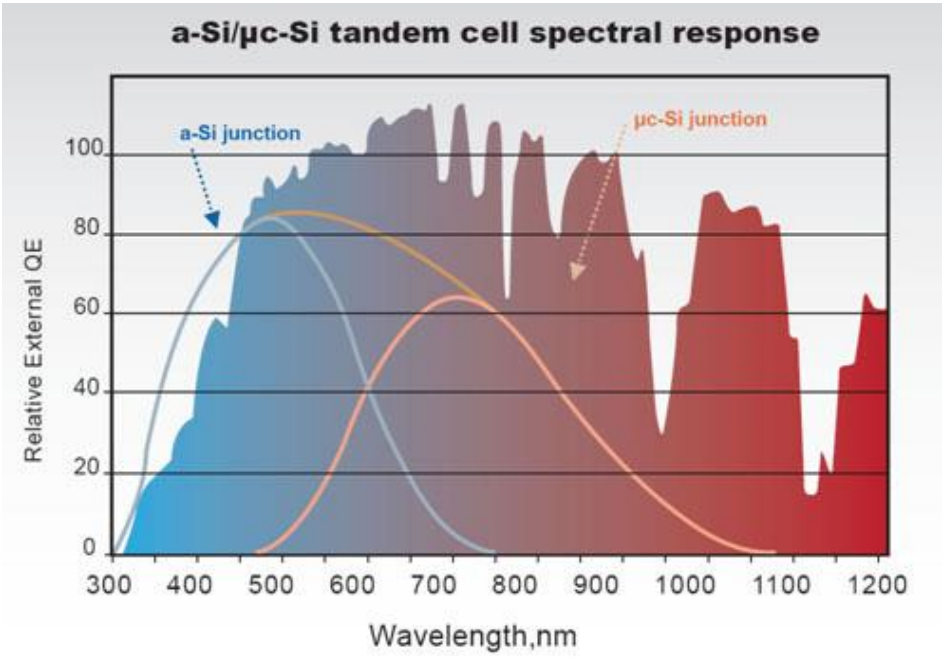
© HowStuffWorks, a System1 Property. All rights reserved. This content is excluded from our Creative Commons license. For more information, see https://ocw.mit.edu/help/faq-fair-use/

Thin film a-Si:H as a solar absorber

- Large-area, high-throughput deposition
- High absorption: reduced material consumption
- Monolithic silicon tandem structures

} Low cost (?)



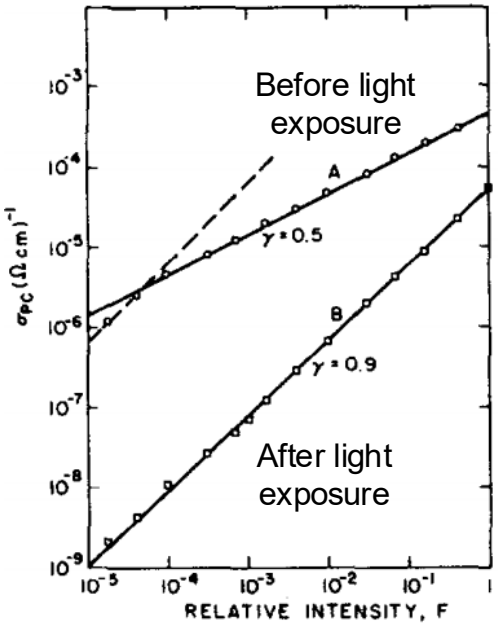


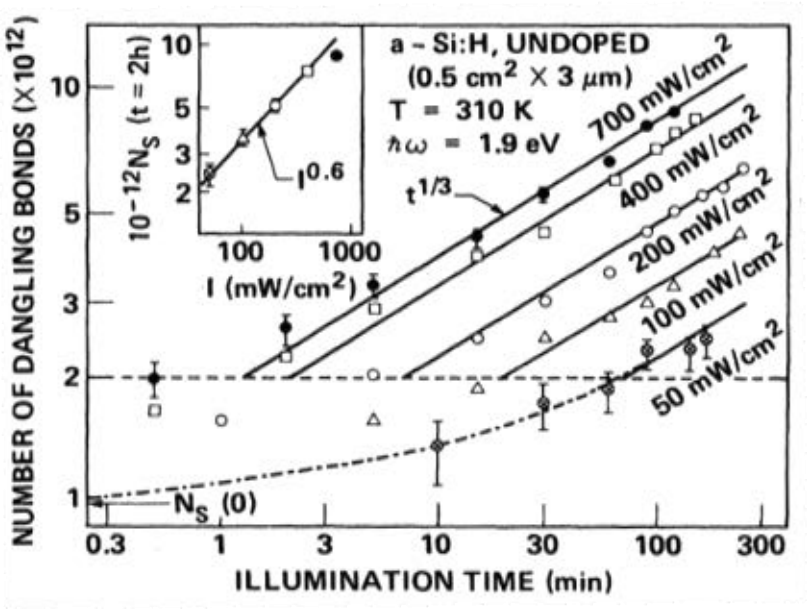
http://www.nexpw.com/Technology/Technology_stt

Figures © NexPower Technology Corp. All rights reserved. This content is excluded from our Creative Commons license. For more information, see http://ocw.mit.edu/help/faq-fair-use/

Staebler-Wronski effect

- Light-induced degradation of hydrogenated a-Si and nano-crystalline Si materials
- Defect generation rate $\propto G^{2/3}t^{1/3}$
- Annealing can partially reverse the effect





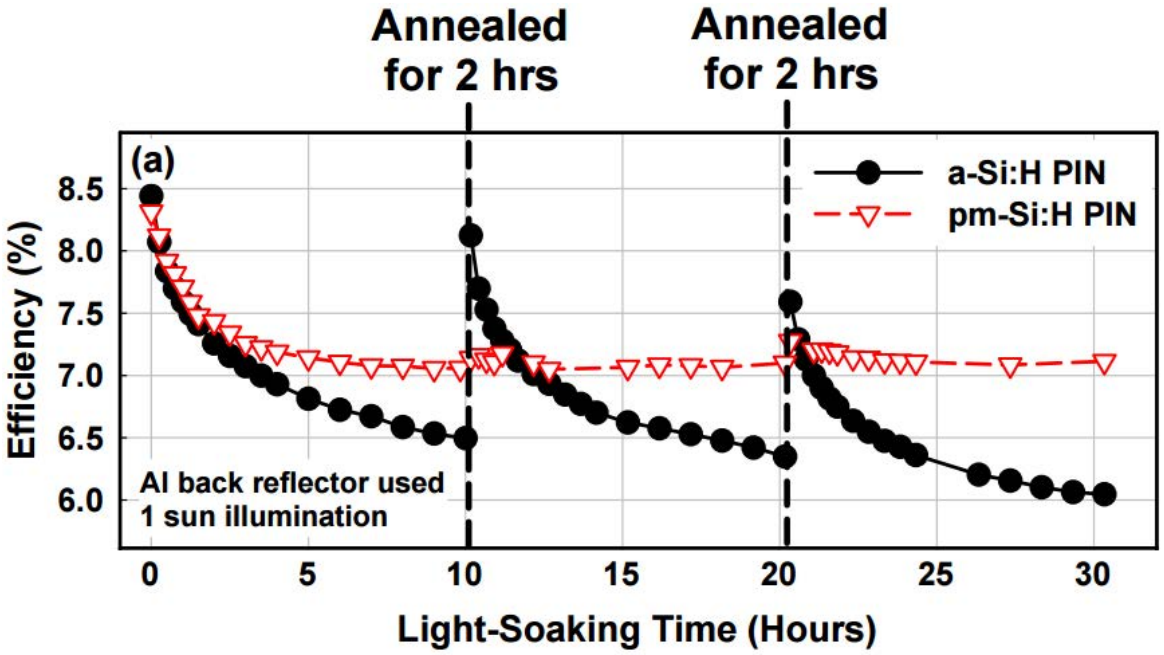
Appl. Phys. Lett. **31**, 292 (1977); *Phys. Rev. B* **32**, 23 (1985)

© AIP Publishing LLC. All rights reserved. This content is excluded from our Creative Commons license. For more information, see https://ocw.mit.edu/help/faq-fair-use/

© American Physical Society. All rights reserved. This content is excluded from our Creative Commons license. For more information, see https://ocw.mit.edu/help/faq-fair-use/

Staebler-Wronski effect

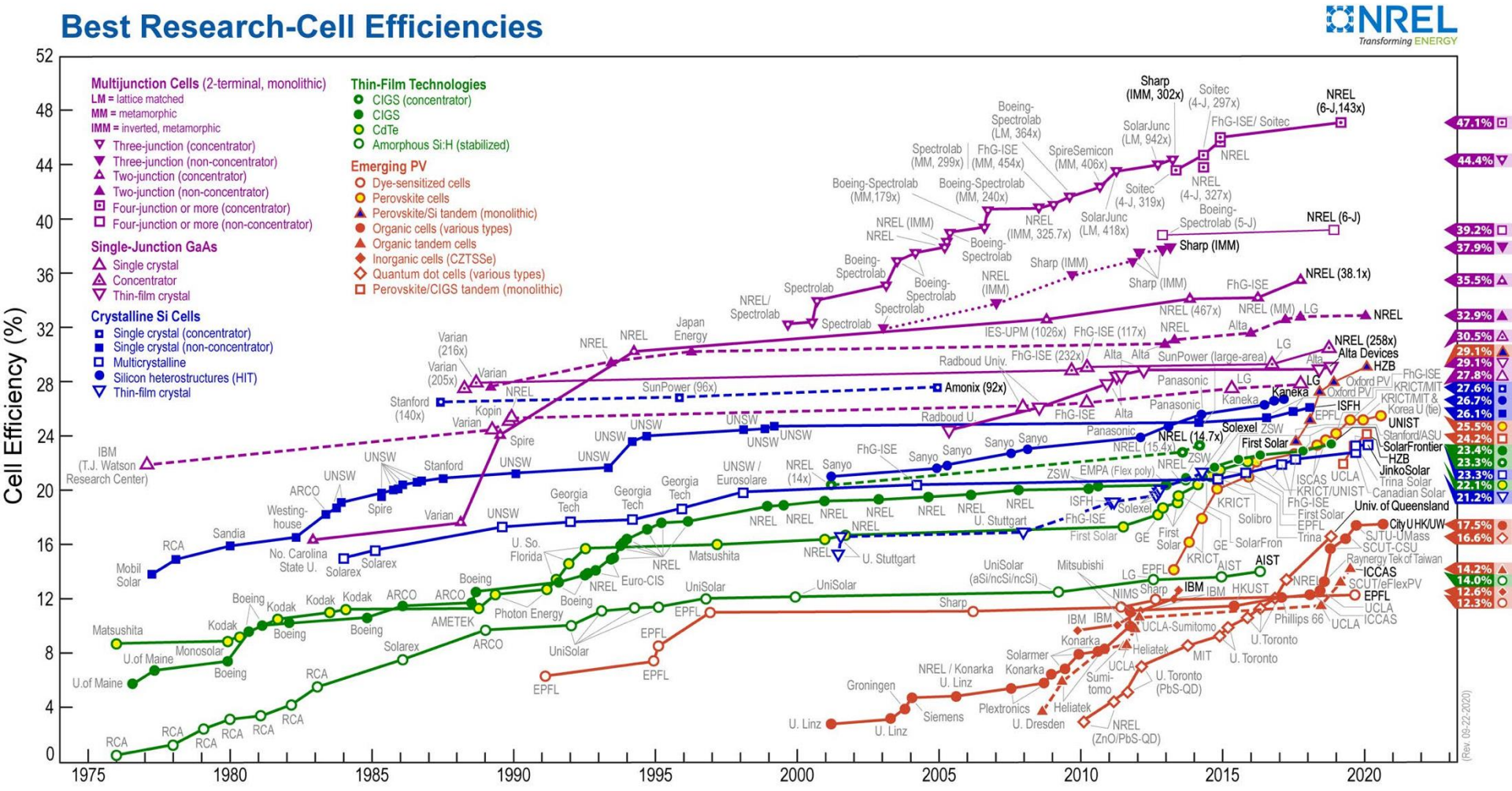
- Light-induced degradation of hydrogenated a-Si and nano-crystalline Si materials
- Defect generation rate $\propto G^{2/3} t^{1/3}$
- Annealing can partially reverse the effect



K. Kim, Diss. Ecole Polytechnique X (2012).

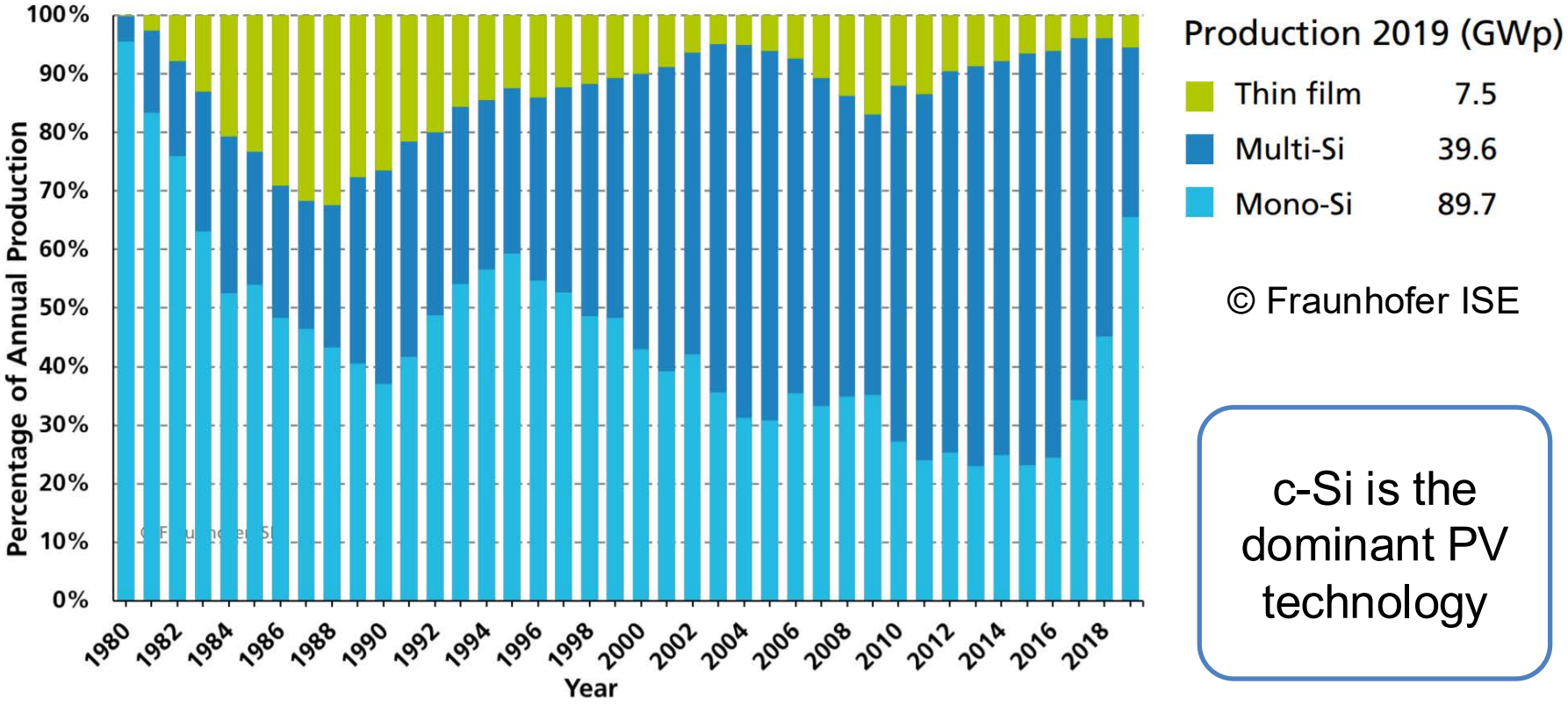
Courtesy of K. Kim. Used with permission. License: CC-BY.

Best Research-Cell Efficiencies



Source: public domain.

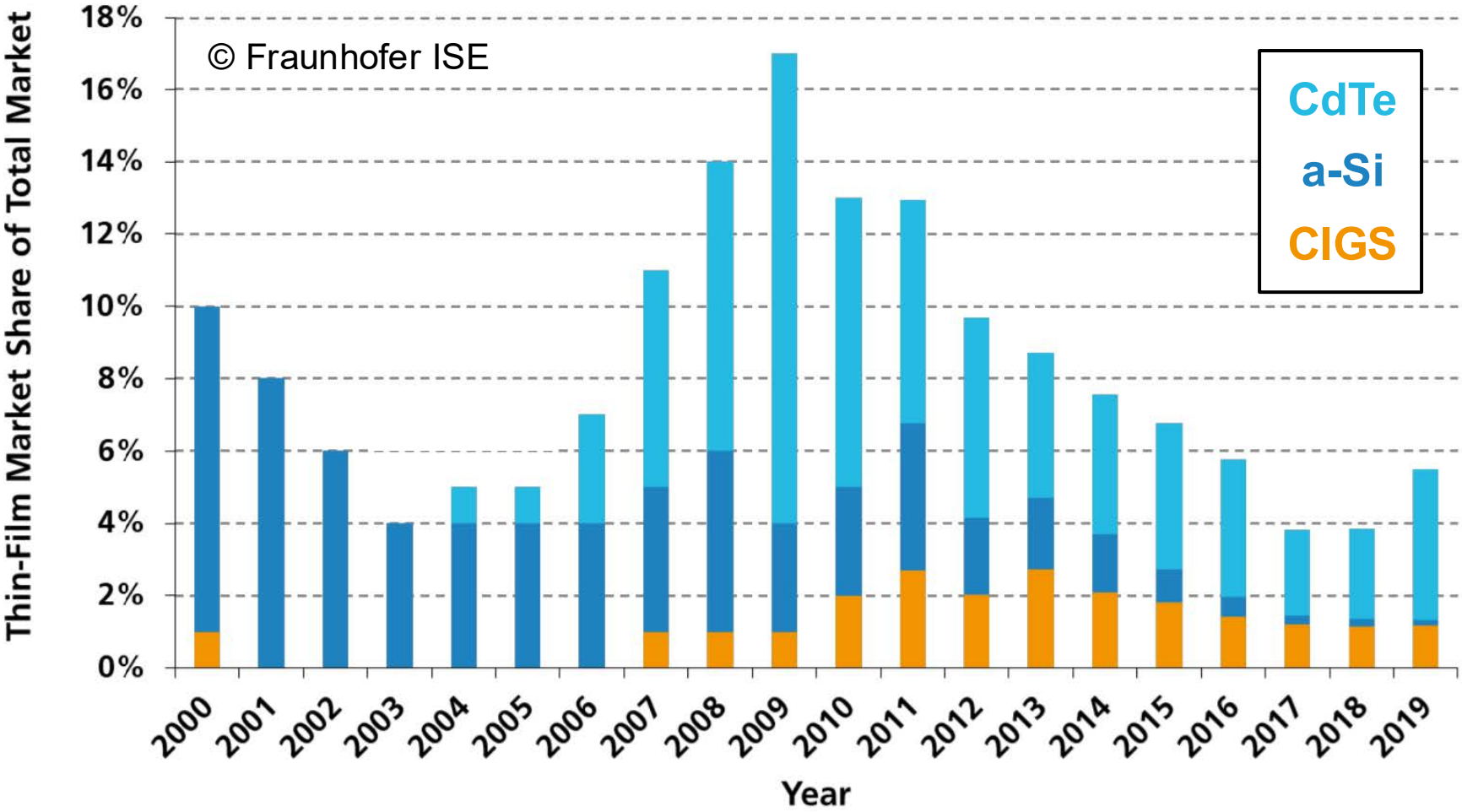
Global PV production by technology



c-Si is the dominant PV technology

© Fraunhofer ISE. All rights reserved. This content is excluded from our Creative Commons license. For more information, see https://ocw.mit.edu/help/faq-fair-use/

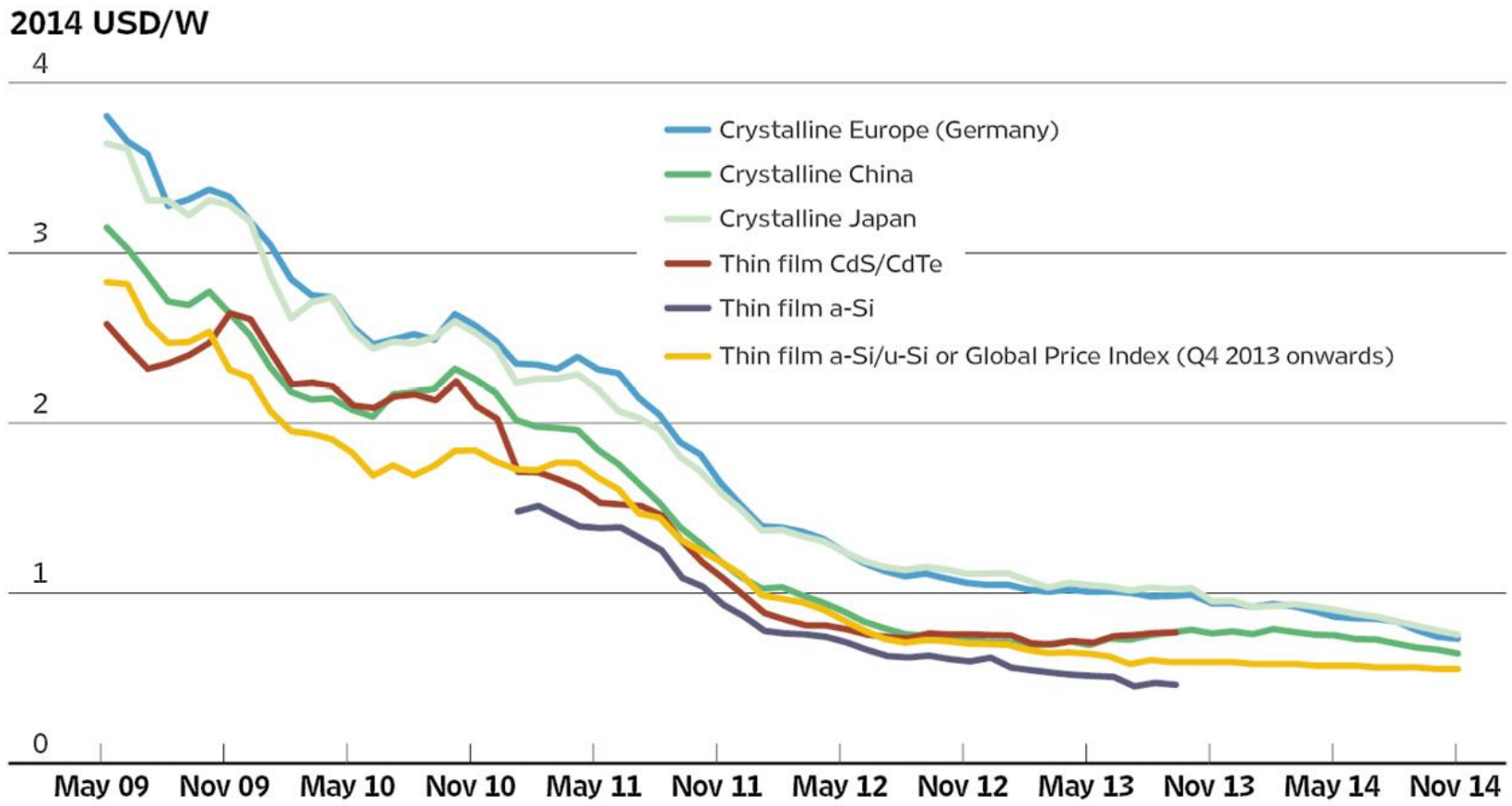
Market share of thin-film technologies



© Fraunhofer ISE. All rights reserved. This content is excluded from our Creative Commons license. For more information, see https://ocw.mit.edu/help/faq-fair-use/

IRENA
International Renewable Energy Agency

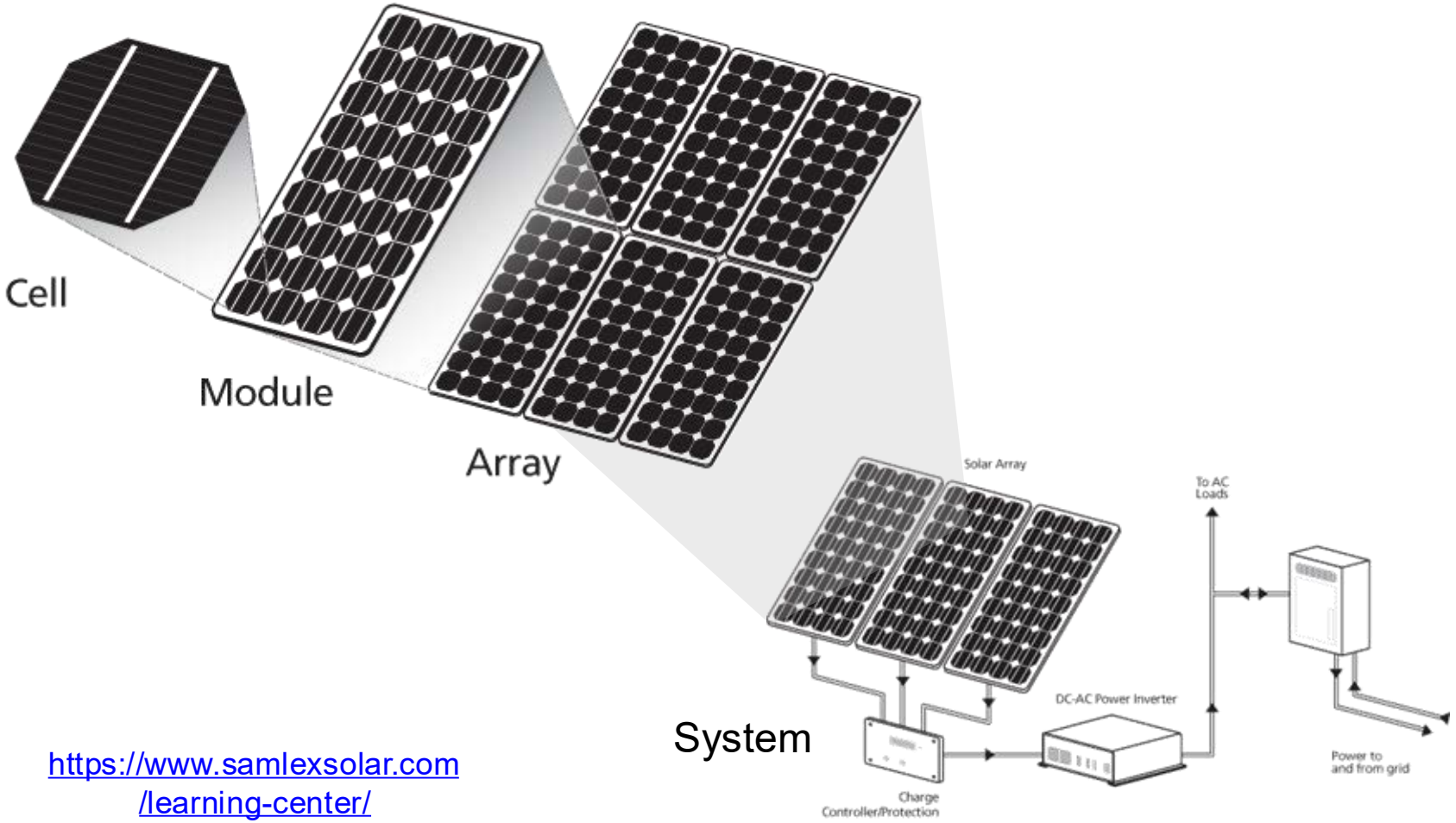
FIGURE 5.2: AVERAGE MONTHLY SOLAR PV MODULE PRICES BY TECHNOLOGY AND MANUFACTURING COUNTRY SOLD IN EUROPE, 2009 TO 2014



Sources: GlobalData, 2014 and pvXchange, 2014.

© IRENA - International Renewable Energy Agency. All rights reserved. This content is excluded from our Creative Commons license. For more information, see https://ocw.mit.edu/help/faq-fair-use/

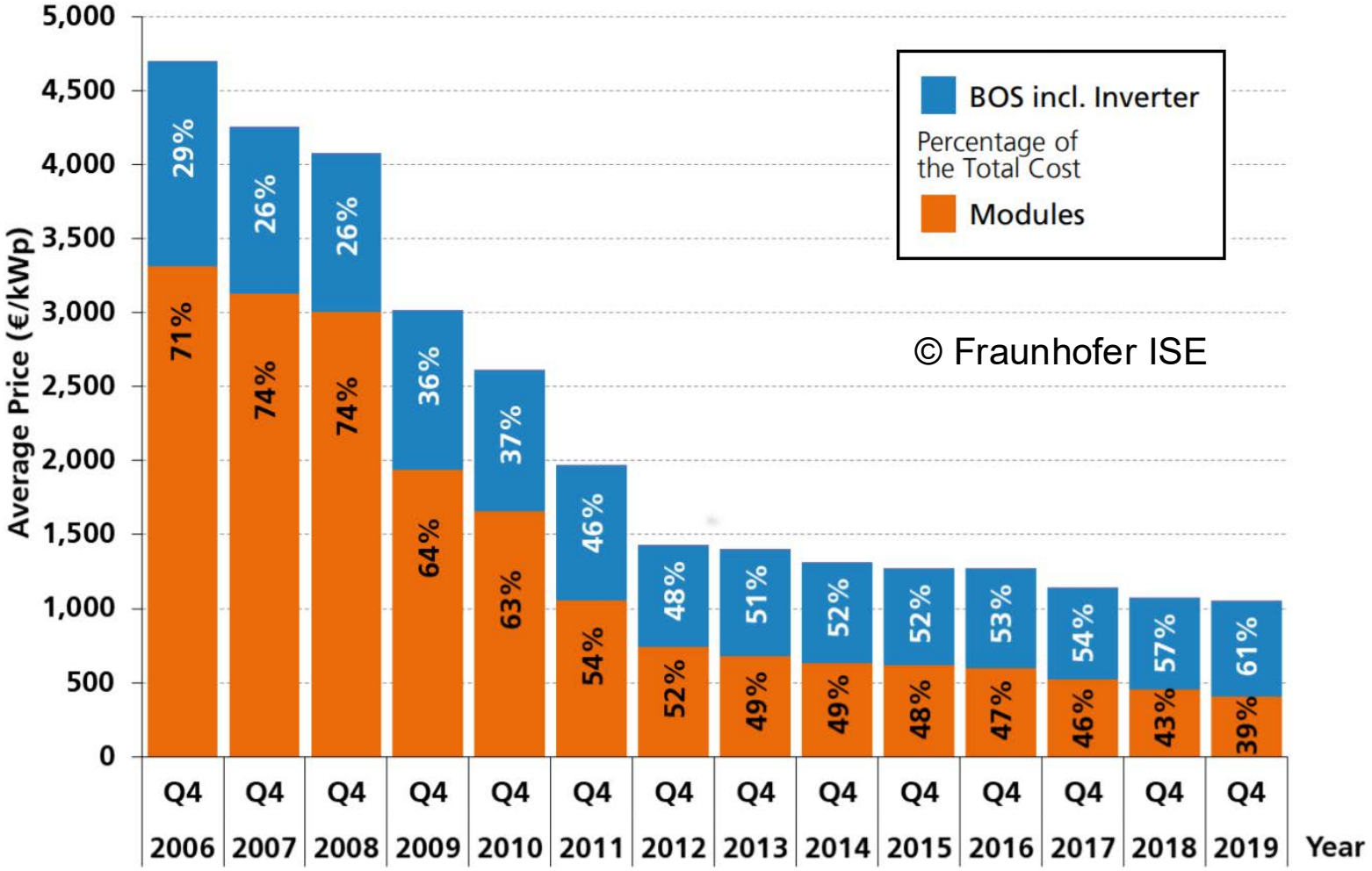
From cell to system



https://www.samlexsolar.com/learning-center/

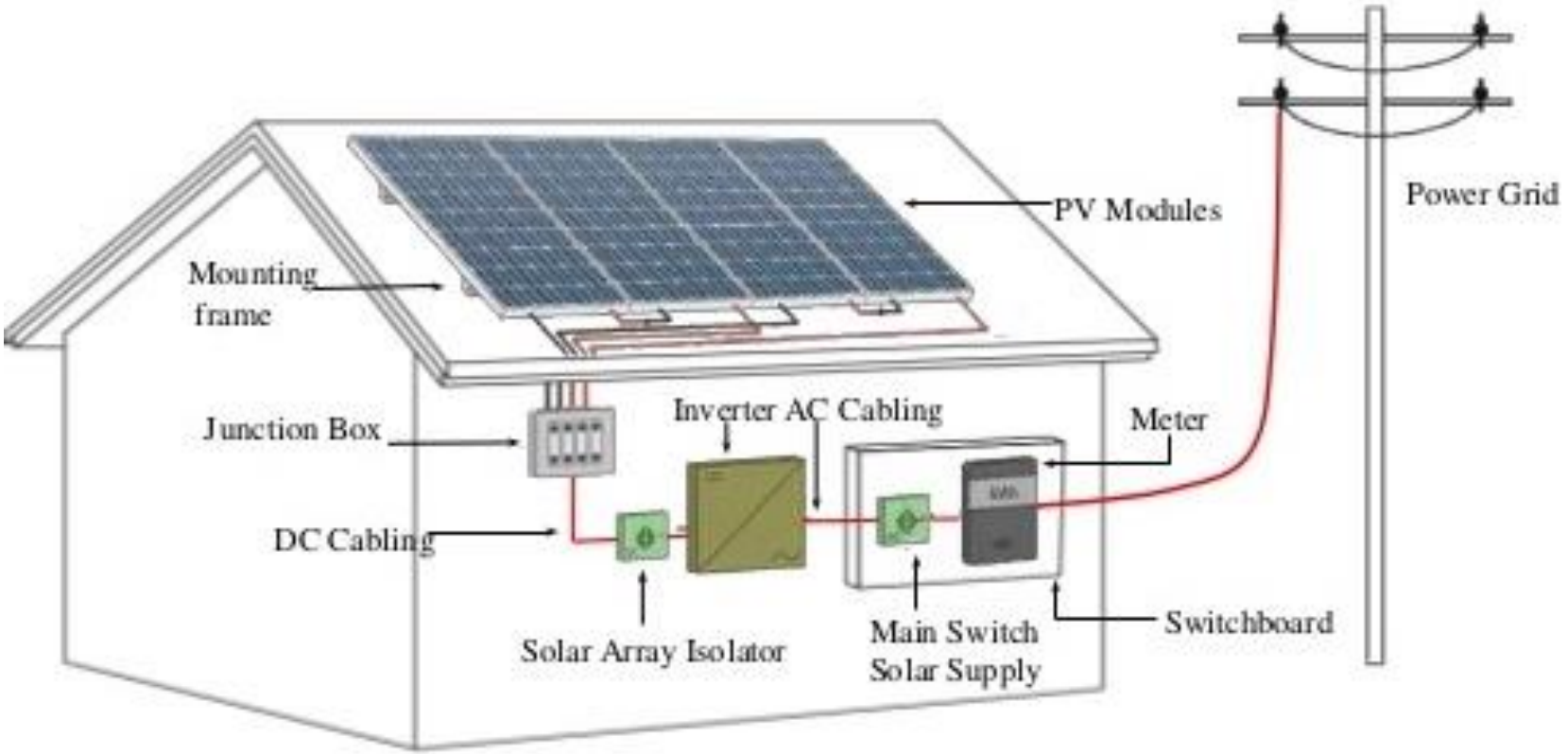
Courtesy of Elsevier, Inc., https://www.sciencedirect.com. Used with permission.

Average price for rooftop systems in Germany



© Fraunhofer ISE. All rights reserved. This content is excluded from our Creative Commons license. For more information, see https://ocw.mit.edu/help/faq-fair-use/

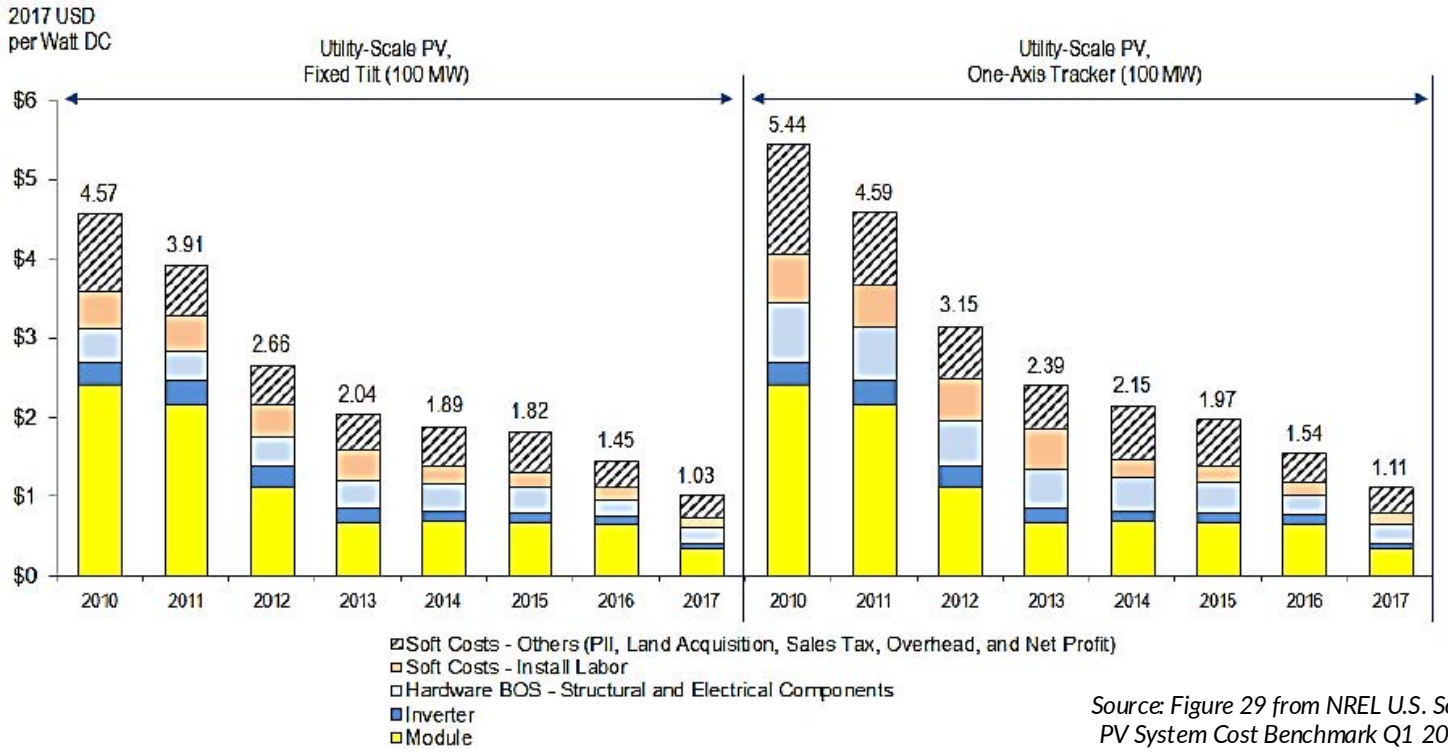
Balance of system (BOS) hardware



cute766.info/session-06-balance-of-system-components/

Source: public domain

PV cost reduction: where and how?

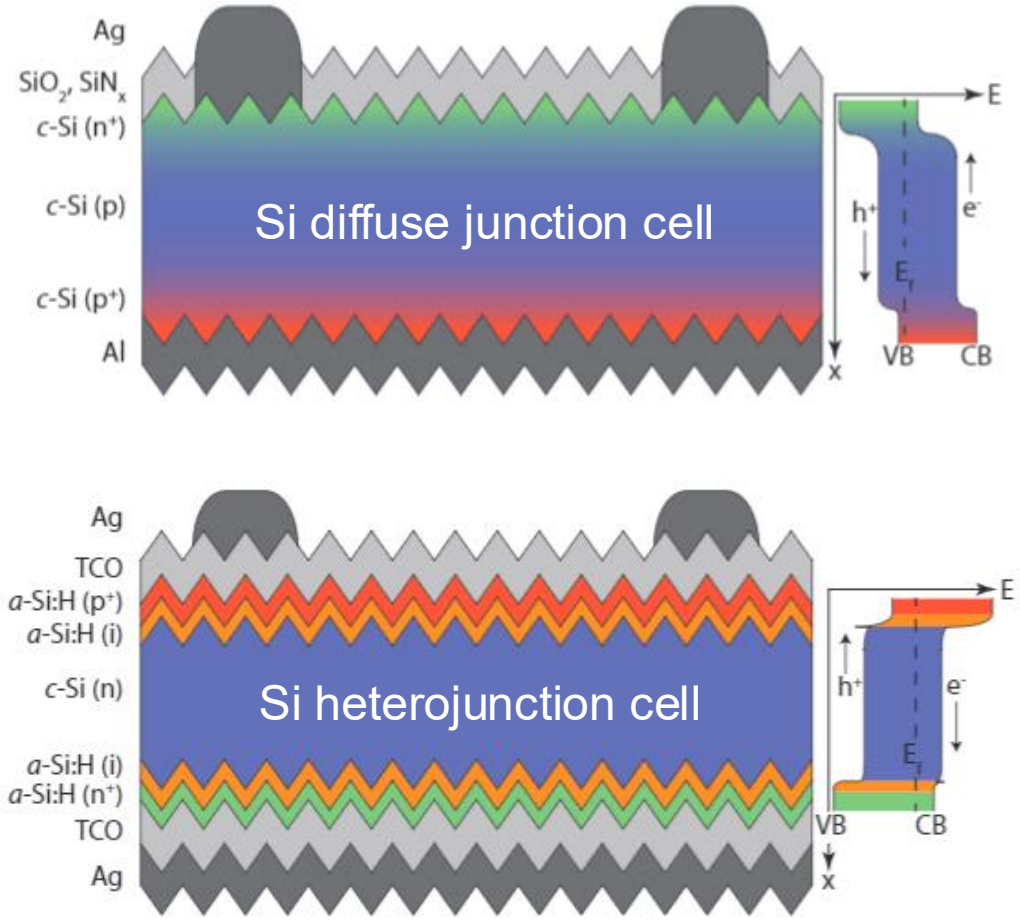


Source: Figure 29 from NREL U.S. Solar PV System Cost Benchmark Q1 2017

Balance of system (BOS) costs is the key to further solar system cost reductions

Source: public domain

Silicon heterojunction (SHJ) cells



- ✓ SHJ reduces recombination at contact surfaces
- ✓ H from a-Si:H passivates c-Si surface

Green **2**, 7 (2012)

© De Gruyter. All rights reserved. This content is excluded from our Creative Commons license. For more information, see https://ocw.mit.edu/help/faq-fair-use/

Summary

- Basic properties of a-Si and a-Si:H
  - Dangling bonds and hydrogenation
  - Electronic properties: Fermi level pinning, factors affecting drift mobility and optical absorption
- Active matrix display based on TFTs
  - Comparison of a-Si and LTPS
- a-Si solar cells
  - Staebler-Wronski effect

Further Readings

- Springer Handbook of Electronic and Photonic Materials
  - Ch. 25: Amorphous Semiconductors: Structural, Optical, and Electrical Properties
  - Ch. 26: Amorphous and Microcrystalline Silicon
  - Springer Link (paste link to a browser window)
- Technology and Applications of Amorphous Silicon
  - R. A. Street, Springer (2000)
  - Springer Link (paste link to a browser window)

MIT OpenCourseWare
https://ocw.mit.edu/

3.071 Amorphous Materials
Spring 2025

For information about citing these materials or our Terms of Use, visit:
https://ocw.mit.edu/terms.