MIT 3.071
Amorphous Materials

11: Amorphous Silicon Macroelectronics

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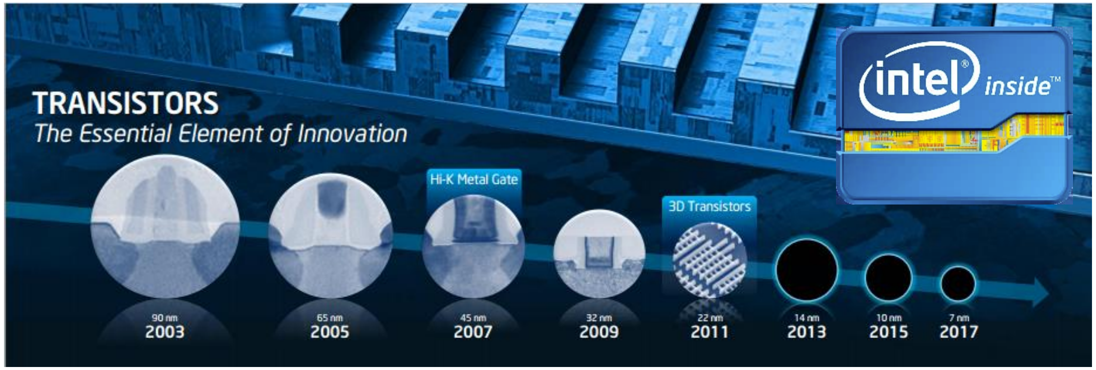
Electron's travels: from Lilliput to Brobdingnag

Microelectronics
"Smaller is smarter"



Macroelectronics
"Bigger is better"

Image from Wikipedia

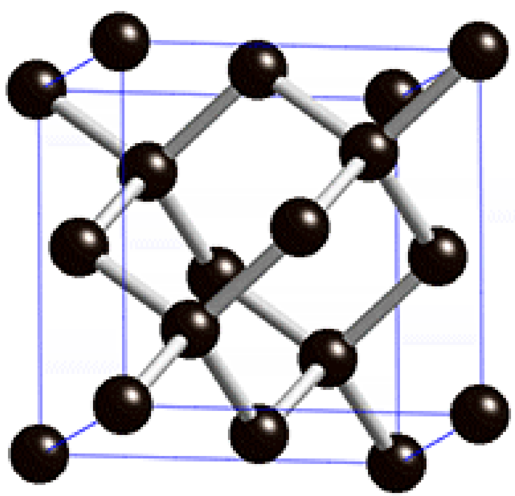
Why amorphous silicon?

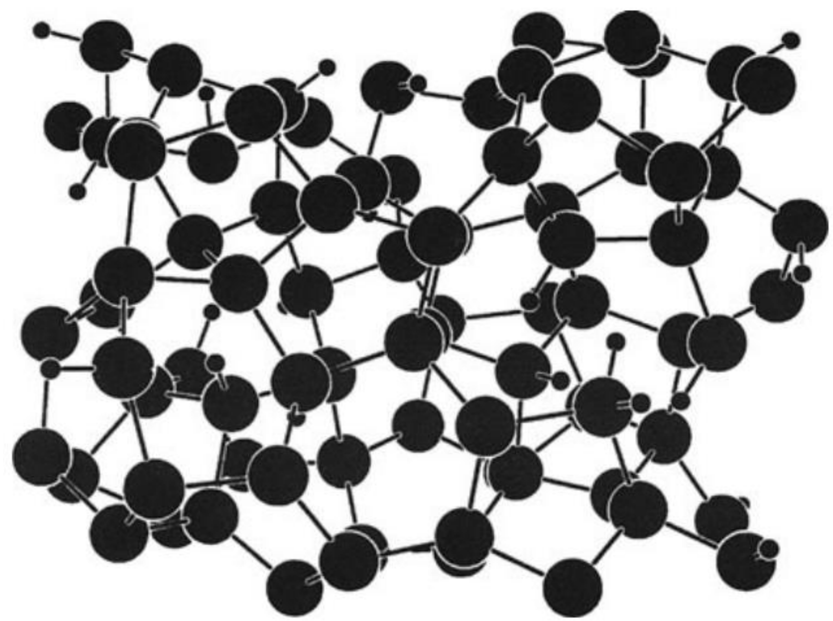
- Large-area, low-temperature, monolithic deposition
  - Low-cost, mature PECVD process
  - Dielectrics and passivation layers can be formed using the same process
- Doping capacity
  - Effective passivation of defects (hydrogenation)
- CMOS compatibility
  - Leveraging existing infrastructure and knowledge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

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

-- George Orwell

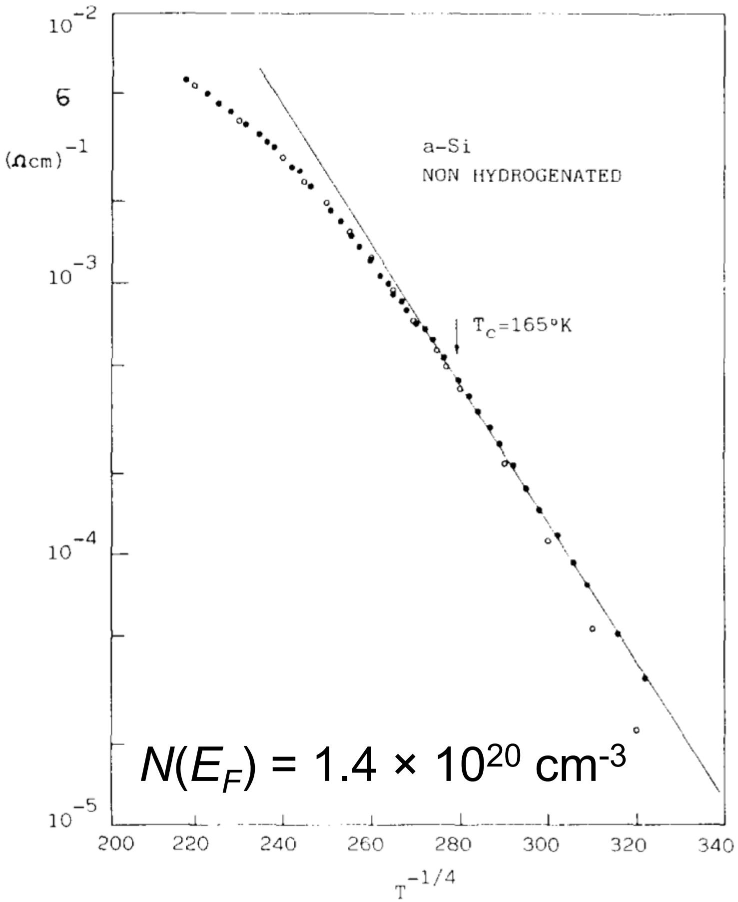
Structure of amorphous silicon





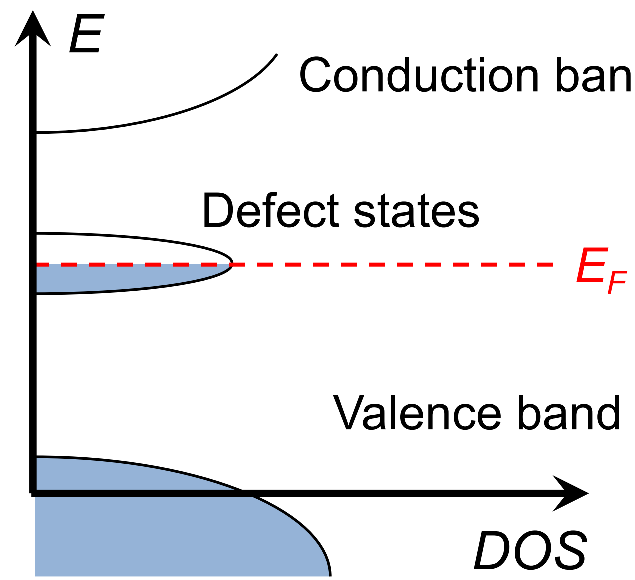
- c-Si: diamond structure consisting of 6-member rings formed by 4-fold coordinated Si atoms
- a-Si: continuous random network consisting of rings of varying sizes formed by <u>mostly</u> 4-fold coordinated Si atoms

Hydrogen passivation (hydrogenation)



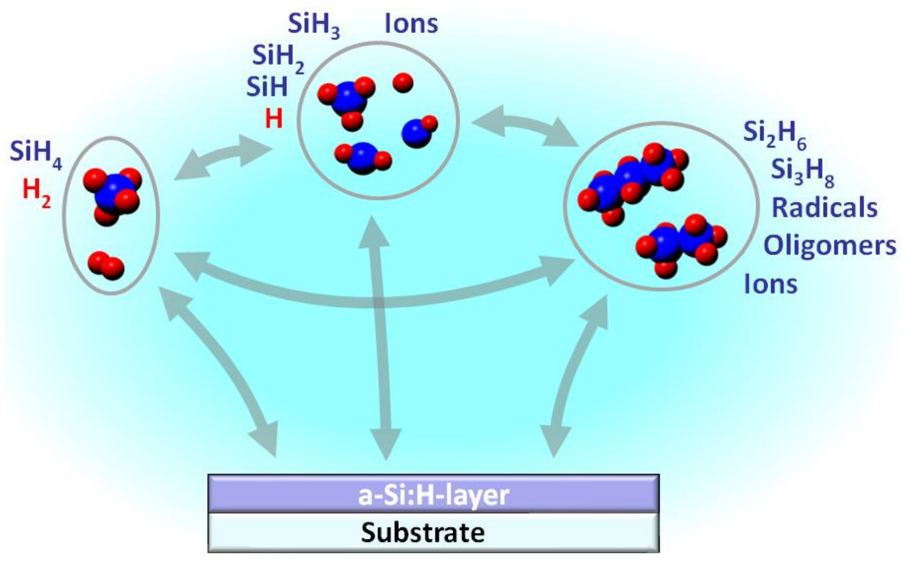
Courtesy of Elsevier, Inc., http://www.sciencedirect.com. Used with permission.
Source: D'Amico, A. and G. Fortunato. "Conductivity and Noise in Thin Films of Nonhydrogenated Amorphous Silicon in the Hopping Regime." Solid-state Electronics 28, no. 8 (1985): 837-844.

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



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

Hydrogen passivation (hydrogenation)

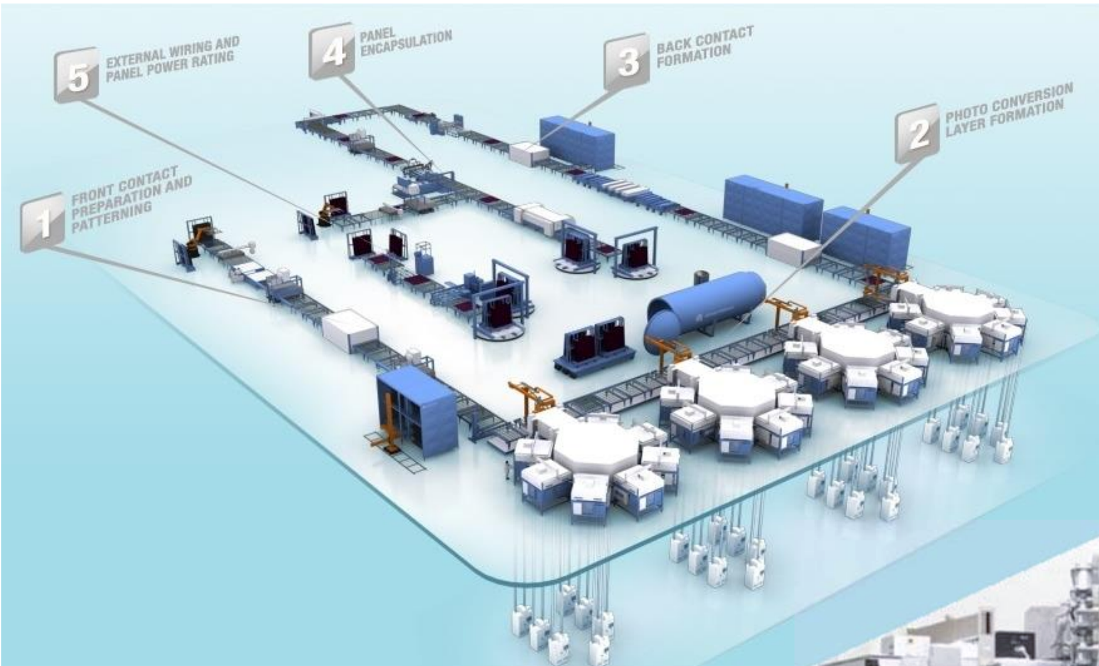


Figures removed due to copyright restrictions. See Figures 26.4, 26.18: *Springer Handbook of Electronic and Photonic Materials*. Kasap, S. and P. Capper (Eds.). Springer, 2007.

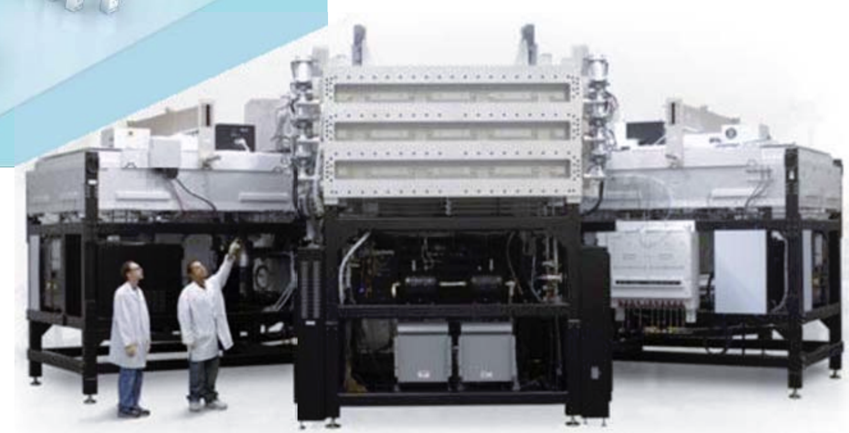
- $SiH_4 \rightarrow$ a-Si:H + H_2
- Dangling bond formation on a-Si:H surface due to H removal by adsorbed SiH_3 radicals

Springer Handbook of Electronic and Photonic Materials, Ch. 26

Large-area PECVD a-Si:H deposition



Applied SunFab
Thin Film Line



Glass substrate size: 5.7 m^2

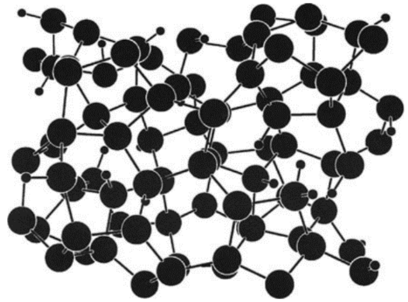
Electronic properties of a-Si:H

	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

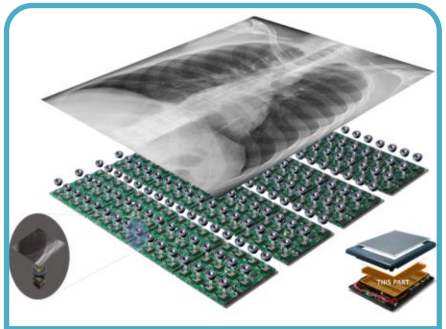
Data from R. Street, *Technology and Applications of Amorphous Silicon*
and http://www.ioffe.rssi.ru/SVA/NSM/Semicond/Si/electric.html

Active matrix display

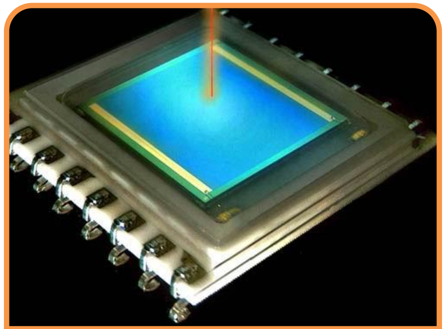


Amorphous silicon macroelectronics

Solar cell



X-ray imager



Position sensitive detector

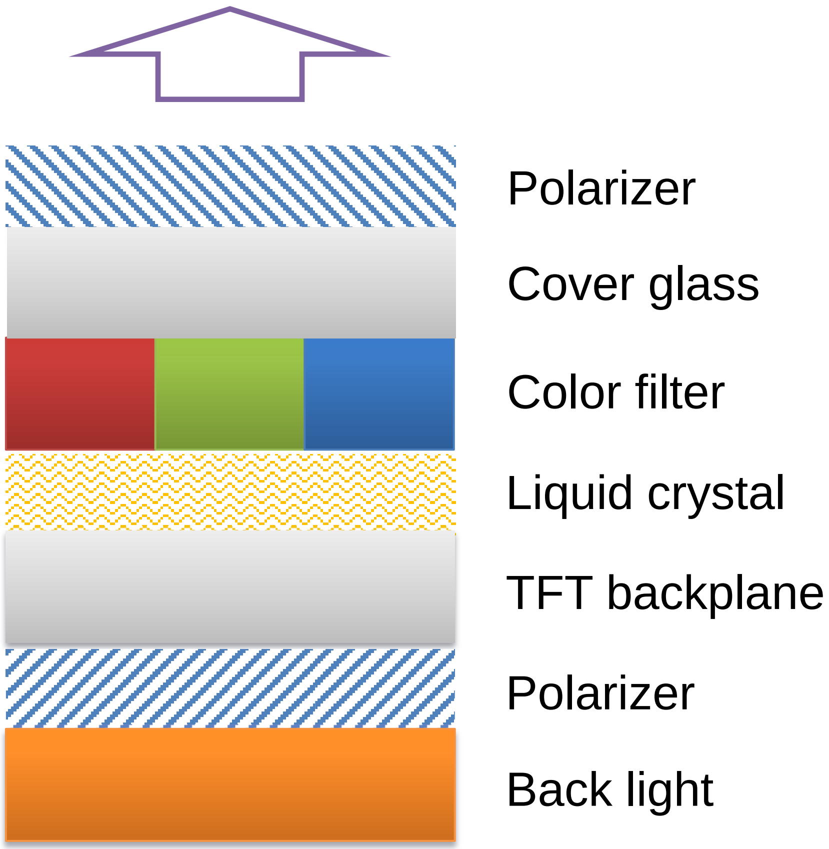
IR bolometer

Passive matrix vs. active matrix (AM) display

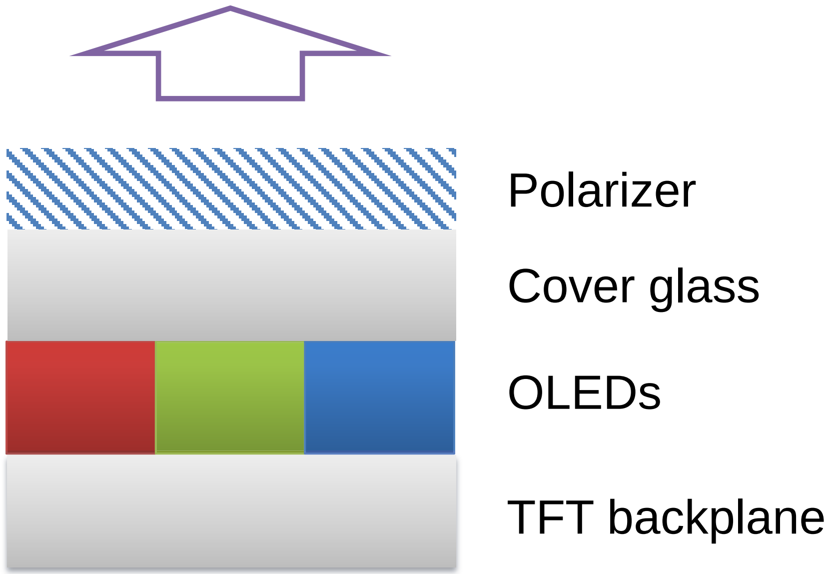
- Passive matrix: $m + n$ control signals address an $m \times n$ display
- Active matrix: each pixel is individually addressed by a transistor
  - High refresh rate
  - Low cross-talk and superior image resolution

OLED Passive Matrix and OLED Active Matrix figures removed due to copyright restrictions. See: How Stuff Works.

Active Matrix Liquid Crystal Display (AMLCD)

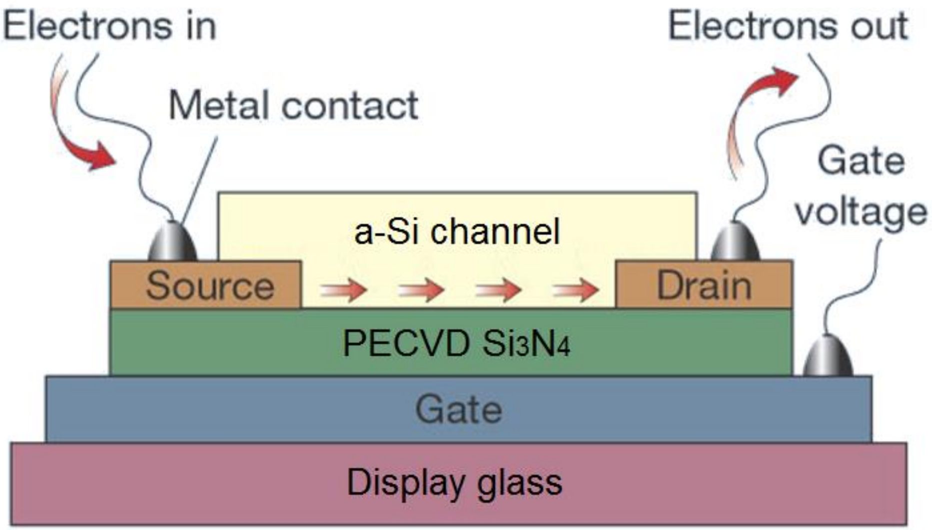


Active Matrix Organic Light Emitting Diode (AMOLED)

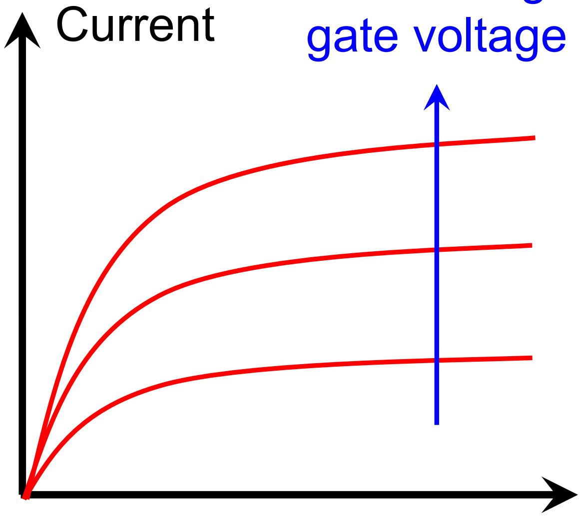


Thin film transistors (TFTs) are made of a-Si or low-temperature poly-silicon (LTPS) obtained by laser annealing of a-Si

a-Si / LTPS thin film transistors



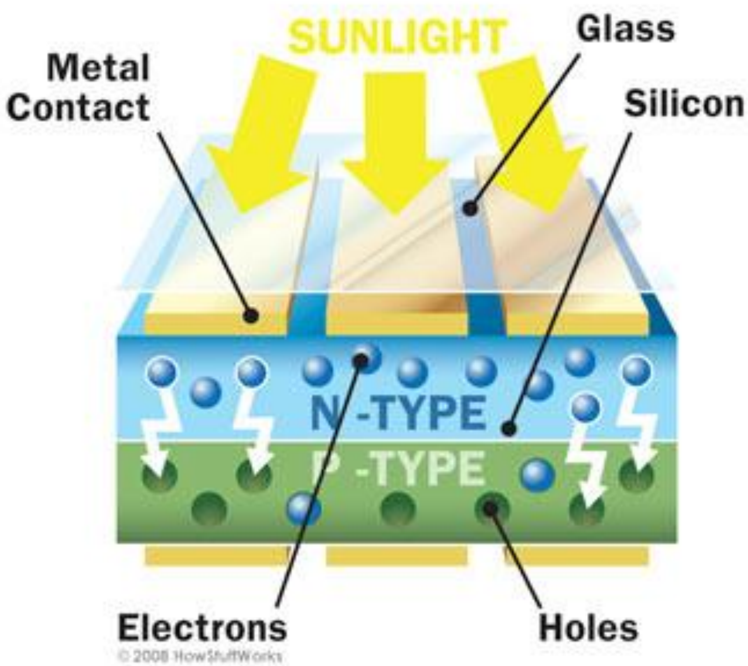
Source: Kanatzidis, M.G. "Semiconductor Physics: Quick-set Thin Films." *Nature* 428 (2004): 269-271.

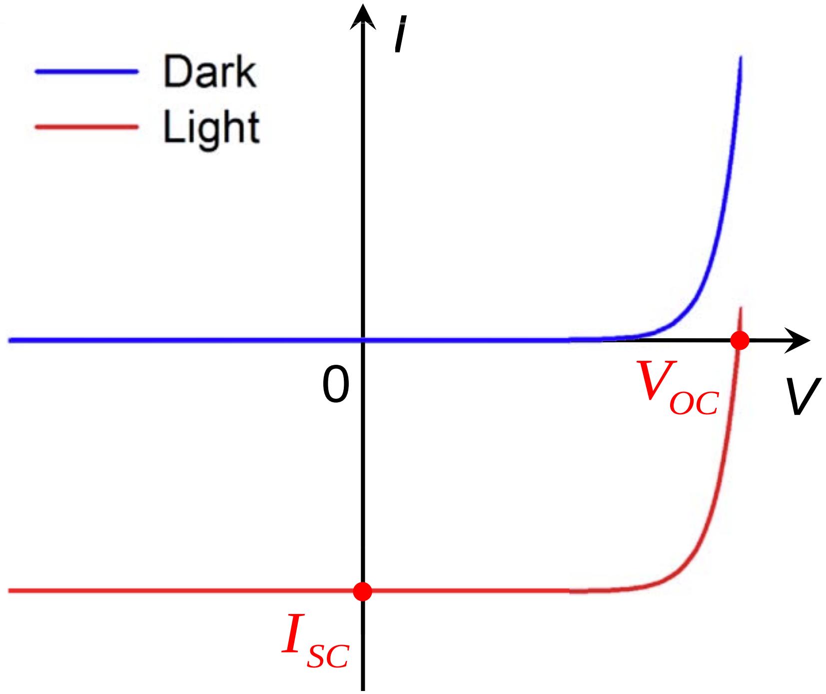


- Applied gate voltage modulates a-Si / LTPS channel conductance and the TFT on/off state
- Si_3N_4 and a-Si can be deposited using the same PECVD system
- Display glass: flat glass produced by down-draw fusion process

Nature **428**, 269 (2004)

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

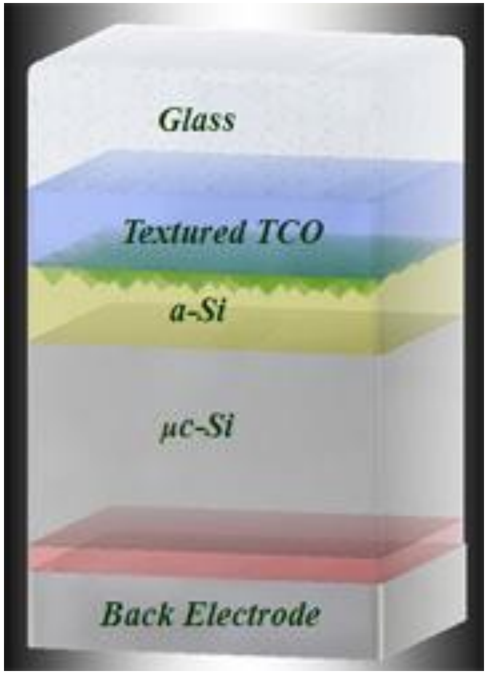
I_s : diode saturation current

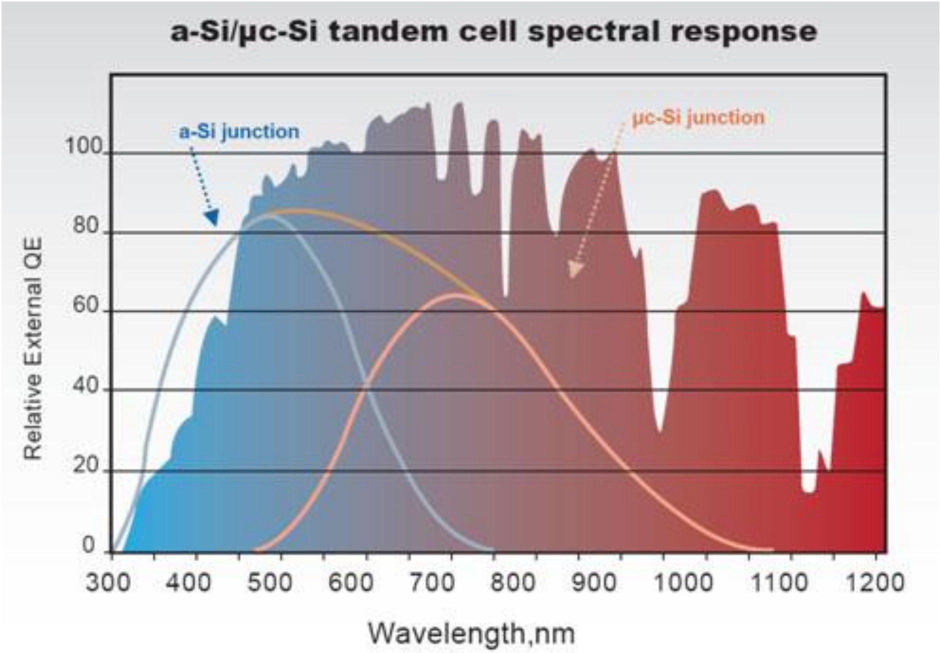
Thin film a-Si:H as a solar absorber

- Large-area, high-throughput deposition
- High absorption: reduced material consumption

} Low cost (?)

- Monolithic silicon tandem structures





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

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

Before light exposure

Figure removed due to copyright restrictions. See Figure 2: Staebler, D.L. and C.R. Wronski. "Reversible Conductivity Changes in Discharge-Produced Amorphous Si." *Applied Physics Letters* 31 (1977): 292-294.

Figure removed due to copyright restrictions. See Figure 6: Stutzmann, M. et al. "Light-induced Metastable Defects in Hydrogenated Amorphous Silicon: A Systematic Study." *Phys. Rev. B* 32 (1985): 23-47.

After light exposure

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

Staebler-Wronski effect

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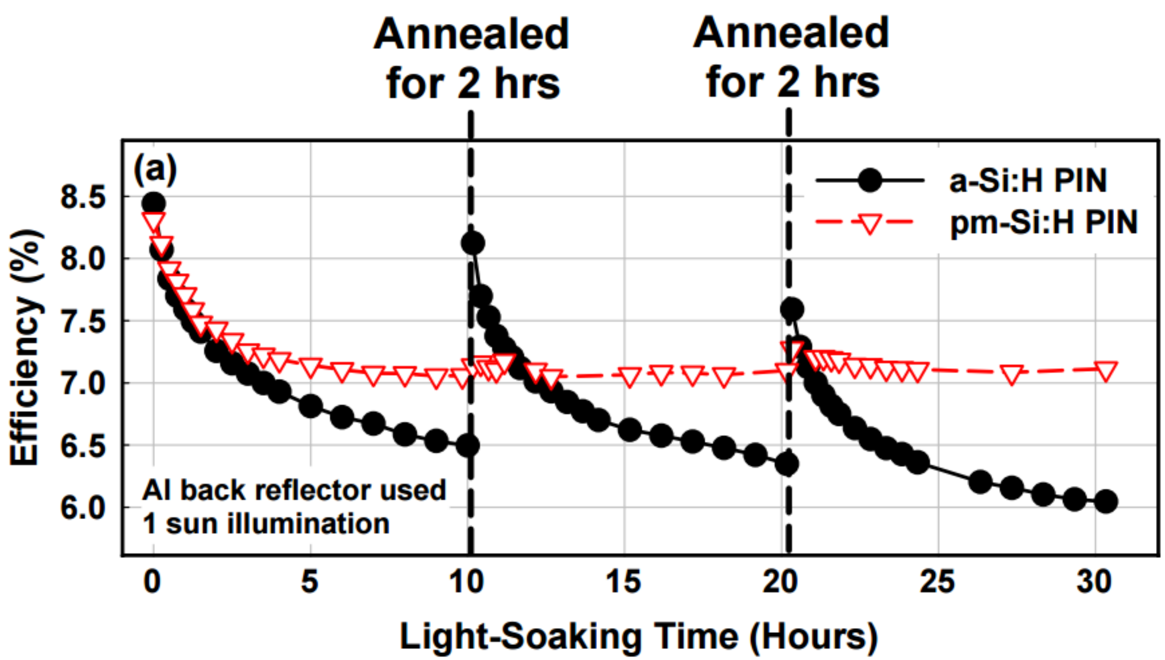
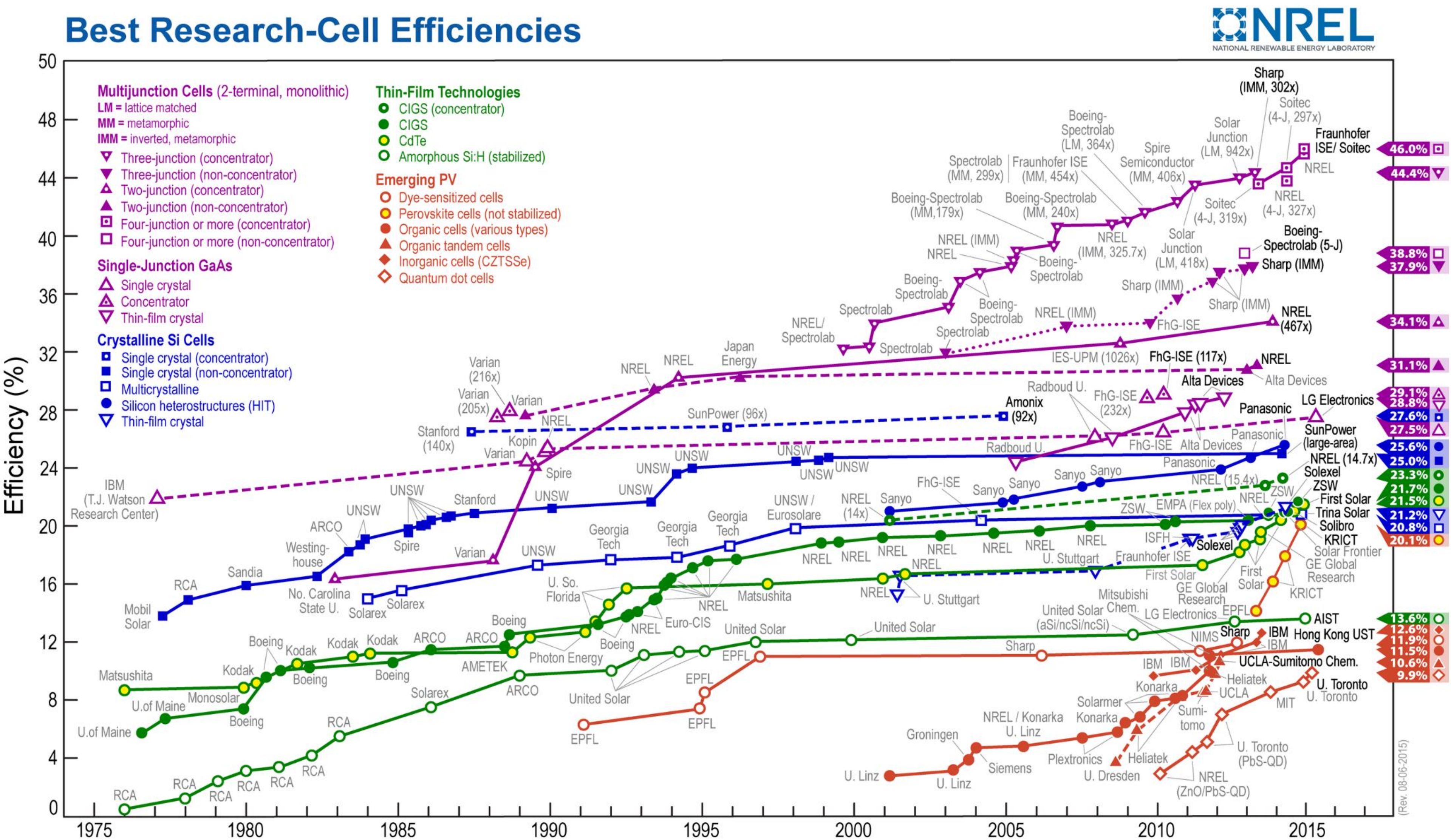


K. Kim, Diss. Ecole Polytechnique X (2012).

Best Research-Cell Efficiencies



Silicon heterojunction (SHJ) cells

Figures of Si diffuse junction cell and Si heterojunction cell removed due to copyright restrictions. See: "High-efficiency Silicon Heterojunction Solar Cells: A Review." Green 2 (2012): 7-24.

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

Green **2**, 7 (2012)

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
- 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
- Technology and Applications of Amorphous Silicon
  - R. A. Street, Springer (2000)