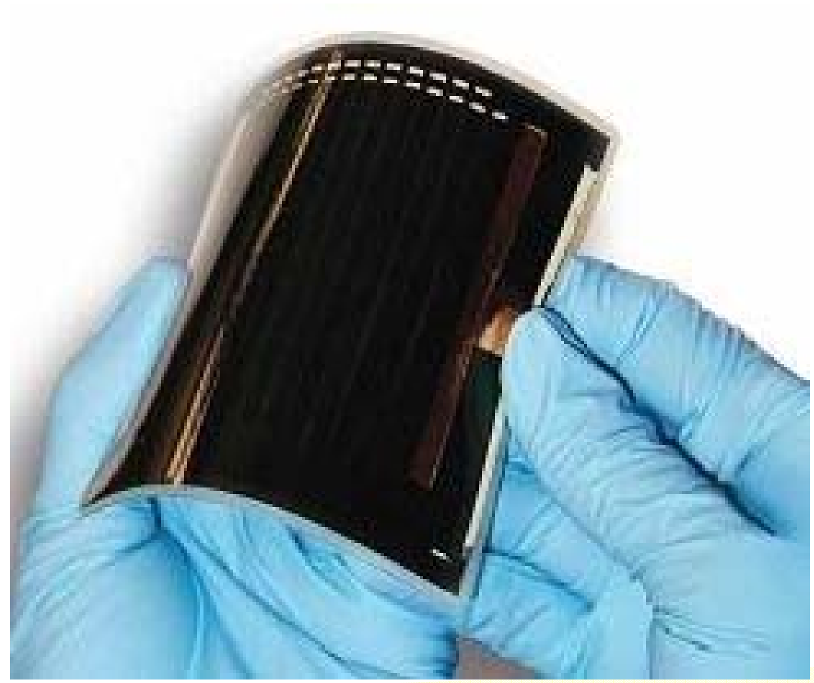
CIGS: Thin-Film Solar



Brendan Gunning

Thin Films vs. Silicon

- Why thin films?
  - High cost of electronic-grade silicon
  - Variety of potential substrates
  - Less semiconductor material = cheaper (a few microns vs. a few hundred microns for c-Si)

→ Really, it all boils down to cost ($/W)

"Generating one watt of electricity requires about 80 cents' worth of silicon, but it only requires a penny's worth of a semiconductor used in a thin-film cell."

http://www.technologyreview.com/Energy/19369/?a=f

Major Thin Film Technologies

- Cadmium Telluride (CdTe)
  - Holds 11% market share (15% total thin films)
  - E_g = 1.44eV -- Record Cell Efficiency: 16.5%
    -- FirstSolar *Module*: 10.9% avg
  - Problems: Cadmium toxicity, Tellurium supply
- Amorphous Silicon (a-Si)
  - E_g = 1.7eV – Record Efficiency: 12%
  - Uses 1% of Si required for c-Si cell
- ....CIGS!

http://www.nrel.gov/pv/thin_film/

What is CIGS?

- Copper Indium Gallium (di)Selenide
  - $CuIn_xGa_{(1-x)}Se_2$
- Semiconductor Alloy
  - Copper Indium (di)Selenide ($CuInSe_2$)
  - Copper Gallium (di)Selenide ($CuGaSe_2$)
  - Both materials have been used independently for solar cells

CIGS: Alloy

- CIS
  - Copper Indium (di)Selenide ($CuInSe_2$)
  - E_g = 1.0 eV
  - Record Efficiency: 15%
  - Challenges: low open-circuit voltage, Indium supply
- CGS
  - Copper Gallium (di)Selenide ($CuGaSe_2$)
  - E_g = 1.7 eV
  - Record Efficiency: 9.5%
  - Challenges: lower efficiencies (materials issue… more later)

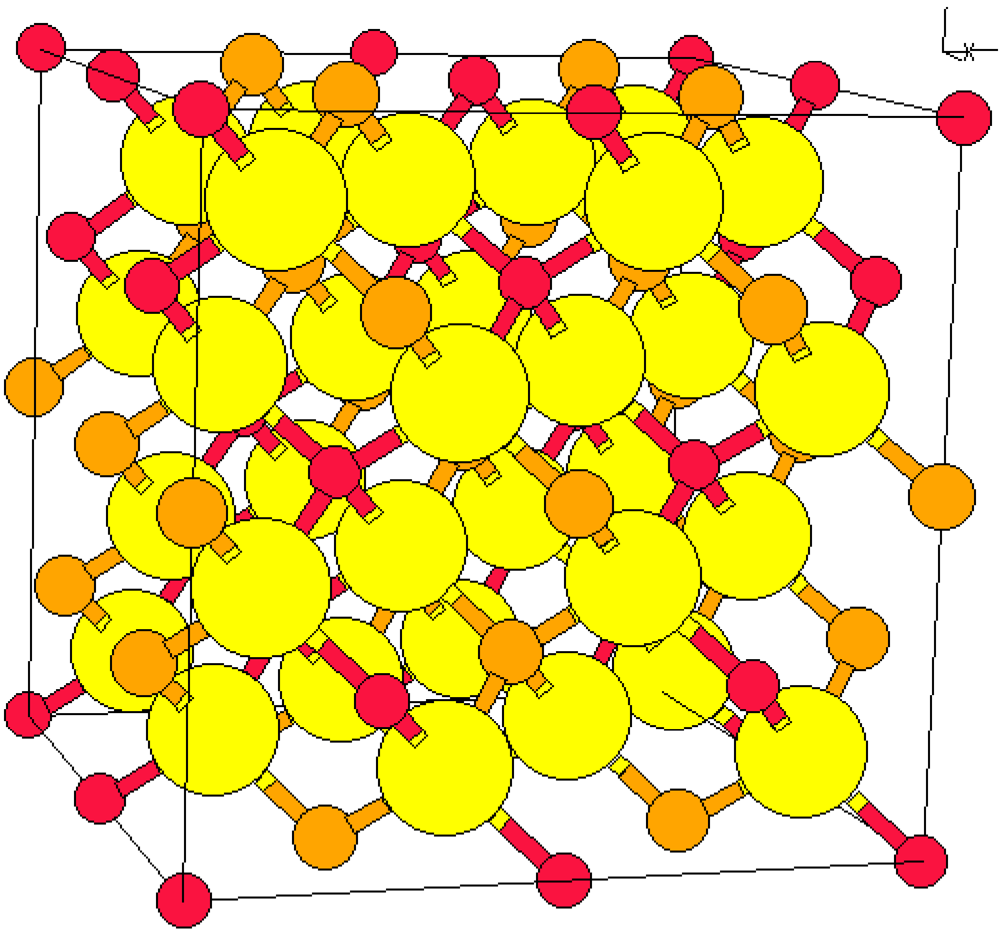
http://www.nrel.gov/pv/thin_film/pn_techbased_copper_indium_diselenide.html

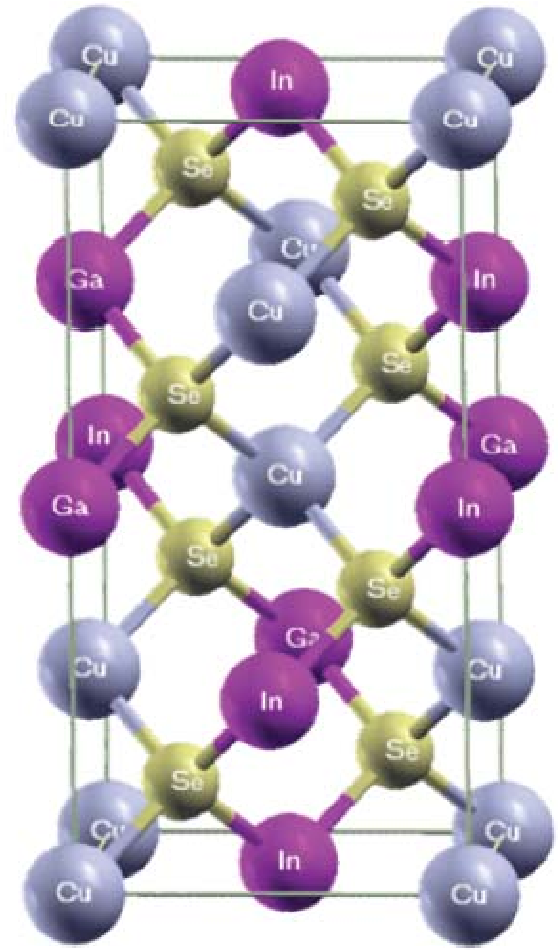
CIS + CGS = CIGS

- Record Efficiency: 19.9%
  - Higher than both CIS <u>and</u> CGS!!
- Direct bandgap → good photonic device
- By varying ratio of CIS/CGS, can achieve any bandgap from 1.0 – 1.7 eV
- In($Ga_{.7}In_{.3}$)Se_2 gives a bandgap around 1.5 eV, which is “ideal” for a single-junction cell

Repin, et al; , "Characterization of 19.9%-efficient CIGS absorbers," *Photovoltaic Specialists Conference, 2008. PVSC '08. 33rd IEEE* , vol., no., pp.1-6, 11-16 May 2008

CIGS: Chalcopyrite Crystal Structure





http://cst-www.nrl.navy.mil/lattice/struk/e1_1.html
http://www.tf.uni-kiel.de/matwis/amat/matwissem_en/kap_6/illustr/gerngross_reverey_paper_ws_08_1.pdf

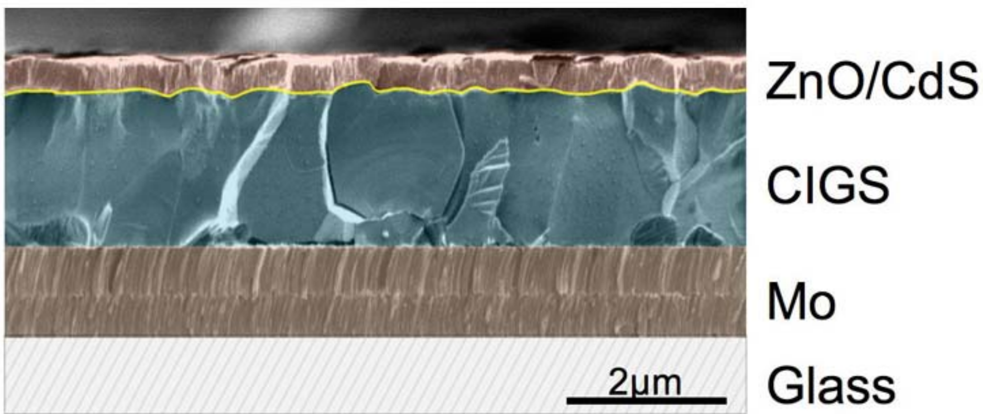
Cell Structure

- Substrate: glass, stainless steel, flexible polymers (more on this later)
- Back Contact: Molybdenum (< 1μm)
- Semiconductor: p-CIGS (1-5μm)
- Buffer: CdS (≤ .1μm, E_g = 2.4eV)

  i-ZnO (≤ .1μm, E_g = 3.2eV)
- Semiconductor: n^+-ZnO (< .5μm, E_g = 3.2eV)
- Anti-Reflective Coating: MgF_2
- Front Contact: Ni/Al, ITO

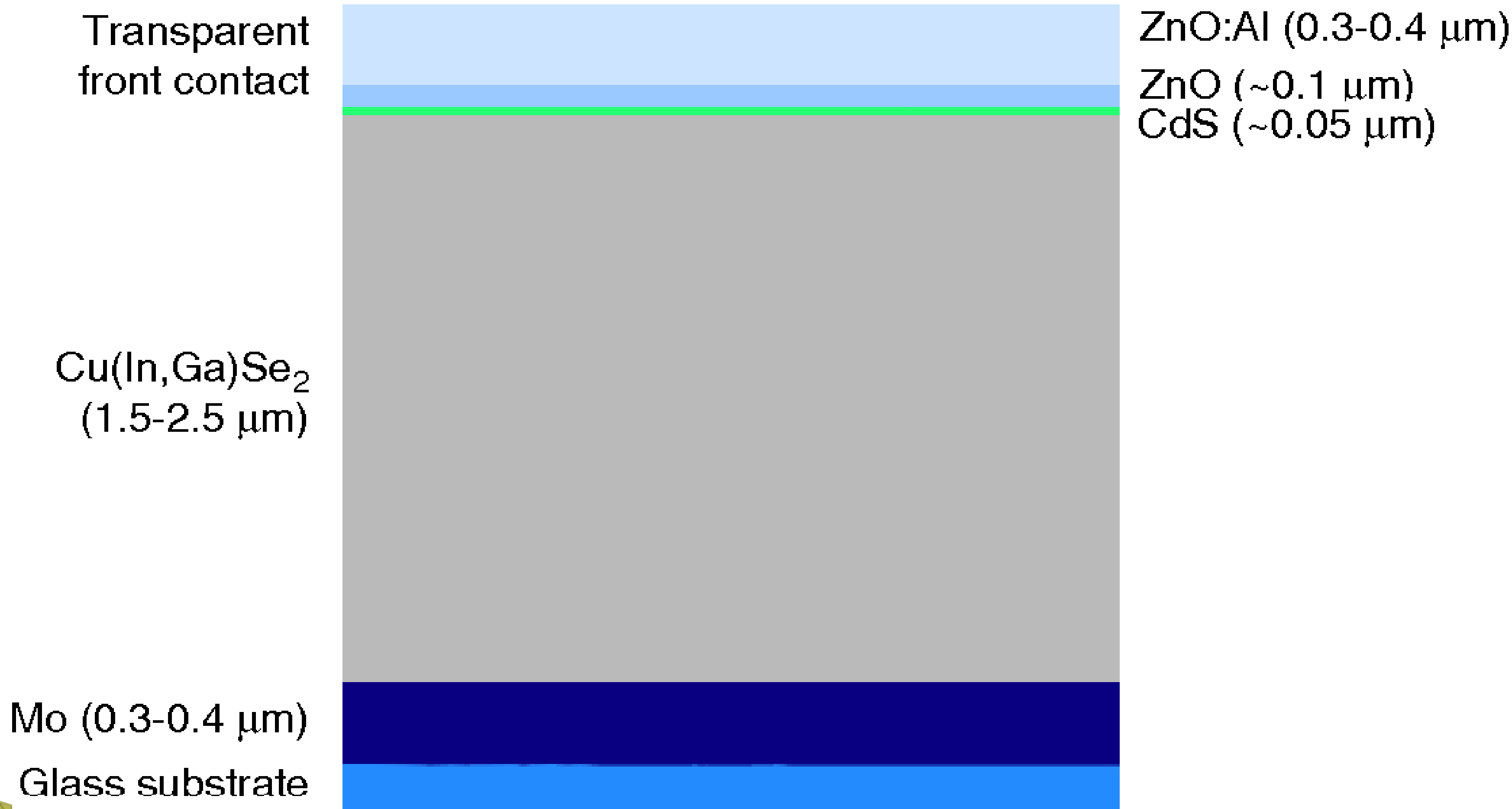
http://www.tf.uni-kiel.de/matwis/amat/matwissem_en/kap_6/illustr/gerngross_reverey_paper_ws_08_1.pdf

Cell Structure



http://www.nrel.gov/pv/thin_film/docs/wc4papernoufi__.doc

Cell Cross Section



http://upload.wikimedia.org/wikipedia/commons/8/83/CIGS-scheme.png

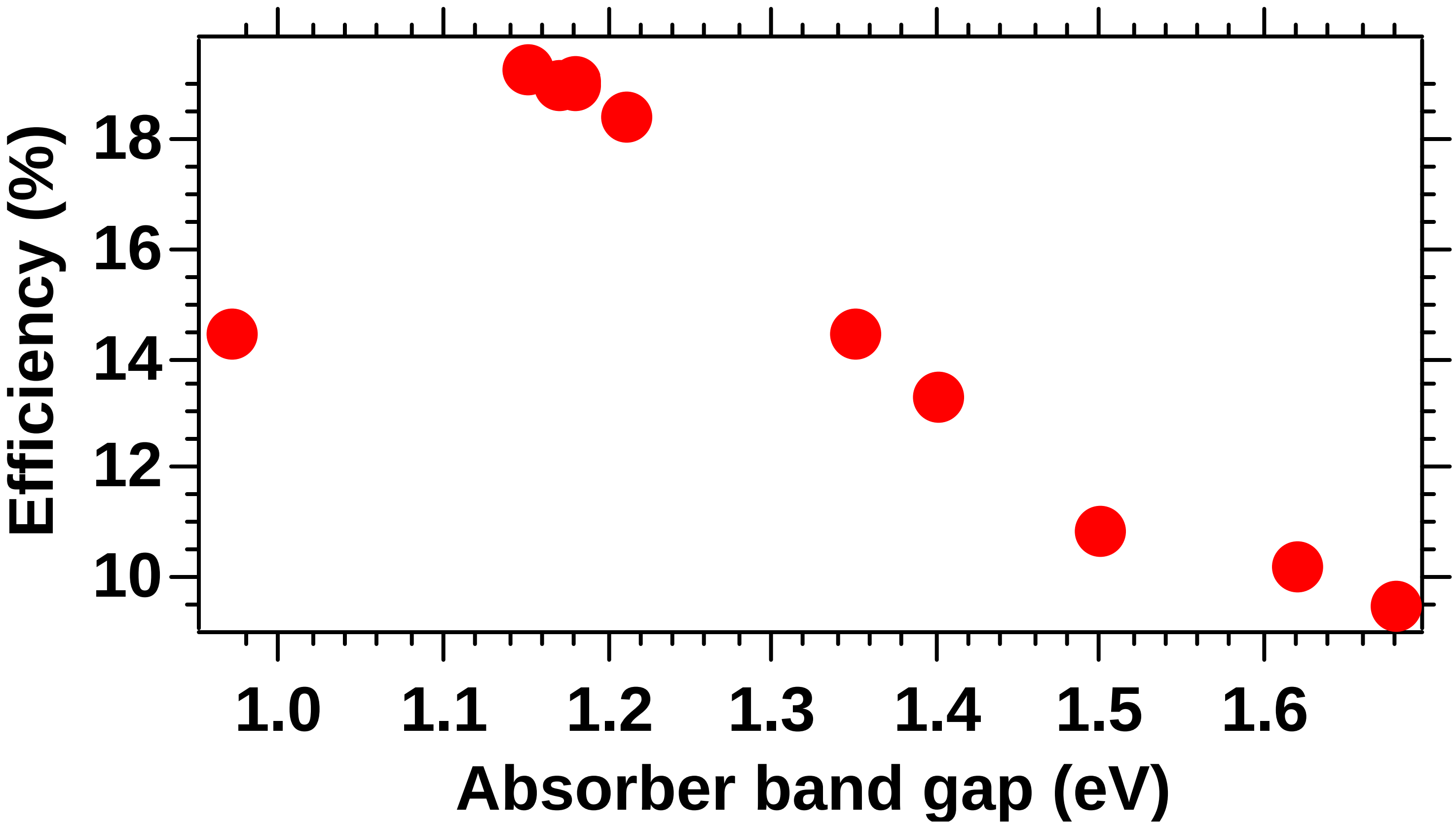
CIGS Subtleties

- Polycrystalline by nature
- Defect-induced self-doping
  - stems from Cu vacancies acting as acceptors
- ODC: Ordered Defect Compound
  - Different composition at film surface
  - Naturally n-type → homojunction with CIGS
  - Homojunction reduces recombination at material interface

"God made solids, but surfaces were the work of the devil." -Wolfgang Pauli

Wennerberg; Design and Stability of Cu (in, Ga) Se2-based solar cell modules; 2002

CIGS Bandgap



→ Why peak at 1.1-1.2 eV?

http://www.nrel.gov/pv/thin_film/docs/ramanathan_cis2005solarreview.ppt

Efficiency Dropoff

- At around 30% Ga ($E_g \approx 1.2$ eV), efficiency dropped off – Why?
- Ordered Defect Compound at the surface starts to disappear with Ga concentration > 30%

  → increased surface recombination, reduced efficiency
- Also helps explain why CuGaSe2 experiences lower efficiencies

http://www.docstoc.com/docs/24850488/CIGS-introduction/

More Subtleties

- Influence of Sodium
- Sodium from the glass substrate diffuses through Mo back into CIGS layer
  - Actually a good thing! (in small concentrations)
  - Increases conductivity and grain sizes
  - Na binds with oxygen in Se vacancies, reducing recombination centers and “donors” (vs. Cu)
- Because of this, Na is often added if a different substrate is used

http://en.wikipedia.org/wiki/Copper_Indium_Gallium_Selenide_Solar_Cells#cite_note-M._Kemell_2005-4

Now… Current state-of-the-art and CIGS in industry

Fabrication Methods

- Co-Evaporation / Co-Sputtering & Anneal
  - evaporate/sputter Cu, Ga, In simultaneously, then anneal in a Se vapor, or…
  - simultaneously evaporate all four onto a heated substrate
- Electroplating
- Wafer bonding
  - Two precursor films on different substrates pressed together and heated to form the CIGS layer
- Nano-particle precursors
  - Water-based solution (ink) containing metal/metal-oxide precursors applied to substrate
  - Dehydrated, reduced in H_2/N_2 gas, sintered, selenized

http://www.nrel.gov/pv/thin_film/docs/wc4papernoufi__.doc
http://en.wikipedia.org/wiki/Copper_Indium_Gallium_Selenide_Solar_Cells#cite_note-J._Stanbery_2002-0

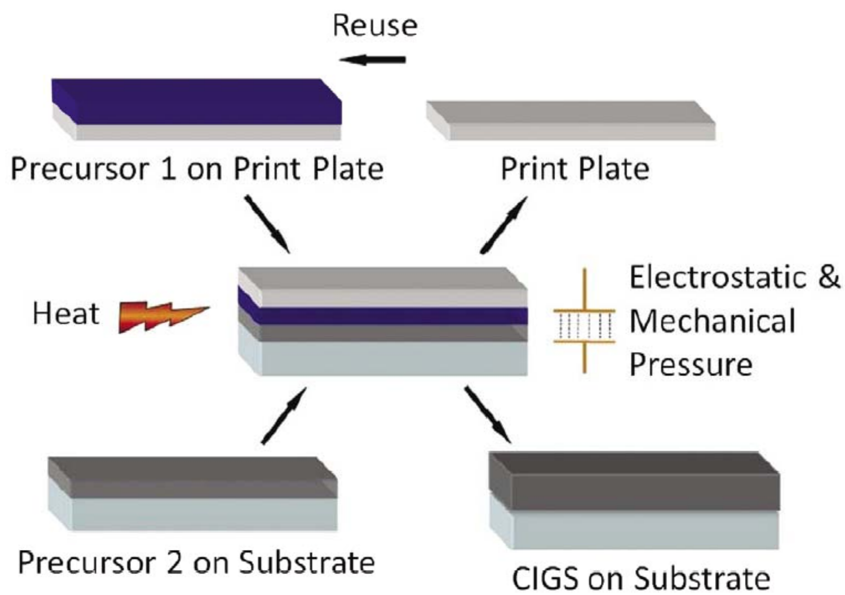
Major Players in CIGS

- Heliovolt
- ISET – International Solar Electric Technology
- Miasolé
- NREL – National Renewable Energy Lab
- Nanosolar
- Solyndra

NREL

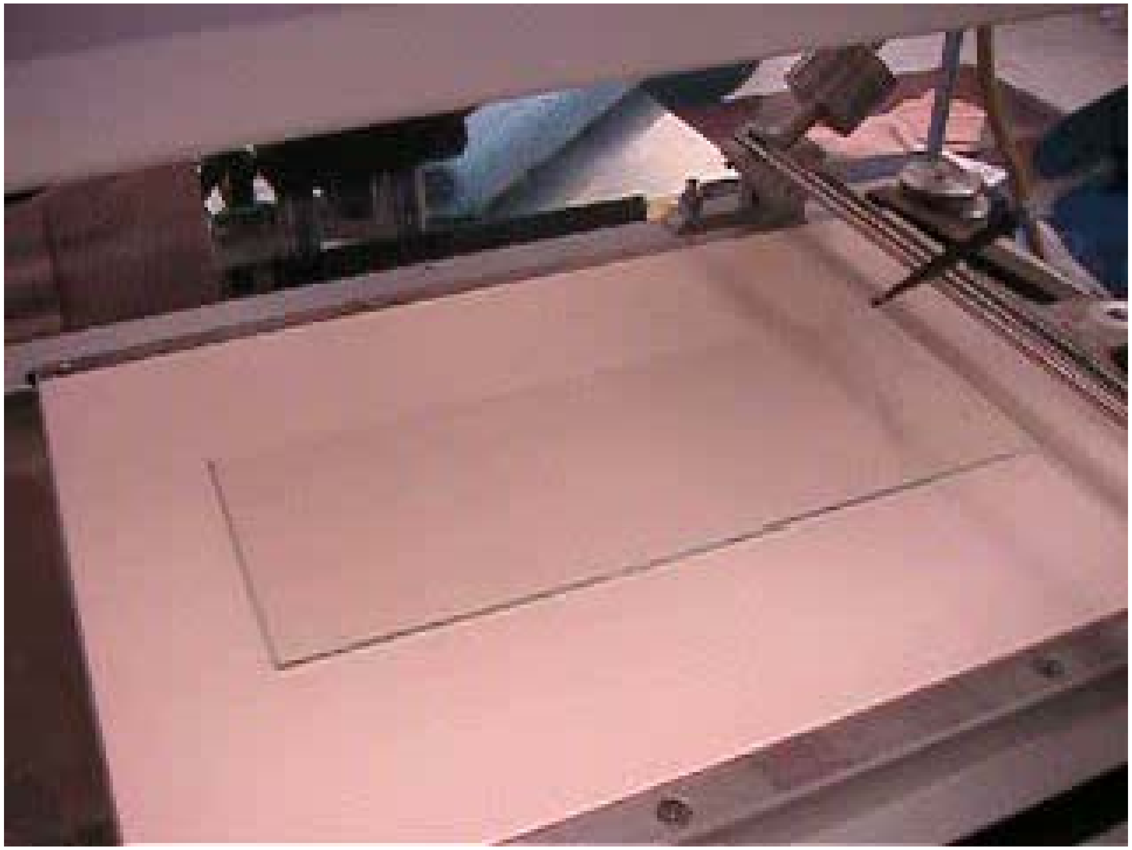
- National Renewable Energy Lab – Golden, CO
  - http://www.nrel.gov/pv/thin_film/pn_techbased_copper_indium_diselenide.html
- Record holder for CIGS cell efficiency (19.9%)
- Responsible for testing cell efficiencies
  - Verifies/refutes data achieved in company labs
- Not a PV company, but their research and services are critical to the industry

- www.heliovolt.com – Austin, TX
- Patented fabrication technique (FASST)
- Cell Efficiency: 14%, Module Efficiency: 12%



ISET

- http://www.isetinc.com/cigs.html
- Chatsworth, CA
- Fabrication using nanopartical precursor inks
- Cell Efficiency: 13.7%
- Materials utilization >95%
- Video…

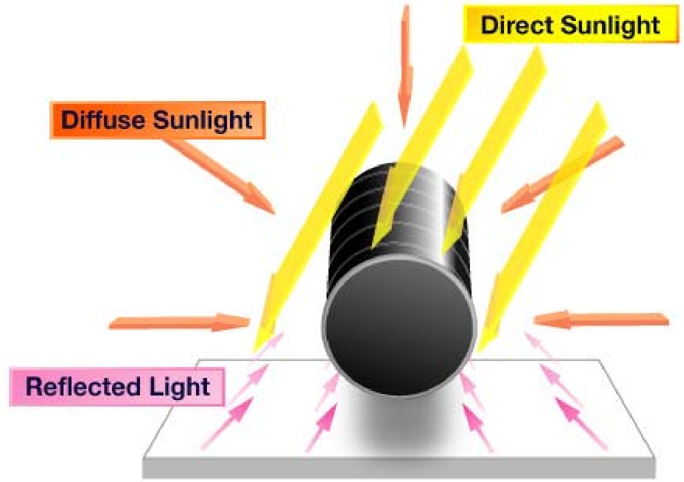


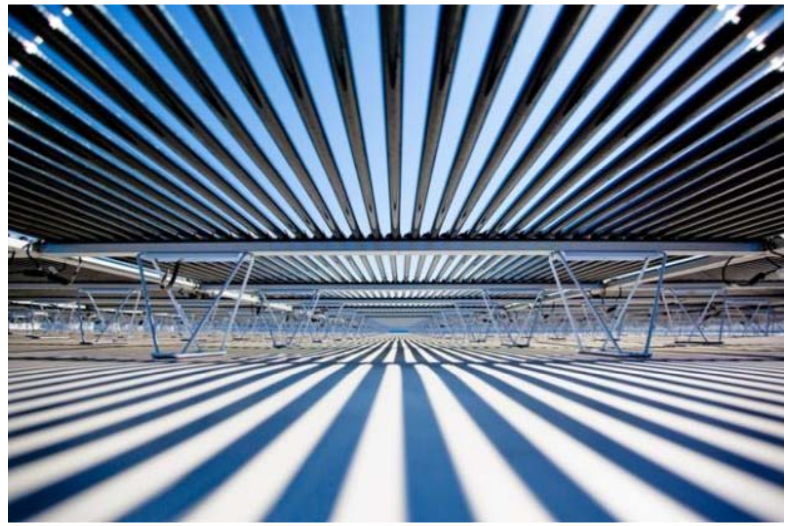
http://www.isetinc.com/cigs.html

- www.miasole.com – Santa Clara, CA
- Very secretive sputtering process
  - Continuous sputtering onto a stainless steel substrate roll 2 miles(!) long by 3 feet wide
- Module efficiency: 10.2%

- www.nanosolar.com – San Jose, CA
- Also very secretive nanoparticle process
  - Similar process to ISET, but different ink
- Foil substrate
- Cell Efficiency: 16.4%, Module: 12.1%
- Production capacity >1GW
- Click!

SOLYNDRA





SOLYNDRA

- www.solyndra.com – Fremont, CA
- Cylindrical solar modules!?
- 40 one-inch diameter cylinders in each rack
- Module Efficiency: 12-14% (not confirmed)
- Captures direct, indirect, reflected light
- Coating over rolled CIGS cell helps concentrate light
- Work best with a white roof
- Can withstand winds up to 135 mph!

Conclusion

- CIGS offers many great advantages
  - More efficient than CdTe, cheaper than c-Si
  - $1/10^{th}$ the amount of Cadmium vs. CdTe
  - Many substrate options including flexible
  - Multiple non-vacuum processing methods
  - Highly durable (Nanosolar 25-year warranty)
- CIGS is a fairly new challenger, but it's gaining momentum in a big way