Materials Availability for TW Scale Photovoltaics

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Survey of audience

a) Current thin film technologies, CdTe, CIGS & thin film Si will grow at rates that will accumulate to ~10 TW by sometime between 2050-2100.

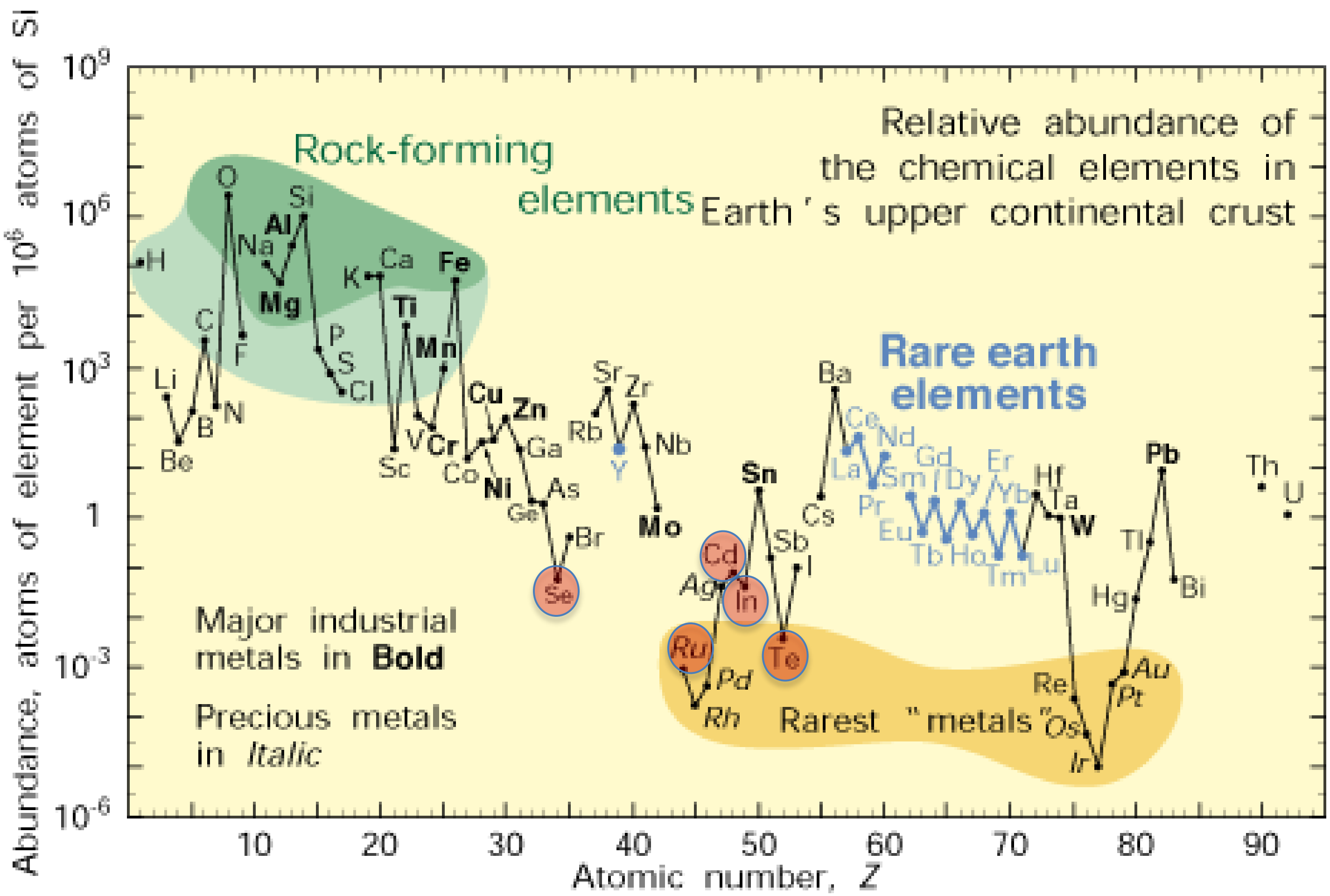
a) Above statement can not be true. We will need other (new) materials and technologies other than or in addition to CdTe, CIGS & thin film Si to achieve ~10 TW by sometime between 2050-2100.

- One can defend any one of these statements with seemingly reasonable assumptions.

References addressing the materials availability issue

- Fthenakis "Sustainability of photovoltaics: the case for thin-film solar cells." *Renewable and Sustainable Energy Reviews* **23**, 2746 (2009).
- Wadia, Alivisatos & Kammen, "Materials availability expands the opportunity for large scale photovoltaics development." *Environ. Sci. Technol.* **43**, 2072 (2009).
- Zweibel, "The Terrawatt challenge for thin film PV: A work in progress" NREL Report (2006).
- Andersson, "Materials availability for large-scale thin-film photovoltaics,"*Prog. Photovoltaics* **8**, 61 (2000).

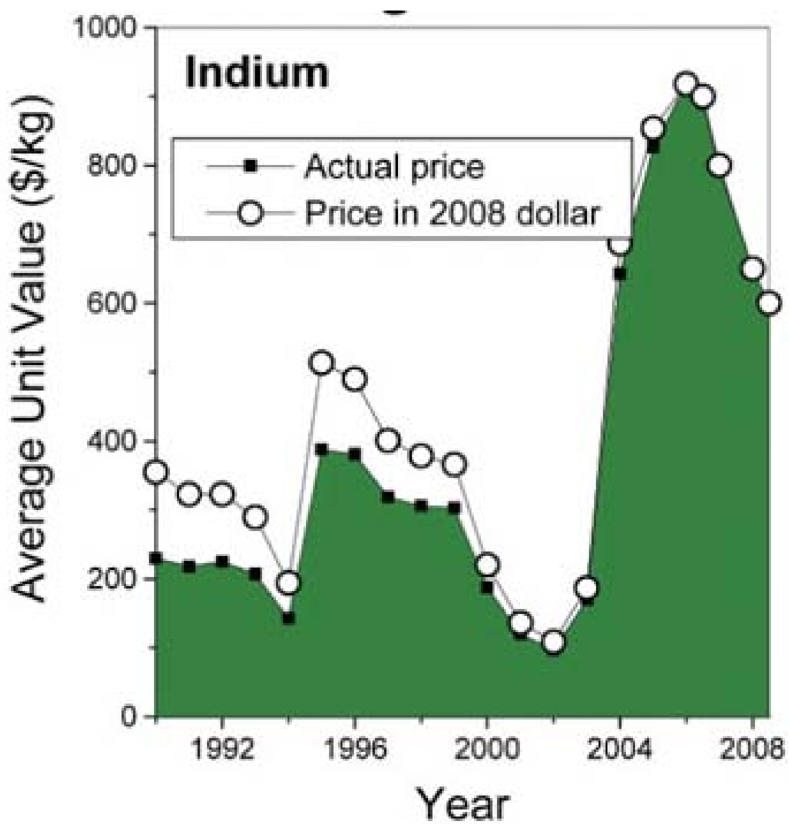
One limitation is abundance of elements



- If rare also difficult to recover and therefore expensive.
- There may not be enough of it to reach ~10 TW

Wikipedia.org

Another limitation could be the price



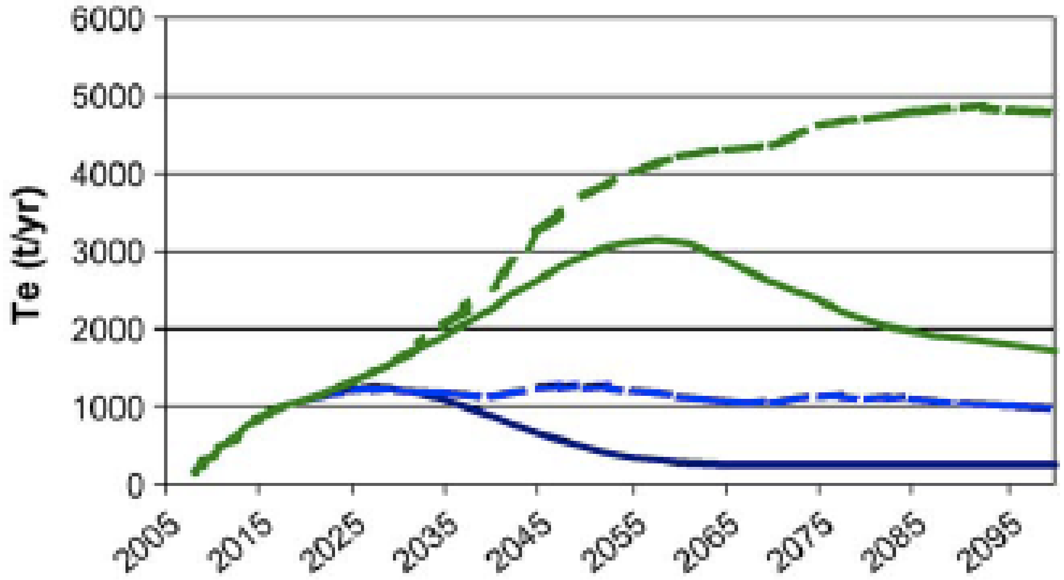
September 2008 - "SMG filed an IPO to raise $55 million on the American Stock Exchange – plans to use the money it raises to stockpile indium in the hope of selling it for higher prices in the future."

- If rare others may want it too.
- Supply & demand difficult to predict

www.greentechmedia.com

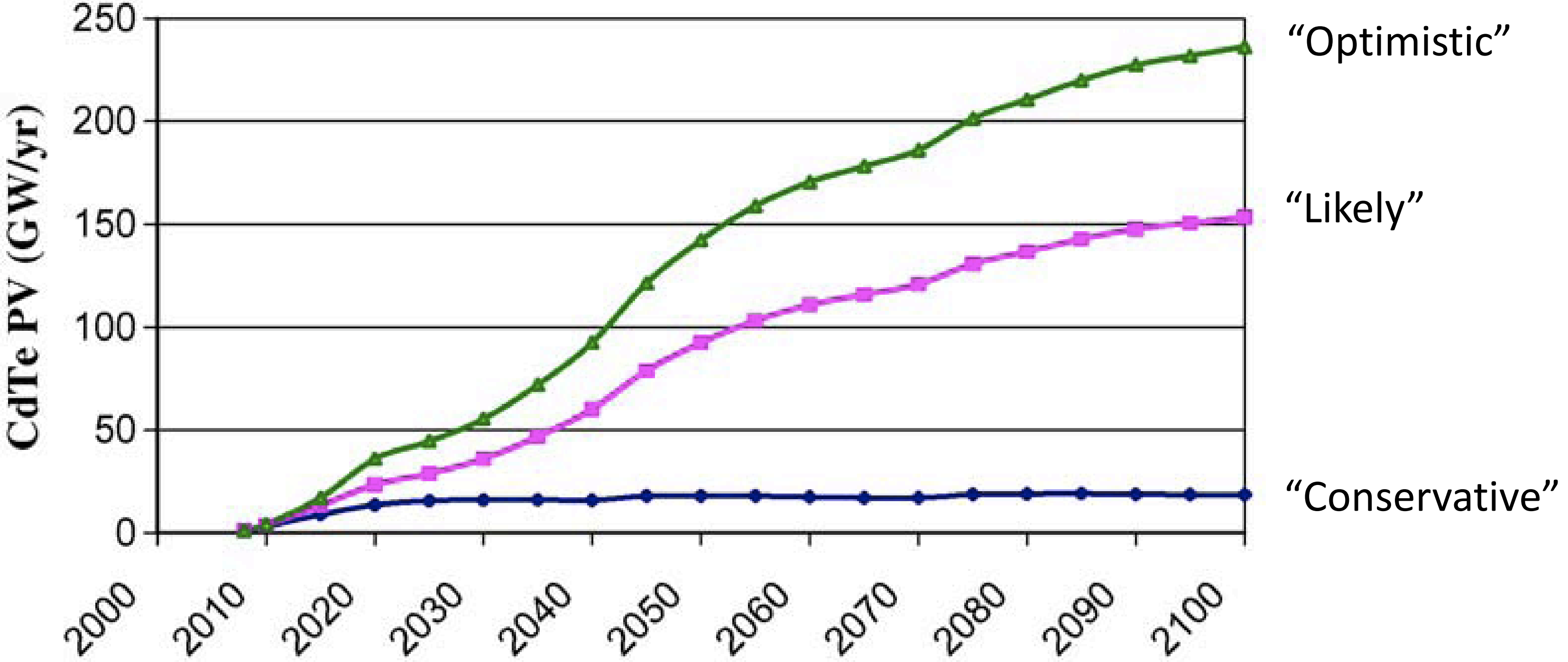
Te availability may limit the growth rate of CdTe PV

- Te is a byproduct of Cu production
- Te production rate tied to Cu production
- ~ 30-40% of available Te is recovered
- Cu production is uncertain



Fthenakis, Renewable & Sustainable Energy Reviews. Sci. Technol. **13**, 2746 (2009).

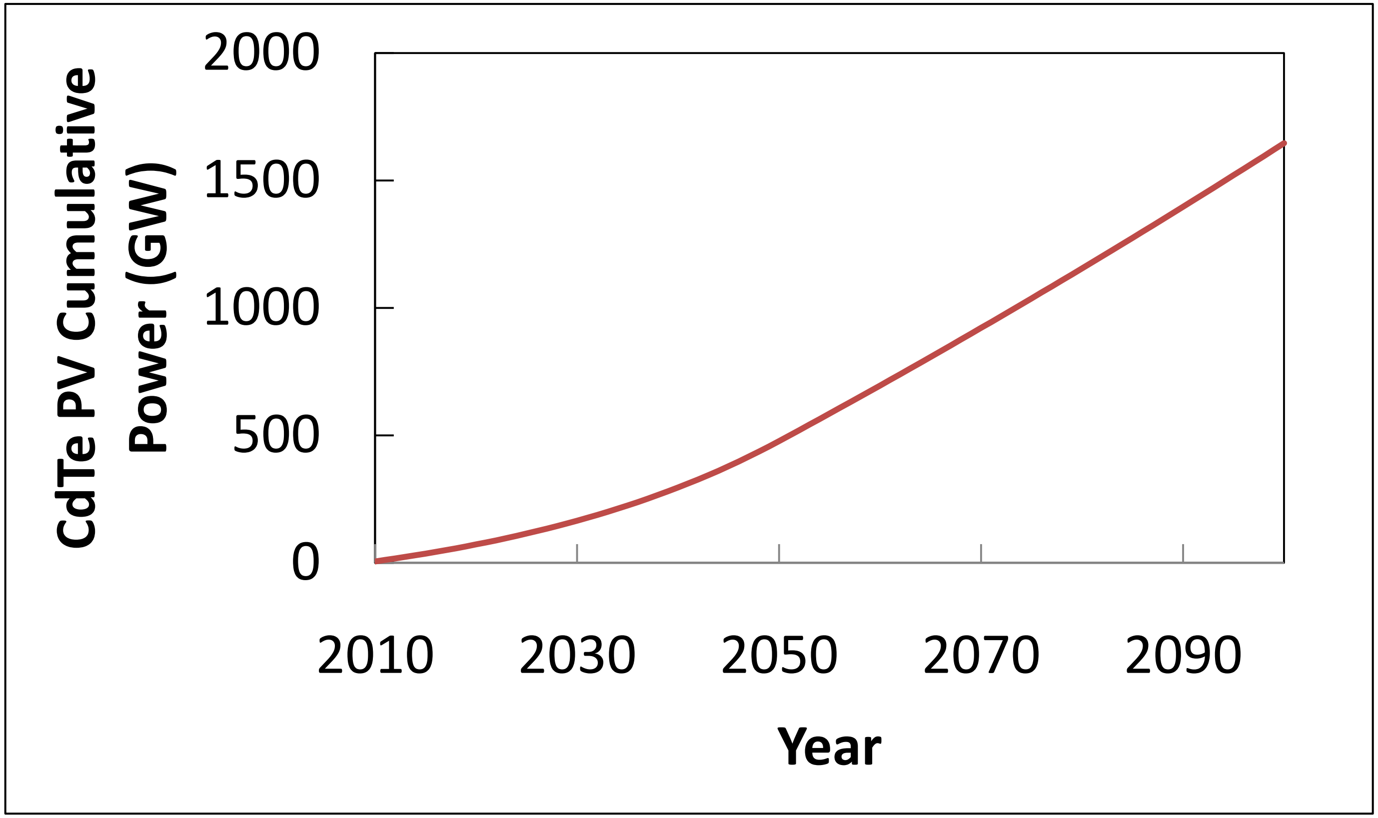
Projected growth rate limits for CdTe solar cells based on Te Availability



- Cu production peaks 2025 or 2060
- ~ 80% of available Te is recovered
- CdTe thickness down to 1 μm, efficiency up to 14%
- All scenarios include secondary recovery

Fthenakis, Renewable & Sustainable Energy Reviews. Sci. Technol. **13**, 2746 (2009).

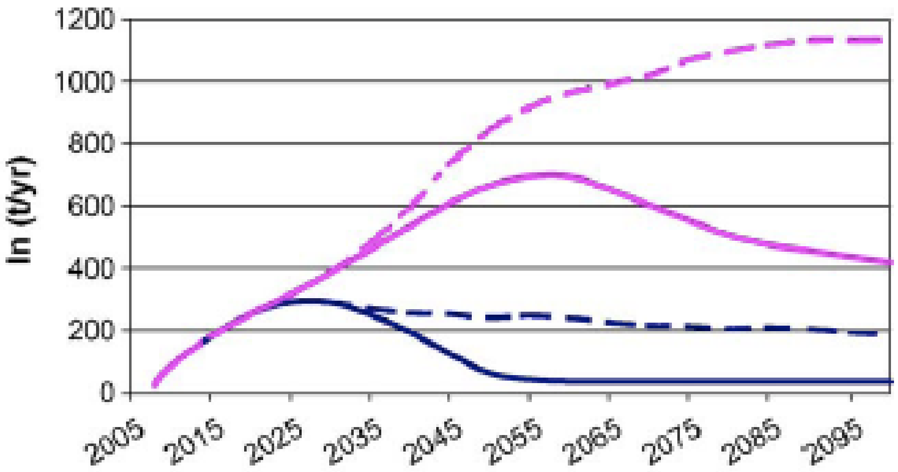
Projected growth rate limits for CdTe solar cells based on Te Availability

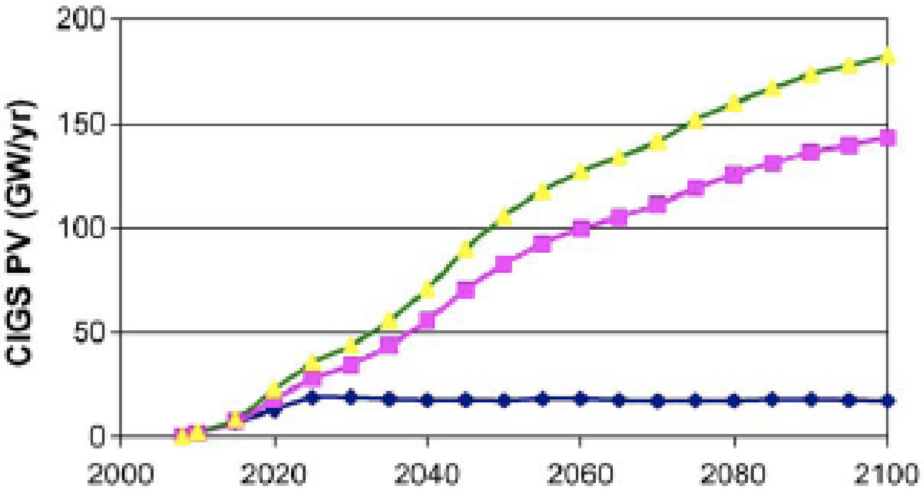


- Cu production grows to 2060 and remains constant at 53 Mt/year
- ~ 33% of available Te is recovered
- CdTe thickness 2 μm, efficiency up to 15 %

In availability may limit the growth rate of CIGS PV

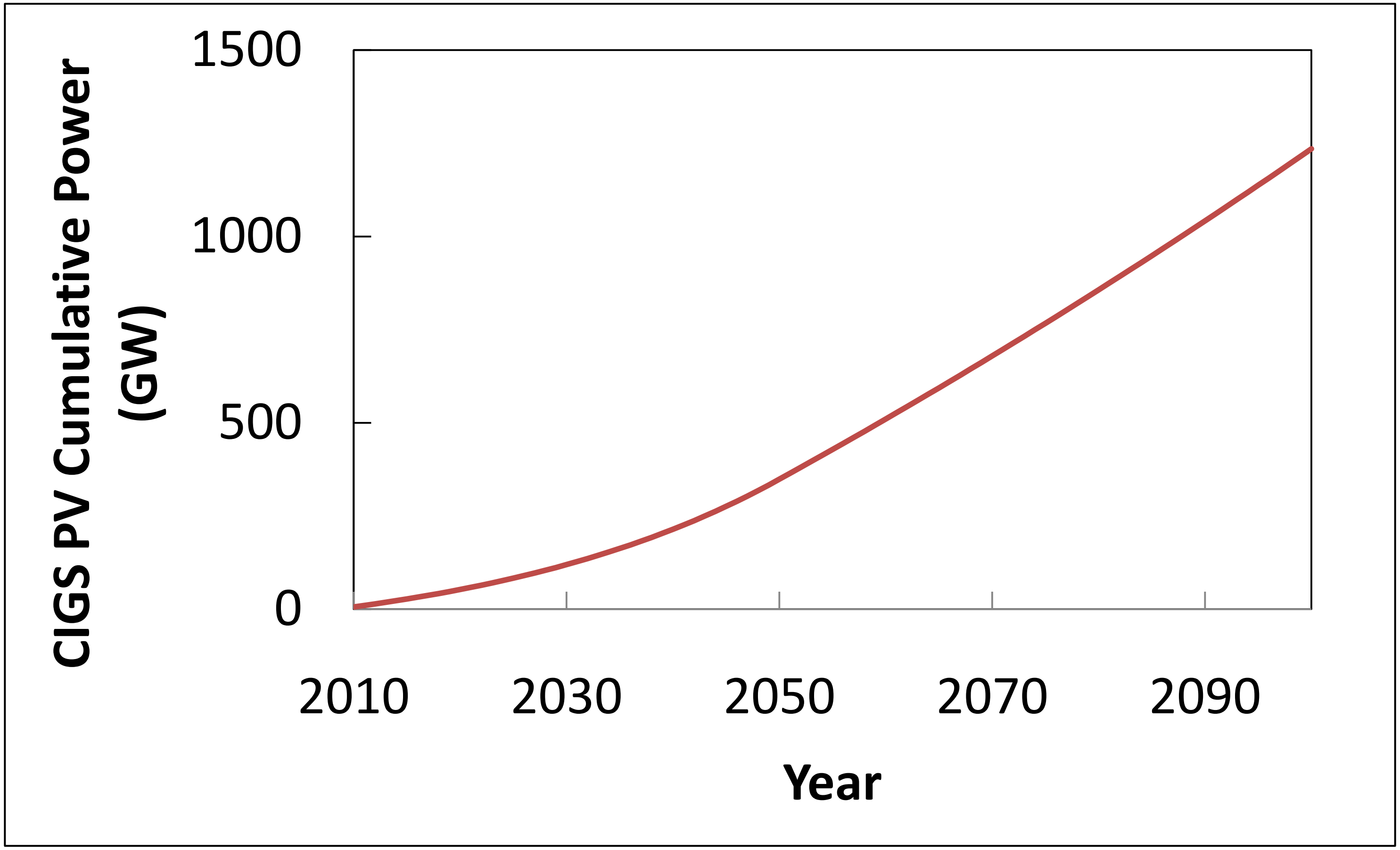
- In is a byproduct of Zn production
- Te production rate tied to Zn production
- ~ 70-80 % of available In is recovered





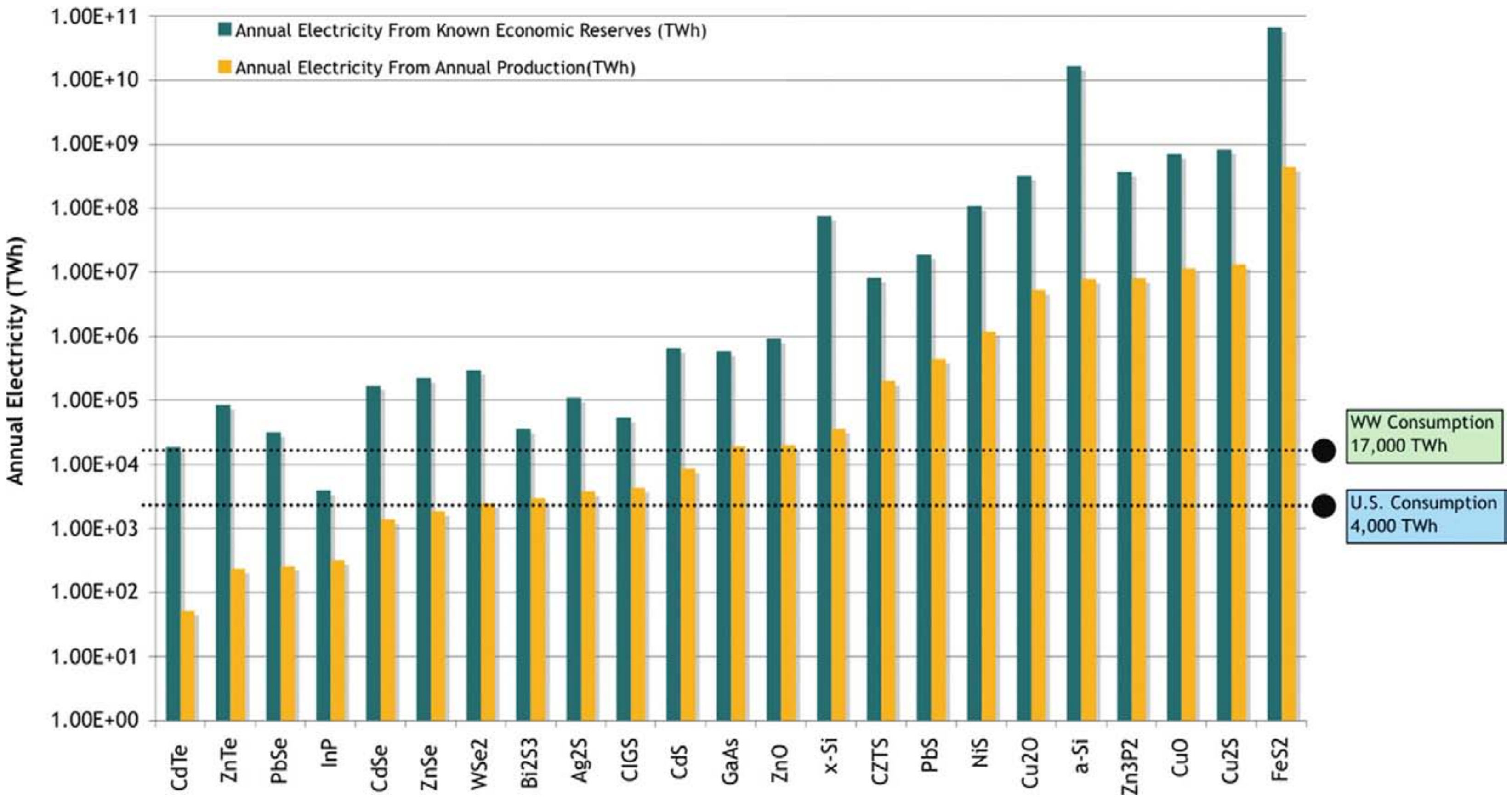
Fthenakis, Renewable & Sustainable Energy Reviews. Sci. Technol. **13**, 2746 (2009).

Projected growth rate limits for CIGS solar cells based on In Availability



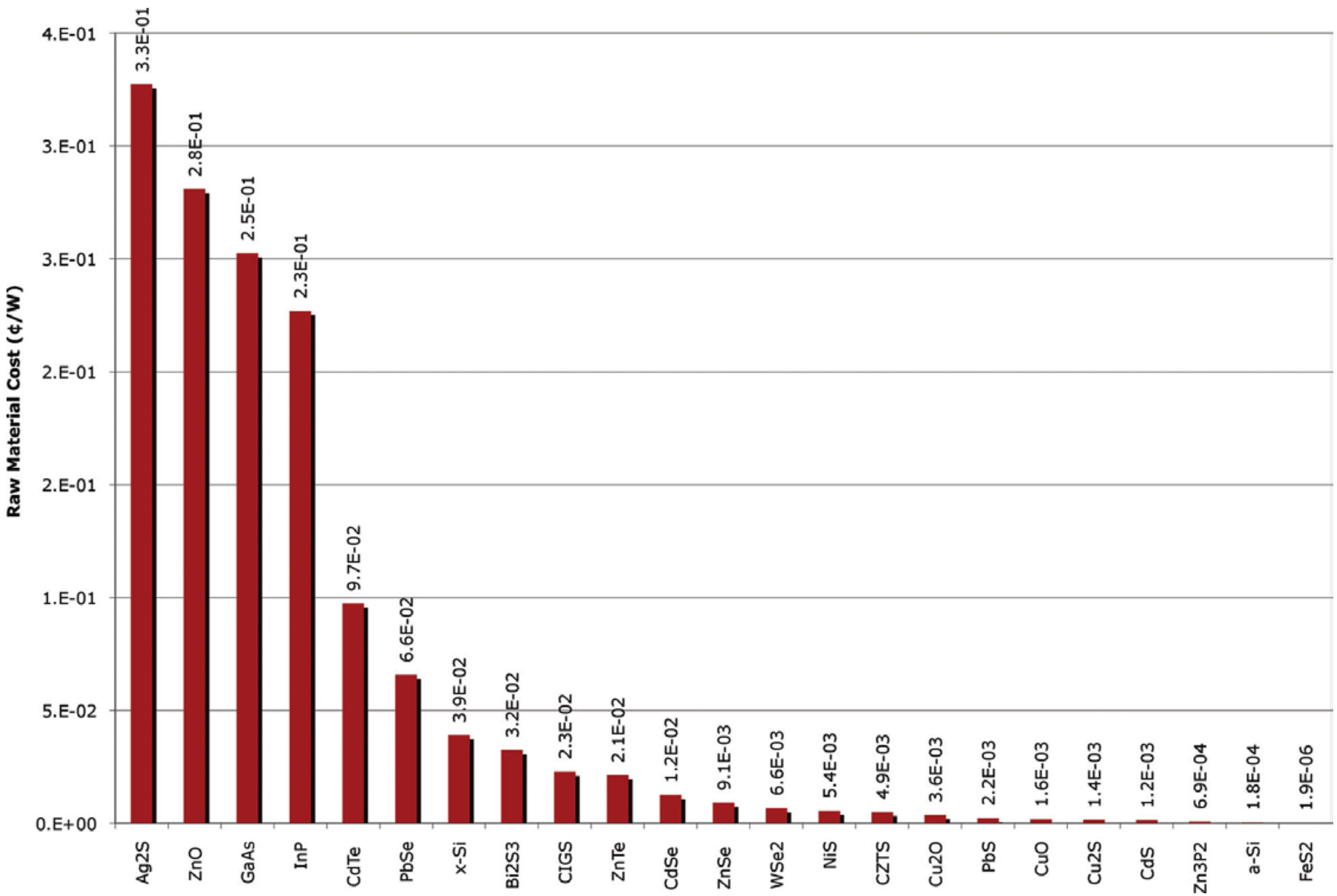
- Zn production grows to 2060 and remains constant at 11 Mt/year
- ~ 80% of available In is recovered
- CdTe thickness 1.6 μm, efficiency up to 17 %

Annual electricity production potential of common inorganic semiconductors



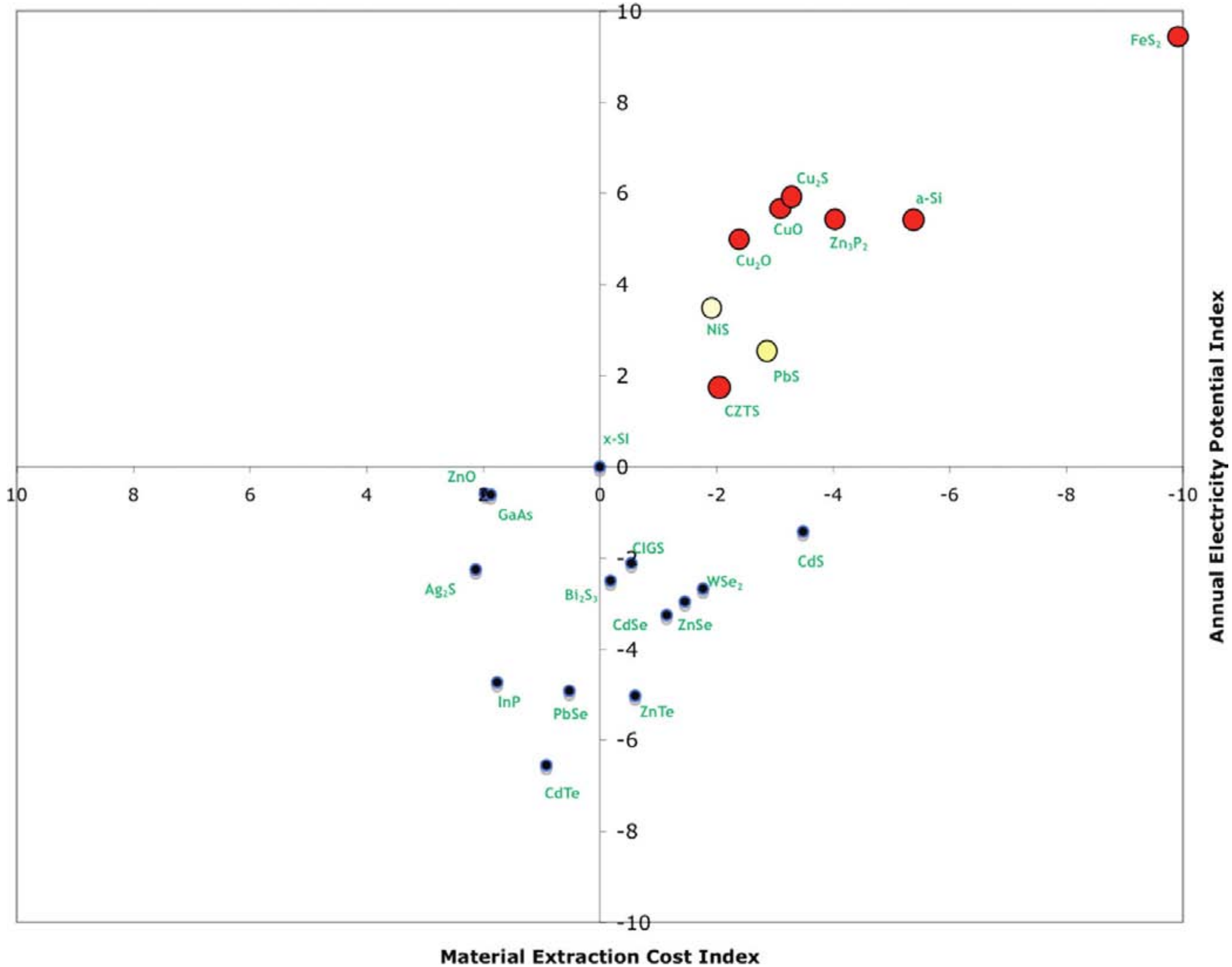
Wadia, Alivisatos & Kammen, Environ. Sci. Technol. **43**, 2072 (2009).

Raw materials cost of common inorganic semiconductors



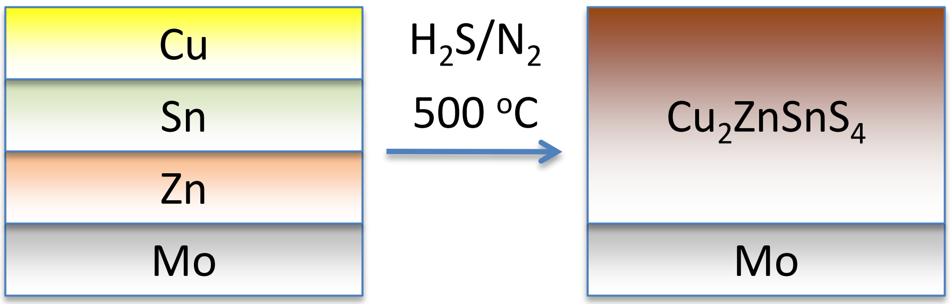
Wadia, Alivisatos & Kammen, Environ. Sci. Technol. **43**, 2072 (2009).

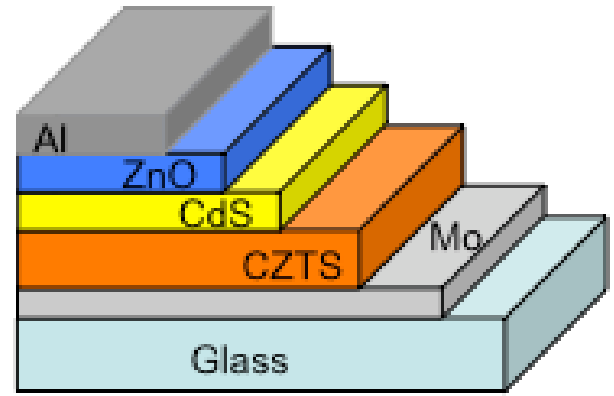
Which materials have extraction costs lower than Si and electricity producing potential greater than Si?

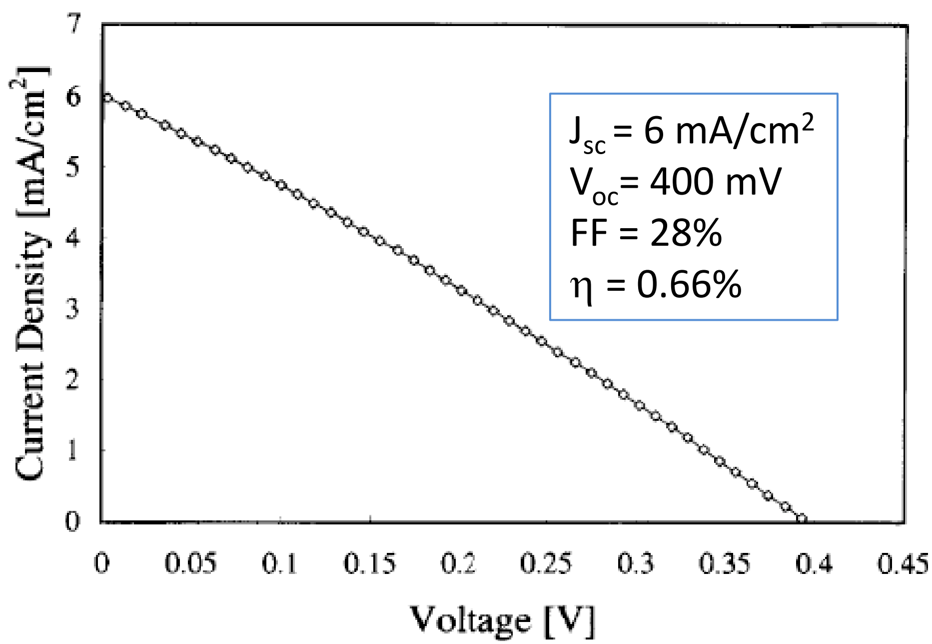


Wadia, Alivisatos & Kammen, Environ. Sci. Technol. **43**, 2072 (2009).

CZTS Solar Cells by Sulfurization of a stack of evaporated Zn/Sn/Cu films

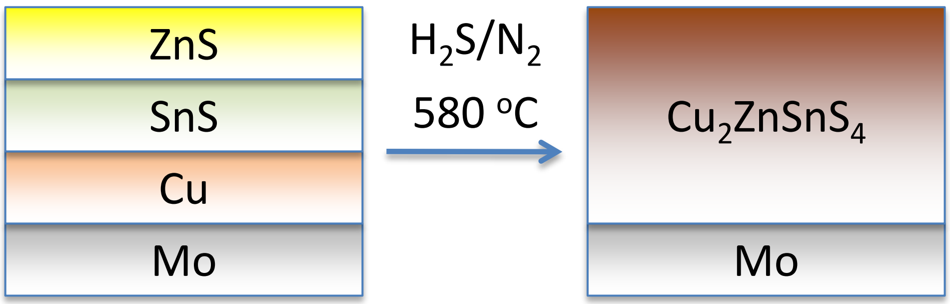


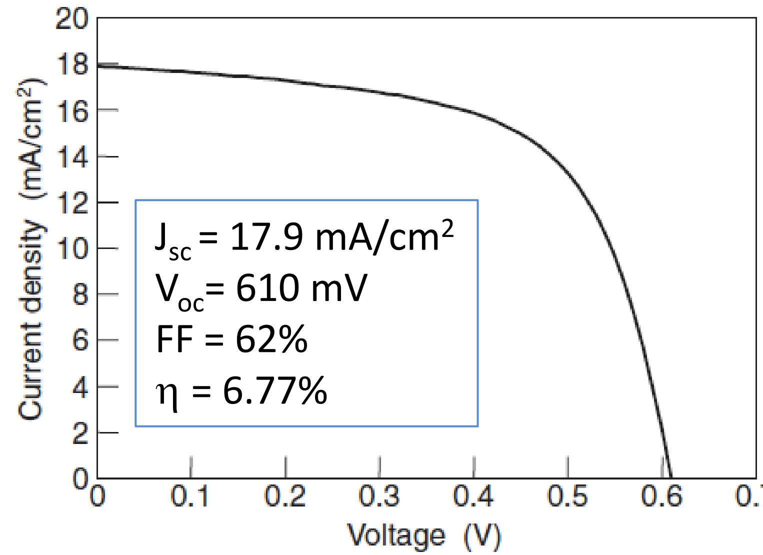


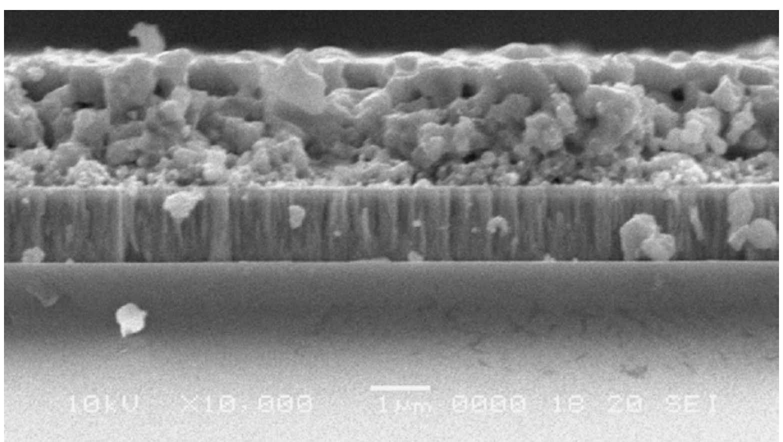


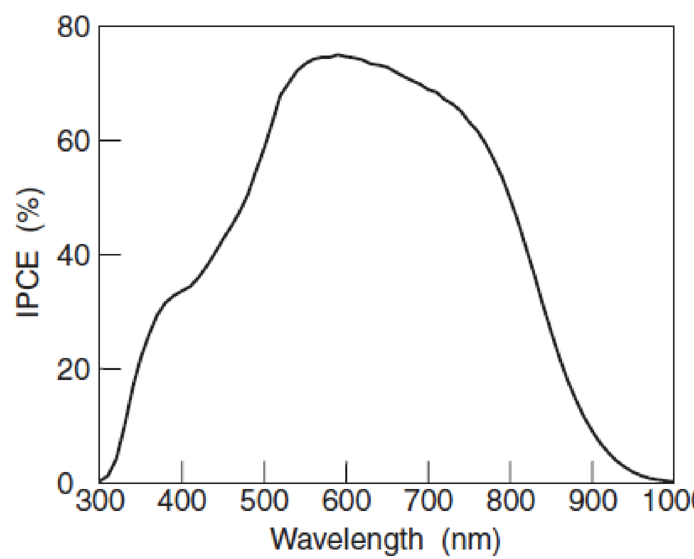
Katagiri et al. Sol Energ. Mater. Sol. C. , **49**, 407 (1997).

CZTS Solar Cells by Sulfurization of co-sputtered Cu, SnS and ZnS film



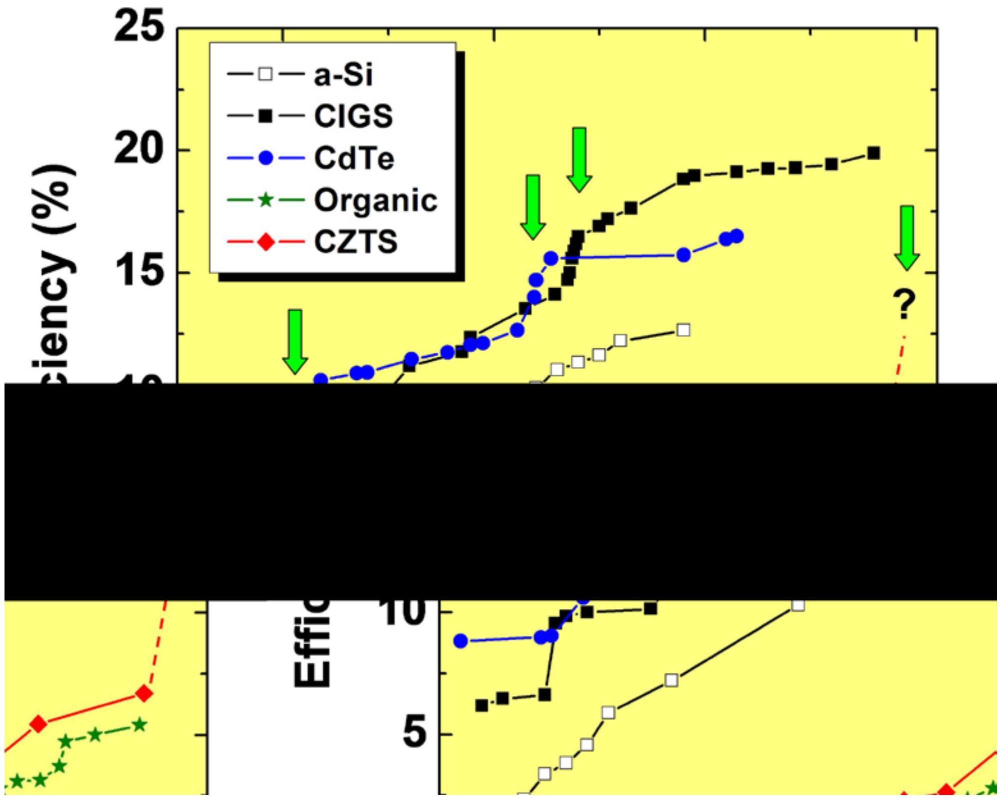






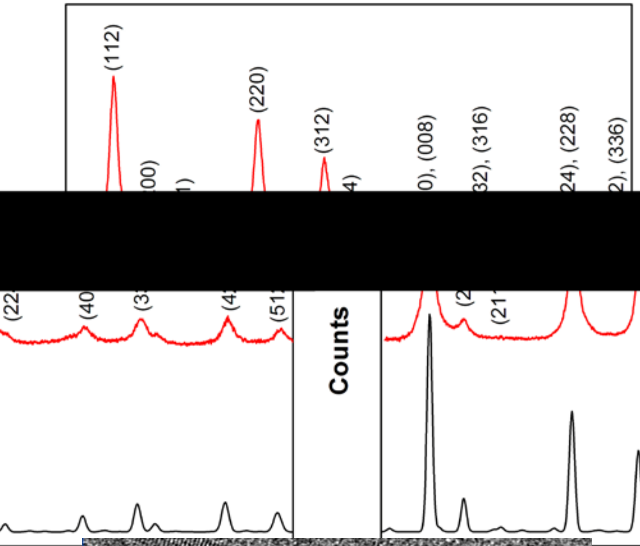
Katagiri et al. Applied Physics Express, **1**, 041201 (2008).

Evolution of CZTS power conversion efficiency



- ~ 600 articles keywords = CIGS and solar
- ~ 1300 articles keywords = CdTe and solar
- ~ 6800 articles keywords = organic and solar
- ~ 7100 articles keywords = a-Si and solar
- ~ 50 articles keywords = CZTS and solar

Cu_2ZnSnS_4 (CZTS)



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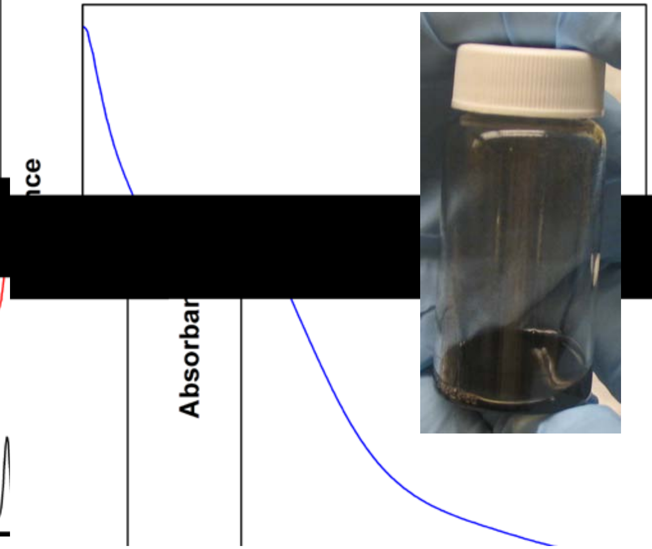
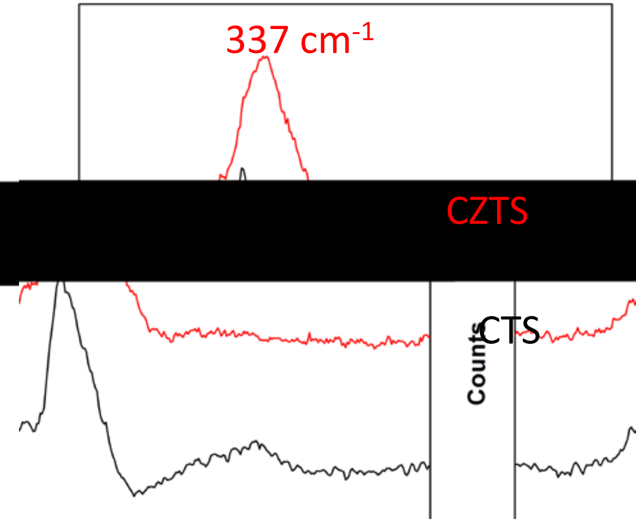
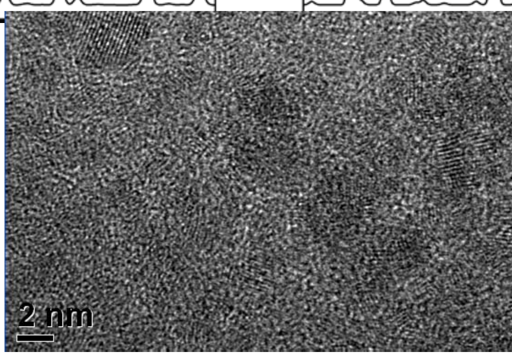
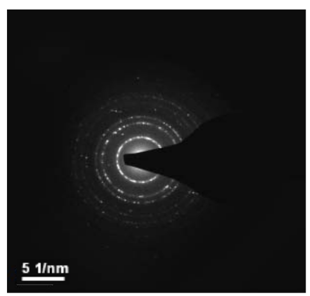
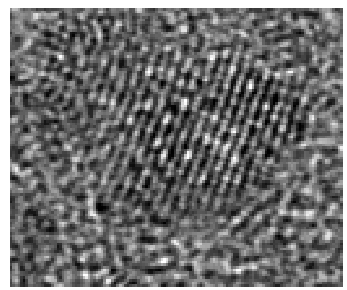


Raman spectra







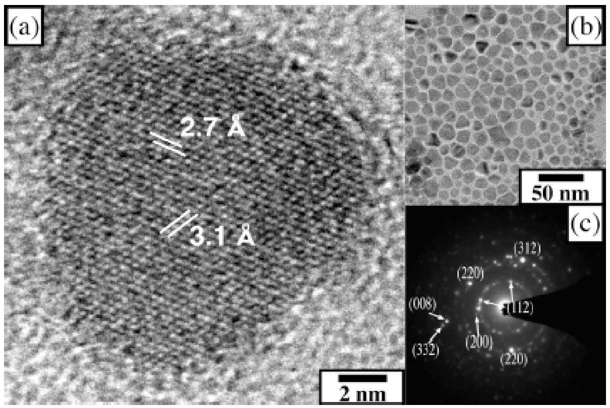


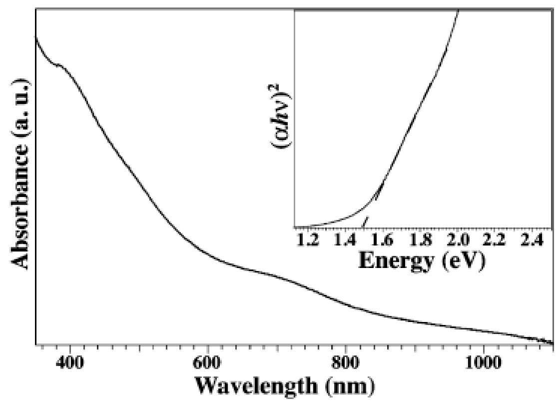
Element	Cu_2ZnSnS_4	NCs by EPMA
Cu	2	1.95±0.03
Zn	1	1.01±0.03
Sn	1	1.01±0.02
S	4	4.02±0.04

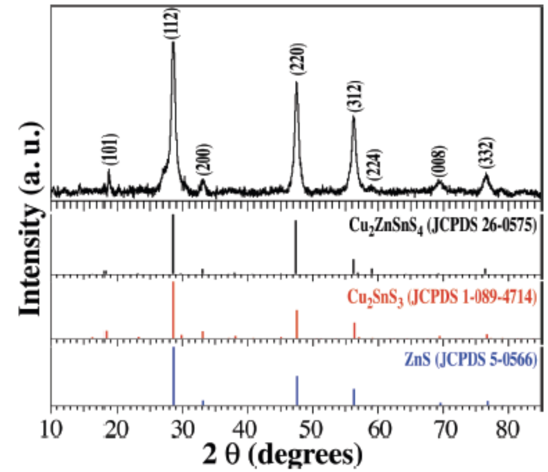
- Synthesized 2-10 nm CZTS nanocrystals from metal dithiocarbamates
- Stable colloidal dispersions in organic solvents
- HRTEM, XRD, Raman, EPMA, optical absorption consistent with CZTS

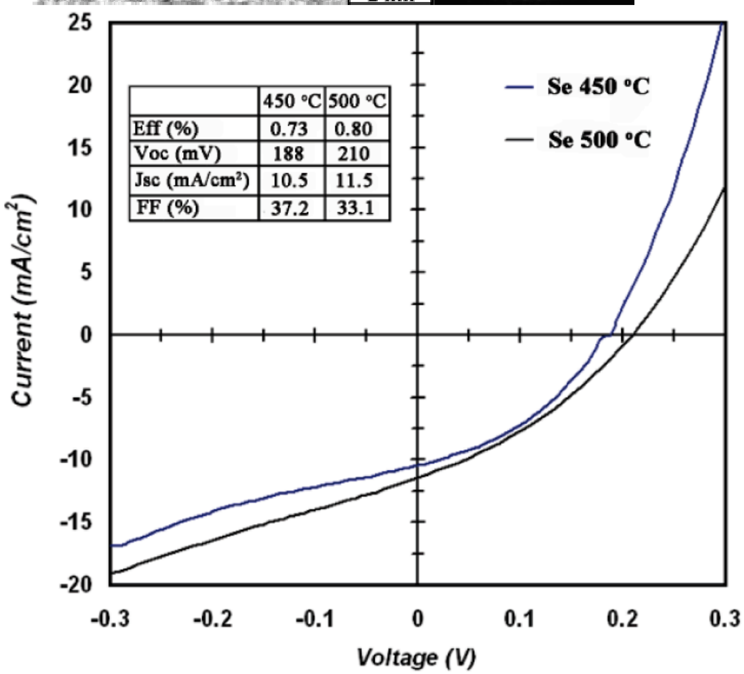
A. Khare, D. J. Norris, and E. S. Aydil, *unnpublished*, (2010).

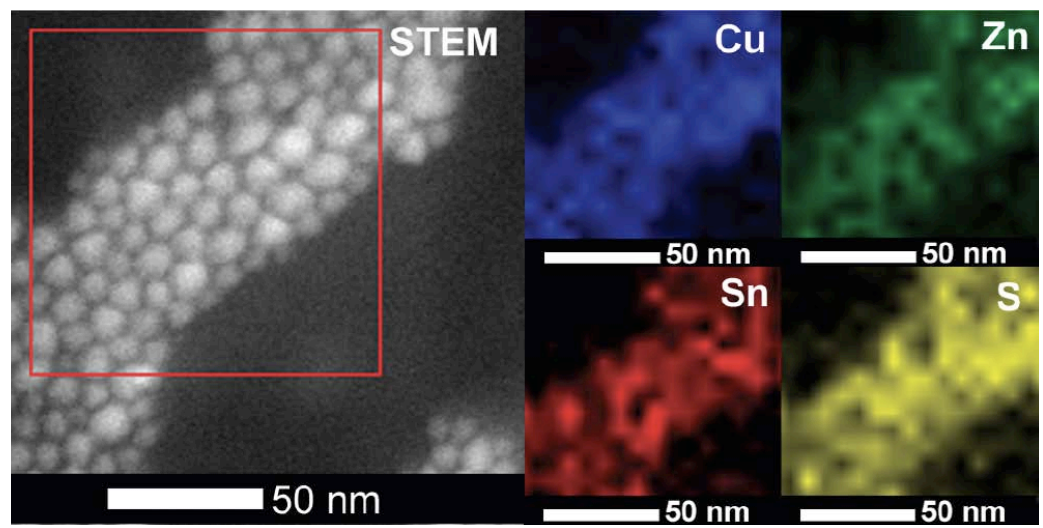
Solar cells with films cast from CZTS colloidal nanocrystal solutions





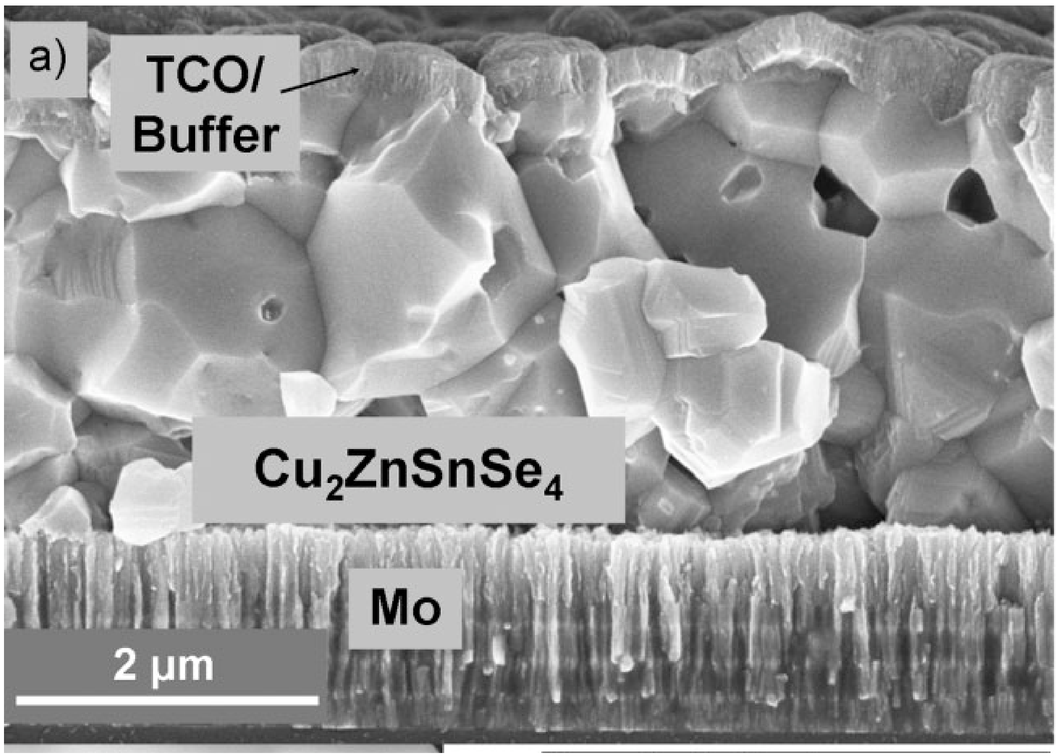


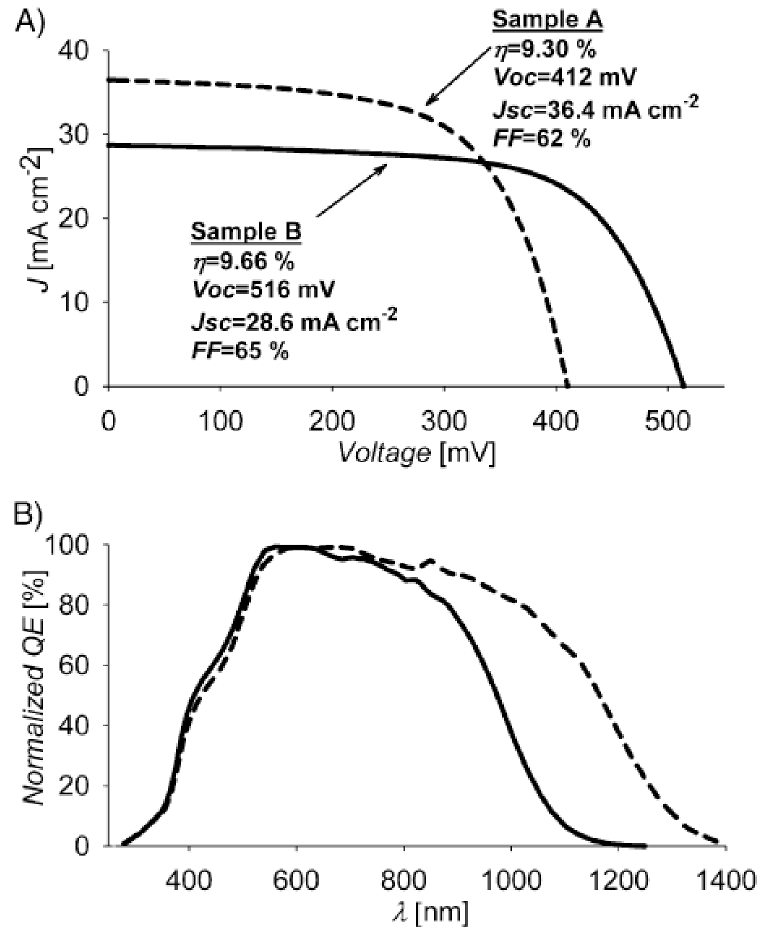




Riha, Parkinson & Prieto, JACS **131**, 1 (2009); Guo, Hillhouse & Agrawal, JACS **131**, 11672 (2009);
Steinhagen, Panthani, Akhavan, Goodfellow, Koo & Korgel, JACS **131**, 12554 (2009);

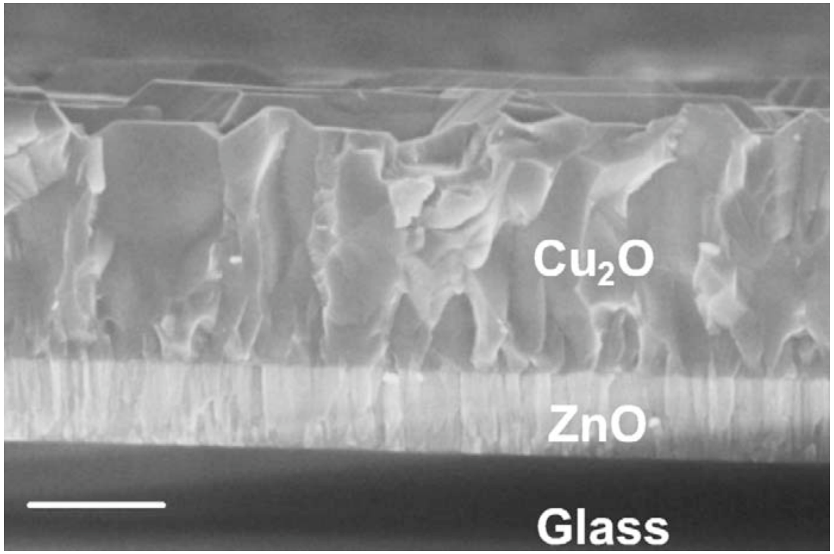
High-Efficiency Solar Cell with Earth-Abundant Liquid-Processed Absorber

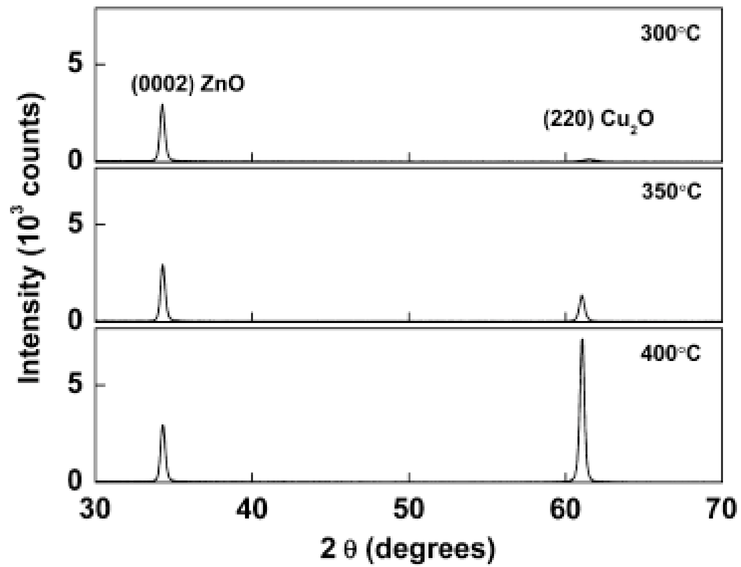


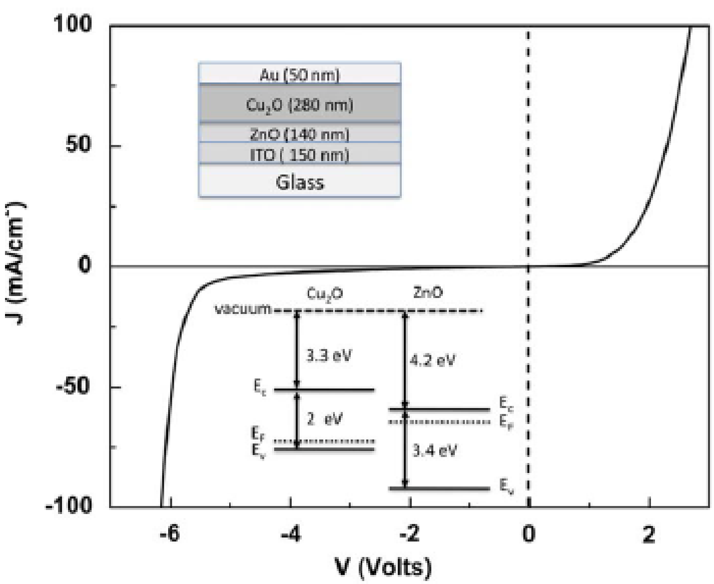


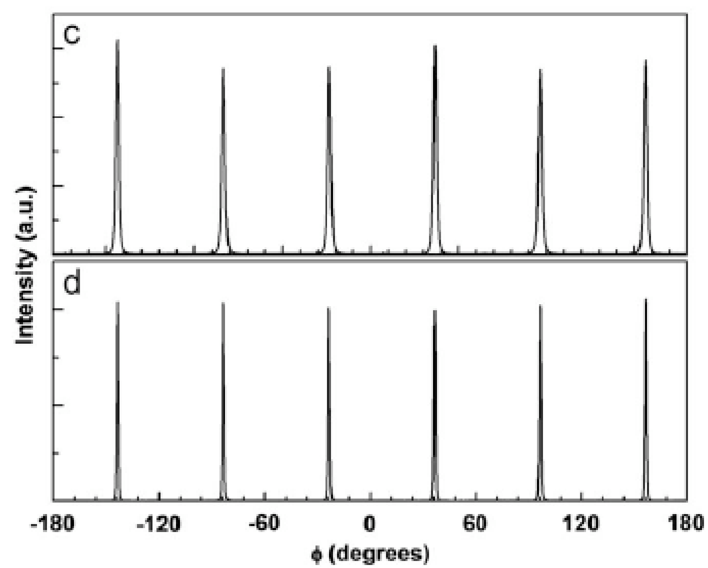
Todorov, Reuter, Mitzi, Advanced Materials **22**, 1 (2010).

Cu_2O-ZnO heterojunction solar cells





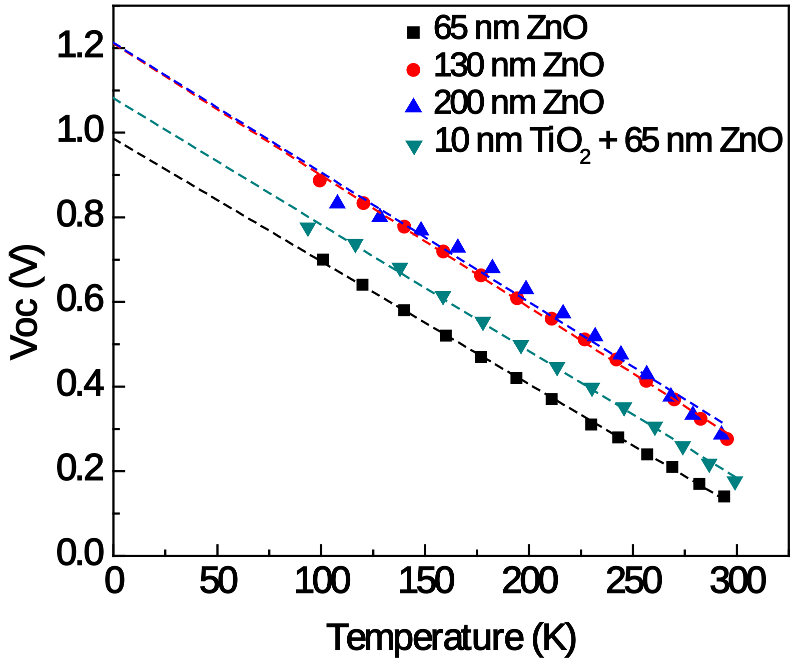




Jeong & Aydil, J. Cryst. Growth **311**, 4188 (2009).

Cu_2O-ZnO heterojunction solar cells

- efficiencies (~1-2%) and V_{oc} (~0.1-0.4 V) so far has been low
- Interface quality and defects implicated for poor performance



Jeong & Aydil, unpublished.

Summary

a) Current thin film technologies, CdTe, CIGS & thin film Si may grow at rates that will accumulate to ~10 TW by sometime between 2050-2100.

a) We will need other (new) materials and technologies in addition to CdTe, CIGS & thin film Si to achieve ~10 TW by sometime between 2050-2100.