Why don't we have inexpensive PV systems made from Earth-Abundant elements?

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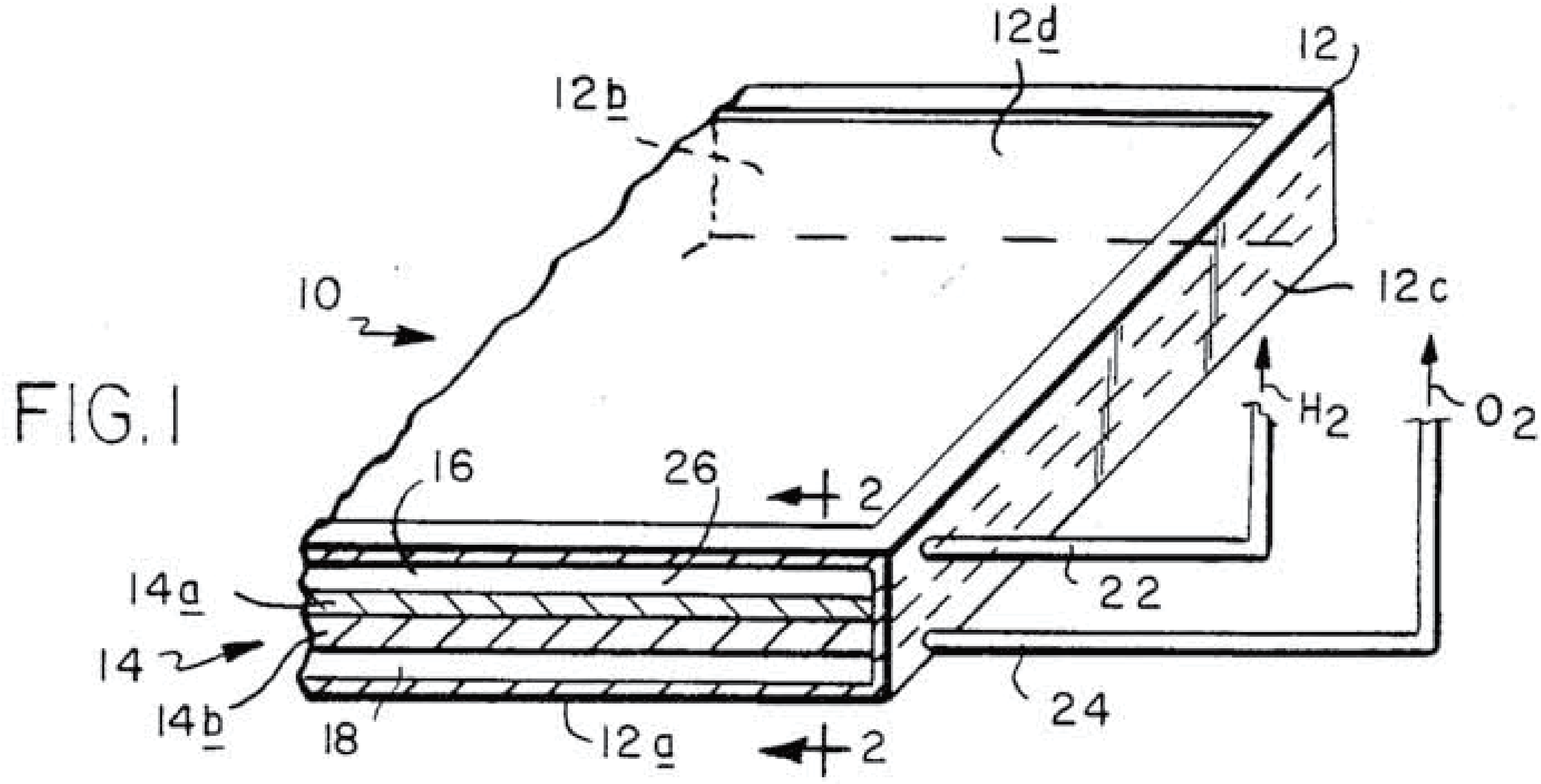
ACS National Meeting, August 12, 2014
San Francisco, CA

Photocatalytic Conversion of H_2O to H_2 and O_2

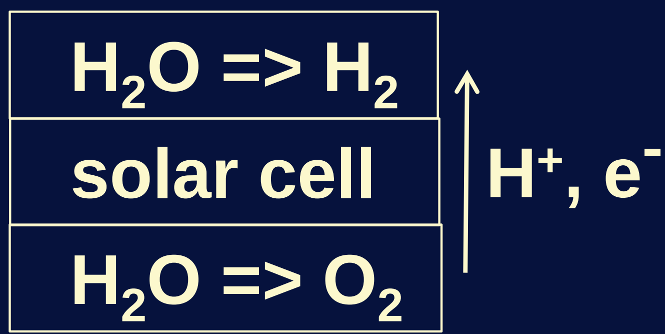
United States Patent [19] | [11] **Patent Number:** 4,650,554

Gordon | [45] **Date of Patent:** Mar. 17, 1987

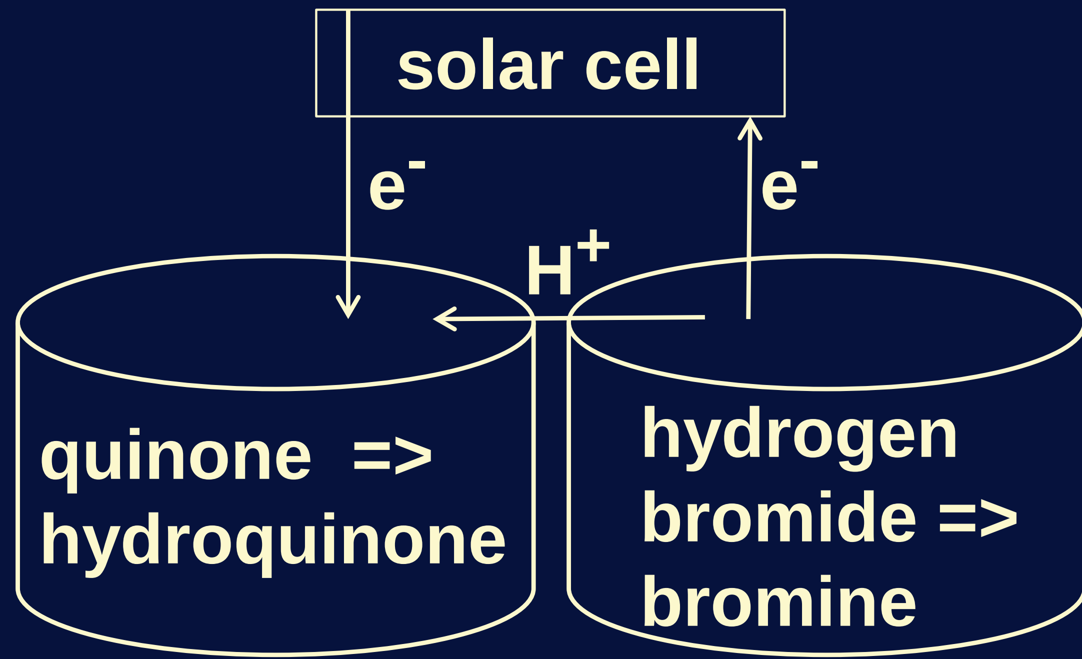


2 Strategies for Solar to Stored Energy

This symposium:



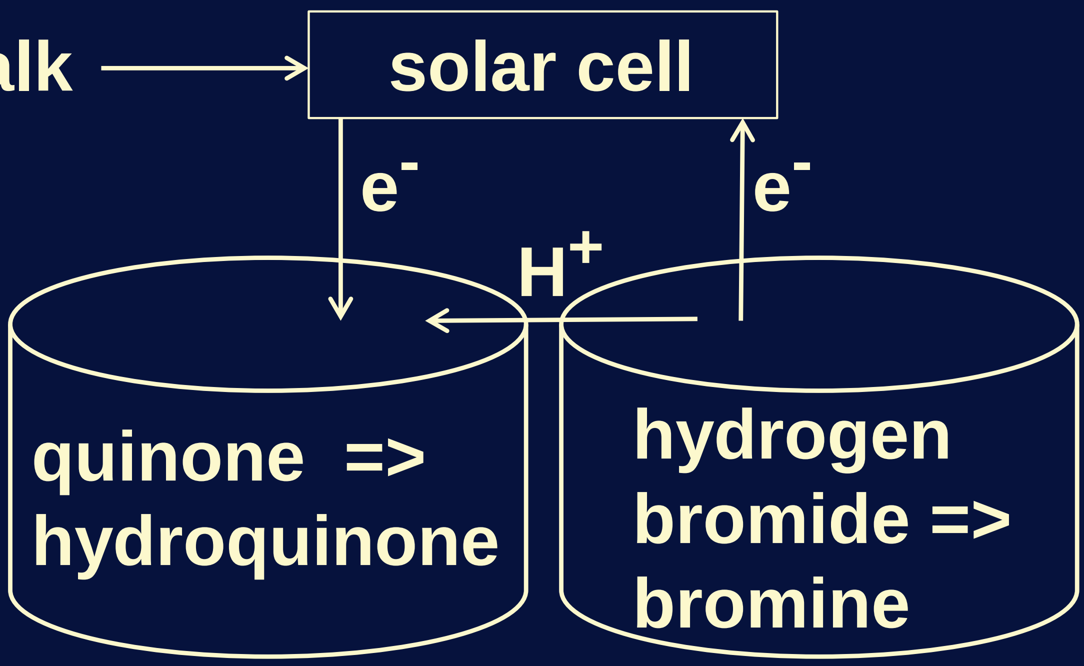
Our strategy:



explosive H_2 gas	**non-flammable water solutions**
electrocatalysts needed	**no electrocatalysts needed**
corrosion of solar cell	**solar cell protected from water**

Harvard Strategy for Solar to Stored Energy

The subject of my talk →



My collaboration on a flow battery for grid-scale storage of electricity: the subject of Mike Aziz's talk at 4pm today.

Outline

amount of solar energy

photovoltaic (PV) solar cells

abundant materials for large-scale thin-film PV

high-volume production of inexpensive thin-film PV

tin oxide – transparent electrode for PV

Solar Land Area Requirements - Global

Generating 15 TW (total primary power used by humans)

with 15 % efficiency requires collector area

= (15 x 10^{12} W) (200 W m^{-2})$^{-1}$ (0.15 efficiency)$^{-1}$ = 5x10^{11} m^2

Total land area of the earth is 1.5 x 10^{14} m^2

Collector fraction = 5 x 10^{11} m^2 / 1.5 x 10^{14} m^2 = 0.0033

0.33 % of land area could generate all the power now used

Solar Land Area Requirements - Global

20 TW from 6 Boxes at 3.3 TW Each

Solar Land Area Requirements - US

U.S. Land Area: 9.1×10^{12} m^2

Average solar insolation: >200 W/m^2

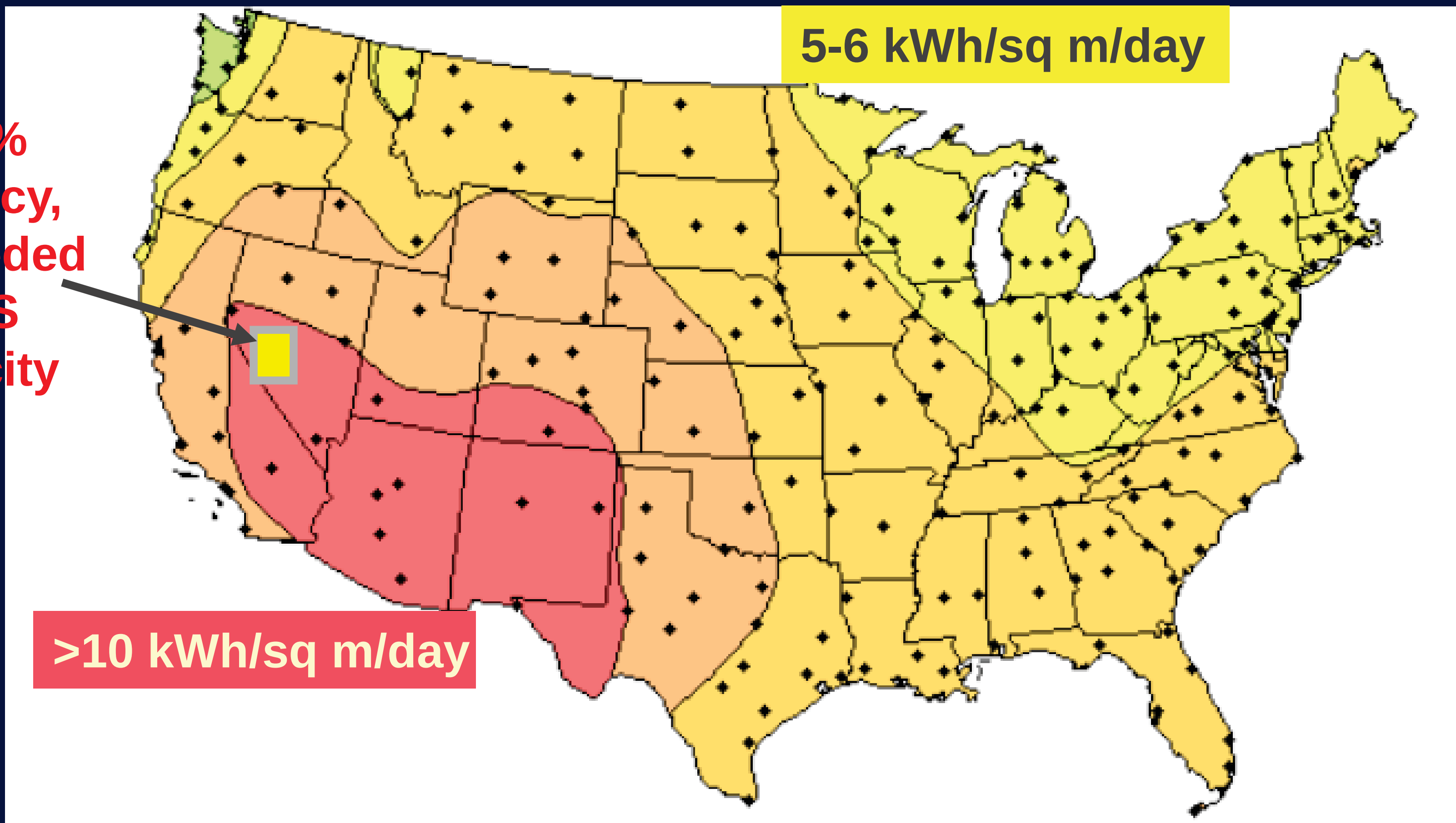
U.S. Primary Power Consumption: 3.3 TW
U.S. Electricity Consumption = 0.4 TW

To supply **all** US **primary** power from PV:
3.3×10^{12} W/(2×10^2 W/m^2 x 15% Efficiency) = 1.1×10^{11} m^2
Requires 1.1×10^{11} m^2/ 9.1×10^{12} m^2 = **1.2% of Land Area**

To supply **all** US **electrical** power from PV:
0.4×10^{12} W/(2×10^2 W/m^2 x 15% Efficiency) = 1.3×10^{10} m^2
Requires 1.3×10^{10} m^2/ 9.1×10^{12} m^2 = **0.15% of Land Area**

Convenient truth: a small area can supply our electricity

At 10% efficiency, area needed for US electricity



PV on all US rooftops could meet US electricity demand

PV on my home in Cambridge, MA

20 panels of polycrystalline Si x 1.5 m^2/panel = 30 m^2

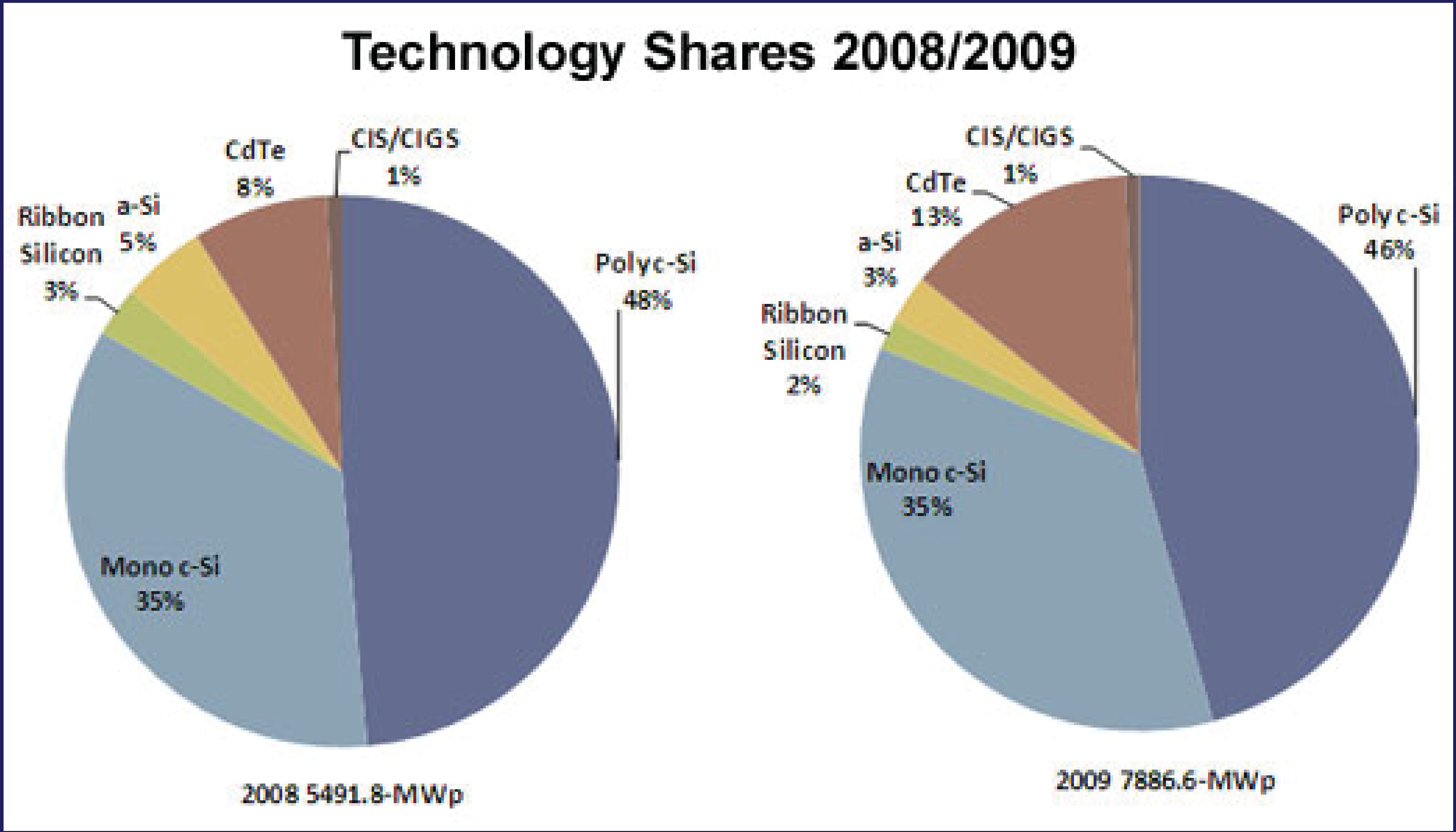
x 3 kWh / m^2 / day x 0.13 efficiency => 12 kWh/day

Average power 12 kWh/day x 1 day/24 h = 0.5kW

Typical household in US uses 1.3kW electric.

By replacing lights with LEDs and old appliances, we should be able to reduce our usage to 0.5 kW, the average input from our solar panels

Market Shares of PV Technologies



Mostly silicon, < 20 % thin films

Current Commercial PV Materials

Crystalline Si:

expensive purification, not integrated, (rare silver)

CdTe:

rare tellurium, toxic cadmium and tellurium

Amorphous Si-Ge:

low efficiency, slow deposition

Cu(In,Ga)Se_2 (CIGS):

rare indium, gallium, toxic selenium

Dye-sensitized:

rare ruthenium and platinum

None of these cell designs meet the criteria:

abundant, inexpensive and non-toxic elements

Why is PV Expensive?

Production is too slow

=> make solar cells very quickly

Too many separate pieces connected by wires

=> integrate directly without wires

Rare, expensive elements now used: Ag, In, Ga, Te, Se

=> use abundant and inexpensive elements:
copper, zinc, tin, oxygen, sulfur, aluminum

How to make lots of inexpensive solar cells

small amounts of materials

high absorption coefficients => thin films

rapid, continuous production on large areas

< few seconds for depositing thin films

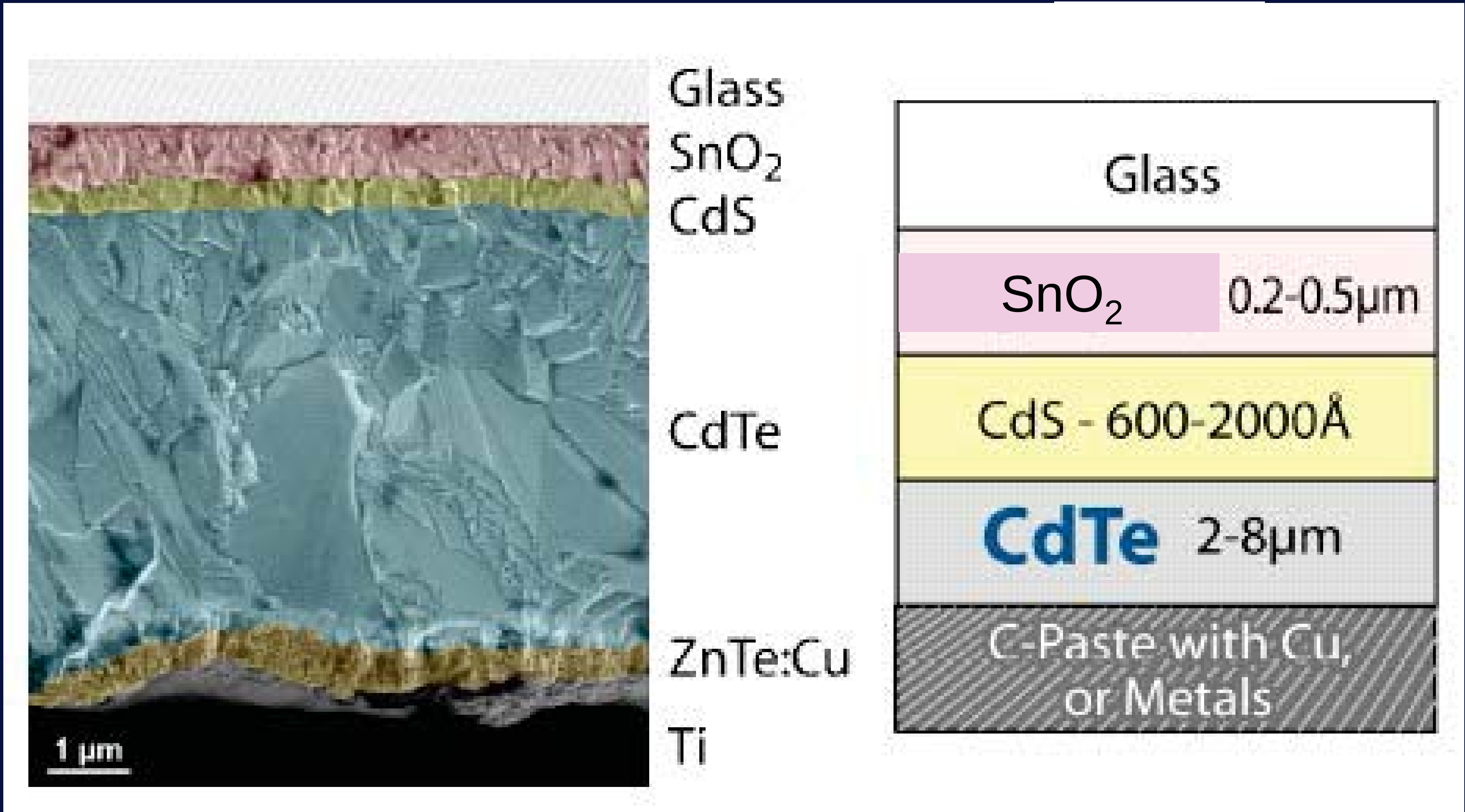
integrated series interconnections of cells

inexpensive, abundant elements

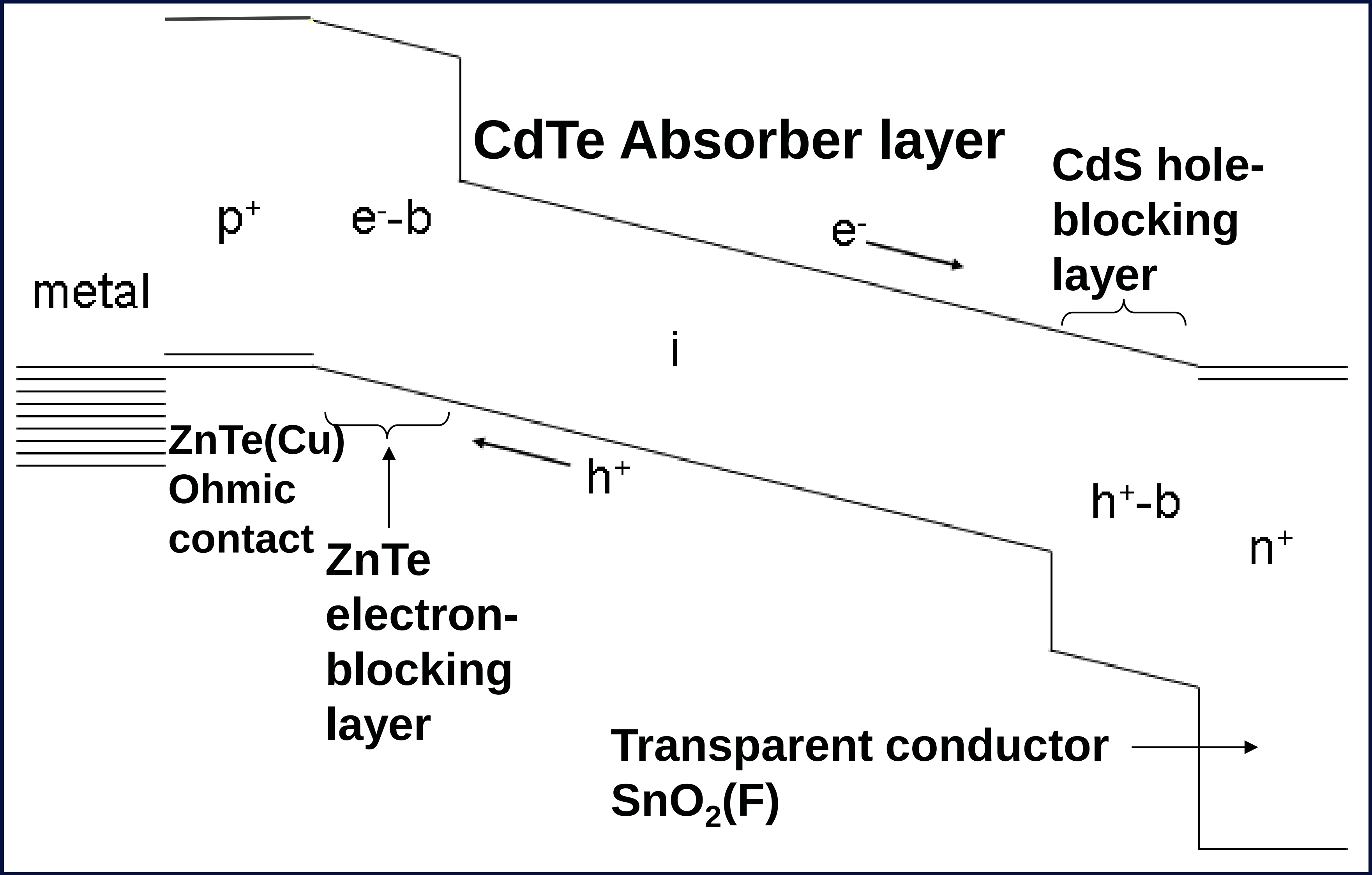
nontoxic elements

product durable for long lifetimes (> 20 years)

Structure of CdTe Thin-Film Solar Cells



Band Diagram for a Thin-Film CdTe Solar Cell



How Much Material is Needed for Solar Cells?

A typical thin-film cell is 2 μm = 2×10^{-6} m thick

The area required to supply current energy use is 5×10^{11} m^2

The volume of thin-film material is
= (2×10^{-6} m) x (5×10^{11} m^2) = 1×10^{6} m^3

10^6 m^3 of $Cu(In,Ga)Se_2$ <=> 1.4×10^{9} kg of indium
Total recoverable reserves of In in Earth's crust ~ 6×10^{6} kg.
enough to make 0.5% of the required solar cells

10^6 m^3 of CdTe <=> 3.3×10^{9} kg of tellurium
Total recoverable reserves of Te in Earth's crust ~ 3.7×10^{7} kg.
enough to make ~ 1 % of the required solar cells

Which Elements are Sufficiently Abundant?

Enough Si, Al, Zn, Cu & Sn to make all the solar cells needed

Enough non-metals C, N, P, O, S, F, Cl, Br, I are available

Transition metals Fe, Mn, etc. don't make efficient solar cells

Organics are unlikely to be stable for 20 years in sunlight

Avoid toxic elements like As, Cd, Se, Te, Be, Pb

Thin-Film PV Absorbers Made of Abundant Elements

Main Absorber Material	Band gap (eV)	Actual Efficiency	Theoretical Maximum
SnS	1.1	5%	32%
Cu_2O	2.0	5%	23%
Zn_3P_2	1.3	6%	33%
$Cu_2ZnSn(S,Se)_2$	1.3	13%	33%
$(CH_3NH_3)Pb(I,Cl)_3$	1.5	16%	33%
$(CH_3NH_3)Sn(I,Br)_3$	1.5	6%	33%

Zn_3P_2 + H_2O => PH_3 (highly toxic phosphine gas)

Selenium (Se) and lead (Pb) are toxic

$(CH_3NH_3)Sn(I,Br)_3$ is air-sensitive and water-soluble

More research is needed to improve their efficeincy.

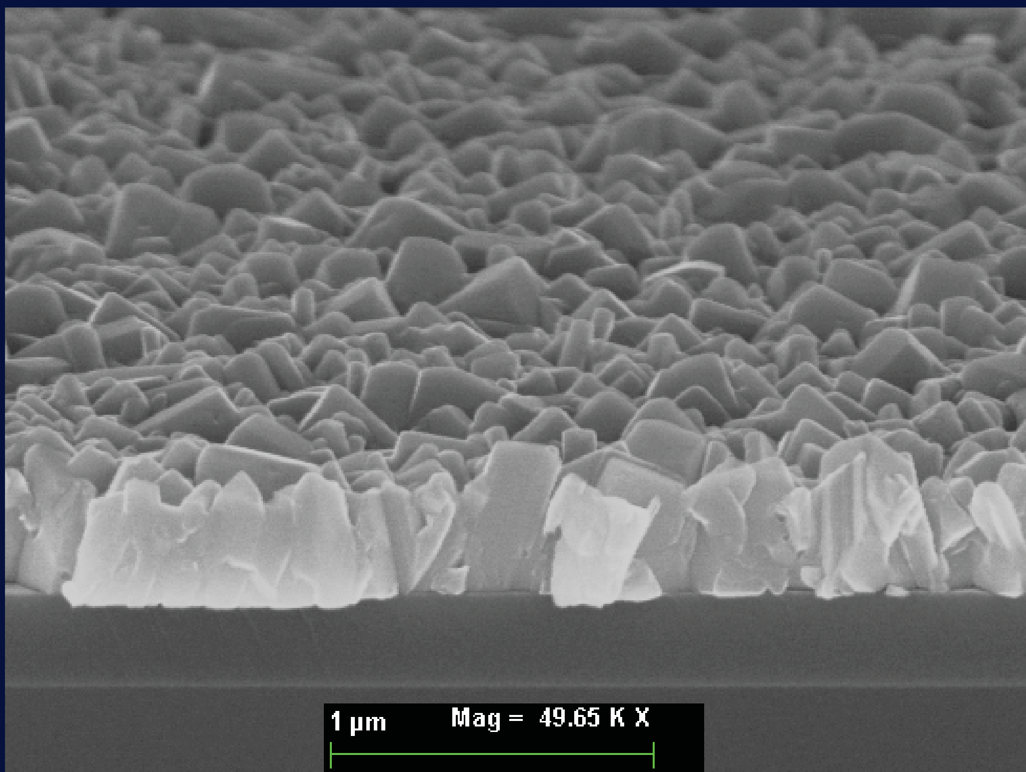
Possible Scalable Materials for Solar Cells

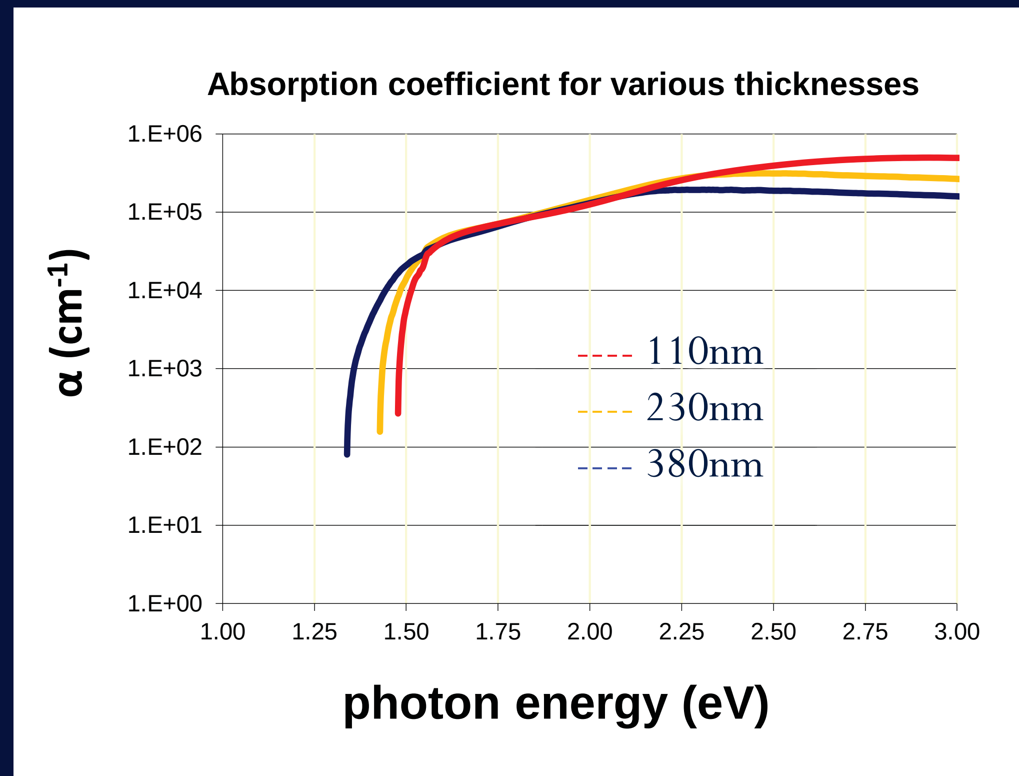
function of layer	possible materials
transparent support, protection	soda-lime glass
n+ transparent conductor, front electrode	SnO_2(F) or ZnO(F)
electron transparent, hole-blocking	Zn(O,S) or (Zn,Mg)O
light absorber, charge separator	SnS or Cu_2O
hole-transparent, electron-blocking	$(Mo,W)O_{3-x}$
reflective conductor, back electrode	Cu or Al

All elements sufficiently abundant, inexpensive & non-toxic

An Absorber with Abundant, Non-toxic Elements

Tin monosulfide, SnS



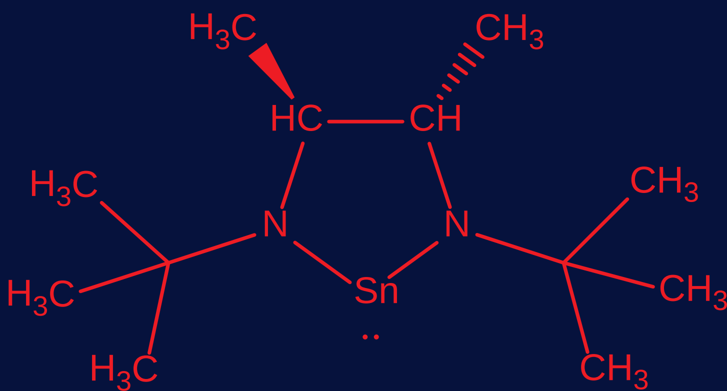


$\alpha > 10^5$ cm^{-1} strong absorption of visible light

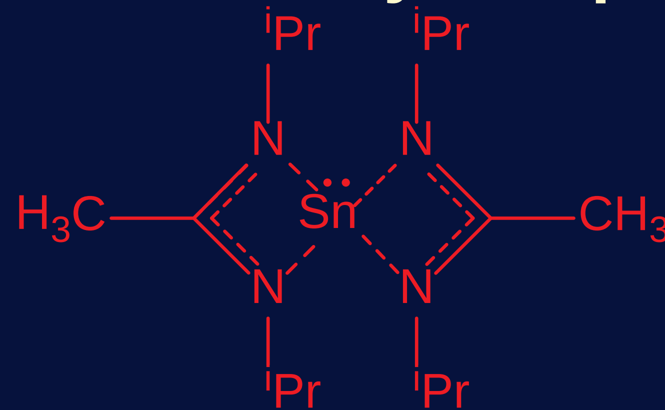
→ need < 0.5 µm thickness to absorb 98% of light

Deposition of SnS Absorber Layer

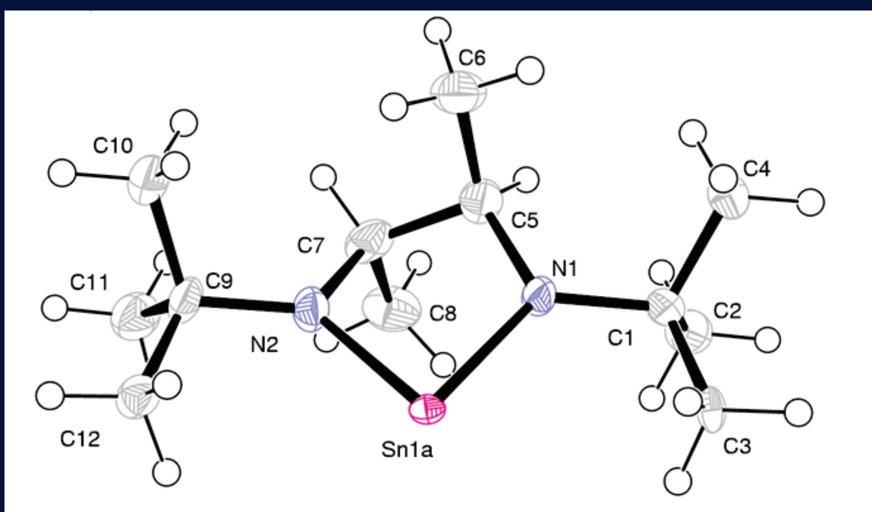
Chemical vapor deposition or atomic layer deposition:

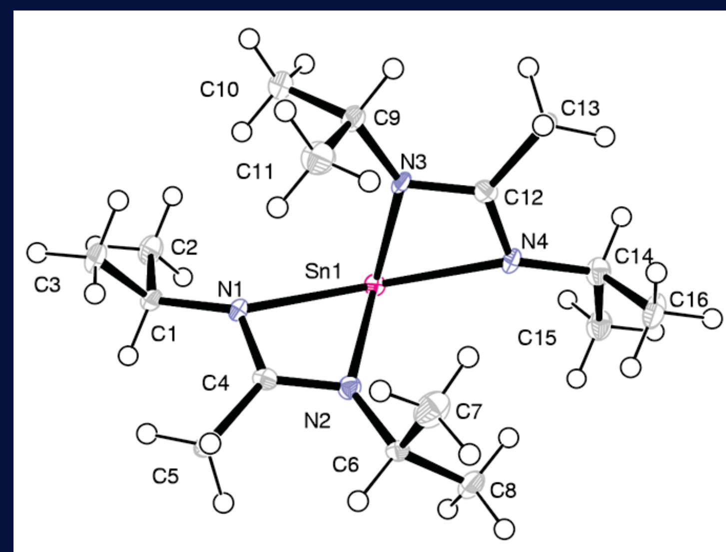


or



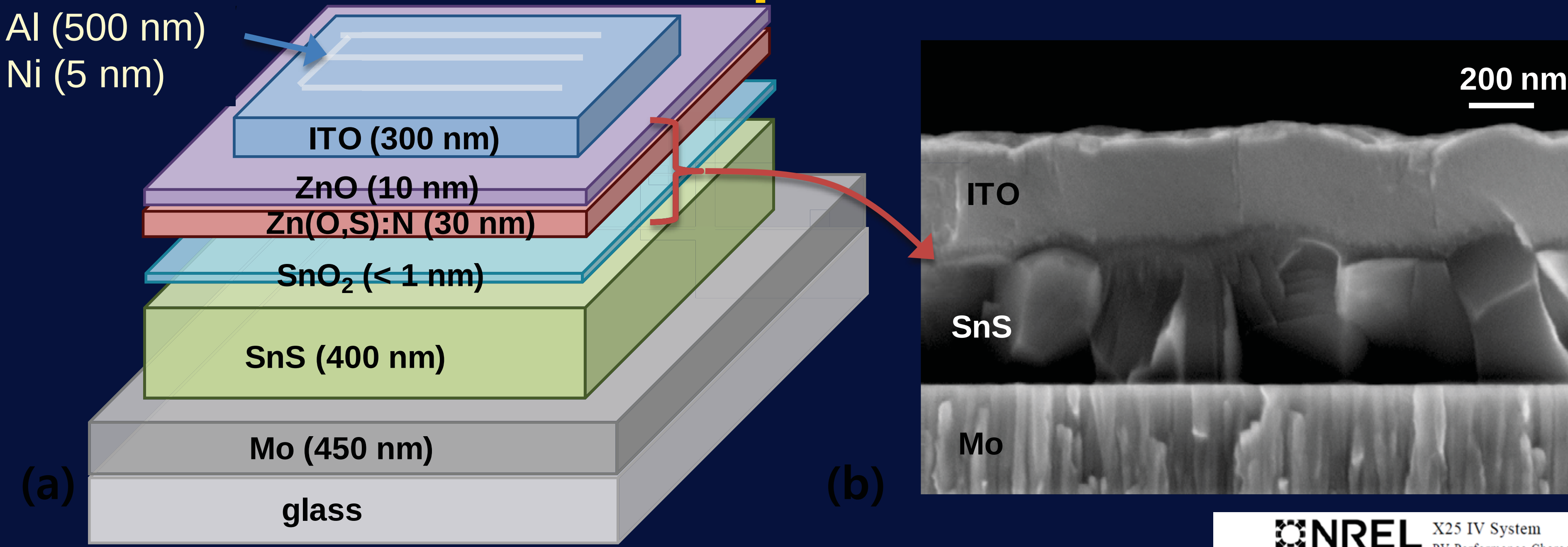
+ H_2S

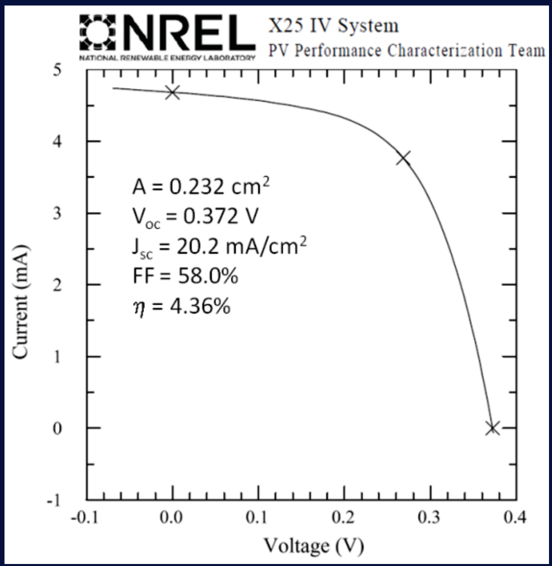




Sang Bok Kim, Prasert Sinsermsuksakul, Adam S. Hock, Robert D. Pike, Roy G. Gordon
Chemistry of Materials **26**,3065 (2014)

Current Champion SnS PV Cells





NREL-certified efficiency 4.36%

Best recent cell: 4.68%

Theoretical maximum: 32%

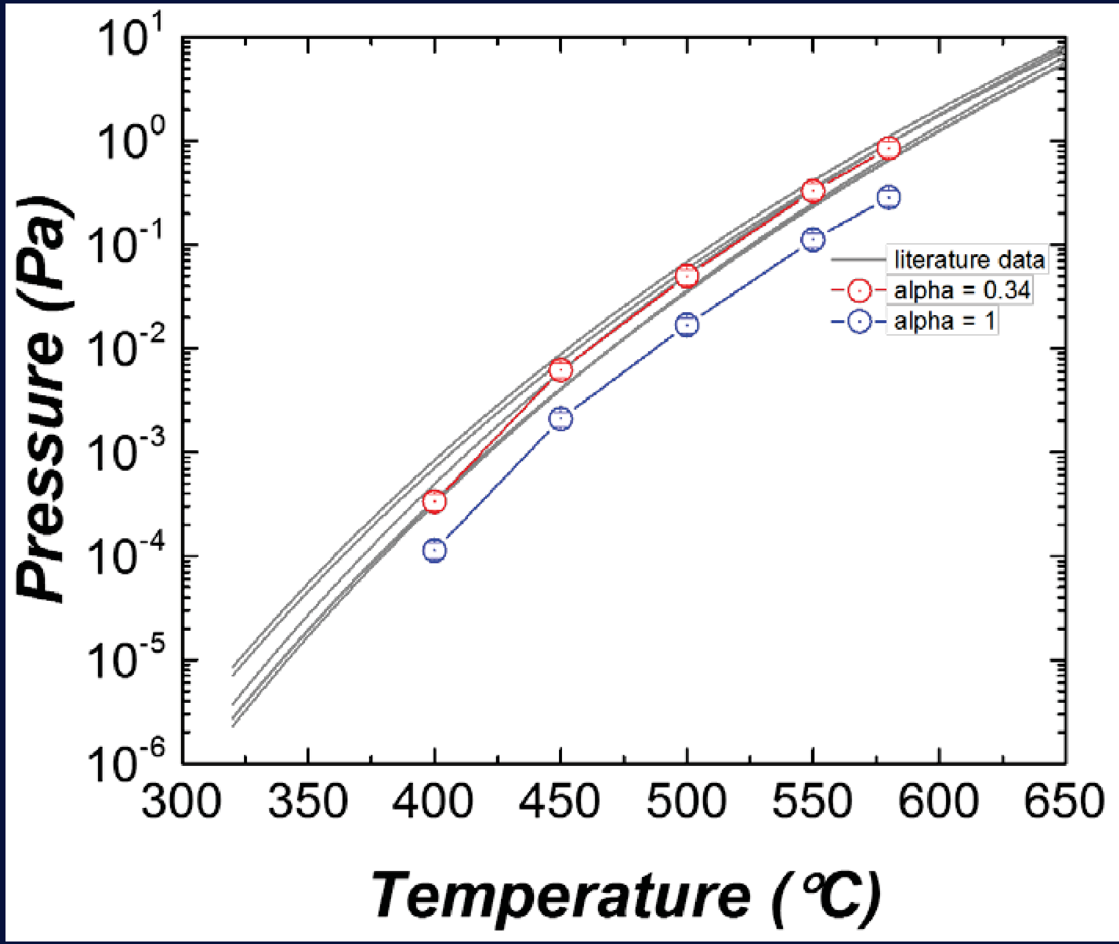
Prasert Sinsermsuksakul, Leizhi Sun, Sang Woon Lee, Helen Hejin Park, Sang Bok Kim, Chuanxi Yang, and Roy G. Gordon, *Advanced Energy Materials* (in press) (2014)

Sublimation of SnS Absorber Layer

SnS evaporates congruently like CdTe

=> 4% efficient solar cells

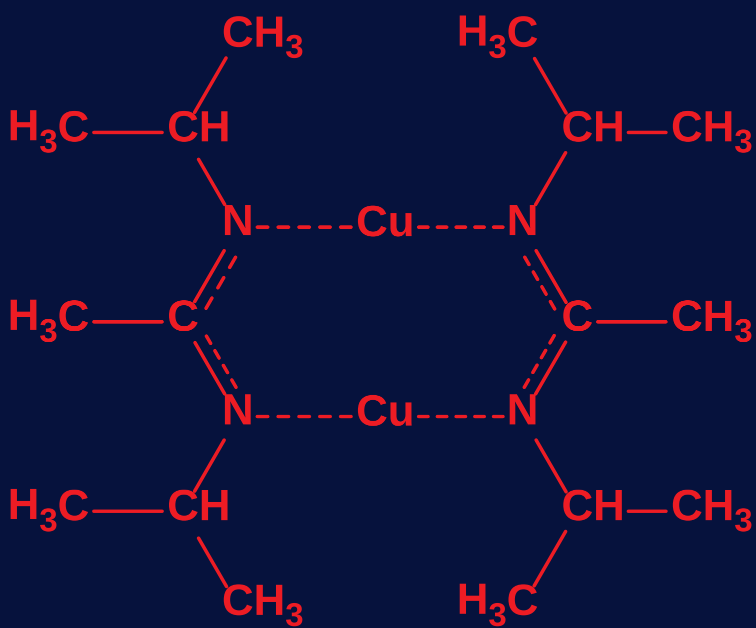
Could be produced rapidly by close-spaced sublimation as in First Solar's CdTe process

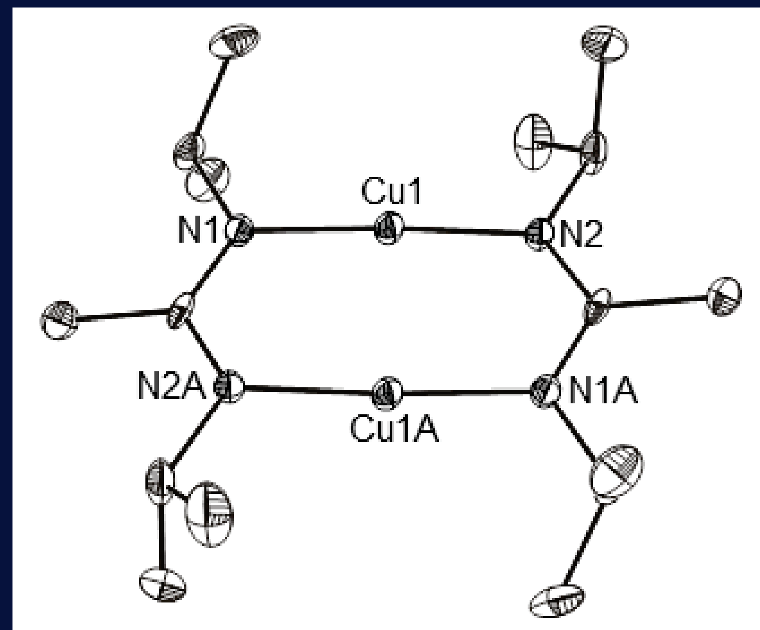


Vera Steinmann, R. Jaramillo, Katy Hartman, Rupak Chakraborty, Riley E. Brandt, Jeremy R. Poindexter, Yun Seog Lee, Leizhi Sun, Alexander Polizzotti, Helen Hejin Park, Roy G. Gordon, and Tonio Buonassisi, *Advanced Materials* (in press, 2014) DOI: 10.1002/adma.201402219

Depositing Cu_2O

By Chemical Vapor Deposition or Atomic Layer Deposition:





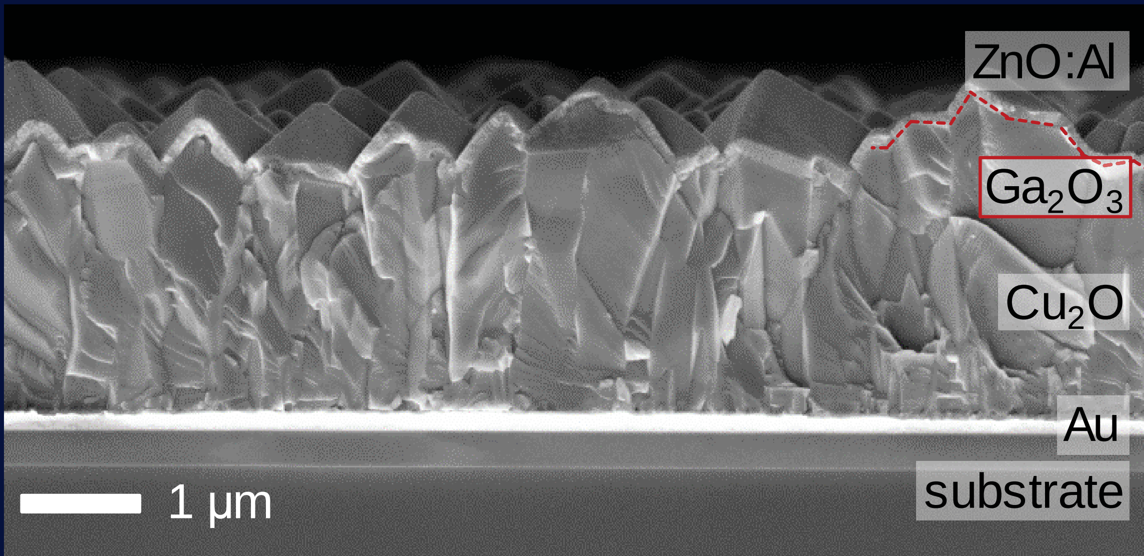
+ H_2O vapor

Hoon Kim, Harish B. Bhandari, Sheng Xu, Roy G. Gordon,
J. Electrochemical Society, **155,** H496 (2008)

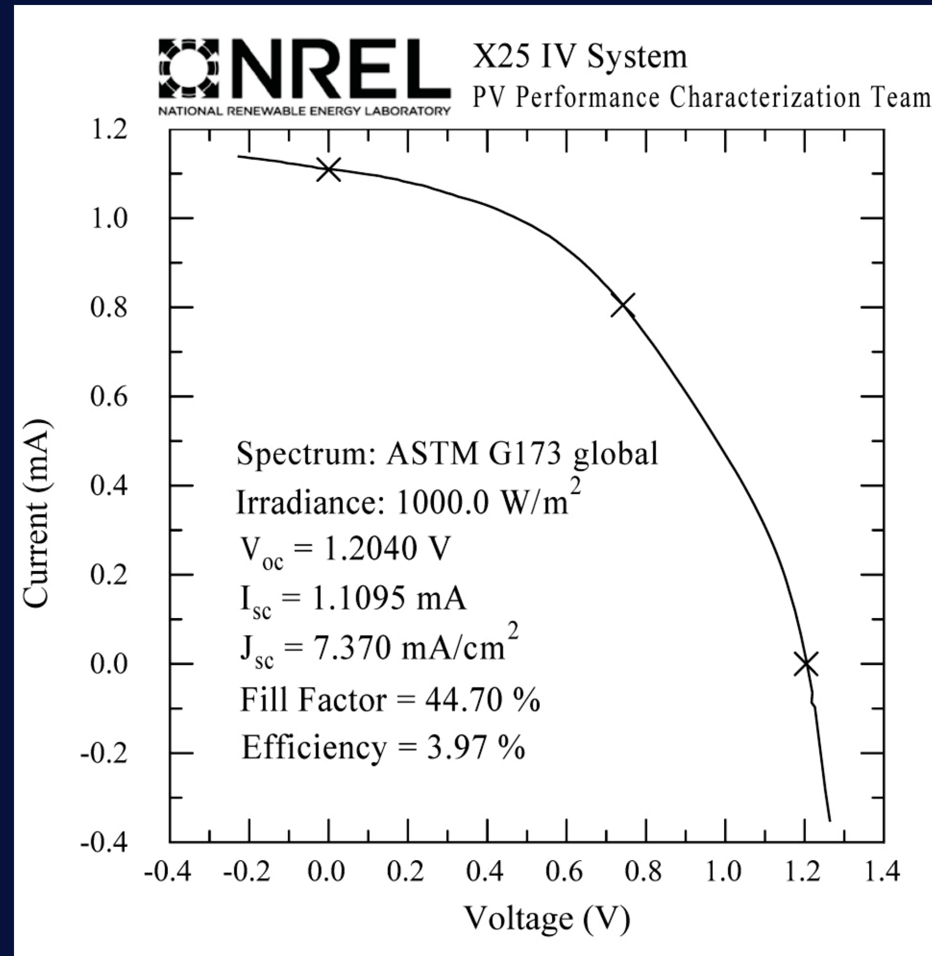
By Electrodeposition from water-based electrolyte:

Yun Seog Lee, Danny Chua, Riley E. Brandt, Sin Cheng Siah, Jian V. Li, Jonathan P. Mailoa, Sang Woon Lee, Roy G. Gordon, and Tonio Buonassisi,
Advanced Materials (2014); 10.1002/adma.201401054

Cu_2O Solar Cells



layer	function	thick
MgF_2	antireflection	95 nm
n+ ZnO(Al)	transparent contact	80 nm
n Ga_2O_3	electron transmission	10 nm
p Cu_2O	absorber	2 µm
Au	reflective back contact	200 nm



Yun Seog Lee, Danny Chua, Riley E. Brandt, Sin Cheng Siah, Jian V. Li, Jonathan P. Mailoa, Sang Woon Lee, Roy G. Gordon, and Tonio Buonassisi, ***Advanced Materials*** (2014); 10.1002/adma.201401054

Methods for Improving SnS & Cu_2O PV Cells

More efficient collection by optimizing depositing and annealing:
- atmosphere with well-controlled activities of elements
- optimized time-temperature profile
- adding dopants to passivate grain boundaries

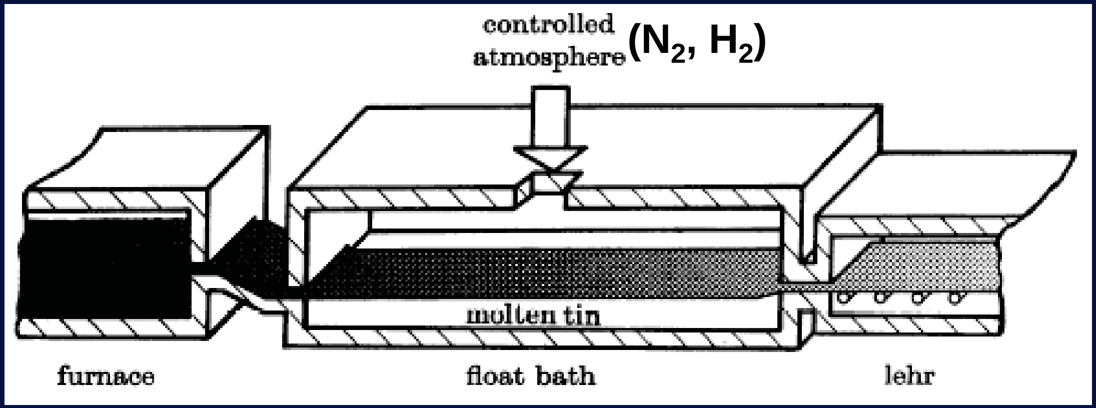
Improve back contact:
- higher reflectivity to near infrared light
- lower recombination velocity by reflecting electrons

Buffer layer
- wider band gap, so more transparent to blue end of spectrum
- reduced recombination rate near the junction
- higher conductivity buffer near the transparent conductor

Front contact:
- transparent conductor with lower work function
- more transparent front conductor
- antireflection coating

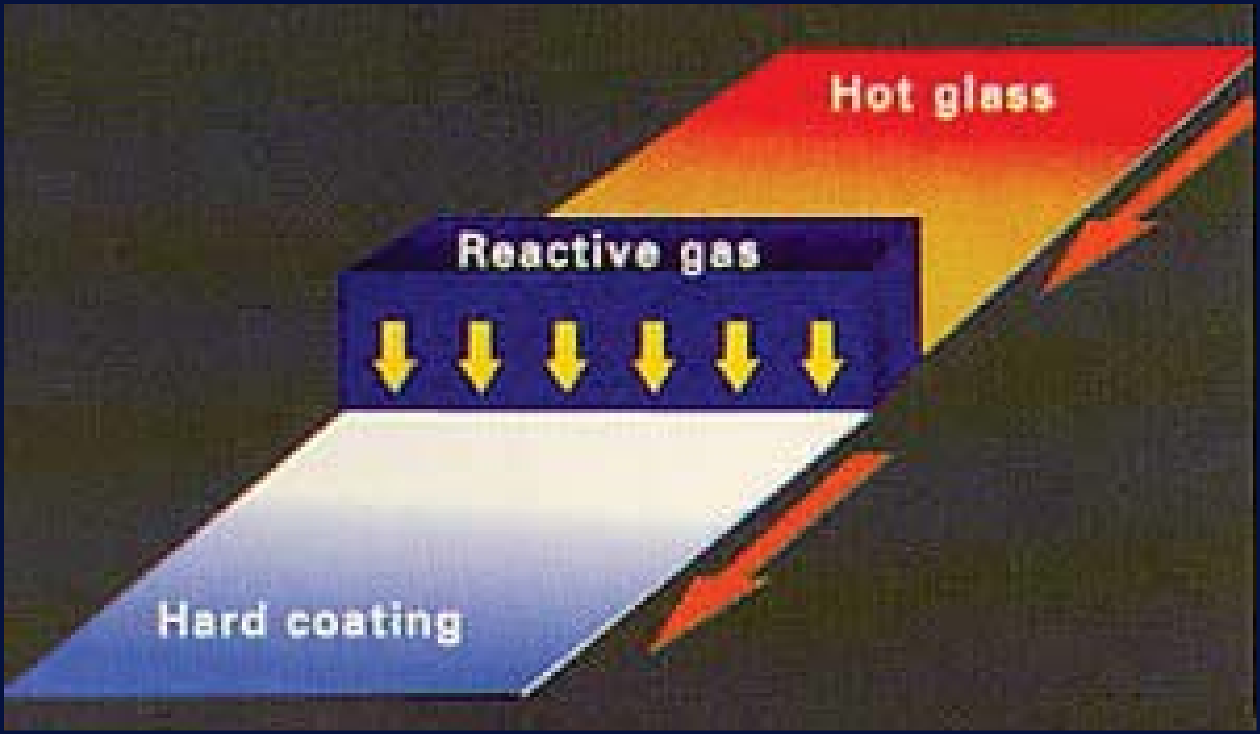
How windows are coated as the glass is made

SiO_2, Na_2CO_3 etc. in →



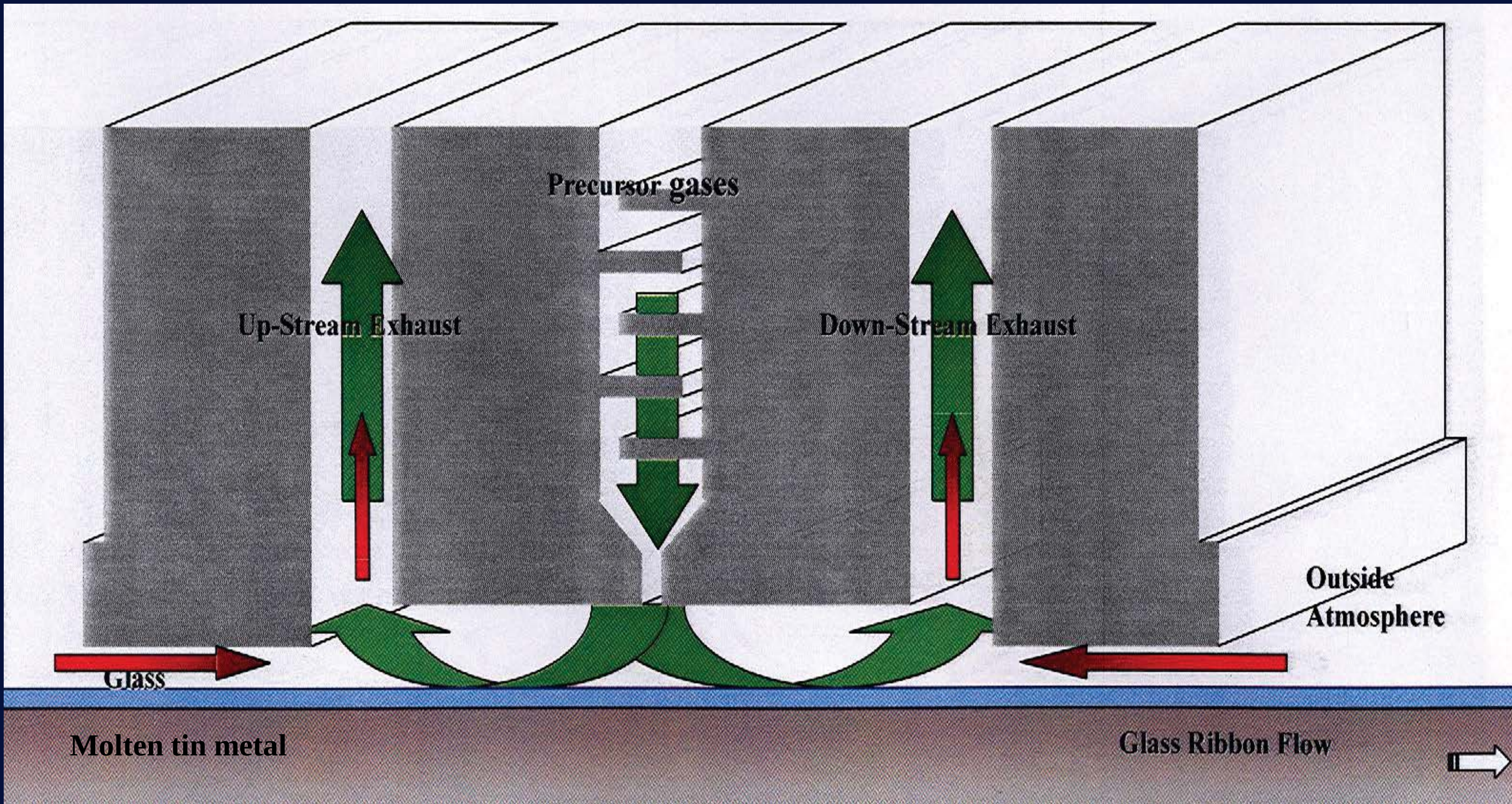
→ glass out

The float process for making flat glass



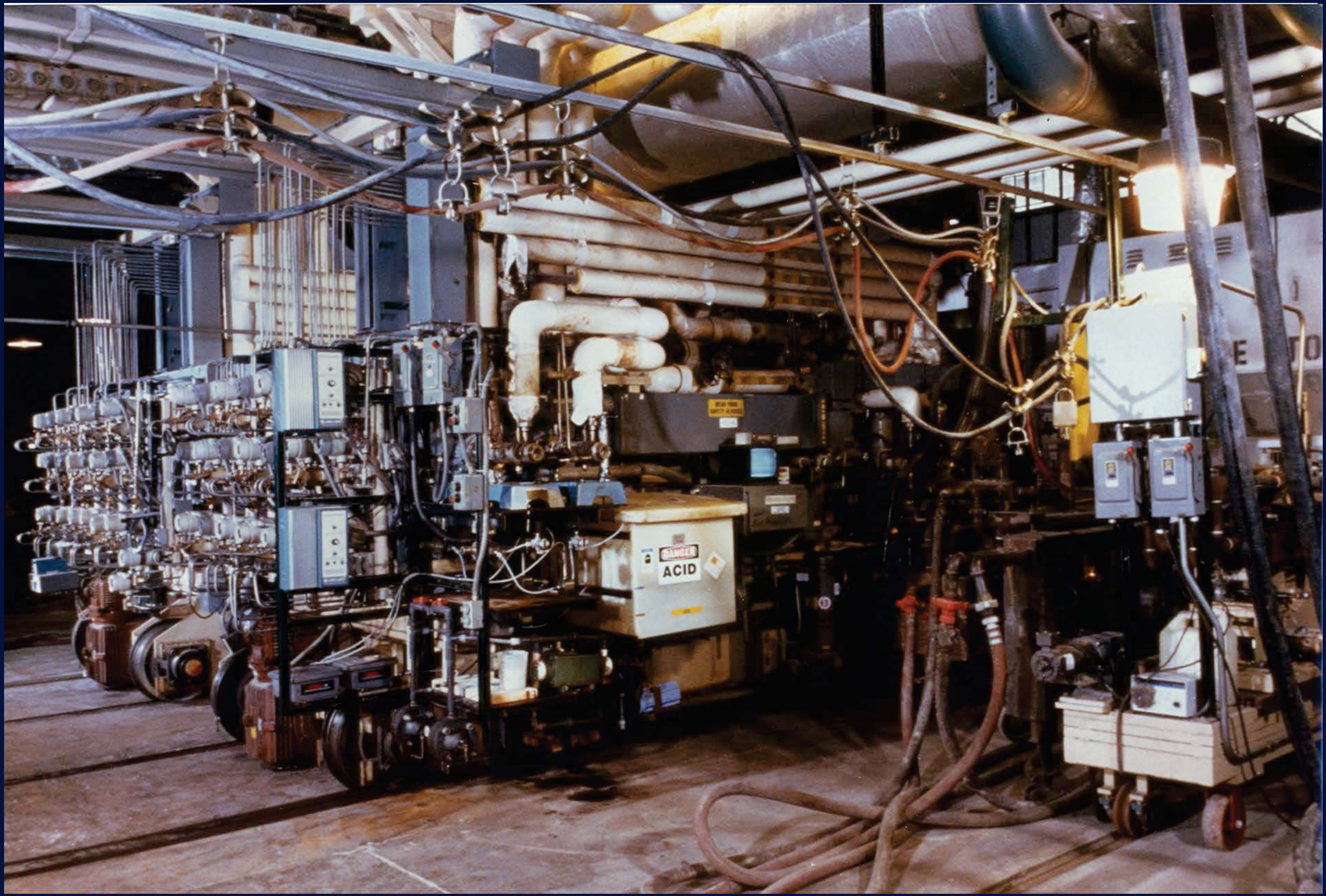
Chemical Vapor Deposition (CVD) on glass just after it is made

CVD SnO_2 on hot glass ribbon



A given area of glass spends a few seconds under the coater.

CVD coaters in a glass factory



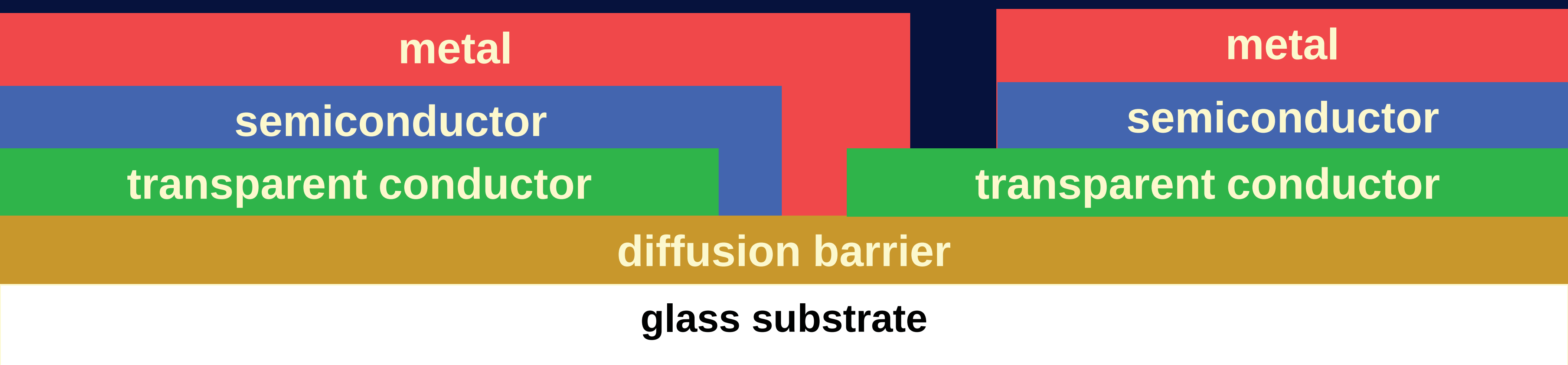
Makes very inexpensive tin oxide coatings (< $1 / m^2$)

Integrated Connections between solar cells

The solar cells also need to be connected in series to increase the output voltage

To do this on-line, lasers should etch one layer selectively without disturbing the layers below.

Avoids the high cost of wired connections between cells



Why will On-line Solar Cells be Inexpensive?

Coater technology already developed for window coatings

Production costs: mainly precursor materials

Little energy input beyond what is used in glass production

Low handling costs because integrated into glass production

Low assembly costs because of integrated cell structure

Scientific and Technical Challenges

Find sufficiently rapid CVD reactions to make materials with

- **only abundant elements**
- **inexpensive precursors**
- **high purity**
- **few defects**
- **high speed deposition**
- **compatible ranges of deposition temperature**
- **stable and strongly adherent interfaces**

Economics of PV

CdTe thin film cells are currently the lowest cost PV

First Solar Co. makes CdTe PV panels at <$0.60/peak watt

The average energy production rate would be about 5 times lower, taking into account night and cloud cover.

Balance of system and installation would ~ triple the cost.

Thus, $0.60 x 5 x 3 ~ $9/average watt produced.

If the lifetime of the modules is 20 years, the cost of power is $9/[(8766 hrs/yr)x(20 yrs)x(1 kW / 1000 W)] ~ $0.05 / kW-hr, less than electricity from fossil fuel plus environmental costs.

"Look up, you fools!"

Summary

Solar energy can supply all human needs for energy

Inexpensive solar electricity can come from PV
using solar cells made from earth-abundant elements

Production of the PV cells should be
- **very fast**
- **integrated interconnections**
- **produced continuously during glass production**

Storing electricity must be less expensive
metal-free flow batteries (Aziz talk: 4pm today)

Acknowledgements

- Prasert Sinsermsaksakul, Leizhi Sun, Helen Heijin Park, Sang Bok Kim, Danny Chua, Chuanxi Yang, Sang Woon Lee, Adam S. Hock, Ashwin Jayaraman, Rachel Heasley
- MIT PVLab: Tonio Buonassisi, R. Jaramillo, Yun Seog Lee, Katy Hartman, Riley E. Brandt, Vera Steinmann, Rupak Chakraborty, Alexander Polizzotti, Sin Cheng Siah, Juan V. Li, Jonathan P. Mailoa, N. Mangan
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- Precursors: Dow Chemical, Sigma-Aldrich and Strem Chemical
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- Facilities at Harvard’s Center for Nanoscale Systems (CNS), a member of the National Nanotechnology Infrastructure Network, supported by the U. S. National Science Foundation

Harvard University Center for Nanoscale Systems

DOW

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How Much Solar Energy?

$1.2x10^5$ terawatts of solar energy reaches earth's surface

1 terawatt = 10^{12} watt = 10^{12} joules / second = 1 trillion watts

= 10^3 gigawatts = 10^6 megawatts = 10 billion 100 watt lights

One year contains about 8766 hours.

$1.2x10^5$ terawatt / 8766 ~14 terawatt ~ total human energy use

Energy in 1 hr of sunlight = total human energy use in a year