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Polarized Wave Probes for Thin Film Photovoltaics: From the Lab to the Production Line

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Department of Physics and Astronomy
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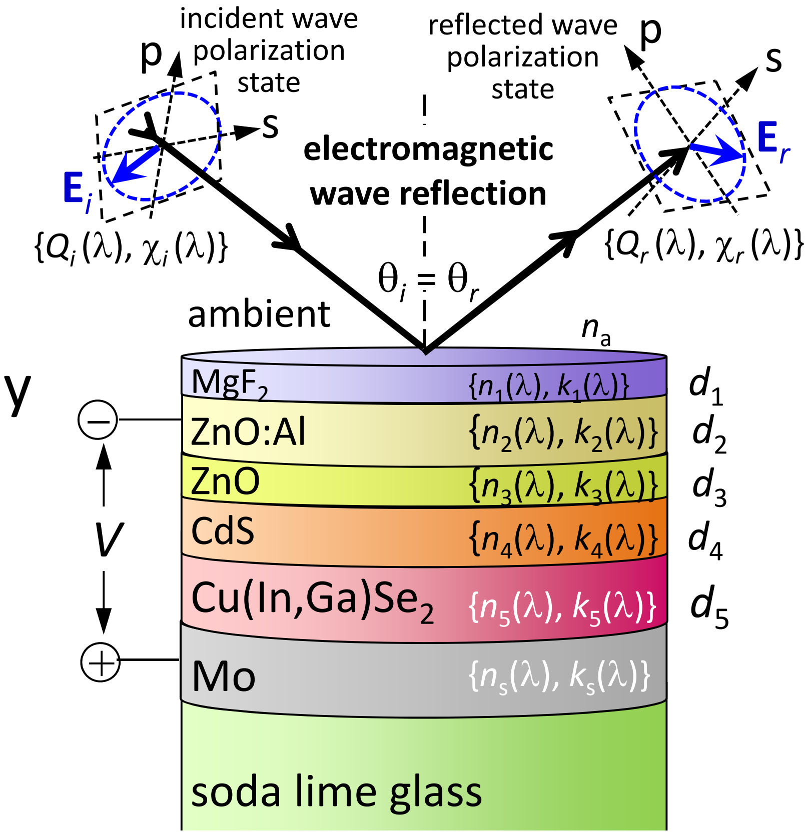
Special thanks to:
Profs. Jian Li and Nikolas Podraza
Prakash Koirala



$Cu(In_{0.7}Ga_{0.3})Se_2$ (CIGS) solar cell

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What is “Solar Energy”?

Useful forms of energy generated from the radiant energy emitted by the sun.

Examples:
Solar Energy Industries Association (SEIA); (www.seia.org)

1. Solar Heating and Cooling

2. Concentrated Solar Power

3. Solar Photovoltaics

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1. **Solar heating and cooling (SHC)**: Solar radiant energy → Thermal energy
2. **Concentrated solar power (CSP)**: Concentrated solar radiant energy → Thermal energy → Mechanical energy → Electrical energy
3. **Solar photovoltaics (PV)**: Direct/diffuse solar radiant energy → Electrical energy

What is “Solar Photovoltaics (PV)”?

Type of solar energy in which radiant energy from the sun is converted directly to electrical energy via absorption within the region of a semiconductor junction

Outline of Major Topics

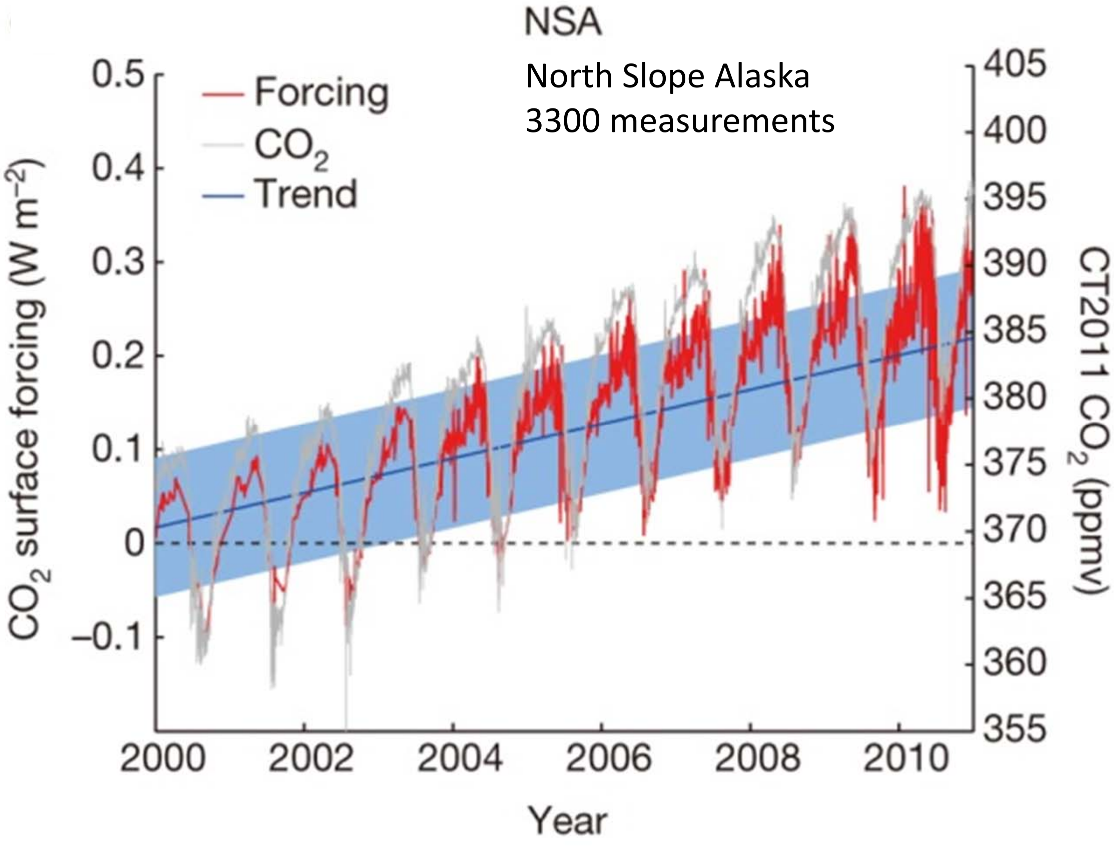
- **Photovoltaics (PV):**
  Motivation, status, and goals (5 slides: 3-7)
- **The first generation (Si) solar cell:**
  Semiconductor physics and operation (7 slides: 8-14)
- **Second generation (thin film) PV:**
  Advantages over 1st generation and its challenges (15 slides: 15-29)
- **Polarized light and its applications in PV:**
  Research on CdTe and CIGS thin film PV technology (15 slides: 30-44)

Motivation: Why Photovoltaics? PV is a clean, sustainable energy technology that generates no emissions during its lifetime.

"Observational determination of surface radiative forcing by CO_2 from 2000 to 2010"

D. R. Feldman, W. D. Collins, P. J. Gero, M. S. Torn, E. J. Mlawer, & T. R. Shippert

Online Feb 26, 2015: Nature **000**, 1-5 (2015); doi:10.1038/nature14240



North Slope Alaska
3300 measurements

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- Although many studies report increasing atmospheric CO_2 concentrations, this study has determined the "surface radiative forcing" due to the increasing CO_2 concentrations.
- Radiative forcing is defined as a change in the difference between the solar irradiance incident on the Earth and the irradiance returning to space (in W/m^2).
- This study by Feldman *et al.* determined radiative forcing as 0.2 W/m^2 per decade.

Earth's area: 5×10^{14} m^2

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Status: Where are we? *SEIA Solar Market Insight Report Q4 2014*:

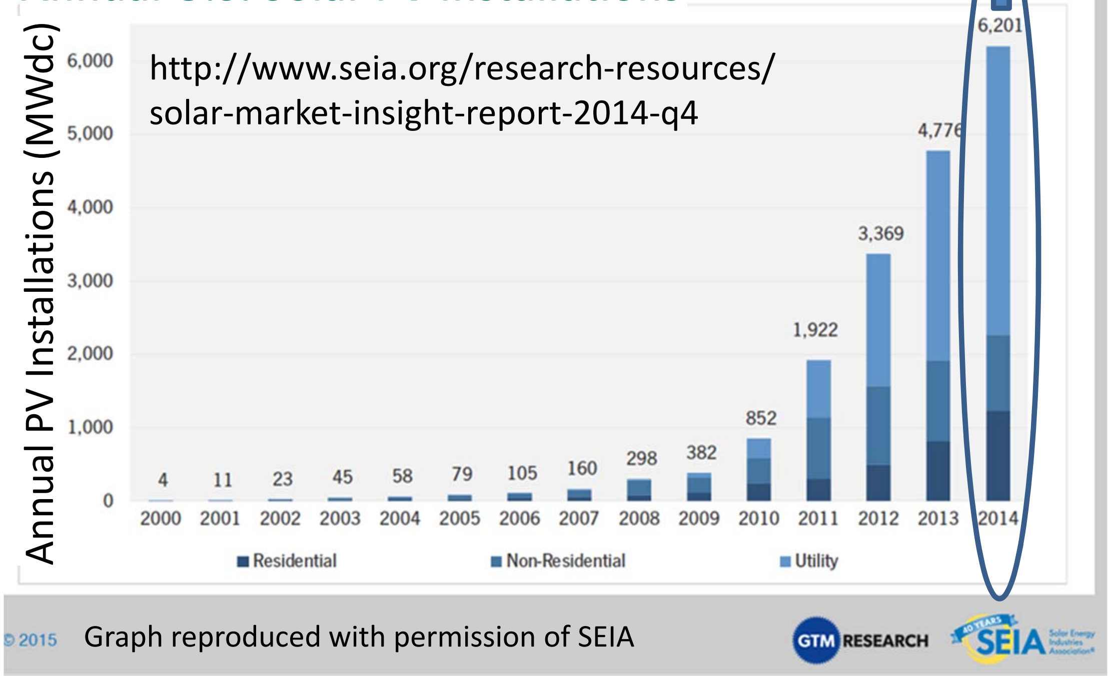
32% OF ALL NEW U.S. ELECTRIC CAPACITY IN 2014 CAME FROM PV

“The U.S. installed 6,201 MWdc of solar PV in 2014, up 30 percent over 2013, making 2014 the largest year ever in terms of PV installations.” -- www.seia.org

The total U.S. PV capacity has surpassed 20,000 MWdc (or 20 GWdc), sufficient to power 4 million U.S. homes* and avoid 10 million metric tons of CO_2.

* 5 kWdc per home

Annual U.S. Solar PV Installations



http://www.seia.org/research-resources/solar-market-insight-report-2014-q4

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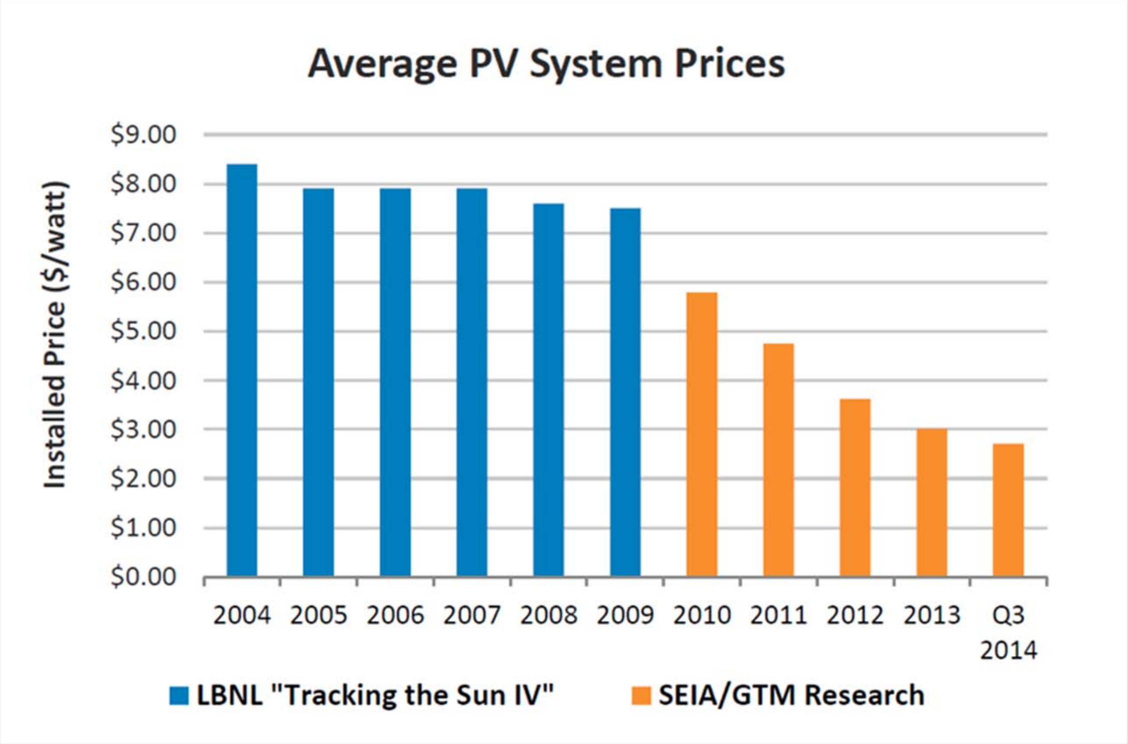
In 2014, energy sources and % share of electricity generation in the US were (www.eia.gov):

• Coal	38.7%
• Natural gas	27.4%
• Nuclear	19.5%
• Hydropower	6.3%
• Other renewable	6.9%
• Biomass	1.57%
• Geothermal	0.41%
• Solar	0.45%
• Wind	4.44%
• Petroleum	0.6%
• Other Gases	0.3%
• Other	0.3%

www.eia.gov: U.S. Energy Information Administration

Goal: Increased Adoption of PV by Reduction of the Installed Price ($/W)

http://www.seia.org/sites/default/files/AveragePVSystemPrices.png



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- Year-over-year, the national average PV installed system price declined by 11% to $2.71/W in 2014 Q3.
- Since the third quarter of 2010, the average price of a PV panel has dropped by 63%.

How many Watts are required to supply 100% of electricity requirements of an average home in Toledo?

$$\frac{29.7\ \text{kW h(ac)/day}}{4.37\ \text{avg. sun h/day}} \quad \frac{1\ \text{(dc)}}{0.8\ \text{(ac)}}$$

$$= 8.5\ \text{kW(dc)}$$

Average cost: $23 K

30% tax credit reduces cost

Average monthly consumption in Ohio (2013): 892 kW h

Monthly bill: $107

Data:
www.eia.gov
http://pvwatts.nrel.gov/version_5.php

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Goal: Continuous Reduction of the Installed Price ($/W) of PV

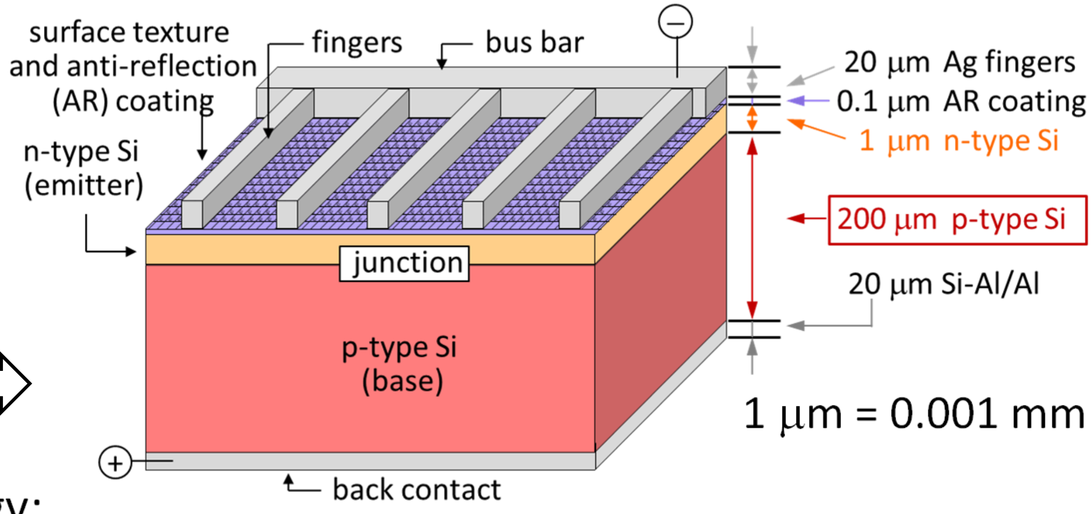
Technology Approaches

Solar radiant energy is converted directly to electrical energy via light absorption within the region of a semiconductor junction

First Generation PV

Based on crystalline silicon semiconductor wafer technology; 90% of total PV production (2013)

(Bell Labs: Chapin, Fuller, Pearson; 1954)

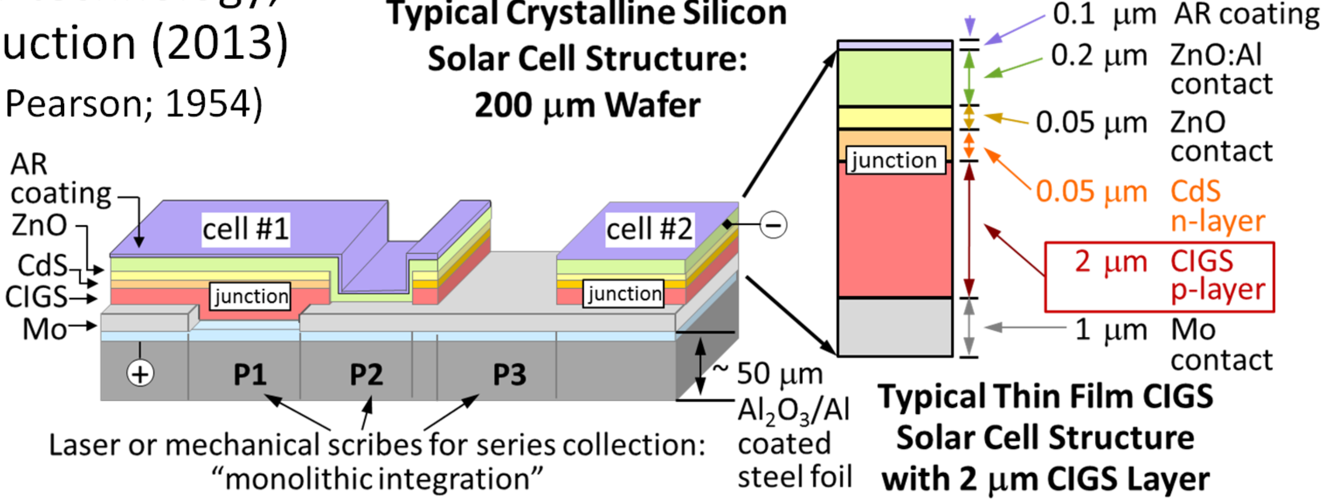


1 µm = 0.001 mm

Typical Crystalline Silicon Solar Cell Structure: 200 µm Wafer

Second Generation PV

Based on thin film semiconductor coating technology on rigid glass and flexible polymer or steel foils (General Electric Labs: Cusano; 1963)



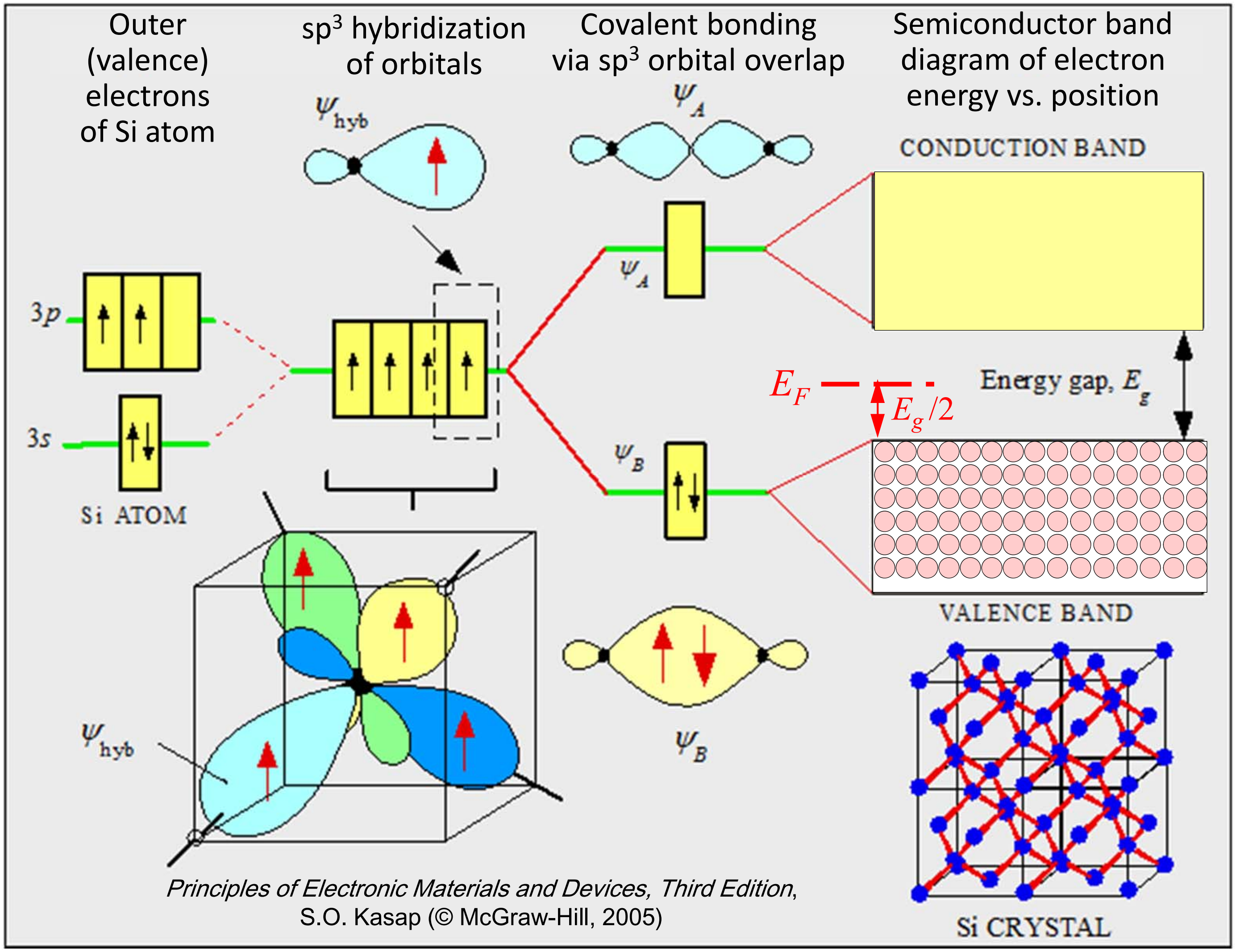
Typical Thin Film CIGS Solar Cell Structure with 2 µm CIGS Layer

Schematics by P. Koirala, UT

Outline of Topics

- **Photovoltaics (PV): Motivation, status, and goals**
- **The first generation (Si) solar cell: Semiconductor physics and operation** **(7 slides: 8-14)**
  - **Bonding and bands in silicon**
  - **Illuminating silicon**
  - **Doping silicon *n* and *p* type**
  - **Forming a silicon *p/n* junction**
  - **Illuminating a silicon *p/n* junction**
  - **Generating electrical power from a solar cell**
- **Second generation (thin film) PV: Advantages and challenges**
- **Polarized light and its applications: Studies of thin film CdTe and CIGS PV**

“Intrinsic” Crystalline Silicon Semiconductor



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S.O. Kasap (© McGraw-Hill, 2005)

In the limit of low temperature ($T \rightarrow 0$ Kelvin), the valence band is completely filled with electrons and the conduction band is empty.

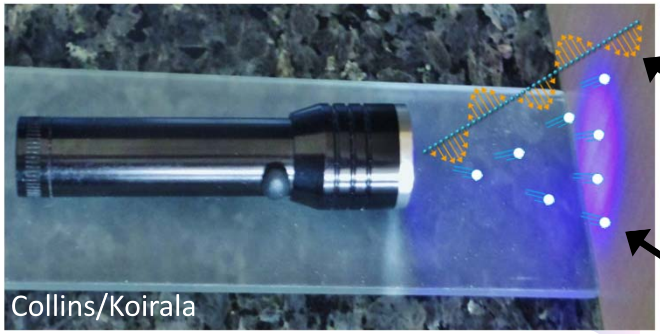
The fraction of electrons n/N in the conduction band follows “Boltzmann statistics”:

$$\frac{n}{N} = \exp\left(-\frac{E_g}{2kT}\right)$$

k is Boltzmann’s constant.
At T = 300 K (room T)

$\frac{n}{N} \approx 10^{-9}$ hence **“semiconductor”**.

Light Absorption in a Crystalline Silicon Semiconductor

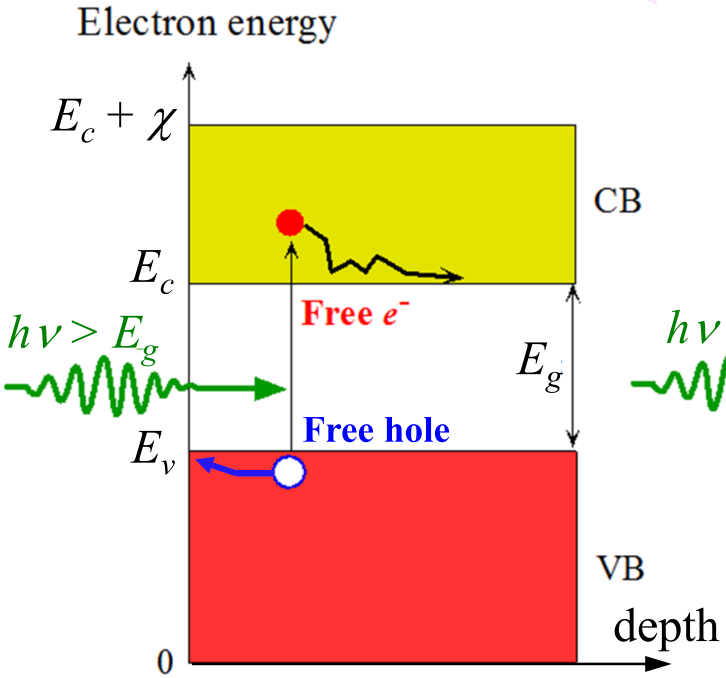

Collins/Koirala

Light as electromagnetic waves or as photons?

electromagnetic wave: orthogonal electric and magnetic fields oscillating at frequency ν; wavelength $\lambda = c/\nu$; c is speed of light

photons: each photon carries energy $E = h\nu$ where h is Planck's constant ; $E = hc/\lambda$

E (eV) $= 1240/\lambda$ (nm)



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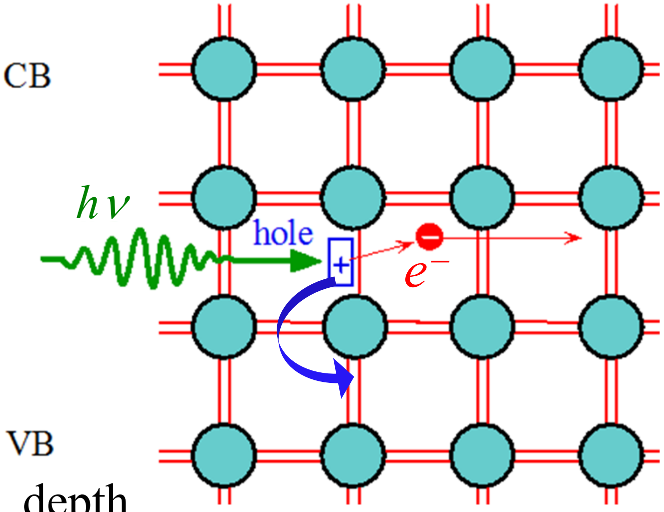


electron and hole separate

Light absorption by a semiconductor is understood in terms of photons:

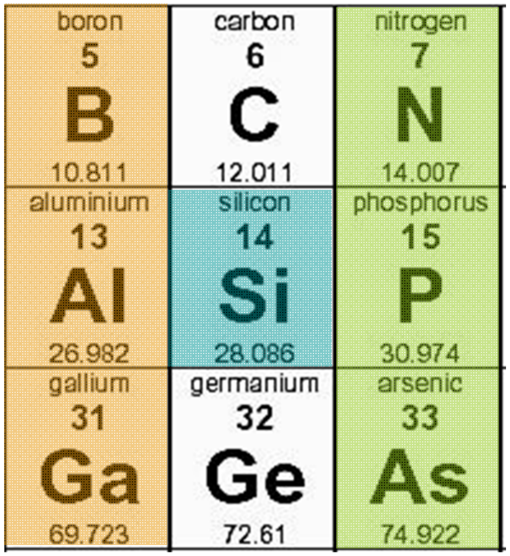
$h\nu < E_g$ no absorption

$h\nu > E_g$ absorption generates free electrons and holes ... and "**photoconductivity**"

Doped Crystalline Silicon Semiconductors

Typical doping levels in solar cells: 0.1 – 100 impurity atoms per million Si atoms

Group



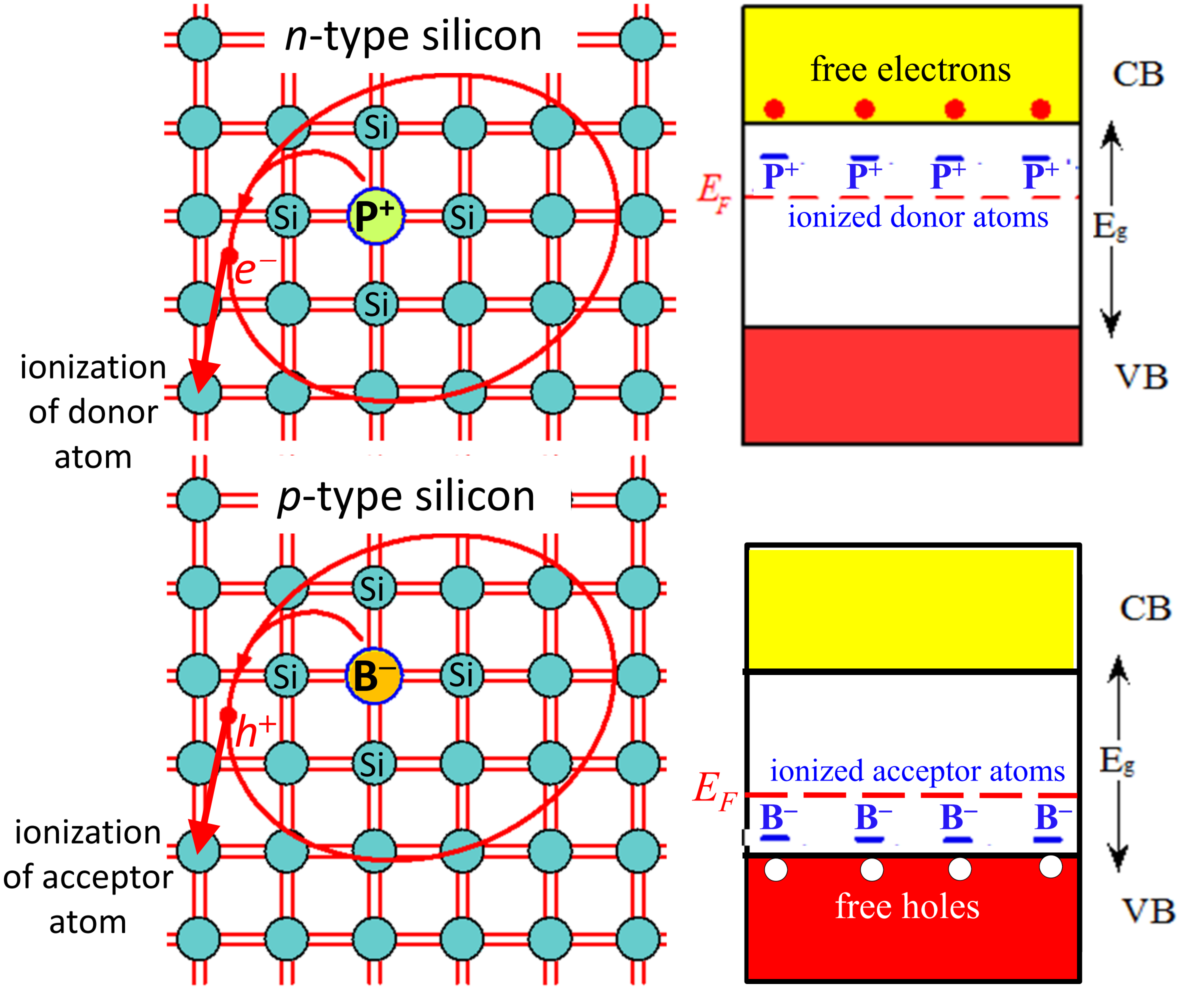
III	IV	V
boron 5 B 10.811	carbon 6 C 12.011	nitrogen 7 N 14.007
aluminium 13 Al 26.982	silicon 14 Si 28.086	phosphorus 15 P 30.974
gallium 31 Ga 69.723	germanium 32 Ge 72.61	arsenic 33 As 74.922

3 4 5
number of s and p valence electrons

p-type dopants

n-type dopants

http://commons.wikimedia.org/wiki/File:Periodic-table.jpg



Principles of Electronic Materials and Devices, Third Edition, S.O. Kasap (© McGraw-Hill, 2005)

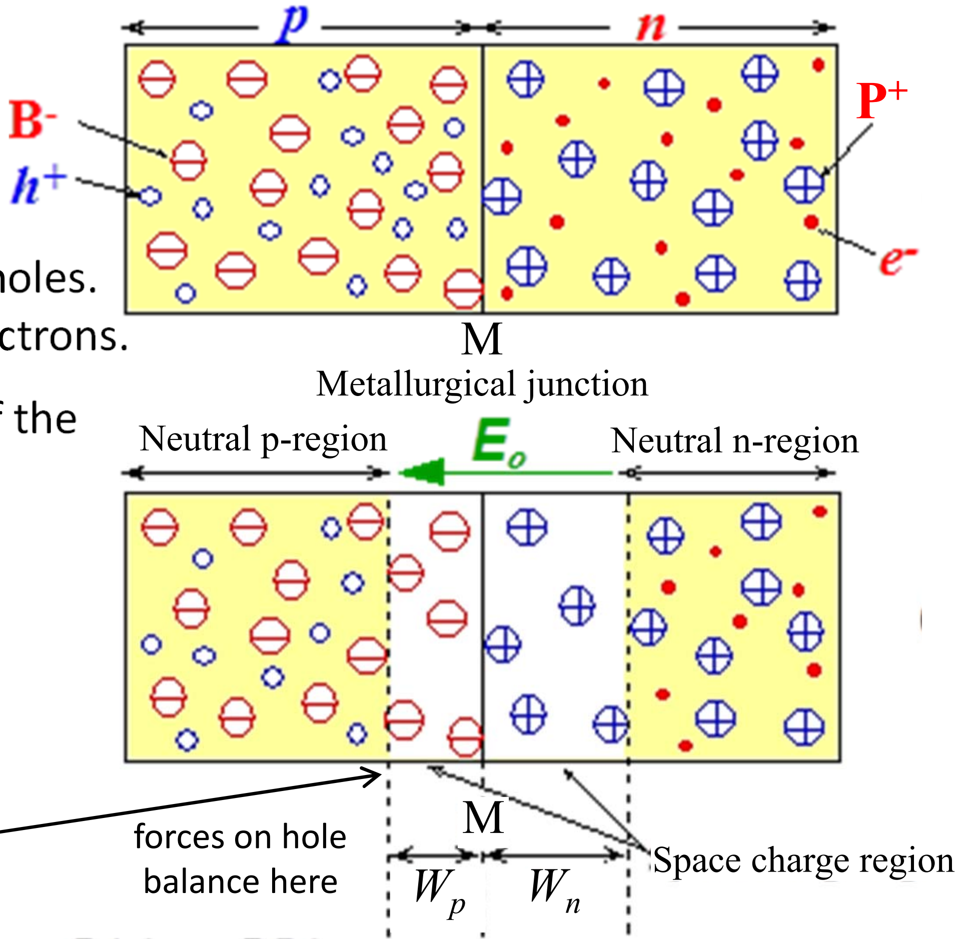
Junction between *n* and *p*-Type Silicon

A junction is shown between electrically neutral *n* and *p*-type silicon.
This system is not in equilibrium.

Electrons move to the left and annihilate holes.
Holes move to the right and annihilate electrons.

Equilibrium is achieved when the forces of the electric field E_o on the electrons and holes balance the “driving forces” of diffusion at the space charge boundaries.

An equation describes this equilibrium at the two space charge boundaries:



forces on hole
balance here

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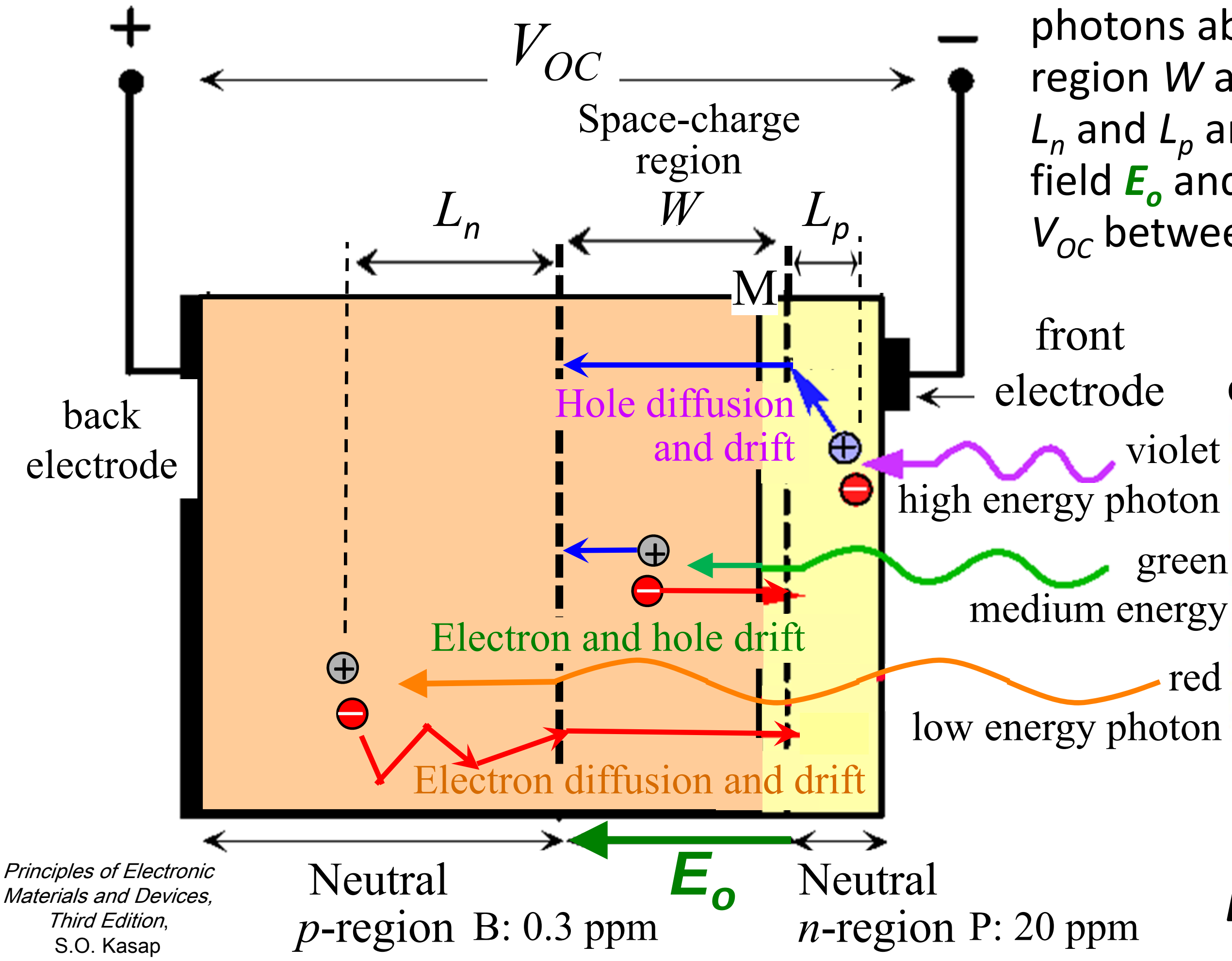
$$F_{net} = eE_o - kT\left(\frac{1}{n}\frac{\Delta n}{\Delta x}\right) = 0$$

force holes
by field (left-ward)

“force” on holes
due to concentration gradient $\Delta n/\Delta x$ (right-ward)

Finally: The Crystalline Silicon *p-n* Junction Solar Cell under Light !

The electrons and holes generated by photons absorbed within the depletion region *W* and the two diffusion regions L_n and L_p are separated by the built-in field $\boldsymbol{E_o}$ and generate a photovoltage V_{OC} between the two electrodes.



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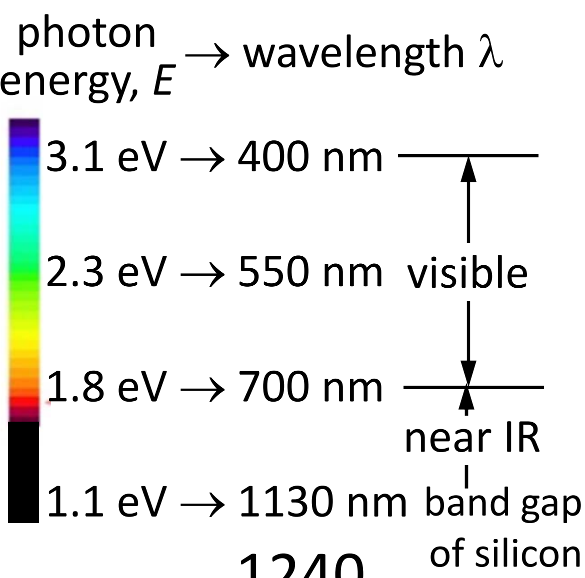
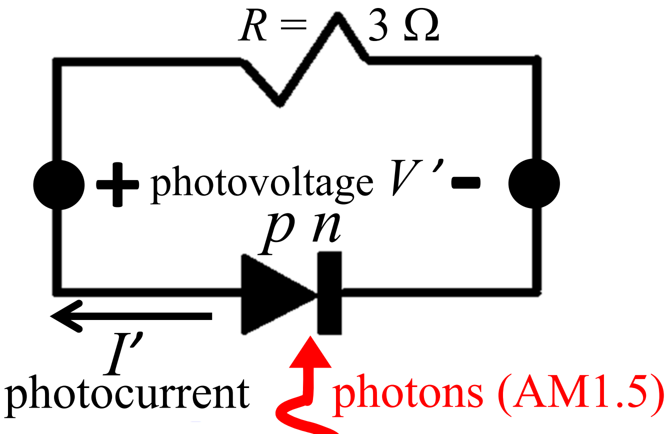
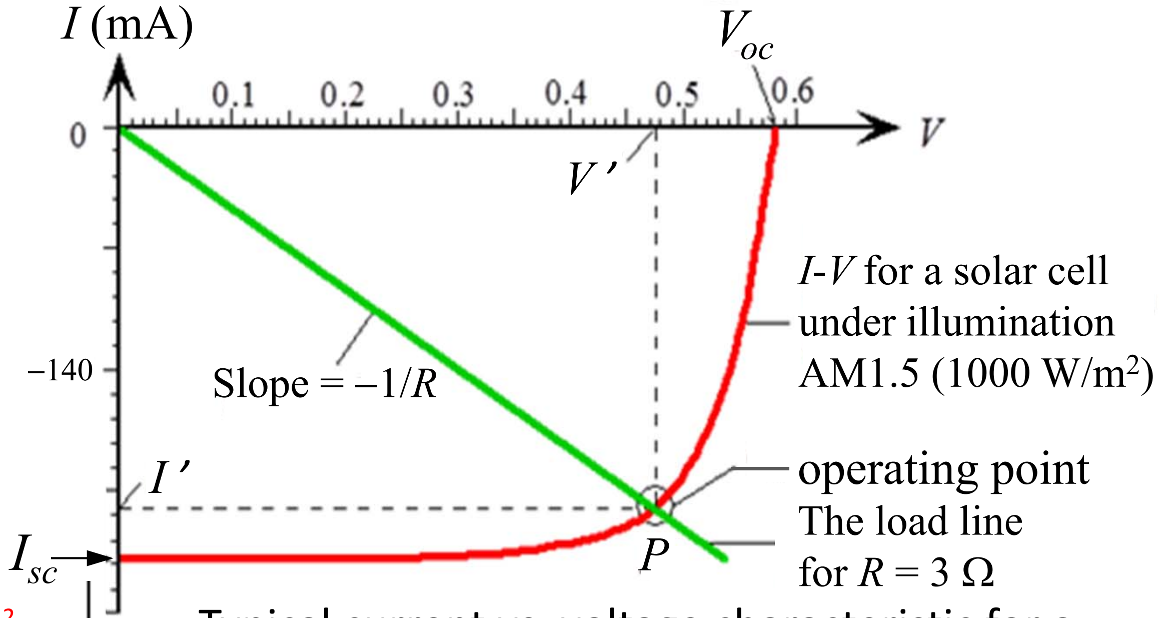
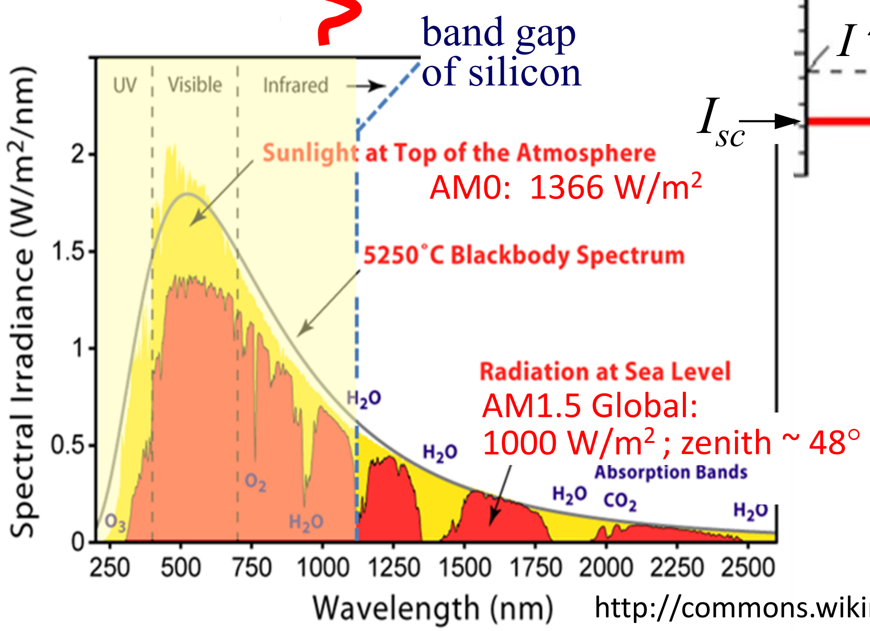


$$E\text{ (eV)} = \frac{1240}{\lambda\text{ (nm)}}$$

Photovoltaic Power from a Crystalline Silicon Solar Cell







http://commons.wikimedia.org/wiki/File:Solar_spectrum_en.svg

Typical current vs. voltage characteristic for a crystalline silicon solar cell showing

V_{OC} : Open circuit voltage $(R \to \infty)$

I_{SC} : Short circuit current $(R \to 0)$

Power = Current x Voltage : $P = I' V'$

$$\text{Efficiency (\%)} = \frac{P_{\max}\,(\text{W})}{[1000\ \text{W/m}^2]\ [\text{Area}\ (\text{m}^2)]} \times 100$$

Principles of Electronic Materials and Devices, 3rd Edition,
S.O. Kasap (© McGraw-Hill, 2005)

Outline of Topics

- **Photovoltaics (PV): Motivation, status, and goals**
- **The first generation (Si) solar cell: Semiconductor physics and operation**
- **Second generation or thin film PV:**
  Advantages over 1st generation and its challenges
  - **> Advantages of thin film technology** **7 slides: 15-21**
    - Much stronger absorption in thin films for lower materials usage
    - Low temperature processes for shorter energy payback time
    - Greater potential for scalability and in-line automation
  - **> Challenges of thin film technology**
- **Polarized light and its applications: Studies of 2nd generation PV**

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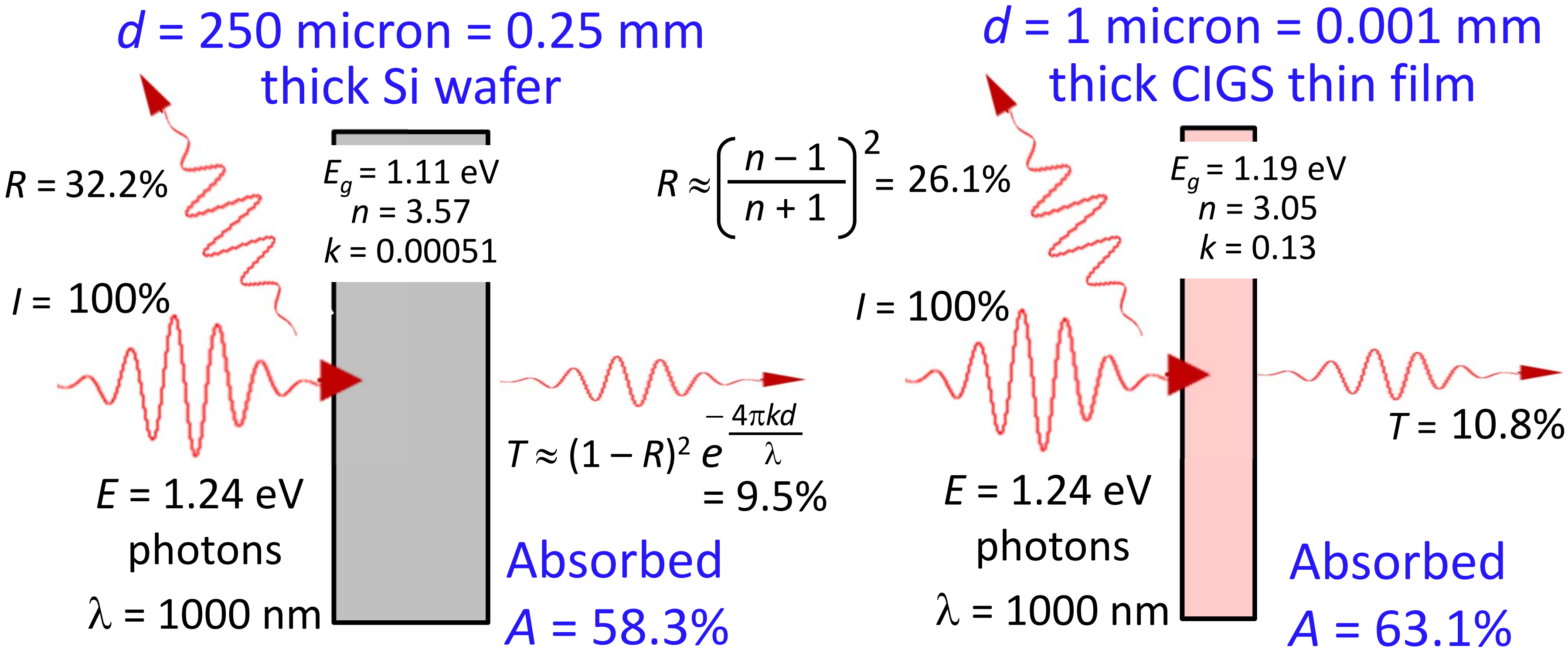
Silicon (Si): Indirect Bandgap vs. Copper Indium-Gallium Diselenide [$Cu(In_{0.7}Ga_{0.3})Se_2$; CIGS]: Direct Bandgap

For a given photon energy just above their bandgaps, the absorption strength (absorbance/volume) of CIGS is ~ 250 times higher than that of Si.



d = 250 micron = 0.25 mm
thick Si wafer

$R = 32.2\%$

$E_g = 1.11$ eV
$n = 3.57$
$k = 0.00051$

$I = 100\%$

$E = 1.24$ eV
photons
$\lambda = 1000$ nm

$$T \approx (1-R)^2 e^{-\frac{4\pi k d}{\lambda}} = 9.5\%$$

Absorbed
$A = 58.3\%$

$$R \approx \left(\frac{n-1}{n+1}\right)^2 = 26.1\%$$

d = 1 micron = 0.001 mm
thick CIGS thin film

$E_g = 1.19$ eV
$n = 3.05$
$k = 0.13$

$I = 100\%$

$E = 1.24$ eV
photons
$\lambda = 1000$ nm

$T = 10.8\%$

Absorbed
$A = 63.1\%$

Reflectance *R*, transmittance *T*, and absorbance *A* of a material is controlled by its index of refraction *n*, and its extinction coefficient *k* which vary with wavelength λ

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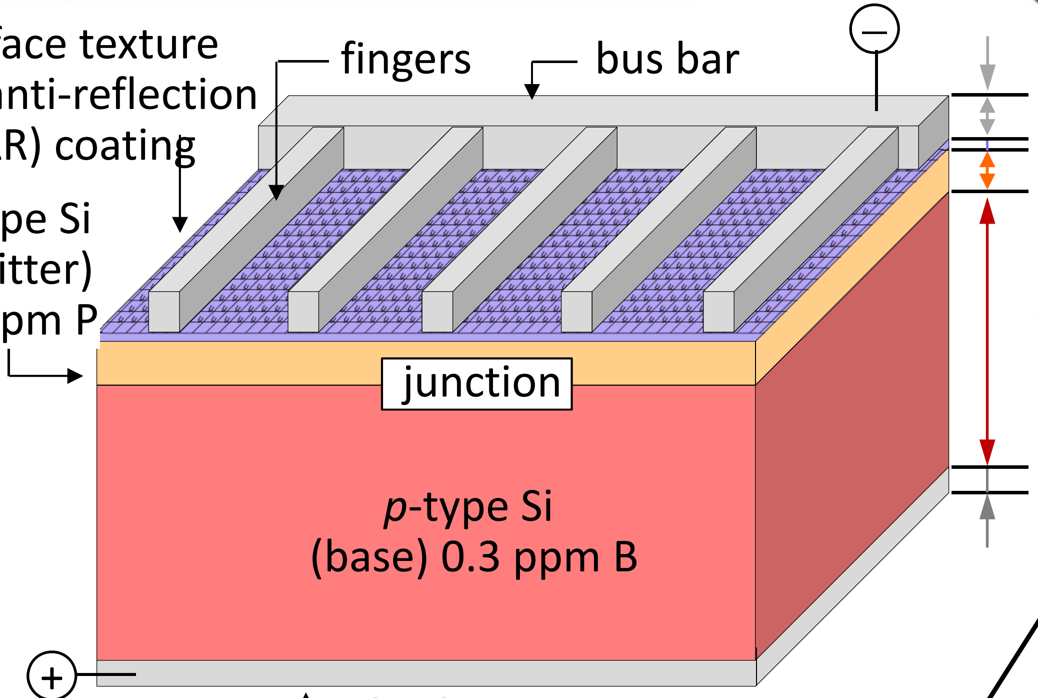
Typical Crystalline Silicon Solar Cell Structure: 200 μm Wafer



20 μm Ag fingers

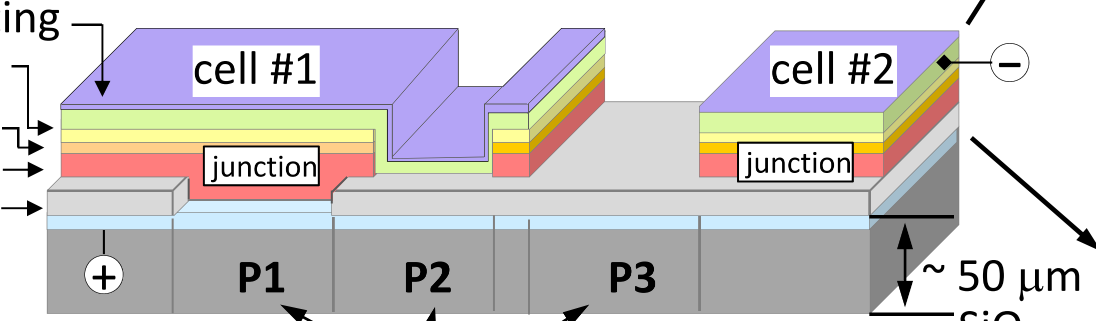
0.1 μm AR coating

0.5 μm *n*-type Si

200 μm *p*-type Si

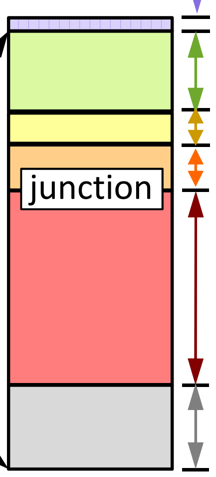
20 μm Si-Al/Al

Typical Thin Film CIGS Solar Cell Structure with 2 μm CIGS Layer



~ 50 μm SiO_2 coated steel foil

Laser or mechanical scribes for series collection: “monolithic integration”



0.1 μm AR coating

0.2 μm ZnO:Al contact

0.05 μm ZnO contact

0.05 μm CdS *n*-layer

2 μm CIGS *p*-layer

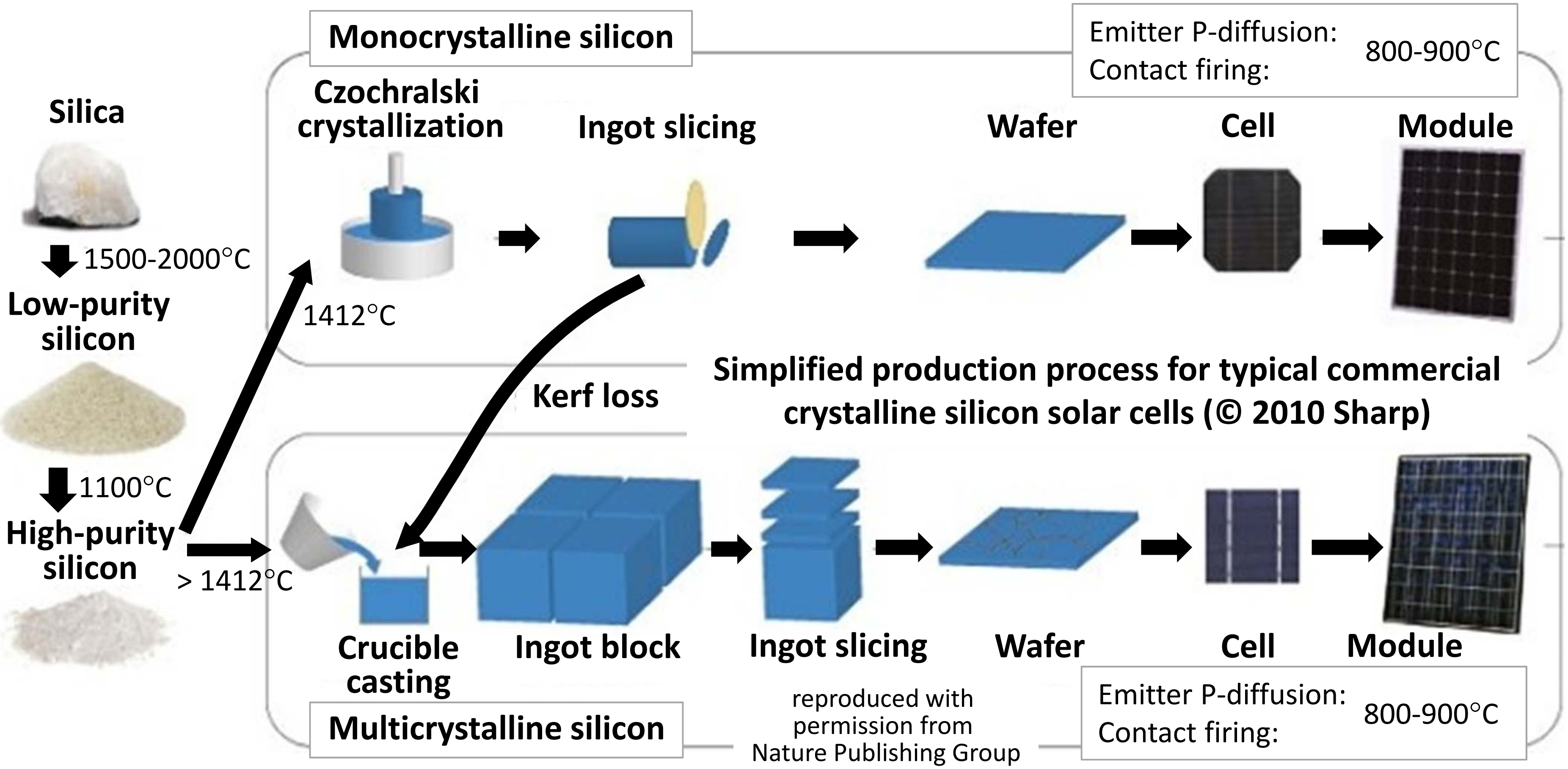
1 μm Mo contact

P. Koirala, UT

Drawbacks of Crystalline Silicon PV: Cost Related Issues

- Higher materials cost
- High temperature processes -- energy intensive
- Capital intensive processes with limited scalability
- Greater challenges in in-line automation due fragility of wafers

Tatsuo Saga,
NPG Asia Materials (2010)
2, 96–102;
doi:10.1038/asiamat.2010.82



Silica

1500-2000°C

Low-purity silicon

1100°C

High-purity silicon

1412°C

> 1412°C

Monocrystalline silicon

Czochralski crystallization → **Ingot slicing** → **Wafer** → **Cell** → **Module**

Emitter P-diffusion:
Contact firing:
800-900°C

Kerf loss

Simplified production process for typical commercial crystalline silicon solar cells (© 2010 Sharp)

Crucible casting → **Ingot block** → **Ingot slicing** → **Wafer** → **Cell** → **Module**

Multicrystalline silicon

Emitter P-diffusion:
Contact firing:
800-900°C

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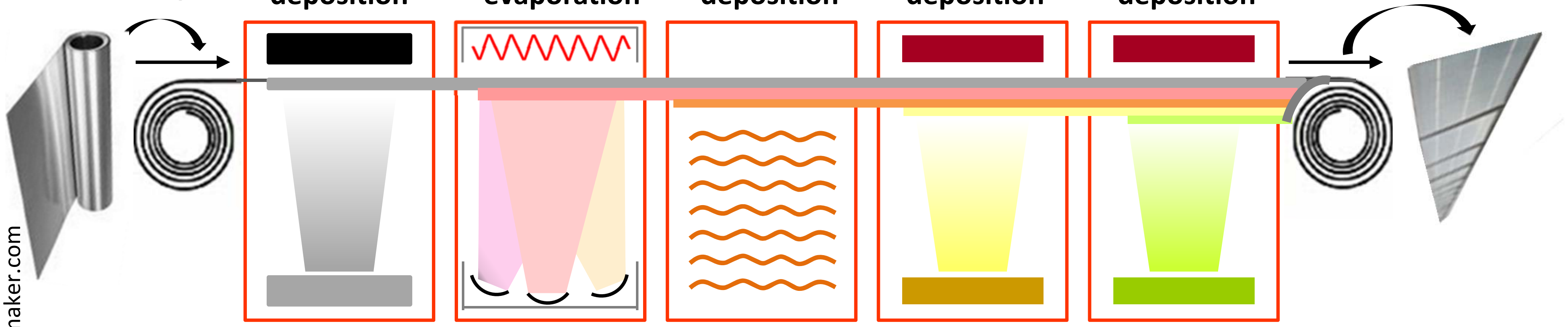
Advantages of Thin Film Photovoltaics: Cost Related Issues

- Lower materials cost due to lower materials usage
- Lower temperature processes – lower thermal budget and shorter energy payback times
- Manufacturing scalability
- Continuous production line with greater automation



Steel with dielectric coating

Mo back contact sputter deposition

p-type CIGS multiple source evaporation

n-type CdS chemical bath deposition

ZnO transparent top contact deposition

ZnO:Al transparent top contact deposition

Coated Roll

Flexible module

25°C 550°C 50°C 25°C 25°C

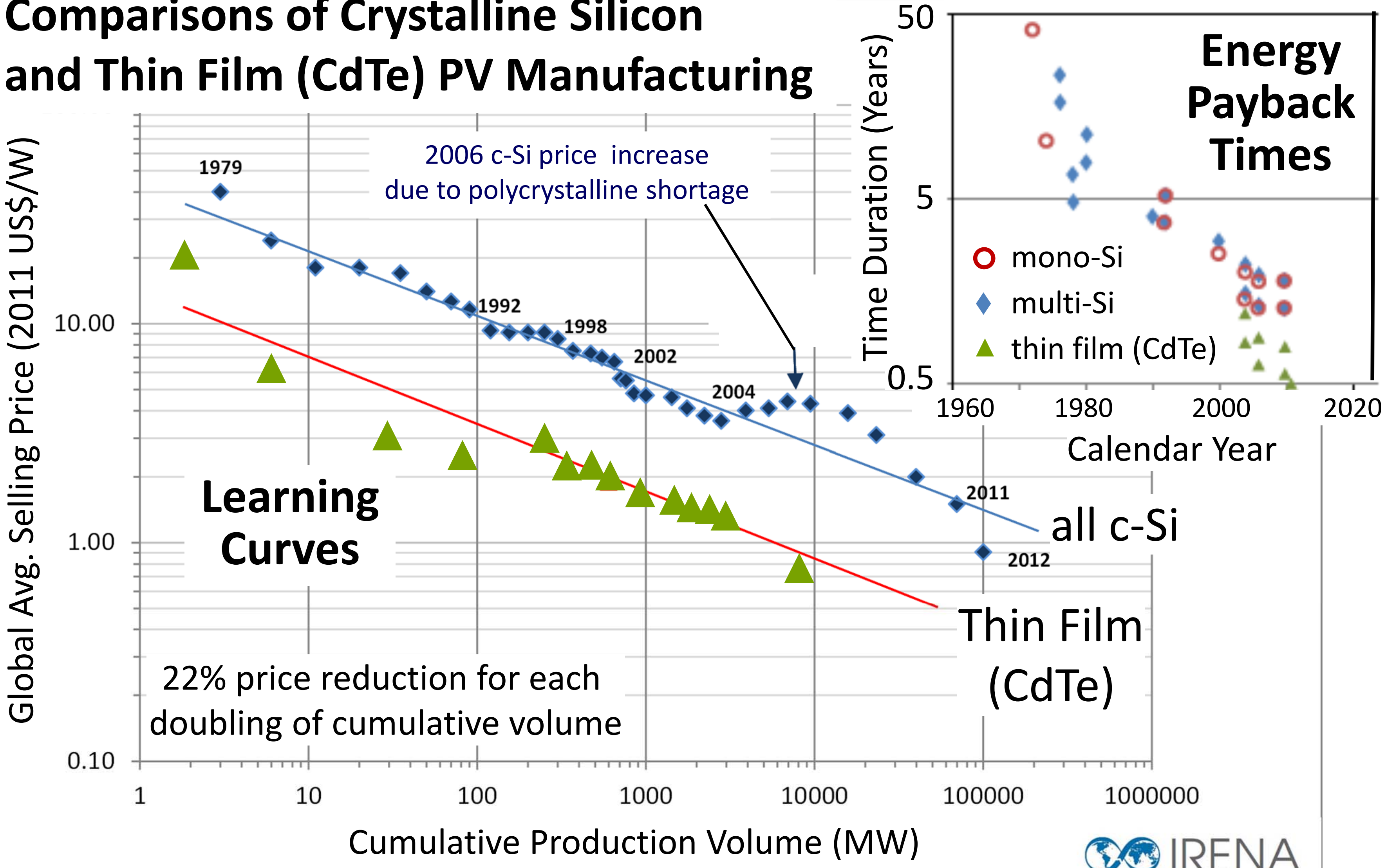
Production line schematic for Cu($In_{0.7}Ga_{0.3}$)Se_2 (CIGS) solar cells on flexible steel foil

See for example: http://www.flisom.ch ; www.nuvosun.com

http://usaknifemaker.com

Acknowledgment: Vasilis Fthenakis

Comparisons of Crystalline Silicon and Thin Film (CdTe) PV Manufacturing



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Example Installations of Thin Film (CdTe, CIGS) Photovoltaics

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http://www.calyxo.com/en/news-events/news/251-completed-anthony-wayne-solar-array-is-providing-power-for-the-toledo-zoo-and-new-life-to-brownfield-site.html

Utility scale power plants from CdTe on glass PV technology

2.1 MW Anthony Wayne Solar Array provides power to The Toledo Zoo

World's largest plants are thin film: Topaz (2014, 550 MW); Desert Sunlight (2015, 550 MW)

Reproduced with permission of Dow Solar

Residential PV power from CIGS on steel foil PV Technology

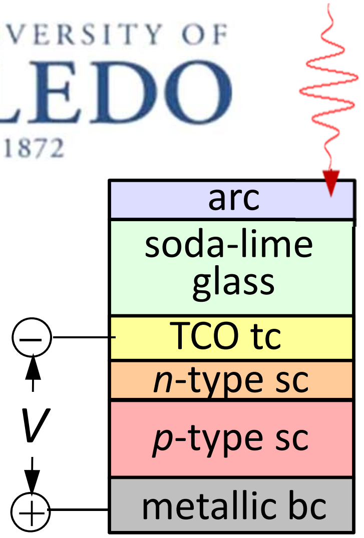
Solar shingles on a residence in Katy, Texas.

thin film PV ⇒ solar anywhere

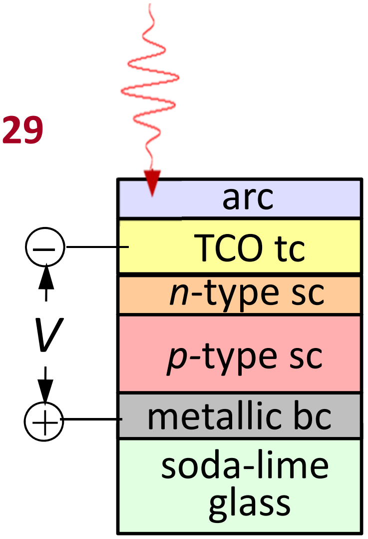
http://www.dowpowerhouse.com/why-powerhouse/index.htm

Outline of Topics

- **Photovoltaics (PV): Motivation, status, and goals**
- **The first generation (Si) solar cell: physics and operation**
- **Second generation or thin film PV:**
  Advantages over 1st generation and its challenges
  - **> Advantages of thin film technology**
  - **> Challenges of thin film technology** **8 slides: 22-29**
    - Materials development for:
      p-type and *n*-type semiconductors (sc's)
      Transparent conducting oxide (TCO) top contact (tc)
      Back contact (bc) and anti-reflection coating (arc)
    - Approaching the performance of 1st generation PV
    - Controlling the fabrication process
- **Polarized light and applications: Studies of 2nd generation PV**

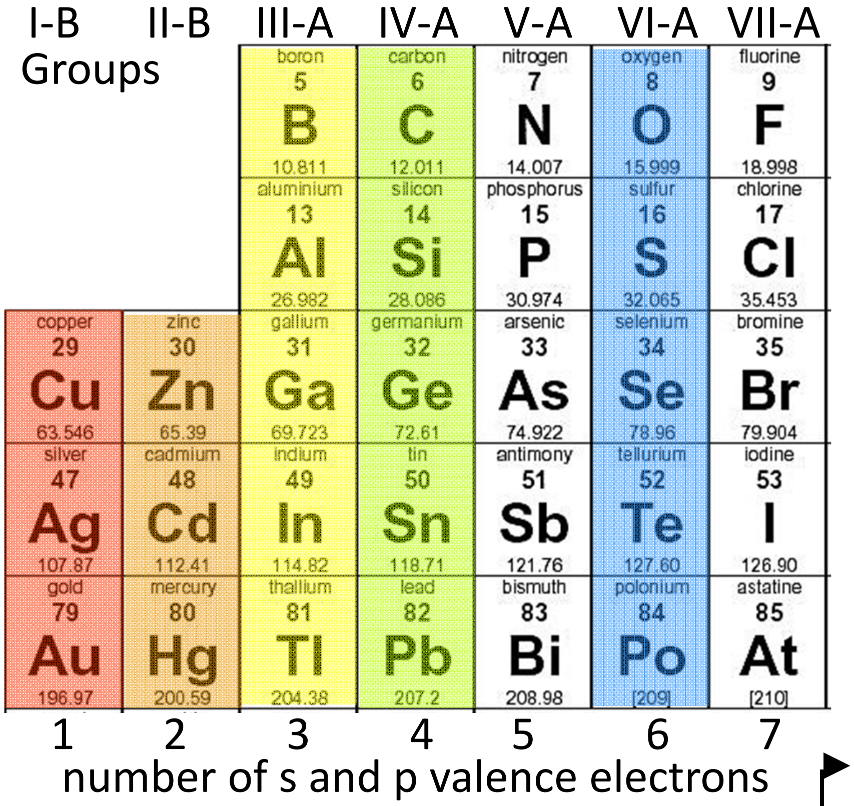


superstrate type cell (CdTe)



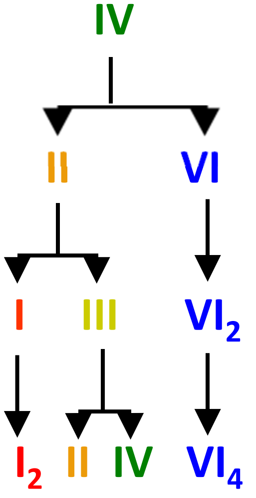
substrate type cell (CIGS)

Tetrahedrally-Bonded Semiconductor Materials Development



Groups	I-B	II-B	III-A	IV-A	V-A	VI-A	VII-A
			boron 5 B 10.811	carbon 6 C 12.011	nitrogen 7 N 14.007	oxygen 8 O 15.999	fluorine 9 F 18.998
			aluminium 13 Al 26.982	silicon 14 Si 28.086	phosphorus 15 P 30.974	sulfur 16 S 32.065	chlorine 17 Cl 35.453
	copper 29 Cu 63.546	zinc 30 Zn 65.39	gallium 31 Ga 69.723	germanium 32 Ge 72.61	arsenic 33 As 74.922	selenium 34 Se 78.96	bromine 35 Br 79.904
	silver 47 Ag 107.87	cadmium 48 Cd 112.41	indium 49 In 114.82	tin 50 Sn 118.71	antimony 51 Sb 121.76	tellurium 52 Te 127.60	iodine 53 I 126.90
	gold 79 Au 196.97	mercury 80 Hg 200.59	thallium 81 Tl 204.38	lead 82 Pb 207.2	bismuth 83 Bi 208.98	polonium 84 Po [209]	astatine 85 At [210]
number of s and p valence electrons	1	2	3	4	5	6	7

http://en.wikipedia.org/wiki/Grimm-Sommerfeld_rule



Type	Family	Examples	No. of Valence e⁻	No. of Valence e⁻ per atom
Elemental	IV	Si	4	4
Binary	II VI	CdTe CdS	8	4
Ternary	I III VI_2	$CuInSe_2$	16	4
Quaternary	I_2 II IV VI_4	Cu_2ZnSnS_4	32	4

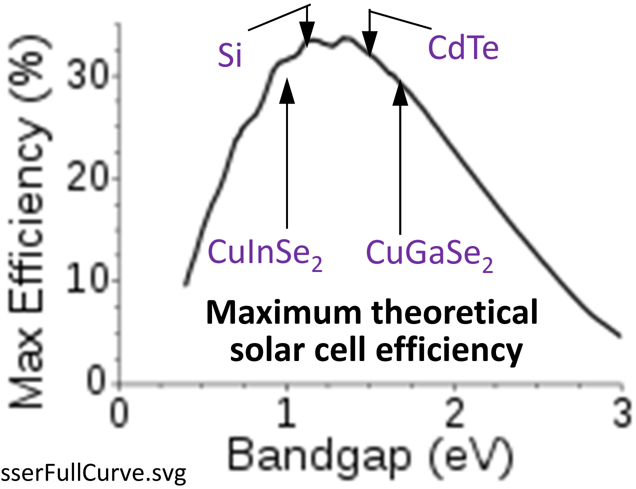
Ternary and quaternary compound semiconductors: provide flexibility in tuning band gap and properties

$CuInSe_2$

Group I alloying: $(Cu_{1-x}Ag_x)InSe_2$

Group III alloying $Cu(In_{1-x}Ga_x)Se_2$

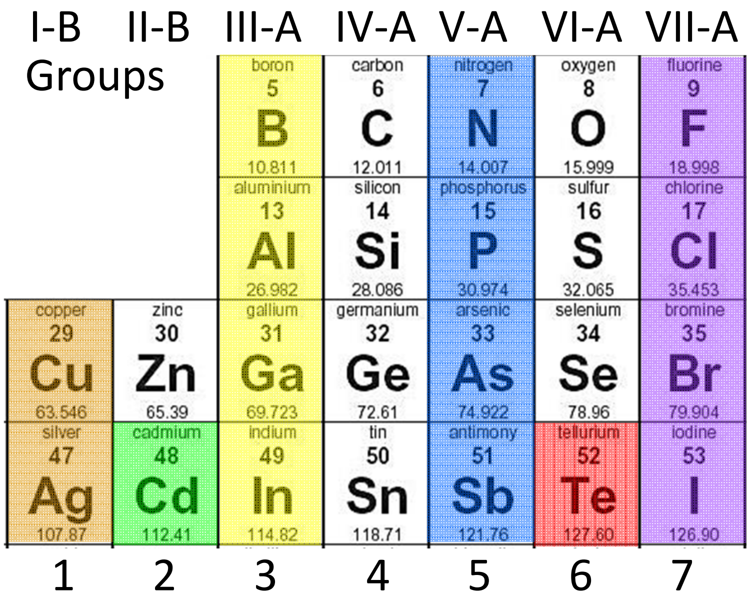
Group VI alloying $CuIn(Se_{1-x}S_x)_2$



Maximum theoretical solar cell efficiency

http://commons.wikimedia.org/wiki/File:Periodic-table.jpg
http://commons.wikimedia.org/wiki/File%3AShockleyQueisserFullCurve.svg

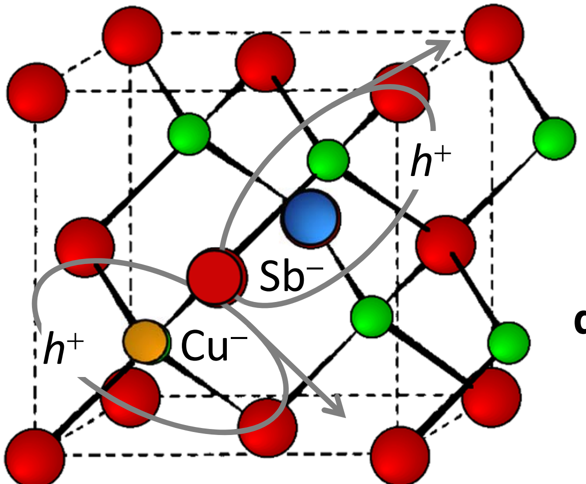
(n,p)-Type Tetrahedrally-Bonded Semiconductor Materials



Groups	I-B	II-B	III-A	IV-A	V-A	VI-A	VII-A
			boron 5 B 10.811	carbon 6 C 12.011	nitrogen 7 N 14.007	oxygen 8 O 15.999	fluorine 9 F 18.998
			aluminium 13 Al 26.982	silicon 14 Si 28.086	phosphorus 15 P 30.974	sulfur 16 S 32.065	chlorine 17 Cl 35.453
	copper 29 Cu 63.546	zinc 30 Zn 65.39	gallium 31 Ga 69.723	germanium 32 Ge 72.61	arsenic 33 As 74.922	selenium 34 Se 78.96	bromine 35 Br 79.904
	silver 47 Ag 107.87	cadmium 48 Cd 112.41	indium 49 In 114.82	tin 50 Sn 118.71	antimony 51 Sb 121.76	tellurium 52 Te 127.60	iodine 53 I 126.90
	1	2	3	4	5	6	7

number of s and p valence electrons

↑	↑	↑	↑
p-type dopants substituting for Cd	*n*-type dopants substituting for Cd	*p*-type dopants substituting for Te	*n*-type dopants substituting for Te



● Te

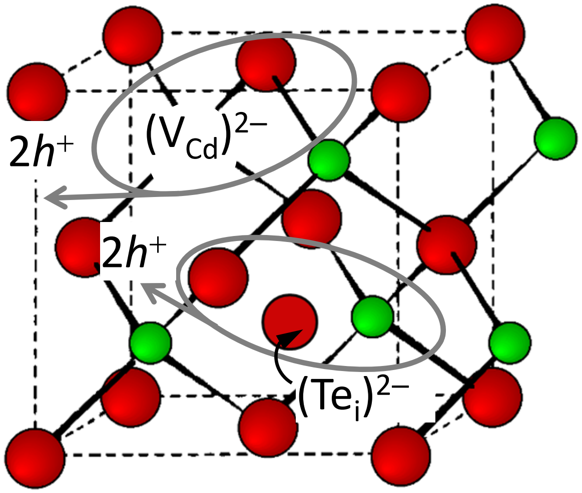
● Cd

p-type substitutional dopants in CdTe

● Cu

● Sb

CdTe - zincblende



p-type point defects in CdTe

$(V_{Cd})^{2-}$: ionized Cd vacancy

$(Te_i)^{2-}$: ionized Te interstitial

http://cnx.org/contents/e90d5161-66b0-4214-bd6c-9f1d20a35bae@10/Crystal_Structure

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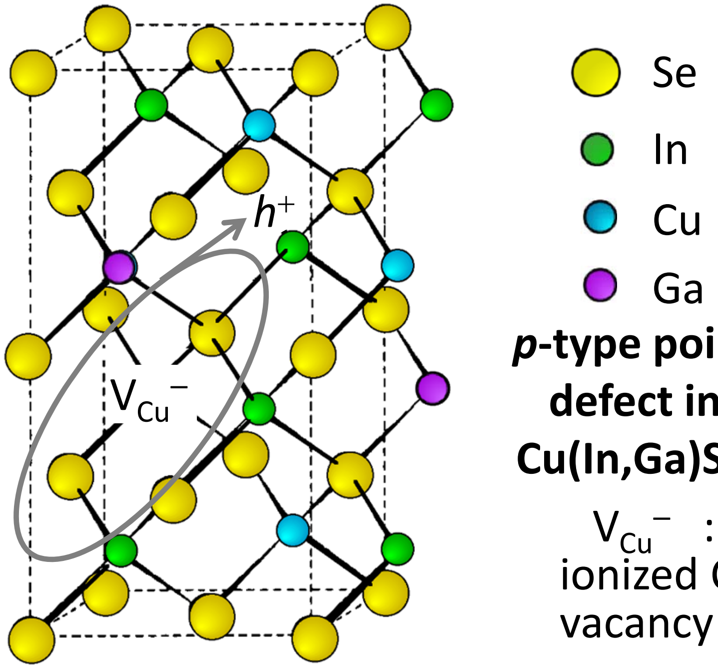
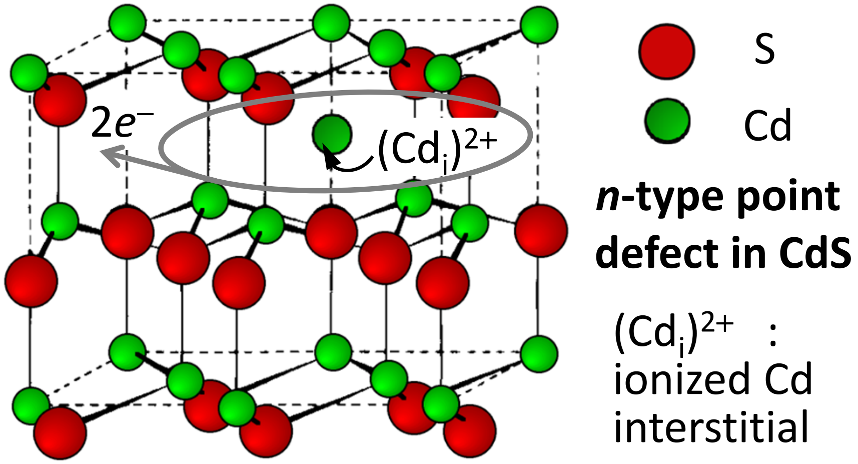
(*n*,*p*)-Type Tetrahedrally-Bonded Semiconductor Materials



$CuIn_{0.7}Ga_{0.3}Se_2$ - chalcopyrite

***p*-type point defect in $Cu(In,Ga)Se_2$**

V_{Cu}^- : ionized Cu vacancy

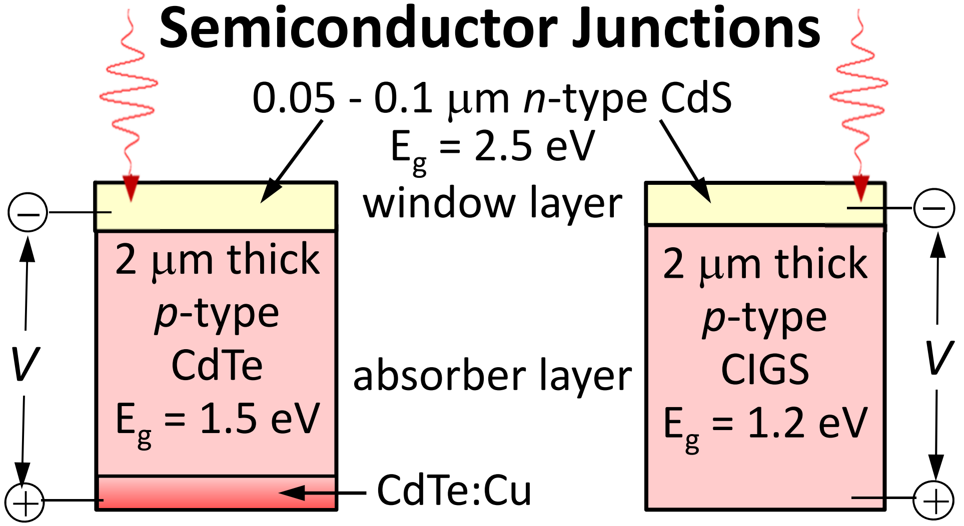


CdS - wurtzite

***n*-type point defect in CdS**

$(Cd_i)^{2+}$: ionized Cd interstitial

Semiconductor Junctions



0.05 - 0.1 μm *n*-type CdS
E_g = 2.5 eV
window layer

2 μm thick
p-type
CdTe
E_g = 1.5 eV

absorber layer

CdTe:Cu

2 μm thick
p-type
CIGS
E_g = 1.2 eV

The most successful solar cell designs incorporate thin *n*-type CdS as an inactive window layer and a thick *p*-type CdTe or CIGS absorber. With the exception of a Cu-doped region at the back of the CdTe cell, materials rely on defects for doping.

http://cnx.org/contents/e90d5161-66b0-4214-bd6c-9f1d20a35bae@10/Crystal_Structure

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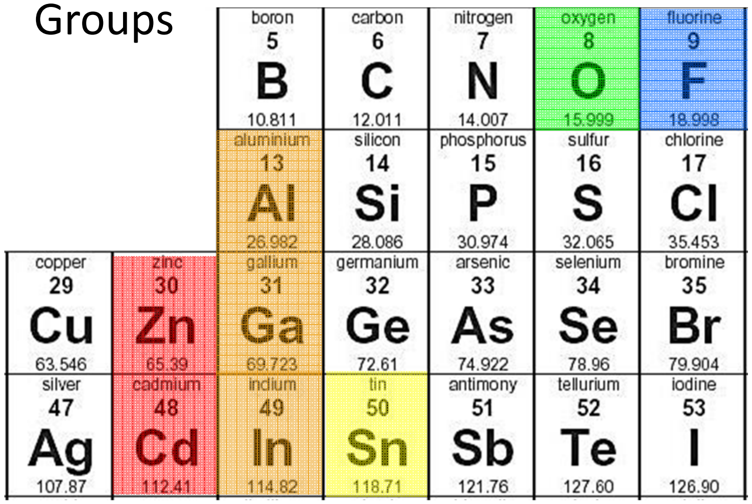
Materials Development: Transparent Conducting Oxide Top Contacts

Groups



I-B	II-B	III-A	IV-A	V-A	VI-A	VII-A
		boron 5 B 10.811	carbon 6 C 12.011	nitrogen 7 N 14.007	oxygen 8 O 15.999	fluorine 9 F 18.998
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1	2	3	4	5	6	7

number of s and p valence electrons

Most common solar cell TCOs (all *n*-type):

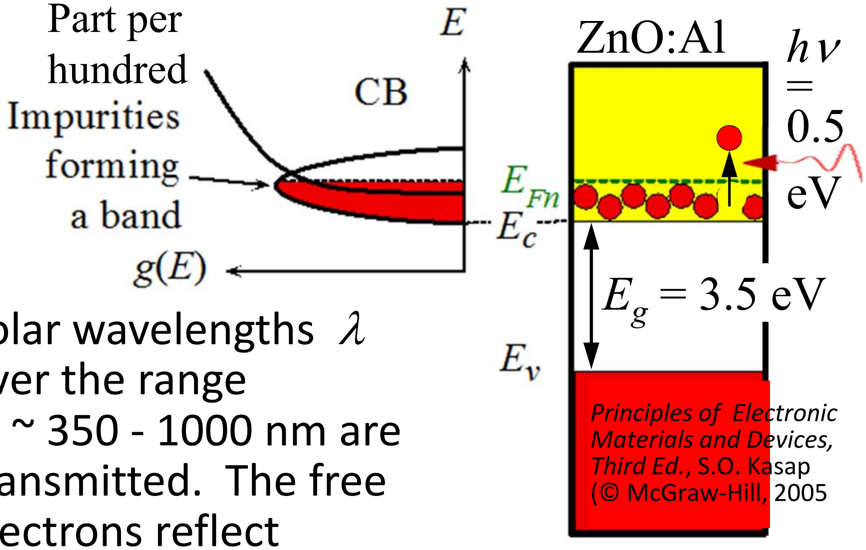
In_2O_3:Sn -- Sn substitutes for In

SnO_2:F -- F substitutes for O

ZnO:Al -- Al substitutes for Zn

http://commons.wikimedia.org/wiki/File:Periodic-table.jpg

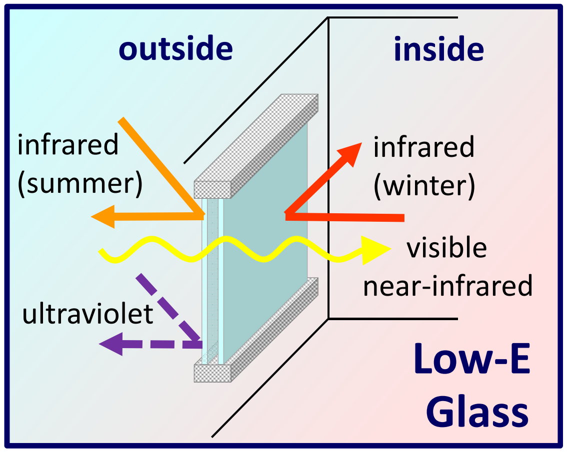
Physical Principle of TCOs



Principles of Electronic Materials and Devices, Third Ed., S.O. Kasap (© McGraw-Hill, 2005

Solar wavelengths λ over the range λ ~ 350 - 1000 nm are transmitted. The free electrons reflect infrared light λ > 2000 nm

Low emissivity glass is coated with TCO layers

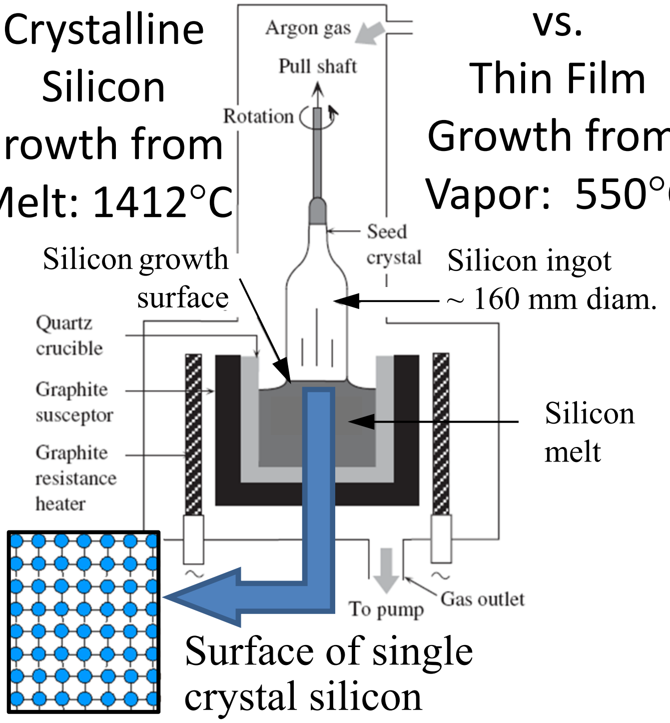


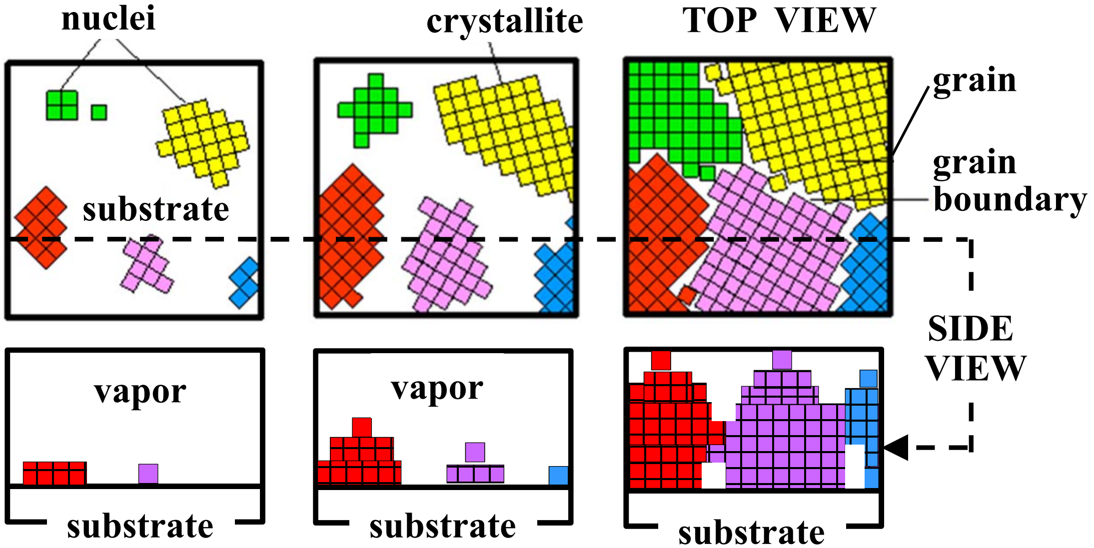
Materials Development: Thin Film Structure and Grain Boundaries

Crystalline Silicon Growth from Melt: 1412°C

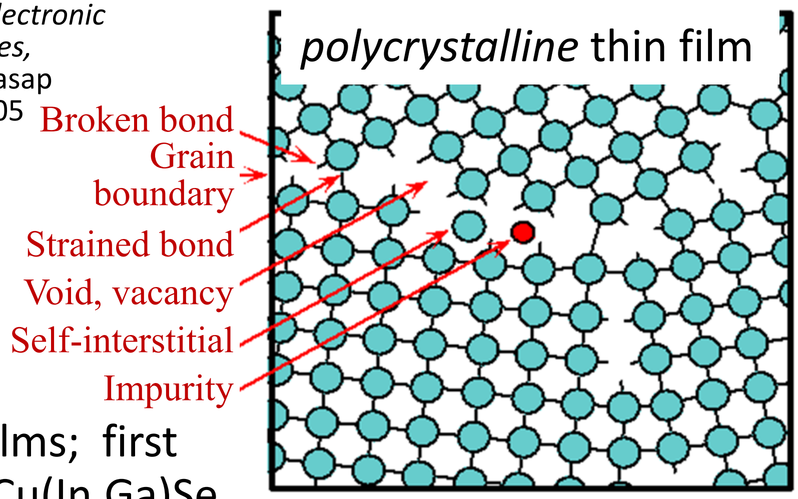
vs.

Thin Film Growth from Vapor: 550°C





From *Principles of Electronic Materials and Devices, Third Edition*, S.O. Kasap (© McGraw-Hill, 2005



Goal in thin film PV: mitigate the role of grain boundaries and associated structural defects:

CdTe: After deposition coat with aqueous $CdCl_2$ solution and anneal at ~ 400°C ⇒ grain growth

CIGS: Diffuse Na and K atoms into the growing films; first grow $(In,Ga)_2Se_3$, then diffuse Cu into it to form $Cu(In,Ga)Se_2$.

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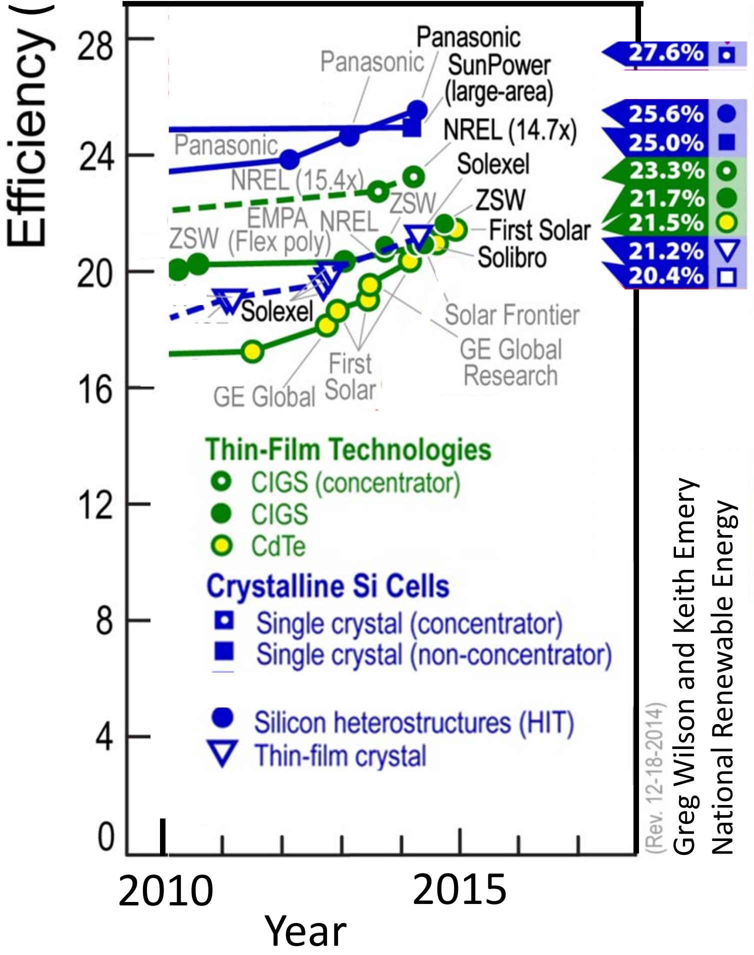
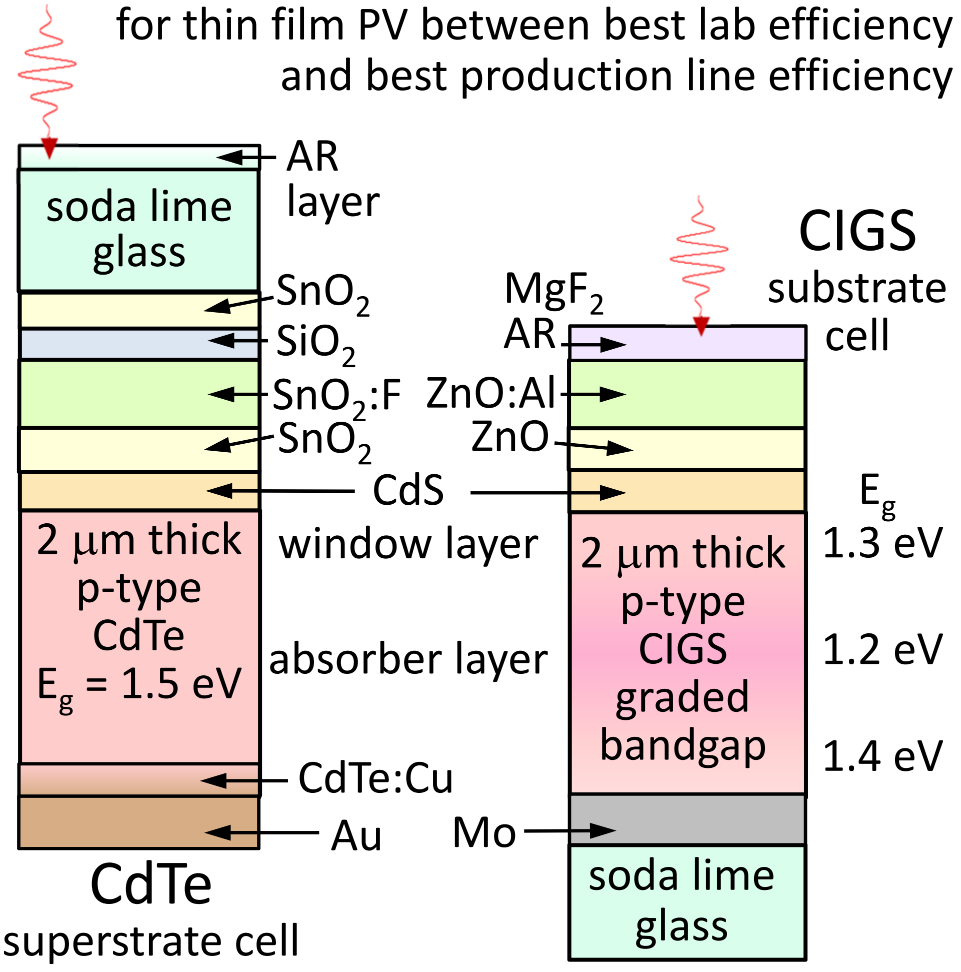
Thin Film PV in the Laboratory: Approaching the Laboratory Performance of Single Crystal Silicon PV

Record Performance Lab Cells



(Rev. 12-18-2014)
Greg Wilson and Keith Emery
National Renewable Energy

Compared to single crystal Si PV, a larger gap exists for thin film PV between best lab efficiency and best production line efficiency



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Controlling Module Fabrication: Achieving the Best Lab Efficiencies on the Production Line

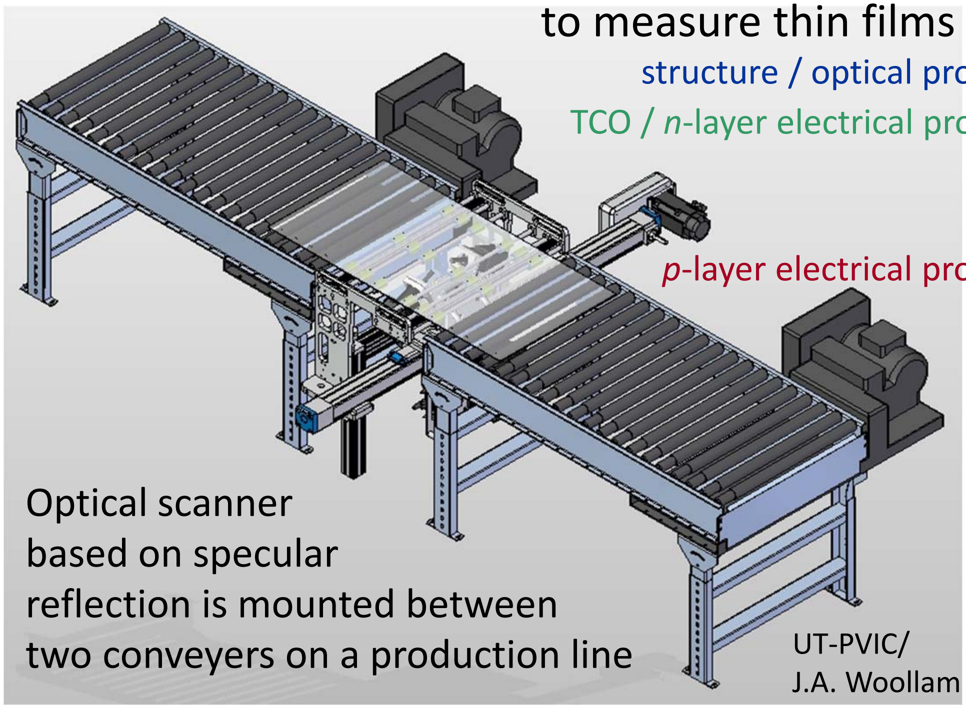
- Rapid optimization and troubleshooting of line
- Enables tracking of fabrication steps for early detection of process deviations before failure
- Potential of on-line control: “adaptive manufacturing”

Non-invasive tools utilize electromagnetic waves to measure thin films on the PV panel

structure / optical properties: 0.2 – 2 μm →

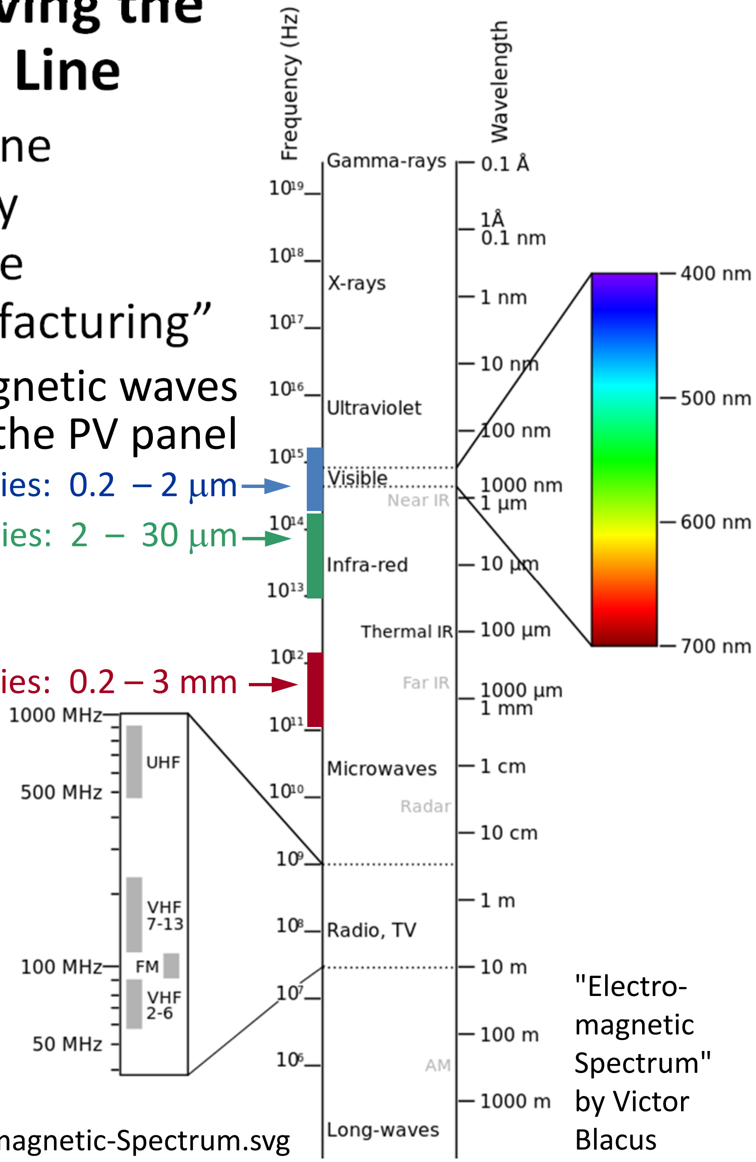
TCO / *n*-layer electrical properties: 2 – 30 μm →

p-layer electrical properties: 0.2 – 3 mm →



Optical scanner based on specular reflection is mounted between two conveyers on a production line

UT-PVIC/
J.A. Woollam Co.



"Electro-magnetic Spectrum" by Victor Blacus

http://commons.wikimedia.org/wiki/File:Electromagnetic-Spectrum.svg

Outline of Topics

- **Photovoltaics (PV): Motivation, status, and goals**
- **The first generation (Si) solar cell: Semiconductor physics and operation**
- **Second generation or thin film PV:**
  Advantages over 1st generation and its challenges
- **Polarized light and its applications:**
  Studies of second generation PV **(15 slides: 30-44)**
  - **Polarized electromagnetic waves: Stokes vectors and Mueller matrices**
  - **Polarized light studies of CdTe PV**
  - **Polarized light studies of $Cu(In,Ga)Se_2$ PV**

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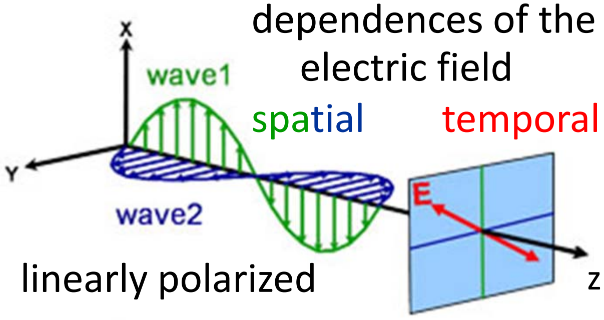
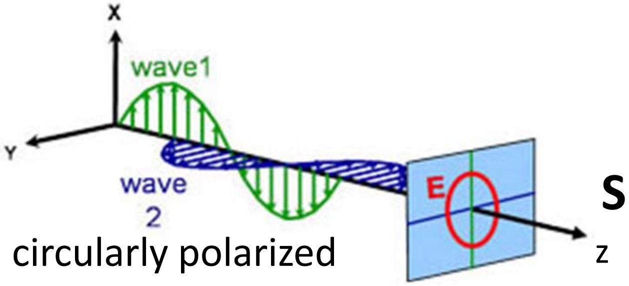
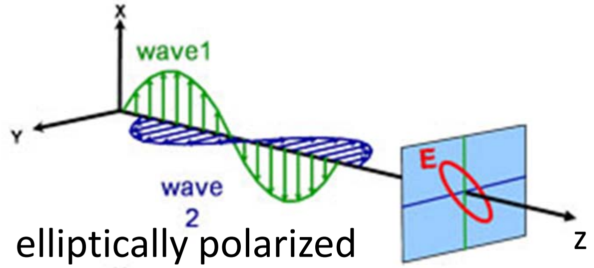
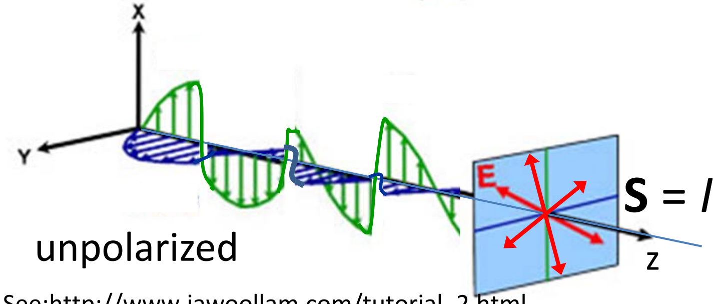
Electromagnetic Waves

Electromagntic waves consist of orthogonal electric and magnetic field vectors that are in turn orthogonal to the ray vector (along z).

Polarization describes the spatial and temporal dependences of the electric field vector projected along x and y axes (waves 1 and 2).

The Stokes vector is a column of 4 numbers used to completely describe the polarization characteristic of the e-m wave.
It includes information on:

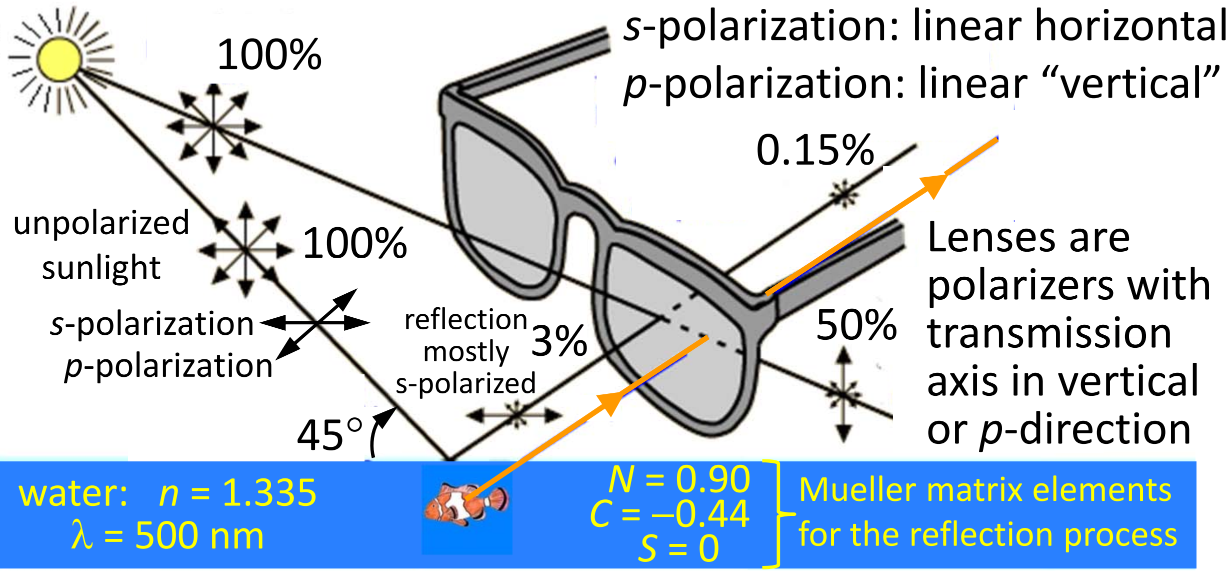
(1) irradiance [power/area] (I_0)
(2) tilt angle of ellipse (Q)
(3) ellipticity angle of ellipse (χ)
(4) degree of polarization (P).

dependences of the electric field spatial temporal	Stokes vectors	degree of polarization
 linearly polarized	$\mathbf{S} = I_0 \begin{pmatrix} 1 \\ 0 \\ 1 \\ 0 \end{pmatrix}$	$P = 1$
 circularly polarized	$\mathbf{S} = I_0 \begin{pmatrix} 1 \\ 0 \\ 0 \\ \pm 1 \end{pmatrix}$	$P = 1$
 elliptically polarized	$\mathbf{S} = I_0 \begin{pmatrix} 1 \\ \cos 2Q \cos 2\chi \\ \sin 2Q \cos 2\chi \\ \sin 2\chi \end{pmatrix}$	$P = 1$
 unpolarized	$\mathbf{S} = I_0 \begin{pmatrix} 1 \\ 0 \\ 0 \\ 0 \end{pmatrix}$	$P = 0$

See:http://www.jawoollam.com/tutorial_2.html

Polarizing Sunglasses

Reflection of light from a surface at oblique incidence leads to a change in the polarization state of the light as described by the Stokes vector.
The reflection and transmission processes can be described by Mueller matrices.



s-polarization: linear horizontal
p-polarization: linear “vertical”

Lenses are polarizers with transmission axis in vertical or *p*-direction

water: $n = 1.335$
$\lambda = 500$ nm

$N = 0.90$
$C = -0.44$
$S = 0$

Mueller matrix elements for the reflection process

Stokes vector for light at the eye | Mueller matrix for sunglass lens | Mueller matrix for water reflection | Stokes vector for unpolarized sunlight

With sunglasses

$$I_0R\begin{pmatrix} \boxed{½(1-N)} \\ ½(1-N) \\ 0 \\ 0 \end{pmatrix} = I_0\,R\begin{pmatrix} ½ & ½ & 0 & 0 \\ ½ & ½ & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix}\begin{pmatrix} 1 & -N & 0 & 0 \\ -N & 1 & 0 & 0 \\ 0 & 0 & C & S \\ 0 & 0 & -S & C \end{pmatrix}\begin{pmatrix} 1 \\ 0 \\ 0 \\ 0 \end{pmatrix}$$

Reduction of Glare:

% reduction

$$= 100\%\left(1 - \frac{½\,(1-N)}{1}\right)$$

= 95%

Without sunglasses

$$I_0R\begin{pmatrix} \boxed{1} \\ -N \\ 0 \\ 0 \end{pmatrix} = I_0\,R \quad \times \quad \begin{pmatrix} 1 & -N & 0 & 0 \\ -N & 1 & 0 & 0 \\ 0 & 0 & C & S \\ 0 & 0 & -S & C \end{pmatrix}\begin{pmatrix} 1 \\ 0 \\ 0 \\ 0 \end{pmatrix}$$

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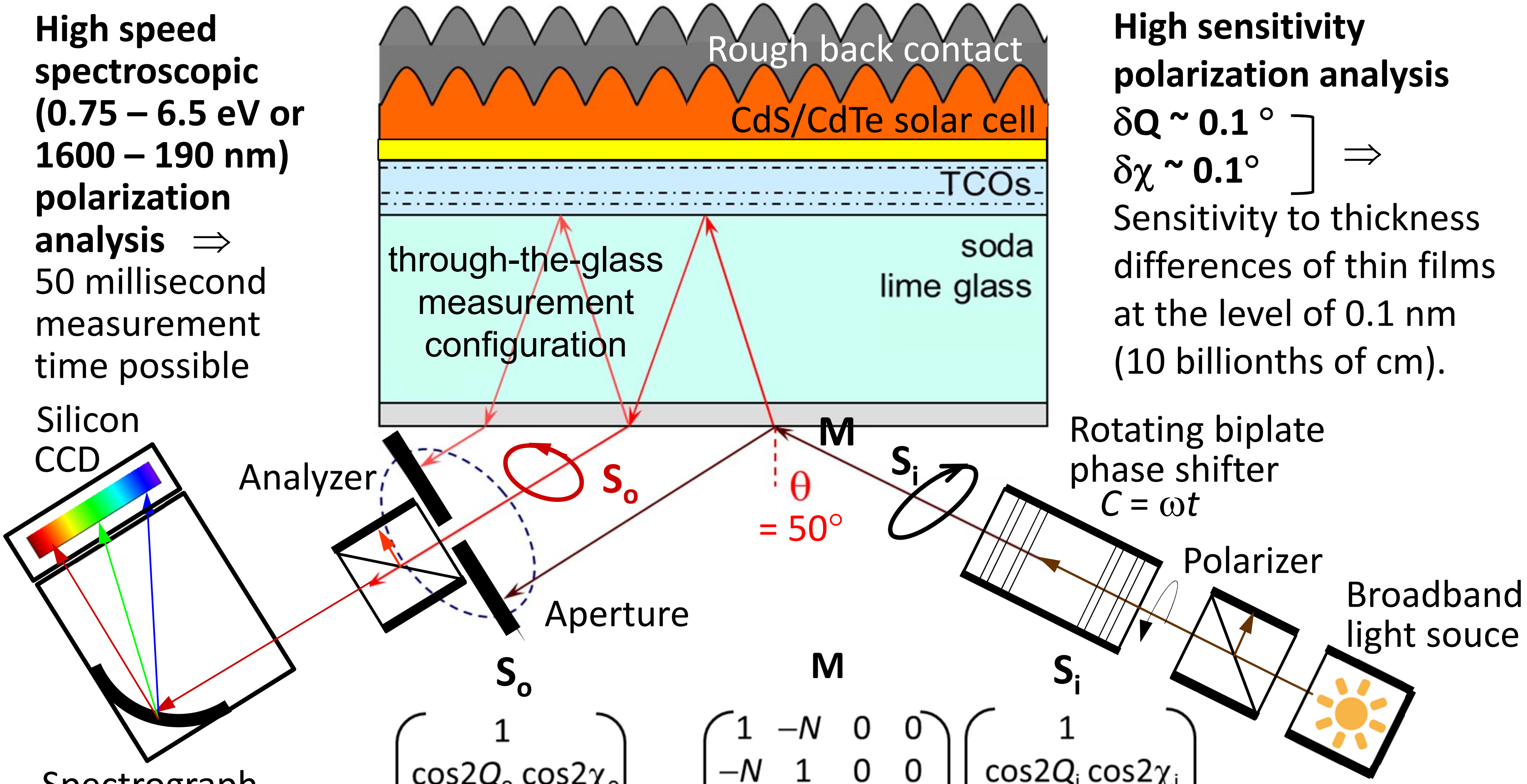
“Spectroscopic Ellipsometry” Measurement of a CdTe Solar Cell

High speed spectroscopic (0.75 – 6.5 eV or 1600 – 190 nm) polarization analysis ⇒ 50 millisecond measurement time possible

High sensitivity polarization analysis
$\delta Q \sim 0.1°$
$\delta\chi \sim 0.1°$ ⇒
Sensitivity to thickness differences of thin films at the level of 0.1 nm (10 billionths of cm).



$$\begin{array}{ccccc} & \mathbf{S_o} & & \mathbf{M} & \mathbf{S_i} \\ \mathbf{S_o} = I_o & \begin{pmatrix} 1 \\ \cos 2Q_o \cos 2\chi_o \\ \sin 2Q_o \cos 2\chi_o \\ \sin 2\chi_o \end{pmatrix} & = I_i & \begin{pmatrix} 1 & -N & 0 & 0 \\ -N & 1 & 0 & 0 \\ 0 & 0 & C & S \\ 0 & 0 & -S & C \end{pmatrix} & \begin{pmatrix} 1 \\ \cos 2Q_i \cos 2\chi_i \\ \sin 2Q_i \cos 2\chi_i \\ \sin 2\chi_i \end{pmatrix} \end{array}$$

Stokes -Mueller analysis

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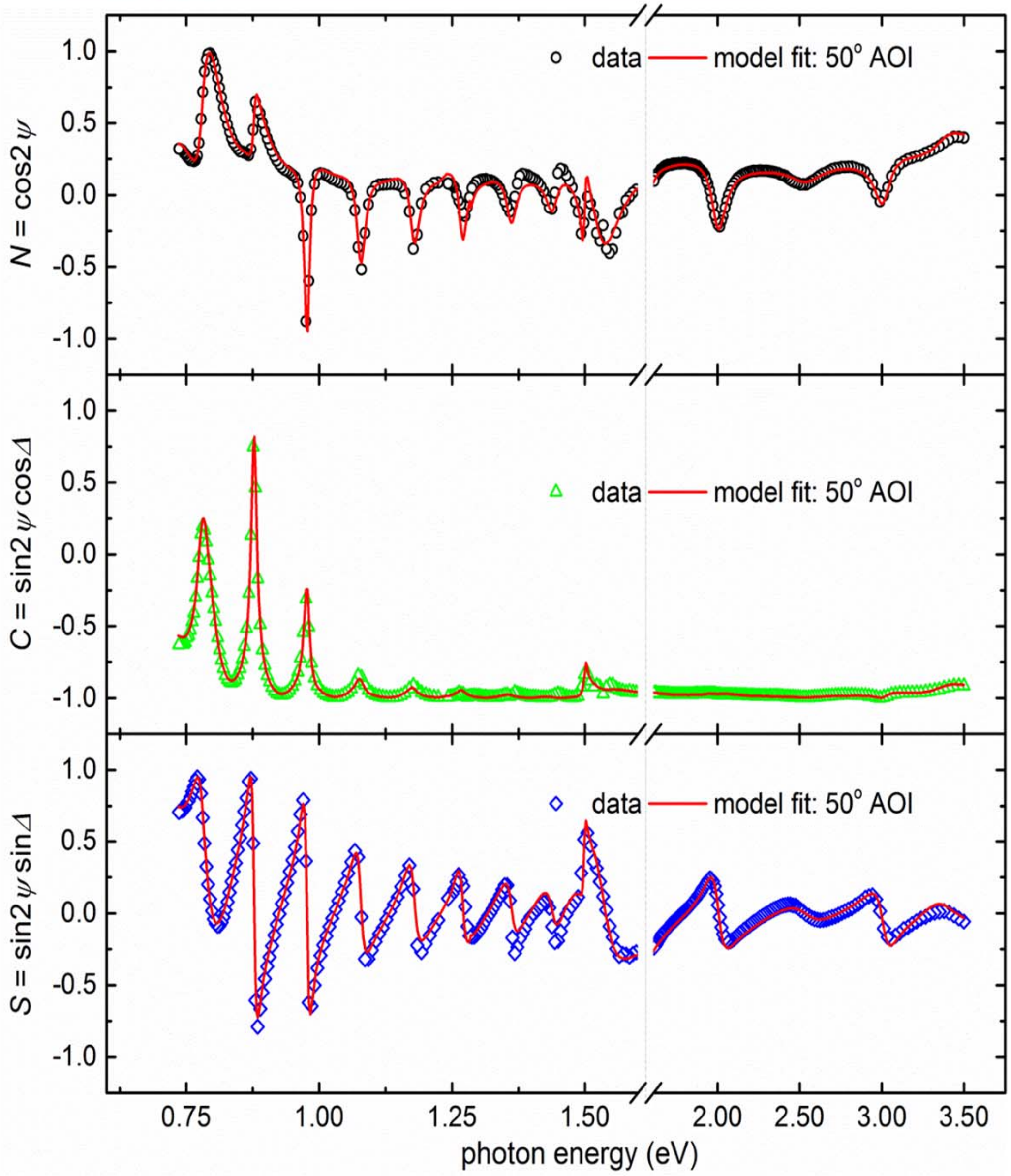
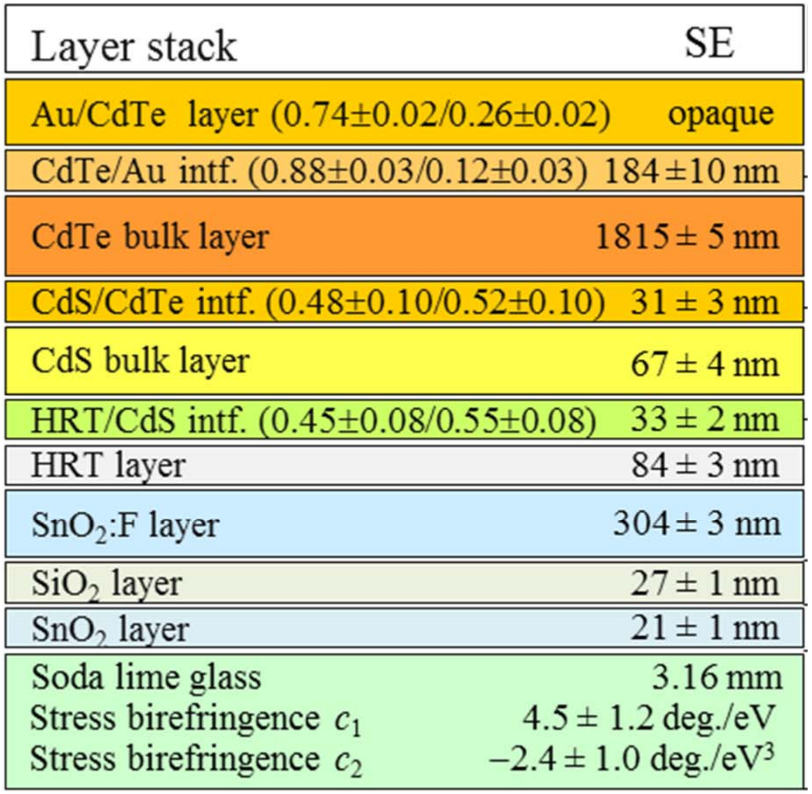


Mueller Matrix Analysis

- 6 bulk and 3 interface thicknesses
- 4 layer compositions
- 7 optical property parameters
- 2 parameters describing glass stress



Layer stack	SE
Au/CdTe layer (0.74±0.02/0.26±0.02)	opaque
CdTe/Au intf. (0.88±0.03/0.12±0.03)	184±10 nm
CdTe bulk layer	1815± 5 nm
CdS/CdTe intf. (0.48±0.10/0.52±0.10)	31 ± 3 nm
CdS bulk layer	67 ± 4 nm
HRT/CdS intf. (0.45±0.08/0.55±0.08)	33 ± 2 nm
HRT layer	84 ± 3 nm
SnO$_2$:F layer	304 ± 3 nm
SiO$_2$ layer	27 ± 1 nm
SnO$_2$ layer	21 ± 1 nm
Soda lime glass Stress birefringence c_1 Stress birefringence c_2	3.16 mm 4.5 ± 1.2 deg./eV -2.4 ± 1.0 deg./eV^3

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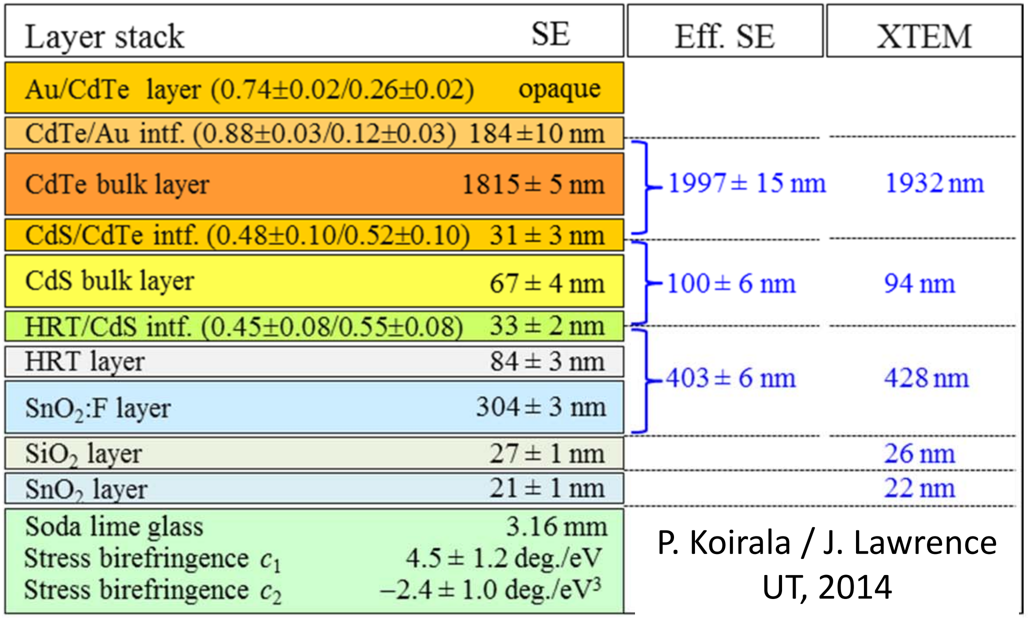
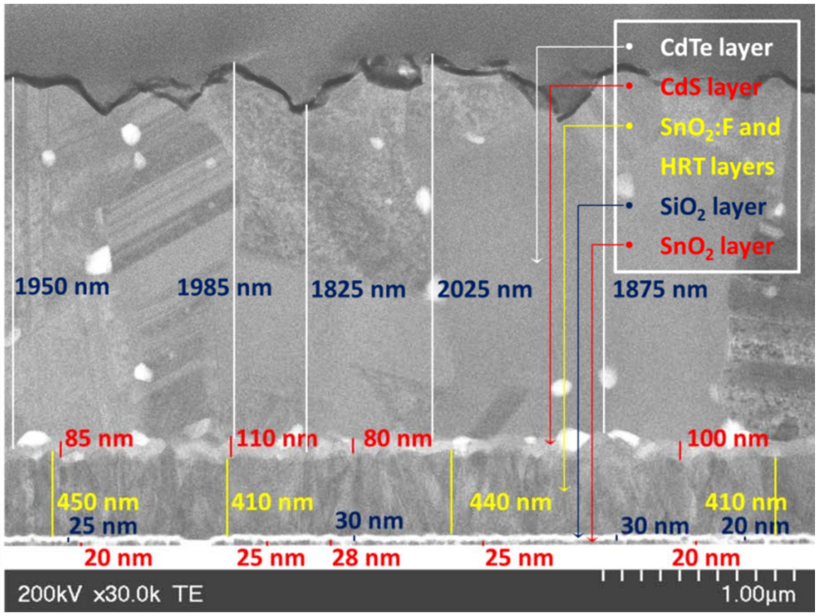
Key TCO / CdTe Optical Parameters and Verification with Microscopy

Layer	Optical parameters from SE analysis		Physical/electrical properties from optical parameters	
CdTe	Bandgap, E_0 (eV)	Broadening, Γ_0 (eV)	Compressive stress (MPa)	Mean free path (nm)
	1.496 ± 0.004	0.044 ± 0.002	70	320
SnO_2:F	Resistivity, ρ (10^{-4} Ω-cm)	Broadening, Γ_D (eV)	Sheet resistance (Ω/sq)	Mean free path (nm)
	3.5 ± 0.3	0.093 ± 0.007	11.5	5.2



Layer stack	SE	Eff. SE	XTEM
Au/CdTe layer (0.74±0.02/0.26±0.02)	opaque		
CdTe/Au intf. (0.88±0.03/0.12±0.03)	184±10 nm		
CdTe bulk layer	1815± 5 nm	1997± 15 nm	1932 nm
CdS/CdTe intf. (0.48±0.10/0.52±0.10)	31 ± 3 nm		
CdS bulk layer	67 ± 4 nm	100± 6 nm	94 nm
HRT/CdS intf. (0.45±0.08/0.55±0.08)	33 ± 2 nm		
HRT layer	84 ± 3 nm		
SnO_2:F layer	304± 3 nm	403± 6 nm	428 nm
SiO_2 layer	27 ± 1 nm		26 nm
SnO_2 layer	21 ± 1 nm		22 nm
Soda lime glass Stress birefringence c_1 Stress birefringence c_2	3.16 mm 4.5 ± 1.2 deg./eV −2.4 ± 1.0 deg./eV^3		

P. Koirala / J. Lawrence
UT, 2014



Prediction of Peformance from Optical Model

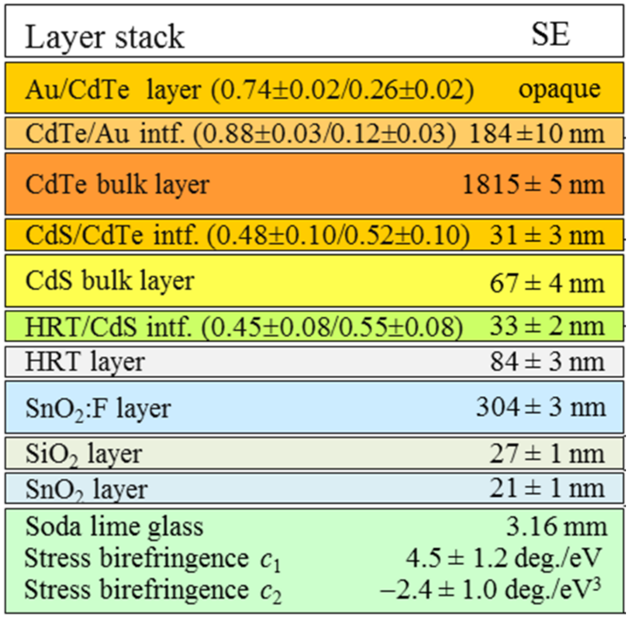
$$EQE(\lambda) = \frac{\text{Electrons collected from cell area / time}}{\text{Photons incident on cell area / time}}$$

$$J_{SC} = \sum_{\lambda} \Phi_{AM1.5G} \times EQE(\lambda)\, \Delta\lambda$$

Short circuit current density

AM 1.5 solar spectral flux

- 6 bulk and 3 interface thicknesses
- 4 layer compositions
- 7 optical property parameters
- 2 parameters describing glass stress



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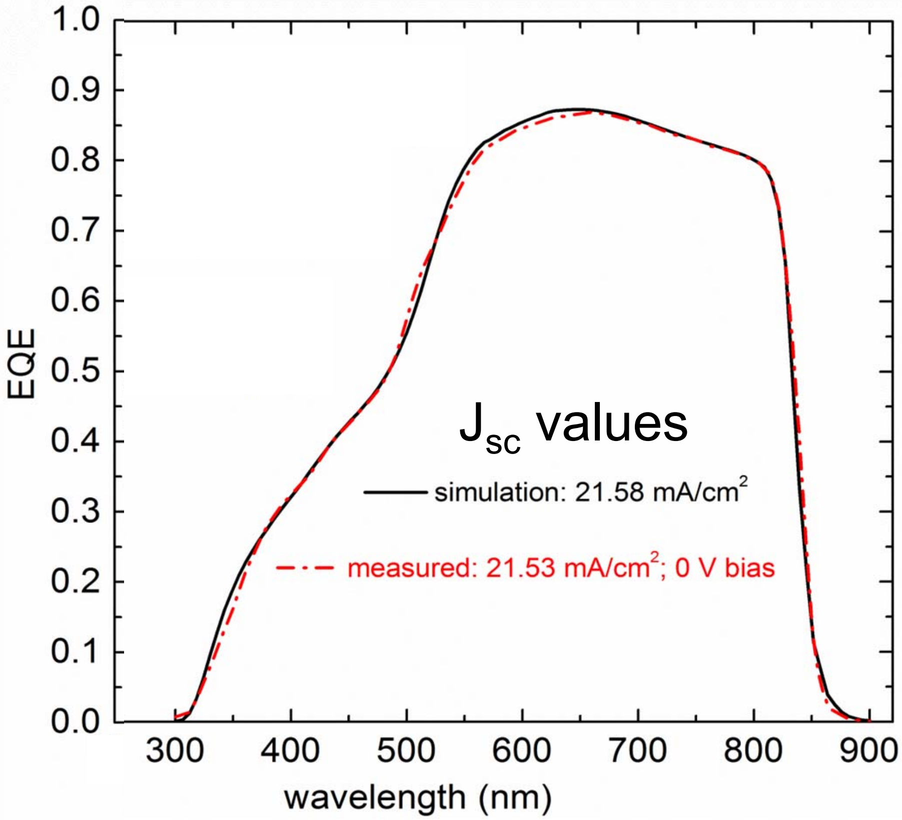
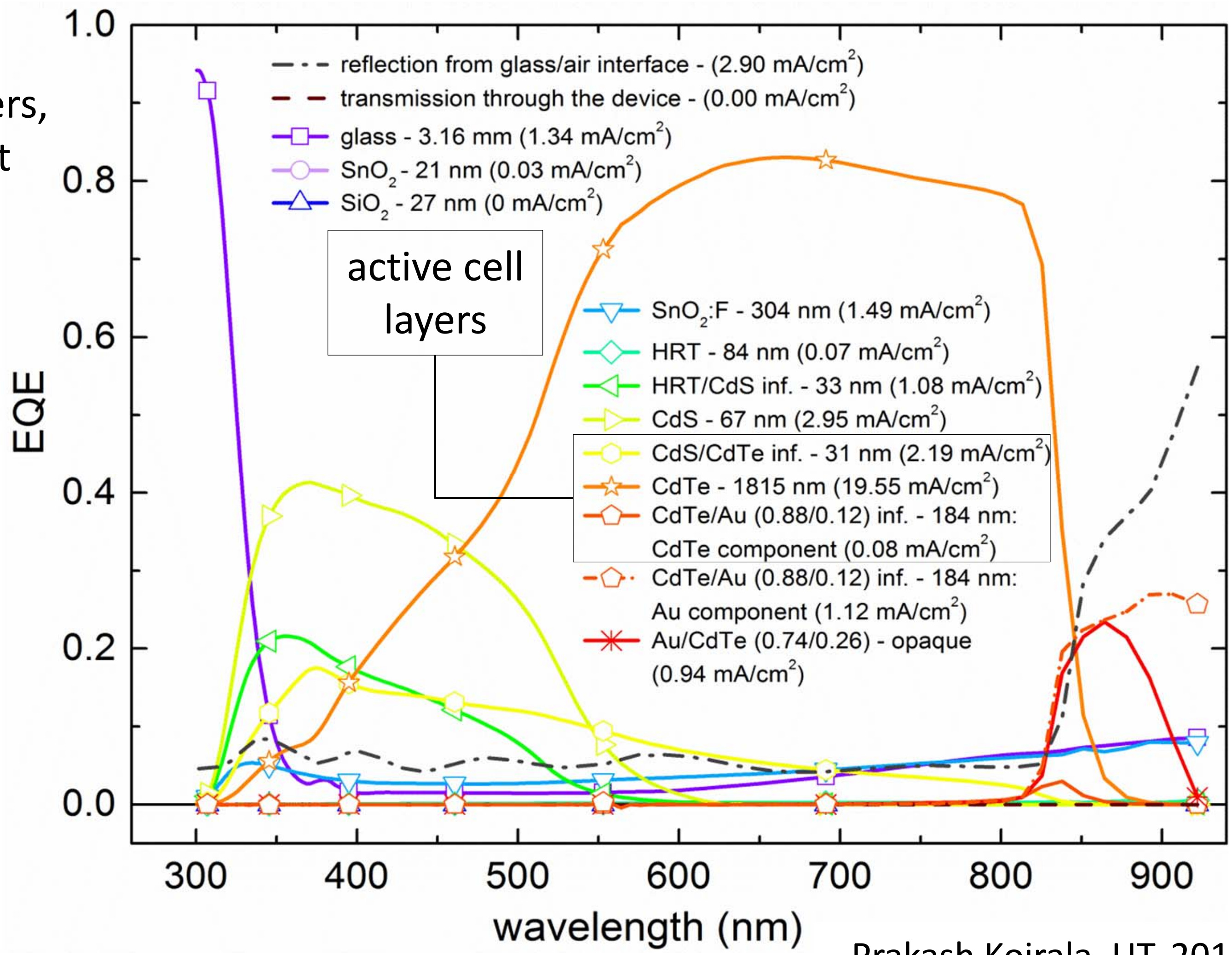


Prediction of Losses from Optical Model

Useful current is collected by the active solar cell layers, i.e. those layers that include CdTe:
J_{sc} = 21.58 mA/cm^2

The largest losses are due to ...

- absorption in CdS layer: 2.95 mA/cm^2
- top surface reflection: 2.90 mA/cm^2
- absorption in SnO$_2$:F layer: 1.49 mA/cm^2



active cell layers

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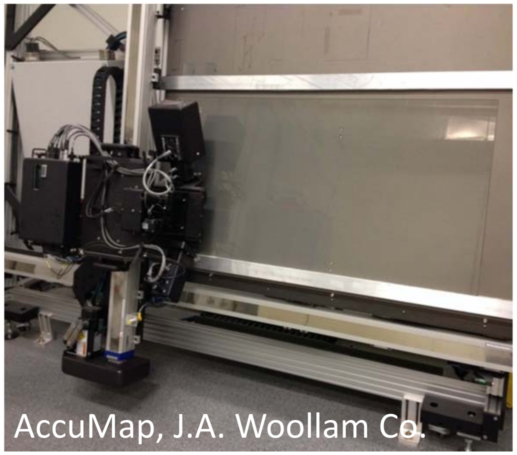
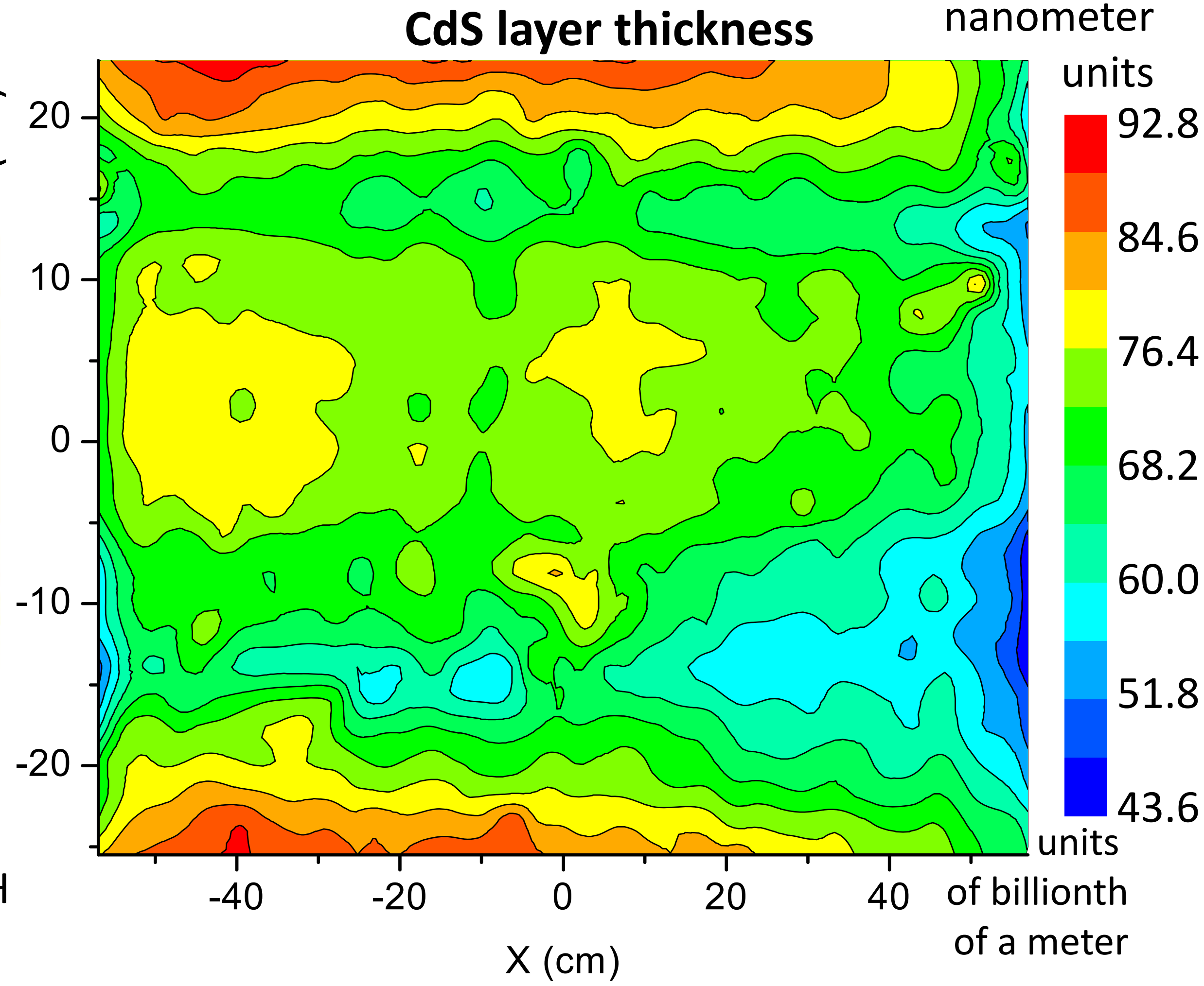
Scaling Up the Spectroscopic Ellipsometry Measurement to PV Module Size: 60 cm x 120 cm: Fast Measurement Desired !

Map of CdS layer
thickness, which
is the major factor
in controlling losses


AccuMap, J.A. Woollam Co.

Non-optimized solar
panel courtesy of
Kenneth Kormanyos
Calyxo USA, Perrysburg OH
J. Chen, J. Li; UT 2013



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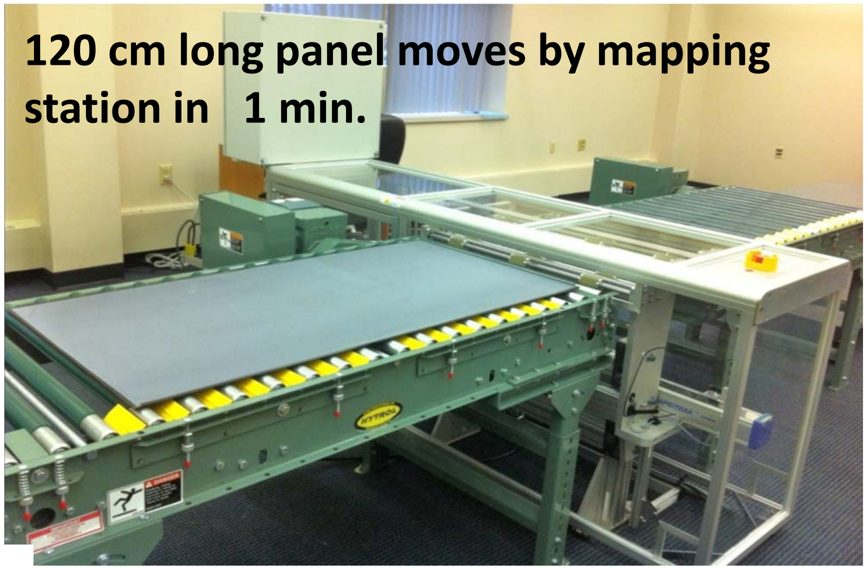
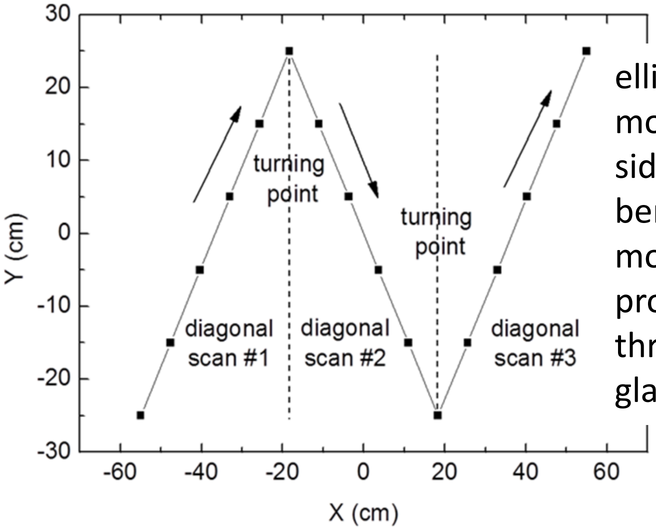
Performing the Spectroscopic Ellipsometry Measurement In-Line on 60 cm x 120 cm PV Module: Fast Measurement a Necessity !

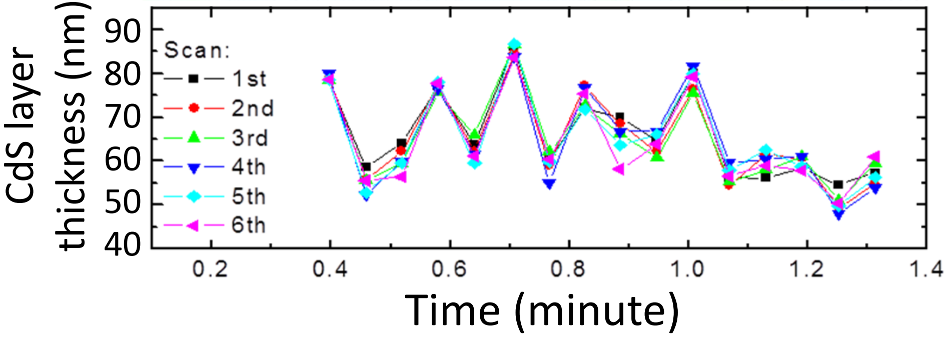


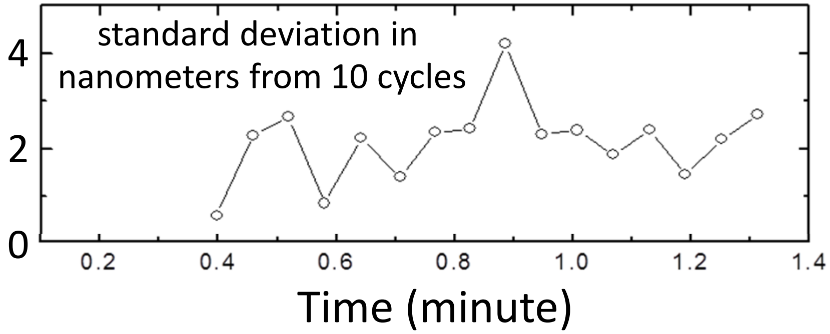
120 cm long panel moves by mapping station in 1 min.



ellipsometer moves side-to-side beneath moving panel, probing through the glass

Standard deviation < 5 nm ⇒ success !





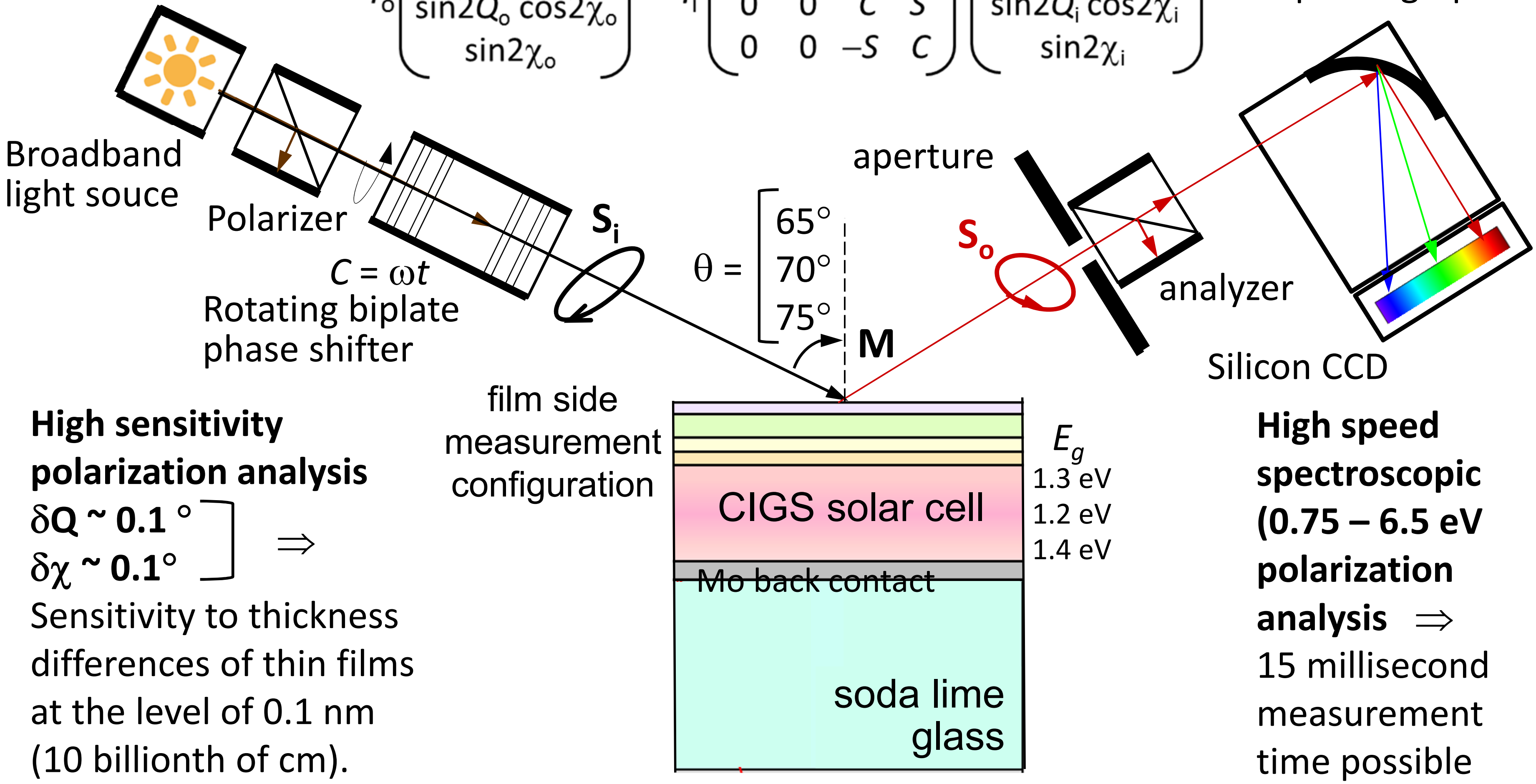
Non-optimized solar panel courtesy of Kenneth Kormanyos Calyxo USA, Perrysburg OH; J. Chen, J. Li; UT 2013

Chen, J.; Koirala, P.; Salupo, C.; Collins, R. W.; Marsillac, S.; Kormanyos, K. R.; Johs, B. D.; Hale, J. S.; and Pfeiffer, G. L., *Conference Record of the 38th IEEE Photovoltaic Specialists Conference (PVSC)*, Austin, TX, June 3-8, 2012, (IEEE, New York, 2012) Article Number: 000377.

“Spectroscopic Ellipsometry” Measurement of a CIGS Solar Cell

Stokes -Mueller analysis

$$\overset{\mathbf{S_o}}{I_o\begin{pmatrix}1\\ \cos 2Q_o\cos 2\chi_o\\ \sin 2Q_o\cos 2\chi_o\\ \sin 2\chi_o\end{pmatrix}} = I_i\overset{\mathbf{M}}{\begin{pmatrix}1 & -N & 0 & 0\\ -N & 1 & 0 & 0\\ 0 & 0 & C & S\\ 0 & 0 & -S & C\end{pmatrix}}\overset{\mathbf{S_i}}{\begin{pmatrix}1\\ \cos 2Q_i\cos 2\chi_i\\ \sin 2Q_i\cos 2\chi_i\\ \sin 2\chi_i\end{pmatrix}}$$



High sensitivity polarization analysis

δQ ~ 0.1 °
δχ ~ 0.1° ⇒

Sensitivity to thickness differences of thin films at the level of 0.1 nm (10 billionth of cm).

High speed spectroscopic (0.75 – 6.5 eV polarization analysis ⇒

15 millisecond measurement time possible

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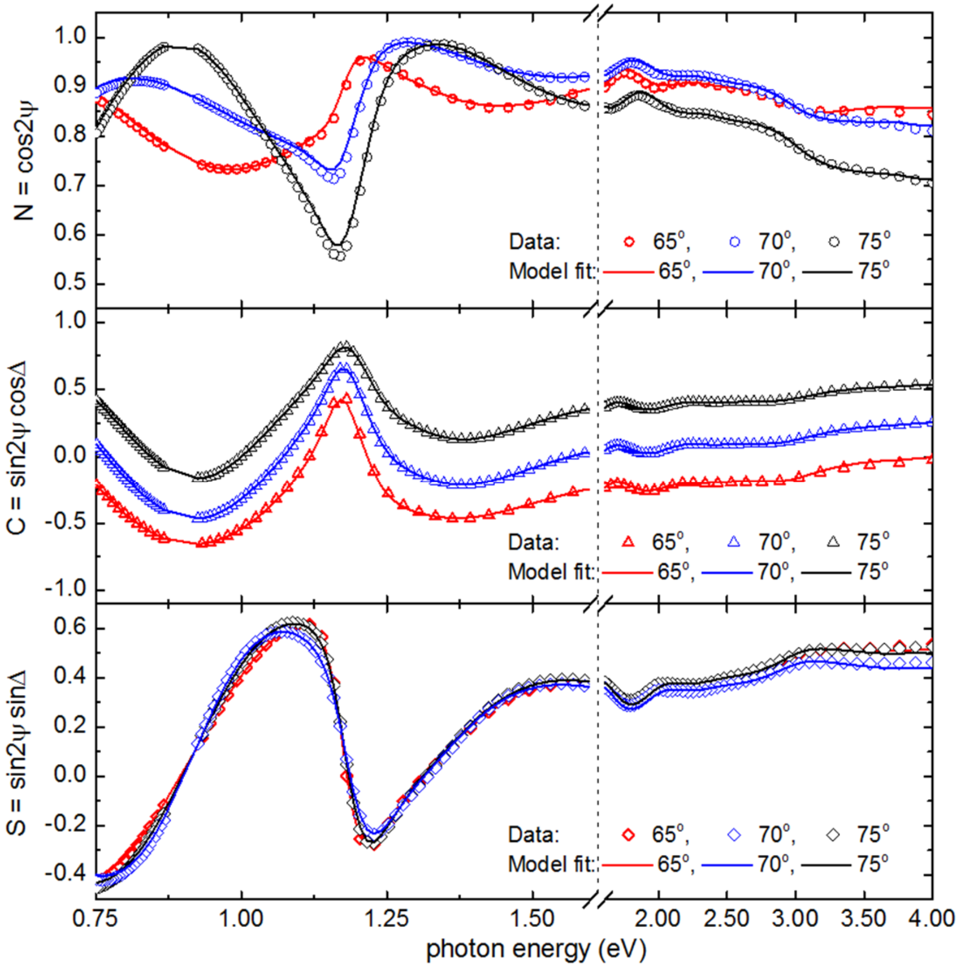
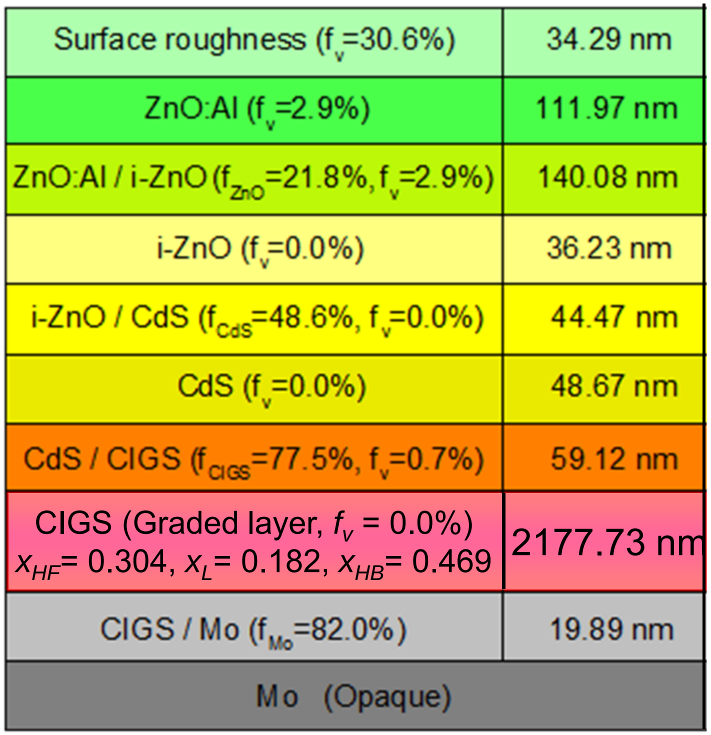
Mueller Matrix Analysis of CIGS Cell at Multiple Angles of Incidence



- 4 bulk and 5 interface thicknesses
- 7 interface compositions
- 3 Ga compositions and
- 1 thickness describing the CIGS composition profile



Surface roughness (f_v=30.6%)	34.29 nm
ZnO:Al (f_v=2.9%)	111.97 nm
ZnO:Al / i-ZnO (f_{ZnO}=21.8%, f_v=2.9%)	140.08 nm
i-ZnO (f_v=0.0%)	36.23 nm
i-ZnO / CdS (f_{CdS}=48.6%, f_v=0.0%)	44.47 nm
CdS (f_v=0.0%)	48.67 nm
CdS / CIGS (f_{CIGS}=77.5%, f_v=0.7%)	59.12 nm
CIGS (Graded layer, f_v = 0.0%) x_{HF}= 0.304, x_L= 0.182, x_{HB}= 0.469	2177.73 nm
CIGS / Mo (f_{Mo}=82.0%)	19.89 nm
Mo (Opaque)	

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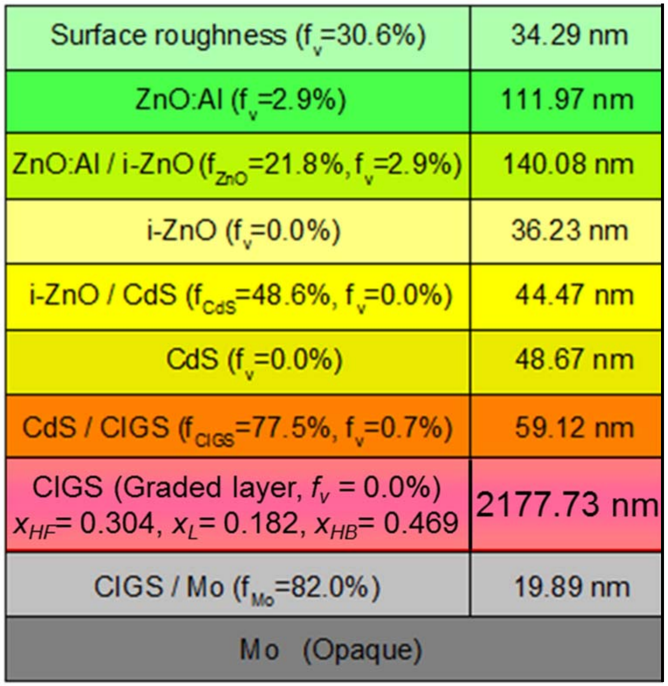
Verification of Optical Model with Destructive Chemical Depth Profiling Method (Secondary Ion Mass Spectrometry)



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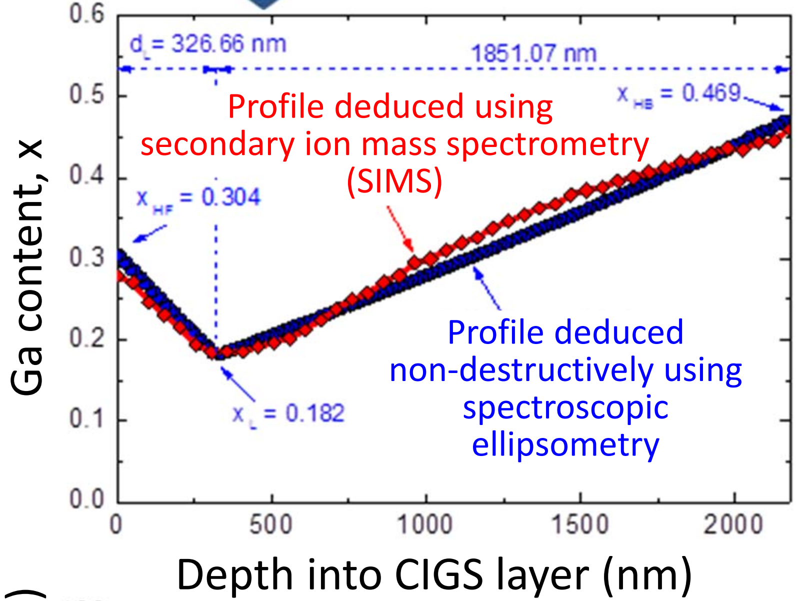
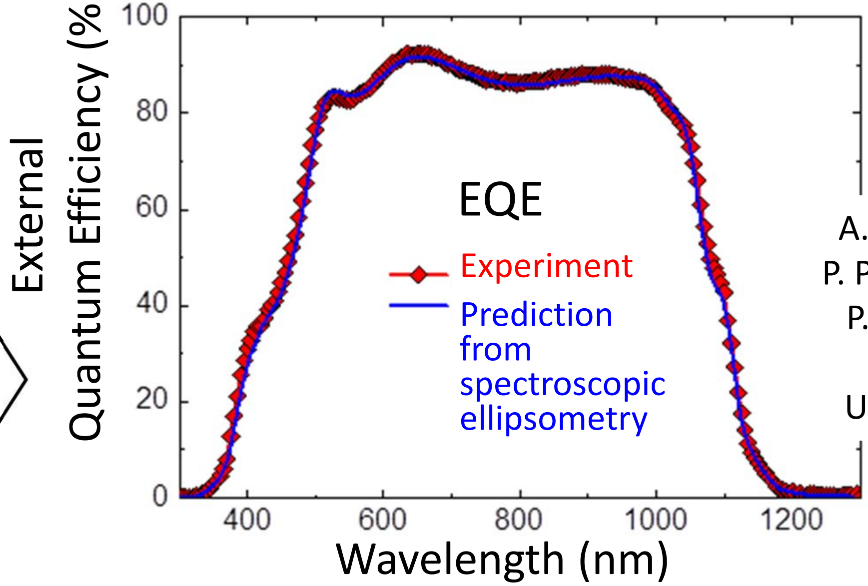
Prediction of Peformance from Optical Model





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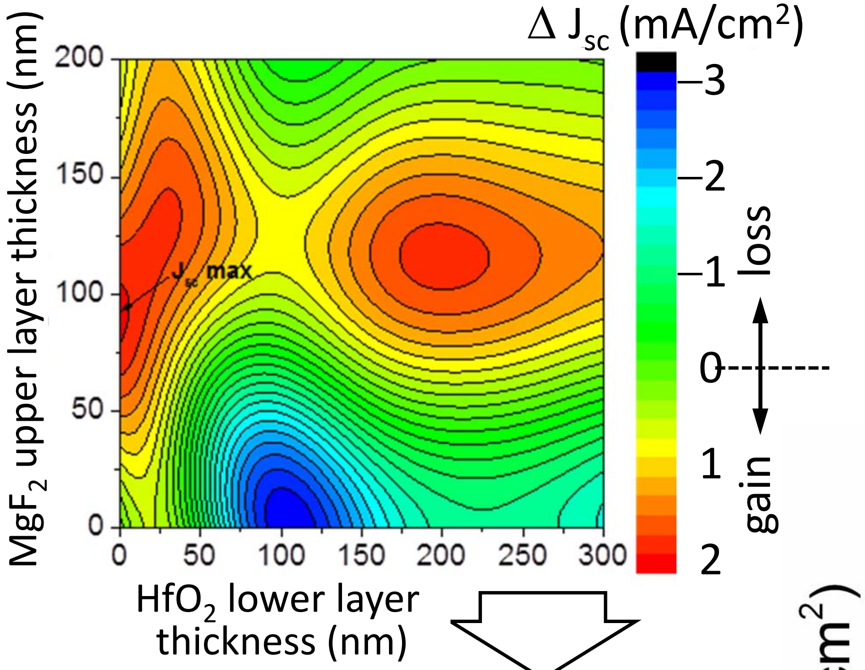
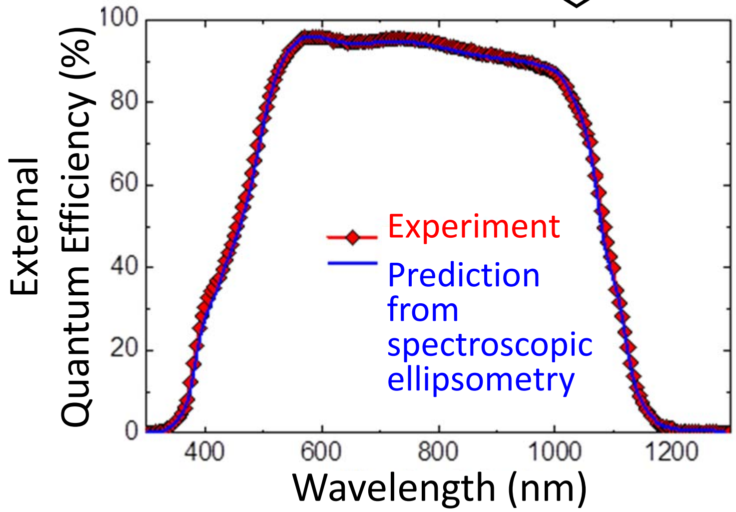
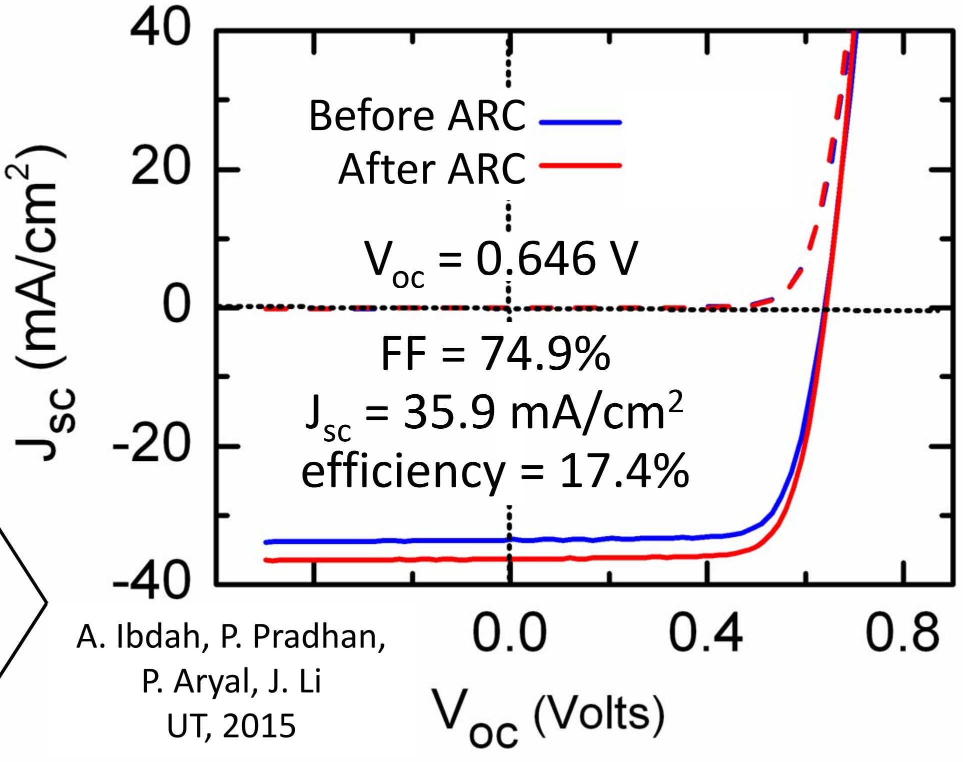
Feed-forward Optimization of Final Antireflection Coating (ARC) on CIGS Solar Cell

- Starting from the multilayer model add two layer ARC and simulate the J_{sc} gain
- Deposit optimum ARC, measure EQE and compare with optimized simulation



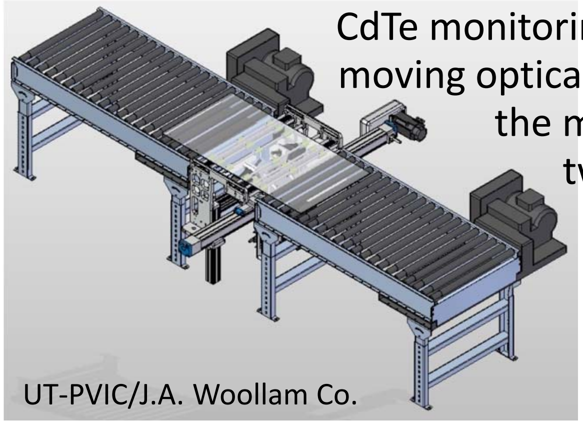




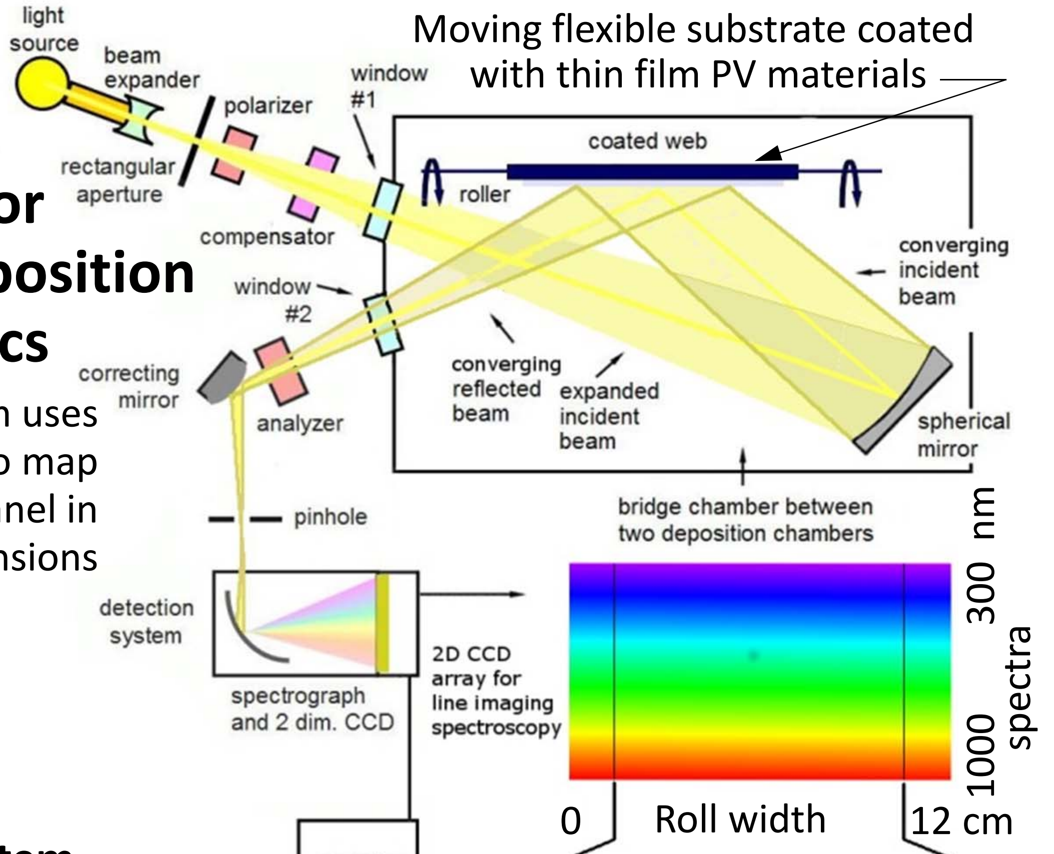
A. Ibdah, P. Pradhan,
P. Aryal, J. Li
UT, 2015

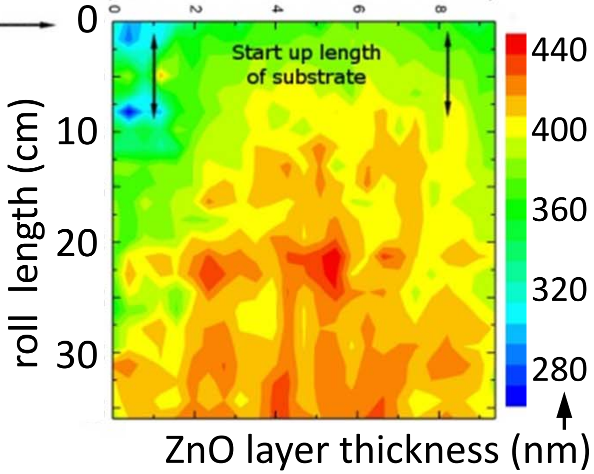
A. Shan, UT 2013; M. Fried *et al.*, Phys. Stat. Sol. (c) **5** (2008) 1081.

In-line Monitoring System for Feedback in Roll-to-Roll Deposition of CIGS Flexible Photovoltaics


UT-PVIC/J.A. Woollam Co.

CdTe monitoring system uses moving optical heads to map the moving panel in two dimensions


Moving flexible substrate coated with thin film PV materials



Characteristics of new monitoring system

- *No* moving optical components are required for mapping; optical system images the width of the flexible PV material as it moves roll-to-roll.
- A two-dimensional CCD array captures lines images along one dimension and spectroscopic data along the second dimension – simultaneously at high speed.
- Multiple angle of incidence measurements are performed over the surface.

Summary

- Second generation or thin film photovoltaics technology continues to provide advantages of lower cost and broader applications compared to first generation or crystalline Si technology.
- The current winning thin film technology, CdTe, is the product of Toledo area expertise emerging from the glass industry; low cost coated glass is the foundation of this success.
- Thin film PV poses scientific and technological challenges in translating recent high-efficiencies achieved for laboratory cells to modules fabricated on automated production lines.
- Advanced metrologies in which polarized electromagnetic waves are reflected from PV modules will serve as critical components of the production lines of the future.

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Dave Strickler, NSG-Pilkington

Support

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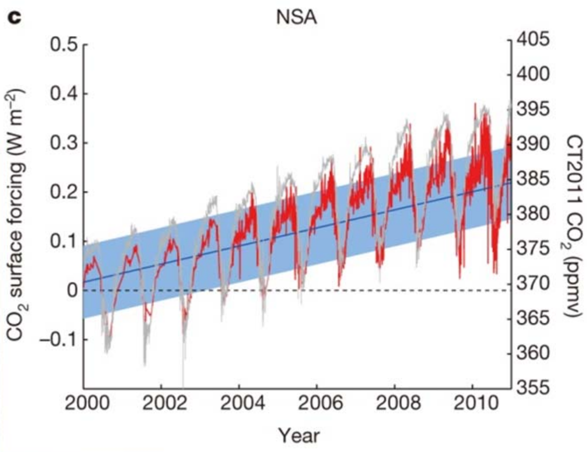
Ohio Development Services Agency
calyxo
Nippon Electric Glass Co., Ltd.
AIR FORCE RESEARCH LABORATORY

Thank you for your attention! Questions?

Grinnell Glacier ... melting, Glacier National Park, 2013



Radiative forcing is defined as a change in the difference between the solar irradiance incident on the Earth and the irradiance returning to space (in W/m^2).

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