6.152J Lecture: Solar (Photovoltaic) Cells

Jifeng Liu (jfliu01@mit.edu)

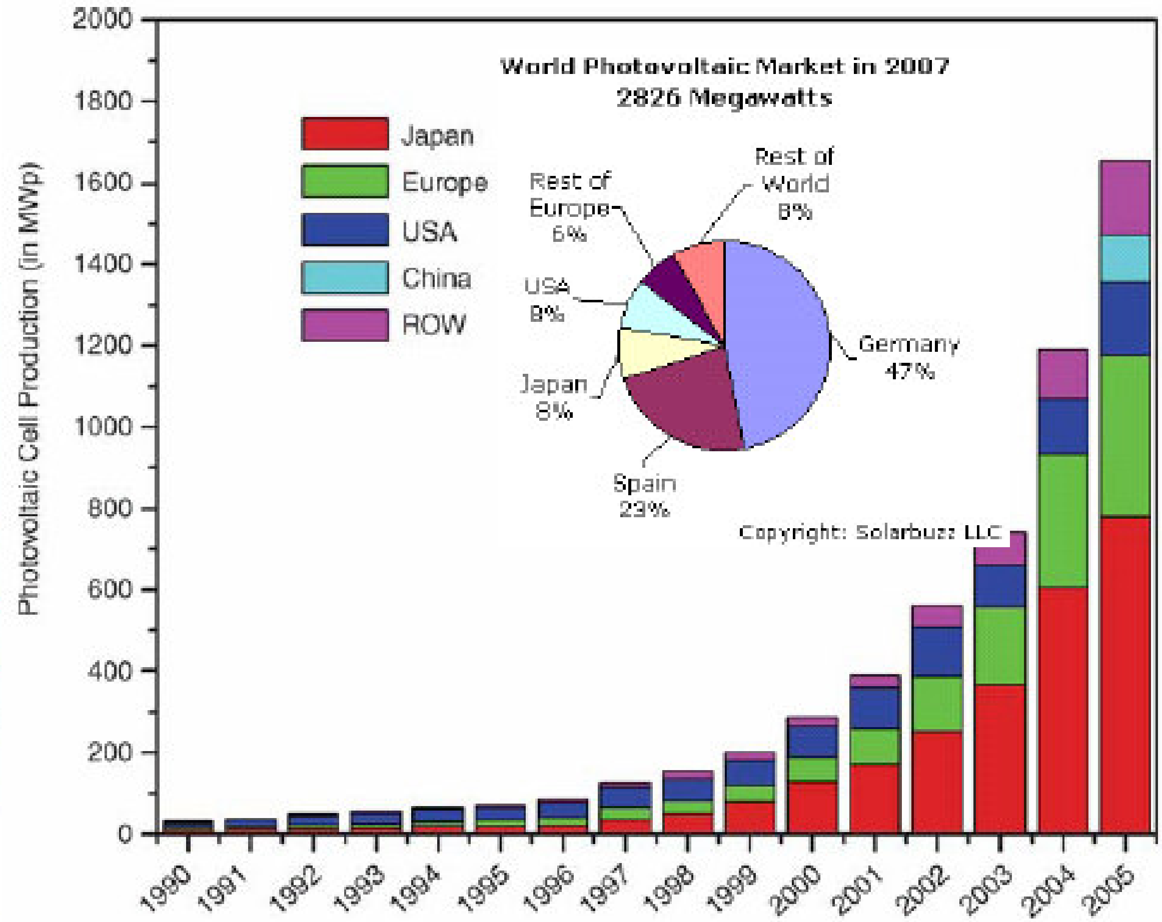
- Driving forces for Solar (PV) Cell R&D
- Solar Energy and Solar Spectrum
- Principle of Solar Cells
- Materials, structures and fabrication of solar cells
- New explorations in solar cell research

Environmental and Market Driving Forces for Solar Cells

Greenhouse gases (g/kWh of CO_2 equivalent)

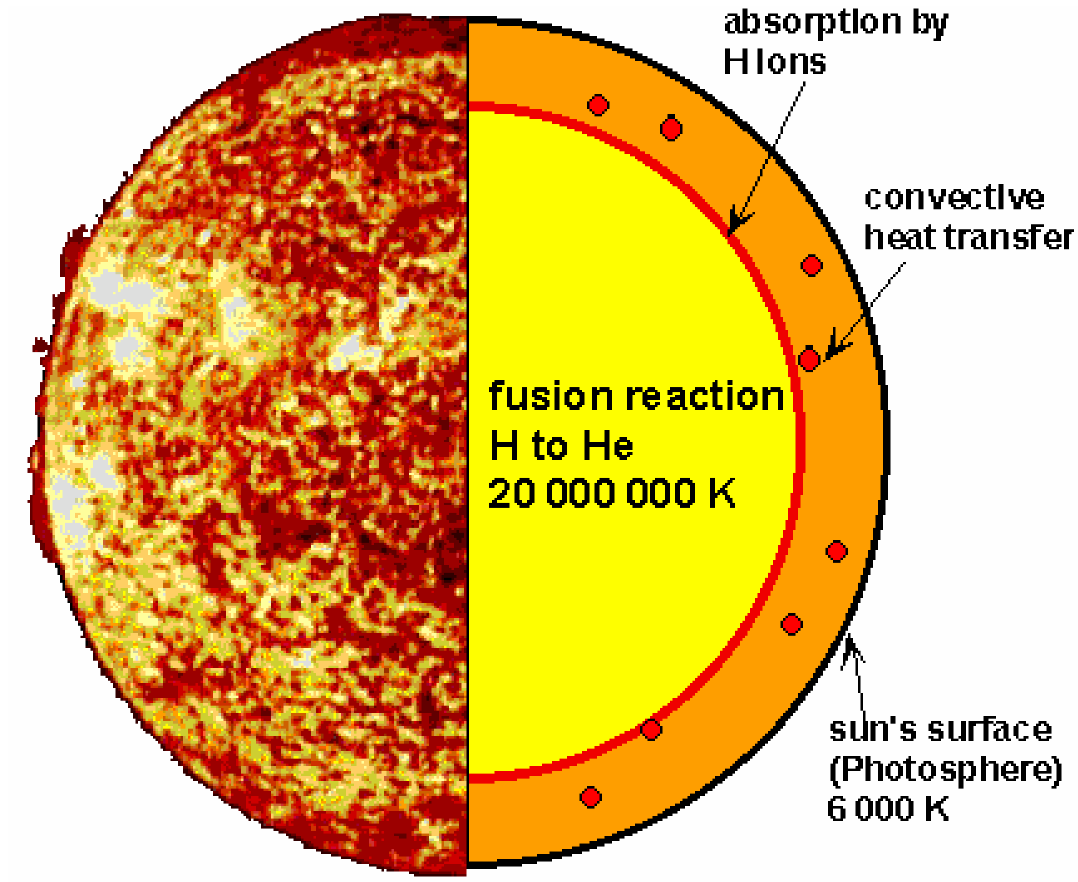
Coal	900
Oil	850
Natural Gas	400
Biomass	45
PV (Bulk Si)	37
PV (Thin Film)	18
Nuclear	24
Wind	11

V. Fthenakis & H.C. Kim, Brookhaven National Lab.; W. Beckman, University of Wisconsin-Madison.



- Solar cells are much more environmental friendly than the major energy sources we use currently.
- Solar cell reached 2.8 GW power in 2007 (vs. 1.8 GW in 2006)
- World's market for solar cells grew 62% in 2007 (50% in 2006). Revenue reached $17.2 billion. A 26% growth predicted for 2009 despite of recession.

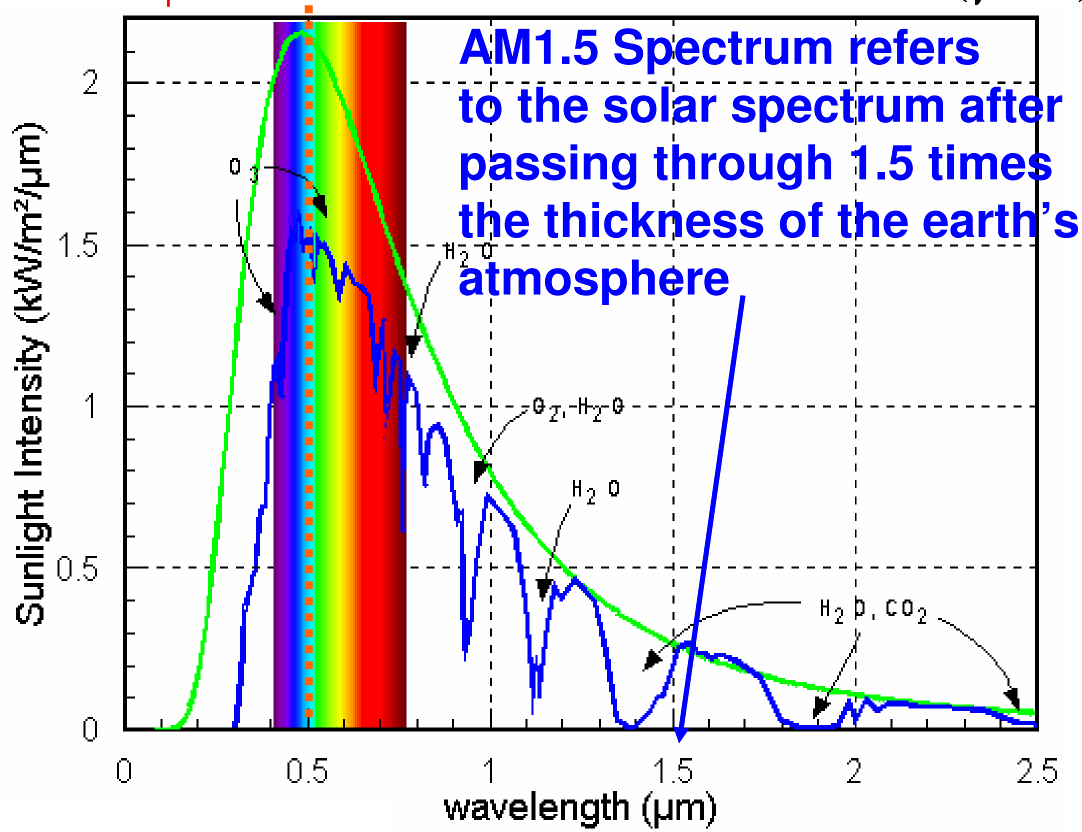
The Sun

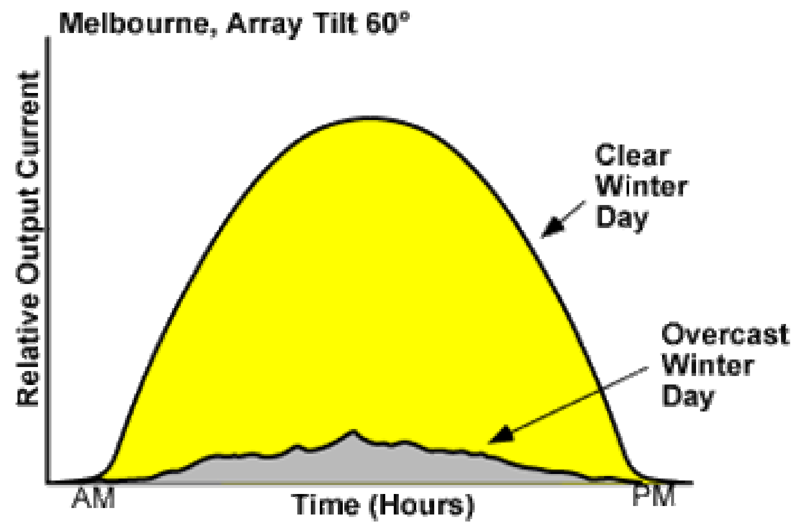


- Sun powered by nuclear fusion. Surface temperature~5800 K
- Will last another 5 billion years!

The Solar Spectrum

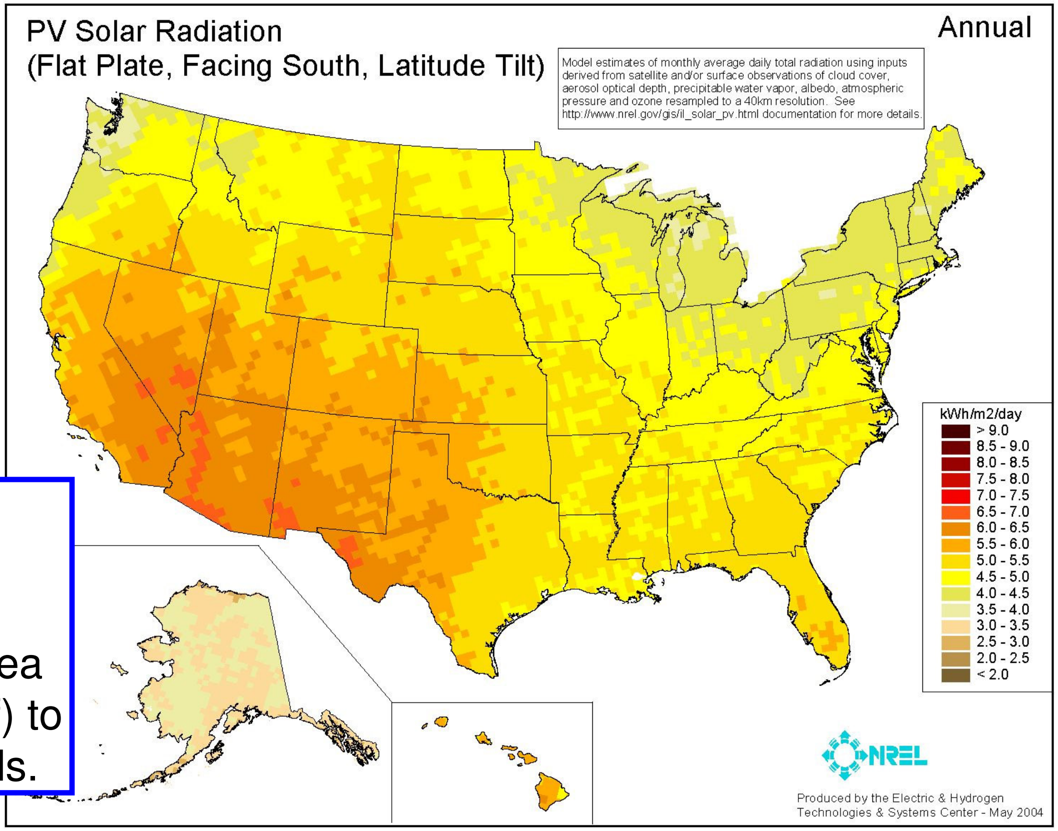
λ_{peak} (µm)=2900/T (K)~0.5 µm $\lambda(\mu m) = 1.24 / h\nu(eV)$





- Solar spectrum on earth is basically black body radiation modified by molecular absorption in the atmosphere.
- Power density ~0.9 kW/m² on a sunny day. Can be significantly affected by weather.
- Total energy delivered to earth~10^{18} kWh/year, about 8000 times the total global energy consumption in 2006!

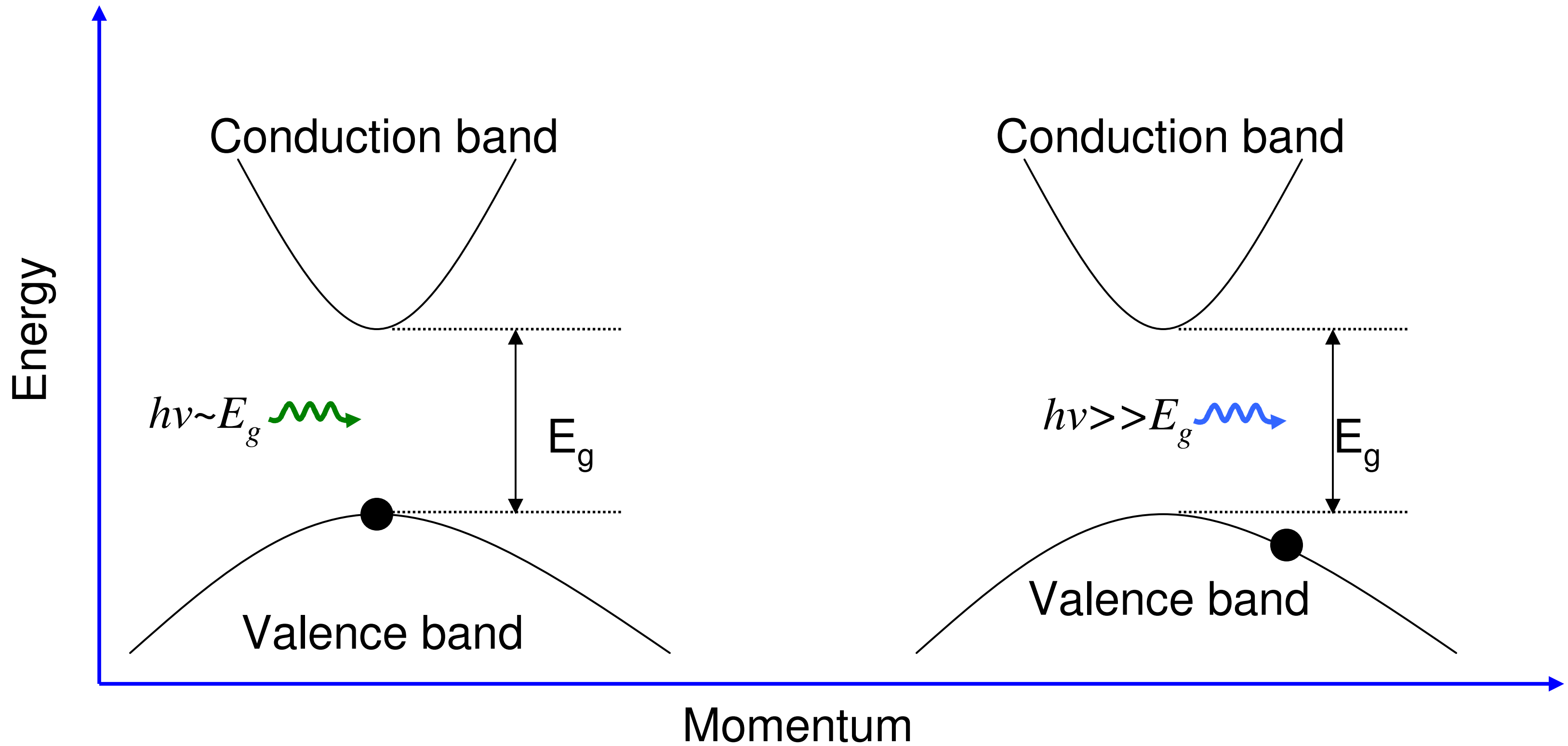
Solar Energy Incident upon the U.S.



Assuming 13% solar power conversion efficiency, an average American needs an area of ~260 m^2 (~3000 sqf) to satisfy the power needs.

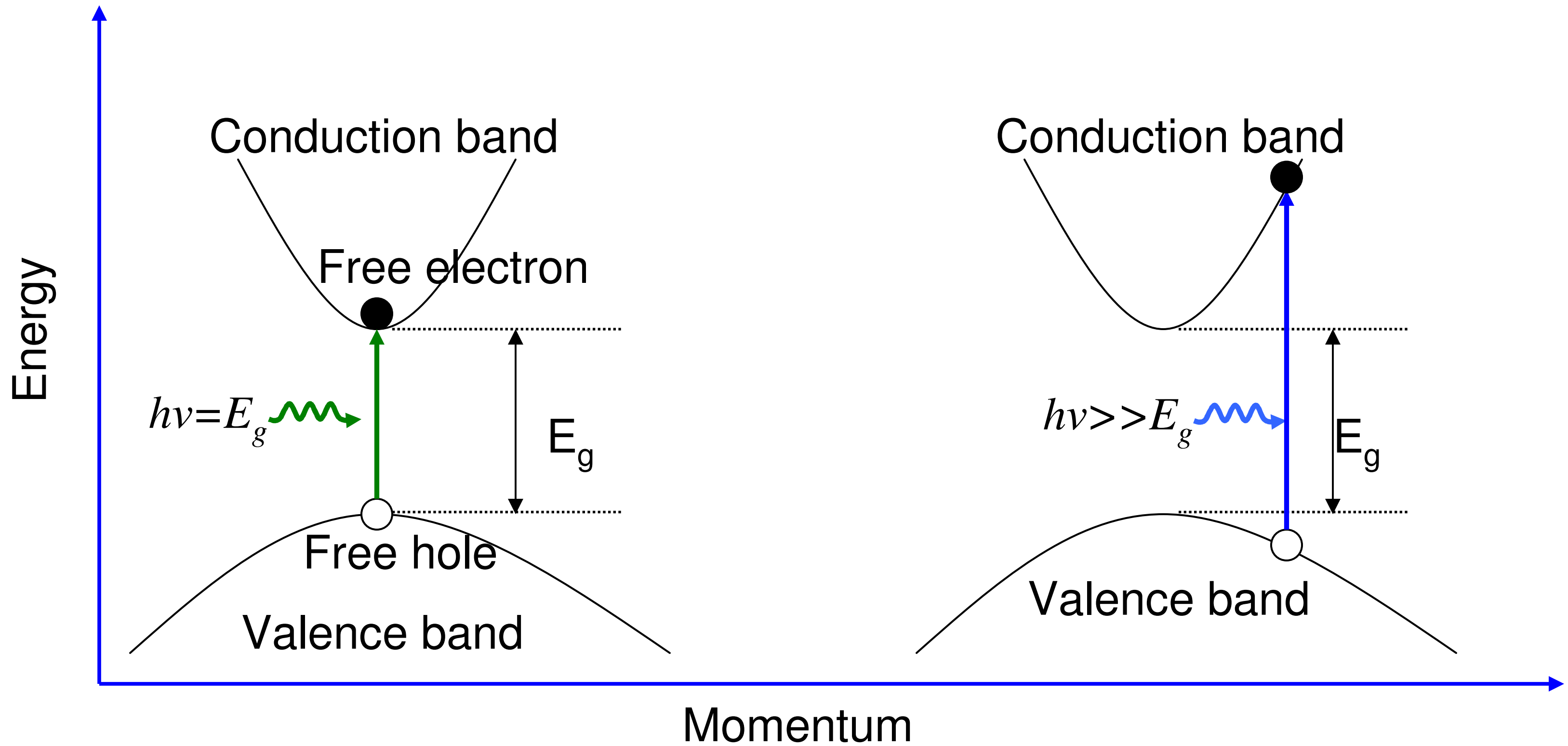
- Average solar energy incident upon the whole United States is ~500 times larger than the total energy consumption. (1/4 of the whole world's energy consumption. Power consumption/person~11 kW, 2x that of Germany and Japan, 16x higher than India.)
- However, solar energy only constitutes <0.1 % of the total electricity in the U.S. in 2006 due to **~10x** higher cost compared to conventional electricity.
- **Key to the success of solar cells: lower cost, higher efficiency!**

Light Absorption by Semiconductors



- Photons have to be absorbed by a material and create free electron-hole pairs in order to generate photocurrent: **$hv \geq E_g$**

Light Absorption by Semiconductors



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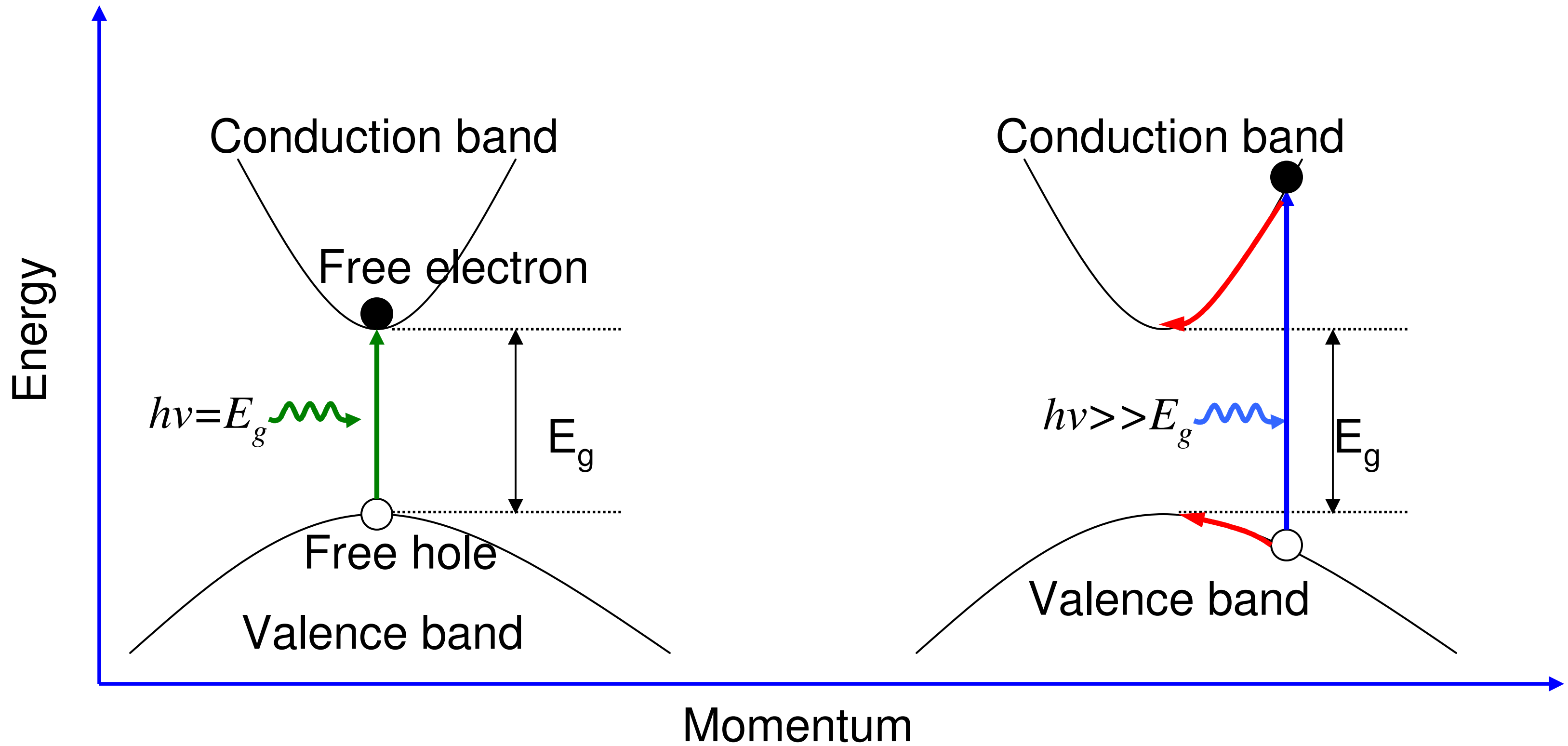
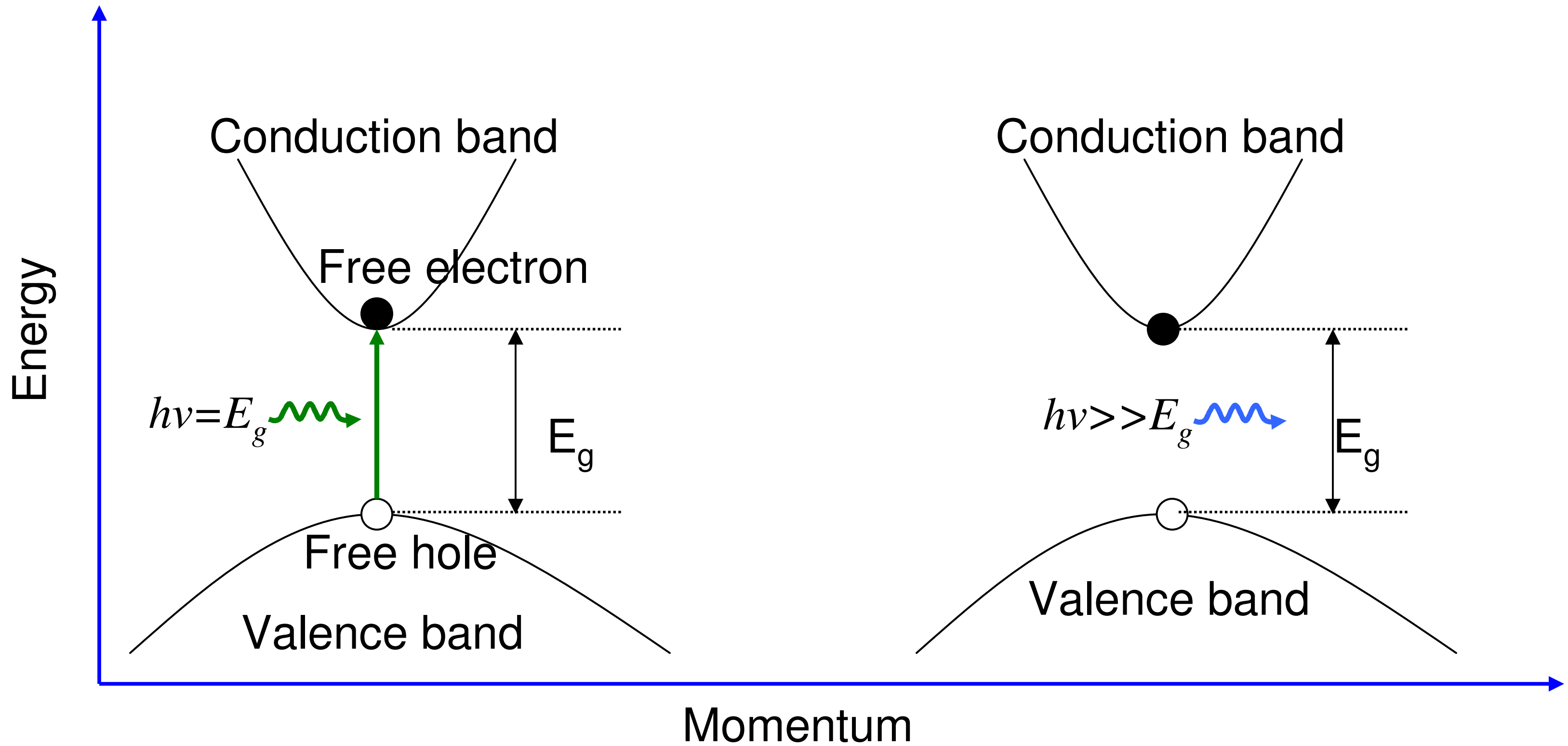
Light Absorption by Semiconductors



- Photons have to be absorbed by a material and create free electron-hole pairs in order to generate photocurrent: **$h\nu \geq E_g$**
- However, if the photon energy hv>>Eg then an significant amount of excess energy **(hv-Eg)** is lost due to the ultrafast relaxation of photon-generated carriers in<1 ps (thermalization)

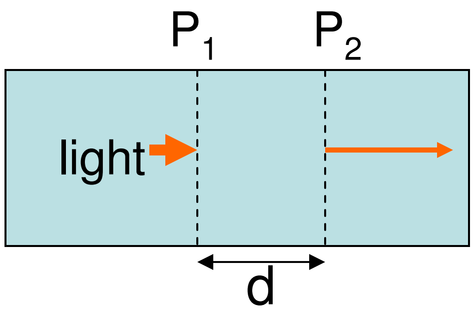
Light Absorption by Semiconductors



- Photons have to be absorbed by a material and create free electron-hole pairs in order to generate photocurrent: **$hv \geq E_g$**
- However, if the photon energy hv>>Eg then an significant amount of excess energy **(hv-Eg)** is lost due to the ultrafast relaxation of photon-generated carriers (in<1 ps)
- Band gaps have to be optimized to obtain the best power conversion efficiency.

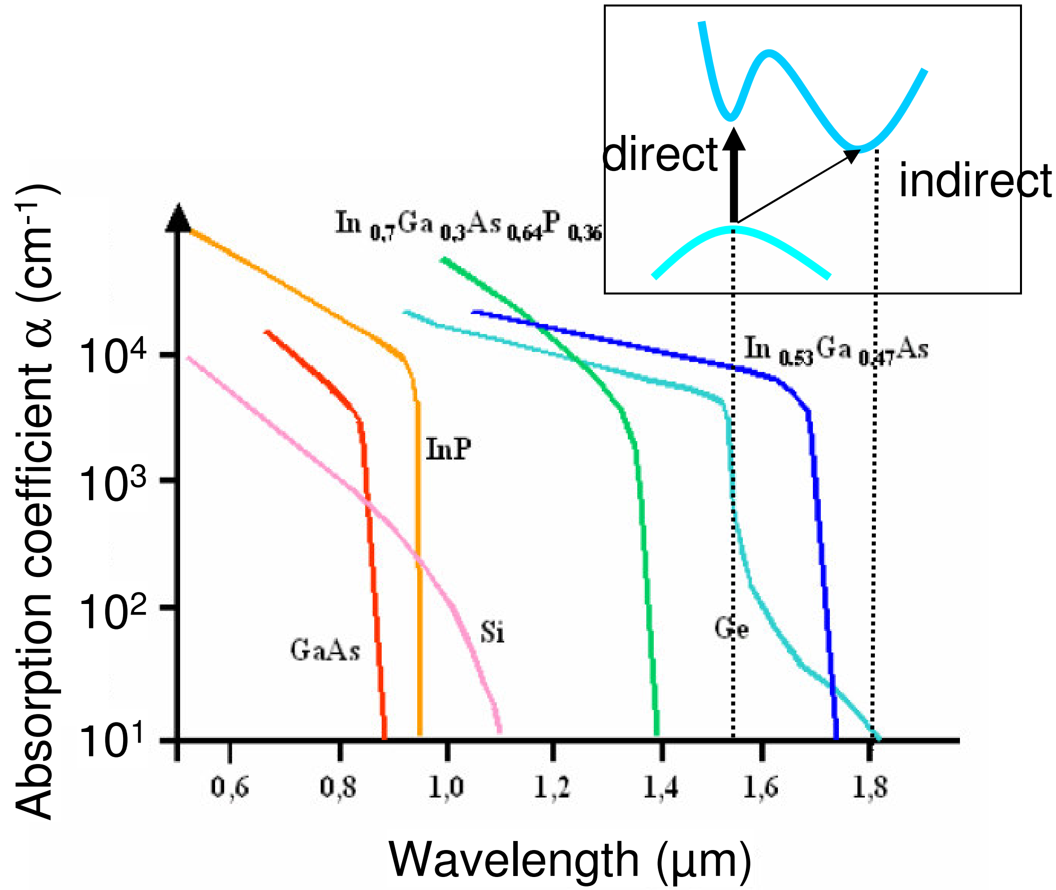
Absorption Spectra of Semiconductors

Definition of Absorption Coefficient



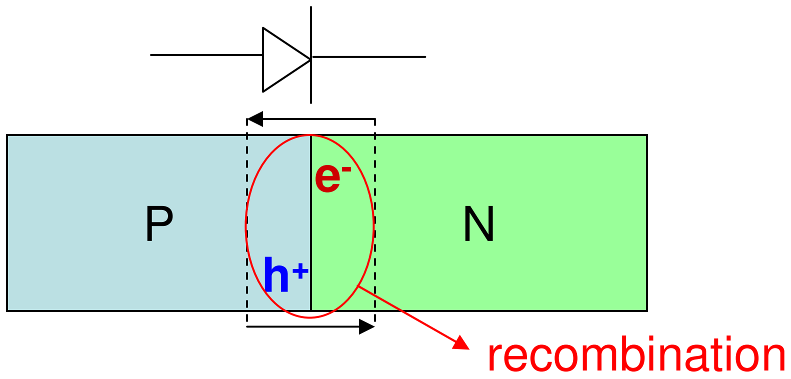
$$P_2 = P_1 \exp(-\alpha d)$$

$$\alpha = -\ln(P_2 / P_1) / d$$

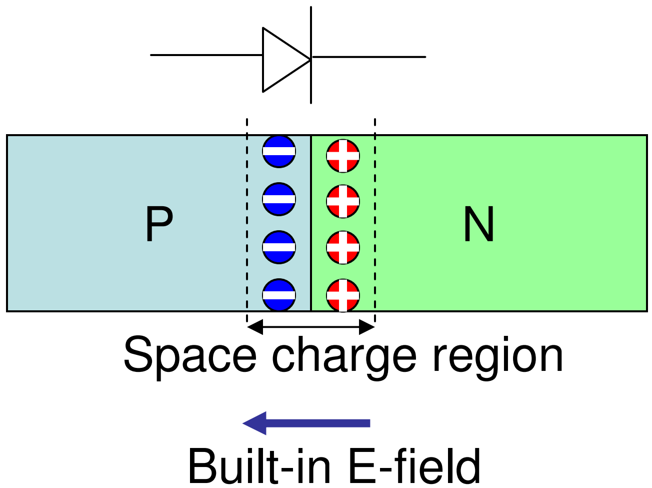


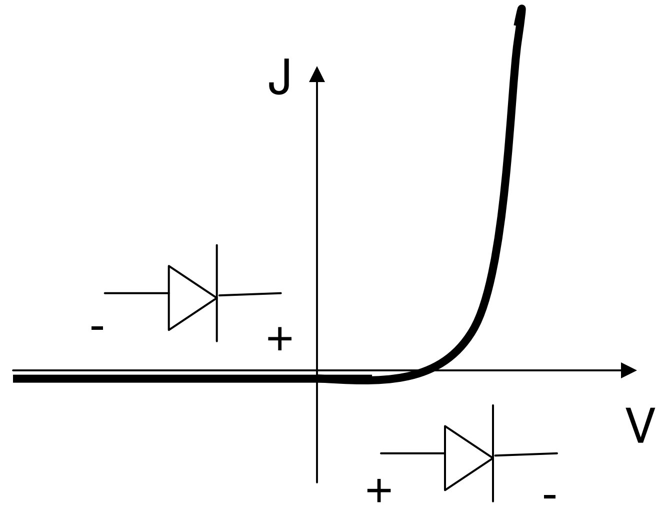
- Absorption coefficient characterizes the efficiency of a material in absorbing optical power.
- Direct gap transitions are much more efficient than indirect transitions and results in much higher α

P-N Junctions



P-N Junction J-V Characteristics



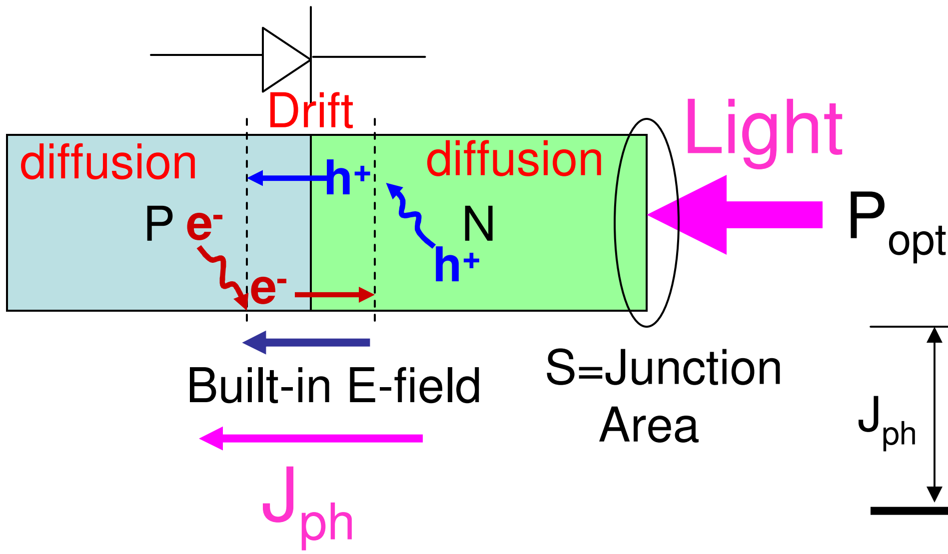


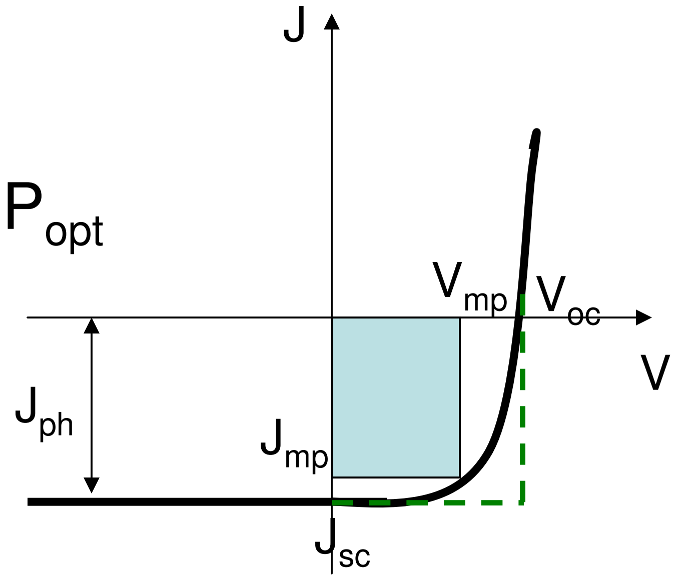
$$J = J_0\left[\exp(qV/kT) - 1\right]$$

$$J_0 \propto n_i^2 \propto \exp(-E_g/kT)$$

Increases significantly with the decrease of band gap. Also increases with defect states.

P-N Junction under Illumination





$$J = J_0\left[\exp(qV/kT) - 1\right] - J_{ph}; \quad J_0 \propto n_i^2 \propto \exp(-E_g/kT)$$

$$J_{sc} = J_{ph}; \qquad V_{oc} = (kT/q)\ln(1 + J_{sc}/J_0) \approx (kT/q)\ln(J_{sc}/J_0)$$

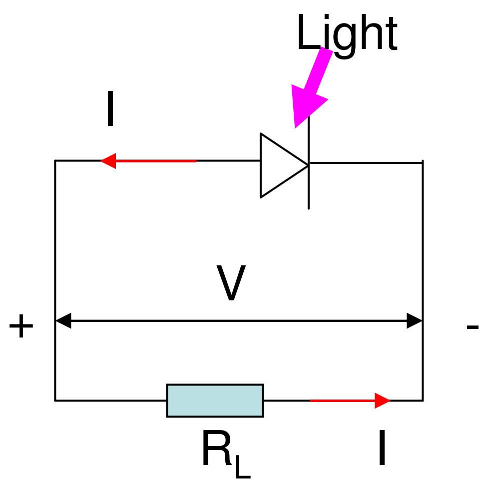
$$= E_g/q - (kT/q)\ln(const/J_{sc})$$ (Related to Eg)

$P_{max} = V_{mp} I_{mp} = V_{mp} J_{mp} S$ *(can be found by setting d(VI)/dV=0))*

Fill Factor (FF) = $V_{mp}J_{mp}/V_{oc}J_{sc}$~0.6-0.8;

Energy conversion efficiency η_{energy}= FF* $V_{oc}{*}J_{sc}/P_{opt}$

Circuit Consideration for Power Generation

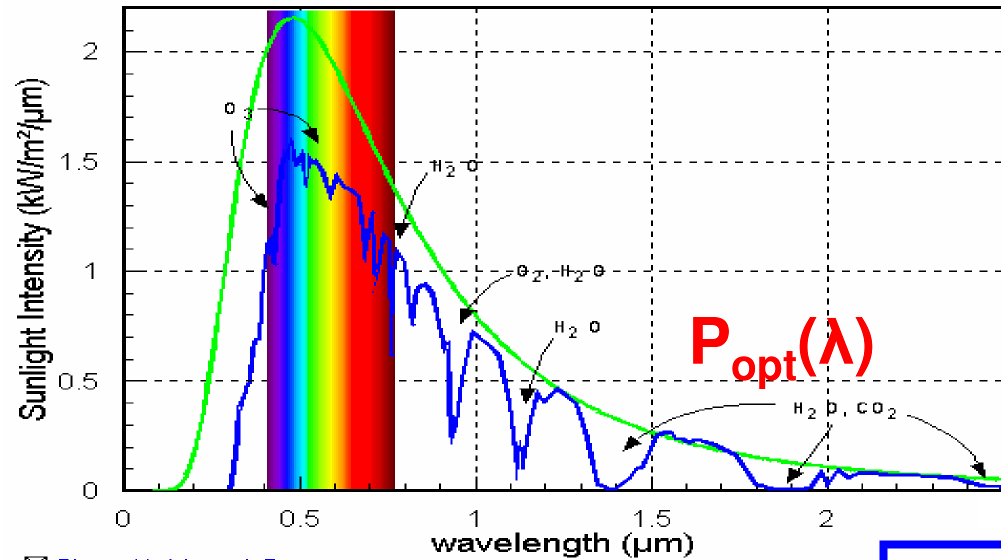


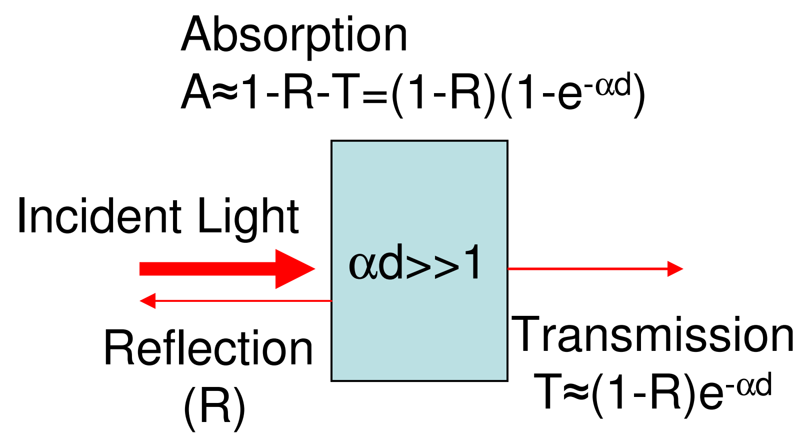
$$I = I_0\left[\exp(qV/kT) - 1\right] - I_{ph}$$

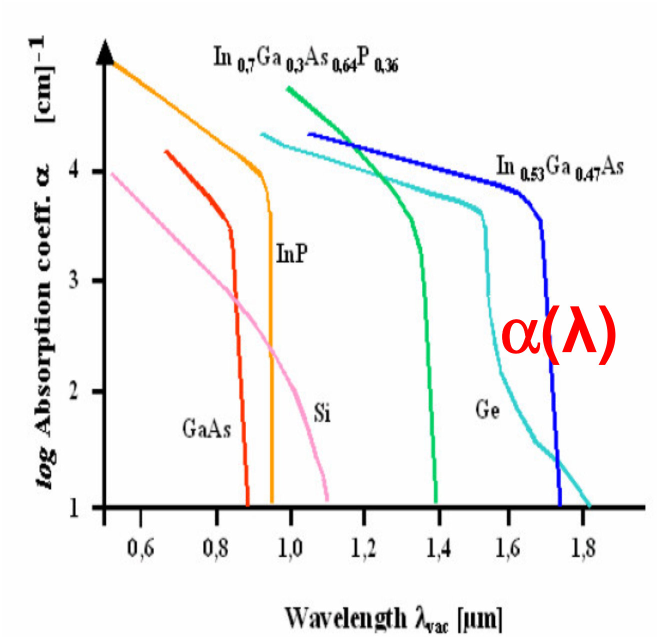
R_L(max power)=V_{mp}/I_{mp}

- An adequate load is required to obtain maximum power output from the solar cell.
- DC-to-AC Inverter is needed if generated power is to be distributed through electricity grid.
- Power generated by solar cell can be used to charge batteries for energy storage.

Absorption Spectrum Overlap with Solar Spectrum







$$J_{sc} = J_{ph} = q \bullet \eta_{collect} \bullet \int \left[P_{opt}(\lambda) / (hc/\lambda) \right] A(\lambda) d\lambda$$

$$< q \int \left[P_{opt}(\lambda) / (hc/\lambda) \right] d\lambda$$ ~60 mA/cm²

(upper limit for standard AM 1.5 spectrum)

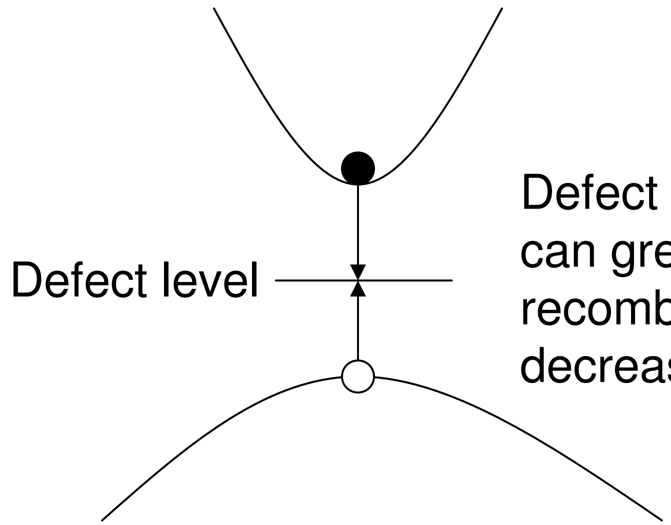
To optimize J_{sc} one needs to

- Maximize Absorption
  - -minimize reflection R
  - -select materials with optimal α spectra
  - -enhance optical path length d
- Maximize collection efficiency
  - -low defect density, high carrier mobility

Considerations on Collection Efficiency $\eta_{collect}$

$$\tau_n = 1/(R_{comb}\, p)$$

$$\tau_p = 1/(R_{comb}\, n)$$

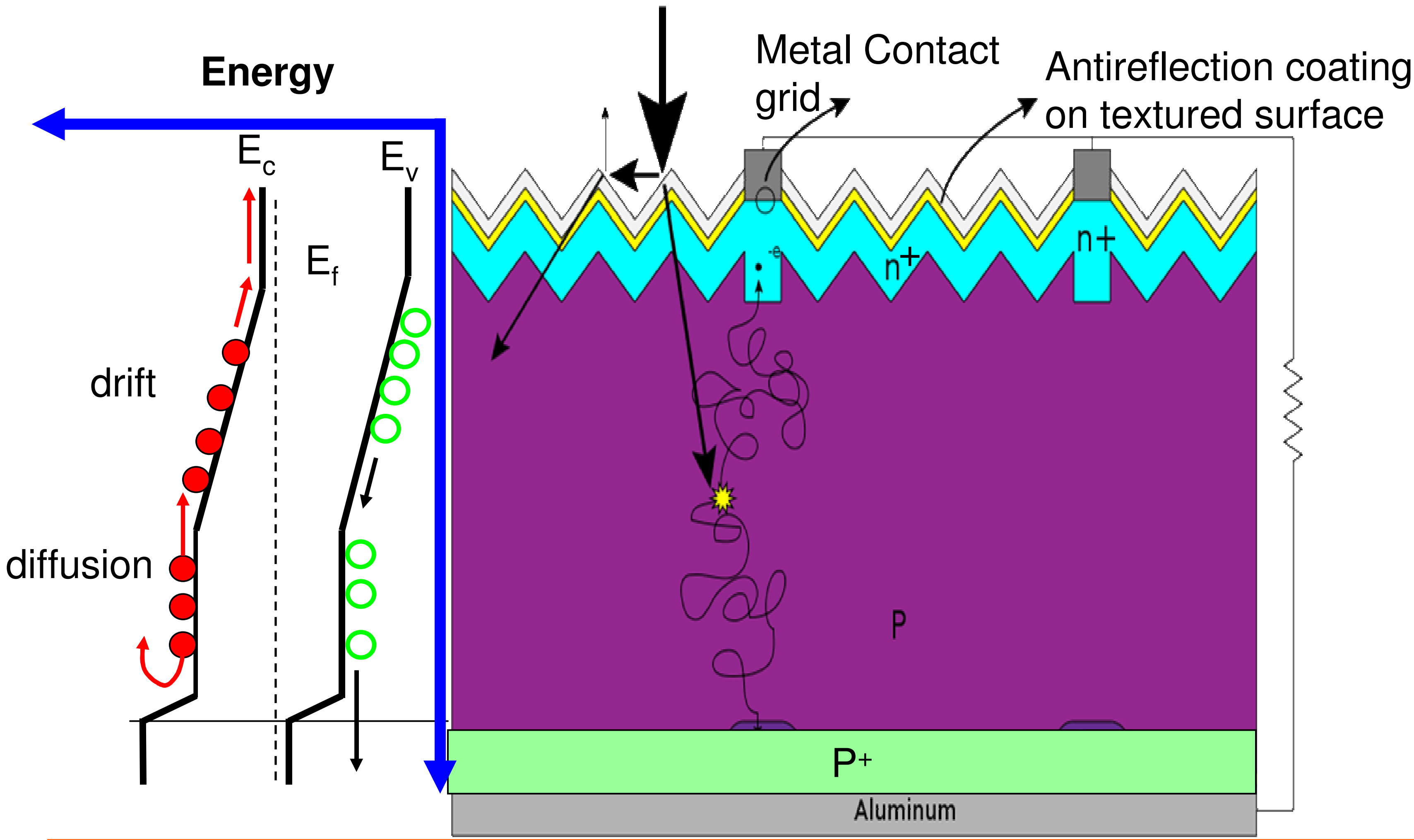


Defect assisted recombination can greatly increase the recombination rate R_{comb} and decrease carrier lifetime

Carrier transit time to reach the electrode has to be << carrier lifetime for $\eta_{collect}$~1

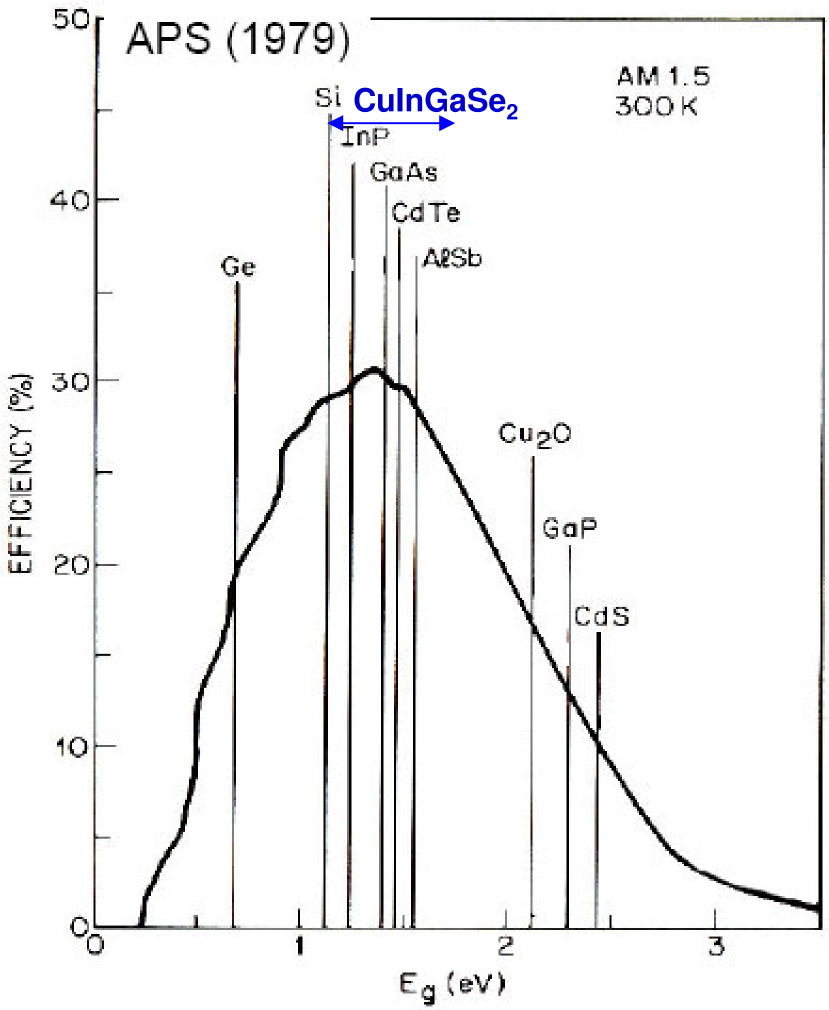
- Minority carrier life time is the most concern
- Mid-gap defect states can significantly increase the recombination rate R_{comb} and decrease the carrier lifetime. They have to be minimized
- High carrier mobility is preferred
- Drift under an E-field is preferred over diffusion for carrier transport.

Typical Solar Cell Structures



- AR coating and textured surface to reduce reflection.
- Use front n+ layer to enhance the electric field in the p substrate
- Choice of p-type substrate for higher minority carrier mobility ($\mu_e > \mu_h$)
- Use backside p^+ layer to reflect e^- and reduce interface recombination

Theoretical Efficiency vs. Band Gap



$$J_{sc} = J_{ph} = q \bullet \int \left[P_{opt}(\lambda)/(hc/\lambda) \right] A(\lambda) d\lambda$$

$$A(\lambda) = \begin{cases} 1 \ (h\nu > E_g) \\ 0 \ (h\nu < E_g) \end{cases}$$

$$V_{oc} = (kT/q)\ln(1 + J_{sc}/J_0)$$

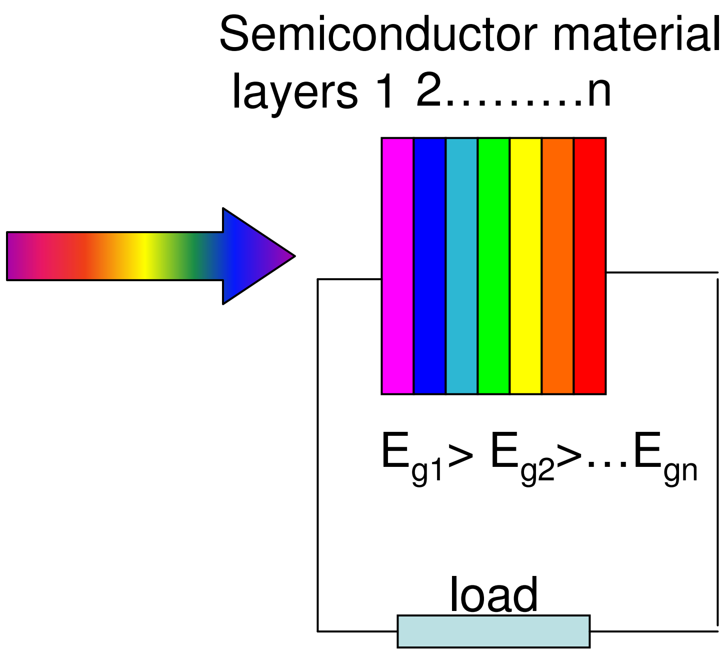
$$\approx 0.026 \ln(J_{sc}/J_0) \ (V)$$

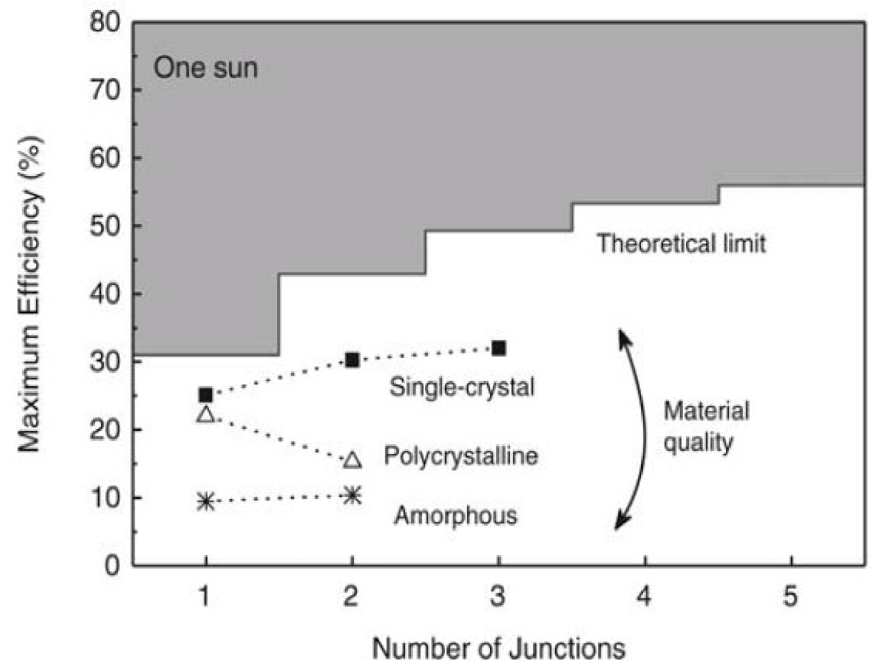
(note J_0 increases exponentially with the decrease of E_g)

$$\eta_{energy} \propto V_{oc} {}^{*} J_{sc}/P_{opt}$$

- Decreasing E_g increases J_{sc} but decreases V_{oc}
- For a single homojunction solar cell the maximum theoretical efficiency is ~31% at Eg~1.35 eV

Tandem Cells for Enhanced Efficiency





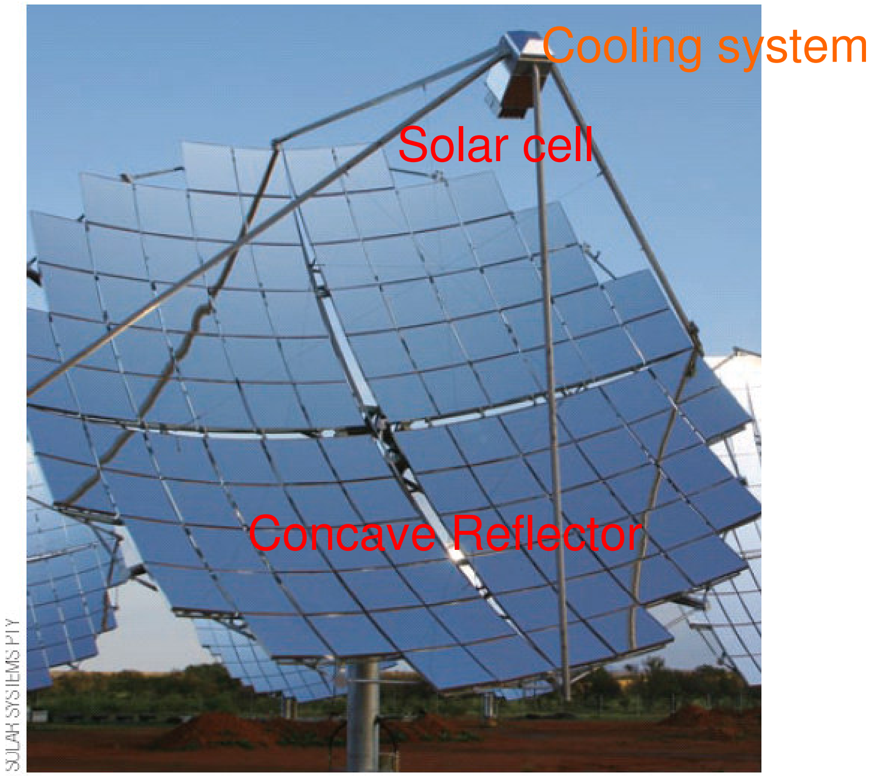
- Efficiency can be significantly enhanced by using a stack of materials with different band gaps. Such structures are called tandem cells.
- Efficiency >50% is possible under standard AM 1.5 illumination
- Disadvantages:

  - Current matching required for series connection of junctions. Sensitive to illumination conditions

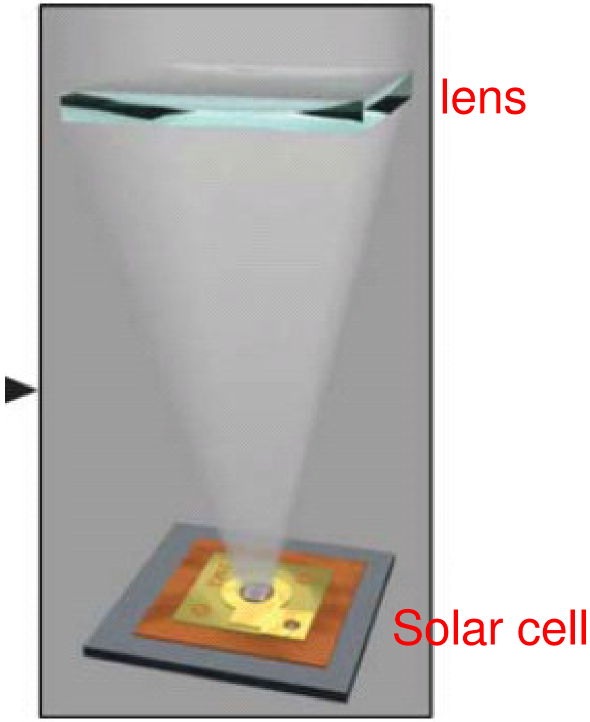
  - Parallel junction connection more complicated to fabricate

  - High cost (high cost substrate; epitaxy involved)

Concentrators for Solar Cells



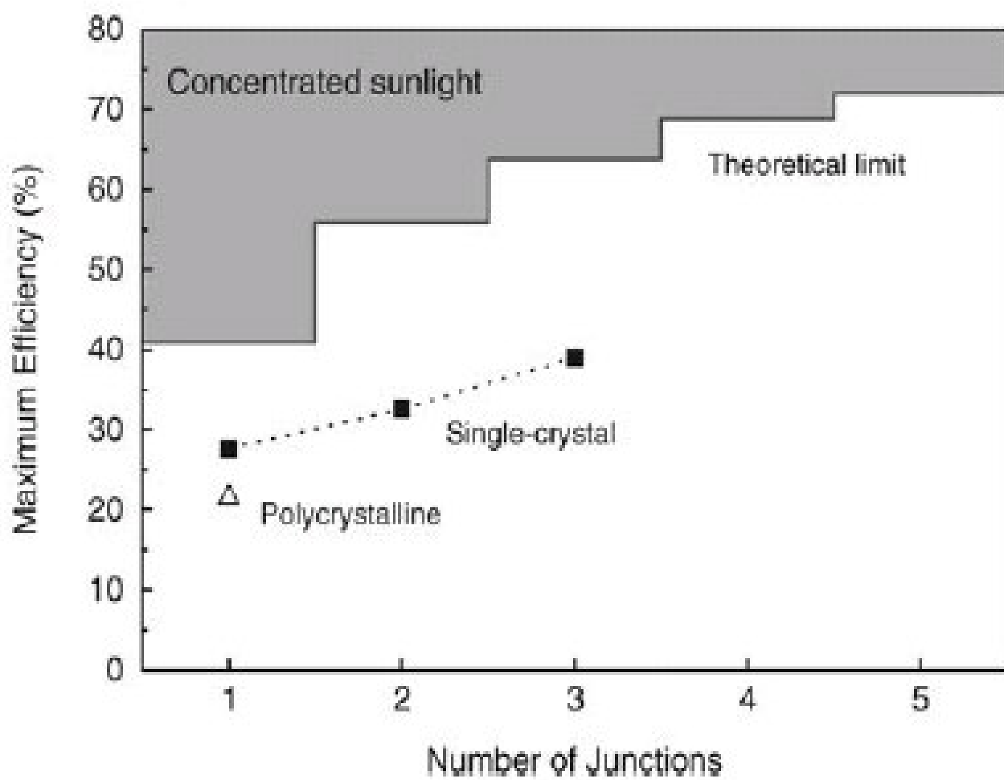
Reflective Concentrators



Transmissive Concentrators

- Concentrators collect the sun light from a large area and focus it to a small area
  - Much smaller cell area is required: semiconductor material cost is greatly reduced
  - Higher incident optical power density also helps to increase the efficiency (provided the cells are not heated up significantly. Cooling usually required)

Efficiency Enhancement by Sunlight Concentration



Bonus!

$\eta_{energy} \propto V_{oc} * J_{sc} / P_{opt} \propto V_{oc}$; $V_{oc}(C*J_{sc}) = kT/q * \ln(CJ_{sc}/J_0) = V_{oc}(J_{sc}) + 0.026*\ln(C)$;

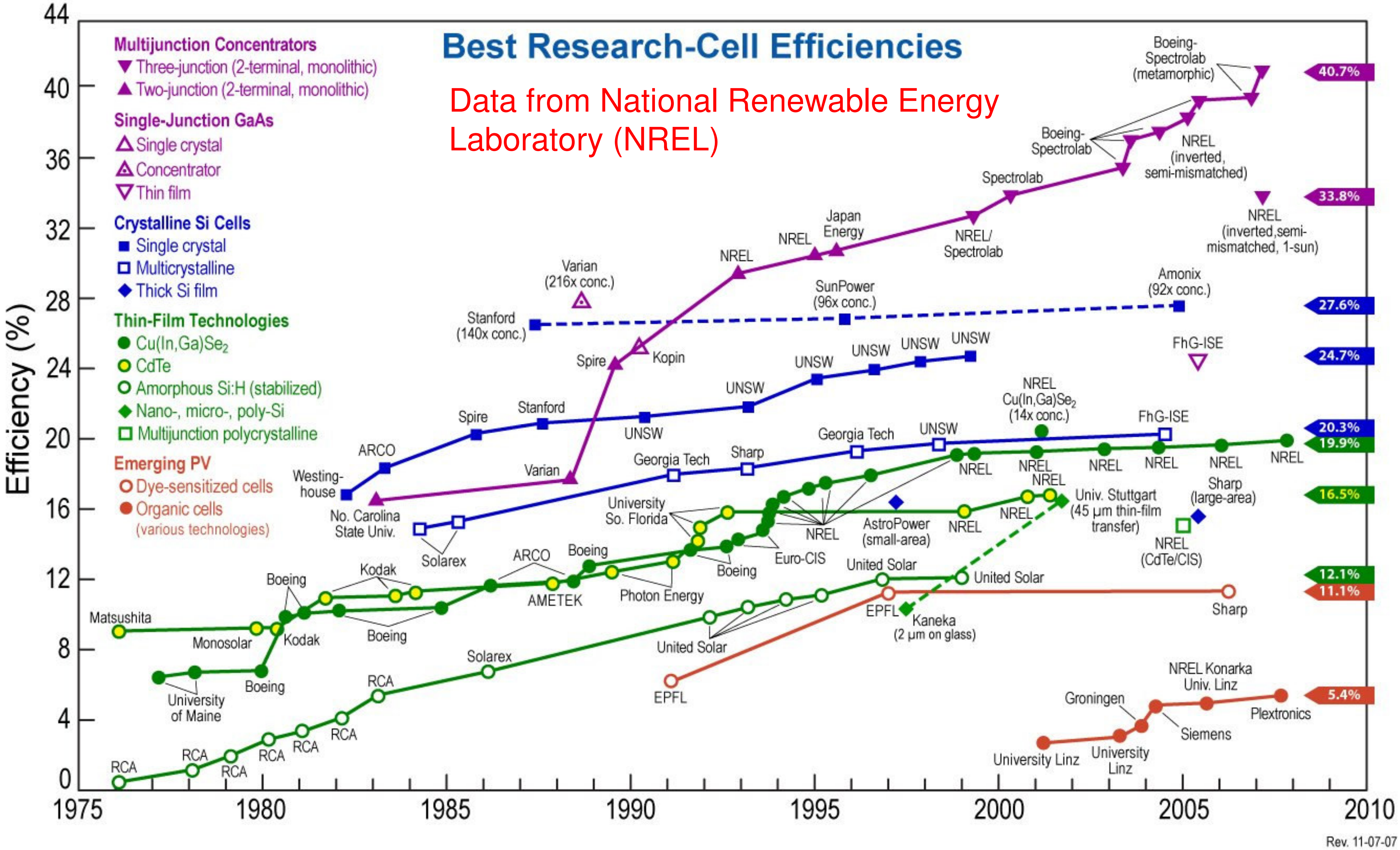
- J_{sc} proportional to incident optical power density P_{opt}
- V_{oc} increases logarithmically with J_{sc}, therefore <u>concentration factor C</u>.
- The total power conversion efficiency increases with C
- Max theoretical efficiency increases to ~40% for single junction and >70 % for multiple junctions with sunlight concentration.

Fundamental Thermodynamic Limit of Solar Energy Conversion Efficiency

- Second law of thermodynamics dictates that the maximum energy conversion efficiency will never exceed the Carnot Limit:

$$\eta_{energy} < 1 - T_{cell}/T_{sun} = 1 - 300K/5800K = 95\%$$

Best Research-Cell Efficiencies



- Higher efficiency achieved by using better materials or device structure.

Distribution of Solar Cell Production by Materials

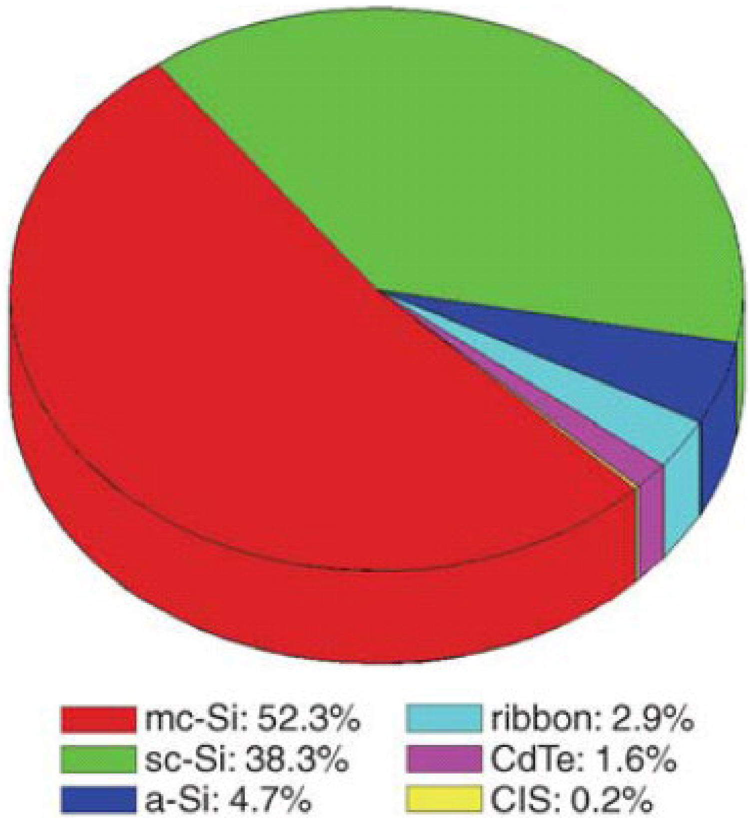


Figure 3. Distribution of photovoltaic cell production by technology in 2006: multicrystalline Si (mc-Si), single-crystal Si (sc-Si), amorphous Si (a-Si), ribbon Si, CdTe, and copper indium diselenide (CIS). [Source: *Photon International* (March 2006).]

Solar cell materials are dominated by Si (98.2%)

Why Si Solar Cells?

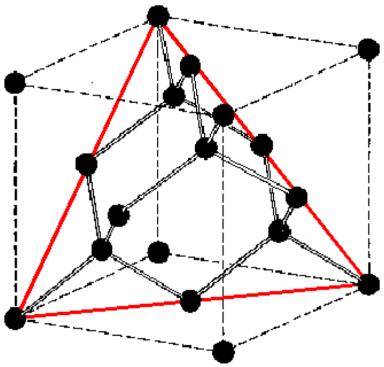
$SiO_2 + C \Rightarrow Si + CO_2$ (Metallurgy grade)

$Si + 3HCl \Rightarrow SiHCl_3 + H_2$ 300C

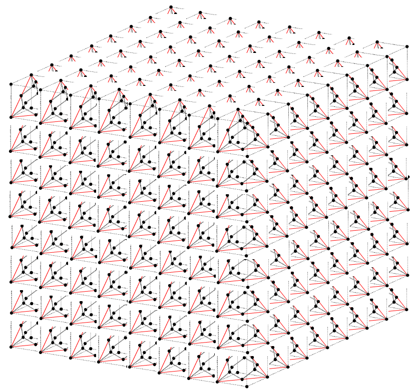
$SiHCl_3 + H_2 \Rightarrow Si + 3HCl$ (1100C, Semicond. Grade)

- Si is the 2nd most abundant element in the earth crust. (26% of the earth crust)
- Si processing technology is mature due to the development in Si ICs

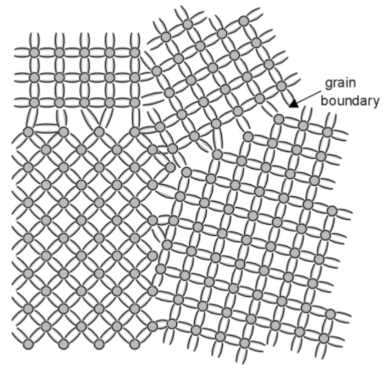
Classification of Si by Crystallinity



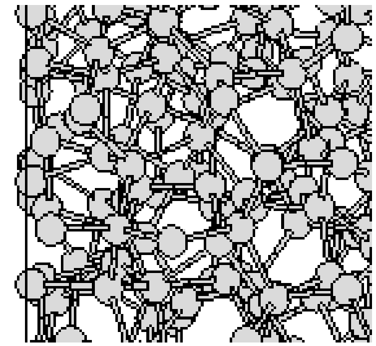
Unit cell of Si
a=0.5431 nm



Single Crystal Si
(completely ordered)



Multicrystalline or poly Si (grains of different orientations)

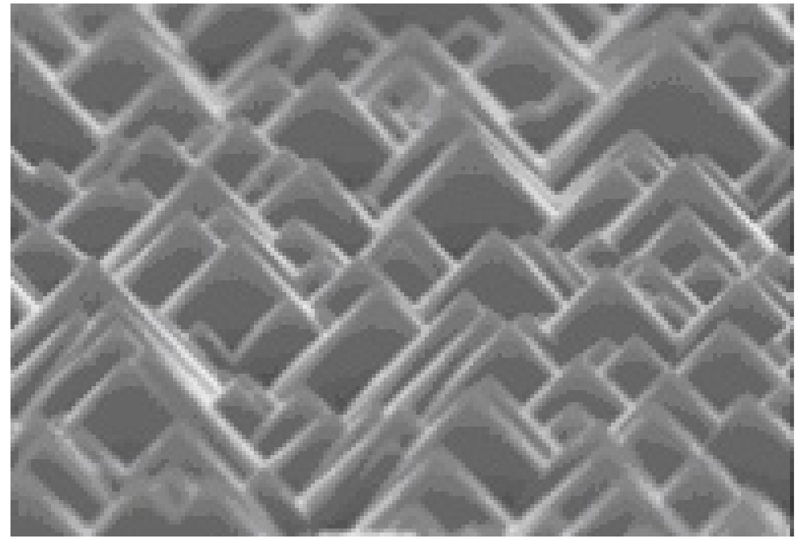


a-Si: H
(very short range order in <1 nm regime)

	Symbol	Grain Size	Mobility (cm^2 V/sec)	Eg (eV)	Common Growth Techniques
Single crystal	sc-Si	Completely ordered	~10^3	1.1	Czochralski (CZ) or float zone (FZ)
Multicrystalline Polycrystalline	mc-Si pc-Si	µm-mm	Mid 10-10^3	1.1	Cast, ribbon, Chemical-vapor deposition (CVD)
Microcrystalline nanocrystalline	µc-Si nc-Si	<1µm <5 nm	Mid 10	1.1 1.1-1.7	CVD, sputtering
Amorphous	a-Si/ a-Si:H	Very short range order <1 nm	1-10	1.7-1.9	CVD

Behaves more like direct gap

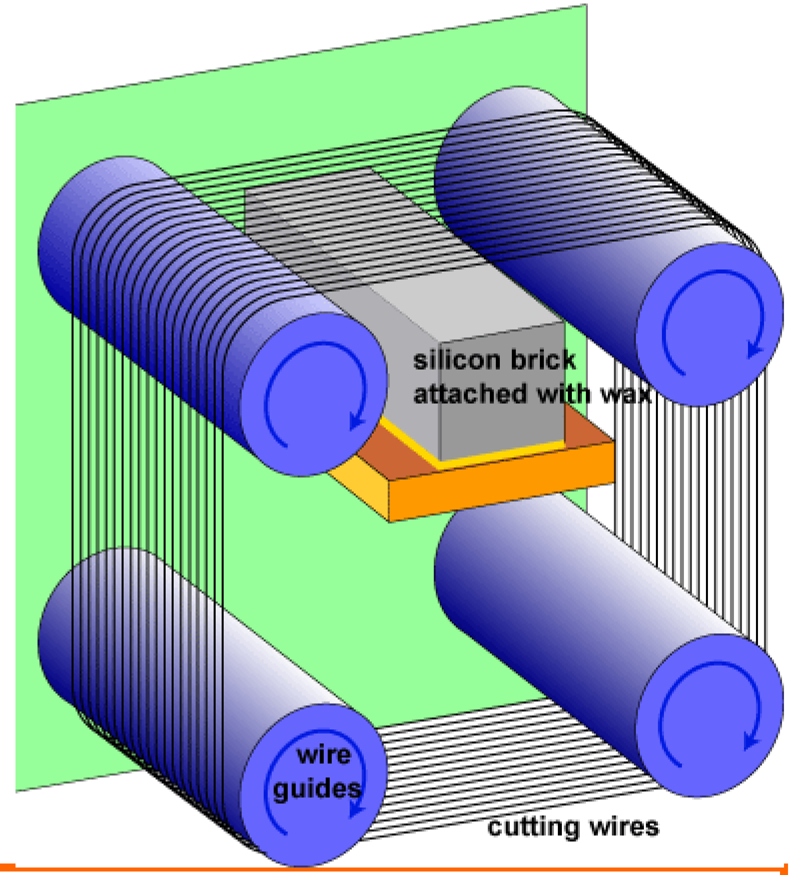
Single Crystal Si Wafers for Solar Cells



Textured Surface after alkaline etching (NaOH, KOH…)

- Single crystal Si typically grown by Czechorosky growth.
- Wafers sliced from an ingot. Si (100) wafers most common due to good surface passivation by SiO_2
- Surface texture achieved alkaline solution etching of Si (100) wafers (exposing 111 facets)
- Advantage: extremely high material quality (defect free)
- Disadvantage: high cost. Cylindrical ingot obtained while rectangular wafers preferred for area coverage.

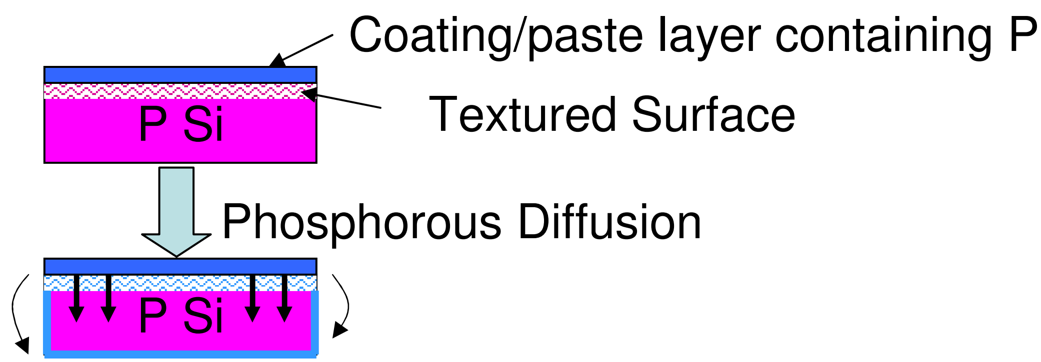
Polycrystalline Si for Solar Cells



- Bulk polycrystalline Si directly cast. Grain sizes can reach several mm. Rectangular wafers directly obtained
- Acidic etch used for uniform surface texturing (e.g. $HF:HNO_3:H_2O$) since alkaline solution etches very differently for grains of different orientations. Plasma etching or laser treatment may also be applied.
- Lower material cost but also lower material quality than sc-Si (max confirmed efficiency: 20% vs. 25%.

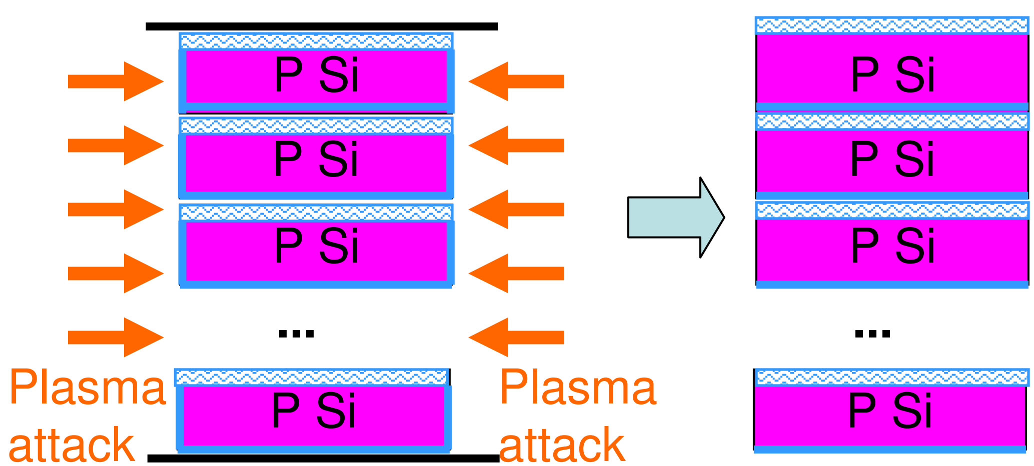
Typical Fabrication Process of Wafer-Based Si Cells

1. Saw damage layer removal etch
2. Surface texturing
3. Shallow emitter diffusion.



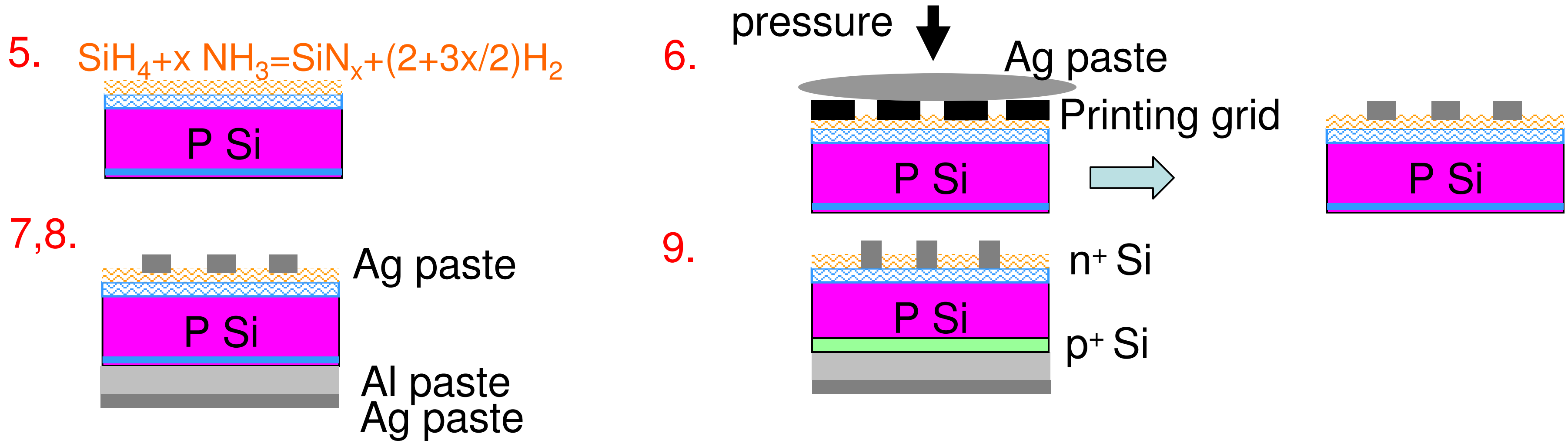
4. Plasma edge isolation

Wafers stacked upon one another and subjected to plasma etching on the edge



Phosphorous doped regions at the edge of the wafers are etched off so that the front and backsides are electrically isolated

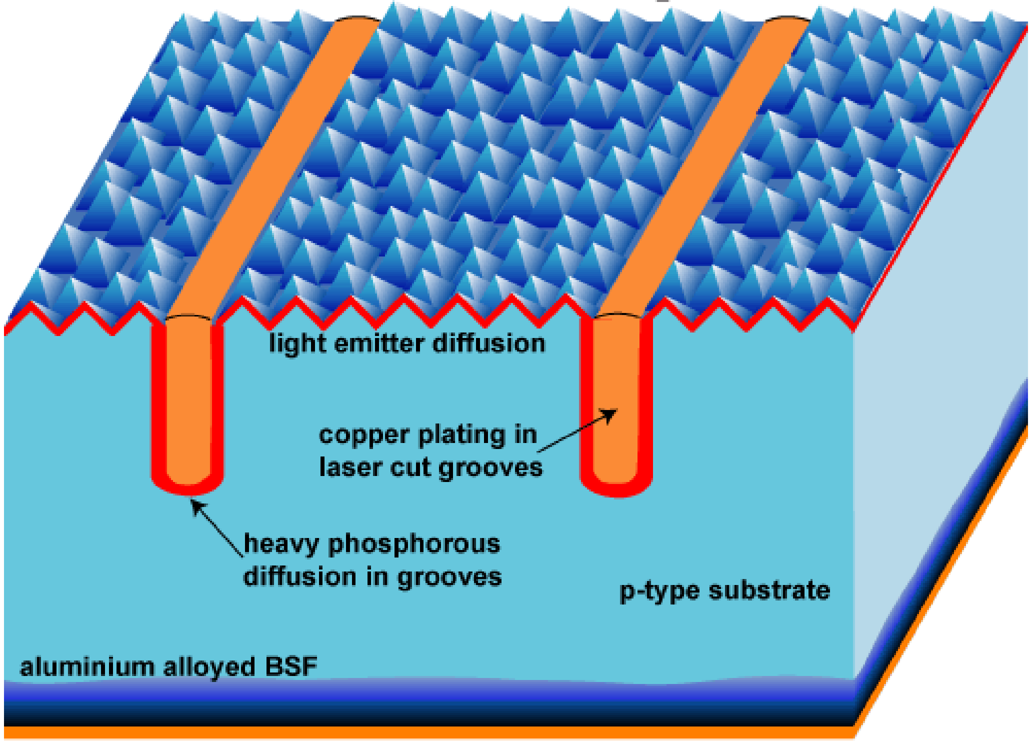
Typical Fabrication Process of Wafer-Based Si Cells



5. Antireflection coating deposition (SiN_x by CVD process)
6. Screen printing Ag paste on the front side and dry
7. Screen printing Al paste on the backside and dry
8. Screening printing Ag paste on the backside and dry (for soldering)
9. Firing

- On the front side the Ag paste can diffuse through the SiN coating and contact n^+ Si
- On the backside the Al paste diffuse into Si to form a p^+ Si layer and established backside field (BSF).

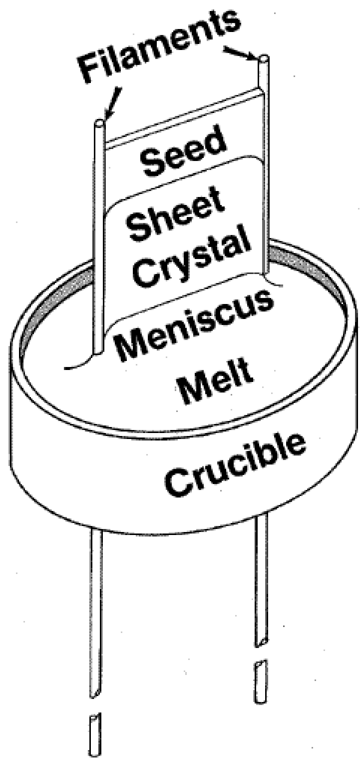
Buried Contact Cells with Improved Performance



- Groves cut by laser
- Front side metal deposited by electroplating to conformally fill the high aspect ratio trenches. Similar to Cu damascene process.

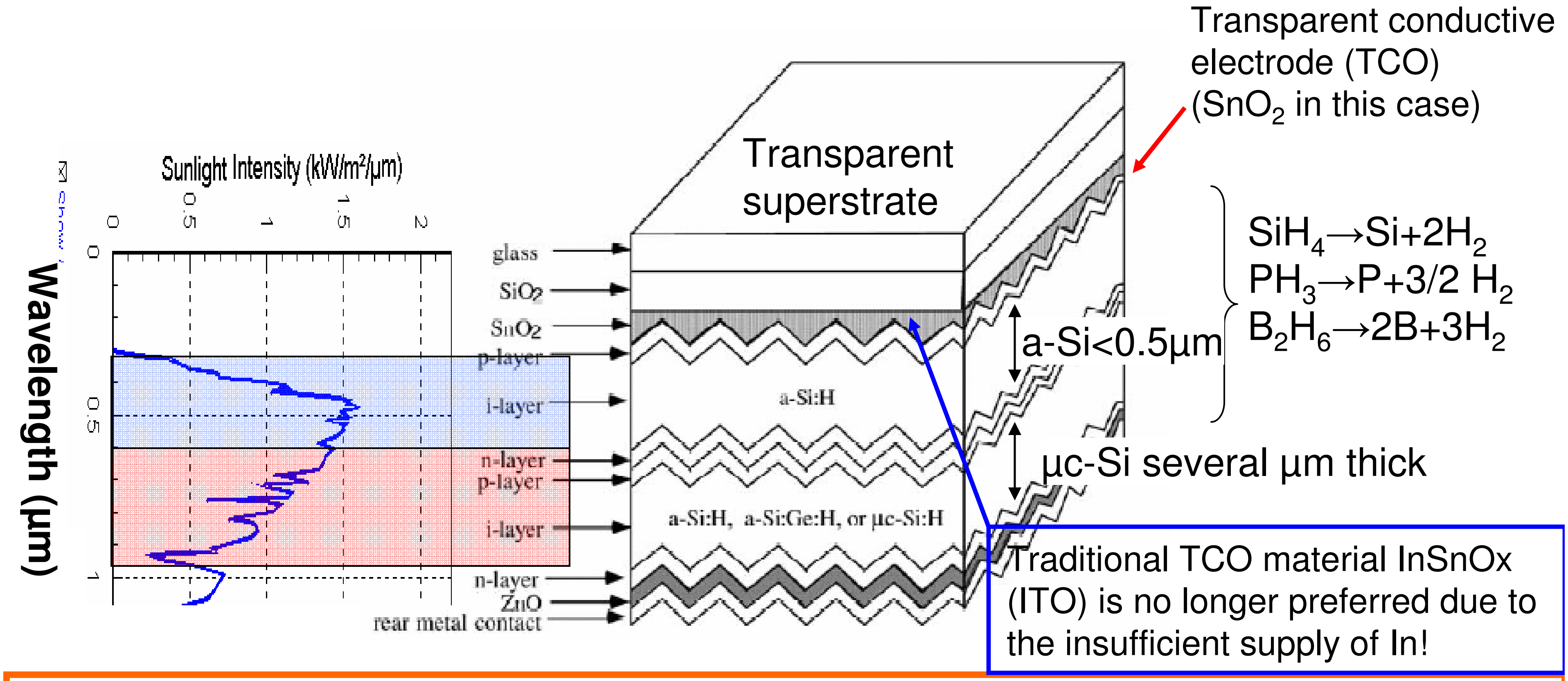
- Groves cut into the front contact region by laser so that the lateral metal/semiconductor contact area is significantly increased
- Can afford narrow metal lines (from top view) and reduce metal electrode shadowing from 10-15% to 2-3%
- Lower series resistance due to larger metal/semiconductor contact area
- Efficiency can be improved by 25% without notably increasing the fabrication cost.

Si Ribbon for Solar Cells



- Material cost constitutes ~50% of the wafer-based Si cells. Thinner cells are preferred to significantly reduce the material cost.
- Thin ribbons of Si can be grown from melt by using surface tension (the same way you play with soapy water!).
- Significantly reduced material consumption (10-50 µm thick, ~10x less than bulk Si), thus material cost
- No need to dice wafers from an ingot.
- Flexible

Thin Film Si Solar Cells: a-Si:H/μC Si cells

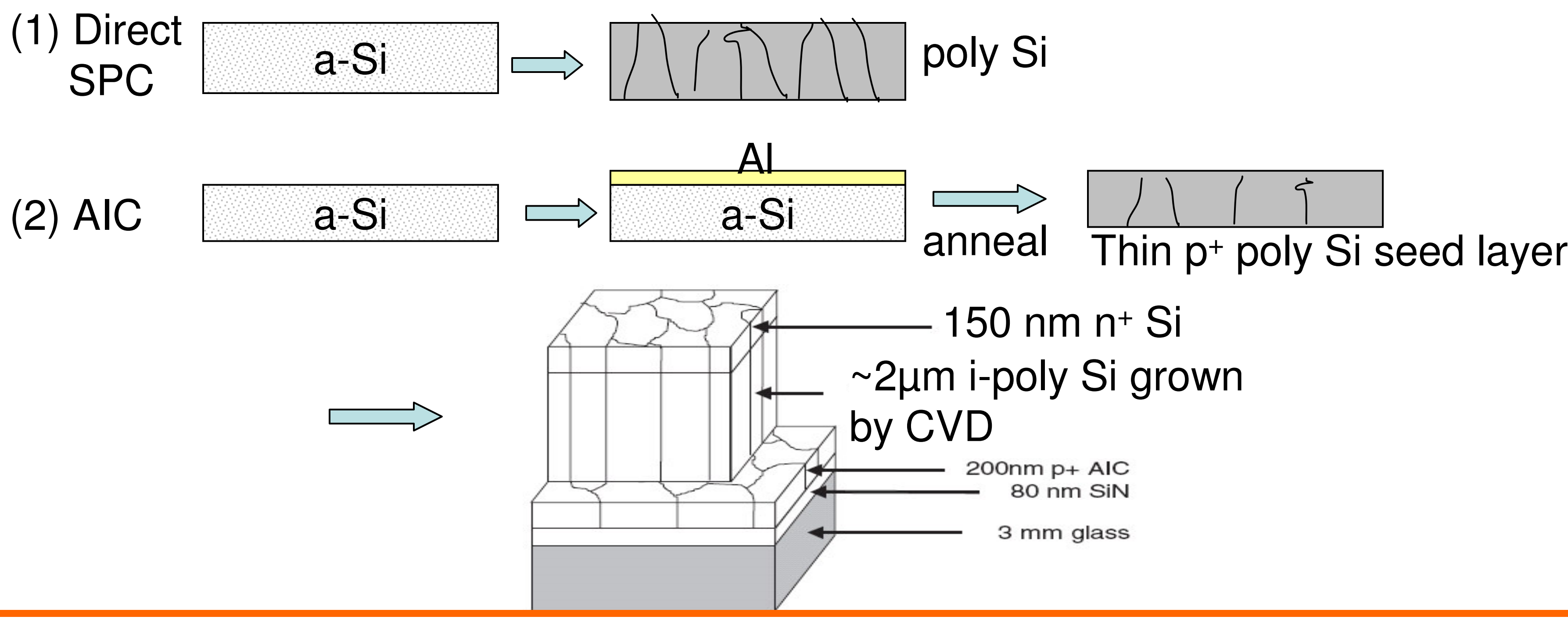


- Thin sc-Si film can be bonded to a transparent substrate yet the cost is high.
- a-Si and μc-Si films can be deposited and doped by plasma enhanced CVD (PECVD) at low temperatures with much lower cost.
- a-Si/μc-Si tandem cells to cover a broader solar spectrum. P-I-N diode structure adopted for strong electric field in the a-Si layer and better $\eta_{collect}$
- Max stablized efficiency ~12% achieved so far
- Aging of a-Si:H due to the loss of H is a big concern for reliability

PECVD System for Large Area a-Si/μc-Si Deposition

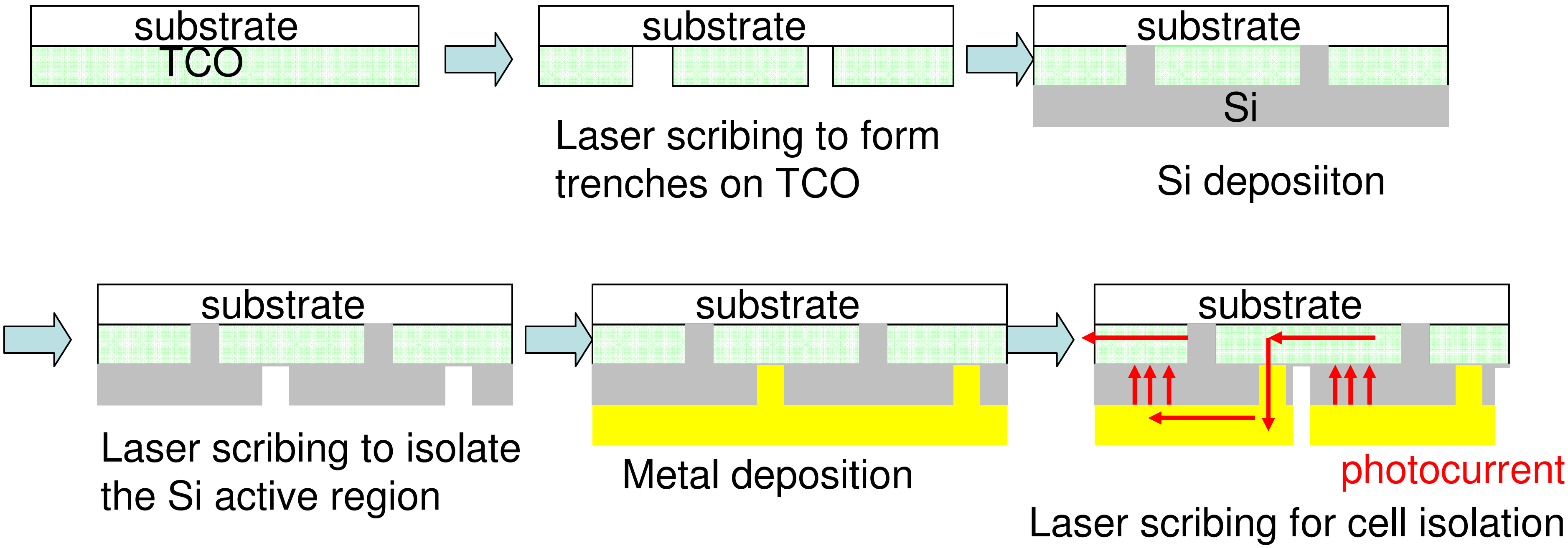
- Applied Materials Inc. has transferred the PECVD technology for large panel displays to solar technology and achieved 5.7 m^2 large area deposition capability

Thin Film Si Solar Cells: Poly Si Cells



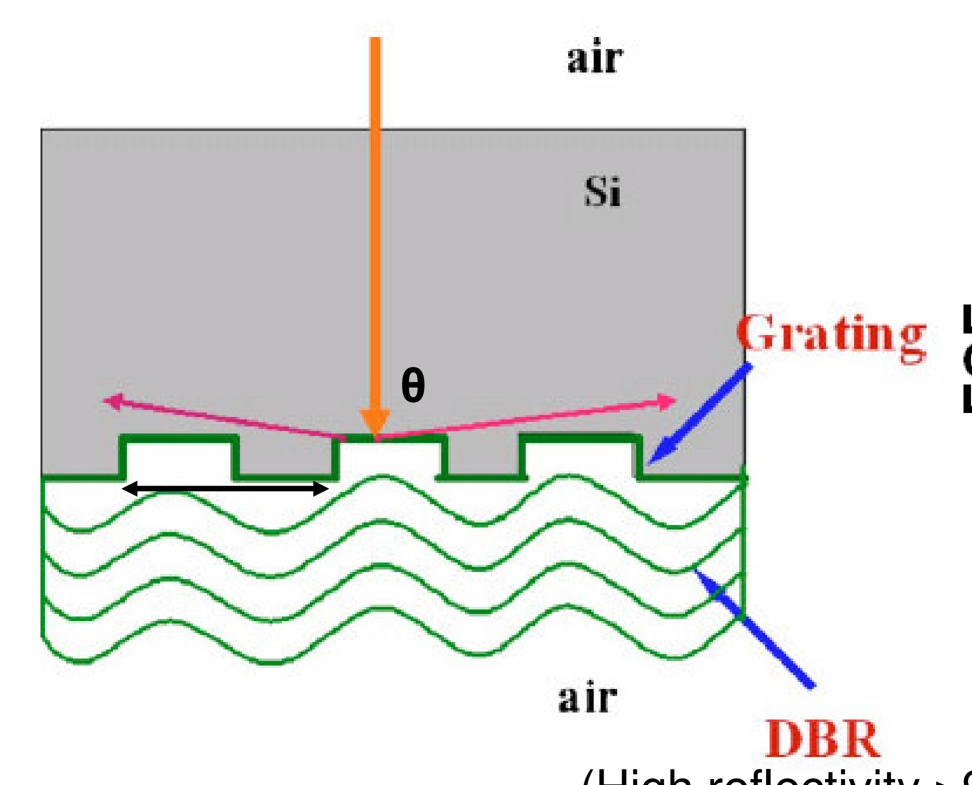
- Poly Si more stable than a-Si and is preferred for reliability
- However, usually it also requires higher processing temperature for Si grains to nucleate or grow (>600 C). Requires special glass or glass-ceramic substrates which increases the cost.
- Best poly Si cells so far obtained by solid phase crystallization (SPC) of a-Si at 550-700C
- Large grain sizes (~10 µm) can be formed by Al induced crystallization of a-Si (AIC) followed by pseudo-epitaxial CVD process for several µm poly Si.
- Best efficiency achieved ~10%.

Connecting Thin Film Si Cells in Series



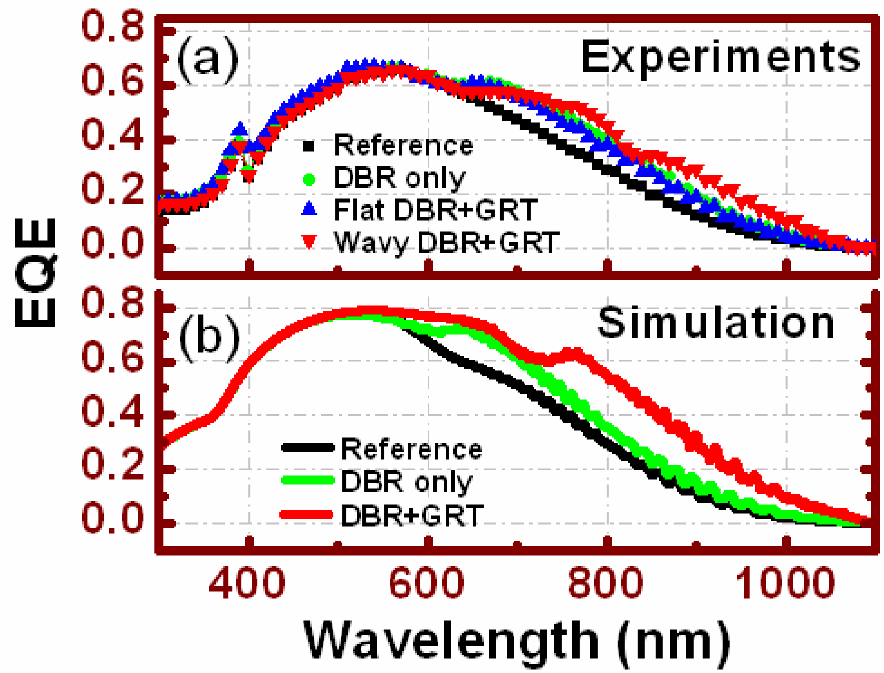
- Cells on a large panel can be isolated and connected in series to generate a high output voltage.

Thin Film Si Solar Cells: Light Trapping



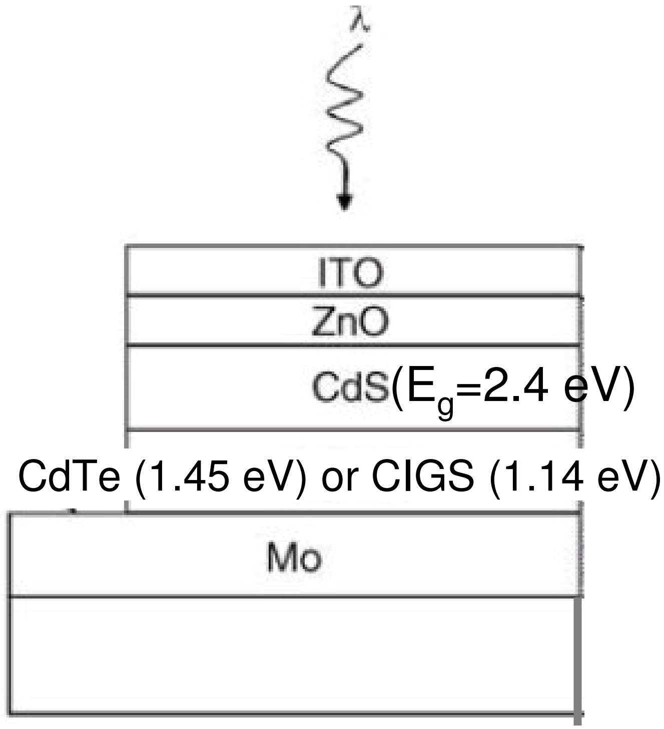
(High reflectivity >99%)

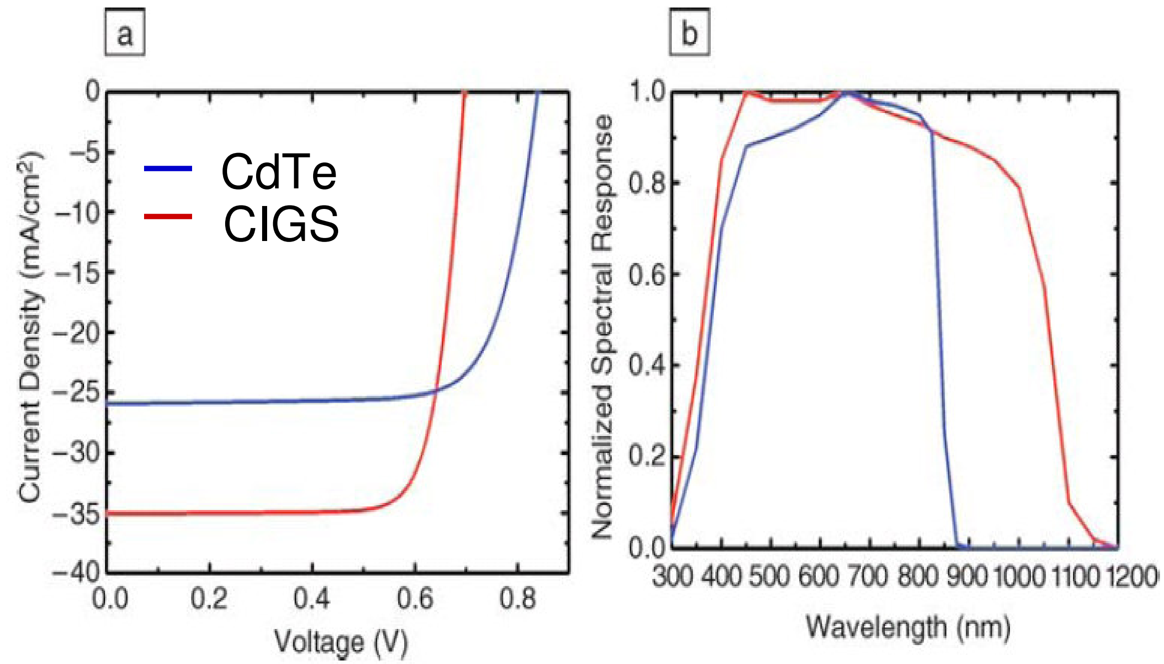
5 µm Si thin film Cell



- Photon absorption in thin film cells limited by the optical path length (~ film thickness).
- Light trapping structures can direct the incident light to the lateral direction for elongated optical path length and enhanced efficiency, e.g., grating+distributed Bragg reflector (DBR) on the backside.
- More significant effect for thinner cells. Theoretically the relative enhancement in efficiency can approach 50% for 2 µm thick Si cells!

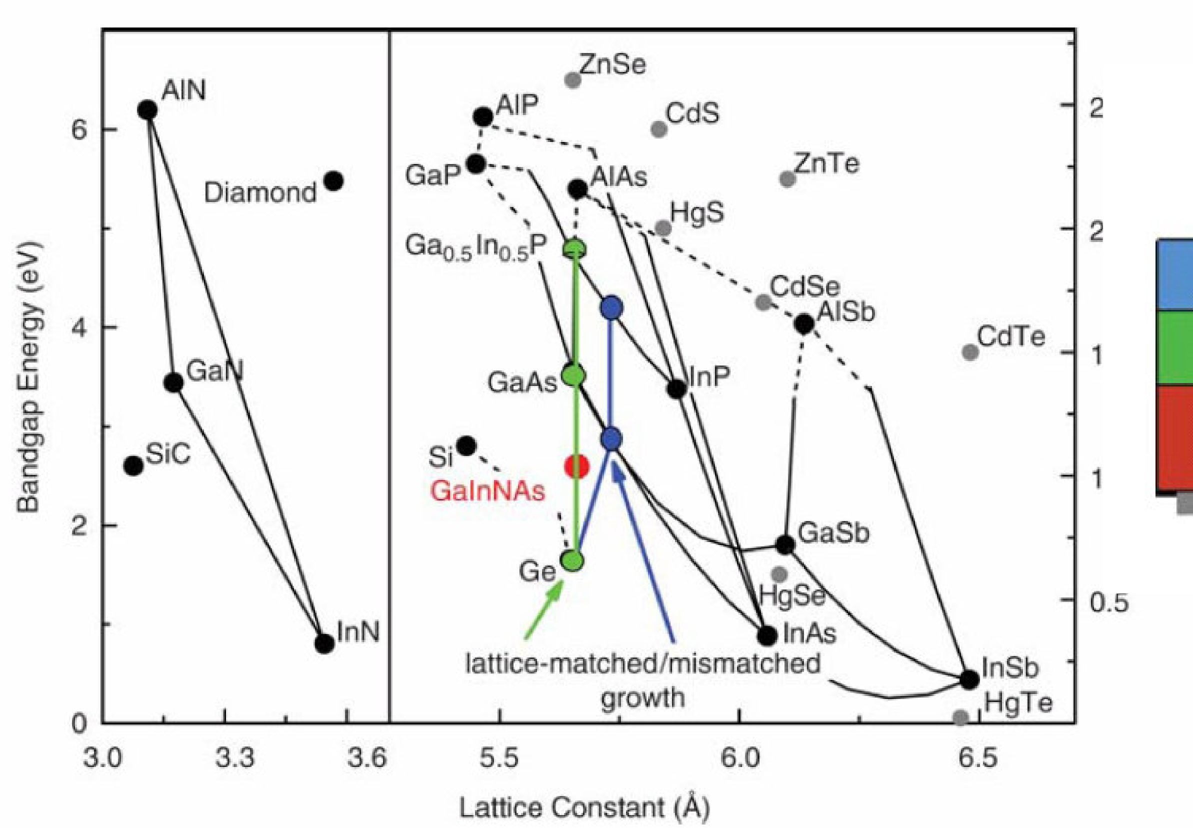
CdTe and $CuInGaSe_2$ (CIGS) Thin Film Solar Cells

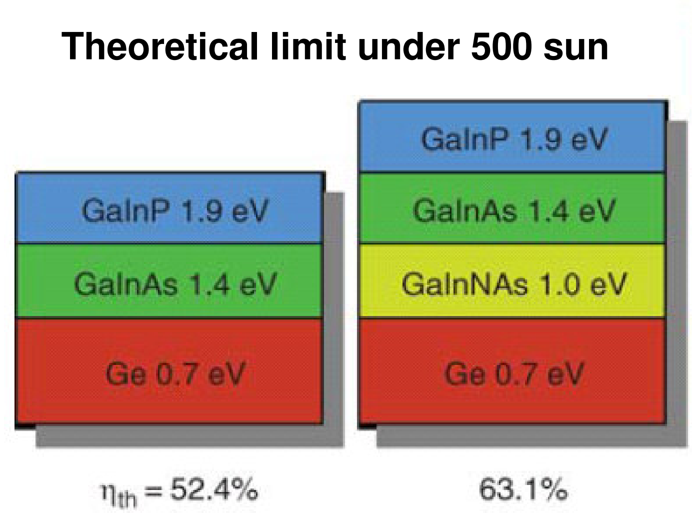




- Advantages: direct gap material, large absorption coefficients (10^4-10^5 cm^{-1}, ~10x higher than Si. Optical absorption still strong in thin film cells
- CdS involved to form heterojunction for enhanced electric field in CdTe or CIGS absorption layer
- Best efficiencies: 16.5% for CdTe and 19.9% for CIGS, limited by the ns carrier lifetime (involve T~500C deposition and post growth annealing in $CdCl_2$+O_2 for CdTe and Se atmosphere for CIGS)
- Concerns: (1) Cd not abundant enough to cover the energy need. (2) toxicity control and disposal of Cd, Te and Se require additional cost.

High Efficiency Multi-junction Cells



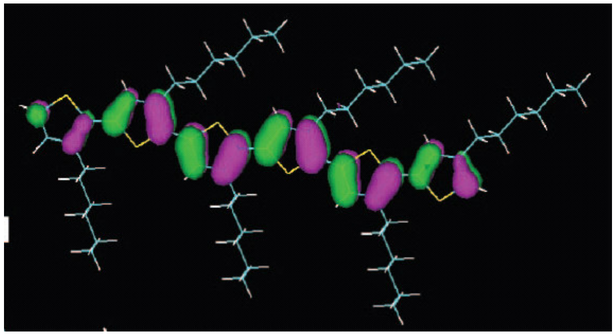


- High quality semiconductor layers obtained by epitaxial growth. 40.8 % efficiency record has been demonstrated by NREL (Aug. 2008)
- Lattice match between materials highly preferred for high quality epitaxy.
- Used together with solar concentrators to reduce cell area and the total cost.

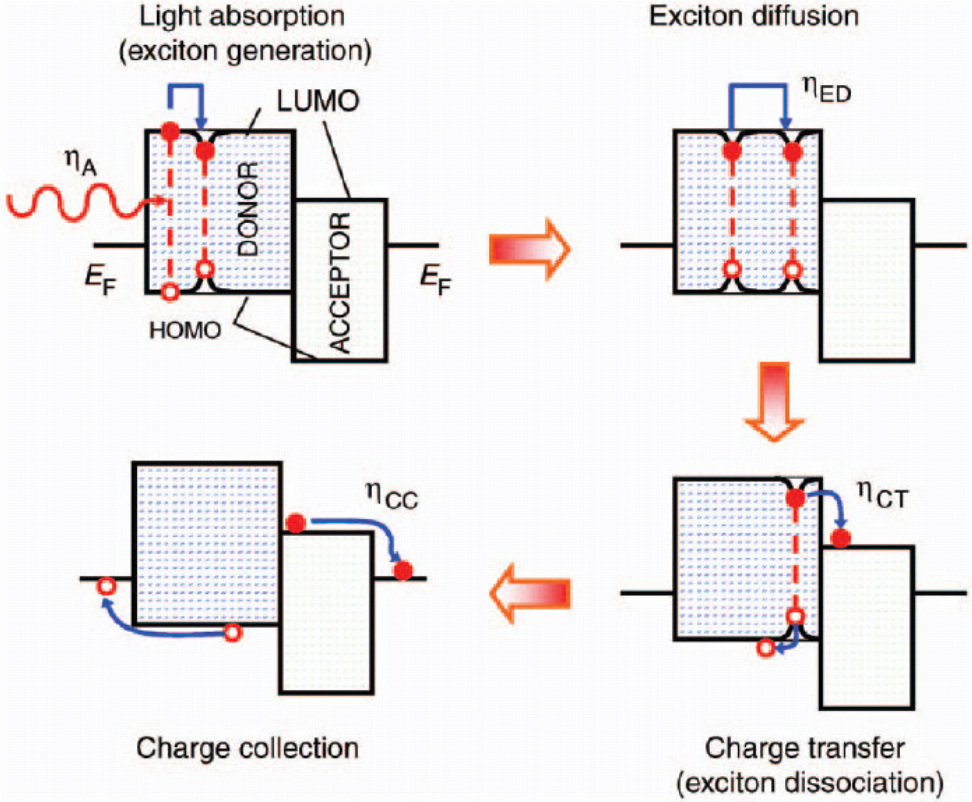
New Investigations: Organic Cells

HOMO= highest occupied molecular orbital (analogous to the top of valance band)

LUMO=lowest unoccupied molecular orbital (analogous to the bottom of conduction band)

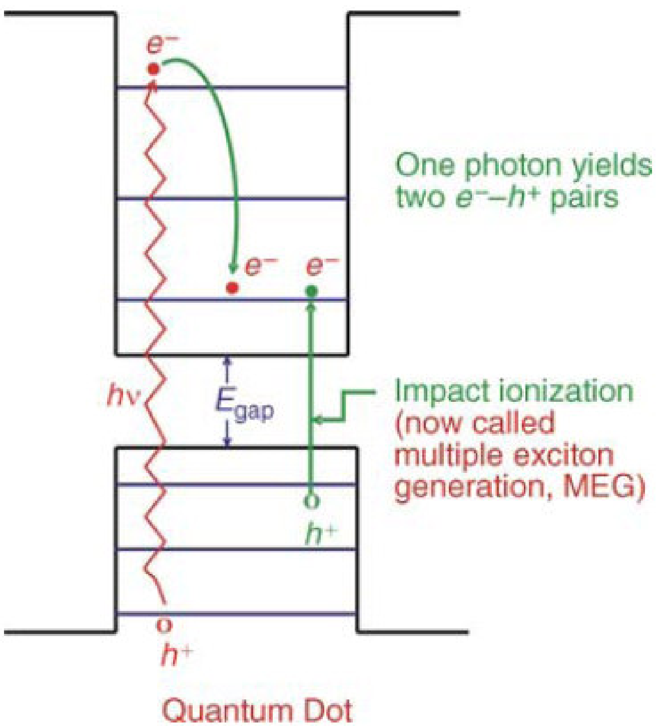


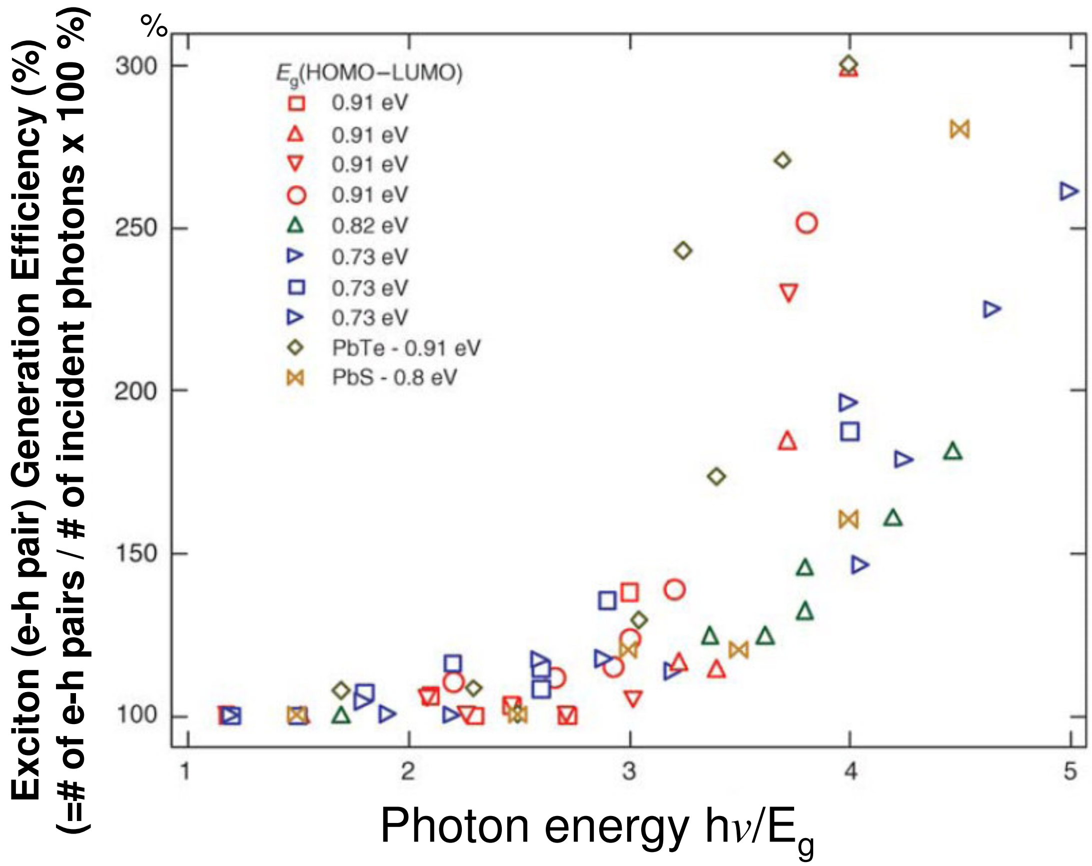
HOMO orbital of π electrons of a conjugated polymer



- Motivation: polymers currently much cheaper than inorganic semiconductor
- Conjugated polymers exhibit semiconductor behavior due to the delocalization of π electrons. Also exhibit good optical absorption.
- Challenges: (1) Hard to separate e-h pairs due to the high exciton binding energy (low dielectric constant) (2) Low mobility of carriers
- Max confirmed efficiency 5.4% so far
- Concerns: (1) Durability (2) Will polymers still be cheap if we run out of oil?

New Investigations: Quantum Dots/Nanostructrues





- Possible to generate multiple e-h pairs (excitons) in a quantum dot to partially compensate for the thermalization loss.
- However, these carriers are not "free" carriers yet since they are confined in the quantum dots. How to extract the carriers out is an important research topic.
- So far no direct demonstration of significant efficiency enhancement

Some Useful Sources on Solar Cells

- http://pvcdrom.pveducation.org/index.html
- MRS Bulletin, Mar. 2007 (Inorganic solar cells)
- MRS Bulletin, Jan. 2005 (organic solar cells)
- Solar Cell Efficiency Table, renewed annually in *Progress in Photovotaics*