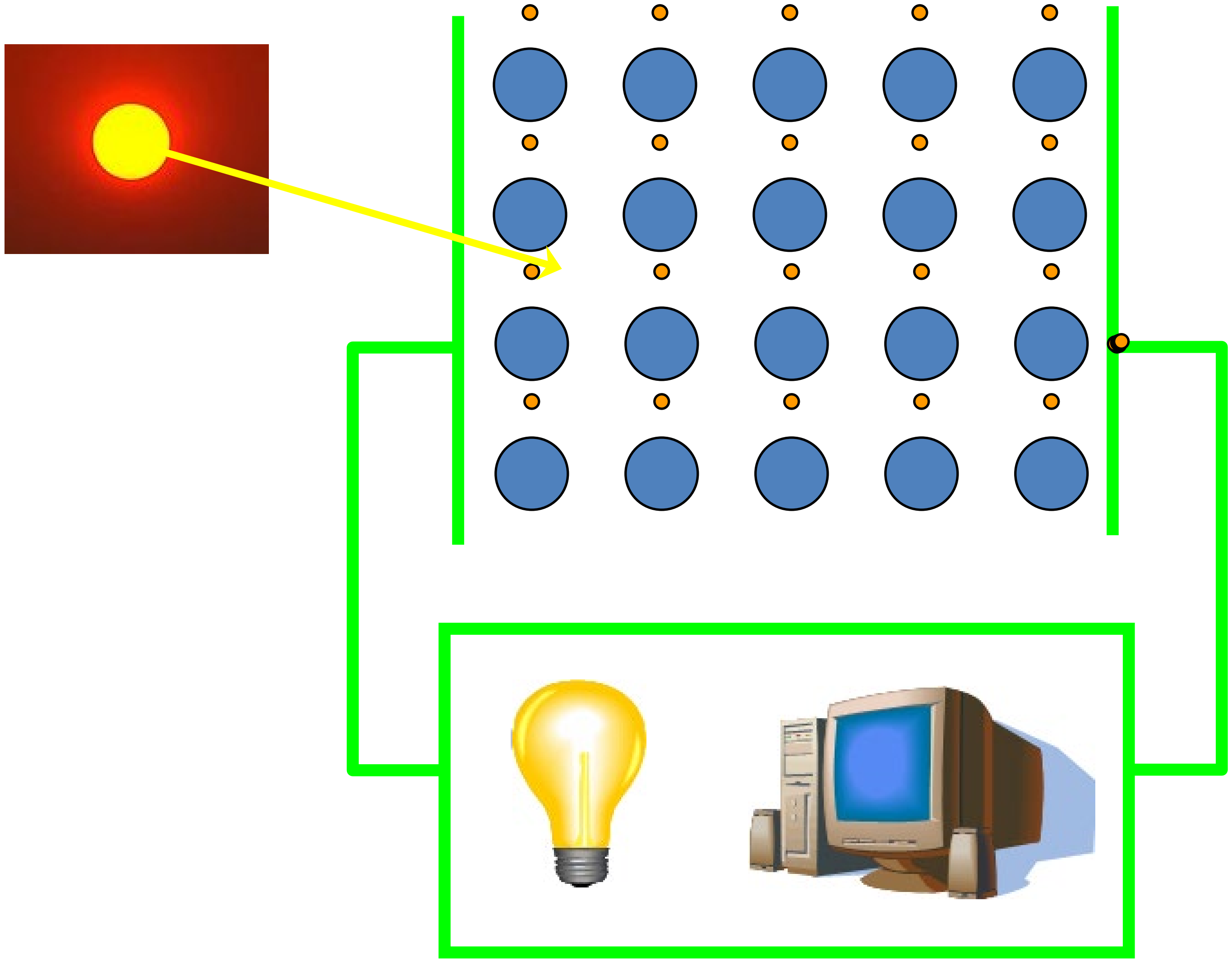
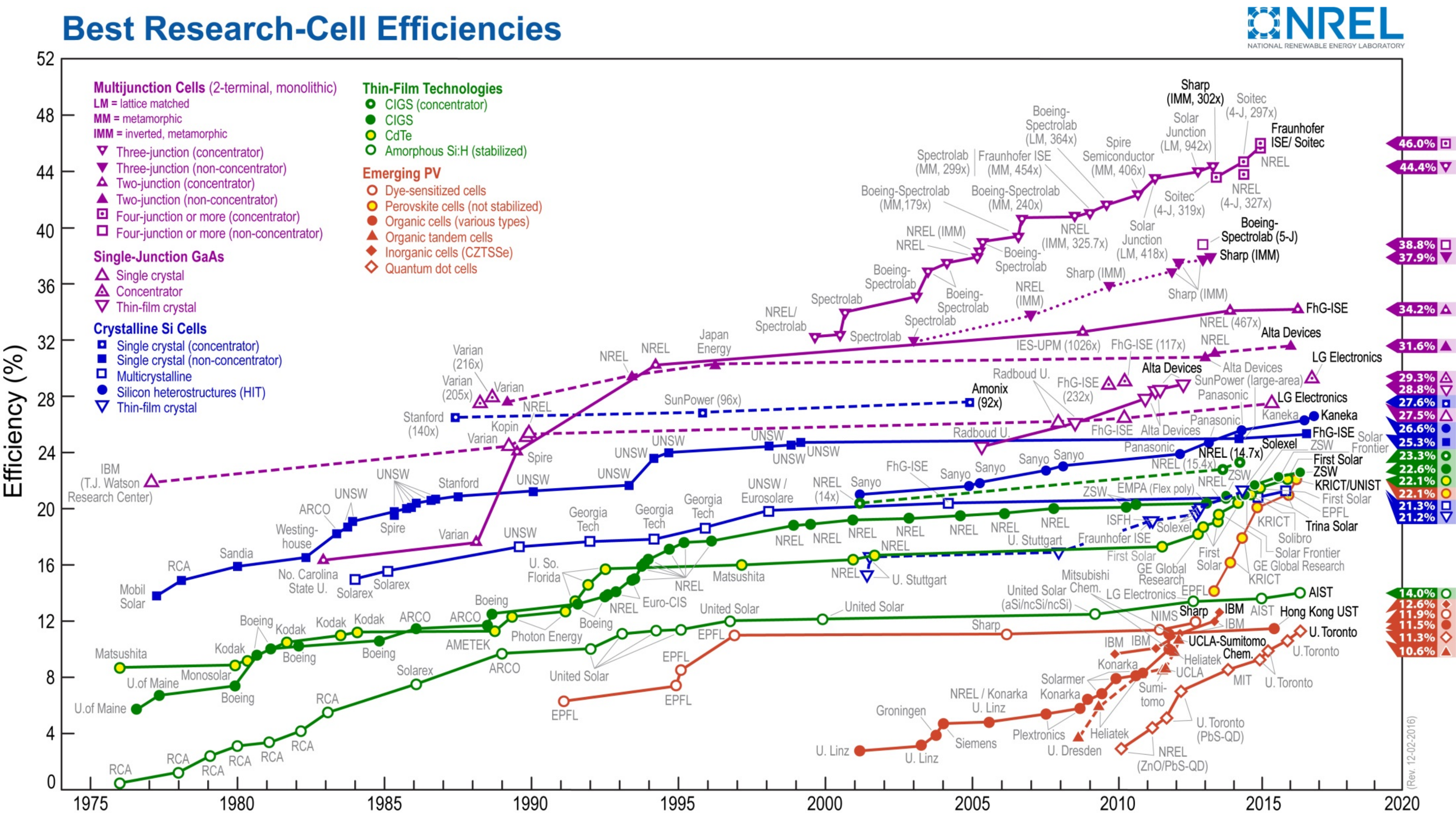
Lecture 1"B": Types of Solar Power Sources

Dr. Alan Doolittle* (needs reorganizing)

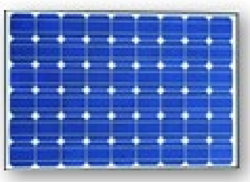
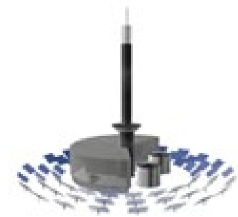
Solar Cells



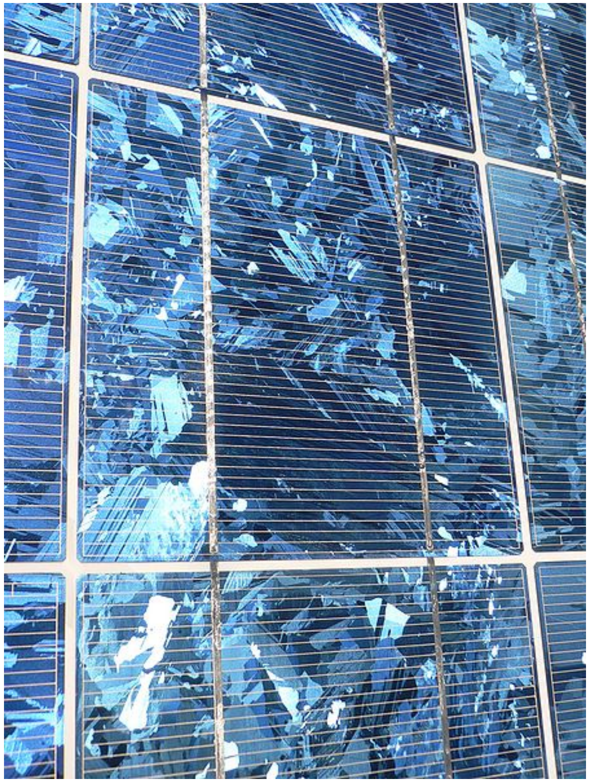

Best Research-Cell Efficiencies
NREL
NATIONAL RENEWABLE ENERGY LABORATORY
Efficiency (%)
52
48
44
40
36
32
28
24
20
16
12
8
4
0
1975
1980
1985
1990
1995
2000
2005
2010
2015
2020
Multijunction Cells (2-terminal, monolithic)
LM = lattice matched
MM = metamorphic
IMM = inverted, metamorphic
Three-junction (concentrator)
Three-junction (non-concentrator)
Two-junction (concentrator)
Two-junction (non-concentrator)
Four-junction or more (concentrator)
Four-junction or more (non-concentrator)
Single-Junction GaAs
Single crystal
Concentrator
Thin-film crystal
Crystalline Si Cells
Single crystal (concentrator)
Single crystal (non-concentrator)
Multicrystalline
Silicon heterostructures (HIT)
Thin-film crystal
Thin-Film Technologies
CIGS (concentrator)
CIGS
CdTe
Amorphous Si:H (stabilized)
Emerging PV
Dye-sensitized cells
Perovskite cells (not stabilized)
Organic cells (various types)
Organic tandem cells
Inorganic cells (CZTSSe)
Quantum dot cells
46.0%
44.4%
38.8%
37.9%
34.2%
31.6%
29.3%
28.8%
27.6%
27.5%
26.6%
25.3%
23.3%
22.6%
22.1%
22.1%
21.3%
21.2%
14.0%
12.6%
11.9%
11.5%
11.3%
10.6%
(Rev. 12-02-2016)

Photovoltaic vs Solar Thermal

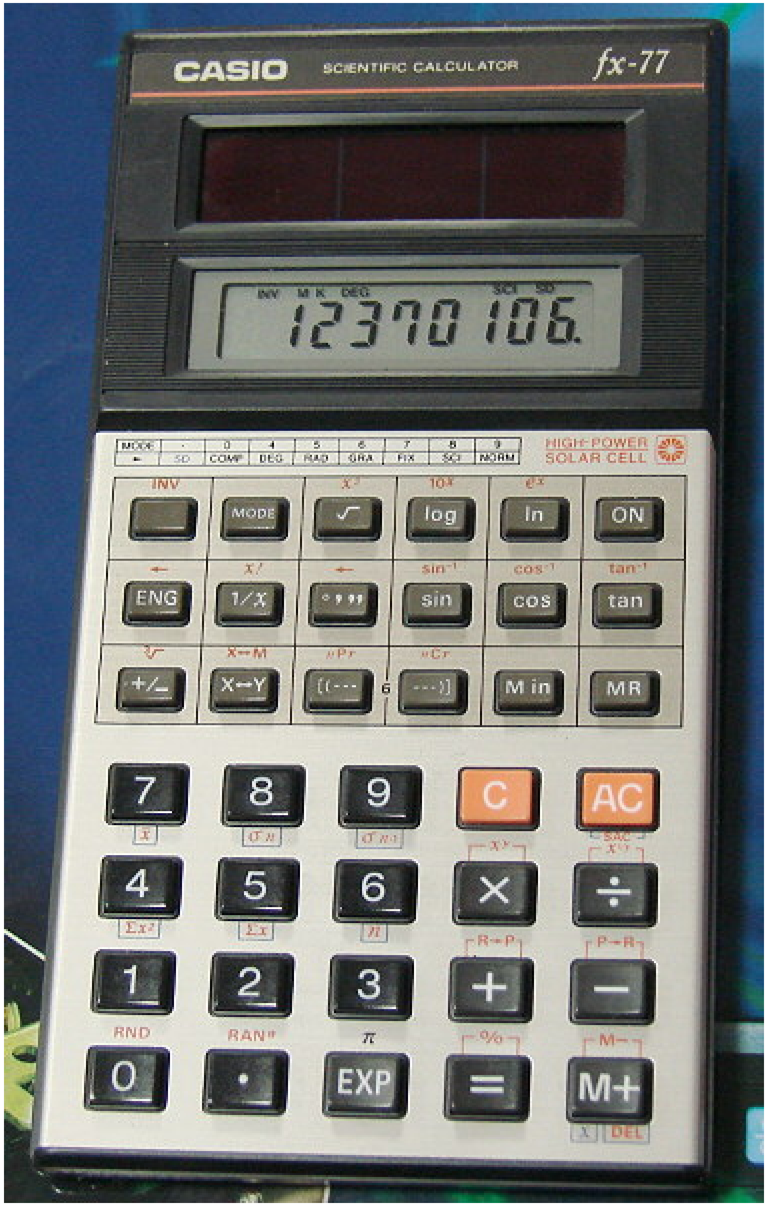
SOLAR TECHNOLOGY LANDSCAPE

Photovoltaic		Solar Thermal			
TRADITIONAL PV	CPV	DISH ENGINE	TROUGH	TOWER	FRESNEL REFLECTOR
					
PV cells (usually silicon based) convert solar energy directly into electrical energy	Mirrors or lenses focus sunlight onto multi-junction PV cell	Dual axis radial concentrator collector made of curved mirrors tracks and focuses sunlight onto Stirling Engine.*	Rows of trough shaped mirrors direct concentrated radiation onto receiver tube	Sun tracking mirrors focus sunlight onto a central receiver (usually tower mounted)	Similar to trough but uses flat (Fresnel) mirrors to concentrate light
<10kW to 10MW	100kW to 100MW	100kW to >100MW	50kW to >100MW	500kW to >100MW	50kW to >100MW

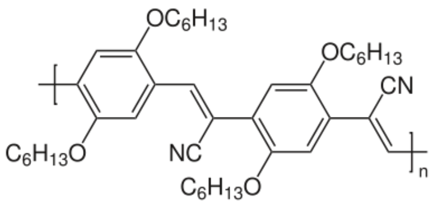
Flat Plate PV - Si



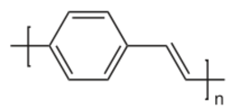
Flat Plate PV – Amorphous Si



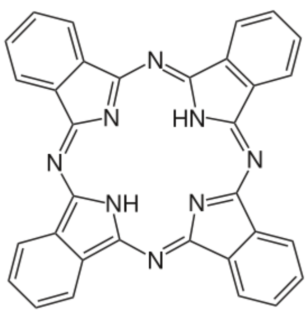
Flat Plate PV – Organic Solar Cells



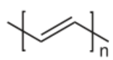
CN-PPV



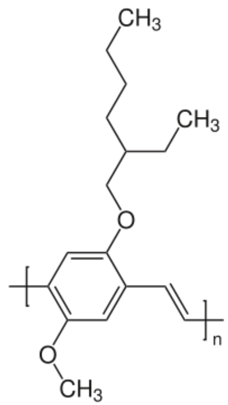
poly(phenylene vinylene) (PPV)



phthalocyanine



polyacetylene



MEH-PPV

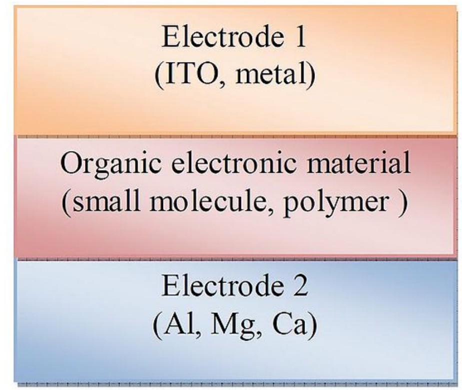
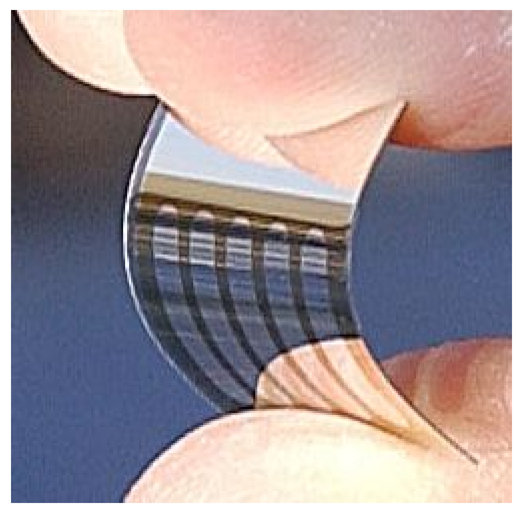
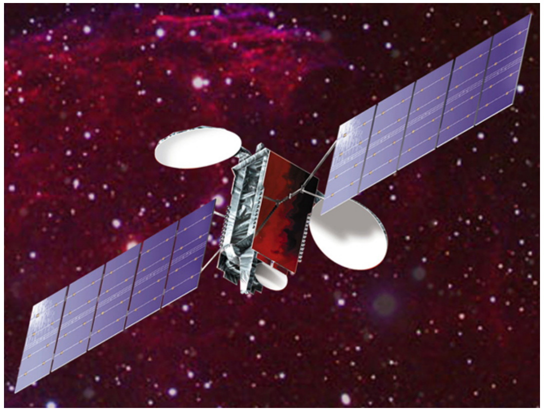


Fig 2. sketch of single layer organic photovoltaic cell

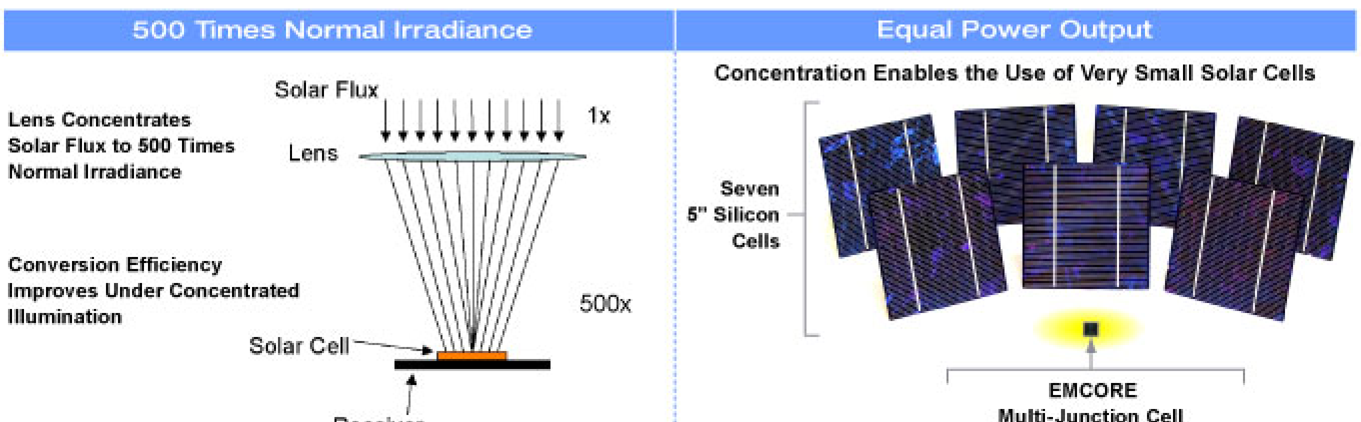


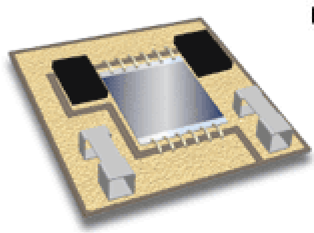
The new organic solar cells are light and flexible.
Credit: Nicole Cappello and the Georgia Institute of Technology

Space Cells

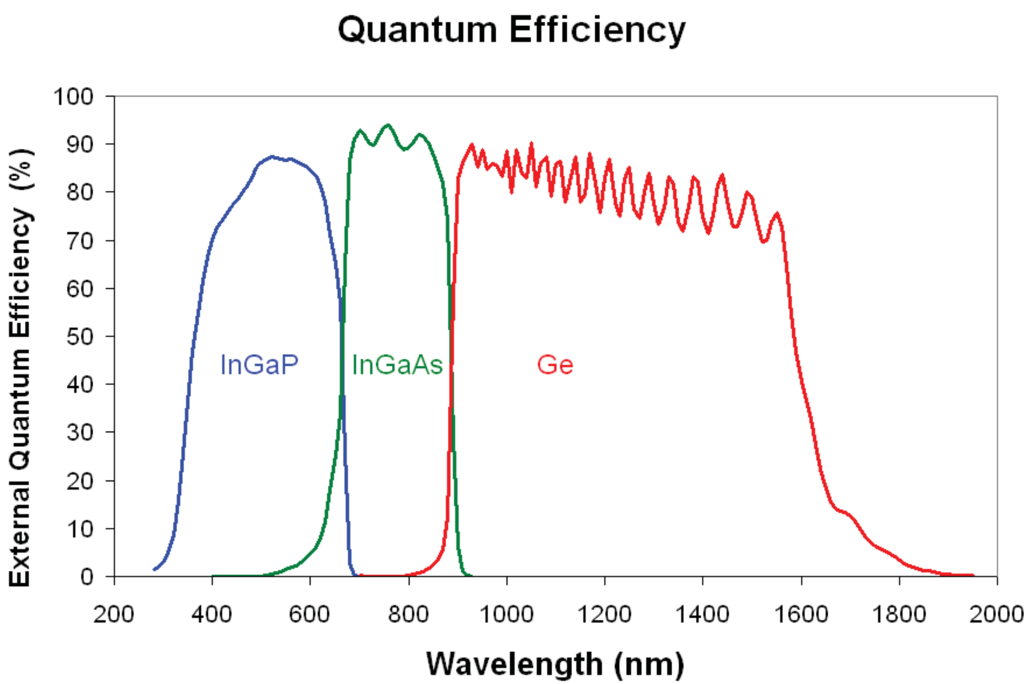


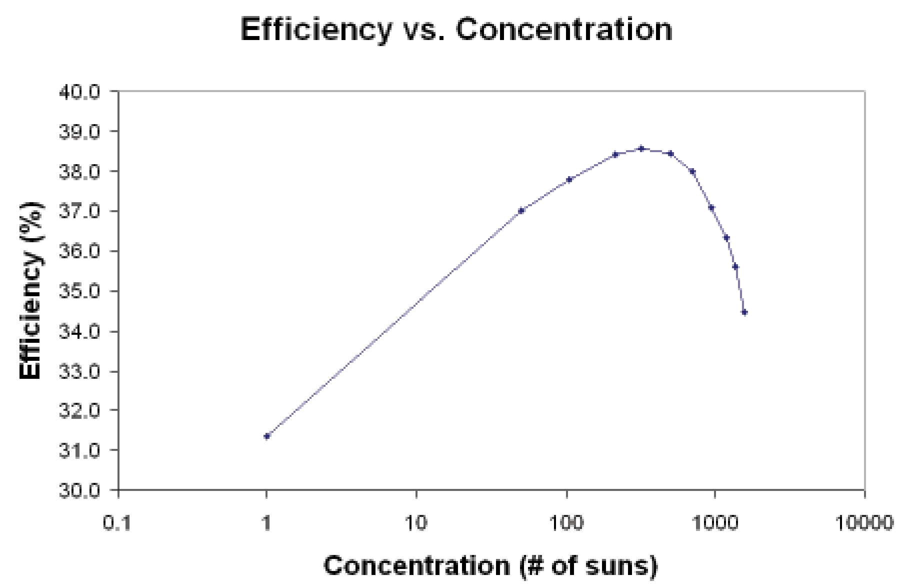
Space Cells Come to Earth – Concentrator PV





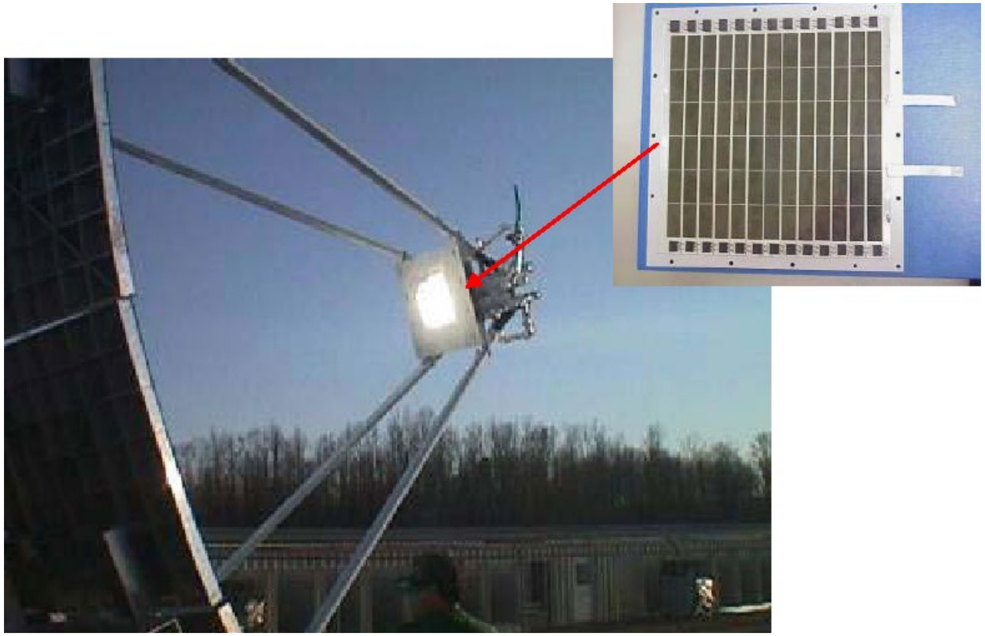
Space Cells Come to Earth – Concentrator PV





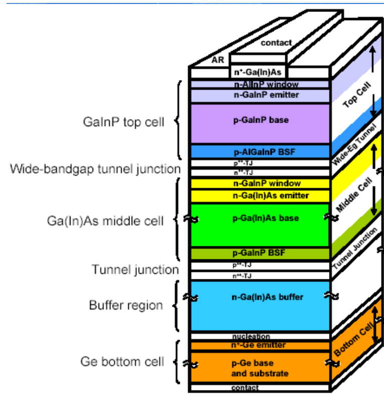
Multijunction (Tandem) Solar Cells

- Monolithic III-V tandem solar cells; Series connected; three or more junctions
- High efficiency used in high concentration, two-axis tracking systems
- High concentration means small area (and lower cost) needed for solar cells
- Trade balance of systems and solar cell cost.

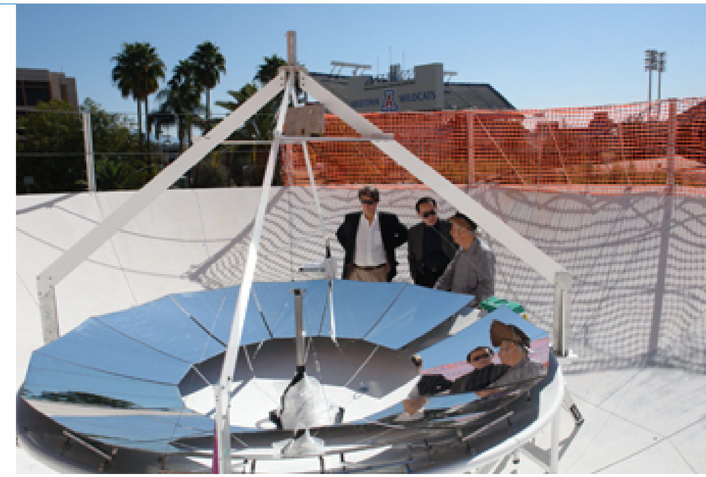


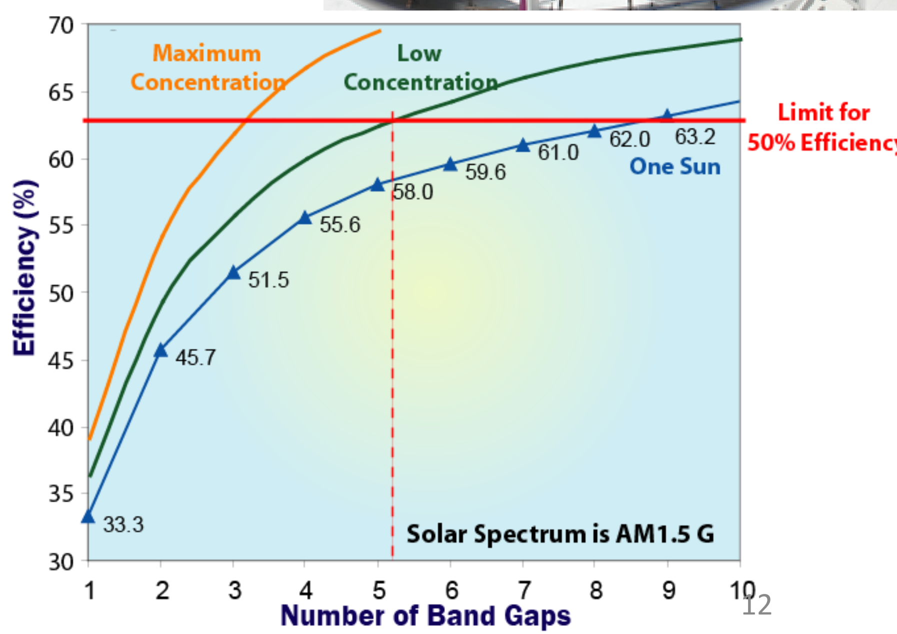
Multiple Junction (Tandem) Solar Cells

- Concentration (CPV) or stacking multiple solar cells increases efficiency
- Costs
  - Substrates
  - Materials growth
  - Optical efficiency
  - Tracking
  - Structure
  - Reliability

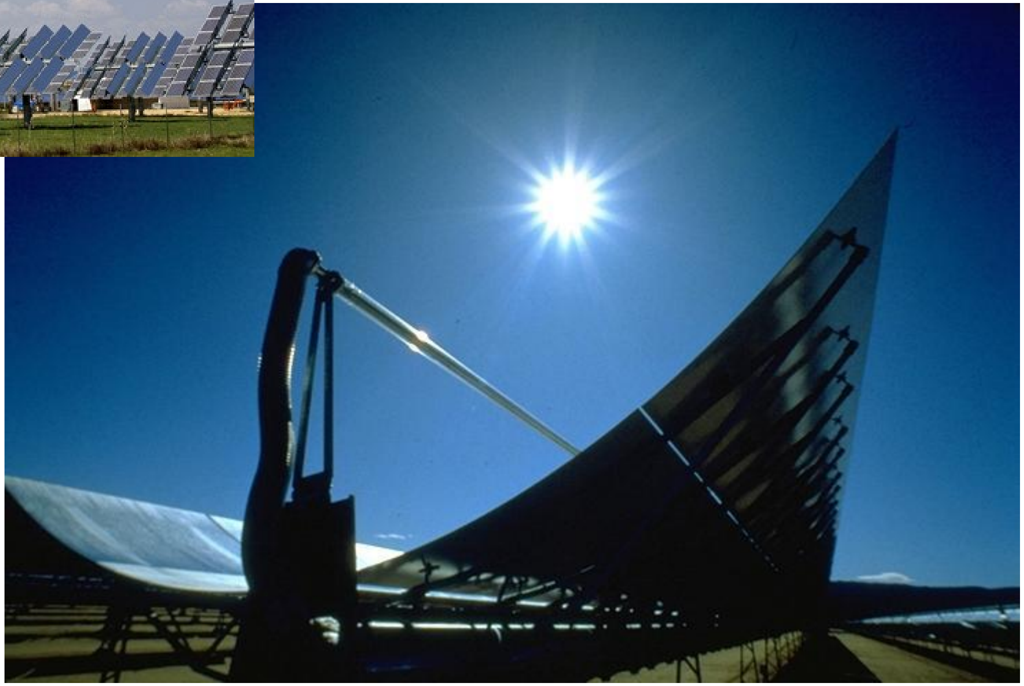


Lattice-Matched (LM)

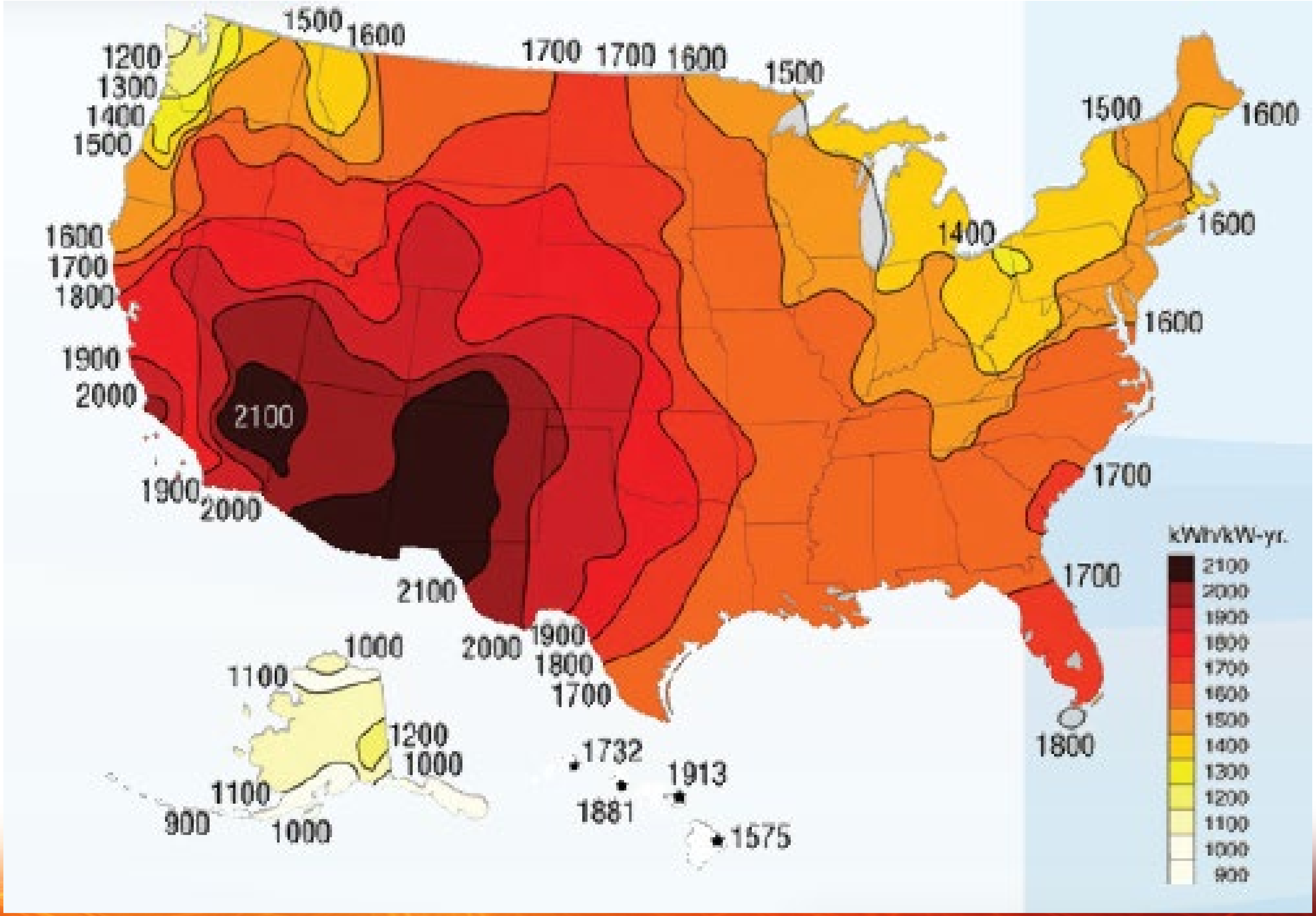




Thermal Solar – NOT PV

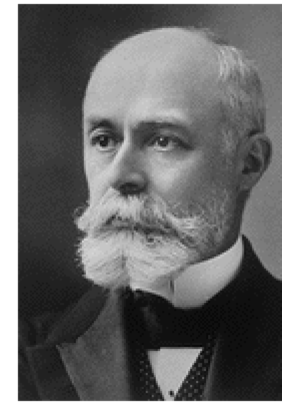


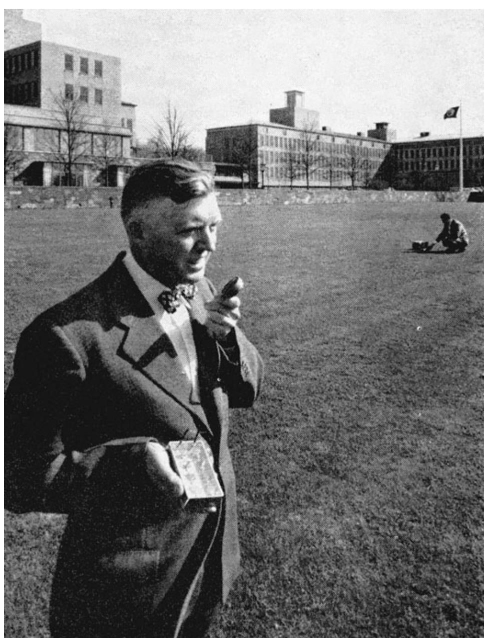
Solar Energy Distribution

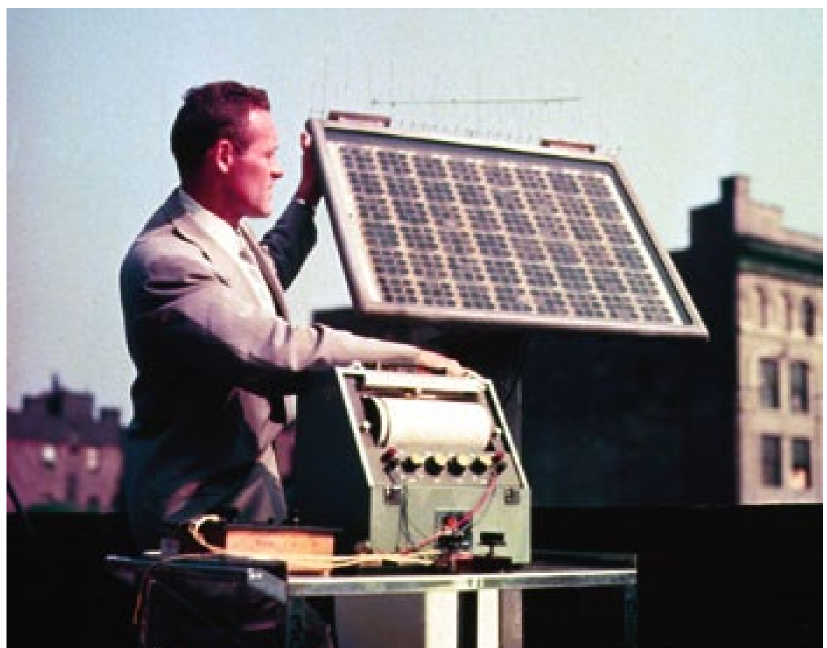


Overview of Photovoltaics

- Direct conversion of sunlight into electricity via the photovoltaic effect
- Photovoltaic effect first discovered by Bequerel (1939); Se/Au solar cell (C. Fritts, 1883)
- Modern junction solar cell (R. Ohl, 1946)
- Silicon junction formation allowed formation of first practical devices, at Bell Labs (1954)







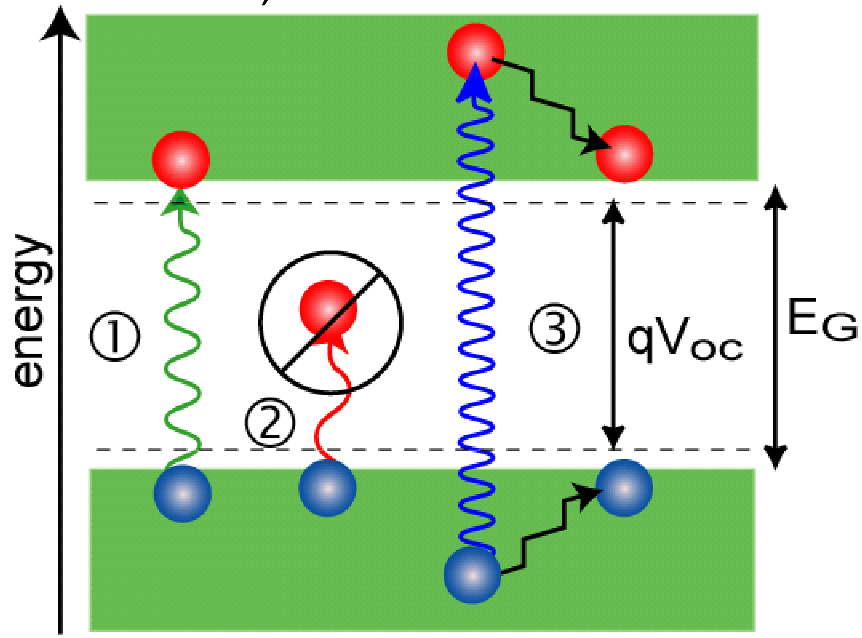
Why and where t… taics

- Features of Photovoltai…
  - High efficiency
  - Distributed energy sourc…
  - Low energy payback tim…
  - Clean energy source
  - Low water usage
  - Modular
- Markets
  - Remote area power
  - Grid-connected: residen… and utility
  - Niche markets

2-Level System and Optical Absorption

- Most optical absorption processes involve excitation of an electron from a filled state, across an energy gap to an unoccupied state

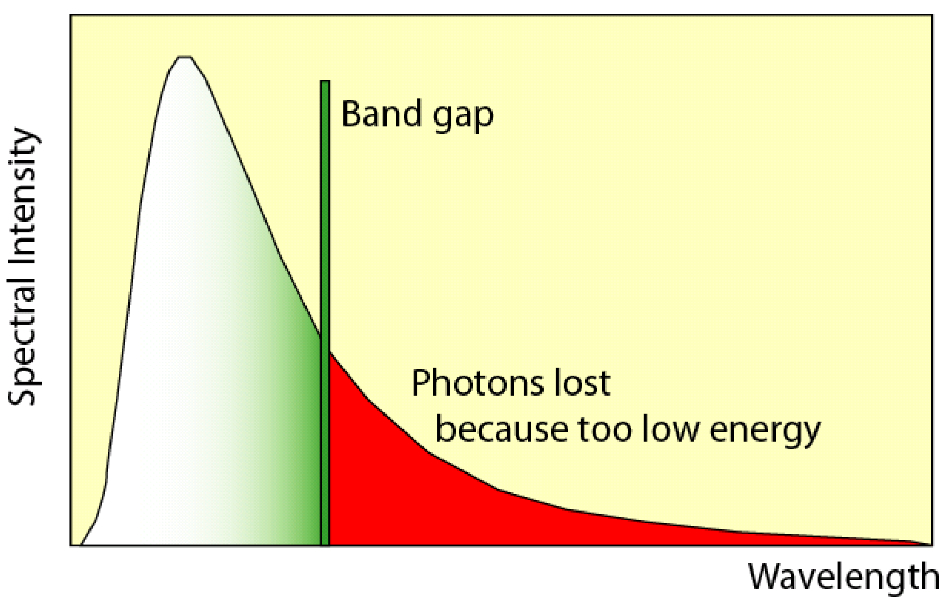
LUMO; Conduction Band

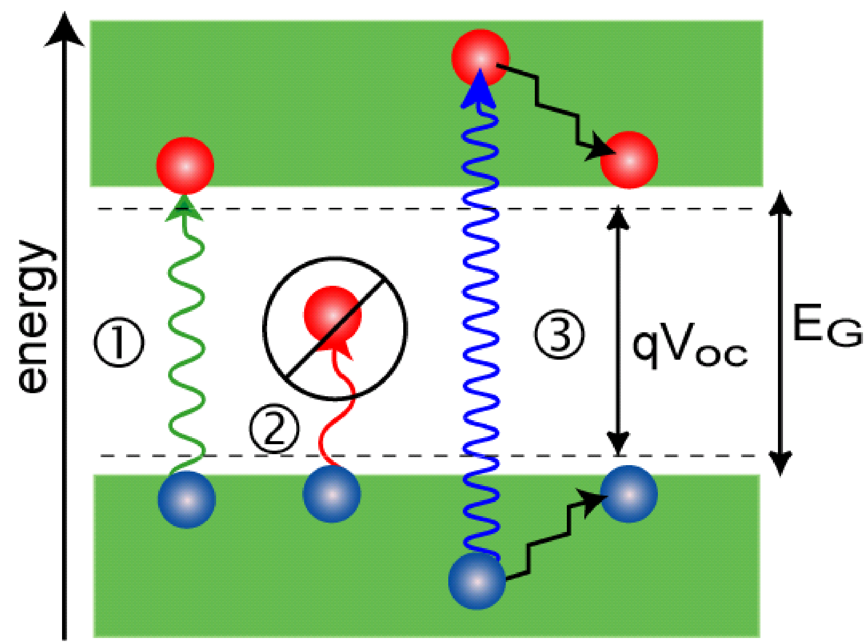


HOMO; Valence Band

Solar Energy Conversion Efficiencies

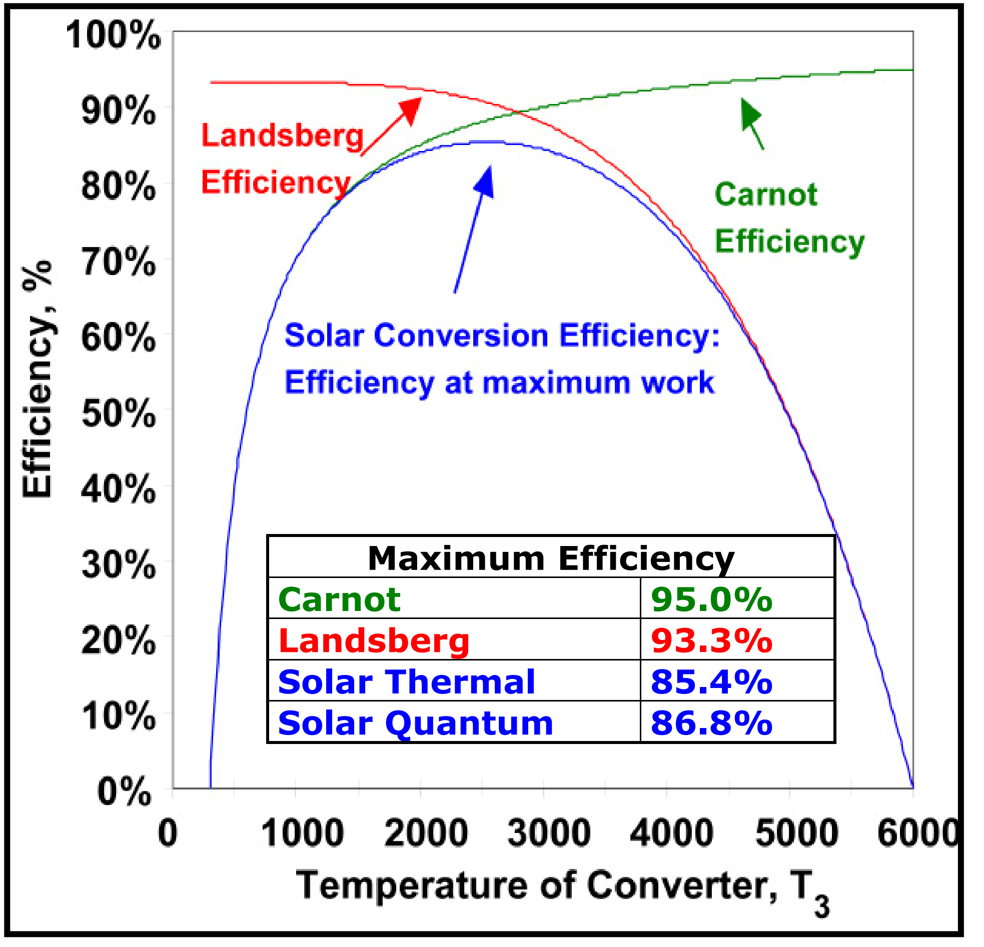
- Losses primarily arise from large range of photon energies in incident spectrum and ability to only utilize energy = band gap.
- In a solar cell, detailed balance calculations quantify these losses, giving single junction efficiency = 30.8% under one sun and 40.8% under max concentration (Shockley-Queisser)





Thermodynamic Efficiencies of Solar Converters

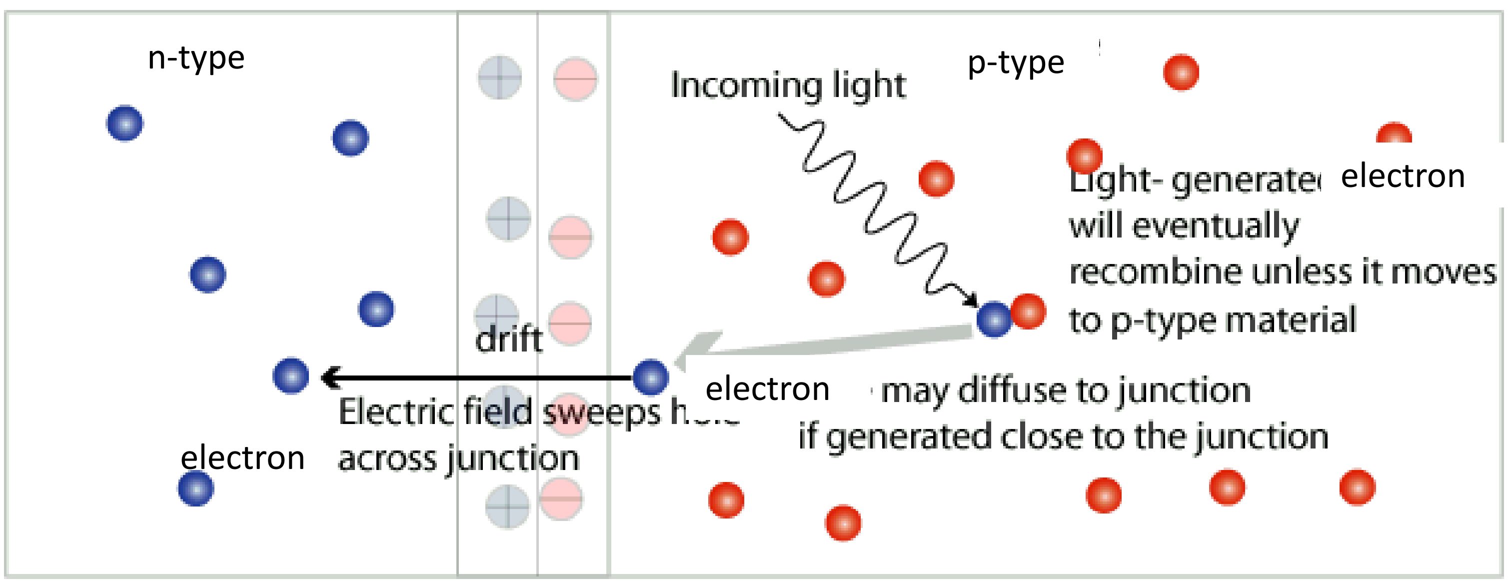
- Carnot Efficiency
  - NET flux as input
  - Max η at 0 work
  - Do NOT want to operate at Carnot efficiency
- Landsberg Efficiency
  - Solar flux as input
  - Max η at 0 work
- Solar Energy Efficiency
  - Maximum work
  - Solar flux as input
  - Conversion process can be either solar thermal or solar quantum



Maximum Efficiency	
Carnot	95.0%
Landsberg	93.3%
Solar Thermal	85.4%
Solar Quantum	86.8%

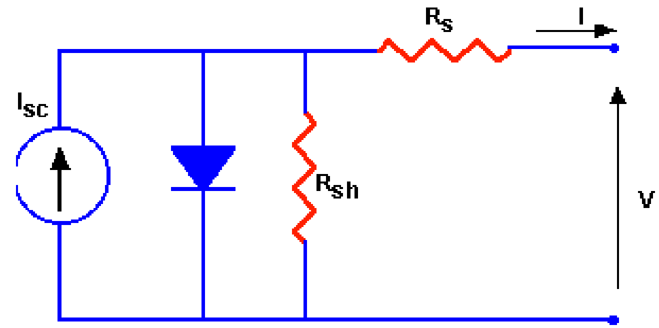
Photovoltaic Energy Conversion

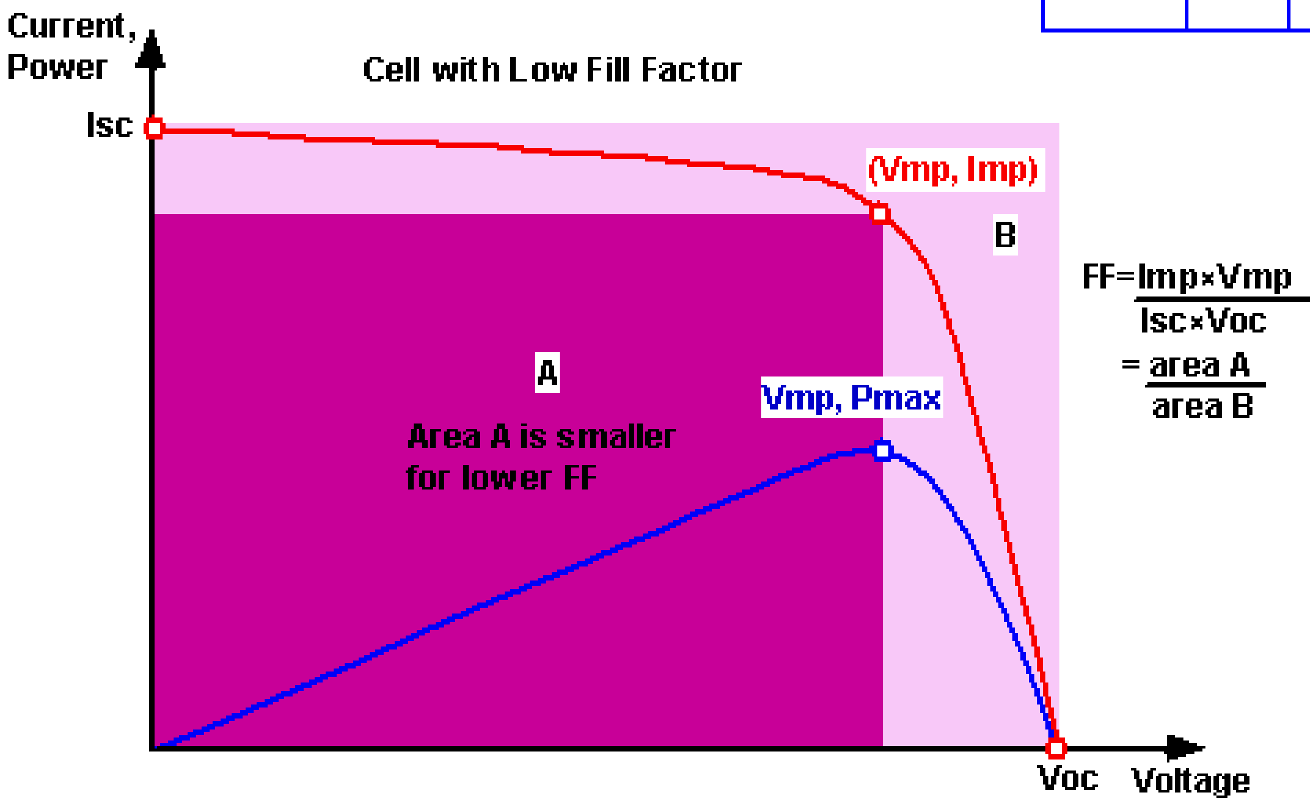
- **A light generated minority carrier can readily recombine.**
- **If it the carrier reaches the edge of the depletion region, it is swept across the junction and becomes a majority carrier. This process is collection of the light generated carriers.**
- **Once a carrier is collected, it will not recombine.**



Phototovoltaic Energy Conversion

FF strongly affected by parasitic series and shunt resistances.



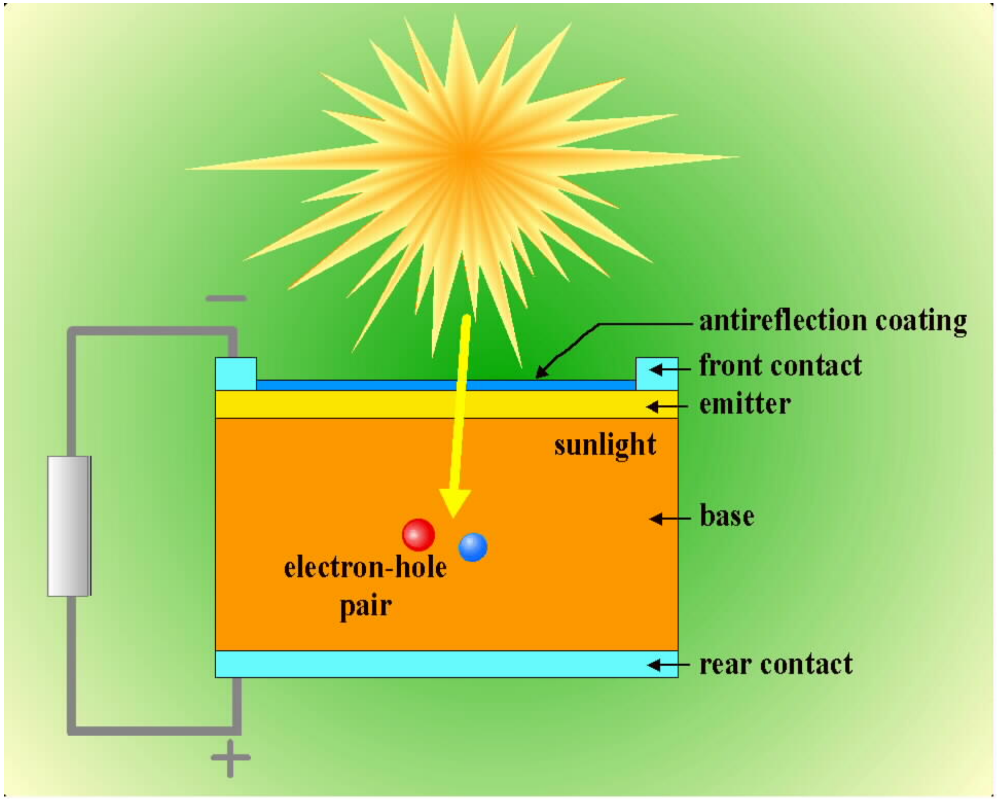


$$\eta = \frac{V_{oc} I_{sc} FF}{P_{in}}$$

Short Circuit Current

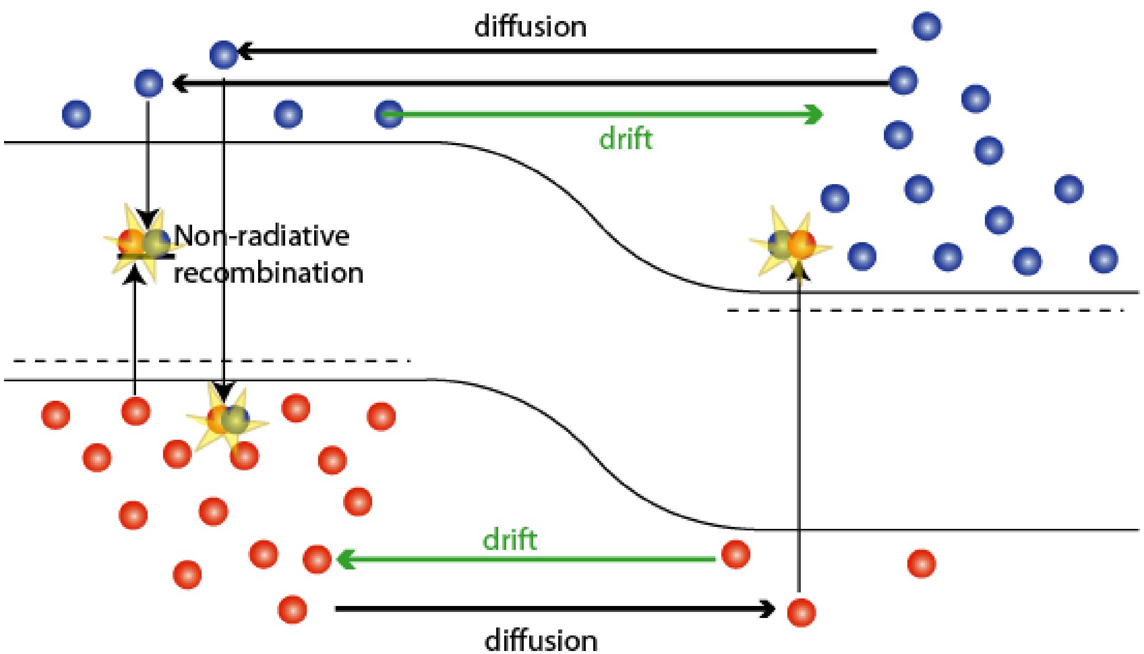
J_{sc} depends on:

1. Generation of light-generated carries
   - Minimize reflection
   - Absorb light in semiconductor and generate carriers
   - Reflection and absorption depend on characteristics of sunlight, solar cell optical properties, E_G, and solar cell thickness
2. Collection of light generated minority carriers
   - Depends on material and device parameters



Recombination

- Recombination may occur at surfaces/interfaces, bulk, metal contacts, defects.
- Any recombination source within a diffusion length of junction reduces Voc



Solar Cell Technologies

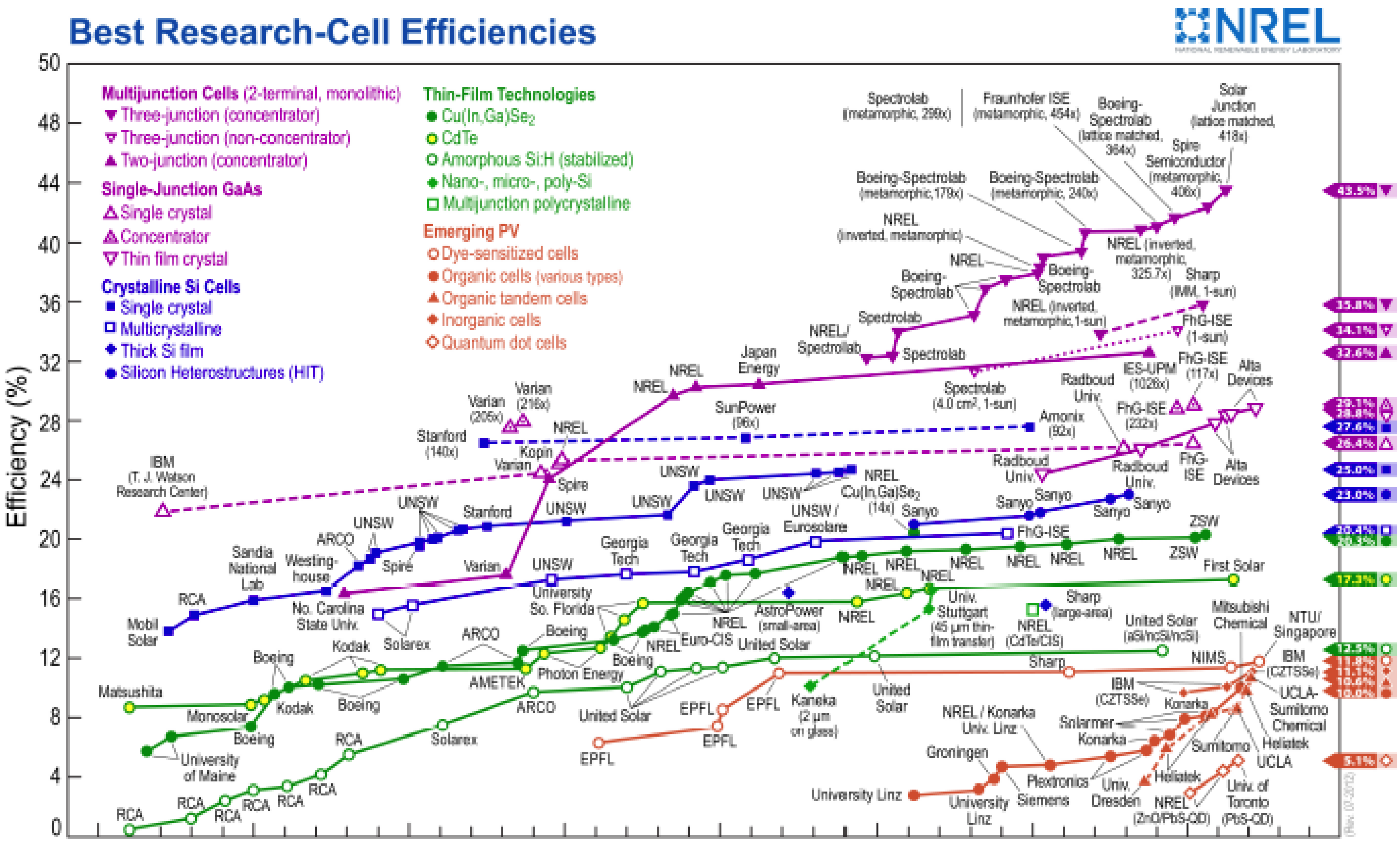
Established technologies

- *First Generation*: Silicon (single and polycrystalline)

  III-V solar cells
  - GaAs/AlGaAs
  - GaAs/InGaAsP
  - InP
- *Second Generation*: Thin Film
  - $CuInSe_2$ (CIS)
  - $CuInGaSe_2$ (CIGS)
  - CdTe
  - Amorphous Si (a-Si)
  - Organic

IB	IIB	IIIA	IVA	VA	VIA	VIIA	VIIIA
							2 He 4.003
		5 B 10.811	6 C 12.011	7 N 14.007	8 O 15.999	9 F 18.998	10 Ne 20.183
		13 Al 26.982	14 Si 28.086	15 P 30.974	16 S 32.064	17 Cl 35.453	18 Ar 39.948
29 Cu 63.54	30 Zn 65.37	31 Ga 69.72	32 Ge 72.59	33 As 74.922	34 Se 78.96	35 Br 79.909	36 Kr 83.80
47 Ag 107.870	48 Cd 112.40	49 In 114.82	50 Sn 118.69	51 Sb 121.75	52 Te 127.60	53 I 126.904	54 Xe 131.30
79 Au 196.967	80 Hg 200.59	81 Tl 204.37	82 Pb 207.19	83 Bi 208.980	84 Po (210)	85 At (210)	86 Rn (222)

- *Third Generation*
  - Multi-junction
  - Nanotechnology advanced concept
  - Organic (advanced concept)
  - Dye sensitized solar cells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Single crystal
Multicrystalline
Thick Si film
Silicon Heterostructures (HIT)
Thin-Film Technologies
Cu(In,Ga)Se2
CdTe
Amorphous Si:H (stabilized)
Nano-, micro-, poly-Si
Multijunction polycrystalline
Emerging PV
Dye-sensitized cells
Organic cells (various types)
Organic tandem cells
Inorganic cells
Quantum dot cells
Efficiency (%)
43.5%
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25.0%
23.0%
20.4%
17.3%
12.5%
11.8%
11.1%
10.6%
10.0%
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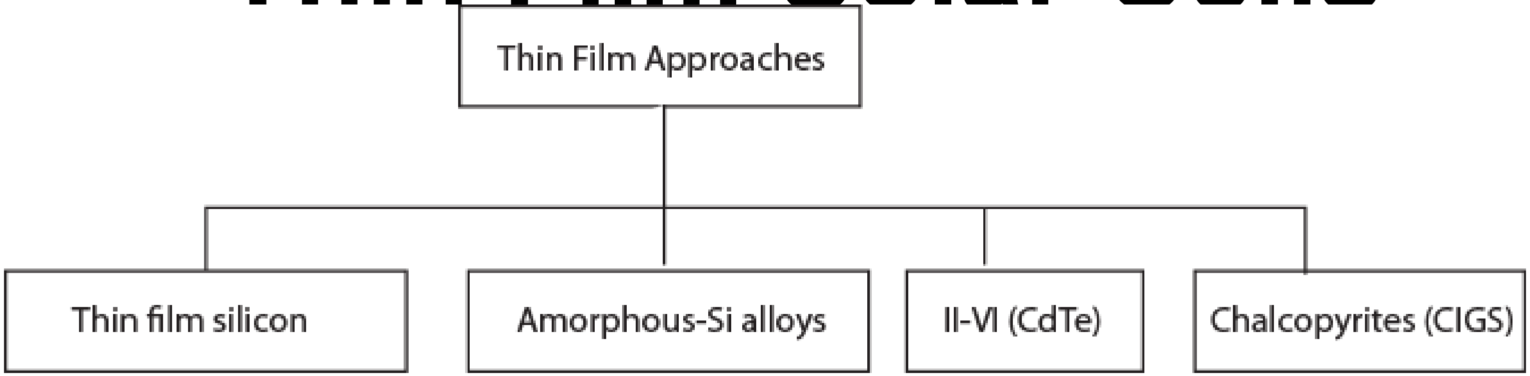
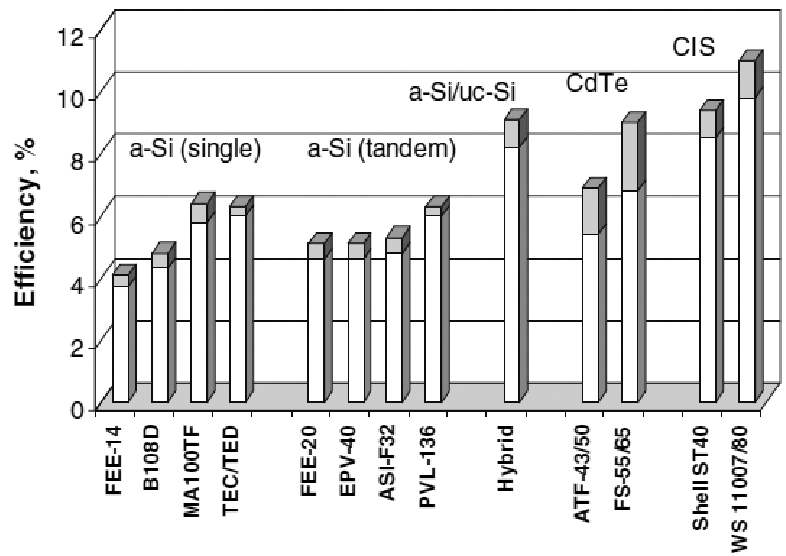
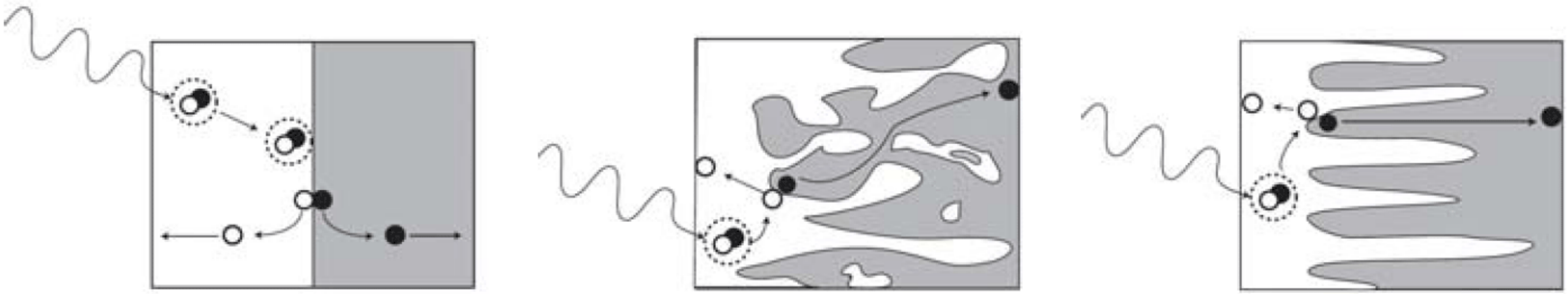
Thin Film Solar Cells



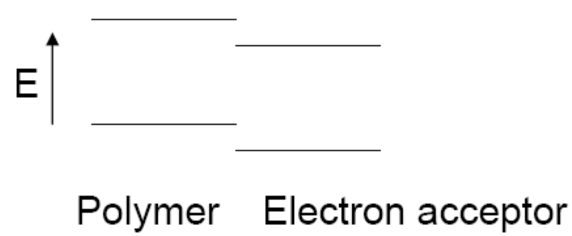
- **In large scale production, cost of the materials dominates the overall solar cells cost.**
- **Goal of thin film approaches is to minimize the materials usage while retaining acceptable efficiency**
- **Central issue is achieving high enough efficiency and cost-efficient deposition approaches**



Organic and Perovskite Solar Cells



Yang, F.; Shtein, M.; Forrest, S. R. "Controlled growth of a molecular bulk heterojunction photovoltaic cell," *Nat. Mater.* 2005, *4*, 37-41.

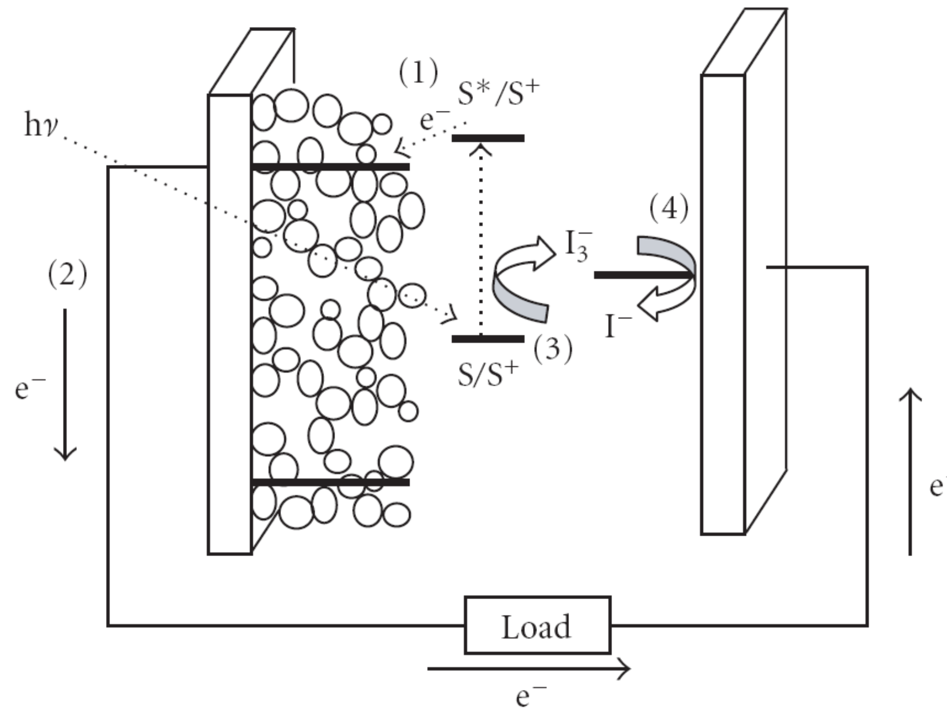


absorber	electron acceptor		Energy conversion efficiency (AM 1.5)
Polymer	C_{60} derivative	Heeger	4.9 %
Polymer	polymer	Friend	1.9 %
Polymer	CdSe nanorods	Alivisatos	1.7 %
Polymer	ZnO nanocrystal	Janssen	1.6 %

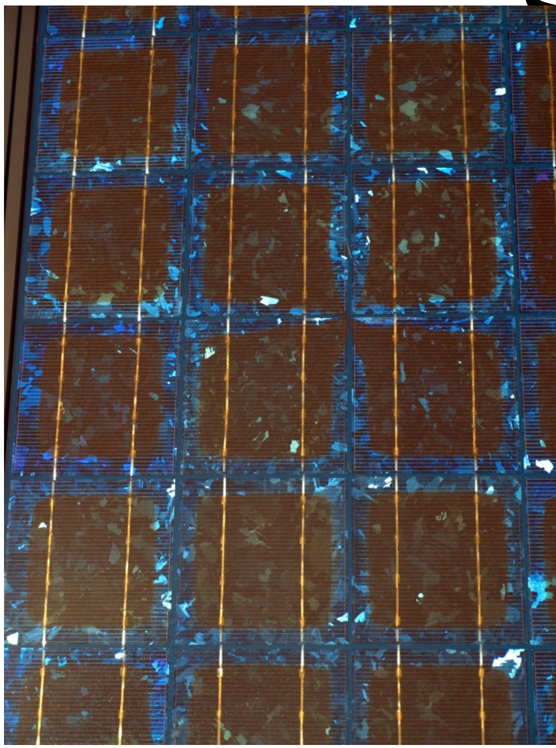
M. McGehee, Stanford

Dye-Sensitized Solar Cells

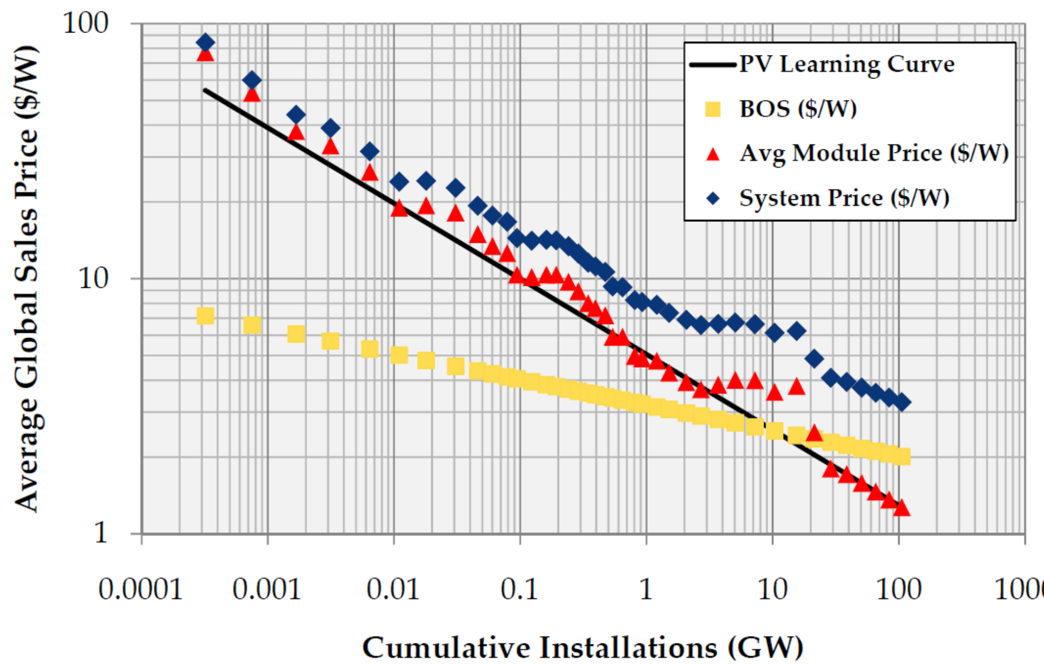
- Voltage is controlled (assuming ideal contacts) by difference between CB of semiconductor charge state of redox.
- Efficient light absorption requires large surface area of TiO2 to which the dye is attached.
- Efficiency limited by:
  - Absorption by dye
  - Low Voc due to recombinati
  - Low FF due to series resistance, non-ideal recombination
- Other common issue is stal associated with the liquid electrolyte



Sol



- Module
- Inverter
- Balance of Systems
- Storage
- Installation



Si Solar Modules

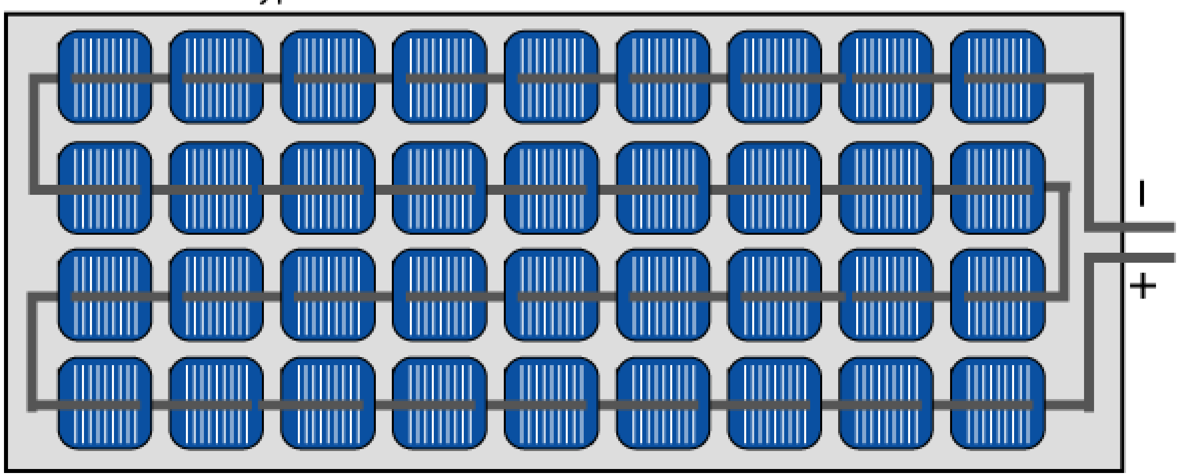
A typical module consists of 36 series connected cells for battery charging (15-16V required):

V≈ 36x0.6 = 21 volts max, and 17-18V at max power and operating temperature

I ≈ 30 to 36 mA/cm^2 x 100cm^2 = 3-3.5A

Power ≈ 70 watts

A typical module has 36 cells connected in series



Module Structure

≈ 36 individual cells are encapsulated in a single stable unit

- mechanical protection
- protection from the environment (water vapor)
- protect the user from electrical shock

Rear view of PV module before encapsulation.

The module consists of the solar cell sandwiched between EVA (a clear polymer), with glass on the front and Tedlar on the rear.

Module Connections – Blocking Diodes

Blocking Diode:

- Only allows current out of the module array
- Prevents discharging of batteries during non-producing times