Solar Photovoltaics, AUA Solar System

IE350

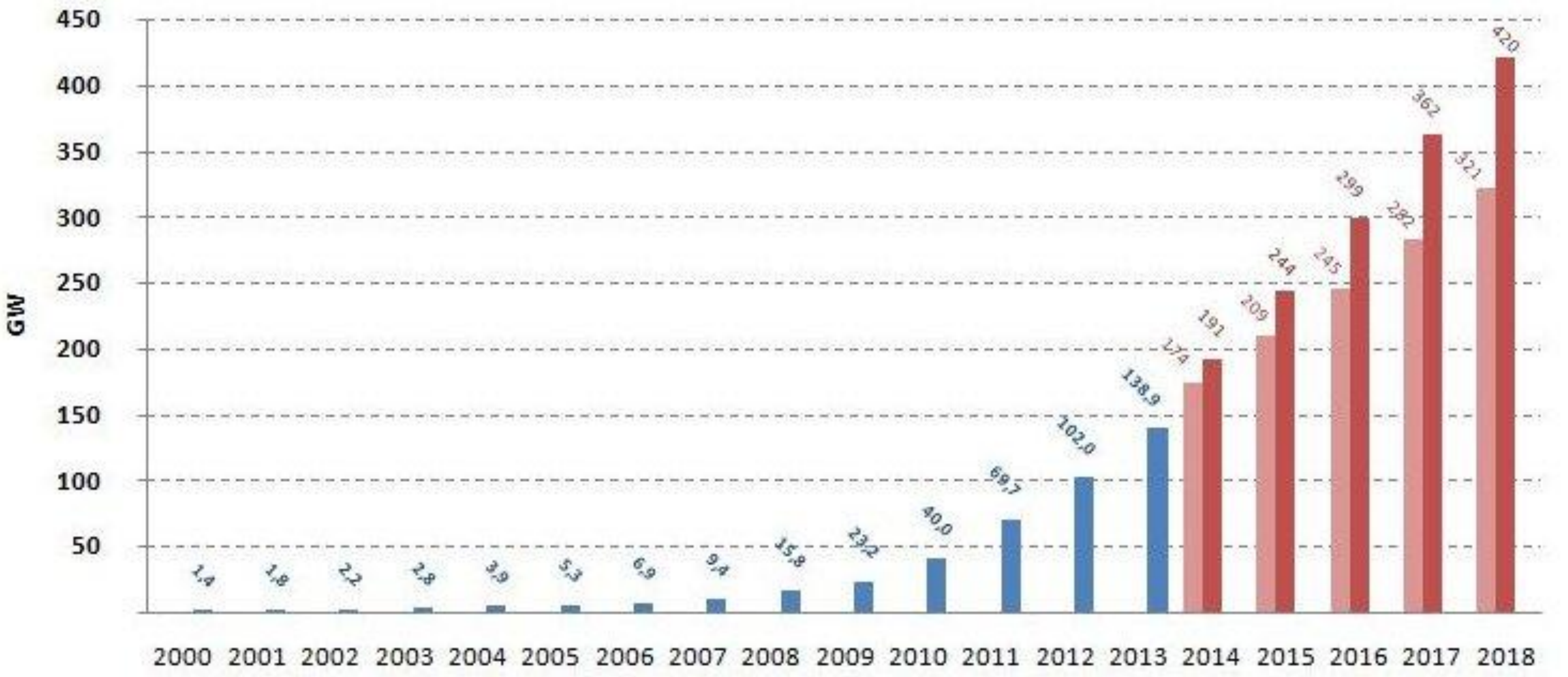
Photovoltaics - PV

- Photo Voltaic effect – phenomenon, when light energy directly converts into electricity.
- First was detected in 1839 by French physicist Alexandre-Edmond Becquerel.
- A quintessential source of energy – operation is absolutely clean environmentally, no moving parts.
- However its production process is not perfect, but overall PV performs environmentally much better than any other source.

Trend: PV capacity growth EPIA

- European Photovoltaic Industry Association -

forecast 2014-2018



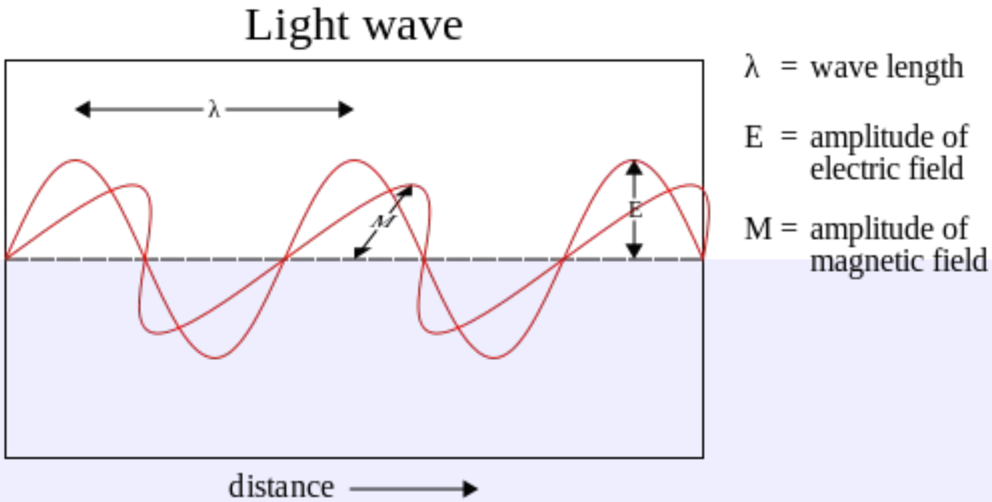
Photovoltaics: Principles

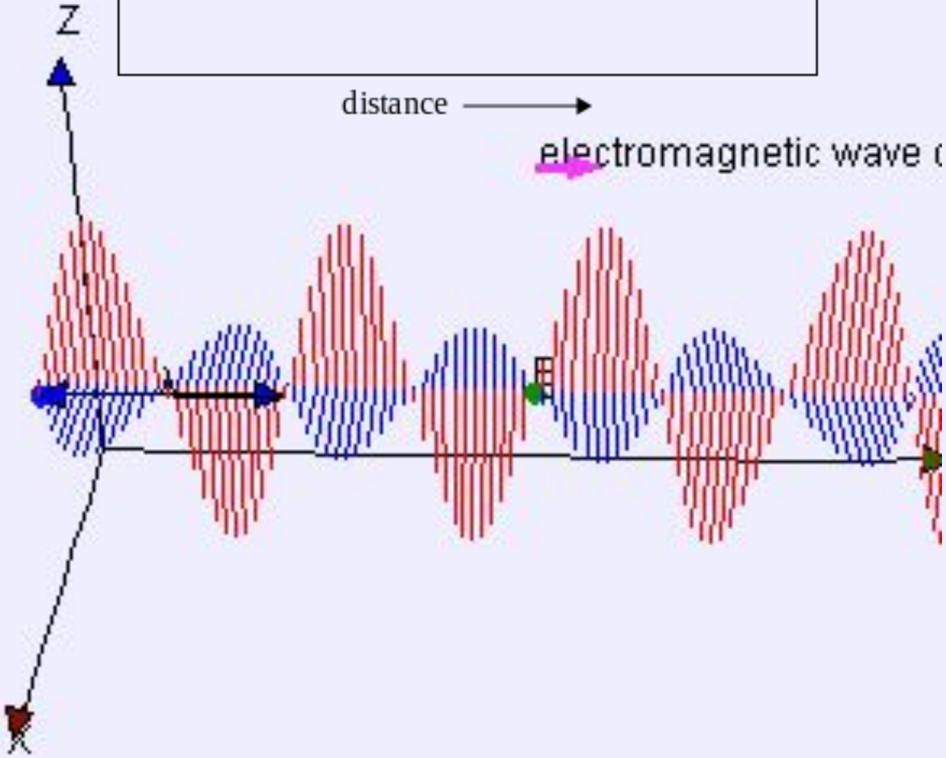
- Introduction - Quantum mechanics
- Physical principles of Photovoltaic (PV) Conversion
- Efficiency, degradation, price
- Various realizations:
  - flat panel
  - concentrator
  - tracking/non-tracking
- Materials: Si, Thin film

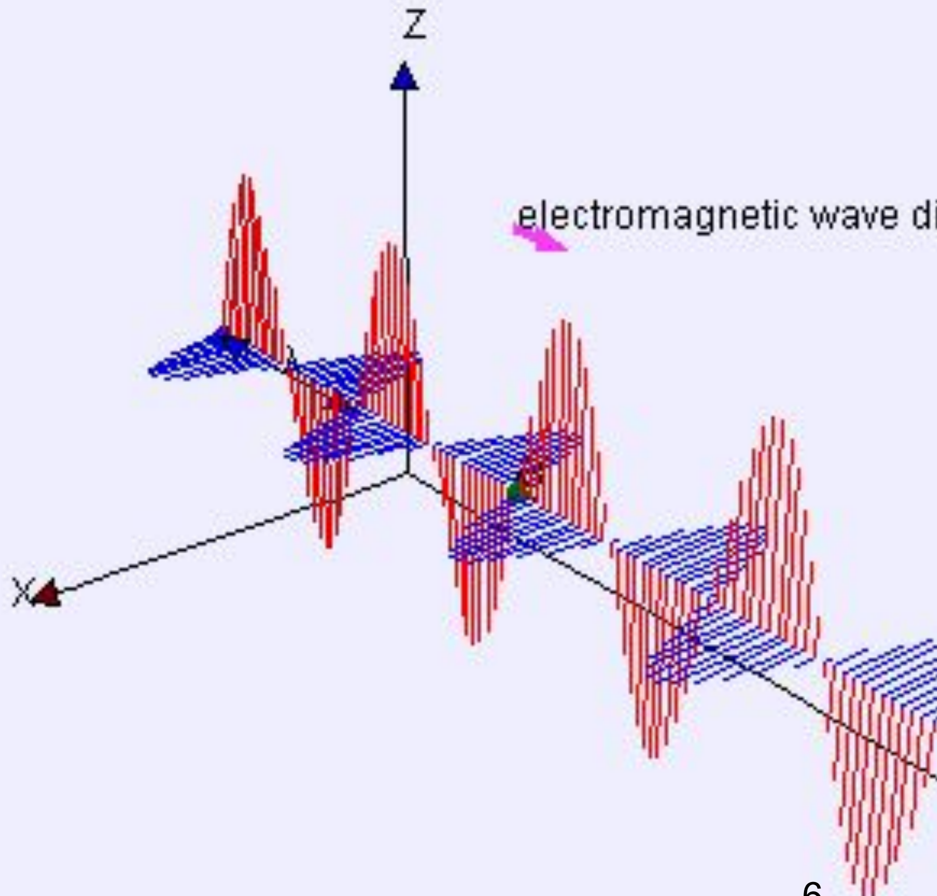
Popular Quantum Mechanics

- Interference of Particles.
- Bohr’s model of atom.
- Energy states in a crystal.
- Metals, semiconductors, insulators.
- P-N-Junction
- PV modules
- PV system components.

Electromagnetic (EM) radiation

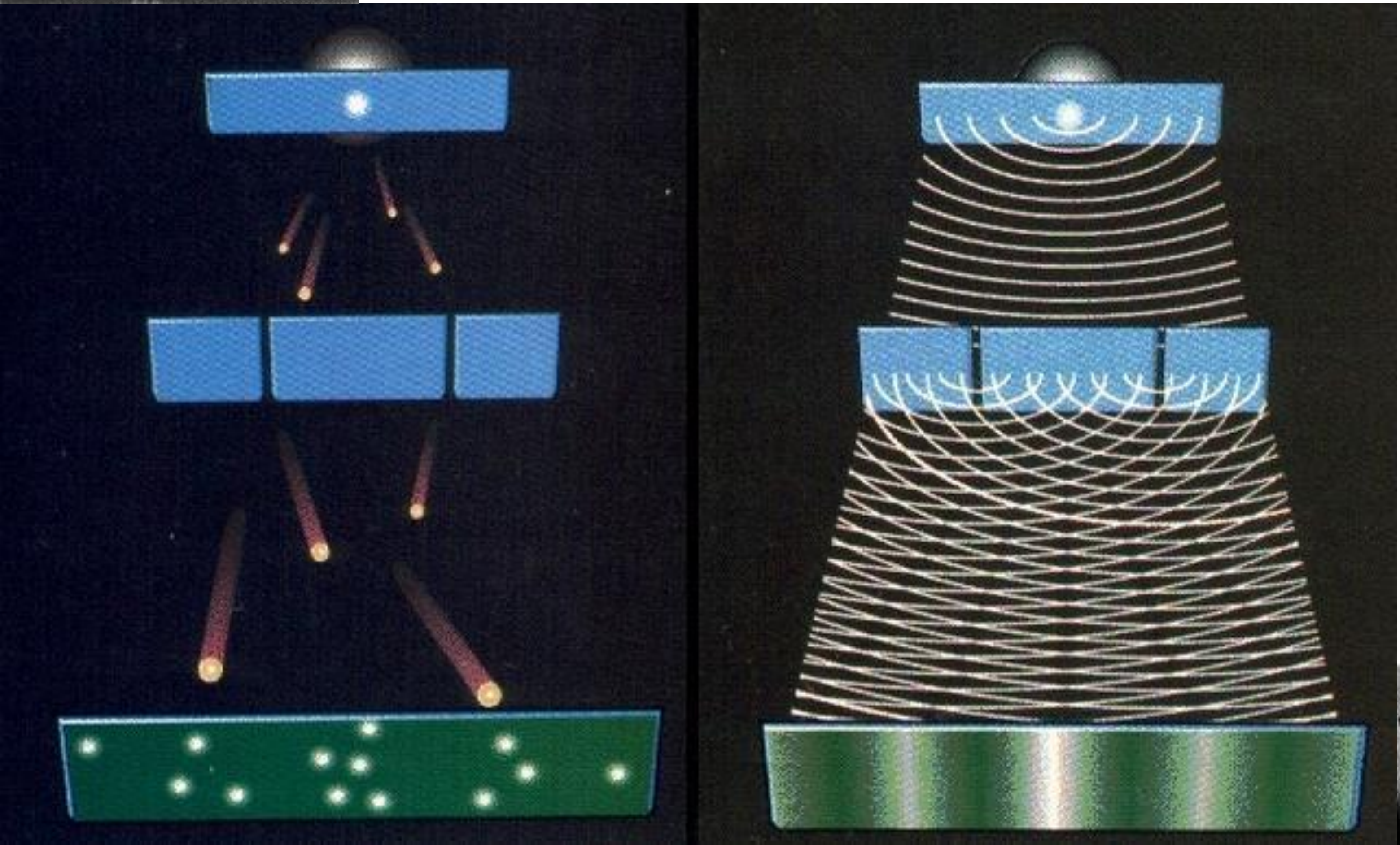






Dualism of EM radiation

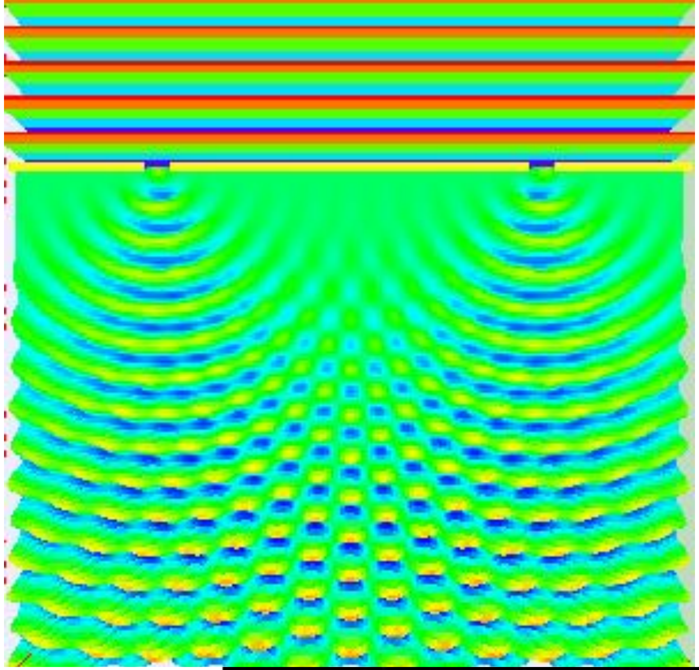
EM radiation exhibits both wave behavior and particle behavior

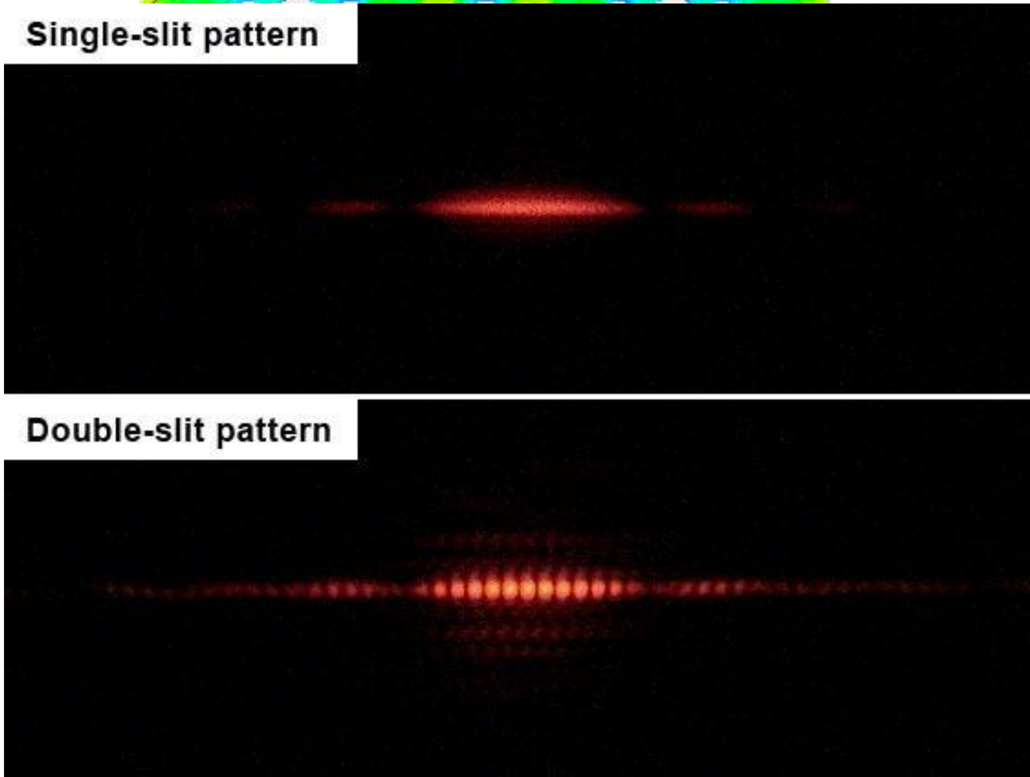


- Thomas young's and Richard Feynman's two-slit experi-s

Double slit experiment

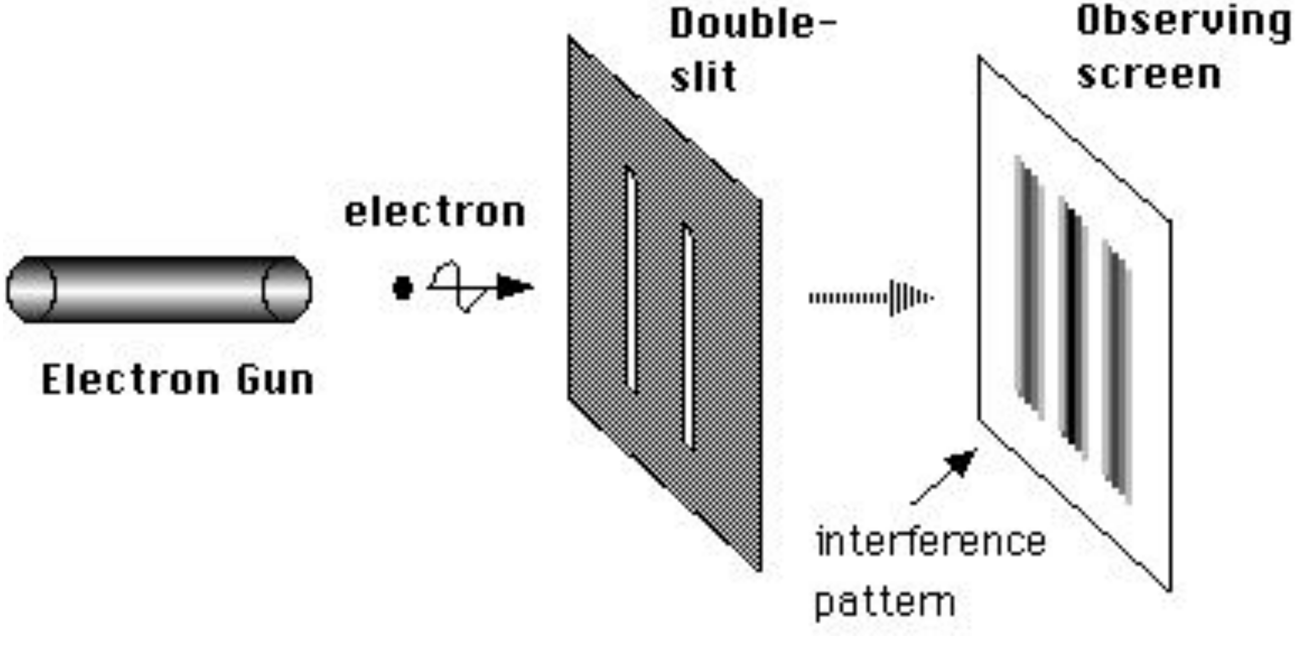
- LIGHT



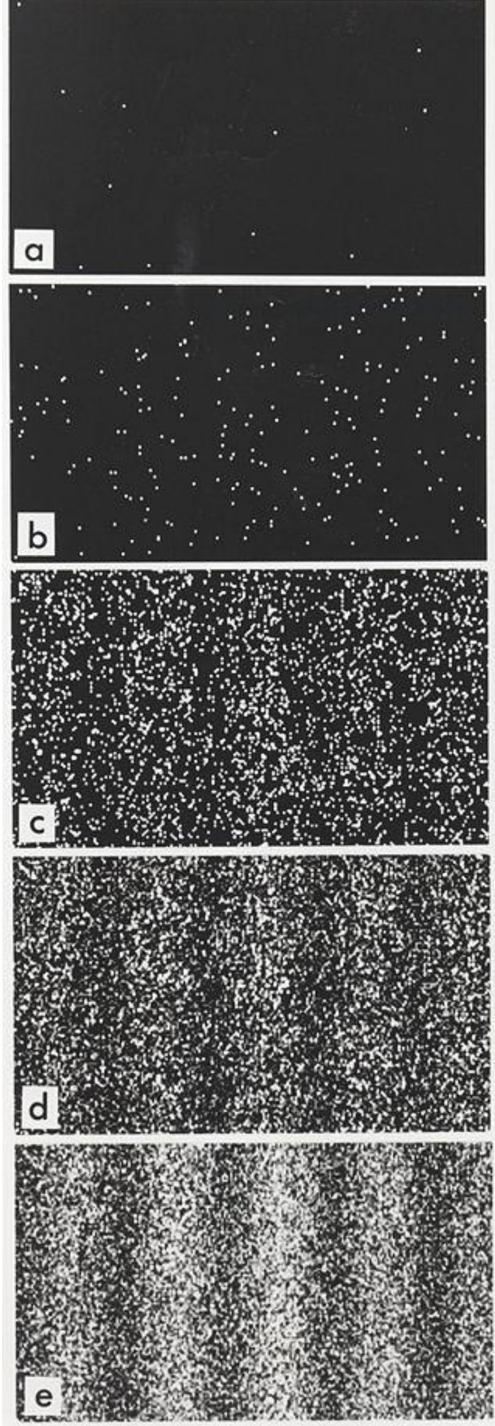


Double slit experiment

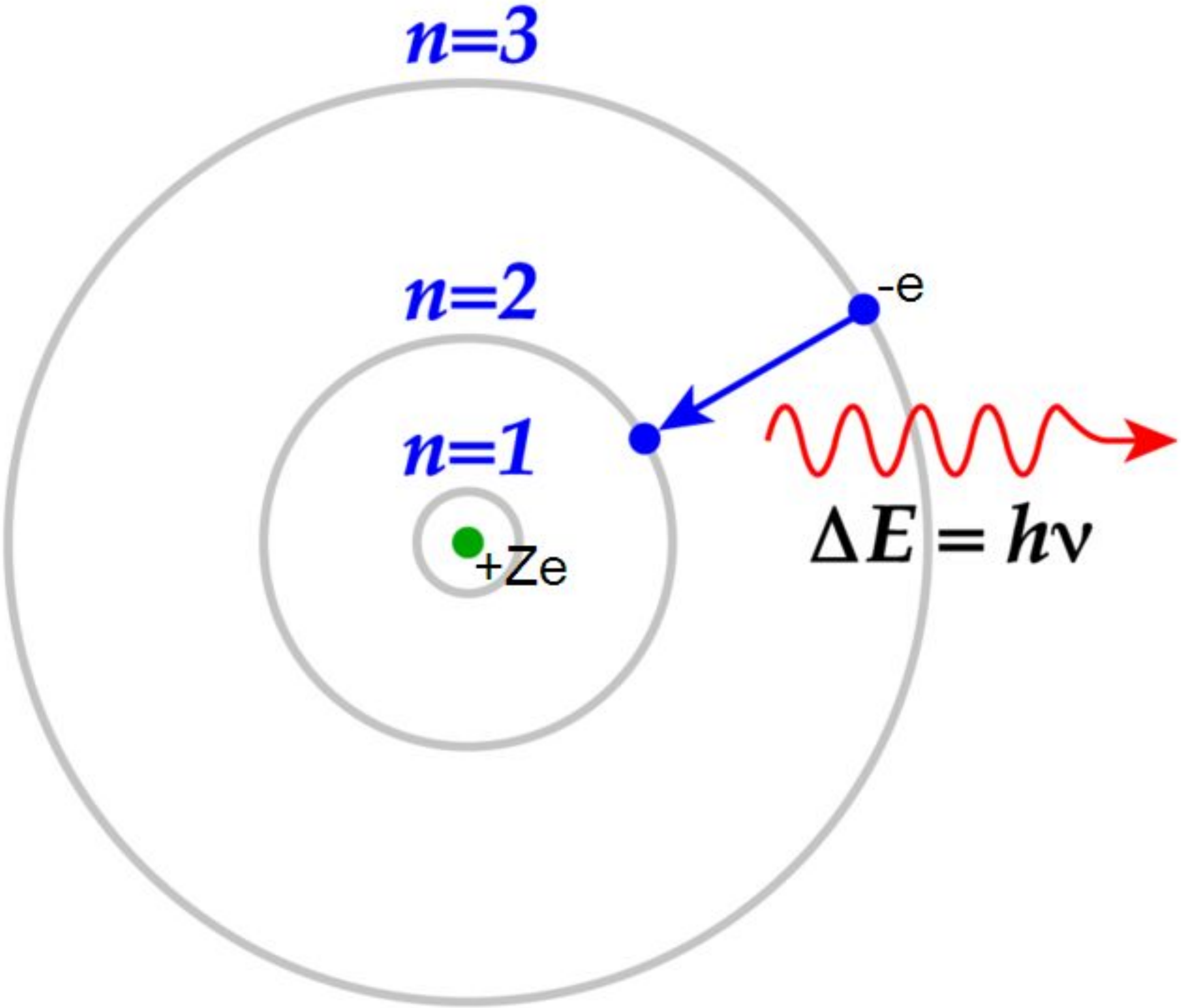
- Electrons

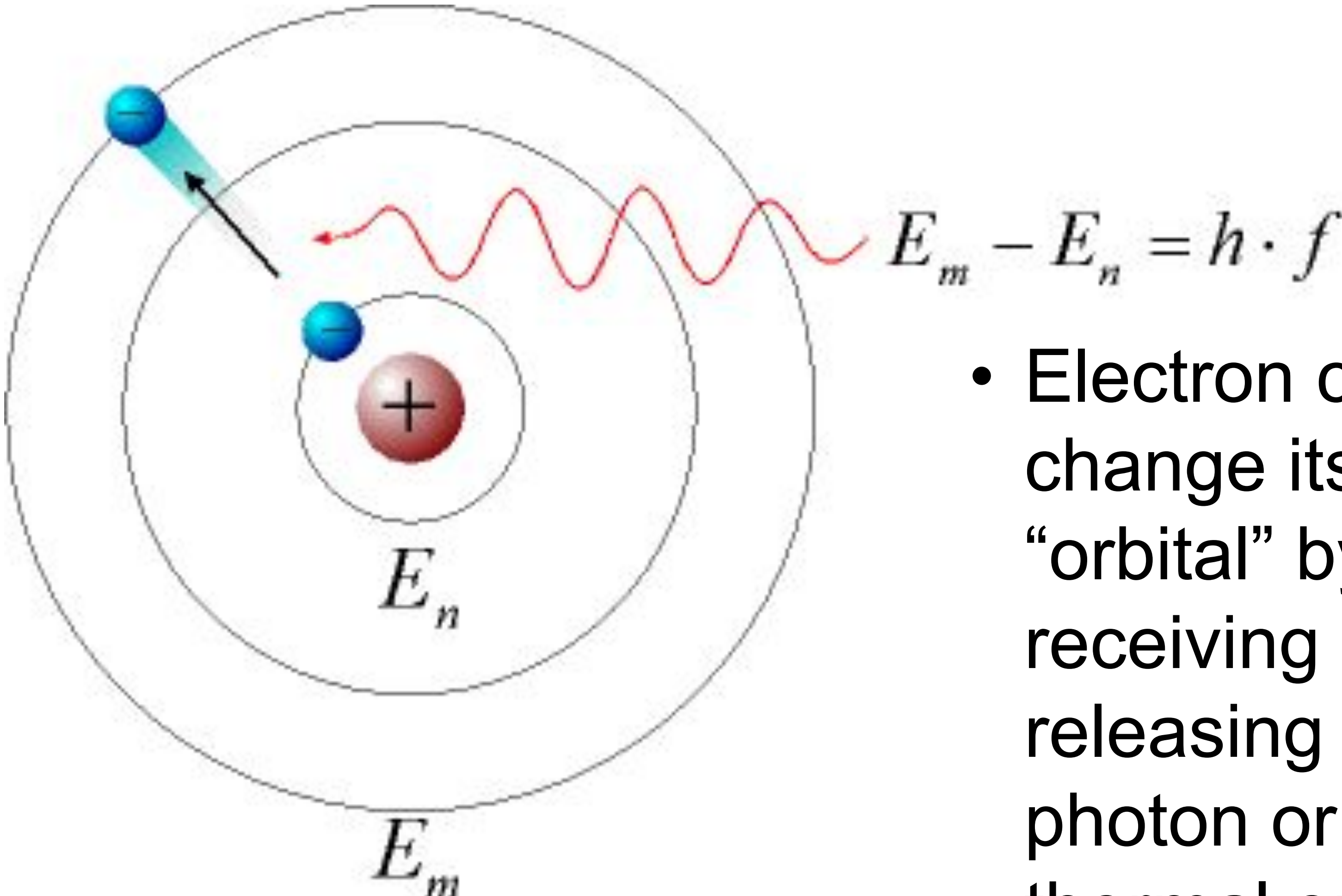


PV1



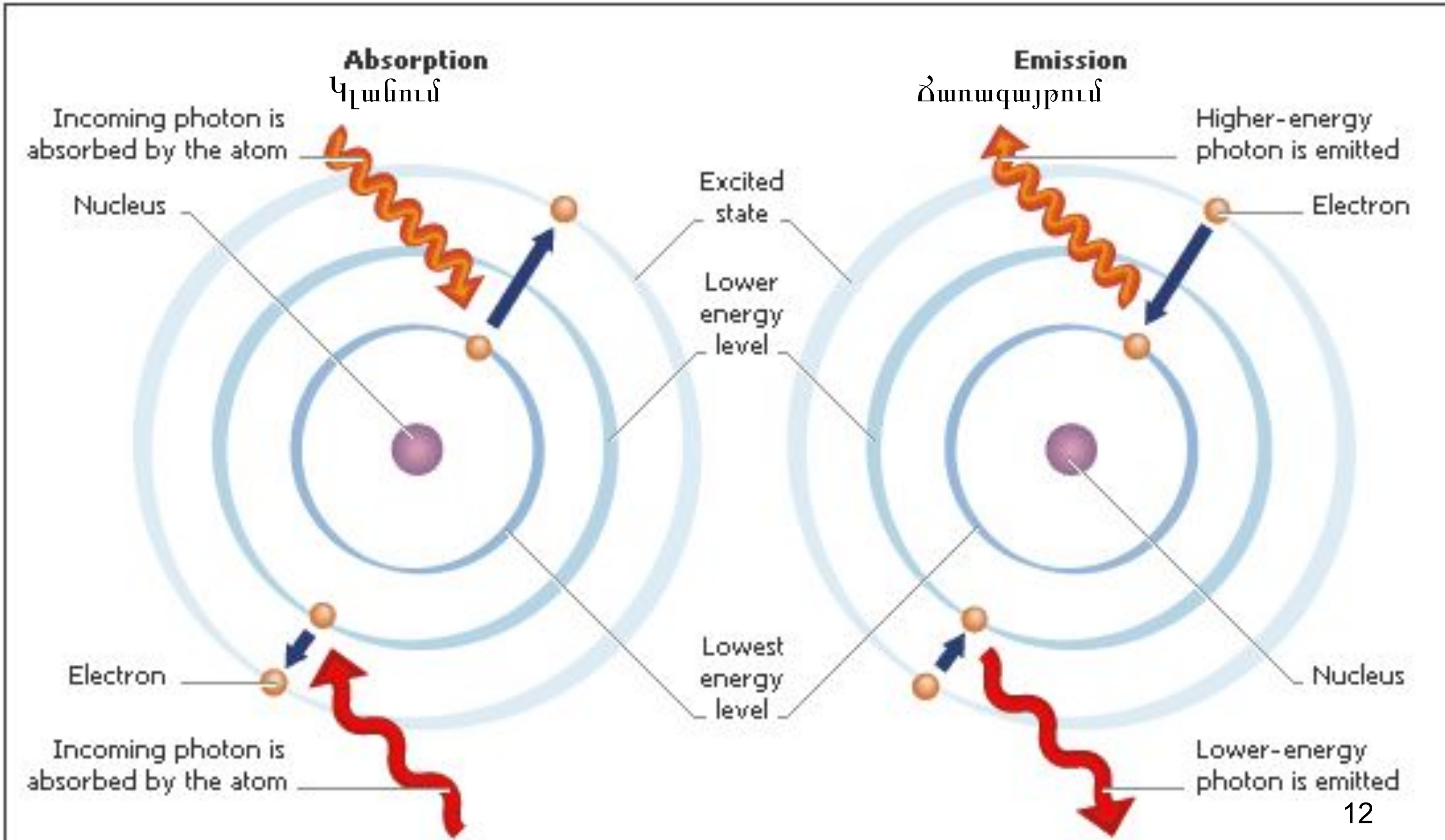
Bohr's model of atom.



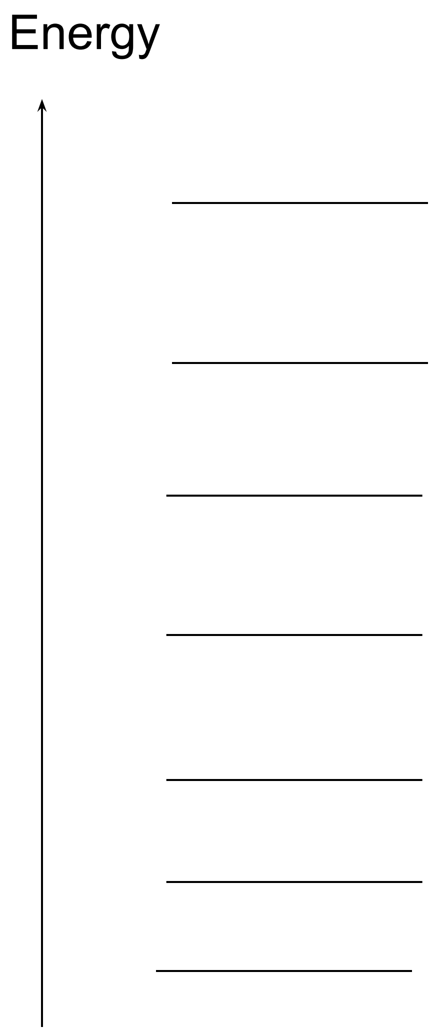


- Electron can change its “orbital” by receiving or releasing a photon or thermal energy.

Absorption only happen if the photon energy match the atom’s energy discrete values! Emission generates a photon with strictly discrete value.

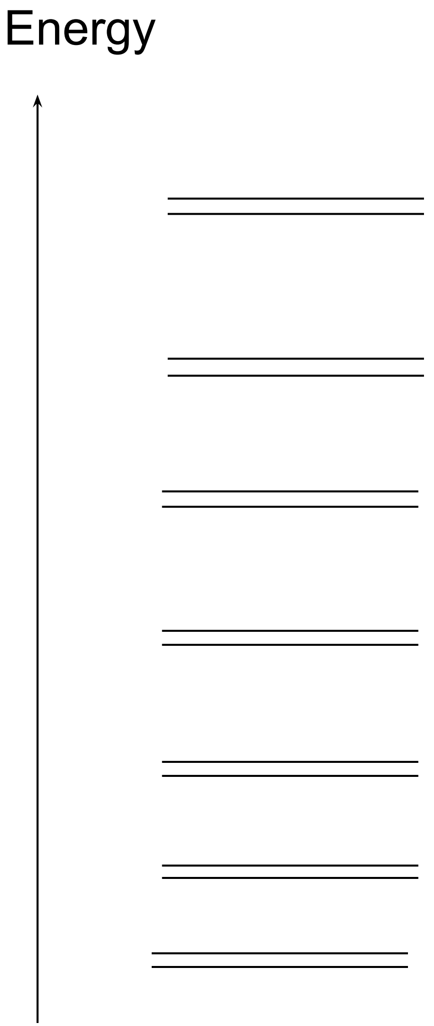


Atom Energy Levels



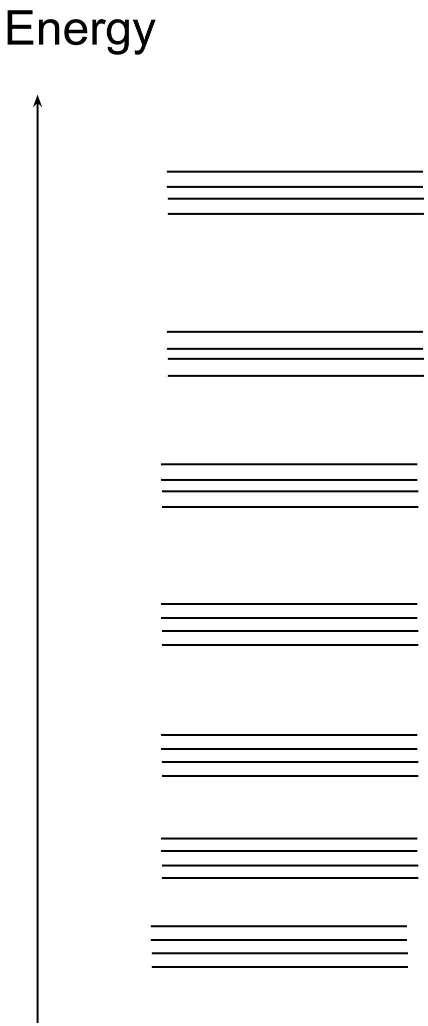
- Isolated atom's energy levels correspond to the orbitals
- The Pauli exclusion principle is the quantum mechanical principle that states that two or more identical fermions (particles with half-integer spin - electrons in our case) cannot occupy the same quantum state within a quantum system simultaneously.

A system of two atoms



- N=2
- Energy levels are split into two levels

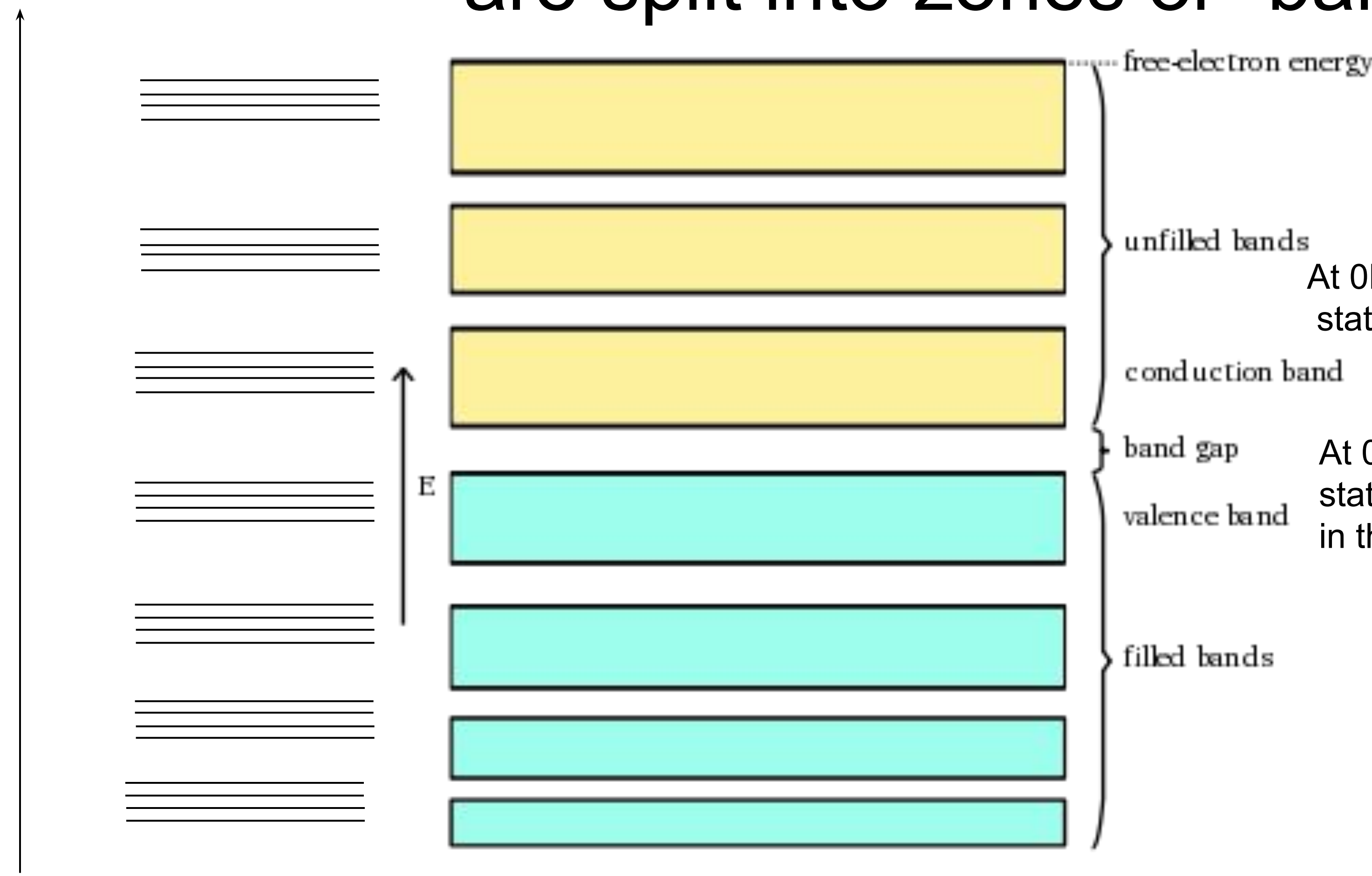
N – atom system



- N=4
- Energy levels are split into 4 levels

Solid body – crystalline lattice:

N >>, primary energy levels are split into zones or "bands"

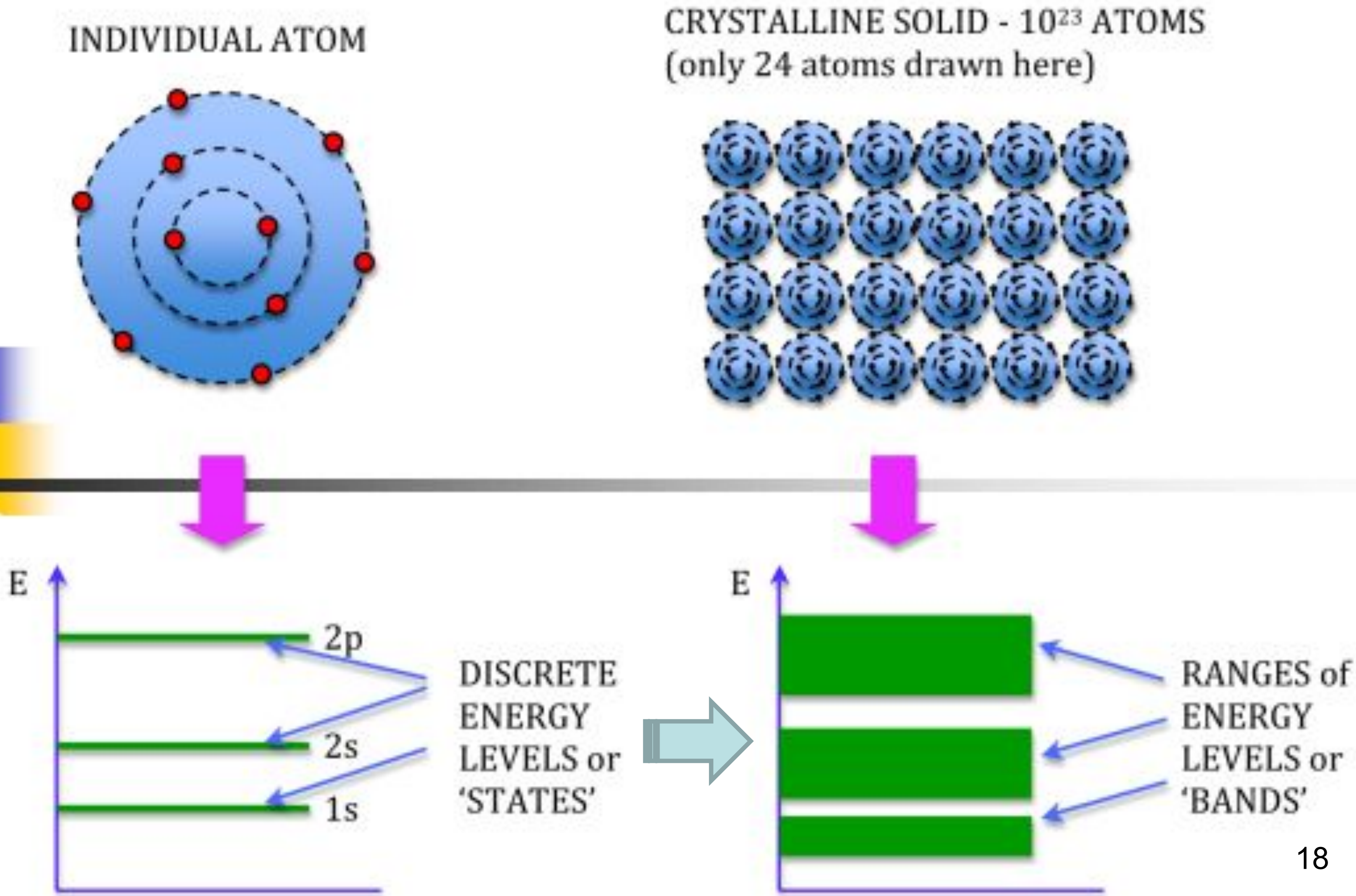


At 0K temperature all states are free in the conduction band

At 0K temperature all states are occupied in the valence band

Solid body – crystalline lattice: formation of bands

When N >>, e.g. in solid bodies, 10^{23} atom per cm^3.



Periodic Table of the Elements

Normal melting points are in °C.
TP = Triple Point
Pressure is listed if not 1 atm.
Allotrope is listed if more than one allotrope.

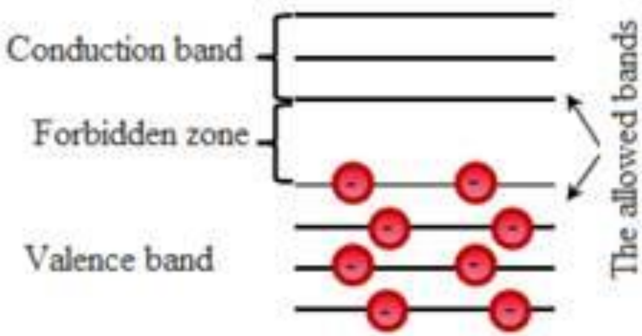
Atomic Number	Melting Point
Symbol	
Name	
Atomic Mass	

1 IA 1A	2 IIA 2A	3 IIIB 3B	4 IVB 4B	5 VB 5B	6 VIB 6B	7 VIIB 7B	8 VIII 8	9 VIII 8	10 VIII 8	11 IB 1B	12 IIB 2B	13 IIIA 3A	14 IVA 4A	15 VA 5A	16 VIA 6A	17 VIIA 7A	18 VIIIA 8A
1 -259.1 H Hydrogen 1.008																	2 -272.20 (2.5 MPa) He Helium 4.003
3 180.5 Li Lithium 6.941	4 1287 Be Beryllium 9.012											5 2075 B Boron 10.811	6 graphite 4489 TP (10.3 MPa) C Carbon 12.011	7 -210 N Nitrogen 14.007	8 -218.79 O Oxygen 15.999	9 -219.67 TP F Fluorine 18.998	10 -248.609 TP (43 kPa) Ne Neon 20.180
11 97.8 Na Sodium 22.990	12 650 Mg Magnesium 24.305											13 660.32 Al Aluminum 26.982	14 1414 Si Silicon 28.086	15 white 44.15 P Phosphorus 30.974	16 115.21 S Sulfur 32.066	17 -101.5 Cl Chlorine 35.453	18 -189.36 TP (69 kPa) Ar Argon 39.948
19 63.5 K Potassium 39.098	20 842 Ca Calcium 40.078	21 1541 Sc Scandium 44.956	22 1668 Ti Titanium 47.88	23 1910 V Vanadium 50.942	24 1907 Cr Chromium 51.996	25 1246 Mn Manganese 54.938	26 1538 Fe Iron 55.933	27 1495 Co Cobalt 58.933	28 1455 Ni Nickel 58.693	29 1084.62 Cu Copper 63.546	30 419.53 Zn Zinc 65.39	31 29.76 TP Ga Gallium 69.732	32 938.25 Ge Germanium 72.61	33 817 TP (3.70 MPa) As Arsenic 74.922	34 gray 220.8 Se Selenium 78.972	35 -7.2 Br Bromine 79.904	36 -157.38 TP (73.2 kPa) Kr Krypton 84.80
37 39.3 Rb Rubidium 84.468	38 777 Sr Strontium 87.62	39 1522 Y Yttrium 88.906	40 1855 Zr Zirconium 91.224	41 2477 Nb Niobium 92.906	42 2623 Mo Molybdenum 95.95	43 2157 Tc Technetium 98.907	44 2334 Ru Ruthenium 101.07	45 1964 Rh Rhodium 102.906	46 1554.8 Pd Palladium 106.42	47 961.78 Ag Silver 107.868	48 321.07 Cd Cadmium 112.411	49 156.6 In Indium 114.818	50 231.93 Sn Tin 118.71	51 630.63 Sb Antimony 121.760	52 449.51 Te Tellurium 127.6	53 113.7 I Iodine 126.904	54 -111.74 TP (81.6 kPa) Xe Xenon 131.29
55 28.44 Cs Cesium 132.905	56 727 Ba Barium 137.327	57-71	72 2233 Hf Hafnium 178.49	73 3017 Ta Tantalum 180.948	74 3422 W Tungsten 183.85	75 3185 Re Rhenium 186.207	76 3033 Os Osmium 190.23	77 2446 Ir Iridium 192.22	78 1768.2 Pt Platinum 195.08	79 1064.18 Au Gold 196.967	80 -38.83 Hg Mercury 200.59	81 304 Tl Thallium 204.383	82 327.46 Pb Lead 207.2	83 271.4 Bi Bismuth 208.980	84 254 Po Polonium [208.982]	85 302 At Astatine 209.987	86 -71 Rn Radon 222.018
87 27 Fr Francium 223.020	88 696 Ra Radium 226.025	89-103	104 unknown Rf Rutherfordium [261]	105 unknown Db Dubnium [262]	106 unknown Sg Seaborgium [266]	107 unknown Bh Bohrium [264]	108 unknown Hs Hassium [269]	109 unknown Mt Meitnerium [268]	110 unknown Ds Darmstadtium [269]	111 unknown Rg Roentgenium [272]	112 unknown Cn Copernicium [277]	113 unknown Uut Ununtrium unknown	114 unknown Fl Flerovium [289]	115 unknown Uup Ununpentium unknown	116 unknown Lv Livermorium [298]	117 unknown Uus Ununseptium unknown	118 unknown Uuo Ununoctium unknown

Lanthanide Series	57 920 La Lanthanum 138.906	58 799 Ce Cerium 140.115	59 931 Pr Praseodymium 140.908	60 1016 Nd Neodymium 144.24	61 1042 Pm Promethium 144.913	62 1072 Sm Samarium 150.36	63 822 Eu Europium 151.966	64 1313 Gd Gadolinium 157.25	65 1356 Tb Terbium 158.925	66 1412 Dy Dysprosium 162.50	67 1472 Ho Holmium 164.930	68 1529 Er Erbium 167.26	69 1545 Tm Thulium 168.934	70 824 Yb Ytterbium 173.04	71 1663 Lu Lutetium 174.967
Actinide Series	89 1050 Ac Actinium 227.028	90 1750 Th Thorium 232.038	91 1572 Pa Protactinium 231.036	92 1135 U Uranium 238.029	93 664 Np Neptunium 237.048	94 640 Pu Plutonium 244.064	95 1176 Am Americium 243.061	96 1345 Cm Curium 247.070	97 996 Bk Berkelium 247.070	98 900 Cf Californium 251.080	99 860 Es Einsteinium [254]	100 1527 Fm Fermium 257.095	101 827 Md Mendelevium 258.1	102 unknown No Nobelium 259.101	103 unknown Lr Lawrencium [262]

Alkali Metal | **Alkaline Earth** | **Transition Metal** | **Basic Metal** | **Semimetal** | **Nonmetal** | **Halogen** | **Noble Gas** | **Lanthanide** | **Actinide**

Electronic Energy Bands



- In solids the atomic energy levels turn into bands

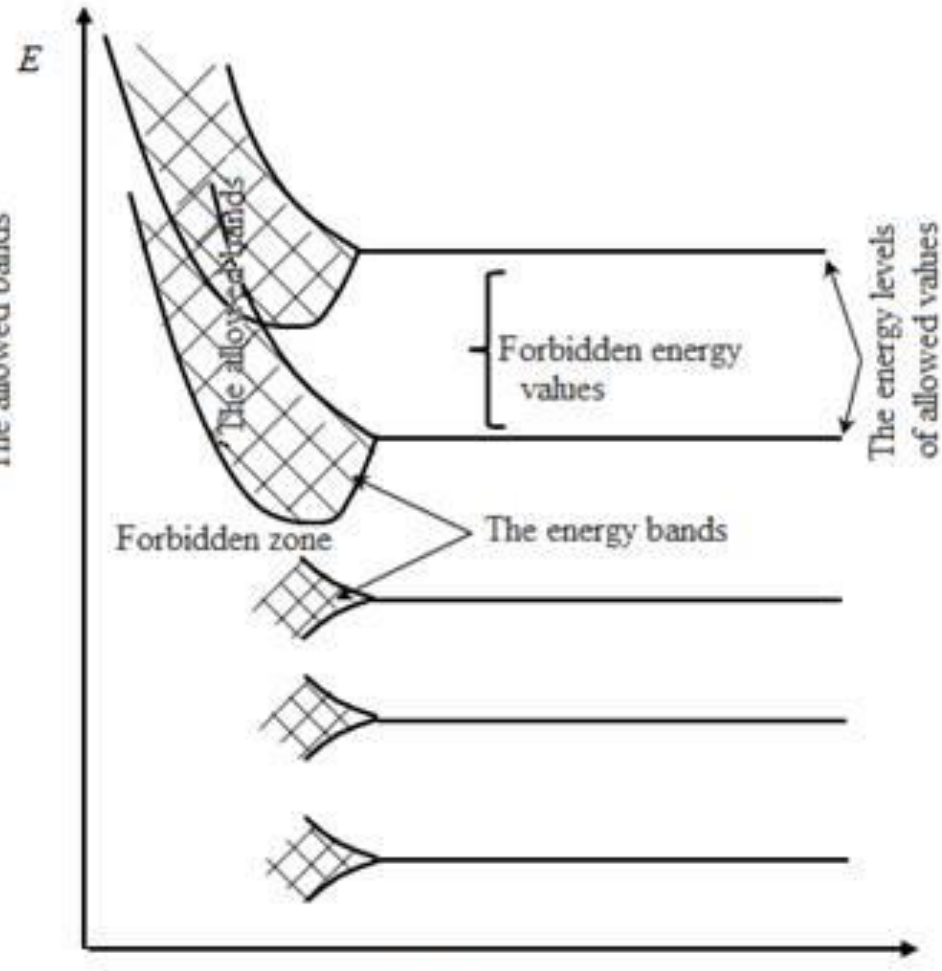
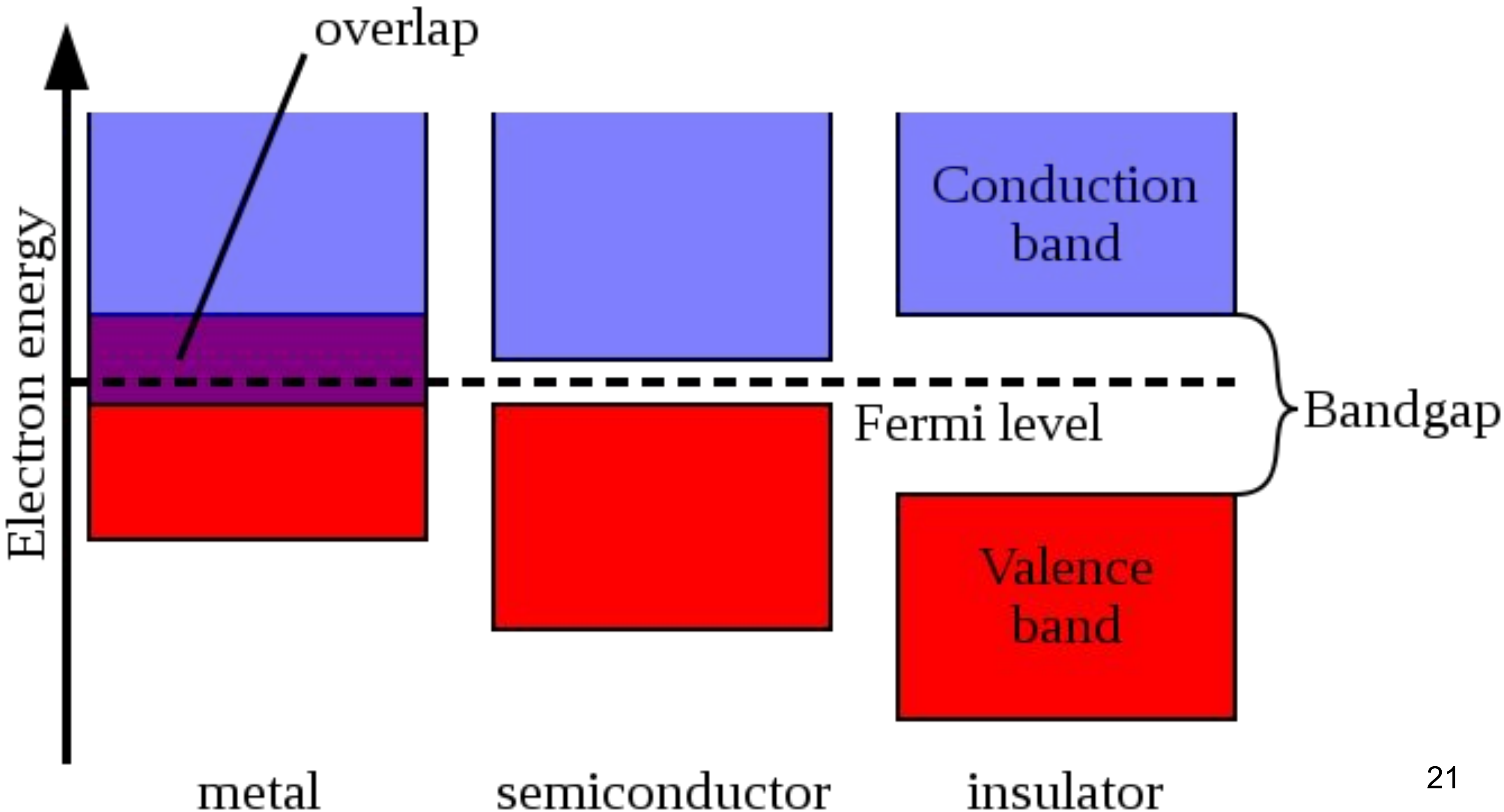


Fig. 1.

r - distance between atoms: gas vs. liquid. vs solid crystalline lattice

Metal vs. Semiconductor, vs. Insulator

the band structure defines if a substance metal, semiconductor or insulator (at 0K temperature).



At non-zero temperatures,

CASE (10) - CARRIER CONCENTRATION

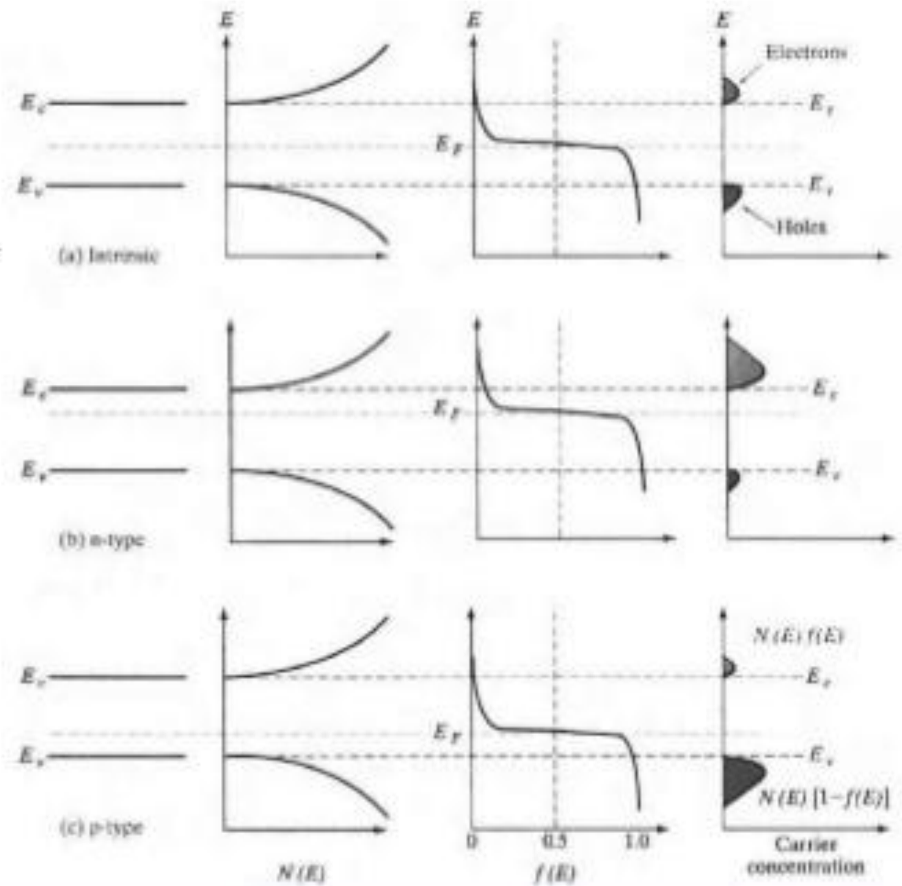
Schematic band diagram, density of states, Fermi-Dirac distribution and the carrier concentrations for :

A. Intrinsic

B. N-type

C. P-type

semiconductors at thermal equilibrium is illustrated.



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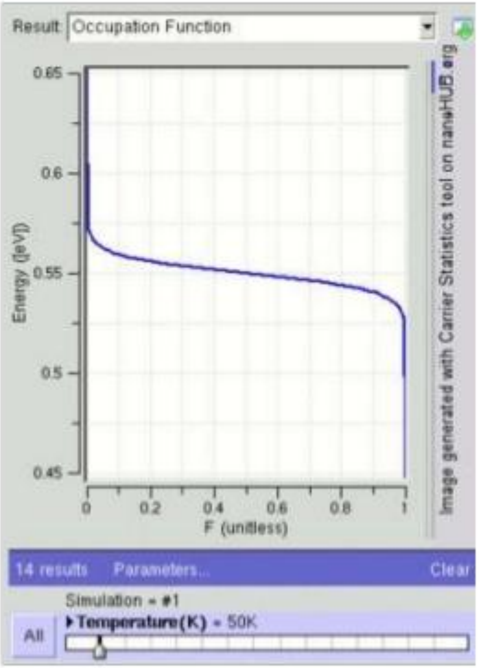
FERMI-DIRAC DISTRIBUTION FUNCTION



The function *f*(E), the Fermi-Dirac distribution function, gives the **probability** that an available energy state at E will be occupied by an electron at absolute temperature T.

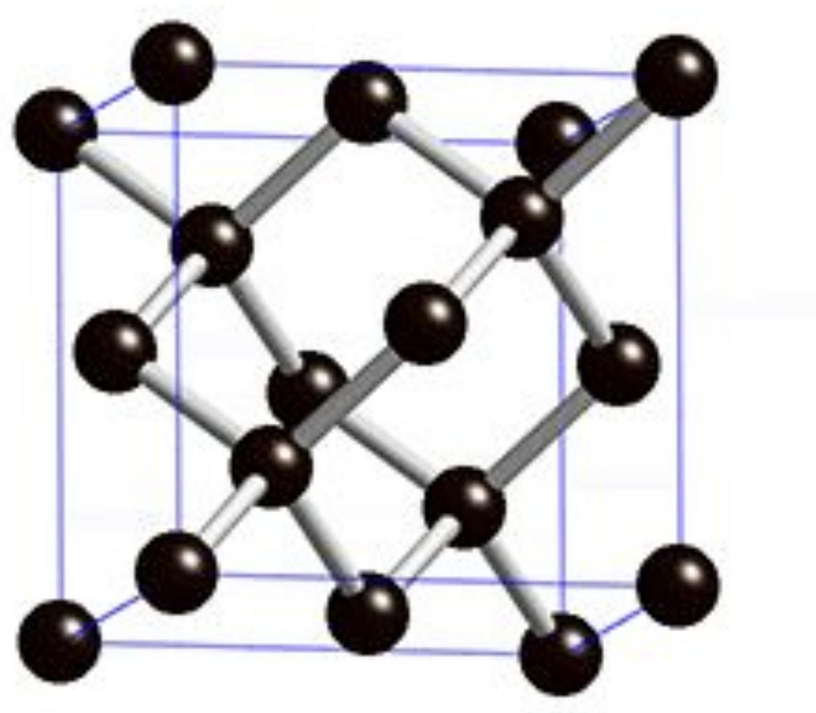
$$f(E) = \frac{1}{1 + e^{\frac{(E - E_f)}{KT}}}$$

k is **Boltzmann's constant** ($k = 8.62 \times 10^{-5}$ eV/K $= 1.38 \times 10^{-23}$ J/K).

T is the **absolute temperature** in Kelvin.

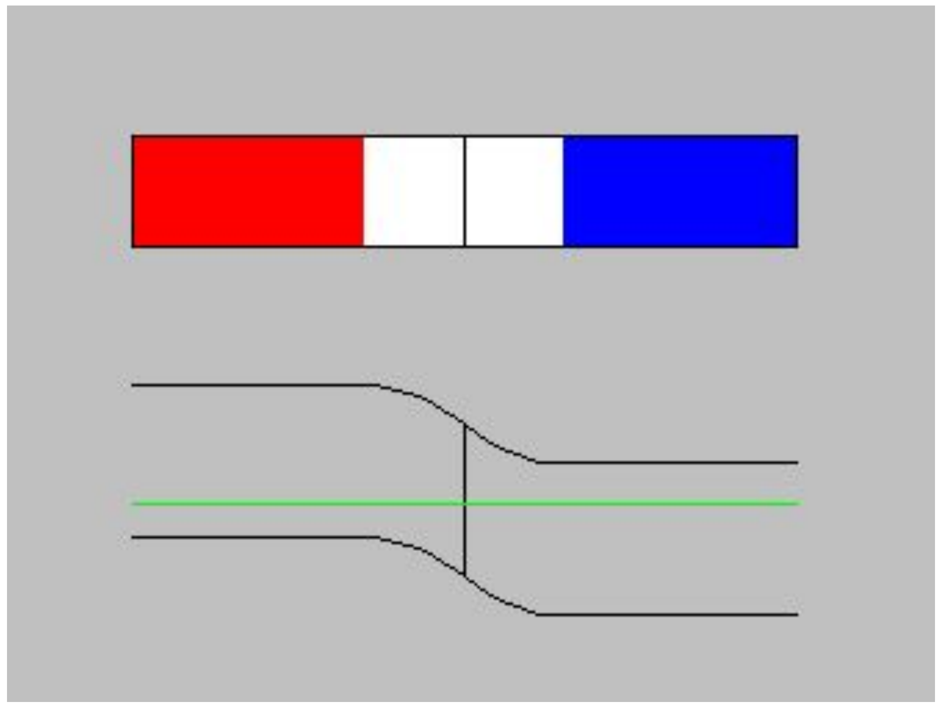
E_f is called the **Fermi energy** or the **Fermi level**.

Silicon crystal structure

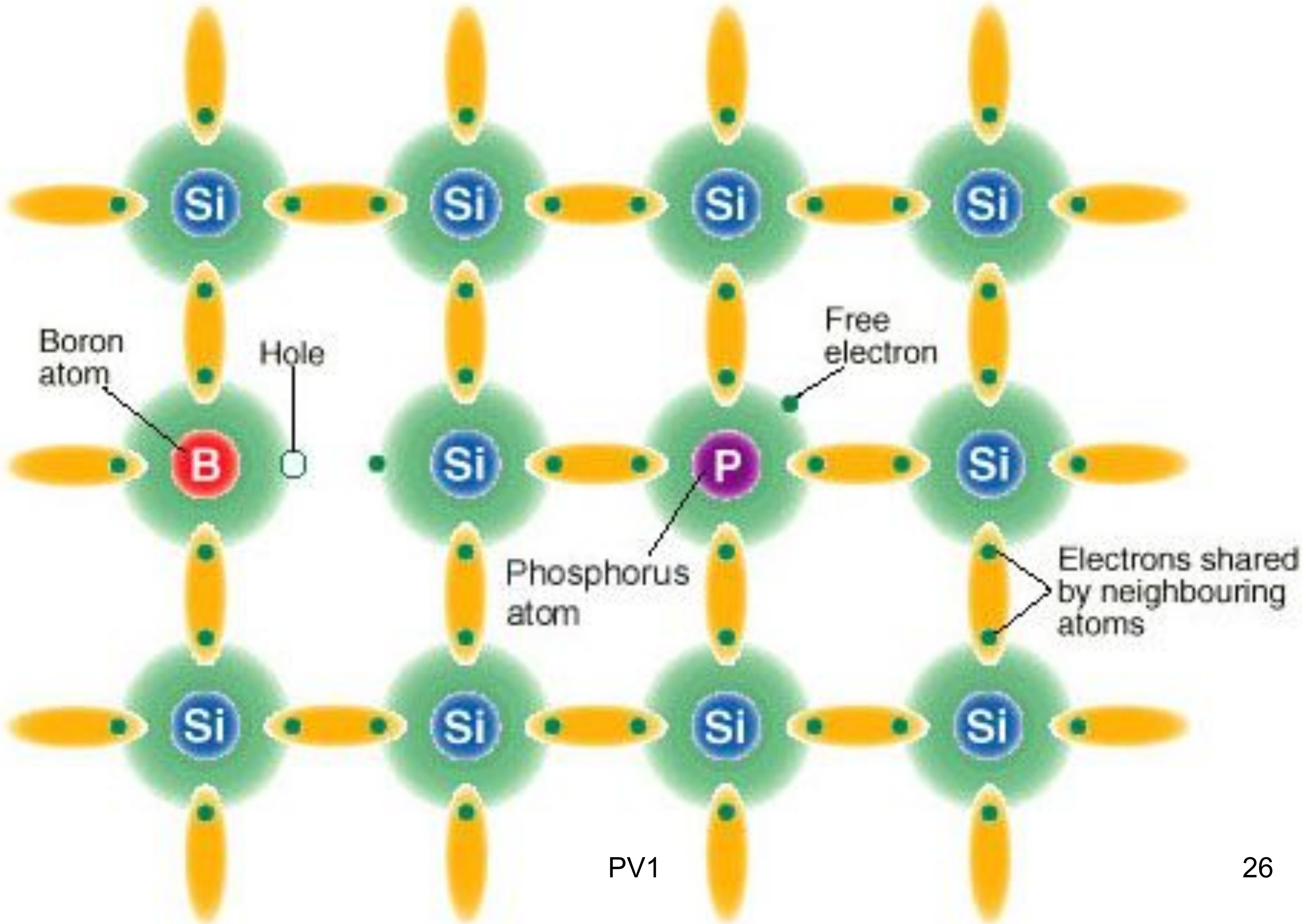


P-N-Junction

- P-N-Junctions have the ability to form built in electric field in the space charge region.

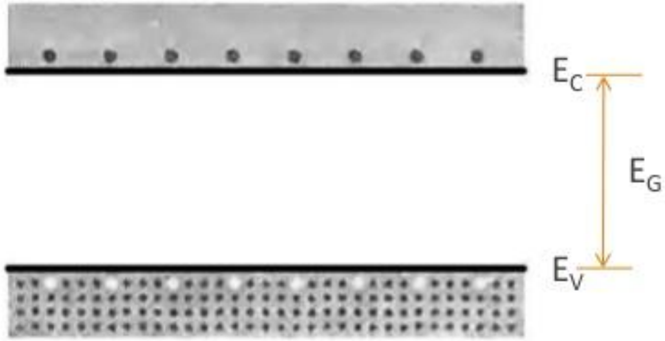


PV power generation



ELECTRONS AND HOLES

As the temperature of a semiconductor is raised from **0 K**, some electrons in the **valence band** receive **enough thermal energy** to be excited across the band gap to the **conduction band**.



The result is a material with **some electrons** in an otherwise empty conduction band and some **unoccupied states** in an otherwise filled valence band.

For convenience, an empty state in the valence band is referred to as a hole. If the conduction band electron and the hole are created by the excitation of a valence band electron to the conduction band, they are called an **electron-hole pair** (abbreviated **EHP**).

Example. 1 : Assum that E=1.1 eV, E_f=0.7 eV, T=0 to 300 K. Compute $f(E)$.

Solution. 1 :

First let us compute the value of **α**. For this, substituting the given values in the equation **α=(E-E_f)/KT**, we get :

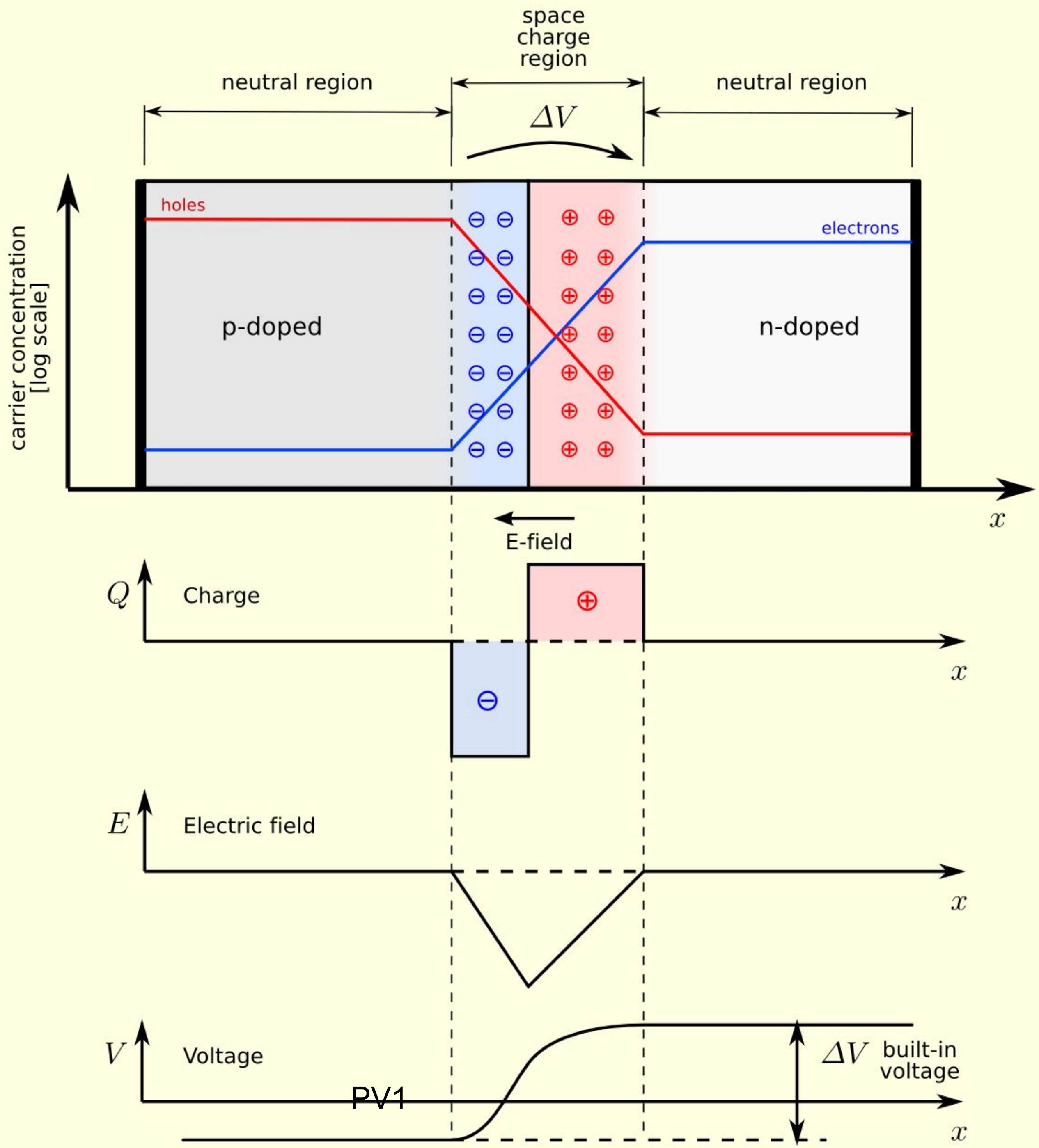
$$\alpha = \frac{E - E_f}{kT} = \frac{(1.1 - 0.6)\times(1.6\times10^{-19})}{1.38\times10^{-23}\times300} = 19.3$$

Then :

$$f(E) = \frac{1}{1+e^{19.3}} = 4.05\times10^{-9} \approx 0$$

The result of computation shows that there exists only a negligible amount of free electron states at 300 K, when **E=1.1 eV** , **E_f=0.7 eV**.

Now, what will happen if a semicon-ductor structure's p-n-junction is bombar-ded with photons?



P-N-Junction

- The interface of the p-doped and n-doped semiconductors is called P-N-Junction
- P-N-Junction in fact is a **diode**
- P-N-Junction has a built in electric field, without spending any electric power
- P-N-Junction electric field separates the photogenerated electron-hole pairs, and creates external voltage and current.

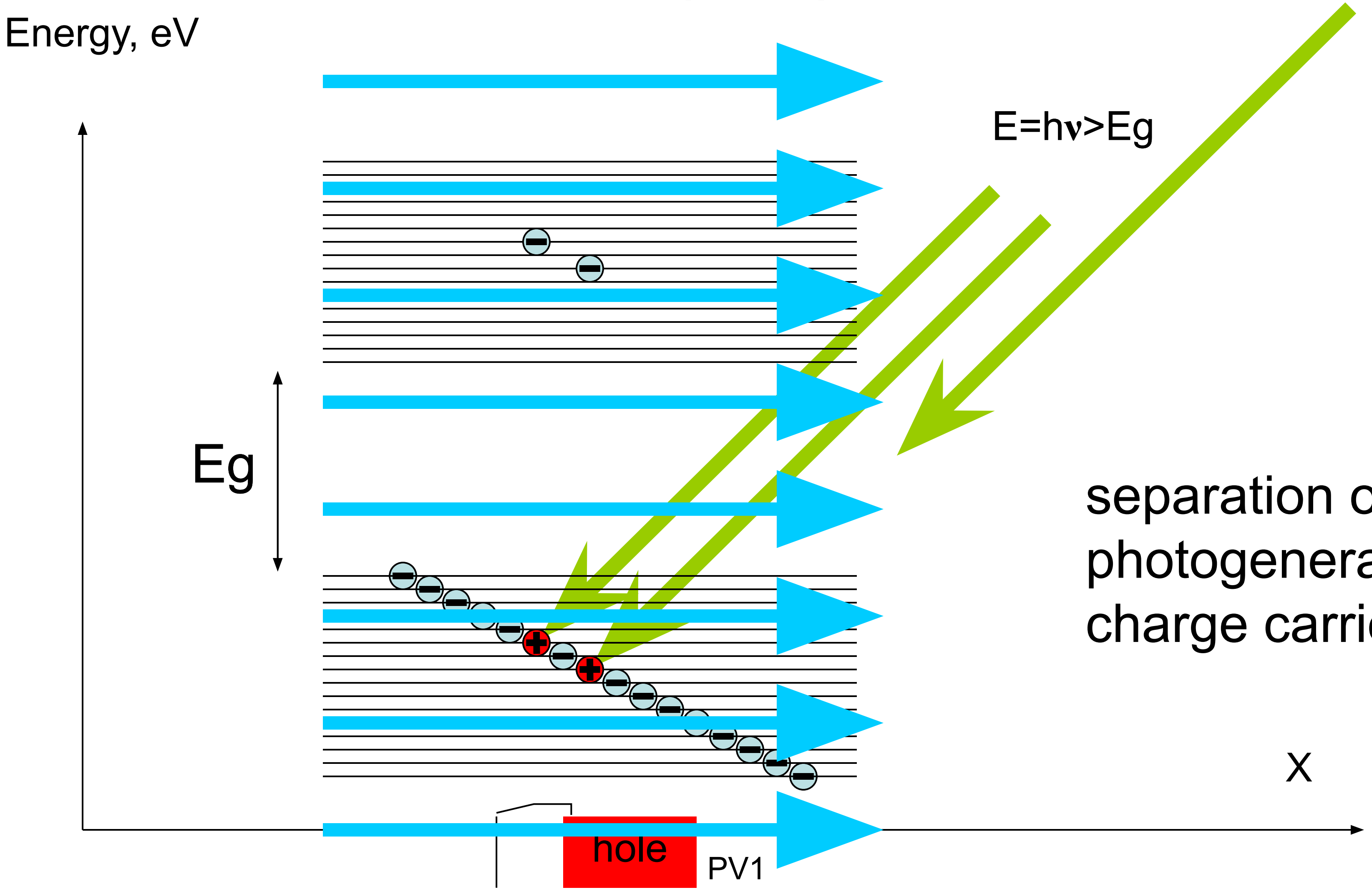
Example. 2 : Compute the number of holes in a heavily doped N-type semiconductor material with intrinsic concentration n_o=1.5×10^{10} cm^{-3}.

Solution. 2 :

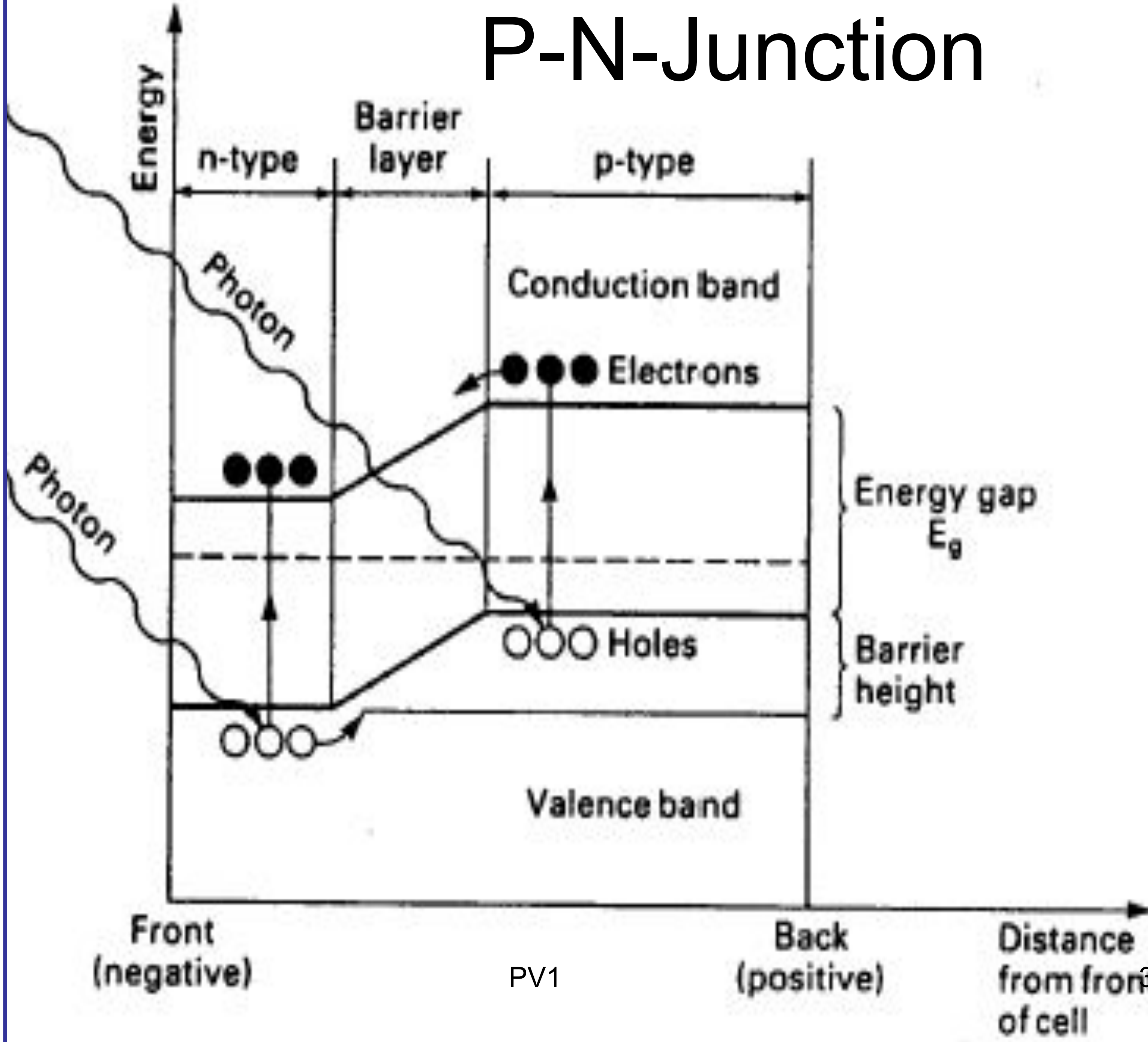
Assume that heavy doping means n=1×10^{18} cm^{-3}. Then using the mass-action law, we get :

$$(1.5\times10^{10})^2 = 10^{18}\,p \Rightarrow p = \frac{2.25\times10^{20}}{10^{18}} = 2.25\times10^{2}\ cm^{-3}$$

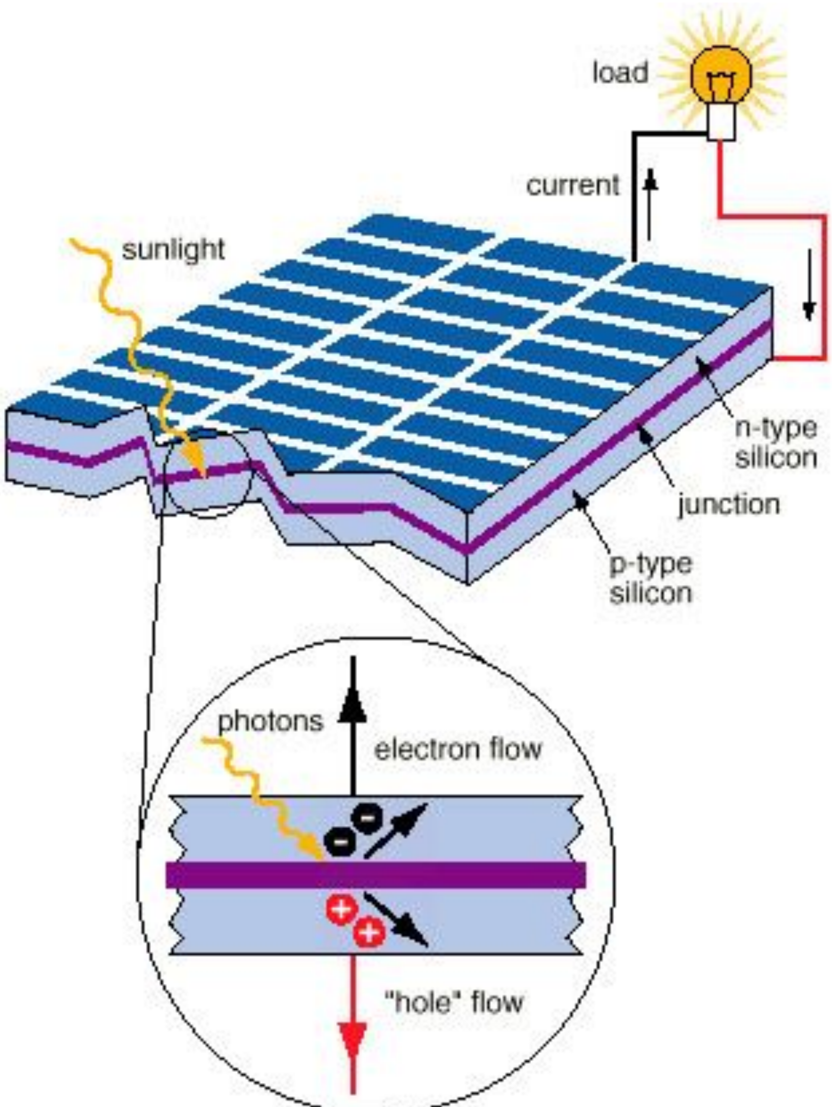
Summary of physical principles of Photovoltaic (PV) Conversion



P-N-Junction


Energy
n-type
Barrier layer
p-type
Photon
Photon
Conduction band
Electrons
Energy gap E_g
Holes
Barrier height
Valence band
Front (negative)
Back (positive)
Distance from front of cell

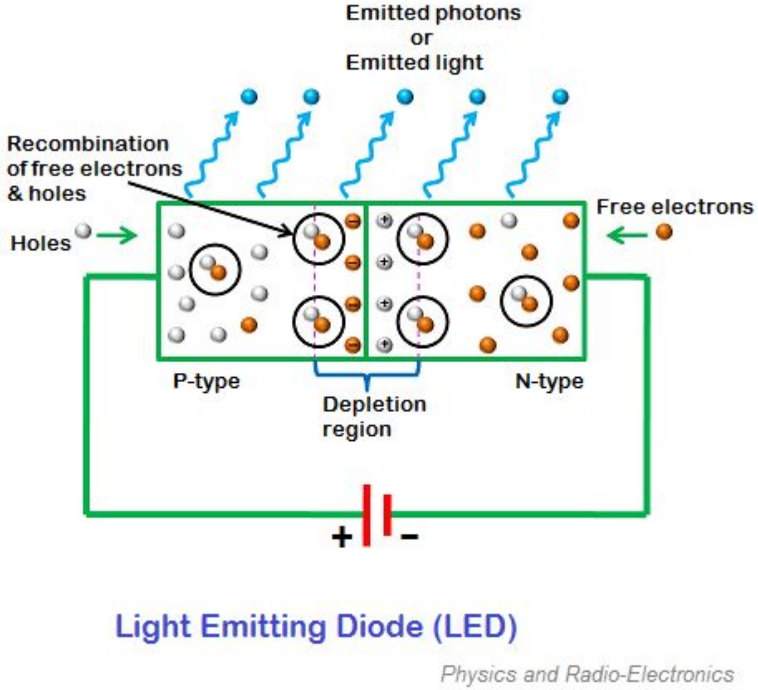
PV power generation

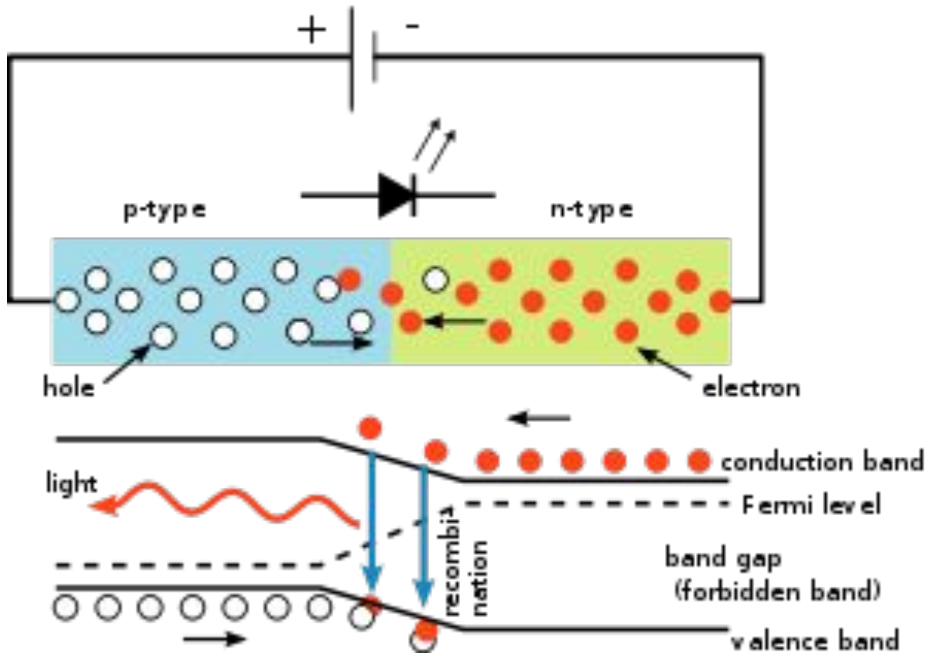


solar PV cell is a diode due to the p-n-junction. This large area diode is capable to convert solar electromagnetic energy into electric power

Light emission diode = LED

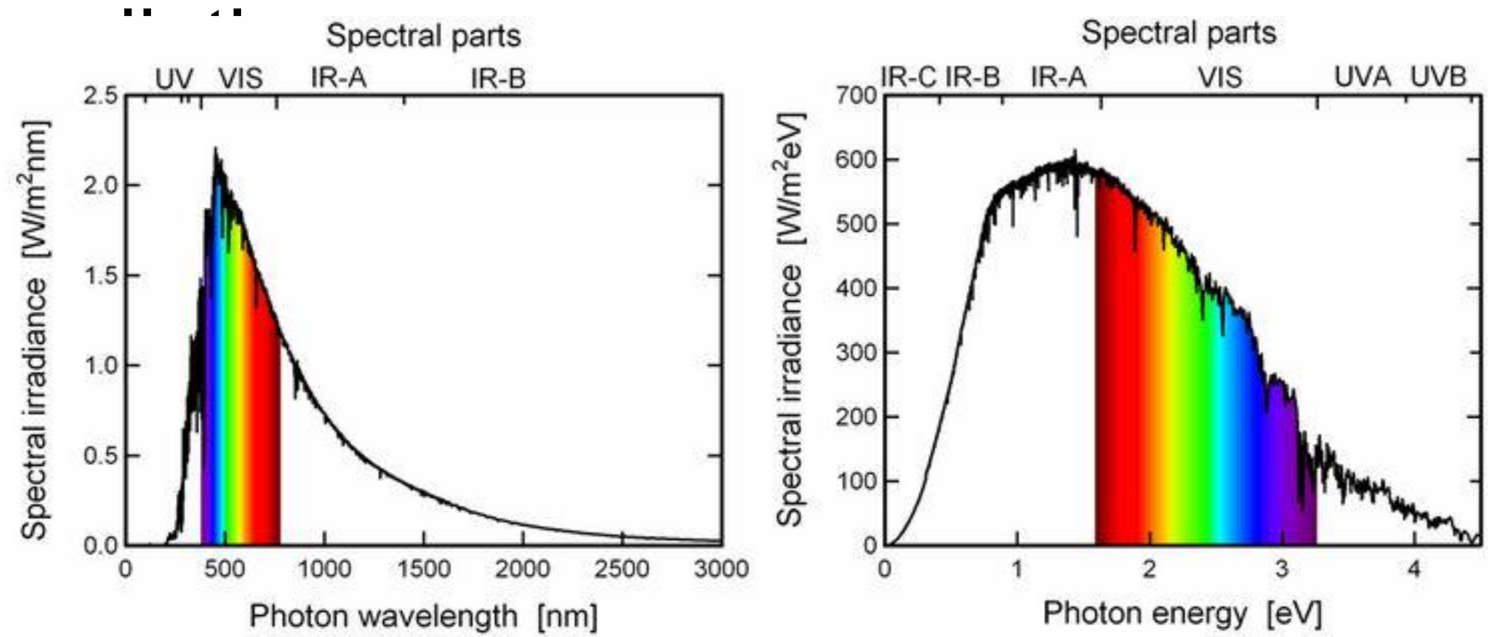
- LED performs the opposite function – converts electric power into visible light.
- Conversion is performed due to recombinative radiation



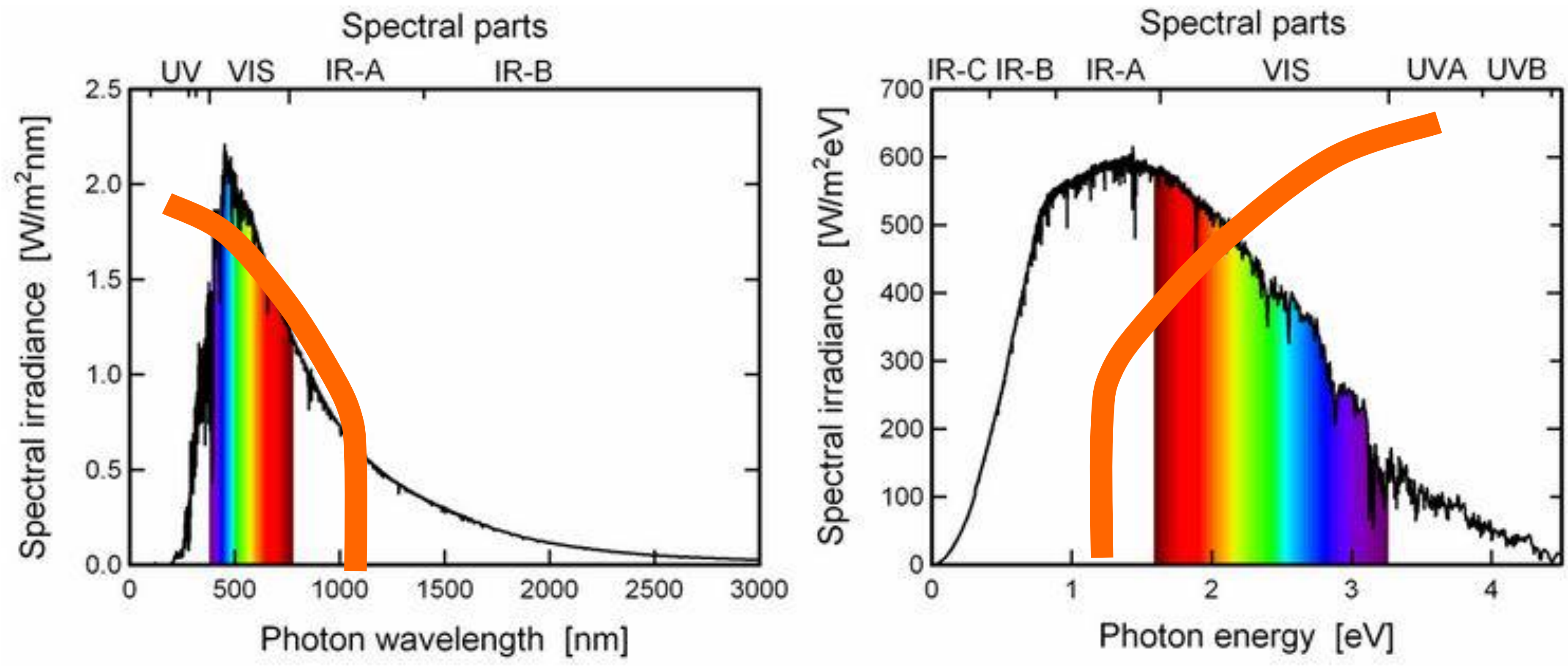


Sensitivity Spectrum

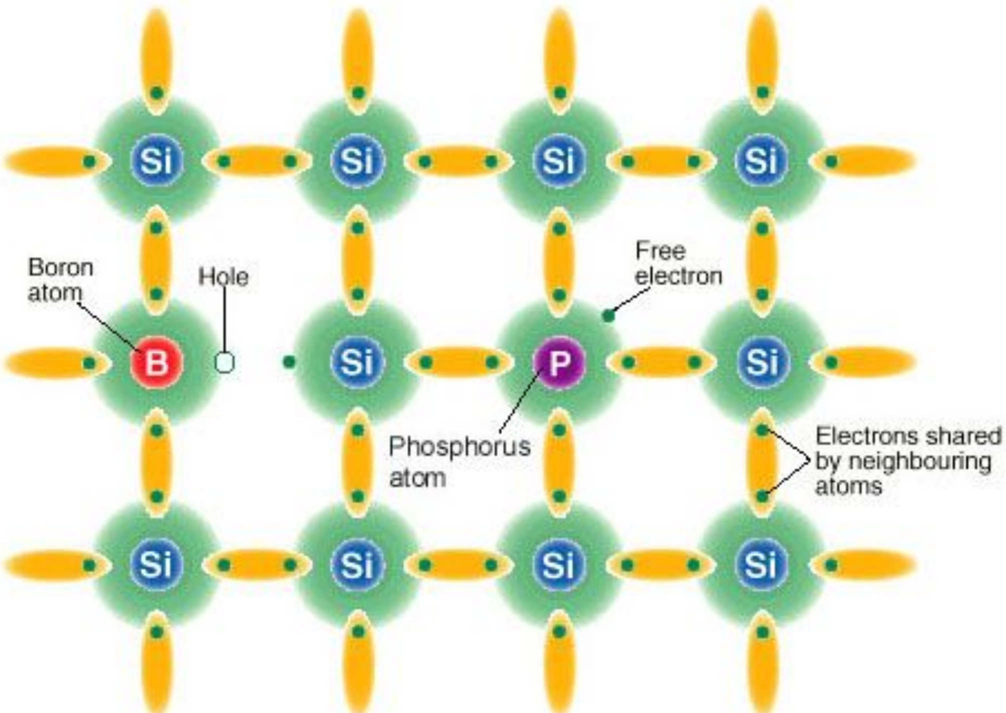
- Why PV cells are sensitive to light spectrum?
- What will happen if a photon, with energy of $h\nu \leq E_g$ will hit the semiconductor?
- Semiconductor will be transparent to this

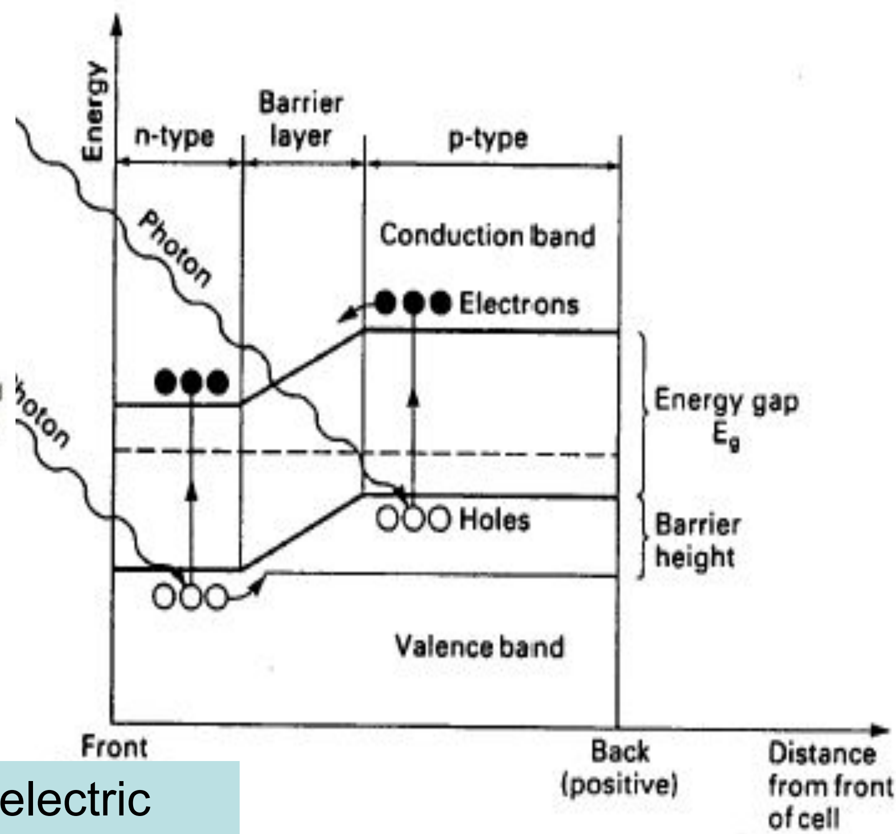


Sensitivity Spectrum – via wavelength or equivalent via photon energy



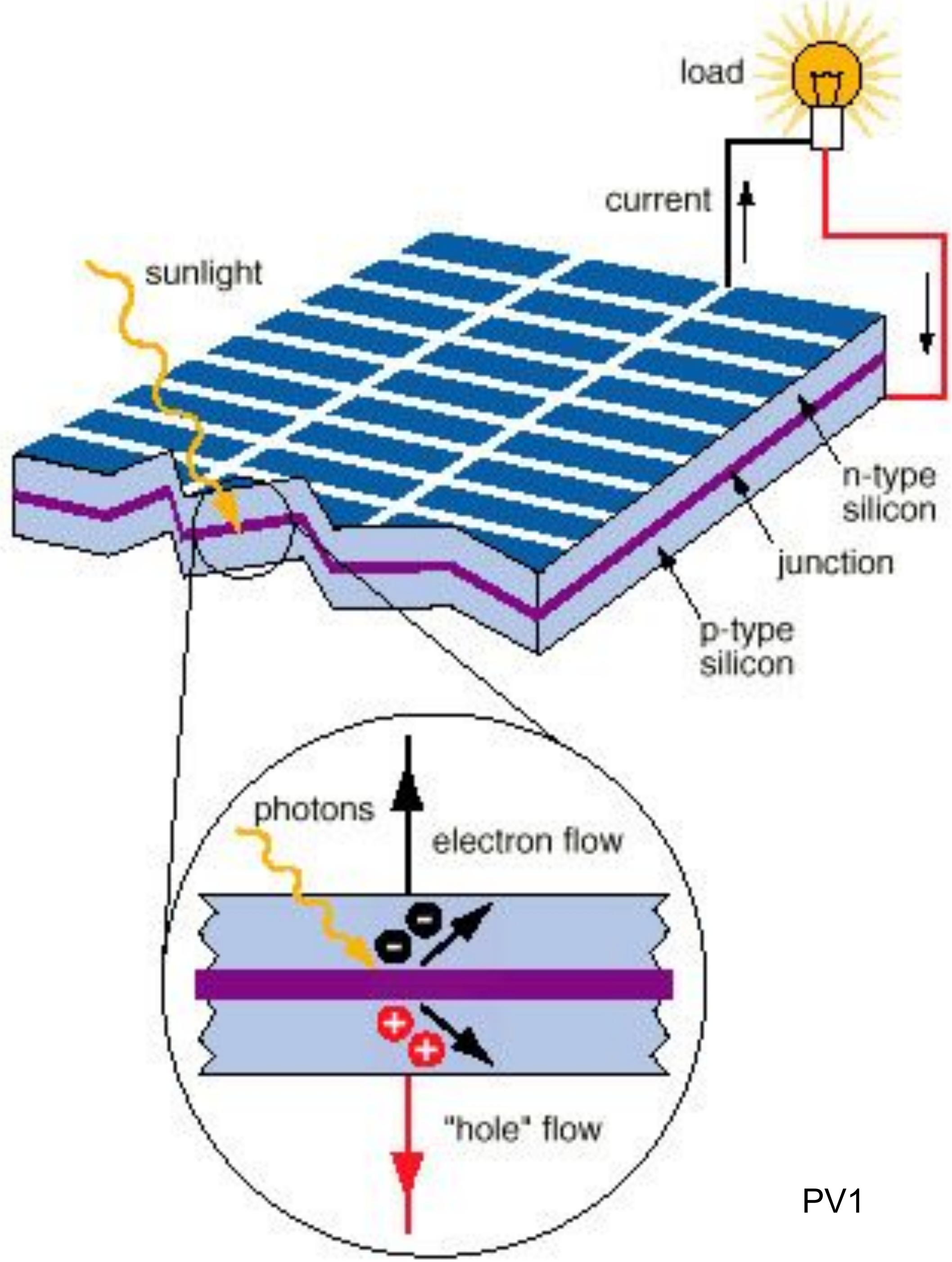
Summary of physical principles of Photovoltaic (PV) Conversion





Existance of electrones and holes

Built in electric field in the semiconductor



solar PV cell is a diode due to the p-n-junction

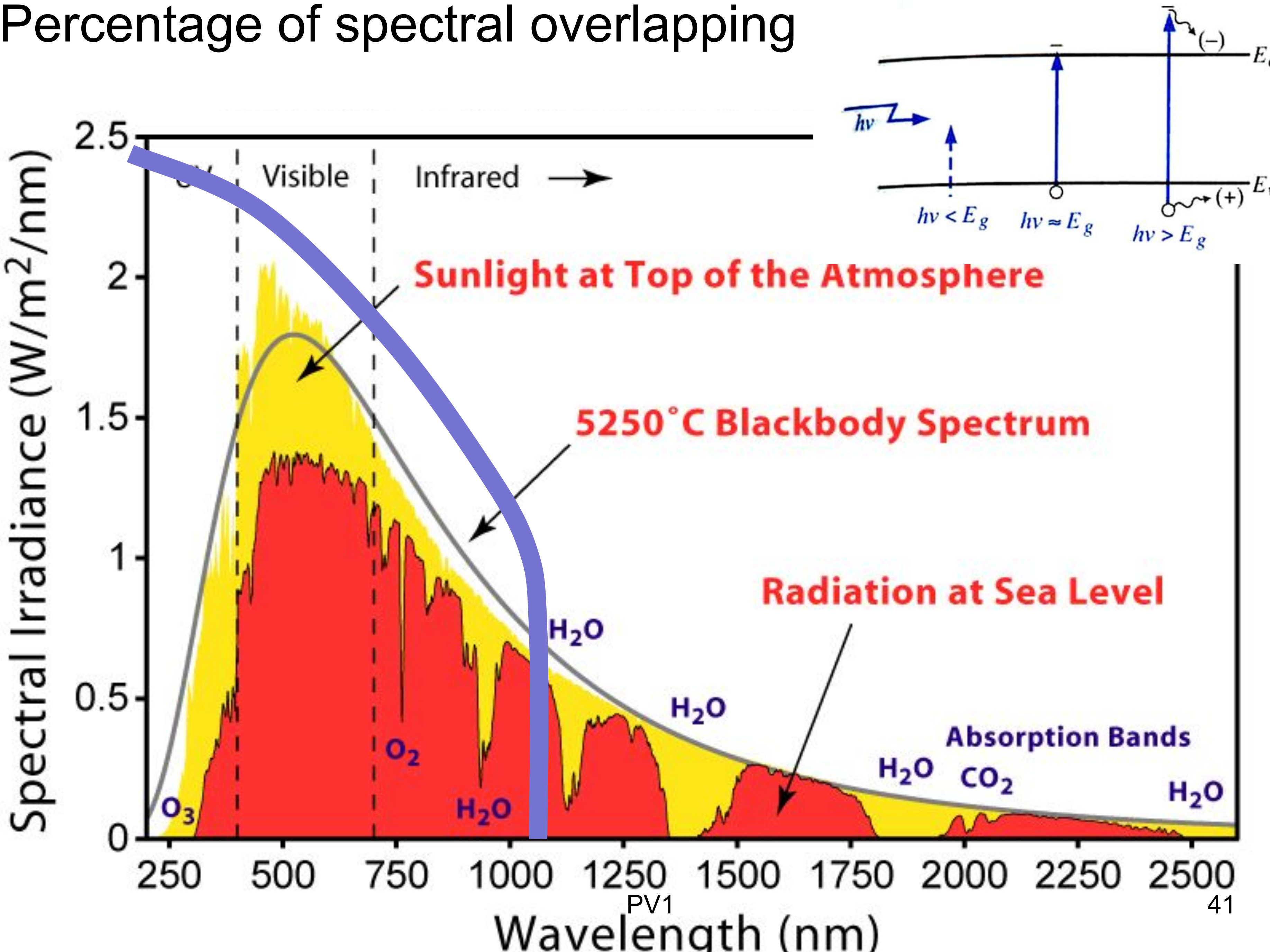
Summary of physical principles of Photovoltaic (PV) Conversion

Factors Influencing Efficiency

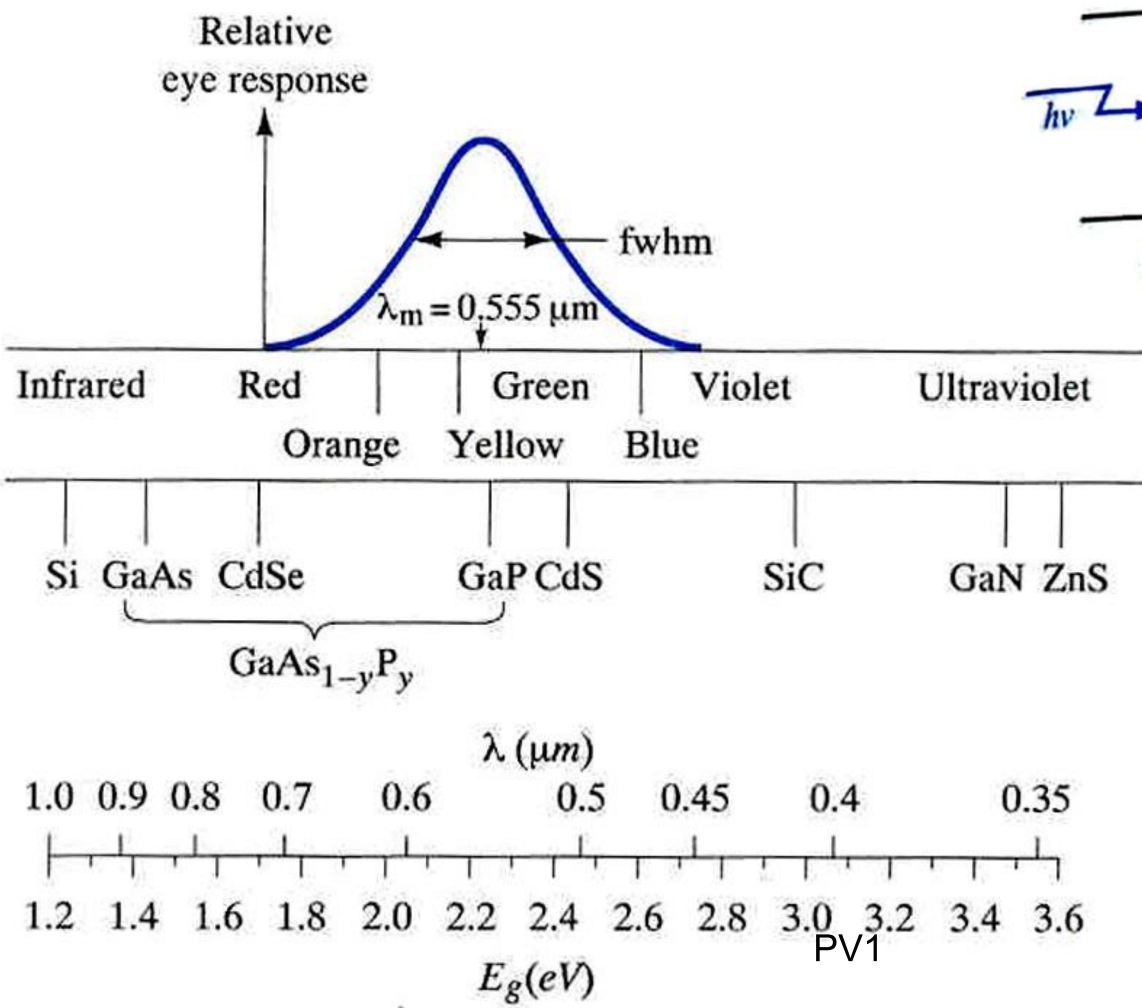
Semiconductor related

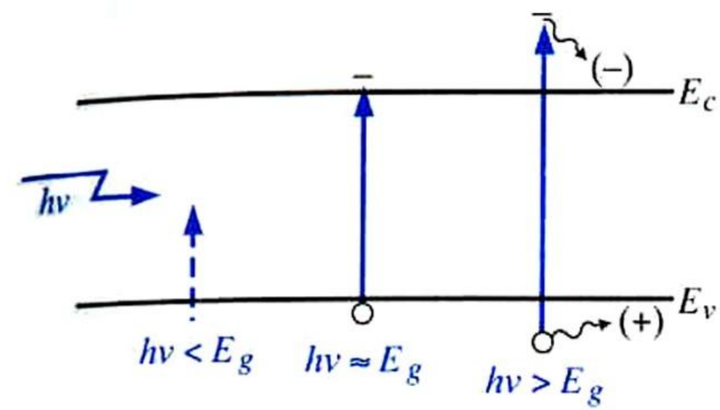
1. Percentage of spectral overlapping
2. Quantum efficiency, Absorption depth vs. p-n-junction depth and thickness
3. Recombination of electrons and holes in the bulk of Si:
   diffusion length L or lifetime τ.
4. The reverse current in the p-n-junction, because of recombination

Percentage of spectral overlapping



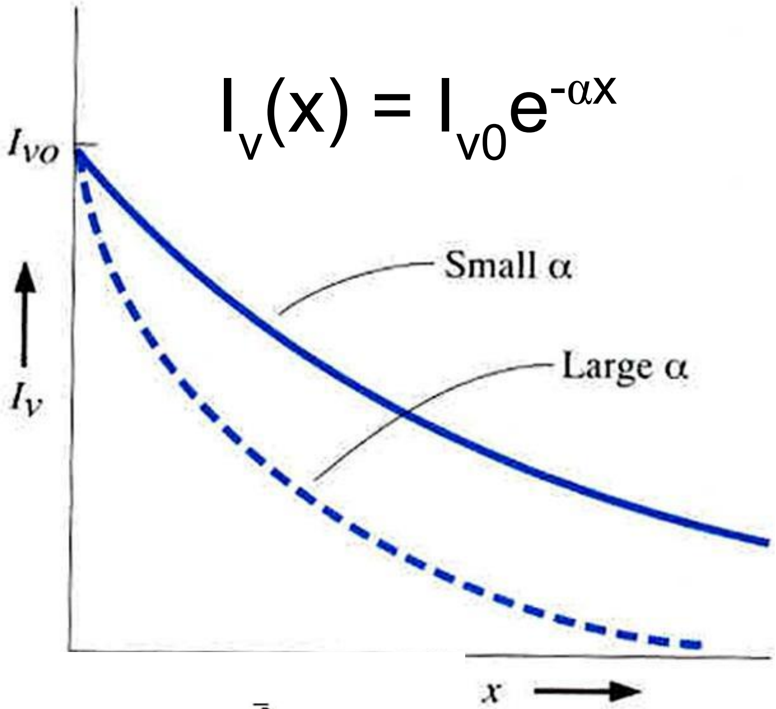
Spectrum vs. Energy

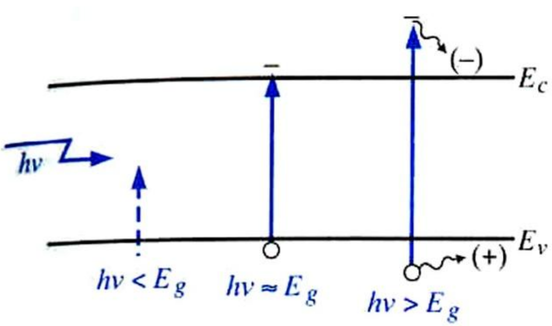


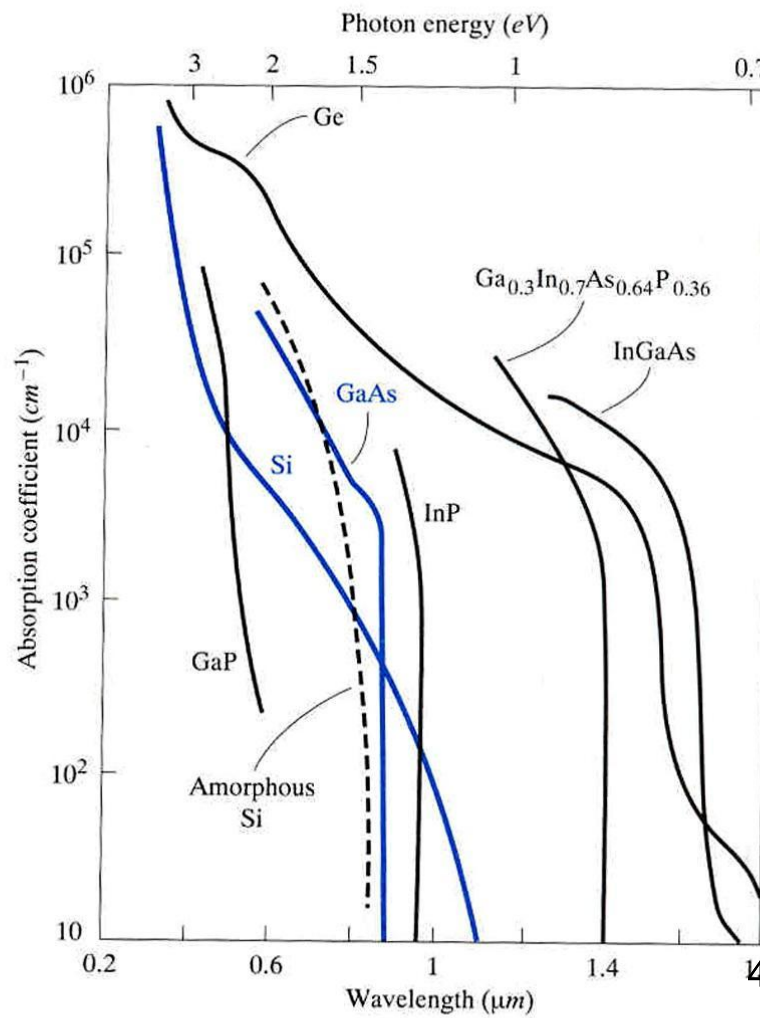


Absorption depth vs. p-n-junction depth and thickness

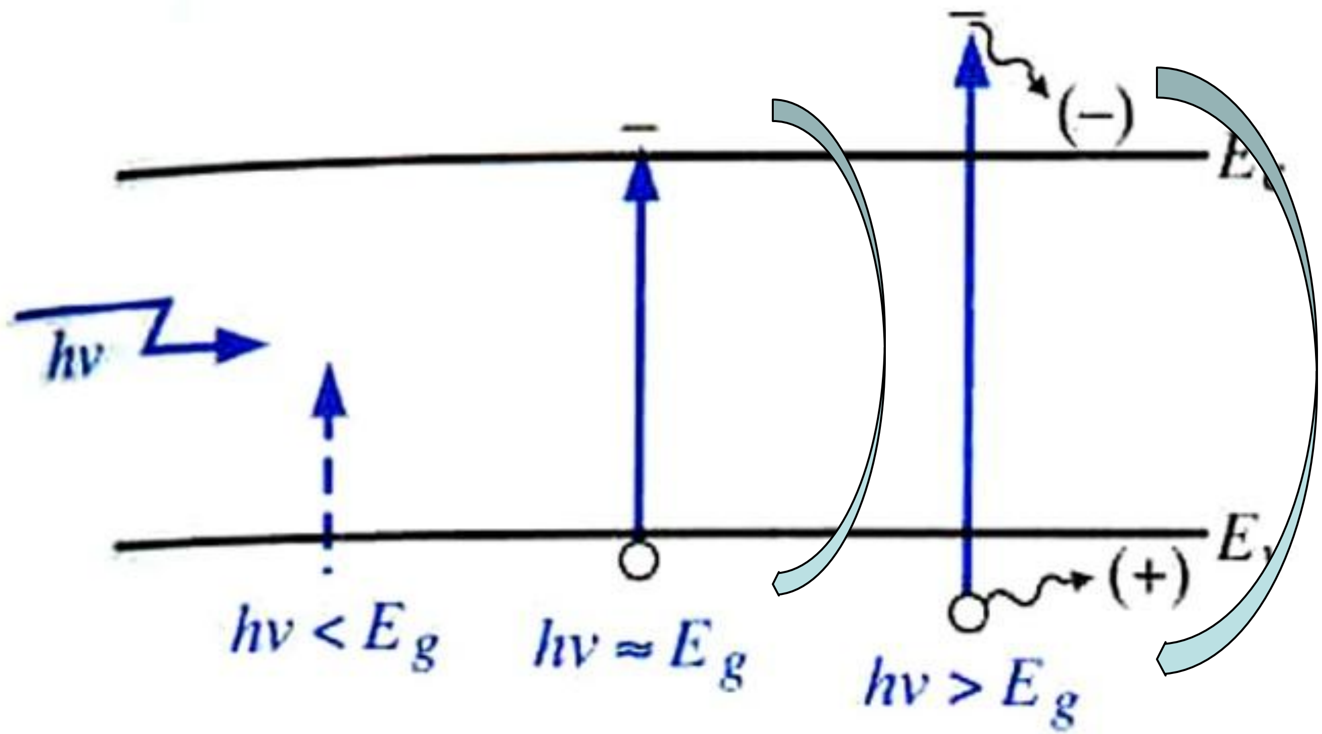
$$I_v(x) = I_{v0}e^{-\alpha x}$$



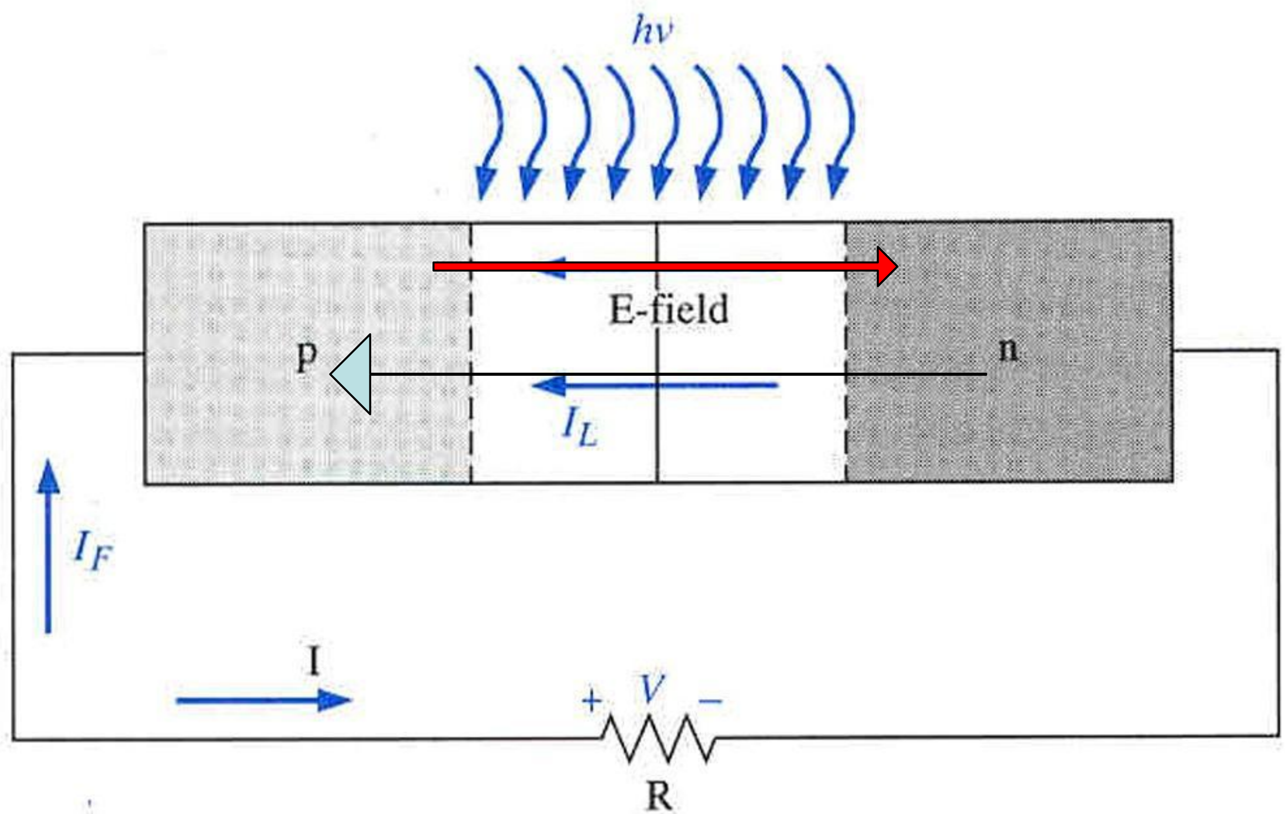




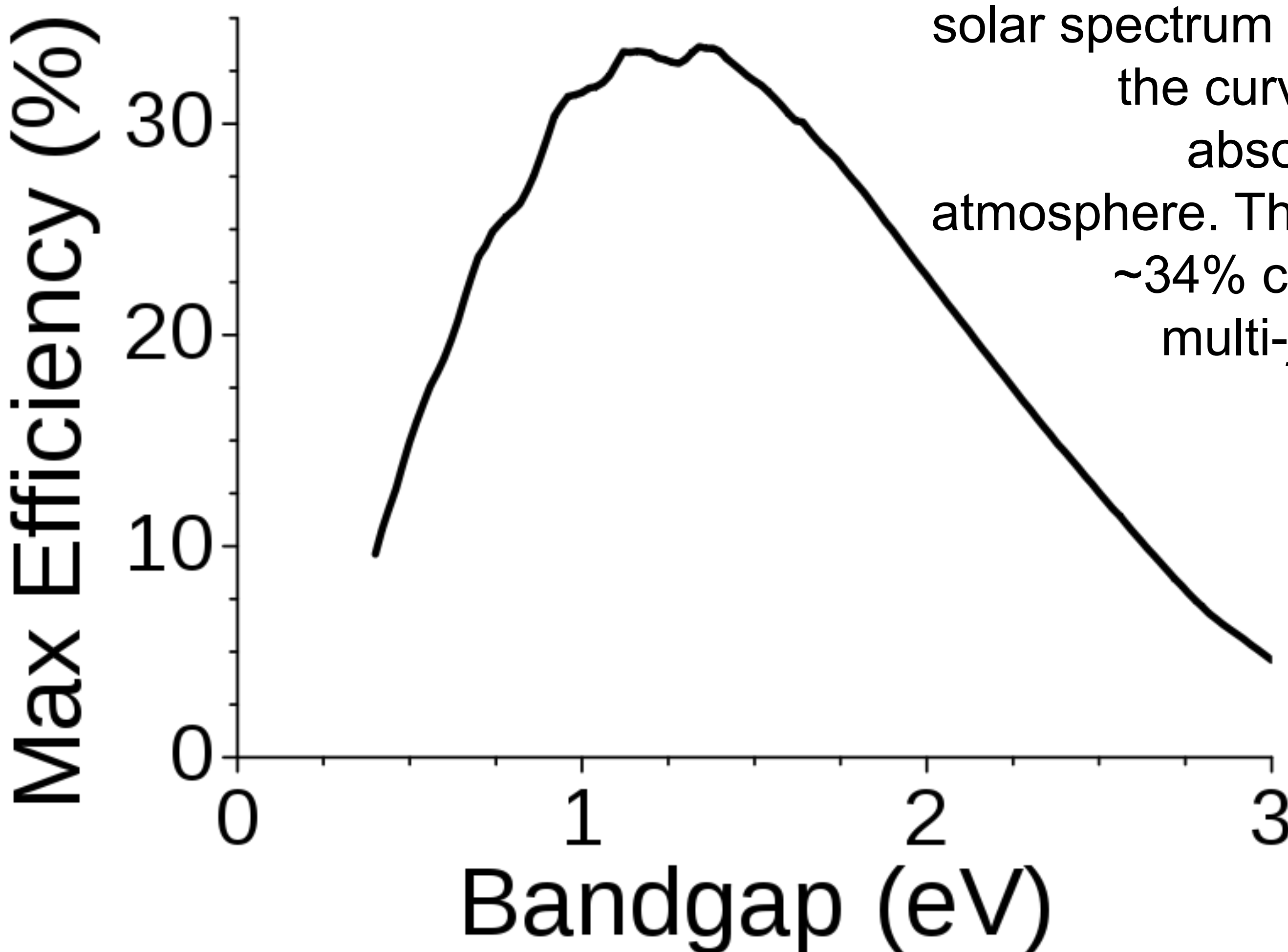
Recombination of electrons and holes



The reverse current in the p-n-junction – defects inside SCR that enhance recombination, i.e. loss of electron-hole pairs.



Shockley-Queisser Limit



The Shockley-Queisser limit for the efficiency of a single-junction solar cell under unconcentrated sunlight. This calculated curve uses actual solar spectrum data, and therefore the curve is wiggly from IR absorption bands in the atmosphere. This efficiency limit of ~34% can be exceeded by multi-junction solar cells.

Factors Influencing Efficiency

Factors outside the semiconductor

1. Surface reflectance
2. Shading by collecting electrode, effective surface. Optical Fill Factor (OFF).
3. Unbalanced load – non-maximal power point. Electrical Fill Factor (EFF).

Surface reflectance

- By the semiconductor surface
- By the weather encapsulation
- By the low-iron, tempered glass
- Anty-reflective coatings decrease the reflectance but are expensive.

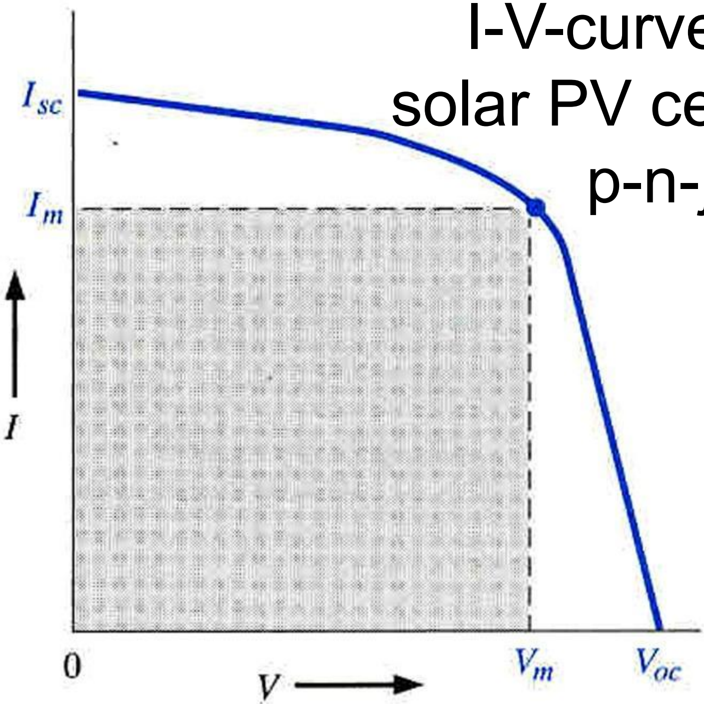
Optical Fill Factor (OFF)

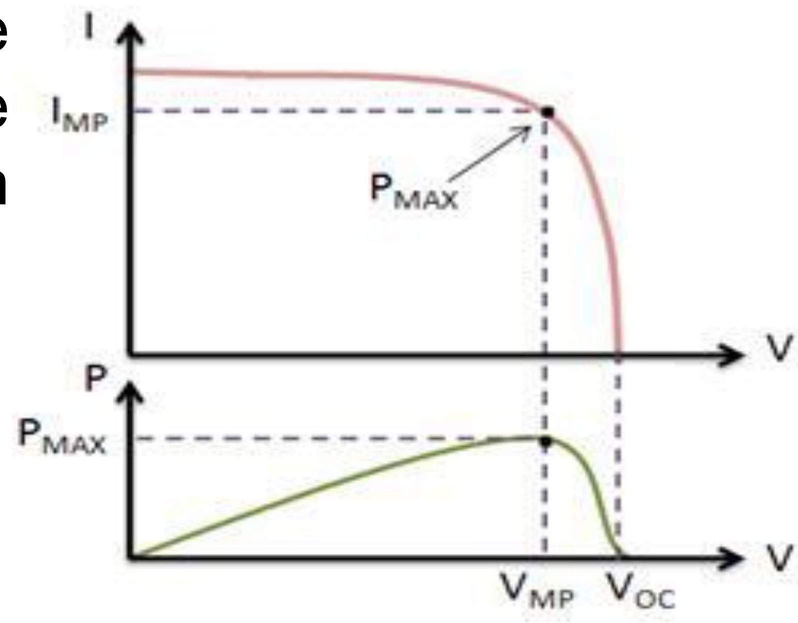
- The area that is open for the radiation
- Shading by collecting electrode
- Effective surface of the module
- Distance between modules
- Distance between rows in the solar field
- The solar system total area

Electrical Fill Factor (EFF) is the $P_{real}/(I_{sc}V_{oc})$,

I_{sc} = short circuit current,
V_{oc} = open circuit voltage

This is a so called I-V-curve for the solar PV cell diode p-n-junction



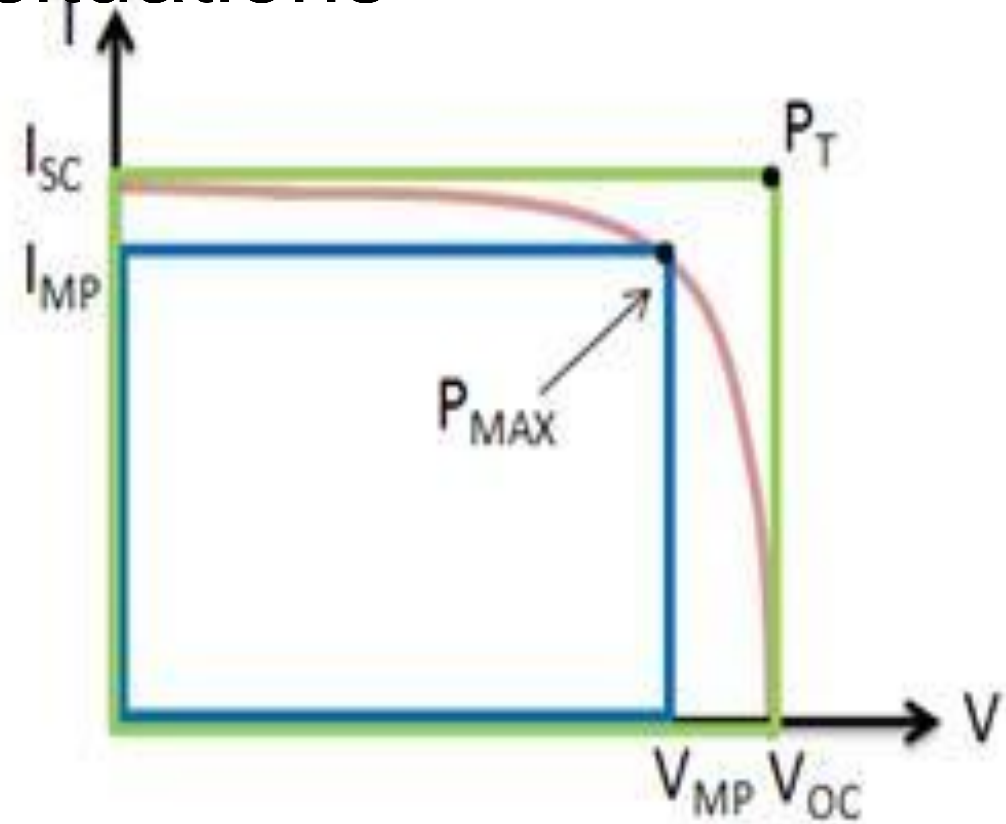


Max Power Point

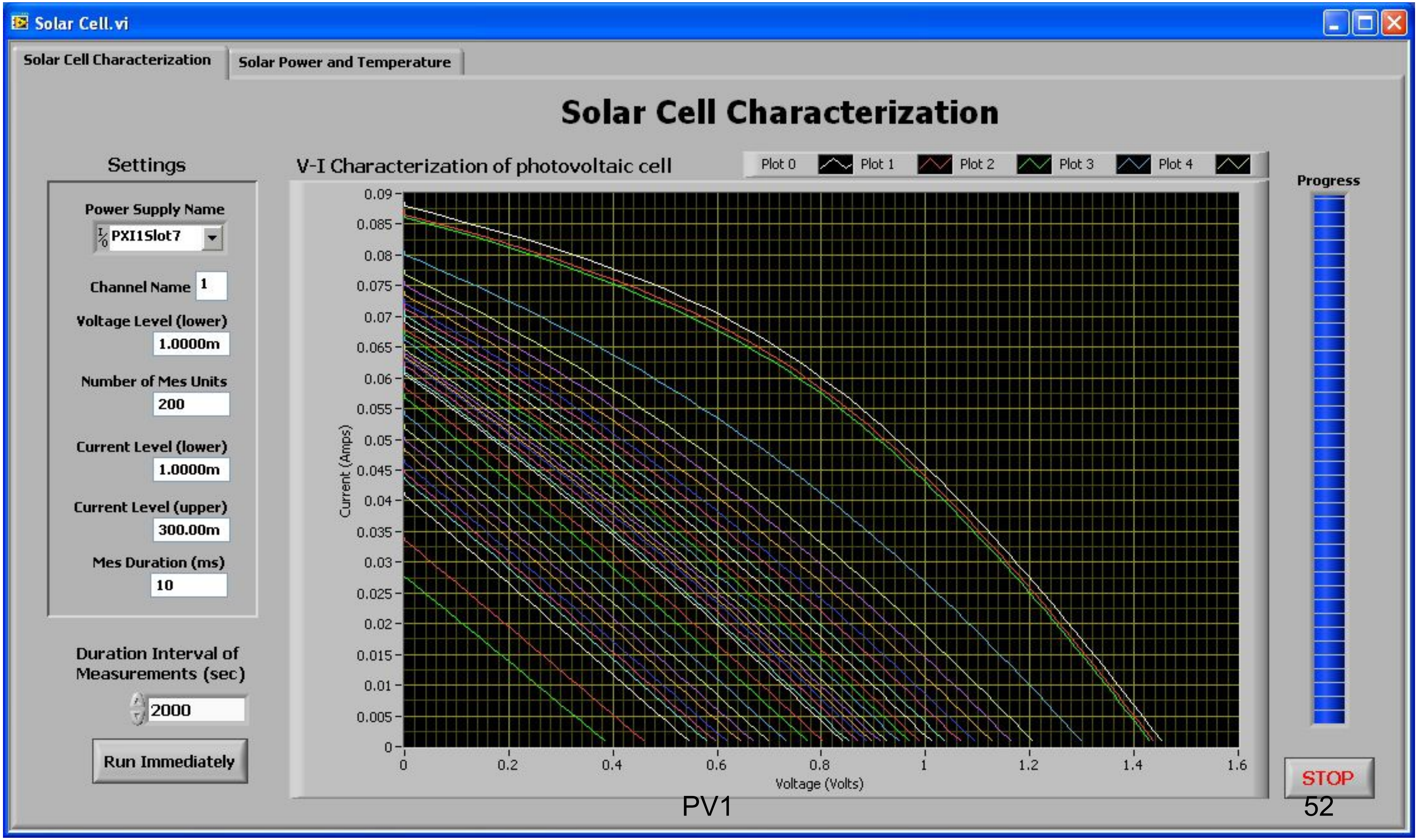
$P_{max} = I_{sc}V_{oc}$ never happens in real situations

$$FF = \frac{P_{MAX}}{P_T} = \frac{I_{MP} \cdot V_{MP}}{I_{SC} \cdot V_{OC}}$$

$$FF = \frac{P_m}{V_{OC} \times I_{SC}} = \frac{\eta \times A_c \times E}{V_{OC} \times I_{SC}}.$$



Organic PV cell test, AUA



Types of Solar Converters

1. Crystalline Silicon: Single-crystal (c-Si) – eff 22%
2. Crystalline Silicon: Multi-crystalline (mc-Si) or Poly-crystalline Si (poly-Si) – eff 17%
3. Amorphous Silicon (Si-A) – eff 9%, degradation.

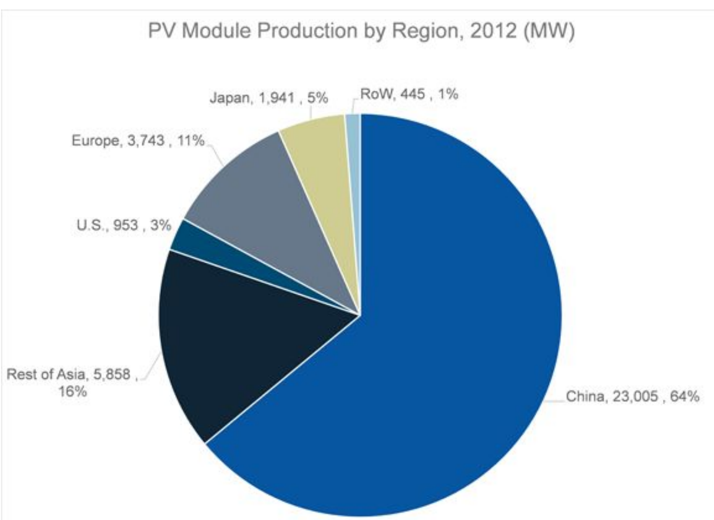
All Si technologies make 86% of the market.

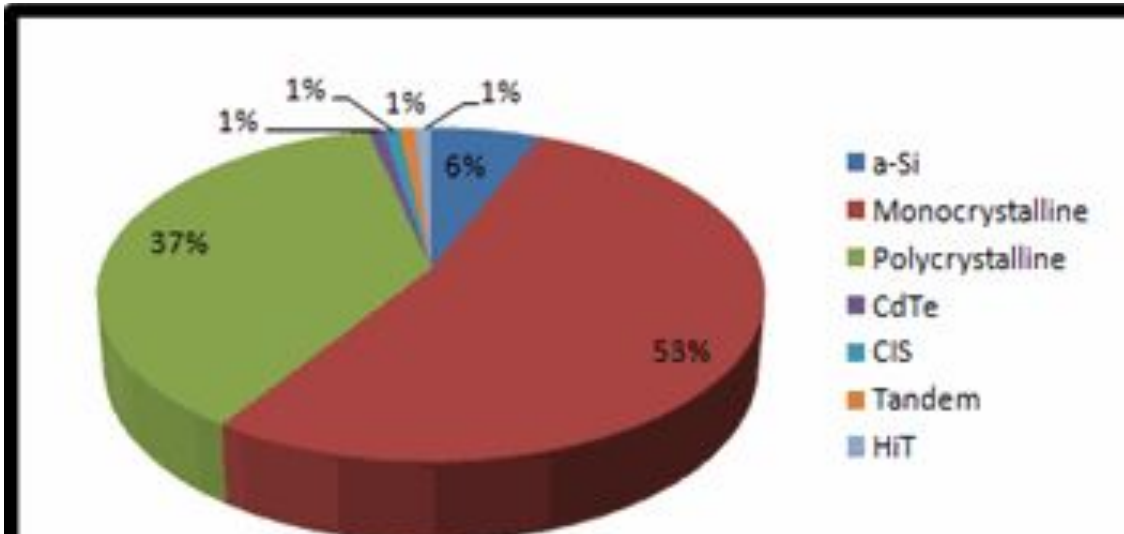
Thin Film:

- CdTe is easier to deposit and more suitable for large-scale production. Eff = ususally 6%-10%, up to 15.8% in experiments.
- Copper Indium Gallium Selenide (CIGS) are multi-layered thin-film heterojunction composites. 19.5% Potentially up to around 30%, could be put on polyamide base.
- Multijunction stacks - Gallium arsenide (GaAs), eff = 47%!!!
  - space applications. Albeit extremely expensive,
  - thus uses in the concentrated PV

PV cell materials in the market

- Market share percentage of PV cell technologies installed in Malaysia until the end of December 2010
- Production by country, 2012





PV cell materials in the market

- Market share percentage of PV cell technologies installed in Malaysia until the end of December 2010
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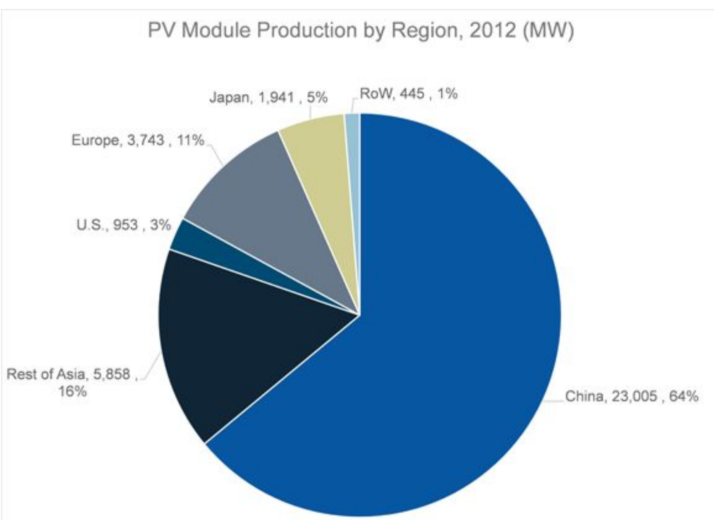
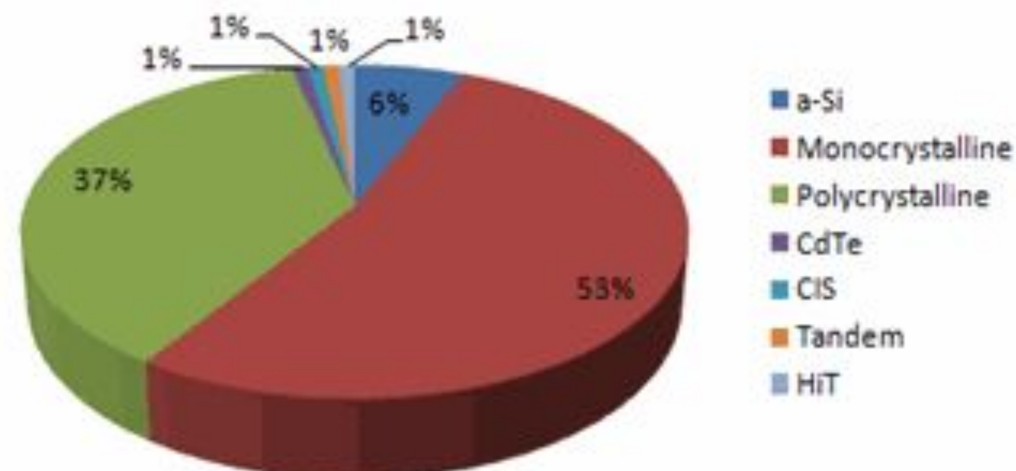
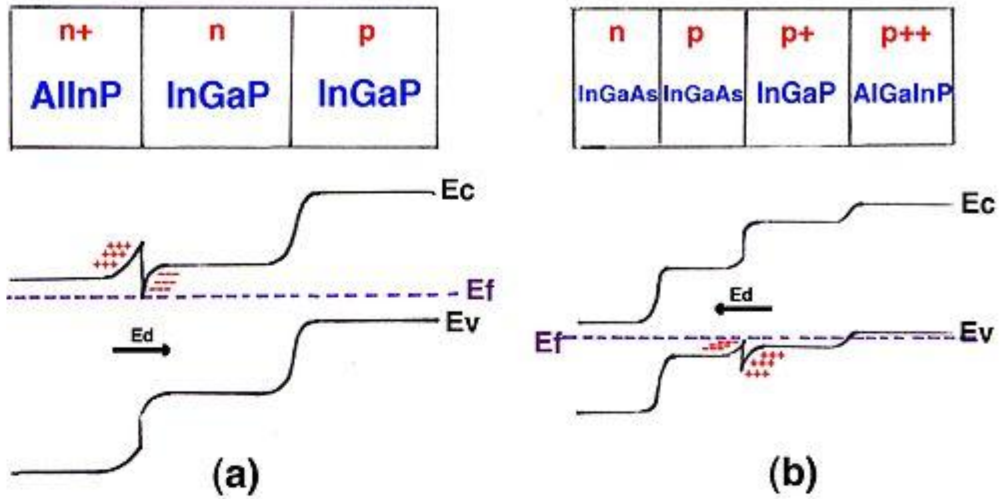


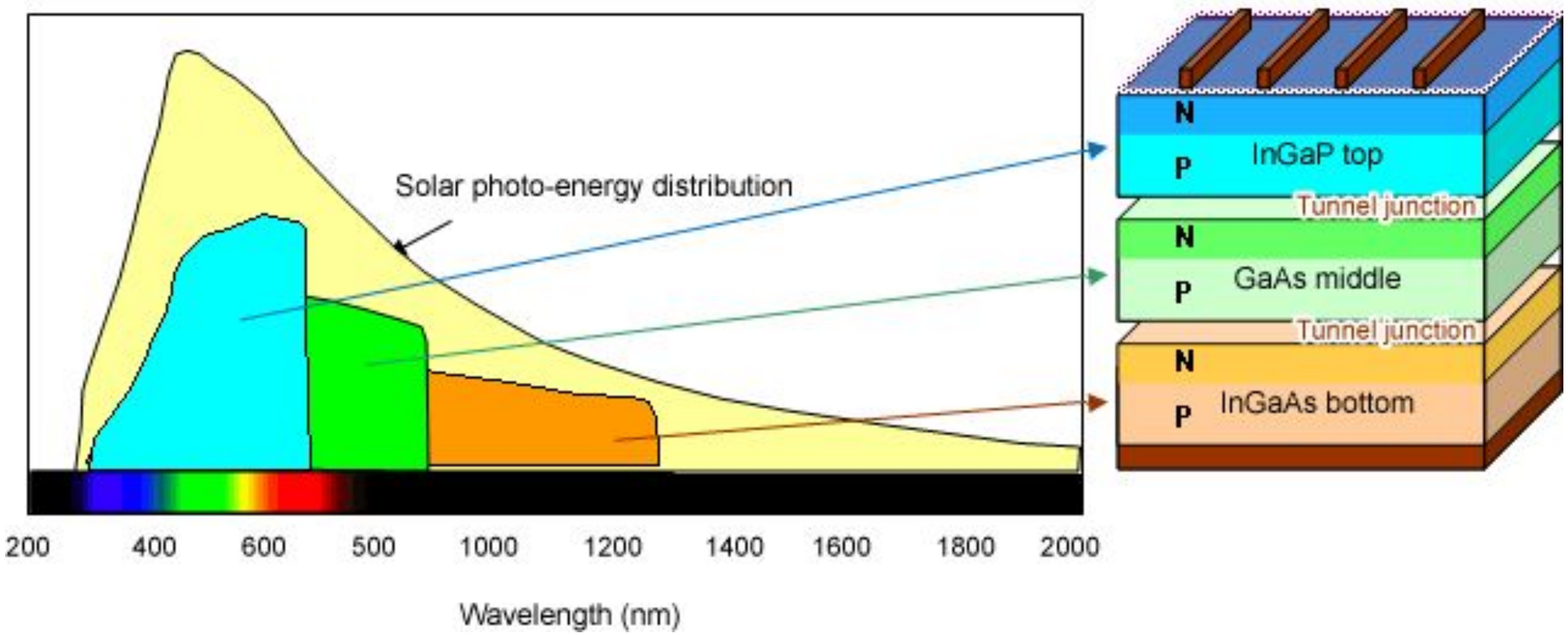


Efficiency

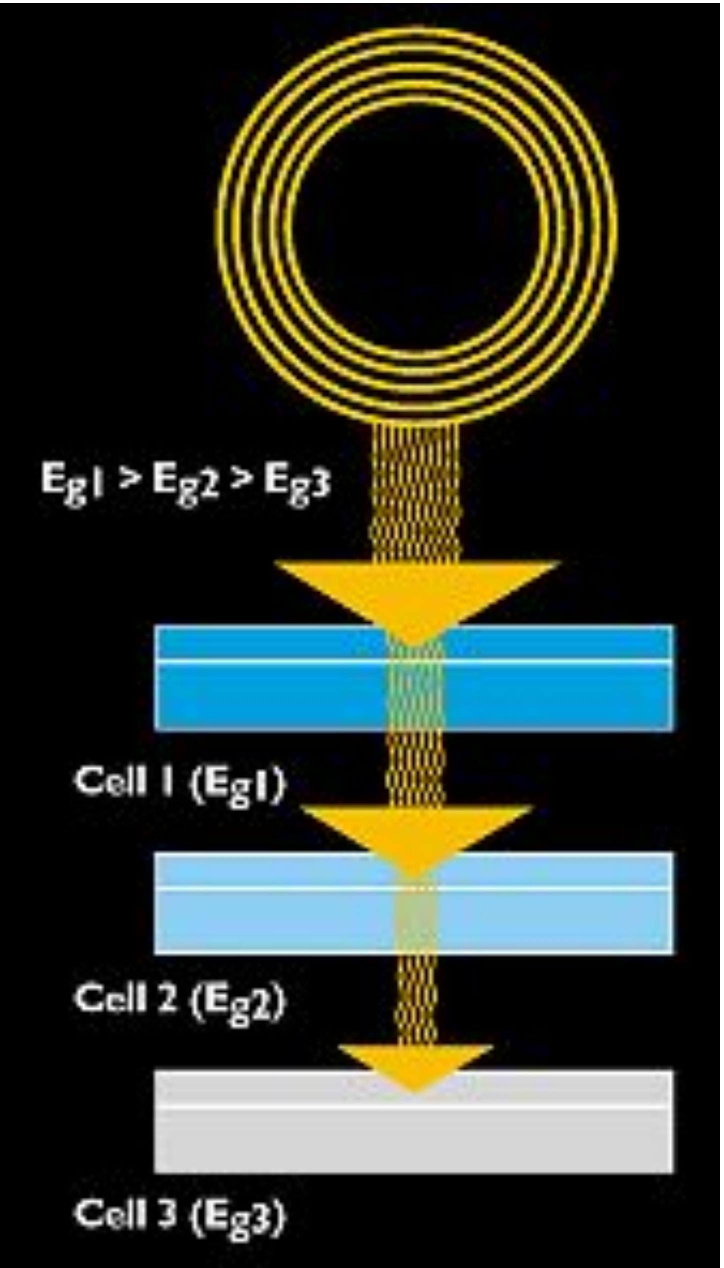
- In 1884 the first Selenium Solar cell had 1% efficiency.
- The theoretical maximum is 64% for stacked PV structures!
- The real, economically productive values are 16% - 24%.

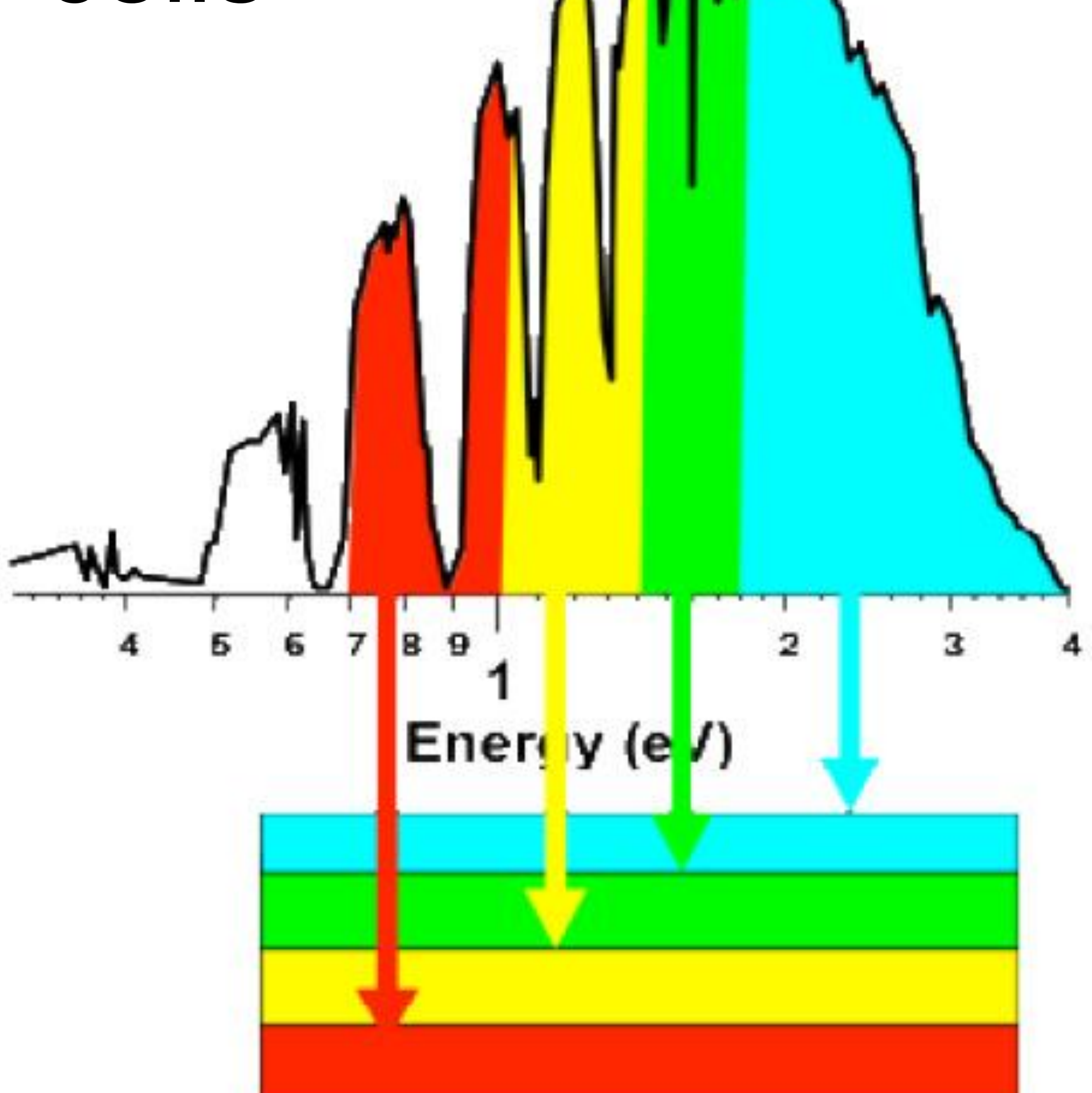
Stacked multi junction solar cells

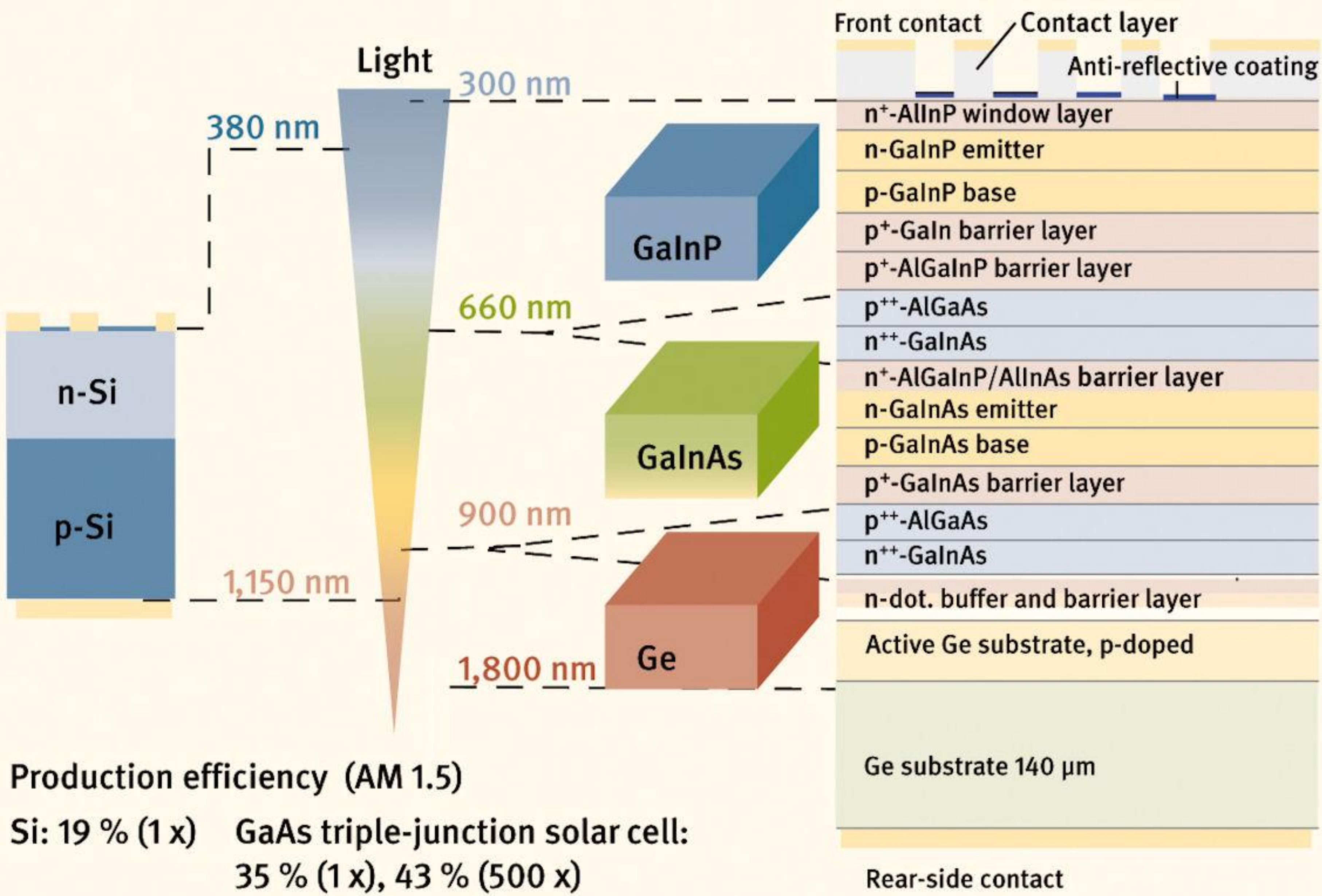




Stacked multi junction – MJ – solar cells





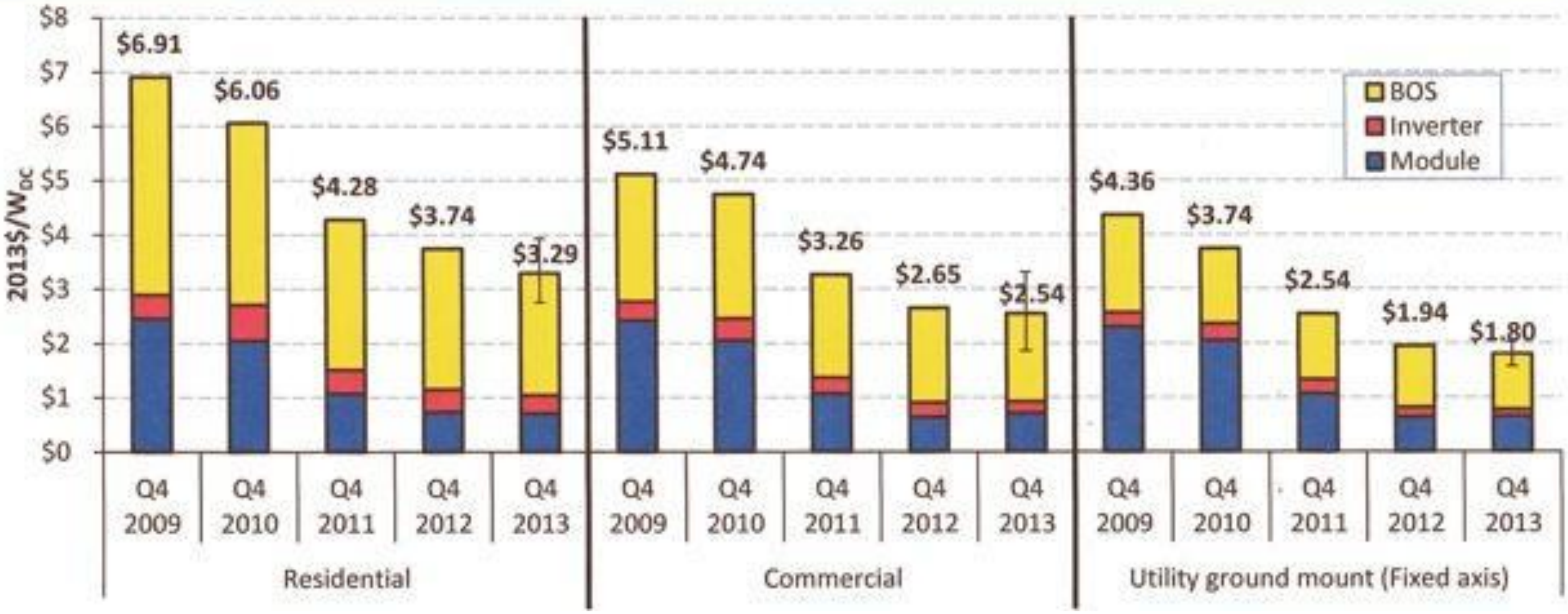


Light
300 nm
380 nm
660 nm
900 nm
1,150 nm
1,800 nm
n-Si
p-Si
GaInP
GaInAs
Ge
Front contact
Contact layer
Anti-reflective coating
n+-AlInP window layer
n-GaInP emitter
p-GaInP base
p+-GaIn barrier layer
p+-AlGaInP barrier layer
p++-AlGaAs
n++-GaInAs
n+-AlGaInP/AlInAs barrier layer
n-GaInAs emitter
p-GaInAs base
p+-GaInAs barrier layer
p++-AlGaAs
n++-GaInAs
n-dot. buffer and barrier layer
Active Ge substrate, p-doped
Ge substrate 140 µm
Rear-side contact
Production efficiency (AM 1.5)
Si: 19 % (1 x)
GaAs triple-junction solar cell:
35 % (1 x), 43 % (500 x)

Components of the PV System

- Photovoltaic (PV) panels
- Battery Bank
- Charge controllers
- Invertors
- Load

Bottom-up Modeled System Price of PV Systems by Sector, Q4 '09 - Q4 '13



PV System calculation approach for net metering case

1. Find out from your monthly bills your total annual kWh-s of consumption - E_e.
2. Find out your local monitoring data – amount of global horizontal (GH) kWh-s (E_m). At tilted angle (30^0 for Yerevan) you can have more than 20% advantage, reaching 1800 kWh/m^2 annually. However due to shading or other losses – you will need to make an assessment – you can take for E_m e.g. 1500 kWh/m^2 for calculation.
3. Remember that since @ 100% efficiency your modules 1 m^2 corresponds to 1 kW of rated power, the $E_e/E_m = P_S$ your needed system power capacity. E.g. @ E_e= 3000; E_m e.g.= 1500 kWh/m^2 annually, P_S = 2 kW. Here 1500 kWh/m^2 is replaced by 1500 kWh/kW.
4. Homework: calculated the price of your system, look at previous slide.

Types of Solar Converters

- Photoelectrochemical cells – now up to eff of 10% in experiments.
- Polymer solar cells = 4-5%
- nanocrystal Si (nc-Si) solar cells, quantum dot technology

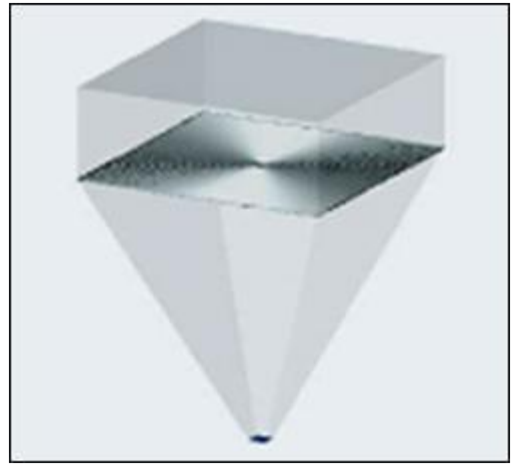
Concentration PV

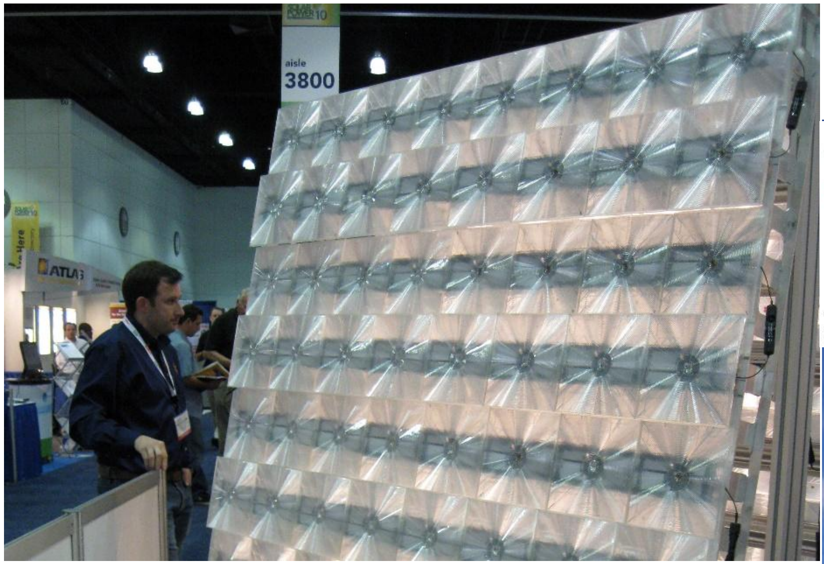
- Photovoltaic concentrators have the added benefit of an increase in efficiency due to the nature of solar cells. Commercial solar cells operate with an efficiency of around 15% in standard sunlight, however when the sunlight is concentrated the efficiency can go above 21%.
- Concentrators reduce the cost. Solar cell are fairly expensive, however mirror and optics are much cheaper. So a small solar cell concentrated can produce more energy with mirrors or optics than the equivalent area with a larger solar array.

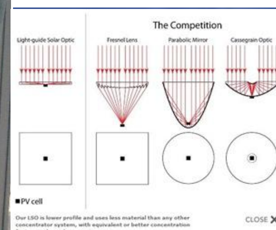
Multi-junction Solar cells

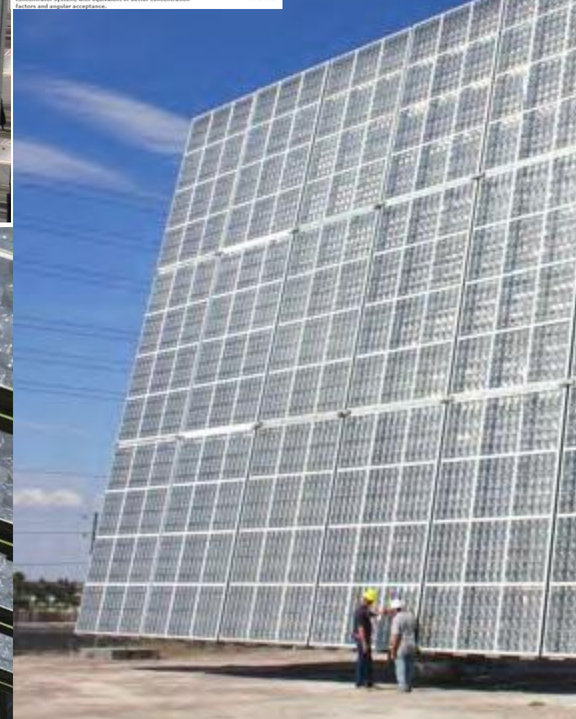
- under illumination of at least 400 suns, MJ solar panels become practical

Amonix concentration systems









Vahan Garbushian

BIPV

BIPV

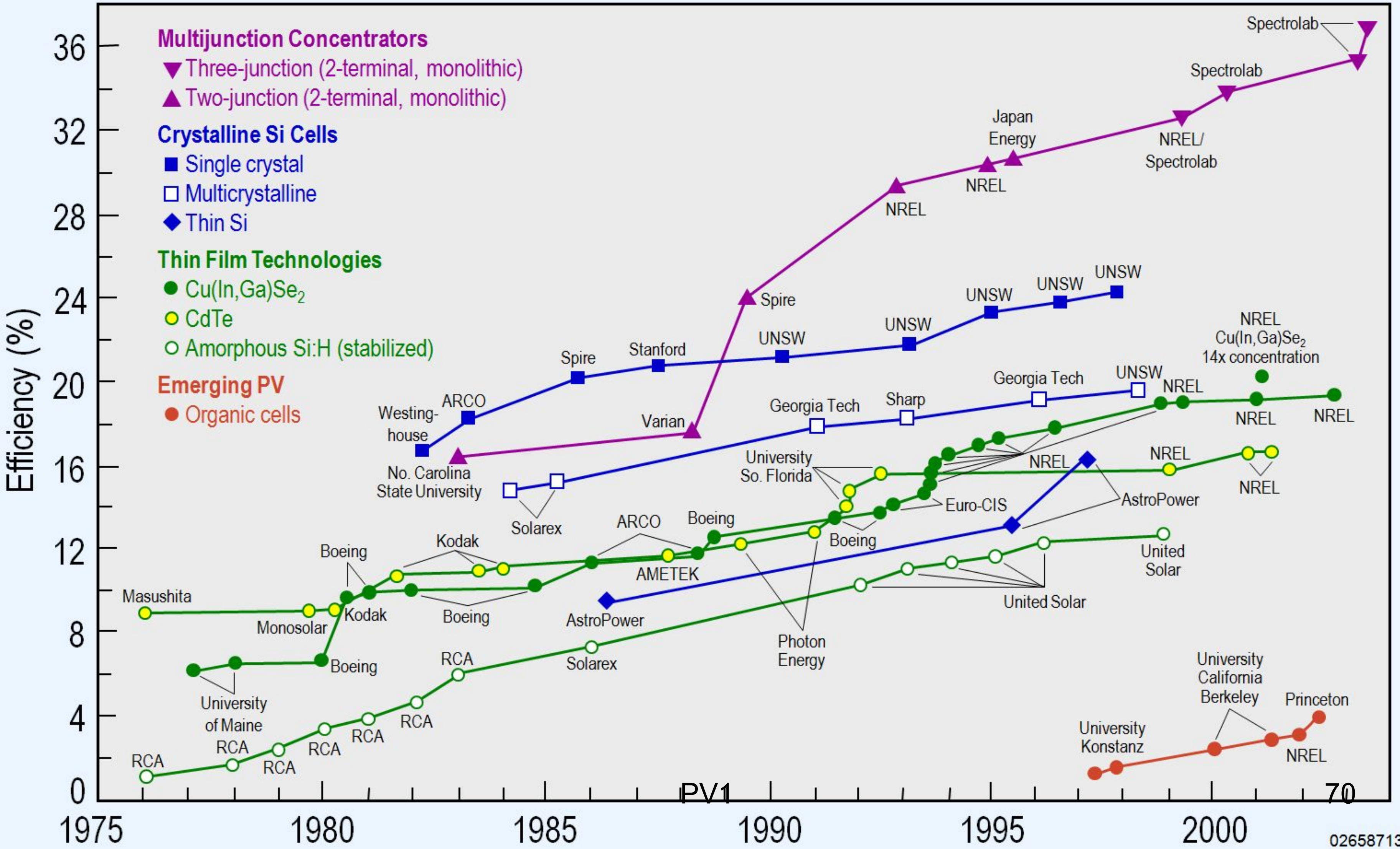
- Similarly, if it is possible to use part of the windows or glazing of the construction to integrate PV cells inside, one can avoid paying for the PV modules’ glazing the second time, as well as economize on the support structure.
- At the same time the Integrated PV is an innovative, aesthetically interesting element that can be a part of the architectural idea - recently popular PV module placement location is the south facing portions of the building envelop, perfectly helping to address both economizing dimensions of the integrated PV.

Efficiency

- In 1884 the first Selenium Solar cell had 1% efficiency.
- The theoretical maximum is 64% for stacked PV structures!
- The real, economically productive values are 16% - 24%.

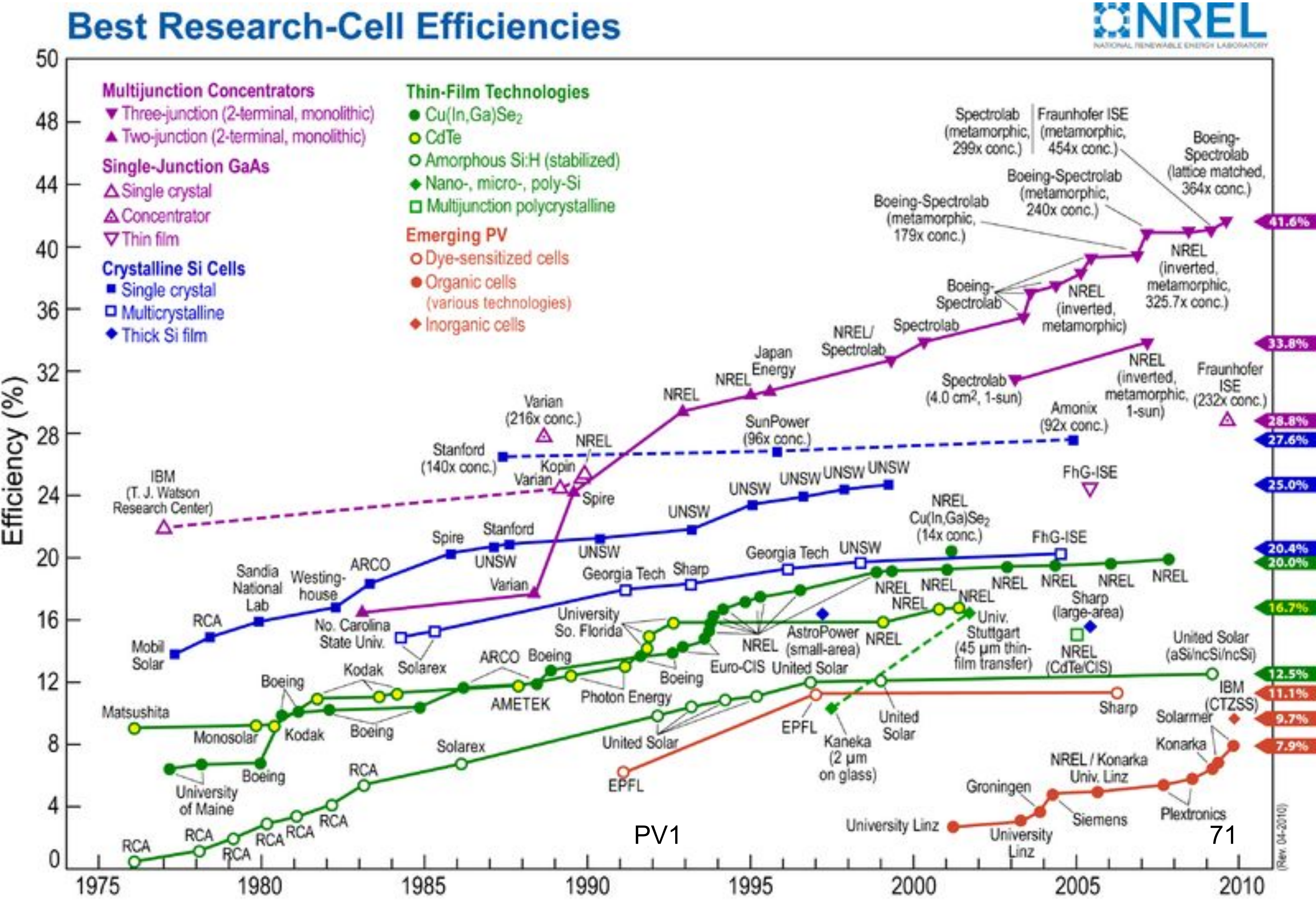
NREL *National Renewable Energy Laboratory* *National Center for Photovoltaics*

Best Research-Cell Efficiencies



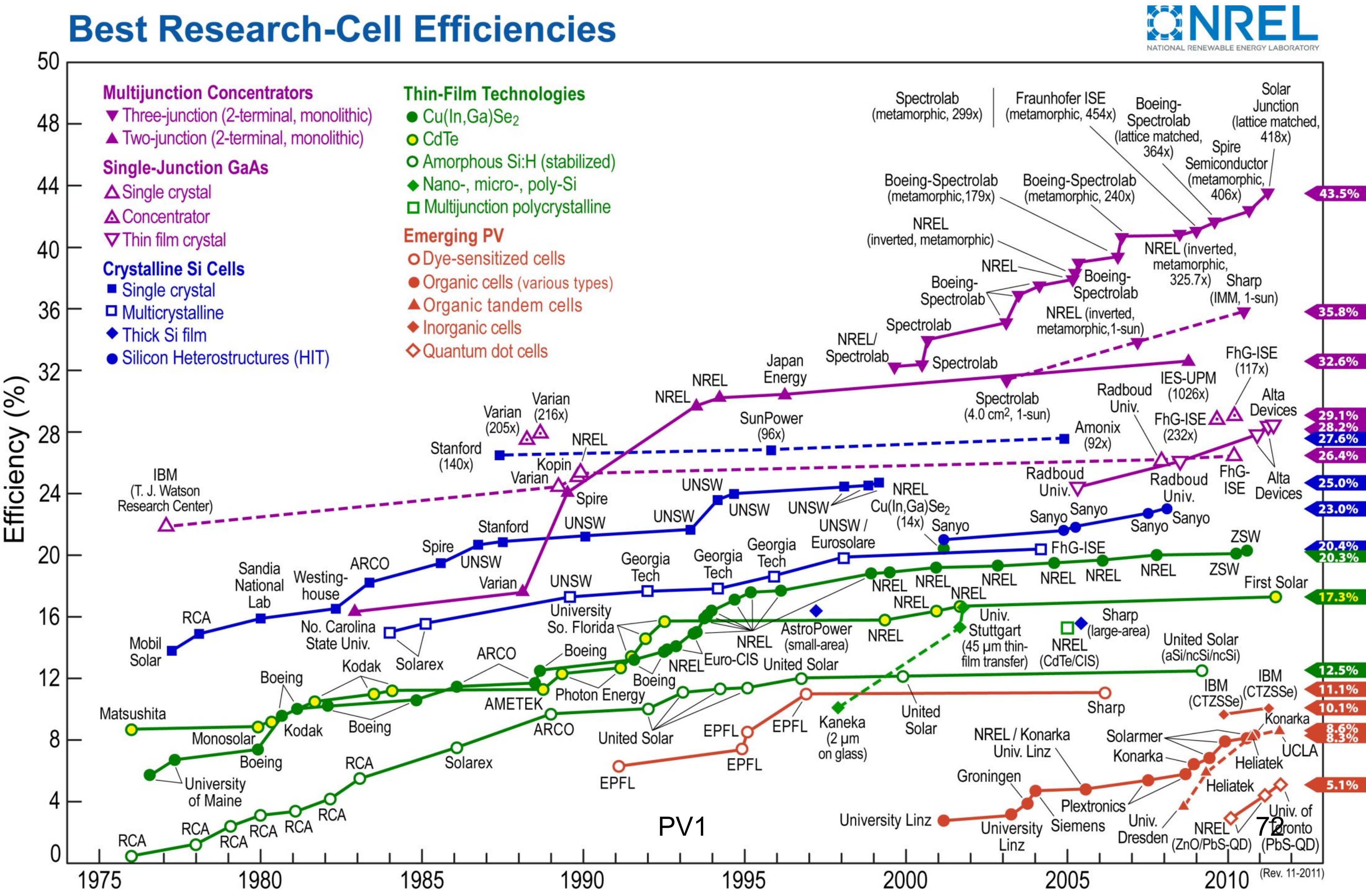
026587136

2009 vs 2003

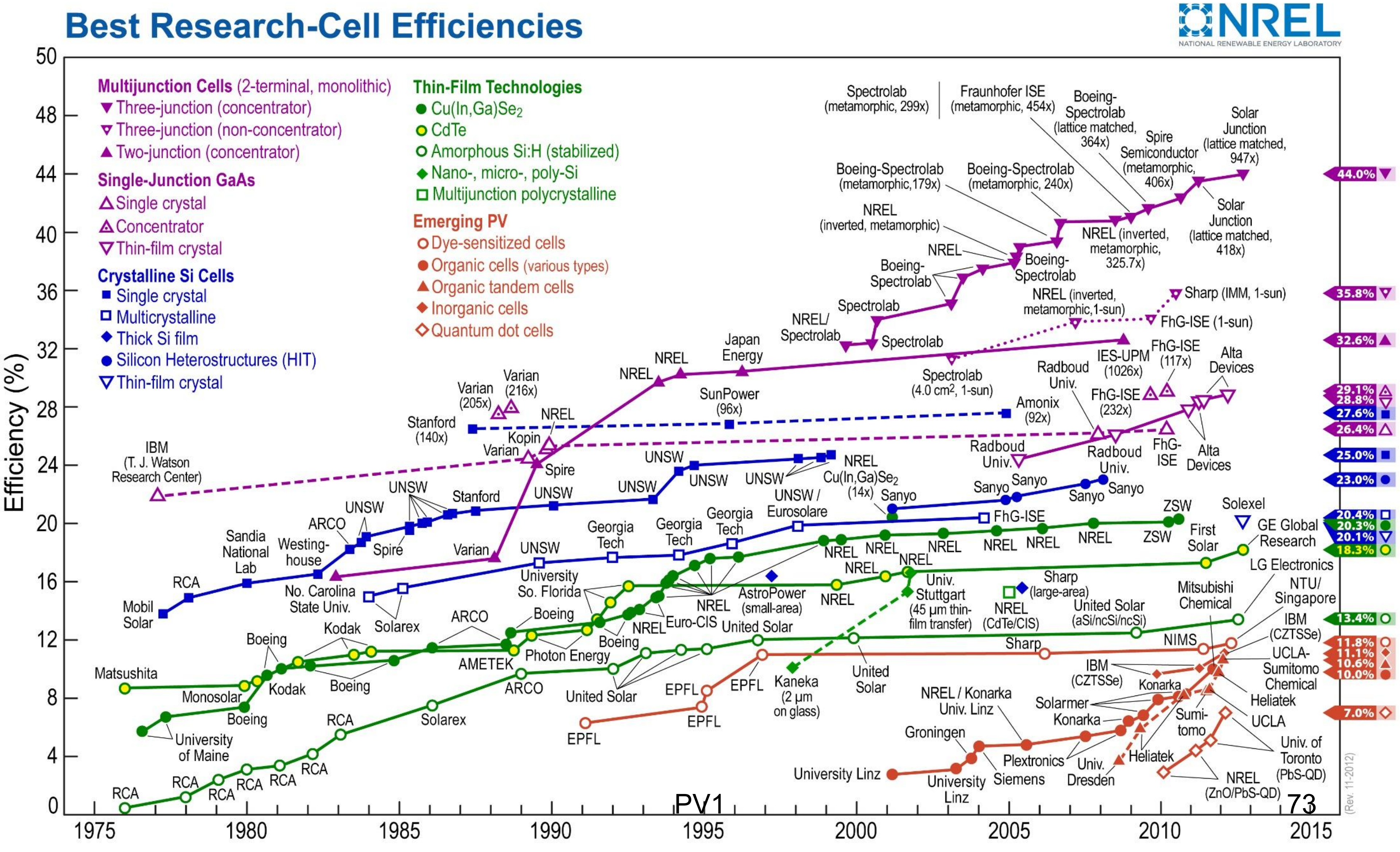


Best Research-Cell Efficiencies
NREL
Multijunction Concentrators
Three-junction (2-terminal, monolithic)
Two-junction (2-terminal, monolithic)
Single-Junction GaAs
Single crystal
Concentrator
Thin film
Crystalline Si Cells
Single crystal
Multicrystalline
Thick Si film
Thin-Film Technologies
Cu(In,Ga)Se2
CdTe
Amorphous Si:H (stabilized)
Nano-, micro-, poly-Si
Multijunction polycrystalline
Emerging PV
Dye-sensitized cells
Organic cells (various technologies)
Inorganic cells
Efficiency (%)
41.6%
33.8%
28.8%
27.6%
25.0%
20.4%
20.0%
16.7%
12.5%
11.1%
9.7%
7.9%
(Rev. 04-2010)

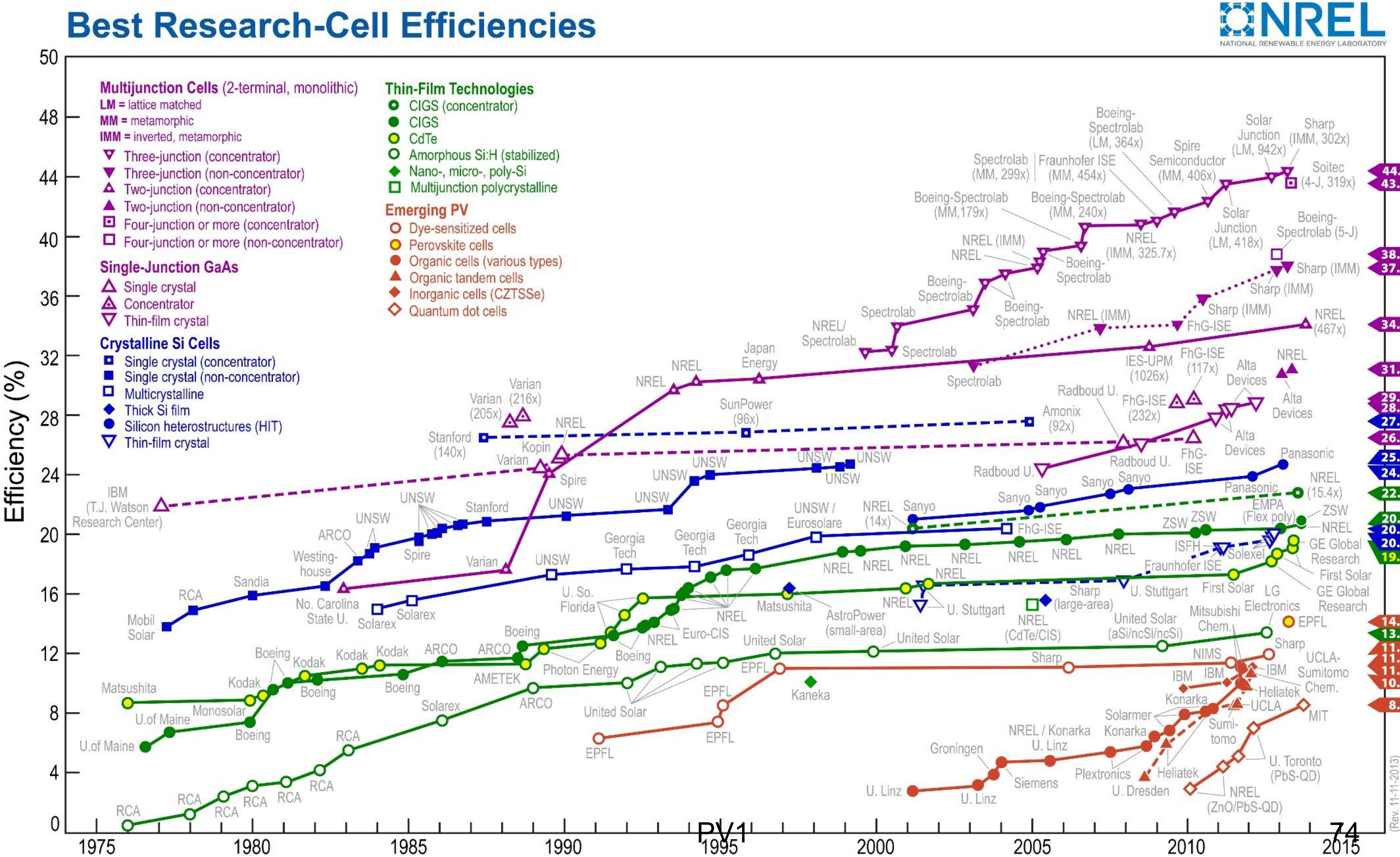
03 November, 2011



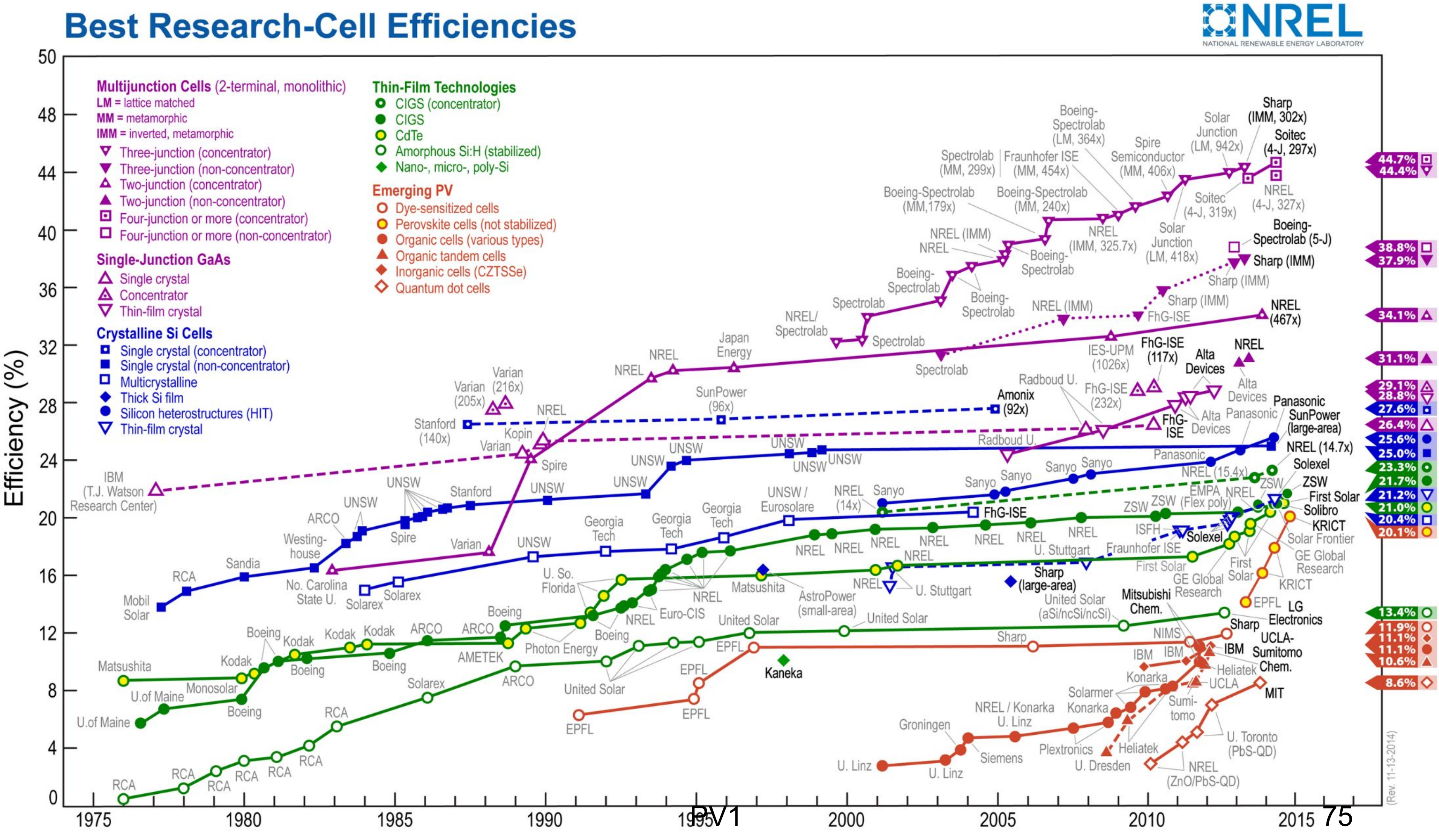
20 November, 2012



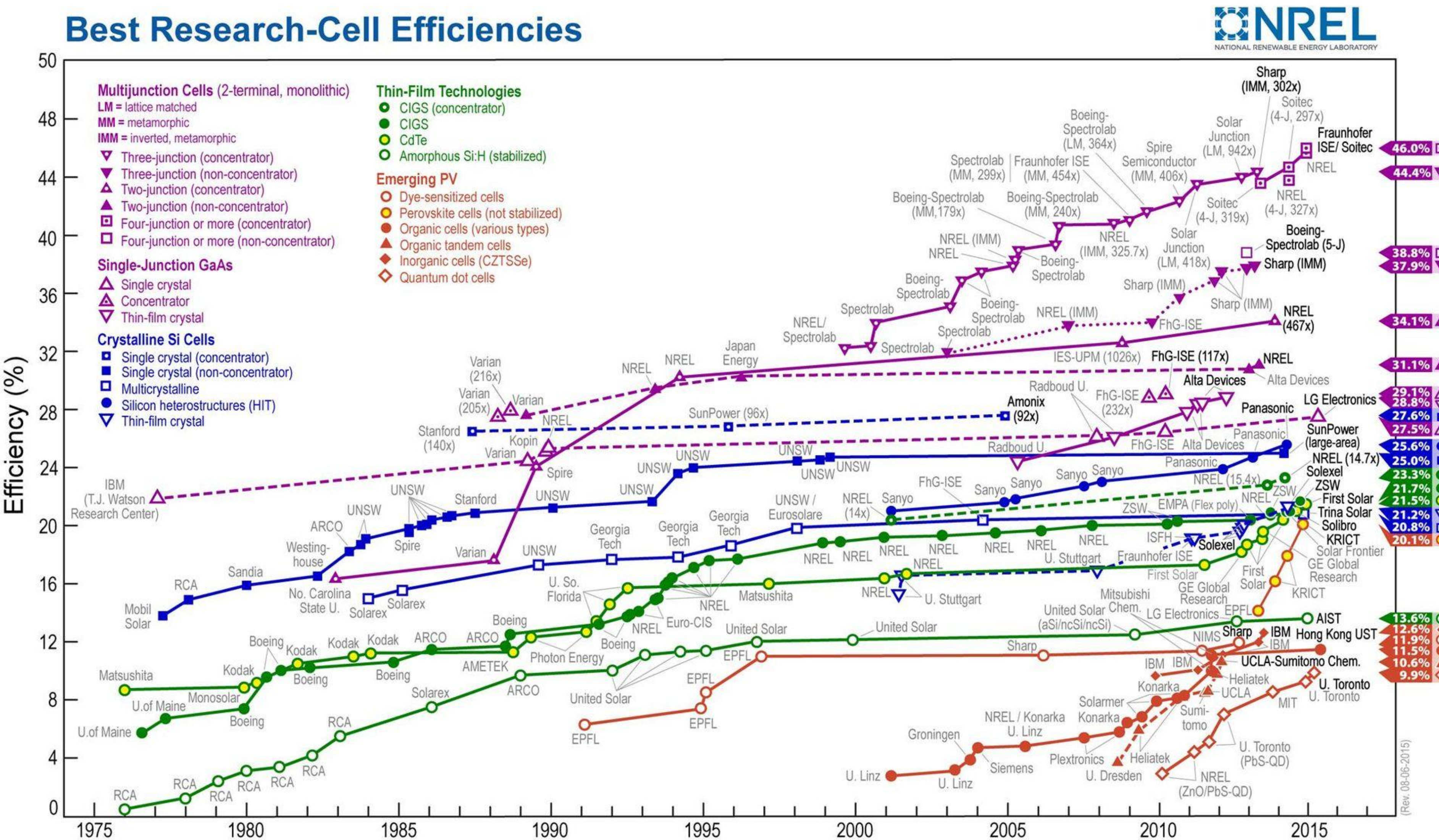
11 November 2013



November 2014



November 2015



How to compare solar cells?

- *Efficiency*
- *Longevity – time to degradation*
- *Peak watt price*

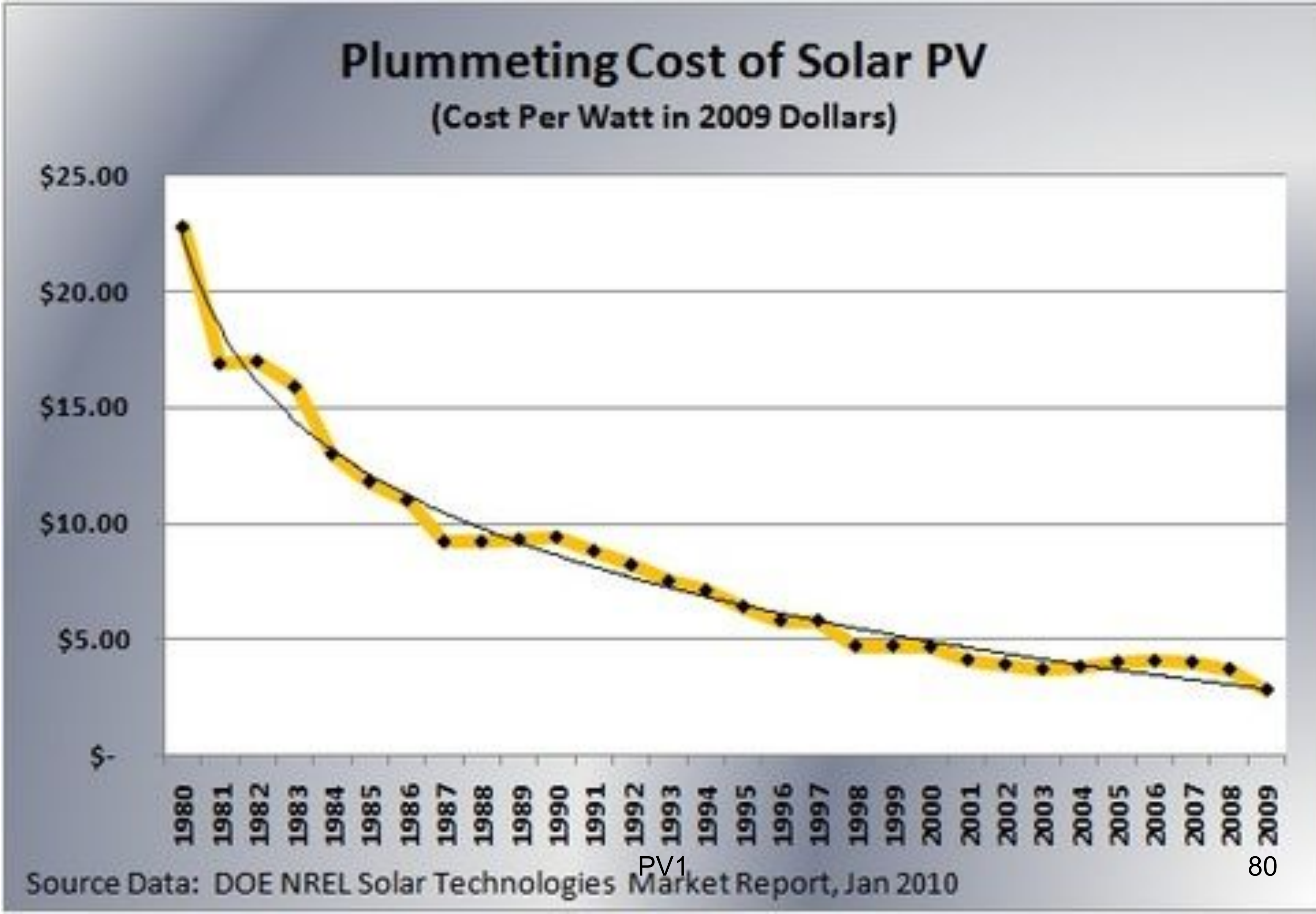
Notion of the peak power price (PPP)

- Price of a cell, module or a system, per conditions when the solar illumination in normal incidence is equal to standard reference radiation, $1000W/m^2$, in $\$/W_{peak}$.
- Note that this is more important than the solely the efficiency.
- Correct way of comparing the prices of various solar options – for any technology.
- Is there a peak watt notion for wind?

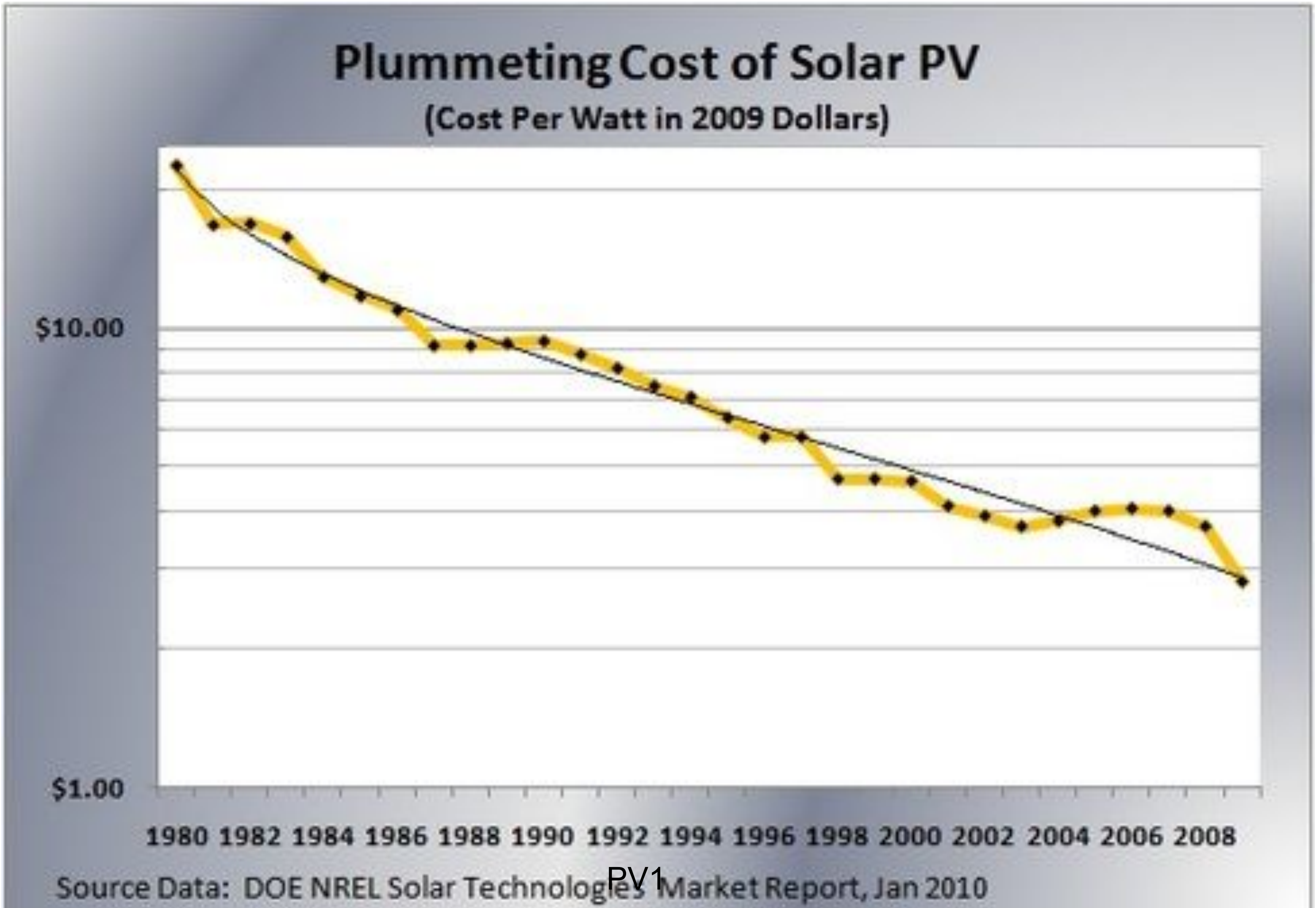
How to compare PV cells, modules?

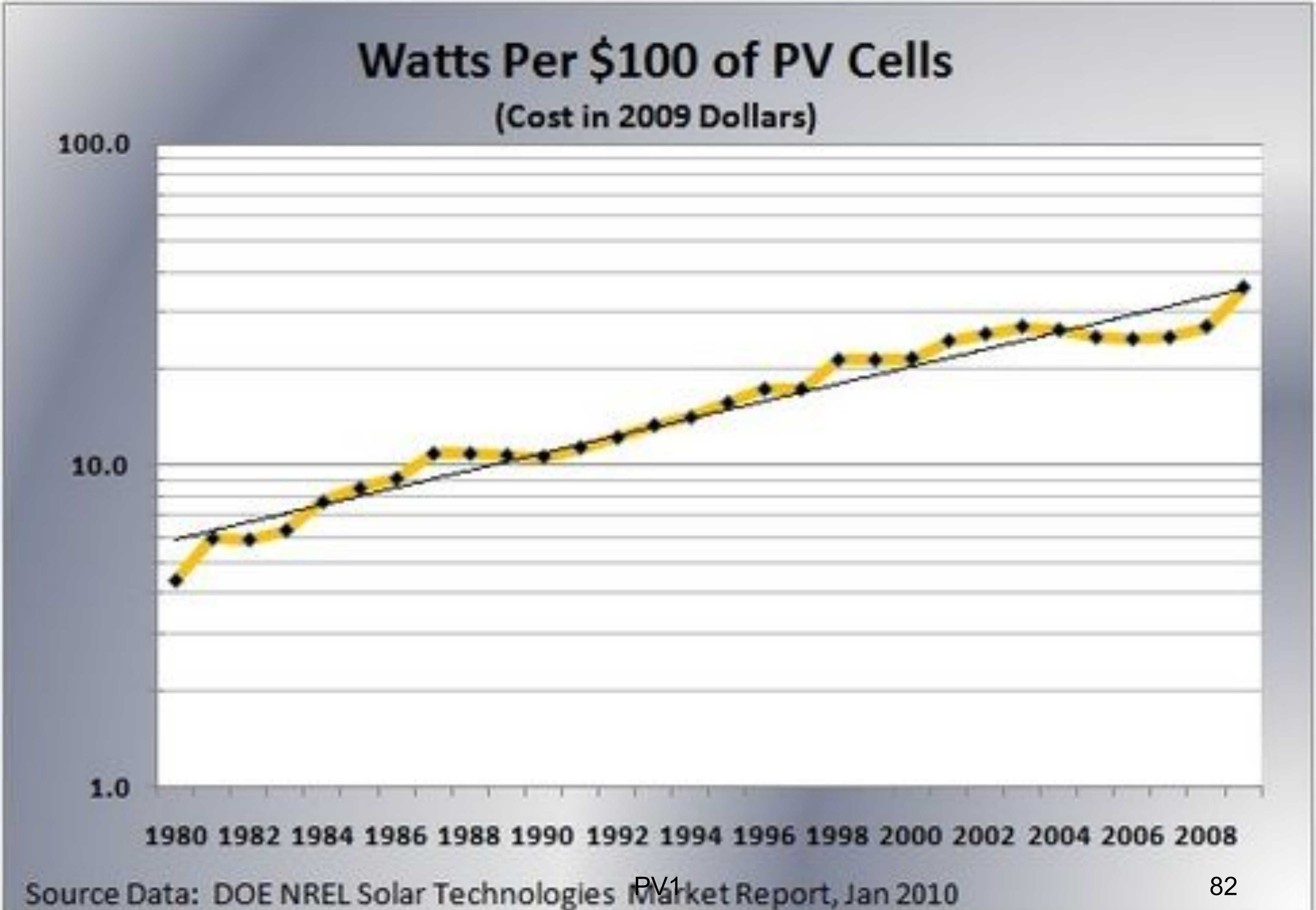
- Peak power price - $\$/W_p$.
- Lifetime – years before substantial degradation, e.g. 15%
- Efficiency, %

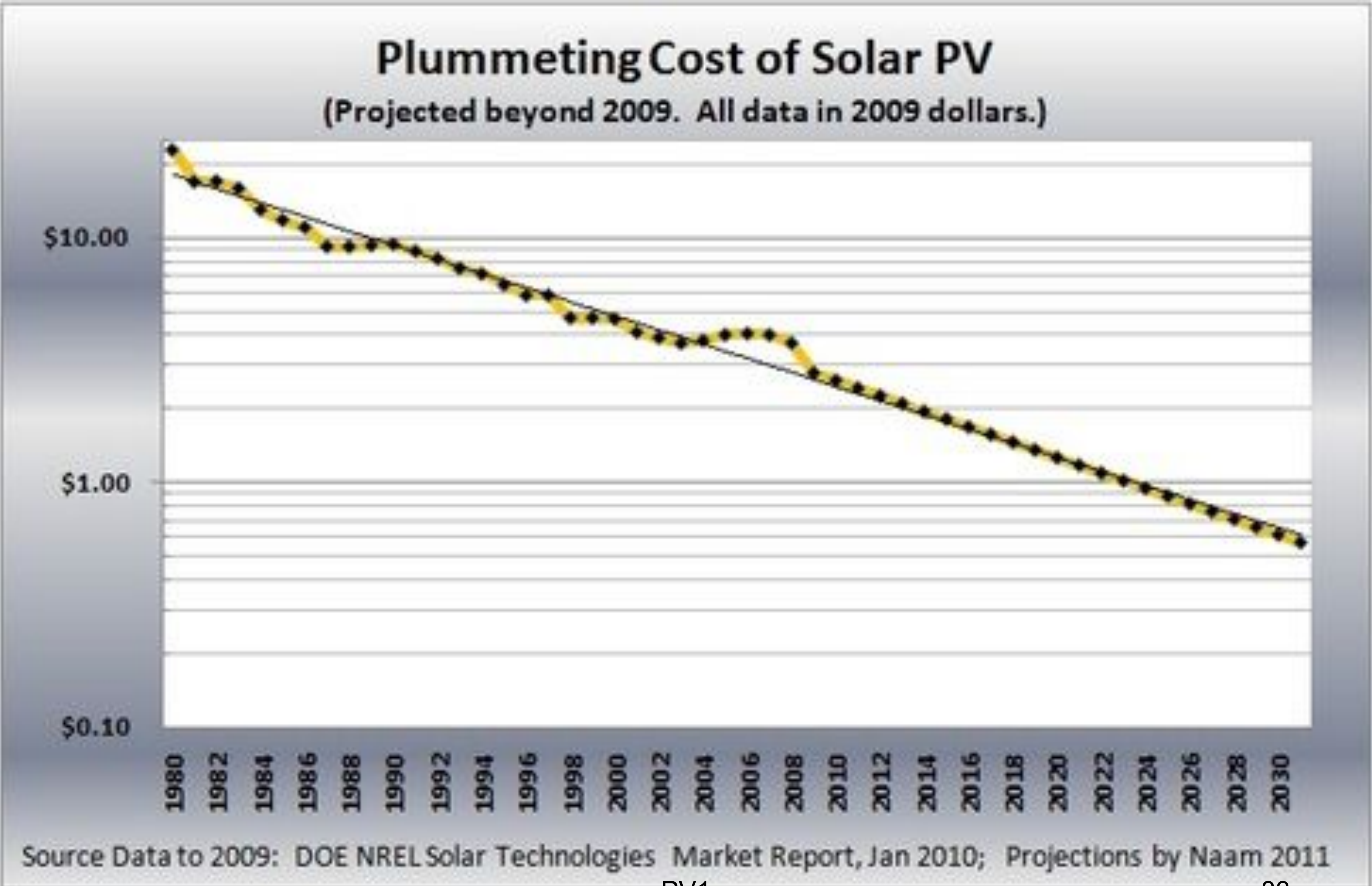
PV module cost per peak watt



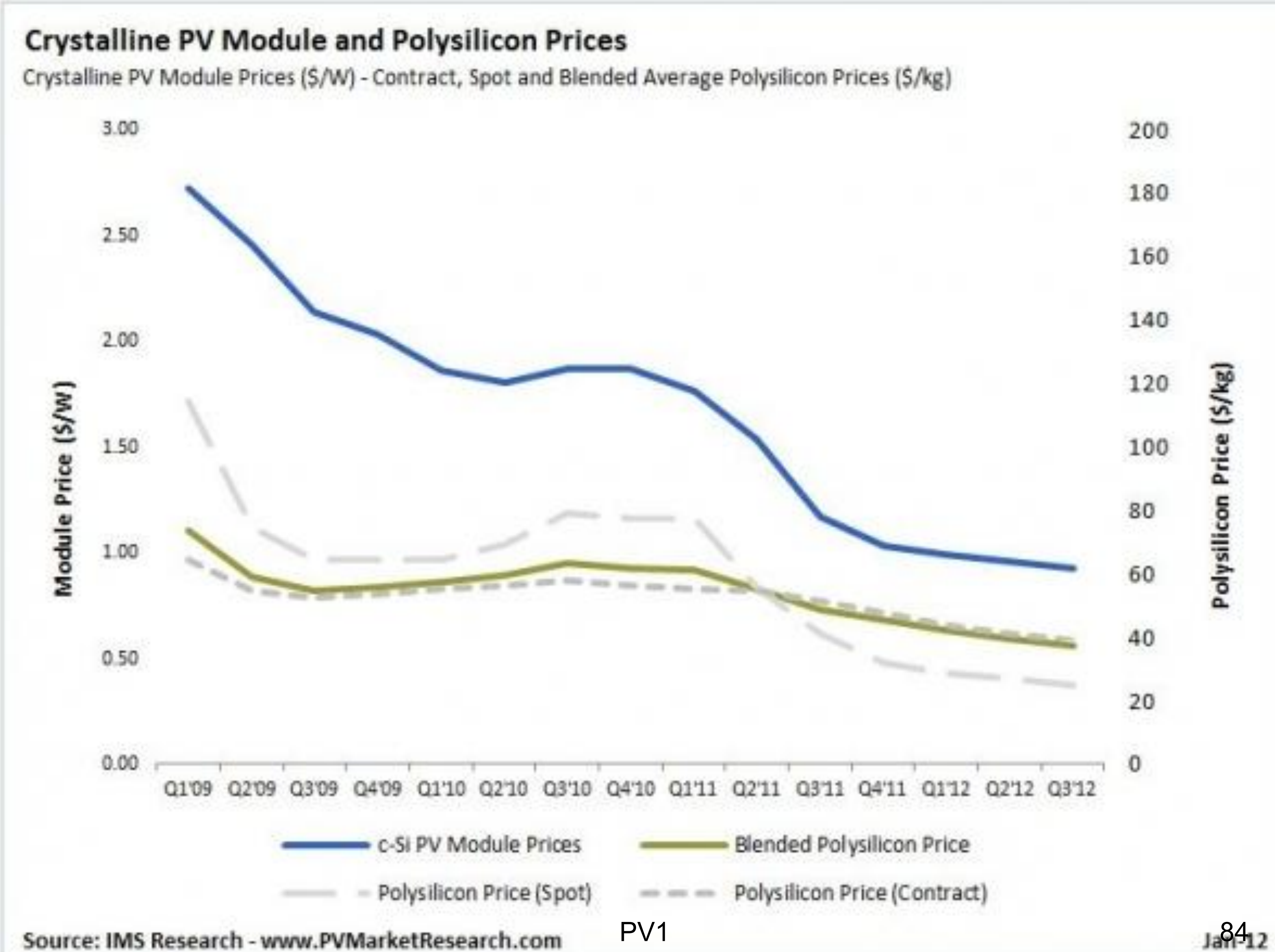
PV module cost per peak watt – logarithmic




Watts Per $100 of PV Cells
(Cost in 2009 Dollars)
100.0
10.0
1.0
1980 1982 1984 1986 1988 1990 1992 1994 1996 1998 2000 2002 2004 2006 2008
Source Data: DOE NREL Solar Technologies Market Report, Jan 2010



Plummeting Cost of Solar PV
(Projected beyond 2009. All data in 2009 dollars.)
$10.00
$1.00
$0.10
1980
1982
1984
1986
1988
1990
1992
1994
1996
1998
2000
2002
2004
2006
2008
2010
2012
2014
2016
2018
2020
2022
2024
2026
2028
2030
Source Data to 2009: DOE NREL Solar Technologies Market Report, Jan 2010; Projections by Naam 2011


Crystalline PV Module and Polysilicon Prices
Crystalline PV Module Prices ($/W) - Contract, Spot and Blended Average Polysilicon Prices ($/kg)
Module Price ($/W)
3.00
2.50
2.00
1.50
1.00
0.50
0.00
Polysilicon Price ($/kg)
200
180
160
140
120
100
80
60
40
20
0
Q1'09
Q2'09
Q3'09
Q4'09
Q1'10
Q2'10
Q3'10
Q4'10
Q1'11
Q2'11
Q3'11
Q4'11
Q1'12
Q2'12
Q3'12
c-Si PV Module Prices
Blended Polysilicon Price
Polysilicon Price (Spot)
Polysilicon Price (Contract)
Source: IMS Research - www.PVMarketResearch.com
Jan-12

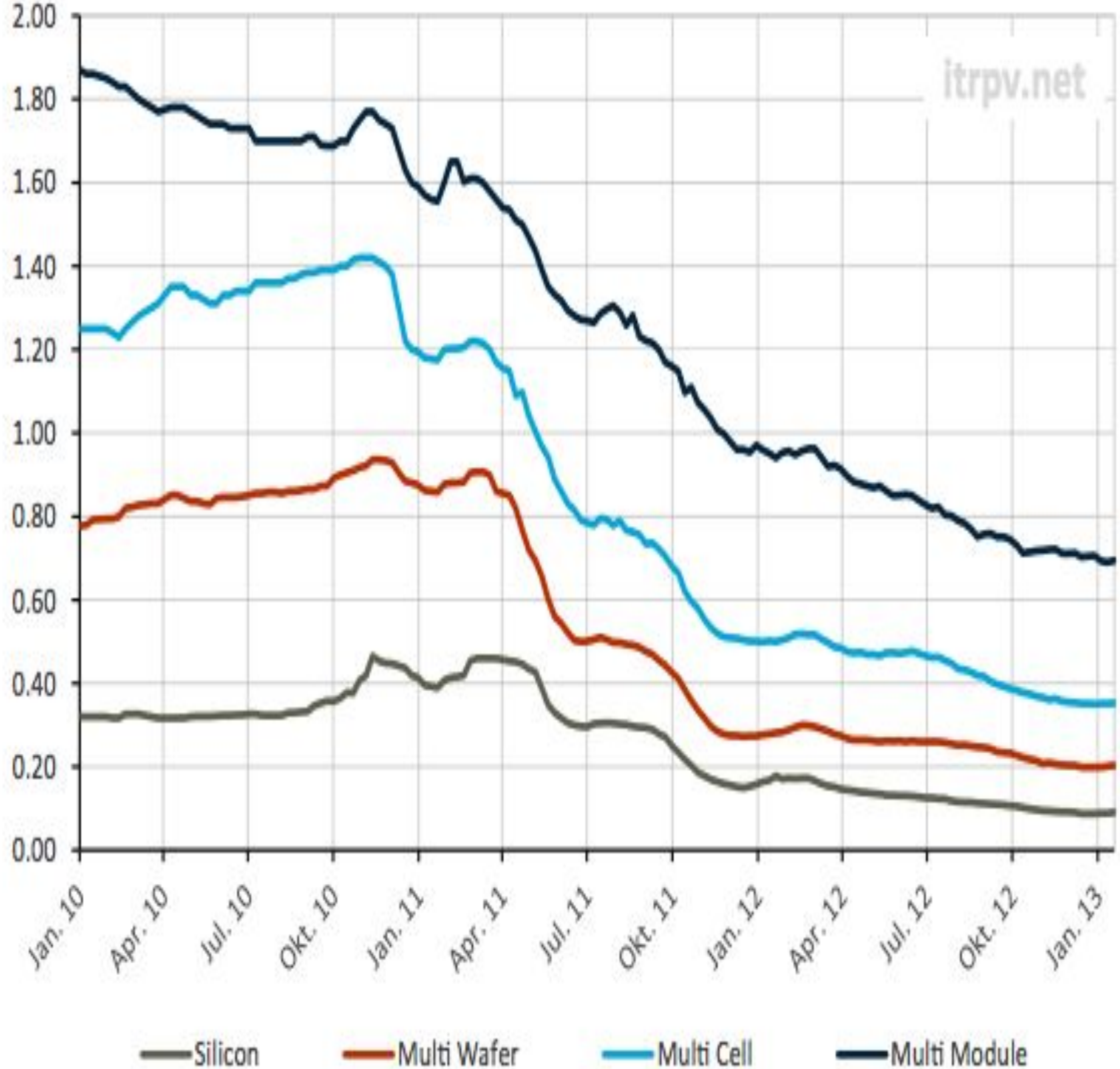
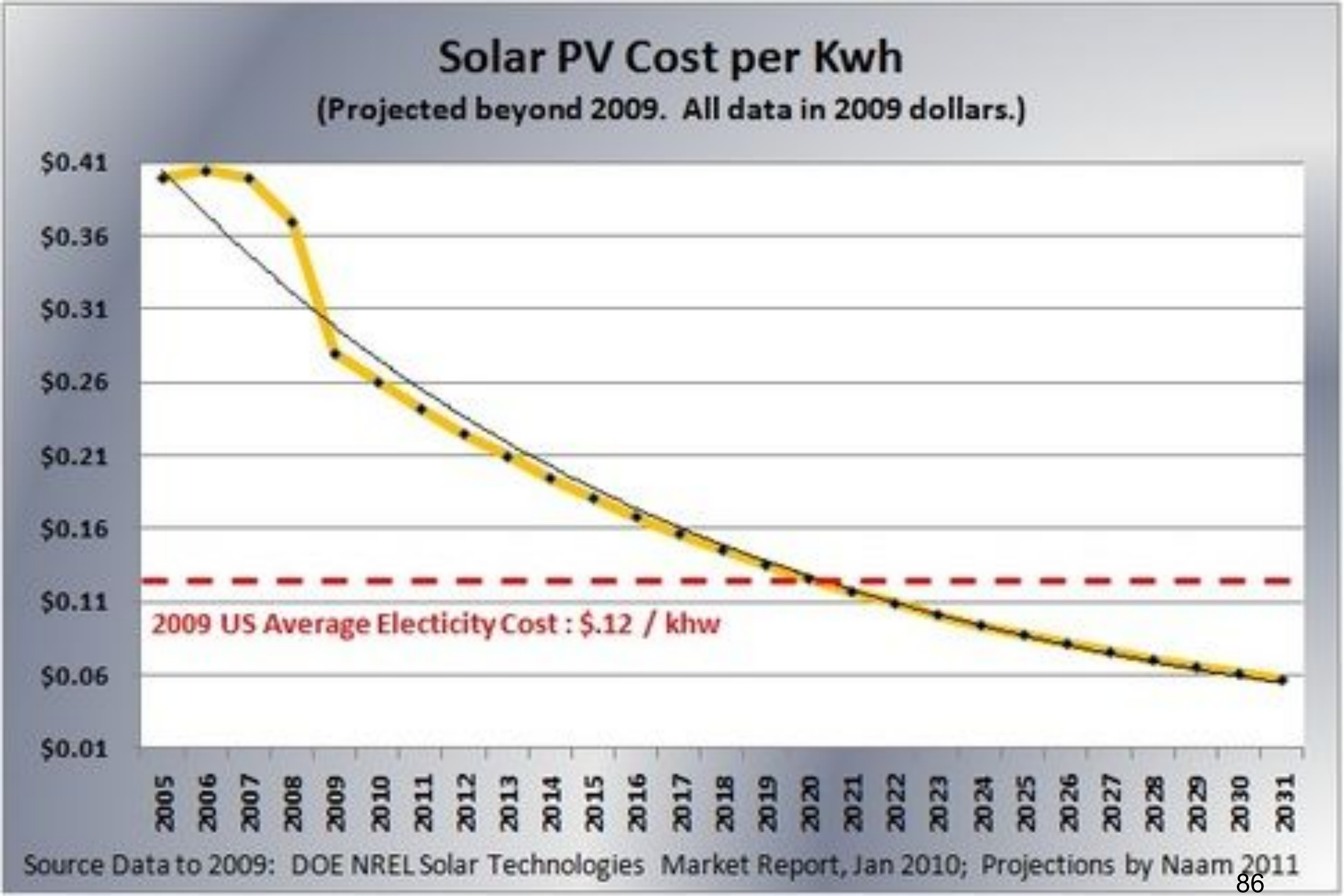


Fig. 2
Price trends for poly-Si, mc-Si wafers, cells and c-Si modules (Assumption: 43,4Wafer/kg poly-Si with ~23,8 g/Wafer and average mc-Si cell power of 4,13 Wp)[6].



Solar PV Cost per Kwh
(Projected beyond 2009. All data in 2009 dollars.)
$0.41
$0.36
$0.31
$0.26
$0.21
$0.16
$0.11
$0.06
$0.01
2009 US Average Electicity Cost : $.12 / khw
2005
2006
2007
2008
2009
2010
2011
2012
2013
2014
2015
2016
2017
2018
2019
2020
2021
2022
2023
2024
2025
2026
2027
2028
2029
2030
2031
Source Data to 2009: DOE NREL Solar Technologies Market Report, Jan 2010; Projections by Naam 2011

PV1

2004 world status of PV industry.

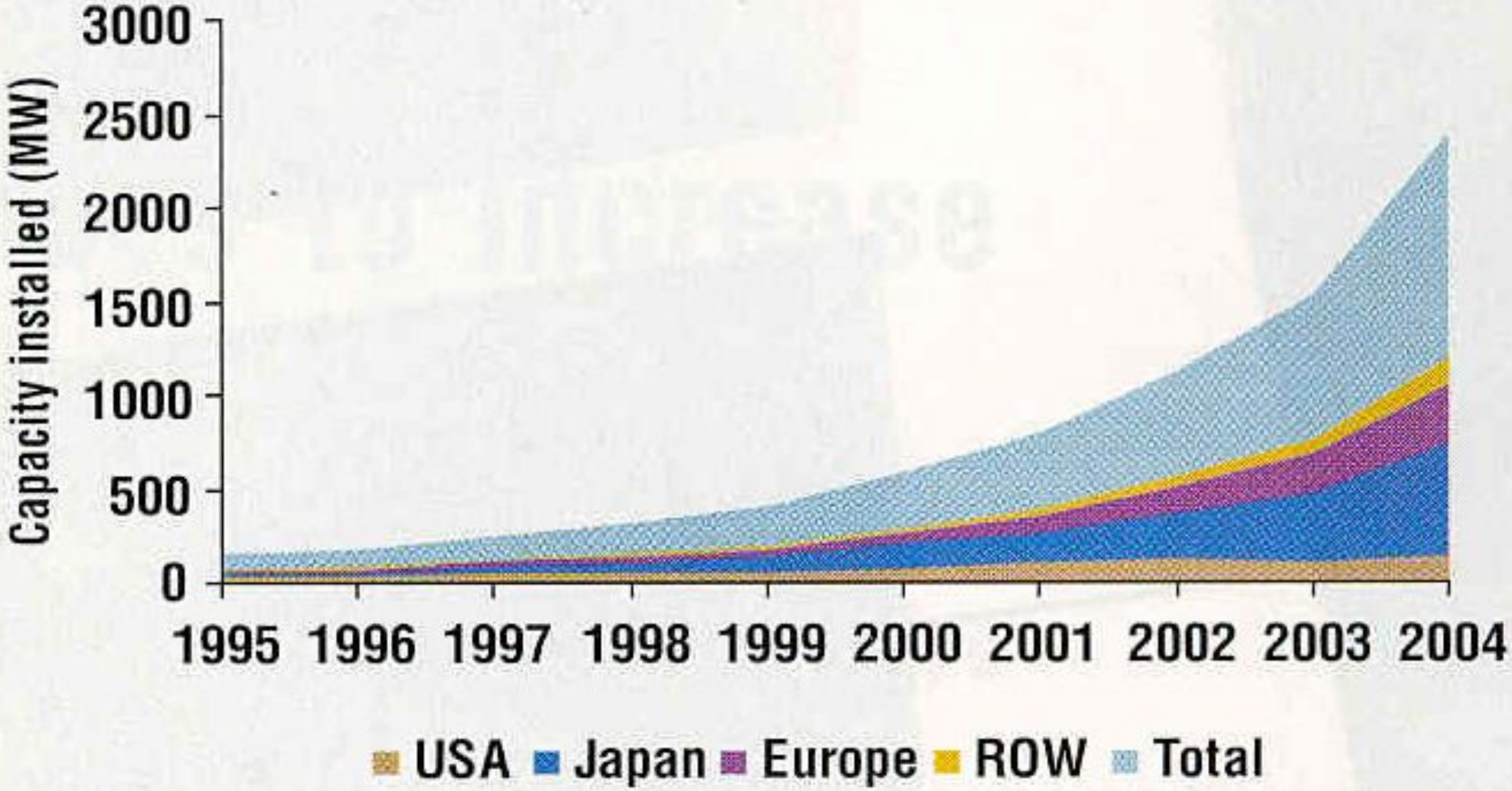
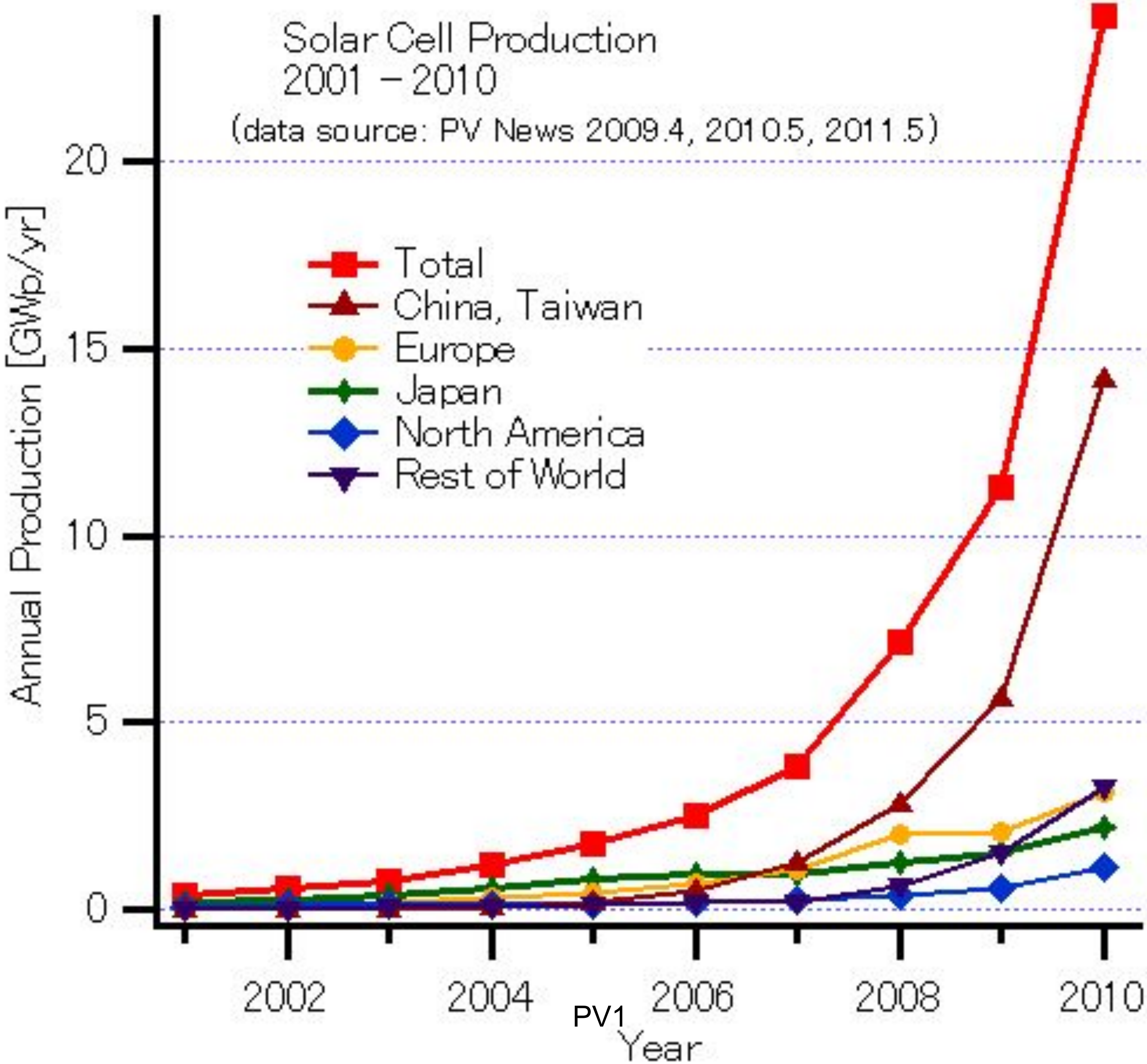


FIGURE 1. World PV production. Source: *PV News*, Volume 24, April 2005

TABLE 3. 2004 world cell production by cell technology (MW)

Technology	US	Japan	Europe	ROW	Total	Share (%)
Single-crystal flat-plate	85	111	115.8	29.6	341.4	29
Polycrystalline	14.2	393.5	158	104	669.2	56
Single and polycrystalline total	*99.2*	*504.5*	*273.8*	*133*	*1010.6*	*85*
Amorphous silicon: outside	14	10	8.6	7	39.6	–
Amorphous silicon: inside	–	7.5	–	–	7.5	–
Amorphous silicon total	*14*	*17.5*	*8.6*	*7*	*47.1*	*3.9*
Crystal Si concentrators	0.5	–	–	–	0.5	–
Ribbon (silicon)	16	–	25	–	41	3.4
Cadmium telluride: indoor	–	–	–	–	–	–
Cadmium telluride: outdoor	6	–	7	–	13	1.1
Copper indium diselenide	3	–	–	–	3	0.3
Microcrystal Si/single Si	–	20	–	–	20	1.7
Si on low-cost substrate	–	–	–	–	–	–
A-Si on Cz slice (HIT)	–	60	–	–	60	5
Total	**139**	**602**	**314.4**	**140**	**1195.2**	**100**


Solar Cell Production
2001 - 2010
(data source: PV News 2009.4, 2010.5, 2011.5)
Total
China, Taiwan
Europe
Japan
North America
Rest of World
Annual Production [GWp/yr]
0
5
10
15
20
2002
2004
2006
2008
2010
Year

Types of Solar Converters

- Photoelectrochemical cells – now up to eff of 10% in experiments.
- Polymer solar cells = 4-5%
- nanocrystal Si (nc-Si) solar cells, quantum dot technology

PV manufacturing from Ore to Cells.

- Silicon resource, abundant, but…
- … stringent requirements to the ore
- Metallurgic silicon
- Silane gas
- Poly-Silicon
- Czochralsky (CZ) method
- Other methods
- New alternate methods

Realizations

- Fixed tilted flat panel
- Concentration PV (Tracking systems)
- Integrated PV

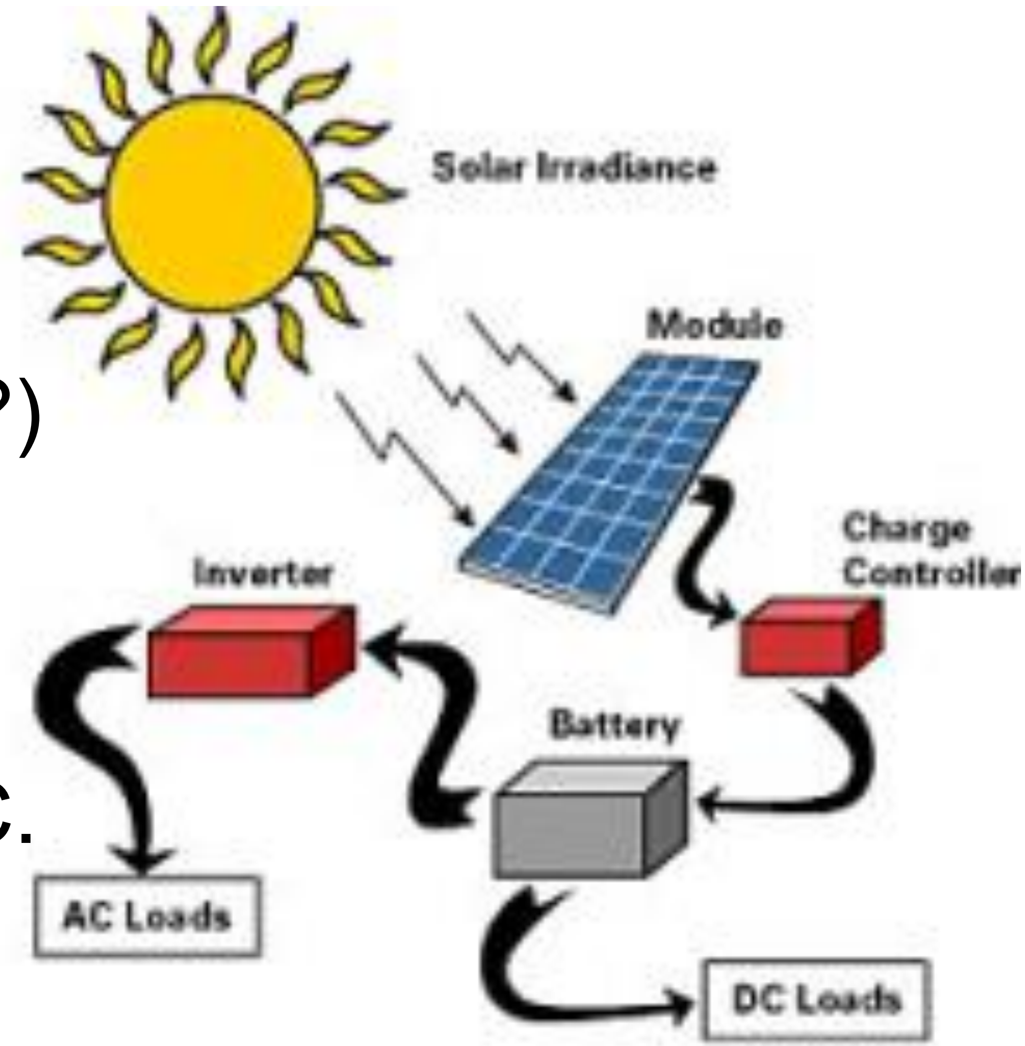
PV systems

The CIS Tower, Manchester, England, was clad in PV panels at a cost of £5.5 million.

Photovoltaic wall at MNACTEC Terrassa in Spain

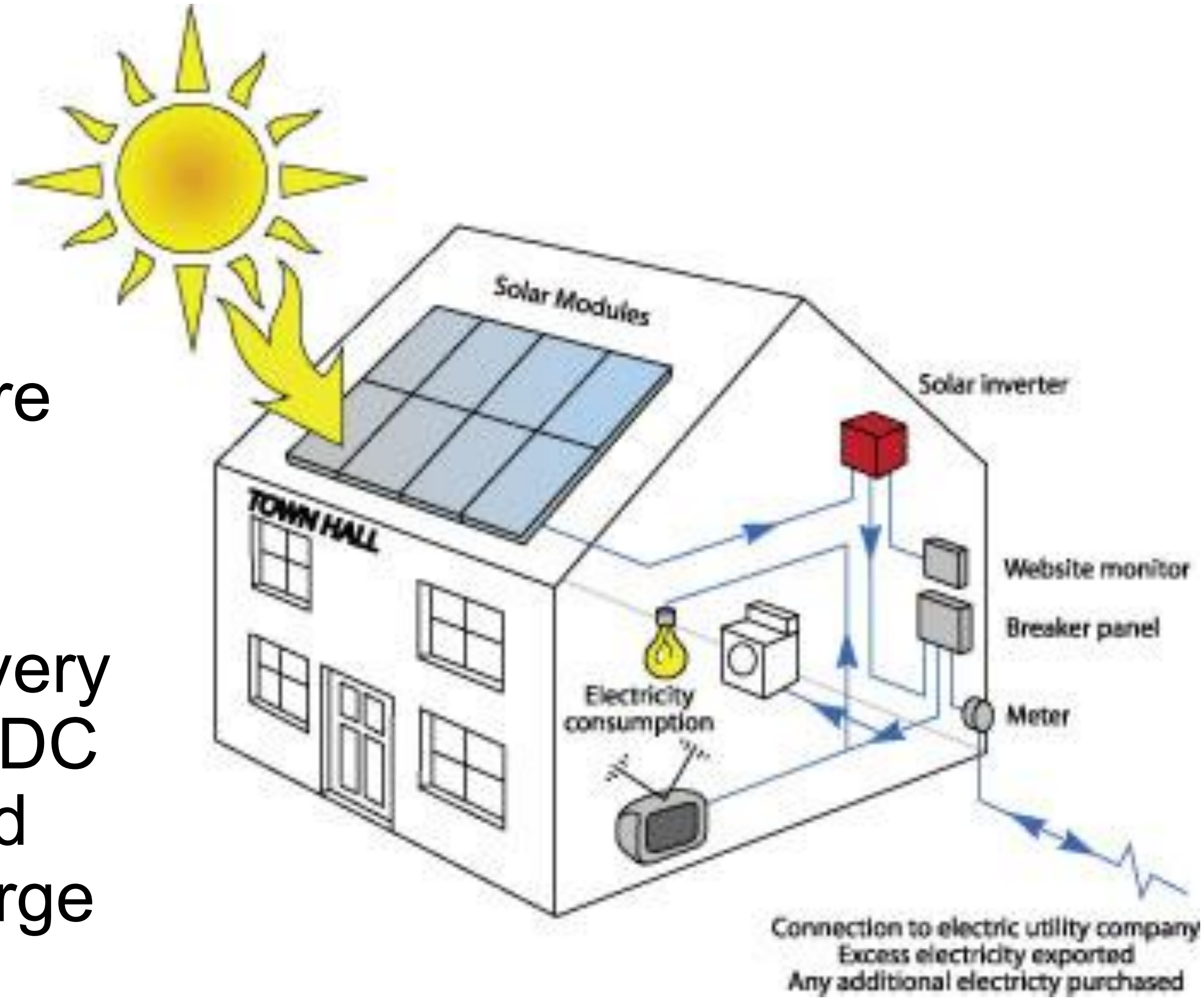
PV standalone solar system

- Solar PV field
- Support Structure
- Batteries (voltage?) and charge controllers.
- Inverter
- Load – DC and AC.

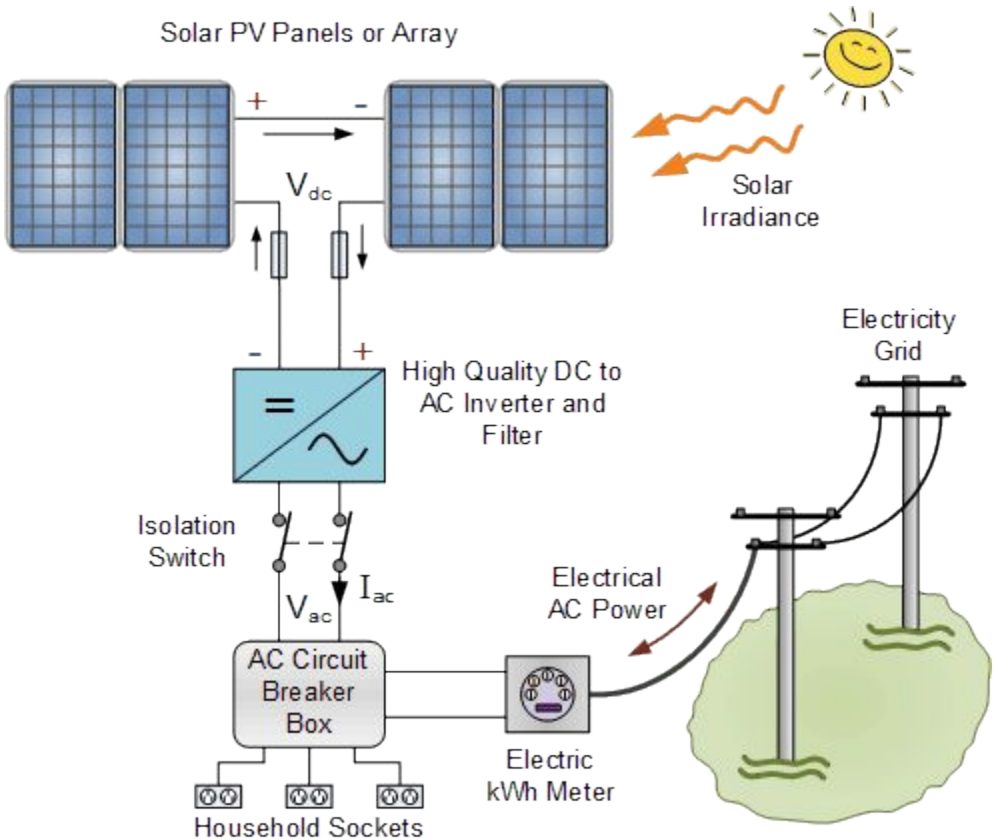


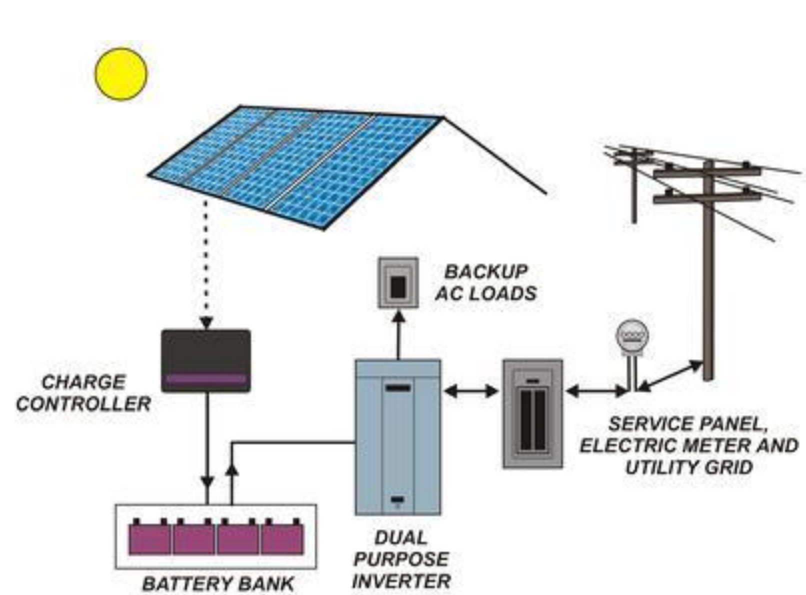
PV grid connected solar system

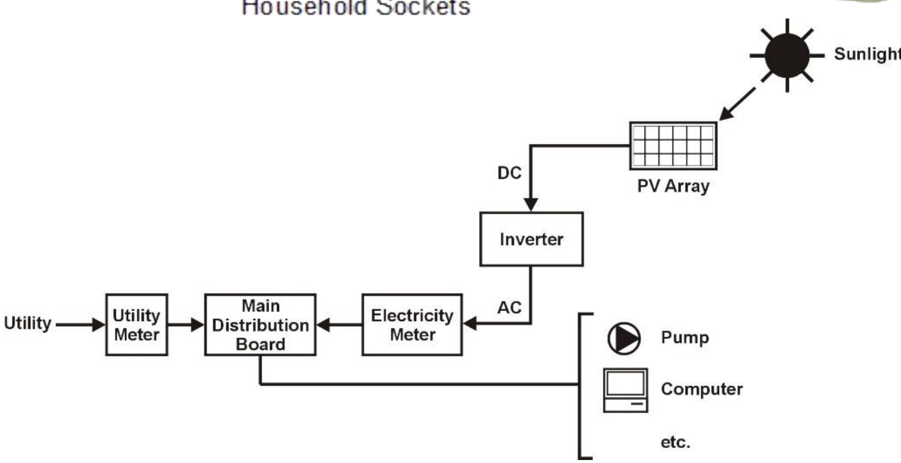
- Solar PV field
- Support Structure
- Grid Inverter
- Load – AC.
- One may have very small, “backup” DC Load and related battery with charge controller.

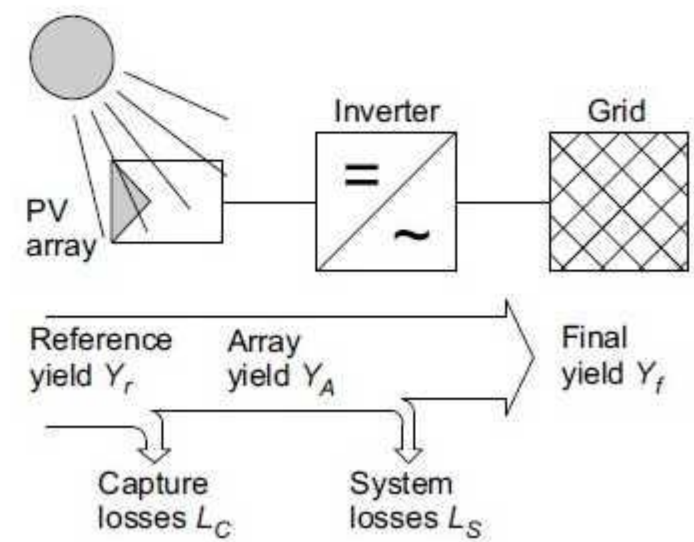


PV grid connected solar system









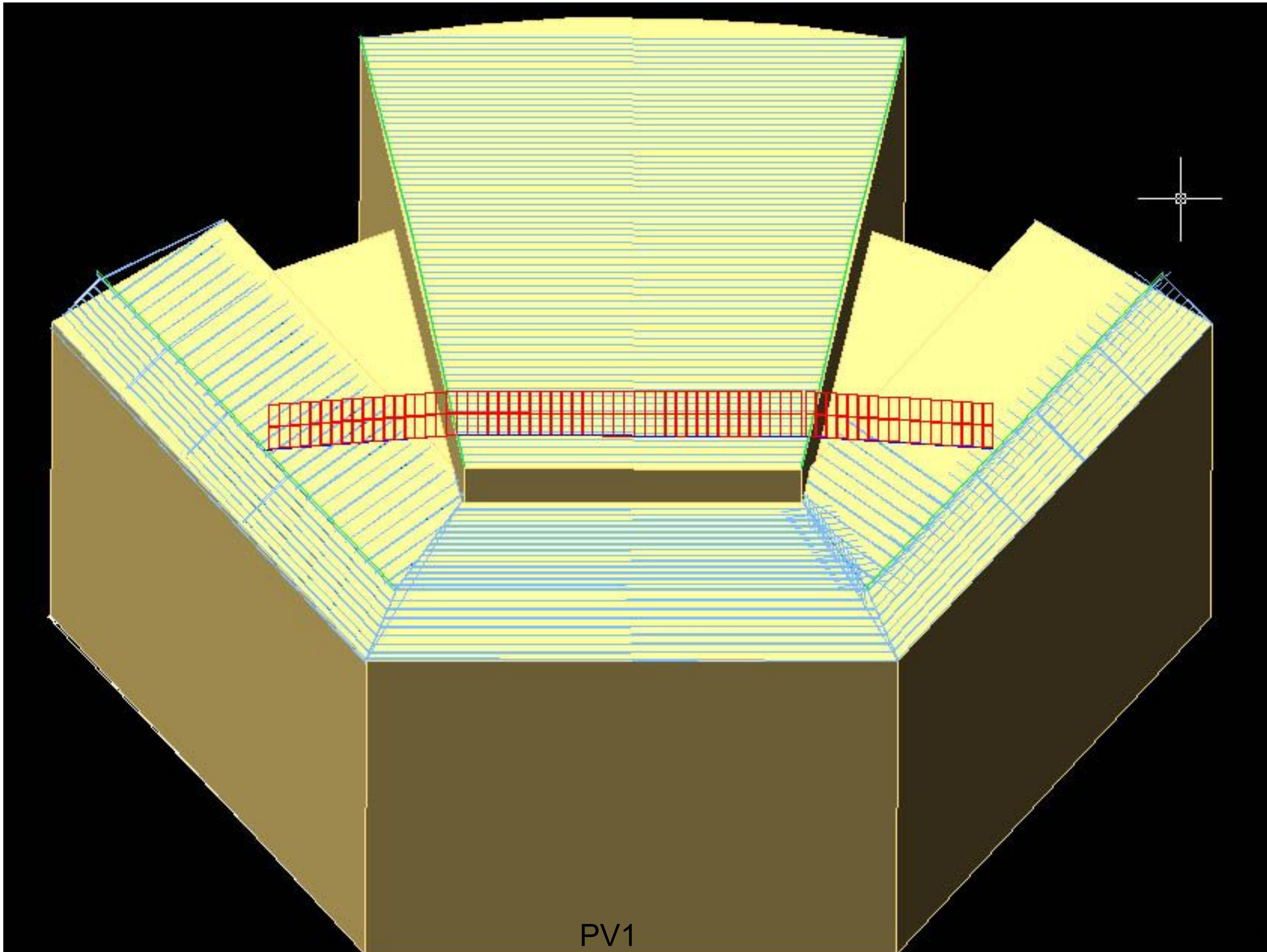
AUA SPVS general information

- Each panel has approximately 0.7 square meters surface and 70 watts of peak power
- The 72 solar photovoltaic panels are installed on a special earthquake resistant structure
- Total battery bank storage is 1150 amper hours at 48 volts. Equiv. of 57.5 kWh
- Output is 3-phase 400 volt through 3 x 230 V, 10 kVA

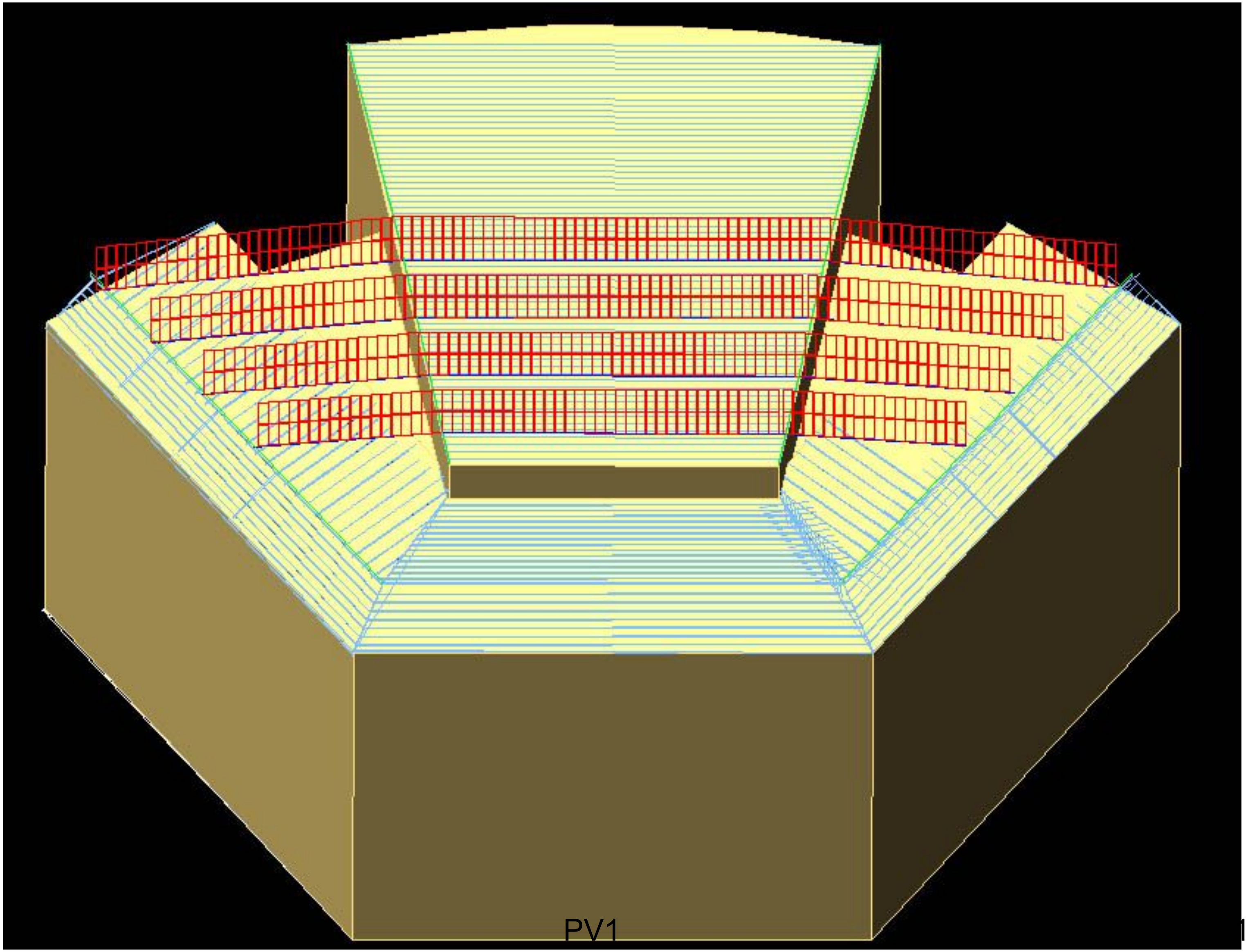
PV Arrays

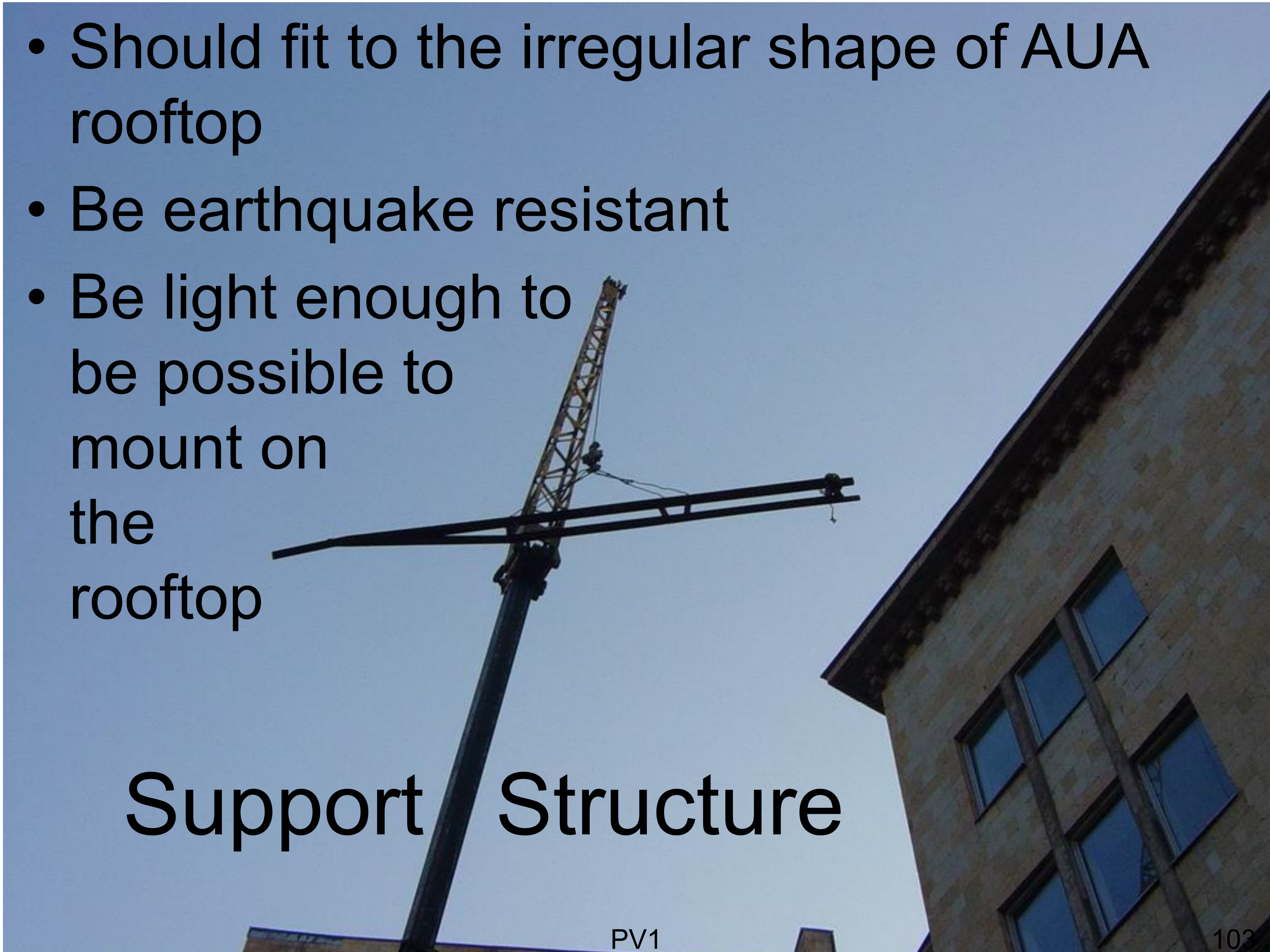
PV Arrays

Current Rooftop Setup



AUA Solar Rooftop Strategy





- Should fit to the irregular shape of AUA rooftop
- Be earthquake resistant
- Be light enough to be possible to mount on the rooftop

Support Structure

PV1

PV1

AUA SPVS general information

Project Participants:

- SEUA Heliotechnics Lab team
- Viasphere Technopark Transistor Plus team
- AUA team with Dr. Melkumyan’s group

Components of the PV System

- Photovoltaic (PV) panels
- Battery Bank
- Charge controllers
- Invertors
- Load

PV Cells

- Manufactured by Krasnoye Znamye, Russia
- 125 x 125 mm rounded square
- Capacity of each cell – 2.2 Watt
- Price of each cell – $4.62
- Price per peak Watt – $2.1
- Number of cells – 2800
- Efficiency – 15% (actually almost 16%)

PV Cells

PV Panels manufactured in Armenia

- PV panels are manufactured by Heliotechnics Laboratory of the SEUA
- Used is a Windbaron Laminator
- Glass bought in the USA – by a price of small lot
- EVA and Tedlar bough by a discount
- Frame manufactured in Armenia

PV Panels manufactured in Armenia

Battery Bank

- The voltage used is DC 48 Volts
- We use eight Rolls Solar Deep Cycle batteries, connected in series
- Each - 6 volt, of 1150 amper-hour capacity
- Total battery bank storage is 1150 amper hours at 48 volts. Equiv. of 57.5 kWh storage

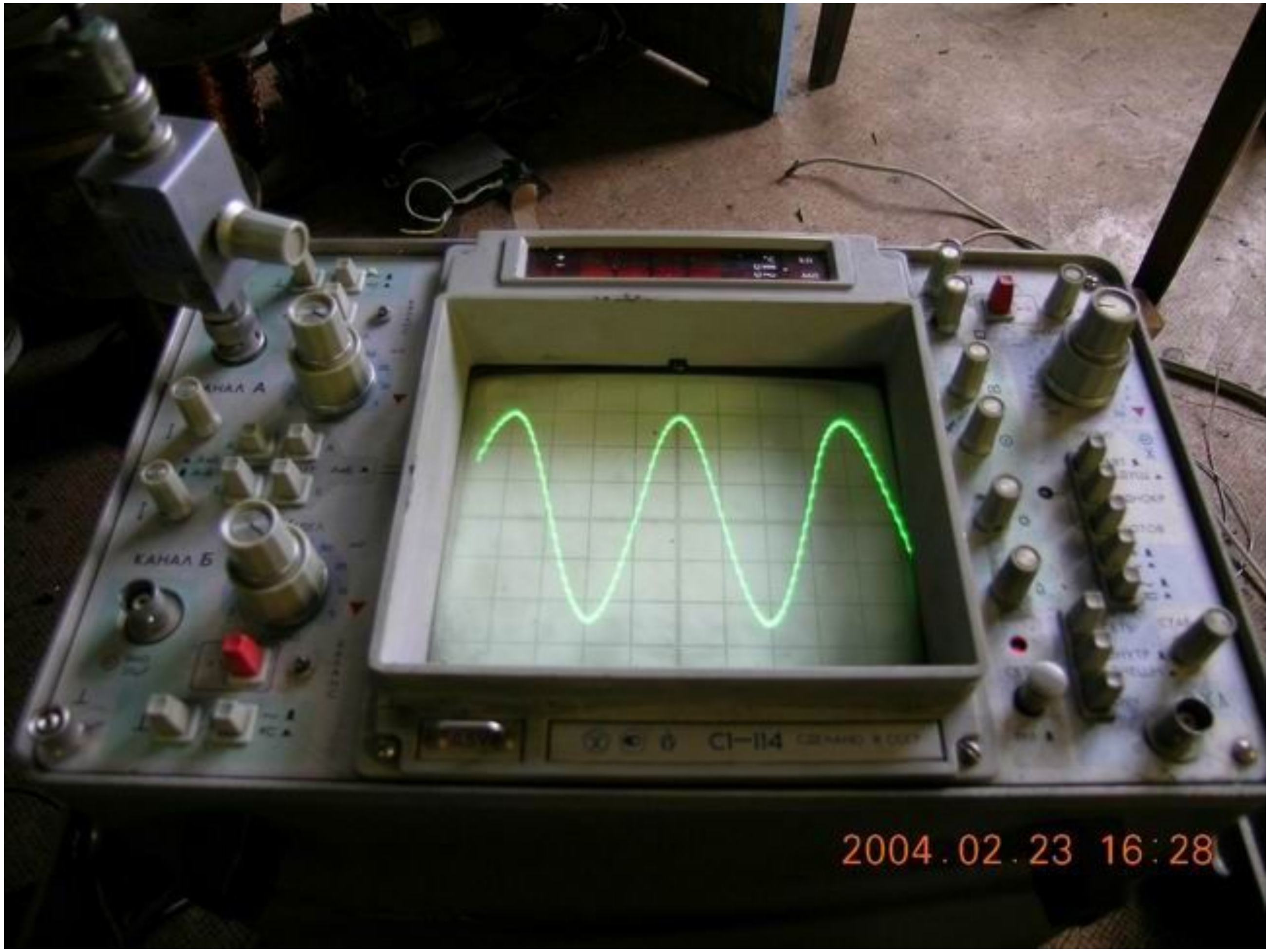
Charge Controllers

- The PV array is devided into 3 sub-arrays:
  - Right
  - Center
  - Left
- Charge controllers use three steps of connection: 1, 2, or 3 subarrays
- Charge controllers are Xantrax, 40 amps, 120 amps total

Inverters – made in Armenia

- Designed and Manufactured by Transistor Plus of the Viasphere Technopark who has a long history of power supply/inverter design and manufacture
- Output is 3-phase 400 volt through 3 x 230 V, 10 kVA, - 3 sine-wave inverters

Inverter Performance



Load

- Currently the load is the DESODEC (Solar HVAC) equipment
- With two controllable powerful duct fans, drives, pumps, valves, controlls, sensors, etc.
- A circuitry automatically switches the load to the electric grid when the battery bank is exhausted

Performance and benefits of the system

- Efficiencies of the different components:
  - PV panels: > 12%
  - cables: 90%
  - batteries 60% - 90%
  - Inverters 90%
- Dependency on weather
- Dependency on load

PV System calculation approach

- See the handout “PV System calculation approach”

Homework

1. List the main components of the solar PV system. Which components can be omitted in urban areas?
2. Imagine your PV system costs $2400 per installed kW. Calculate the cost of 1 kWh in Yerevan if the system lifecycle is 50 years. Remember AUA solar monitoring data.
3. In which cases a solar PV system is feasible or more economical in contrast to electric power supplied from the grid? Explain.