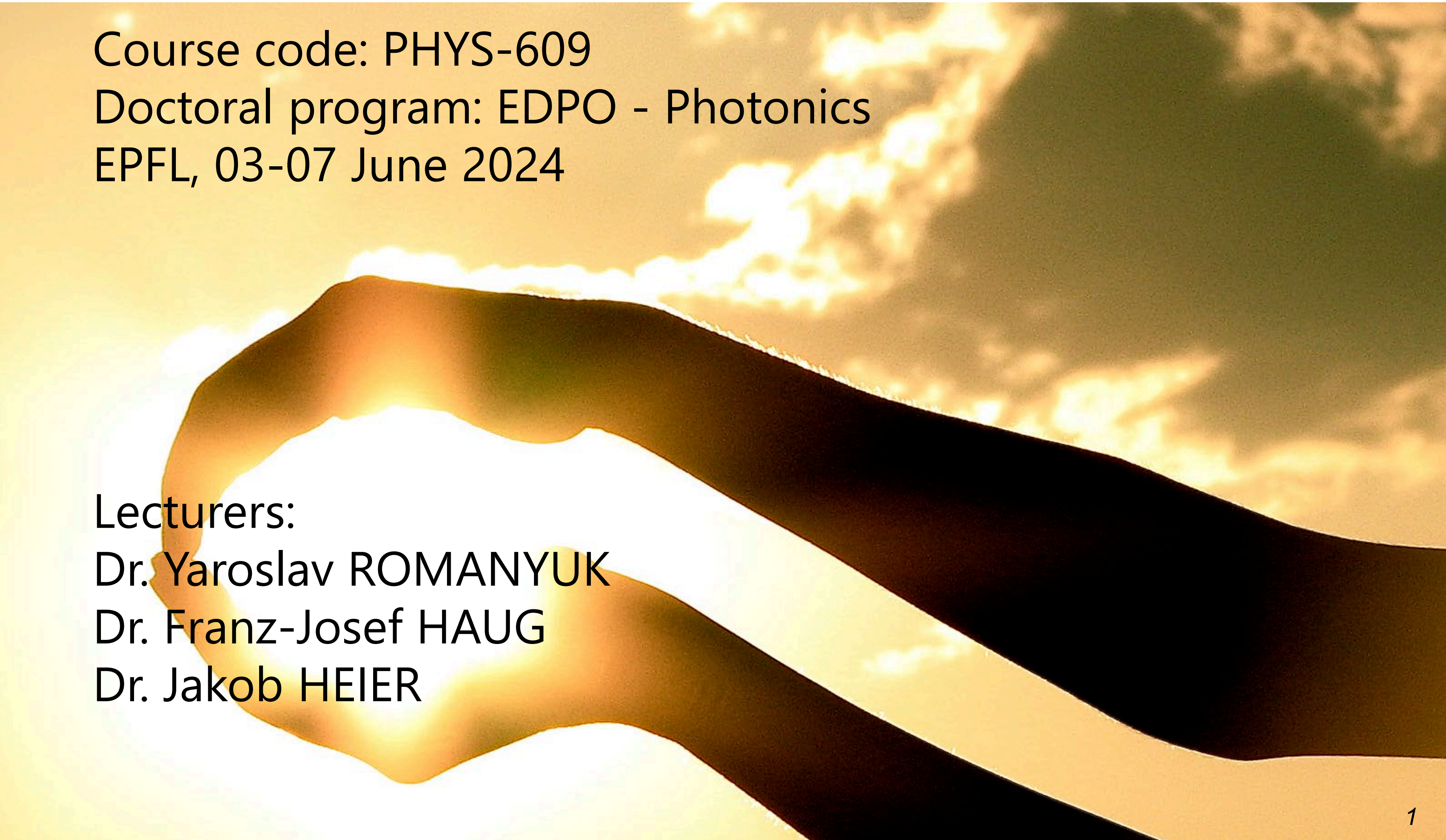
Modern photovoltaic technologies



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Part 1.1 Introduction into PV

- Solar energy and photovoltaics
- Semiconductor physics
- Solar cell parameters
- Generations of solar cells

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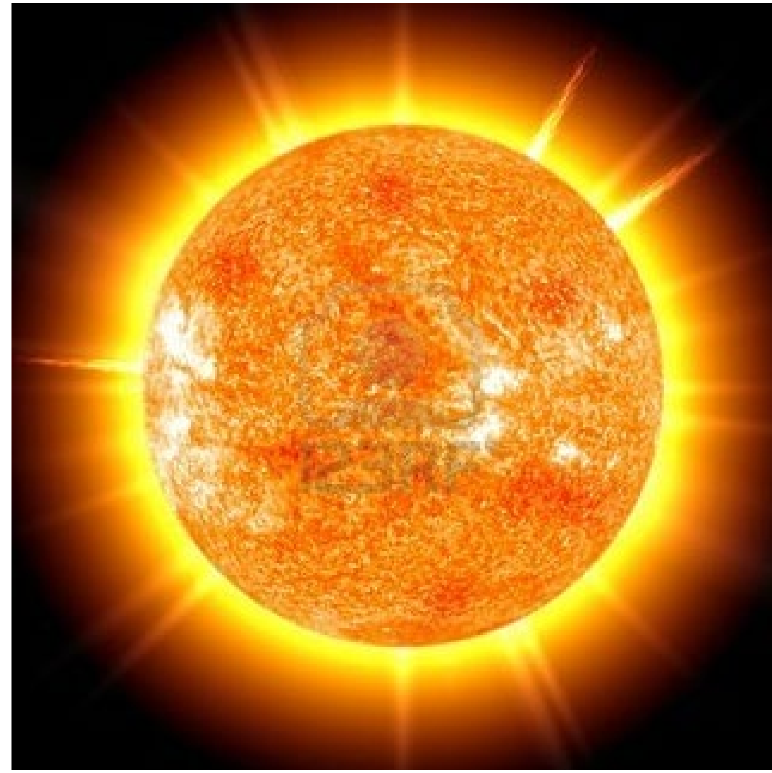
Solar energy
and photovoltaics

Solar energy

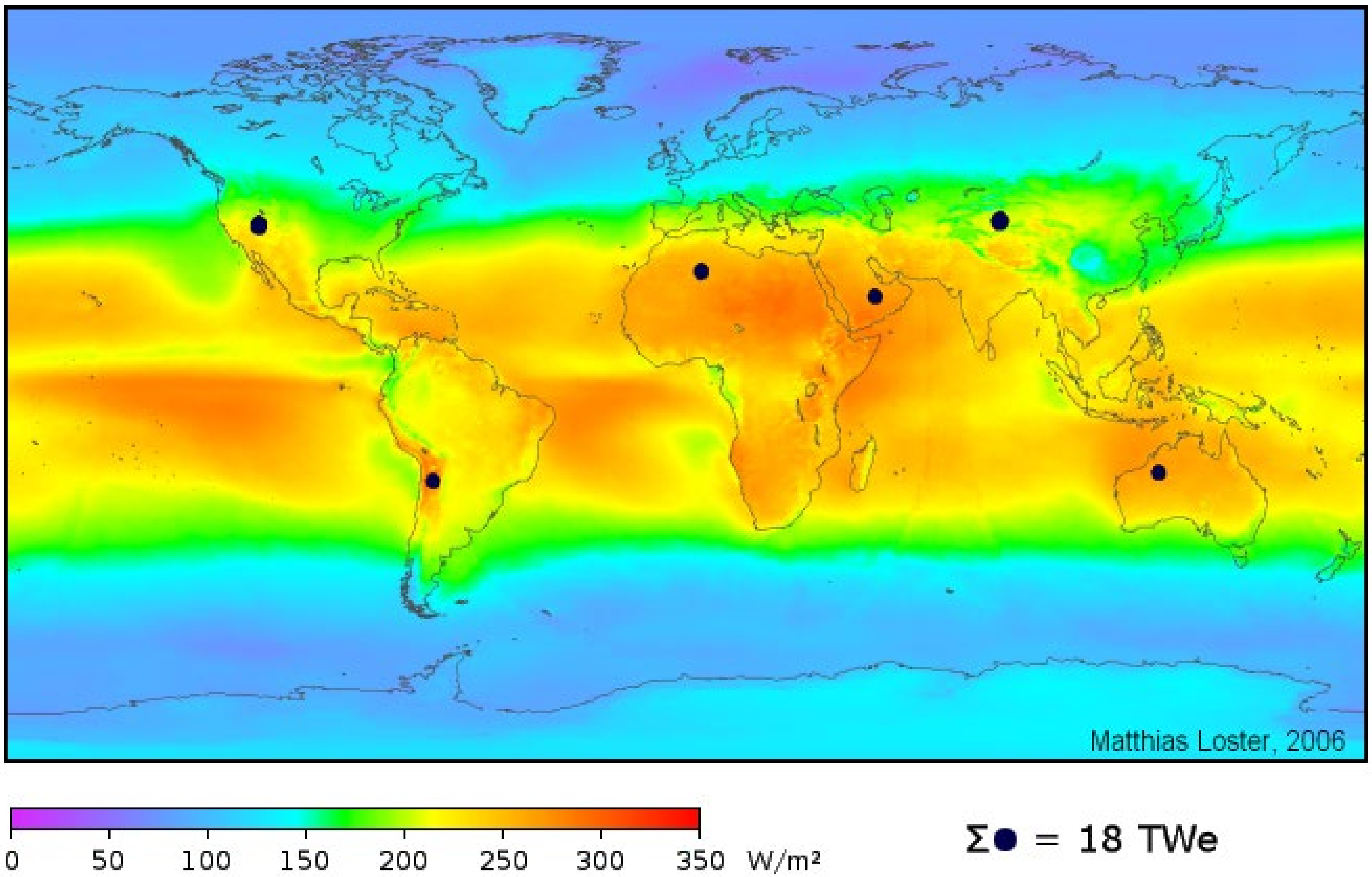


Solar energy received by the Earth within one hour

equals the world electricity consumption in one year

(25`000 TWh in 2022)

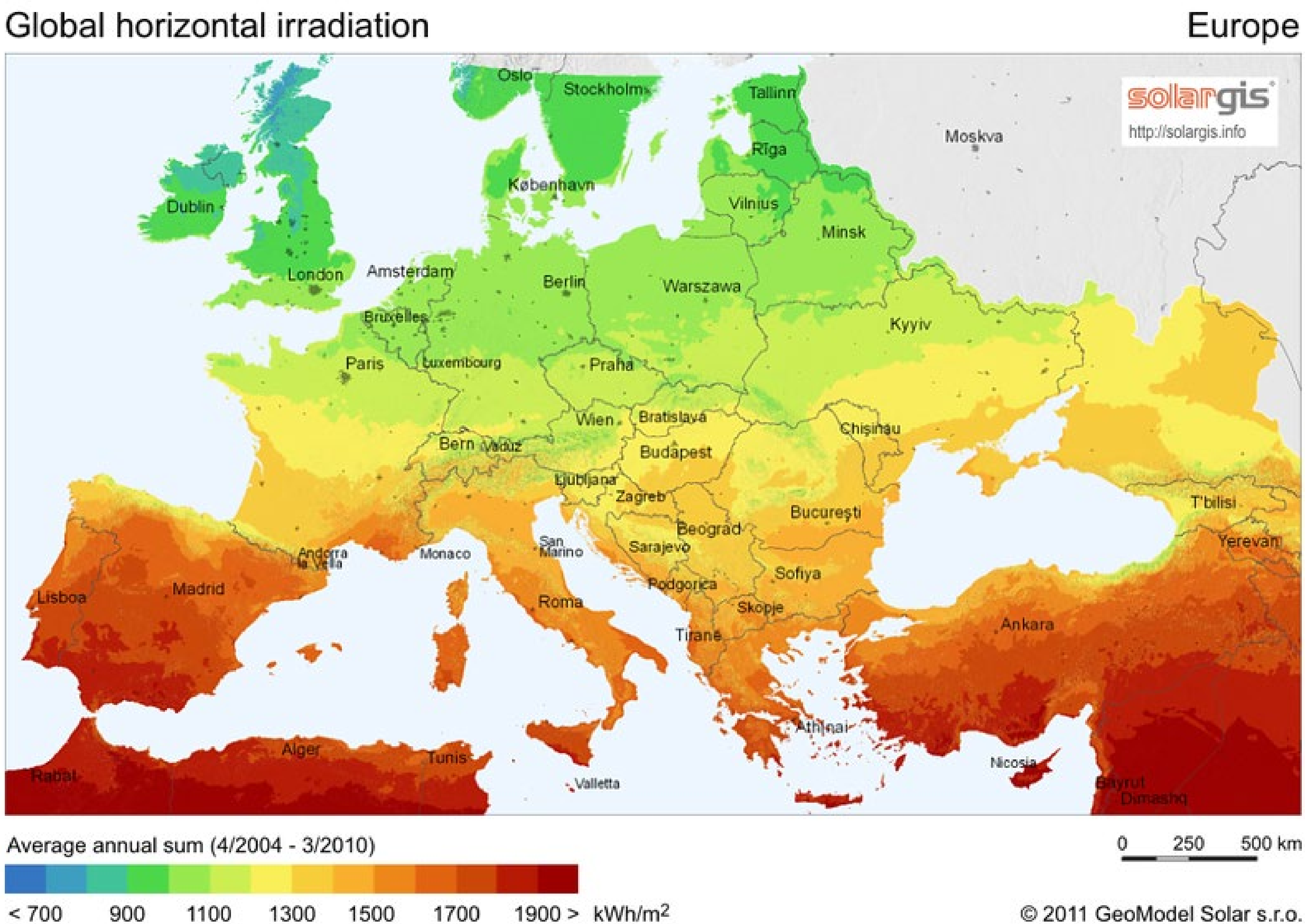
Solar irradiation



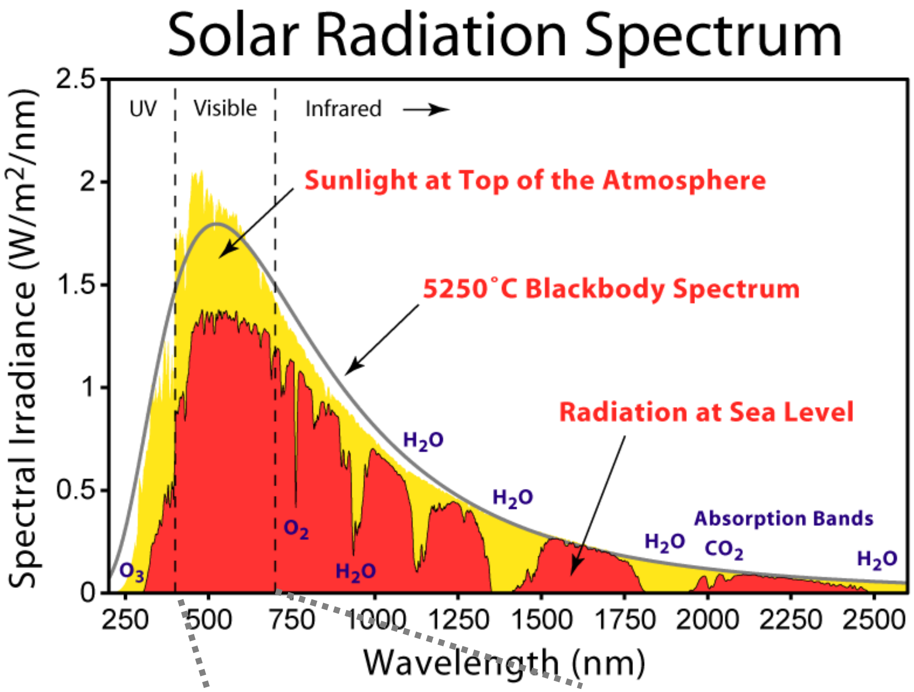
http://en.wikipedia.org/wiki/Solar_energy

- 4% of existing desert area can provide PV power equivalent to the world energy consumption

Solar radiation in Europe



Solar radiation



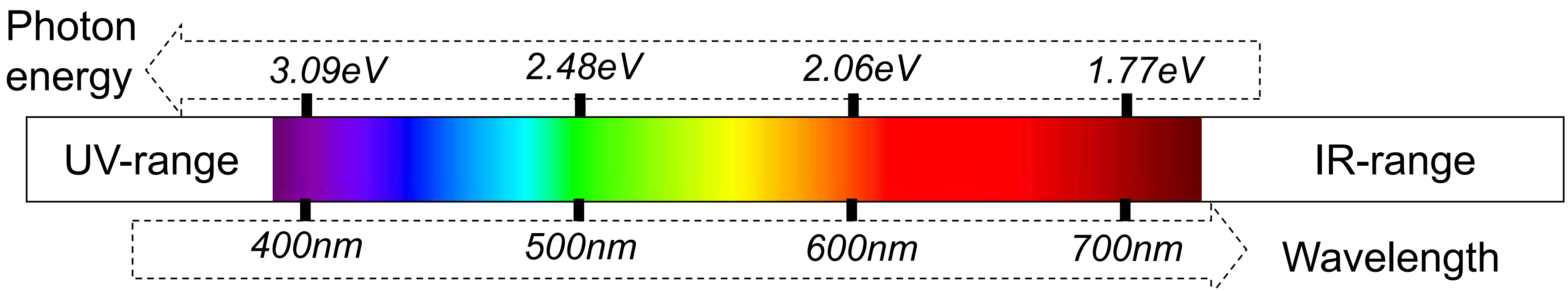
$$\text{Photon Energy} = h\upsilon = \frac{hc}{\lambda}$$

ν – frequency, λ - wavelength

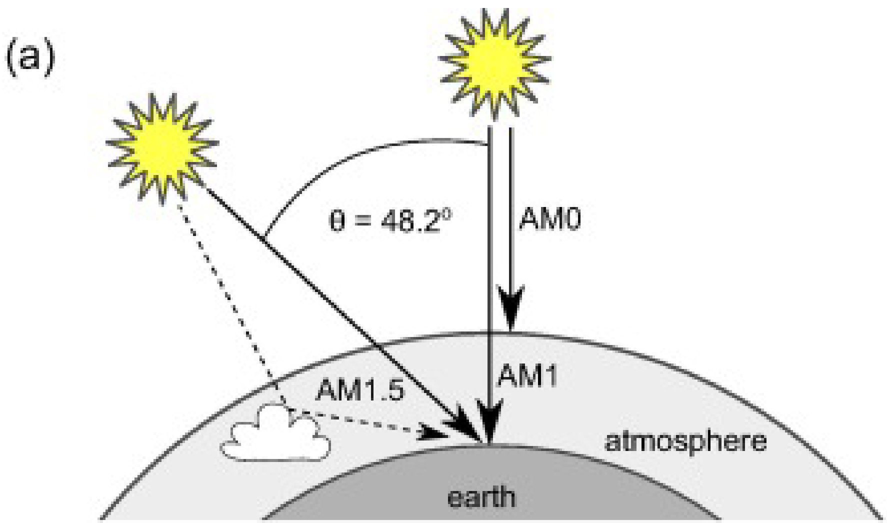
h = Planck constant = $6.6\text{x}10^{-34}$ J s

c = speed of light = $3\text{x}10^{8}$ m s^{-1}

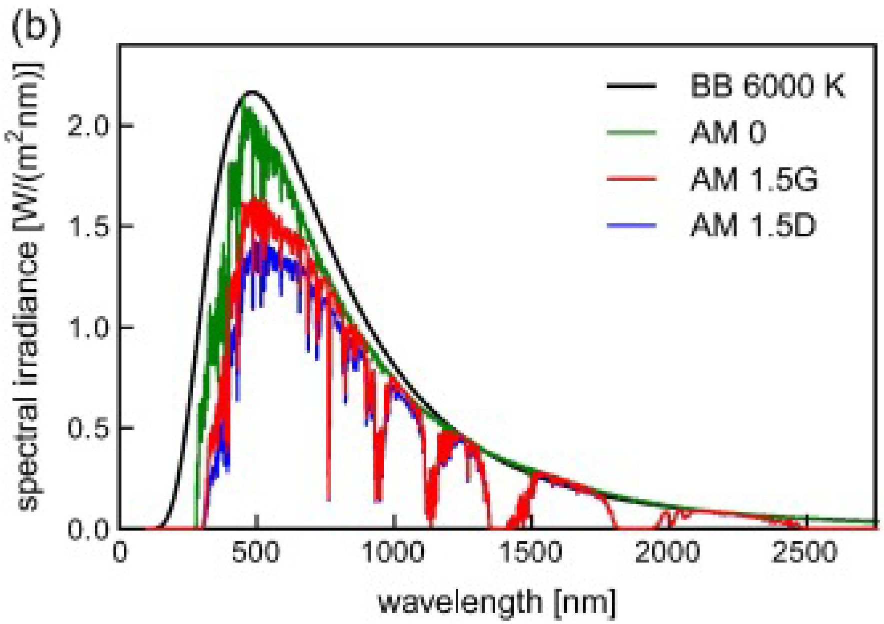
$$E_{photon}\,[\text{eV}] = \frac{1240}{\lambda[nm]}$$



Air mass (AM) coefficient



AM = 1/cos z, where z is the angle between sun and the normal



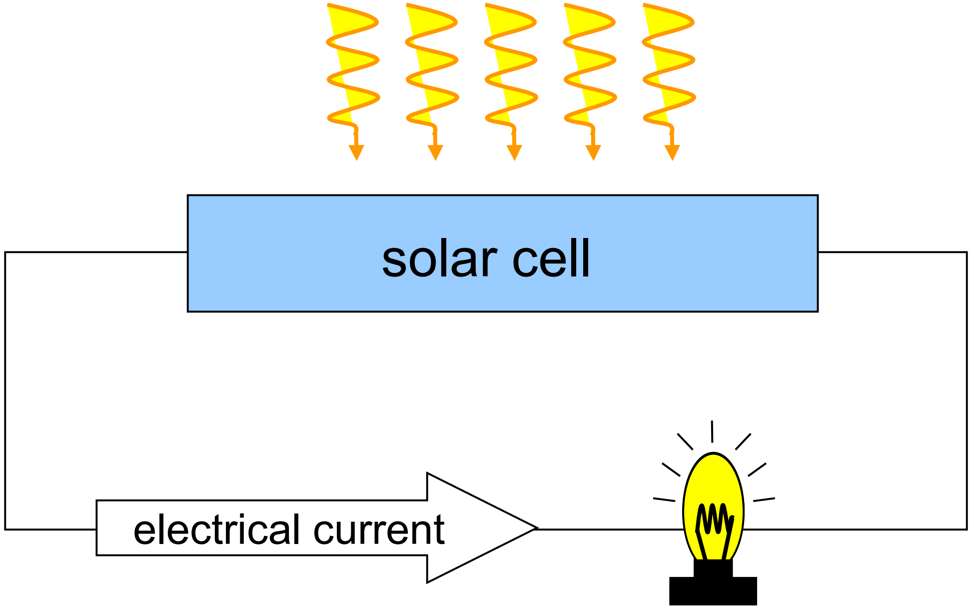
Black body: spectrum at 6000 K

AM 0 spectrum: outside Earth atmosphere

AM 1.5G (global) at zenith angle of 48.2° (realistic for central Europe)

AM 1.5D (direct only)

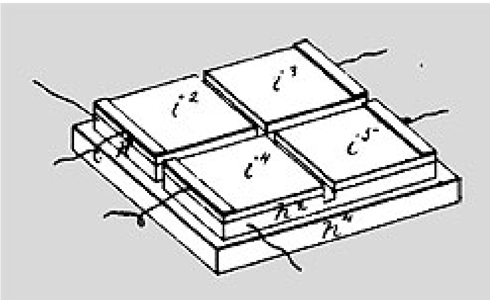
Solar cell (photovoltaic cell)



- Solar cell is a device that converts the **light energy directly into electricity** by the photovoltaic effect

- Most solar cell use **semiconductors**: Si, GaAs, $CuInSe_2$, CdTe, etc., which can be crystalline, polycrystalline, amorphous

Brief history of photovoltaics



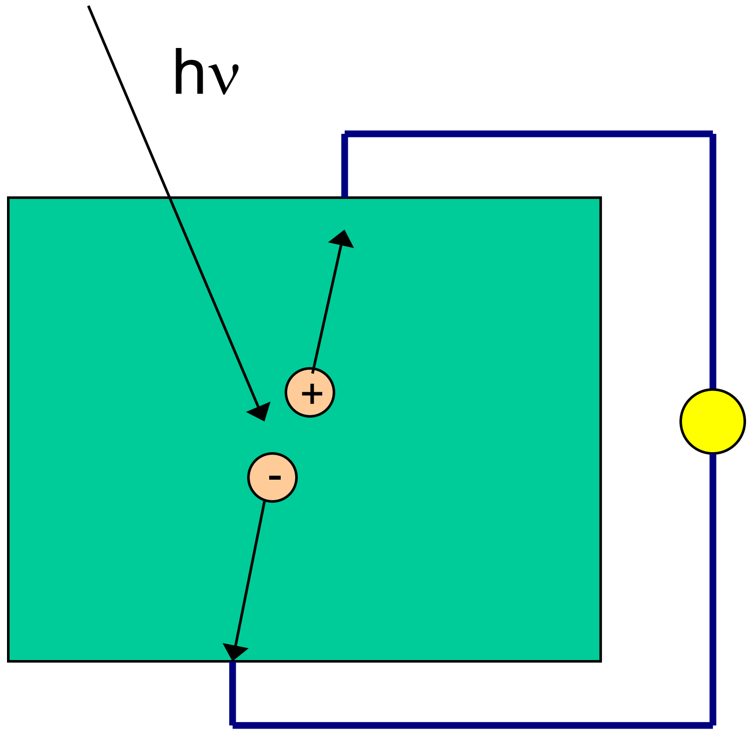
From a patent application in 1884

Vanguard 1, 1958-1964

1883	First solar cell made of selenium crystal and a layer of gold by Charles Edgar Fritts, efficiency 1%
1954	First Si cell, Bell Labs (US) efficiency 6%
1958	PV-powered satelite Vanguard 1 (US)
1973	World energy crisis
1989	1`000 rooftops in Germany
1997	100`000 rooftops in Germany
2011	Fukushima disaster,
	Swiss Energy Strategy 2050

Semiconductor physics

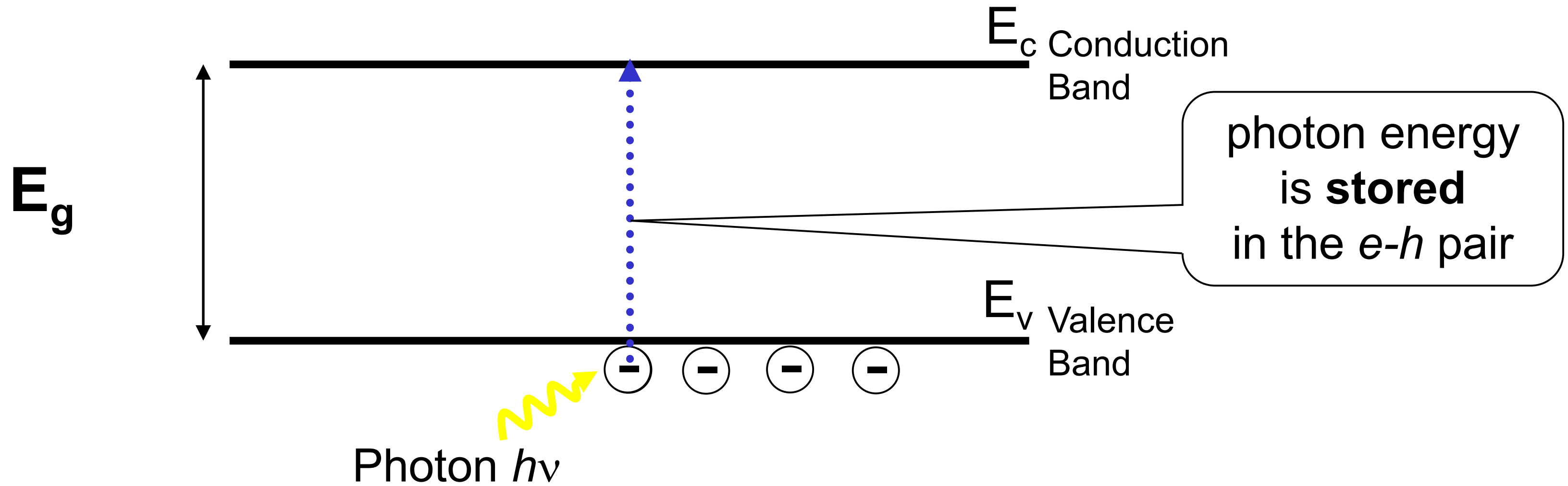
Solar cell and photovoltaic effect



1. Light absorption
2. Generation of „free“ charge carriers
3. Separation of the charges

Source: Dr. Karl Molter / FH Trier, Clemson Summer School 2011

Photogeneration



Absorption of photon ⇒ Generation of electron-hole pair

Band gap determines absorption:

$$E_{photon} \geq E_g = h\upsilon_c = \frac{hc}{\lambda_c}$$

Only photons with energy larger than band gap can generate e-h pair:
⇒ semiconductor absorbs if $l \leq l_c$
⇒ semiconductor is transparent to $l \geq l_c$

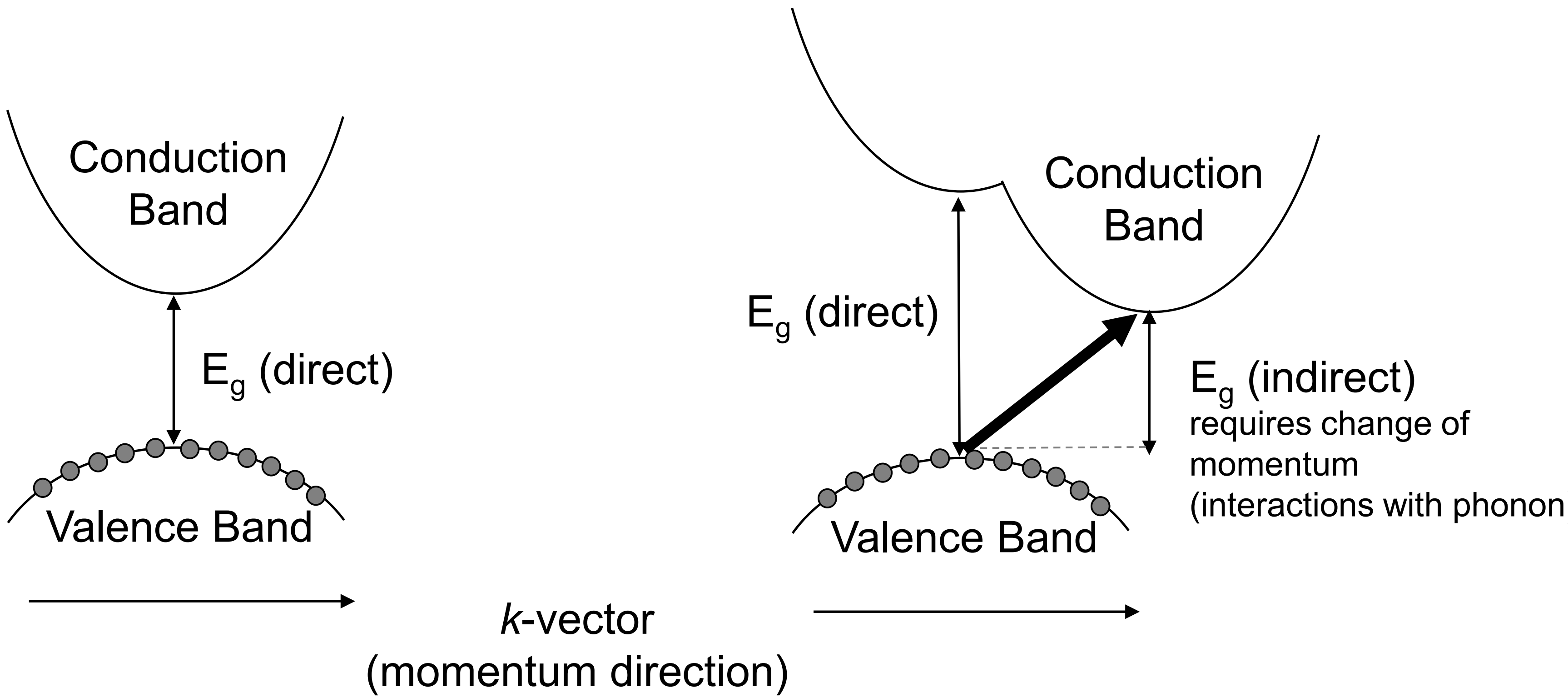
υ_c = cut off frequency

λ_c = cut off wavelength

Direct *vs* Indirect bandgap

E_g (GaAs) =1.42eV
direct gap (strong)

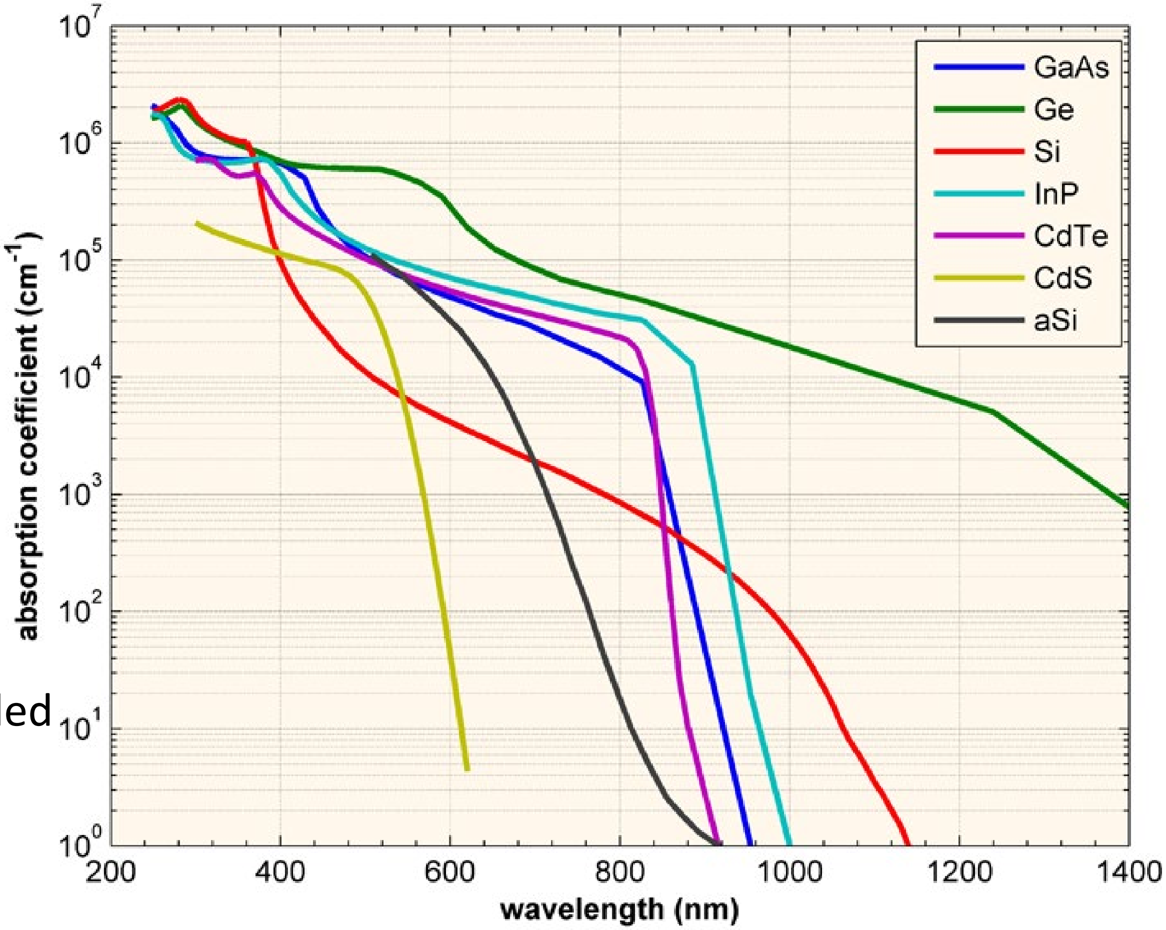
E_g(Si) =1.12eV
indirect gap (weak)



Light absorption in semiconductors

Direct bandgap
(GaAs, CdTe, a-Si):
⇒ thin layer of 1-2 μm
enough for absorption

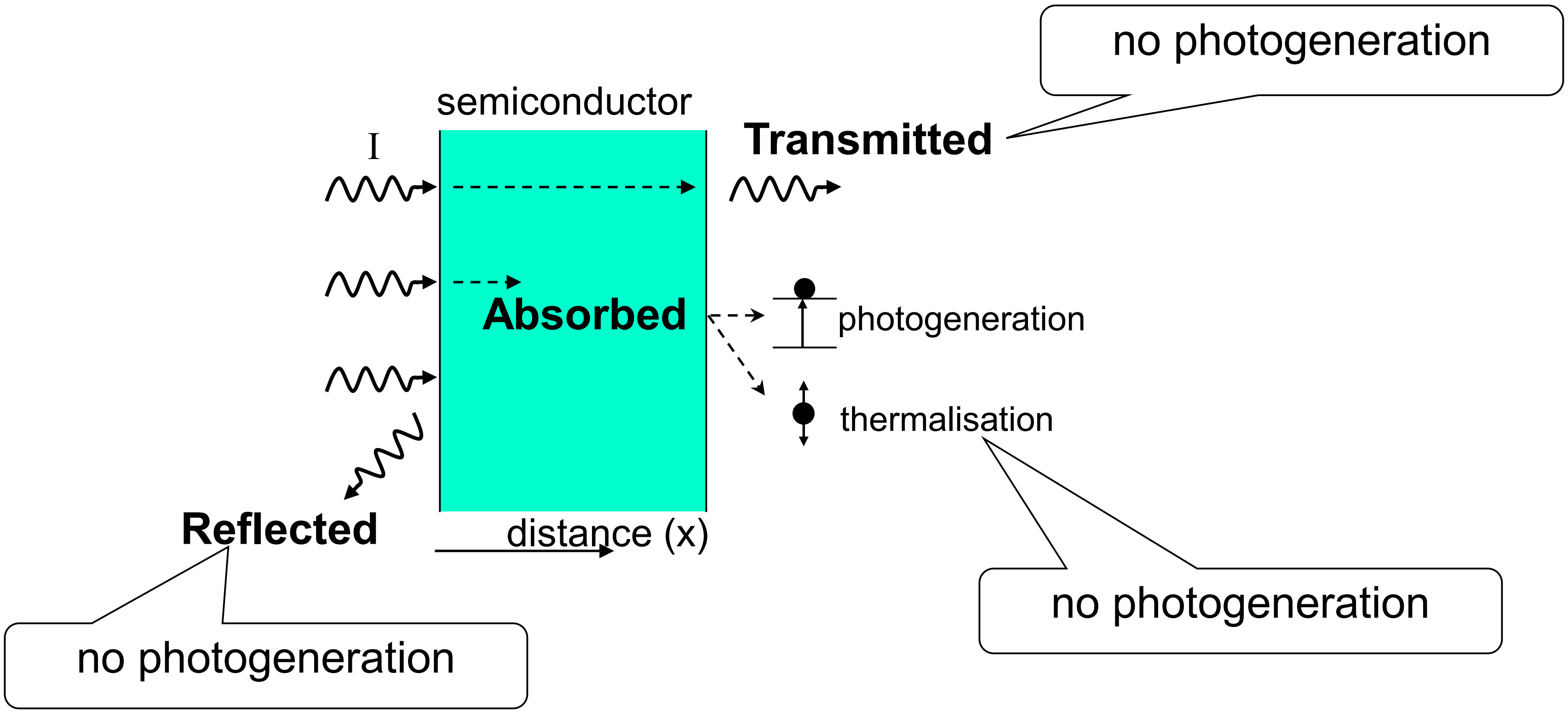
Indirect bandgap (c-Si):
⇒ thick wafer 100 μm needed
for absorption



Wide bandgap (a-Si, CdTe):
⇒ better response for
«blue» photons

Low band-gap (Ge, Si):
⇒ collection of
IR photons

Optical Absorption

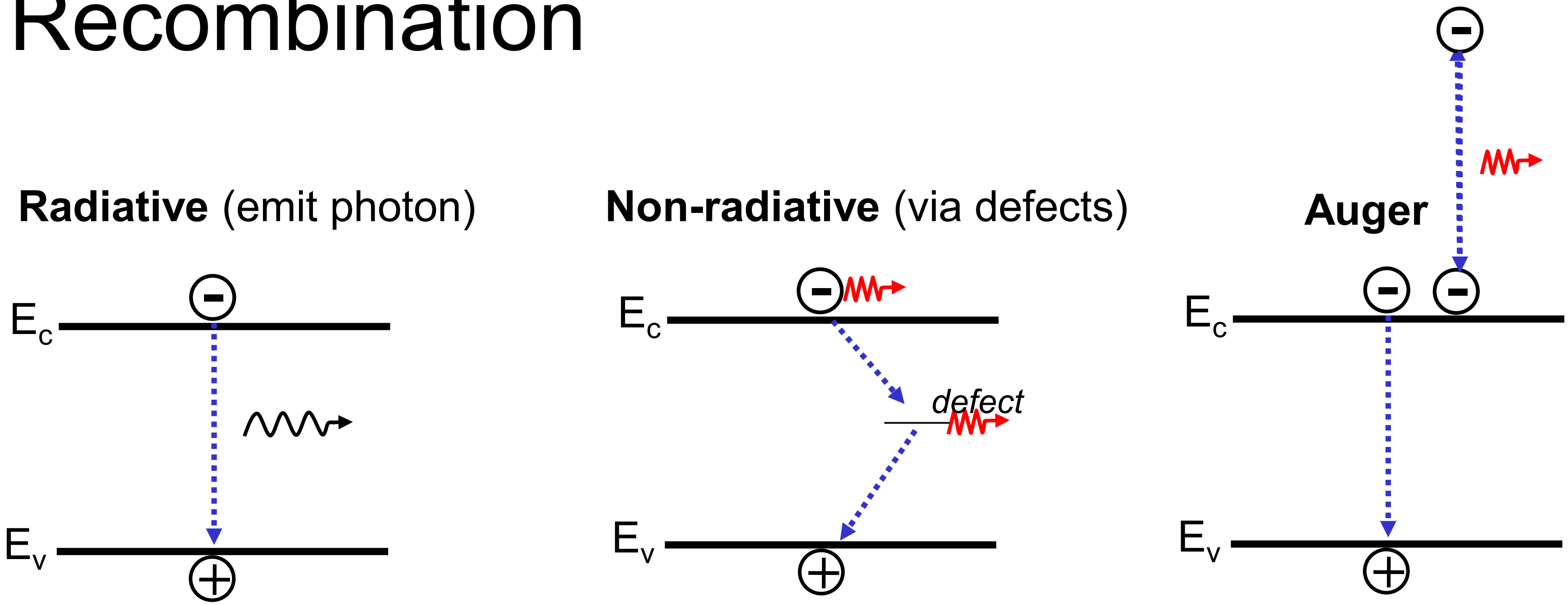


Reflection: R (%)

Transmission: T (%)

Absorption: absorption coefficient α (cm^{-1})

Recombination



Recombination mechanisms:

1. **Radiative** (emission of photons = photoluminescence)
2. **Non-radiative** (Shockley-Read-Hall or SRH)
3. **Auger** (energy transfer to another electron)

Undesirable in solar cells (applies to 2 and 3)

Carrier lifetime and diffusion length

$$\tau = \frac{\Delta n}{R}$$

τ – lifetime
Δn – excess minority carrier concentration
R – recombination rate

$$\frac{1}{\tau_{bulk}} = \frac{1}{\tau_{Band}} + \frac{1}{\tau_{Auger}} + \frac{1}{\tau_{SRH}}$$

τ_{bulk} – bulk lifetime
τ_{Band} – radiative band-to-band lifetime
τ_{Auger} – Auger recombination lifetime
τ_{SRH} – defect recombination lifetime

- **Lifetime is an indicator of the efficiency of a solar cell - the key consideration in choosing materials for solar cells.**

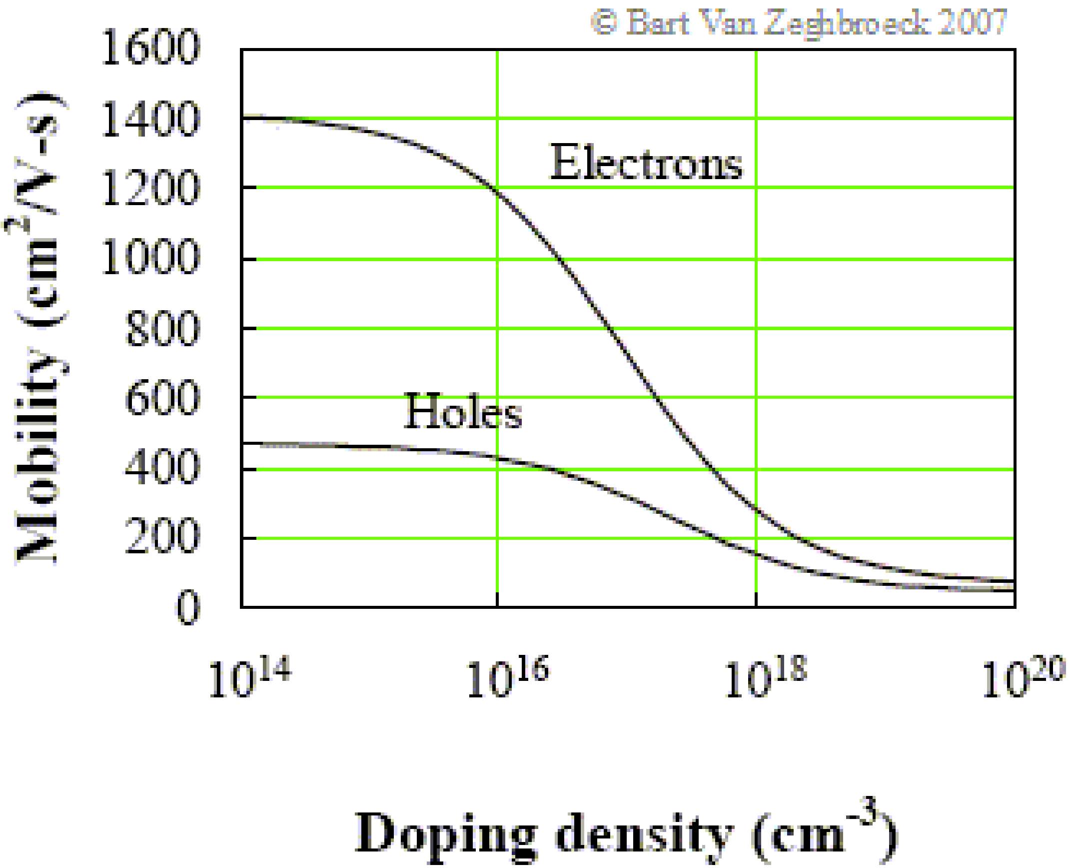
$$L = \sqrt{D\tau}$$

L – diffusion length (m)
D – diffusivity bulk lifetime (m^2/s)
τ – carrier lifetime (s)

Carrier mobility

$$\mu = \frac{v_d}{E}$$

μ – carrier mobility ($m^2/(Vs)$)
υ_d – drift velocity (m/s)
E – applied electric field (V/m)



Charge carriers in semiconductors

Electron (n) & hole (p) concentration in semiconductor:

equal amount of holes & electrons in intrinsic semiconductors

$$n = p = n_i$$

$$np = n_i^2 = N_c N_v e^{\frac{-E_g}{kT}}$$

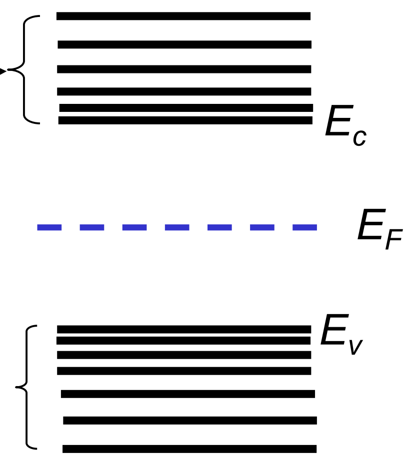
N_c and N_v are the *effective densities of states*

k is Boltzmanns constant (1.38×10^{-23} J K^{-1})

Carrier concentrations in equilibrium related to the band edges:

$$n = N_c e^{-(\frac{E_c - E_f}{kT})}$$

$$p = N_v e^{-(\frac{E_f - E_v}{kT})}$$



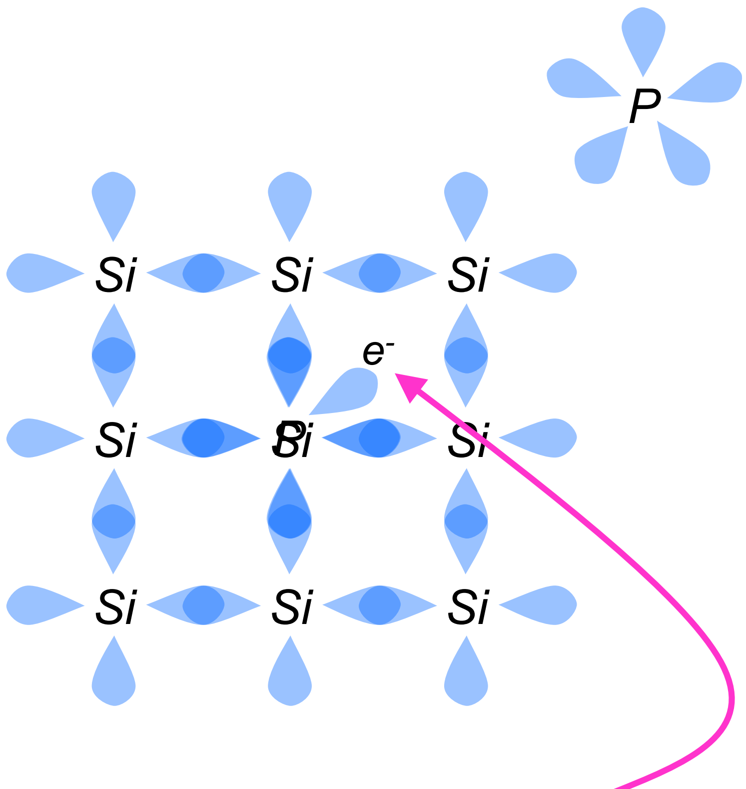
Fermi level: probability to find an electron at this energy level is 50%

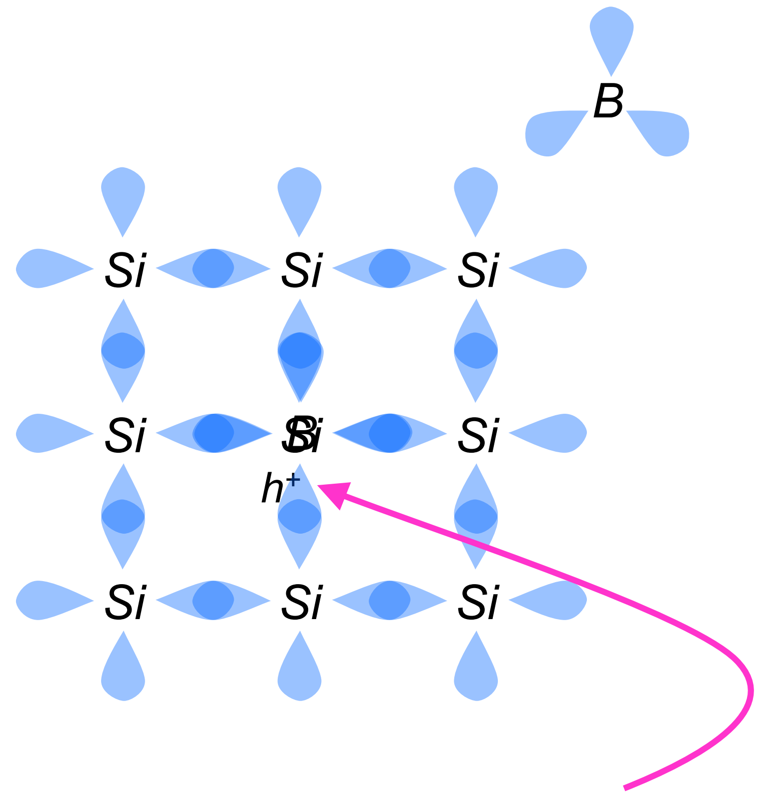
located at midgap in instrinsic semiconductors

Doping of semiconductors (e.g. Silicon)

Phosphorus (P)
5 outer electrons vs Si’s 4

Boron (B)
3 outer electrons vs Si’s 4





One electron per donor atom

⇒ **n-type doping**

One hole per acceptor atom

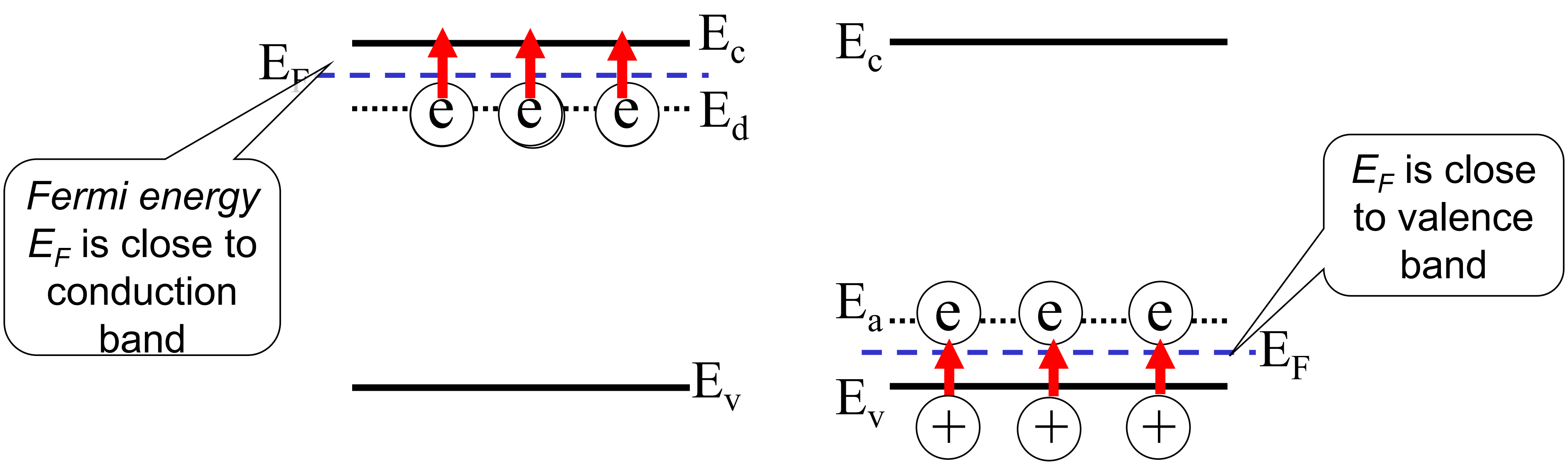
⇒ **p-type doping**

Doping of Semiconductors

- Undoped (intrinsic) semiconductors have low conductivity because the concentration of free (mobile) charge carriers is very low.
- Doping with impurities can add free (mobile) electrons or holes:

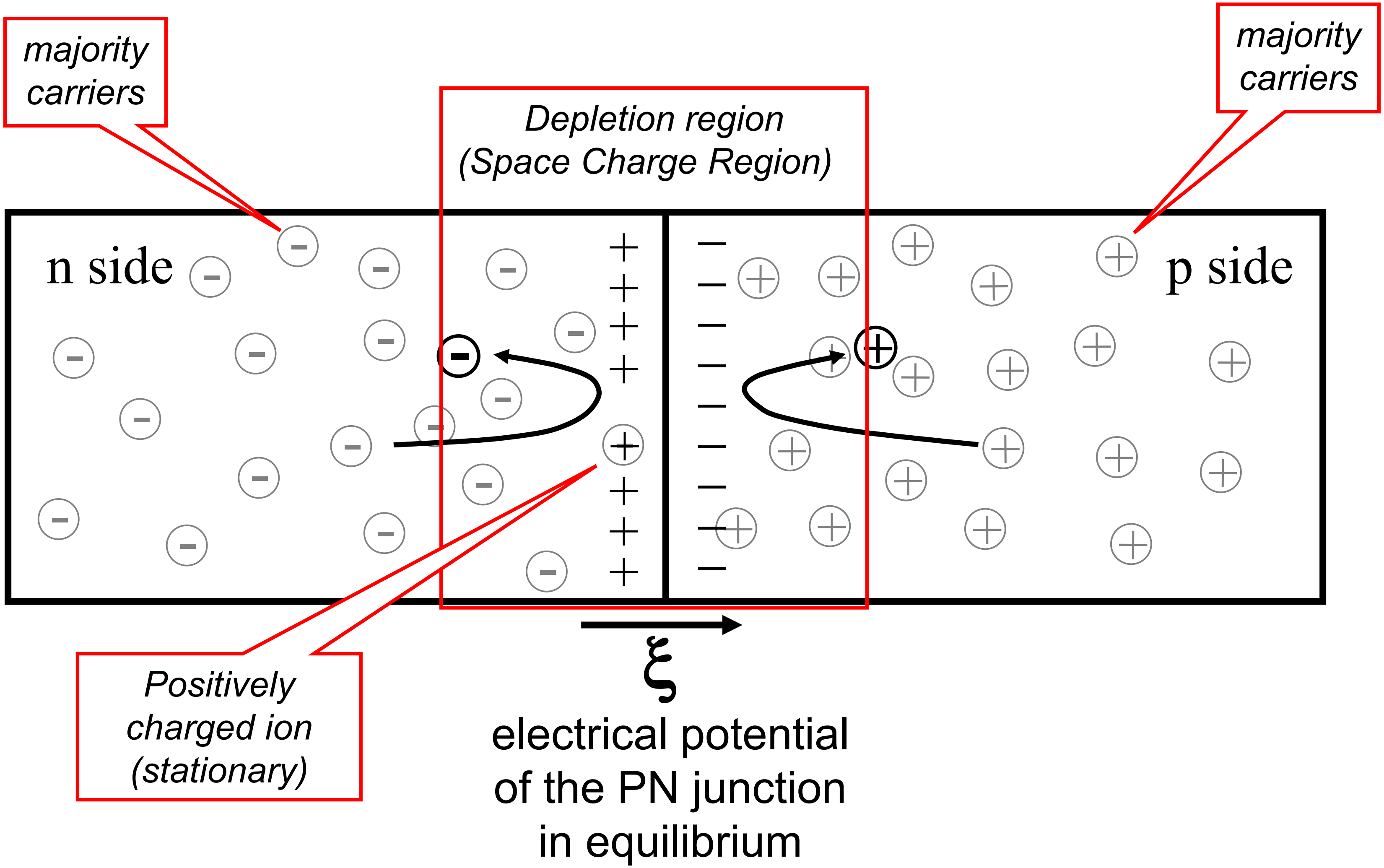
Donors ⇒ donate electrons **Acceptors** ⇒ accept electrons

n-type **p-type**



thermal energy (~kT) is sufficient to "activate" the carriers

The PN Junction (1)



P-N junction provides charge separation

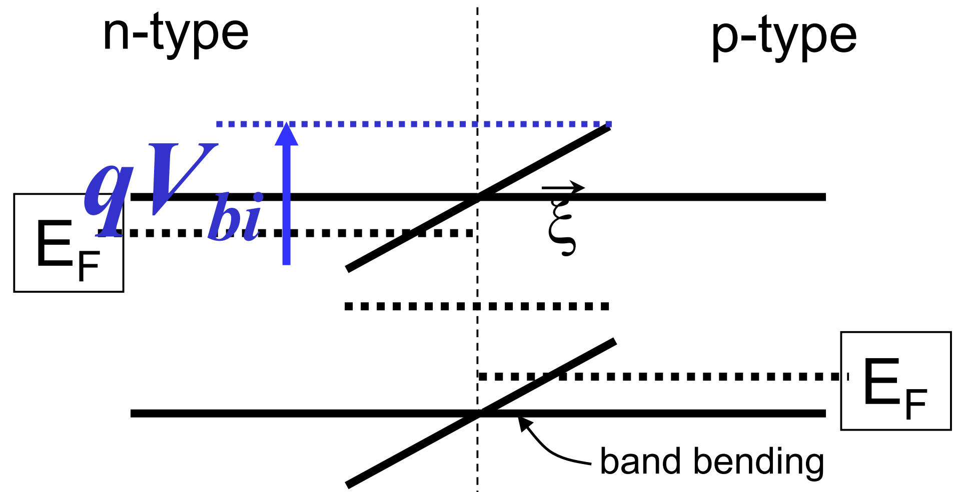
Built-in Voltage & Depletion Width

Built in voltage V_{bi}

$$qV_{bi} \approx kT\ln\left(\frac{N_a N_d}{n_i^2}\right)$$

N_a, N_d – concentration of acceptors (donors)

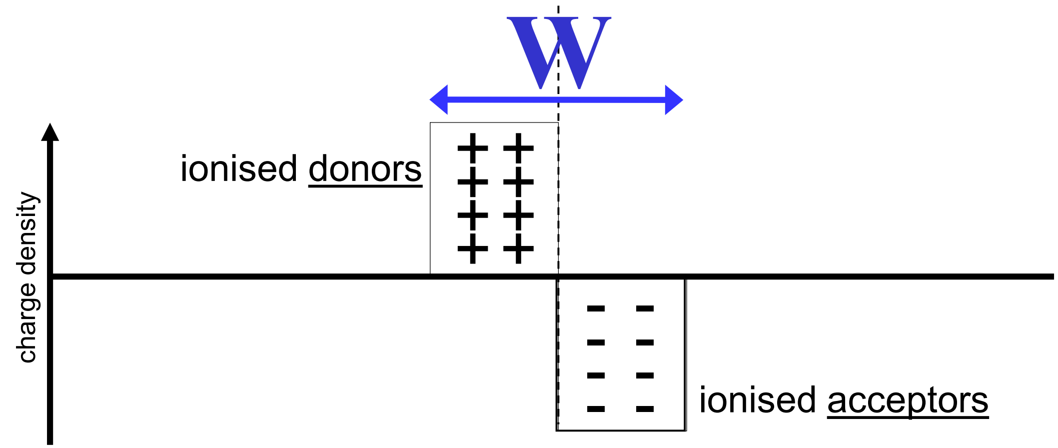
n_i – intrinsic carrier concentration



Depletion width *W*

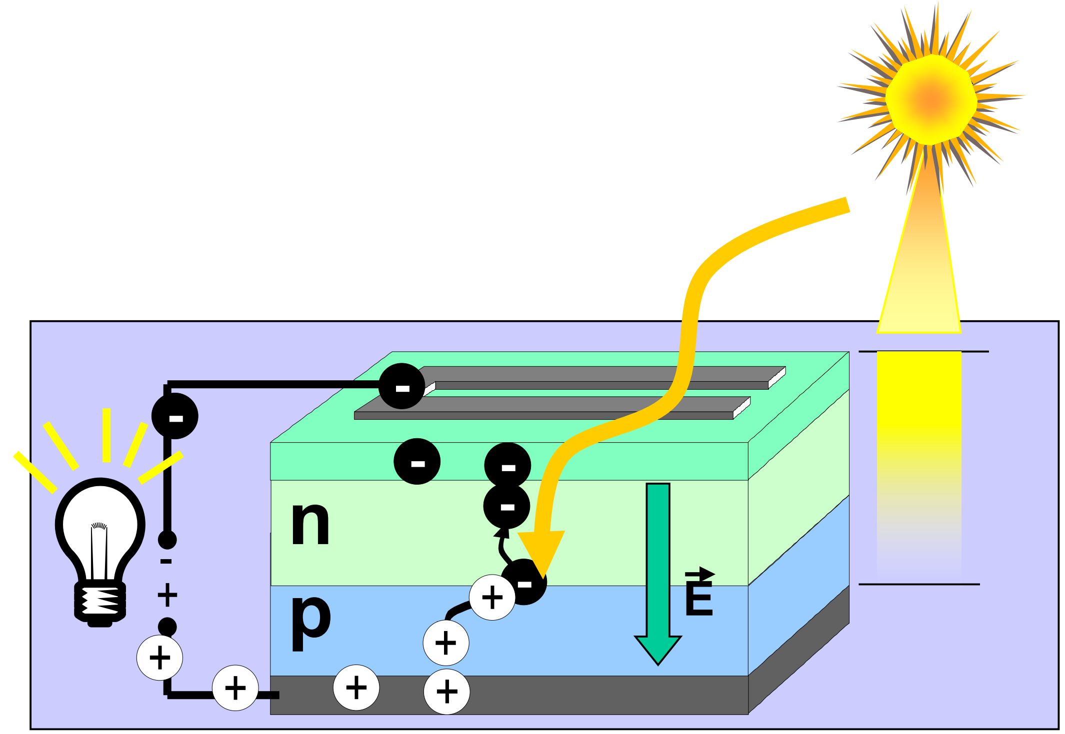
$$W = \sqrt{\frac{2\varepsilon}{q}\left(\frac{N_a + N_d}{N_a N_d}\right)V_{bi}}$$

ε – dielectric constant



Solar cell parameters

Operation of p-n junction solar cell

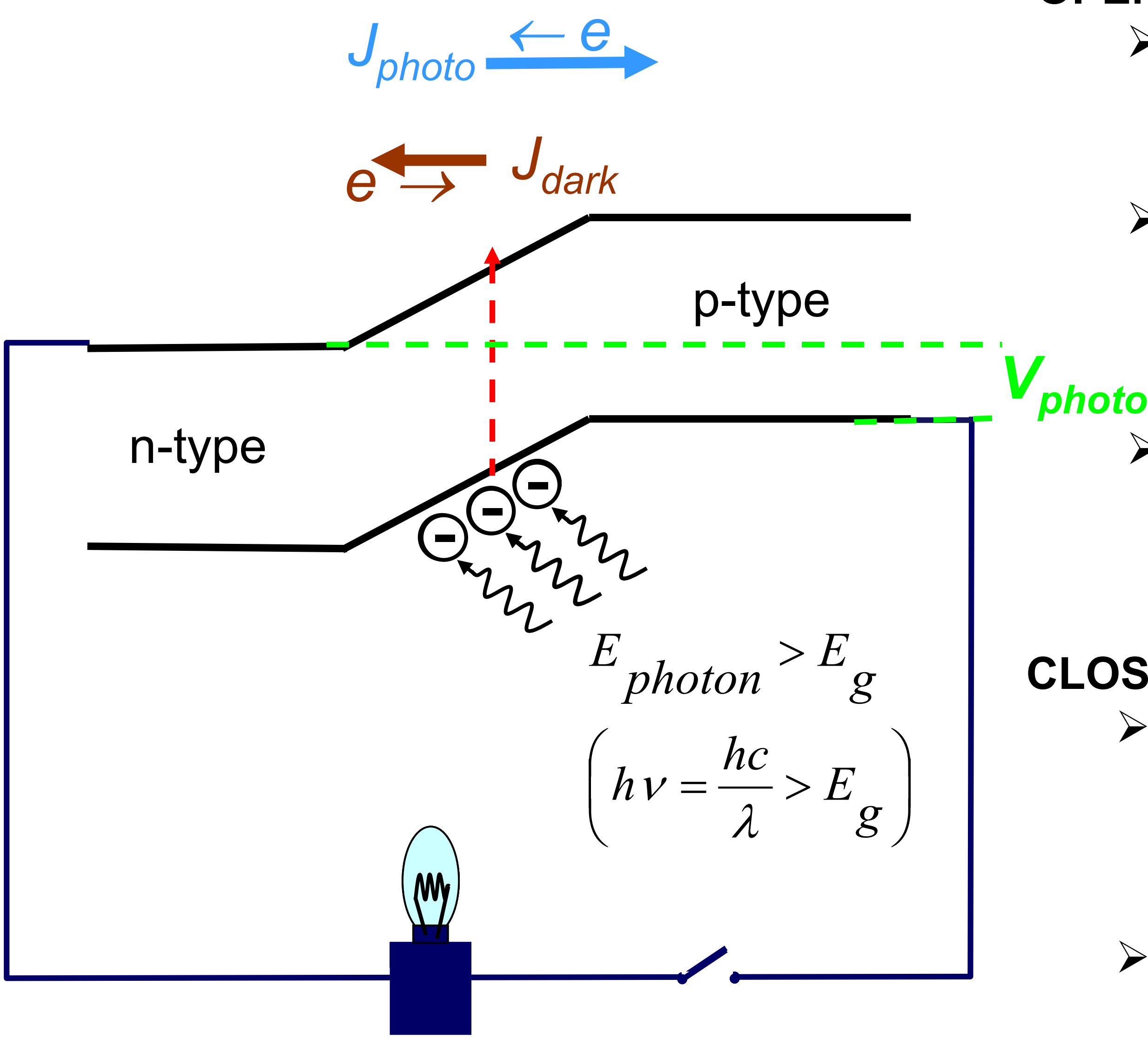


1. Light absorption

2. Generation of free mobile carriers

3. Separation of the free carriers

P-N junction under illumination



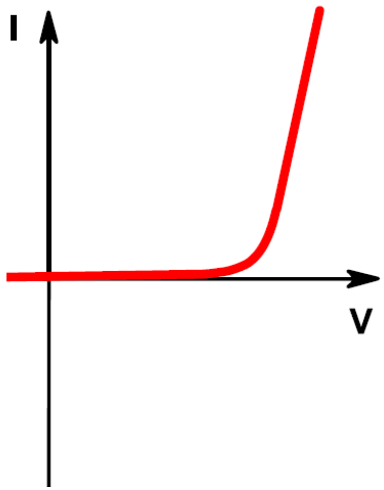
OPEN CIRCUIT:

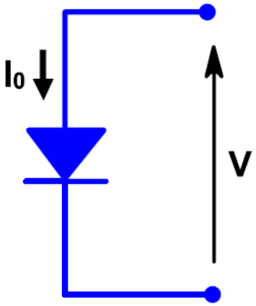
- Opposite charges build up on the contacts
- photovoltage V_{photo} is produced (maximum is open circuit voltage V_{oc})
- Dark curent (J_{dark}) equilibrates new photogenerated

CLOSED CIRCUIT:

- Charges flow via external circuit as photocurrent J_{photo}
- J_{photo} flows in the opposite direction to J_{dark}

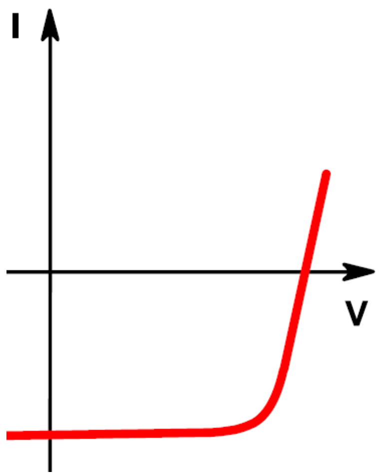
Effect of light on I-V curve

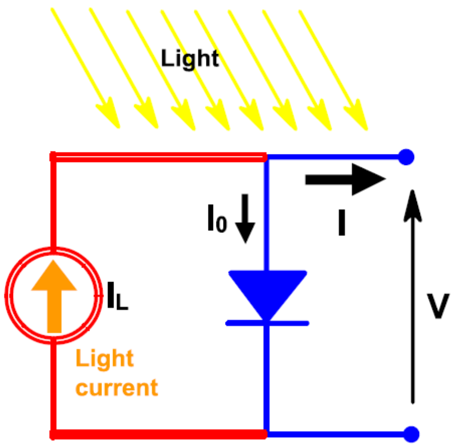




Without illumination, a solar cell acts like a diode

=> I-V curve is identical



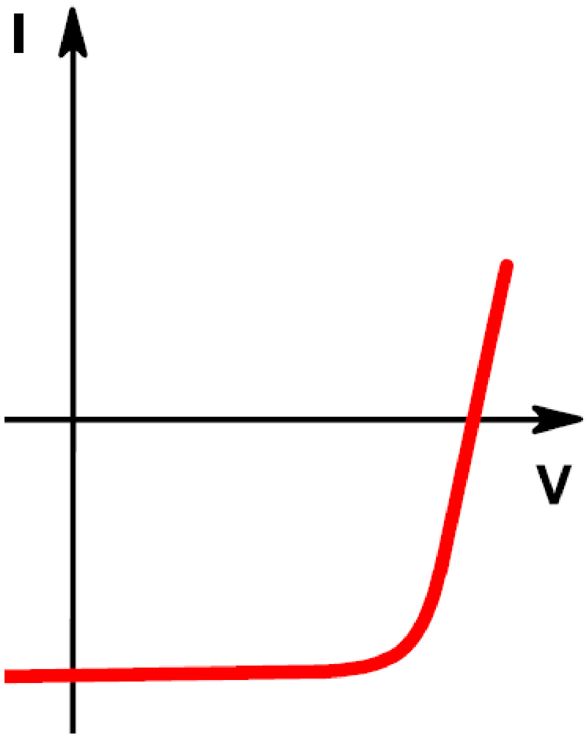


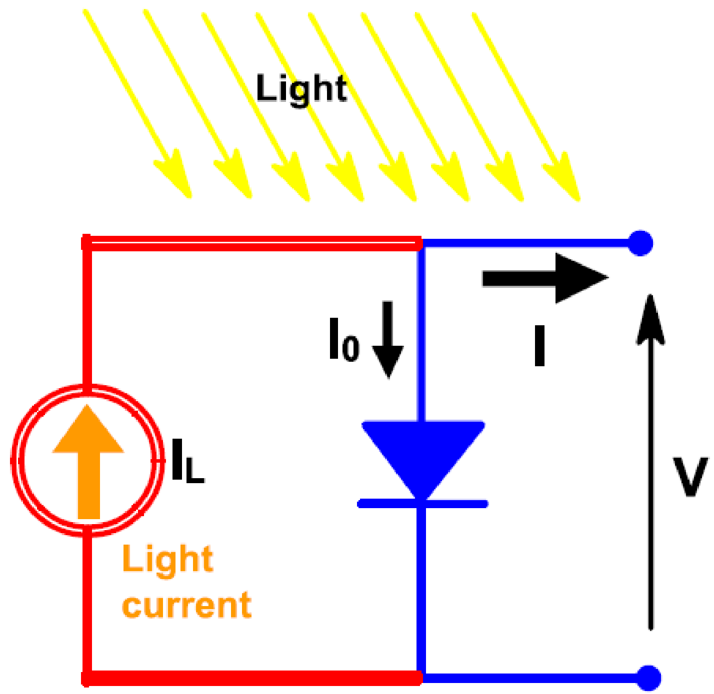
Under illumination, solar cell produces photocurrent

=> I-V curve shifts down by the value of light current

Image: www.pveducation.org

Current equation

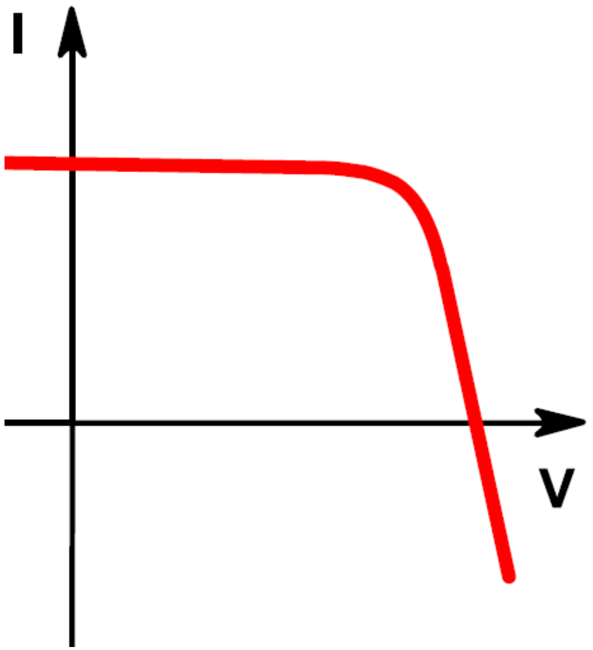


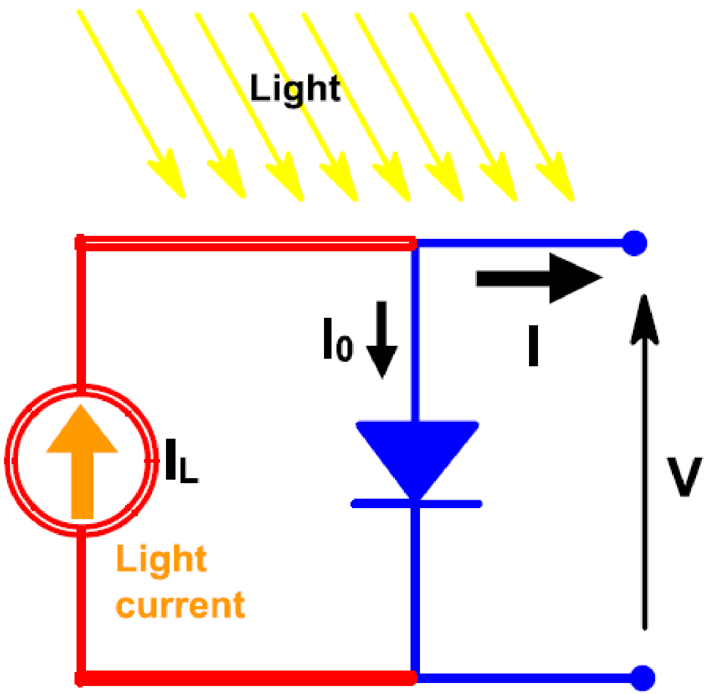


$$I = I_0(\exp(\frac{qV}{kT}) - 1) - I_L$$

Light-induced current (photocurrent) is proportional to the incident light intensity

Current equation (mirrored form)

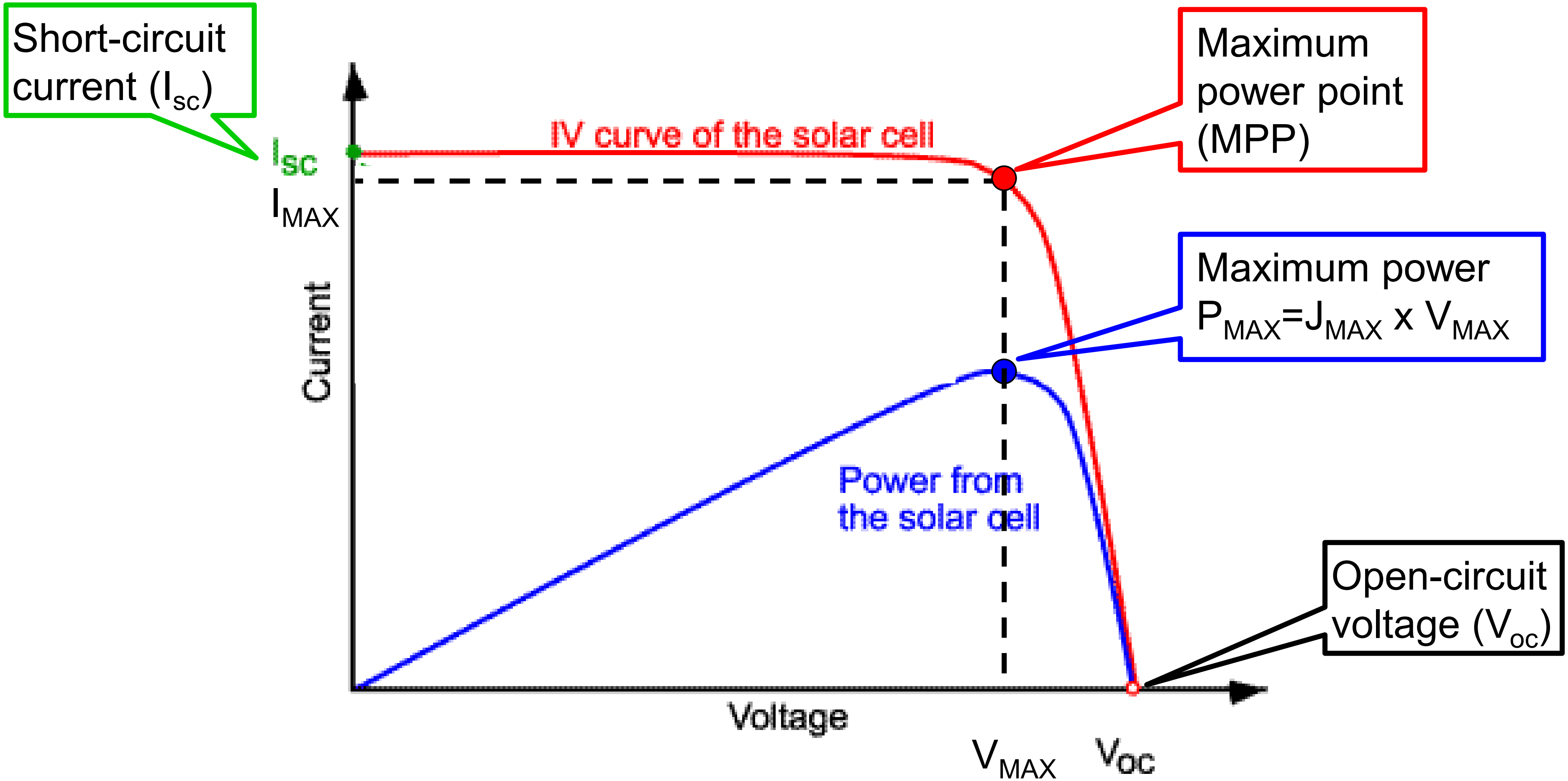




Since the cell is generating power, the convention is to invert the current axis

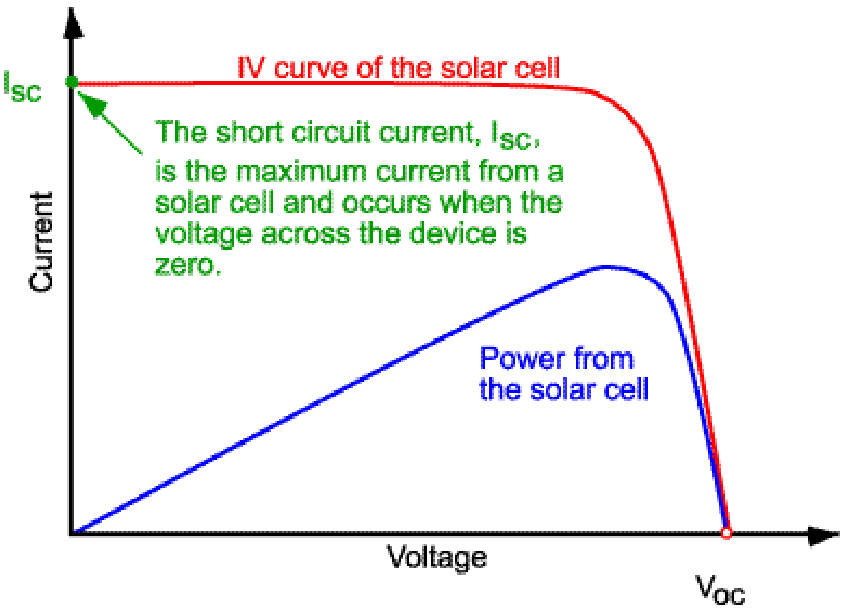
$$I = I_L - I_0(\exp(\frac{qV}{kT}) - 1)$$

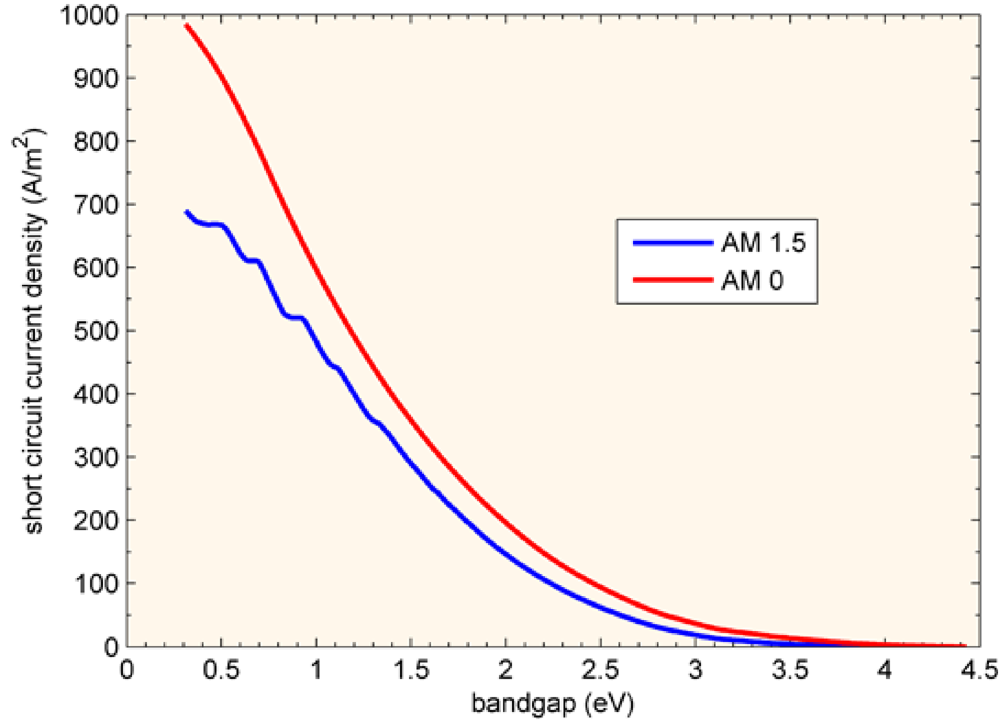
I-V curve & power curve



- I-V curves are measured under **Standard Test Conditions (STC):**
  - light intensity 1000 W/m^2
  - spectrum AM1.5G
  - cell temperature T=25°C

Short circuit current I_{sc}





- Short circuit current Isc is the current when voltage across the device is zero
- I_{SC} is essentially the light-induced current if we neglect series resistance ($I_{sc} = I_L$)
- To remove the dependence on the solar cell area, it is more common to use the **short-circuit current density** (J_{sc} in mA/cm^2) rather than absolute current

Open circuit voltage V_{oc}

START HERE → $$I = I_L - I_0\left(\exp\left(\frac{qV}{kT}\right) - 1\right)$$

(the diode equation)

At V_{oc} $I=0$ $$\Rightarrow 0 = I_L - I_0\left(\exp\left(\frac{qV_{oc}}{kT}\right) - 1\right)$$

$$\frac{I_L}{I_0} + 1 = \exp\left(\frac{qV_{oc}}{kT}\right)$$

$$V_{oc} = \frac{kT}{q}\ln\left(\frac{I_L}{I_0} + 1\right)$$

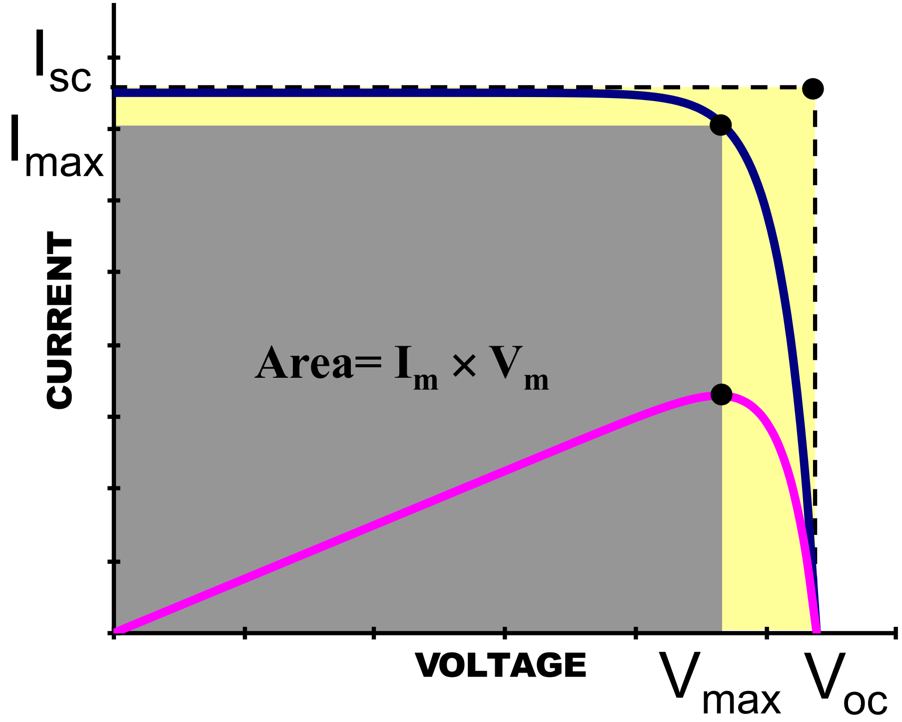
$I_L \sim A$ $I_0 \sim 10^{-9} A$

$\Rightarrow I_L >> I_0$

$\Rightarrow I_L / I_0 >> 1$

$$V_{oc} \approx \frac{kT}{q}\ln\left(\frac{I_L}{I_0}\right)$$

Fill Factor FF



Maximum theoretical power

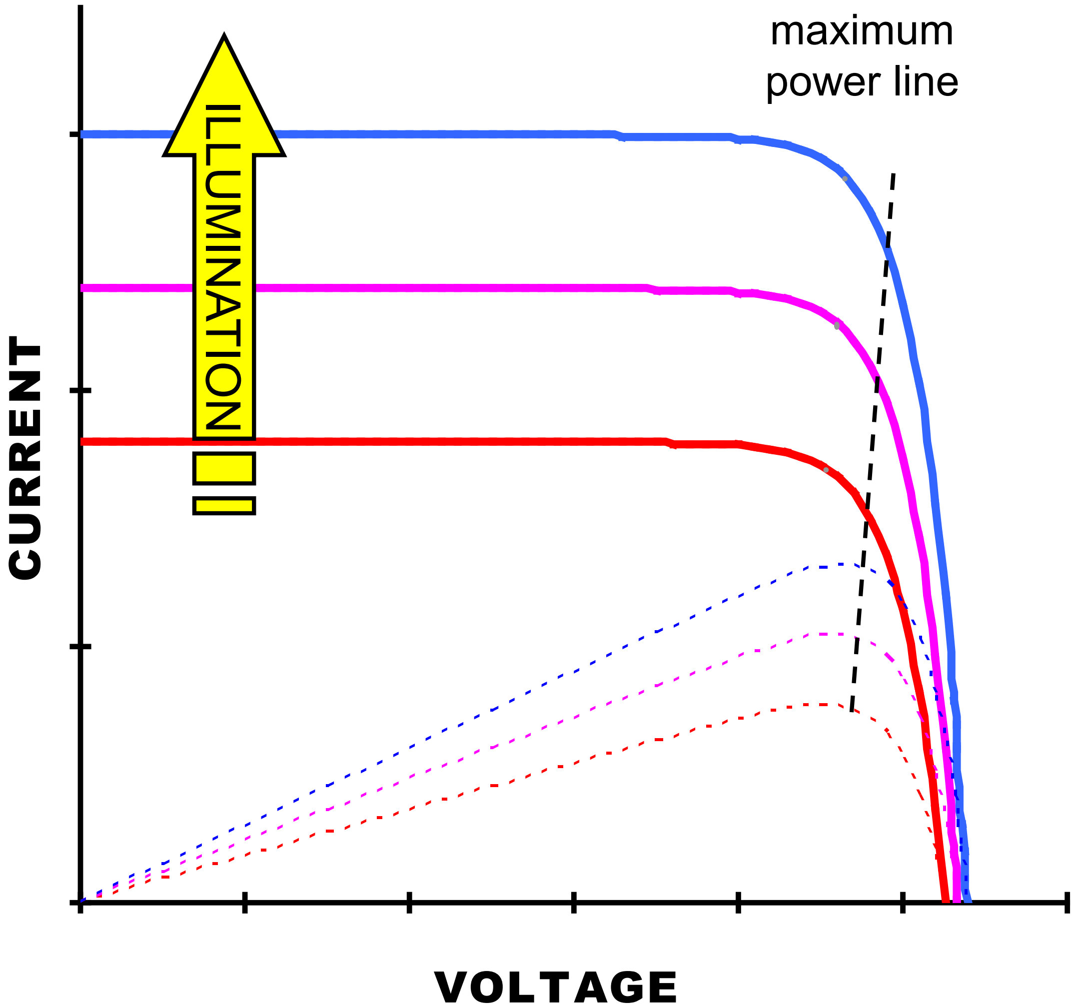
$$P_m = I_{sc} V_{oc}$$

Maximum power point (MPP)

$$P_{MPP} = I_{\max} V_{\max}$$

$$FF = \frac{\text{area } I_{max} \times V_{max}}{\text{area } I_{sc} \times V_{oc}}$$

Effect of illumination



Light intensity increases:

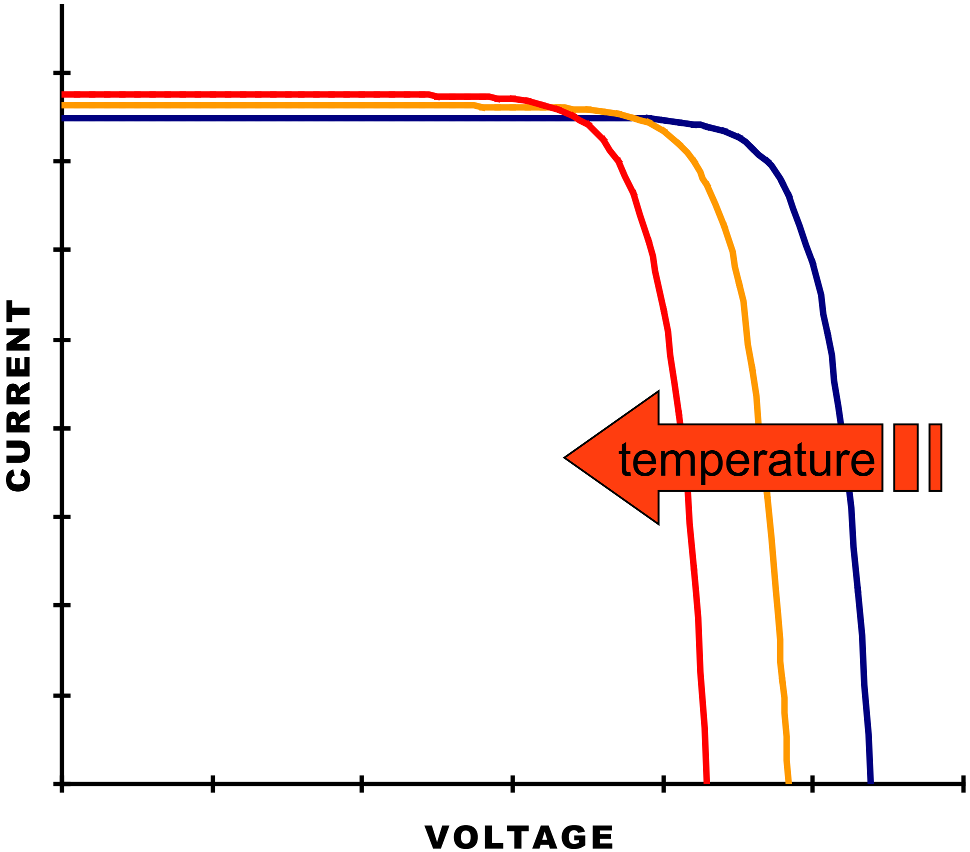
⇒ Jsc increases proportionally

⇒ Voc goes up

⇒ overall η increases (used in concentrated PV)

$$V_{oc} \approx \frac{kT}{q} \ln\left(\frac{I_L}{I_0}\right)$$

Effect of temperature



Temperature increases:

⇒ band gap E_g is reduced

⇒ the current density goes up
⇒ but the voltage goes down
⇒ overall η decreases.

For Si cell: $$\frac{dJ_{sc}}{dT} \approx 0.1 A m^{-2} K^{-1}$$

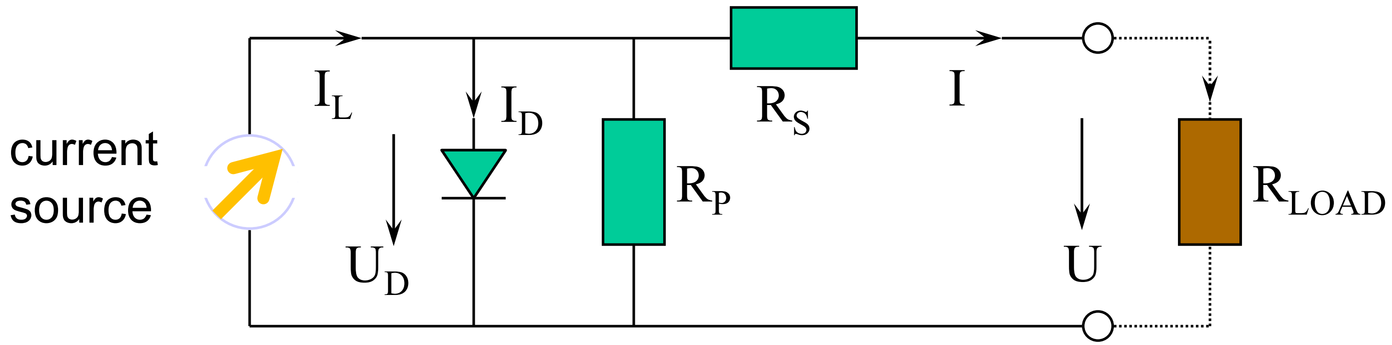
$$\frac{dV_{oc}}{dT} \approx -2.2 mV K^{-1}$$

$$\frac{d\eta}{dT} \approx -0.5\% K^{-1}$$

Solar cell characteristics

- Short-circuit current density J_{SC}:
  - proportional to irradiation
  - Typical 30-40 mA cm^{-2}
  - Increases by 0.07% per Kelvin
- Open-circuit voltage V_{OC}:
  - This is the voltage along the internal diode
  - Typical values 0.6…0.7 V depending on semiconductor
  - decreases by 0.4% per Kelvin
- Power (MPP, Maximum Power Point)
  - Power decreases by 0.4% per Kelvin
- The nominal power of a cell is measured at standard test conditions (STC): G_0 = 1000 W/m^2, T_{cell} = 25°C, AM 1.5G spectrum

Equivalent circuit of a real solar cell



$I_{L:}$ Light-induced current of the solar-cell

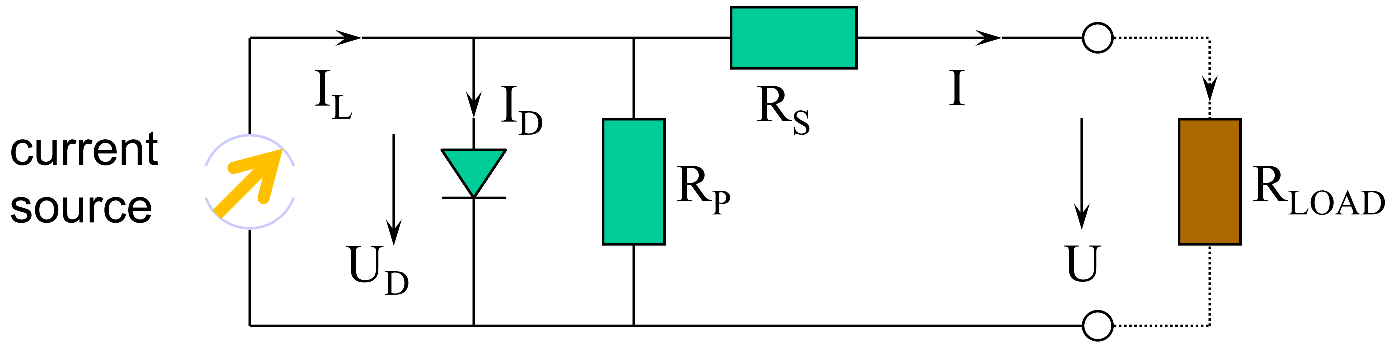
I_D /U_D: dark current and voltage of the internal p-n diode

R_P: parallel (shunt) resistor due to inhomogeneity of the surface and current loss at the solar-cell edges

R_S: serial resistor due to resistance of the bulk and contacts

R_{LOAD}: load resistance

Full current equation

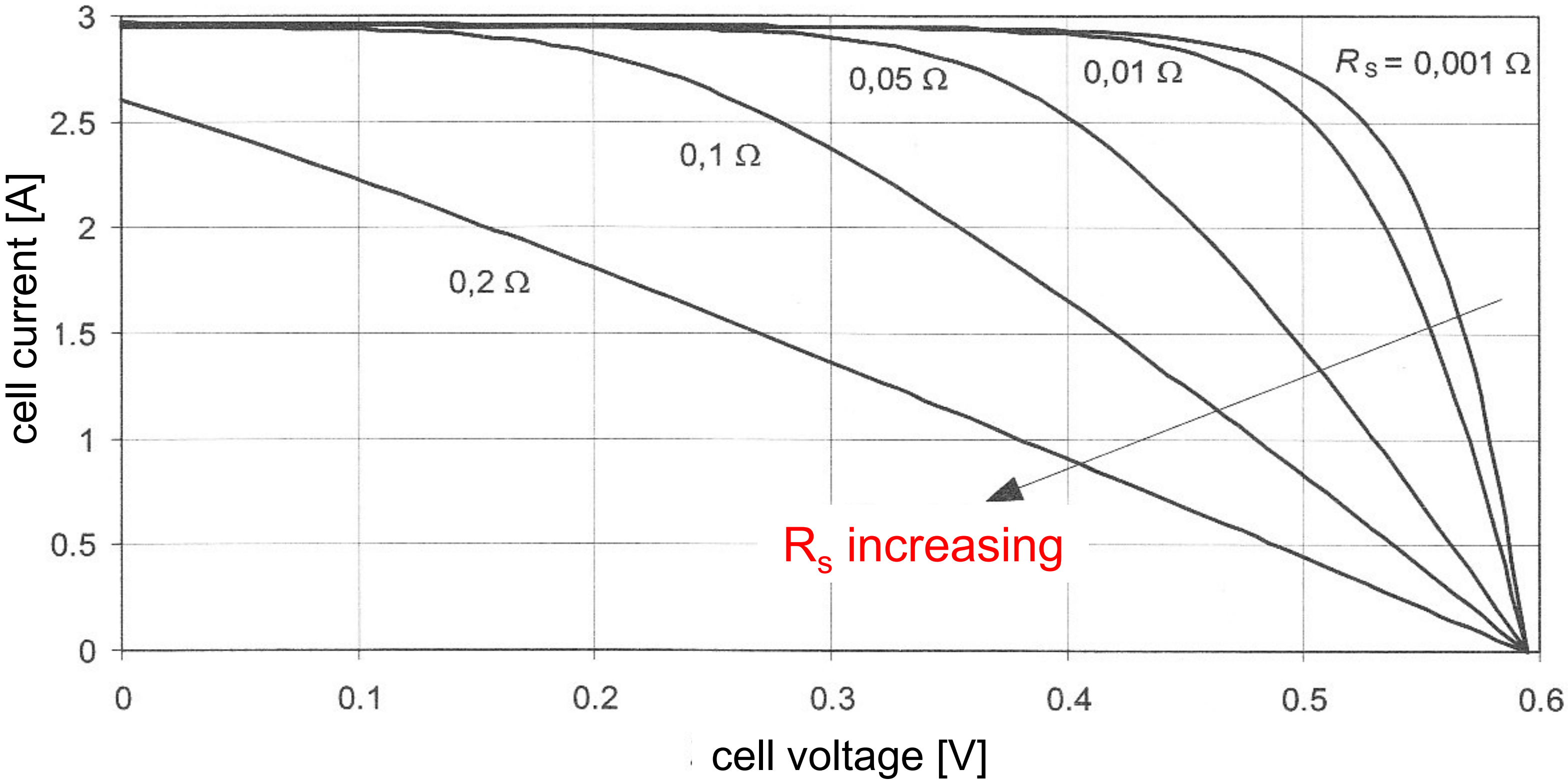


$$I = I_L - I_0 \left\{ \exp\left(\frac{q\left(V + IR_s\right)}{nkT} \right) - 1 \right\} - \frac{V + IR_s}{R_p}$$

diode ideality factor
$n = 1 \ldots 2$

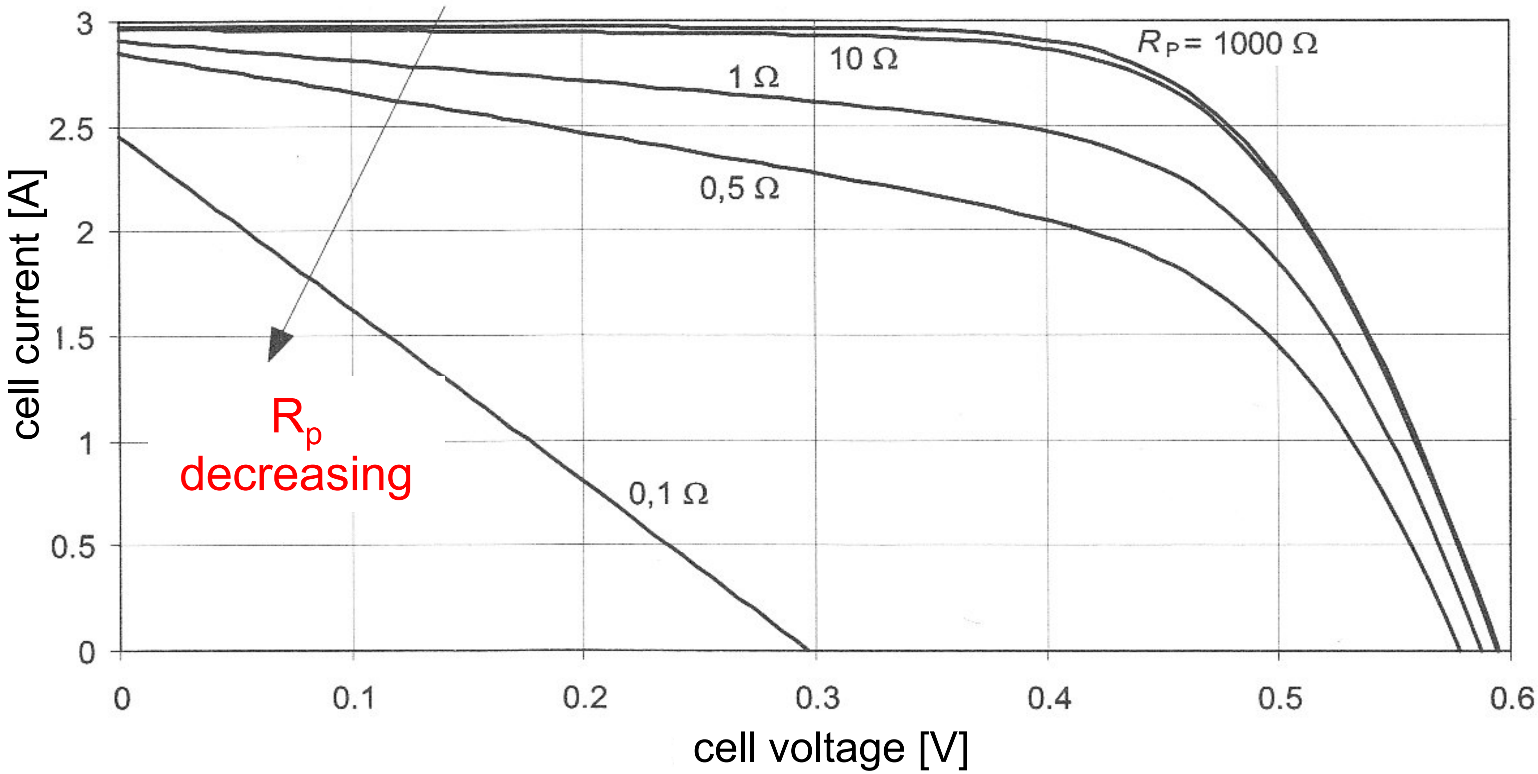
Effect of series resistance R_s

$$I = I_L - I_0\left\{\exp\left(\frac{q(V+IR_s)}{nkT}\right)-1\right\} - \frac{V+IR_s}{R_p}$$



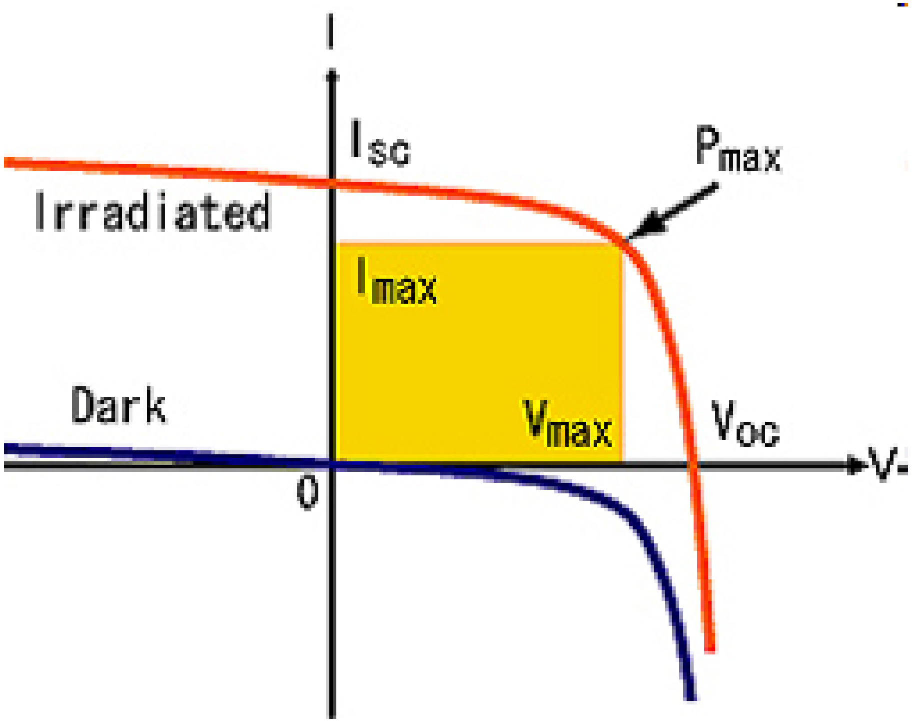
Effect of parallel resistance R_p

$$I = I_L - I_0\left\{\exp\left(\frac{q(V+IR_s)}{nkT}\right)-1\right\}-\frac{V+IR_s}{R_p}$$



Power conversion efficiency

Efficiency: the ratio of the generated power to the power of incident light



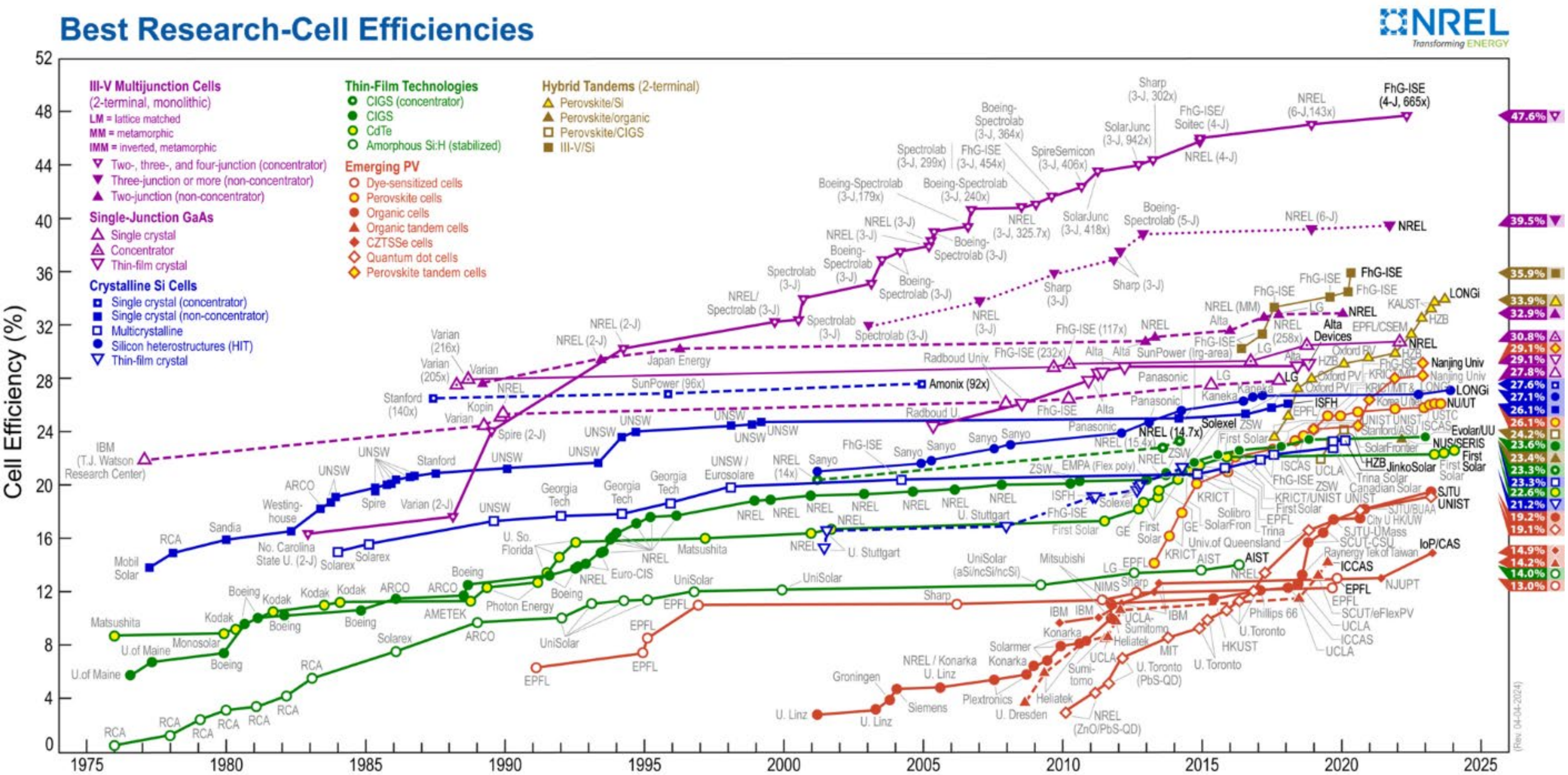
$$\eta = \frac{P_{electrical}}{P_{light}} = \frac{V_{MAX} \times I_{MAX}}{P_{IN}}$$

Standard test conditions:

- Light intensity P_{IN} = 1000 W/m^2
- AM1.5G spectrum
- Temperature 25°C

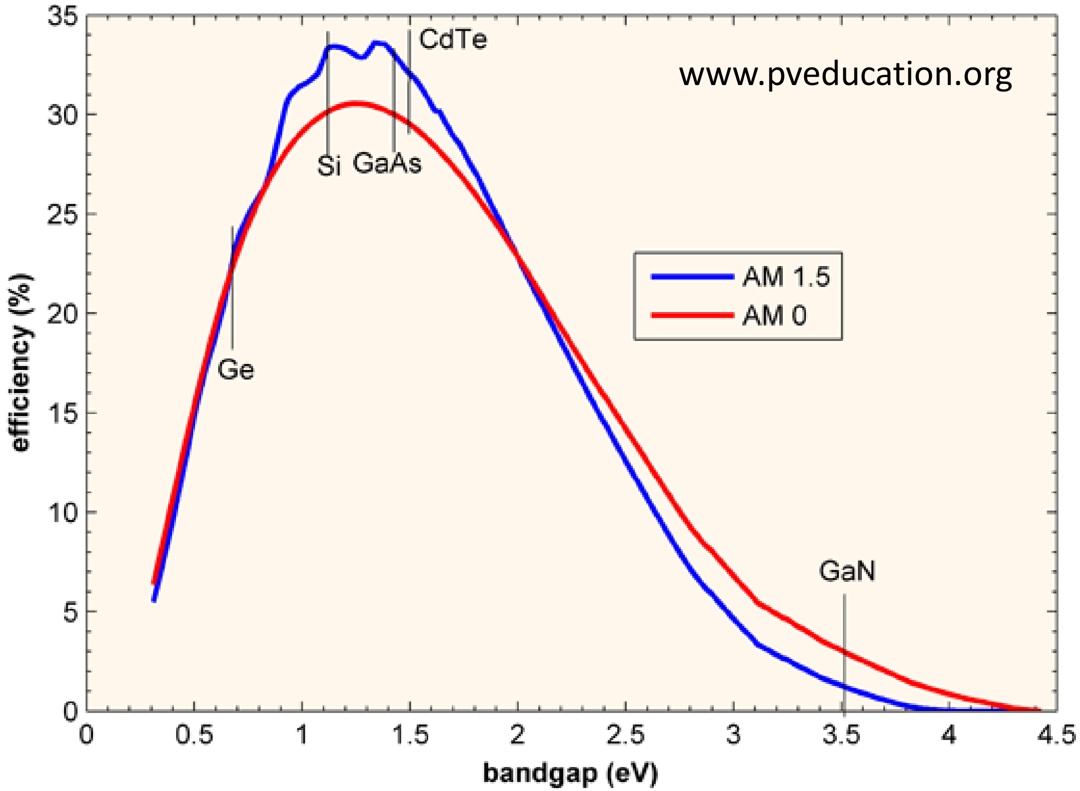
$$FF = \frac{I_m V_m}{I_{sc} V_{oc}} \quad => \quad I_{max} V_{max} = I_{sc} V_{oc} FF \quad \Rightarrow \quad \eta = \frac{I_{sc} V_{oc} FF}{P_{in}}$$

Progress in solar cell efficiency



https://en.wikipedia.org/wiki/Solar_cell_efficiency, May 2024

Shockley-Queisser limit



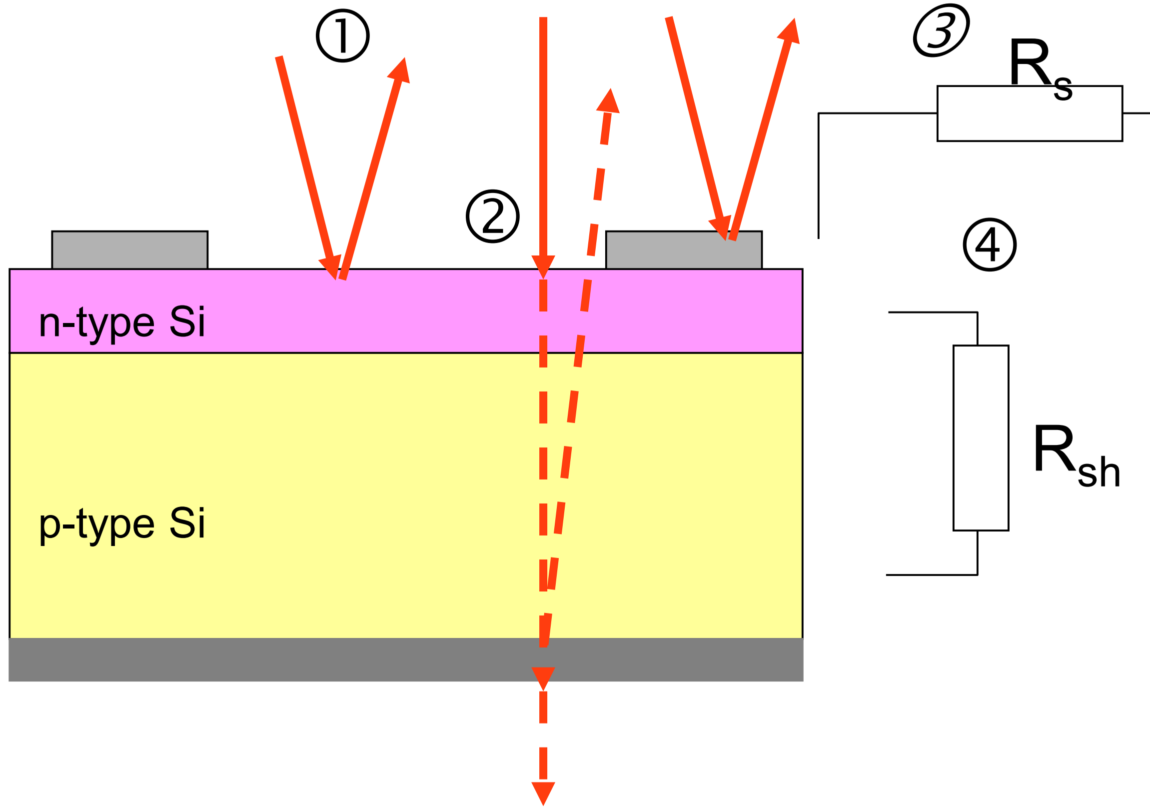
- Maximum efficiency of single-junction solar cell is **33.7%**
- Higher efficiencies are possible for **multi-junction** solar cells

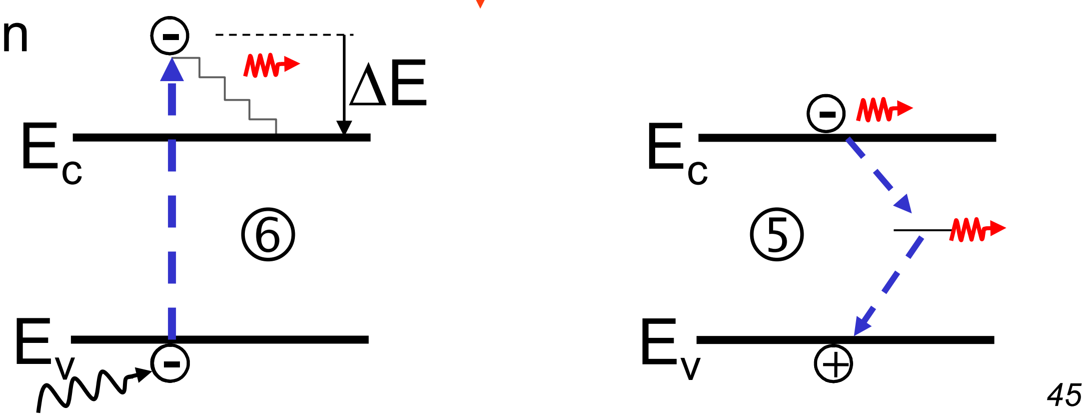
W. Shockley and H.J. Queisser, "Detailed Balance Limit of Efficiency of p-n Junction Solar Cells", J. Appl. Phys. 1961

Main losses

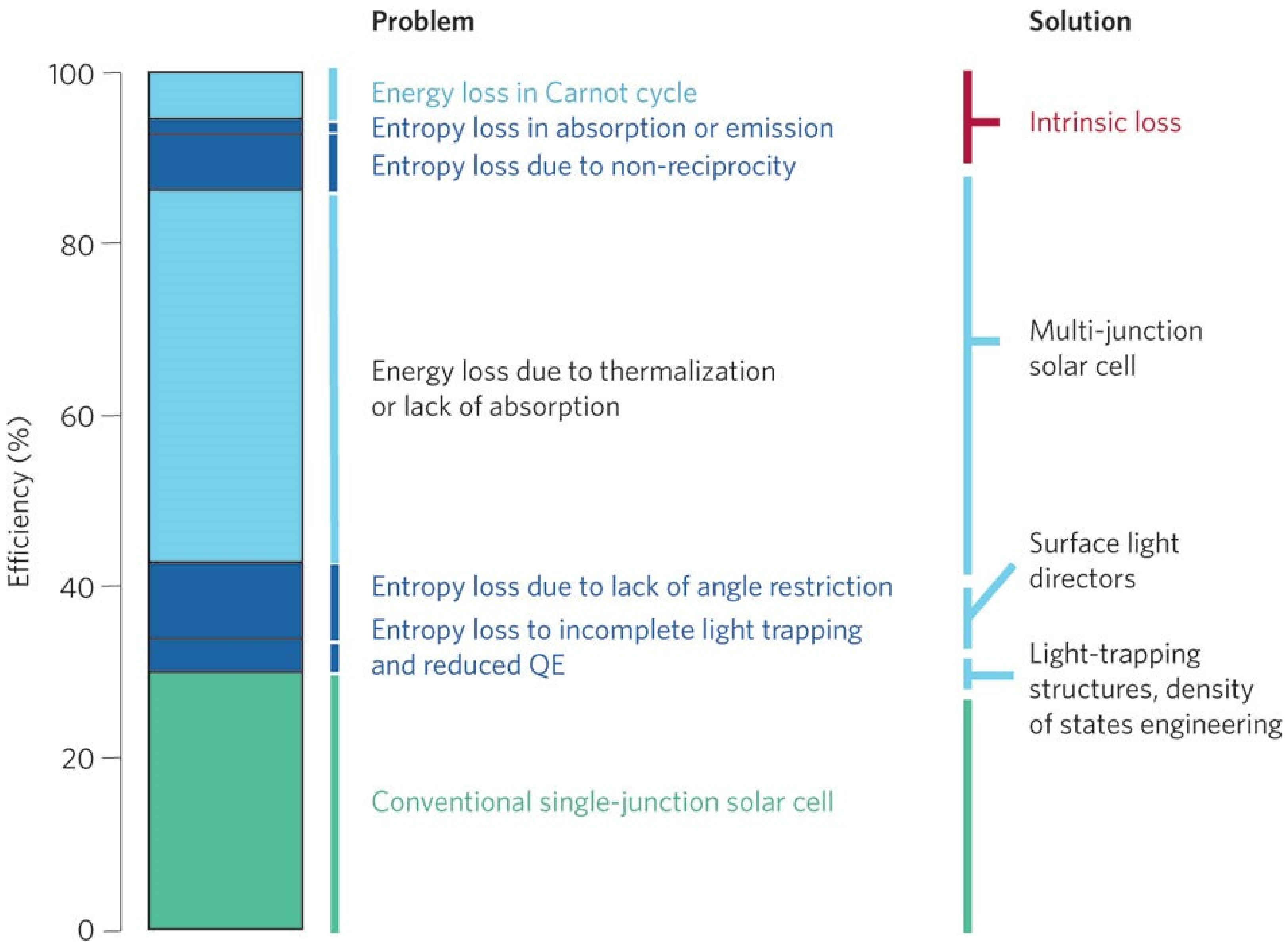
<u>MAIN LOSSES</u>

1. Reflection
2. Incomplete absorption
3. Shading
4. Parasitic resistance
   a. series resistance
   b. shunt resistance
5. Non radiative recombination
6. Thermalisation





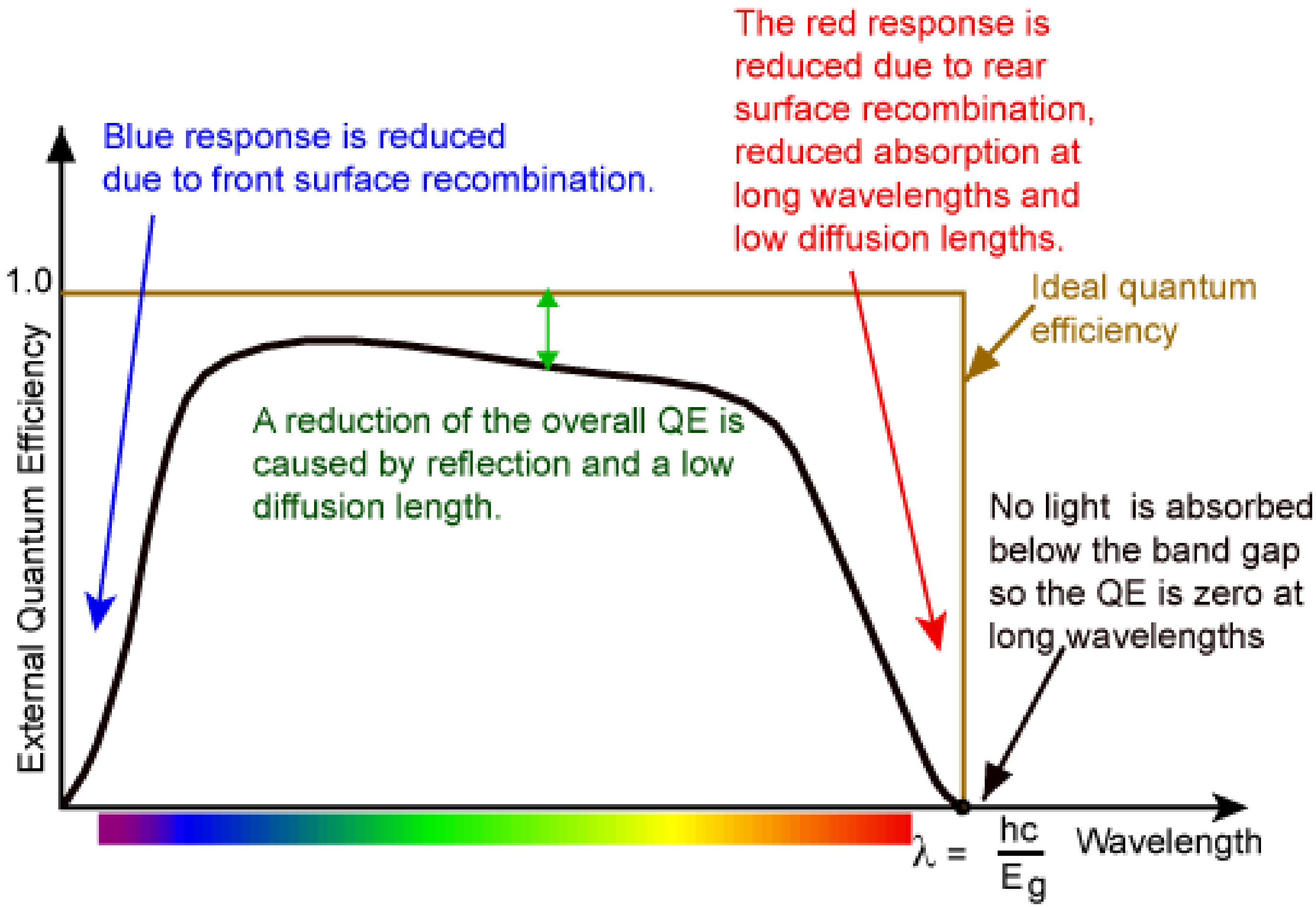
Efficiency losses



Polman and Atwater, Nature 2012

Quantum efficiency

$$QE = \frac{electrons}{photons} \times 100\%$$



Quantum efficiency for different cells

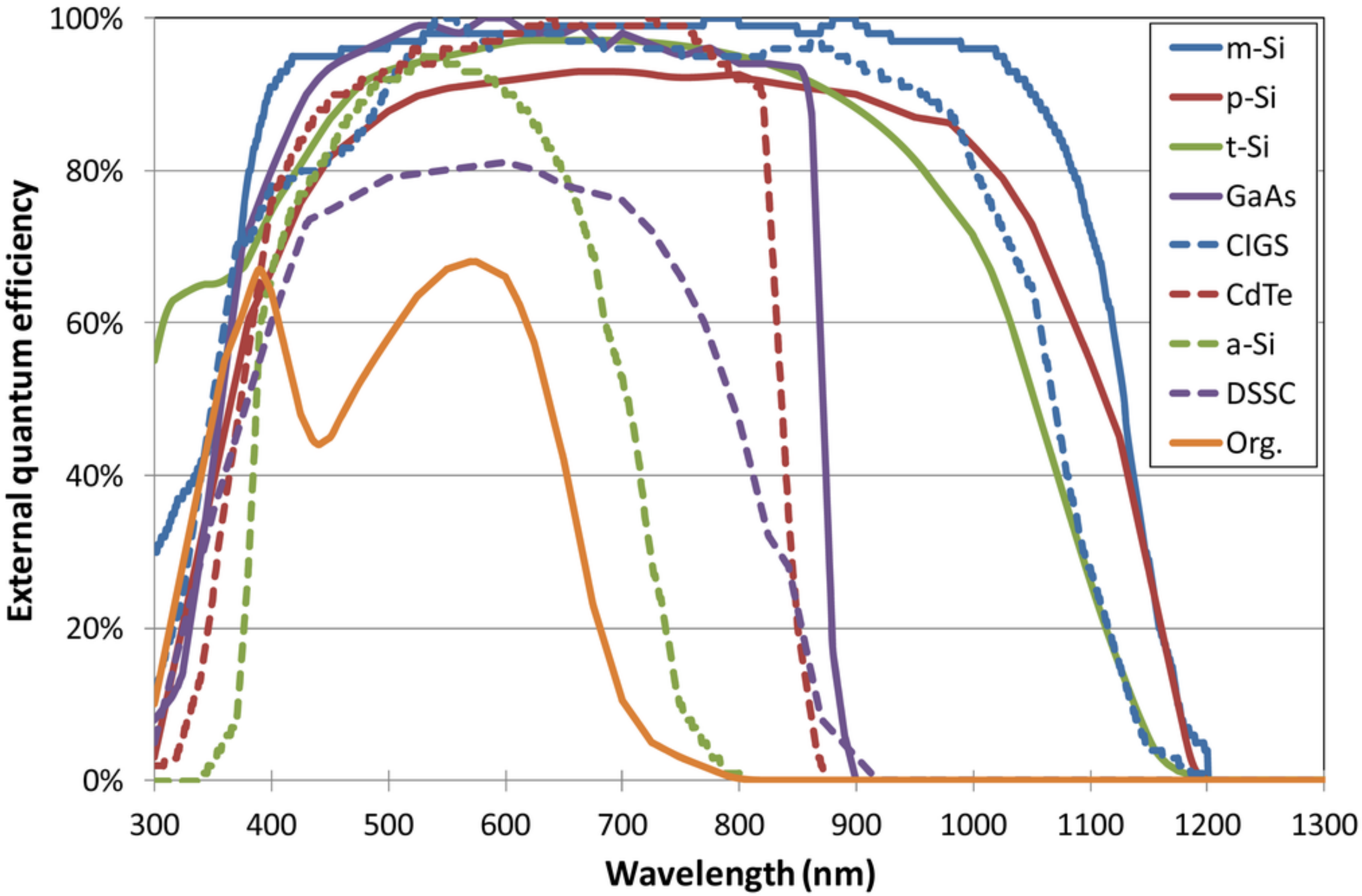
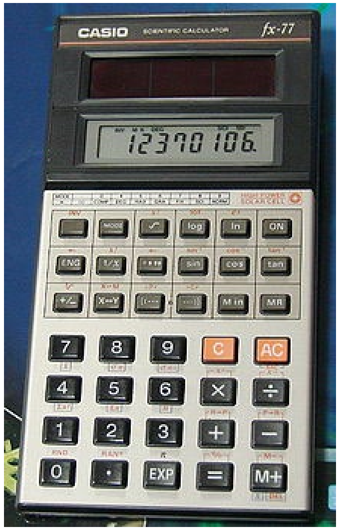


Image from: Energies 2014, 7(3), 1500-1516; doi:10.3390/en7031500

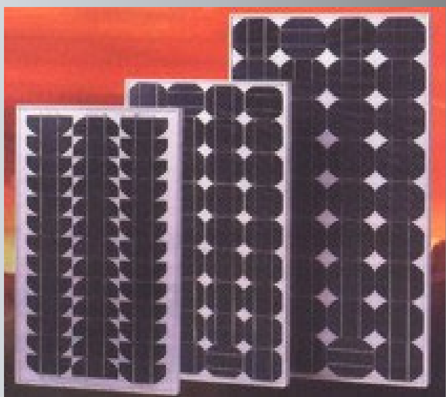
Generations of solar cells

Different PV techs for various applications



Generations of solar cells

1st Generation: **Silicon - Wafer based**



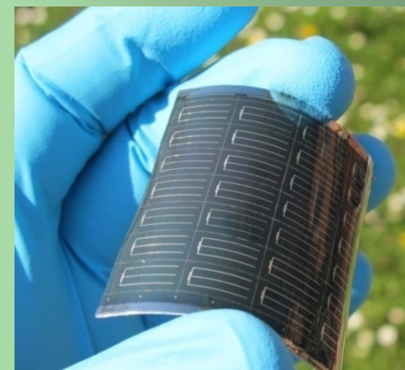
- Absorber thickness: 100-200µm
- Limited by wafer size

- Rigid
- Heavy

- 55 years old (mature technology, 95% market)

- Limited cost reduction potential

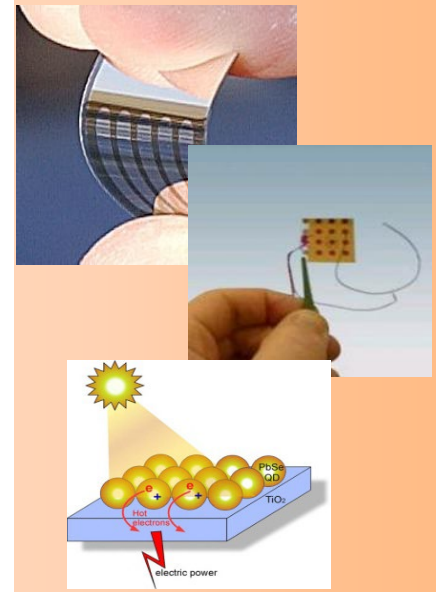
2nd Generation: **Thin-films: a-Si, CdTe, CIGS, DSSC perovskites**



Rigid substrate	**Flexible substr**
➢ Absorber thickness: <3µm	
➢ Large area deposition	R-2-R
➢ Monolithic integration	
➢ Rigid	Flexible
➢ Heavy	Light-weight
➢ 20 years old	pilot production

- Low-cost potential for mobile apps, BIPV, light-weight

3rd Generation: **Quantum dot, tundem, new concepts**



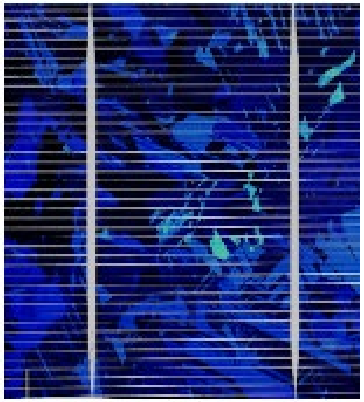
- Mainly in R&D stage

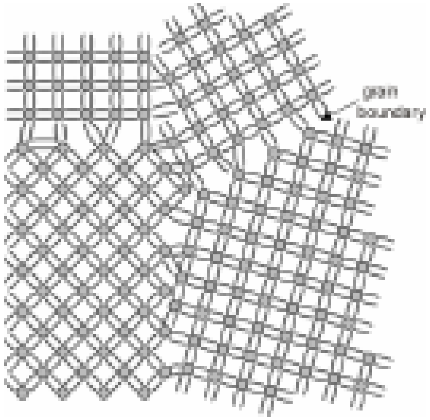
- Possibly low-cost & high-eff

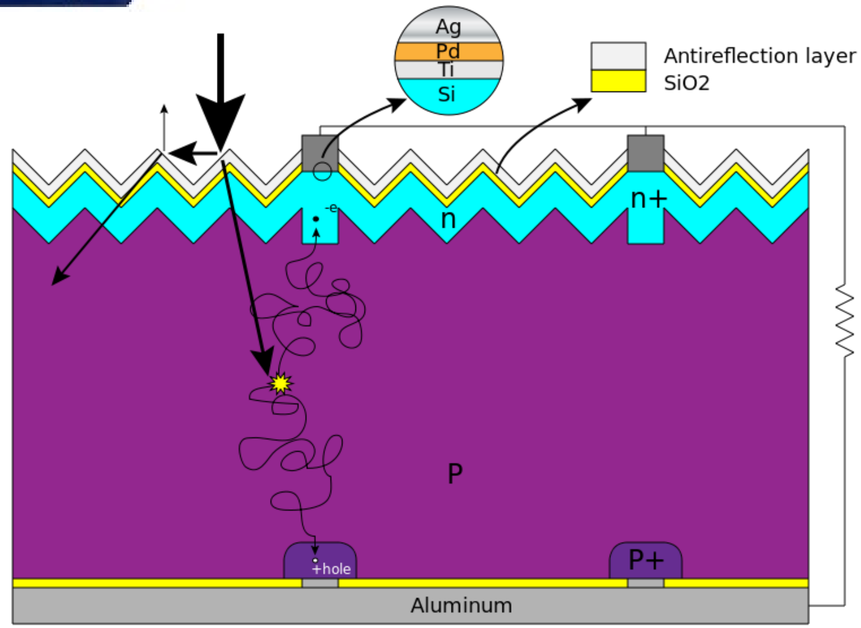
1st generation: crystalline silicon

Monocrystalline Si

Polycrystalline Si

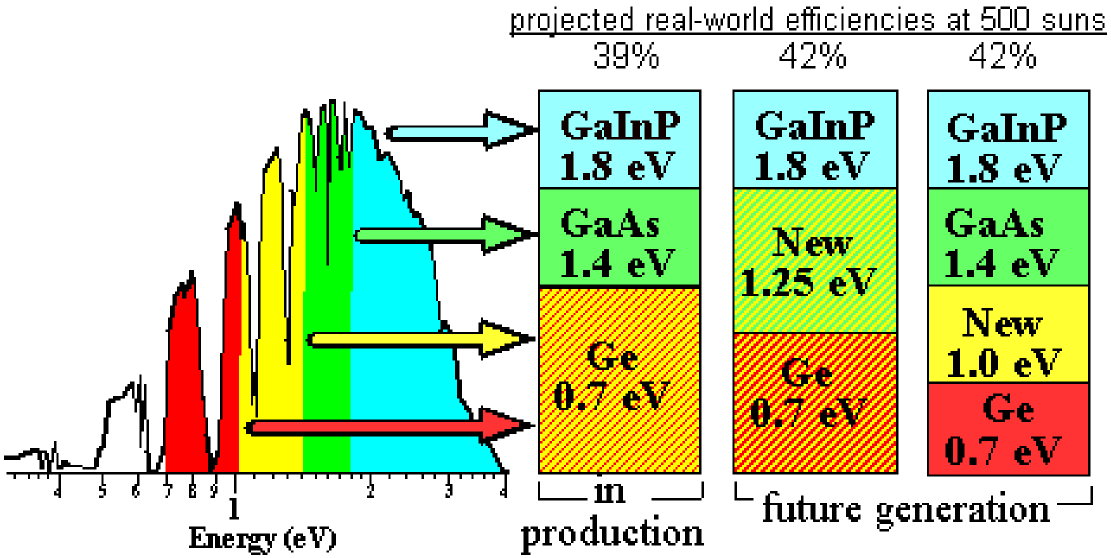


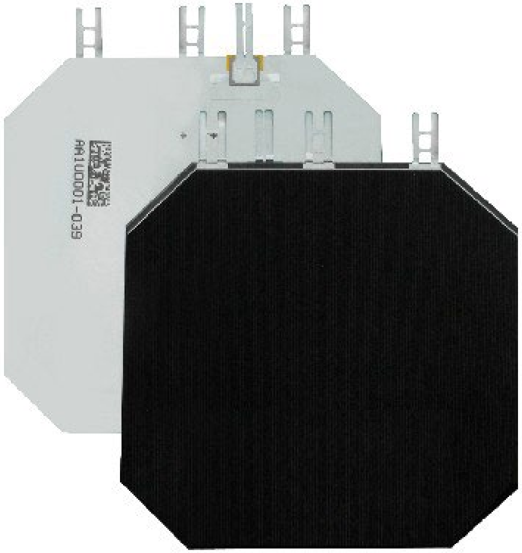




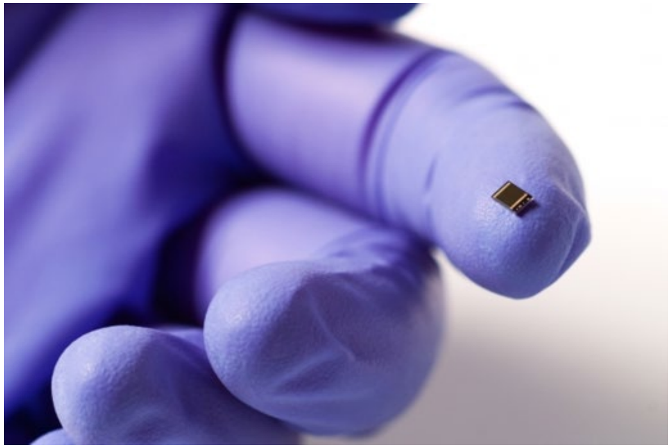
www.wikimedia.org

III-V and multi-junction solar cells



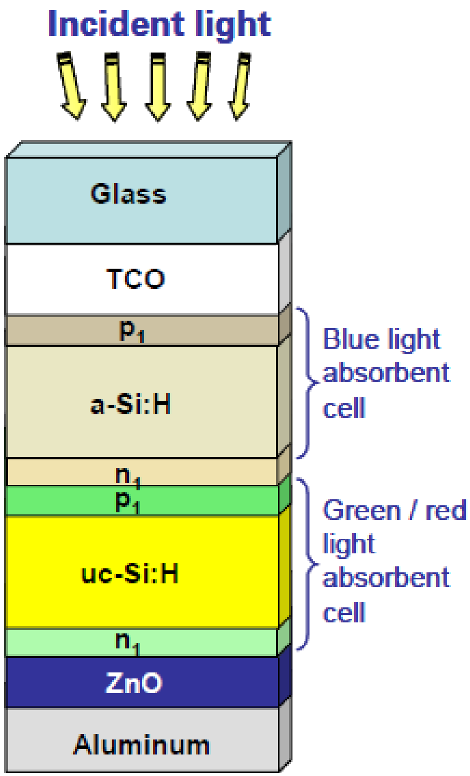


- Combination of wafer and thin-film technology based on GaAs compounds
- More complete utilization of solar spectrum in multi-junction cells
- Highest efficiency of 47.6%
  (4-junction, under concentrated light)

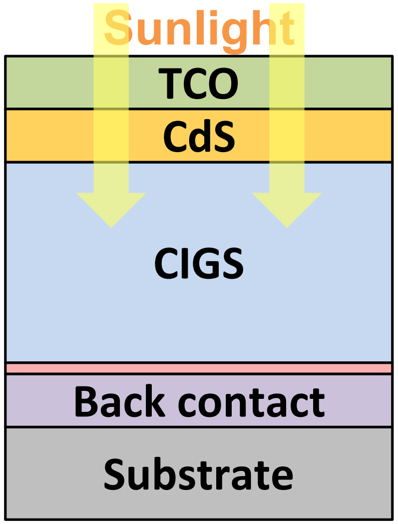


2nd generation: thin film solar cells

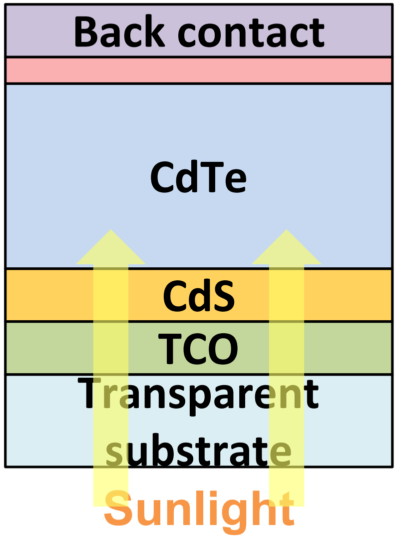
Amorphous Si
(a-Si)



$Cu(In,Ga)Se_2$
(CIGS)

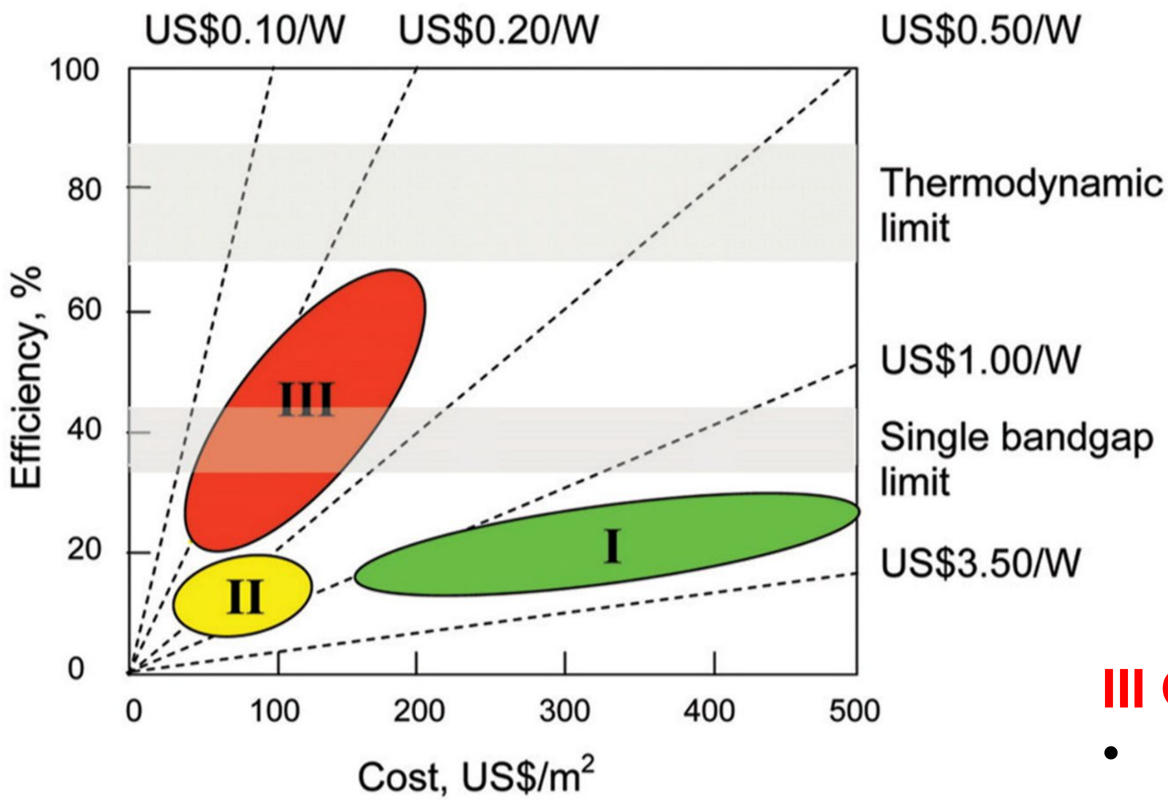


CdTe



- Thin films are deposited on substrates
- Thickness of light-absorbing layer 0.5…10 μm

3rd generation PV



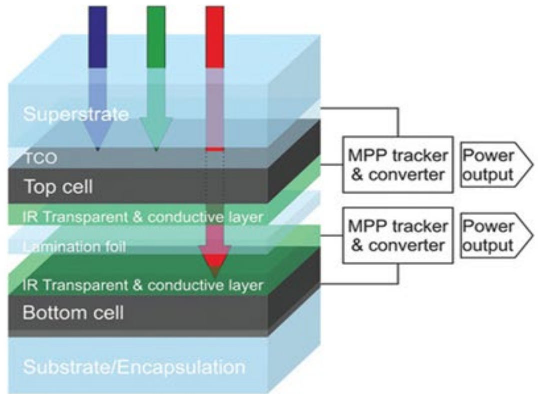
Prof. M. Green, 2001

III Gen concepts:

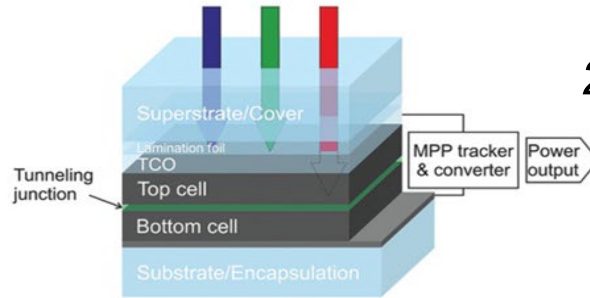
- Multijunction cells
- Concentrated PV
- Intermediate-level cells
- Multiple carrier excitation
- up/down conversion
- Hot carrier cells

Tandem solar cells:
4-terminal vs 2-terminal (monolithic)

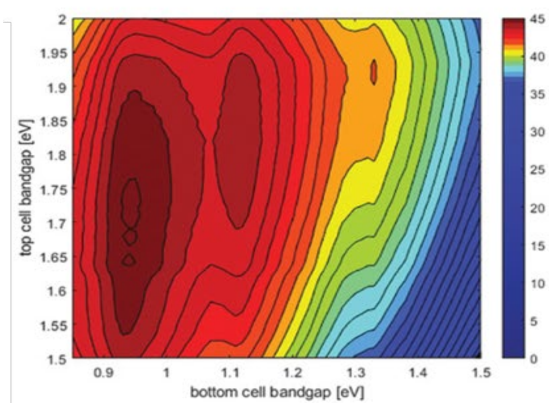
4-terminal

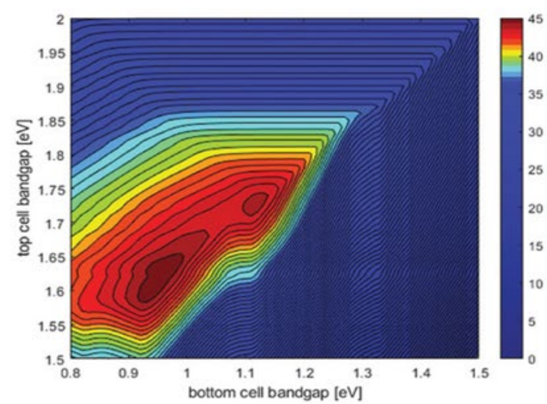


2-terminal



R. Kothandaraman et al., Small Methods 2020





+ individual processing & operation
+ no current matching
- parasitic optical losses
- two electrical circuits (add cost)

+ One electrical circuit
+ Less optical loss
- Current matching
- Process compatibility