

Modern photovoltaic technologies

Course code: PHYS-609

Doctoral program: EDPO - Photonics

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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

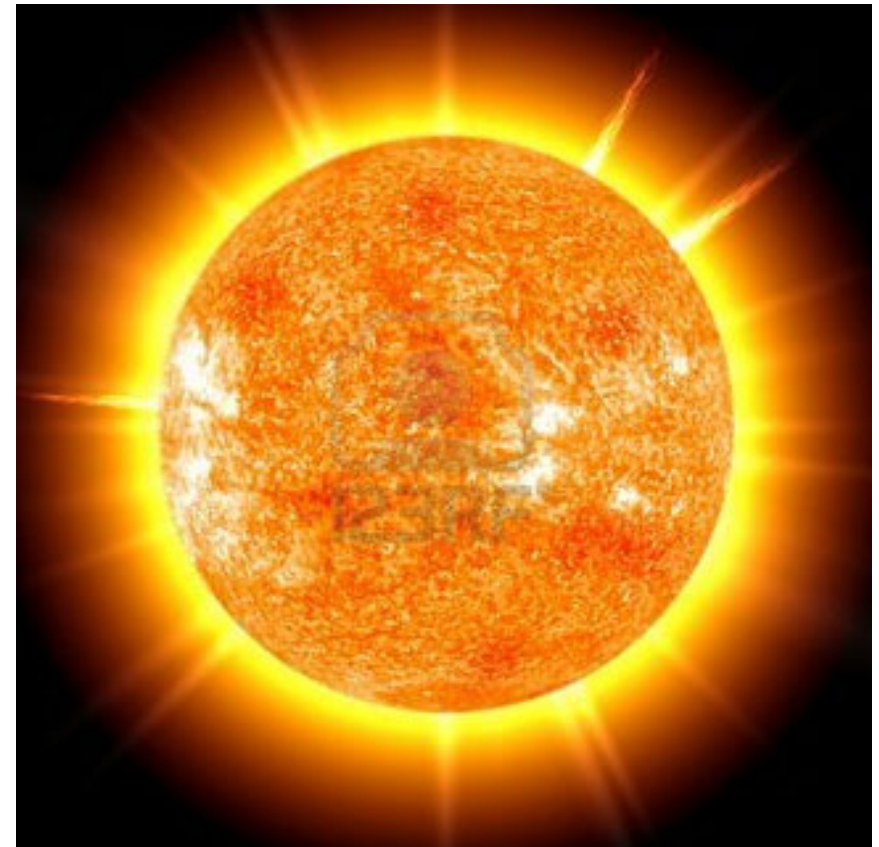
*Humanity's Top Ten Problems
for next 50 years*

1. ENERGY
2. WATER
3. FOOD
4. ENVIRONMENT
5. POVERTY
6. TERRORISM & WAR
7. DISEASE
8. EDUCATION
9. DEMOCRACY
10. POPULATION



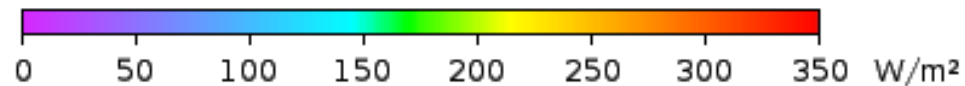
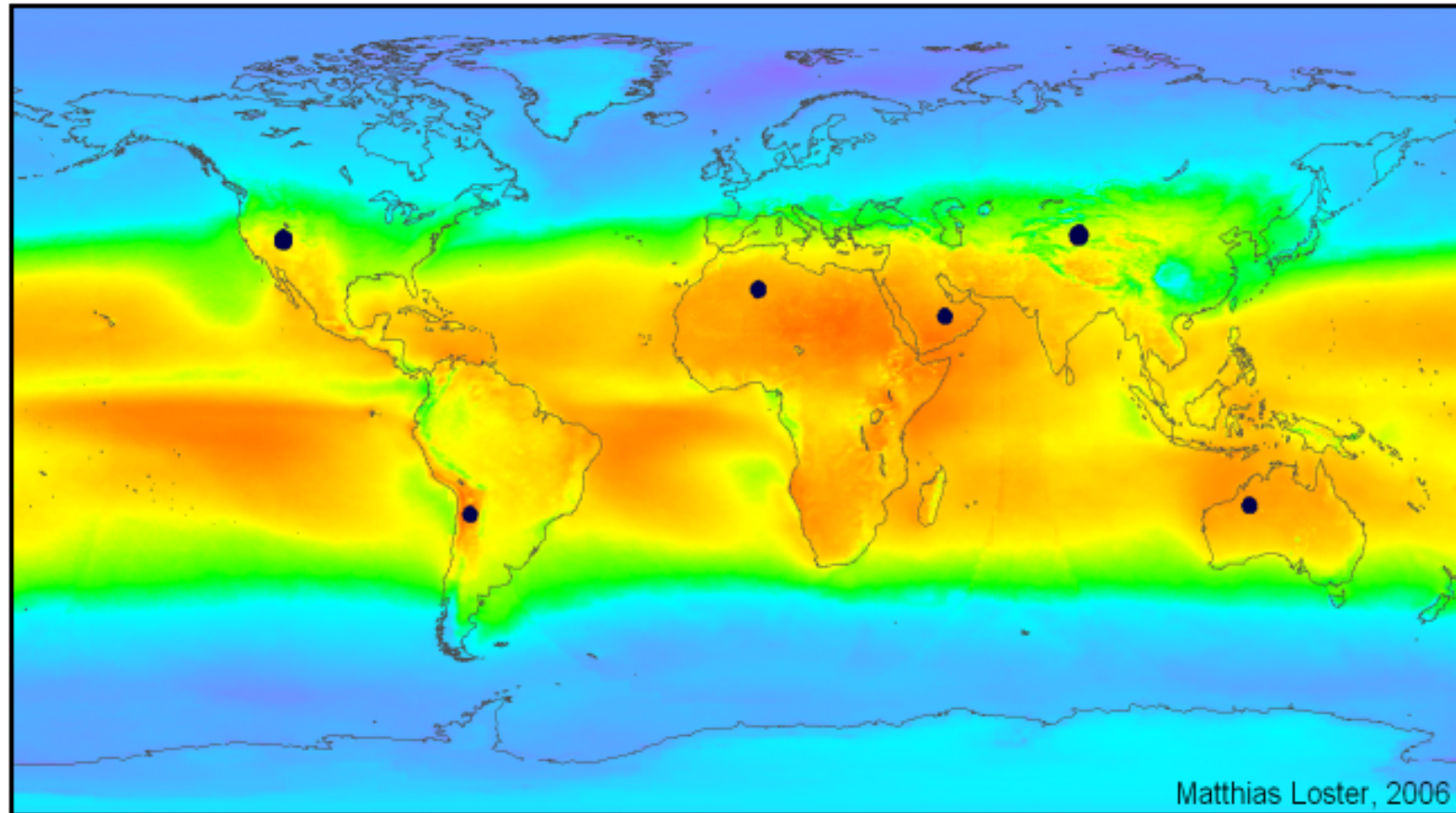
2003	6.3	Billion People
2050	8-10	Billion People

Source Richard Smalley Energy & Nanotechnology Conference
Rice University, Houston May 3, 2003



Solar energy received by the Earth within **one hour**
equals the world electricity consumption in **one year**
(30`000 TWh in 2024)

Solar irradiation



$\Sigma \bullet = 18 \text{ TWe}$

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

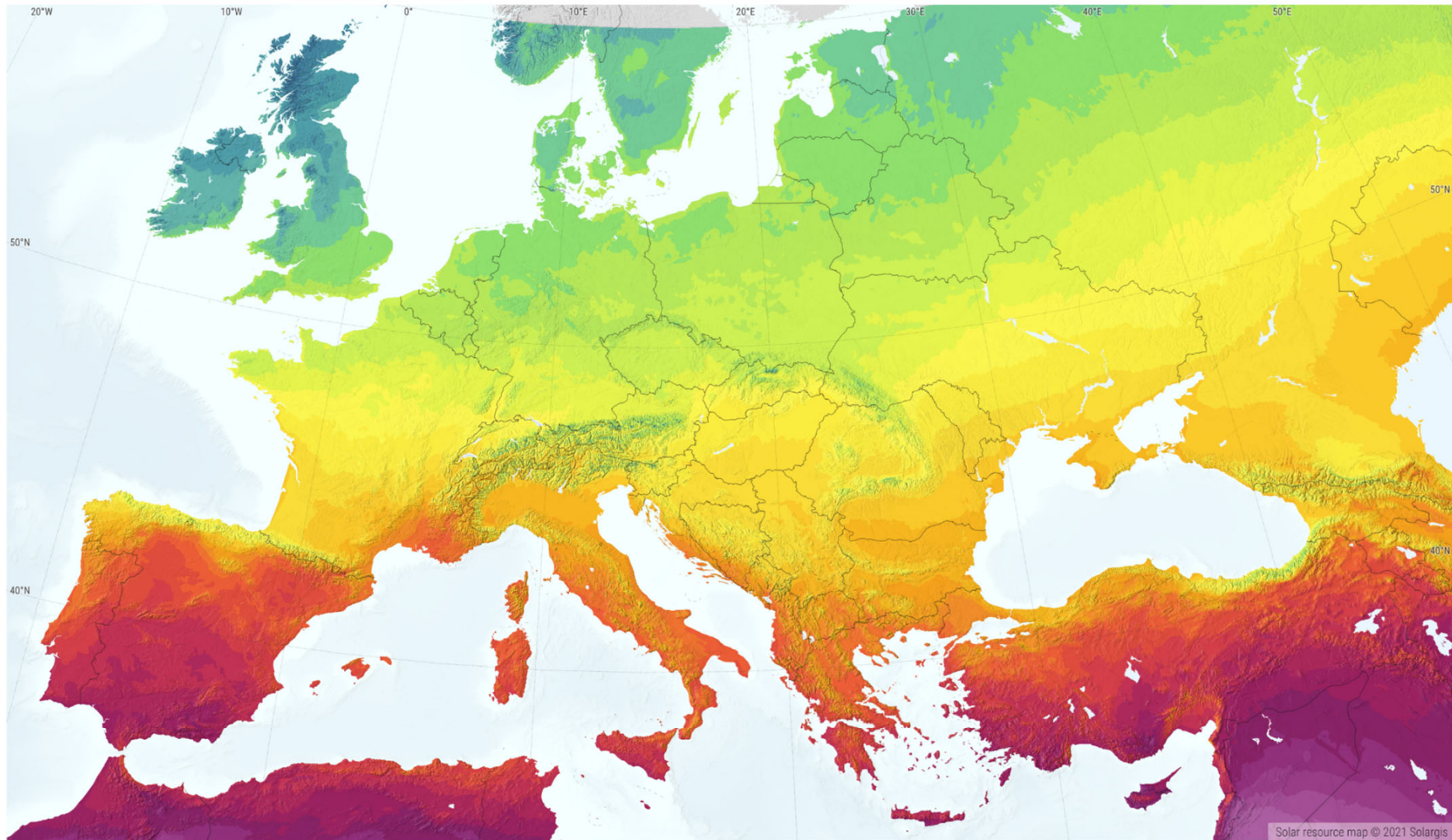
- 4% of existing desert area can provide PV power equivalent to the world energy consumption

Solar radiation in Europe

GLOBAL HORIZONTAL IRRADIATION

EUROPE

SOLARGIS



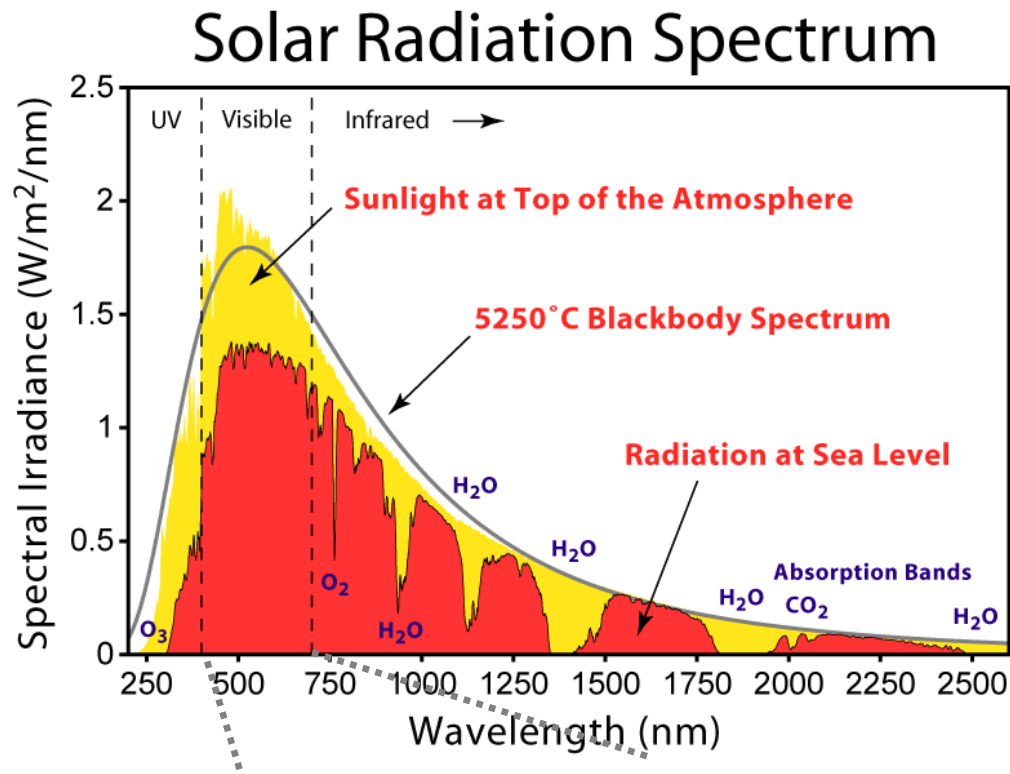
GHI: Long-term average of global horizontal irradiation, period 1994-2020 (1999-2020 in the Southeast part of this map)

Yearly totals: 800 900 1000 1100 1200 1300 1400 1500 1600 1700 1800 1900 2000 2100

Daily totals: 2.19 2.46 2.74 3.01 3.29 3.56 3.83 4.11 4.38 4.65 4.93 5.20 5.48 5.75 kWh/m²

This map is licensed by Solargis under the Creative Commons Attribution license (CC BY-SA 4.0). You are encouraged to use content of the map to benefit yourself and others in creative ways. For more information, please visit <http://solargis.com/download>.

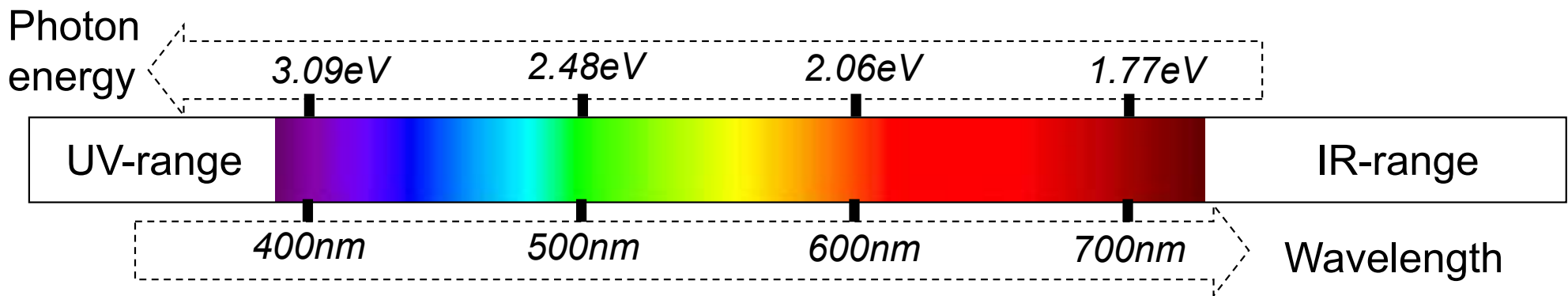
Solar radiation



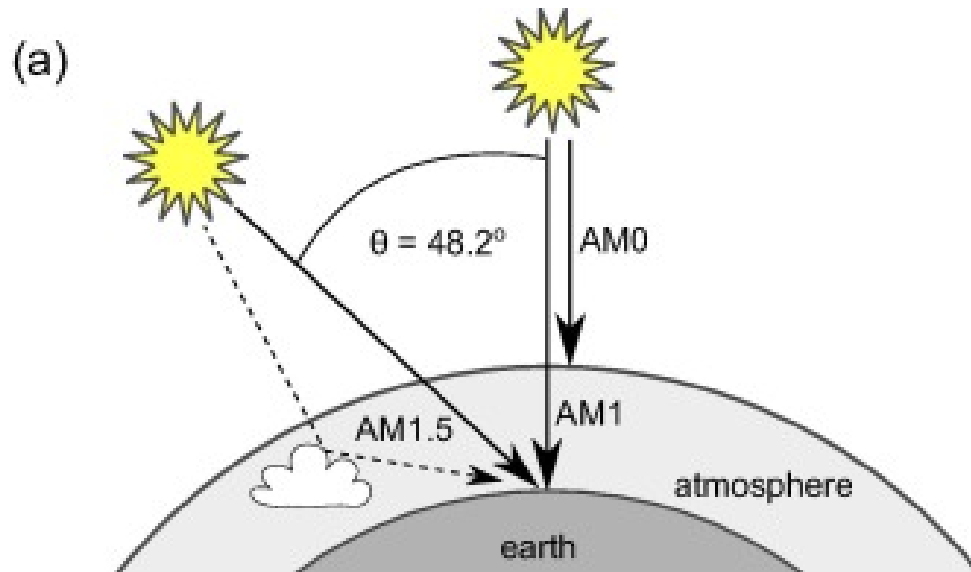
$$\text{Photon Energy} = h\nu = \frac{hc}{\lambda}$$

ν – frequency, λ - wavelength
 h = Planck constant = 6.6×10^{-34} J s
 c = speed of light = 3×10^8 m s⁻¹

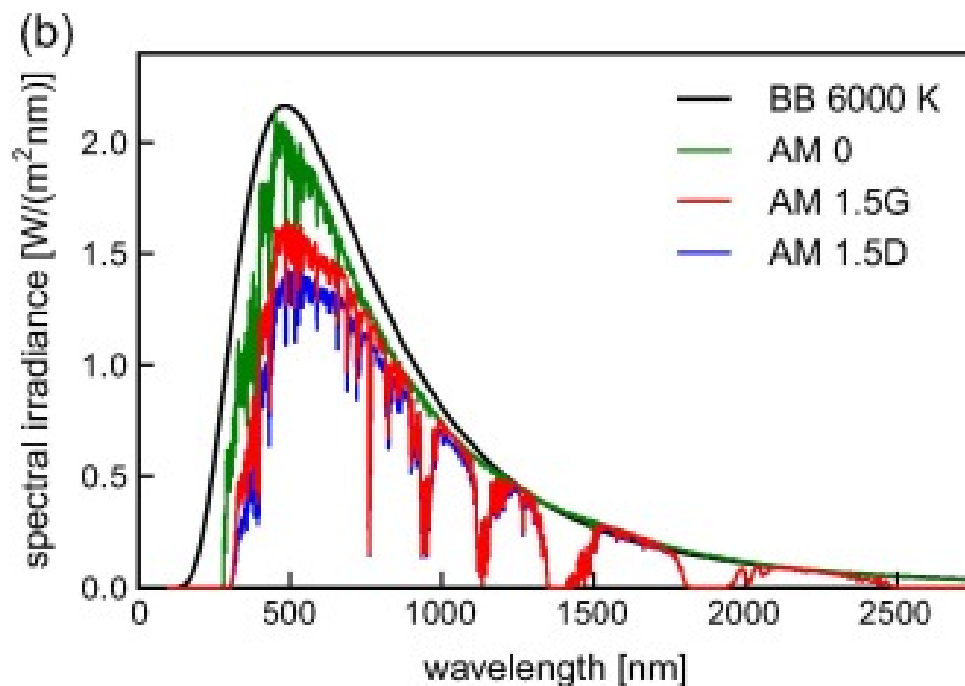
$$E_{\text{photon}} [\text{eV}] = \frac{1240}{\lambda [\text{nm}]}$$



Air mass (AM) coefficient



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



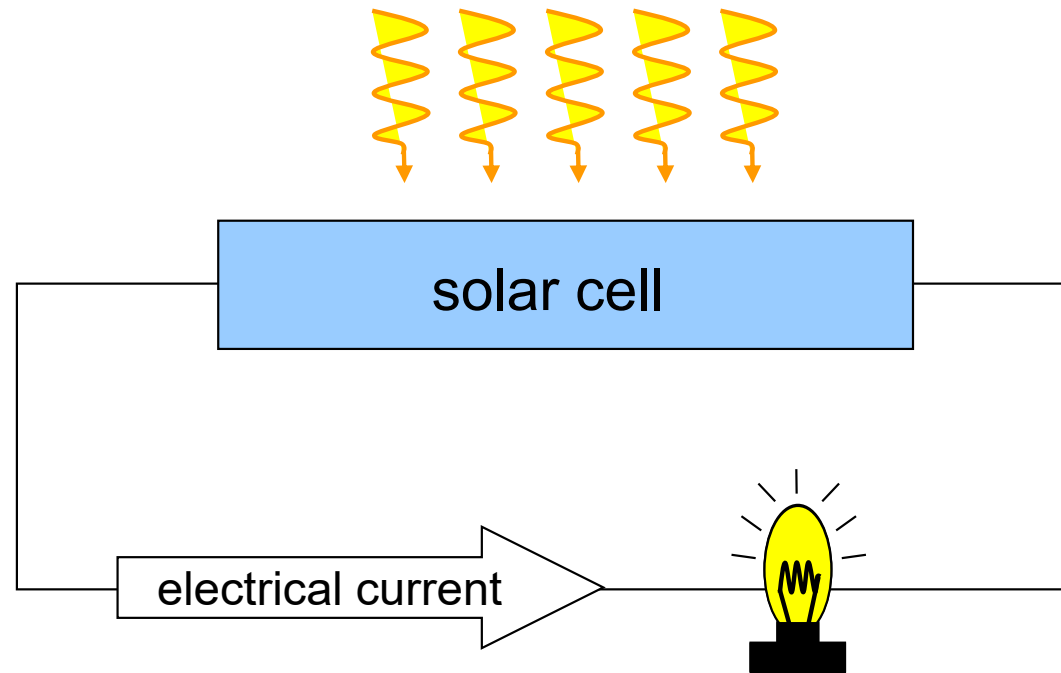
Black body: spectrum at 6000 K

AM 0 spectrum: outside Earth atmosphere

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

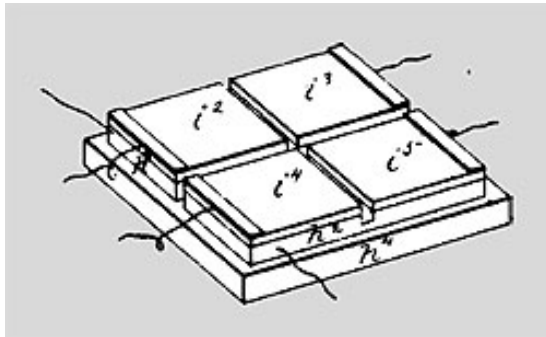
AM 1.5D (direct only)

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

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%



Vanguard 1, 1958-1964

1958 PV-powered satellite Vanguard 1 (US)

1973 World energy crisis

1989 1`000 rooftops in Germany

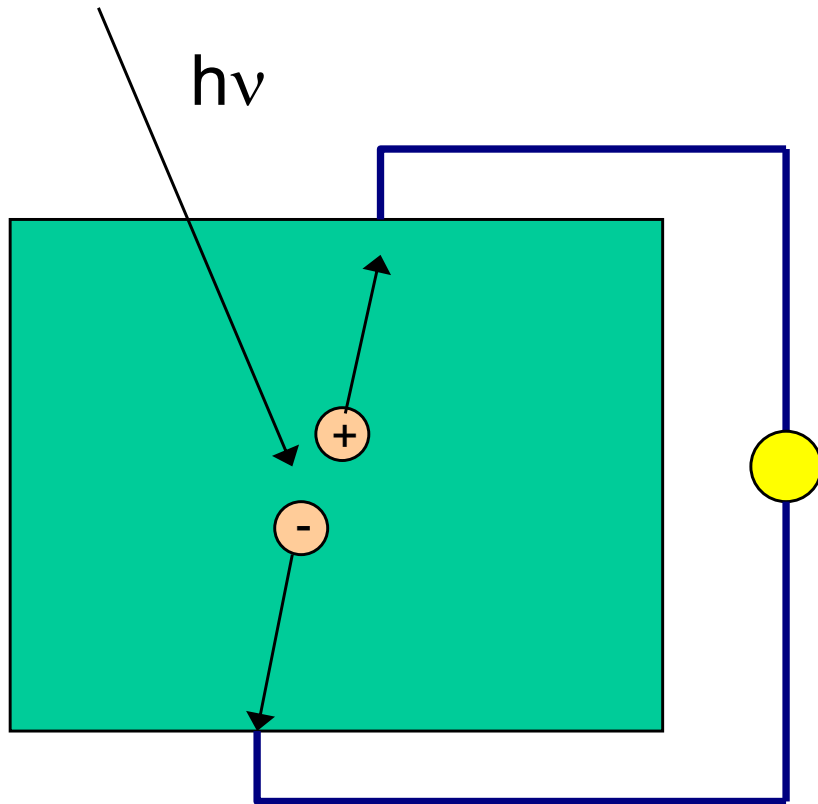
1997 100`000 rooftops in Germany

2011 Fukushima disaster,
Swiss Energy Strategy 2050



Semiconductor physics

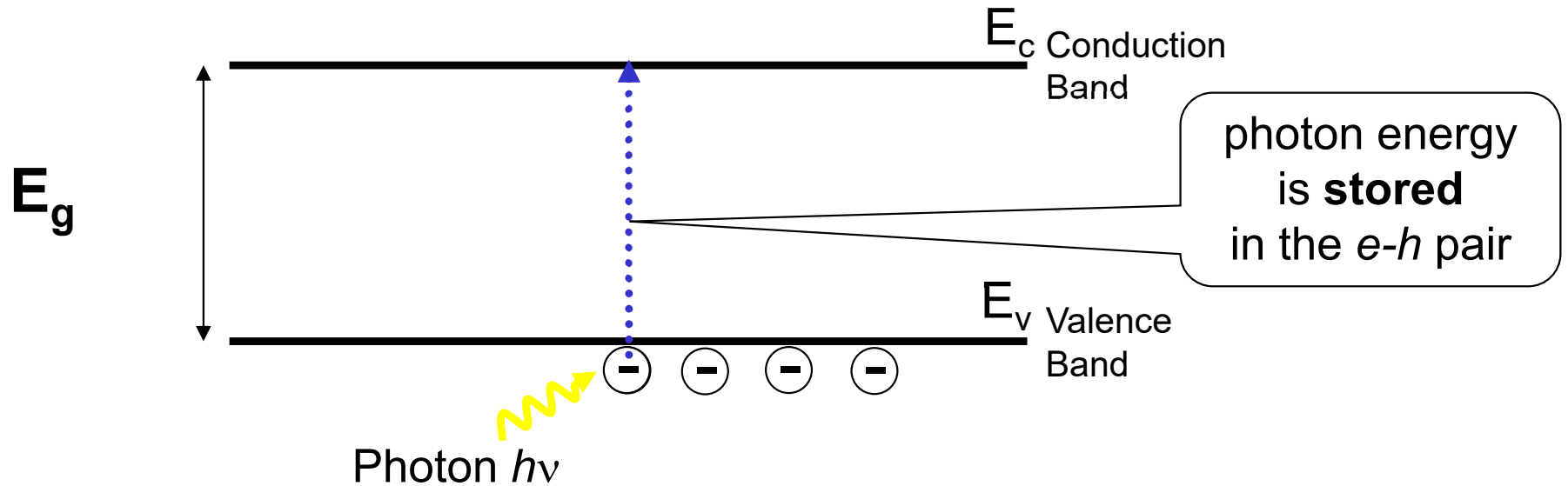
Solar cell and photovoltaic effect



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 \Rightarrow Generation of electron-hole pair

Band gap determines absorption:

Only photons with energy larger than band gap can generate e-h pair:

\Rightarrow semiconductor absorbs if $l \leq l_c$

\Rightarrow semiconductor is transparent to $l \geq l_c$

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

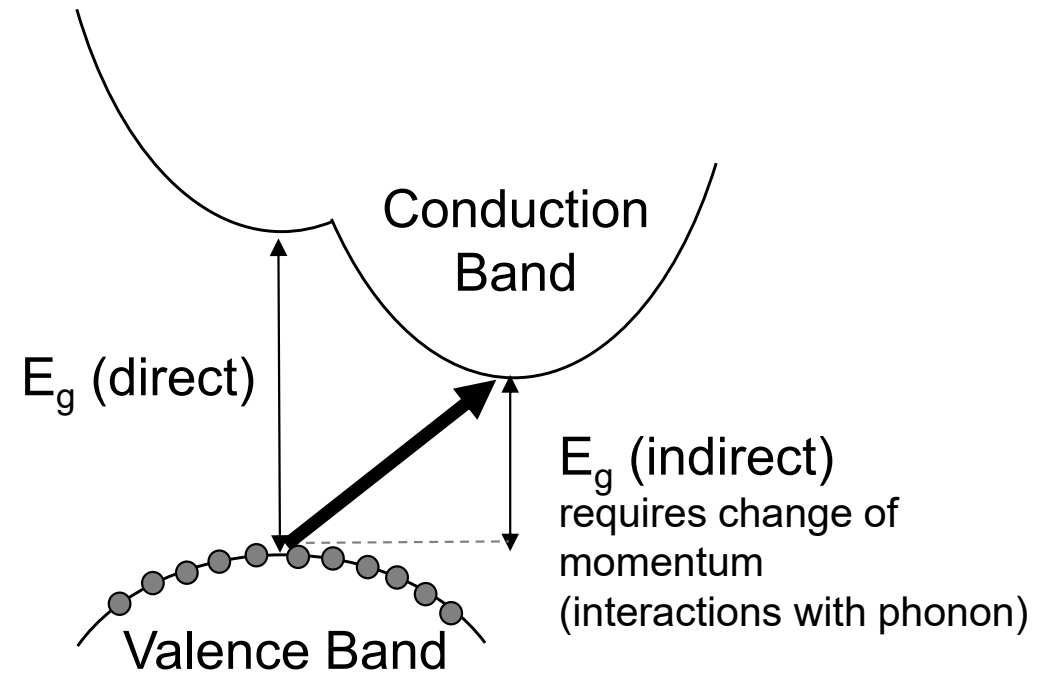
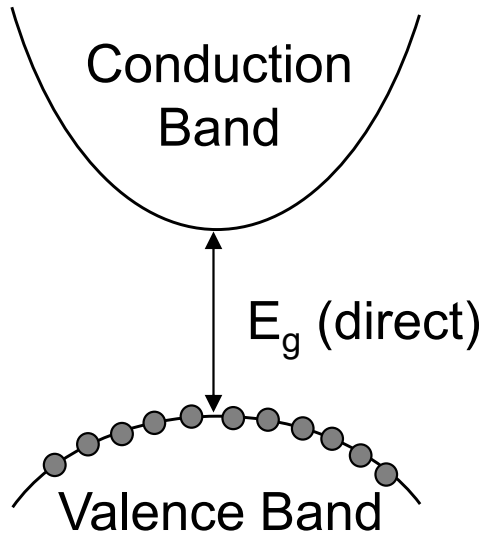
ν_c = cut off frequency

λ_c = cut off wavelength

Direct vs Indirect bandgap

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

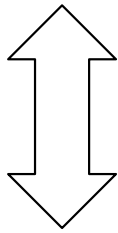
E_g (Si) = 1.12eV
indirect gap (weak)



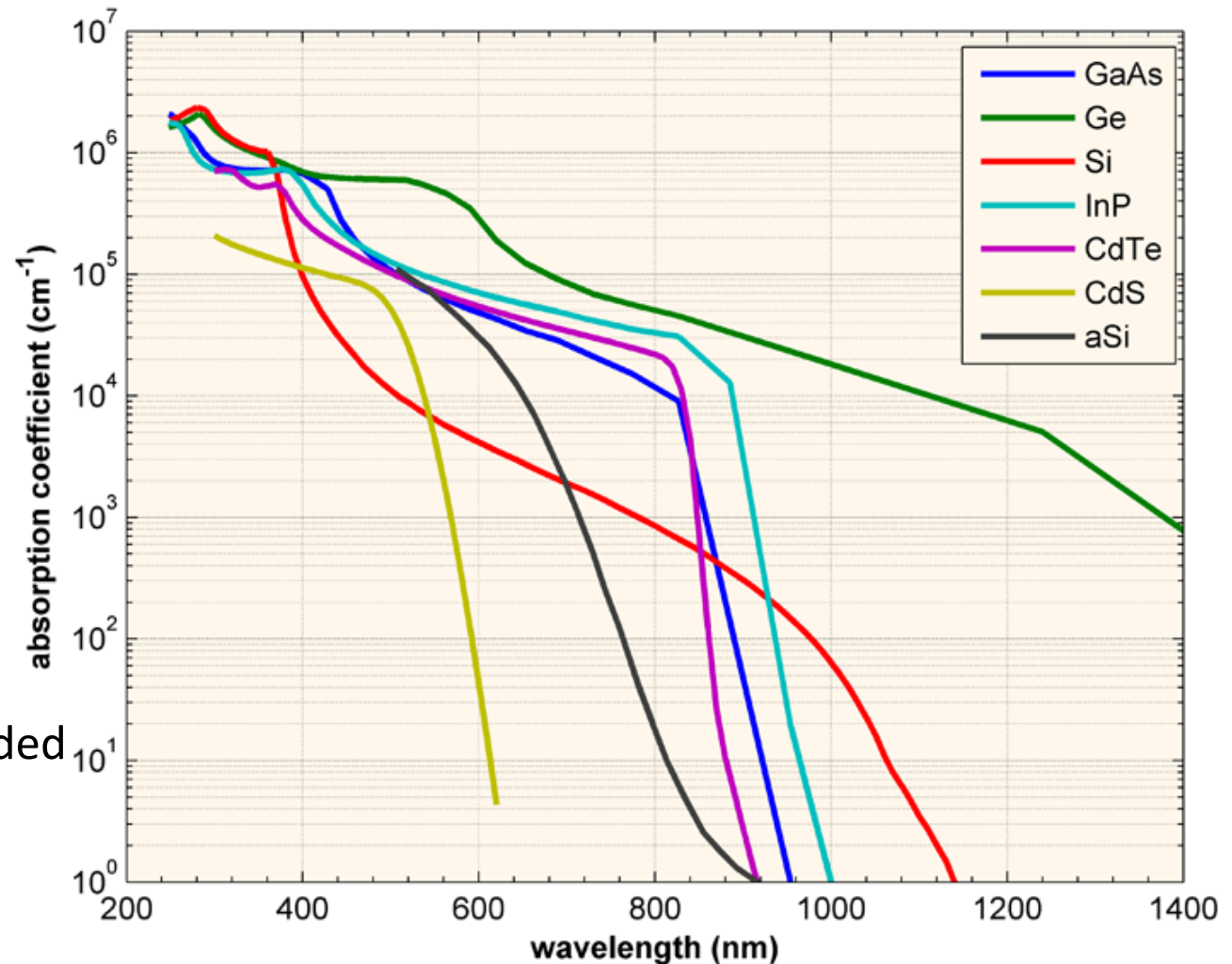
k -vector
(momentum direction)

Light absorption in semiconductors

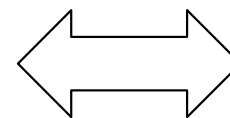
Direct bandgap
(GaAs, CdTe, a-Si):
⇒ thin layer of 1-2 μm
enough for absorption



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

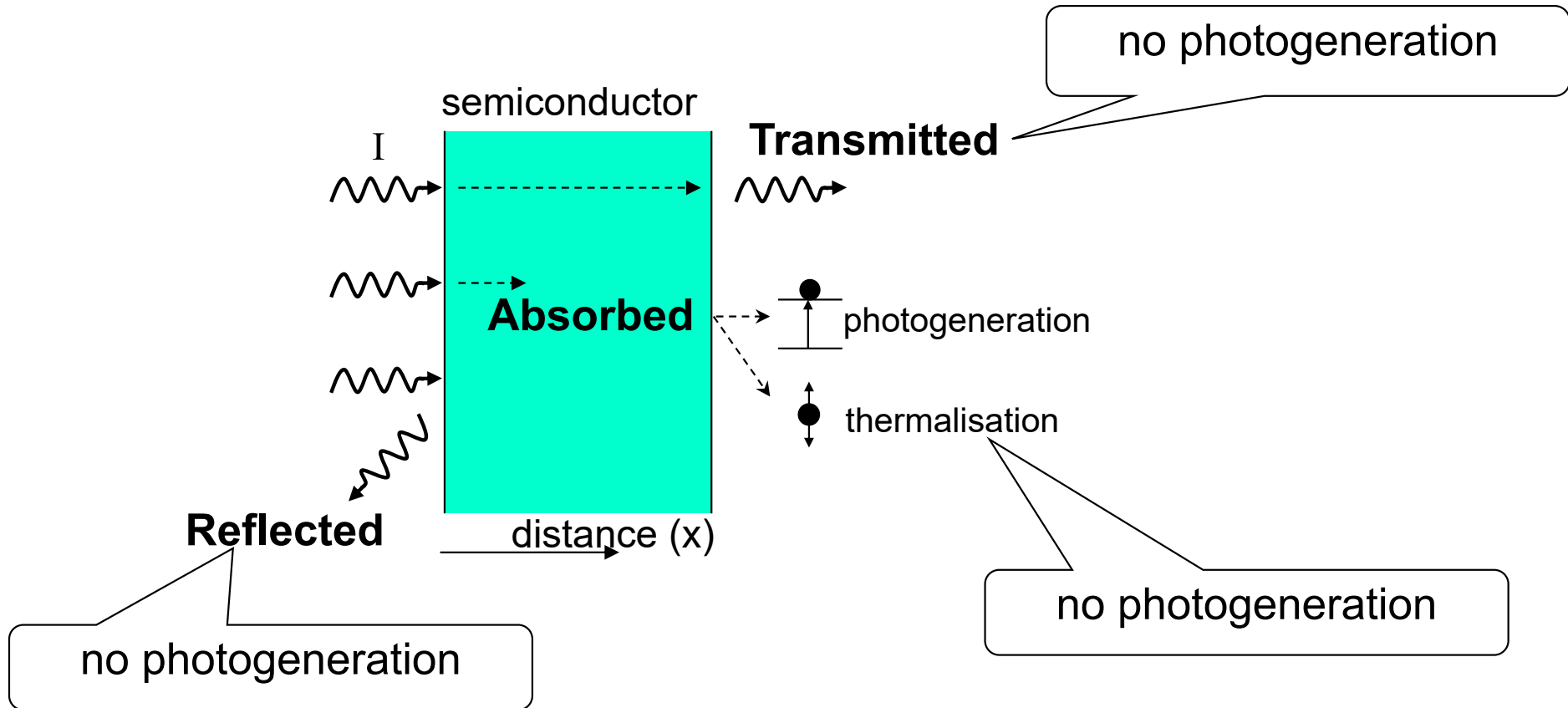


Wide bandgap (a-Si, CdTe):
⇒ better response for
«blue» photons



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

Optical Absorption



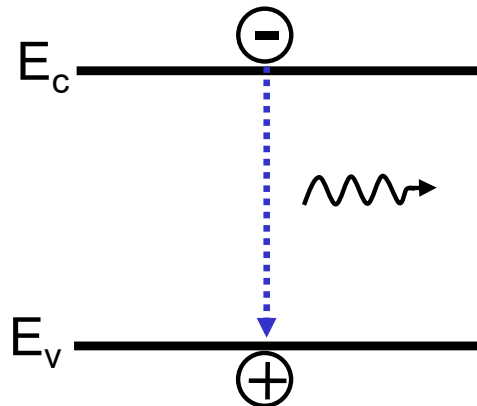
Reflection: R (%)

Transmission: T (%)

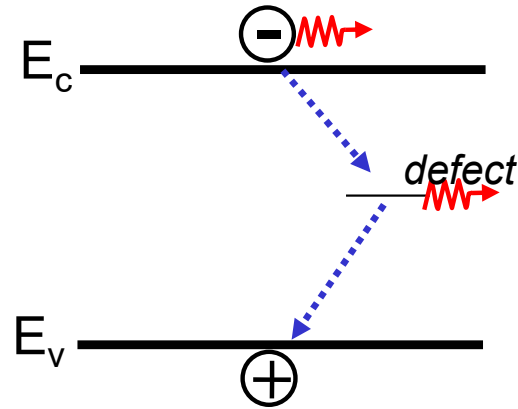
Absorption: absorption coefficient α (cm^{-1})

Recombination

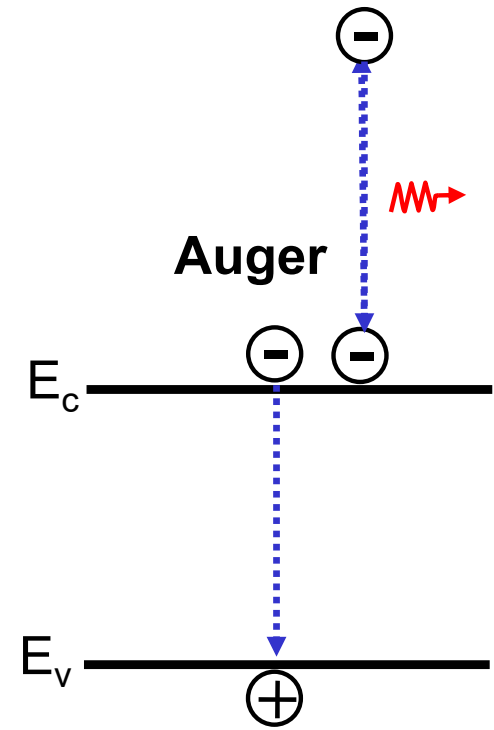
Radiative (emit photon)



Non-radiative (via defects)



Auger



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**

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 (m²/s)

τ – carrier lifetime (s)

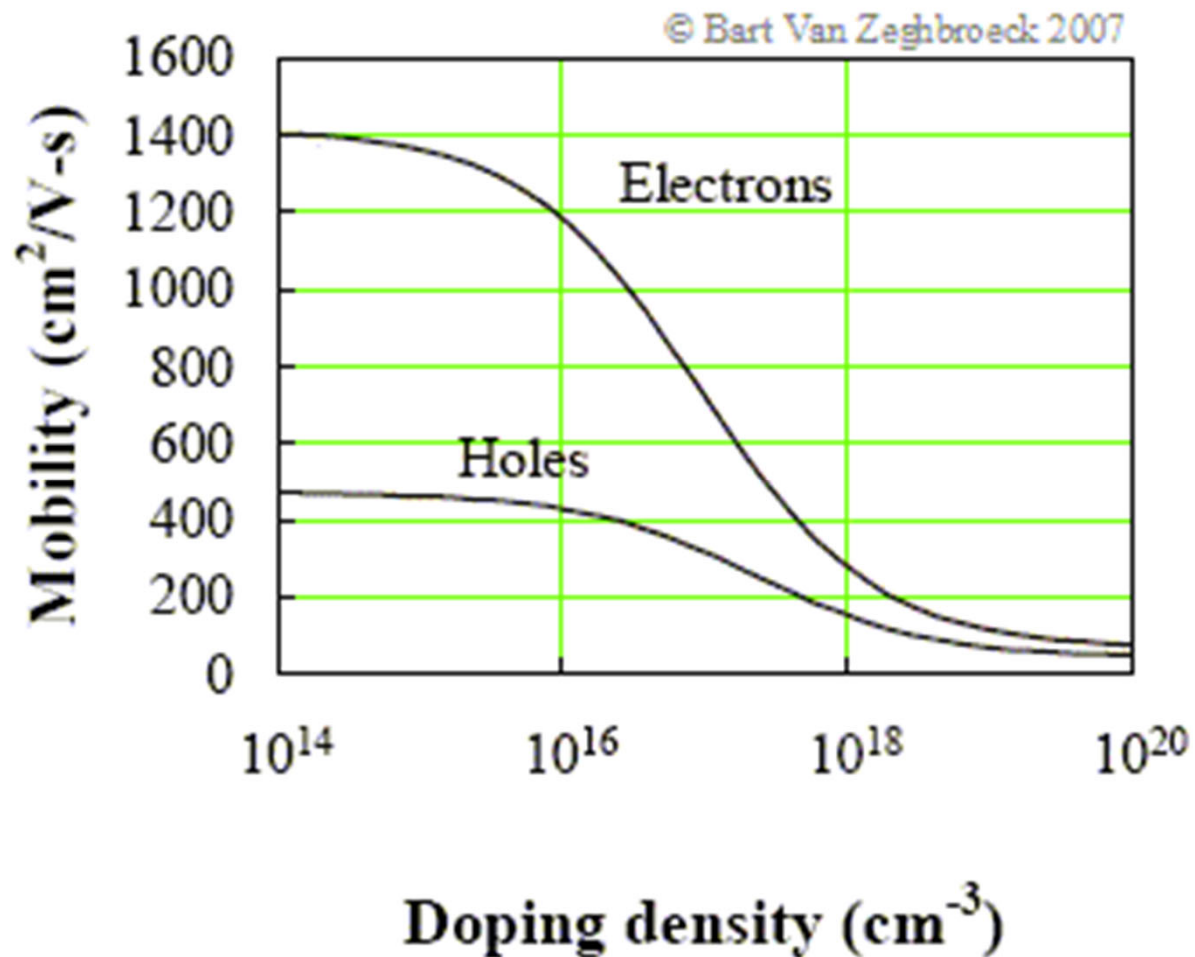
Carrier mobility

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

μ – carrier mobility ($\text{m}^2/(\text{Vs})$)

v_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

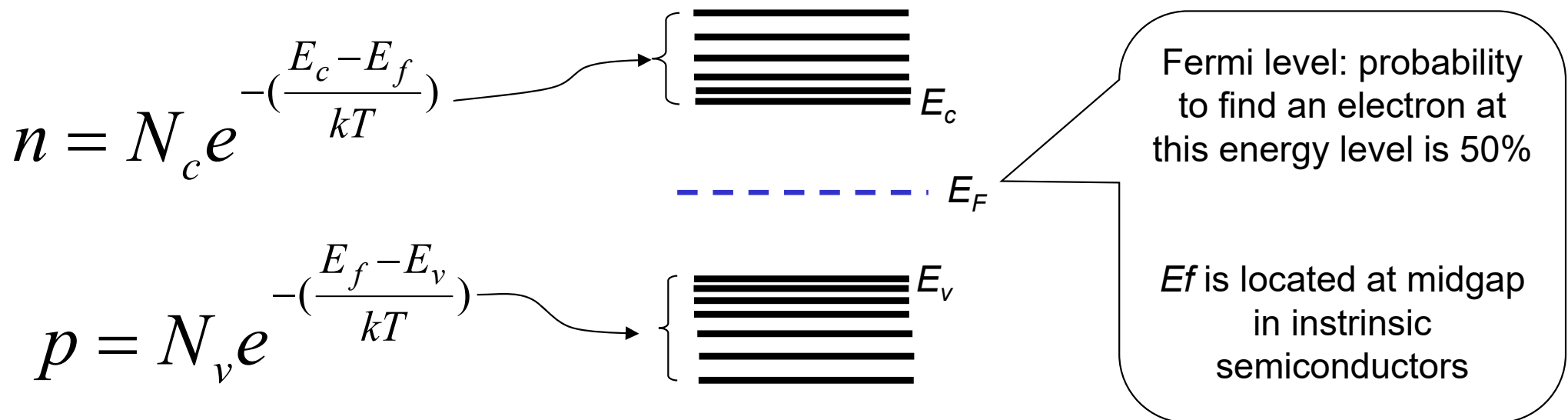
$$n = p = n_i$$

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

N_c and N_v are the *effective densities of states*

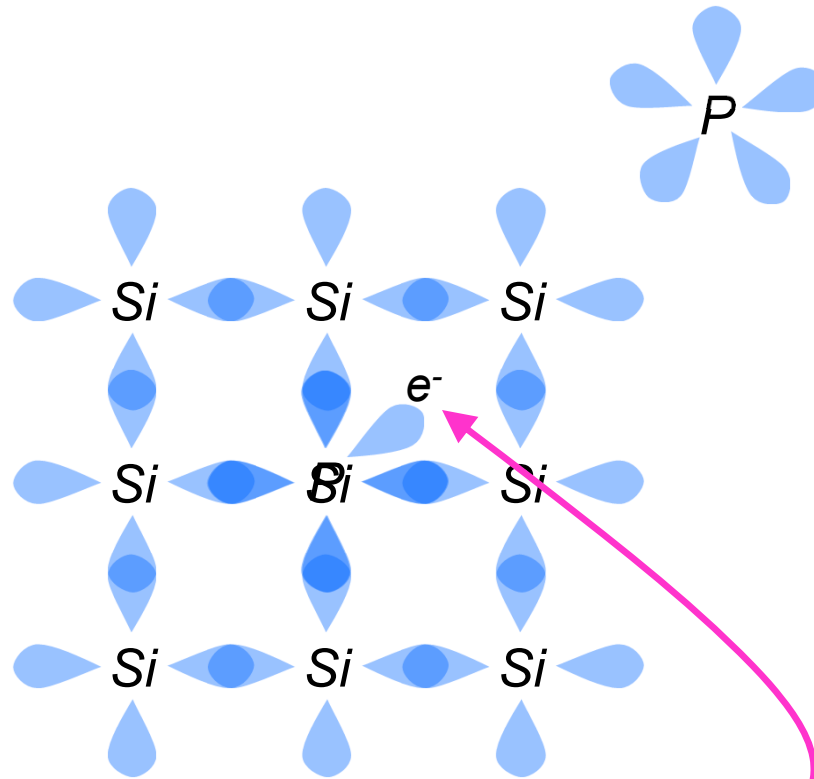
k is Boltzmanns constant ($1.38 \times 10^{-23} \text{ J K}^{-1}$)

Carrier concentrations in equilibrium related to the band edges:



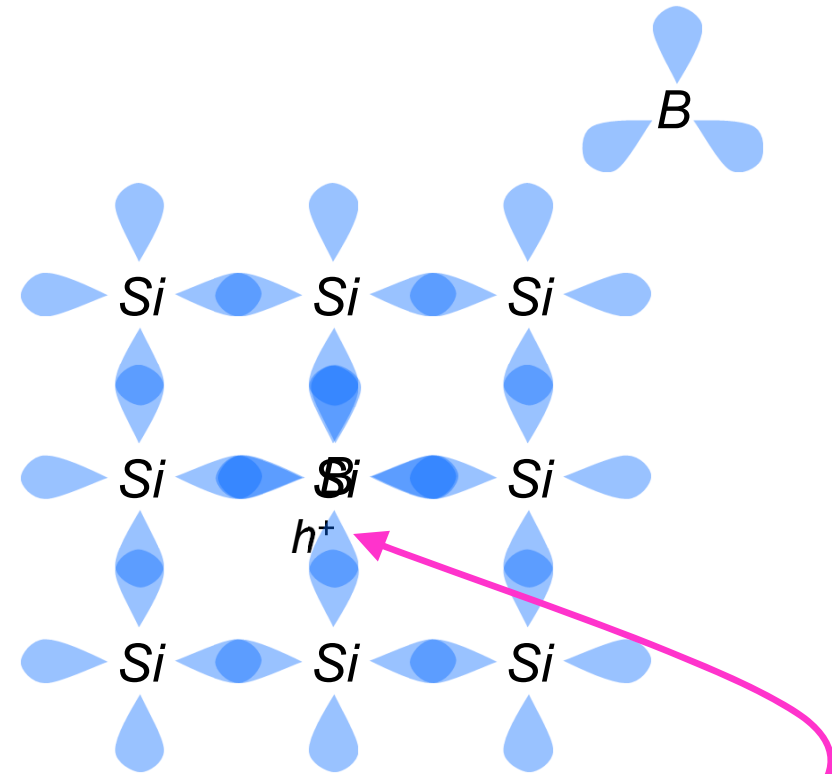
Doping of semiconductors (e.g. Silicon)

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



One electron per donor atom
 \Rightarrow **n-type doping**

Boron (B)
3 outer electrons vs Si's 4



One hole per acceptor atom
 \Rightarrow **p-type doping**

Doping of semiconductors

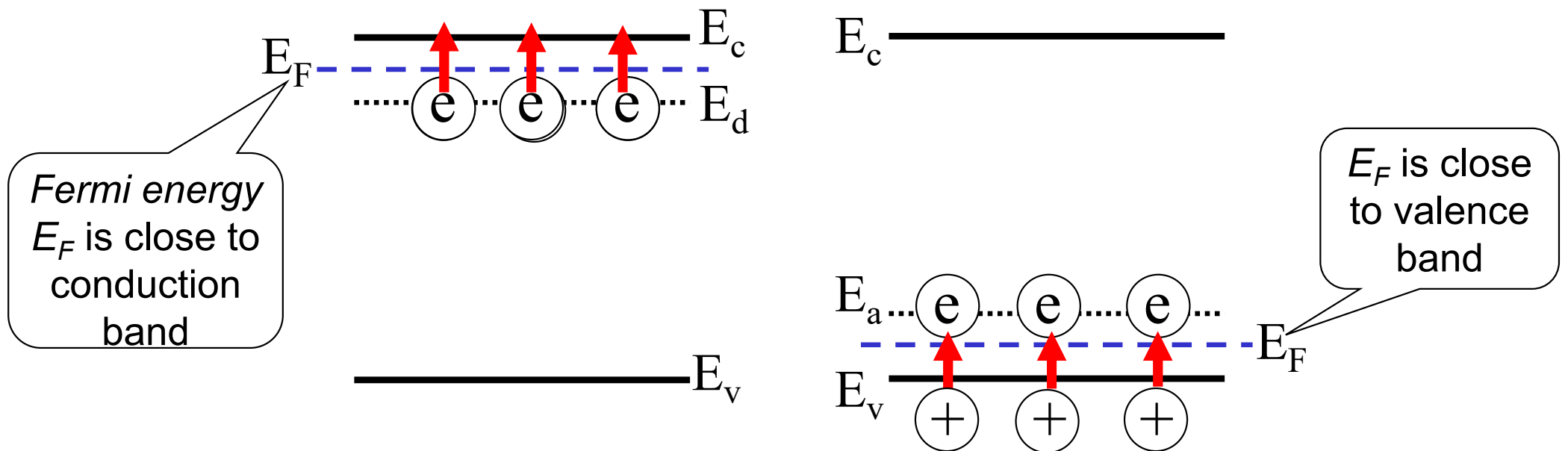
- Undoped (intrinsic) semiconductors have low conductivity because the concentration of free (mobile) charge carriers is very low.
- Doping with impurities can add free (mobile) electrons or holes:

Donors \Rightarrow donate electrons

Acceptors \Rightarrow accept electrons

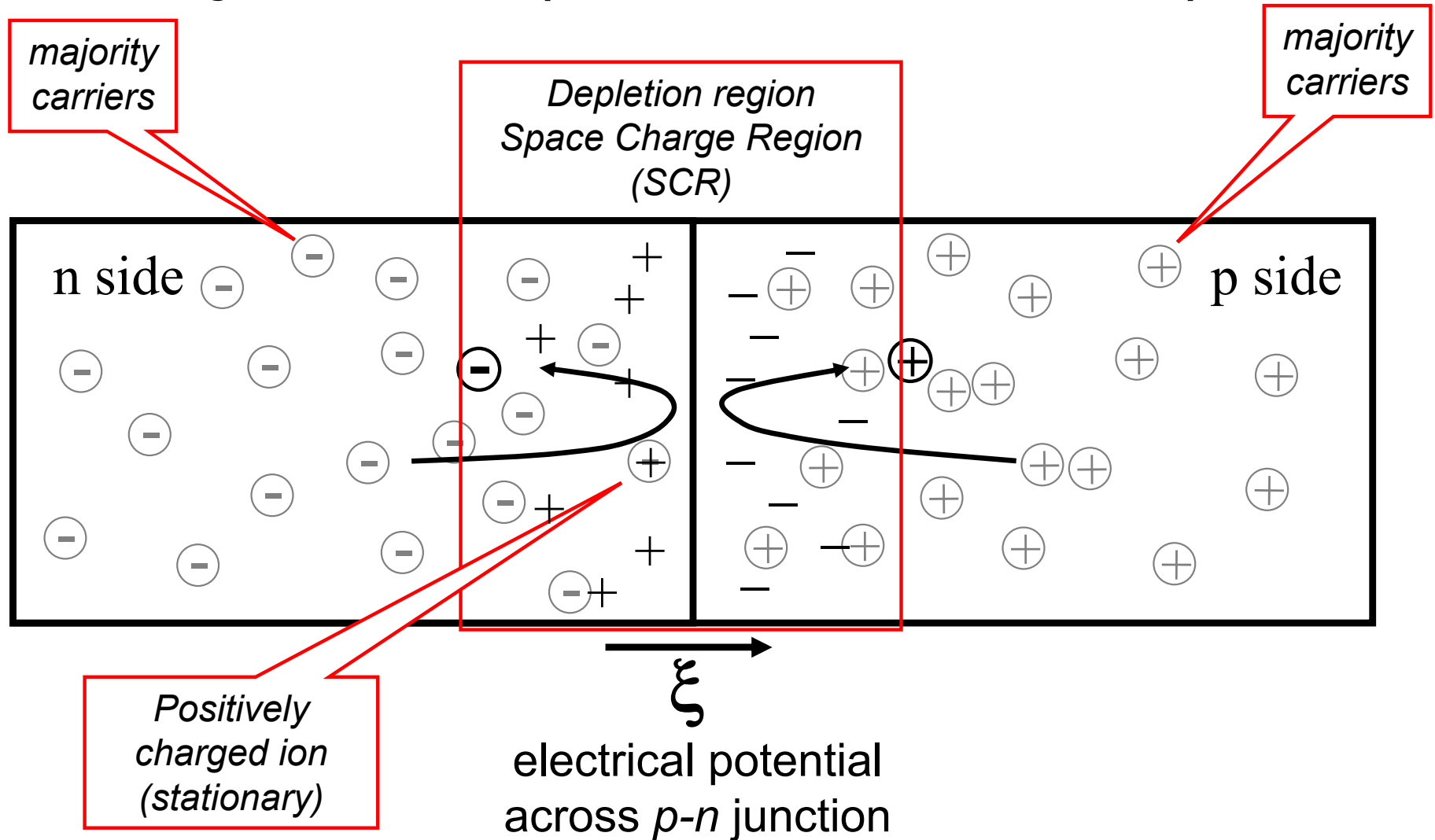
n-type

p-type



thermal energy ($\sim kT$) is sufficient to "activate" the carriers

The p - n junction (microscopic view)



p - n junction provides charge separation

Built-in Voltage & Depletion Width

Built in voltage V_{bi}

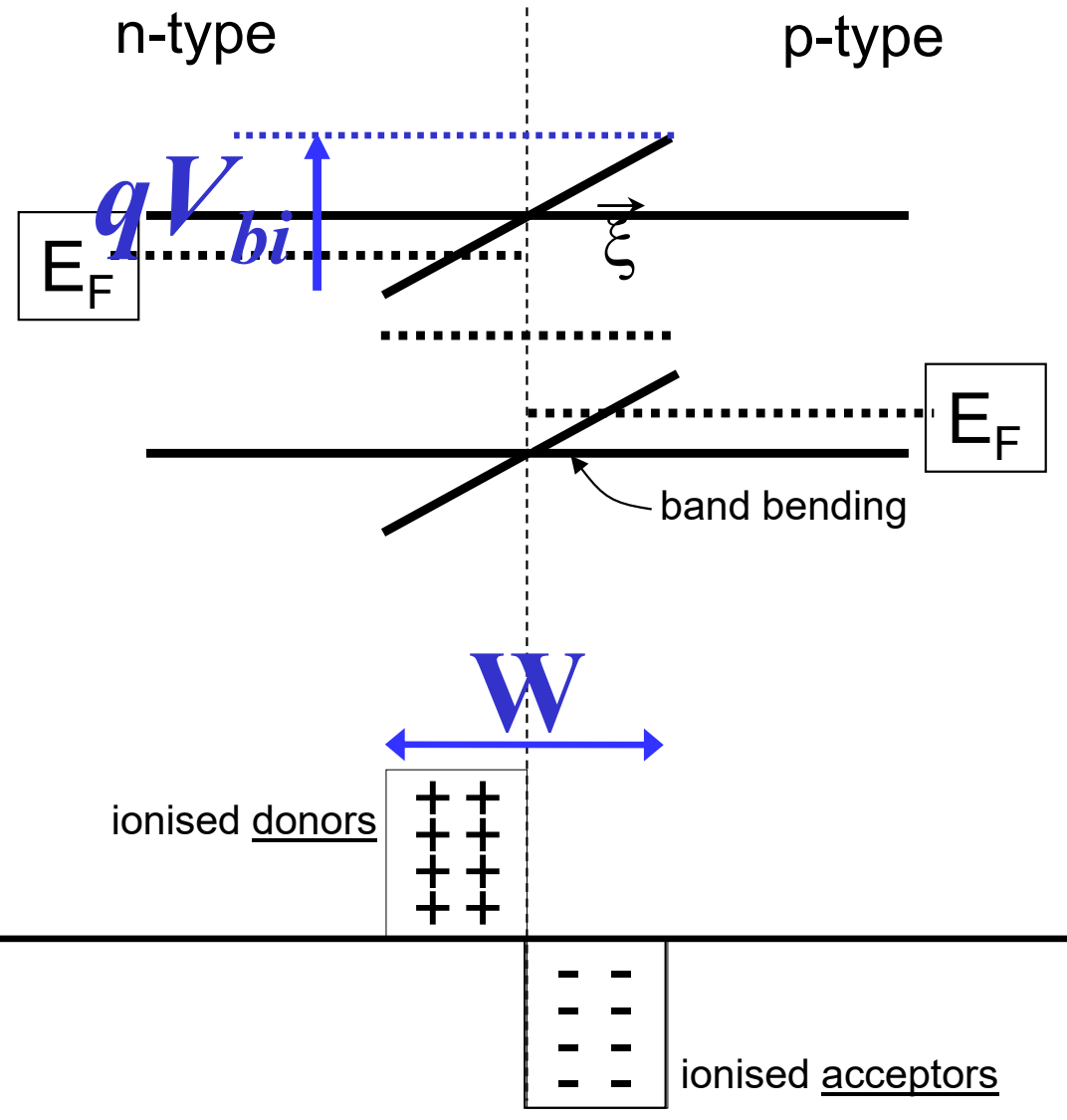
$$qV_{bi} \approx kT \ln\left(\frac{N_a N_d}{n_i^2}\right)$$

N_a, N_d – concentration of acceptors (donors)
 n_i – intrinsic carrier concentration

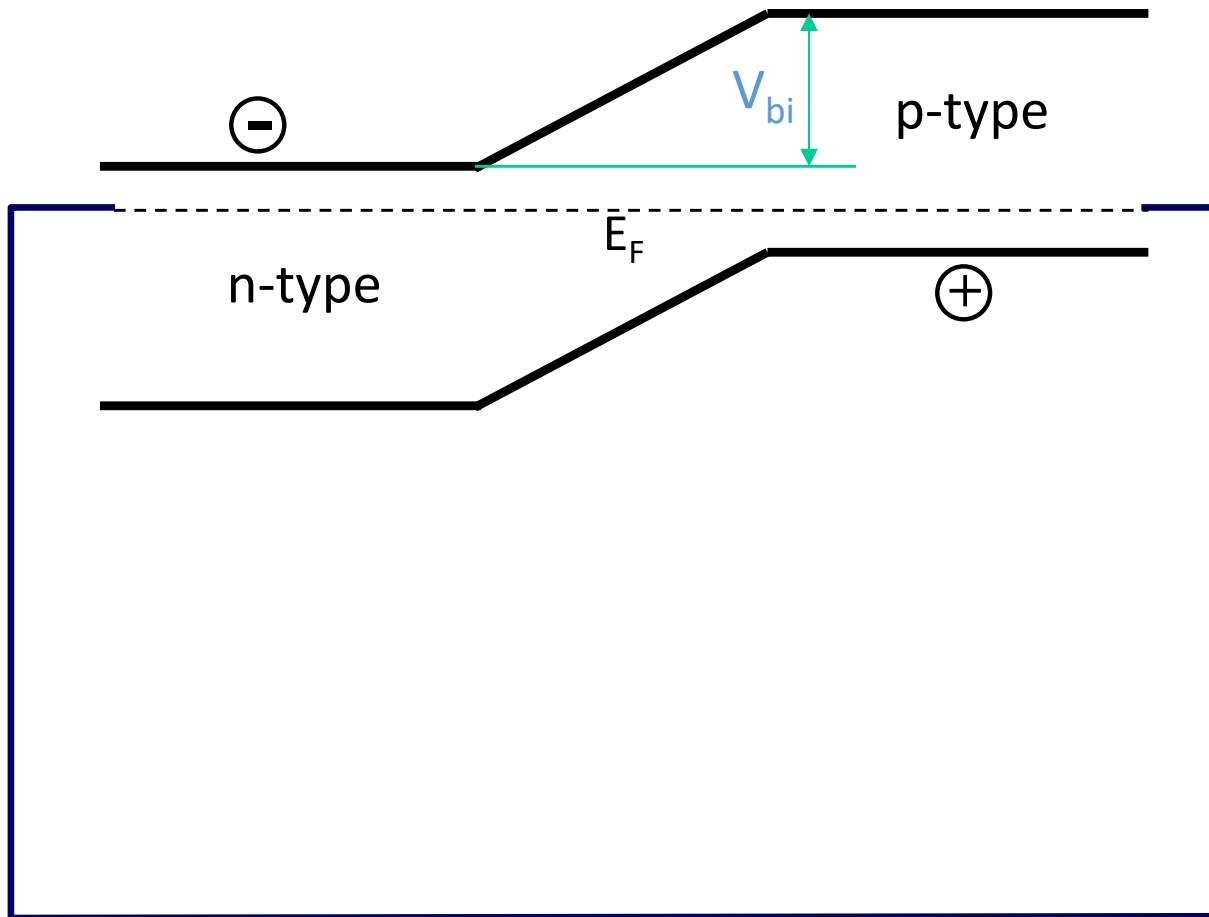
Depletion width W

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

ϵ – dielectric constant

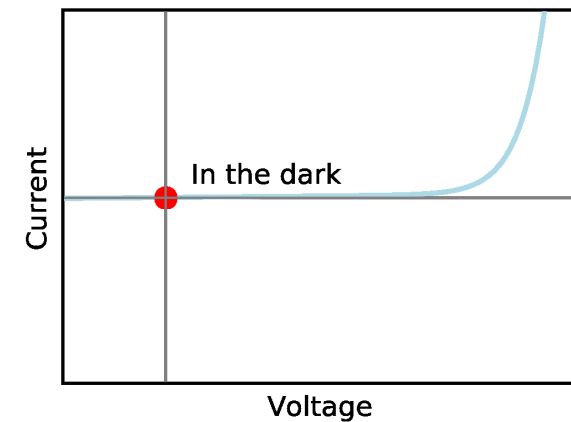


p - n junction in dark (no illumination)

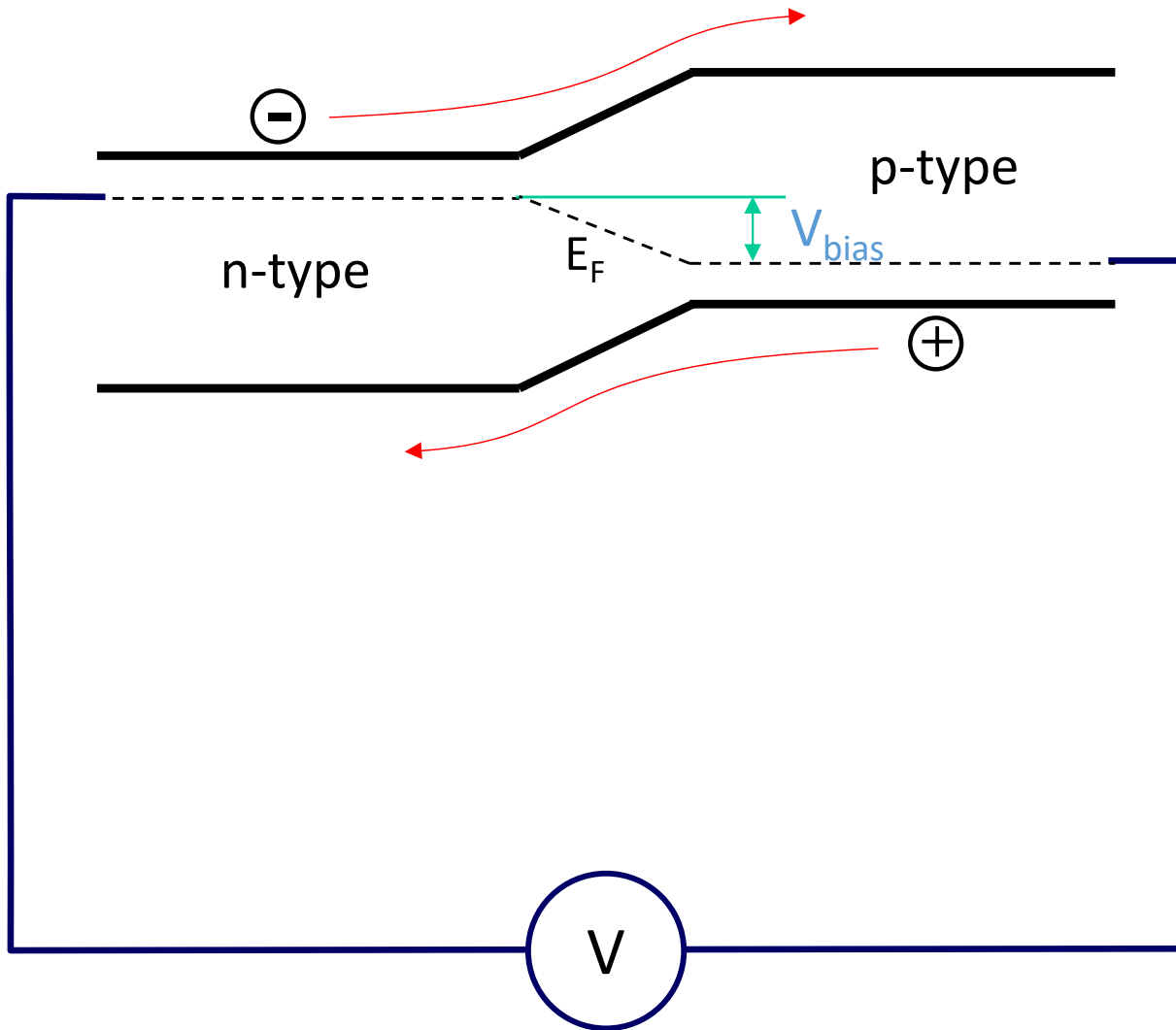


Under short-circuit:

- Equilibrium: $J_{\text{drift}} = J_{\text{diffusion}}$ across the junction
- Fermi level E_F is flat

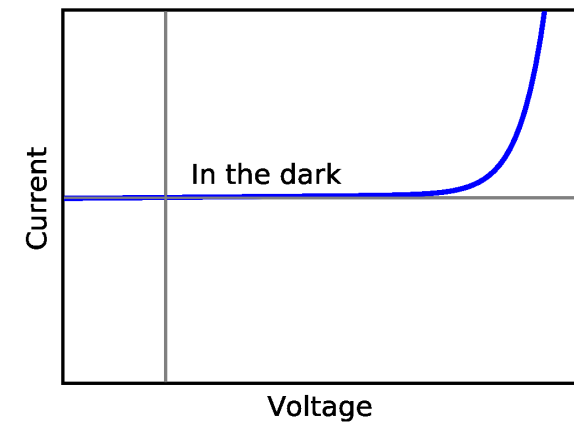


p - n junction in dark under bias

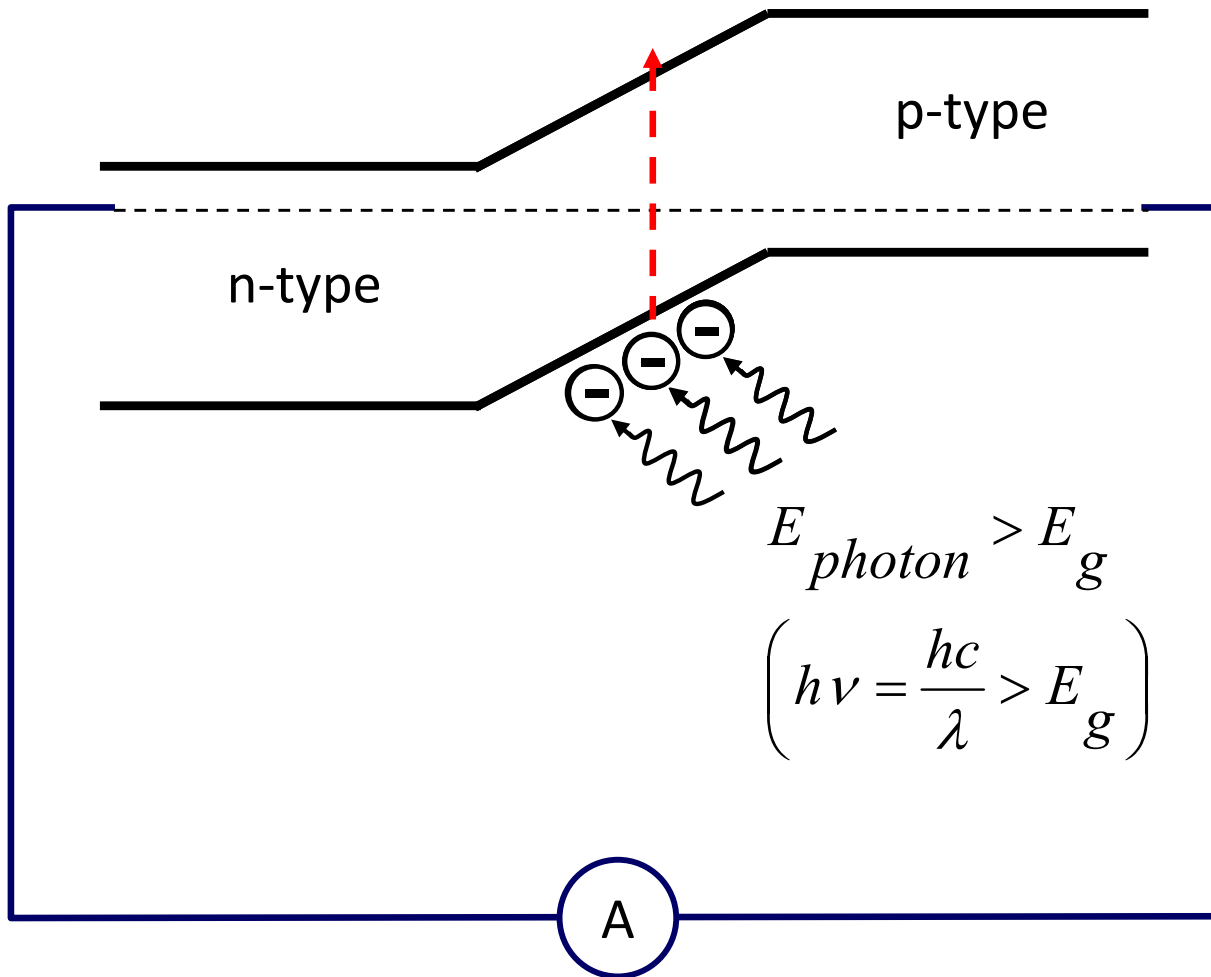


Under forward bias:

- V_{bias} lowers E_F on p-side
- $J_{diffusion}$ increases
- Diode “opens” once $V_{bias} > V_{built-in}$

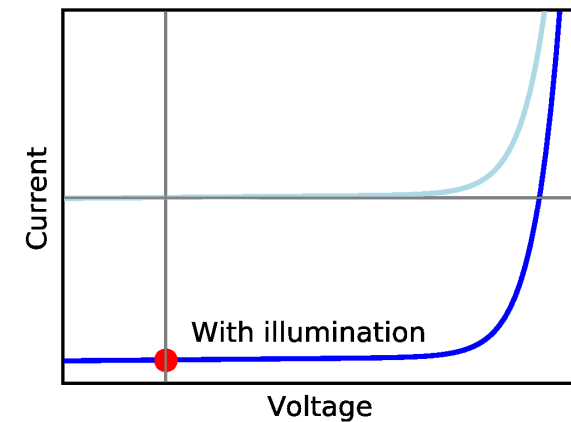


p-n junction under illumination

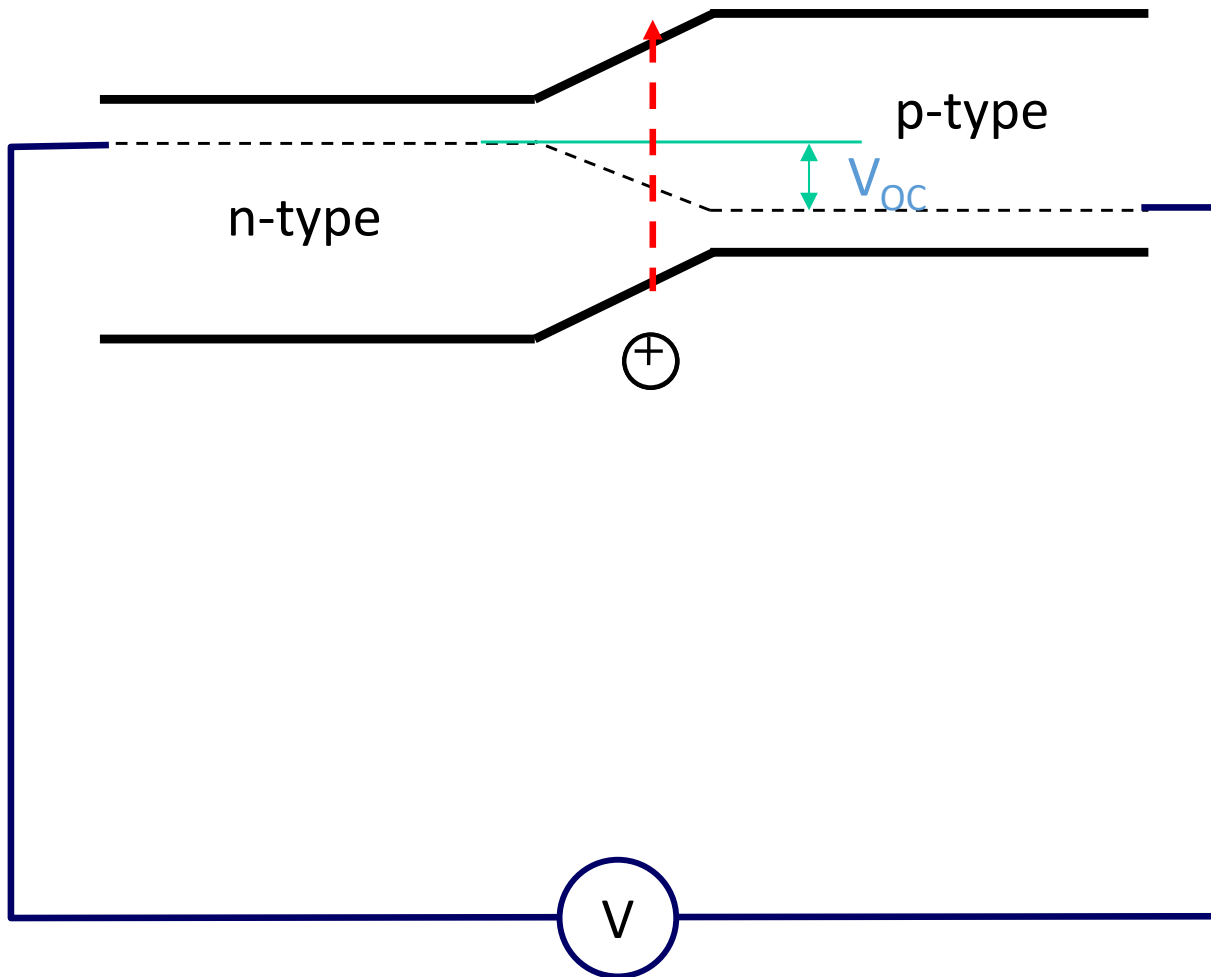


Short-circuit condition:

- Photogenerated current flows via external circuit
- Maximum current $J_{\text{SC}} = J_{\text{photo}}$
- Voltage is zero

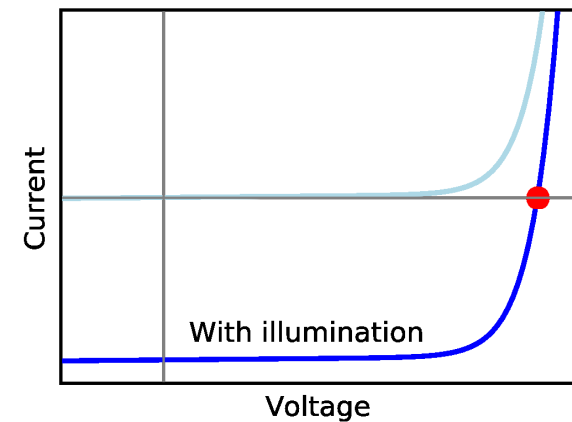


p-n junction under illumination



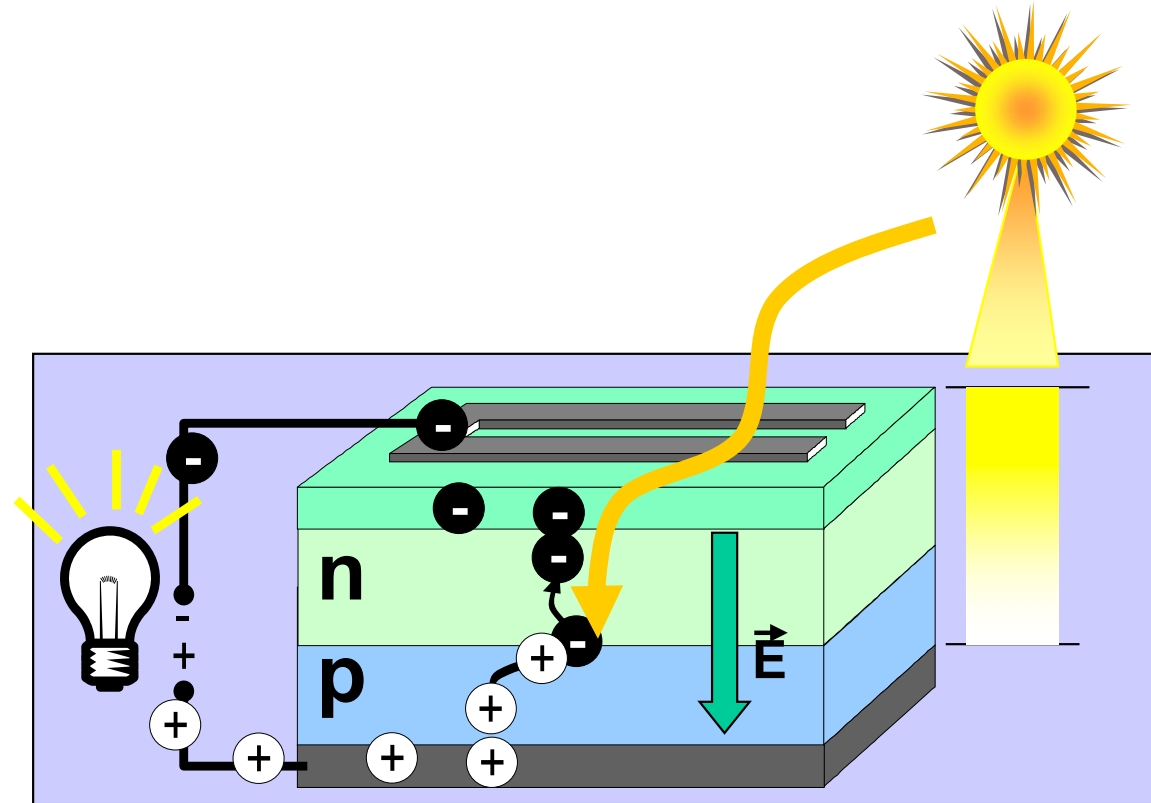
Open circuit condition:

- no current via external ($J=0$)
- J_{drift} , $J_{diffusion}$, J_{photo} compensate
- Photogenerated charges accumulate on opposite sides => voltage build-up (V_{oc})



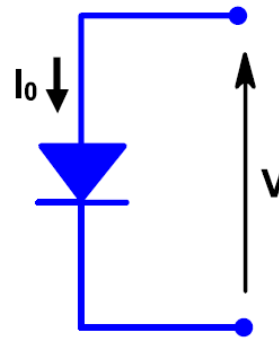
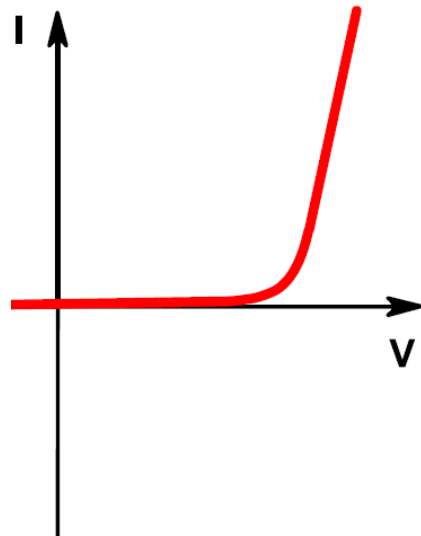
Solar cell parameters

Operation of p-n junction solar cell



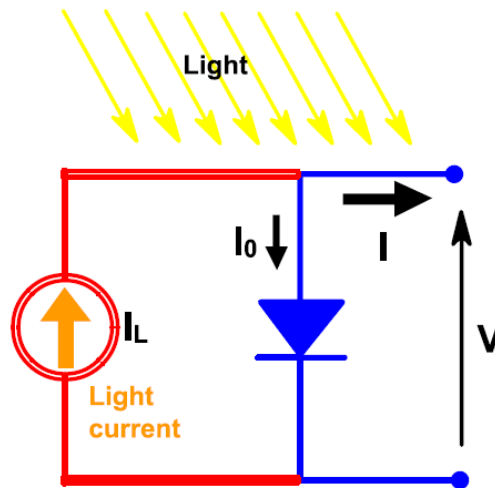
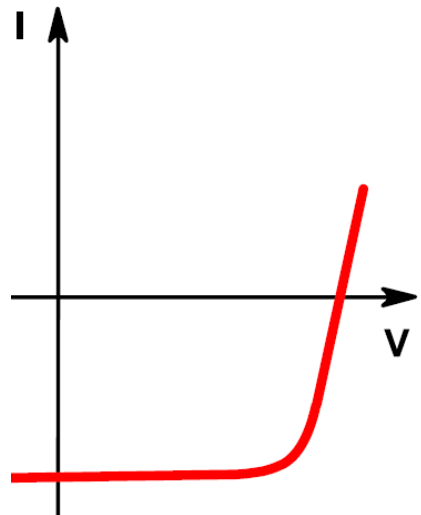
1. Light absorption
2. Generation of free mobile carriers
3. Separation of the free carriers

Effect of light on I-V curve



Without illumination, a solar cell acts like a diode

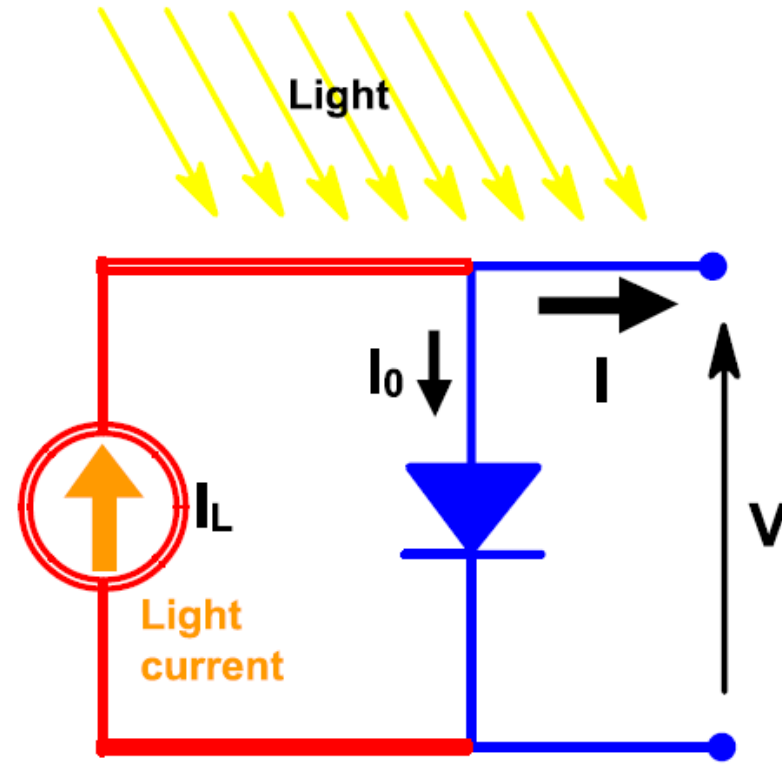
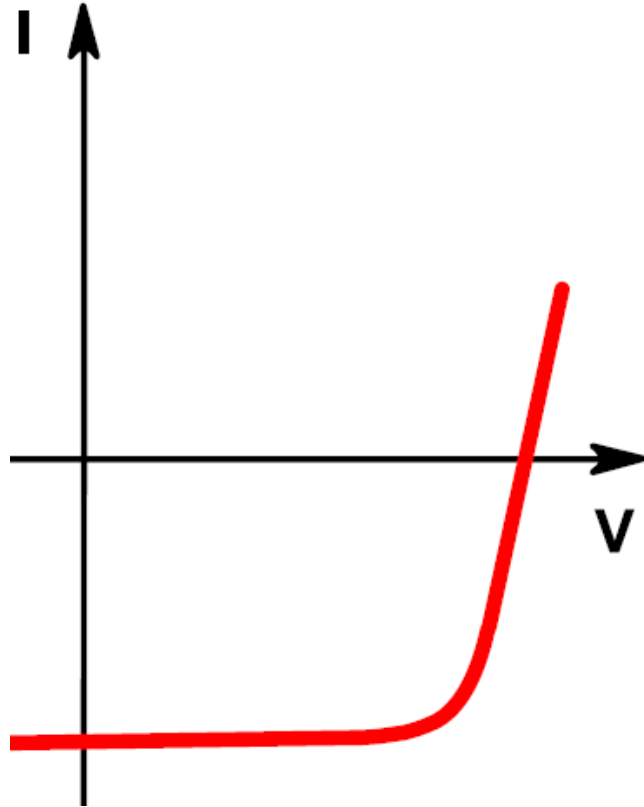
=> I-V curve is identical



Under illumination, solar cell produces photocurrent

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

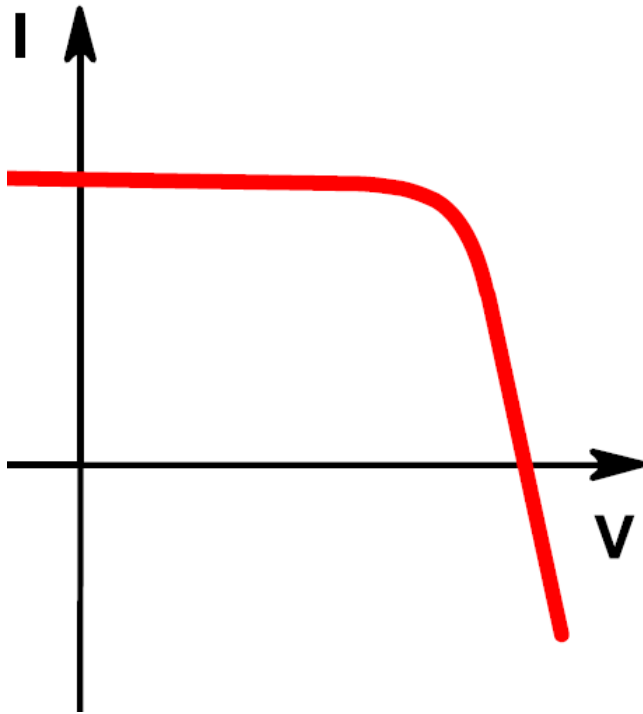
Current equation



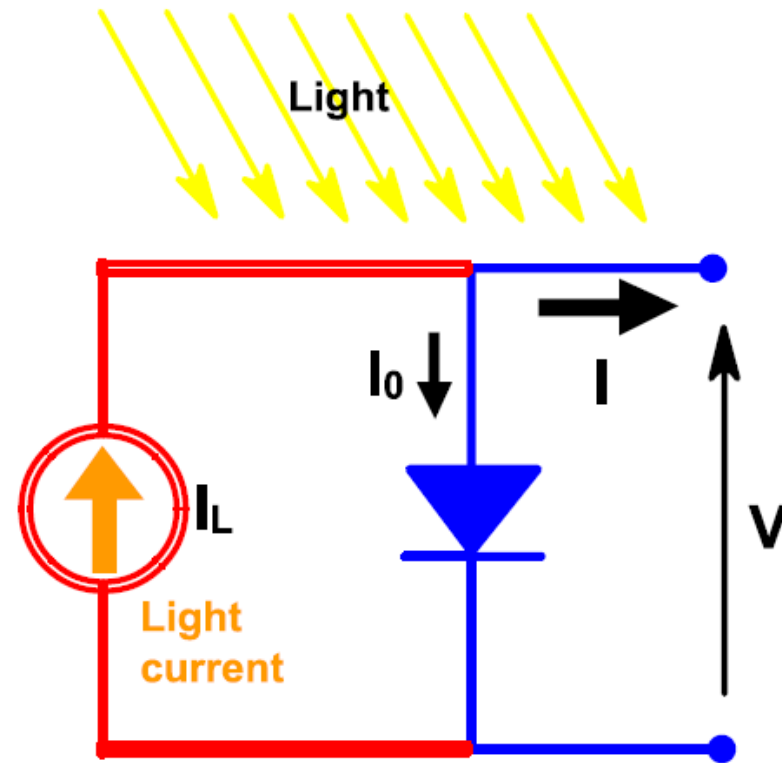
$$I = I_0 \left(\exp\left(\frac{qV}{kT}\right) - 1 \right) - I_L$$

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

Current equation (mirrored form)

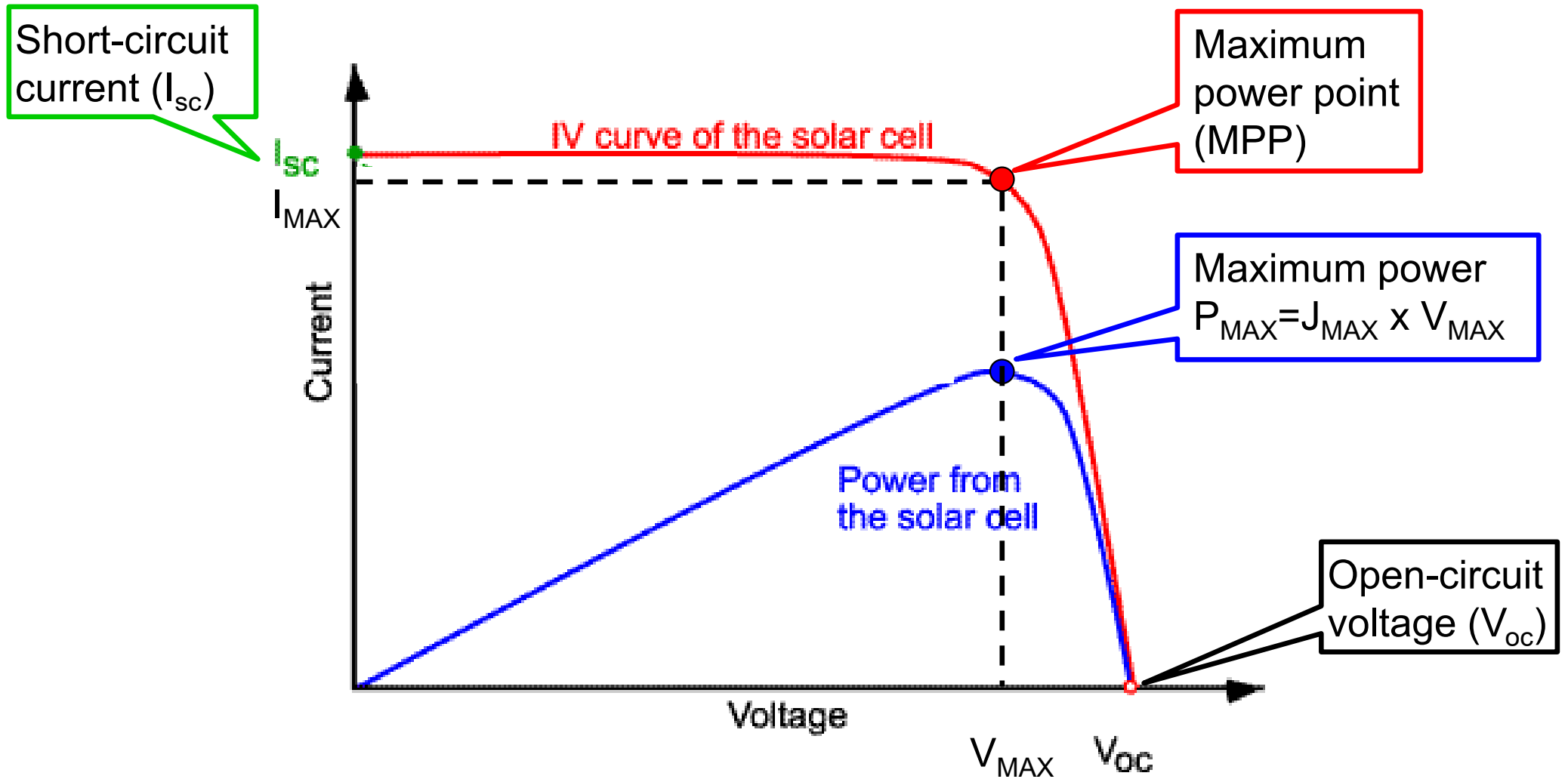


Since the cell is generating power, the convention is to invert the current axis



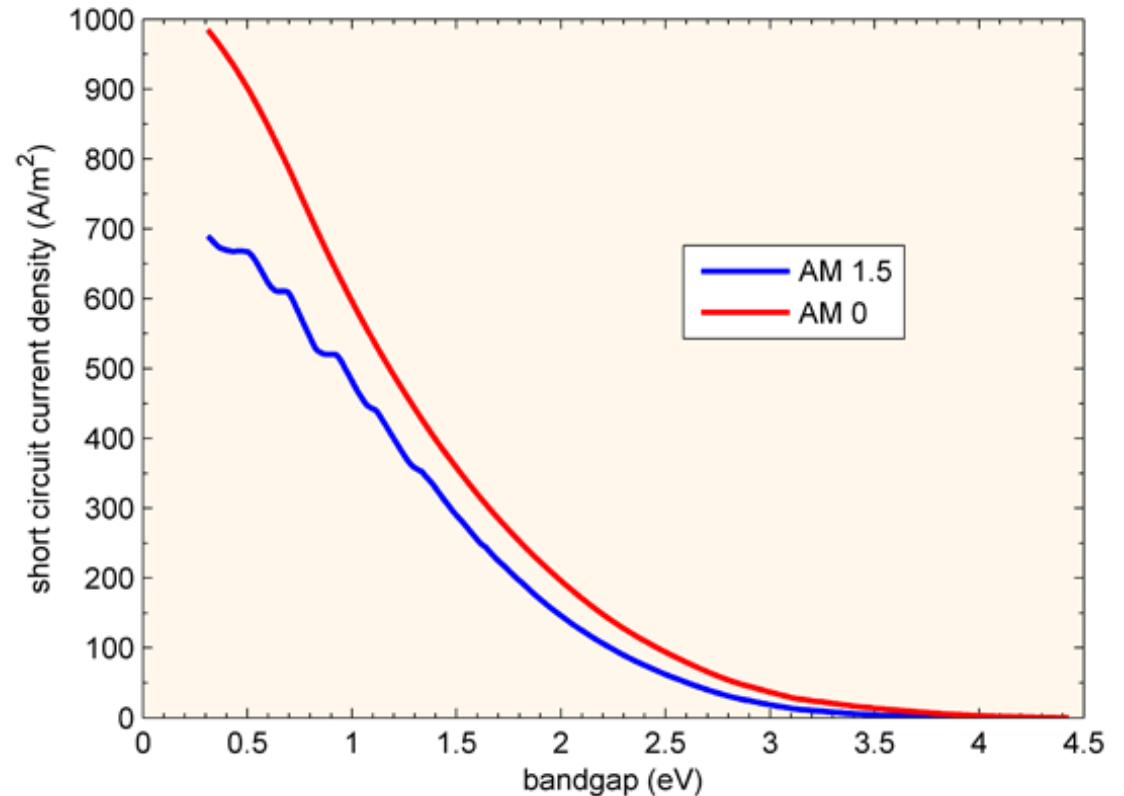
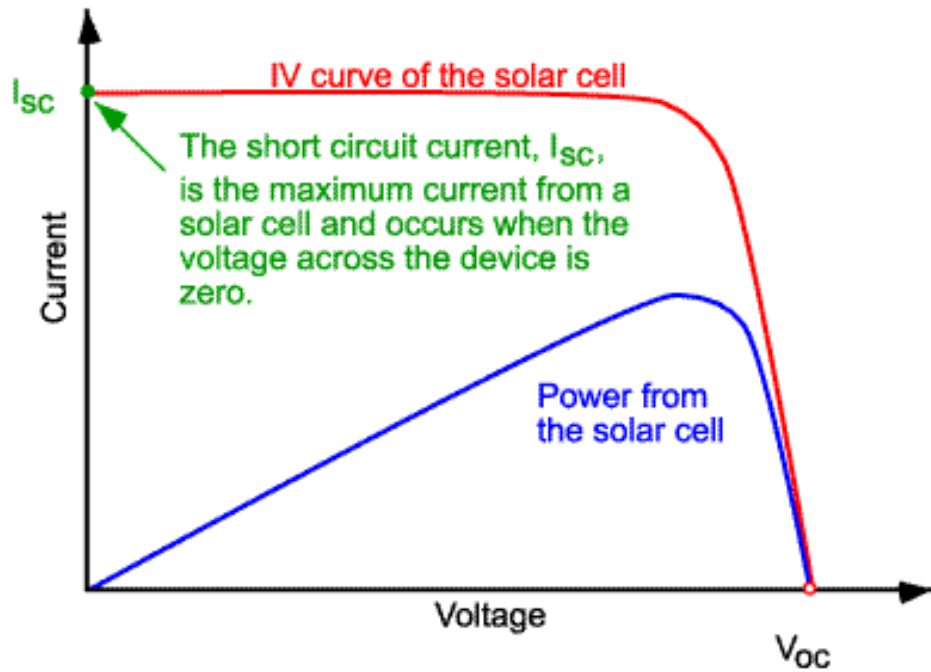
$$I = I_L - I_0 \left(\exp\left(\frac{qV}{kT}\right) - 1 \right)$$

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 $T=25^\circ\text{C}$

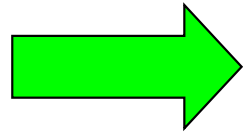
Short circuit current I_{sc}



- Short circuit current I_{sc} 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
(the diode equation)



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

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

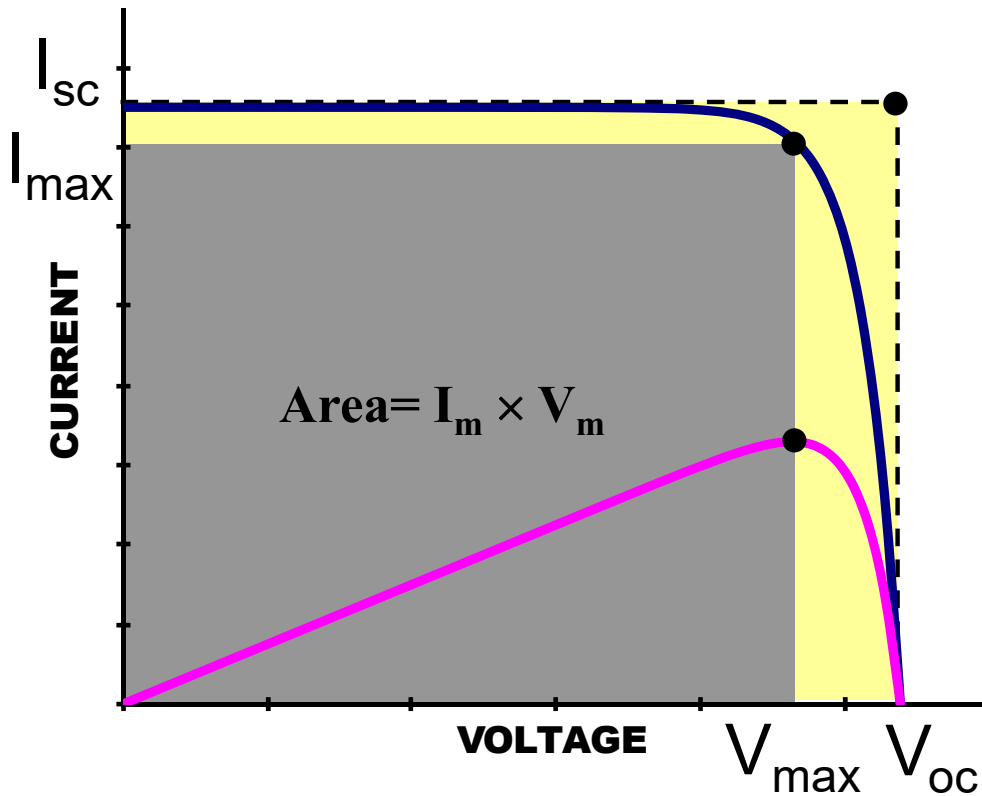
$$\frac{I_L}{I_0} + 1 = \exp\left(\frac{qV_{oc}}{kT}\right)$$

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

$I_L \sim A$ $I_0 \sim 10^{-9}A$
 $\Rightarrow I_L \gg I_0$
 $\Rightarrow I_L / I_0 \gg 1$

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

Fill Factor FF



Maximum theoretical power

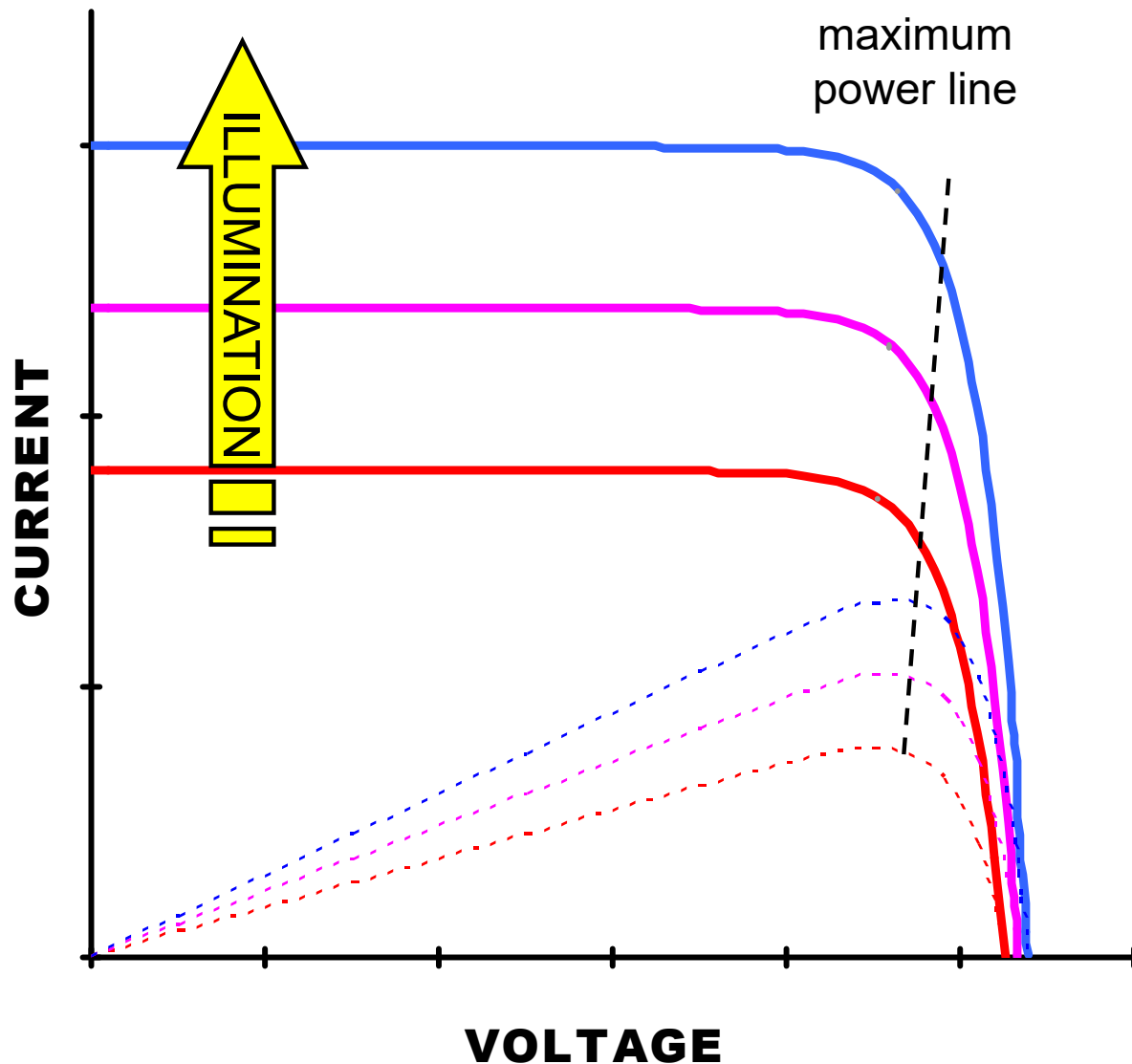
$$P_m = I_{sc} V_{oc}$$

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:

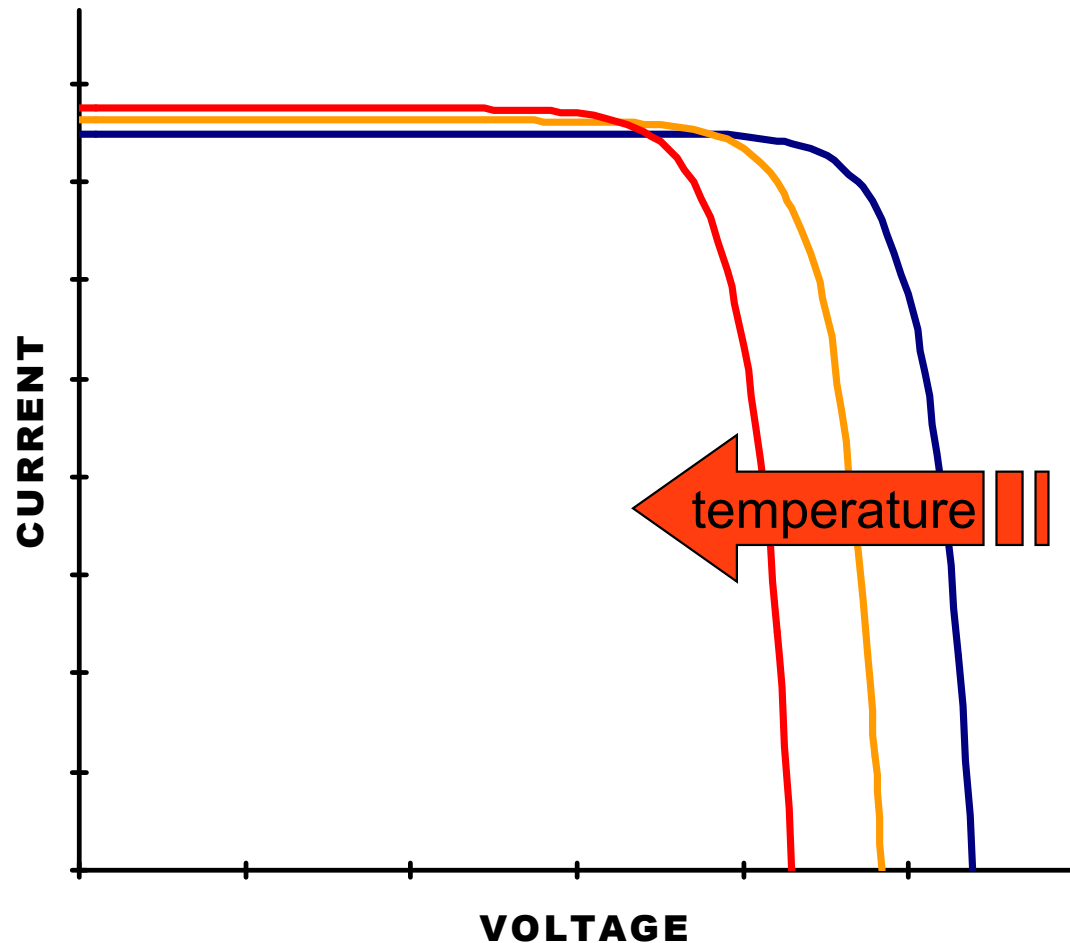
⇒ J_{sc} increases proportionally

⇒ V_{oc} 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:

$$\frac{dJ_{sc}}{dT} \approx 0.1 \text{ Am}^{-2} / K$$

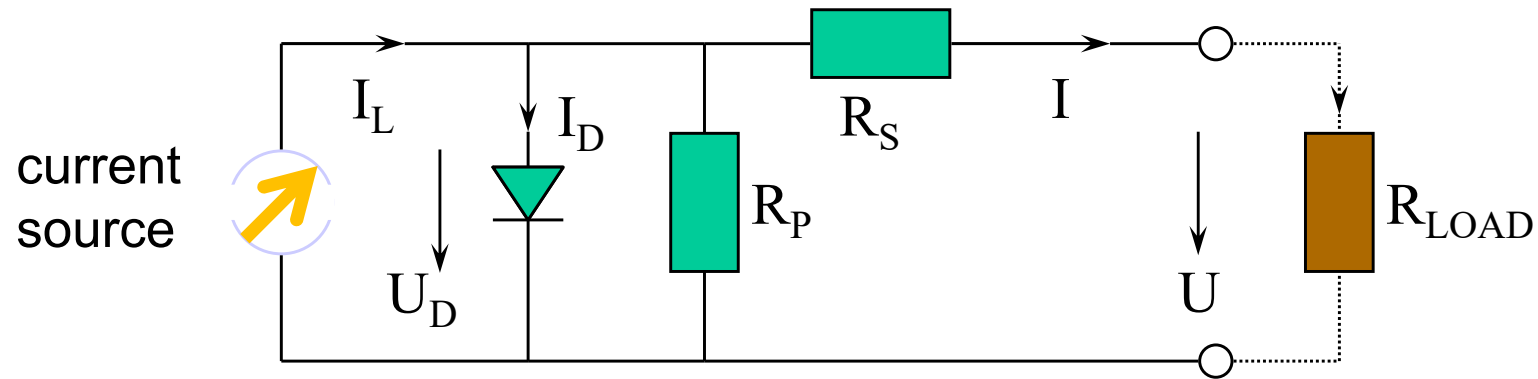
$$\frac{dV_{oc}}{dT} \approx -2.2 \text{ mV} / K$$

$$\frac{d\eta}{dT} \approx -0.4\% / K$$

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):
 $G_0 = 1000 \text{ W/m}^2$, $T_{cell} = 25^\circ\text{C}$, AM 1.5G spectrum

Equivalent circuit of a real solar cell



I_L : Light-induced current of the solar-cell

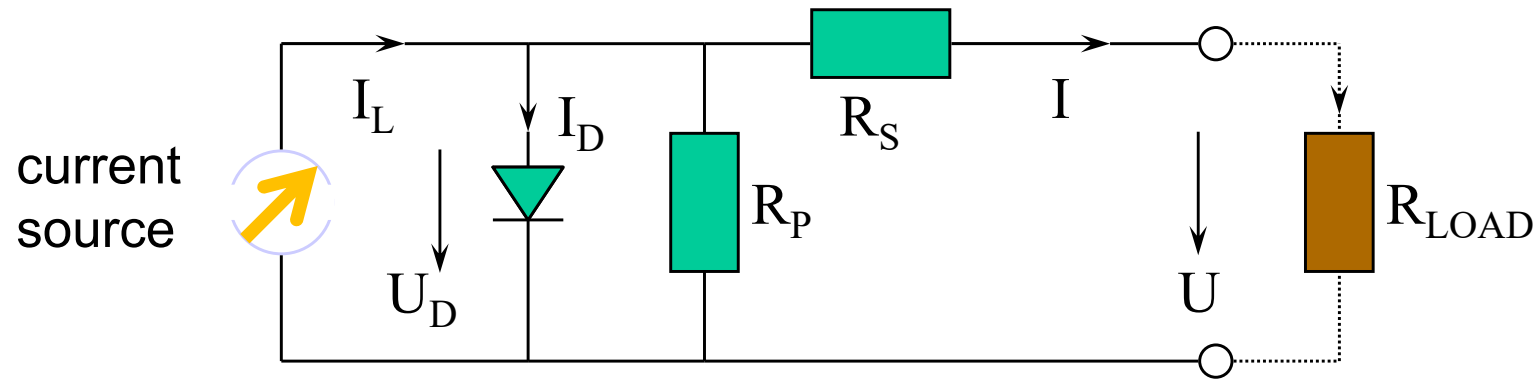
I_D / U_D : dark current and voltage of the internal p-n diode

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



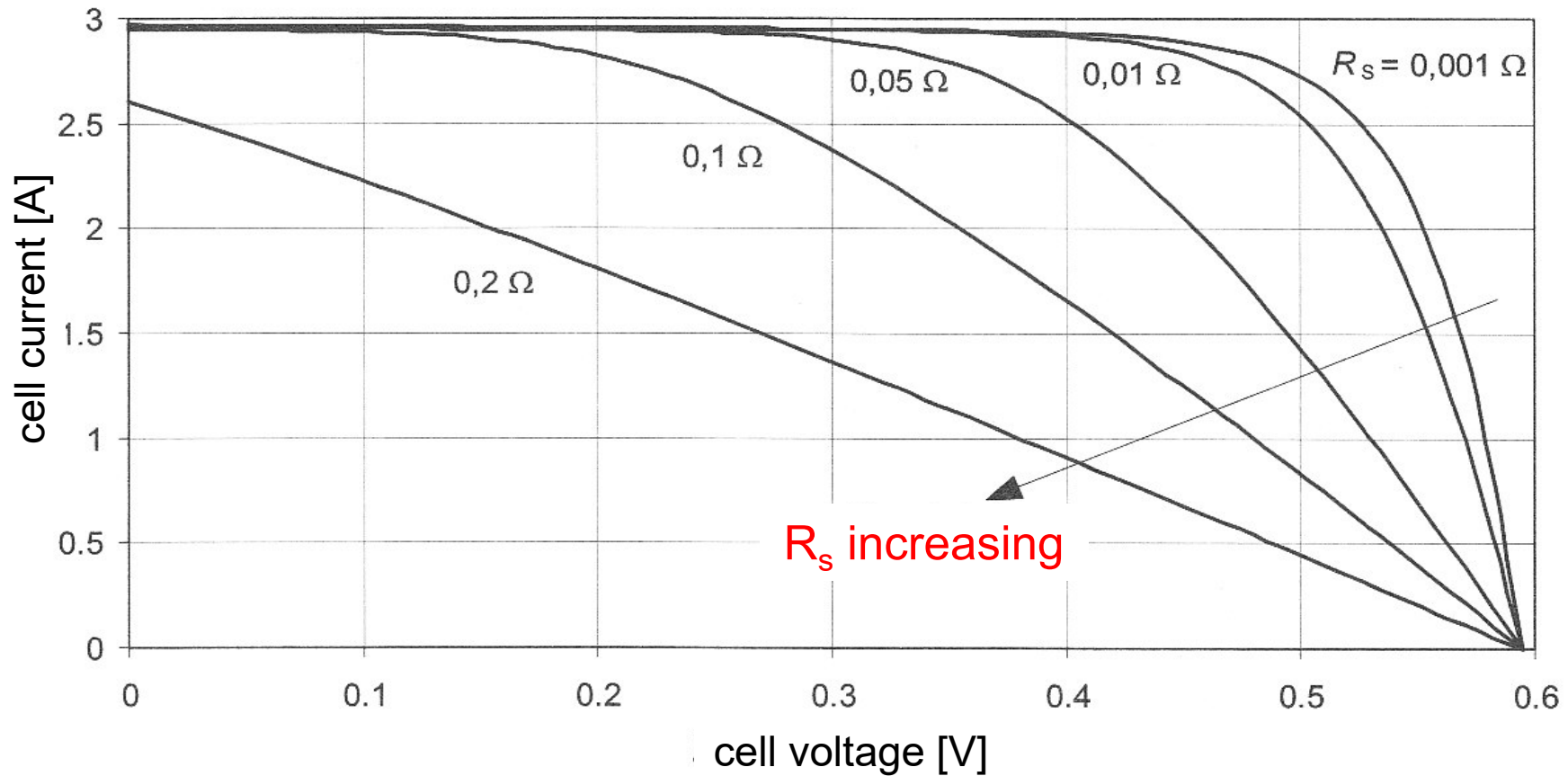
$$I = I_L - I_0 \left\{ \exp \left(\frac{q(V + IR_s)}{nkT} \right) - 1 \right\} - \frac{V + IR_s}{R_p}$$

diode ideality factor

$$n = 1 \dots 2$$

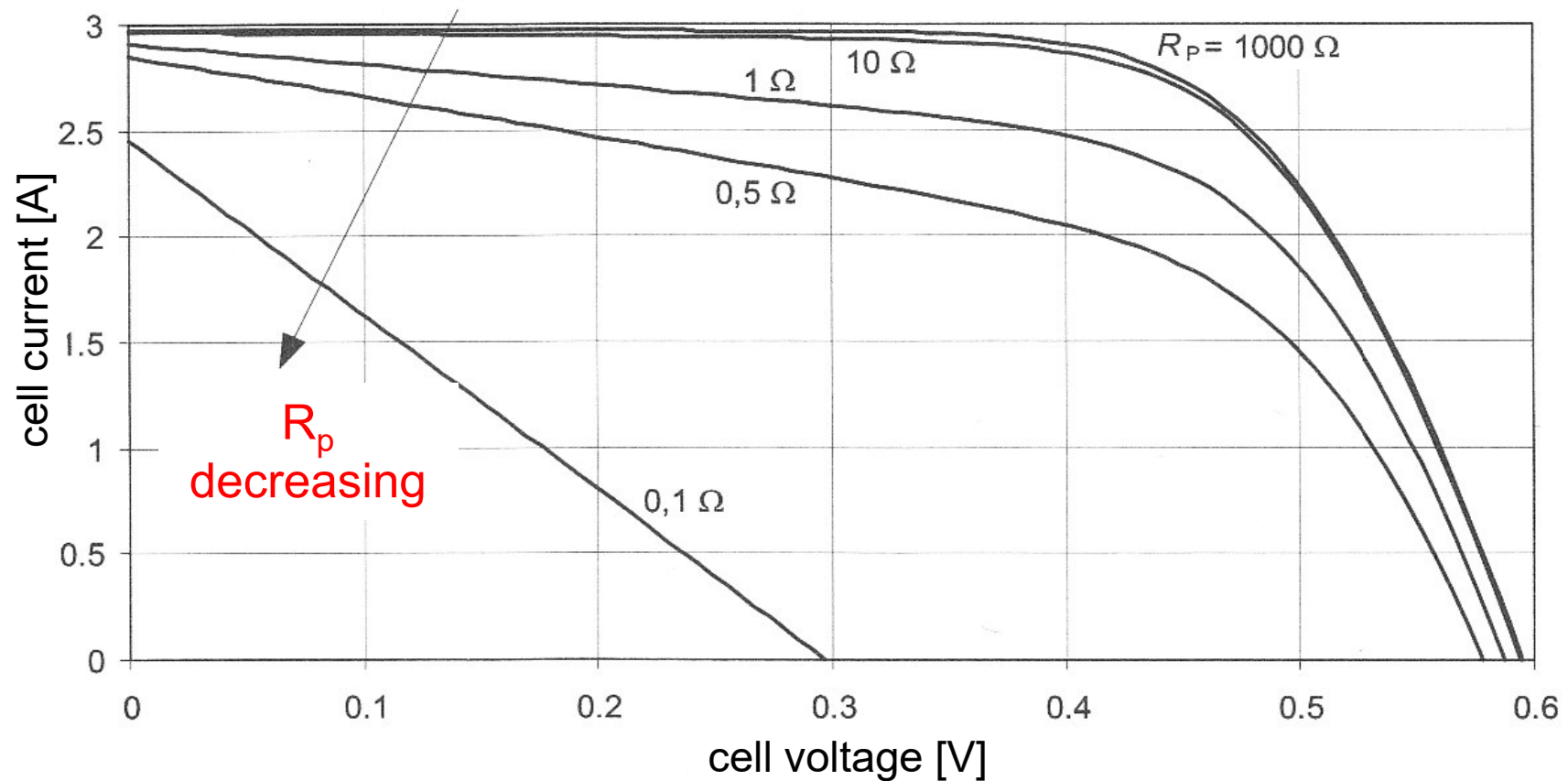
Effect of series resistance R_s

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



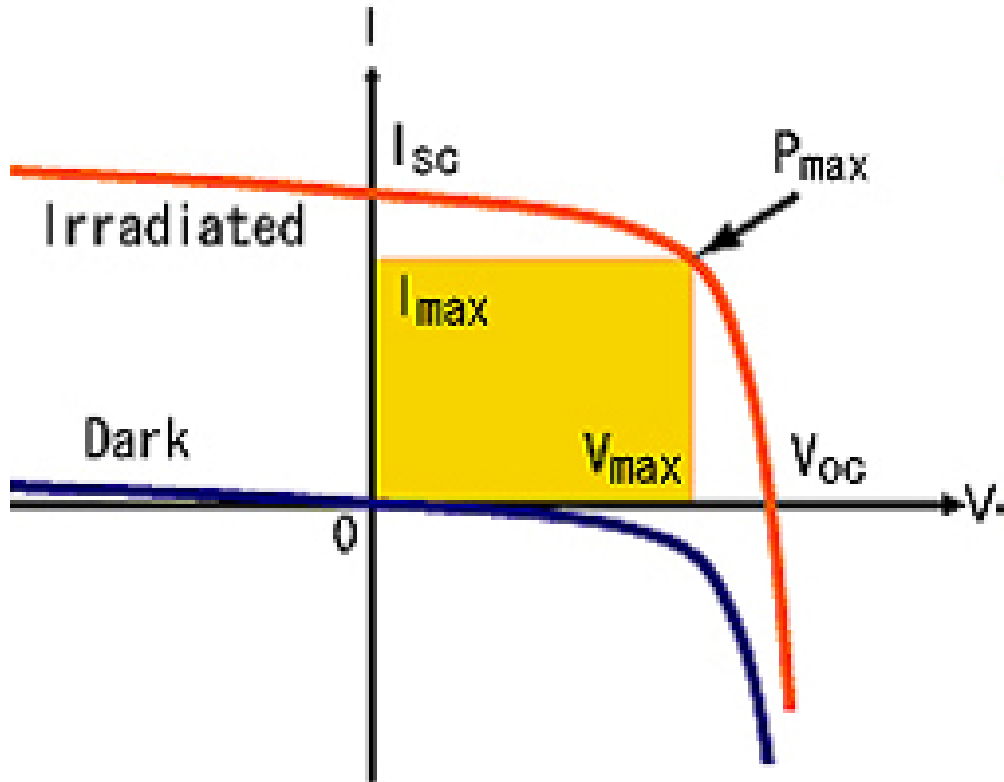
Effect of parallel resistance R_p

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



Power conversion efficiency

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



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

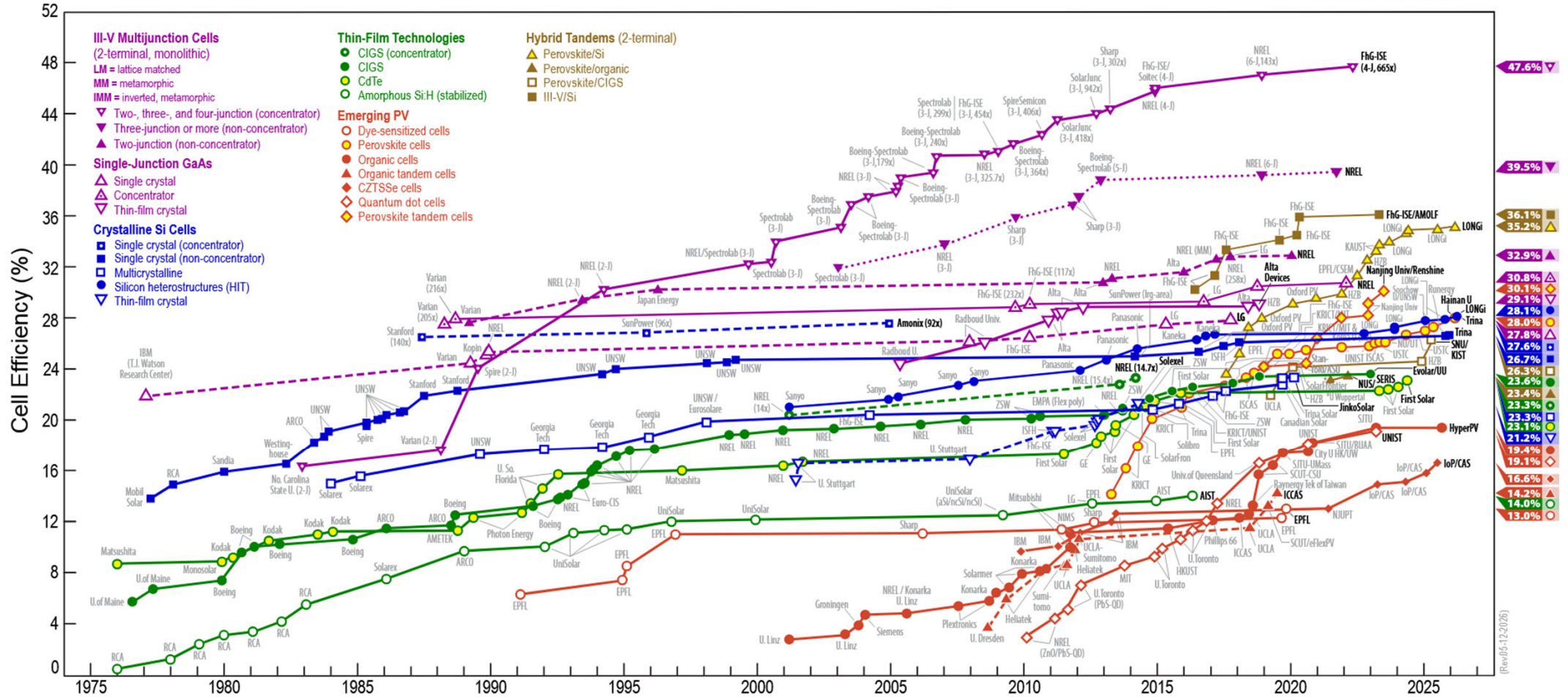
Standard test conditions:

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

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

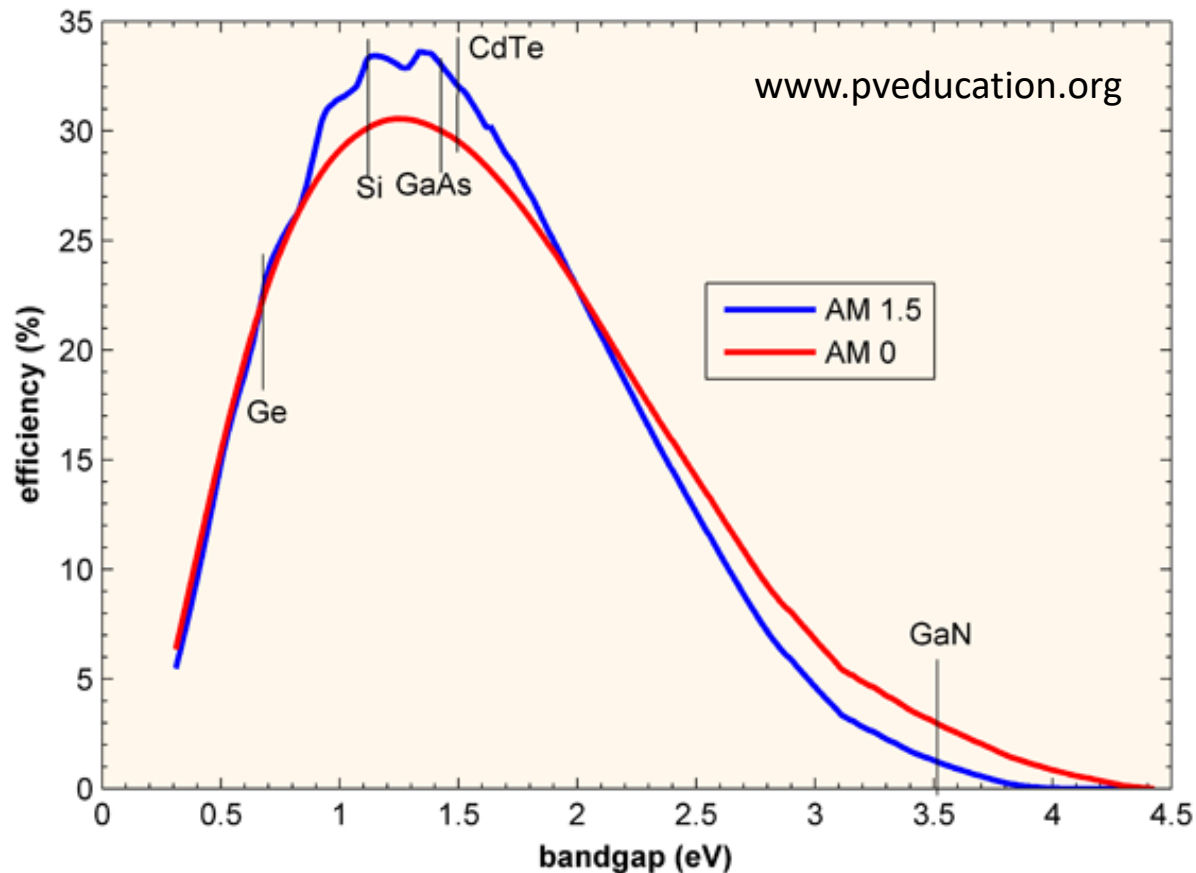
Progress in solar cell efficiency

Best Research-Cell Efficiencies



<https://nrel.gov/media/docs/libraries/pv/cell-pv-eff.pdf> June 2026

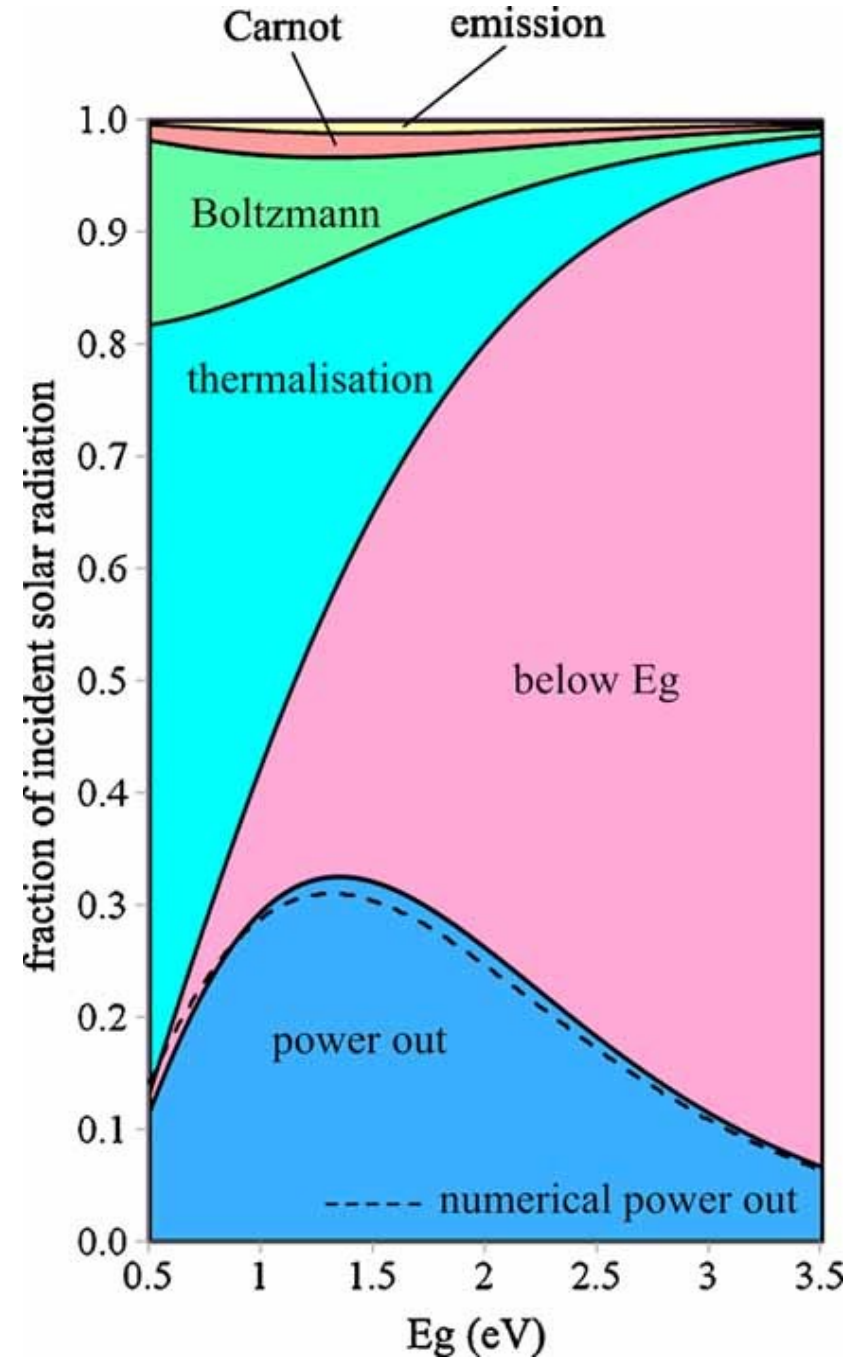
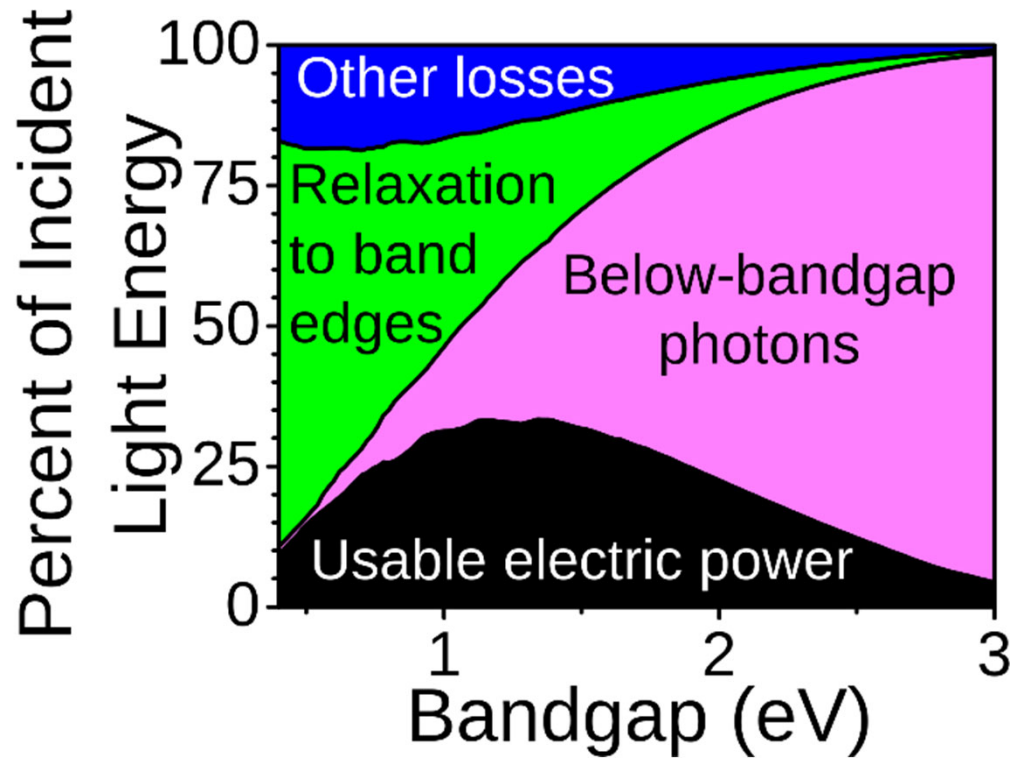
Shockley-Queisser limit



- 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

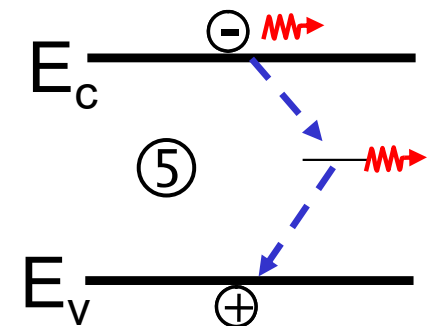
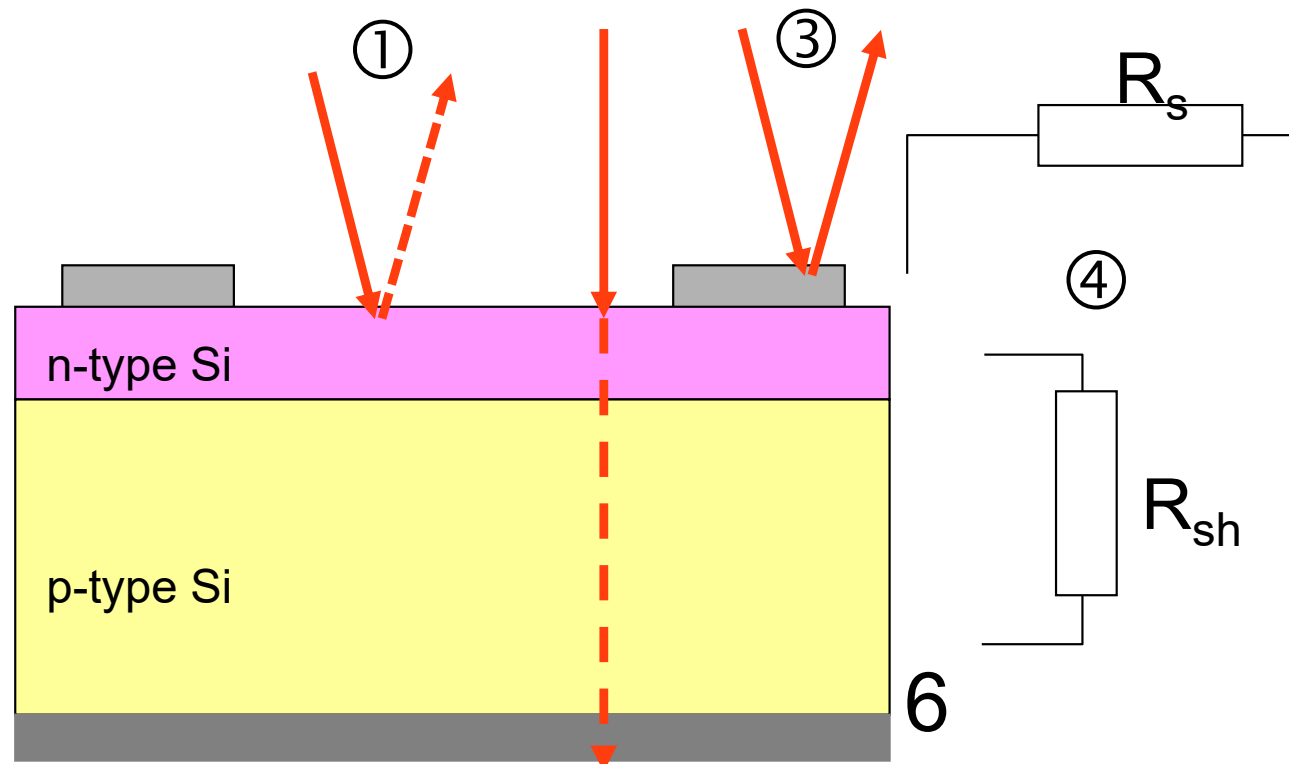
Fundamental losses



<https://doi.org/10.1002/pip.1024>

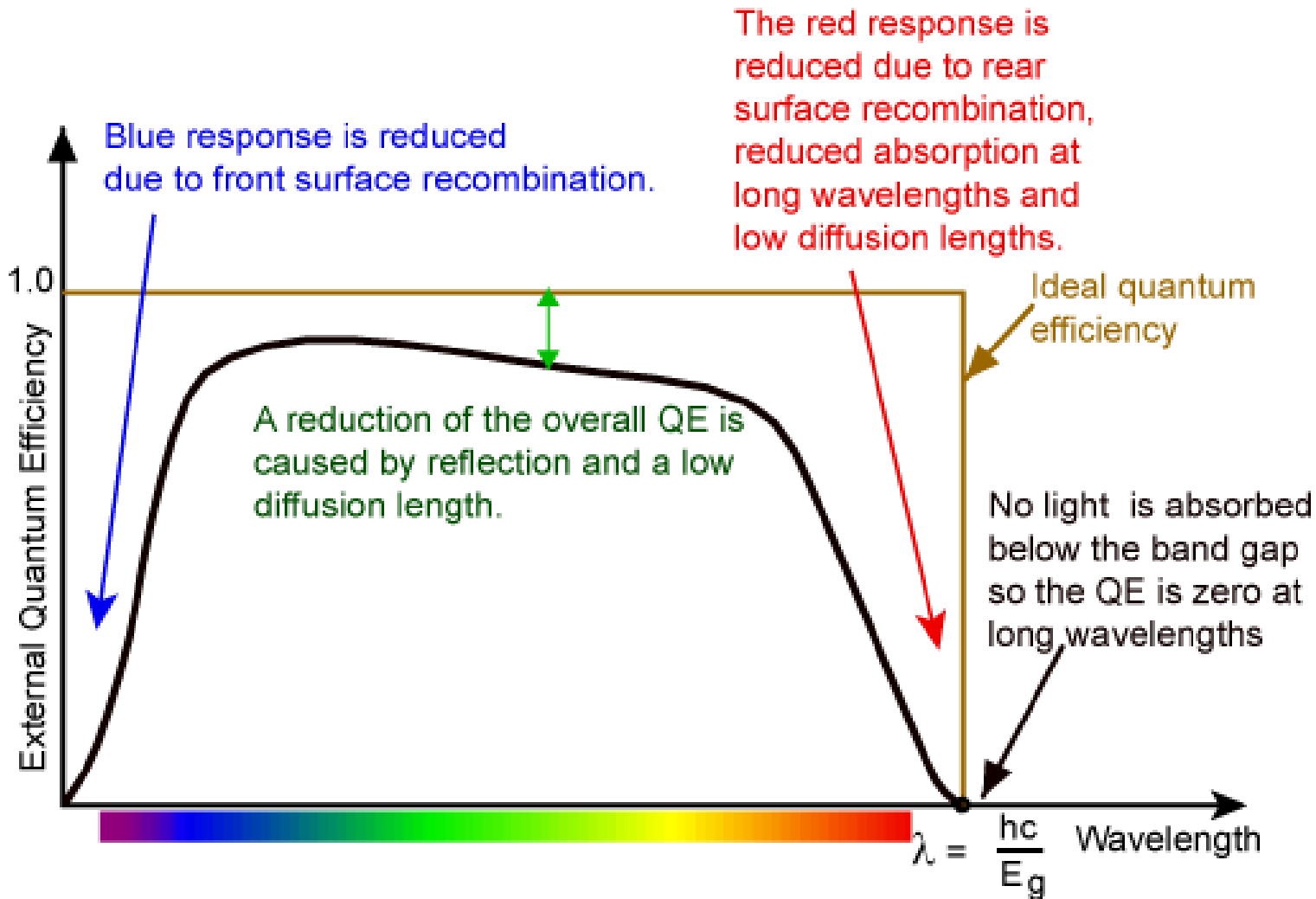
Practical losses

1. Reflection
2. Incomplete absorption
3. Shading
4. Resistances
 - a. series R_s
 - b. parallel R_p
5. Non radiative recombinations, Auger
6. Surface recombination (back, front, contact)



Quantum efficiency

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



Quantum efficiency for different cells

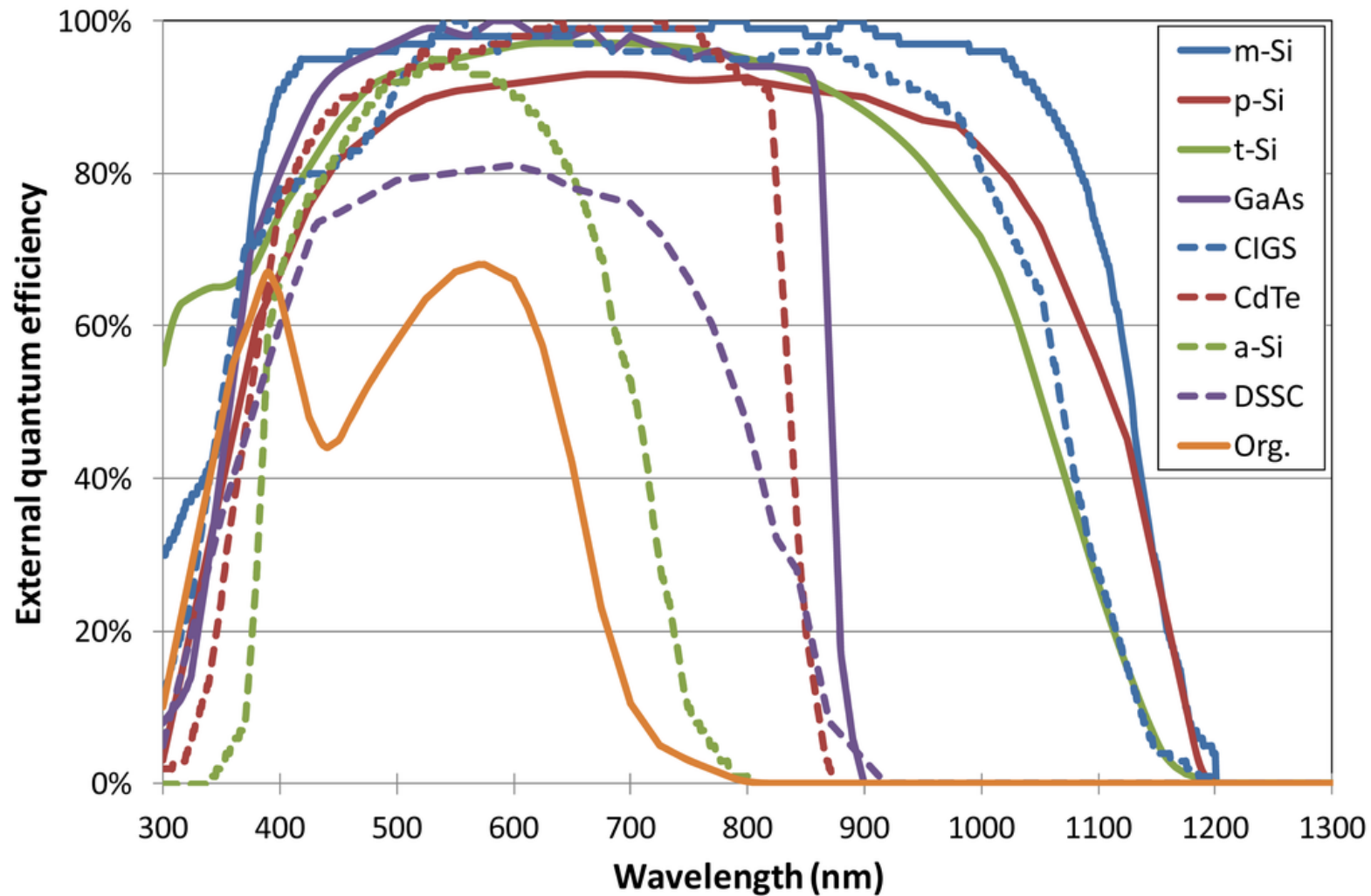
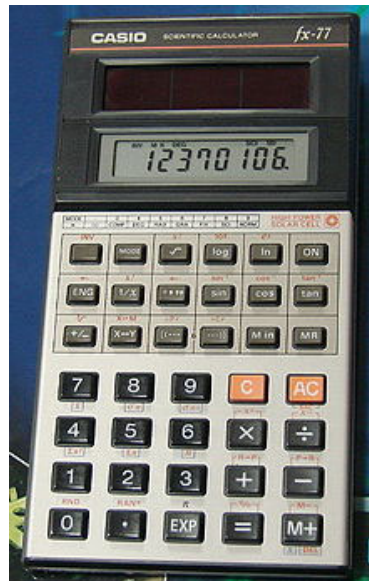


Image from: Energies 2014, 7(3), 1500-1516; doi:10.3390/en7031500

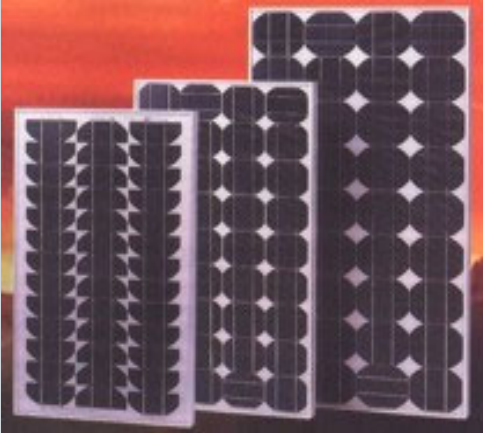
Generations of solar cells

Different PV techs for various applications



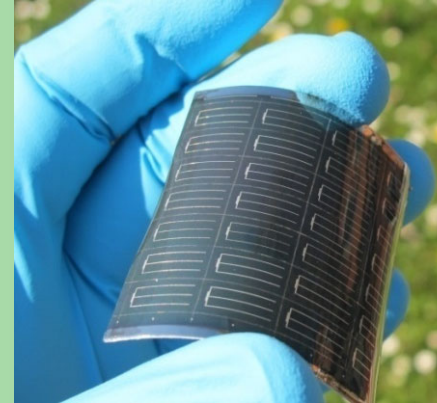
Generations of solar cells

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

- Absorber thickness: 0.5...10 µm
- Large area deposition
- Monolithic integration
- Rigid
- Heavy
- 20 years old

Flexible substr

R-2-R

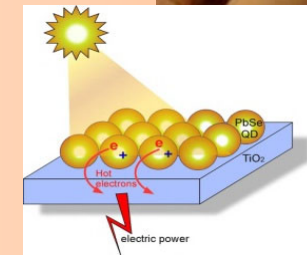
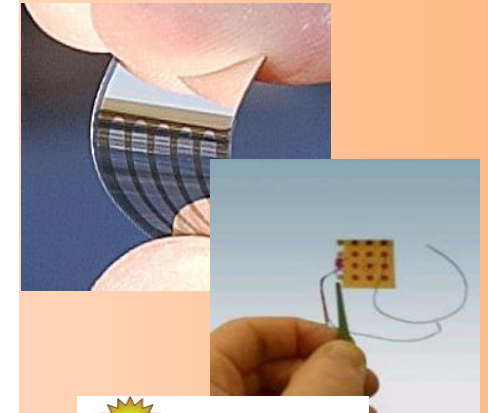
Flexible

Light-weight

pilot production

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

3rd Generation: Quantum dot, tandem, new concepts



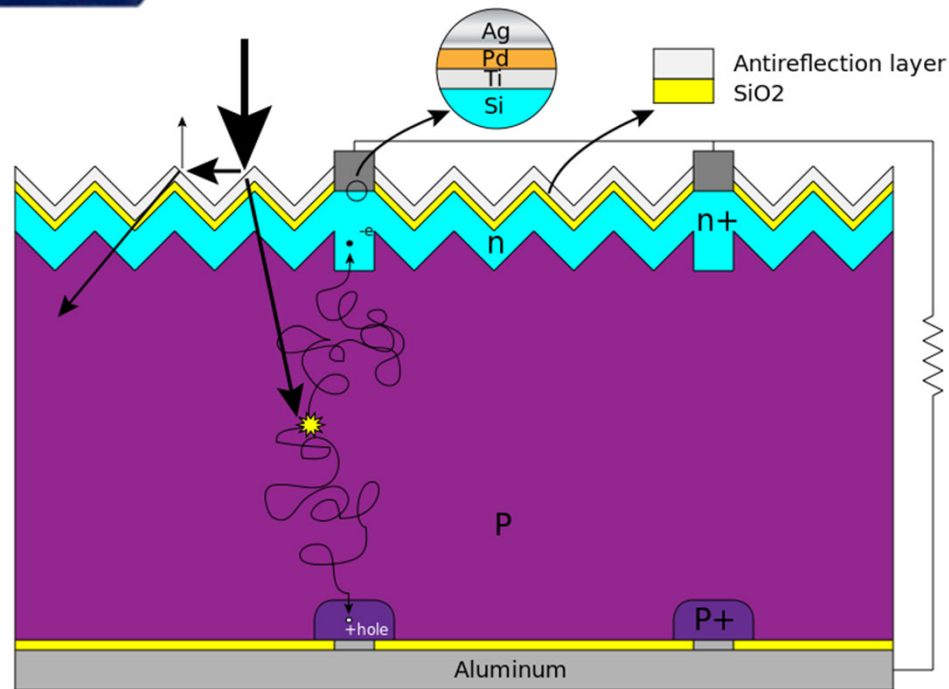
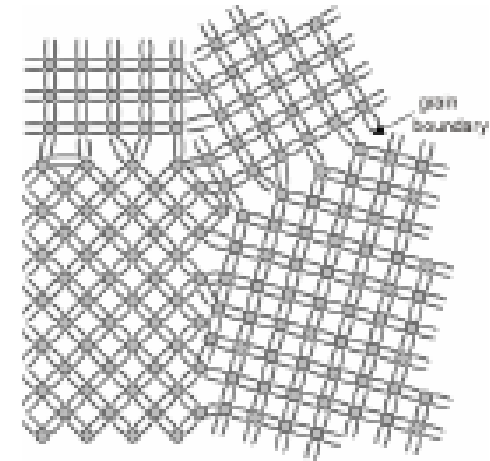
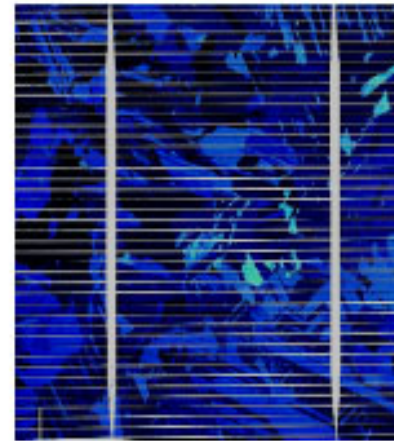
- Mainly in R&D stage
- Possibly low-cost & high-eff

1st generation: crystalline silicon

Monocrystalline Si

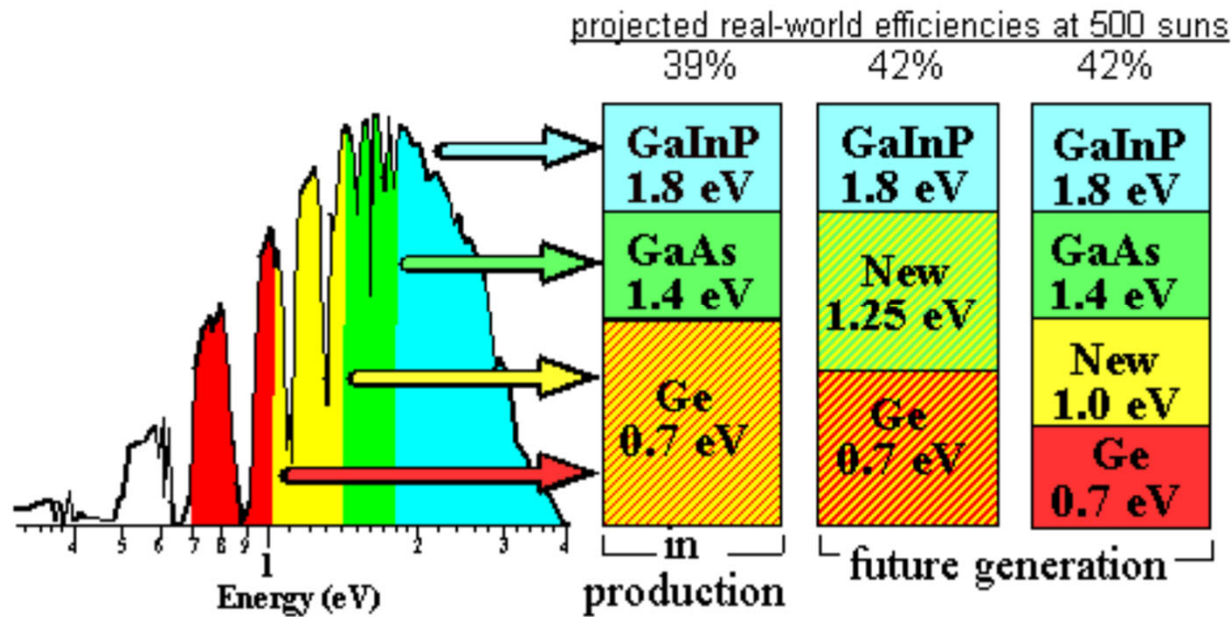


Polycrystalline Si

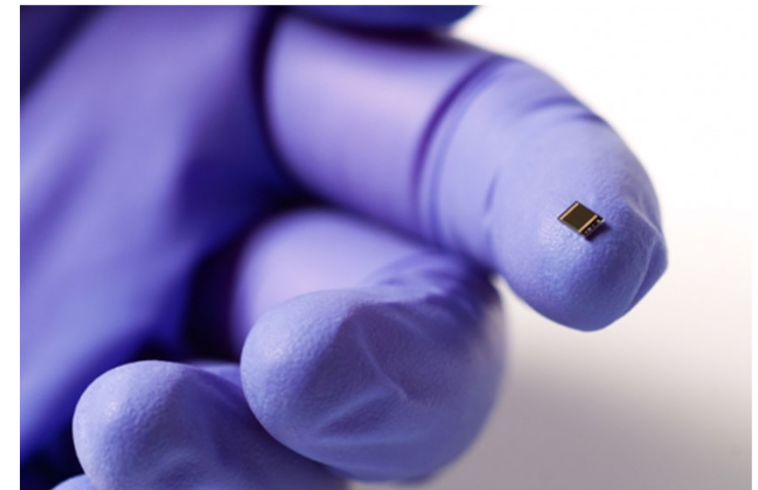


www.wikimedia.org

III-V and multi-junction solar cells

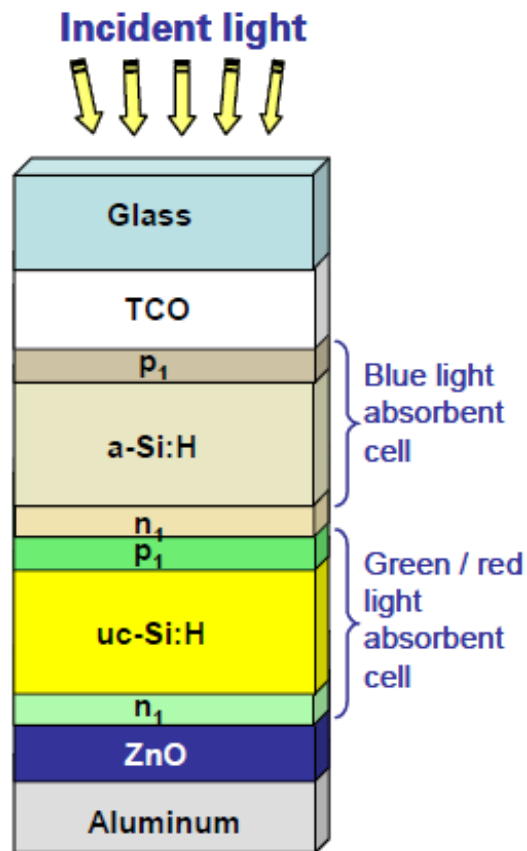


- Combination of wafer and thin-film technology based on GaAs compounds
- More complete utilization of solar spectrum in multi-junction cells
- Highest efficiency of 47.6%
(4-junction, under concentrated light)

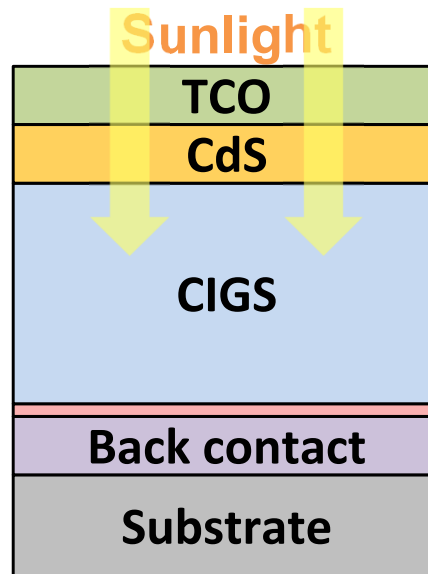


2nd generation: thin film solar cells

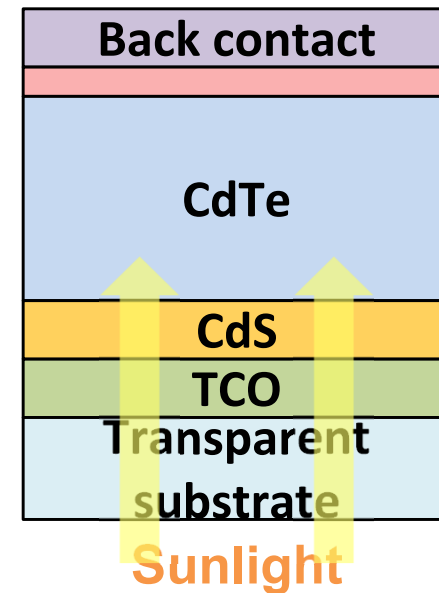
Amorphous Si
(a-Si)



Cu(In,Ga)Se₂
(CIGS)

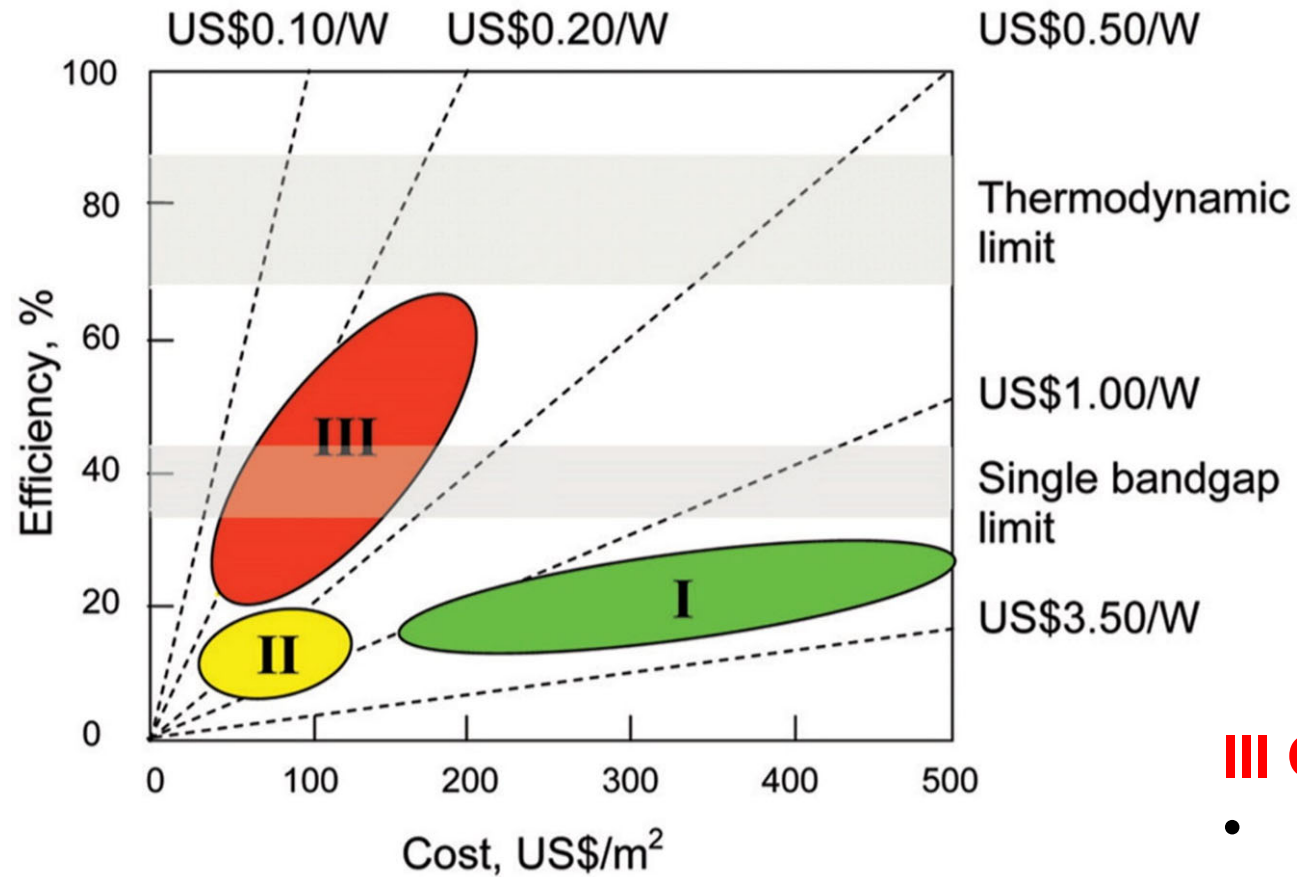


CdTe



- 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