

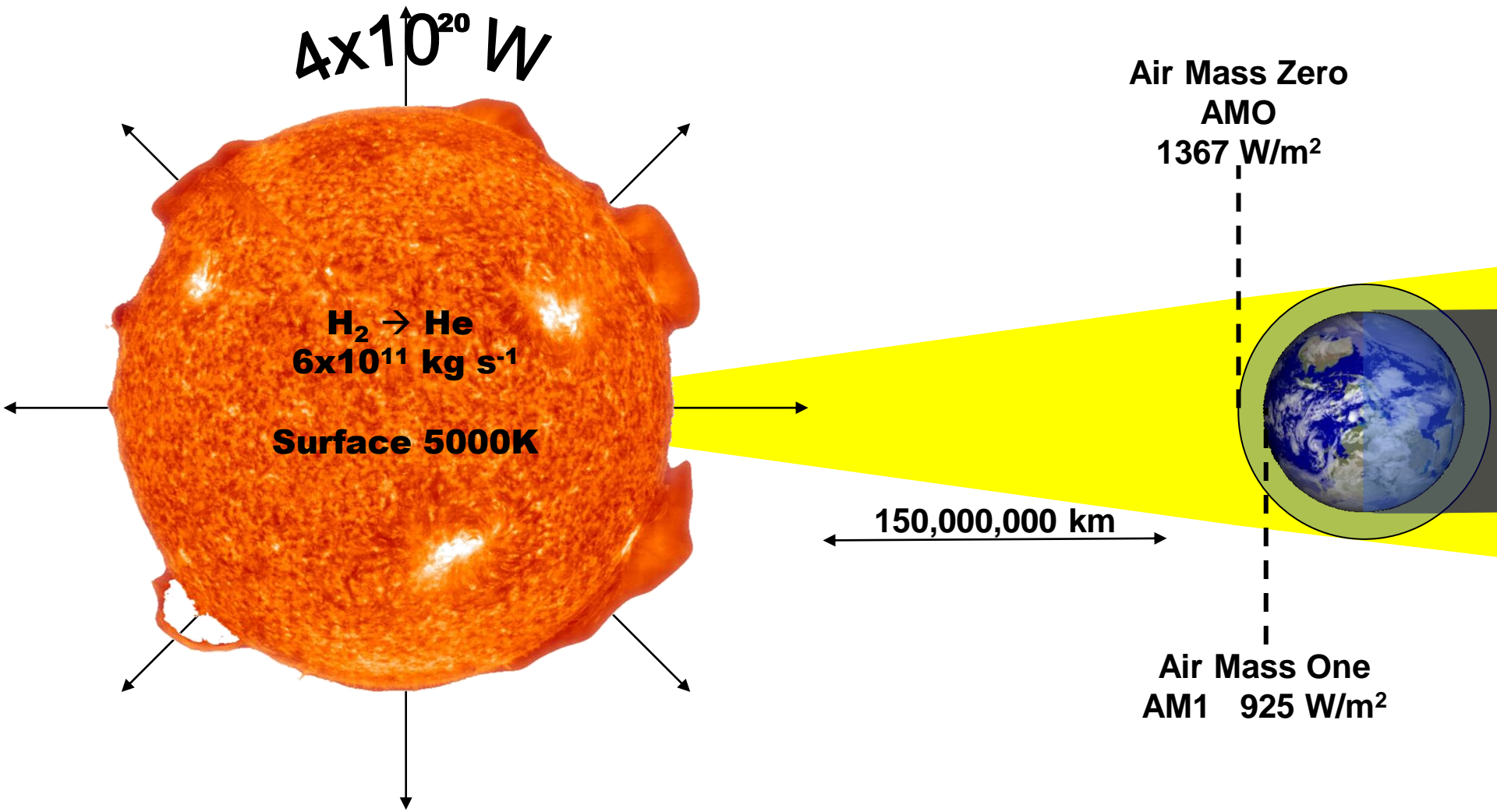


PV basics

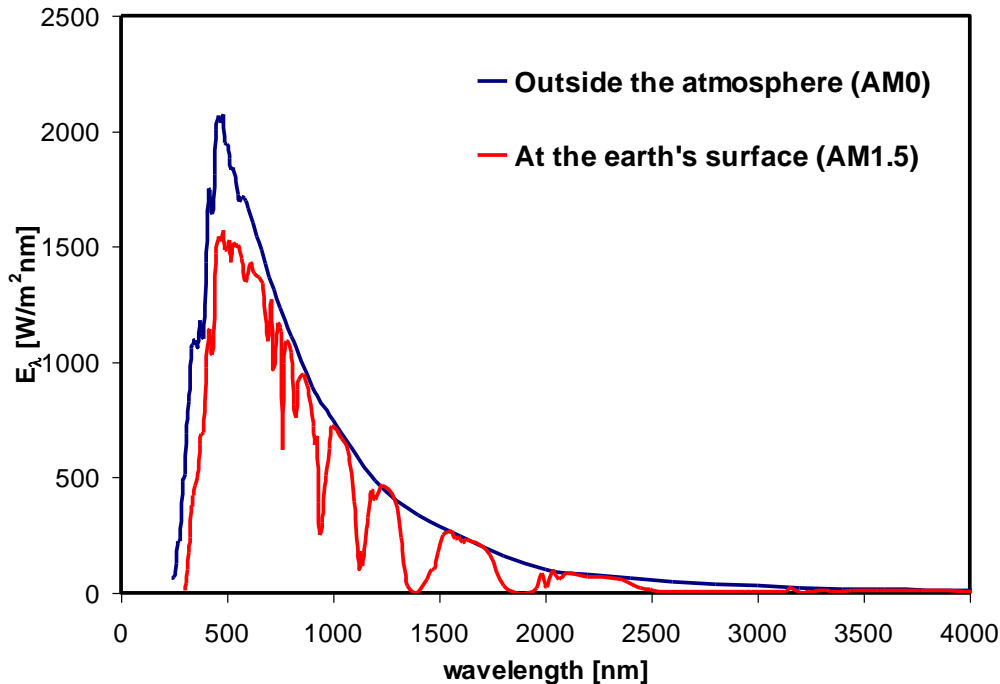
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Introduction: The Sun – a resume



Solar Output



Solar energy comes in photons

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

Where:

c = speed of light = 3×10^8 ms⁻¹

h = Planck's constant = 6.6×10^{-34} Js

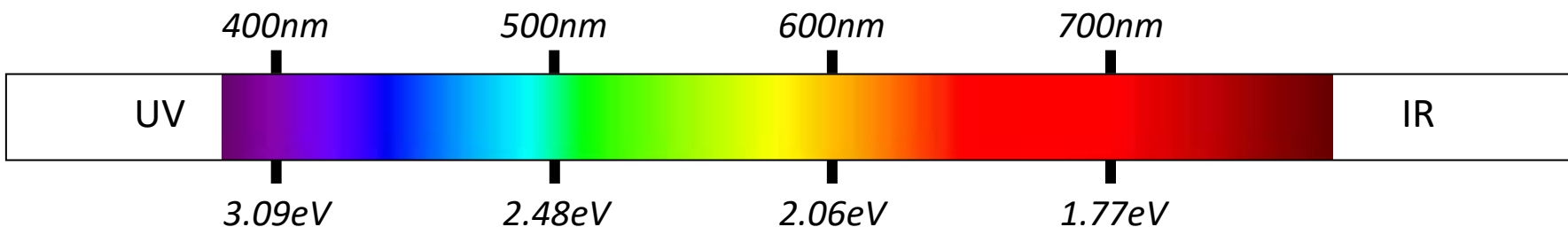
ν = frequency

λ = wavelength

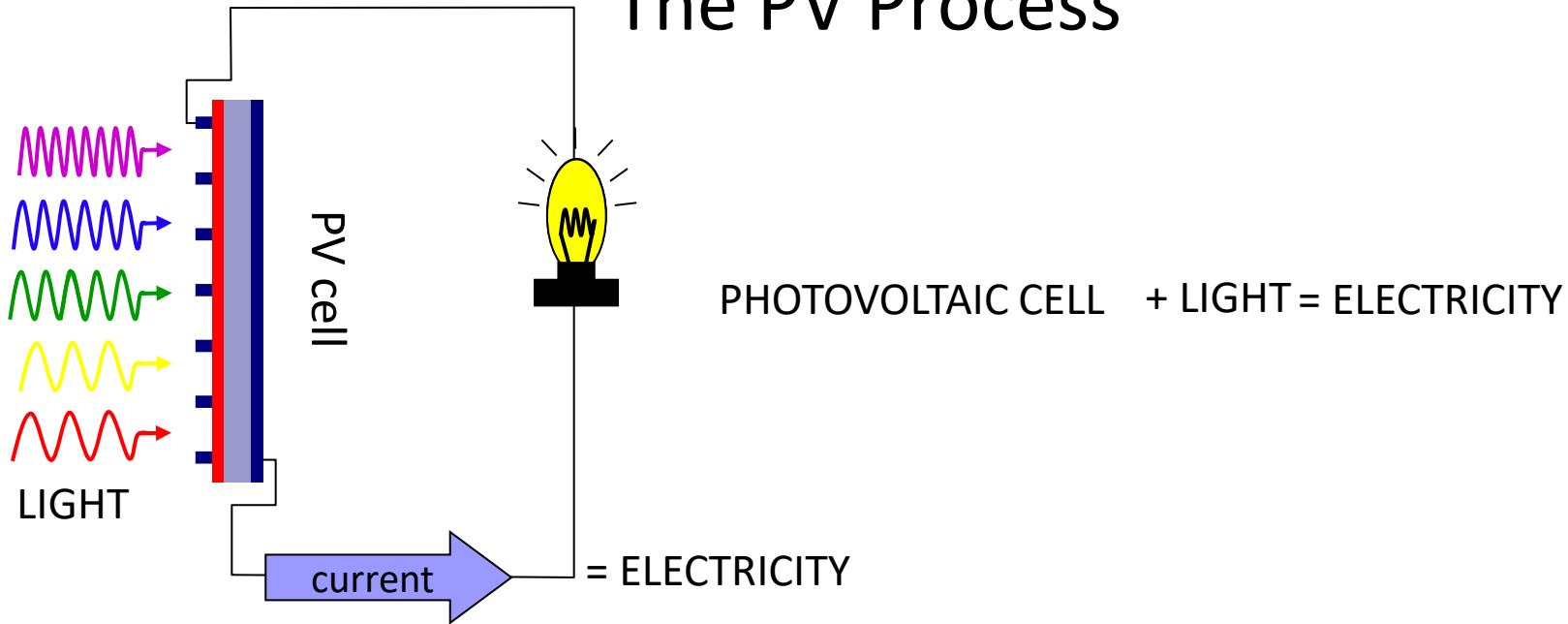
Measured in eV (electron-volt)

(1eV corresponds to 1.24nm)

spectrum



The PV Process



Most common materials used for **semiconductors**

eg: Si, GaAs, InP, CIGS, CdTe, CIS

Different structure:

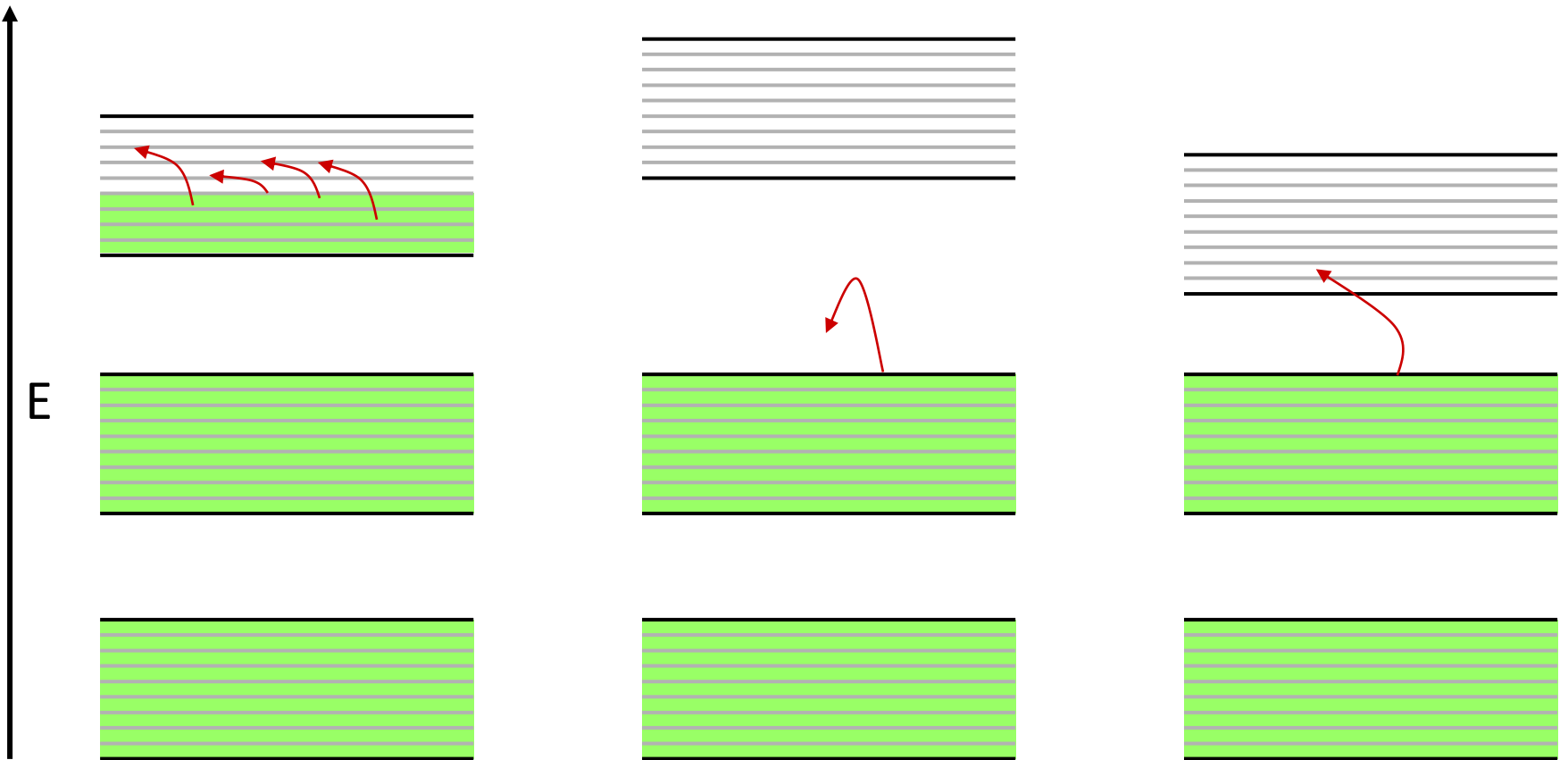
(Crystalline, Polycrystalline, Amorphous, Compound)

Terms that are crucial for PV conversion

- Absorption (photogeneration/recombination)
- Charge Separation (how to take the charge and do something ..)
- Transport
- Efficiency

Conductors – Insulators – Semi-conductors

- Bands of allowed energy states for electrons form when atoms join to make solids
- Empty energy states are needed for free electrons to move

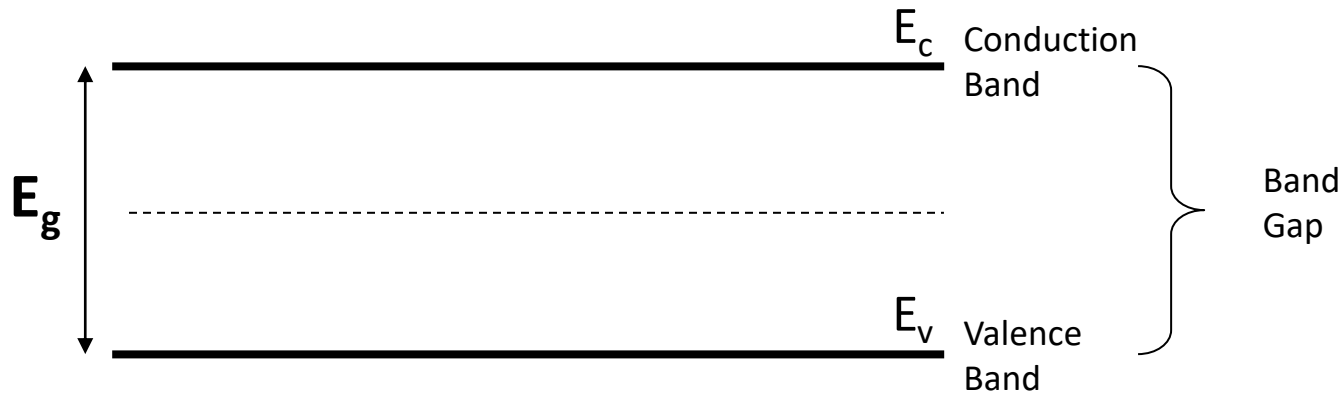


METALS
½ full top band
Easy conduction

INSULATORS
Empty top band
No conduction

SEMICONDUCTORS
Empty top band
BUT small gap

The Semiconductor Band Gap



•GaAs $E_g=1.42\text{eV}$
direct gap (strong)

•Si $E_g=1.12\text{eV}$
indirect gap (weak)

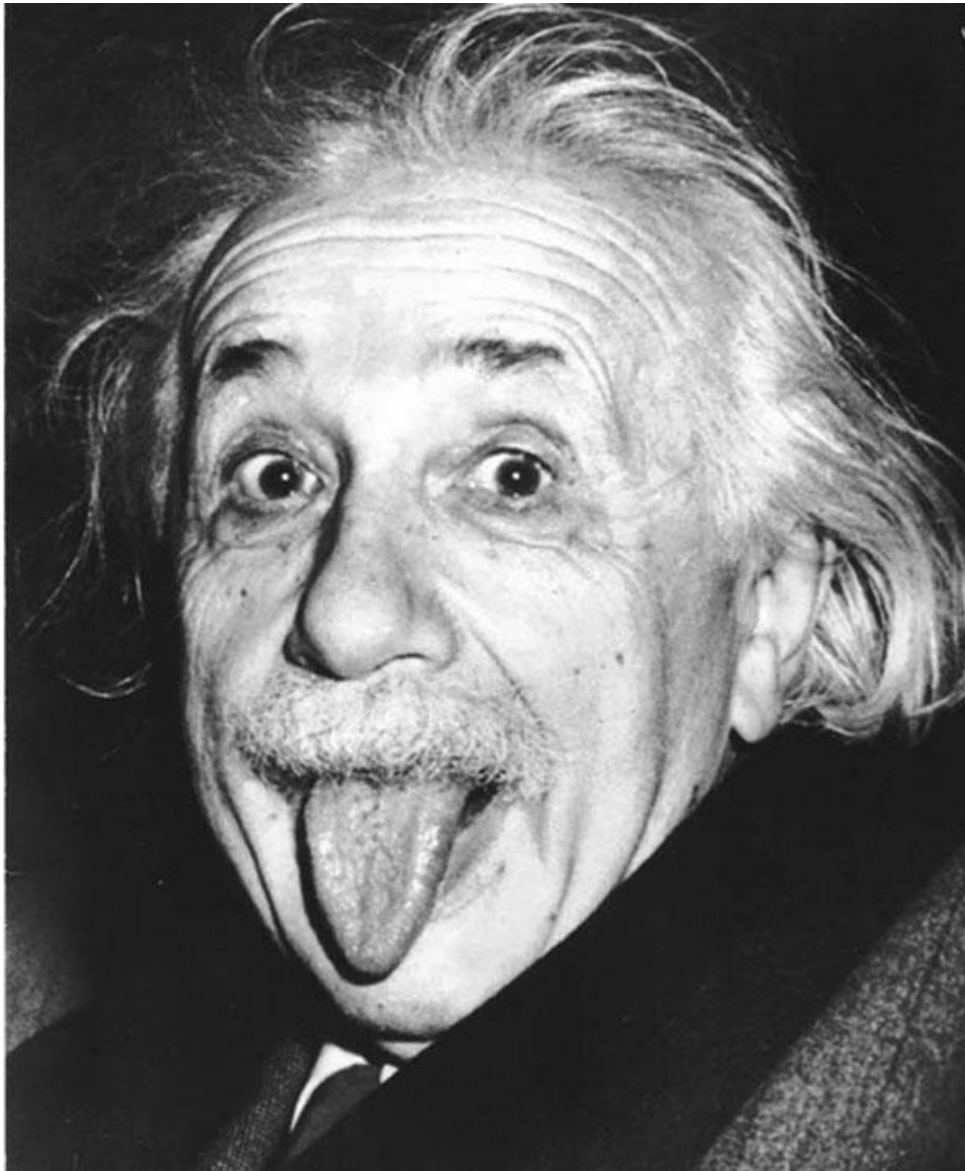
Band gap is the central parameter that sets absorption behaviour

Band gap = $E_g = h\nu_c = hc/\lambda_c$ (has an energy content)

ν_c =cut off frequency, λ_c =cut off wavelength

h =Planck's constant, c =speed of light

Photoelectric effect

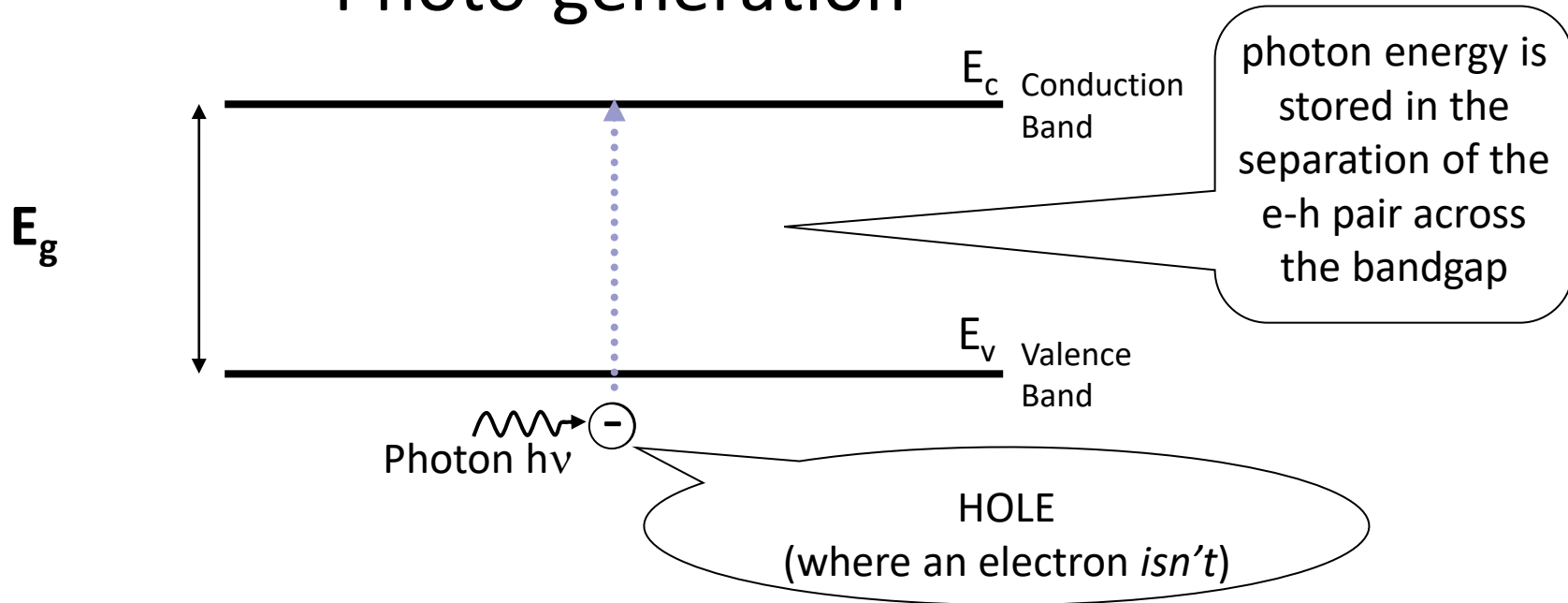


Materials emit electrons when light shines upon them

Gave Albert Einstein his Nobel prize in 1921

When a photon of energy $h\nu$ interacts with matter it is able to give up its energy to promote an electron to a higher energy level. If the excited electron can be prevented from returning immediately to its ground state, its increased electrical energy may be harnessed.

Photo-generation



For absorption photon energy $h\nu > E_g$ (ie $\frac{hc}{\lambda} > E_g$)

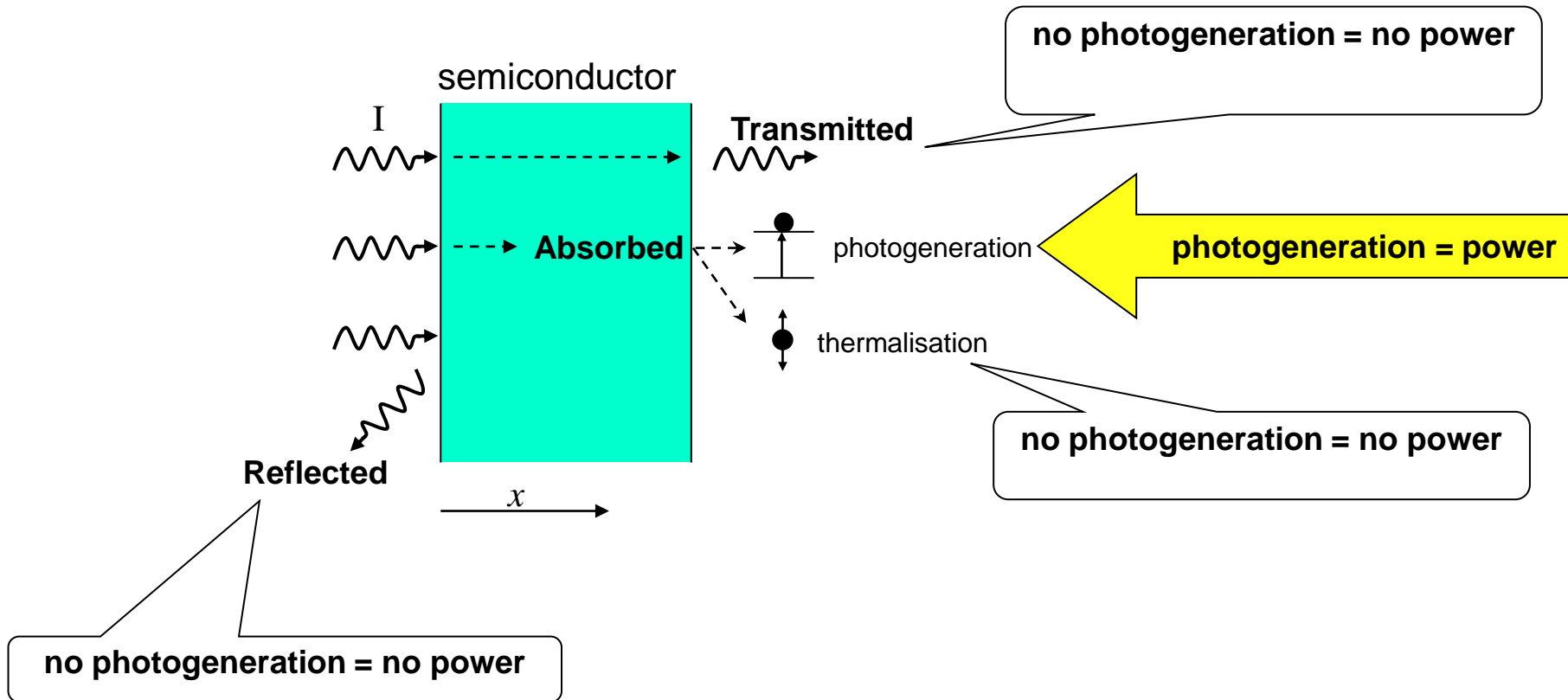
\Rightarrow Semiconductors are transparent to wavelengths $\lambda > \lambda_c$

Absorption of Photon \Leftrightarrow Generation of electron-hole pair

What do we need for an effective photogeneration

- a high probability of photon ***absorption***
- a ***charge separation mechanism*** for removing the excited electron before it naturally recombines with the vacancy it left behind. This can be effected by some kind of **interface or junction** where different electronic or electrochemical properties attract the electron irreversibly away from the point of excitation.
- ***Electronics*** (wires etc) to move the separated charge to an external circuit where it can be used

How much absorption is there?



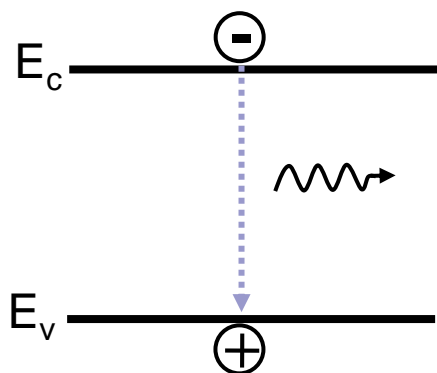
Reflection: described by the reflection coefficient (%)

Absorption & Transmission: described by the absorption coefficient $\alpha(\lambda)$, which is wavelength dependant.

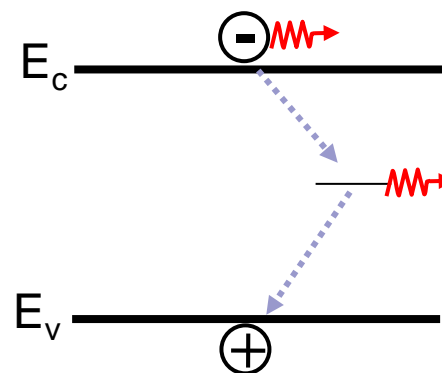
Recombination: Photogeneration in reverse – our enemy

An optically created electron-hole pair can recombine

Radiative (emit photon)



Non-radiative (emit phonon(s), i.e. heat)



- Both are undesirable in solar cells = loss of charge carriers = loss of current
- Need to collect the excited electron (or hole) before recombination.
- In poor quality materials → high defect densities,
→ very fast non-radiative recombination
- e^- & h^+ needed for recombination

need
charge
collection

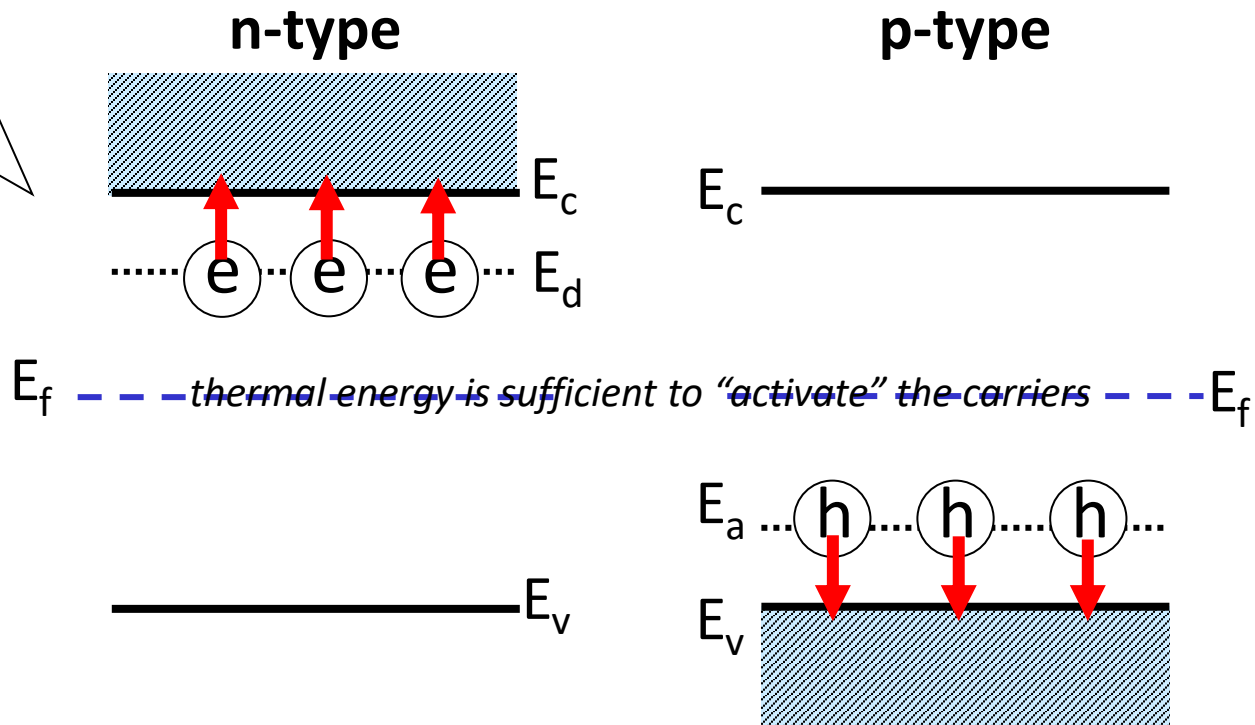
Doping of Semiconductors

- Undoped (intrinsic) semiconductors have low conductivity because of the filled energy band limits the number of carriers available for conduction.
- Adding impurities can add electrons and holes near the band edge

Donors \Rightarrow donate electrons
~ one e^- per donor atom

Acceptors \Rightarrow accept electrons
~ one h^+ per acceptor atom

E_F near
conduction
band in
n-type



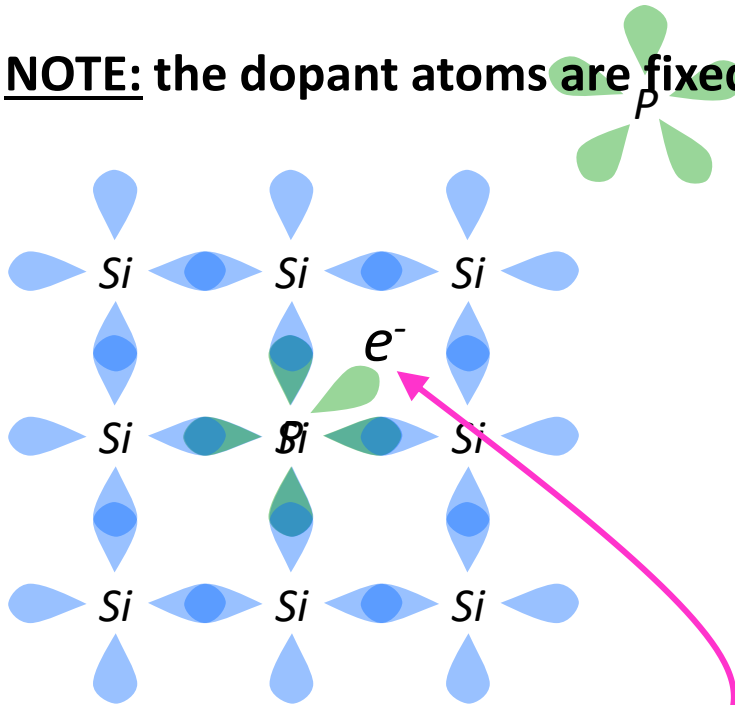
E_F near
valence
band in
p-type

Examples of dopants

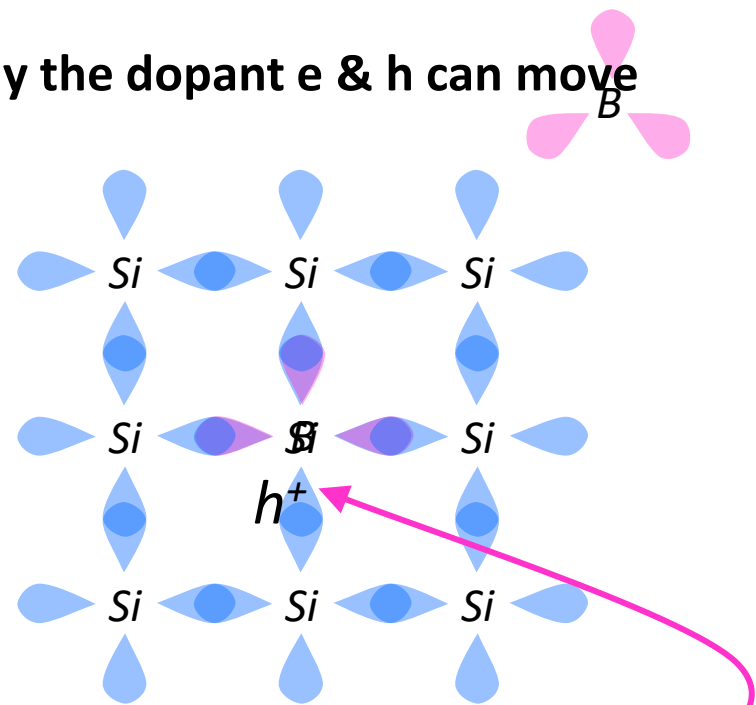
Silicon : Phosphorus (P)
5 outer electrons vs Si's 4
⇒ **donor** n-type

Boron (B)
3 outer electrons vs Si's 4
⇒ **acceptor** p-type

NOTE: the dopant atoms are fixed only the dopant e & h can move



One electron per donor atom

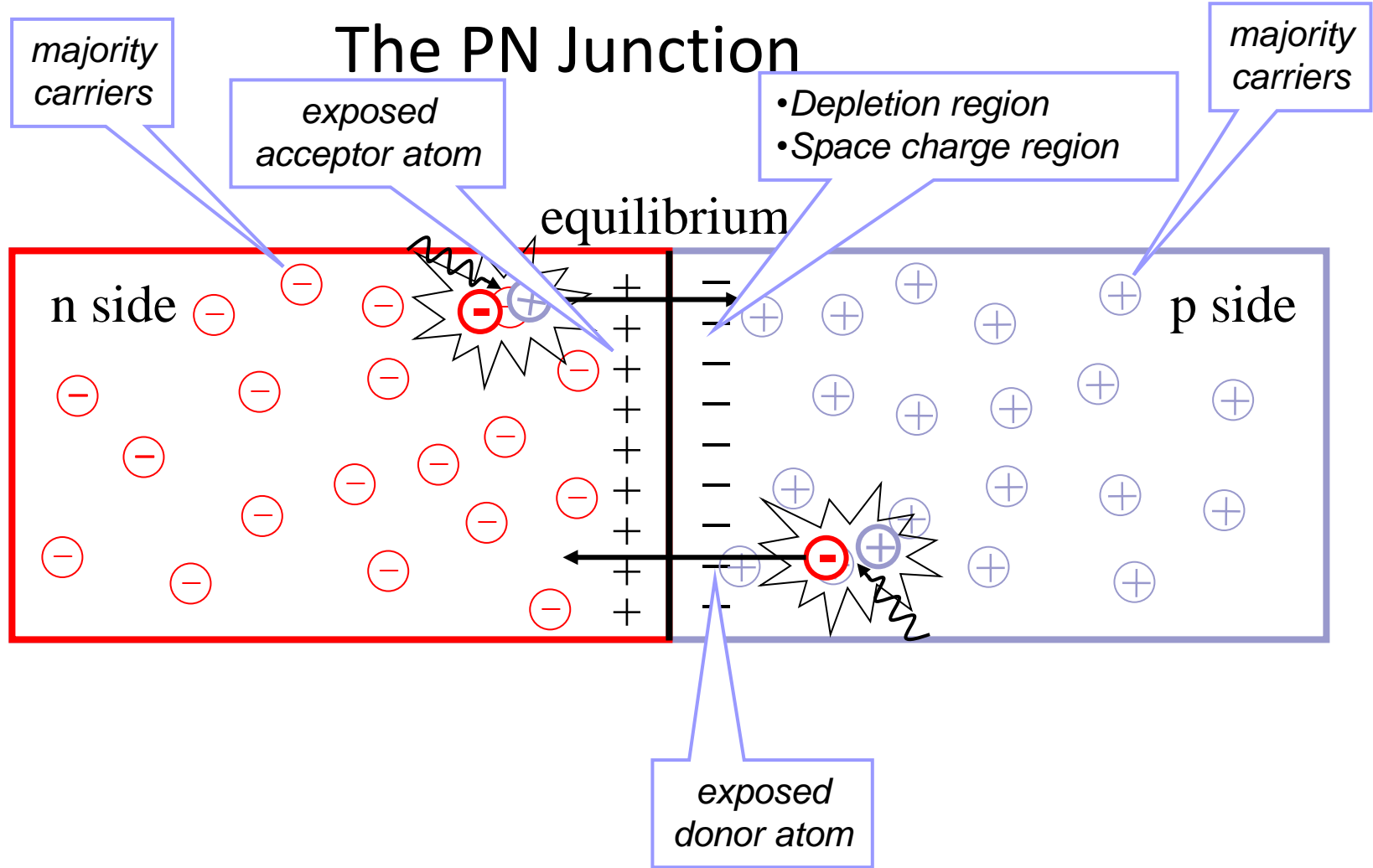


One hole per acceptor atom

The P-N junction

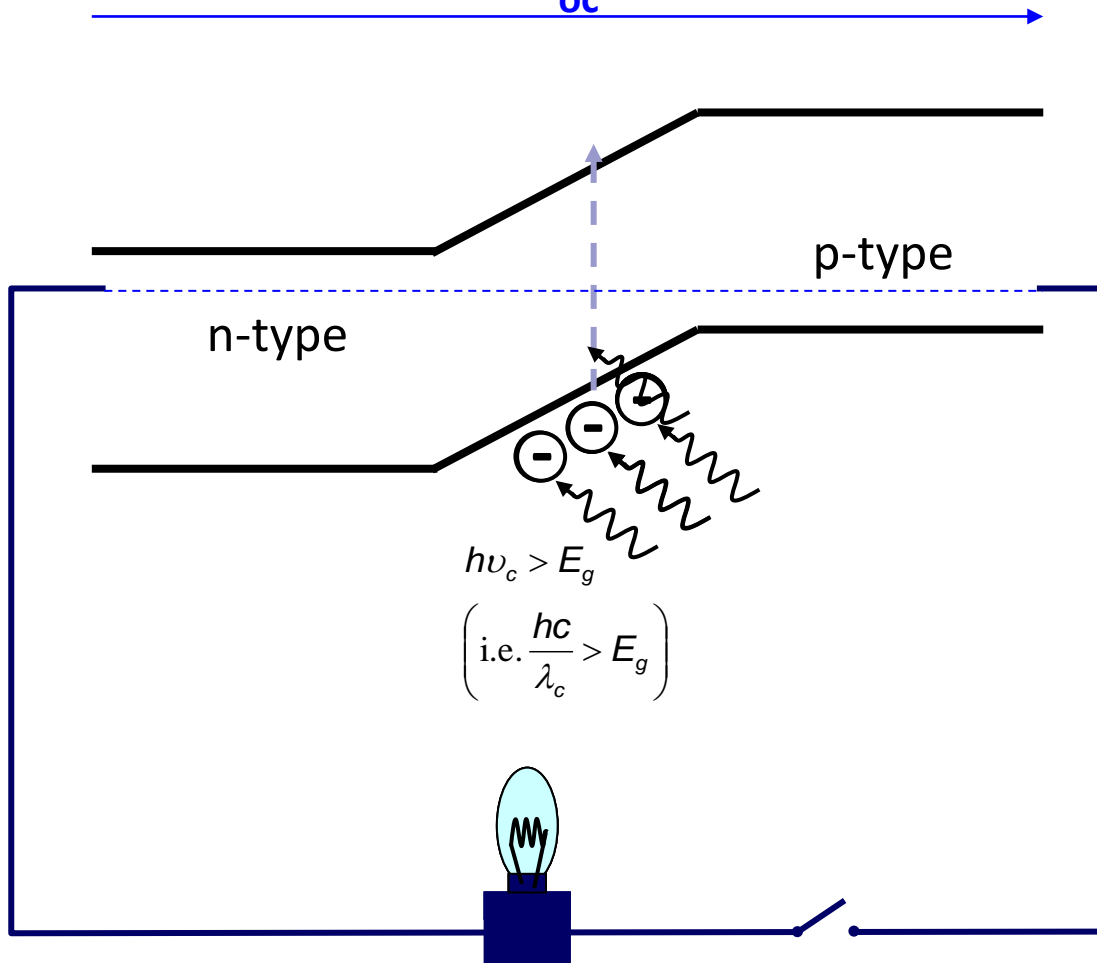
- When a P-type semiconductor and an N-type semiconductor come together they form a P-N junction.
- Excess electrons move across the junction, leaving behind positive charges (holes). Once the electrons move across, they meet up with excess holes and they disappear
- Ditto with holes
- A “dead” zone with no carriers is created called the depletion zone
- The left over positive and negative charges create an electric field
- Once light hits the junction a new electron-hole pair is formed. The formed electric field will cause the electron to go to the n-type material and the hole to go to the p-type material.
- The separation of these charges causes a potential difference/voltage.
- Connecting that voltage to a circuit allows for flow of electrons-current.

The PN Junction



The Photo Current

V_{oc}




OPEN CIRCUIT:

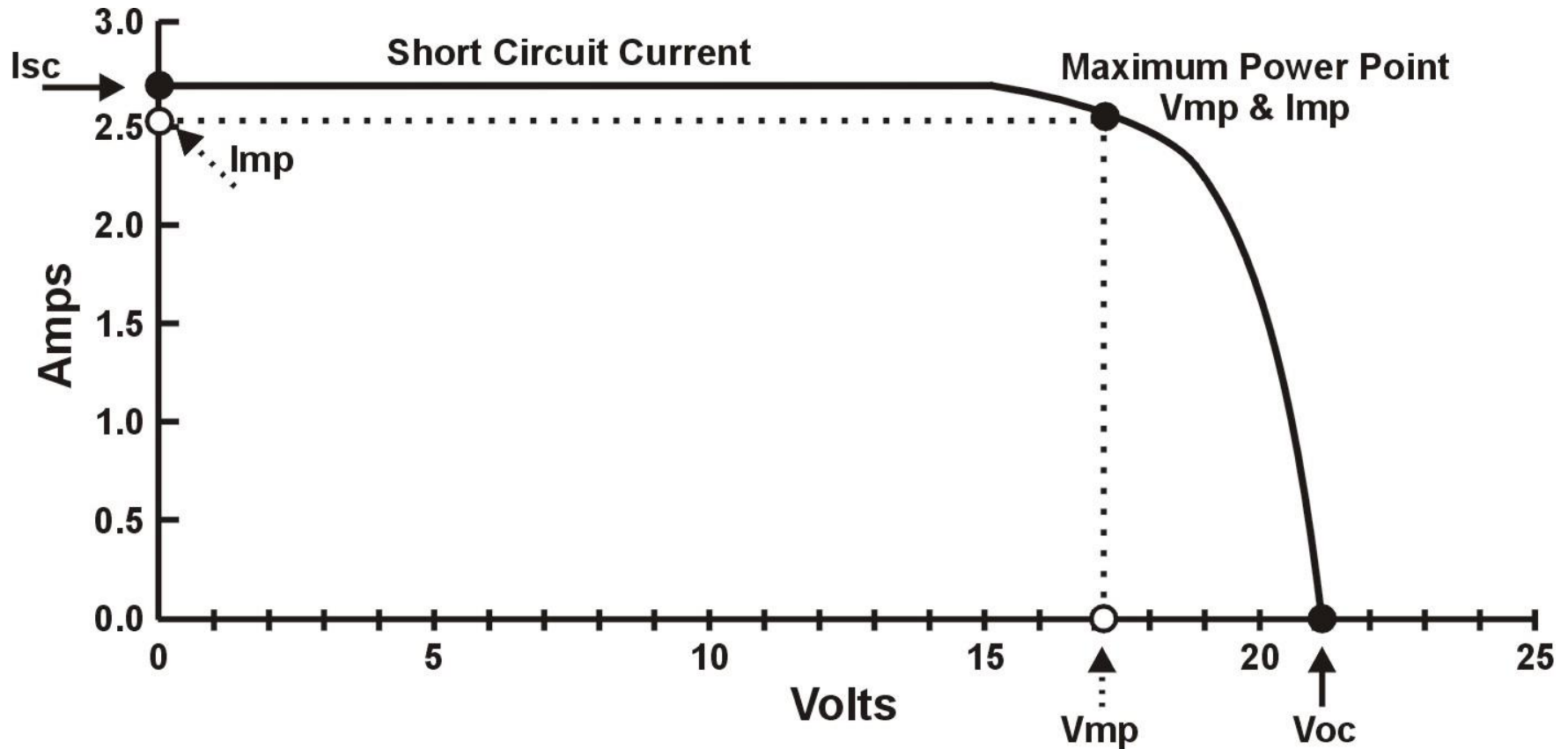
- charge builds up on the contacts
- charge buildup produces a potential voltage (V_{oc})
- only while illuminated

LOADED CIRCUIT

- **photo current** will flow & the voltage will drop
- only while illuminated

- 
- When the terminals are connected together the photo-current (I_L) has its maximum value, the short circuit current I_{sc} , or, per unit cell area, the short circuit density J_{sc} .
 - Short circuit current and short circuit current density can be used interchangeably.
 - When the contacts are isolated, (a load of infinite resistance) the potential difference has its maximum value, the open circuit voltage V_{oc}

IV curve of a solar cell



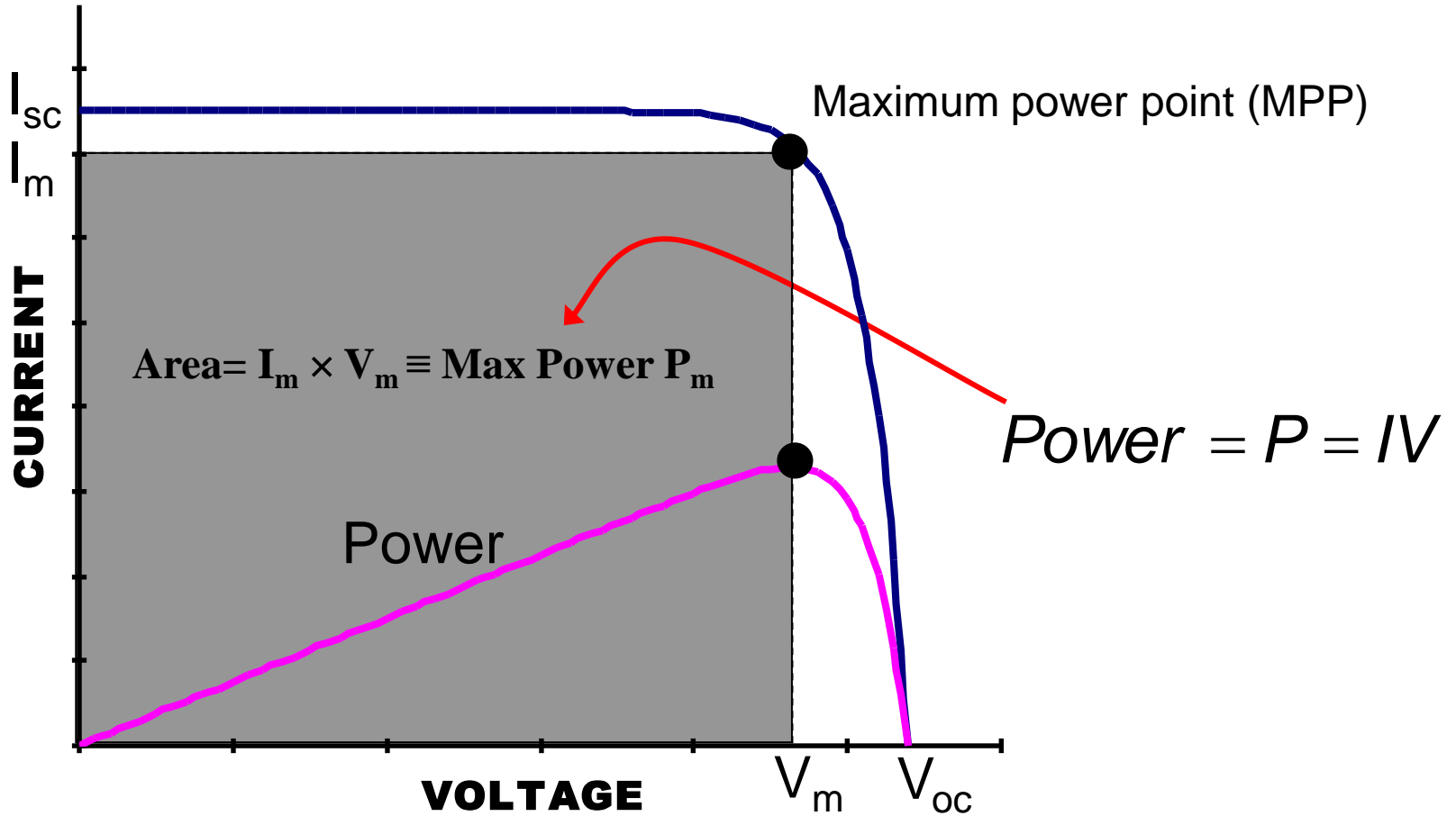
Remember that $\text{Power} = V \cdot I$, so maximum power doesn't happen when V or I have their maximum values

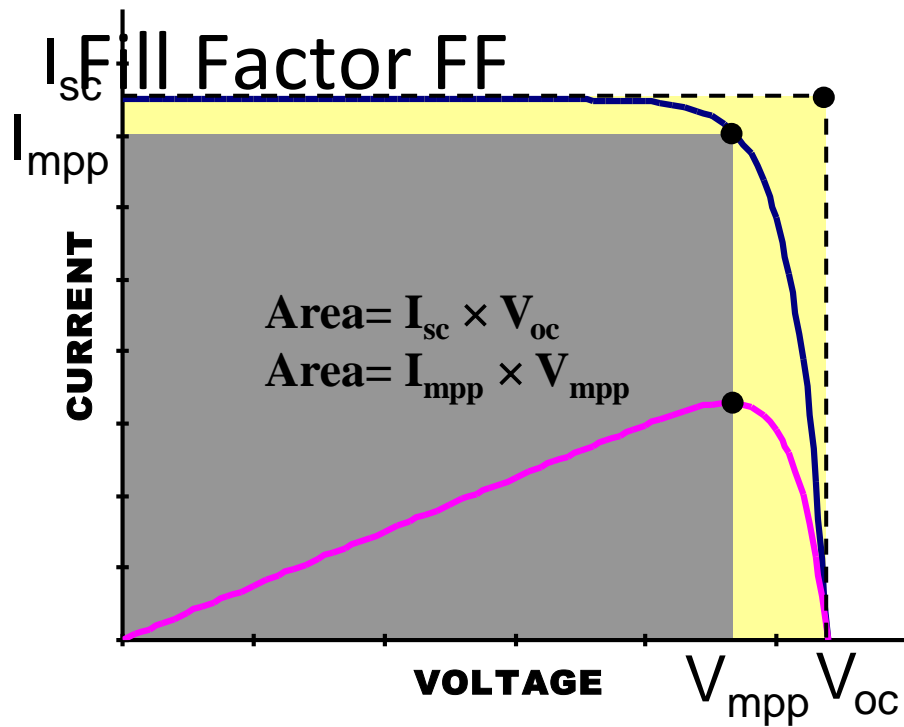
Voc
Open
Circuit
Voltage

Performance

- There are four key performance characteristics in a solar cell.
- Its short circuit current I_{sc} (or short circuit current density J_{sc})
- Its open circuit voltage V_{oc}
- Its fill factor FF
- The power conversion efficiency η .

IV and power curves





The fill factor (FF) is defined by

$$FF = \frac{I_{mpp} V_{mpp}}{I_{sc} V_{oc}}$$

At best
~0.8

Maximum theoretical power

$$P_{mpp} = I_{sc} V_{oc} \text{ (Area of yellow rectangle)}$$

Maximum actual power (MPP)

$$P_{mpp} = I_{mpp} V_{mpp} \text{ (Area of grey rectangle)}$$

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

The ratio of the two areas:

- equivalent to the fill factor FF
- a measure of how much the MPP square “fills” the theoretical potential for power

Conversion Efficiency

Efficiency: *the power density delivered at the operating point as a fraction of the incident light power density*

$$\eta = \frac{P_{mpp}}{P_{in}} = \frac{I_{mpp} V_{mpp}}{P_{in}}$$

MPP related to V_{oc} & I_{sc} by $FF = \frac{I_{mpp} V_{mpp}}{I_{sc} V_{oc}} \rightarrow I_{mpp} V_{mpp} = I_{sc} V_{oc} FF$

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

All of these quantities should be defined for a particular spectrum

i.e. **efficiency changes with spectrum**

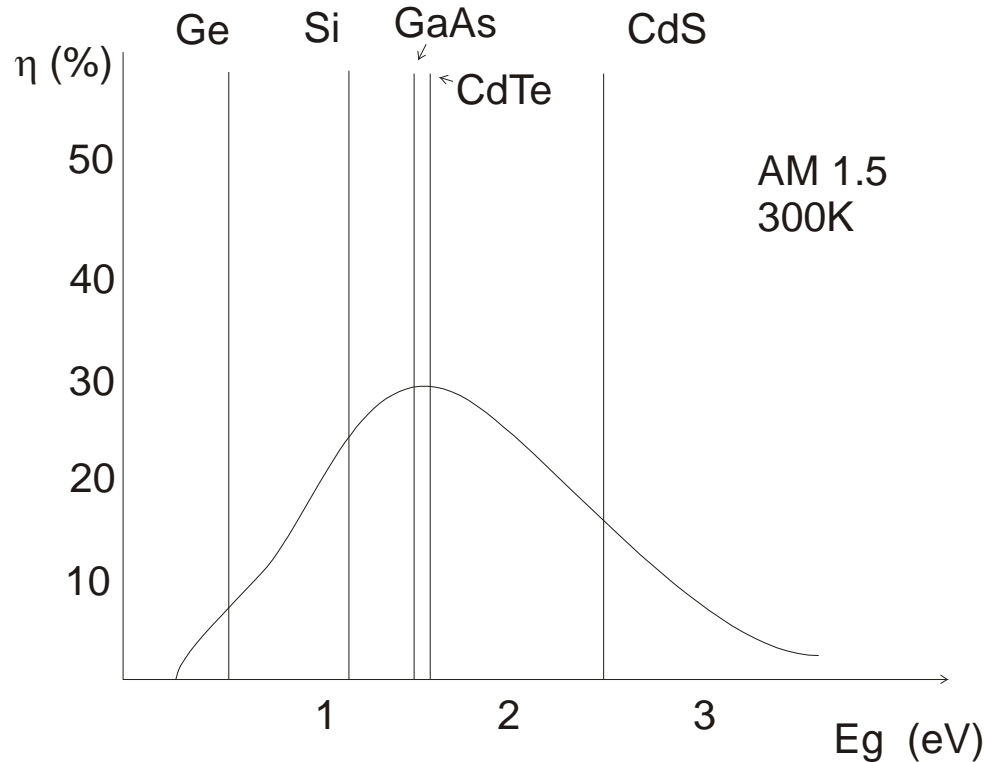
Typical numbers

- $V_{oc} \sim 0.5 - 1V$ (limited by band gap)
- J_{sc} around 20 - 40 mA cm⁻²
- Wider band gap materials give higher Voc but lower Jsc
- FF $\sim 0.7-0.8$ (ideal diode has 0.86)
- The optimum band gap for the AM1.5 solar spectrum is around 1.3-1.4 eV.
- The standard test condition (STC) for solar cells is the Air Mass 1.5 spectrum, an incident power density of 1000W/m², and a temperature of 25°C.
- The efficiency of a solar cell in AM1.5 has a theoretical limit of around 31%.
- In practice, efficiencies are much lower. Commercial modules typically have $\eta = 15-18 \%$.

Theoretical Efficiency vs Band-Gap

Band gap is most important factor for initial choice of material...

optimum band gap for the AM1.5 solar spectrum is around 1.3-1.4 eV.

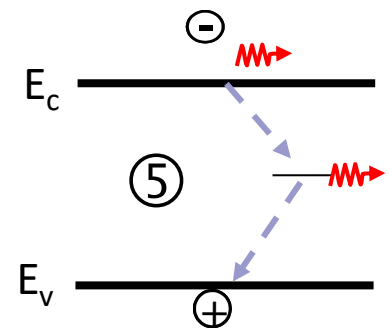
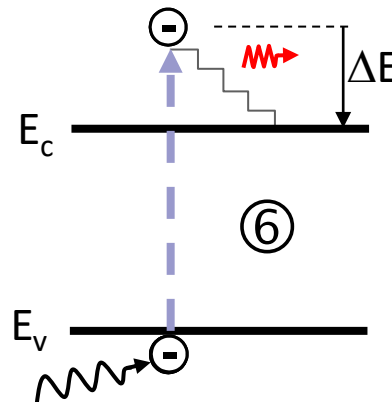
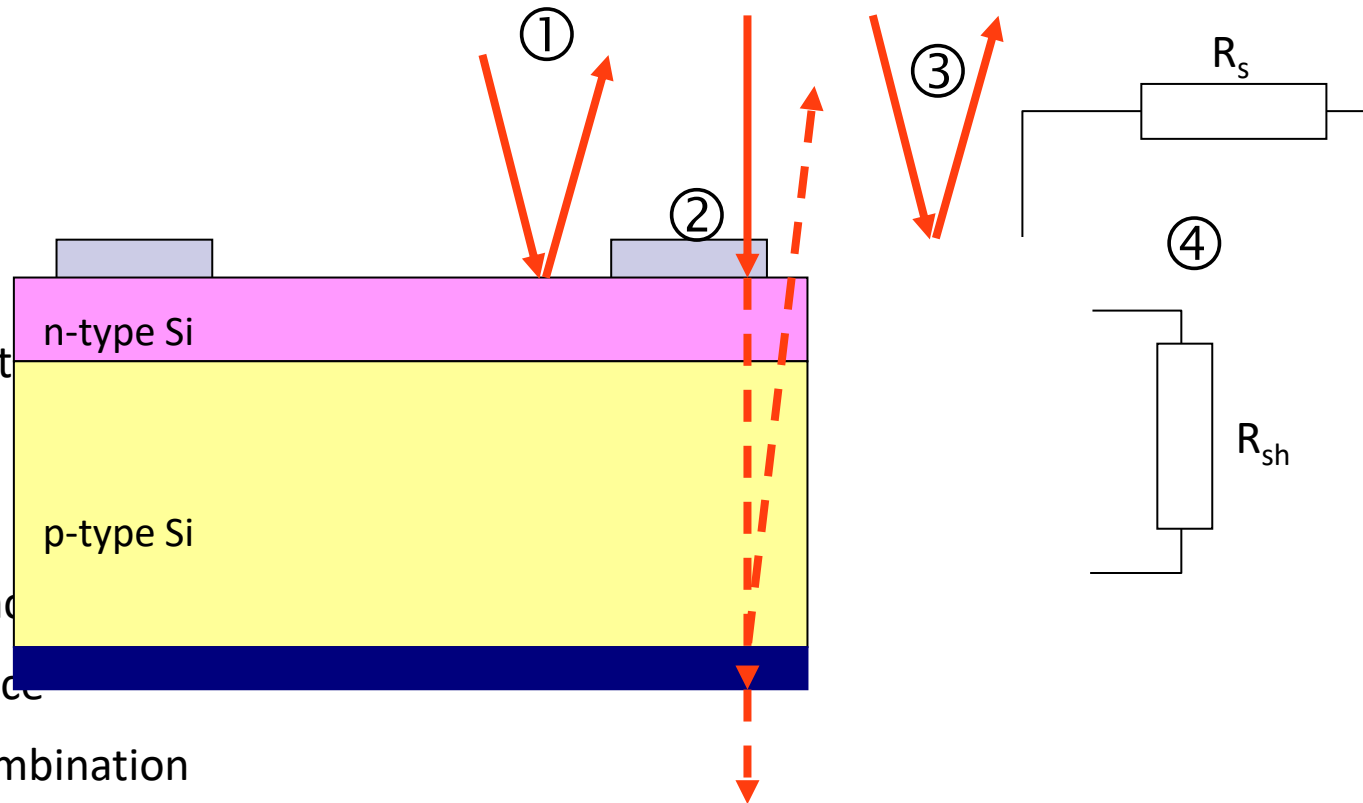


- GaAs is highest efficiency but expensive → limited to space
- Si is a lot cheaper and still high efficiency (also benefits from electronics industry symbiosis)
- New thin film materials have potential for reduced material costs (CIGS, CdTe,...)

Non-Ideal Solar Cells (performance losses)

MAIN LOSSES

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



Effect of Temperature

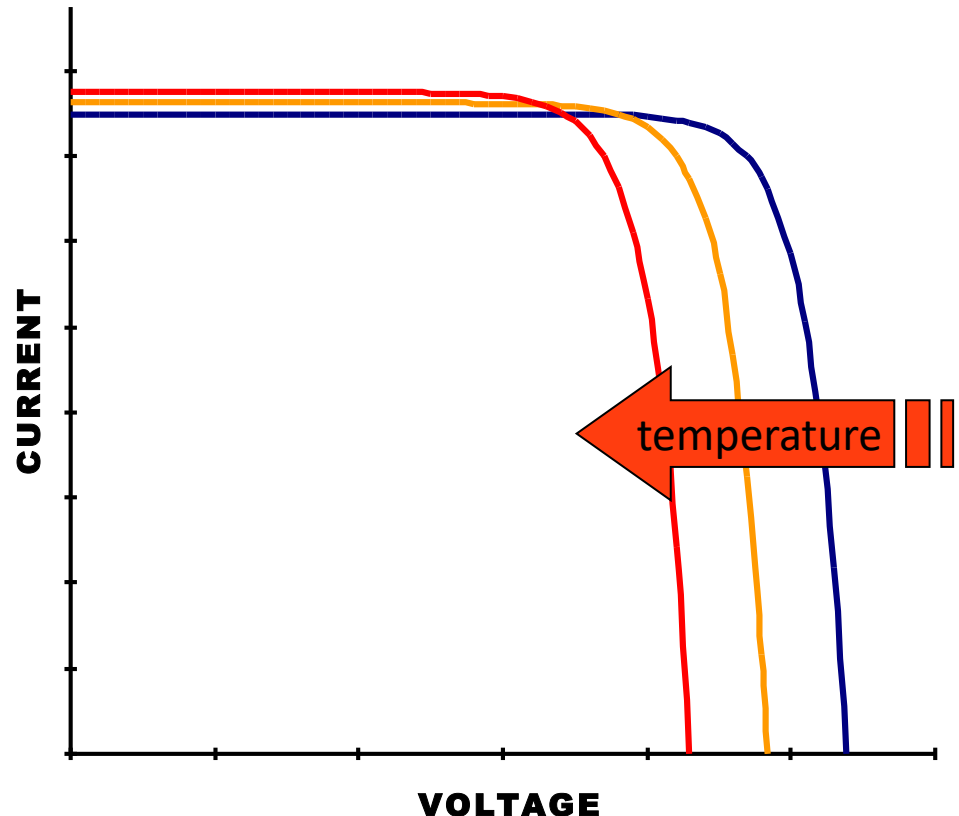
At higher temperature the band gap of a semiconductor shrinks. The reduced band gap increases the photo-current, since lower energy photons can now be absorbed, but recombination reduces Voc faster than Jsc is increased, and thus a net reduction in efficiency results.

For a typical Si solar cell

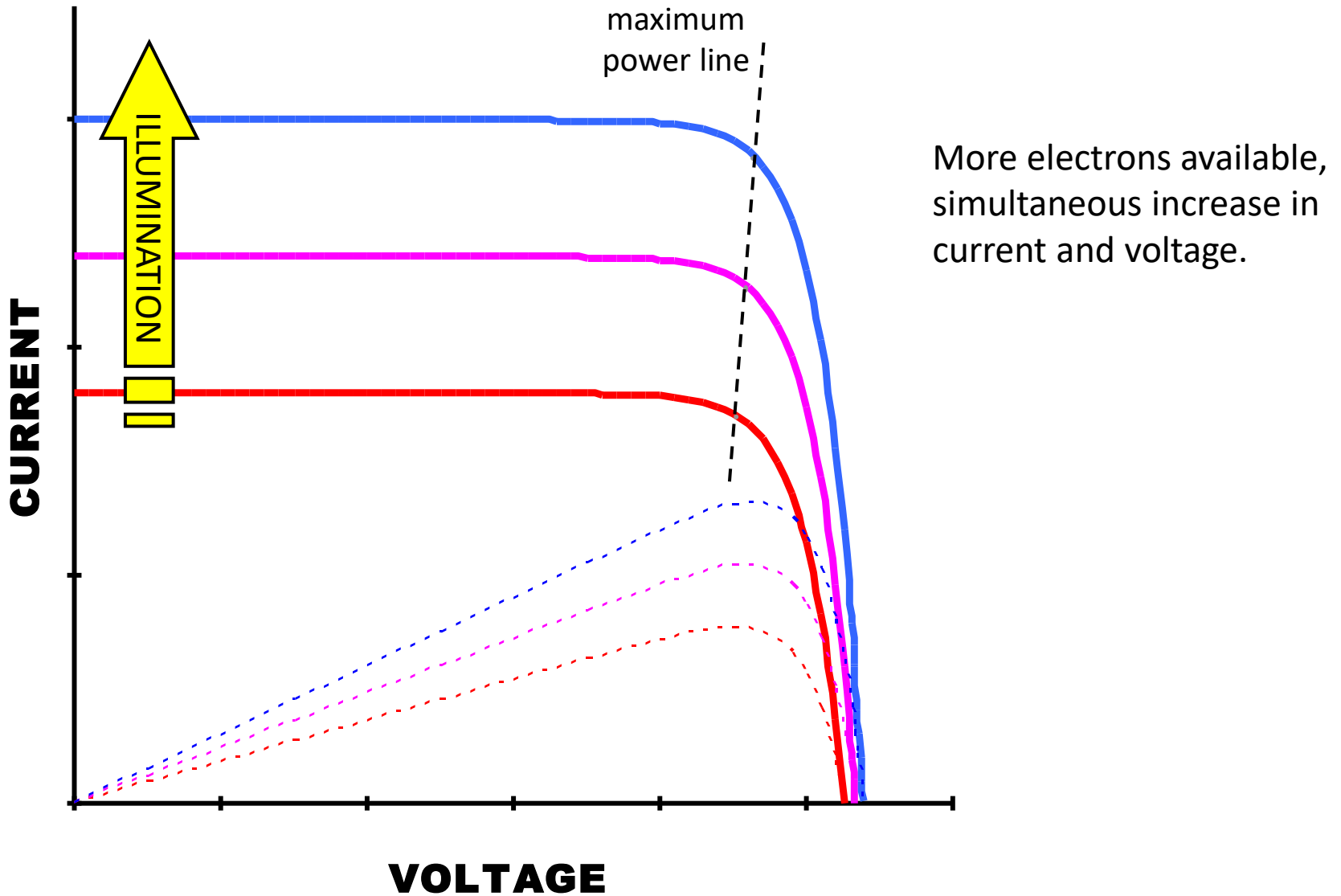
$$\frac{dJ_{sc}}{dT} \approx 0.1 \text{Am}^{-2} \text{K}^{-1}$$

$$\frac{dV_{oc}}{dT} \approx -2.2 \text{mVK}^{-1}$$

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

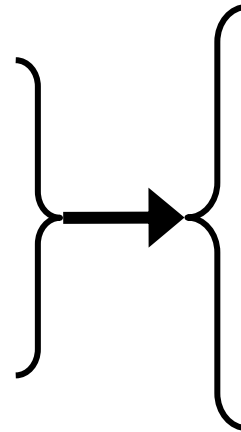


Effect of increasing irradiance



Ingredients for a high efficiency solar cell

- Good optical absorption
- Efficient charge separation
- Efficient charge transport



- Thick cell
- Good optical design
- High built in potential
- Good quality material

BUT...
the doping should not be *too* high,
or the cell *too* thick,
or....
i.e. *the optimisation game*

So why (mostly) silicon?

- Dominant terrestrial technology (started in space)
- >80% market share... equal mono/multi-crystalline split
- Junction made by furnace diffusion a shallow layer of phosphorus (n-type) into a lightly doped p-type wafer. (200-300 μm)
- Typical spec's: $E_g \sim 1.1 \text{ eV}$ (c.f. 1.4eV ideal), $V_{oc} \sim 0.5-0.7\text{V}$ (low), $J_{sc} \sim 30-40\text{mAcm}^{-2}$ (AM 1.5) (high)

Pre-production advances:

Sanyo HIT **cell** >20% (18% in production)

SunPower A300 **cell** > 20%

BP Solar LGBG **cell** > 18%

Commercial Modules \sim 13-16% typical

Second most abundant element on Earth, after oxygen

High Performance = High Quality Material = High Cost (*typically*)

BUT it's getting cheaper **AND** there are options besides Si