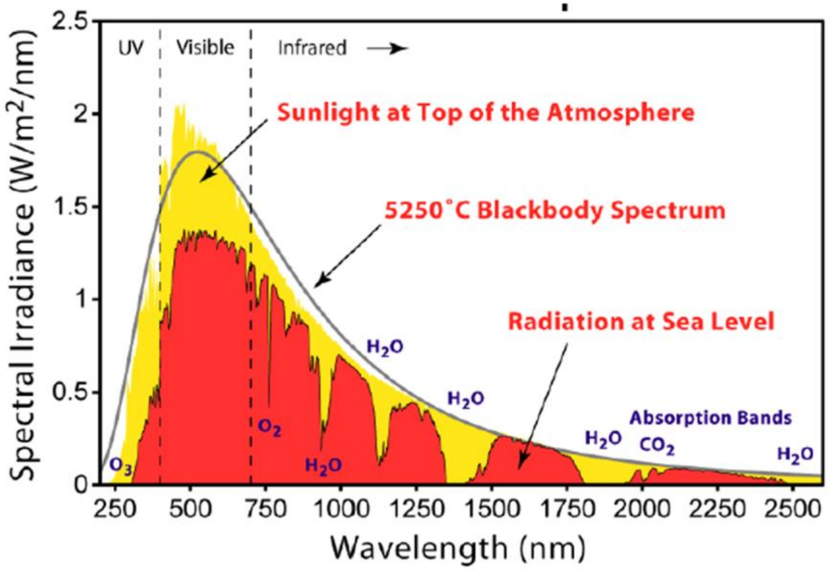
Class 10
Solar cells and light emitting diodes

01.04.2025

- Photovoltaic devices
  - Working mechanisms
  - Figures of Merit
  - Considerations on the PV materials
  - Device generations

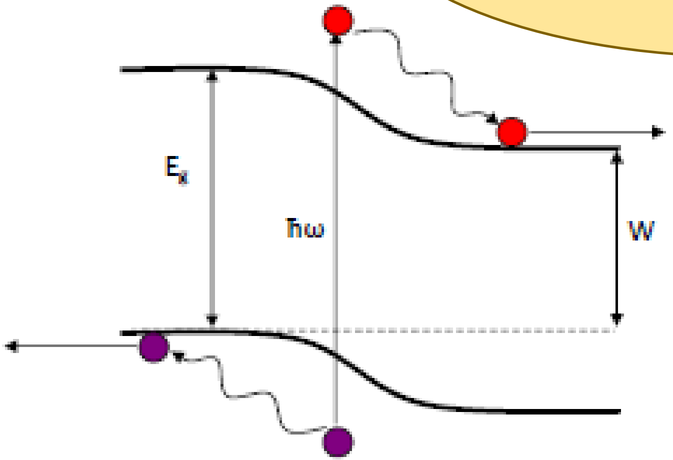
- Light Emitting Diodes (LEDs)
  - Working mechanism
  - Figures of Merit
  - Challenges

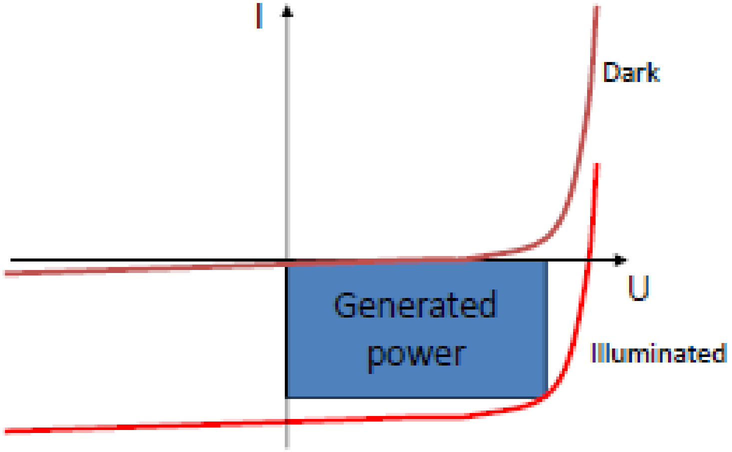
(Inorganic) Solar Cells: Working Principle



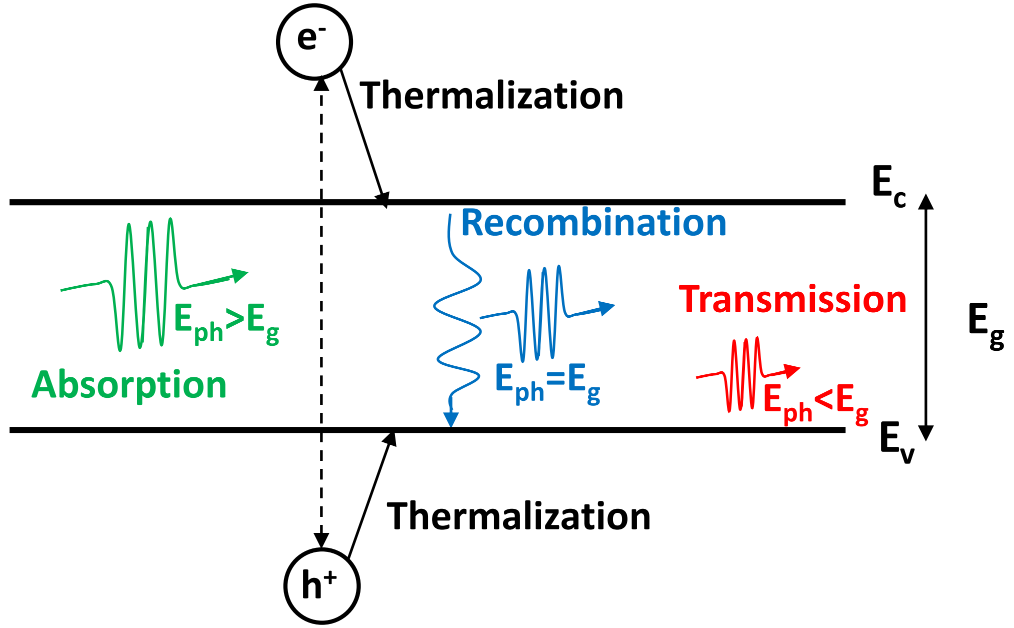
- Optical Absorption
- Carrier Generation (energy conversion)
- Current extraction

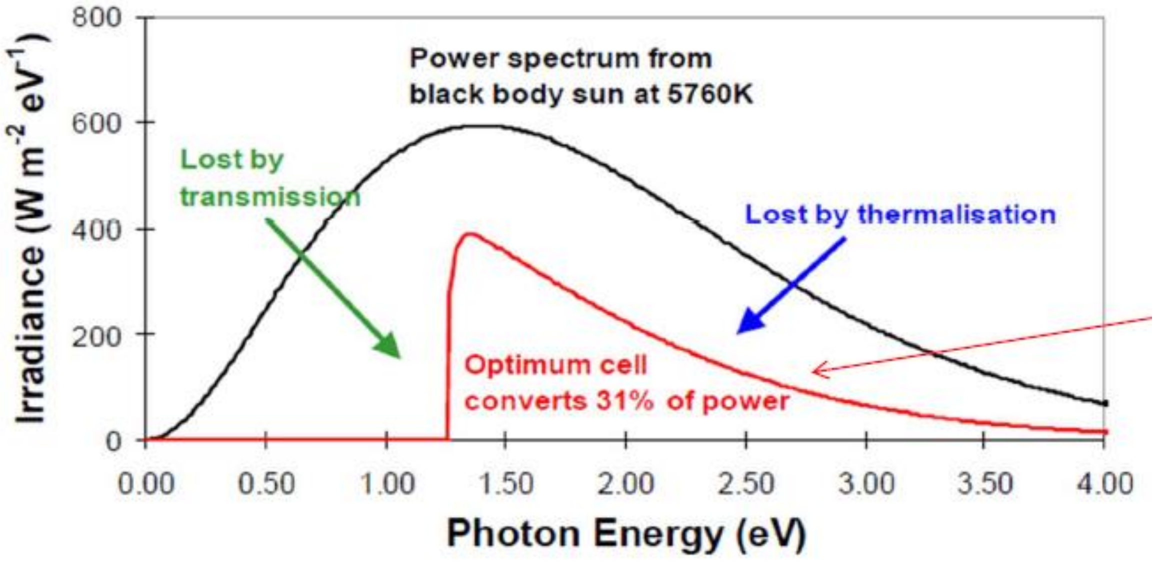
A solar cell (or photovoltaic cell) is a device which converts the light emitted by the Sun into electric power.





Photon absorption and optical losses





Absorption occurs if $E_{ph} > E_g$

- Thermalization of carriers (reaching the band min/max)
- Non-radiative recombination (ex. trap-assisted mech.)
- Radiative recombination (photon emission with $E_{ph} = E_g$)

Transmission occurs if $E_{ph} < E_g$(energy loss)

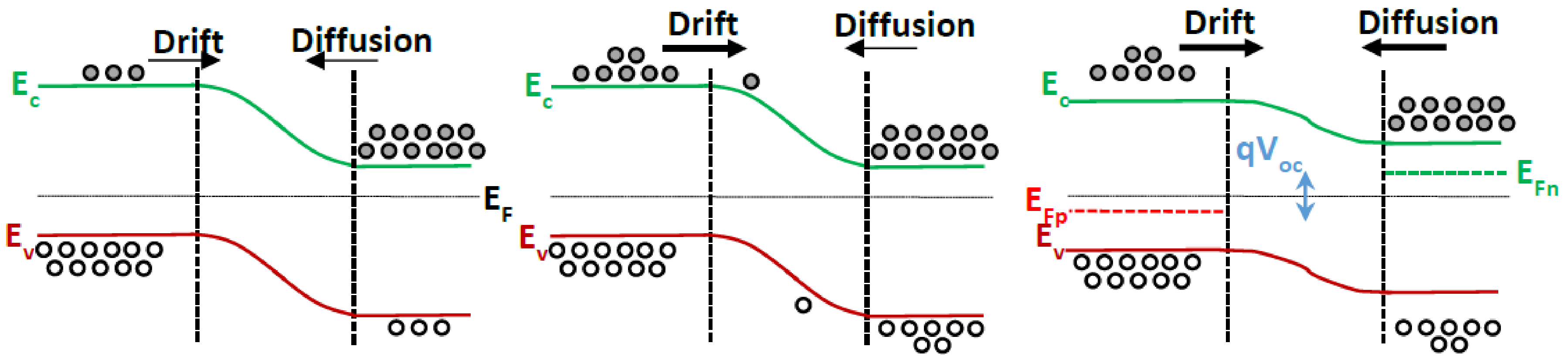
The balance of these mechanisms strongly depends on the band gap energy, which in turn determines the portion of solar spectrum that can be converted.

For this reason the maximum theoretical efficiency of a solar cell (thermodynamic limit known detailed balance limit) depends only on E_g.

The detailed balance limit set the maximum theoretical efficiency of a single junction solar cell to 33%.

Charge transport in solar cell

a) *Equilibrium in dark* b) *Short-circuit under light* c) *Open Circuit under light*

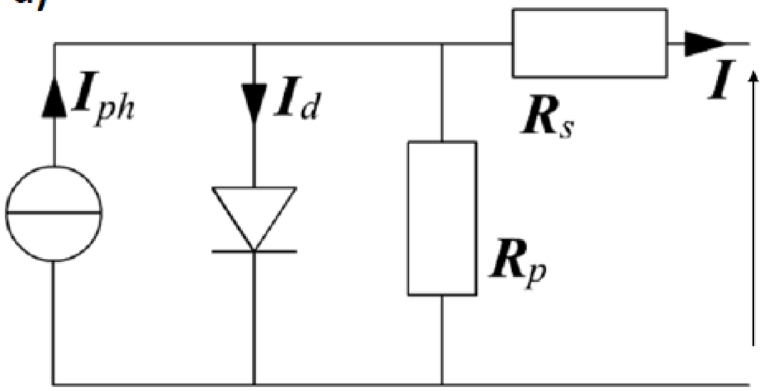


Drift = Diffusion

Drift > Diffusion

Drift = Diffusion

d)



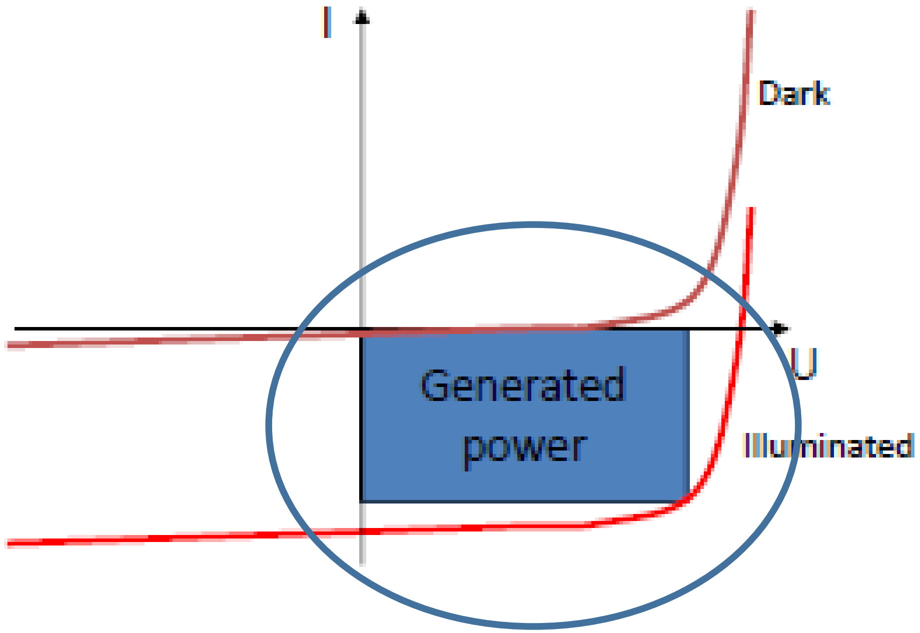
Equivalent electric circuit of a photovoltaic cell:

- I_{ph} (photocurrent generator)
- I_d (ideal diode)
- R_p (parallel or shunt resistance)
- R_s (series resistance)

Figures of Merit

$$J = J_{ph} - \underbrace{J_0\left(\exp\left(\frac{e(V + JAR_S)}{nkT}\right) - 1\right)}_{\text{Characteristic of the diode in dark conditions}} - \underbrace{\frac{(V + JAR_S)}{AR_P}}_{\text{Leakage current}}$$

↑ Photocurrent generation



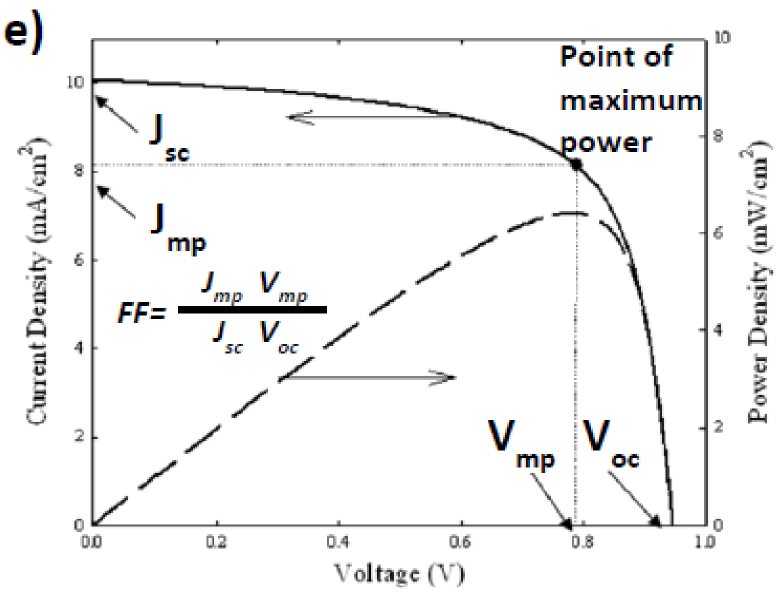
Figures of Merit

$$J = J_{ph} - J_0\left(\exp\left(\frac{e(V + JAR_S)}{nkT}\right) - 1\right) - \frac{(V + JAR_S)}{AR_P}$$

Photocurrent generation

Characteristic of the diode in dark conditions

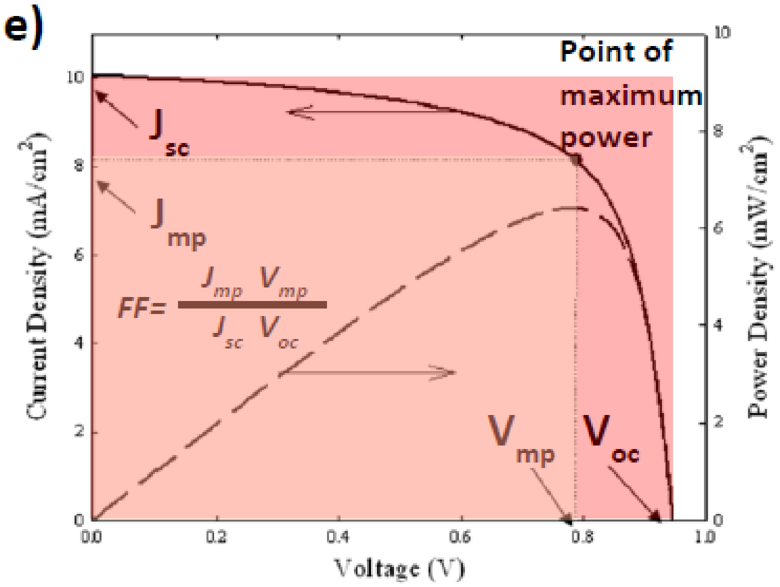
Leakage current



Figures of Merit

$$J = J_{ph} - J_0\left(\exp\left(\frac{e(V + JAR_S)}{nkT}\right) - 1\right) - \frac{(V + JAR_S)}{AR_P}$$

Photocurrent generation — Characteristic of the diode in dark conditions — Leakage current



$$\mathbf{FF} = \frac{J_{mp}V_{mp}}{J_{sc}V_{oc}}$$

$$\boldsymbol{P_{max}} = J_{sc}V_{oc}FF$$

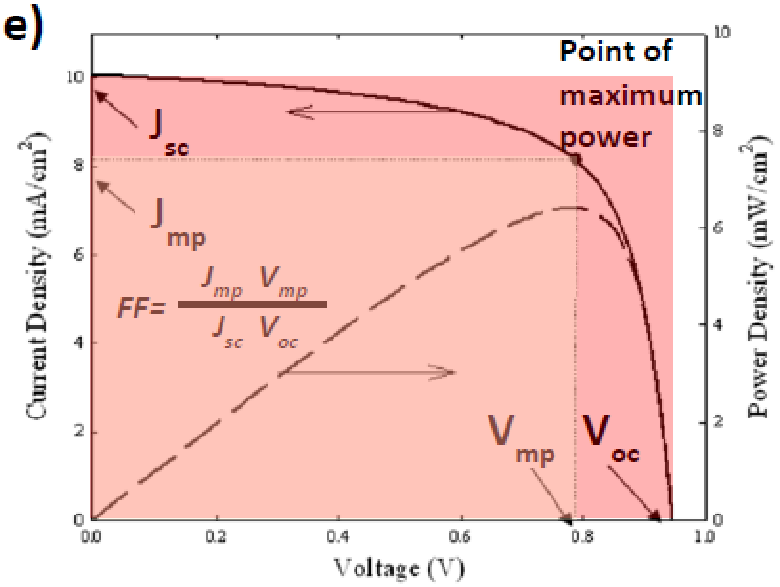
$$\boldsymbol{\eta} = \frac{J_{sc}V_{oc}FF}{P_{in}}$$

Four experimental parameters:
$J_{sc}, V_{oc}, J_{mp}, V_{mp}$

Figures of Merit

$$J = J_{ph} - J_0\left(\exp\left(\frac{e(V+JAR_S)}{nkT}\right)-1\right) - \frac{(V+JAR_S)}{AR_P}$$

Photocurrent generation — Characteristic of the diode in dark conditions — Leakage current



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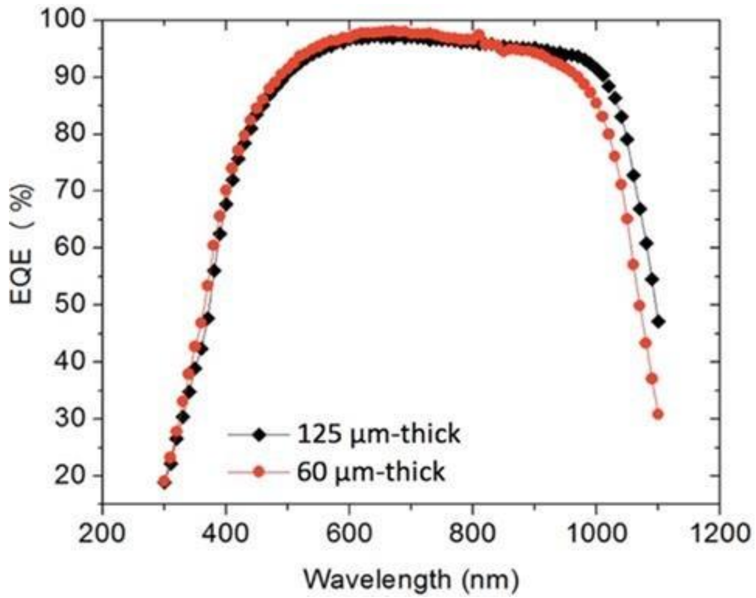
Four experimental parameters:

$J_{sc}, V_{oc}, J_{mp}, V_{mp}$

External Quantum Efficiency (EQE)



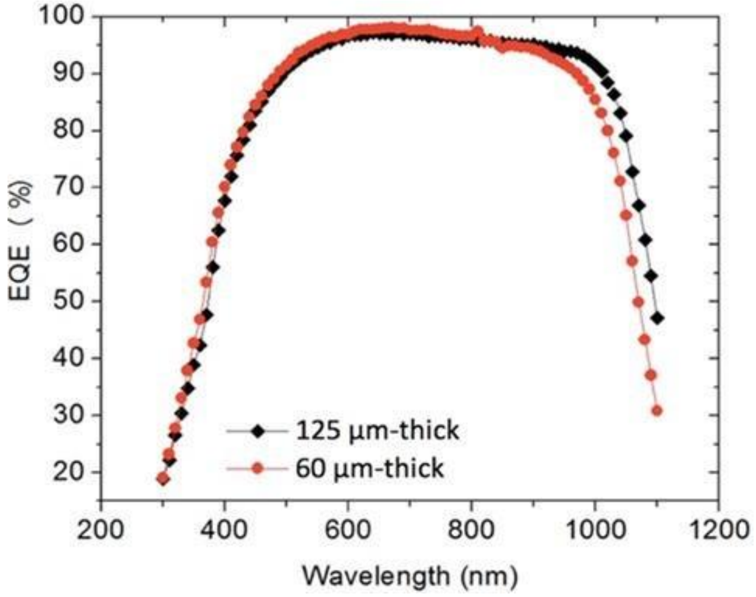
$$\boldsymbol{\eta(\lambda)} = \frac{J_{sc}V_{oc}FF}{P_{in}(\lambda)}$$

Questions:

Can you guess which semiconductor can have such an EQE?

Exercise

How the EQE curves vary with the thickness? Why?

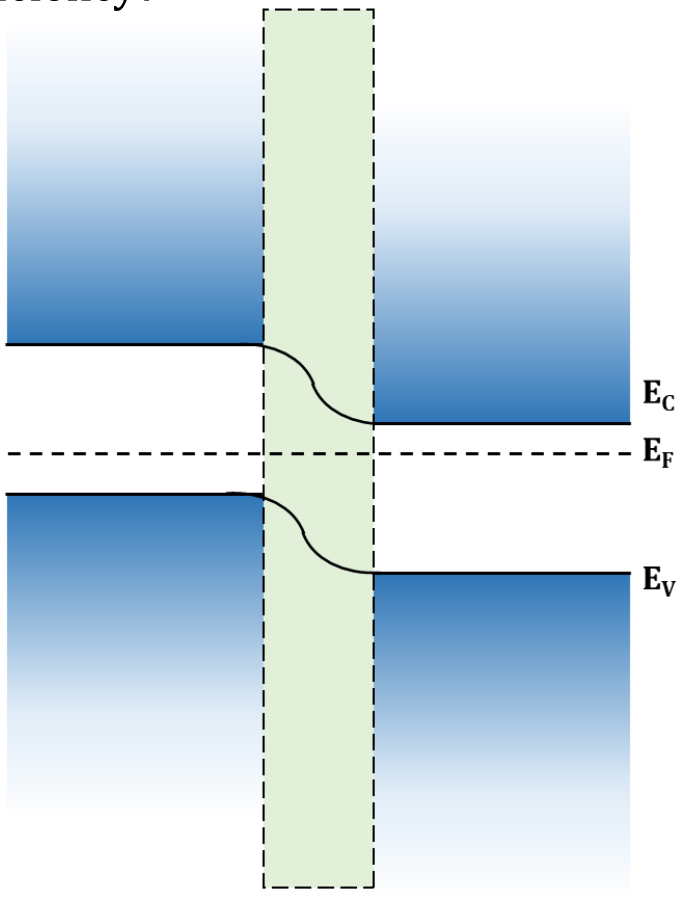


10 minutes

Consider a solar cell containing a pn homojunction.

Is the space charge region extension affecting the performance of the PV device? If so, how?

Which material parameters are relevant to maximize the efficiency?



Exercise

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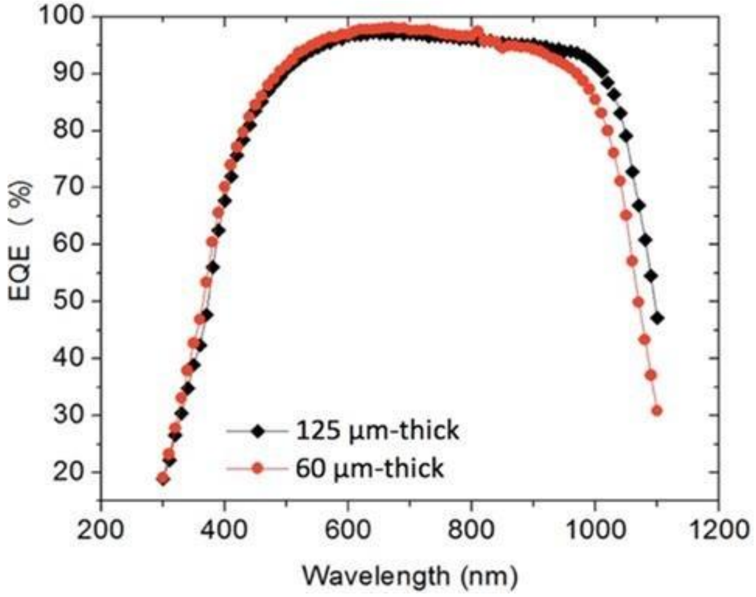

To be solved in Class

Exercise

To be solved in Class

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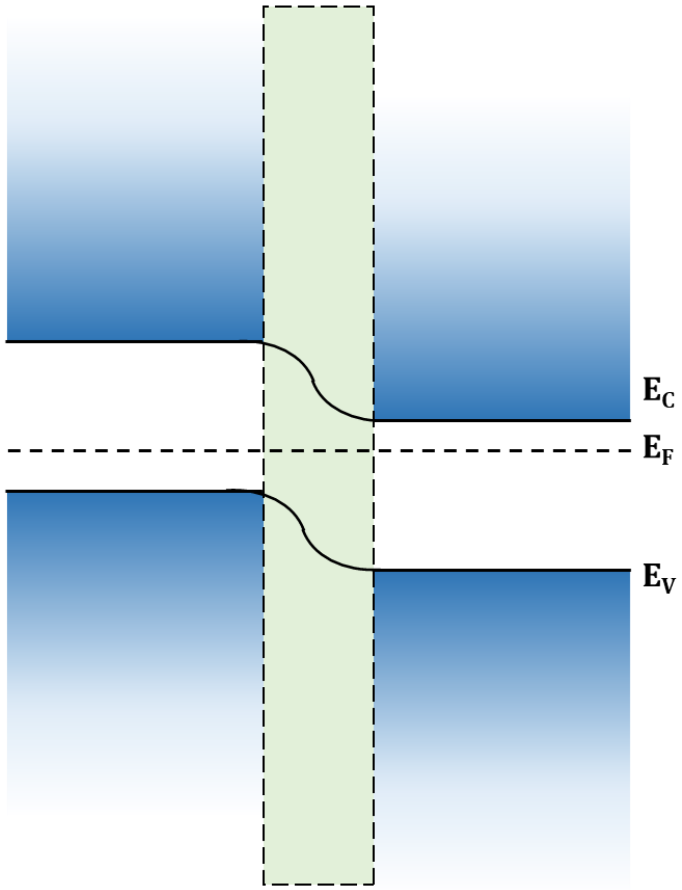

Exercise

To be solved in Class

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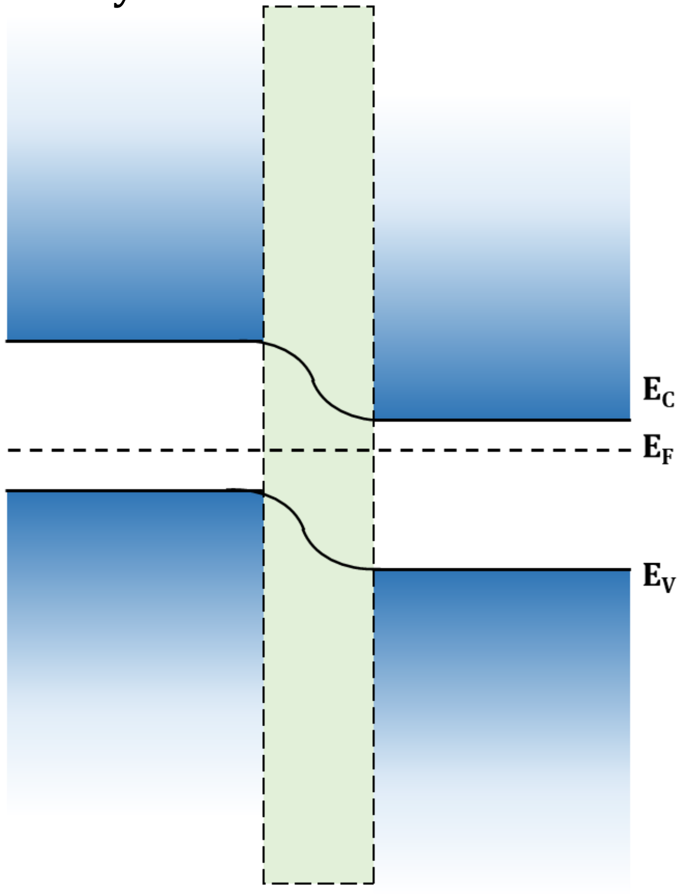
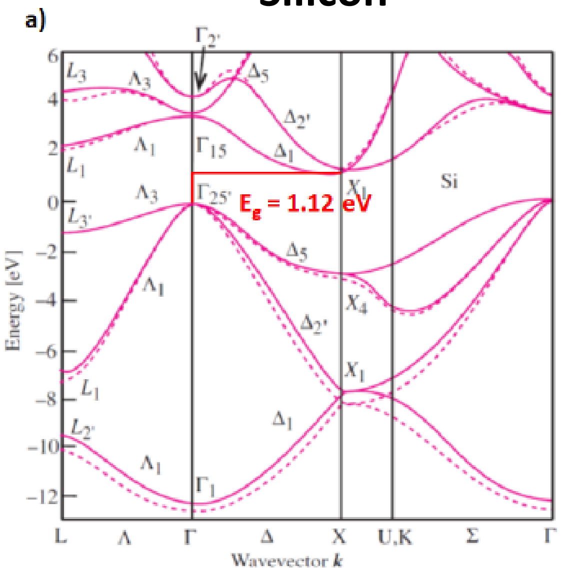


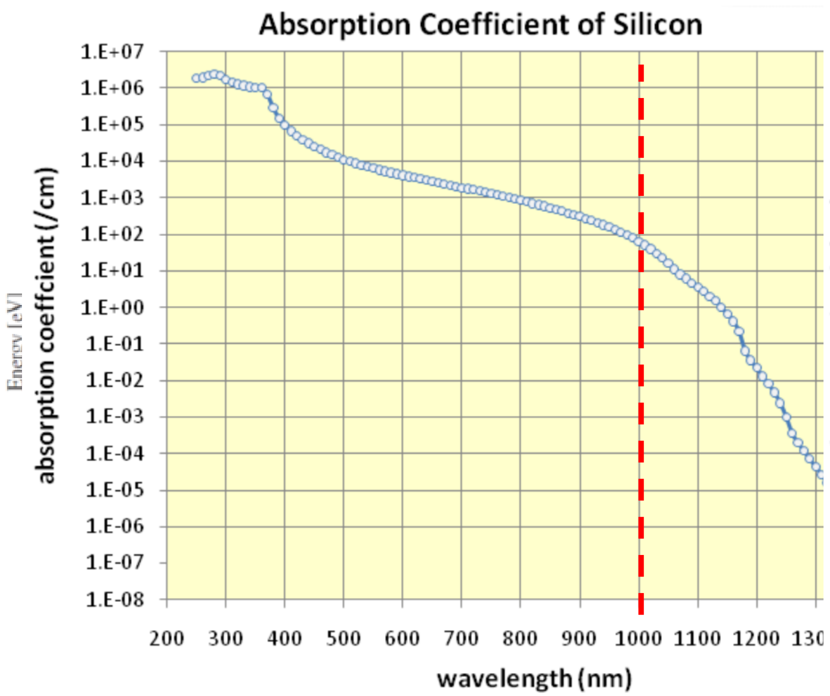
Which one is the best photovoltaic material?

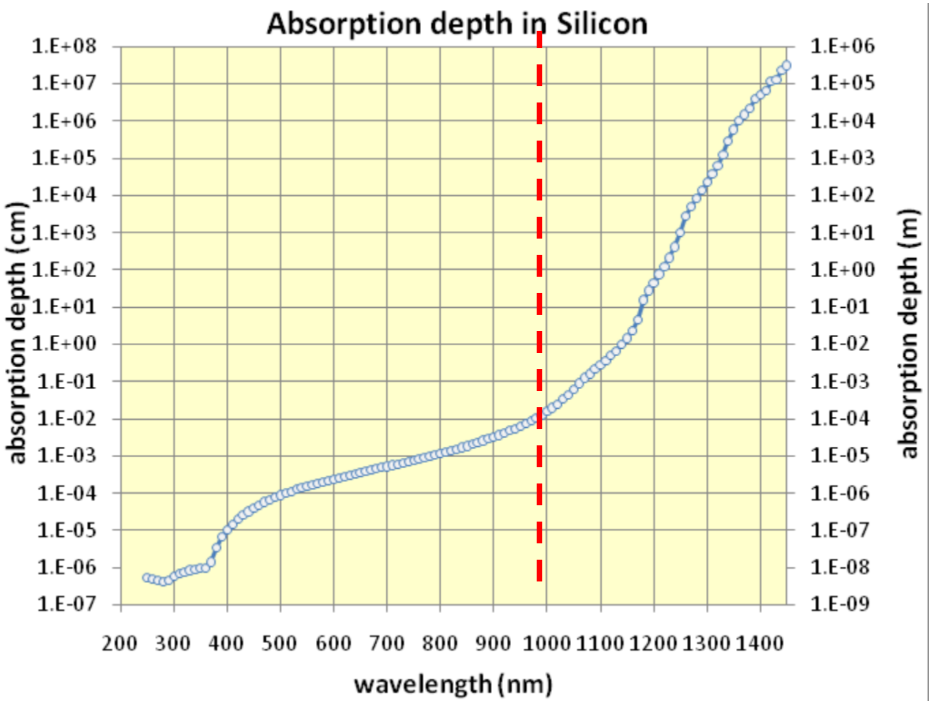
Why?

Material comparison: Silicon

Silicon





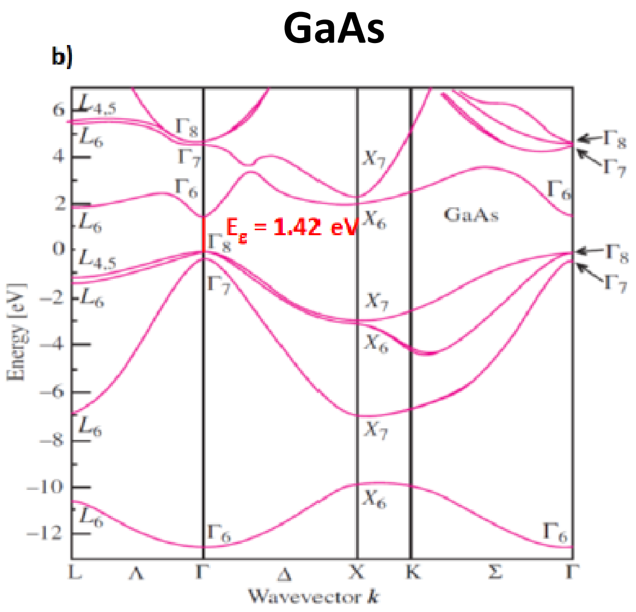


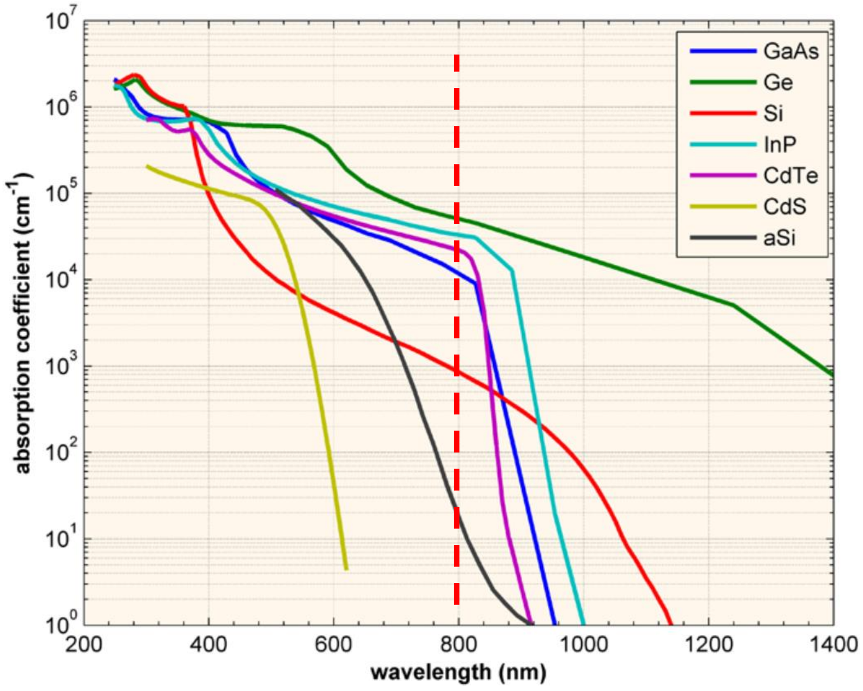
Absorption Coefficient @1000 nm ~ 10^2 cm^{-1}

Penetration depth @1000 nm ~ 100 µm

Minority carrier diffusion length 100-300 µm

Material comparison: GaAs





The thickness of the active region can be reduce by 100 times

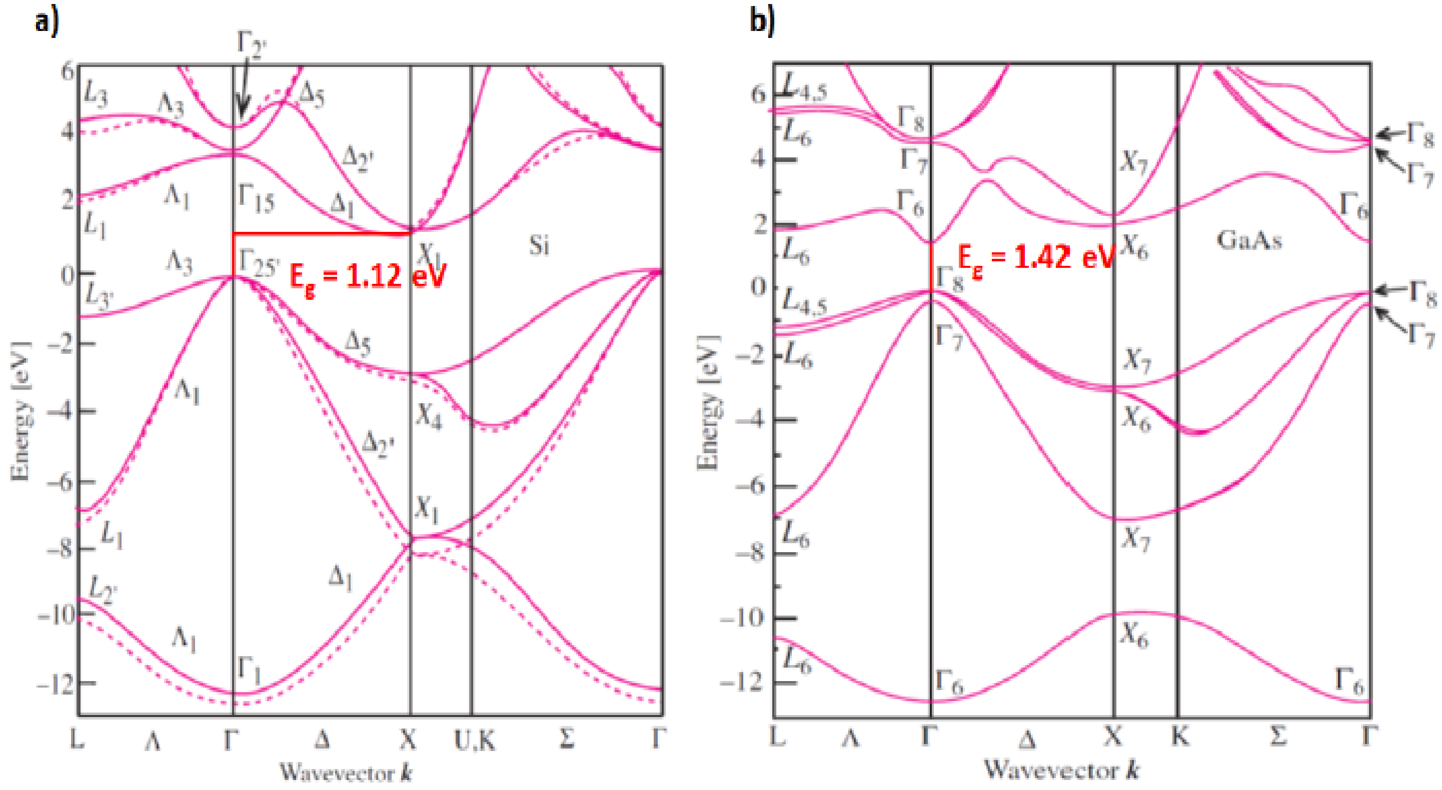
GaAs absorbs 100 time more than Si

Absorption Coefficient @800 nm	~ 10^4 cm^{-1}	Penetration depth @800 nm	~ 0.1-1 µm	
	Minority carrier diffusion length	0.1-10 µm	L is 100 times lower in GaAs	

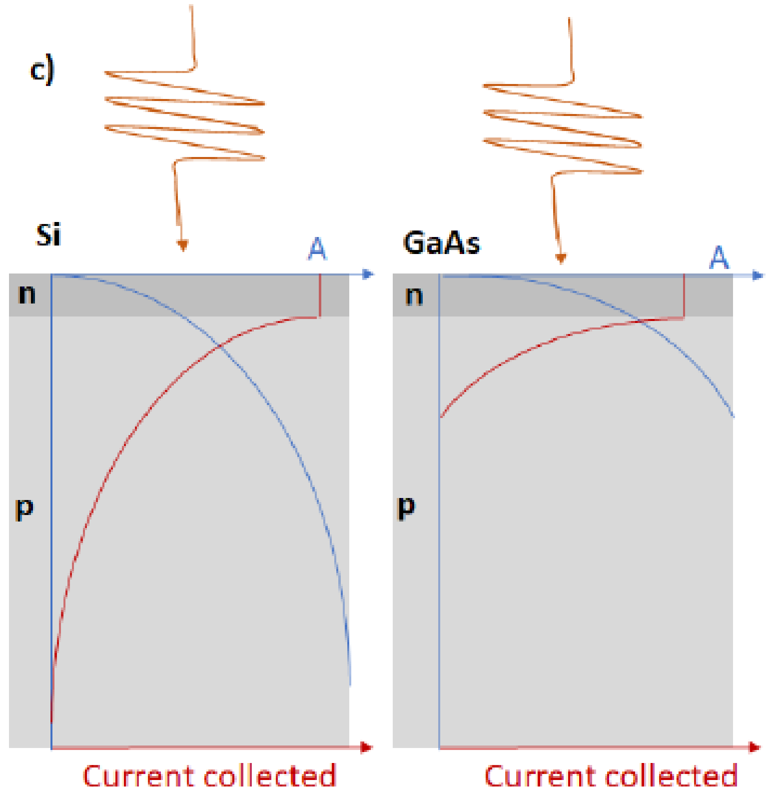
Material comparison: Silicon vs GaAs

Band Structure

Silicon **GaAs**

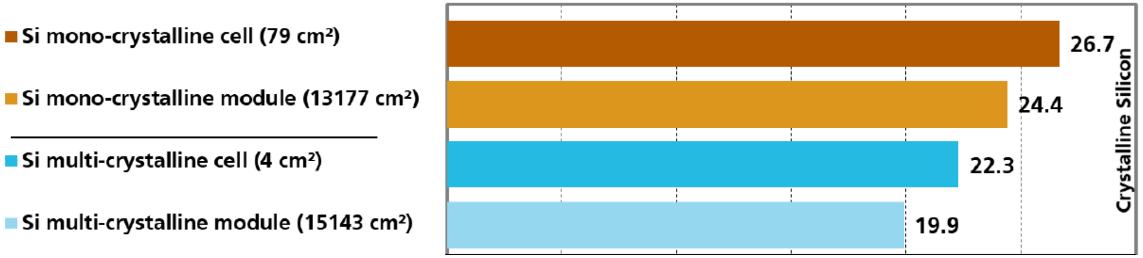


Effect on PV active region



1° and 2° generation solar cells

1° generation solar cells



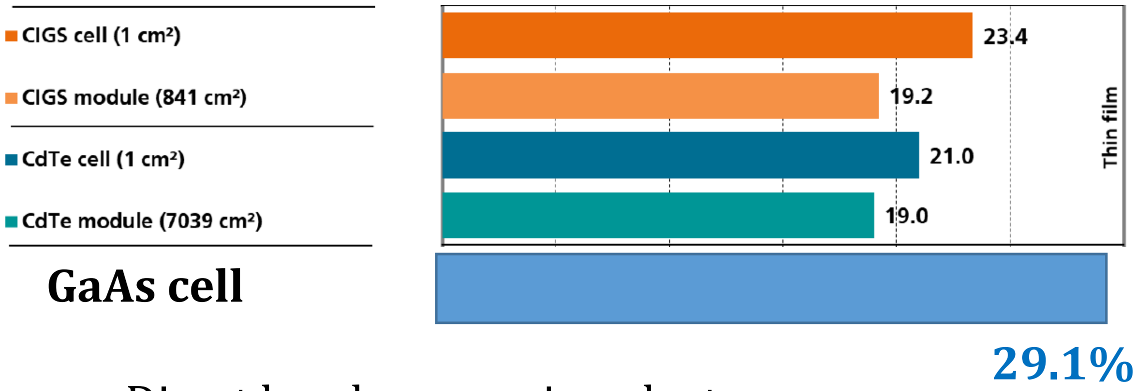
Monocrystalline polycrystalline Si

Large thickness (200-300 μm)

Non-toxic, cheap* active material

* Si is an earth-abundant material but it must undergo to several manufacturing process to make it suitable for high-efficiency PV application (solar-grade silicon)

2° generation solar cells



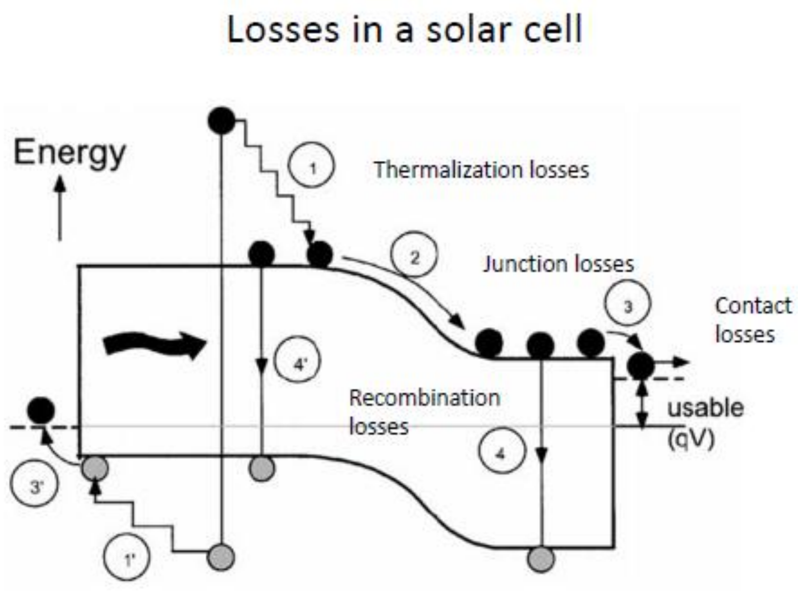
Direct band gap semiconductor

Thin films (usually below 5 μm)

Typical semiconductors for II generation solar cells are:

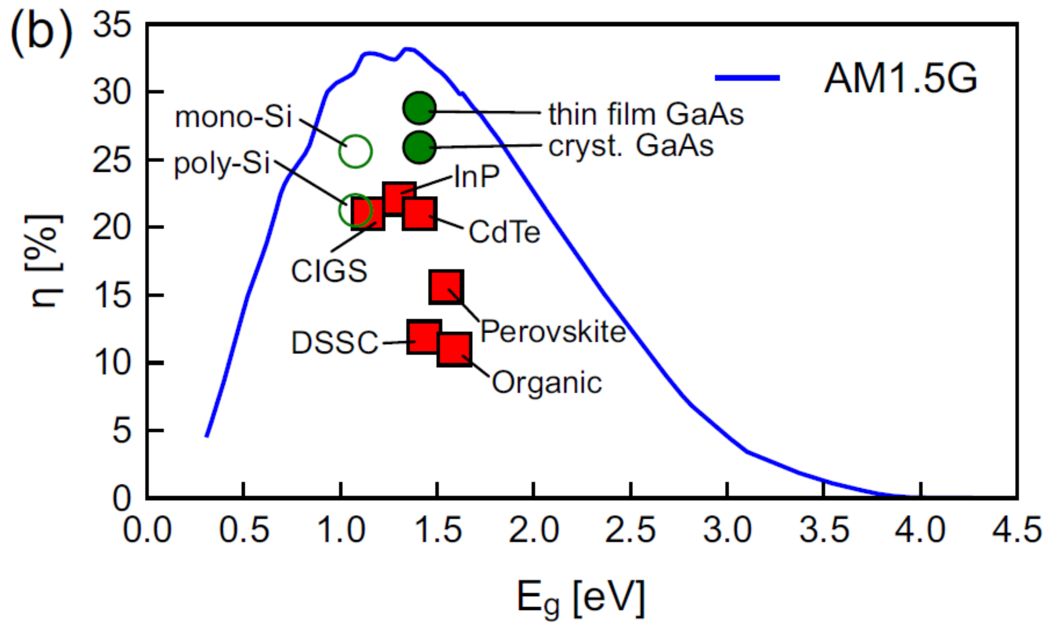
- III-V (GaAs, InP, ternary alloys),
- CIGS, CIS
- CdTe
- CdS

Intrinsic and extrinsic losses



Pagliaro et al, Flexible solar cells, John Wiley, NY 2008

Detailed Balance Limit
(= thermodynamic limit)



Extrinsic Losses:

- Contact Losses
- Non-radiative recombination

Intrinsic Losses:

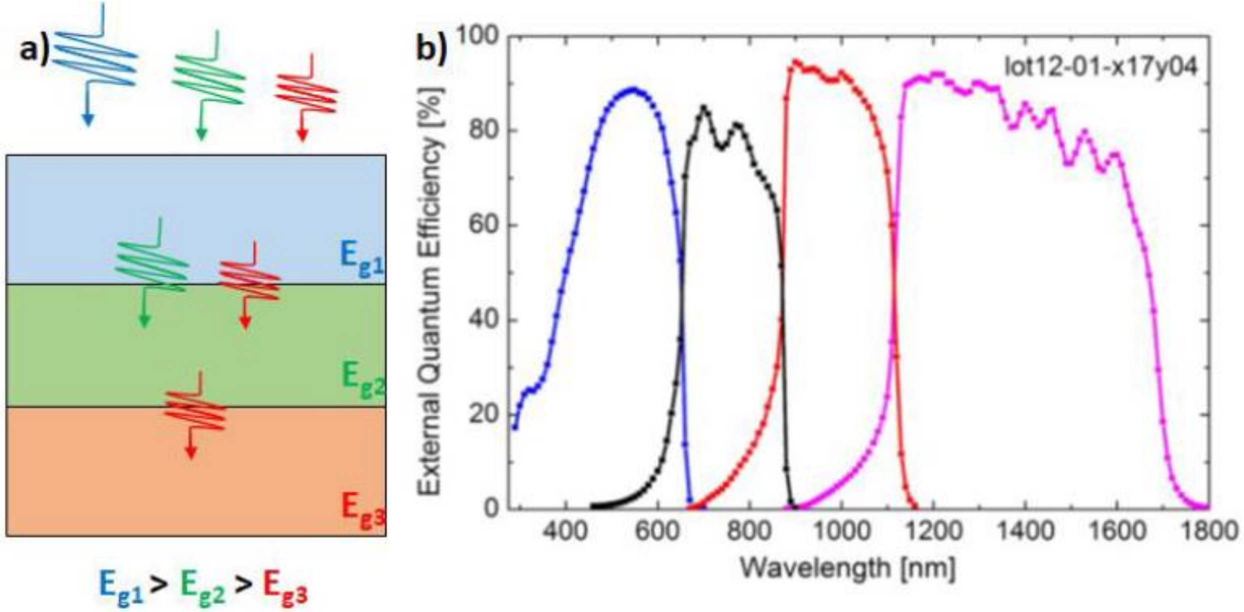
- Transmission
- Thermalization
- Radiative recombination

How to overcome this themodynamic limit?

3° generation solar cells – case study: multijunction solar cells

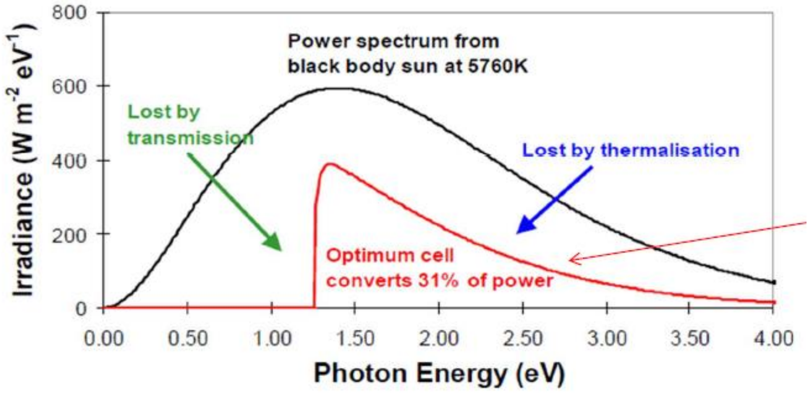
3° generation Solar Cells: all the technologies who aim at overcoming the thermodynamic limit such as hot carrier extraction solar cells and multijunction solar cells.

Multijunction solar cells

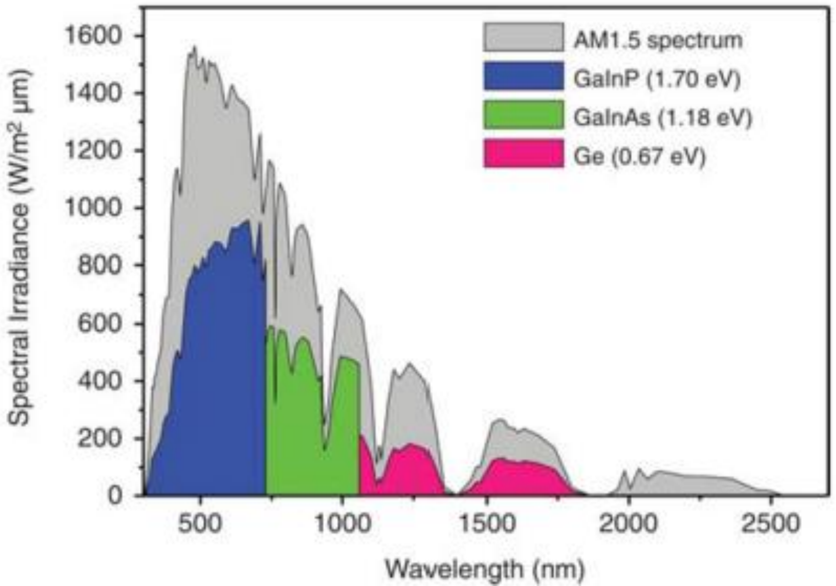


Stacking together semicoductors with different band-gap the transmission losses are reduced.

Single junction solar cell

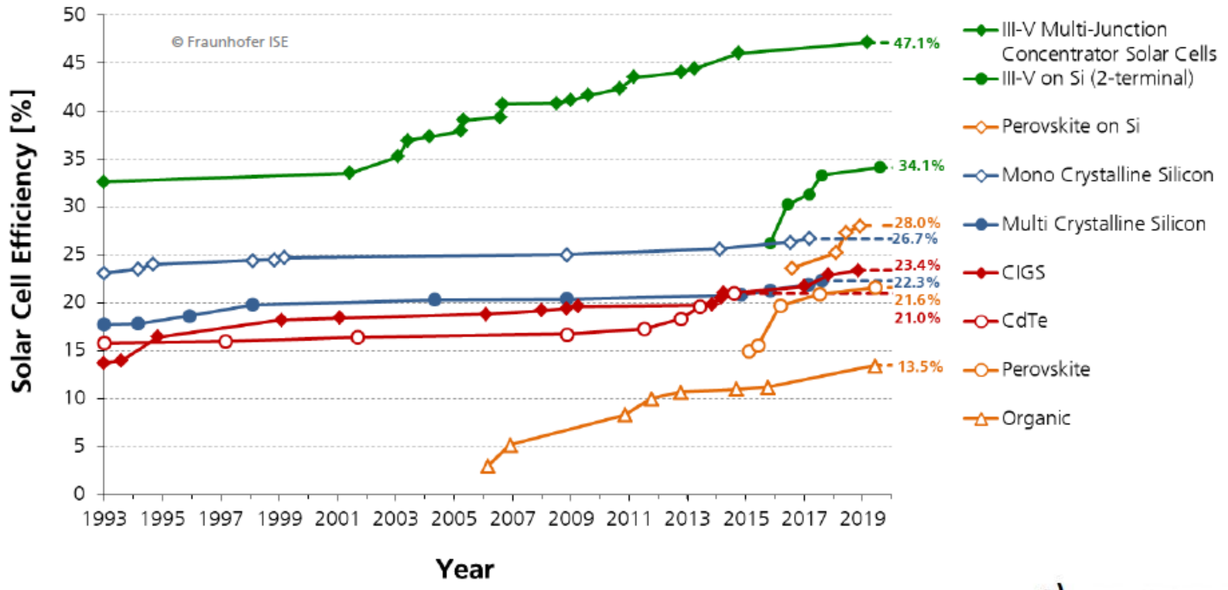


Multi junction solar cell



3° generation solar cells – case study: multijunction solar cells

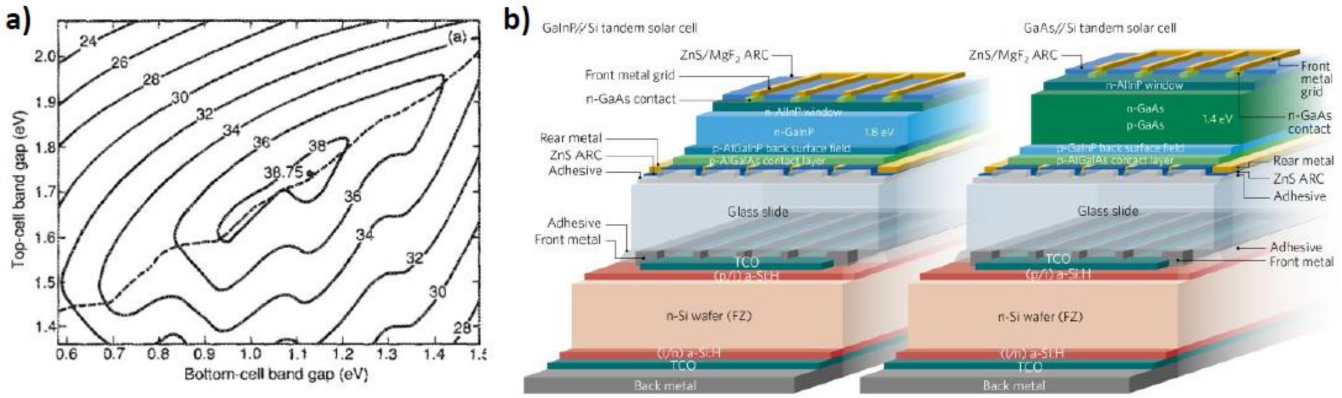
Efficiency of Multijunction (Tandem) Solar Cells



47.1 % → III generation

26.7 % → Standard - I generation

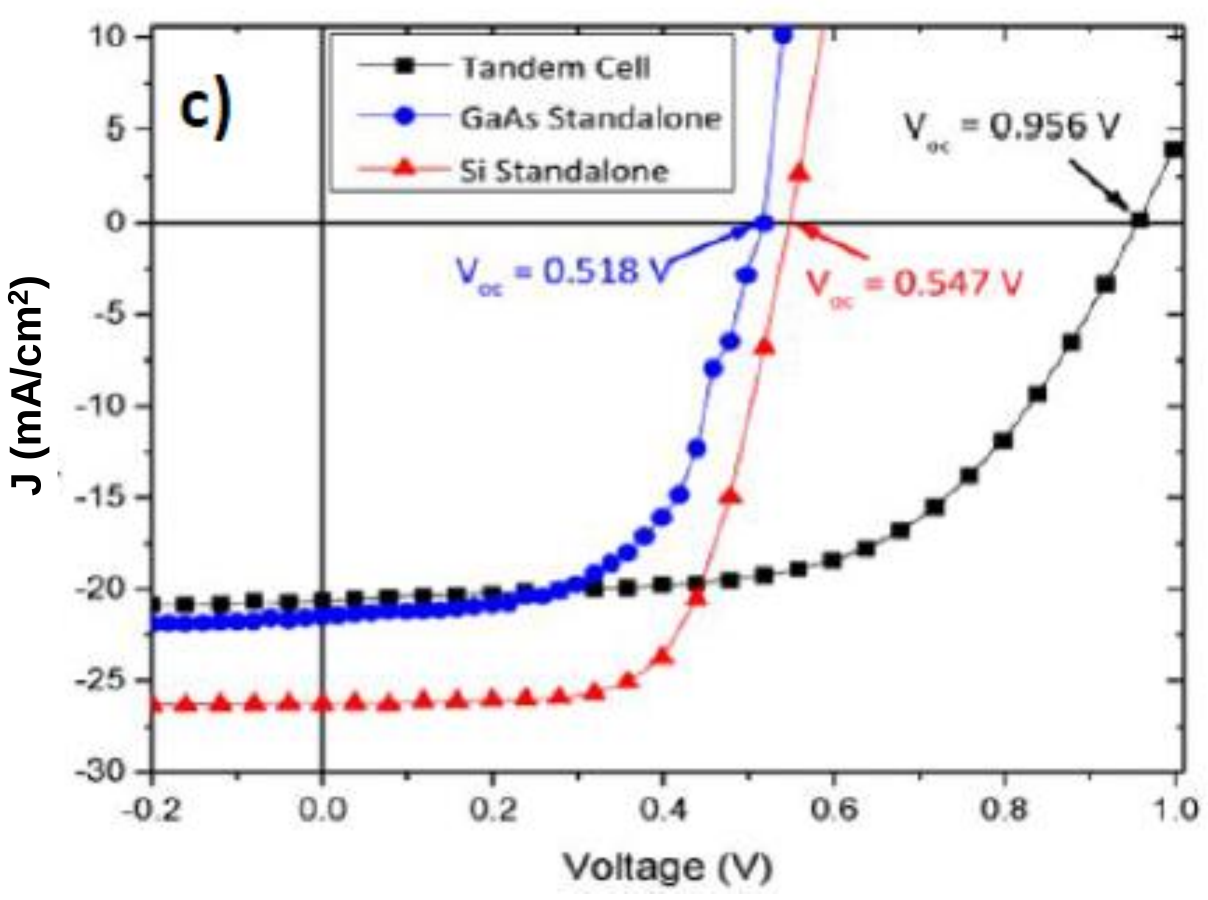
Design of Tandem Solar Cells



Coupling the proper materials

Highly complex architecture

Exercise



This plot shows the characteristics of the single subcells (GaAs NWs, Si) and the overall combination achieved by the tandem device.

Why is the V_{oc} from the tandem much higher than the ones of single subcells?

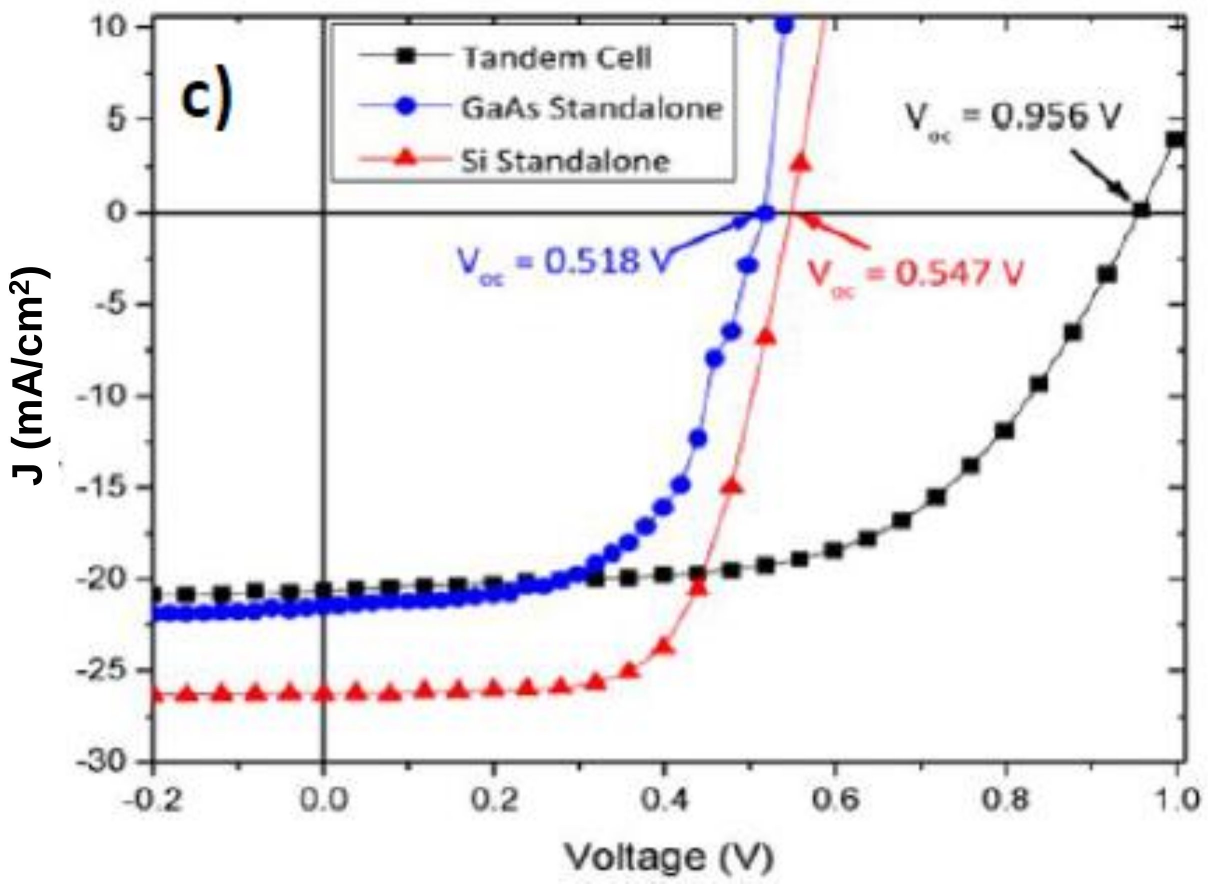
Why is the J_{sc} the same for the GaAs subcell and for the tandem?

Estimate the FF for the three curves using the parameters in the plot and here below. Comment on the results.

Si (red)	GaAs (blue)	Tandem (black)
J_{mp} = 23.88 mA/cm^2	J_{mp} = 17.50 mA/cm^2	J_{mp} = 14.7 mA/cm^2
V_{mp} = 0.378 V	V_{mp} = 0.375 V	V_{mp} = 0.738 V

5 minutes

Exercise



To be solved in Class

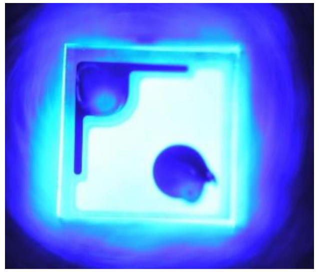
Light Emitting Diodes (LEDs)

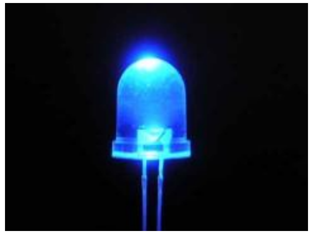
	Tungsten	Halogen	CFL	LED
Lifetime (hrs)	800	5000	5000	50000
Efficiency (lm/W)	8-10	20-30	50-60	60-80

Light emitting diodes are solid-state devices that efficiently convert electric power into light.

LEDs contribute to the sustainable transition of the energetic system.

First LED (red) by Holonyak (1962)





Blue GaN/InGaN LED
First demonstrated in 1993

The Nobel Prize in Physics 2014

© Nobel Media AB. Photo: A. Mahmoud

Isamu Akasaki

Prize share: 1/3

© Nobel Media AB. Photo: A. Mahmoud

Hiroshi Amano

Prize share: 1/3

© Nobel Media AB. Photo: A. Mahmoud

Shuji Nakamura

Prize share: 1/3

Awarded jointly to Isamu Akasaki, Hiroshi Amano and Shuji Nakamura

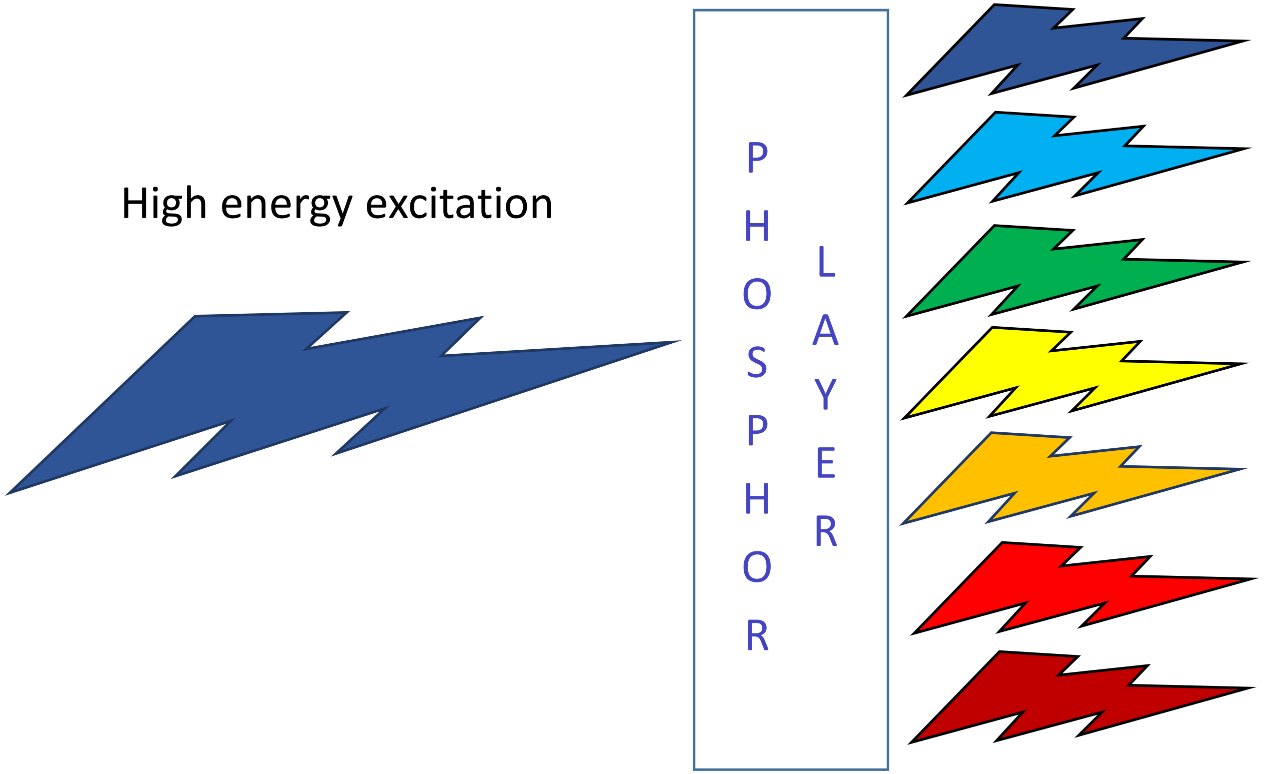
"for the invention of efficient blue light-emitting diodes which has enabled bright and energy-saving white light sources".

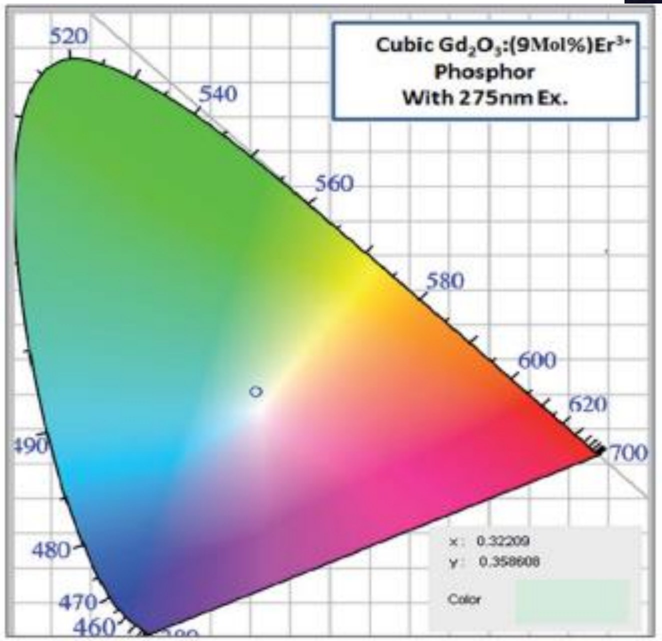
Phosphor downconversion

Down converting phosphors are materials able to absorb high energy photons and convert them efficiently in low energy photons

Metal oxide compounds often containing Y, Ce, Eu

High energy excitation

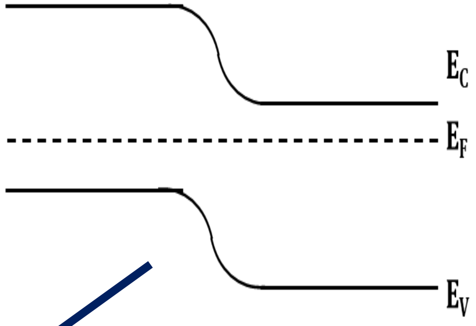


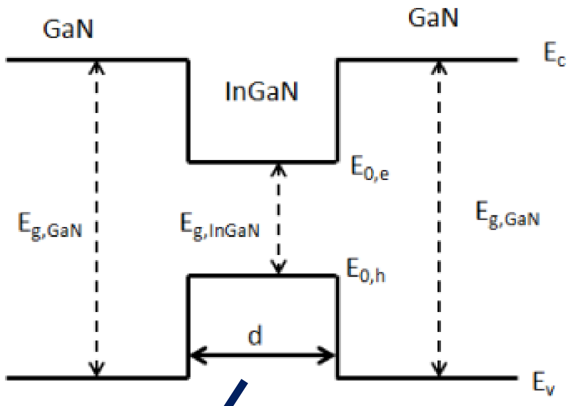


Chromaticity diagram
CIE diagram

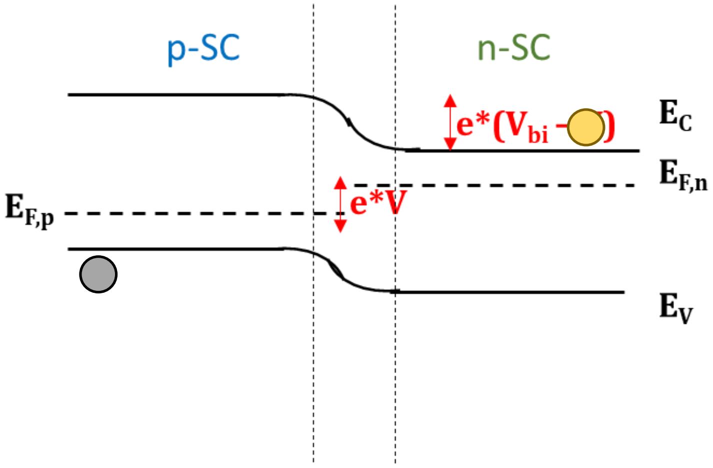
Working principle

Main elements:
- Type I band alignment
- p-n junction

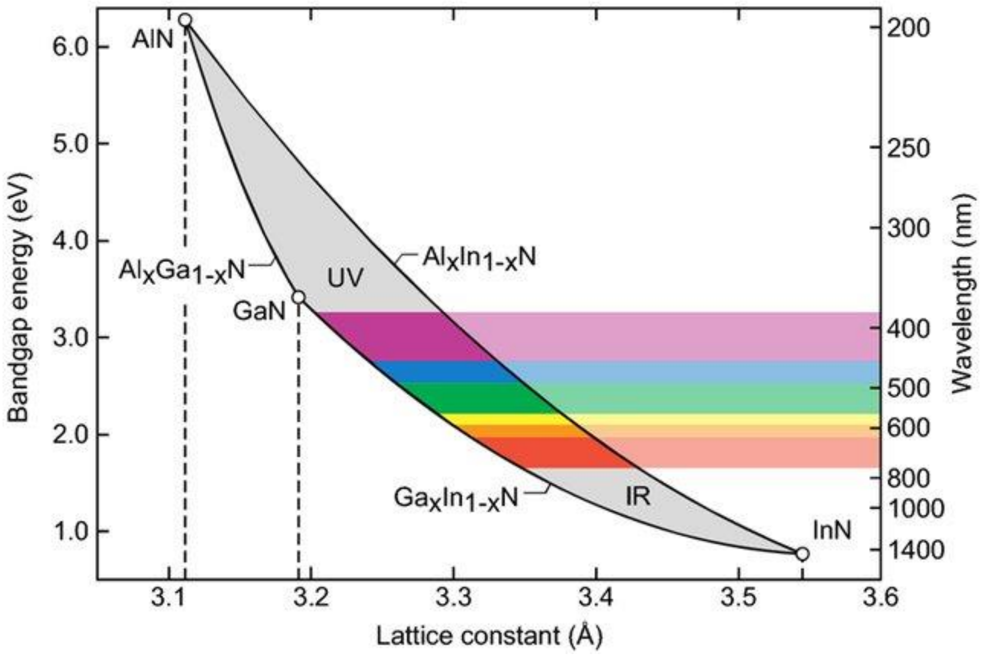




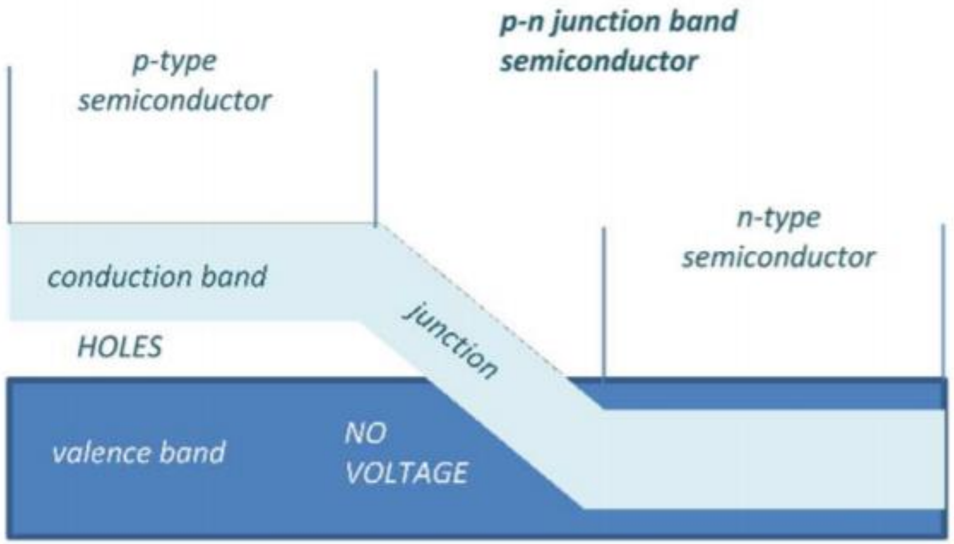
Forward bias (V>0)

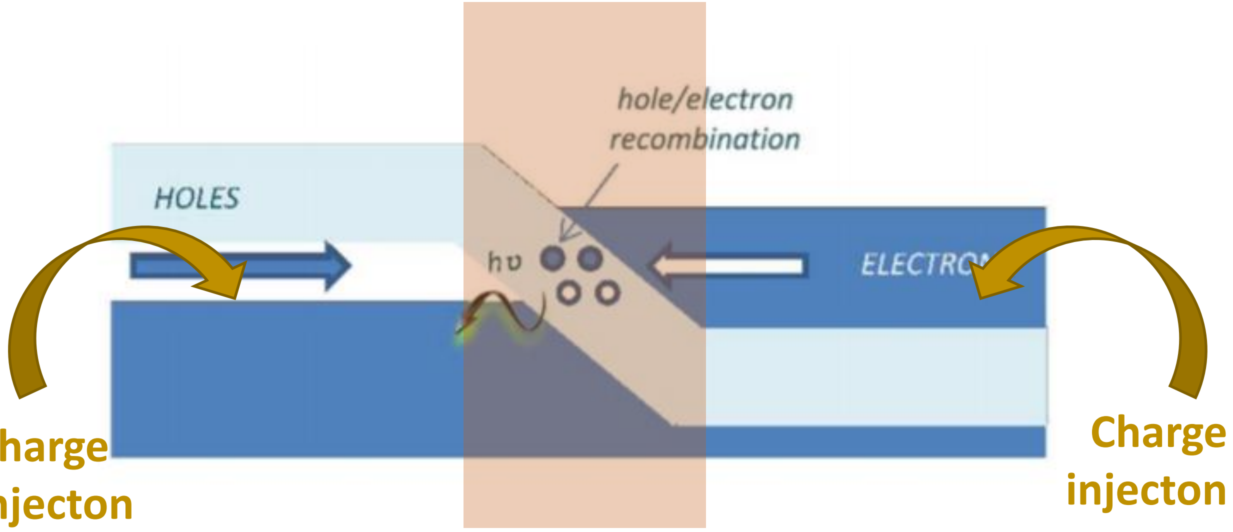


Majority carrier current

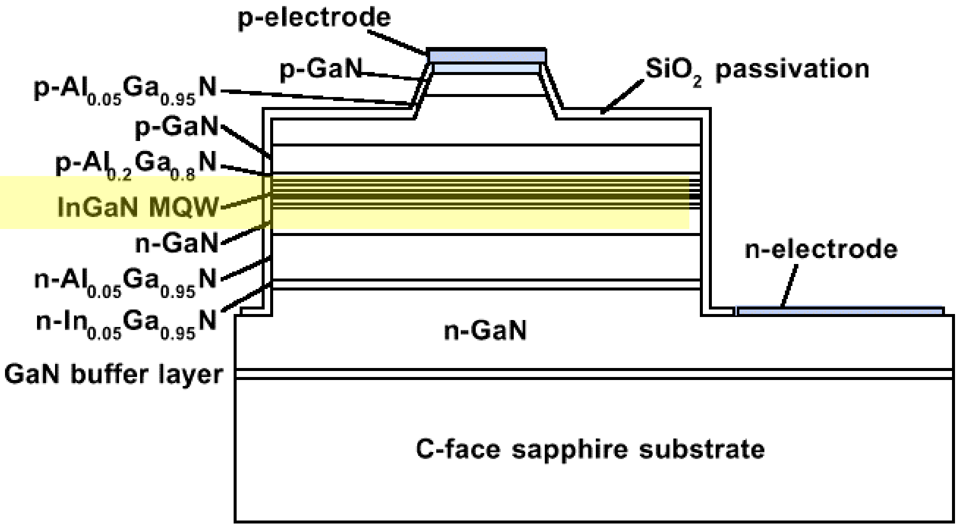


Working principle





Radiative Recombination = Light emission



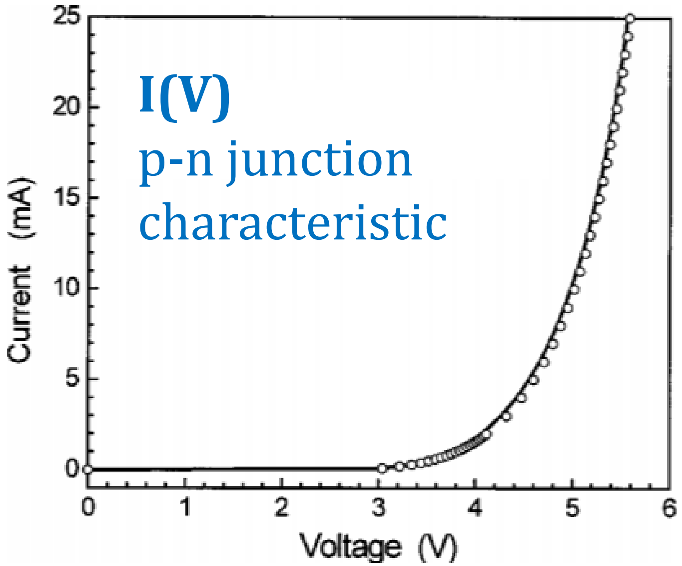
InGaN

E_g can be tuned with the composition

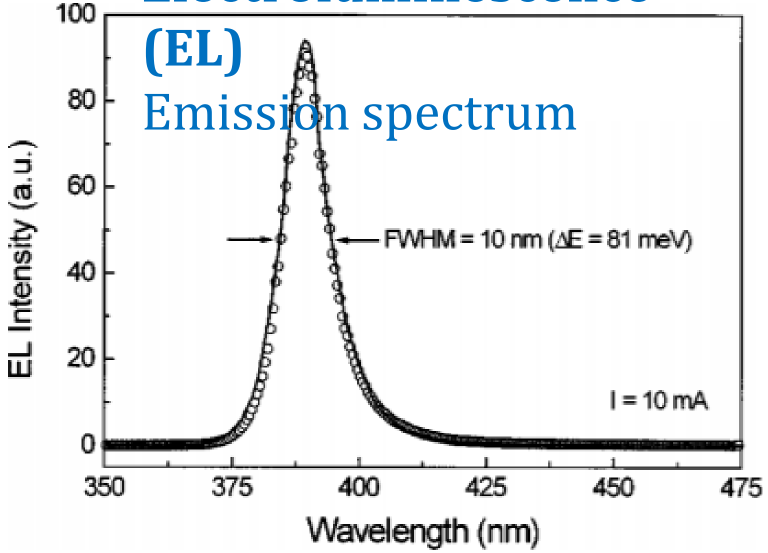
pn junction in GaN ensures the control over the charge injection

The InGaN (M)QW region ensures control over the radiative recombination region

Figures of Merit

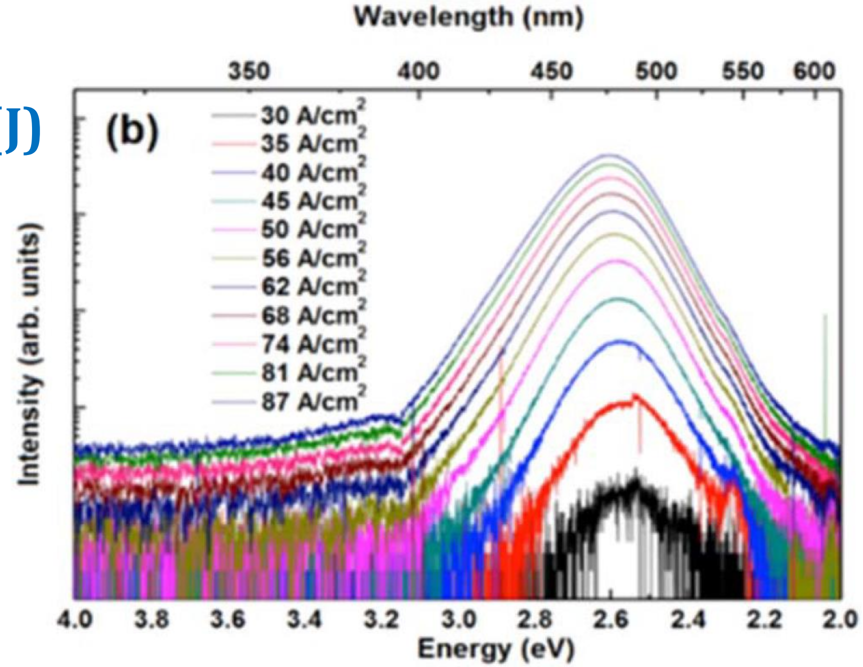


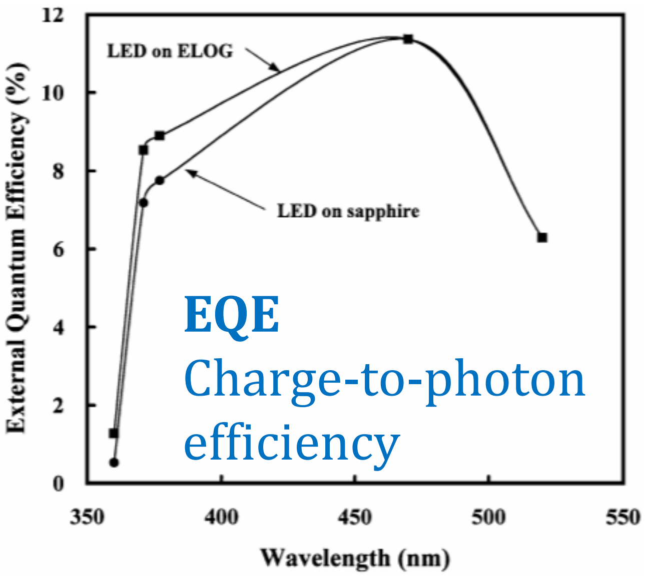
I(V)
p-n junction characteristic



Electroluminescence (EL)
Emission spectrum

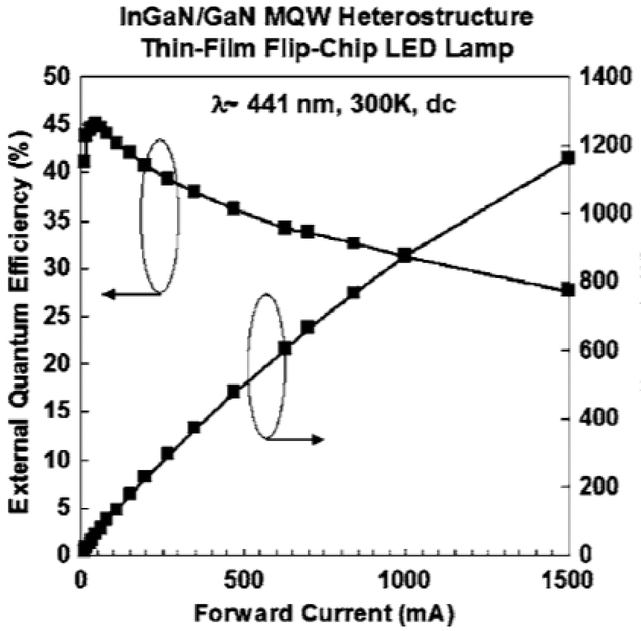
EL(J)





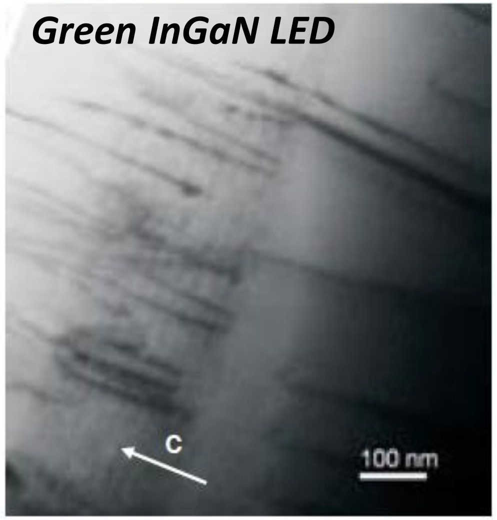
EQE
Charge-to-photon efficiency

EQE(J)

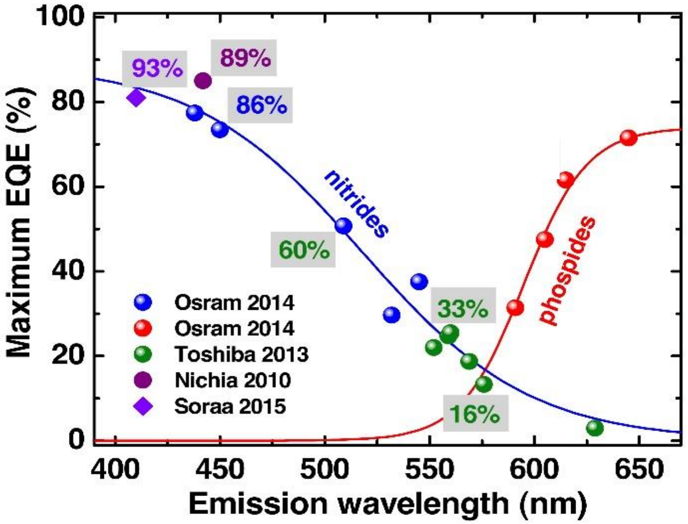


Open Challenges

Defect density with increasing In%



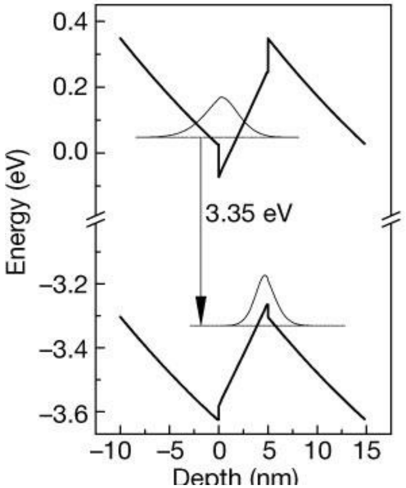
Green gap



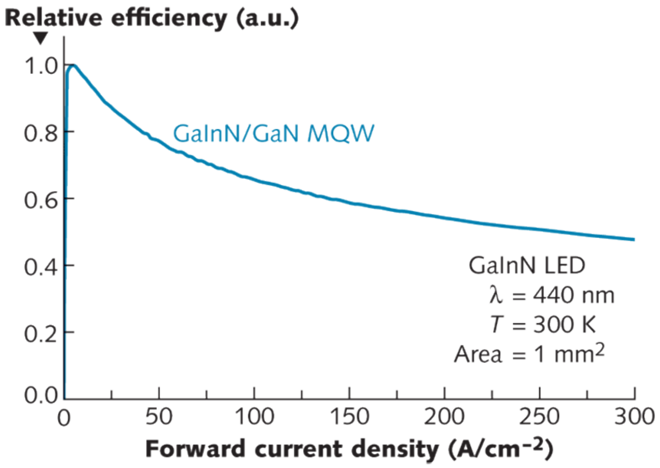
Optimization of heterostructures with increasing In content.

New charge injection strategies to maximize the electrical pumping and the radiative recombination

QCSE



Efficiency droop



Material science challenges:

- Close the «green gap»
- Reduce/Eliminate the efficiency droop (Auger effect)

Quantum Confined Stark Effect

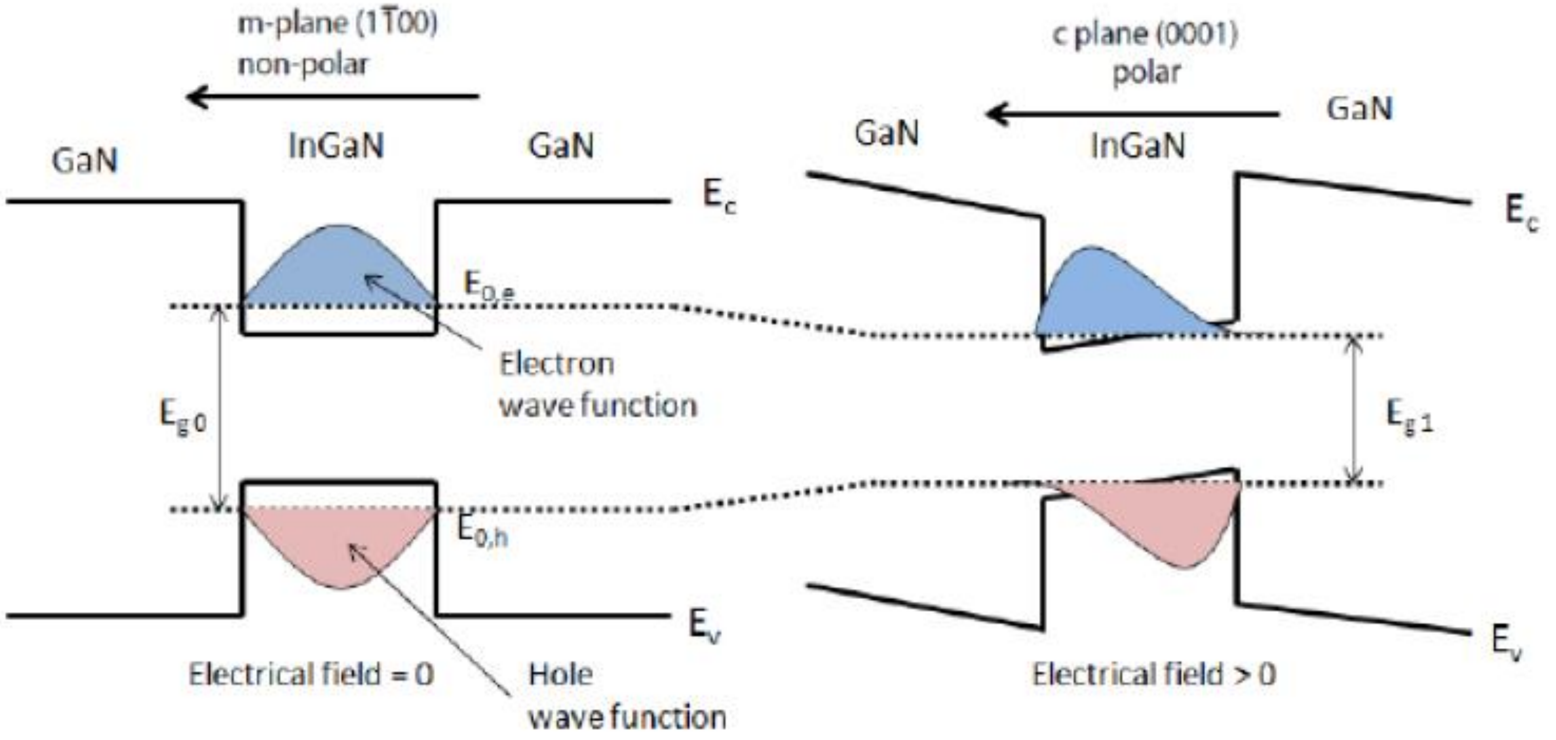
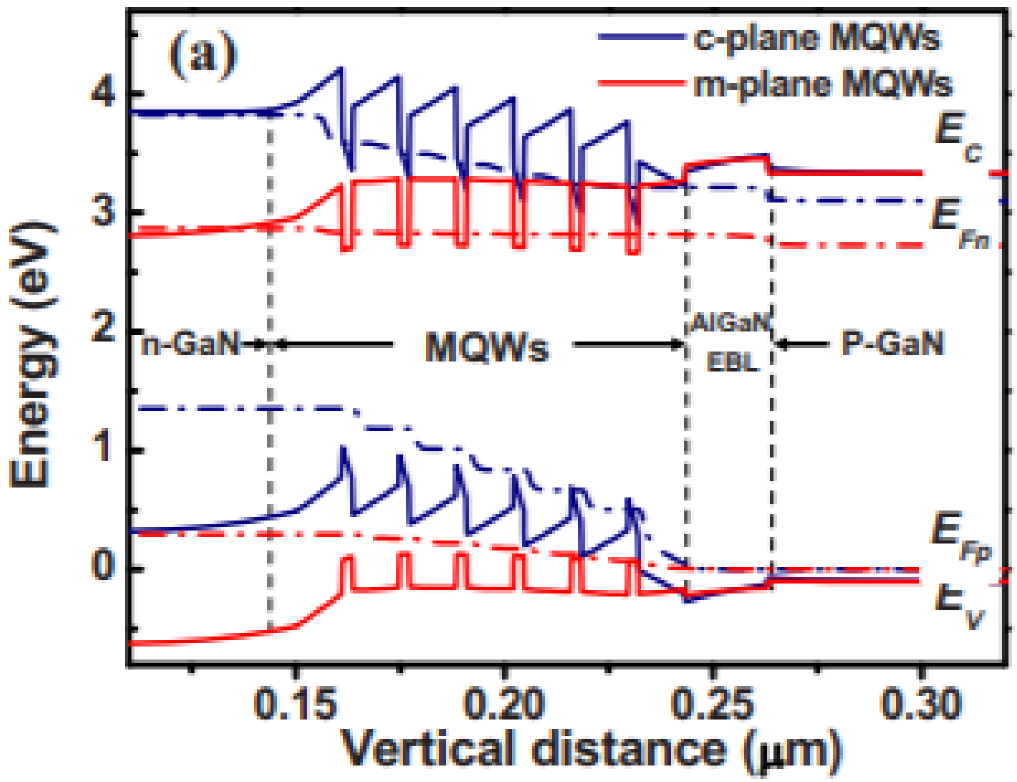
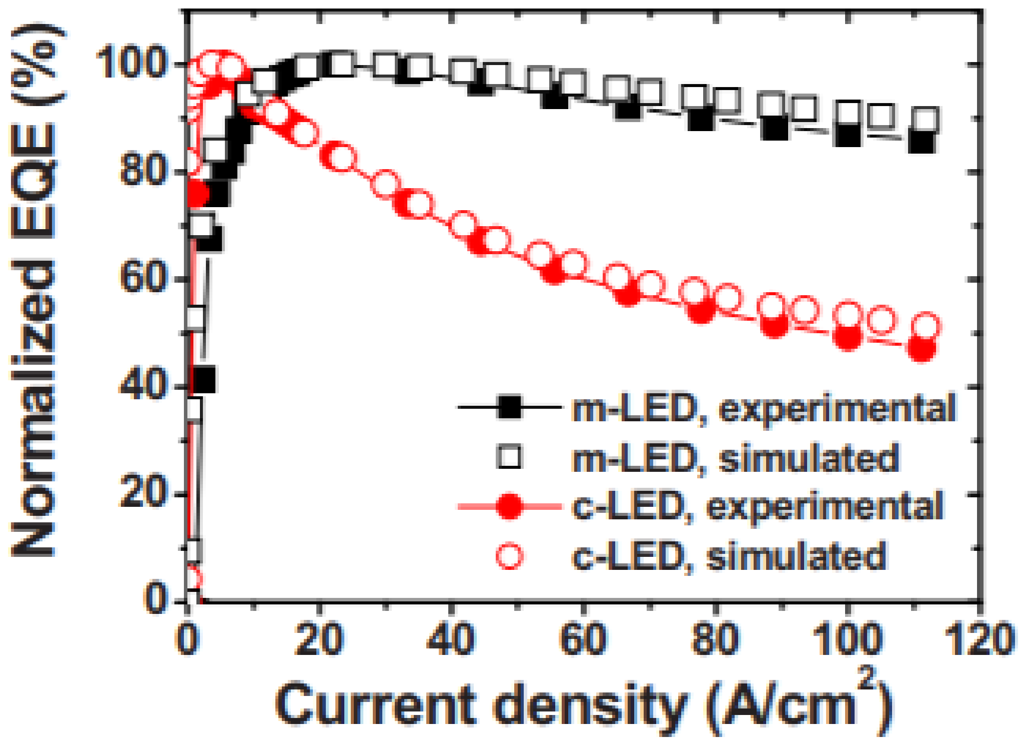


Figure 3.7: Quantum confined Stark effect: electron and hole wavefunctions without (left) and with electric field (right) within the QW [22].

Effect of QCSE: band structure and EQE



1D band diagram



EQE vs J