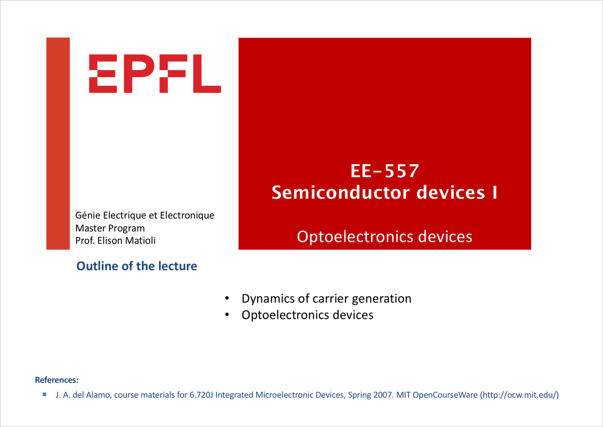
Course 7

Wednesday, 1 October 2025 09:54

EE557
Course 7 -...



EE-557
Semiconductor devices I

Optoelectronics devices

Génie Electrique et Electronique
Master Program
Prof. Elison Matioli

Outline of the lecture

- Dynamics of carrier generation
- Optoelectronics devices

References:

- J. A. del Alamo, course materials for 6.720J Integrated Microelectronic Devices, Spring 2007. MIT OpenCourseWare (http://ocw.mit.edu/)

Generation and Recombination - Low-level Injection (LLI) case

Generation and Recombination - Low-level Injection (LLI) case

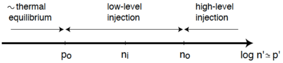
Low-level Injection (LLI) case

Define *excess* carrier concentrations:

$$n = n_o + n'$$

$$p = p_o + p'$$

LLI: Equilibrium minority carrier concentration overwhelmed, but majority carrier concentration negligibly disturbed


~thermal equilibrium
low-level injection
high-level injection
po
ni
no
log n'≃ p'

- for n-type:

$$p_o \ll \boxed{n' \simeq p'} \ll n_o$$

- for p-type:

$$n_o \ll n' \simeq p' \ll p_o$$

Generation and Recombination out of equilibrium

$n = n_o + n'$

$p = p_o + p'$

$\boxed{p' \sim n'}$

In LLI:

$$np - n_op_o = \overset{n_o \ n'}{\cancel{n_op_o}} + n_op' + p_on' + \cancel{n'p'} - \cancel{n_op_o} \simeq (n_o + p_o)n'$$

All expressions of *U* follow the form:

$$U_i \simeq \frac{n'}{\tau_i}$$

define - lifetime

τ_i is *carrier lifetime* of process *i*, a constant characteristic of each G&R process:

$$\tau_{rad} = \frac{1}{r_{rad}(n_o + p_o)}$$

$U = r_{rad}(np - n_op_o)$

$\shortparallel$

$U = r_{rad} \cdot (n_o + p_o)n'$

$$\tau_{Auger} \simeq \frac{1}{(r_{eeh}n_o + r_{ehh}p_o)(n_o + p_o)}$$

$$\tau_{tr} \simeq \frac{\tau_{ho}n_o + \tau_{eo}p_o}{n_o + p_o}$$

Under LLI, net recombination rate depends linearly on *excess carrier concentration* through a constant that is characteristic of material and temperature.

Generation and Recombination out of equilibrium

If all G&R processes are independent, combined process:

$$\frac{1}{\tau} = \frac{1}{\tau_{rad}} + \frac{1}{\tau_{tr}} + \frac{1}{\tau_{Aug}}$$

$$U \simeq \frac{n'}{\tau} \qquad \frac{1}{\tau} = \Sigma \frac{1}{\tau_i}$$

The G&R process with the ***smallest*** **lifetime dominates.**

Physical meaning of ***carrier lifetime***:

- *U* is net recombination rate in unit volume in response to excess carrier concentration *n'* (linear with *n'*) [$cm^{-3} \cdot s^{-1}$]

- *U/n'* is net recombination rate in unit volume per unit excess carrier [s^{-1}]
- τ = n'/U is the mean time between recombination event *per excess carrier* [*s*] or average time excess carrier will "survive" before recombining → constant characteristic of material

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Generation and Recombination out of equilibrium

EPFL

For n-type material, $n_o >> p_o$:

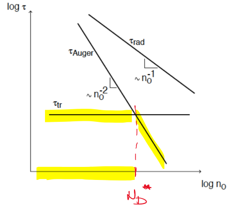
$N_D = 10^{17}\,cm^{-3} \Rightarrow n_o = 10^{17}\,cm^{-3}$

$p_o = 10^{3}\,cm^{-3}$

$$\tau_{rad} = \frac{1}{r_{rad} n_o}$$

$$\tau_{Auger} = \frac{1}{r_{eeh} n_o^2}$$

$$\tau_{tr} = \tau_{ho} \approx \frac{1}{N_t}$$



$$\tau_{rad} = \frac{1}{r_{rad} \cdot n_o} = \frac{1}{2\times10^{-15}\,cm^{-3}/s \cdot 10^{17}\,cm^{-2}} = 5\,ms$$

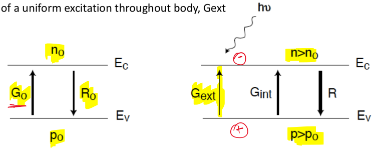
$$\tau_{Aug} = \frac{1}{r_{eeh} \cdot n_o^2} = \frac{1}{1.8\times10^{-31} \times (10^{17})^2} = 0.56\,ms$$

$$\tau_{tr} = \frac{1}{N_t \cdot c_e} = \frac{1}{10^{16} \times 10^{-11}} = 10\,\mu s$$

$$\tau = \left(\sum_i \tau_i^{-1}\right)^{-1} = \frac{1}{1/\tau_{rad} + 1/\tau_{tr} + 1/\tau_{Aug}} = \underline{9.8\,\mu s}$$

Dynamics of excess carriers in uniform situations

Let’s consider the case of a uniform excitation throughout body, Gext


hυ
n₀
Ec
G₀
R₀
Ev
p₀
n>n₀
−
Gext
Gint
R
Ec
Ev
+
p>p₀

thermal equilibrium

under external illumination

If there is imbalance between total generation and recombination, carrier concentrations change in time:

$$① \quad \frac{dn}{dt} = \frac{dp}{dt} = G - R$$

- if $G > R \Rightarrow n,\ p \uparrow$
- if $G < R \Rightarrow n,\ p \downarrow$

Distinguish between internal and external generation:

$$G = G_{ext} + G_{int}$$

Under Low Level injection (LLi)

$$U_i = \frac{n'}{\tau_i} = R - G \qquad n = n_0 + n' \Rightarrow \frac{dn}{dt} = \frac{dn'}{dt}$$

$$① \quad \frac{dn'}{dt} = G_{ext} - \frac{n'}{\tau_i}$$

$$\frac{dn'}{dt} = 0 \Rightarrow \boxed{n' = G_{ext} \cdot \tau}$$

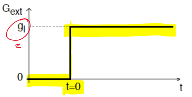
Dynamics of excess carriers in uniform situations

Example 1: Turn-on transient

$$\begin{cases} t = 0 & n' = 0 \\ t = \infty & n' = g_l \cdot \tau \end{cases}$$

$$n'(t) = g_l \cdot \tau \left(1 - e^{-t/\tau}\right)$$

Semiconductor is subject to a uniform generation rate g_l



$$n'(t) = g_l \tau (1 - e^{-t/\tau}) \qquad \text{for } t \geq 0$$

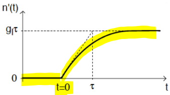
steady-state ≡ initial transient died out (need a few τ's)

In steady state:

$$generation = recombination$$

or

$$g_l = \frac{n'}{\tau}$$

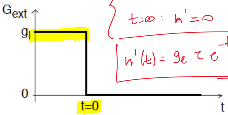


Then

$$n' = g_l \tau$$

Dynamics of excess carriers in uniform situations

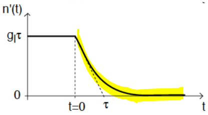
Example 2: Turn-off transient



$t=0 : n' = g_l \cdot \tau$

$t=\infty : n' = 0$

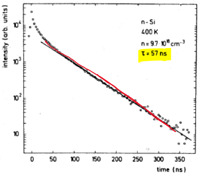
$$\boxed{n'(t) = g_l \cdot \tau \, e^{-t/\tau}}$$



$n = n_0 \cancel{+n'}$

$$n'(t) = g_l \tau e^{-t/\tau} \qquad \text{for } t \geq 0$$

By observing the luminescence decay, one can extract the carrier lifetime



J., and W. Schmid. "Auger Coefficients for Highly Doped and Highly Excited Silicon."*Applied Physics Letters* 31, no. 5 (1977): 346-348. Copyright 1977, American Institute of Physics

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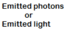
Carrier Generation and Recombination

Key questions

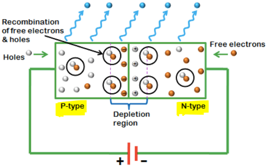
How are these principles applied to optoelectronic devices?

Light emitting diodes

A simplified picture

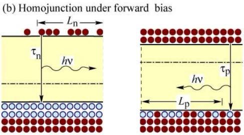


Emitted photons
or
Emitted light


Recombination
of free electrons
& holes
Holes
Free electrons
P-type
N-type
Depletion
region
+
–

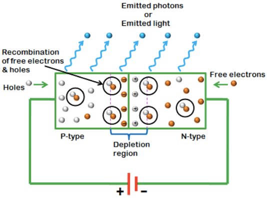
Light Emitting Diode (LED)

Physics and Radio-Electronics


(b) Homojunction under forward bias
L_n
τ_n
$h\nu$
τ_p
$h\nu$
L_p

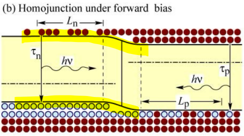
Light emitting diodes

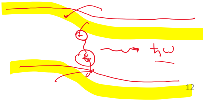
A simplified picture


Emitted photons
or
Emitted light
Recombination
of free electrons
& holes
Holes
Free electrons
P-type
N-type
Depletion
region
+
–

Light Emitting Diode (LED)

Physics and Radio-Electronics

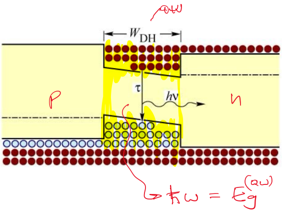

(b) Homojunction under forward bias
L_n
τ_n
$h\nu$
τ_p
$h\nu$
L_p


$\ominus$
$\oplus$
$\hbar\omega$

Light emitting diodes

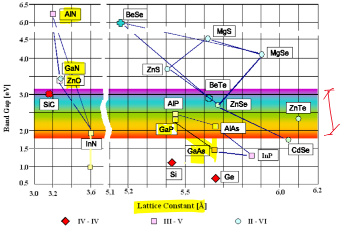
Improving the efficiency in emitting photons:

internal quantum efficiency (IQE): ratio of emitted photons per electron-hole recombinations


QW
W_{DH}
τ
$h\nu$
p
n
$\hbar\omega = E_g^{(QW)}$

Quantum wells (QW)
- materials with smaller band gap
- Increase the interaction between electrons and holes: more recombinations
- Photons are emitted with the energy of the smaller band-gap material

What does the band gap represent



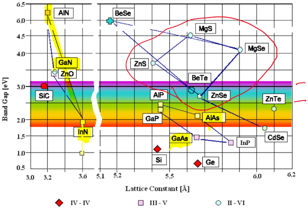
How to convert eV into wavelength?

Calculate the wavelength of a photon with energy 3.1 eV.

$$E = hf = \frac{hc}{\lambda}, \text{ so } \lambda = \frac{hc}{E} = \frac{1240 \text{ eV}\cdot\text{nm}}{3.1 \text{ eV}} = \boxed{400 \text{ nm}}.$$

Optoelectronic devices

1. **Most III-V compounds** radiate at wavelengths above the visible region, i.e. in the **infrared**. However, adding some Al to GaAs **producing AlxGa1-xAs**, will shift the wavelength into the red region of the spectrum - here are our red luminescence diodes and Lasers!
2. **Very fortunate:** GaAs and AlAs have almost the same lattice constant; we can thus make any combinations of these materials without encountering mechanical stress.
3. **Very unfortunate:** For a long time, there were **no III-V compounds in the diagram that emit blue light** - this is a severe problem for many potential applications. While SiC could be used to some extent, **it was only with the recent advent of InGaN that this problem was solved**. SiC and GaN crystals, however, are not of the "zinc-blende" type common to all the III-Vs in the diagram but have a hexagonal unit cell: wurtzite. They therefore do not easily mix with the others!

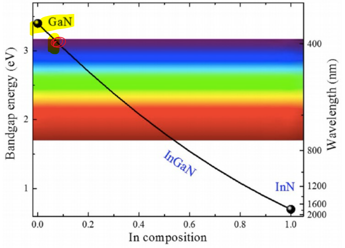


4. If we **want to radiate at 1.3 µm or 1.5 µm** - infrared wavelength of prime importance for optical communications - we should work with combinations of **InAs, GaAs, and AlSb.**
5. **Most interesting**: **The II-VI compounds are all direct semiconductors and span a much larger range of wavelengths than the III-V's.** The fact that they are not much used for products tells us that there must be big problems!
6. Before the 90's, most research was on II-VI compounds: ZnSe, ZnTe and ZnS (compatible with GaAs)
7. But they suffered from severe stability problems, short lifetime, degradation due to the propagation of defects
8. GaN has a much stronger covalent bond: much more stable!

Light emitting diodes

Quantum wells:

- In GaN system, quantum wells are typically made out of InGaN
- The In content determines the energy of the photons (color of the light)



Bandgap energy versus In composition for InGaN ternary within visible spectrum energy range

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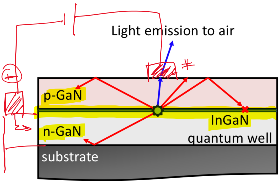
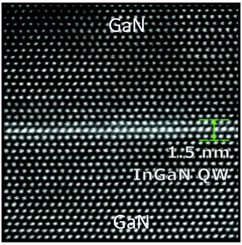
Light emitting diodes

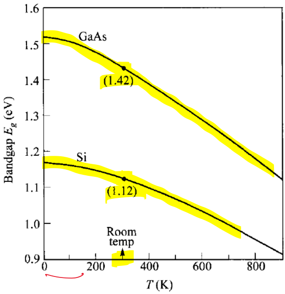
Simplified case of InGaN/GaN quantum well


Light emission to air
+
p-GaN
InGaN
quantum well
n-GaN
substrate


GaN
1.5 nm
InGaN QW
GaN

Temperature dependence of band-gap:

How should light emission in LEDs be affected at low temperature?



	$E_g(0)$ (eV)	α (eV/K)	β (K)
GaAs	1.519	5.4×10^{-4}	204
Si	1.169	4.9×10^{-4}	655

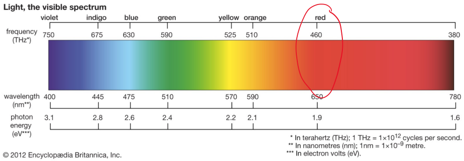
$$E_g(T) = E_g(0) - \frac{\alpha T^2}{T+\beta}$$

At high temperatures, the interatomic spacing increases when the amplitude of the atomic vibrations increases due to the increased thermal energy - the material expands!

Thus the band gap lowers at high temperature and increases at low temperatures

Temperature dependence of band-gap:

How should light emission in LEDs be affected at low temperature?


Light, the visible spectrum
violet
indigo
blue
green
yellow
orange
red
frequency (THz*)
750
675
630
590
525
510
460
380
wavelength (nm**)
400
445
475
510
570
590
650
780
photon energy (eV***)
3.1
2.8
2.6
2.4
2.2
2.1
1.9
1.6

* In terahertz (THz); 1 THz = 1×10^{12} cycles per second.
** In nanometres (nm); 1nm = 1×10^{-9} metre.
*** In electron volts (eV).

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What happens for red LEDs? https://www.youtube.com/watch?v=dSXGlhrtamI

What happens for blue LEDs? https://www.youtube.com/watch?v=891ybm5zsy0

Current issue in LEDs

Two examples of current issues in LEDs

1. "Green-gap": Quantum well efficiency drops significantly at longer wavelengths

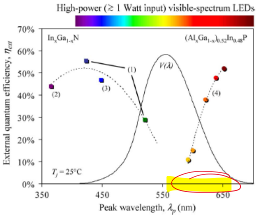
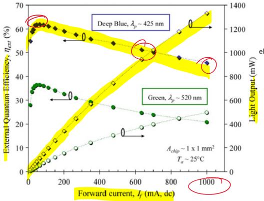


Fig. 2. State-of-art external quantum efficiencies for high-power visible-spectrum LEDs ($T_j = 25$ °C): (1) InGaN TFFC LEDs, 350 mA (this paper); (2) InGaN VTF LED, 1000 mA [42]; (3) InGaN CC LEDs employing patterned substrates [35]; and (4) Production performance, AlGaInP TIP LEDs [9], Philips Lumileds Lighting Co., 350 mA. $V(\lambda)$ is the luminous eye response curve from CIE. Dashed lines are guides to the eye.

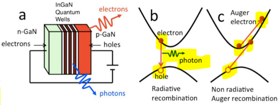
Current issue in LEDs

2. Auger recombination: major problem in GaN LEDs today

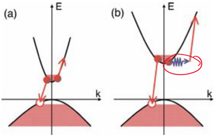


Krames et al., JDT, vol. 3, n. 2, 2007

The efficiency drops when current density increases:
”Droop problem”


a
InGaN Quantum Wells
electrons
n-GaN
electrons
p-GaN
holes
photons
b
electron
photon
hole
Radiative recombination
c
Auger electron
Non radiative Auger recombination

Phonon-assisted Auger recombination:



Auger recombination:

- 3-particle process (proportional to np^2 or pn^2)
- energy given to third carrier; **needs lots of carriers**: **shows up at large carrier densities**

State of the art in GaN LEDs

internal external light

Emitter	Recent best IQE	Recent best EQE	Extraction (LEE)	Wall-plug (WPE)	Key recent/anchor re
Blue InGaN (~450 nm)	≈86% @ RT (measured)	>80% (record class)	≈80% (optimized flip-chip)	≈70–75% (calc*)	Titkov 2014; Zhao 2023; Li 2023; NAS/Krames 2007; UIUC 2023
Green InGaN (~520–540 nm)	≈32% (c-InGaN demo)	≈44% (record report)	≈70–80% (w/ advanced optics)	≈35–40% (calc*)	Hu 2019; CompoundSemi 2024(c-GaN IQE); NAS/Krames 2007
Red InGaN on GaN (≈620–640 nm)	≈16% (device-level report)	10.5% @ 625 nm (APL 2024)	Device-dependent; tens of % typical (emerging)	≈7–10% (calc* / demo)	APL 2024; Ewing 2023; Lumileds 2024
White pc-LED (blue pump + phosphor)	Blue chip near-unity; phosphor PLQY high	Package efficacy proxy: 200–220 lm/W (lab/hi-end)	High (packaging dependent)	≈60–70% (calc* from 206–220 lm/W)	ACS Photonics 2022; LER refs

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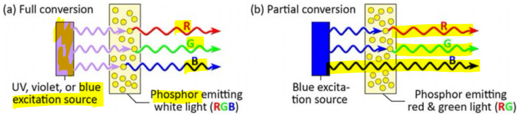
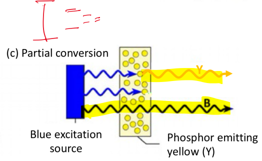
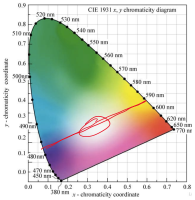
How to produce white LED for lighting?

Phosphors:
particles that convert large energy blue photons in smaller energy photons (RED, GREEN OR YELLOW)


(a) Full conversion
R
G
B
UV, violet, or blue excitation source
Phosphor emitting white light (RGB)
(b) Partial conversion
R
G
B
Blue excitation source
Phosphor emitting red & green light (RG)

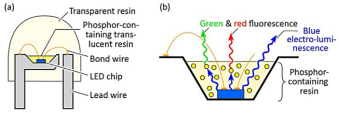

(c) Partial conversion
Y
B
Blue excitation source
Phosphor emitting yellow (Y)

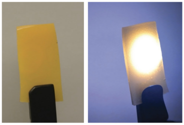


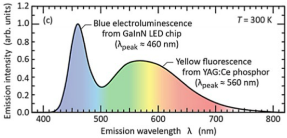
J. Cho et al., Laser Photonics Rev. 11, No. 2, 1600147 (2017)

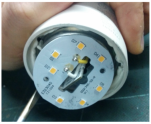
To produce white light, mix the correct ratio of colors

How to produce white LED for lighting?


(a)
Transparent resin
Phosphor-containing translucent resin
Bond wire
LED chip
Lead wire
(b)
Green & red fluorescence
Blue electro-luminescence
Phosphor-containing resin




(c)
T = 300 K
Blue electroluminescence from GaInN LED chip (λ_{peak} ≈ 460 nm)
Yellow fluorescence from YAG:Ce phosphor (λ_{peak} ≈ 560 nm)
Emission intensity (arb. units)
Emission wavelength λ (nm)
0.0
0.2
0.4
0.6
0.8
1.0
1.2
400
500
600
700
800



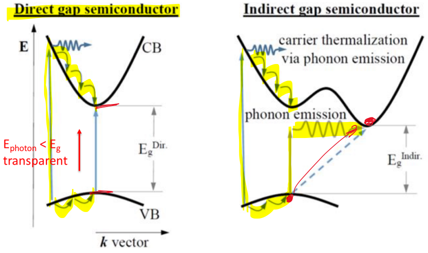
J. Cho et al., Laser Photonics Rev. 11, No. 2, 1600147 (2017)

Solar cells

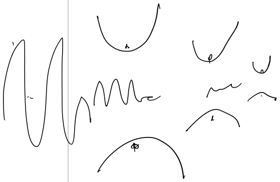
Direct bad gap semiconductors:

GaAs, InP, InGaAs, InGaAsP, GaN, InGaN **emit light very efficiently**

and **indirect bad gap semiconductors**: Si, Ge, SiC **don't**


Direct gap semiconductor
Indirect gap semiconductor
E
CB
VB
$E_g^{Dir.}$
k vector
carrier thermalization via phonon emission
phonon emission
$E_g^{Indir.}$

$E_{photon} < E_g$
transparent

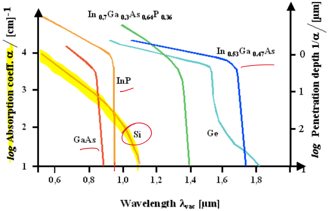


Below band gap: the material is transparent
Above the band gap: material absorbs photons

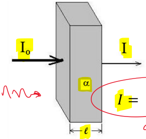
Solar cells

Direct band gap semiconductors:
GaAs, InP, InGaAs, InGaAsP, GaN, InGaN **emit light very efficiently**
and **indirect band gap semiconductors**: Si, Ge, SiC **don't**

Absorption coefficient of various semiconductors



Beer-Lambert law



$I = I_o e^{-\alpha l}$

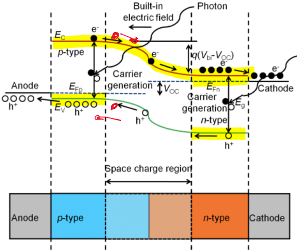
absorption coefficient [cm⁻¹]

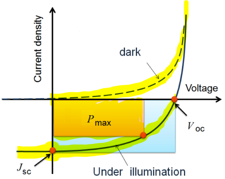
Absorption at the edge of the band gap is not sharp for indirect band gap materials

$\alpha_{Si} < \alpha_{DBG}$

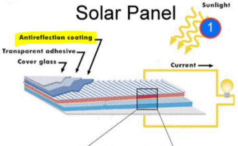
So why are most solar cells made out of silicon?

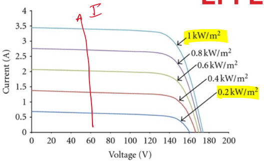
Solar cells

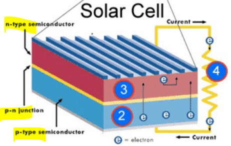

Built-in electric field
Photon
Photon
E_C
e⁻
p-type
e⁻
$q(V_{bi}-V_{OC})$
e⁻
e⁻
Carrier generation
Anode
E_{Fp}
V_{OC}
E_{Fn}
Cathode
h⁺
E_V
h⁺
h⁺
Carrier generation
E_g
n-type
h⁺
Space charge region
Anode
p-type
n-type
Cathode

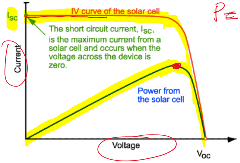


Solar cells


Solar Panel
Sunlight
1
Antireflection coating
Transparent adhesive
Cover glass
Current




Solar Cell
n-type semiconductor
p-n junction
p-type semiconductor
Current
Current
3
2
4
e
e = electron



$P = I \times V$

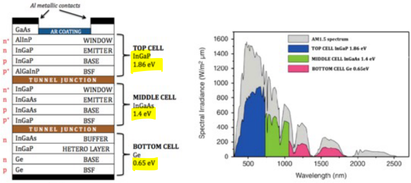
Increasing the solar intensity:

linear increase in short-circuit current (I_{SC}), but sub-linear increase in open-circuit voltage (V_{OC})

Thus the need for **maximum power point tracking (MPPT)** to extract the maximum power of the the PV

Solar cells

Multijunction solar cells


Al metallic contacts
GaAs
AR COATING
n⁺ AlInP WINDOW
n InGaP EMITTER
p InGaP BASE
p⁺ AlGaInP BSF
TUNNEL JUNCTION
n⁺ InGaP WINDOW
n InGaAs EMITTER
p InGaAs BASE
p⁺ InGaP BSF
TUNNEL JUNCTION
n InGaAs BUFFER
InGaP HETERO LAYER
n Ge BASE
p Ge BSF
TOP CELL
InGaP
1.86 eV
MIDDLE CELL
InGaAs
1.4 eV
BOTTOM CELL
Ge
0.65 eV
Spectral Irradiance (W/m² μm)
1600
1400
1200
1000
800
600
400
200
0
500
1000
1500
2000
2500
Wavelength (nm)
AM1.5 spectrum
TOP CELL InGaP 1.86 eV
MIDDLE CELL InGaAs 1.4 eV
BOTTOM CELL Ge 0.65eV

(a) (b)