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

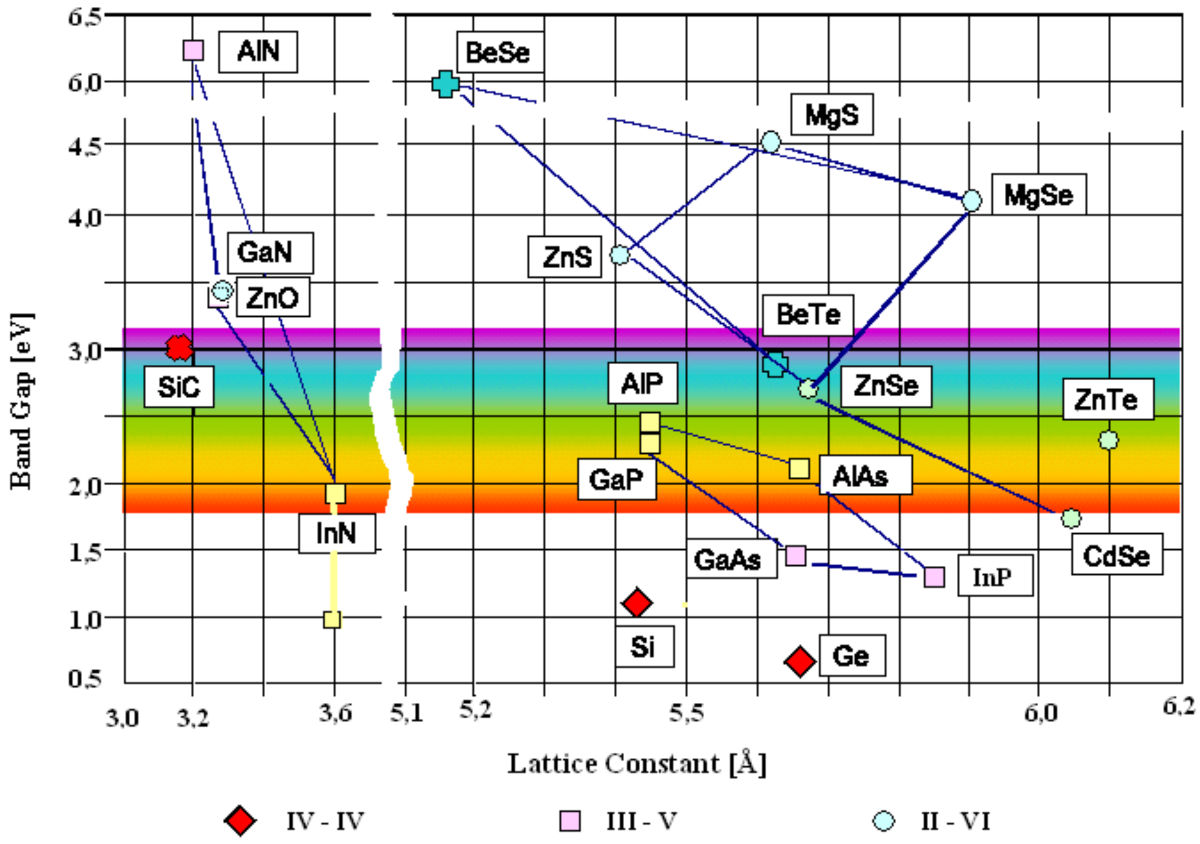
References:

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

Key questions

How are these principles applied to optoelectronic devices?

What does the band gap represent



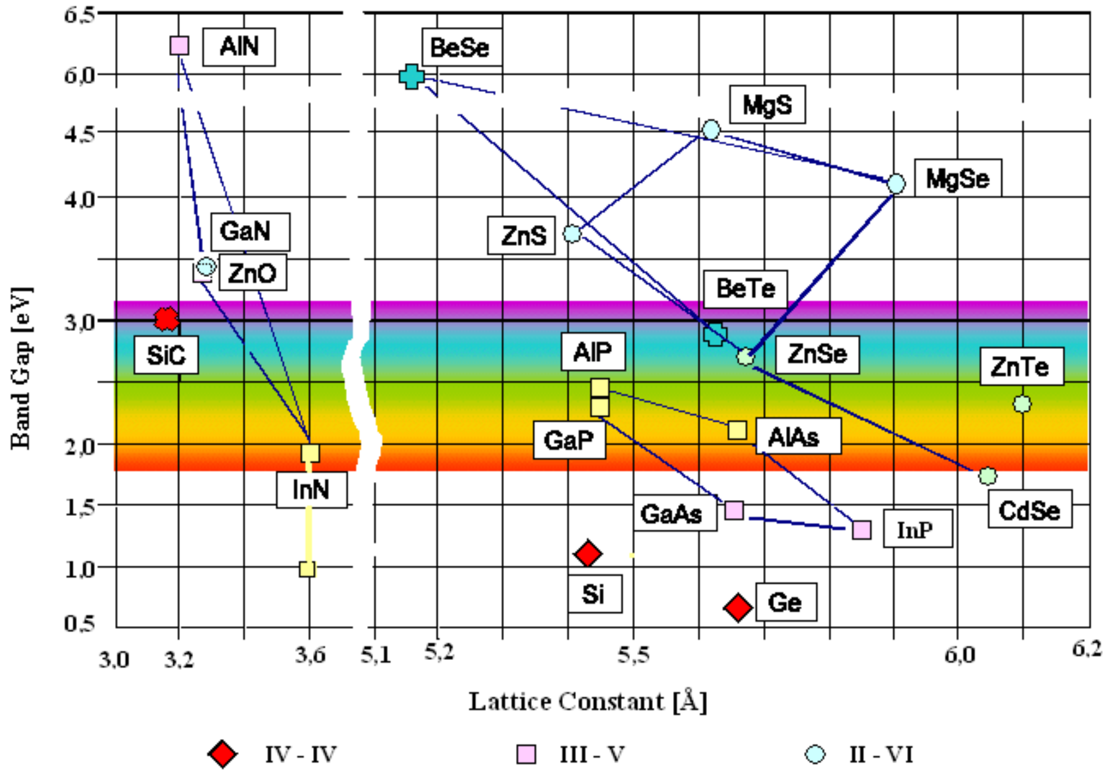
How to convert eV into wavelength?

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

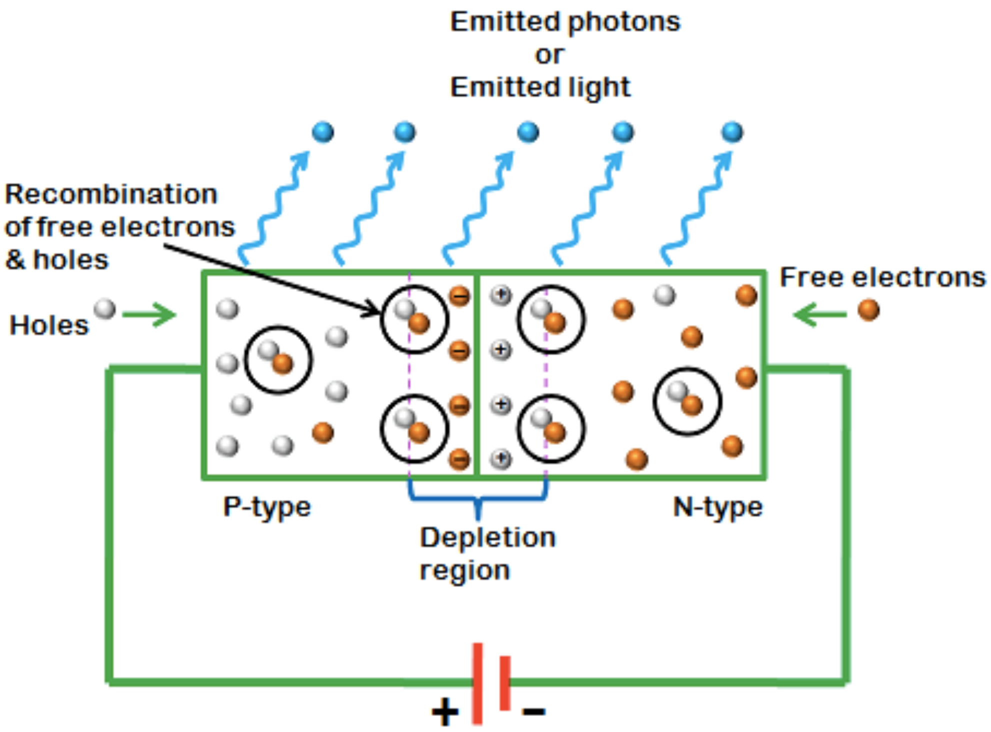
1. **Most III-V compounds** radiate at wavelengths above the visible region, i.e. in the **infrared**. However, adding some Al to GaAs **producing AlxGa1-xAs**, will shift the wavelength into the red region of the spectrum - here are our red luminescence diodes and Lasers!
2. **Very fortunate:** GaAs 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!

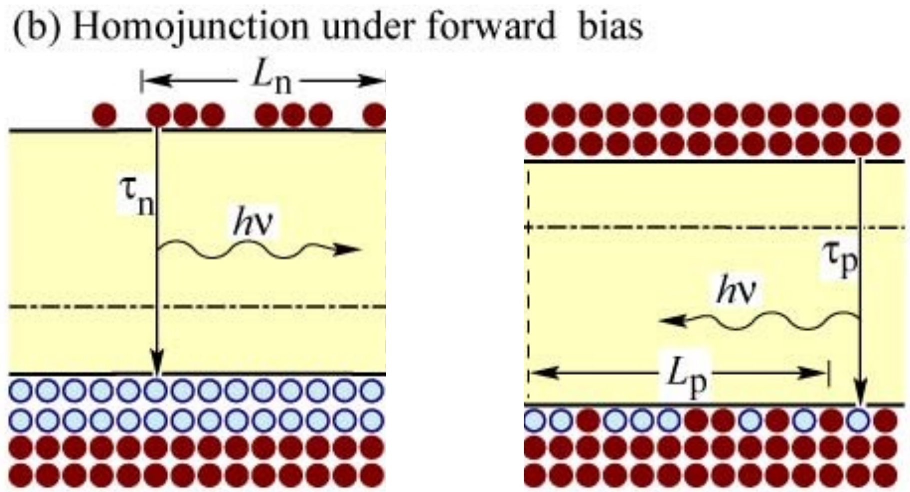
Light emitting diodes

A simplified picture



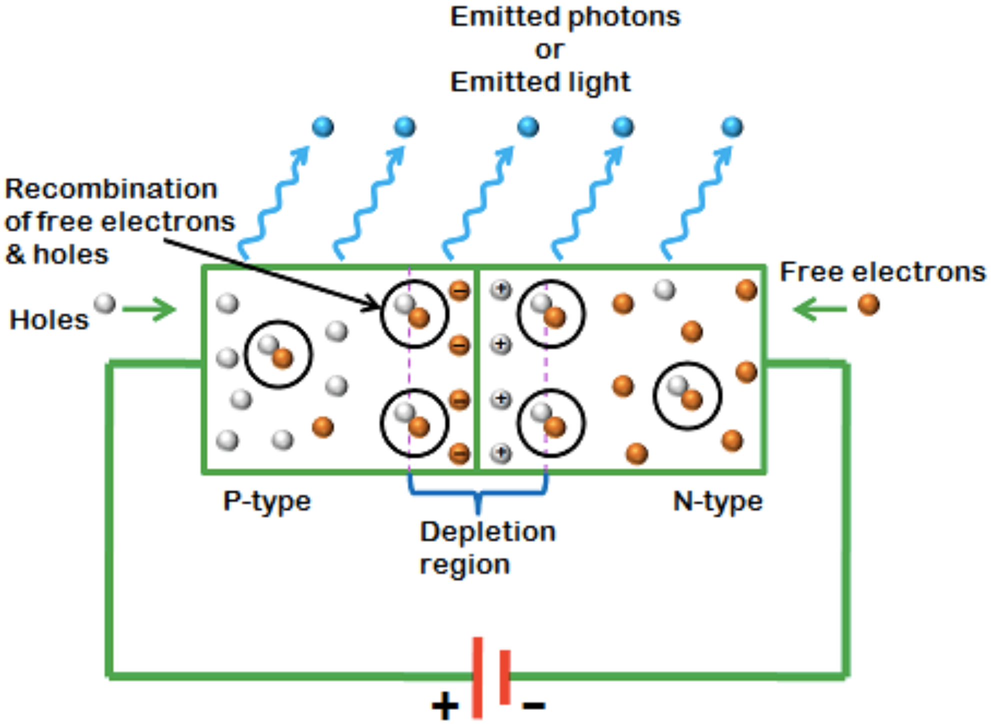
Light Emitting Diode (LED)

Physics and Radio-Electronics



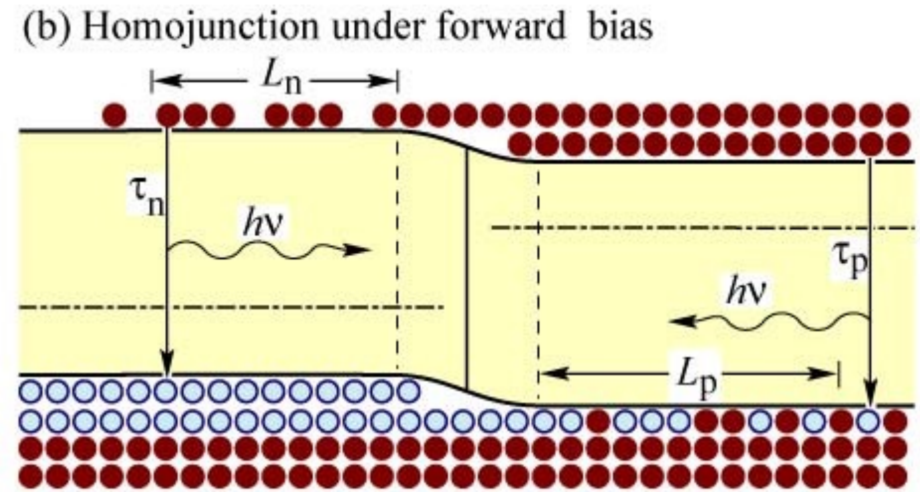
Light emitting diodes

A simplified picture



Light Emitting Diode (LED)

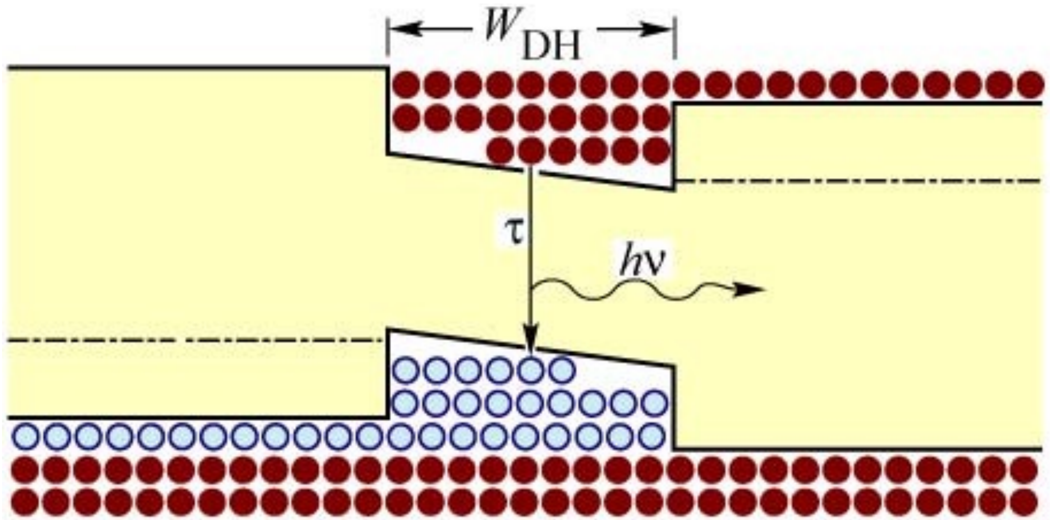
Physics and Radio-Electronics



Light emitting diodes

Improving the efficiency in emitting photons:

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



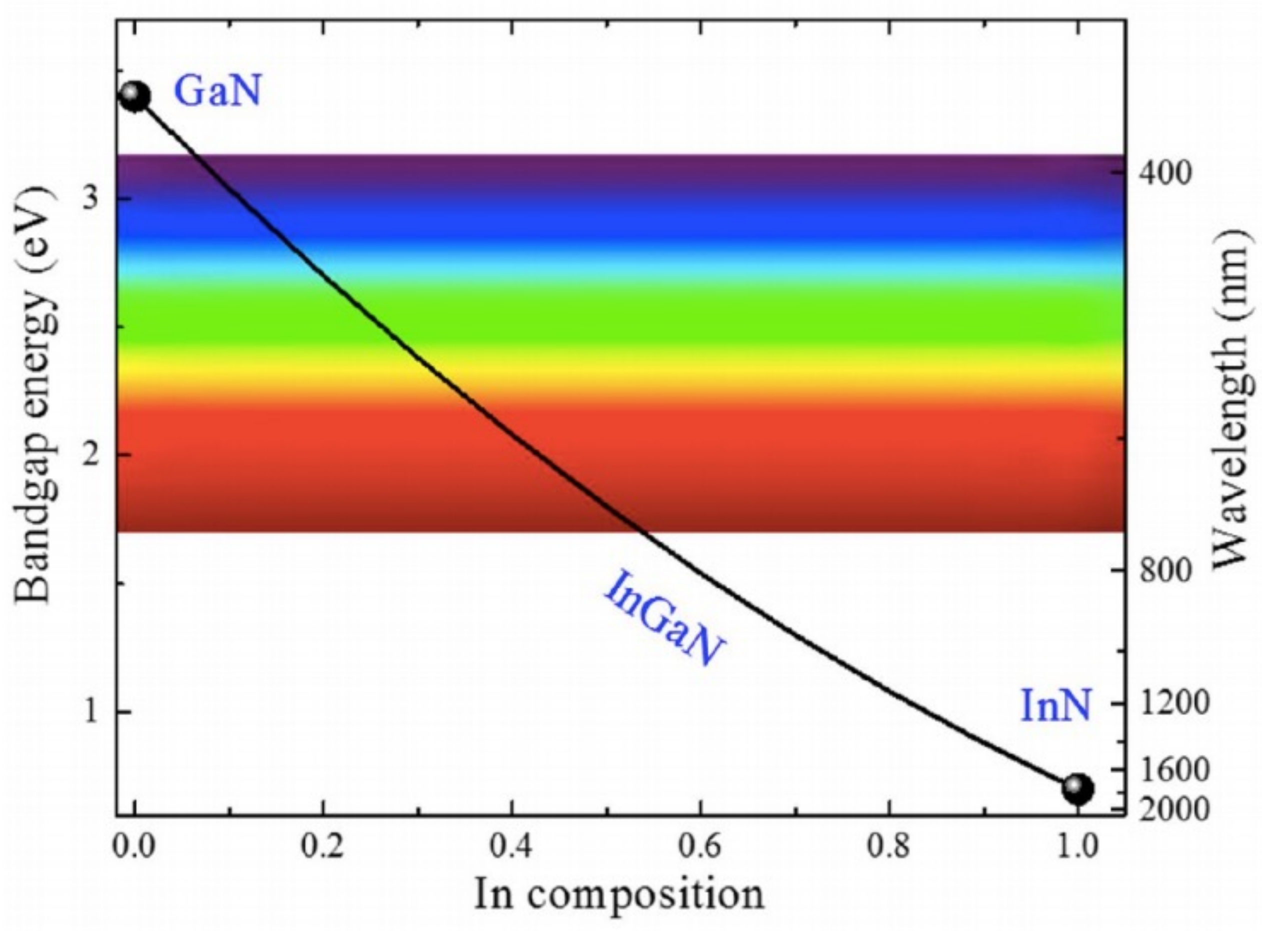
Quantum wells:

- 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

Light emitting diodes

Quantum wells:

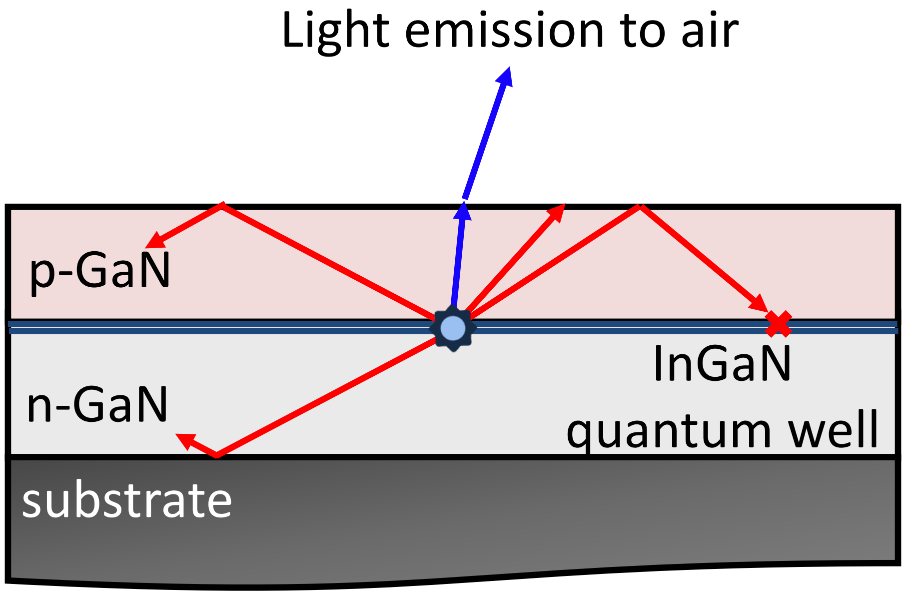
- In GaN system, quantum wells are typically made out of InGaN
- The In content determines the energy of the photons (color of the light)

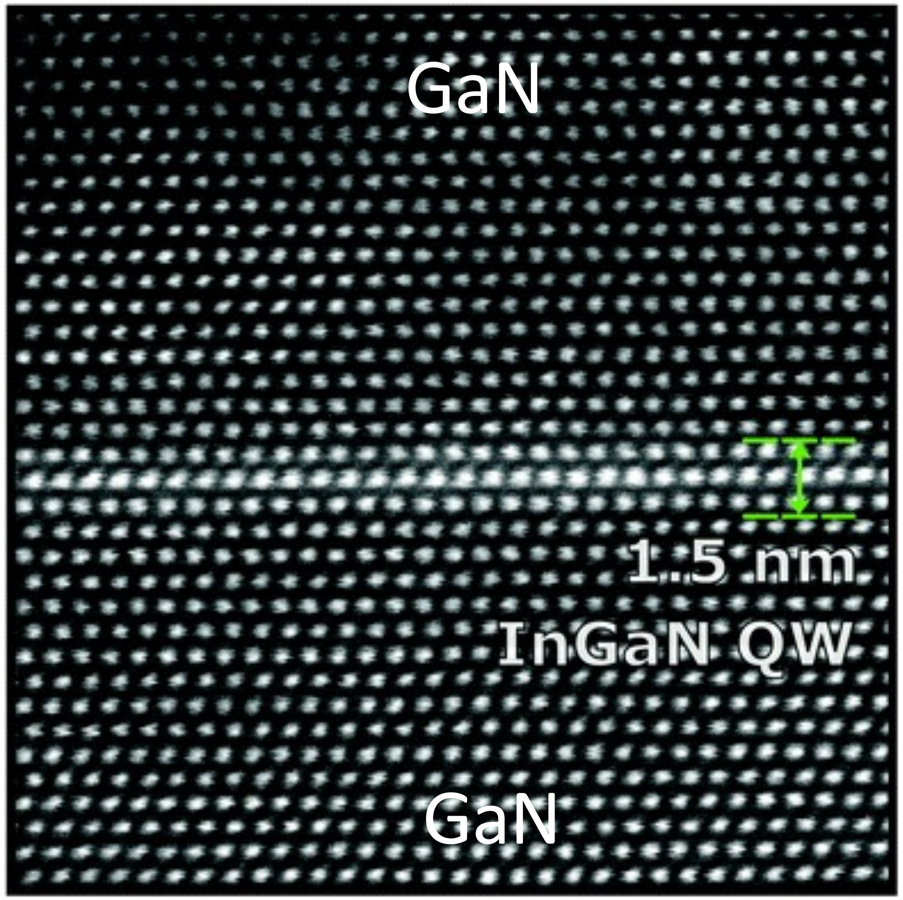


Bandgap energy versus In composition for InGaN ternary within visible spectrum energy range

Light emitting diodes

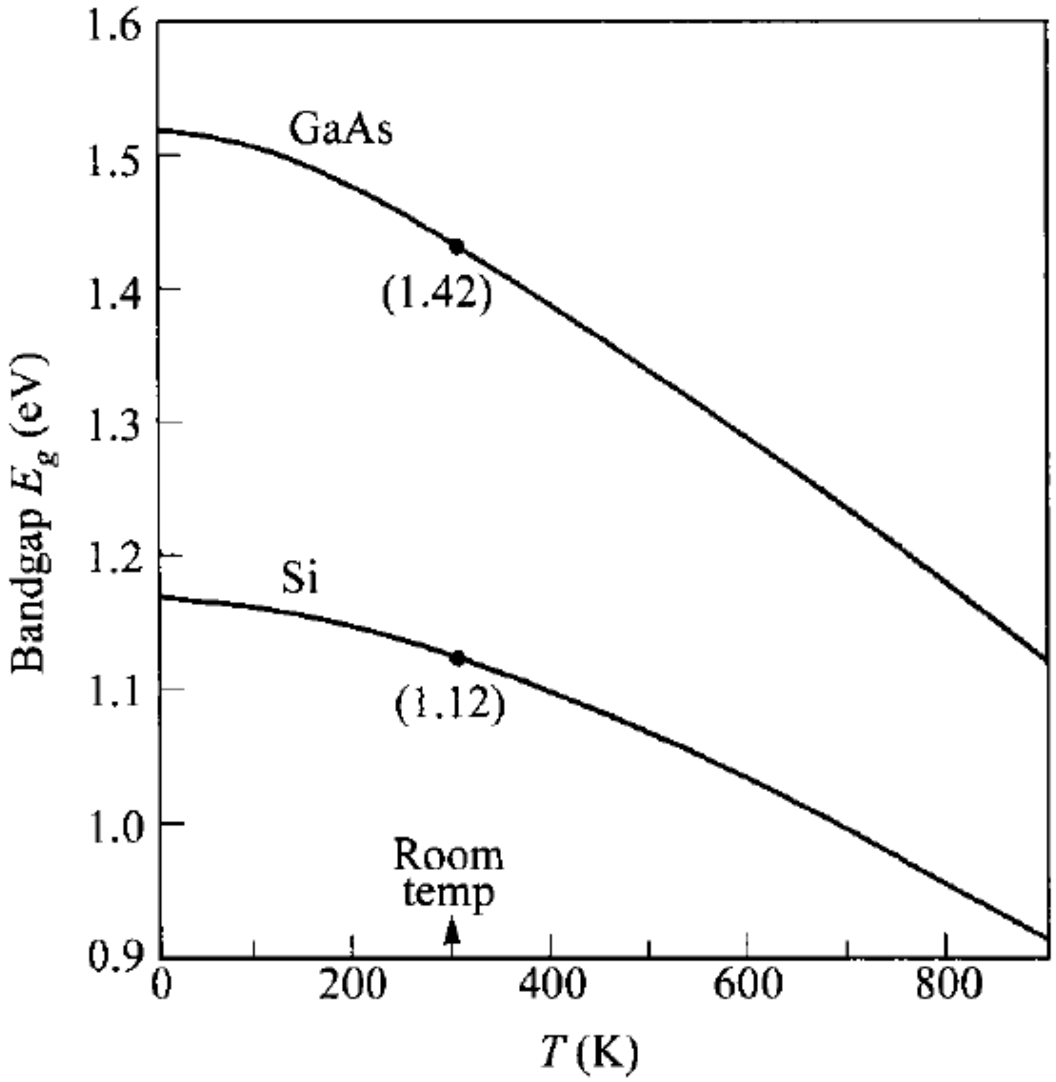
Simplified case of InGaN/GaN quantum well





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

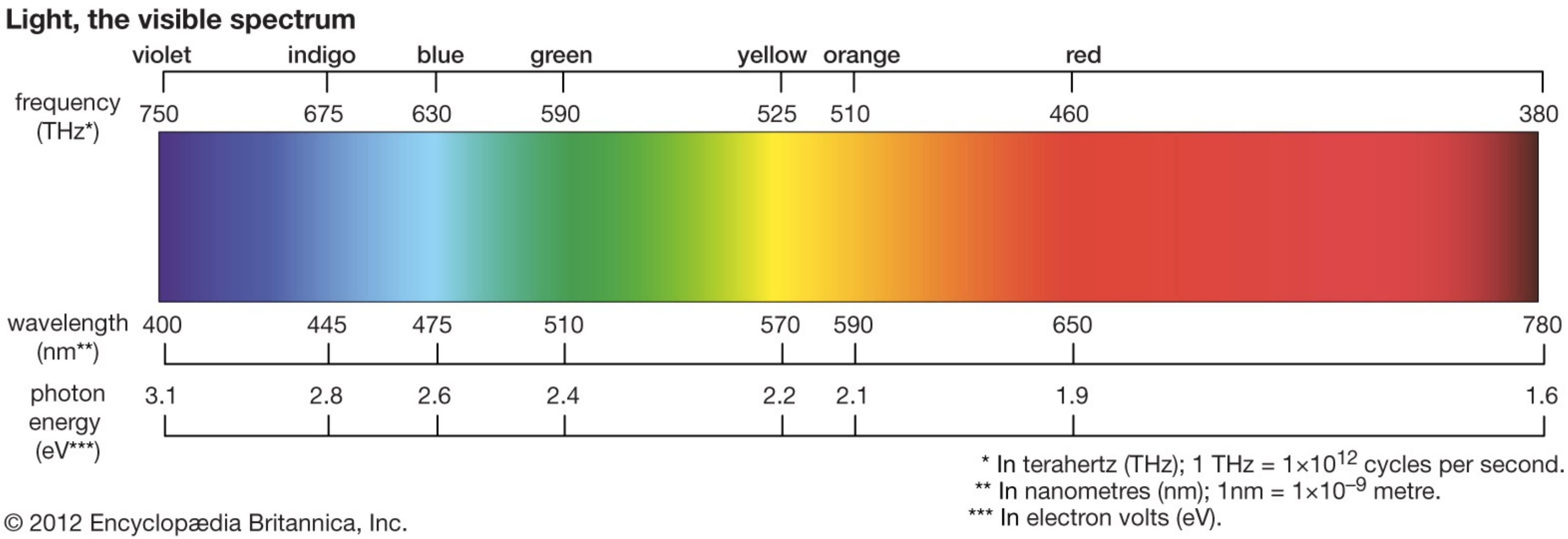
$$E_g(T) = E_g(0) - \frac{\alpha T^2}{T+\beta}$$

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?



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

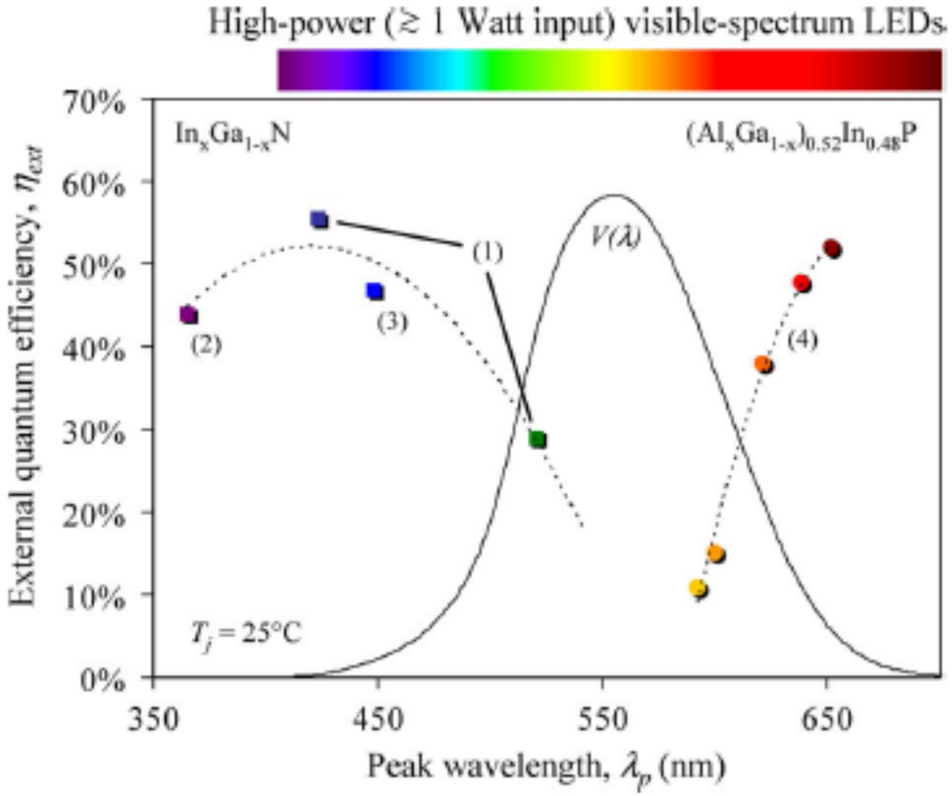
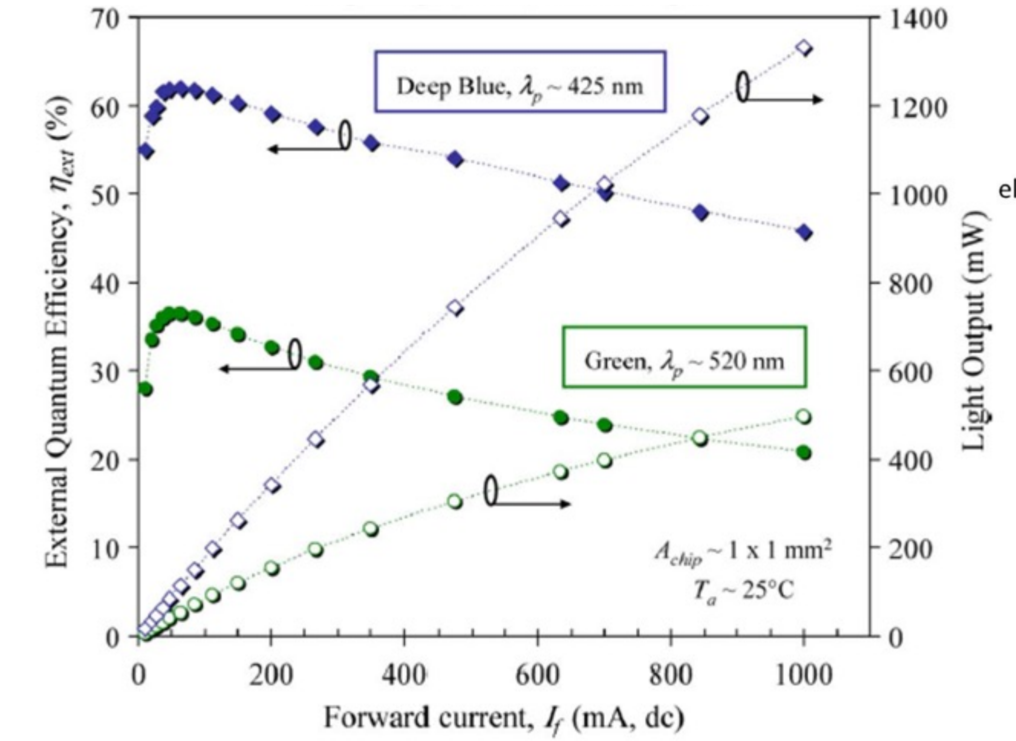
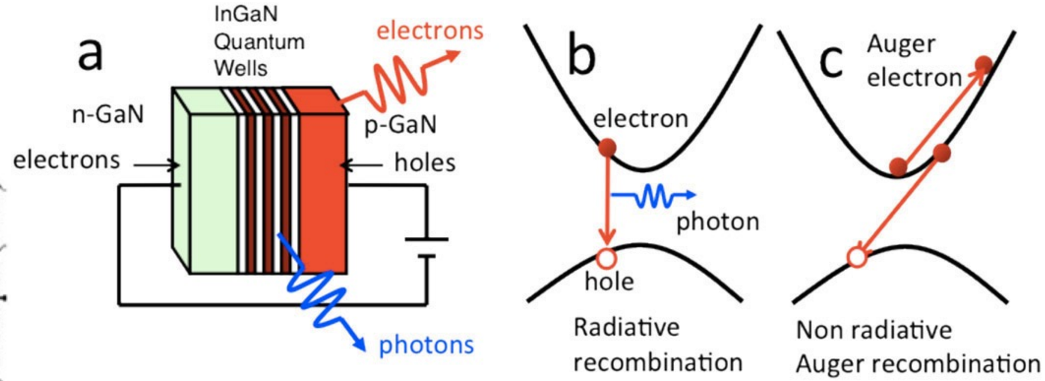


Fig. 2. State-of-art external quantum efficiencies for high-power visible-spectrum LEDs ($T_j = 25$ °C): (1) InGaN TFFC LEDs, 350 mA (this paper); (2) InGaN VTF LED, 1000 mA [42]; (3) InGaN CC LEDs employing patterned substrates [35]; and (4) Production performance, AlGaInP TIP LEDs [9], Philips Lumileds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

2. Auger recombination: major problem in GaN LEDs today

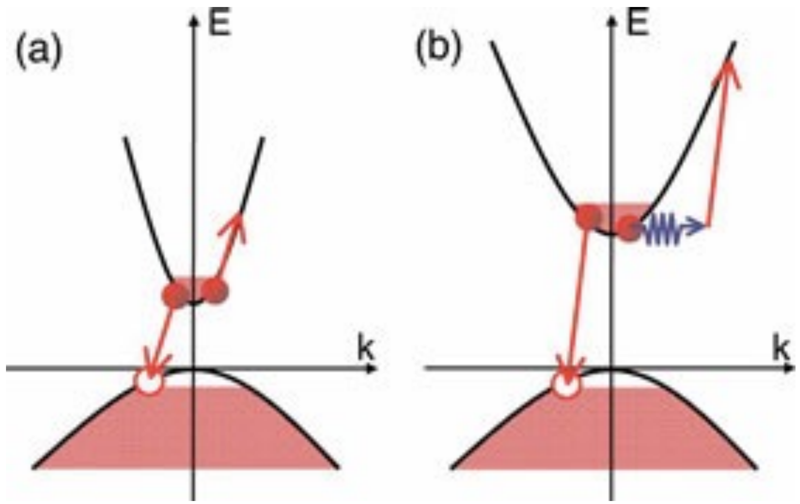


Krames et al., JDT, vol. 3, n. 2, 2007



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

Phonon-assisted Auger recombination:



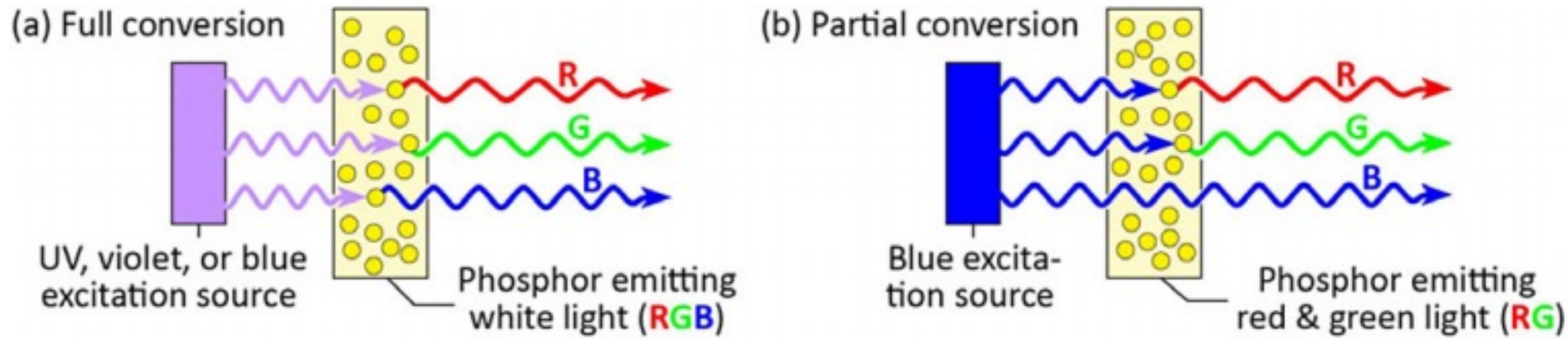
Auger recombination:

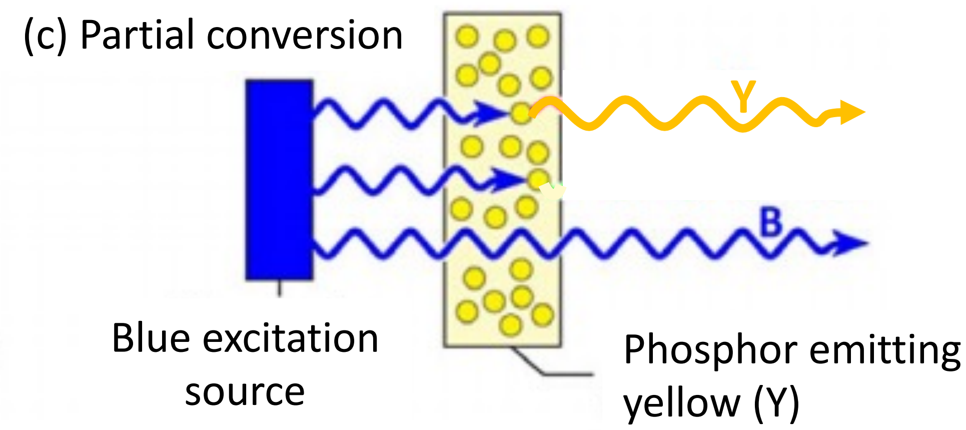
- 3-particle process (proportional to np^2 or pn^2)
- energy given to third carrier; **needs lots of carriers**: **shows up at large carrier densities**

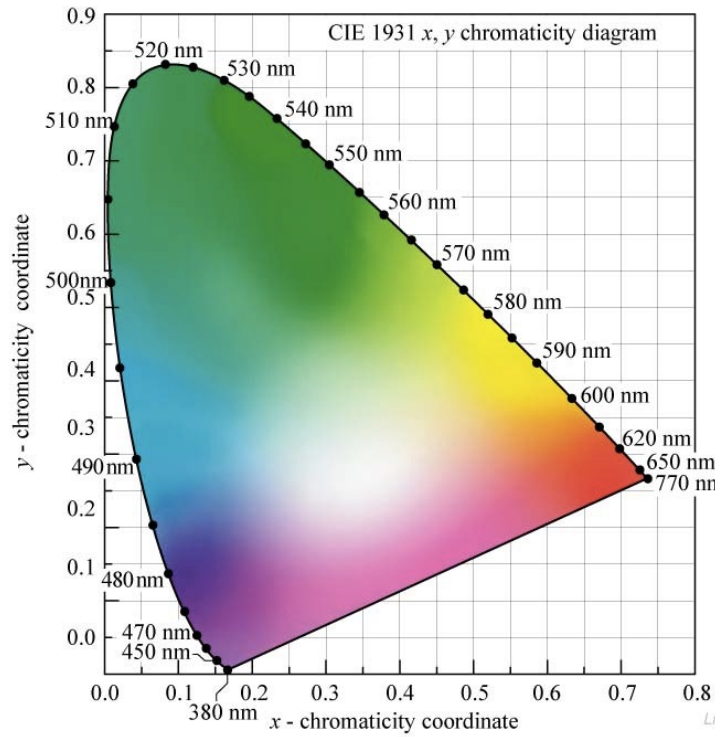
How to produce white LED for lighting?

Phosphors:

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





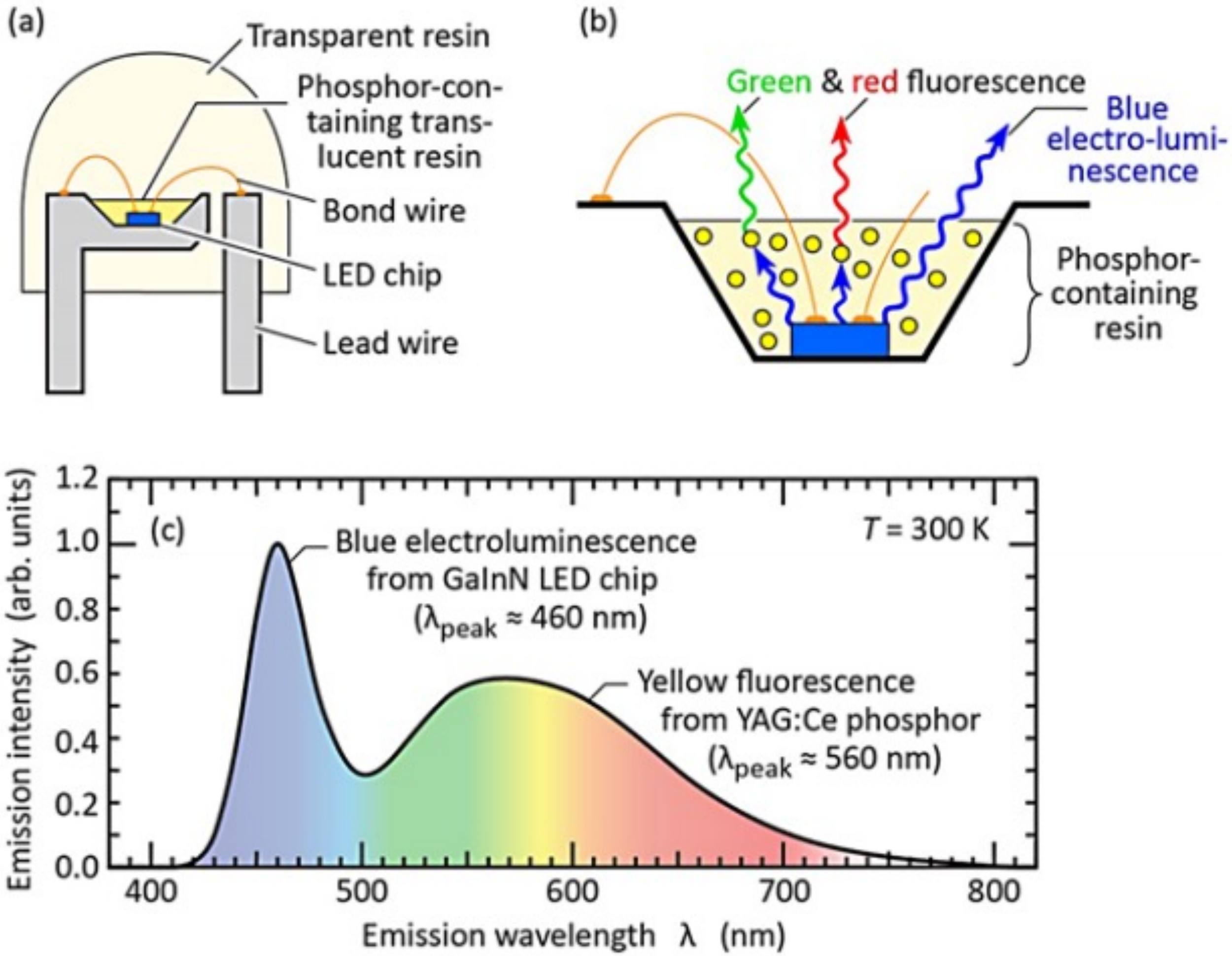


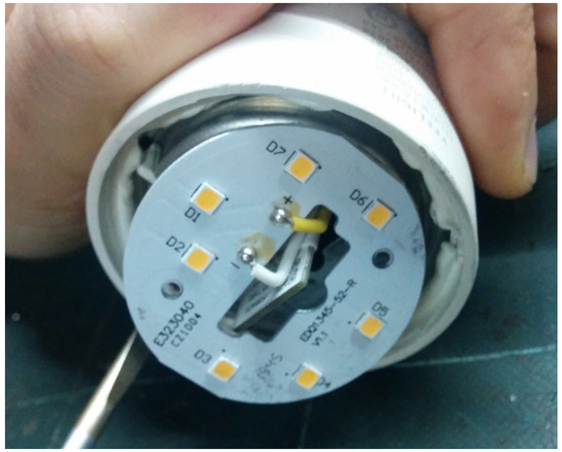
J. Cho et al., Laser Photonics Rev. 11, No. 2, 1600147 (2017)

To produce white light, mix the correct ratio of colors

How to produce white LED for lighting?

EPFL

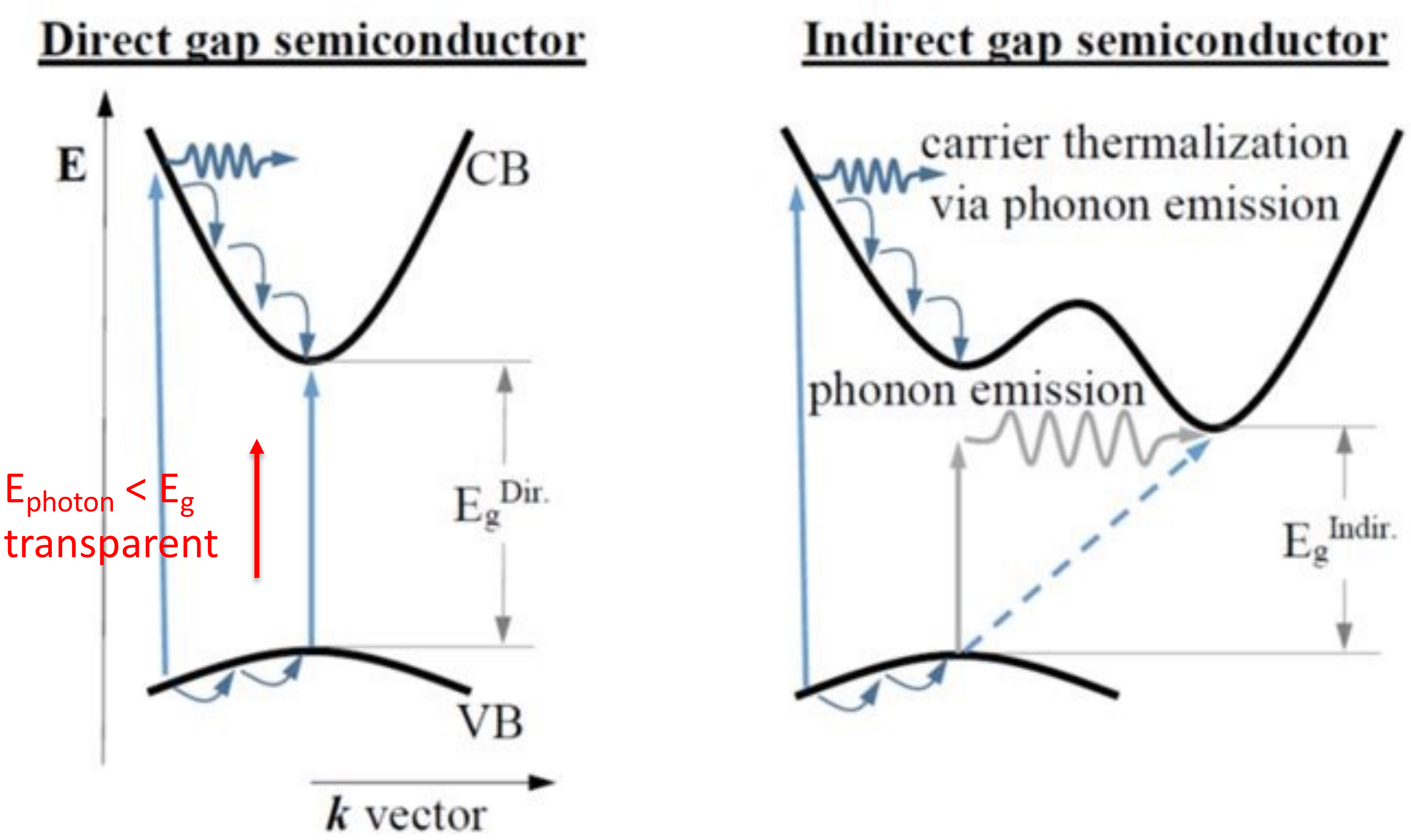




J. Cho et al., Laser Photonics Rev. 11, No. 2, 1600147 (2017)

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**



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**
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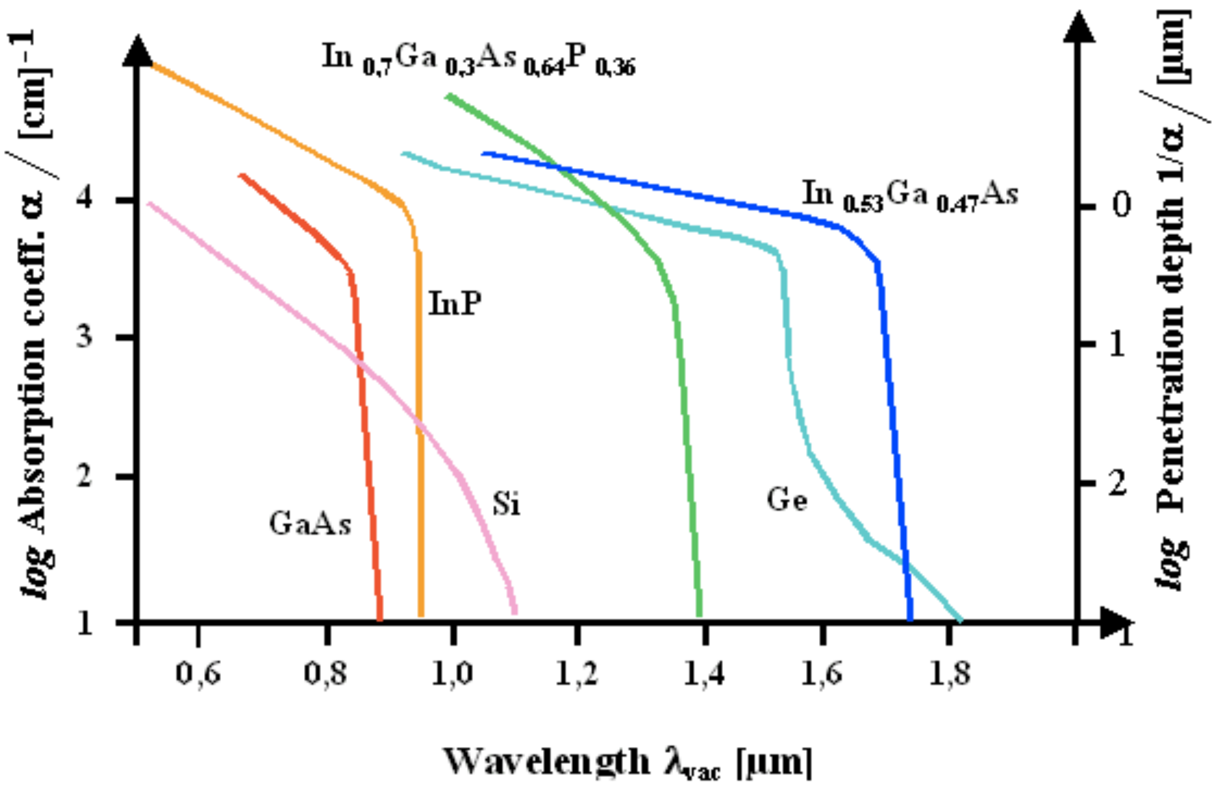
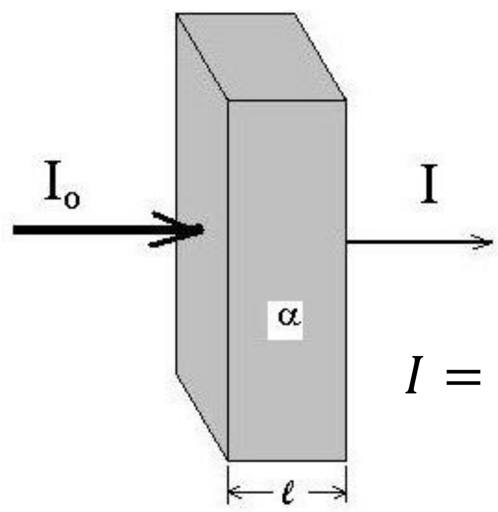
Absorption coefficient of various semiconductors



Beer-Lambert law

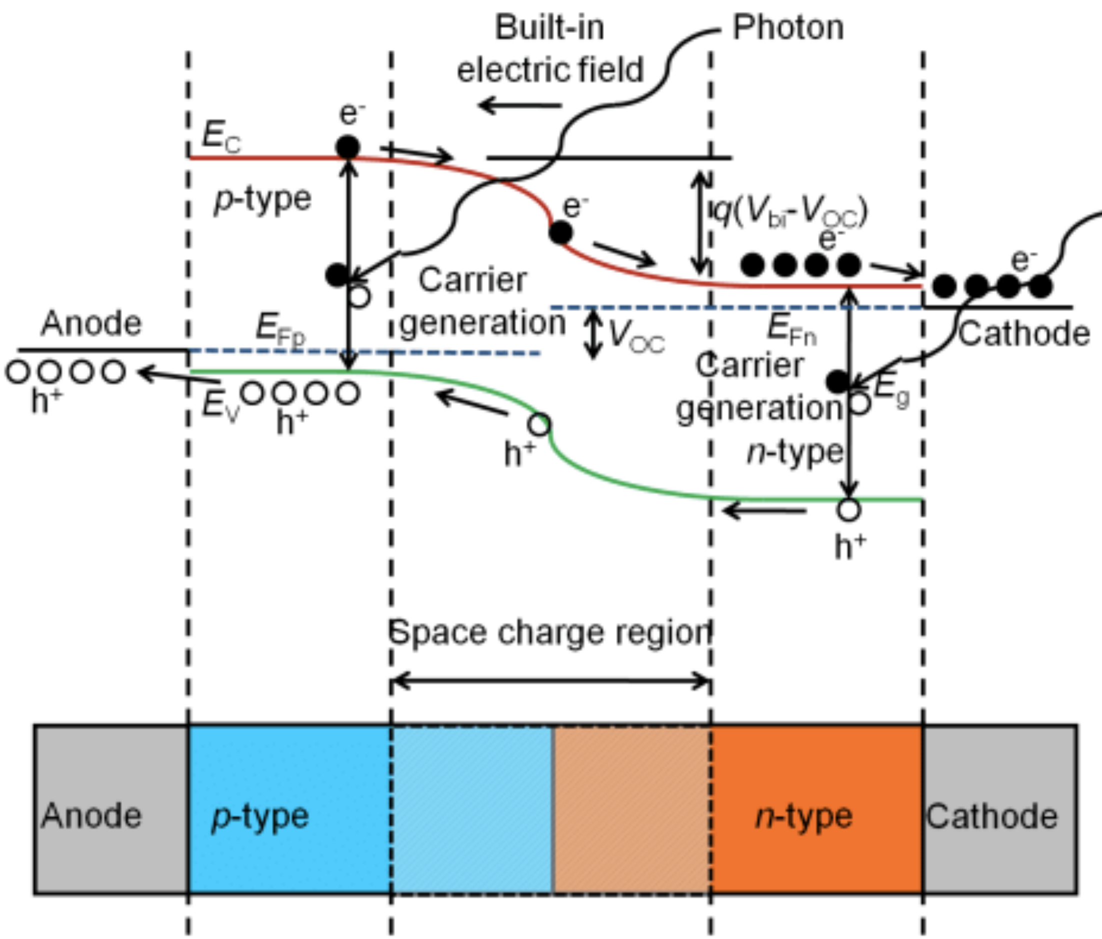


$$I = I_o e^{-\alpha l}$$

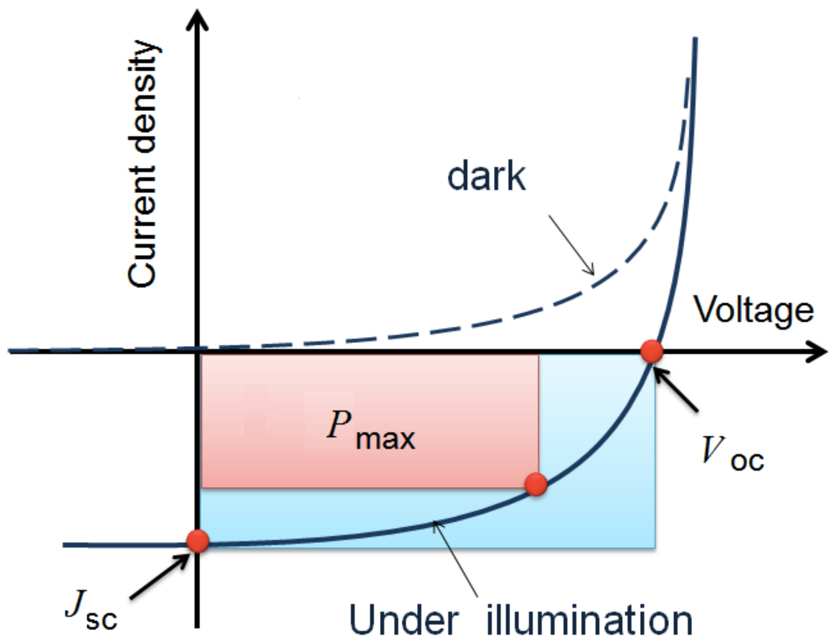
Absorption at the edge of the band gap is not sharp for indirect band gap materials

So why are most solar cells made out of silicon?

Solar cells

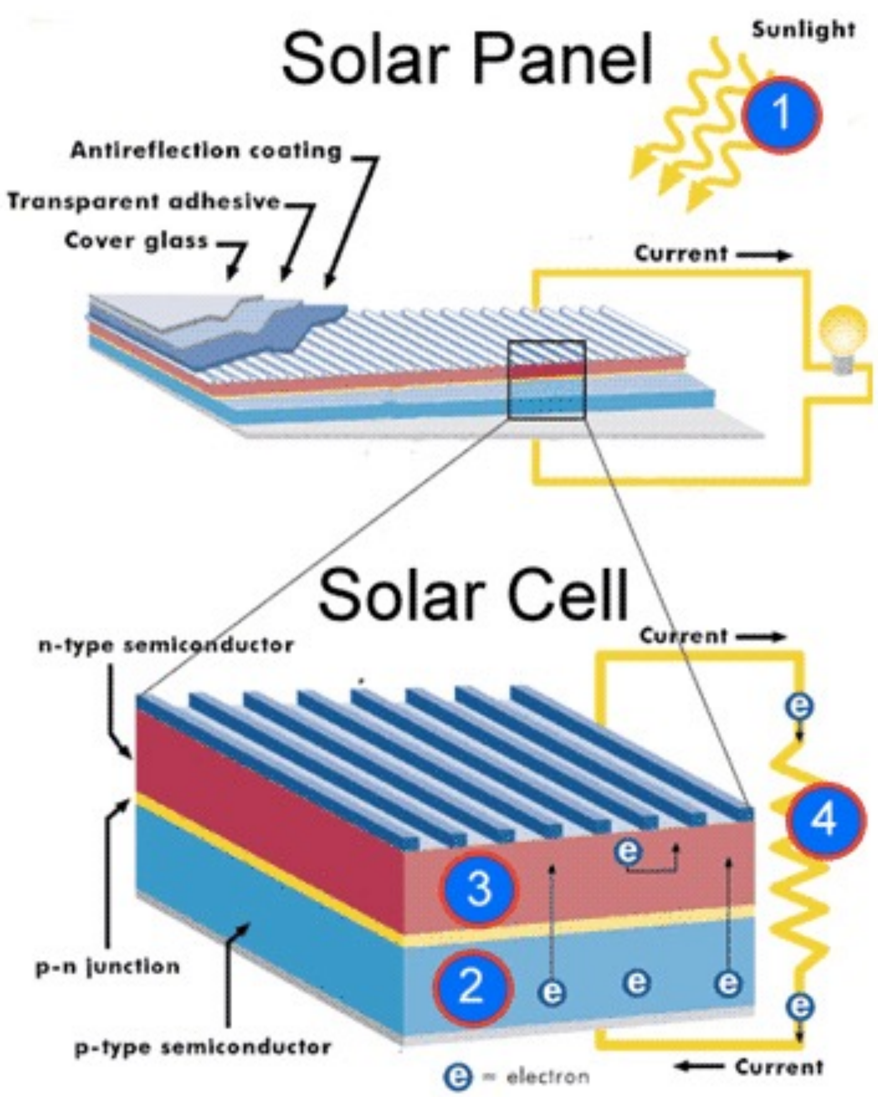


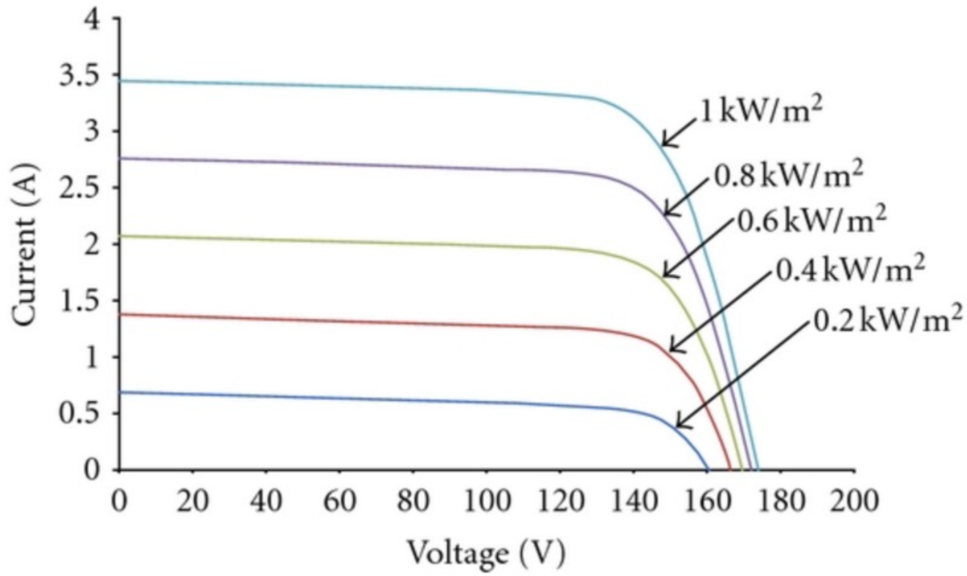
Built-in
electric field
Photon
Photon
E_C
e⁻
p-type
e⁻
$q(V_{bi}-V_{OC})$
e⁻
e⁻
Carrier
generation
V_{OC}
Anode
E_{Fp}
E_{Fn}
Cathode
Carrier
generation
E_g
E_V
h⁺
h⁺
h⁺
n-type
h⁺
Space charge region
Anode
p-type
n-type
Cathode

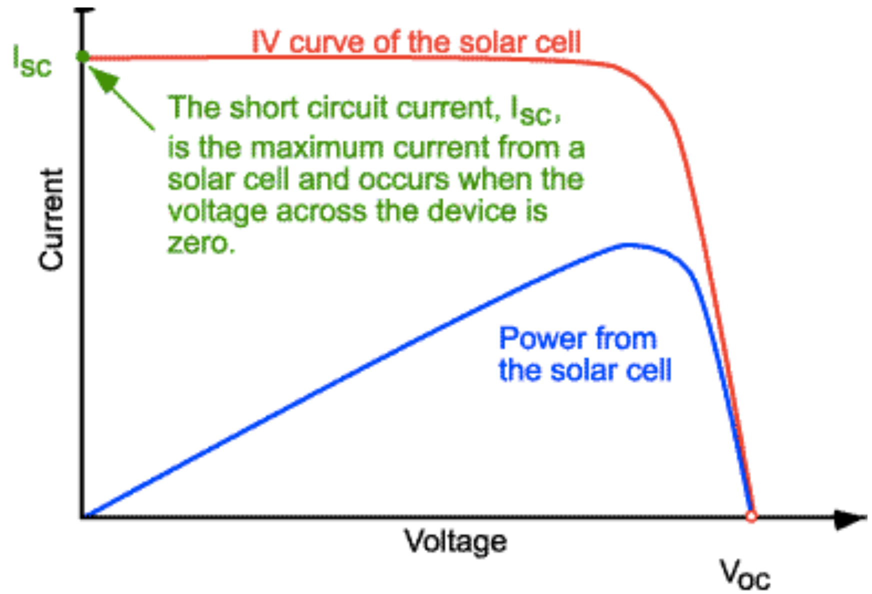


Current density
dark
Voltage
P_{max}
V_{oc}
J_{sc}
Under illumination

Solar cells





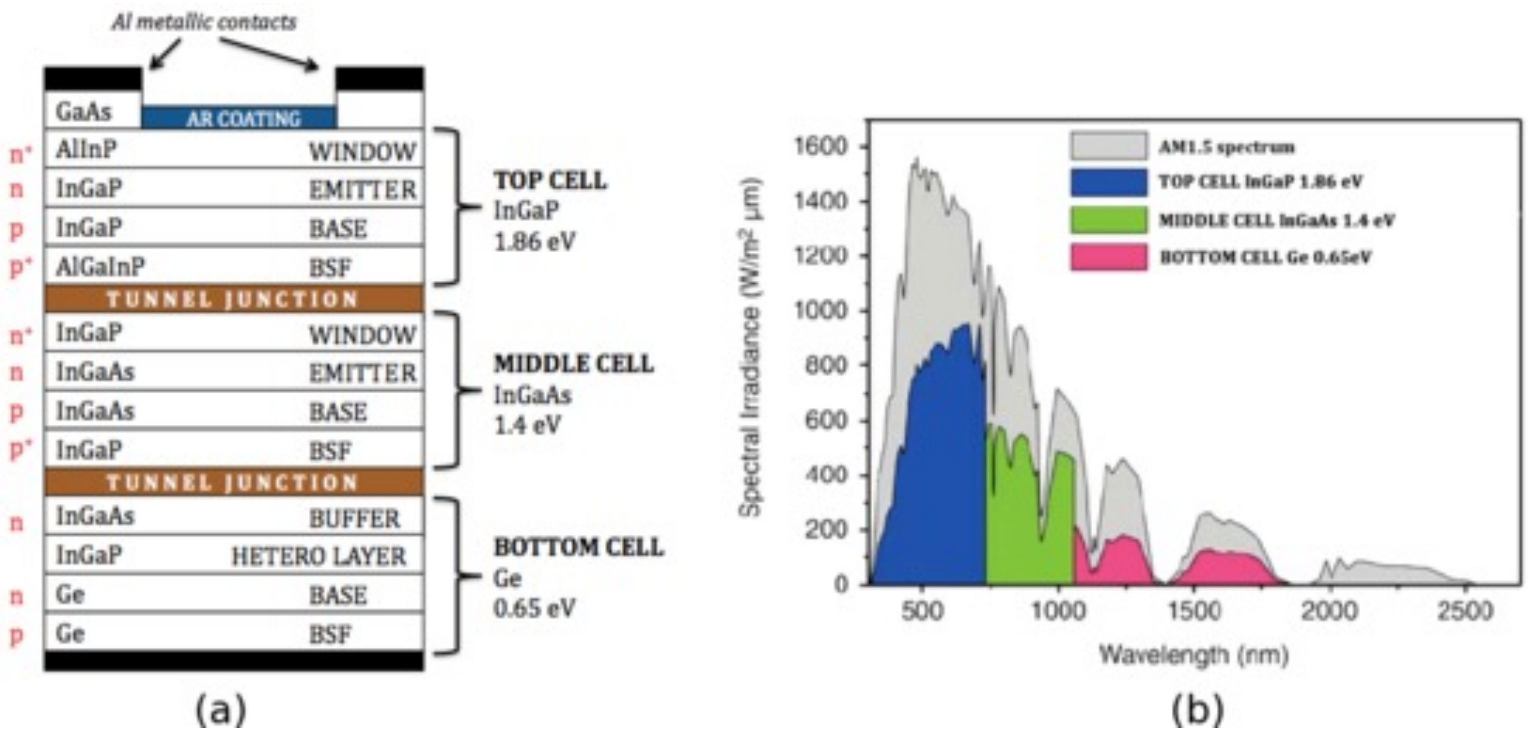


Increasing the solar intensity:

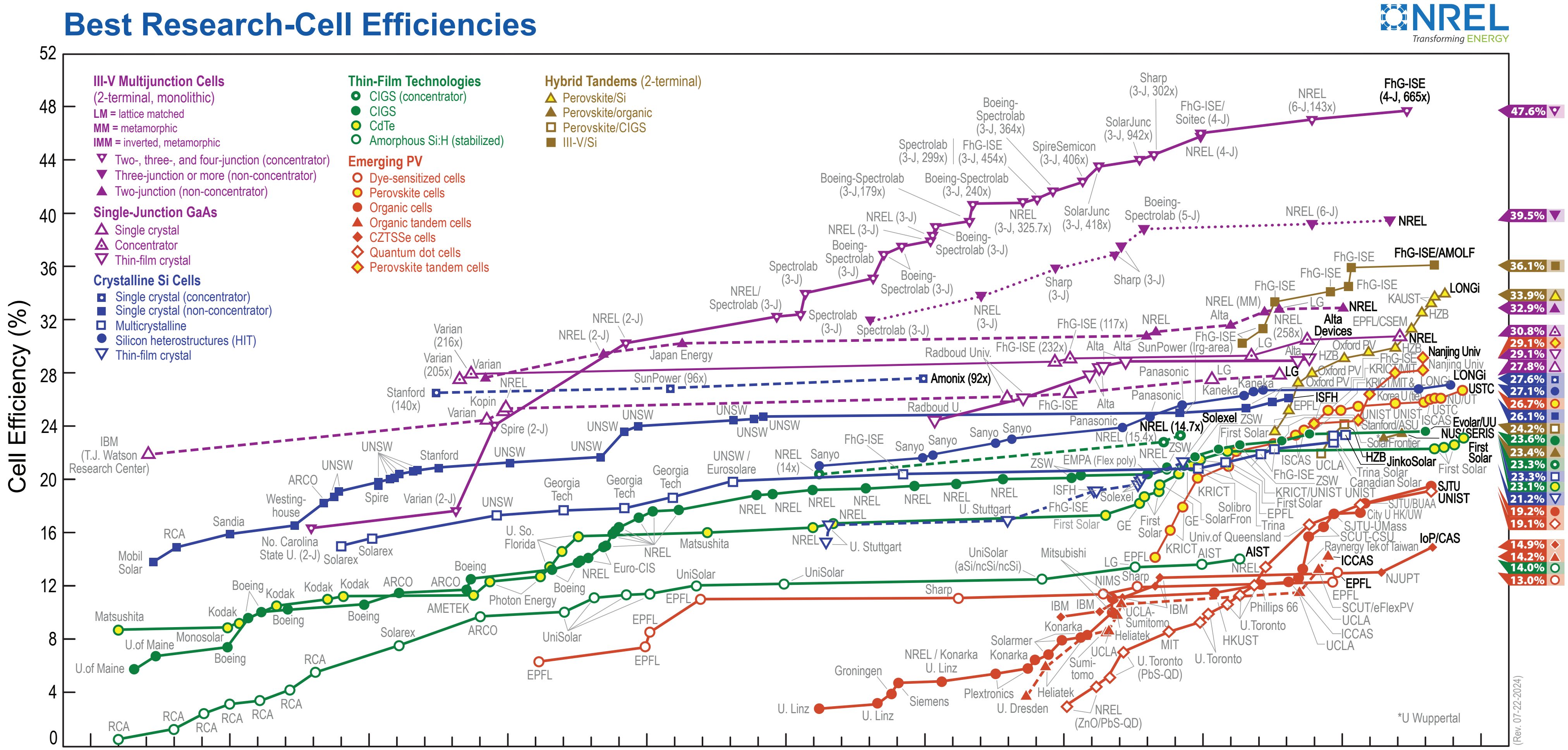
linear increase in short-circuit current (I_{SC}), but sub-linear increase in open-circuit voltage (V_{OC})

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

Multijunction solar cells



Solar cells



https://www.nrel.gov/pv/cell-efficiency.html