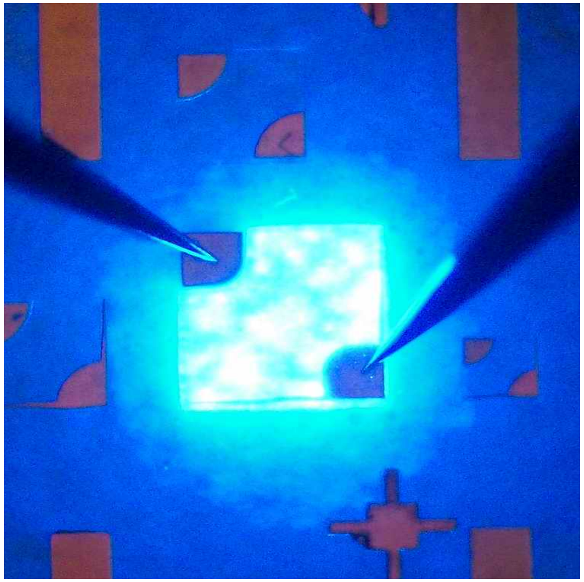
Optoelectronics
ELEC-E3210



Lecture 1

Aalto University
School of Electrical
Engineering

Light-emitting diodes

Outline

1. **III-V's for LEDs**
2. **Electrical and optical properties**

P. Bhattacharya: chapter 5
J. Singh: chapter 9

Eye sensitivity function and luminous efficacy

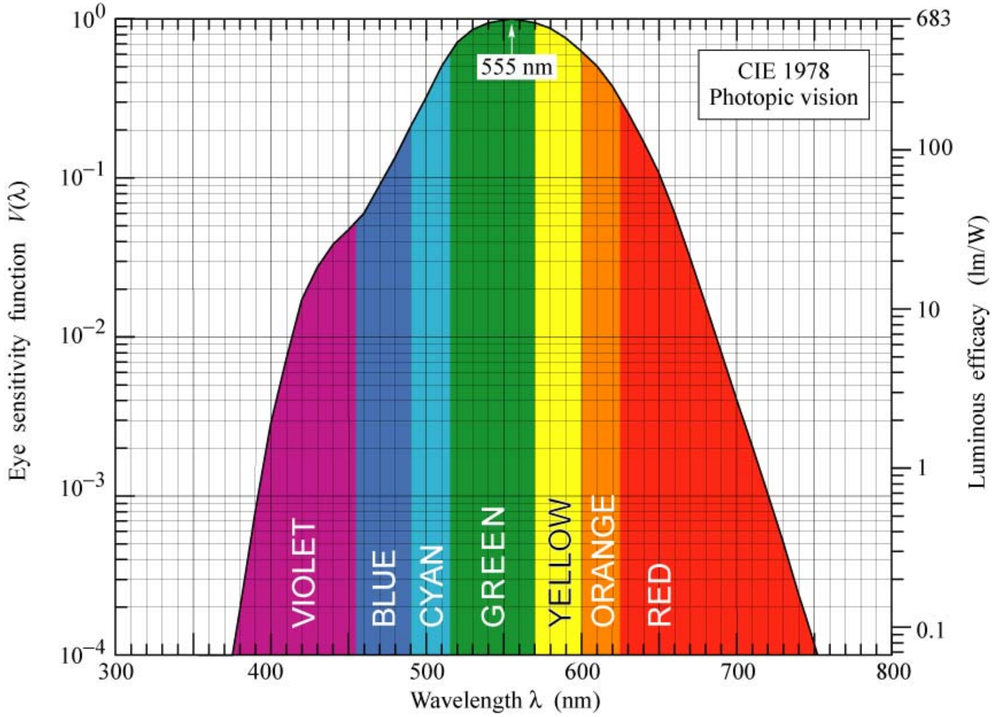


Fig. 16.7. Eye sensitivity function, $V(\lambda)$, (left ordinate) and luminous efficacy, measured in lumens per Watt of optical power (right ordinate). $V(\lambda)$ is greatest at 555 nm. Also given is a polynomial approximation for $V(\lambda)$ (after 1978 CIE data).

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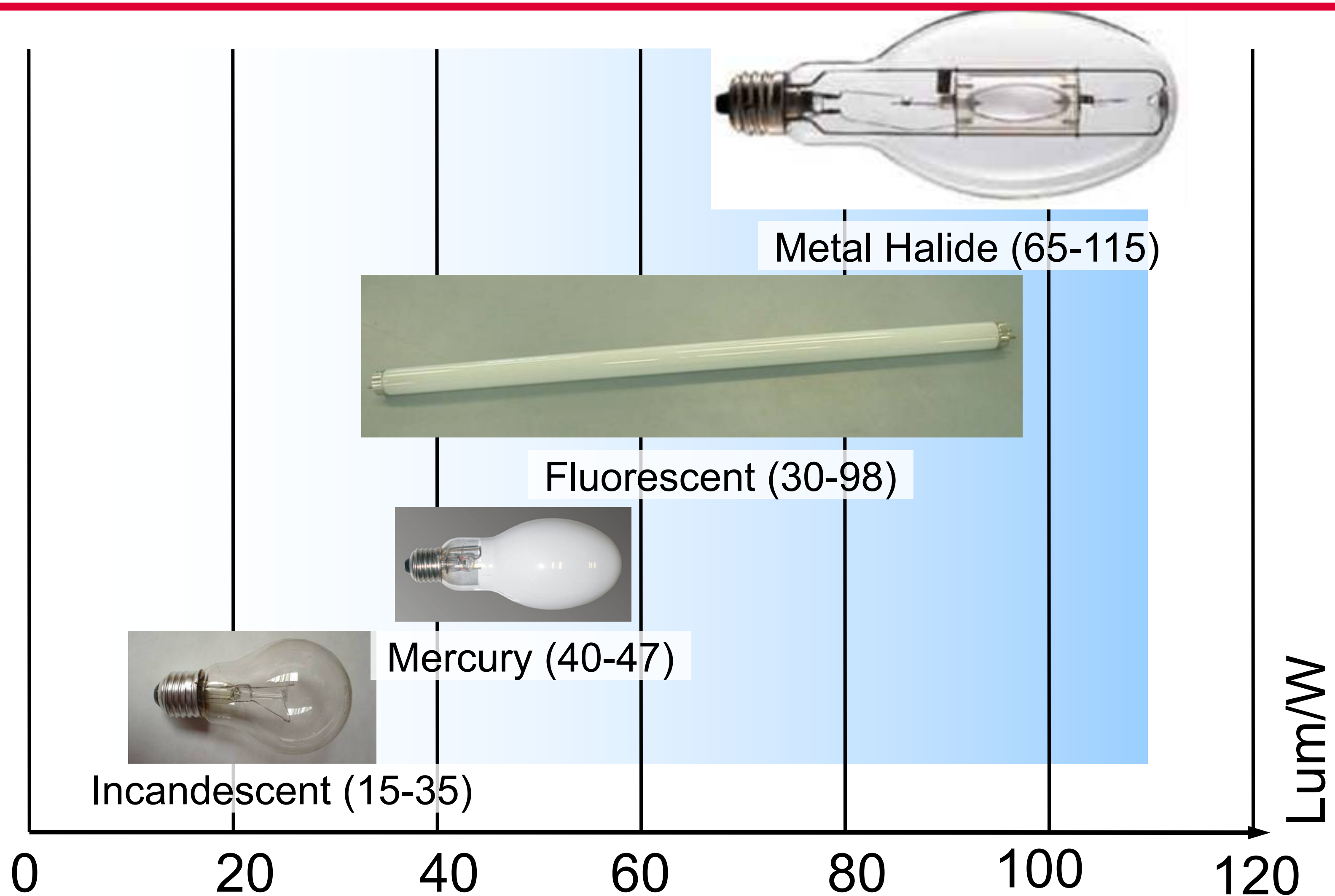
$$\eta_{eff} = \frac{683 \cdot \int_{\lambda} V(\lambda) P_{out}(\lambda) d\lambda}{UI}$$

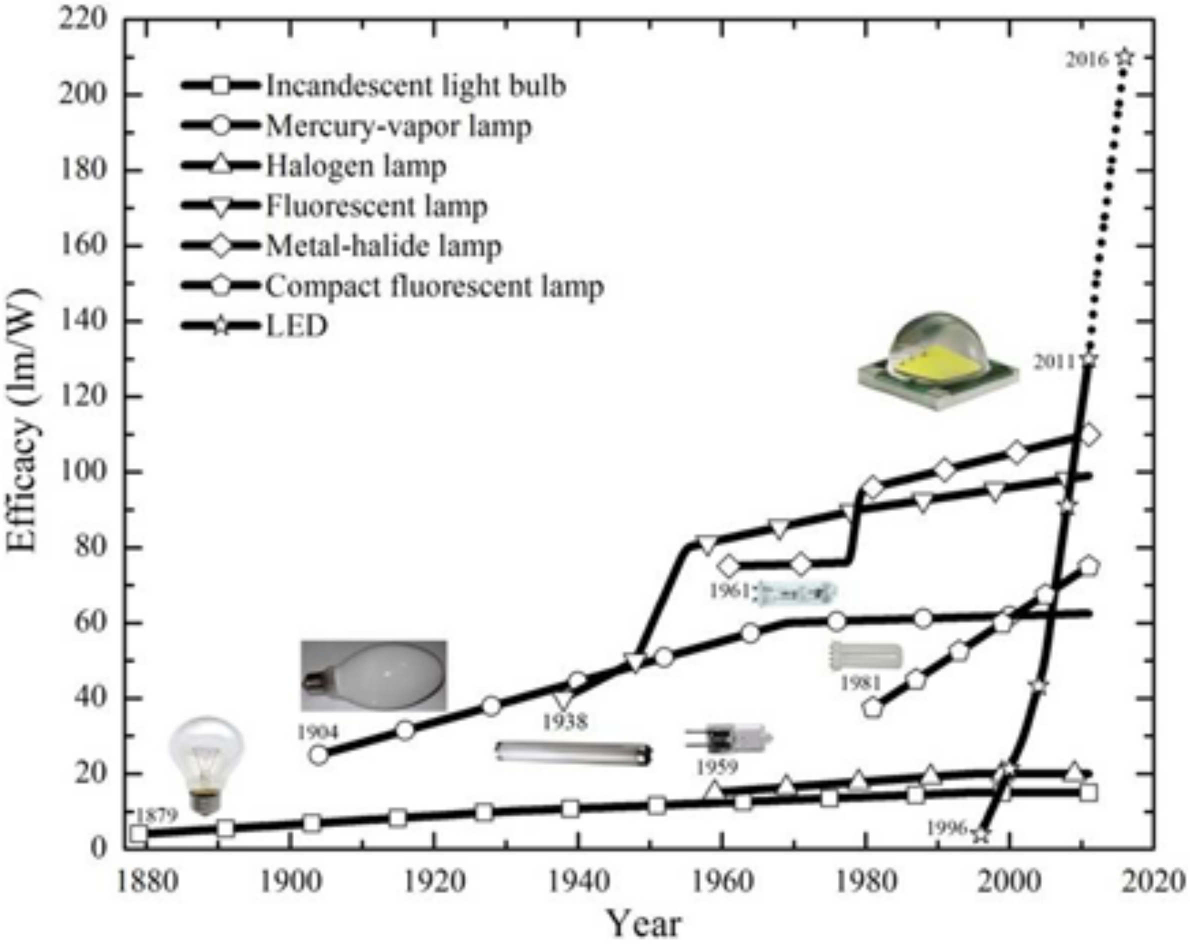
Output power of the LED in lumen

- Definition of lumen: Green light (555nm) with power 1W has luminous flux of 683 lm
- Efficacy defines how well a LED converts electrical power into visible light; it gives number of lumens per optical watt
- Candela cd=lm/str (luminous flux per unit solid angle)

Efficacy of classical light sources



LED Efficiency



Blue-UV LED with phosphor, theoretical limit ~280 lm/W

Internal and external quantum efficiency

- Internal quantum efficiency η_{int}

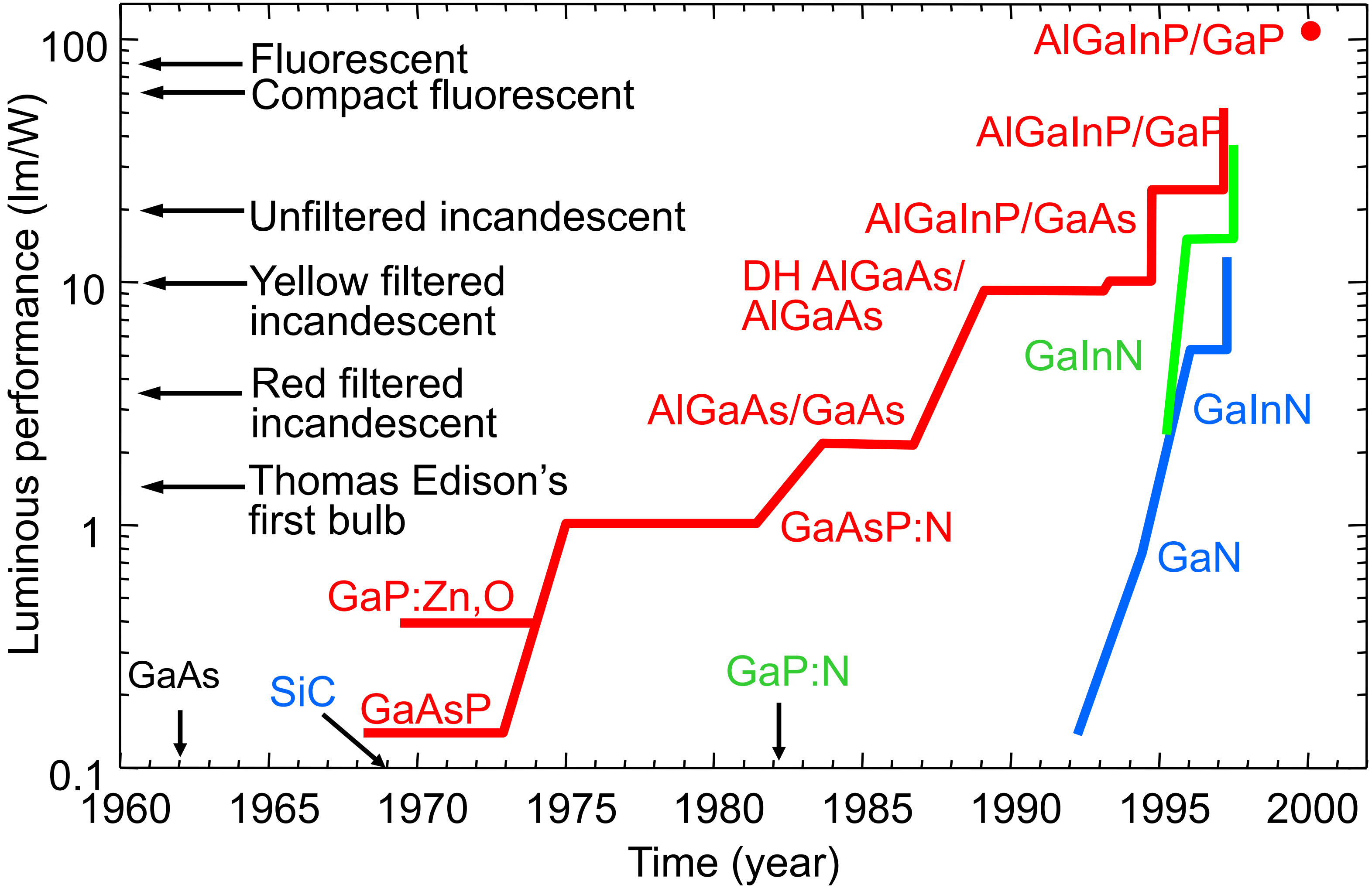
$$\eta_{int} = \frac{\text{Number of electron-hole pair recombination per second}}{\text{Number of electrons injected per second}}$$

- External quantum efficiency η_{ext}

$$\eta_{ext} = \frac{\text{Number of photons emitted per second}}{\text{Number of electrons injected per second}}$$

Typically $\eta_{int} > \eta_{ext}$

Evolution of LED performances



GaAs LEDs

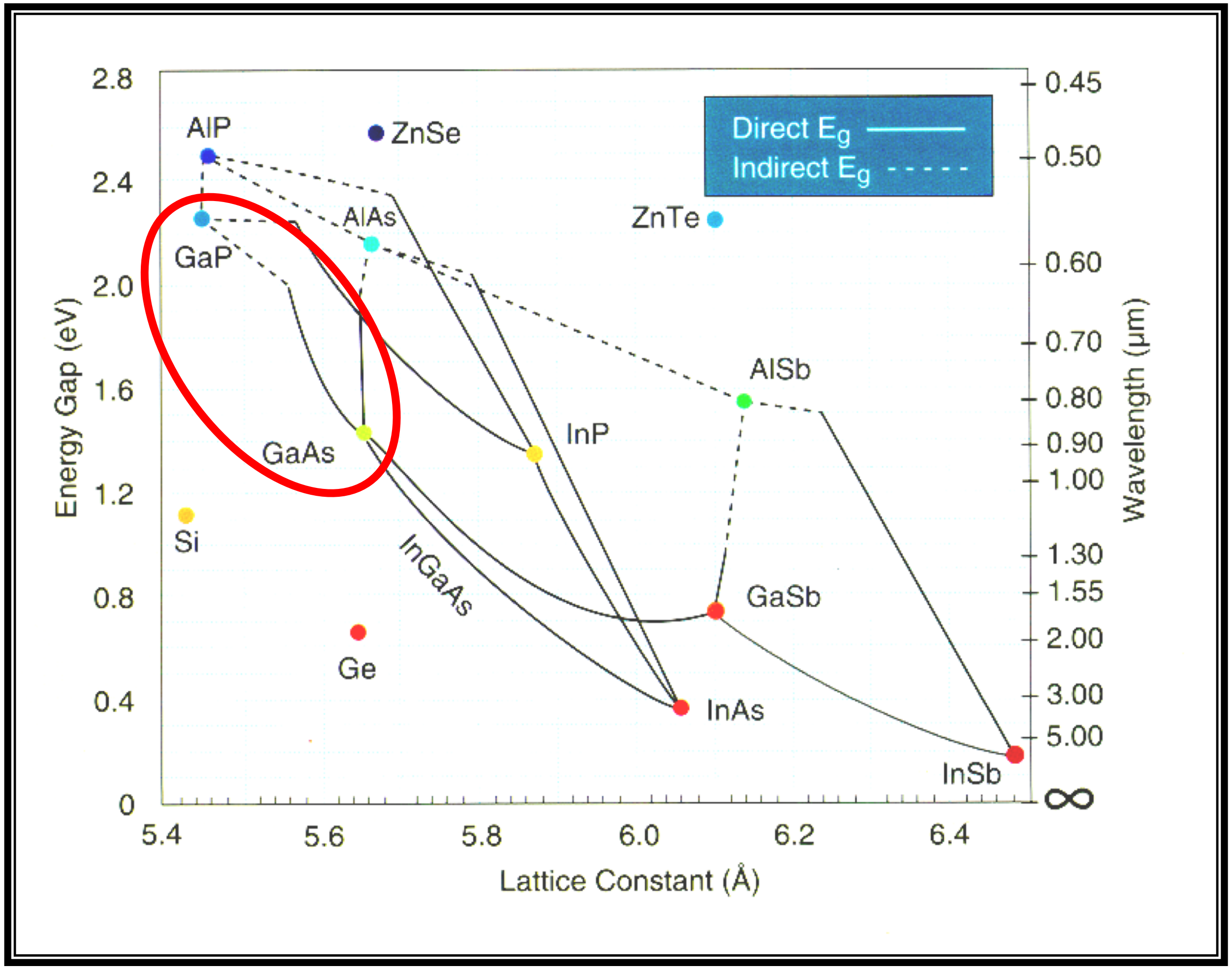
IR

- GaAs is a direct bandgap semiconductor with E_g = 1.44eV (860nm)
- First demonstration in 1962 by Radio Corporation of America, General Electrics, IBM and MIT
- Hereafter, small number of GaAs LEDs emitting at around 870nm sold by Texas Instruments for 130$ a piece. External efficiency η_{ext}=0.2%
- Efficiency of GaAs can be improved by doping with silicon. Si is an **emphoteric dopant** for GaAs (it can act as a p or n dopant)
- In Si-doped GaAs LEDs the main radiative transition is between the conduction band and the Si acceptor level (λ= 910-1020nm)

No reabsorption by GaAs

$\boldsymbol{\eta_{ext} = 10\%}$

GaP and GaAsP LEDs



GaP and GaAsP LEDs

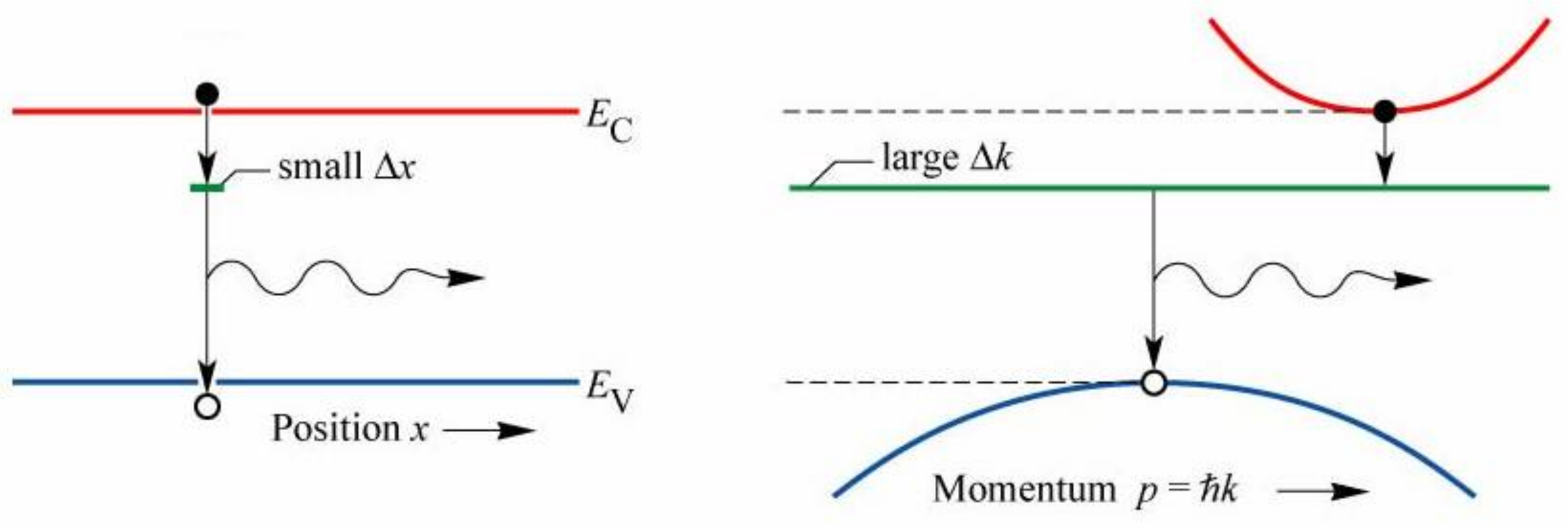
- GaP is an **indirect** bandgap with E_g = 2.26eV (549 nm = green)
- $GaAs_{1-x}P_x$ is a direct semiconductor for *x*<0.45
- At *x*=0.35 the band gap is about 1.97 eV (630 nm = orange)
- Radiative recombination in indirect $GaAs_{-x}P_x$ can be enhanced by introducing radiative deep impurity levels (N complexes or Zn-O defects)!

- The spread of the impurity states in k-space allows transitions to band edges without phonons
- Oxygen produces a deep donor level 0.8 eV below the CB, together with Zn it forms a trap with a binding energy of 0.3 eV. Bound exciton associated with this level produces emission at 640 nm.
- N-N complexes result in yellow emission at 590 nm.

Deep level mediated radiative recombination

Real space

Reciprocal space



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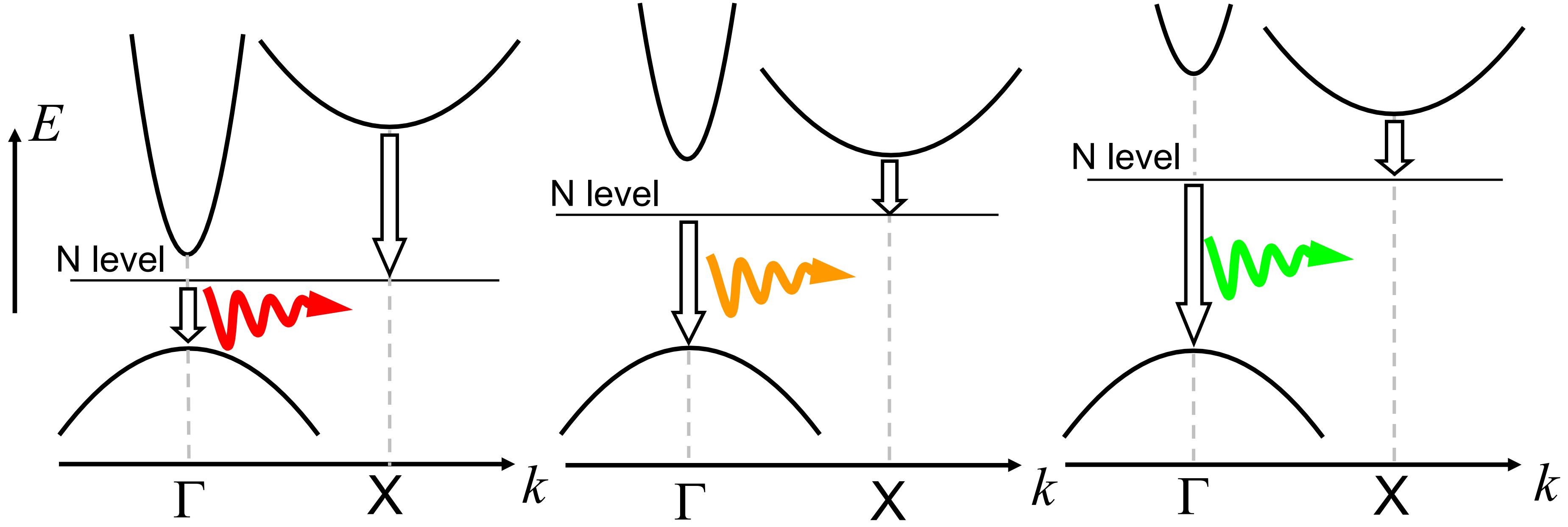
Heisenberg uncertainty principle: $\Delta x \Delta p \geq \hbar$

- If a charge carrier is well localized (Δx small) then its momentum can take a wide range of values
- No phonons are needed for transitions between impurity states and band edges! → this increases the radiative efficiency of indirect bandgap semiconductors

N-doped GaAsP and GaP: band structure

Nitrogen complexes in GaAsP system form a **radiative deep level** or **recombination centers** or **isoelectronic traps.**



Direct gap GaAs

Crossover $GaAs_{0.5}P_{0.5}$

Indirect-gap GaP

GaP and GaAsP LEDs

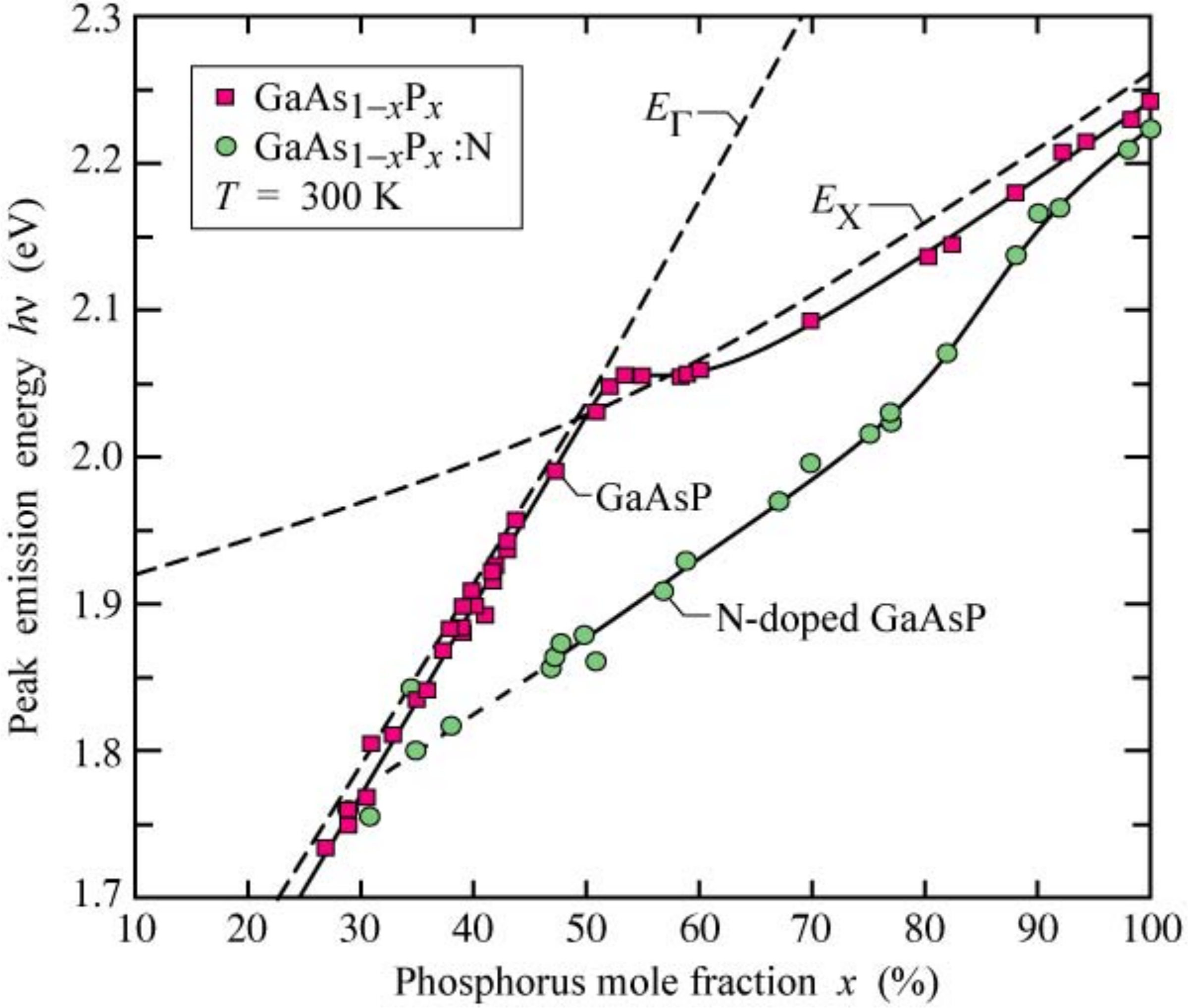


Fig. 12.2. Room-temperature peak emission energy versus alloy composition for undoped and nitrogen-doped GaAsP LEDs injected with a current density of 5 A/cm^2. Also shown is the energy gap of the direct-to-indirect (E_Γ-to-E_X) transition. The direct–indirect crossover occurs at $x \approx 50\,\%$ (after Craford *et al*., 1972).

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GaAsP and GaP LEDs

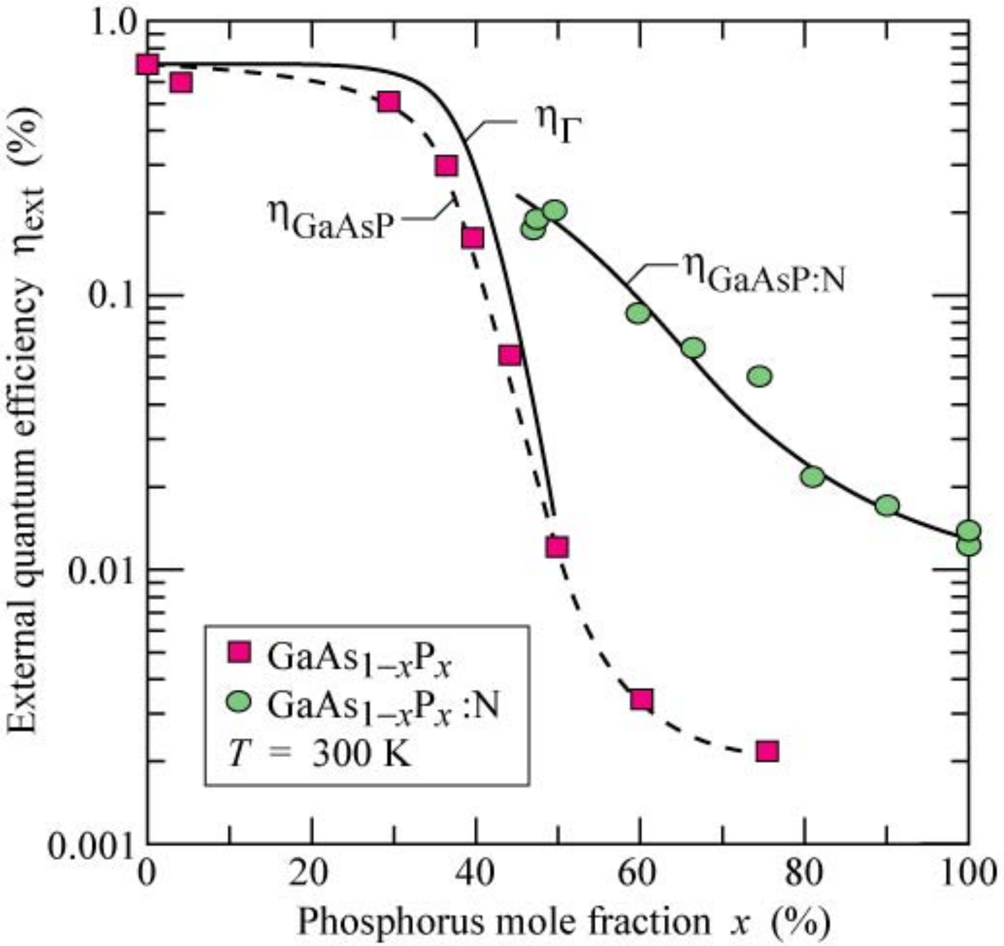

Fig. 12.3. Experimental external quantum efficiency of undoped and N-doped GaAsP versus the P mole fraction. Also shown is the calculated direct-gap (Γ) transition efficiency, η_Γ, and the calculated nitrogen (N) related transition efficiency, η_N (solid lines). Note that the nitrogen-related efficiency is higher than the direct-gap efficiency in the indirect bandgap (x > 50%) regime (after Campbell *et al.*, 1974).

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GaP and GaAsP LEDs

The Texas Instruments programmable pocket calculator Model SR-56 was manufactured for the first time in 1976. The seven-segment numeric characters of the display are made of red GaAsP diodes

- Displayed number were not visible in daylight
- LEDs consumed so much power that rechargeable batteries were required

GaP and GaAsP LEDs

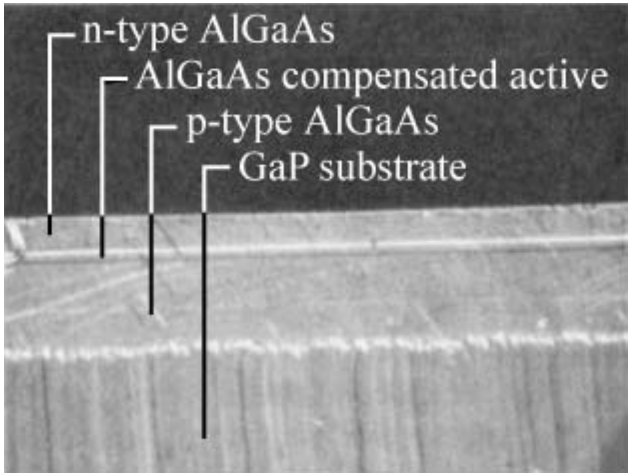
1968: first GaP:N LED emitting at 550nm.
External efficiency: 0.3%

AT&T telephone set ”Trimline” has a dial pad illuminated by two GaP:N LEDs

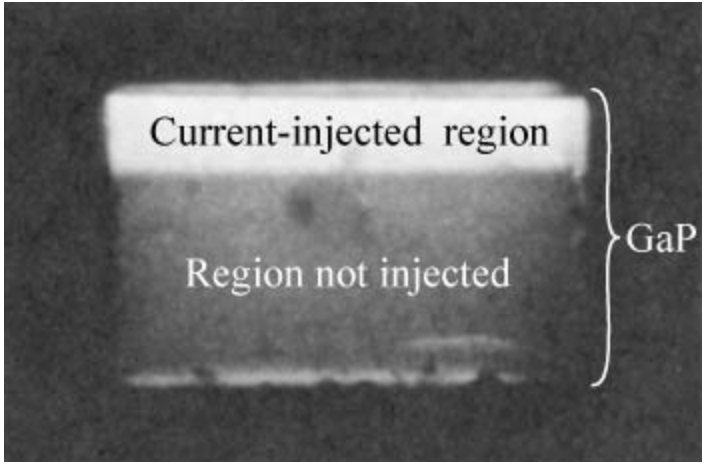
AlGaAs LEDs

IR 🟥

- The ternary compound $Al_xGa_{1-x}As$ has only a small lattice mismatch with GaAs. Therefore AlGaAs diodes are grown on GaAs. However GaAs is absorbing since it has a smaller bandgap than $Al_xGa_{1-x}As$
- $Al_xGa_{1-x}As$ can also be grown on GaP at the cost of misfit dislocations which reduce the internal efficiency



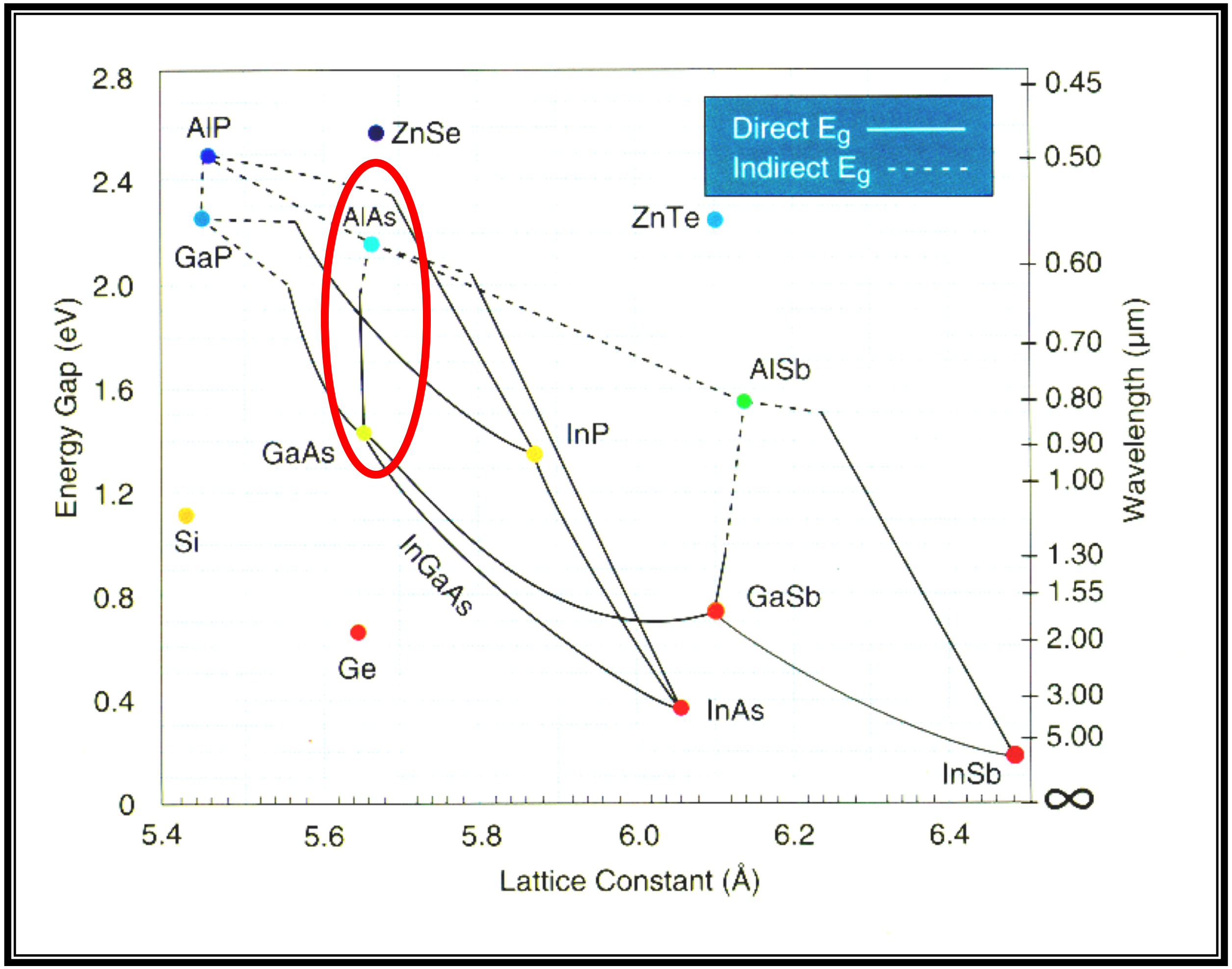
Cross section of a AlGaAs/AlGaAs LED on GaP (Woodall et al., 1972)



Luminescence from the AlGaAs active layer is visible through the transparent GaP substrate

AlGaAs LEDs

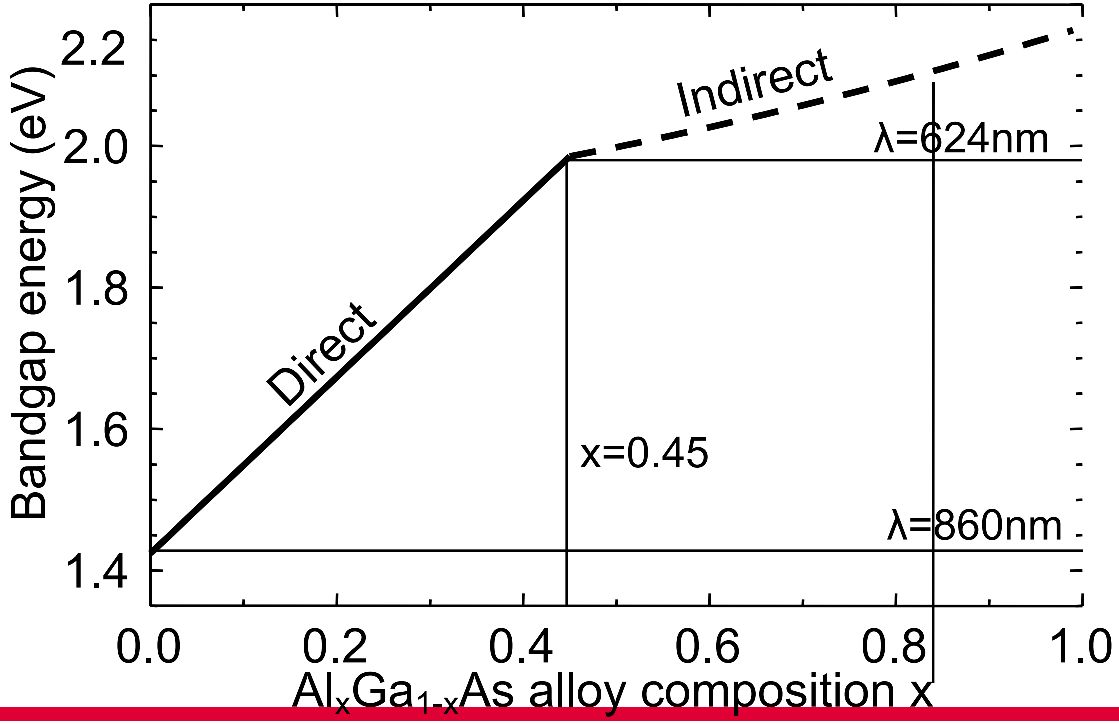
IR 🟥



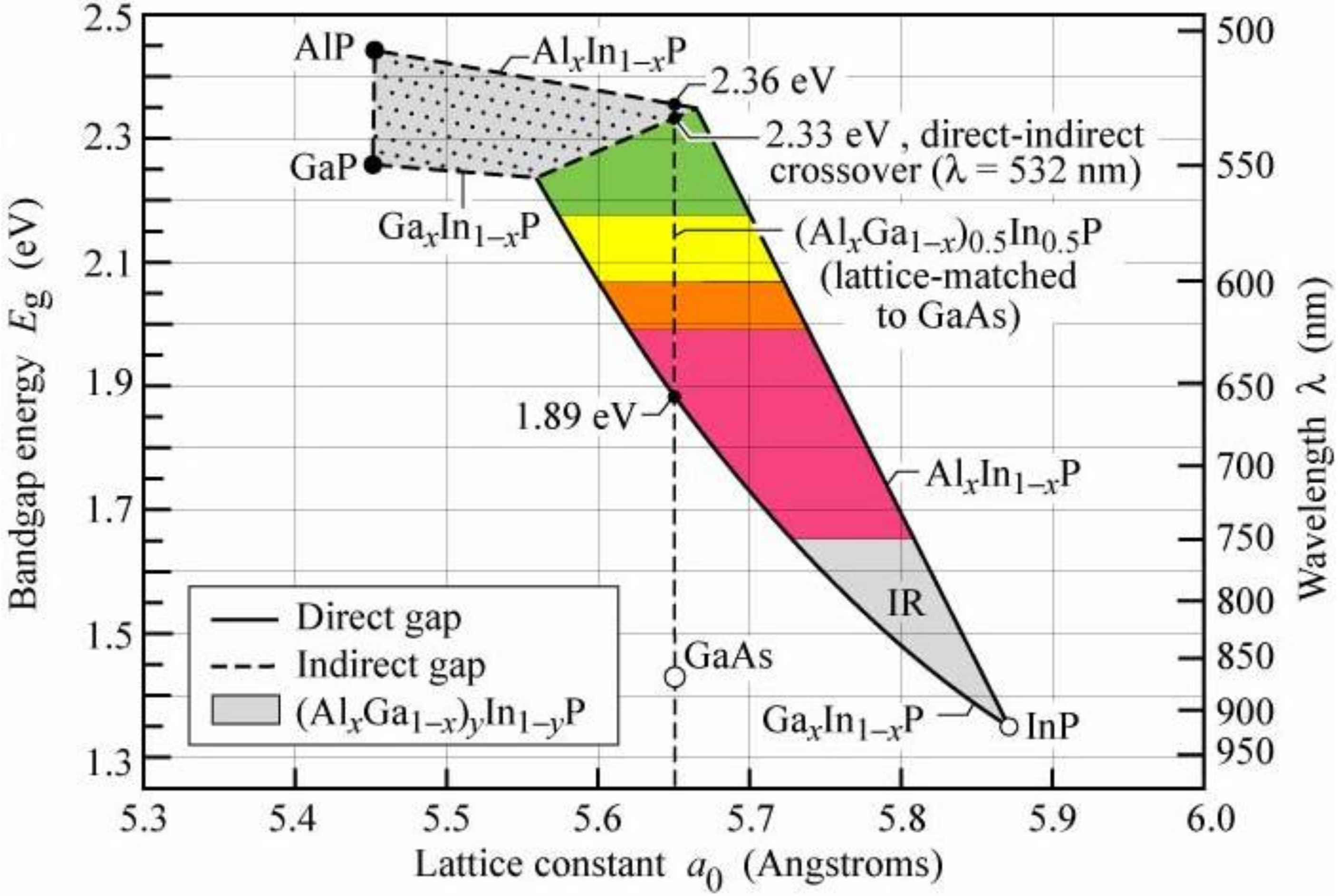
AlGaAs LEDs

IR 🟥

- For $Al_{0.4}Ga_{0.6}As/Al_{0.7}Ga_{0.3}As$ heterojunctions $\eta_{int} \sim 100\%$, $\lambda \sim$ 650nm. The emission from the p-doped $Al_{0.4}Ga_{0.6}As$ layer is NOT absorbed by the $Al_{0.7}Ga_{0.3}As$ layer which has a larger bandgap.
- AlGaAs/AlGas are still used in **video and audio remote controls** and as sources for **short-haul communication networks**.



AlGaInP LEDs

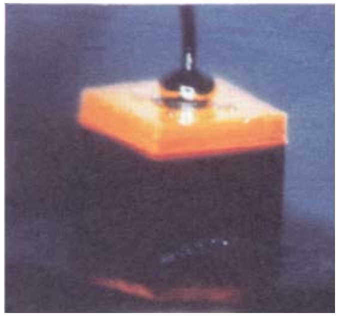


(Chen et al., 1997)

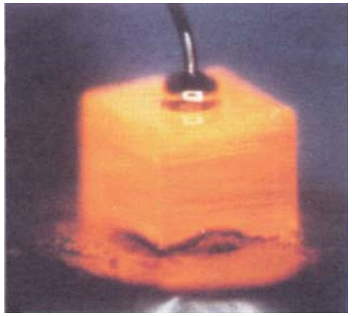
AlGaInP LEDs

- AlGaInP LEDs are the most powerful red, orange LEDs on the market, they are used a lot in luminous signalisation.

- $(Al_xGa_{1-x})_{0.5}In_{0.5}P$ is lattice-matched to GaAs
- However GaAs has a smaller bandgap than $(Al_xGa_{1-x})_{0.5}In_{0.5}P$, therefore it is reabsorbing the emitted light in AlGaInP/GaAs LEDs
- The GaAs substrate can be removed and replaced by transparent GaP by bonding



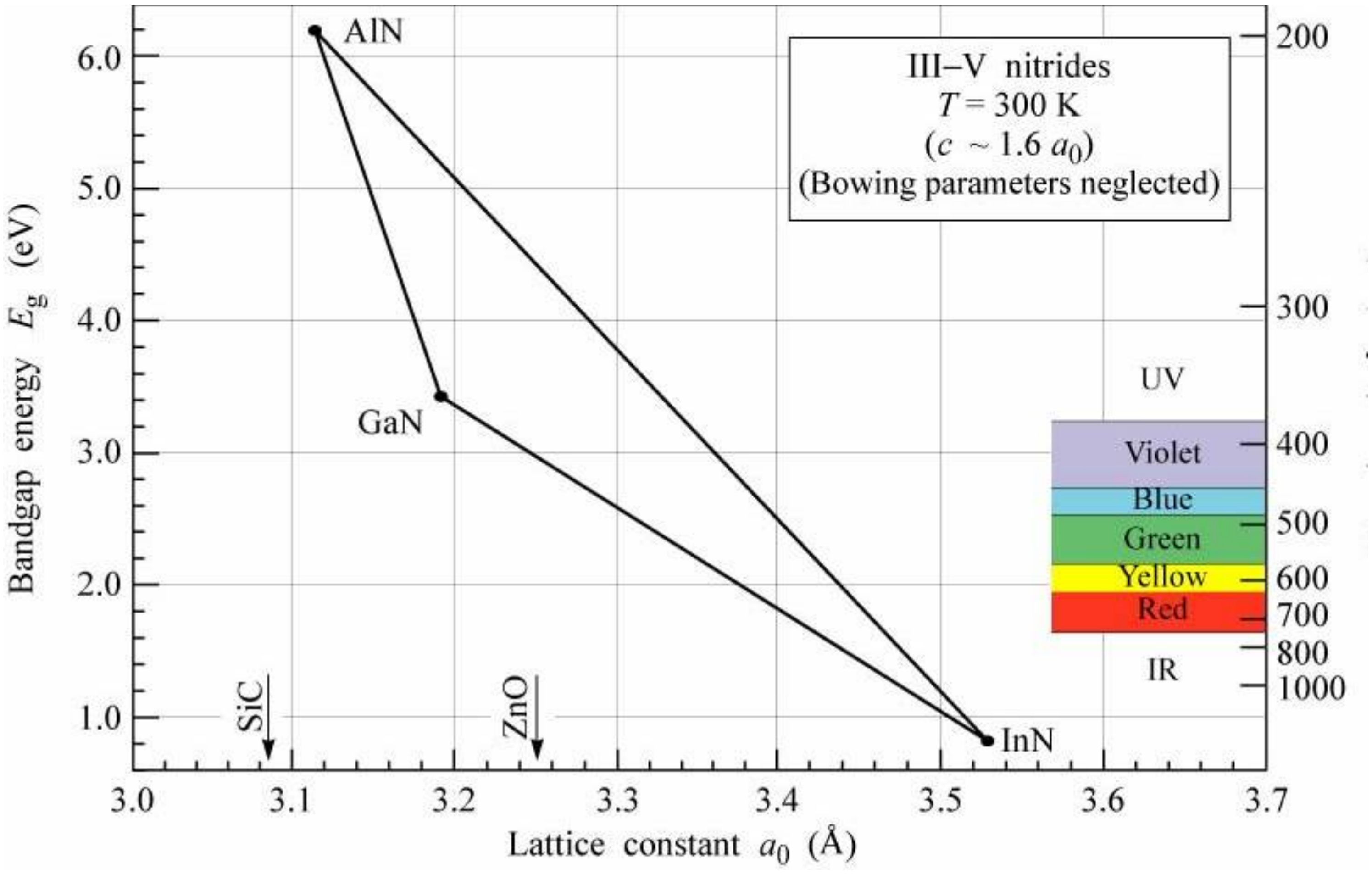
AlGaInP grown by epitaxy on GaAs (absorbing substrate)



AlGaInP wafer bonded on GaP (transparent substrate)

III-V Nitrides

🟩 🟦 UV



III-V Nitrides

🟩 🟦 UV

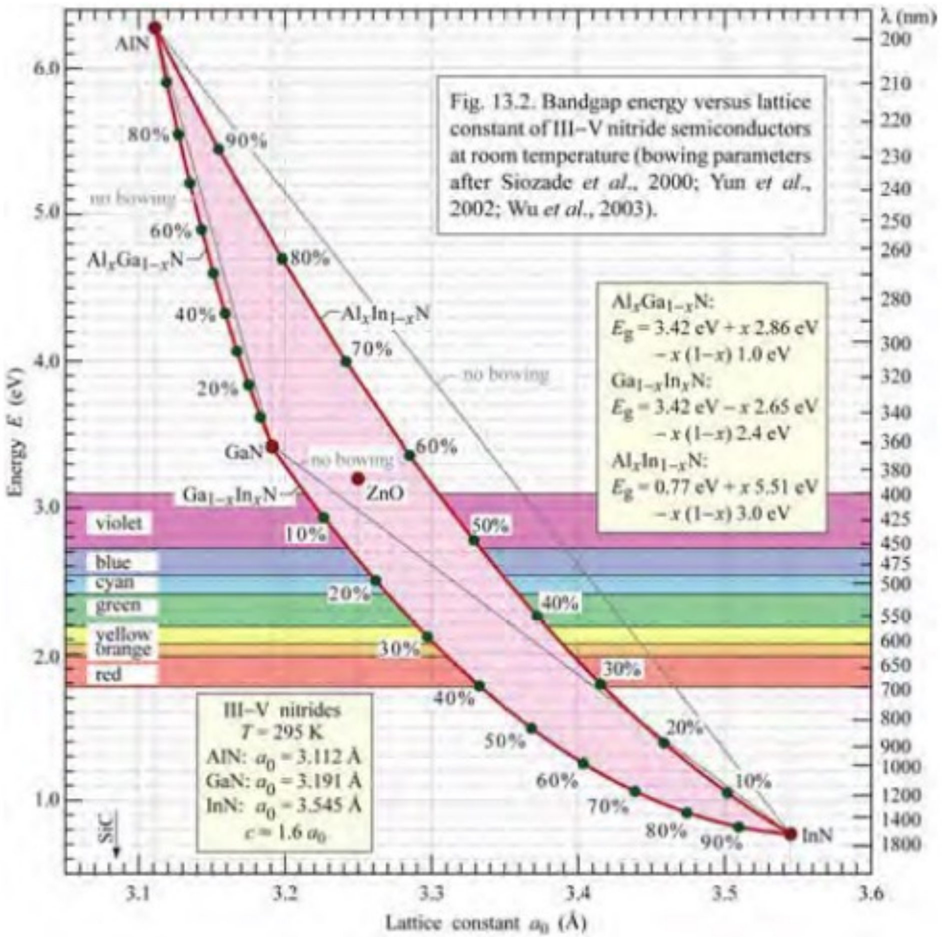
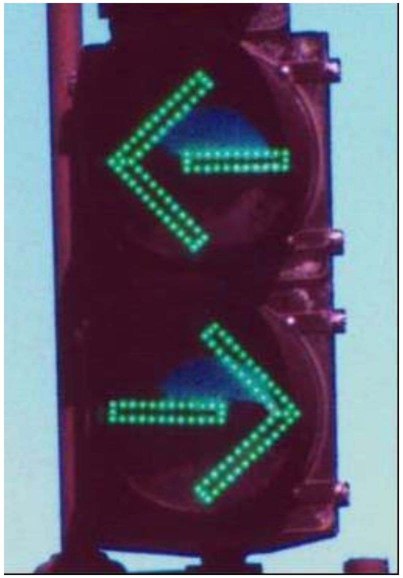


Fig. 13.2. Bandgap energy versus lattice constant of III–V nitride semiconductors at room temperature (bowing parameters after Siozade *et al.*, 2000; Yun *et al.*, 2002; Wu *et al.*, 2003).

- ***Summary***: The GaInN material system is suited for UV, violet, blue, cyan and green high-power LEDs. Efficiency decreases in the green spectral range.

GaInN/GaN LEDs

After a decade of intense research, a GaN based blue LED was successfully produced by Nichia Chemical of Japan in 1994



Green traffic lights made of GaInN/GaN LEDs

Applications:

- CD/DVD
- displays
- white LEDs
- remote sensing
- image scanners
- color printers
- biomedical diagnostic instruments

Luminous efficiency of visible-spectrum LEDs

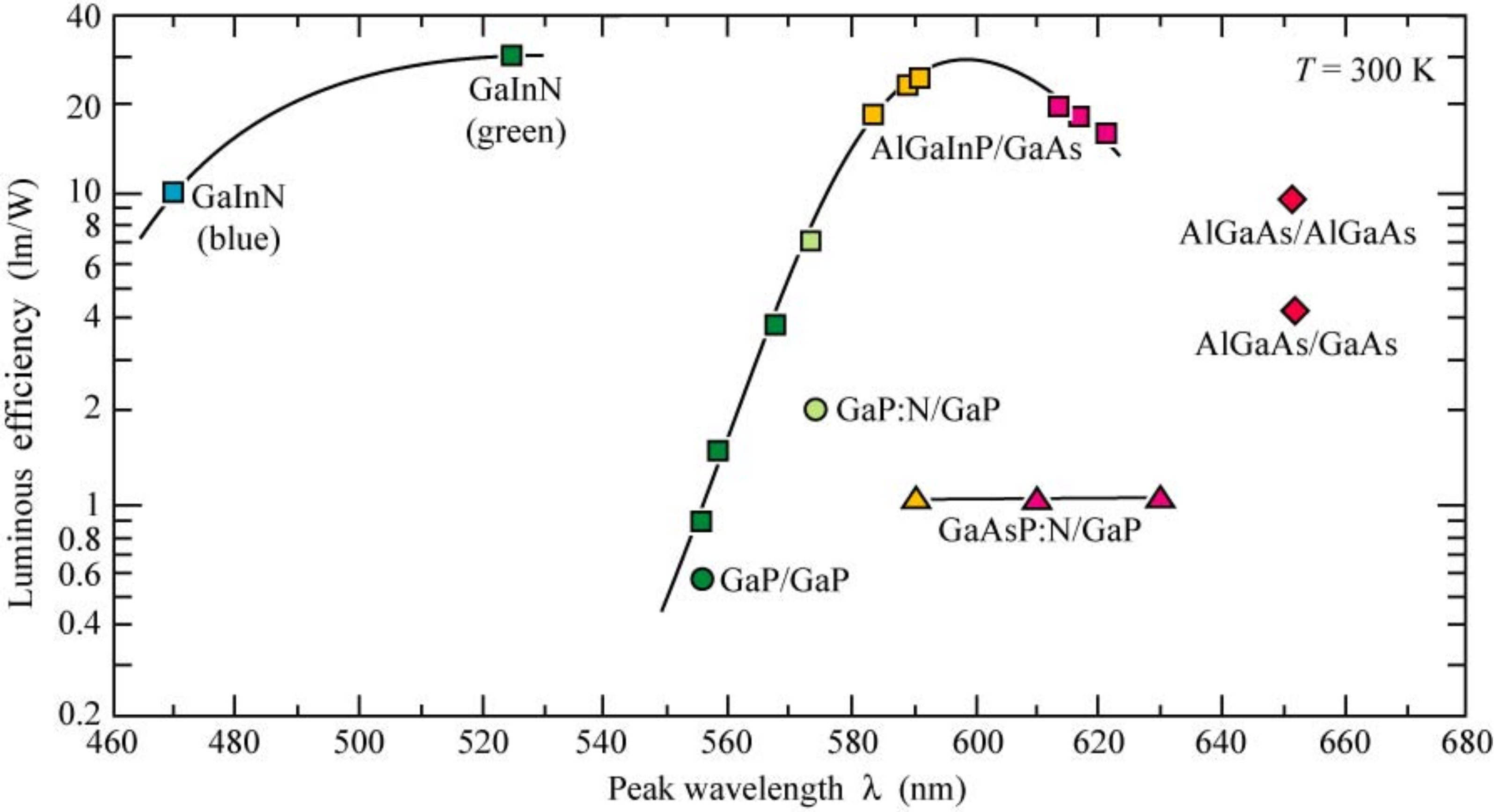


Fig. 12.14. Overview of luminous efficiency of visible LEDs made from the phosphide, arsenide, and nitride material system (adopted from United Epitaxy Corporation, 1999; updated 2000).

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Blue LEDs - structure

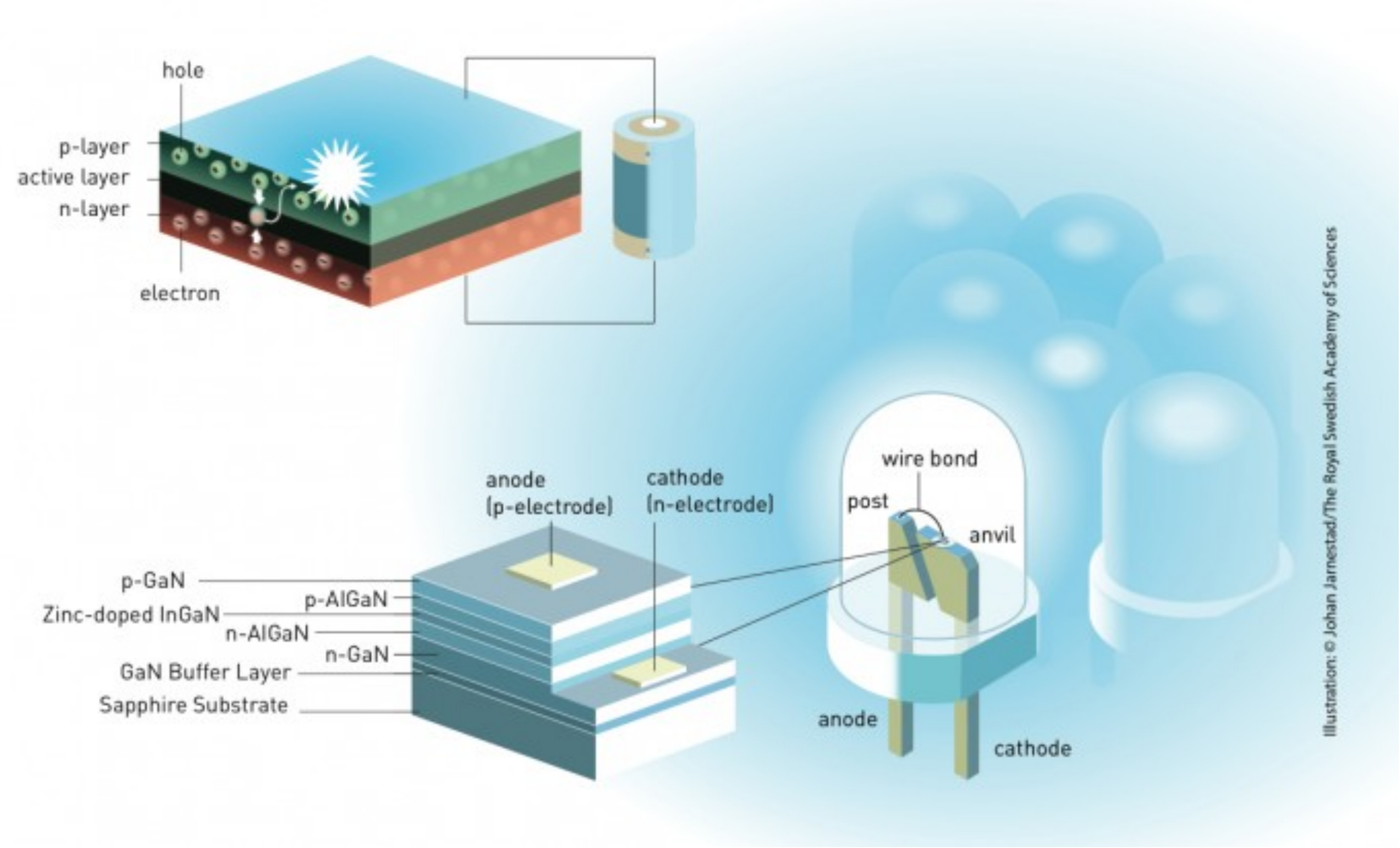
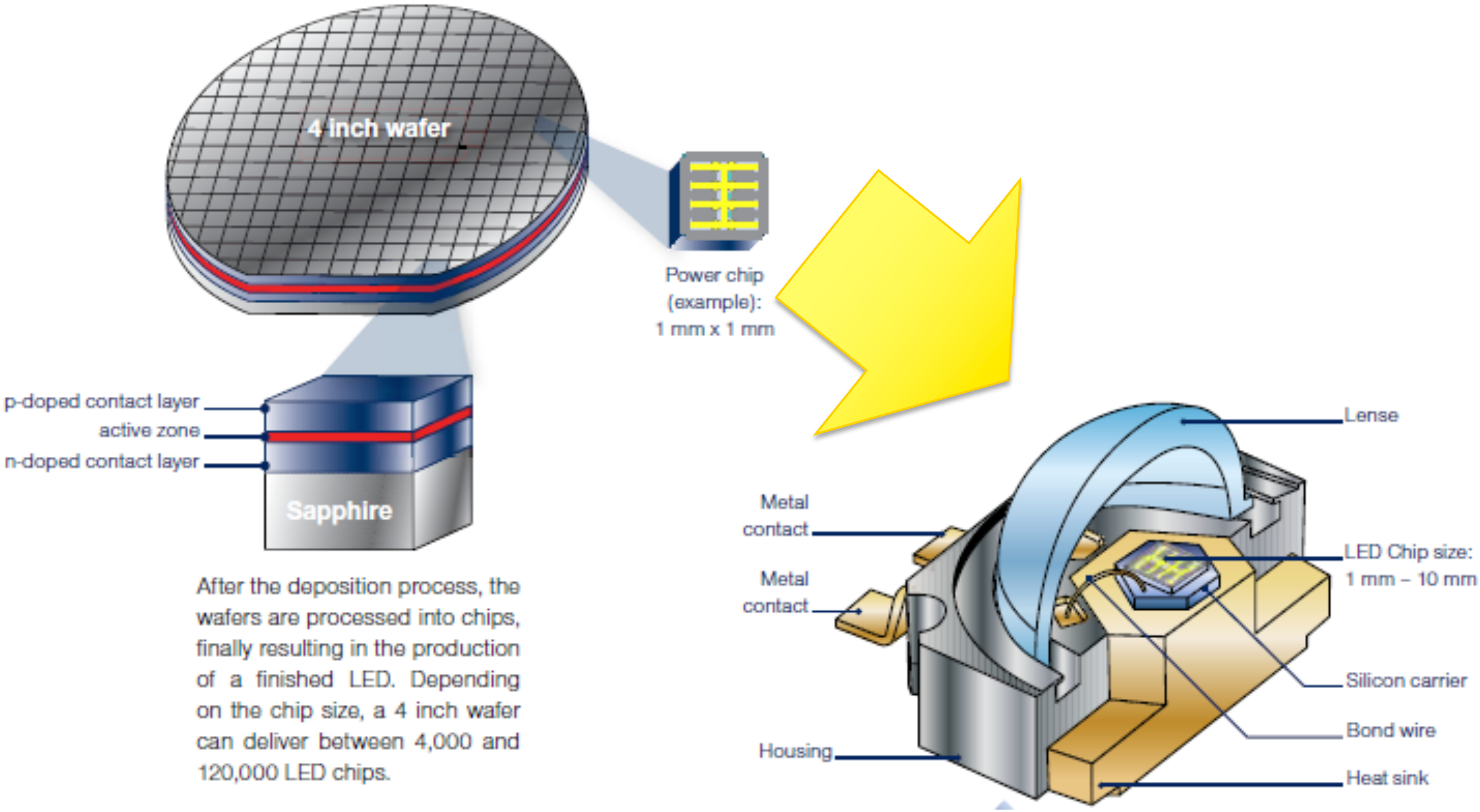


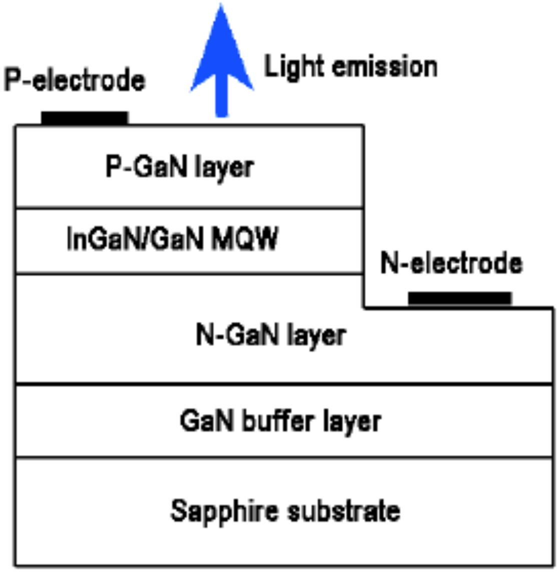
Illustration: © Johan Jarnestad/The Royal Swedish Academy of Sciences

LED construction



After the deposition process, the wafers are processed into chips, finally resulting in the production of a finished LED. Depending on the chip size, a 4 inch wafer can deliver between 4,000 and 120,000 LED chips.

InGaN/GaN LEDs @ Micronova



Light emission

P-electrode

P-GaN layer

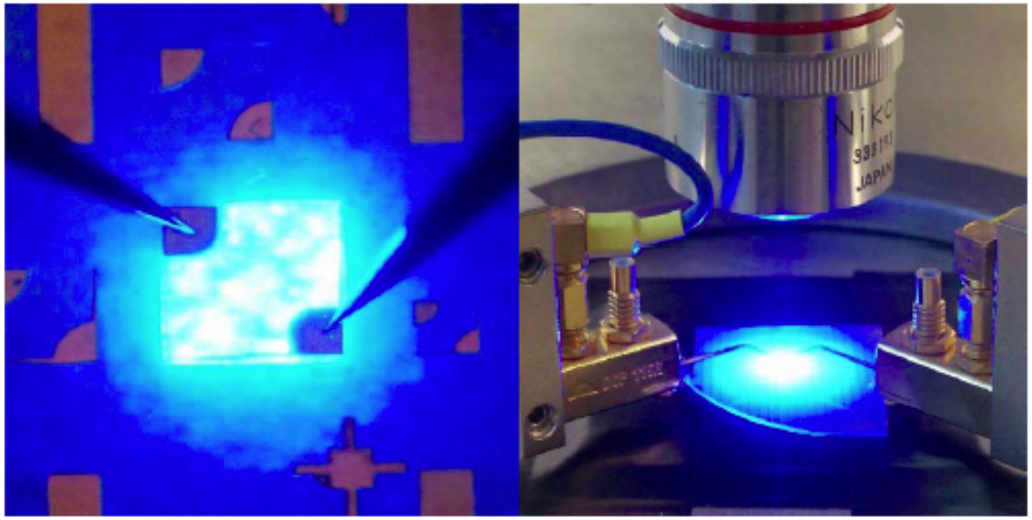
InGaN/GaN MQW

N-electrode

N-GaN layer

GaN buffer layer

Sapphire substrate



- Sapphire substrate
- ICP etching of mesa structure
- Both electrical contacts on top side
- Emission from $In_{15}Ga_{85}N$ / GaN quantum wells

Problems

- High dislocation density due to sapphire / GaN lattice mismatch
- Different growth regimes for InGaN and GaN
- P-type doping
- Non uniform current spreading

2014 Nobel Prize in Physics

Amano

Akasaki

Nakamura

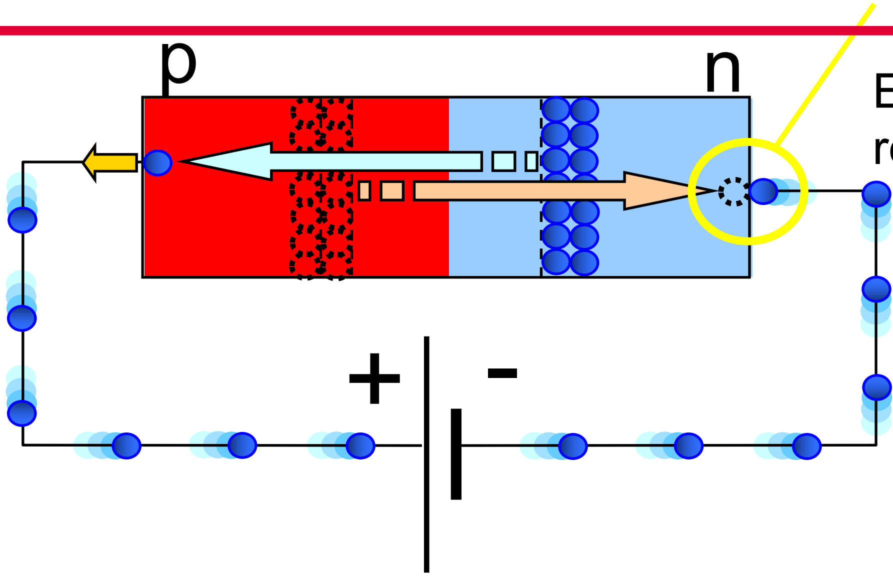
“for the invention of efficient blue light-emitting diodes which has enabled bright and energy-saving white light sources"

Outline

1 **III-V's for LEDs**

2 **Electrical and optical properties**

Forward bias



Electron-hole pair recombination

In general LEDs are optimized so that radiative recombination takes place on the **p-side** of the junction (injected minority carriers, electrons, will recombine with the majority carriers, holes, near the surface).

To be able to modulate the output, it has to be possible to modulate the injected carriers.

A key issue in the device speed is the time taken to extract the charge. The time is controlled by the carrier recombination time.

Recombination rates in p-doped layers

- **Shockley-Read-Hall recombination at defects and traps:**

$$R_{traps} = An$$

Shockley-Read-Hall recombination coefficient (s^{-1})

- **Radiative recombination rate**:

$$R_{sp} = Bnp_{PO} = \frac{n}{\tau_{rad}} \qquad \tau_{rad} = \frac{1}{Bp_{PO}}$$

Coefficient for band-to-band
recombination ($cm^3.s^{-1}$)

- **Auger recombination rate**:

$$R_{Auger} = Cp_{PO}^2 n$$

Auger recombination coefficient ($cm^6.s^{-1}$)

Electron lifetime

$$R = R_{traps} + R_{sp} + R_{Auger} = \left(A + Bp_{PO} + Cp_{PO}^2\right)n$$

$$= \frac{n}{\tau_{rad}} + \frac{n}{\tau_{non-rad}}$$

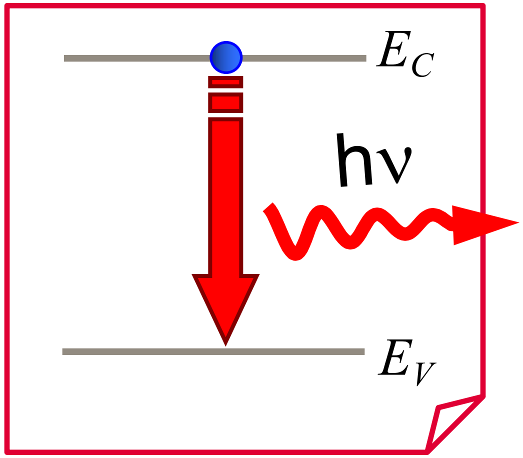
$$= \frac{n}{\boxed{\tau_e}} \text{ — electron lifetime}$$

$$\frac{1}{\tau_e} = \frac{1}{\tau_{rad}} + \frac{1}{\tau_{non-rad}}$$

The **radiative** and **non-radiative lifetimes** are defined as:

$$\tau_{rad} = \frac{1}{Bp_{PO}} \qquad \tau_{non-rad} = \frac{1}{A + Cp_{PO}^2}$$

Spontaneous emission



Generates photons

Useful in Light Emitting diodes (LED)

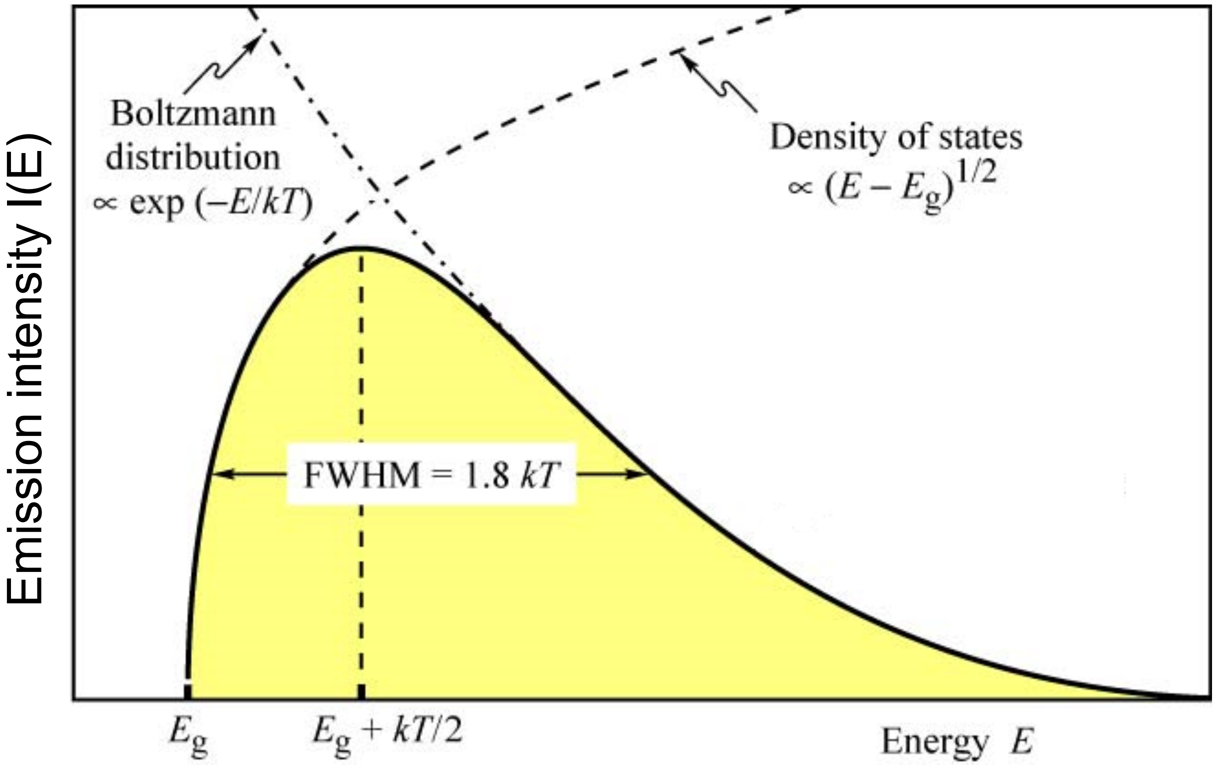
1. Transitions from many energy levels contribute to the radiation → **wide spectral width**
2. Photons radiate in arbitrary directions → low efficiency of current-to-light conversion and relatively **low output power**
3. Photons propagate within a wide cone (**poor directiveness**)
4. Photons are created independently of one another → no phase correlation and **incoherent** light

Theoretical emission spectrum

$$I(E) \propto \sqrt{E - E_g}\, \exp(-E/kT)$$

Energy value at maximum: $E_g + kT/2 \approx E_g$ at room temperature

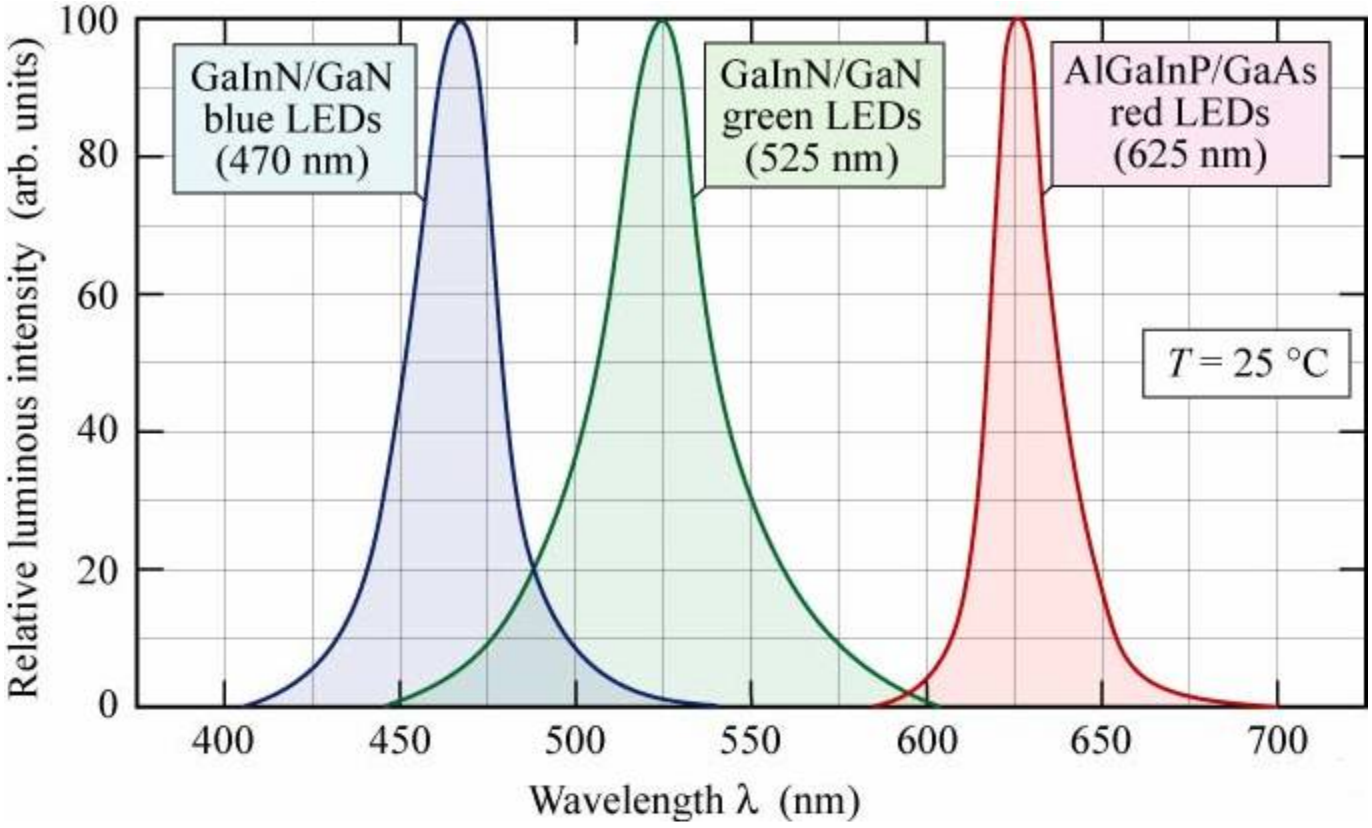
Bandwidth: $\Delta E = 1.8kT$ or $\Delta\lambda = \dfrac{1.8kT\lambda^2}{hc}$



For GaAs LED @ 870 nm

$$\Delta E = 46\ meV \text{ or } \Delta\lambda = 28 \text{ nm}$$

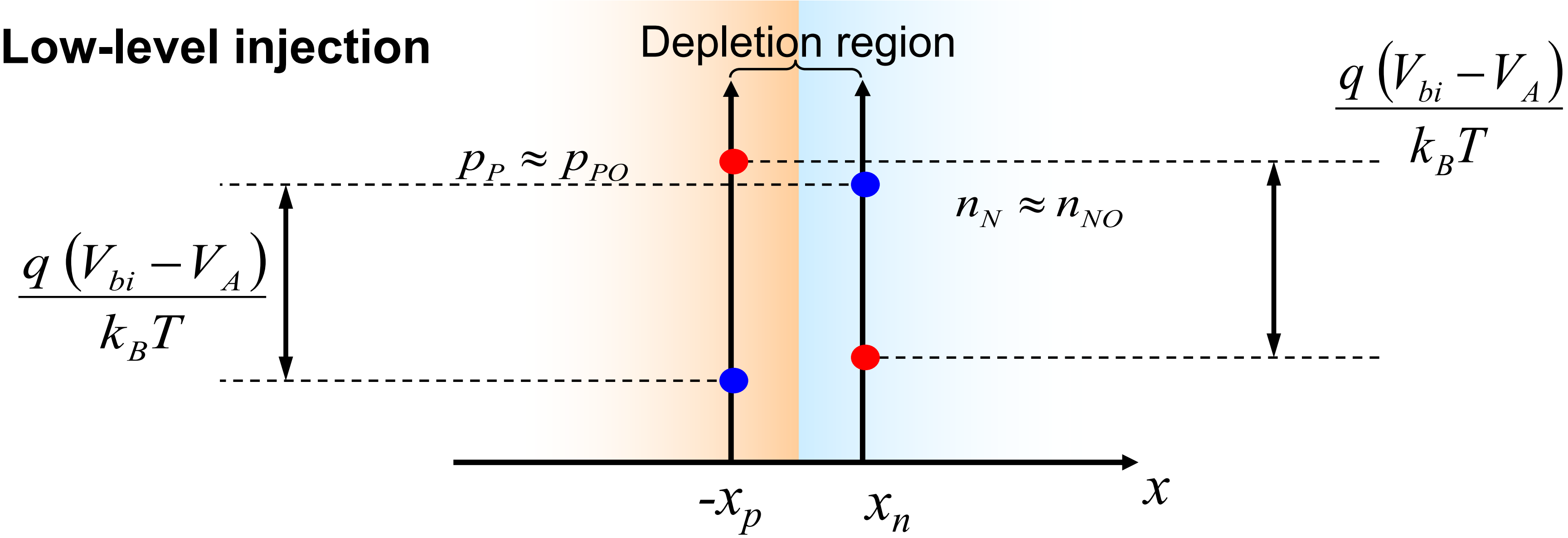
LED emission spectra



Green emitters have broadest emission lines and need further development.
Typical linewidths broader than the theoretical 1.8 kT.

PN-junction: carrier concentration under bias

Low-level injection



Equilibrium ($V_A = 0$)

Holes: $p_{NO} = p_{PO}\, e^{-\frac{qV_{bi}}{k_BT}}$

Electrons: $n_{PO} = n_{NO}\, e^{-\frac{qV_{bi}}{k_BT}}$

PN-junction: carrier concentration under bias

Quasi-equilibrium ($V_A \neq 0$) (at the edge of the depletion region ONLY!!!)

Holes:

$$p_N^{edge} = p_{NO}\exp\left(qV_A / k_BT\right)$$

$$= p_{PO}e^{-\frac{q\left(V_{bi}-V_A\right)}{k_BT}}$$

$$\frac{p_N^{edge}}{p_{NO}} = e^{\frac{qV_A}{k_BT}}$$

$$\Delta p_N^{edge} = p_N^{edge} - p_{NO}$$

$$= p_{NO}\left(e^{\frac{qV_A}{k_BT}} - 1\right)$$

Electrons:

$$n_P^{edge} = n_{PO}\exp\left(qV_A / k_BT\right)$$

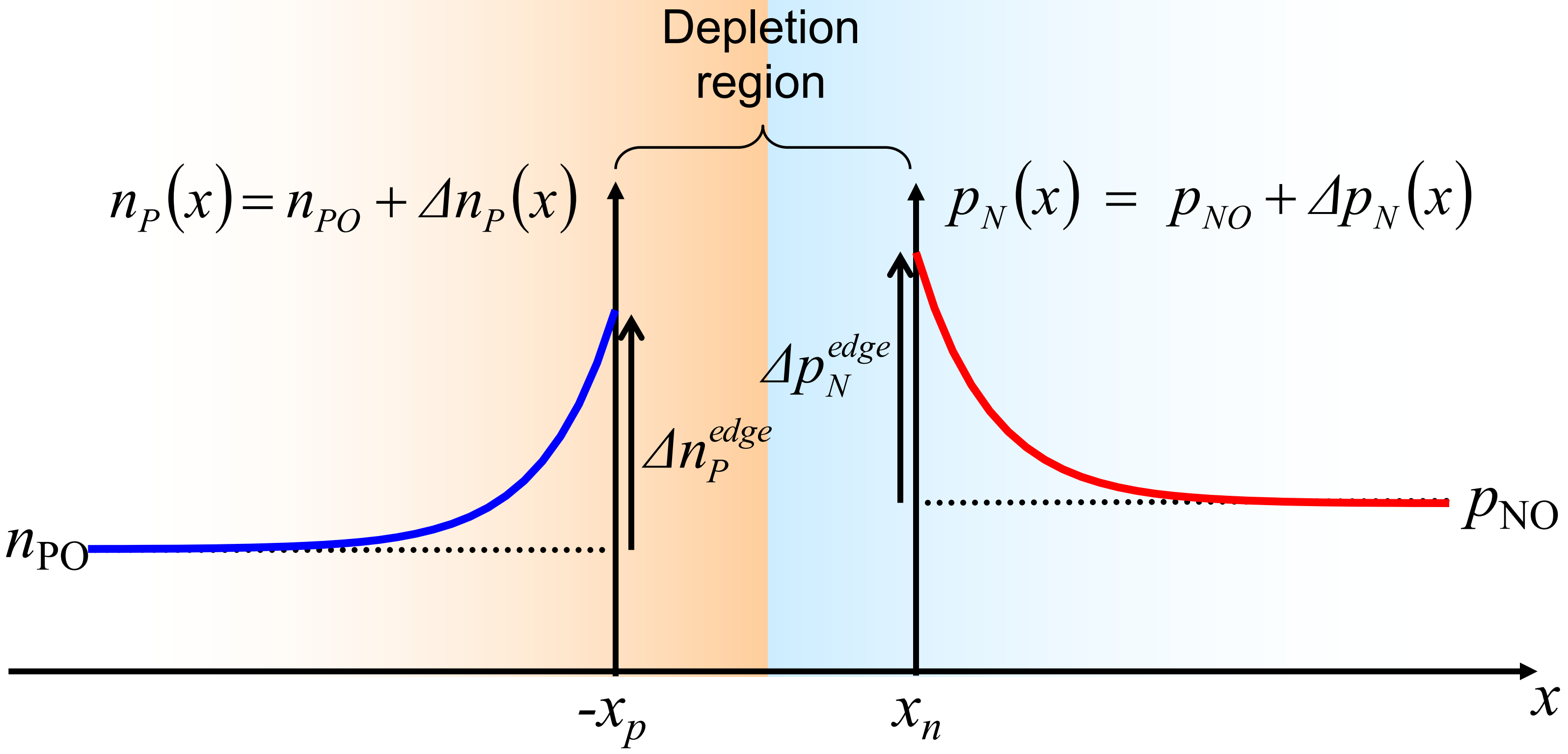
$$= n_{NO}e^{-\frac{q\left(V_{bi}-V_A\right)}{k_BT}}$$

$$\frac{n_P^{edge}}{n_{PO}} = e^{\frac{qV_A}{k_BT}}$$

$$\Delta n_P^{edge} = n_P^{edge} - n_{PO}$$

$$= n_{PO}\left(e^{\frac{qV_A}{k_BT}} - 1\right)$$

Minority carrier concentration profile under **forward** bias



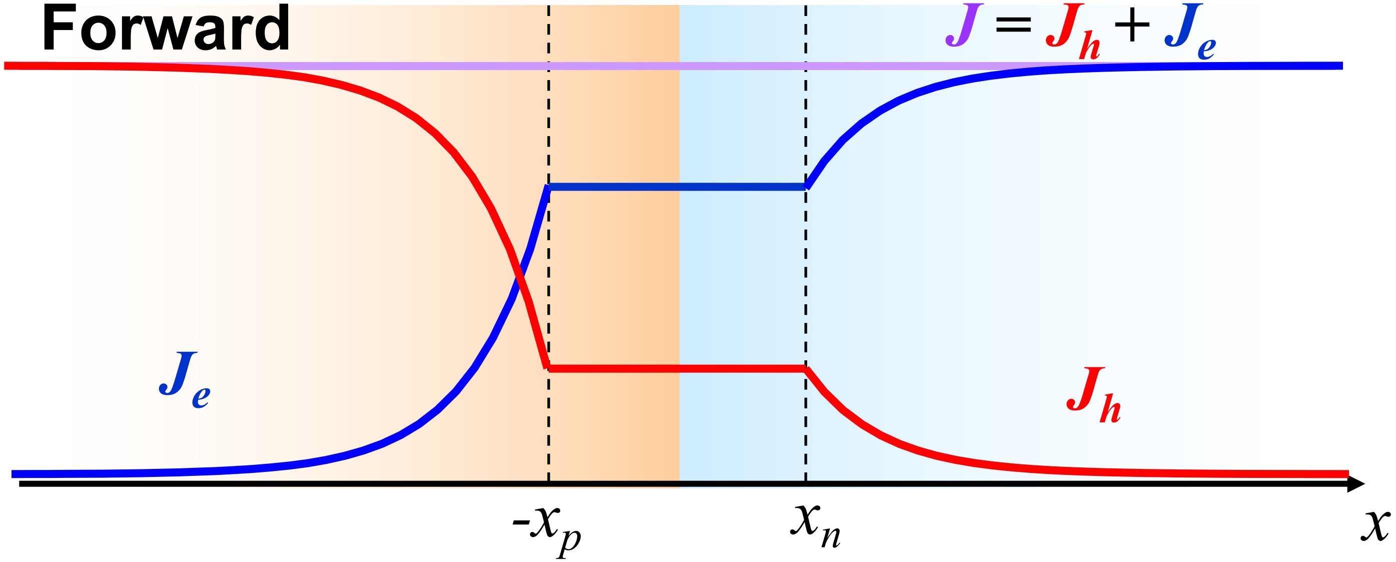
$$\Delta n_P(x) = \Delta n_P^{edge} \exp(x / L_e) \qquad \Delta p_N(x) = \Delta p_N^{edge} \exp(-x / L_h)$$

Diffusion lengths: $L_e = \sqrt{D_e \tau_e}$ $L_h = \sqrt{D_h \tau_h}$

Total current density

- The total current flow is constant over the junction
- Total current flow in the depletion region:

$$J = J_e + J_h = qD_e \frac{d\Delta n_P}{dx}\bigg|_{-x_p} - qD_h \frac{d\Delta p_N}{dx}\bigg|_{x_n}$$



Total current density

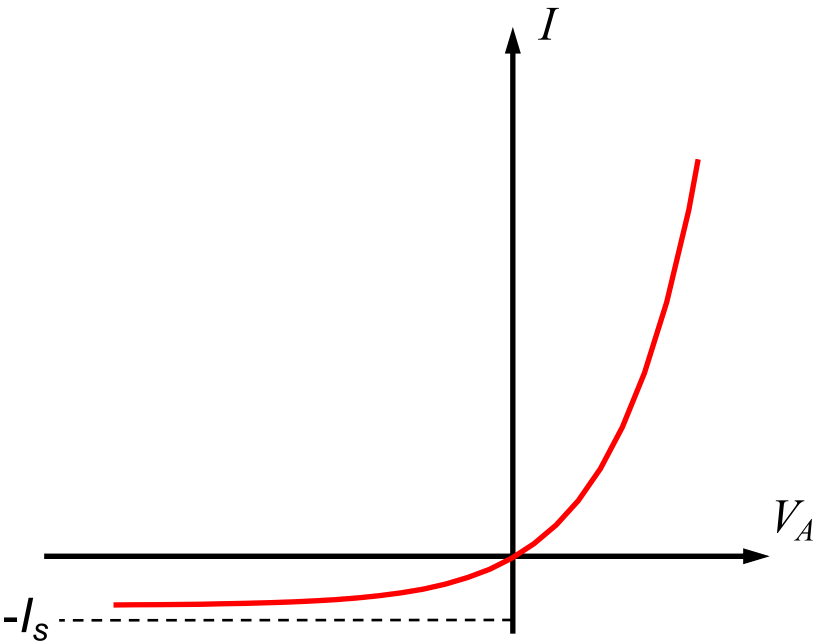
$$J = J_e + J_h = qD_e \frac{d\Delta n_P}{dx}\bigg|_{-x_p} - qD_h \frac{d\Delta p_N}{dx}\bigg|_{x_n}$$

$$\Delta n_P(x) = \Delta n_P^{edge} e^{\frac{x+x_p}{L_e}} \qquad \Delta p_N(x) = \Delta p_N^{edge}\, e^{\frac{x_n - x}{L_h}}$$

$$\Rightarrow \quad J = \frac{qD_e}{L_e}\Delta n_P^{edge} + \frac{qD_h}{L_h}\Delta p_N^{edge}$$

$$J = \underbrace{\left(\frac{qD_h p_{NO}}{L_h} + \frac{qD_e n_{PO}}{L_e}\right)}_{\text{Saturation current density } J_S}\left(\exp\left(\frac{qV_A}{k_B T}\right) - 1\right)$$

I-V curve



$$I = I_s\left(\exp\left(\frac{qV_A}{k_BT}\right)-1\right)$$

Saturation current:

$$I_s = A\left(\frac{qD_h p_{NO}}{L_h}+\frac{qD_e n_{PO}}{L_e}\right)$$

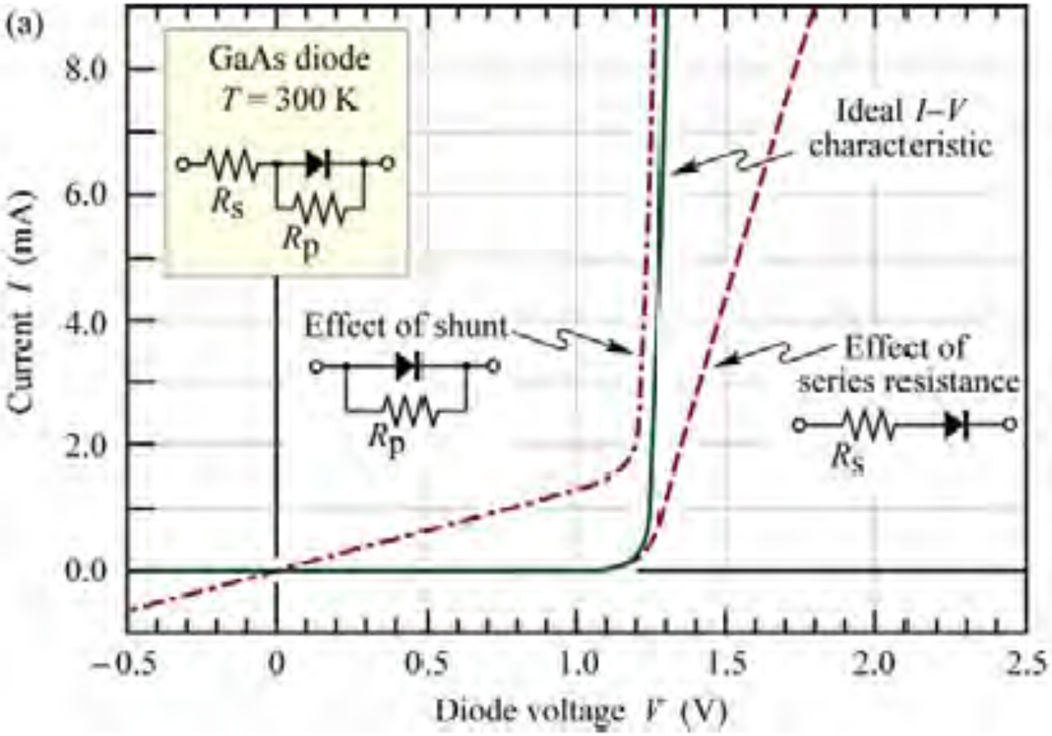
(Shockley equation)

Diffusion lengths: $L_h = \sqrt{D_h\tau_h}$ $L_e = \sqrt{D_e\tau_e}$

I-V curve

$$I = I_s \left(\exp\left(\frac{qV_a}{\eta_{ideal} k_B T} \right) - 1 \right)$$

Deviations from ideal characteristics



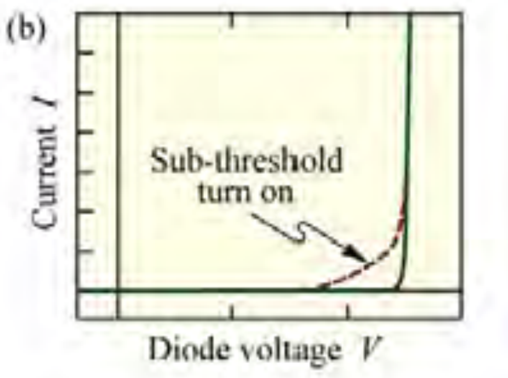


Fig. 4.4. (a) Effect of series and parallel resistance (shunt) on I–V characteristic. (b) I–V with clearly discernable sub-threshold turn-on, caused by defects or surface states.

Continuity equation

For electrons:

$$\frac{\partial n}{\partial t} = -R + \cancel{G} + \frac{1}{q}\frac{\partial J_e}{\partial x}$$

Electron recombination

$$R = \left(A + Bp_{PO} + Cp_{PO}^2\right)n$$

Electron generation

= 0 in our case

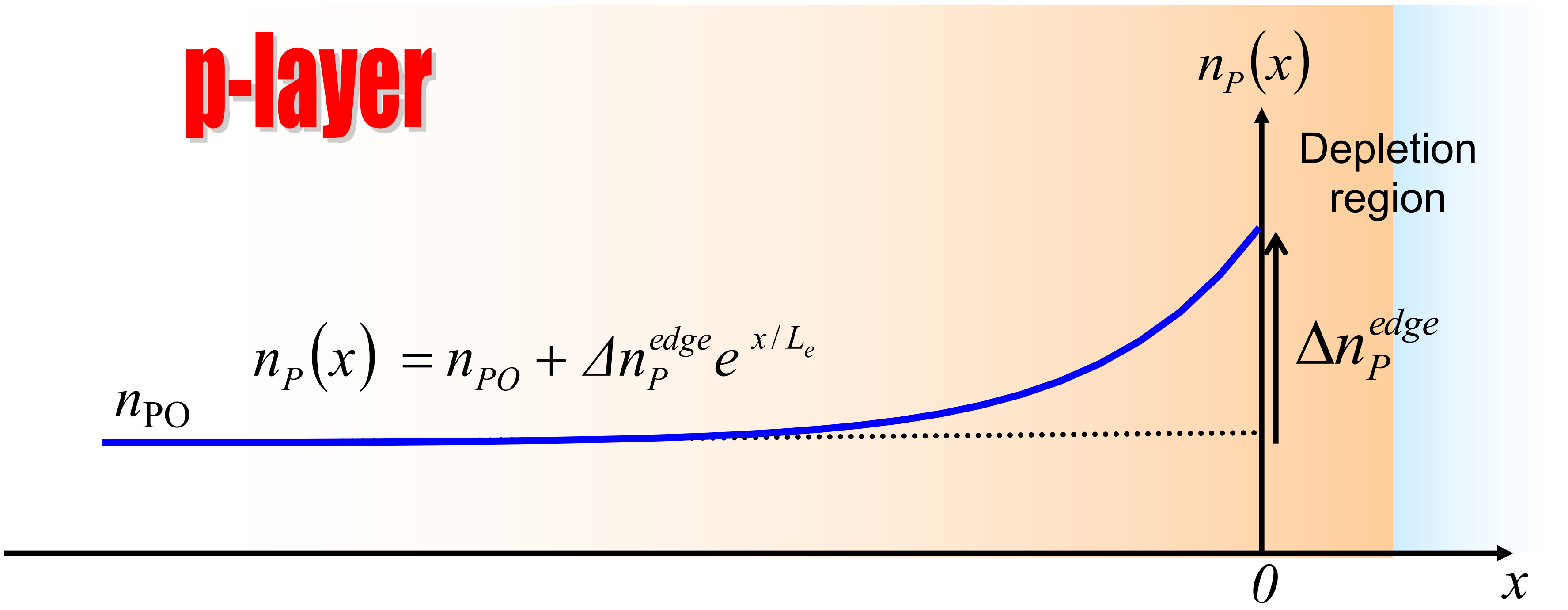
At quasi-equilibrium:

$$0 = -\frac{n}{\tau_e} + \frac{1}{q}\frac{dJ_e}{dx}$$

Total number of recombination per second in the p-layer:

$$R_{p-layer} = \iiint_{p-layer} \frac{n}{\tau_e} dV = \int_{p-layer} \frac{S}{q}\frac{dJ_e}{dx} dx$$

Electron induced current density



$$n_P(x) = n_{PO} + \Delta n_P^{edge} e^{x/L_e}$$

$$J_e(x) = qD_e \frac{dn_P}{dx} = q\Delta n_P^{edge} \frac{D_e}{L_e} e^{x/L_e}$$

$$L_e = \sqrt{D_e \tau_e}$$

Electron induced current density

$$J_e(x) = qD_e \frac{dn_P}{dx} = q\Delta n_P^{edge} \frac{D_e}{L_e} e^{x/L_e}$$

We suppose that the p-layer is thick enough so that **all injected electrons** recombine before reaching the contact layer.

Number of electrons recombining per second:

$$R_{total} = SJ_e(0)/q$$

$$J_e(0) = \frac{qD_e}{L_e}\Delta n_P^{edge}$$

$$\Delta n_P^{edge} = n_{PO}\left(e^{\frac{qV_A}{k_BT}} - 1\right)$$

$$R_{p-layer} = \frac{SD_e n_{PO}}{L_e}\left(e^{\frac{qV_A}{k_BT}} - 1\right)$$

Output power

$$P_{out} = \eta_e \, h\nu \iiint_{p-layer} n/\tau_{rad}$$

extraction efficiency

Overall device efficiency:

$\eta_o = \eta_{inj}\eta_{rad}\eta_e$

$$P_{out} = \eta_e h\nu \left(\frac{\tau_e}{\tau_{rad}}\right) R_{p-layer}$$

$$P_{out} = h\nu \frac{I}{q} \, \eta_{inj} \, \eta_{rad} \, \eta_e$$

injection efficiency

radiation efficiency

Responsivity

$$R = \frac{P_o}{I} = \eta_o \frac{h\nu}{q}$$

$$\eta_{rad} = \frac{\tau_e}{\tau_{rad}}$$

$$\eta_{inj} = \frac{qR_{p-layer}}{I} = \frac{SJ(0)}{I}$$

Injection efficiency

The **injection efficiency** is the ratio between the number of electrons injected in the active layer (p-layer) per second and the total current:

$$\eta_{inj} = \frac{SJ_e(0)}{I}$$

$$J_e(0) = \frac{qD_e n_{PO}}{L_e}\left(e^{\frac{qV_A}{k_B T}} - 1\right) \qquad I = S\left(\frac{qD_e n_{PO}}{L_e} + \frac{qD_h p_{NO}}{L_h}\right)\left(e^{\frac{qV_A}{k_B T}} - 1\right)$$

$$\eta_{inj} = \frac{\dfrac{D_e n_{PO}}{L_e}}{\dfrac{D_e n_{PO}}{L_e} + \dfrac{D_h p_{NO}}{L_h}} = \left(1 + \frac{D_h p_{NO} L_e}{D_e n_{PO} L_h}\right)^{-1}$$

Injection efficiency

Einstein relation: $$\frac{D_e}{\mu_e} = \frac{D_h}{\mu_h} = \frac{k_B T}{q} \Rightarrow \frac{\mu_h}{\mu_e} = \frac{D_h}{D_e}$$

pn-junction theory: $$\frac{n_{NO}}{n_{PO}} = \frac{p_{PO}}{p_{NO}} = e^{\frac{qV_{bi}}{k_B T}} \Rightarrow \frac{p_{NO}}{n_{PO}} = \frac{p_{PO}}{n_{NO}}$$

$$\Rightarrow \eta_{inj} = \left(1 + \frac{D_h p_{NO} L_e}{D_e n_{PO} L_h}\right)^{-1} = \left(1 + \frac{\mu_h p_{PO} L_e}{\mu_e n_{NO} L_h}\right)^{-1}$$

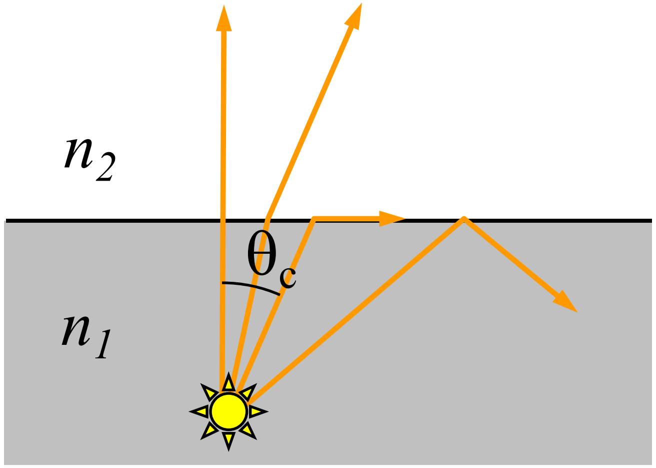
In III-V: $\mu_e >> \mu_h$

$L_e \approx L_h$

For high η_{inj}: $n_{NO} >> p_{PO}$ (highly doped n-layer)

External quantum efficiency

Although the internal quantum efficiency of some LEDs may approach 100%, external efficiencies are considerably lower. It is because some of the radiation remains trapped in the LED due to **total internal reflection**



Critical angle: $\theta_c = \sin^{-1}\left(\frac{n_2}{n_1}\right)$

$$\eta_{extraction} \approx \frac{1}{4}\left(\frac{n_2}{n_1}\right)^2\left[1-\left(\frac{n_1-n_2}{n_1+n_2}\right)^2\right]$$

For GaAs: $n_1 = 3.5$

$\eta_{extraction} = 7\%$

The light escape cone

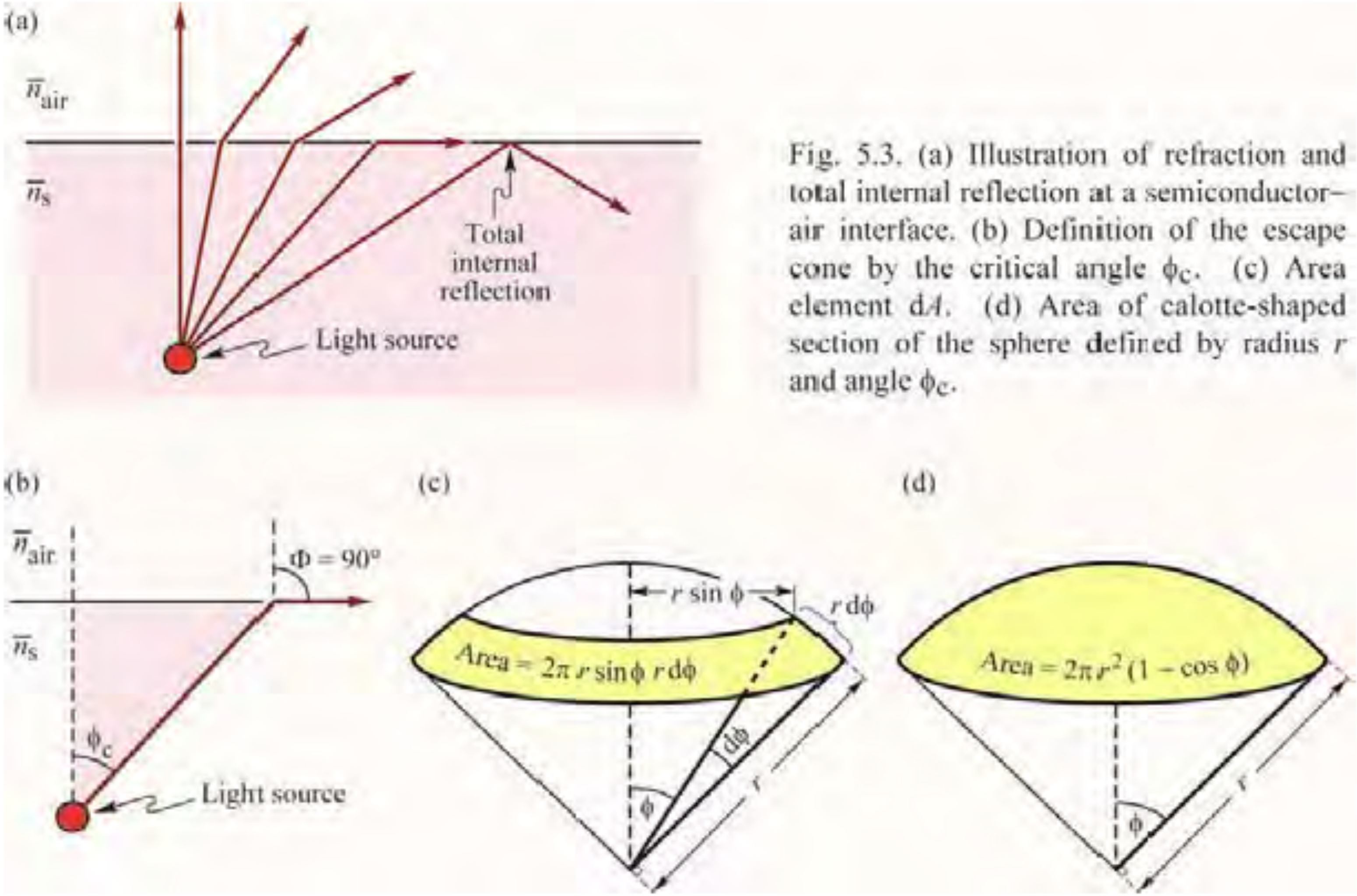
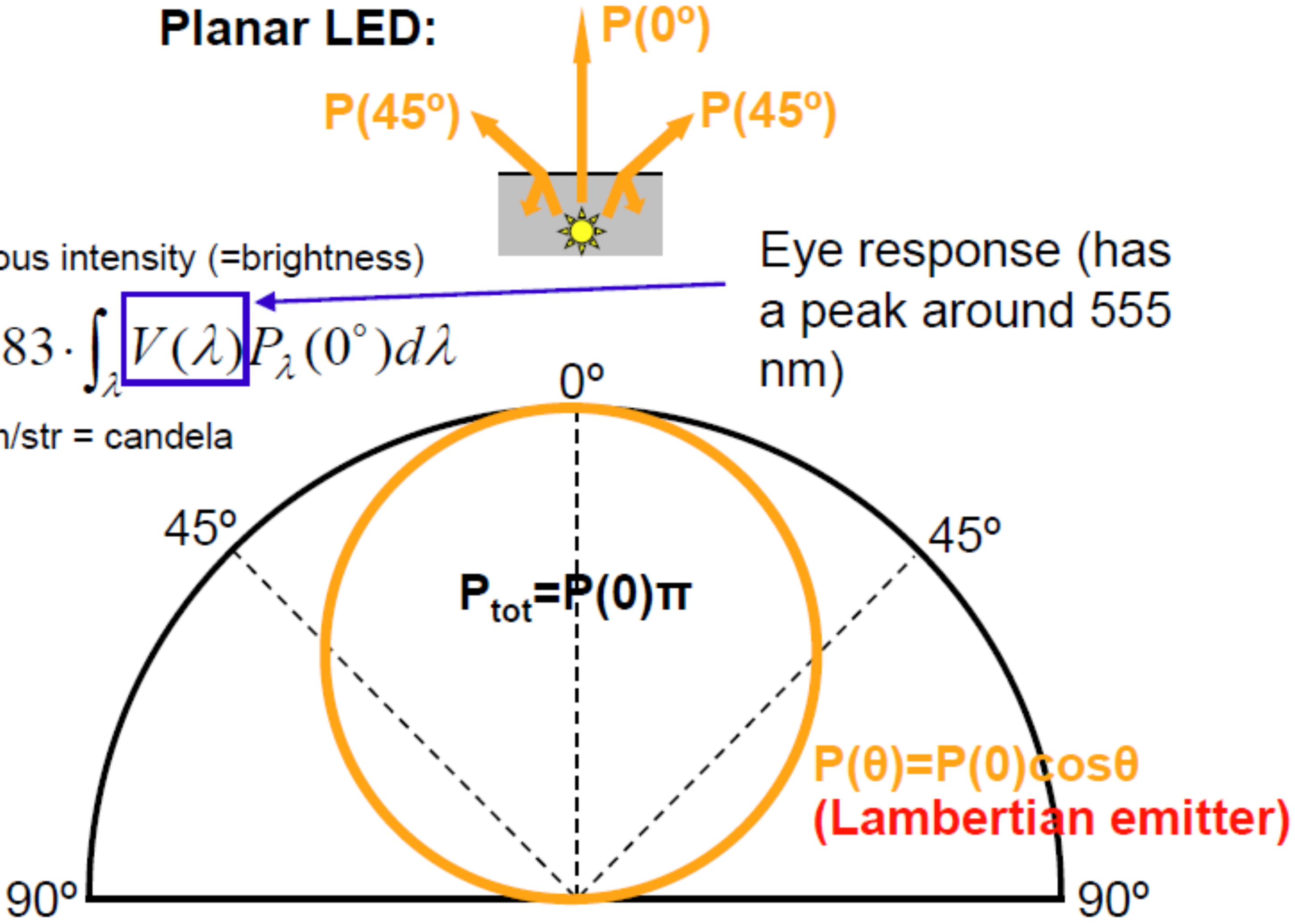


Fig. 5.3. (a) Illustration of refraction and total internal reflection at a semiconductor–air interface. (b) Definition of the escape cone by the critical angle ϕ_c. (c) Area element dA. (d) Area of calotte-shaped section of the sphere defined by radius r and angle ϕ_c.

Lambertian emitter

Planar LED:



Luminous intensity (=brightness)

$$I = 683 \cdot \int_{\lambda} \boxed{V(\lambda)} P_{\lambda}(0^{\circ}) d\lambda$$

Unit: lm/str = candela

Eye response (has a peak around 555 nm)

$P_{tot}=P(0)\pi$

$P(\theta)=P(0)\cos\theta$

(Lambertian emitter)

Far-field patterns

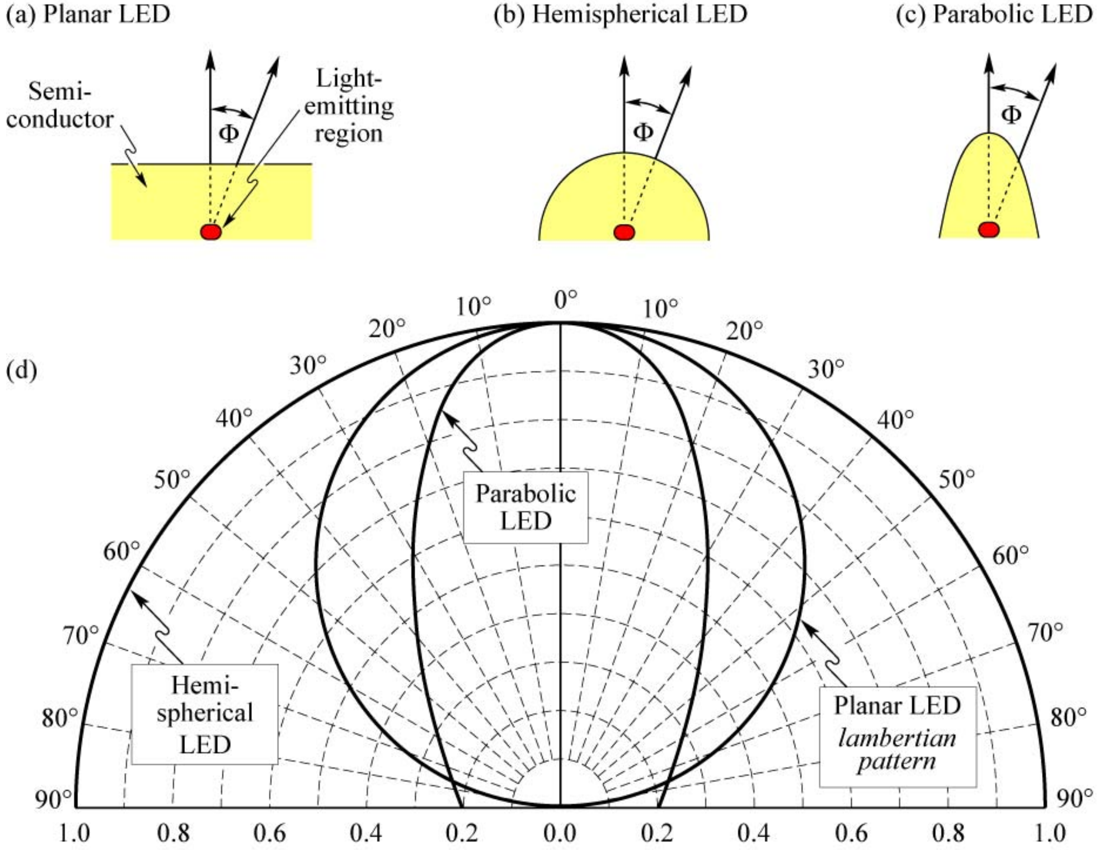


Fig. 5.5. Light-emitting diodes with (a) planar, (b) hemispherical, and (c) parabolic surfaces. (d) Far-field patterns of the different types of LEDs. At an angle of Φ = 60°, the lambertian emission pattern decreases to 50 % of its maximum value occurring at Φ = 0°. The three emission patterns are normalized to unity intensity at Φ = 0°.

E. F. Schubert
Light-Emitting Diodes (Cambridge Univ. Press)
www.LightEmittingDiodes.org

”Natural” LED has a planar surface

Die shaping can change emission pattern

Temperature dependence of emission intensity

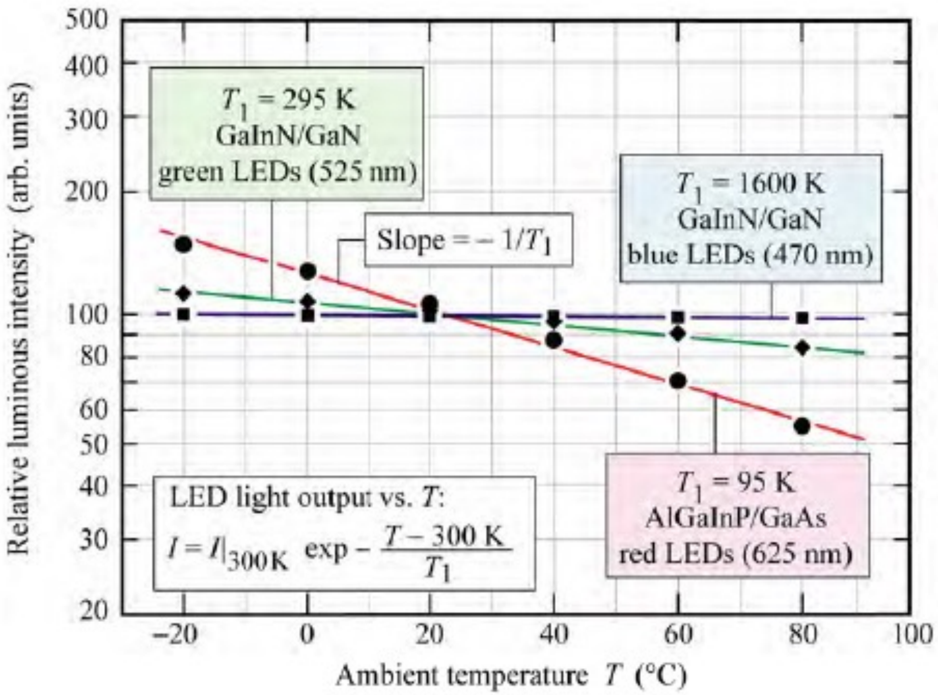


Fig. 5.7. Characteristic temperature T_1 of GaInN/GaN blue, GaInN/GaN green, and AlGaInP/GaAs red LEDs near room temperature (after data from Toyoda Gosei Corp., 2000). More recent data (Toyoda Gosei Corp., 2004) show the following values for T_1: Blue GaInN LED, 460 nm, T_1 = 1600 K; Cyan GaInN LED, 505 nm, T_1 = 832 K; Green GaInN LED, 525 nm, T_1 = 341 K; Red AlGaInP LED, 625 nm, T_1 = 199 K.

- Temperature dependence is characterized in terms of a characteristic temperature T_1
- $I = I_0 \exp(-T / T_1)$
- High T_1 is desirable