Advanced III-nitride semiconductor devices

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LEDs

- Basics

- IQE, EQE, …

LEDs - Introduction

First LED (1907)

A Note on Carborundum.

To the Editors of Electrical World:

SIRS:—During an investigation of the unsymmetrical passage of current through a contact of carborundum and other substances a curious phenomenon was noted. On applying a potential of 10 volts between two points on a crystal of carborundum, the crystal gave out a yellowish light. Only one or two specimens could be found which gave a bright glow on such a low voltage, but with 110 volts a large number could be found to glow. In some crystals only edges gave the light and others gave instead of a yellow light green, orange or blue. In all cases tested the glow appears to come from the negative pole, a bright blue-green spark appearing at the positive pole. In a single crystal, if contact is made near the center with the negative pole, and the positive pole is put in contact at any other place, only one section of the crystal will glow and that the same section wherever the positive pole is placed.

There seems to be some connection between the above effect and the e.m.f. produced by a junction of carborundum and another conductor when heated by a direct or alternating current; but the connection may be only secondary as an obvious explanation of the e.m.f. effect is the thermoelectric one. The writer would be glad of references to any published account of an investigation of this or any allied phenomena.

NEW YORK, N. Y. H. J. ROUND.

SiC

H.J. Round, *Electrical World* **49**, 309 (1907)

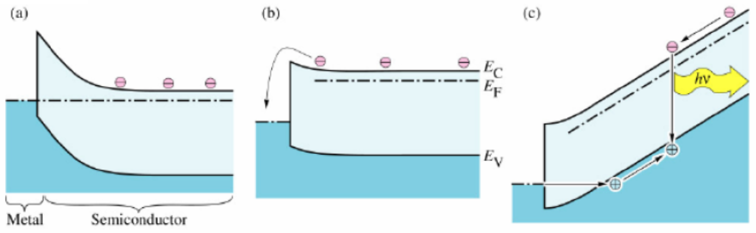


Fig. 1.2. Band diagram of Schottky diode under (a) equilibrium conditions, (b) forward bias, and (c) strong forward bias. Under strong forward bias, minority carrier injection occurs making possible near-bandgap light emission.

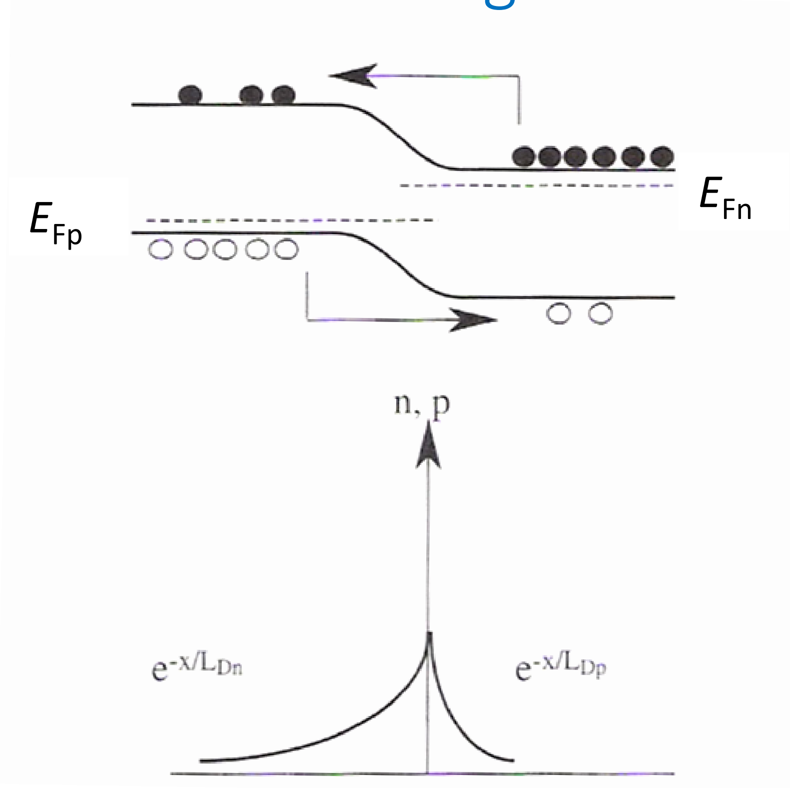
First LED did not operate with a PN junction !

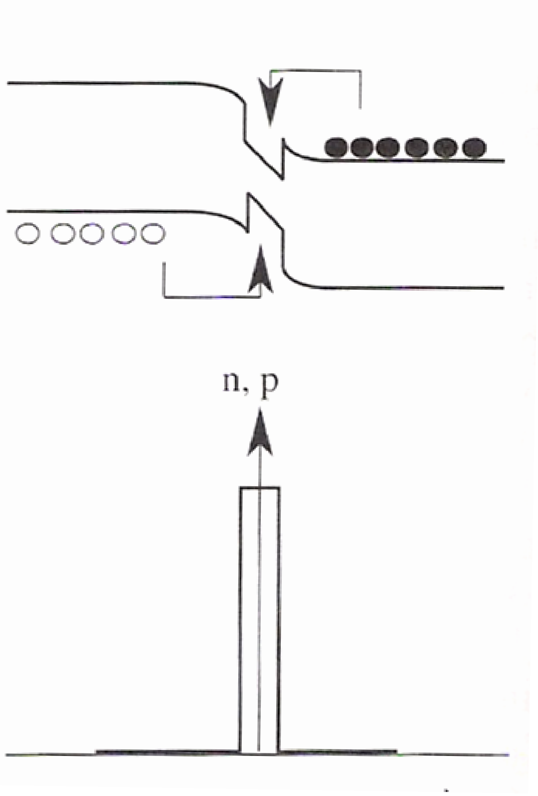
Key milestones:

- 1962: first visible (red) LED – Holonyak (GE, US)
- 1972: first yellow/red-orange high-brightness LED – Craford (HP, US)
- 1993: first high-brightness blue LED – Nakamura (Nichia, Japan)

Basic properties of LEDs

LED: a p-n junction that emits light





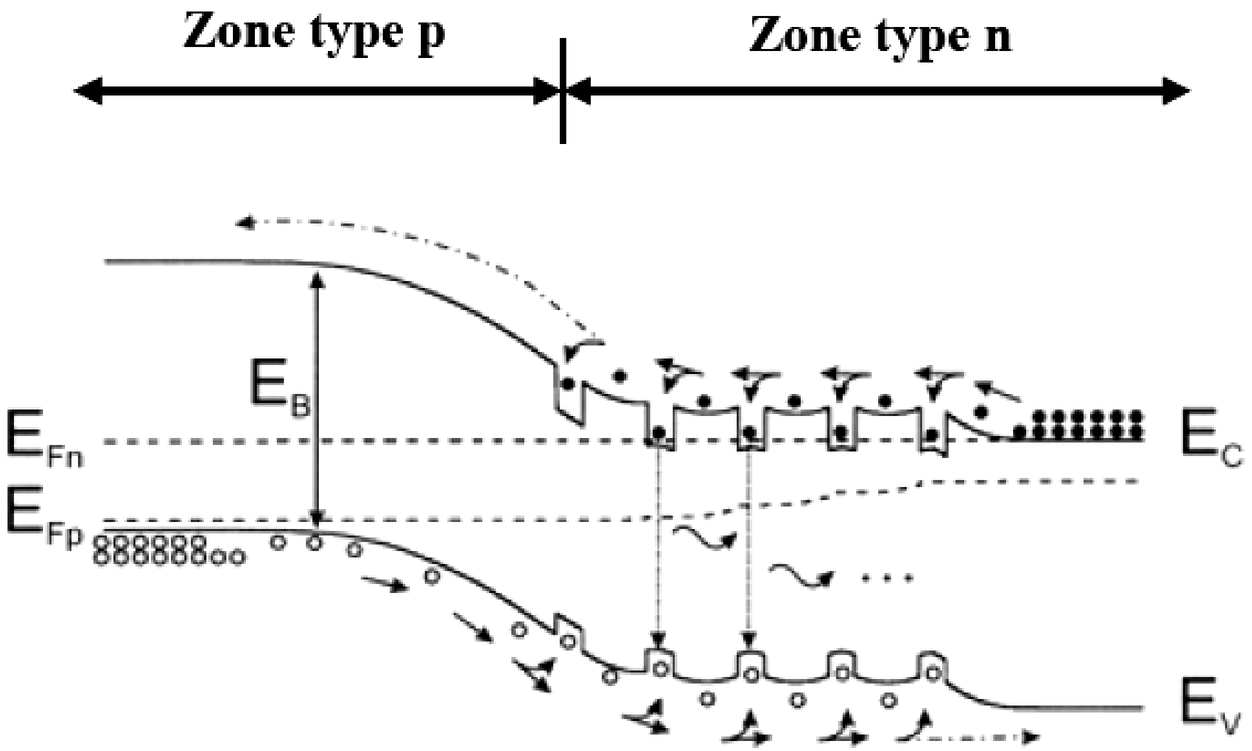
Homojunction

Heterojunction

Heterojunctions allow for an efficient spatial trapping of injected carriers ⇒ increased radiative efficiency, improved operating characteristics (*L-I* & *I-V* curves)

Basic properties of LEDs

Multiple quantum well based LED



The active region consists of several QWs to enhance the carrier collection (efficiency) as they could overflow

Efficiency of LEDs

External quantum efficiency (EQE, η): [emitted photons from the LED]/[electrons]

$$\eta = \eta_{inj}\eta_i\eta_{ext}$$

η_{inj} : carrier injection efficiency (CIE) ⇒ [electrons injected in the QWs] /[electrons injected in the LED]

η_i : internal quantum efficiency (IQE) ⇒ [generated photons from the QWs] /[electrons injected in QWs]

η_{ext} : light extraction efficiency (LEE) ⇒ [emitted photons out of the LED] /[emitted photons from the QWs]

Wall plug-efficiency (WPE): [emitted power]/[injected power]

$$WPE = \mathrm{P_{out}}/\mathrm{P_{in}}$$

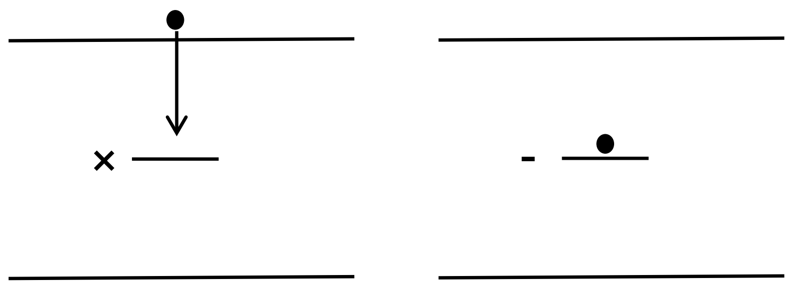
Rem: WPE is THE relevant figure of merit. Most often not mentioned in publications as it strongly depends on device processing

Efficiency of LEDs

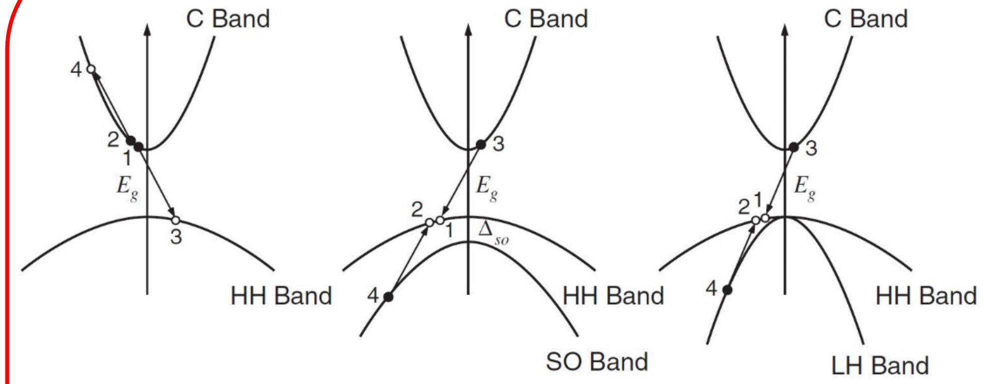
Carrier recombination in the active region

Different paths for electron-hole recombinations

- Non-radiative (Shockley-Read-Hall recombination) $A\,n$
- Radiative (spontaneous recombination) $B\,n^2$ — B bimolecular coefficient ~10^{-12}-10^{-10} cm^3s^{-1}
- Auger (non-radiative recombination) $C\,n^3$



Shockley-Read-Hall recombination



Auger recombination

Efficiency of LEDs

Internal quantum efficiency (IQE, η_i)

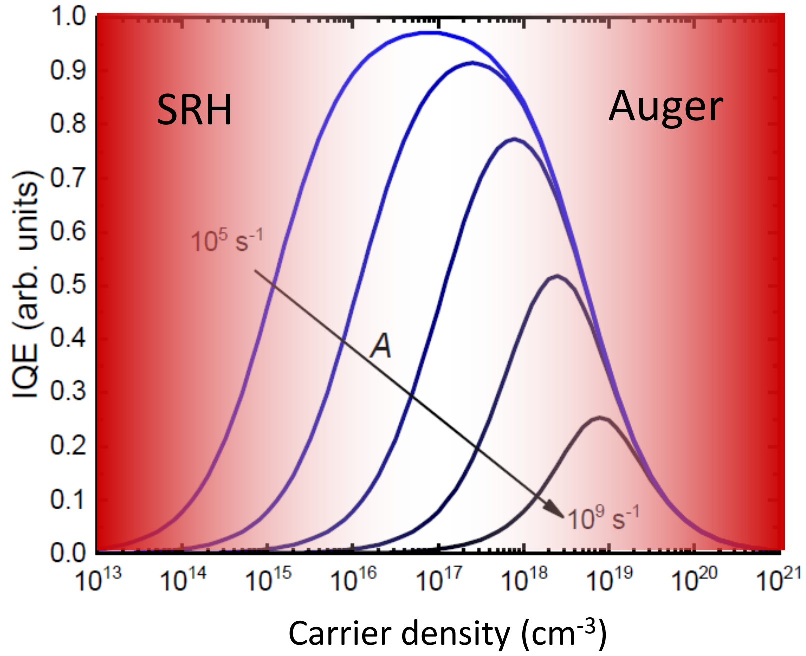
η_i = [generated photons from the QWs]/[injected electrons in the QWs]

$$\eta_i = \frac{\tau_{tot}}{\tau_r} = \frac{\tau_{nr}}{\tau_{nr} + \tau_r} = \frac{Bn}{A_{nr} + Bn + Cn^2}$$

$$\frac{1}{\tau_{tot}} = \frac{1}{\tau_r} + \frac{1}{\tau_{nr}}$$

with τ_{nr} *non-radiative lifetime*
τ_r *radiative lifetime*

Rem: IQE can be as high as nearly 100% at 300 K for InGaN QWs

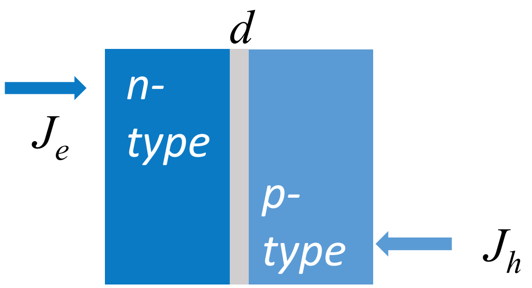


The photon flux is $\Phi = \eta_{inj} \eta_i J/q$ *with J the electron current density*

Injection efficiency ≡ capture of carriers by the active region (QWs)

Efficiency of LEDs

Carrier density in the active region



$$\frac{J_e}{qd} = \frac{J_h}{qd} = \frac{J}{qd} = \frac{n}{\tau_{tot}} = An + Bn^2 + Cn^3$$

$$d = \frac{V}{S}$$ d is the thickness of the active region (total QW thickness)

$$\frac{1}{\tau_{nr}} = A + Cn^2$$

$$\frac{1}{\tau_r} = Bn$$

$$\frac{1}{\tau_{tot}} = \frac{1}{\tau_{nr}} + \frac{1}{\tau_r}$$

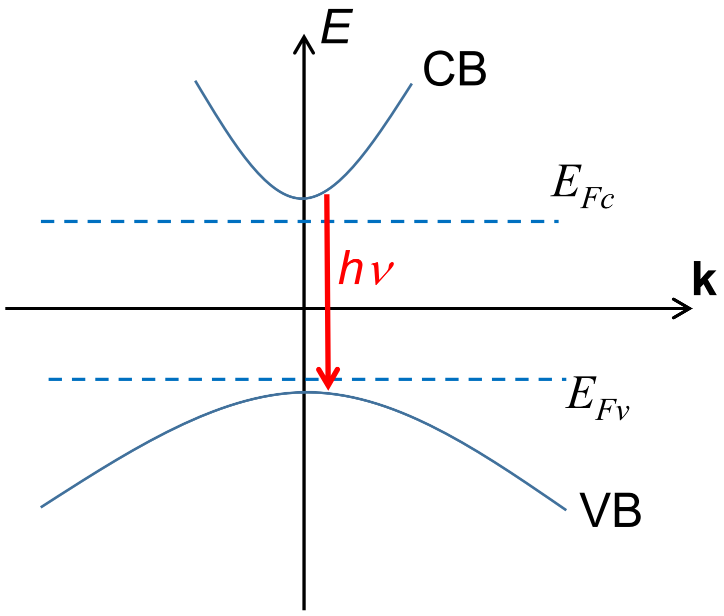
Out of equilibrium carrier density : $$n = \frac{J\tau_{tot}}{qd}$$ $\Rightarrow$ Strong dependence on the thickness of the active region

Once n is known, one can derive the position of the quasi-Fermi levels E_{Fn} and E_{Fp}

Efficiency of LEDs

Position of the quasi-Fermi levels

- Both the valence and the conduction bands get more and more filled upon increasing current injection
- The carrier populations are described by the quasi-Fermi levels E_{Fc} and E_{Fv}



Density of electrons (n)

$$n = \int_{E_c}^{\infty} \frac{1}{\exp\left(\frac{E - E_{F_c}}{k_B T}\right) + 1} \rho_c(E)\, dE$$

idem for E_{Fv} with $p=n$ using $\rho_v(E)$, $f_v(E), Ev$

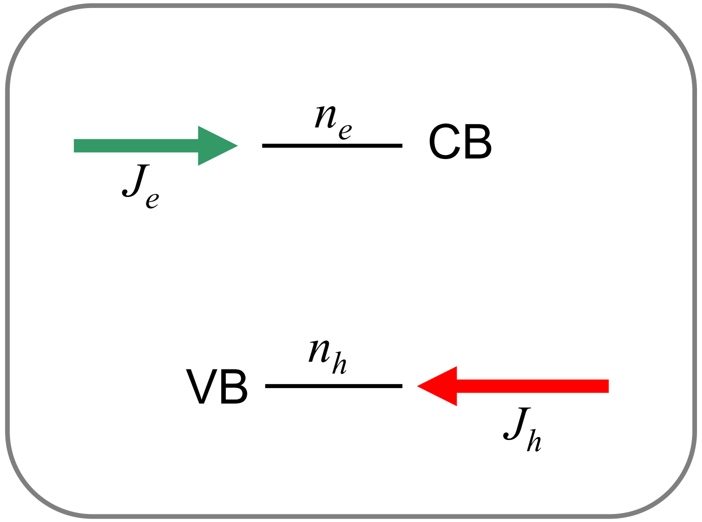
$$f_c(E) = \frac{1}{\exp\left(\frac{E - E_{F_c}}{k_B T}\right) + 1}$$

$$f_v(E) = \frac{1}{\exp\left(\frac{E - E_{F_v}}{k_B T}\right) + 1}$$

Note that here $f_v(E)$ describes the evolution of the electron population in the valence band

Emission properties

Spontaneous emission rate



$J_e = J_h = J$ electrical neutrality

and $n_e = n_h = n$

Steady-state $\Rightarrow$ recombination in the active region

The number of emitted photons is then given by

$R_{tot} \times$ Volume = $J/q \times S$ ← device active region area

with R_{tot} the total recombination rate (per unit volume)

In an intrinsic bulk semiconductor, the spontaneous recombination rate between the CB and the VB is given for a state with a wavevector $\boldsymbol{k}$ by

$$r_{sp}(\boldsymbol{k}) = (1/\tau_R)\, f_c(E_c(\boldsymbol{k}))\, (1-f_v(E_v(\boldsymbol{k}))) \qquad (s^{-1})$$

Emission properties

Spontaneous emission rate

The spectral distribution of spontaneous recombination rate $R_{sp}(h\nu)$ due to a quasi-equilibrium distribution of carriers is given by

Spin-related

$$R_{sp}(h\nu) = 2\sum_{\mathbf{k}} r_{sp}(\mathbf{k}) = 2\sum_{\mathbf{k}} \frac{1}{\tau_R(\mathbf{k})} f_c(\mathbf{k})\big(1 - f_v(\mathbf{k})\big)\delta(E_c - E_v = h\nu)$$

The summation is performed over all **k**-vectors verifying the energy conservation condition (hence the Dirac delta)

$$E_c(\mathbf{k}) - E_v(\mathbf{k}) = h\nu = E_g + \frac{\hbar^2 k^2}{2m_r}$$

Expression relying on the verticality of optical transitions in **k**-space

$$\frac{1}{m_r} = \frac{1}{m_C^*} + \frac{1}{m_V^*}$$

which leads (after integration over all energy states) to

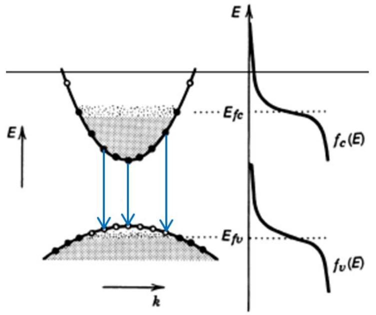
$$R_{sp}(h\nu) = r_{sp}(h\nu)\rho_j(h\nu)$$

$$R_{sp}(h\nu) = \frac{1}{\tau_R} f_c\big(E_c(h\nu)\big)\Big(1 - f_v\big(E_v(h\nu)\big)\Big)\rho_j(h\nu)$$

Spectral distribution of spontaneous recombination rate

Joint density of states (JDOS)

$$\rho_j(h\nu) = \frac{1}{2\pi^2\hbar^2}(2m_r)^{\frac{3}{2}}(h\nu - E_g)^{\frac{1}{2}}$$



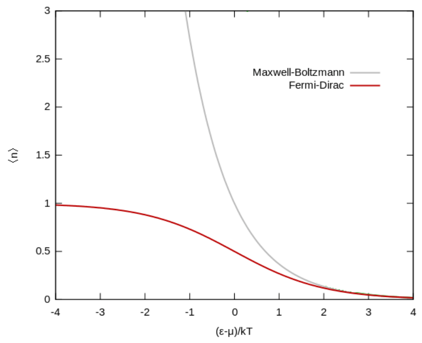
Emission properties

Spontaneous recombination rate : Boltzmann approximation

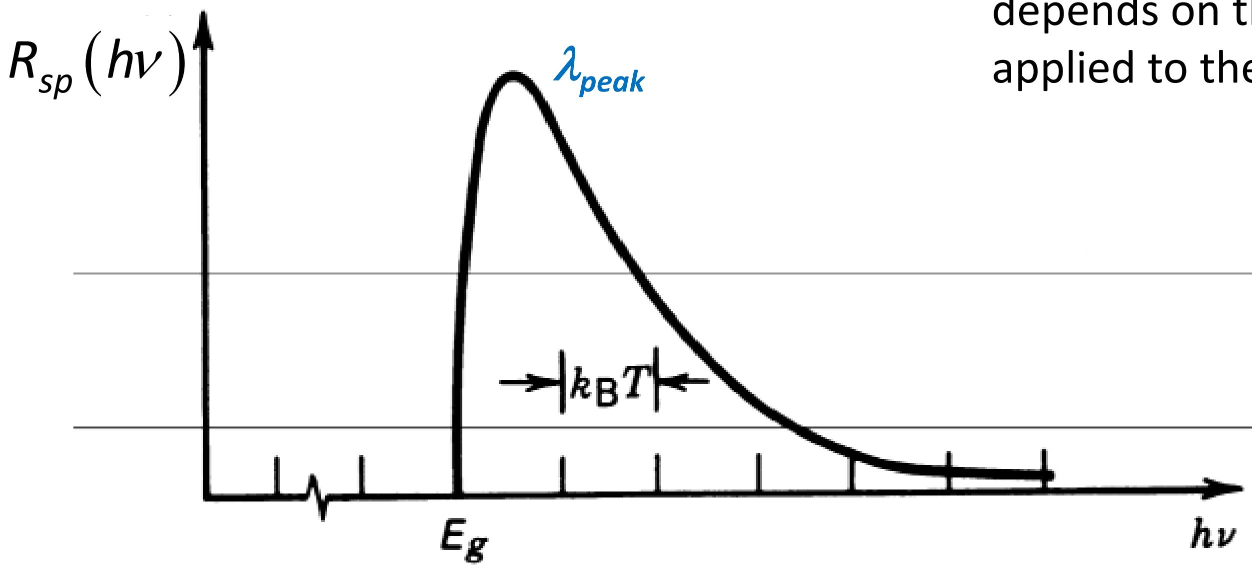
$$R_{sp}(h\nu) = K_{sp}(h\nu - E_g)^{\frac{1}{2}} \exp\left(-\frac{h\nu - E_g}{k_B T}\right)$$

$$\text{with} \quad K_{sp} = \frac{1}{2\pi^2\hbar^2\tau_R}(2m_r)^{\frac{3}{2}} \exp\left(\frac{\Delta E_F - E_g}{k_B T}\right)$$

$$\Delta E_F = E_{F_n} - E_{F_p}$$

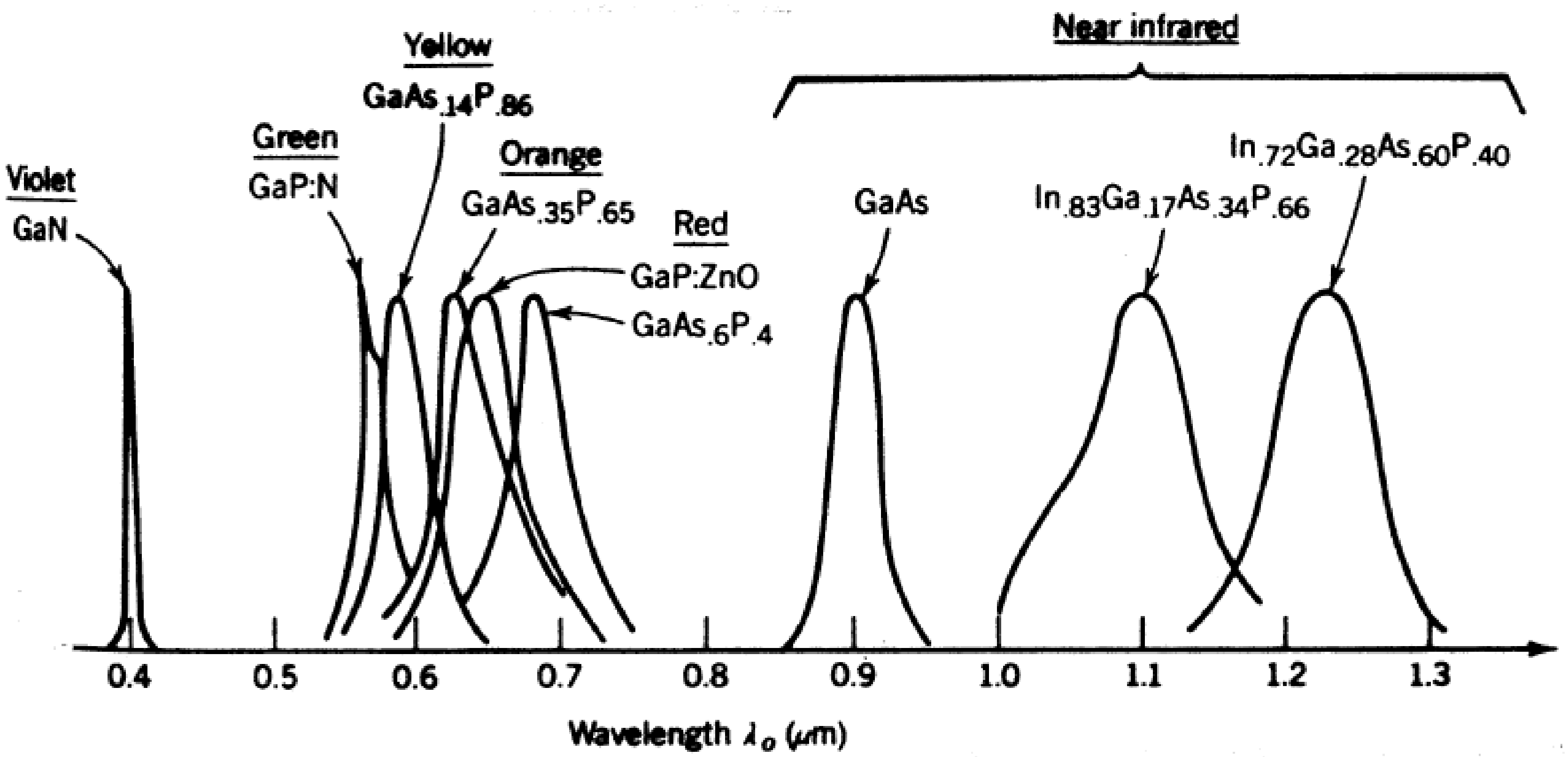


depends on the voltage applied to the p-n junction



Emission properties

LED emission spectra

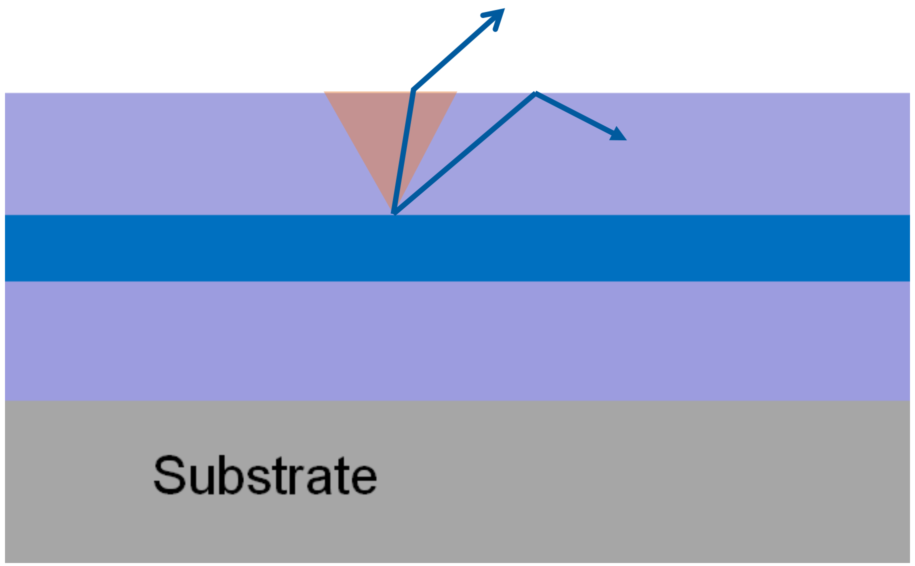


$$\Delta\lambda \propto \lambda_{peak}^2 k_B T$$

Emission properties

External quantum efficiency (EQE, η): η =[emitted photons]/[electrons]

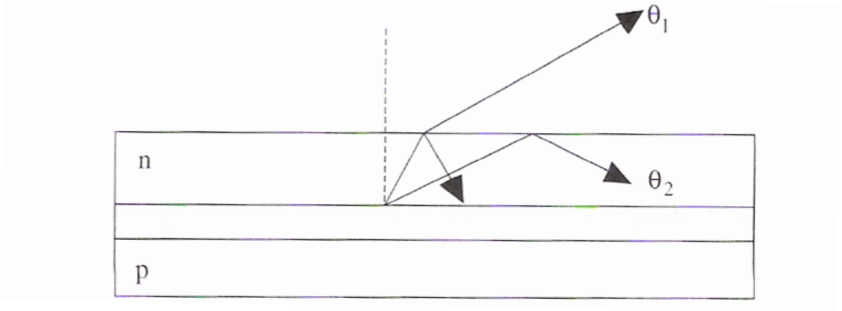
$$\eta = \eta_{inj}\eta_i\eta_{ext}$$ → extraction efficiency



Emission properties

Extraction efficiency (η_{ext})

Key issue: photons must escape the material



Transmission: $\theta_1 \approx 0 \Rightarrow T = 1 - [(n_{sc}-1)^2/(n_{sc}+1)^2]$

Critical angle for total internal reflection (TIR): $\theta_c = \arcsin(1/n_{SC})$

For GaAs, $n_{sc} = 3.6 \Rightarrow \theta_c = 16°$ and $T = 0.7$

Solid angle leading to light extraction →

$$\frac{\Omega_c}{\Omega_{tot}} = \frac{\Omega_c}{4\pi} = \frac{1}{4\pi}\int_0^{2\pi} d\phi \int_0^{\theta_c} \sin\theta \, d\theta = \frac{1}{2}\left(1 - \cos\theta_c\right)$$

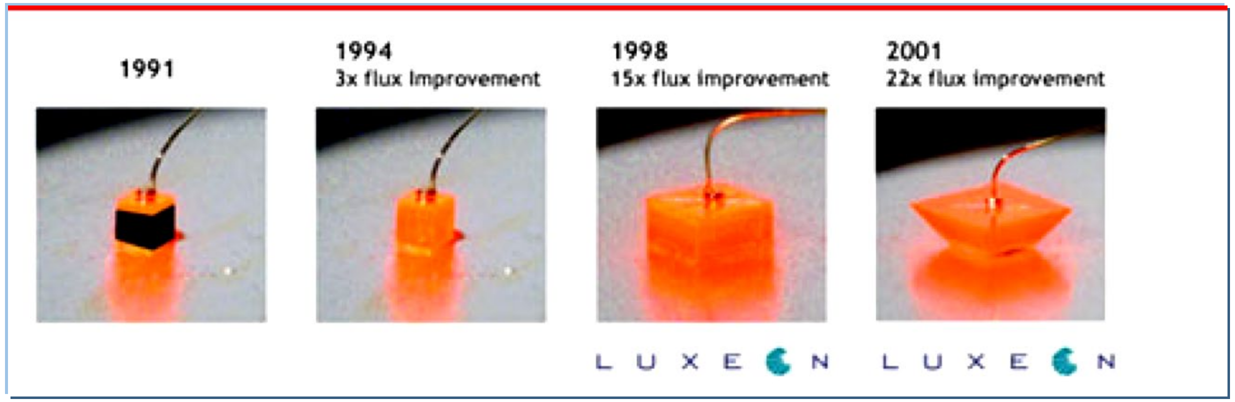
For GaAs, only 2% of photons are extracted per facet

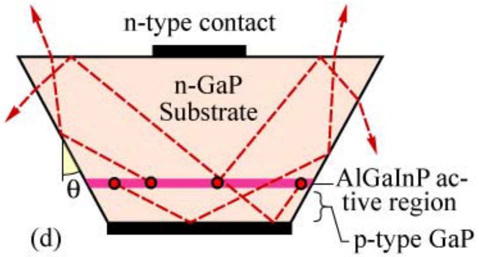
The extraction efficiency η_{ext} is very low for a simple geometry (planar one)

Emission properties

Extraction efficiency (η_{ext})

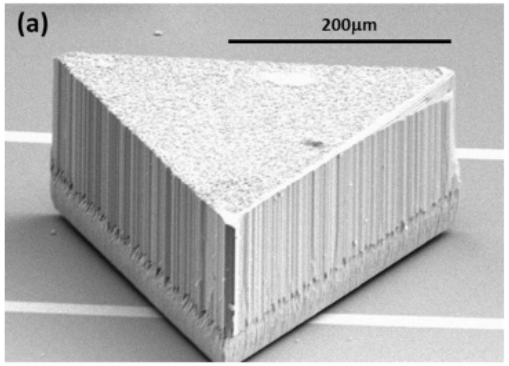
How can we improve the EQE compared to the planar geometry?

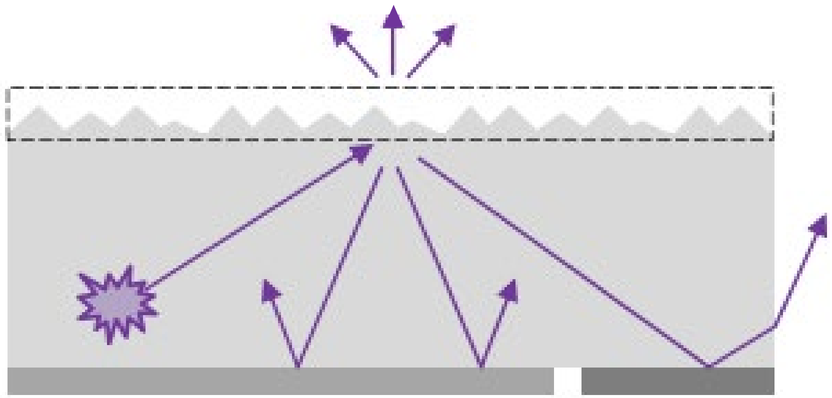


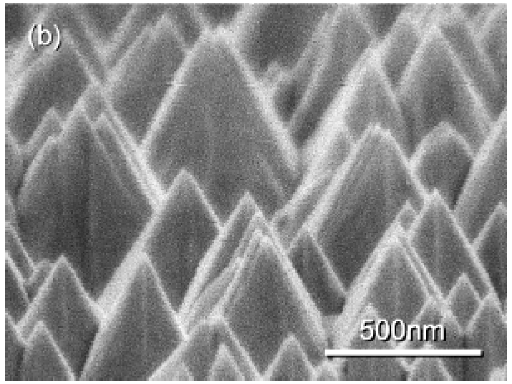


After a 1st total internal reflection, photons reach the second interface with an incident angle < θ_c

M. Krames *et al.*, J. Display Tech. **3**, 160 (2007)







A. David *et al.*, Appl. Phys. Lett. **105**, 231111 (2014)

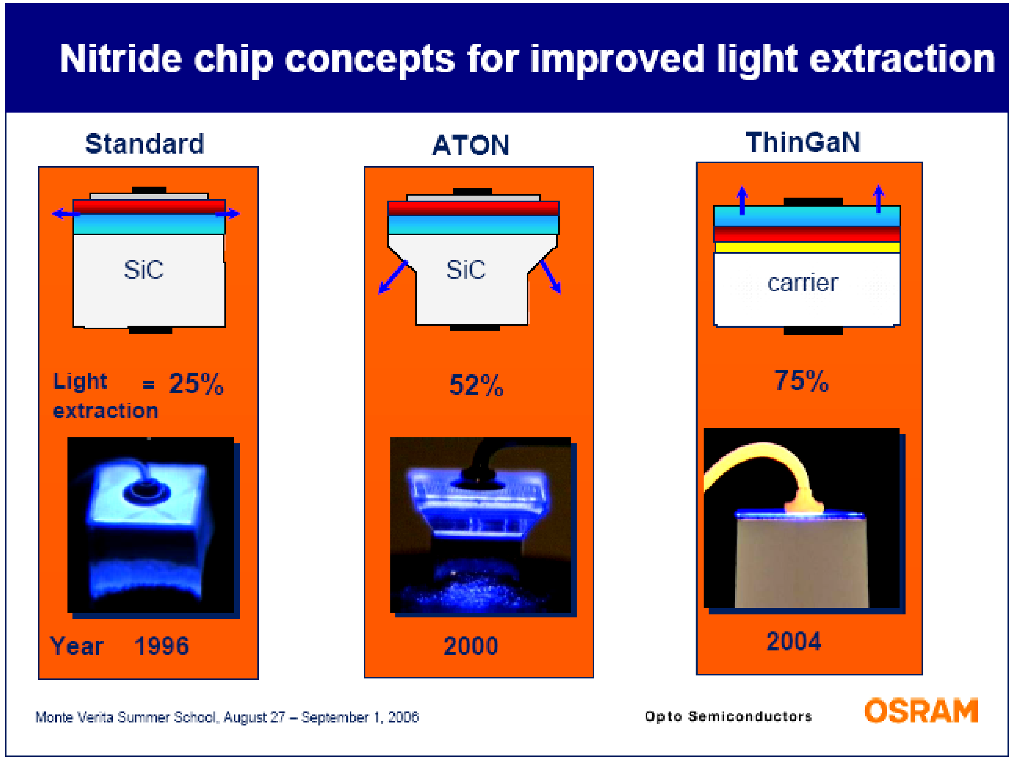
T. Fujii et *al.*, Appl. Phys. Lett. **84**, 855 (2004)

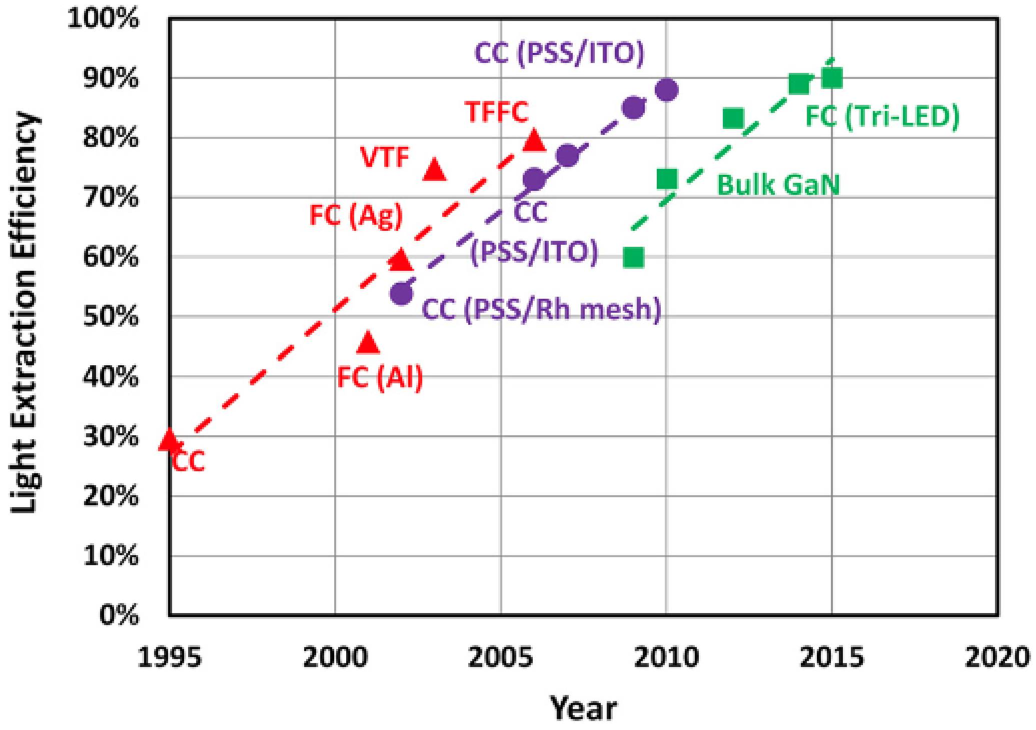
Emission properties

Extraction efficiency (η_{ext})

How can we improve the EQE compared to the planar geometry?

$\eta_{ext} = 90\%$





D. Feezell and S. Nakamura / C. R. Physique **19** , 113(2018)