# Light extraction in nitride LEDs

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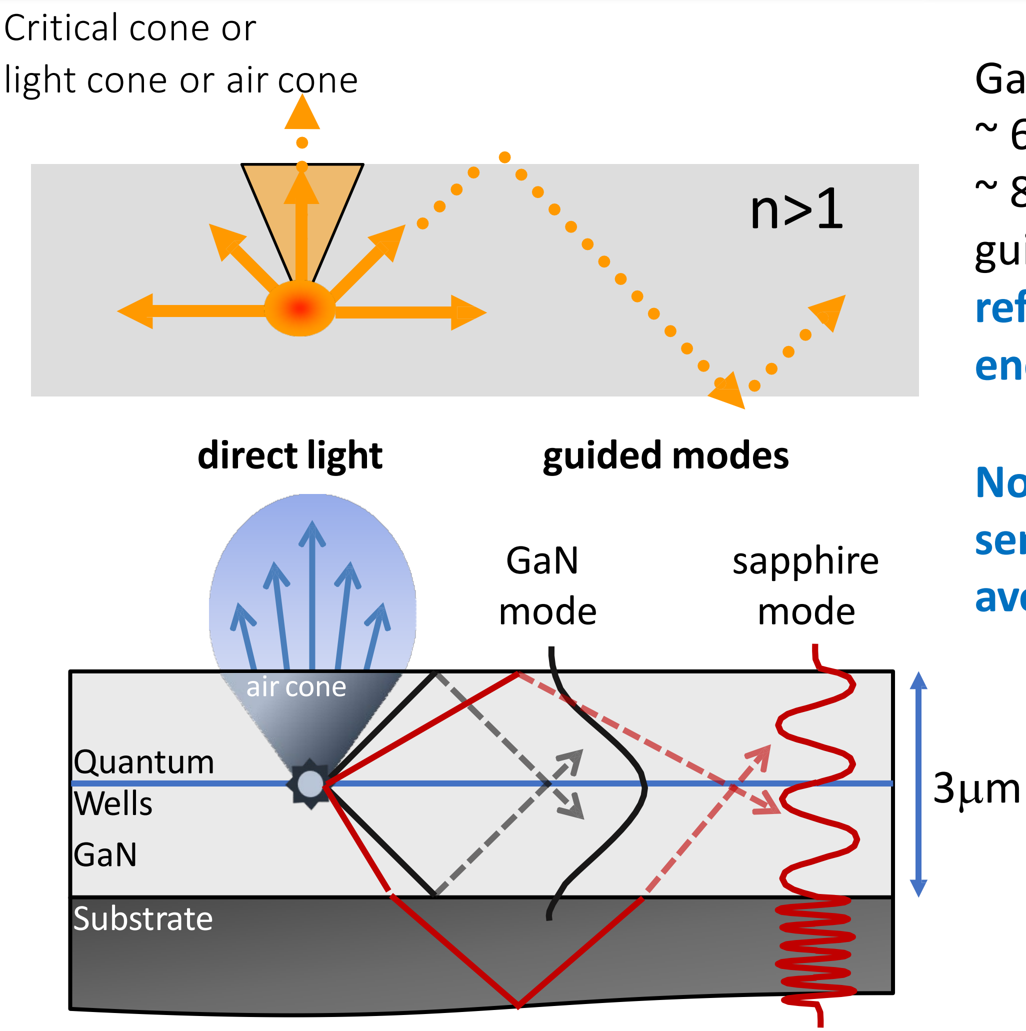
# Light extraction in nitride LEDs




GaN index of refraction 2.5
~ 6 % of emitted light is extracted each side
~ 88 % is trapped in the semiconductor as guided modes due to **total internal reflection at the semiconductor air or encapsulant interface**

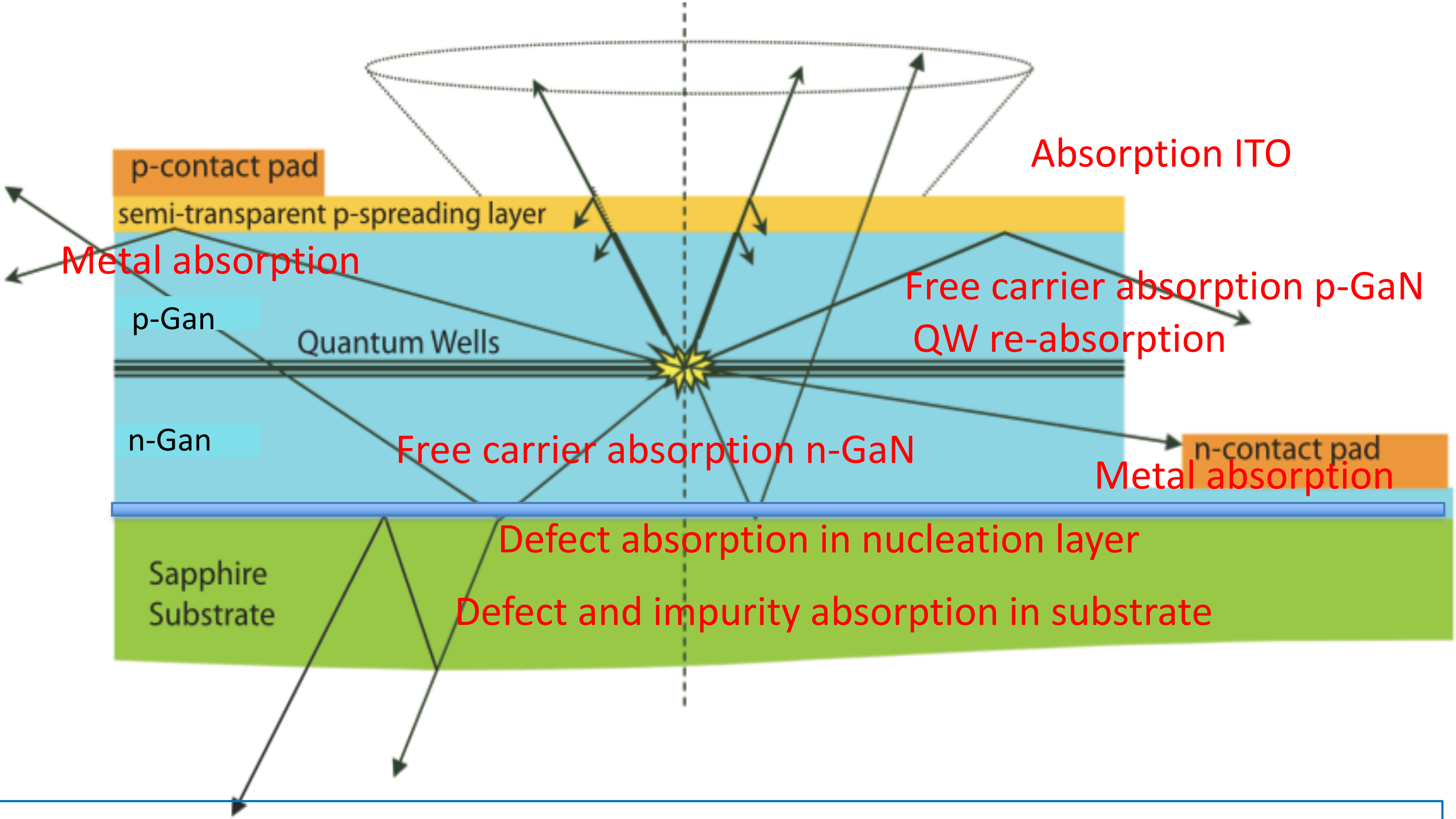
**No encapsulant with index matching the semiconductor has been found/used to avoid total internal reflection**

In planar structures on sapphire, light is emitted in modes guided either in the nitride layers (66%) or in the substrate (22%)

Dominant light extraction schemes are based on destruction of the propagating guided modes by using nonlplanar structures. The physics of extraction is well described by geometrical optics concepts and ray tracing simulations

# Light should be absorbed after many passes ?

In real LEDs many dissipation opportunities are competing with multipass extraction




Goal: optimize extraction path to **minimize encounters with absorbing materials**

# Different ways to improve light extraction efficiency

| Wished improvement | Idea | Realization |
|---|---|---|
| Increased extraction efficiency by multiple ray escape attempts at different angles | Redirecting light rays | • Shaped susbstrates (with transparent substrates)<br>• Surface roughening/volume scatterers<br>• patterned substrate |
| Increased extraction efficiency by directional control of emission and propagation | Microcavity effects photonic crystals | Planar microcavities<br>Limit: 45% for nitrides, 70% for OLEDs<br>Photonic crystals |

# … and internal quantum efficiency

| | | |
|---|---|---|
| **Increase internal quantum efficiency by photon engineering** | **Purcell effect** | • **Microcavities**<br>• **Photonic crystals**<br>• **Plasmons**<br>• **Light-matter strong coupling (cavity-polaritons)**<br>• **3D cavities/micropillars** |

# Different ways to improve light extraction efficiency

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| --- | --- | --- |
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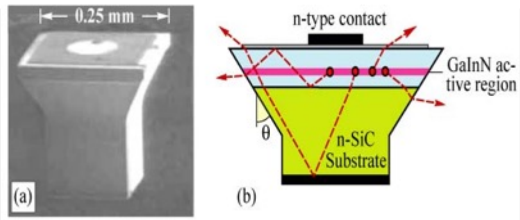
| | | |

Many ray-tracing computations of LEDs in
Lalau Keraly, C.; Kuritzky, L.; Cochet, M.; Weisbuch, C. Ray Tracing for Light Extraction Efficiency (LEE) Modeling in Nitride LEDs. In Topics in Applied Physics 133; III-Nitride Based Light Emitting Diodes and Applications ,2nd edition; T.-Y. Seong et al. eds., Ed.; Springer Netherlands, 2017; p 301.

# Light extraction in LEDs: present techniques

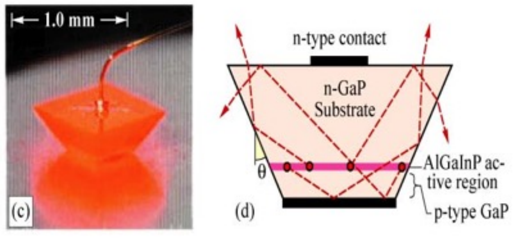
Up to 90%+
Complex process



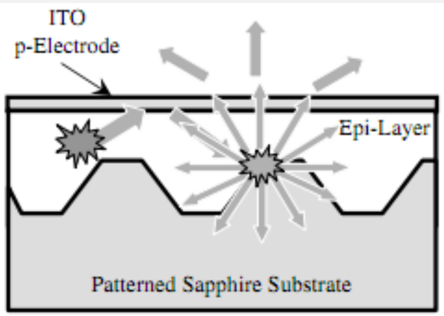

Shaped SiC substrate
Cree

## Shaped transparent substrate

- non planar process
- light propagates long distance; requires ultra low internal loss



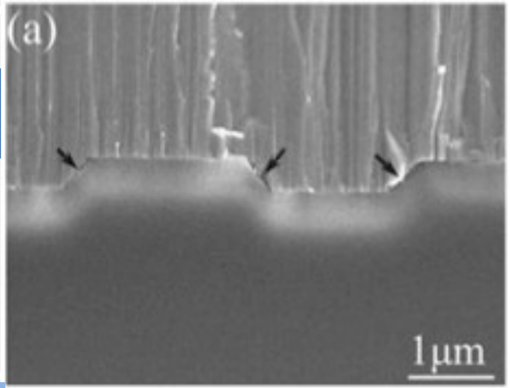

Krames, Craford
philips lumileds 1994




## **PSS:** Patterned Sapphire Substrate

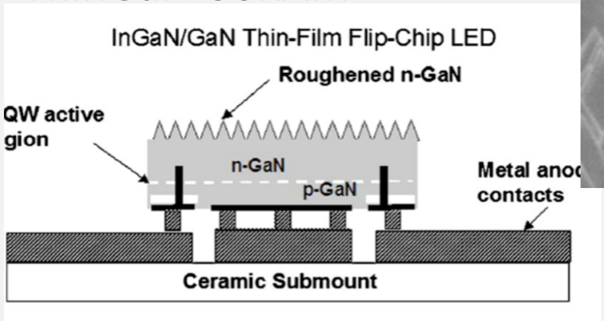
- poor thermal properties
- Improved IQE

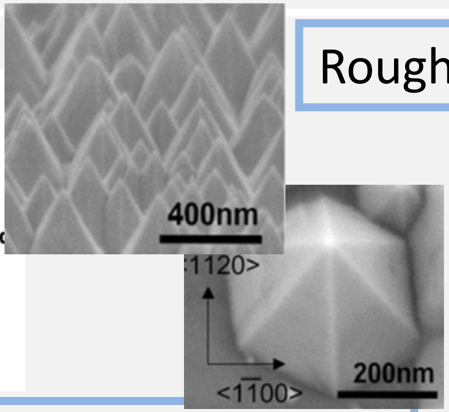
**Mitsubishi 2001, Nichia 2002**




**Fujii, Nakamura 2004**

Micromirrors
ThinGaN OSRAM



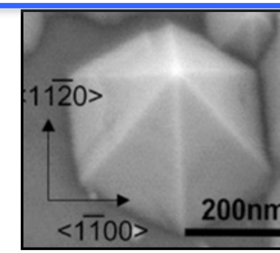




## Roughened surface

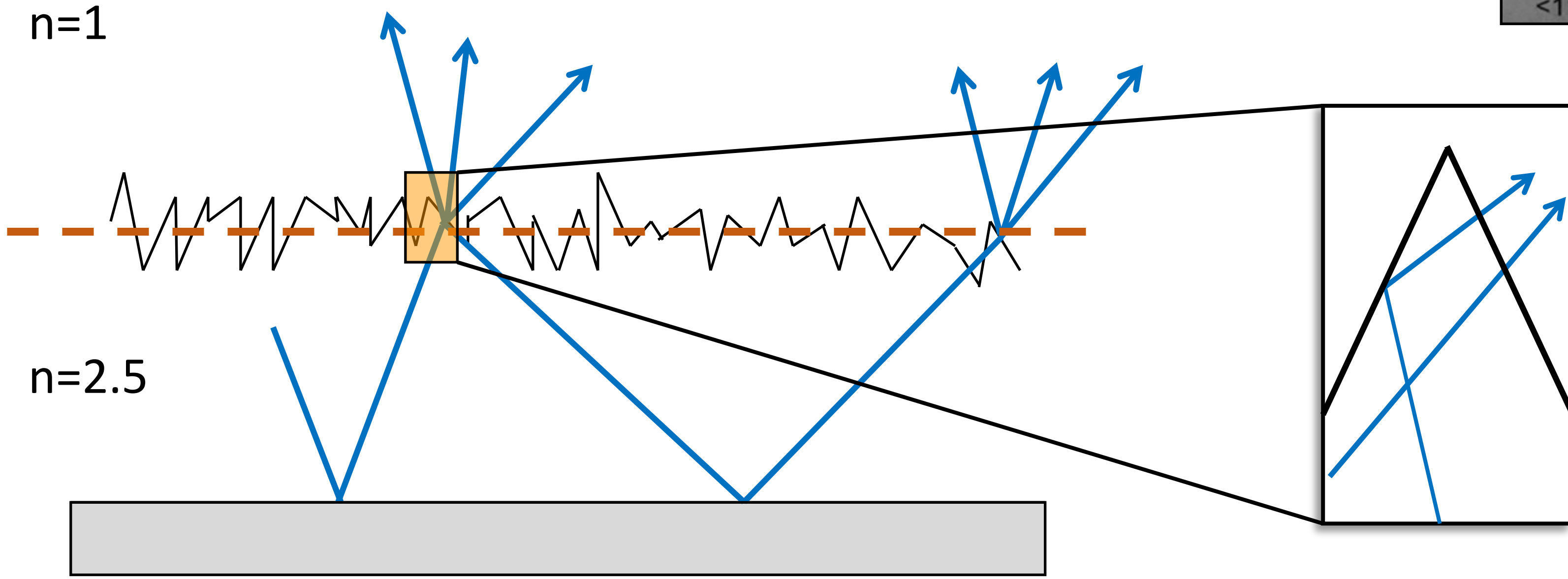
- not efficient if substrate not removed
- needs thinning down to minimize materials absorption
- complex and expensive fabrication

Flip Chip + Roughened surface Philips Krames

# Surface Roughening:
# Two Mechanisms that Increase Extraction



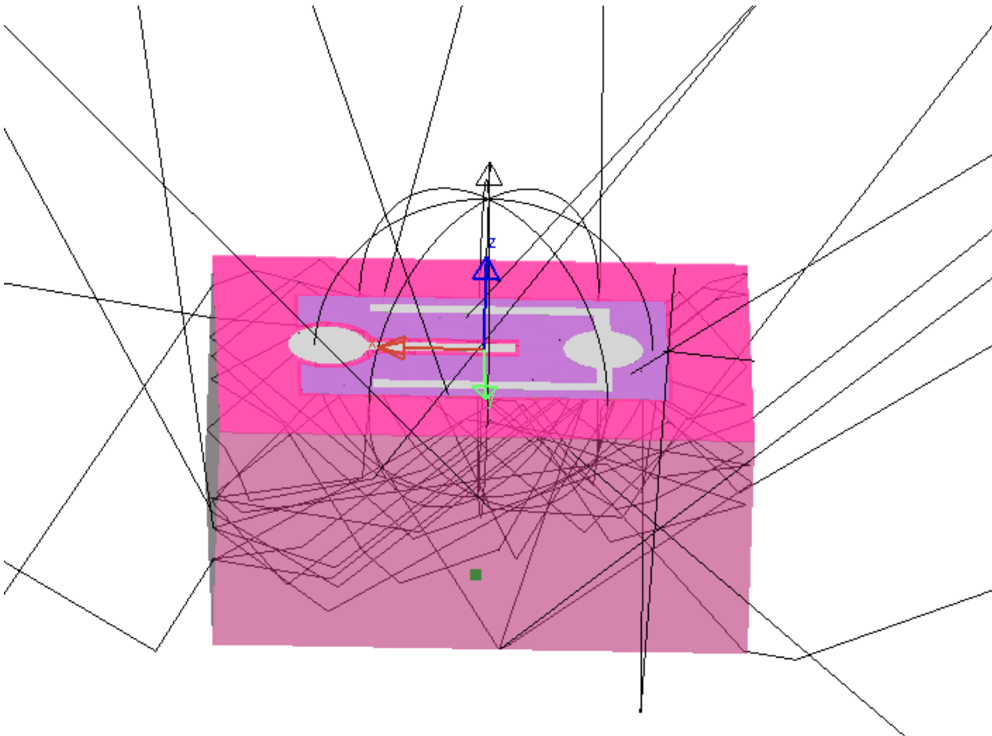

**Increased First Pass Extraction and** Randomization




**Reflected Angle≠ Incident Angle**

**Either direct extraction or one bounce + Extraction**

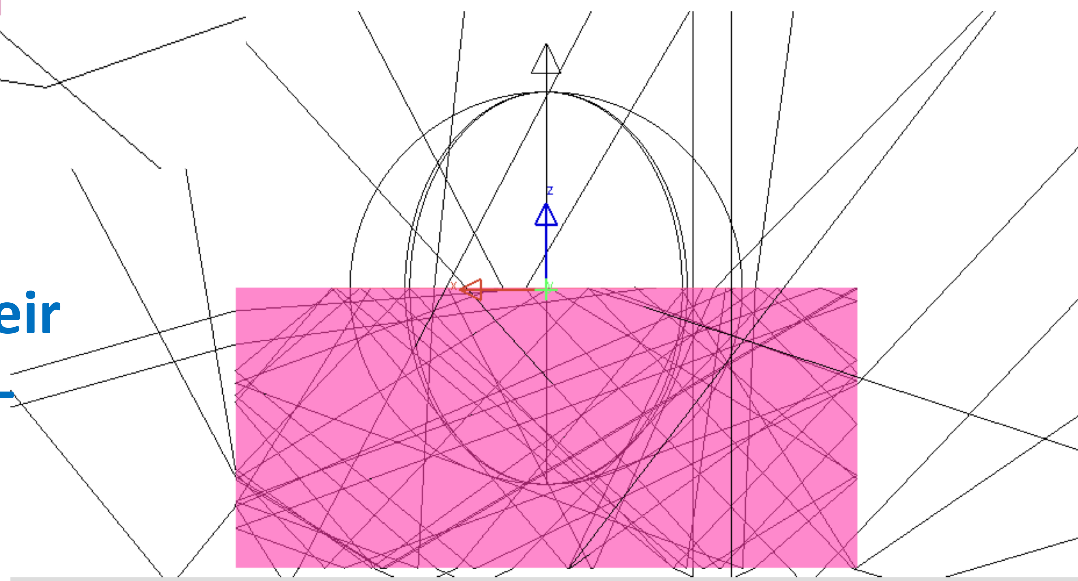
# Ray Tracing for Light Extraction Modeling



We generate random light rays from source area and look for their fate: escaping volume (radiation out of the LED), absorption in metals or semiconductor materials, etc..

Statistics of fates gives losses and LEE

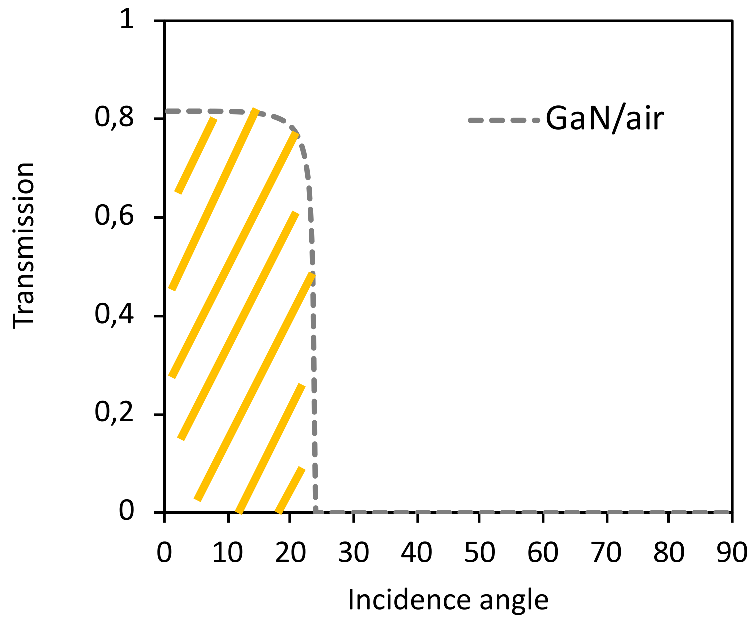
**The exact structure with all their features ca be modelled in ray-tracing**



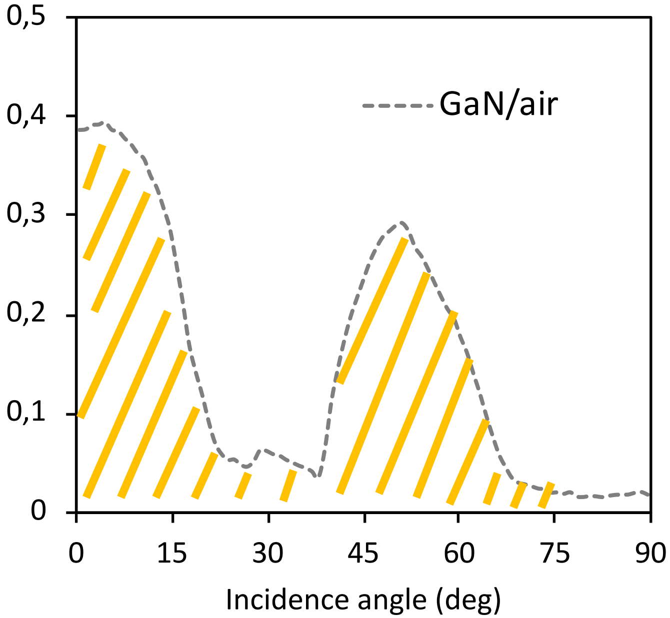
LightTools

# Surface Roughening: Increasing First Pass Light Extraction

FLAT SURFACE TRANSMISSION




ROUGHENED SURFACE TRANSMISSION



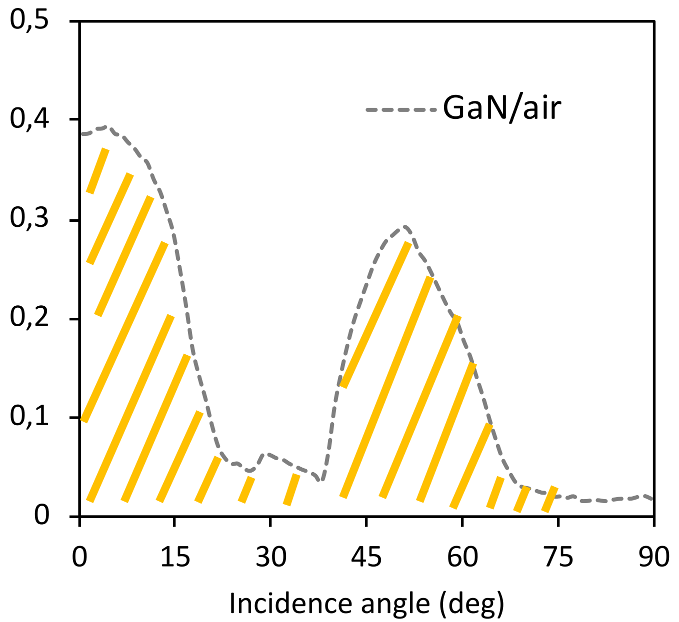

First-attempt escape probability from GaN (n=2.5) to air:**6%** flat surface
Next attempts: 0% !
Light bounces back and forth

First-attempt escape probability **13.5%** roughened surface
(Averaged over all solid angles)
All further attempts **13.5%**
**(doubled in encapsulant)**

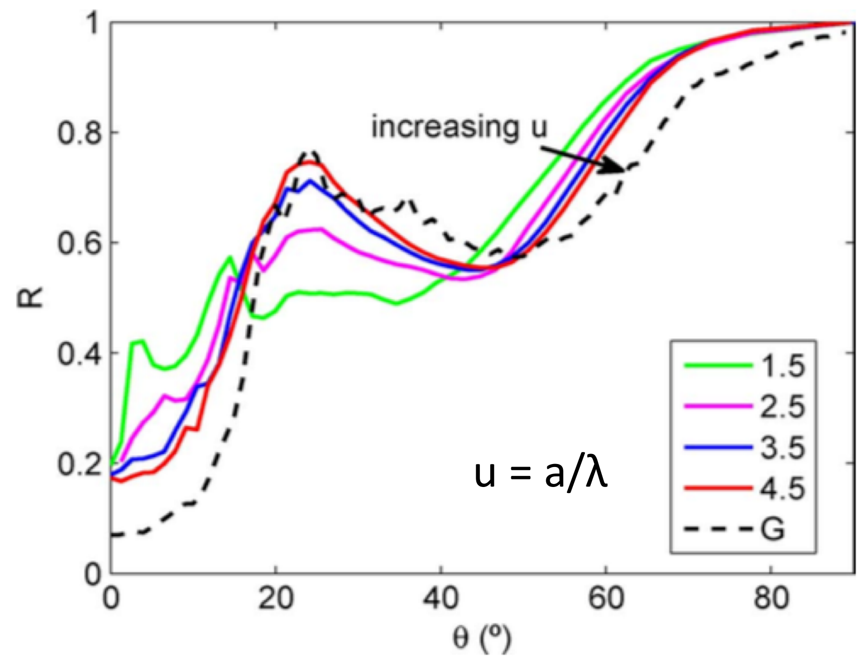
# Surface Roughening: ray-tracing vs. wave scattering

What happens if scattering features are of the order or smaller than the wavelength? Wave optics should apply

ROUGHENED SURFACE TRANSMISSION




ROUGHENED SURFACE REFLECTION




A. David, J. Displ. Technol.9, 301 (2013)

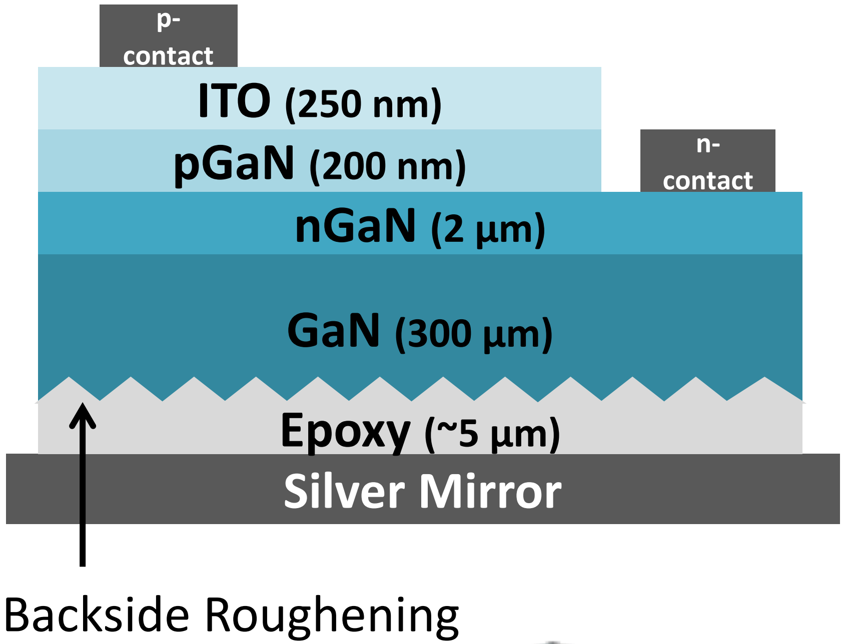
Results do not change significantly with feature size u = a/λ

Light is extracted after $\approx 3-4$ roundtrips - **light travels ≈ 10μm in the LED**

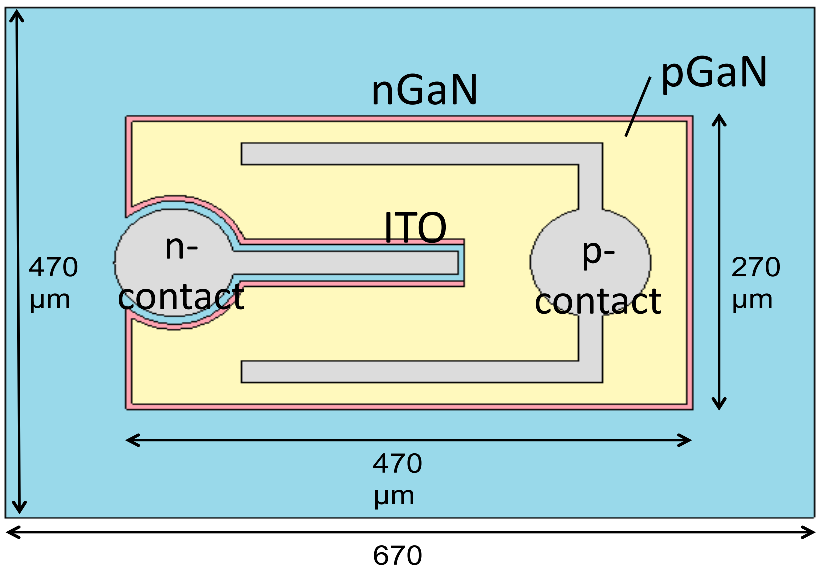
**(difference with lasers: light travels there 2-4 mm! Even weak mechanisms have an impact)**.

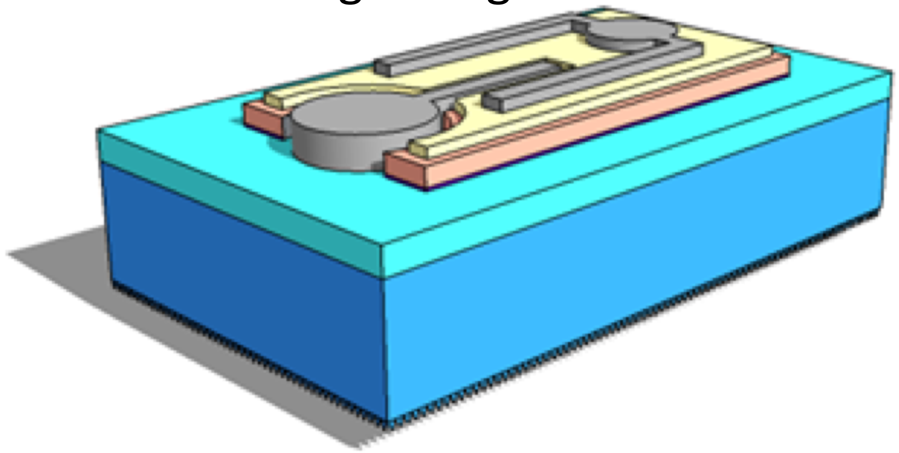
# Ray tracing simulations of full LEDs

**Side View**




**Top View**



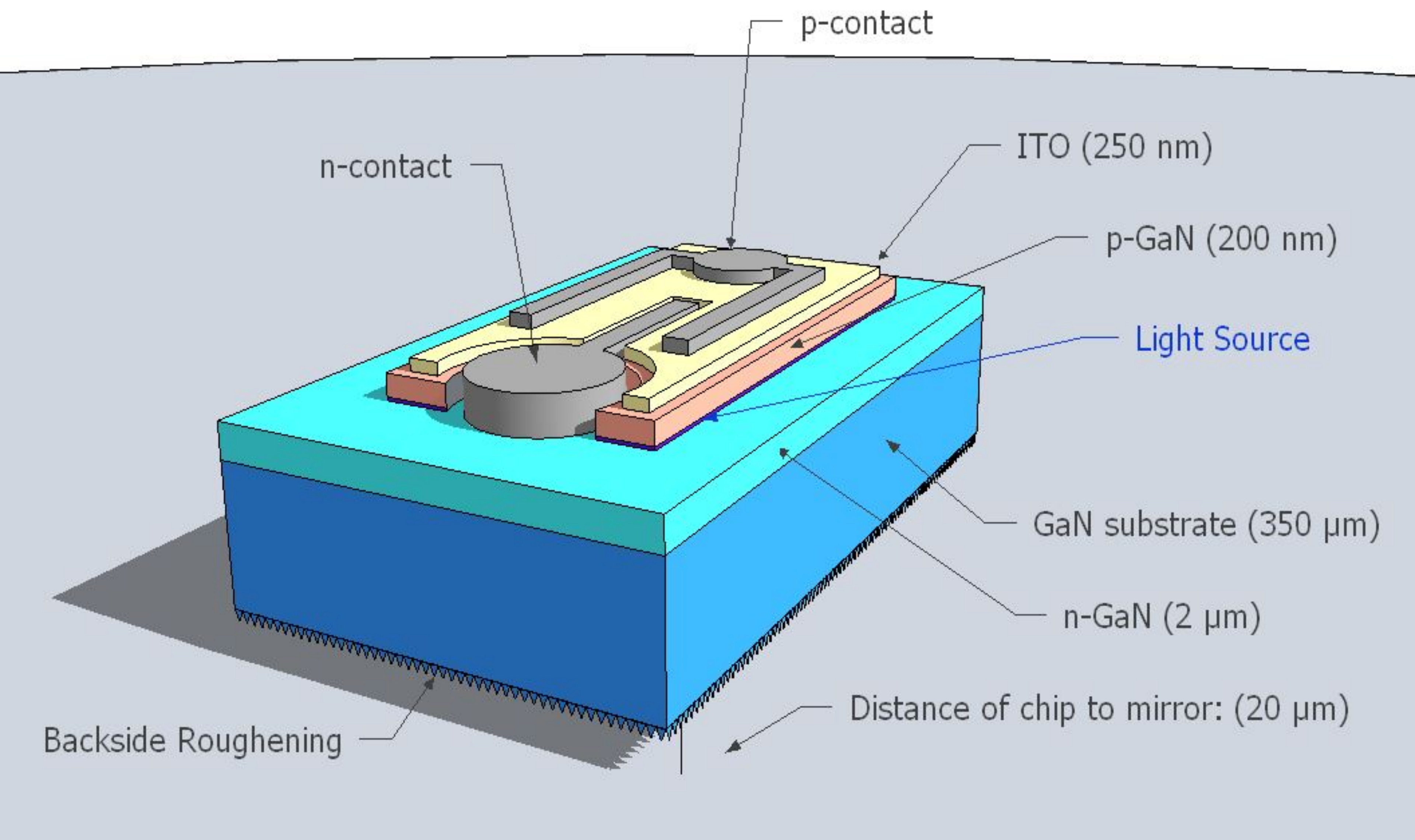
**The exact structure with all their features ca be modelled in ray-tracing**

# Materials Parameters

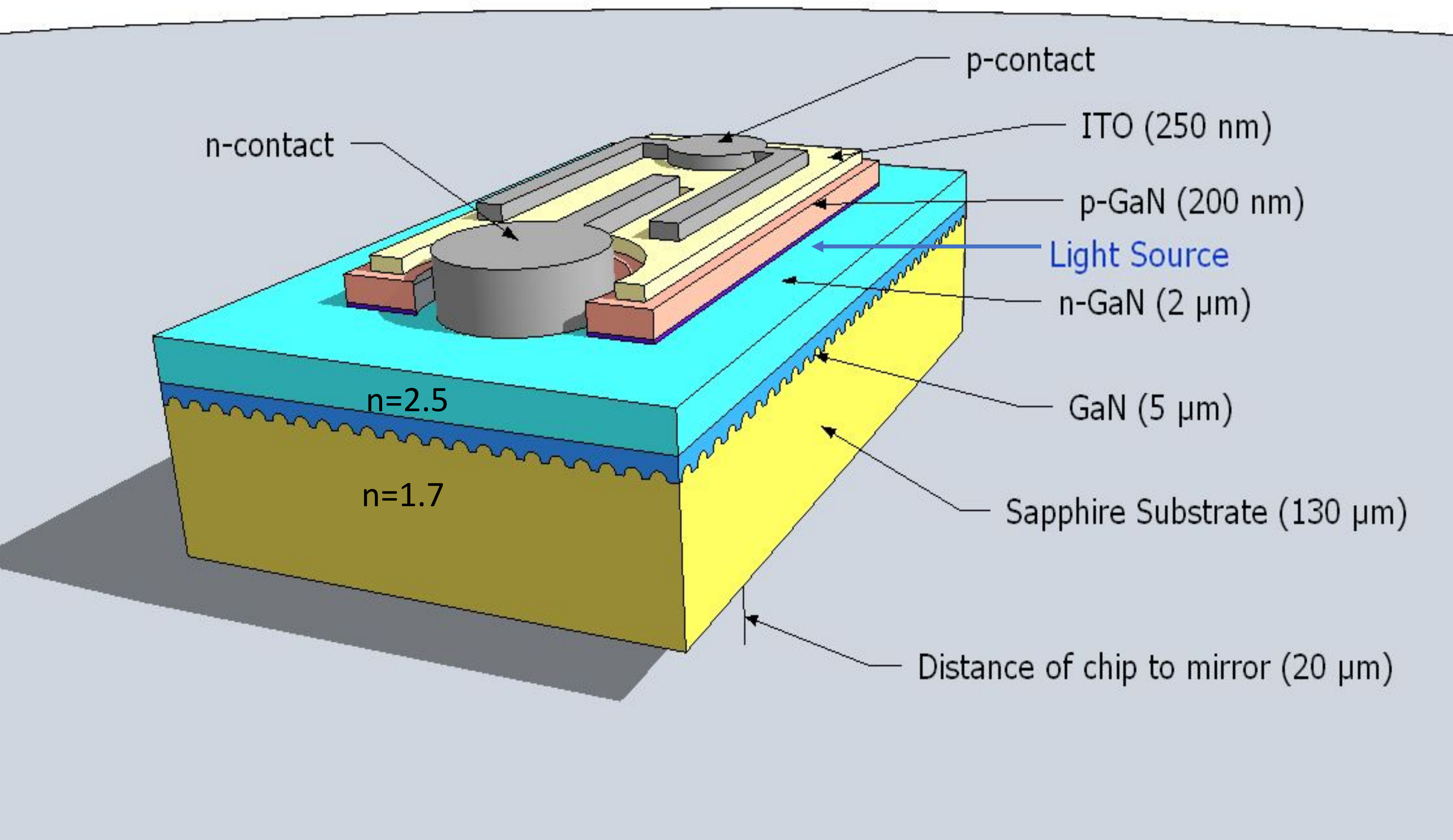
| | Refractive Index | Absorption Coefficient ($cm^{-1}$) |
|---|---|---|
| GaN substrate | 2.5 | **1** |
| Sapphire | 1.7 | 0.1 |
| n-GaN | 2.5 | 7 |
| p-GaN | 2.5 | 100 |
| ITO | 2.1 | 500 |
| Silver | - | 92% isotropic reflectivity |
| Titanium | 1.69 | $3x10^5$ |
| Epoxy | 1.5 | 0 |

In ray optics, the materials properties of interest are the refractive index and absorption coefficient.

# Three Chip Designs:
# #1 Roughened GaN Substrate

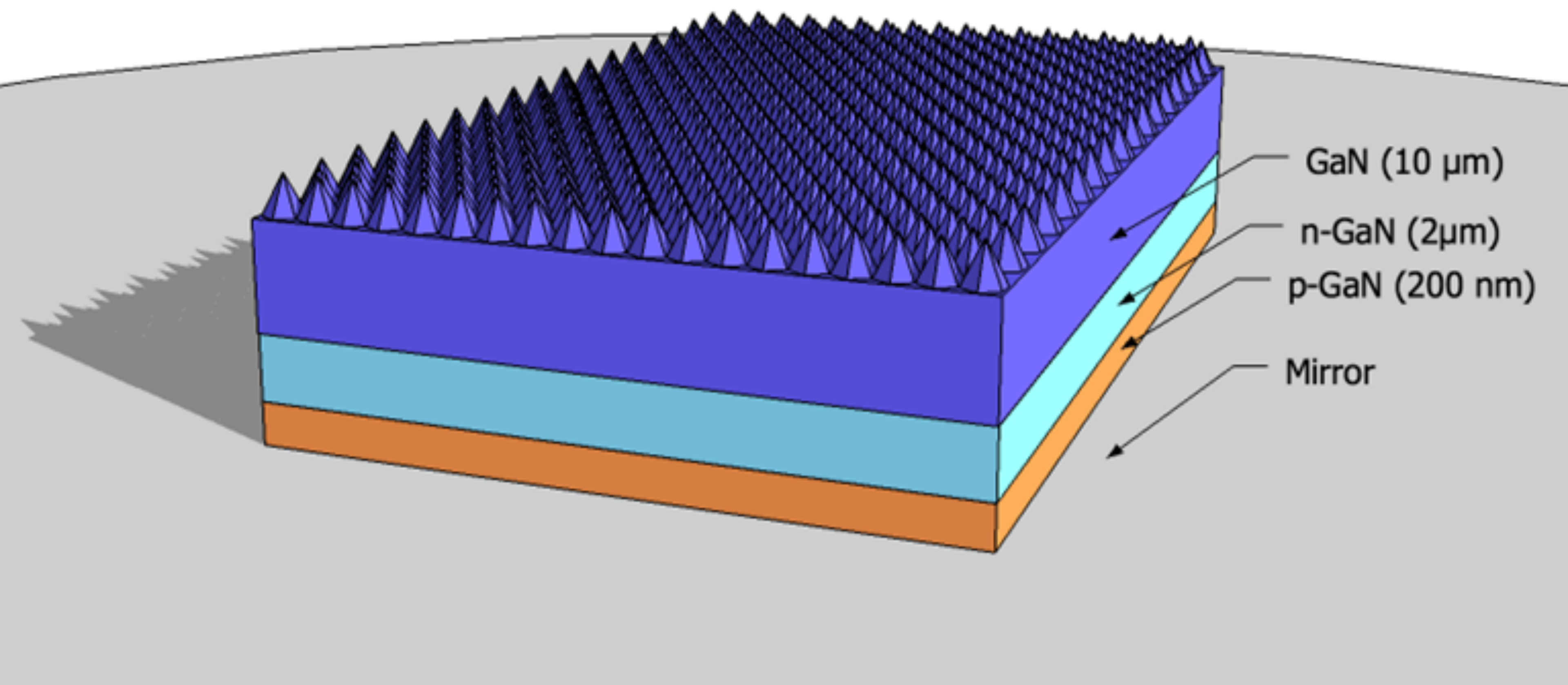


# Three Chip Designs:
# #2 Patterned Sapphire (PSS) Substrate



# Three Chip Designs:
# #3 Laser Liftoff GaN Flip Chip

Area=1700 μm x 1500 μm



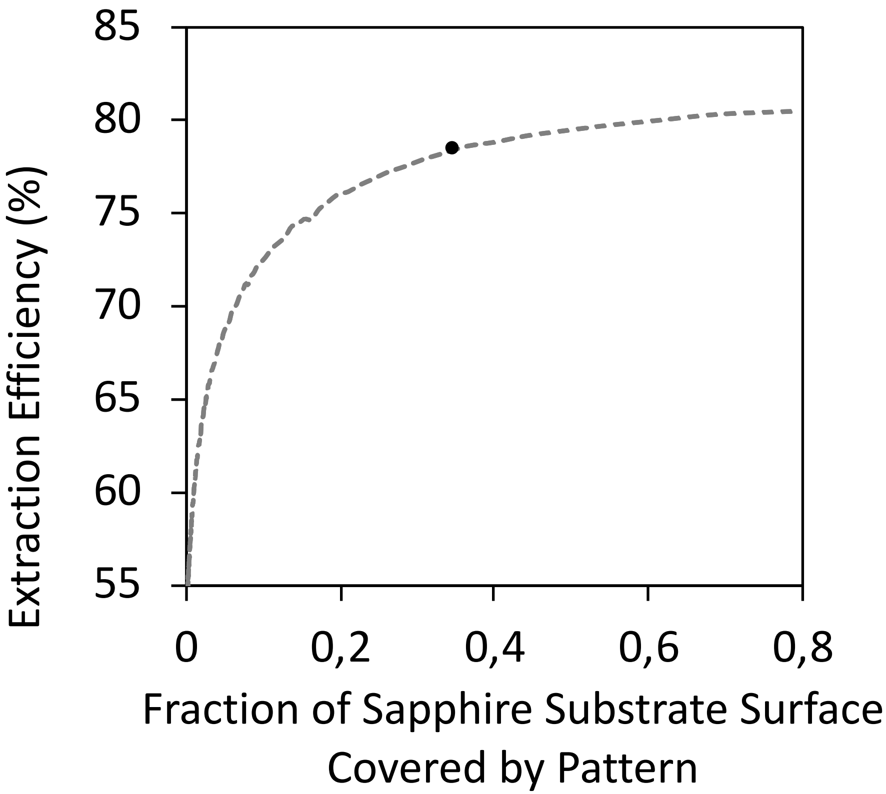
# LEE Comparison for the Three Chip Designs

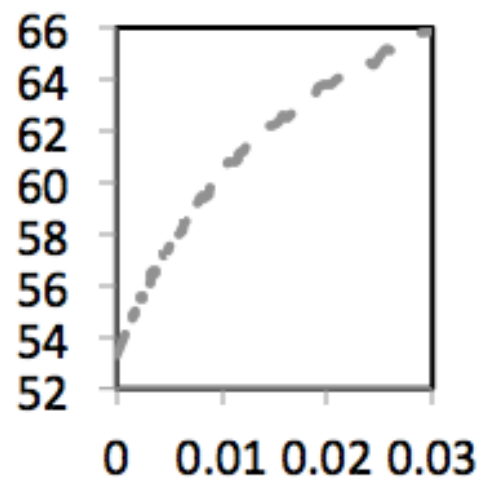
Chips encapsulated in epoxy with the structure and materials properties given above

| Losses in % | Roughened GaN Substrate Chip | PSS Chip | Flip Chip roughened |
|---|---|---|---|
| **Total Efficiency** | **72.1** | **78.1** | **77.8** |
| **Loss in PSS** | | 0.3 | - |
| **Loss in GaN substrate or buffer layer** | 12.1 | 0.2 | 1.1 |
| **Loss on n-contact** | 0.8 | 0.6 | - |
| **Loss on Mirror** | 5.6 | 4.5 | 18.0 |
| **Loss in ITO** | 3.6 | 6.8 | - |
| **Loss on p-contact** | 3.5 | 5.1 | - |
| **Loss in n-GaN** | 1.5 | 2.0 | 1.4 |
| **Loss in p-GaN** | 0.8 | 2.4 | 1.8 |

**Very conservative designs and parameters; Best values well above:**
**Nichia (Narakuwa et al. J. Phys. D. 43, 354002 (2010) EQE (IQE x LEE) = 86%**
**Soraa: LEE= 90% (Hurni et al., Appl. Phys. Lett. 106, 031101 (2015)**
**UCSB optimized PSS design for high LEE (Kuritzky et al., Opt. Expr. 25, 30696 (2017): LEE= 90+% range**

# PSS Fill Factor




**20% suffices to have quasi-full randomization**

**Very small dependence on pattern shape**

# Different ways to improve light extraction efficiency

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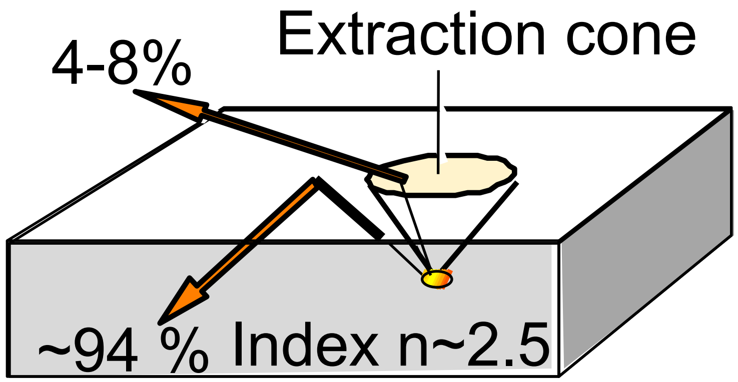
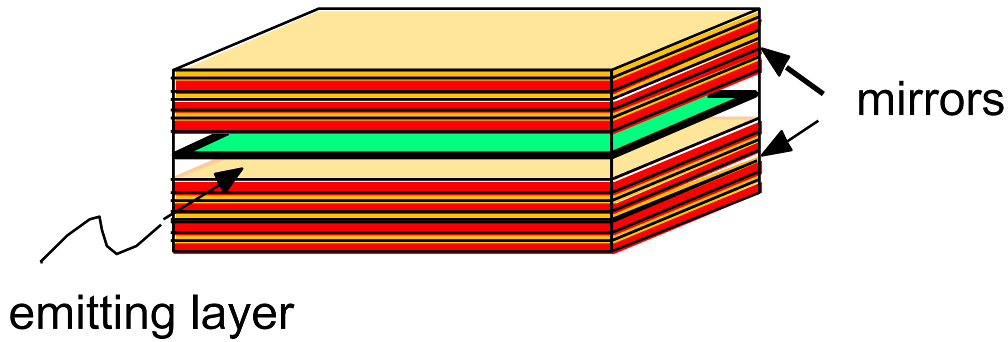
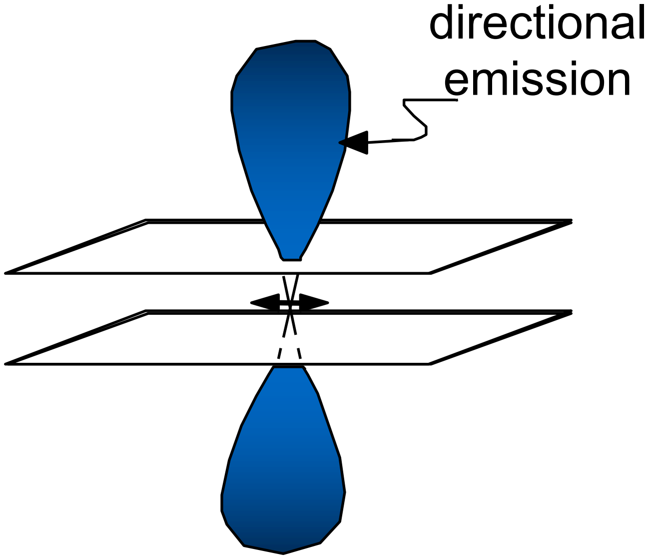
| Increased extraction efficiency by directional control of emission and propagation | Microcavity effects | Planar microcavities<br>Limit: 45% for nitrides, 70% for OLEDs<br>Photonic rsytals |

# Increasing through microcavity effects in LEDs



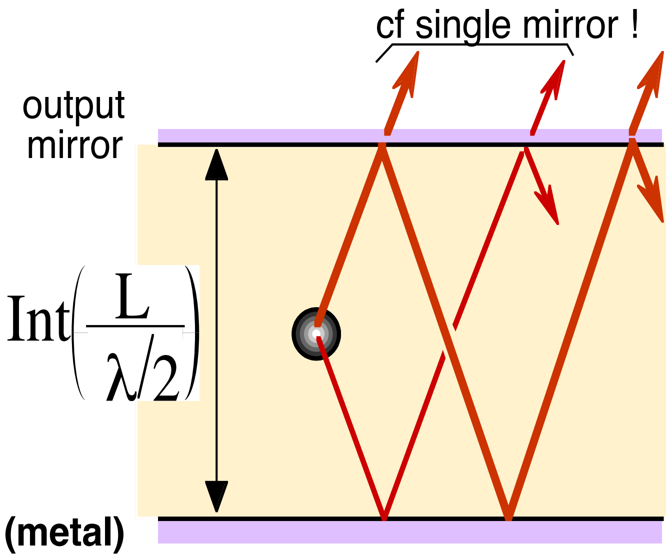




*Most of the light is trapped in the high index material*

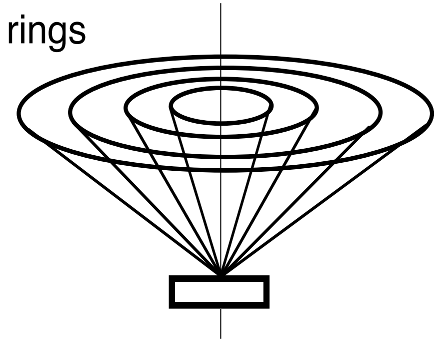


# Microcavity emission: atoms in a Fabry-Pérot resonator

Idea from ~1960 (**Kastler**, Schawlow&Townes), Applied Optics, 1, p.17 (January 1962)




$$m_c = \mathrm{Int}\left(\frac{L}{\lambda/2}\right)$$




For a point source :

( Fabry-Perot interf.) × (2-beam interf)

$$|E|^2 = |E_o|^2 \times \frac{T_1}{\left|1 - r_1 r_2 e^{2i\varphi}\right|^2} \times \left|1 + r_2 e^{2i\varphi'}\right|^2 = |E_o|^2 \times \frac{T_1}{\left|1 - r_1 r_2 e^{2i\varphi}\right|^2} \times 2\zeta(z,\theta)$$

Exaltation or Inhibition due to the modal structure of the whole cavity

Factor from 0 to 4 depending on the source location with respect to the mode antinodes at the considered angles

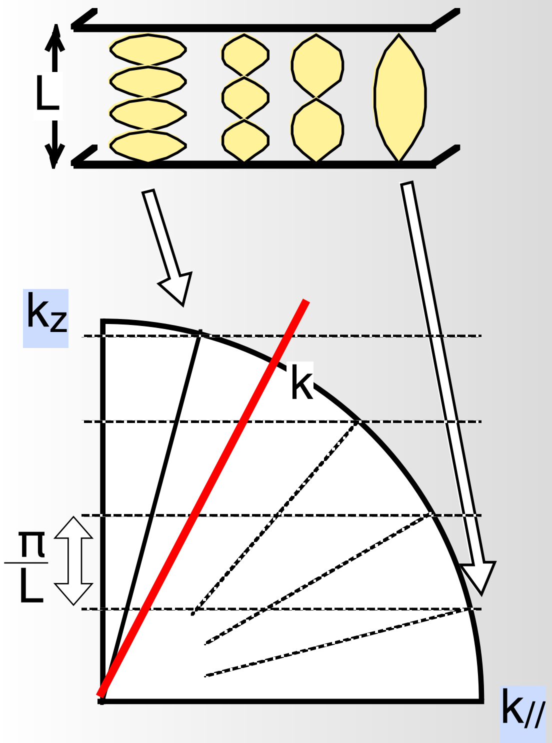
**Each mode carries the same power**
**Emission is as much concentrated in the resonant modes as it is suppressed in non-resonant ones**

# Cavity mode number in real cavities: $m_c$ cavity modes

### *ideal cavity*

$E = \sin(k_z z) \times \exp(i\, k_{//}\, x)$

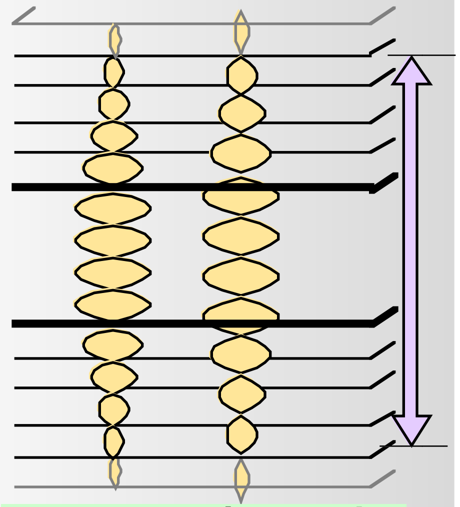
$k_z = \frac{\pi}{L}, \frac{2\pi}{L}, \frac{3\pi}{L}$, ...but < k




$m_C$ =4 in this example

$m_C = L/(\lambda/2)$ in general

### *symmetric DBR cavity*

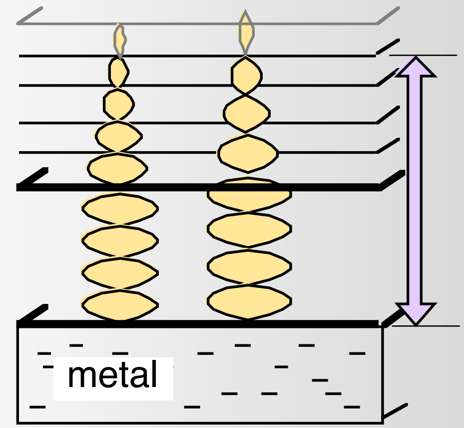


**two successive modes**

PENETRATION DEPTHs
(<=>  $\phi \neq 0$)
=> higher $m_C$

$m_C = L/(\lambda/2) + n/\Delta n$

### *asymetric cavity*



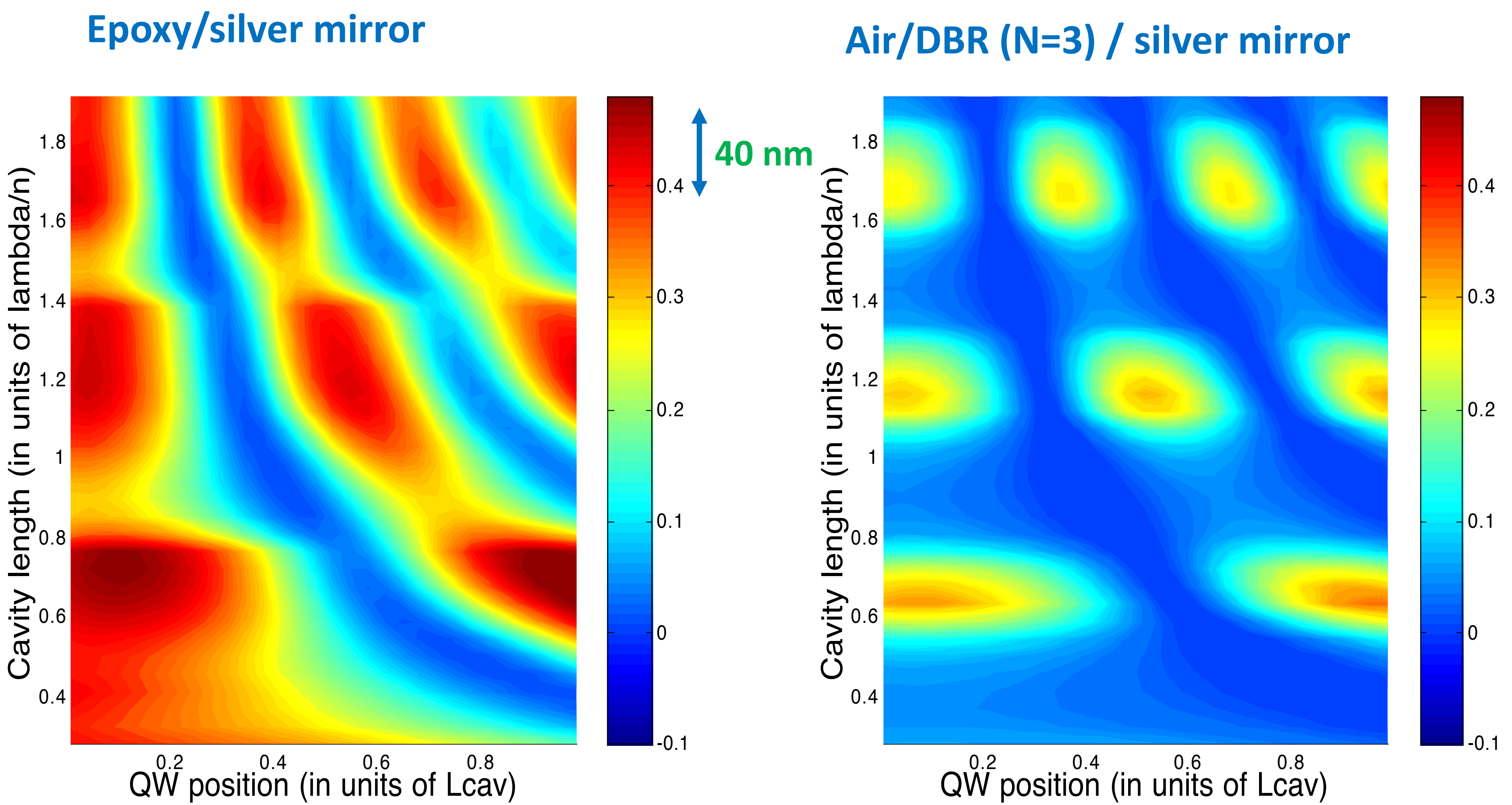

**two successive modes**

PENETRATION DEPTH

$m_C = L/(\lambda/2) + n/2\Delta n$

**In real microcavities, min. mode number 2 to 4**
**Efficiency 25-50%**

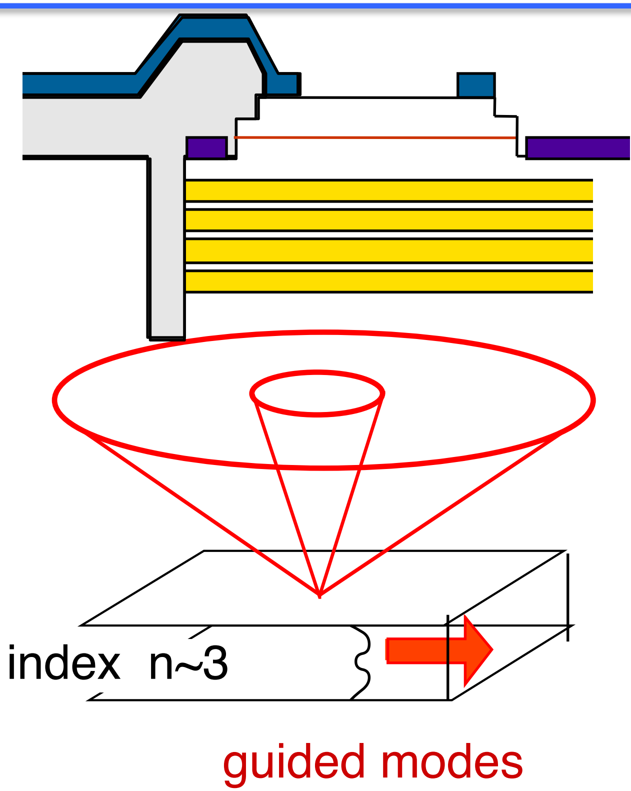
# GaN microcavity emitter modeling

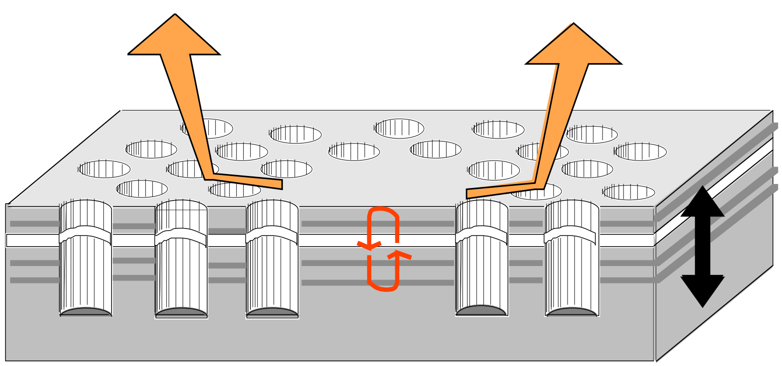



- **Required precision for thickness and QW position ~ 20nm**
- **Maximum LEE ~ 40% , however directionality**
- **Brightness x10**

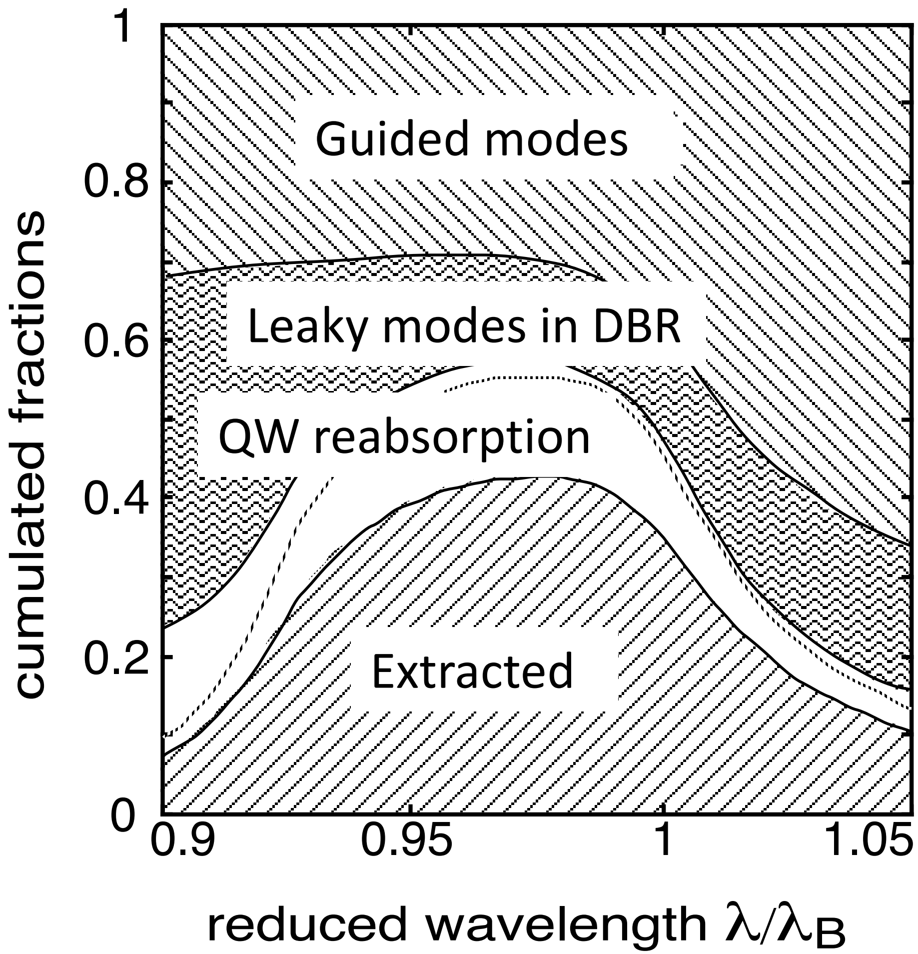
Weisbuch et al., Proceedings SPIE 5366, 1 (2004)
Benisty et al. IEEE J. Qu. Elect. 34, 1612 (1998)

# Where does the light go? How to extract it?



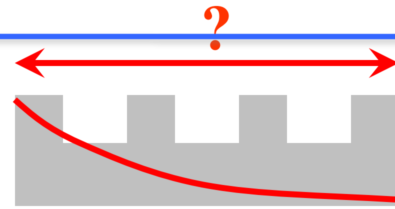
Where the light goes in a GaAs microcavity LED



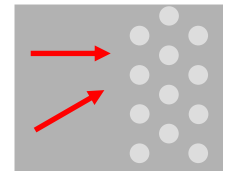

**Guided mode extraction by diffraction by gratings (photonic crystals)**

# Wish-list for efficient light extraction by photonic crystals

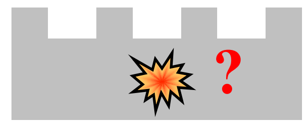
1. **Extraction length**



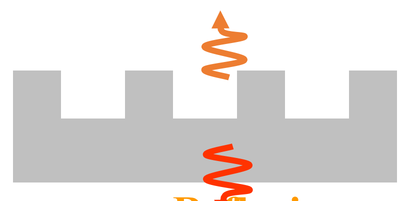

2. **Isotropy (or *omnidirectionality*)**



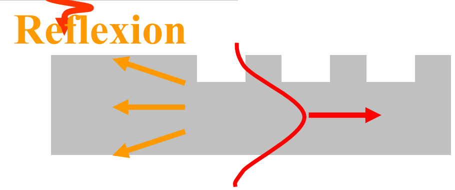
3. **Current injection**




4. **Air/substrate competition**



5. **Coupling of incoming light into PhC**

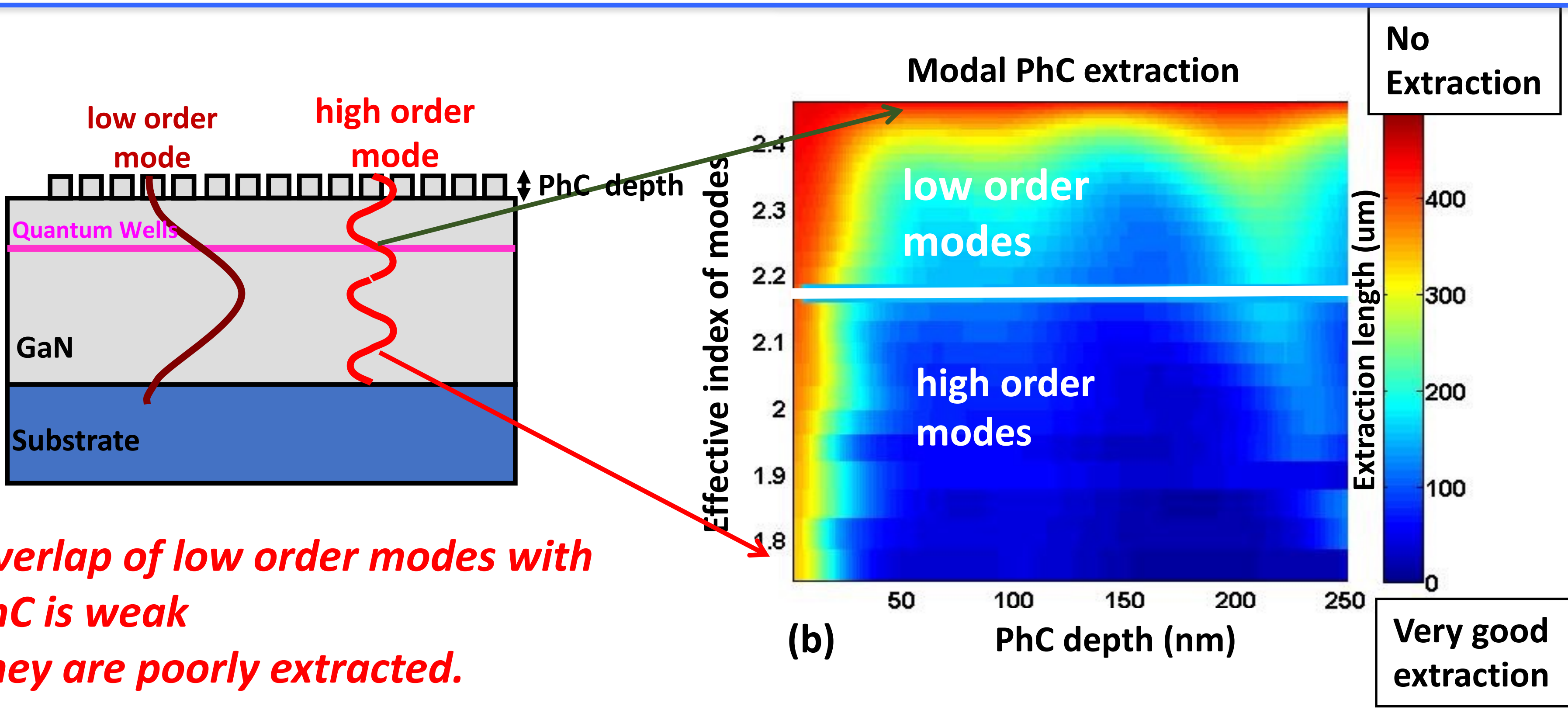



## Design opportunities

- **Vertical LED multi-layer design**
- **PhC thickness (etch depth)**
- **PhC symetry (triangular, square, higher order (Archimedean tiling, …)**

Design rules:
David et al., J.Displ. Technol.3, 133 (2007)

# Simulation of extraction length for top photonic crystals




***Overlap of low order modes with PhC is weak***
***They are poorly extracted.***

**Extraction lengths in the 100 micron range**

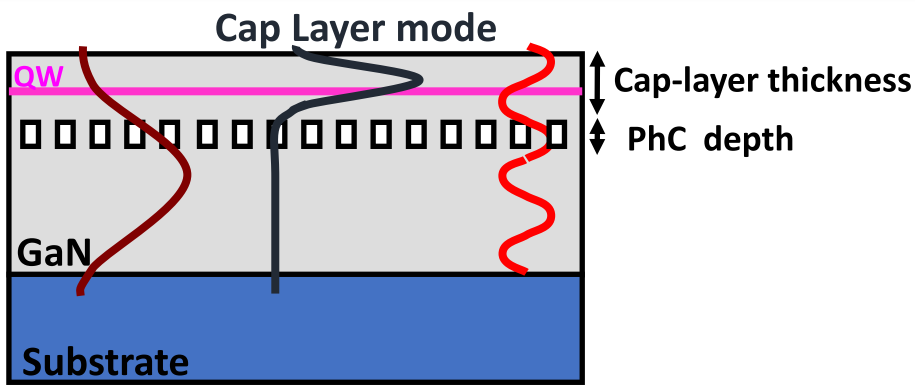
*Simulation of the extraction length for all the modes guided in the GaN slab versus the PhC depth.*

**Record efficiency 73% in air**

Design rules:
David et al., J.Displ. Technol.3, 133 (2007)

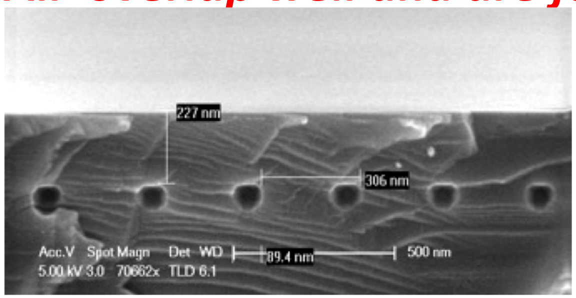
Wierer et al., NATURE PHOTONICS 3, 163 (2009)

# Simulation of extraction length embedded photonic crystals




*Embedded PhC LED with the profiles of low and high order modes.*

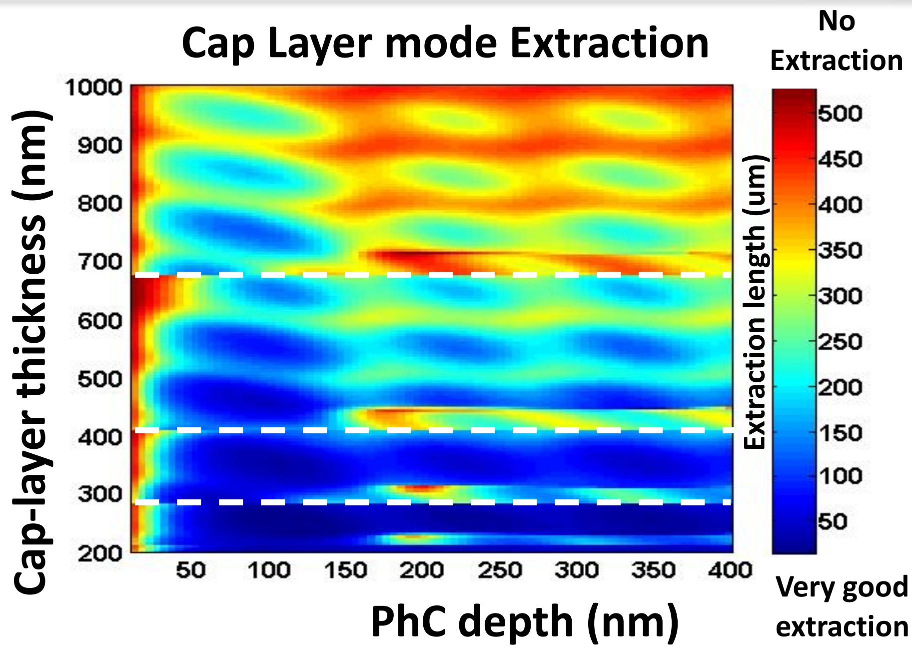
***All overlap well and are fast extracted.***



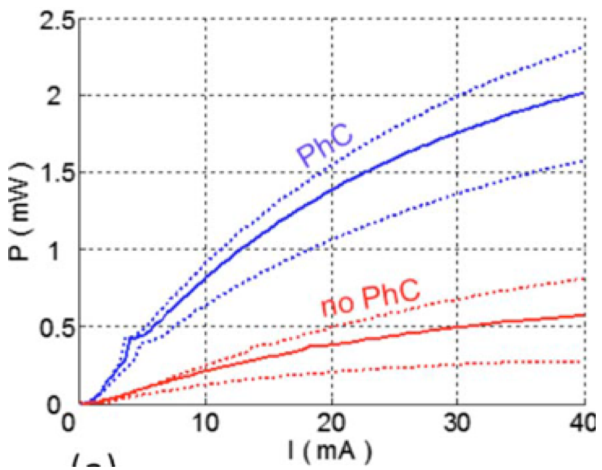

Extraction efficiency 94% in epoxy

All low order modes $L_{extraction}$ ~ 60-80 µm

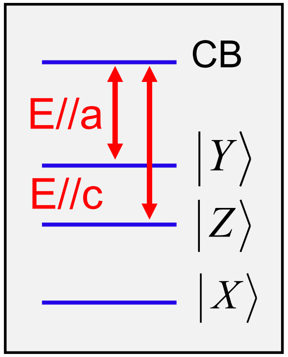
Matioli et al., *Appl. Phys. Lett.* **96**, 031108 (2010)

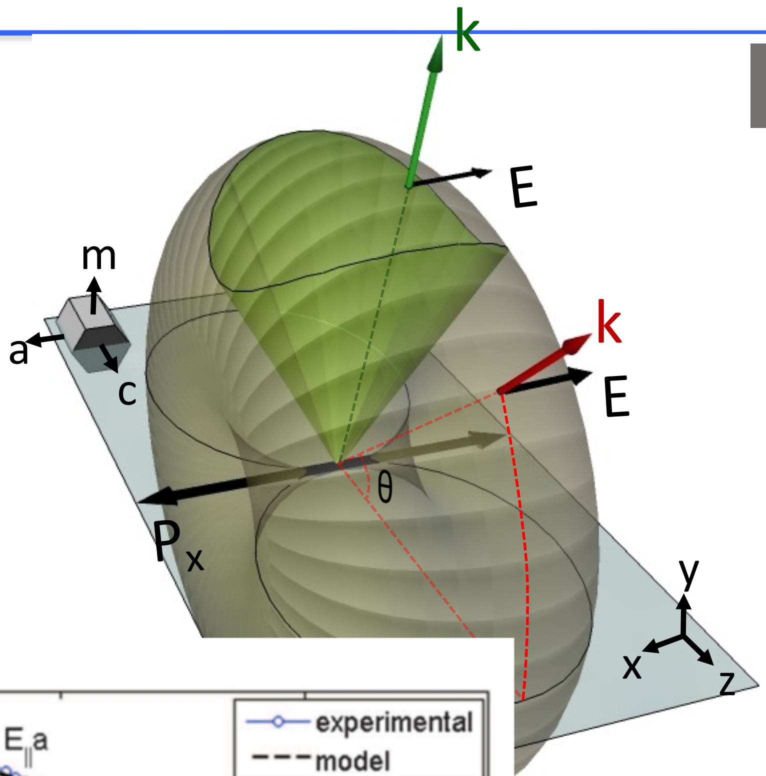


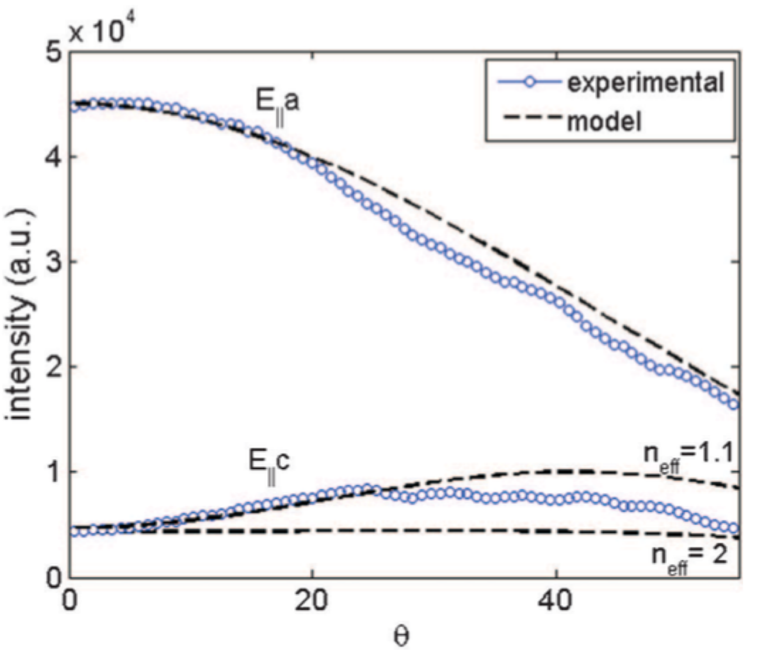

*Simulated embedded PhC extraction length versus cap-layer thickness and PhC depth*

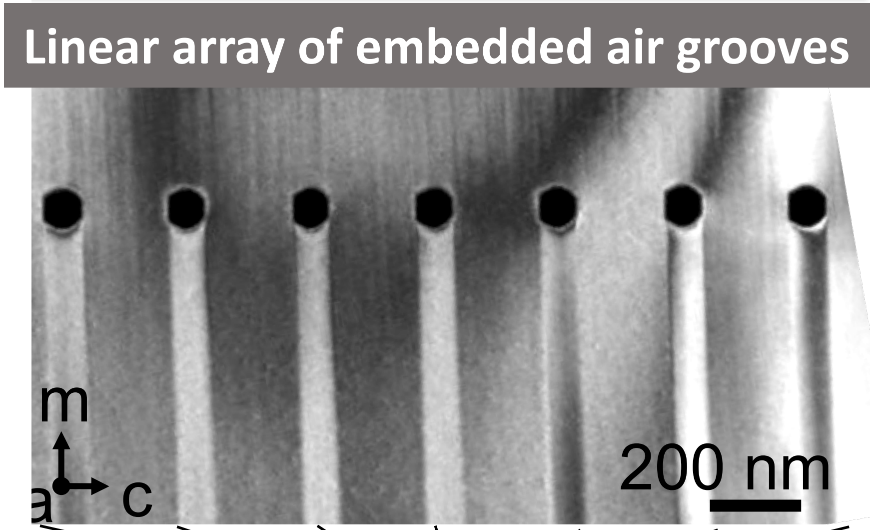


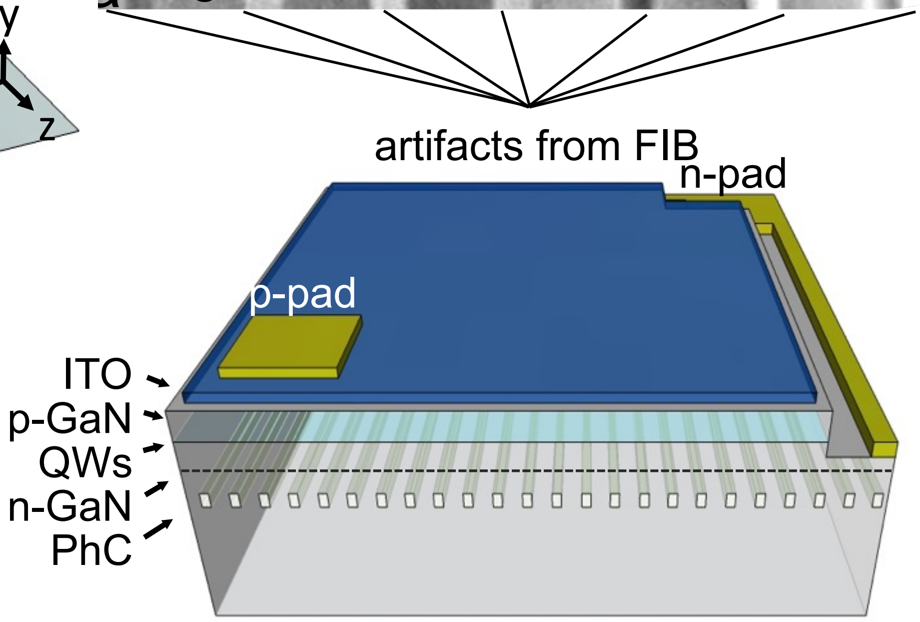
# Polarisation-preserving embedded PhCs for m-plane GaN




**High polarization ratio: ρ=88.7%**

# Different ways to improve light extraction efficiency

| Wished improvement | Idea | Realization |
| --- | --- | --- |
| Increased extraction efficiency by multiple ray escape attempts | Redirecting light rays | • Shaped susbstrates (with transparent substrates)<br>• Surface roughening/volume scatterers<br>• patterned substrate |
| Increased extraction efficiency by directional control of emissionand propagation | Microcavity effects | Planar microcavities<br>Limit: 45% for nitrides, 70% for OLEDs<br>Photonic crystals |

# … and internal quantum efficiency

| | | |
| --- | --- | --- |
| **Increase internal quantum efficiency by photon engineering** | **Purcell effect** | • **Microcavities**<br>• **Photonic crystals**<br>• **Plasmons**<br>• **Light-matter strong coupling (cavity-polaritons)**<br>• **3D cavities/micropillars** |

# The Purcell effect: controlling the spontaneous emission rate

## The spontaneous emission rate is given by Fermi's Golden Rule

$$\Gamma(\mathbf{r}) = \frac{2\pi}{\hbar}\left\langle(\mathbf{d}\cdot\mathbf{E}(\mathbf{r}))\right\rangle^2 \rho(\omega)$$

d is the electric dipole of the transition, **E** (**r**) is the local zero-point rms electric field, and $\rho(\omega)$ is the density of electro- magnetic modes

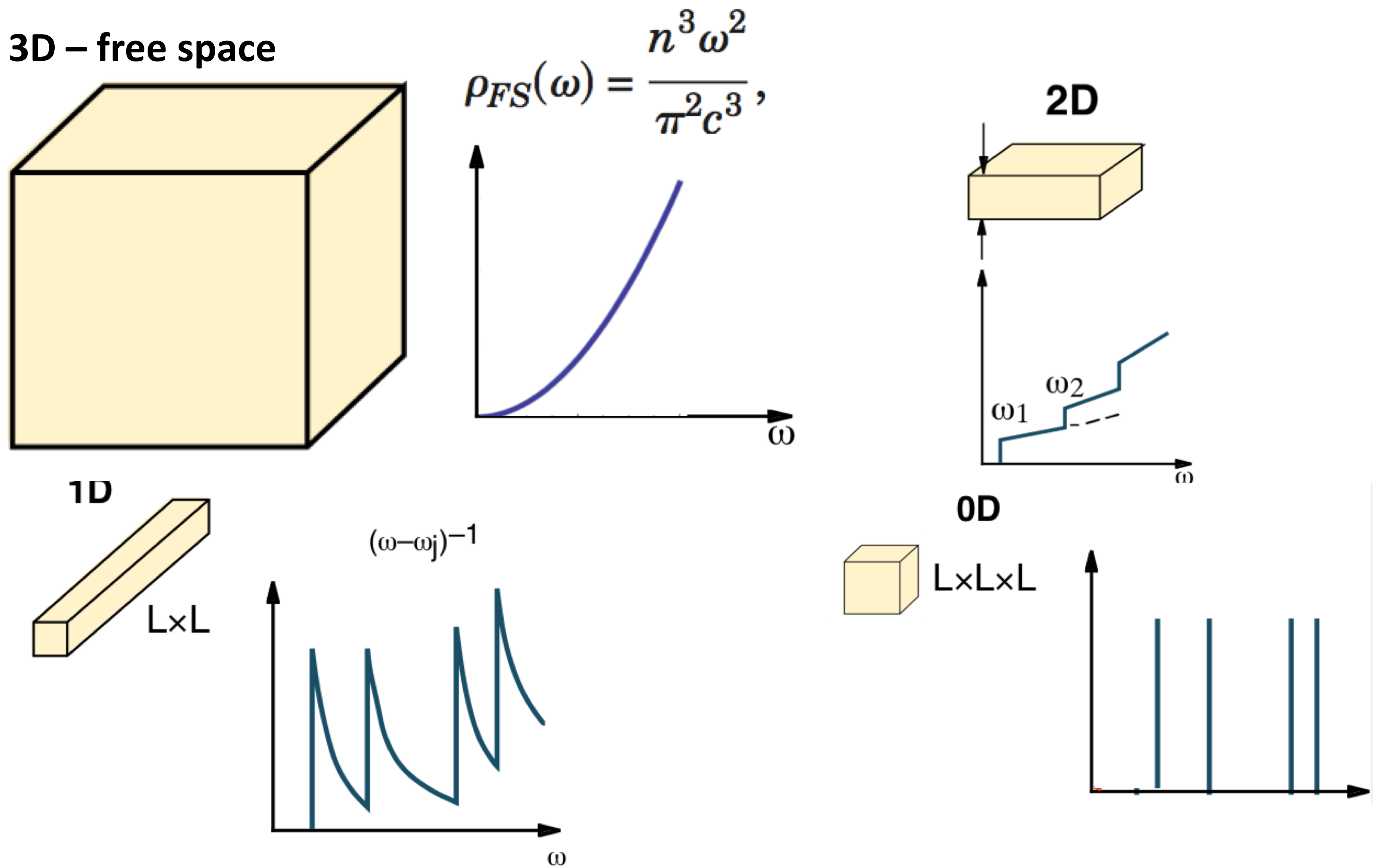
**When emitting species are subject to a modified electromagnetic environment, both E (r) and $\rho(\omega)$ can change. This is the *Purcell effect*.** The resulting modified emission rate $\Gamma_{mod}$(r) can be larger or smaller than $\Gamma$(r)

The relative change of rate is the ***Purcell factor***

$$F_p = \frac{\Gamma_{mod}(r)}{\Gamma(r)}$$

# The photon density of states

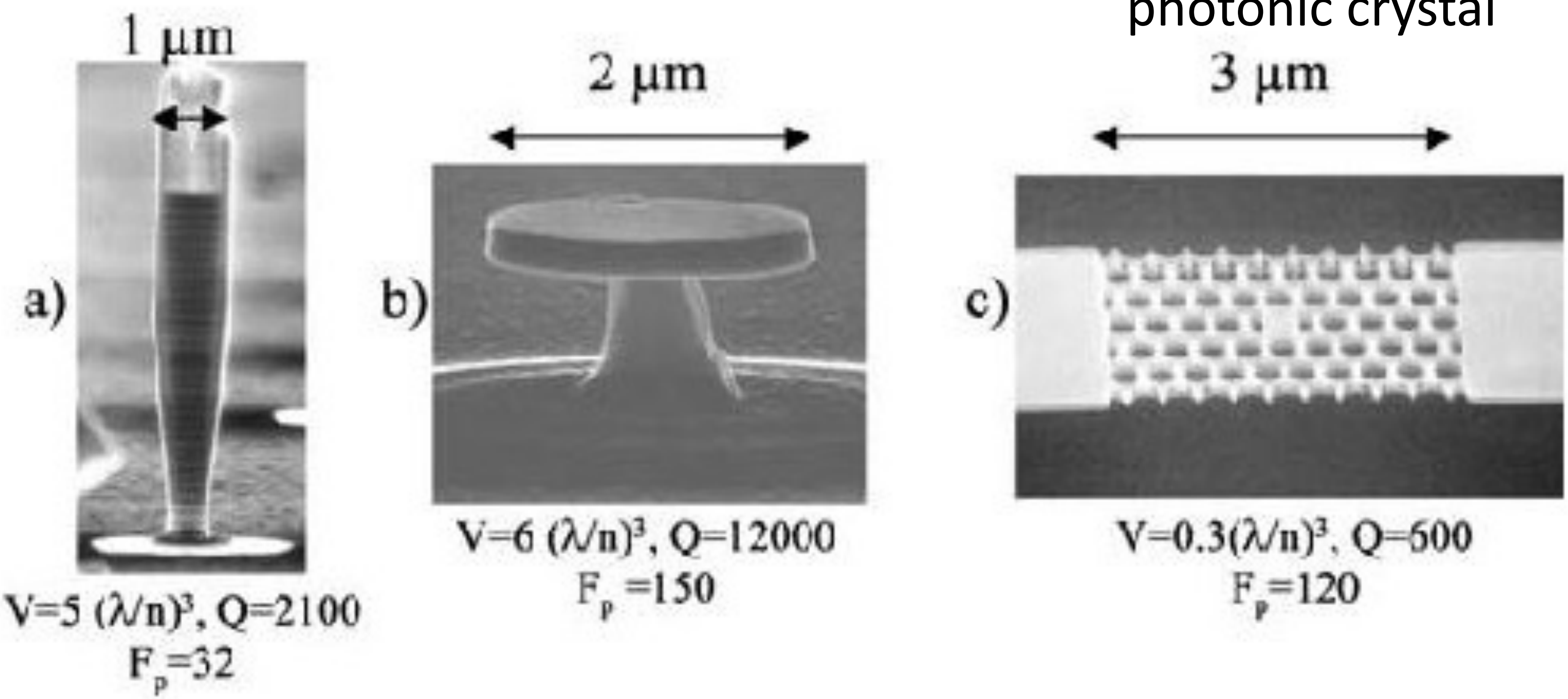
$$\rho_{FS}(\omega) = \frac{n^3\omega^2}{\pi^2 c^3},$$




Only 1 D photonic wires and better 0D microcavities are expected to significantly modify spontaneous emission rate through the Purcell effect

# Various types of microcavities with quantum dots

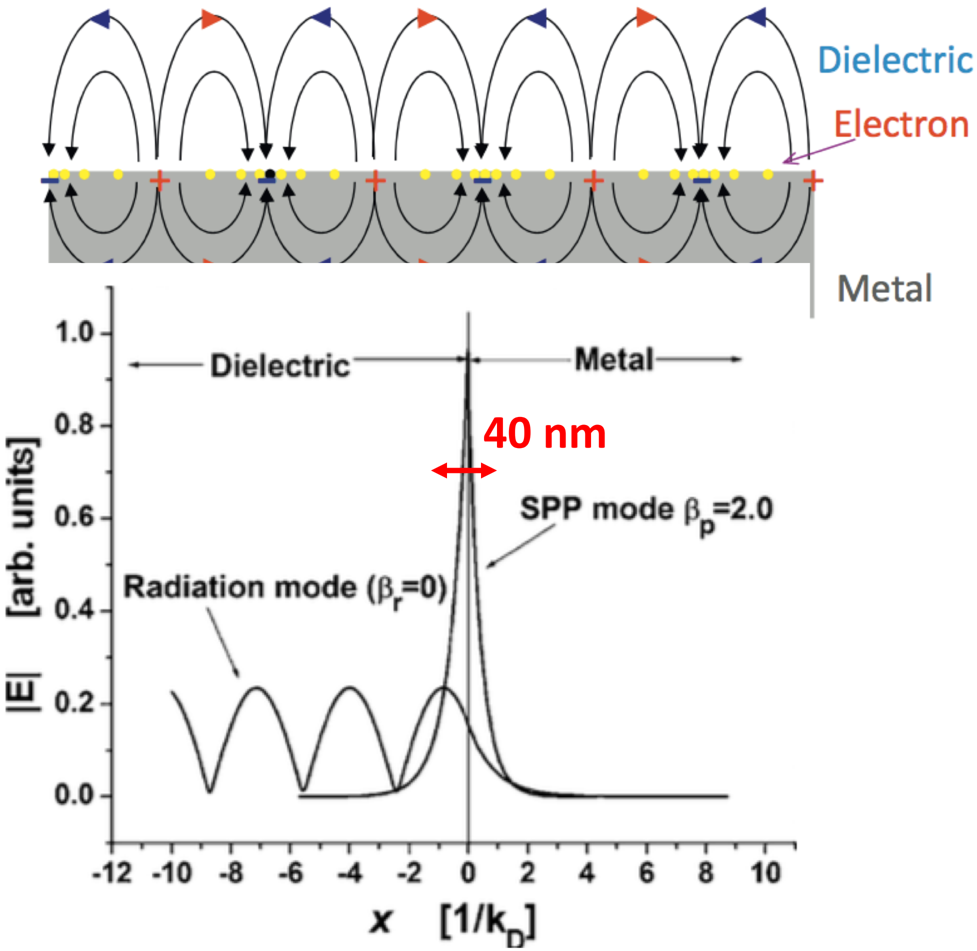
micropillar | microdisk | Point defect in photonic crystal




**But active volume is very small: good for single photon emitters (quantum cryptography sources), not for SSL**

# Surface plasmons (SPs) and the Purcell effect

## SPs are EM waves propagating along the interface are very localized




Profiles of electric field for SPP and radiation modes.

Khurgin et al., 1968 J. Opt. Soc. Am. B24, 1968 (2007)

The SP resonance wavelengths are (220 nm, 430 nm), 540 nm) for Al/GaN, Ag/GaN, and Au/GaN interfaces, respectively..

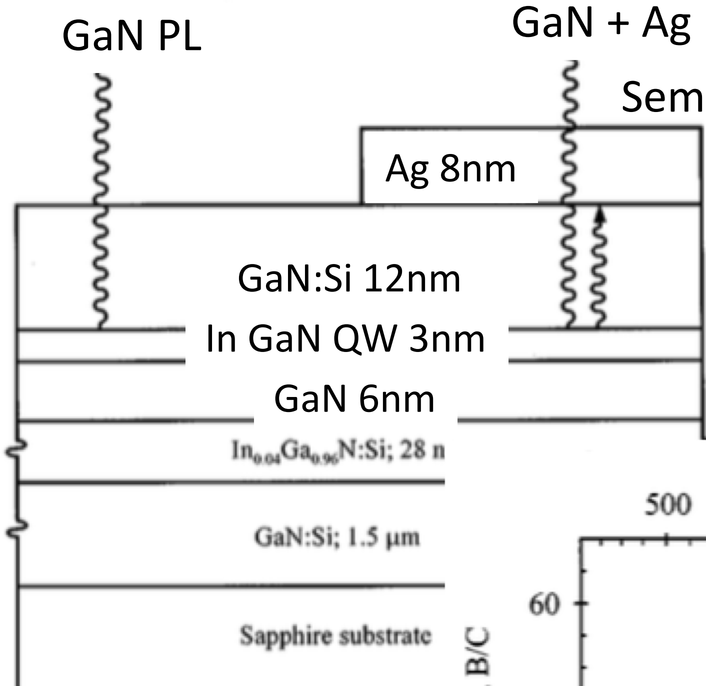
**If you put a light source in the electric field of SPs (within 10-30nm from a metal), light will be emitted as SPSs due to their high local electric field.**

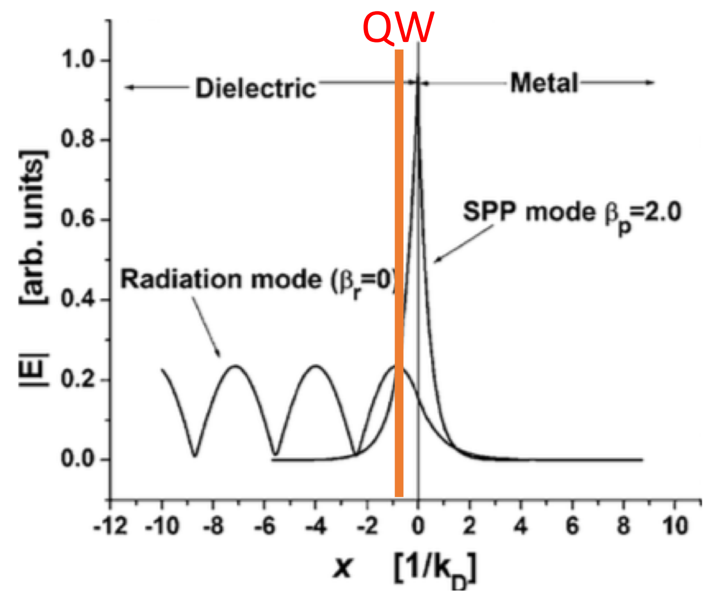
**The SPs act as a loss mechanism in OLEDS as emitting layers are very near injecting metal contacts.**

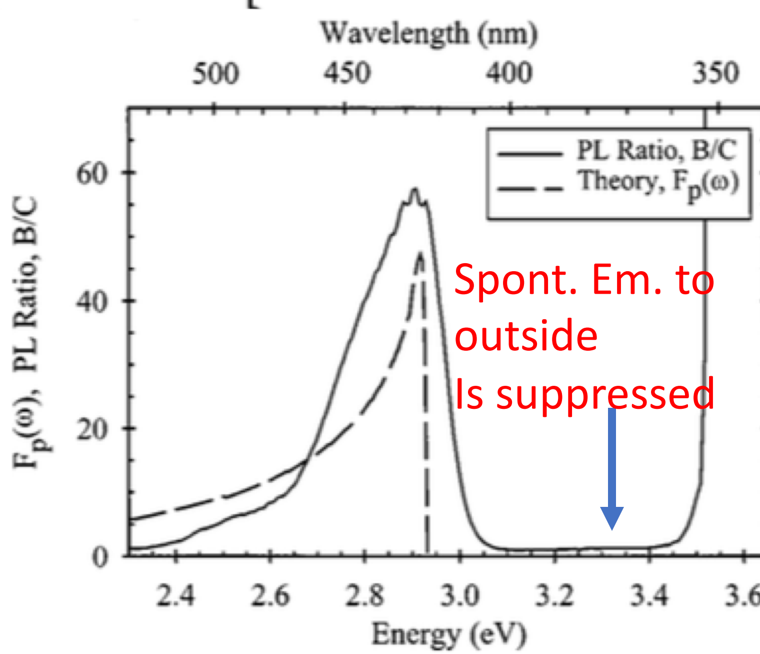
An approach to **use beneficial effects of SPs** is to use them to beat non-radiative recombination due to their high photon energy density which captures the rcombination of e-h pairs

# Surface plasmons (SPs) and the Purcell effect

Not so new story: Gontijo et al., PRB 60 11 564 (1999)




Due to coupling of QW with Ag SPs all recombination occurs through transfer of e-h energy to SPs.

**No light is to be seen as planar SPs do not radiate.**

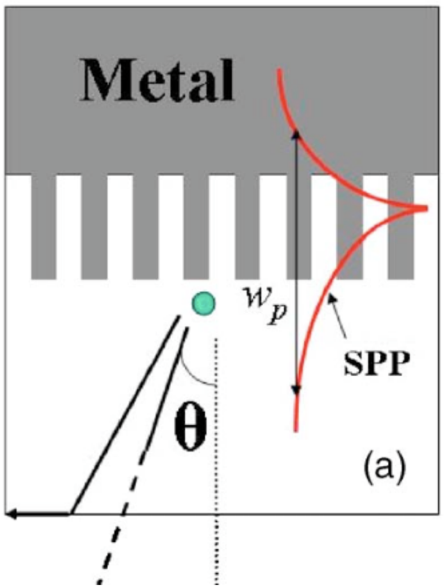
**This is what happens in OLEDs**

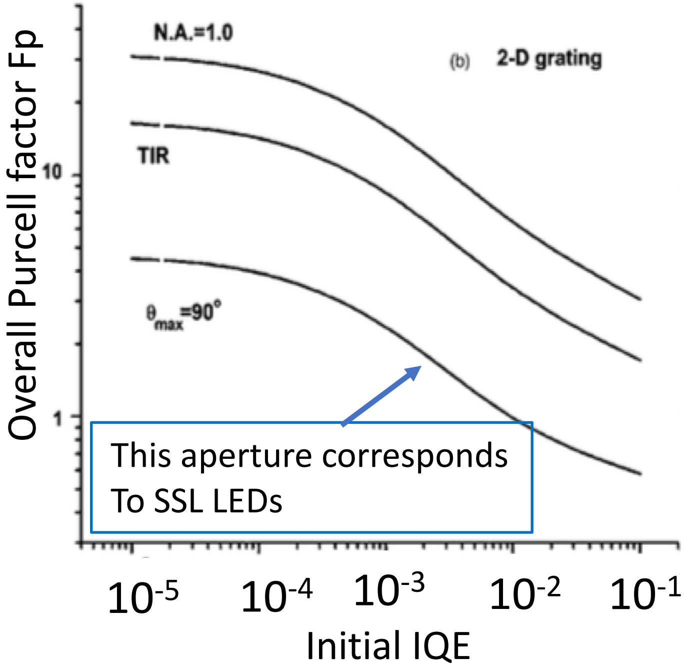
# Objective: use surface plasmons to increase LED efficiency

# How to get photons back from surface plasmons ?

**Use a grating to diffract SPs away from interface**

**Overall efficiency** is represented by the overall Purcell factor, the result of **efficiency transfer to SPs**, competing with NR recombination of semiconductor, and of **radiative efficiency of SPs**.




**When initial efficiency is larger then 10%, due to losses of SPs before extraction from the metal, the Purcell factor is unity (or less)**

Khurgin *et al.* J. Opt. Soc. Am. B 24 (2007) 1968

# Summary

- Nitride (and other inorganic) semiconductors reach **ultimate LEE performance through light randomization techniques**, either disorder or shaped substrates or both
- Losses are minimized because **light travels about 3 roundtrips** before escaping
- Losses can diminish with **improved designs and materials**
- Other techniques based on **mode manipulation** (instead of mode destruction) are **less effective** as either light travels too much in the LED (microcavities and photonic crystals) or interact too much with metals and their losses (surface plasmons).
- However these techniques can provide **better directionality** or **polarization conservation** (in the case of polarized emission, as for m-plane grown LEDs).

# Comparison with OLEDs (view from the enemy?)

- Due to **large thickness**, inorganic LEDs avoid metal losses (due to proximity of SPs to emitting layer in OLEDs). Light only undergoes reflection losses on metals (effect of bulk plasmons). Ray-tracing simulations perform well as thickness is much larger than wavelength.

- Only two guiding layers in inorganic LEDs to deal with. **Disorder at either outer surfaces or at interface will randomize light rays**. There are no intermediate layer guided modes, like in OLEDs, which do not feel disorder. Growth on disordered substrate is not perturbed by surface roughening due to the thick buffer layers grown before active layers (actually IQE is improved). In contrast. OLED growth on roughened substrate is not possible: the thin multilayers would be disrupted.

- Thanks to the high enough materials lateral conductivity, **electrode area** is a small fraction of inorganic LED area, diminishing losses on contacts

- The **higher index of inorganics** seems at first a nuisance as direct extraction is much lower. However the same **higher index of inorganics** is very effective in randomizing a large fraction of unextracted rays. There is no need to include diffusing particles as in some OLEDs.