Resonant cavity light emitting diodes

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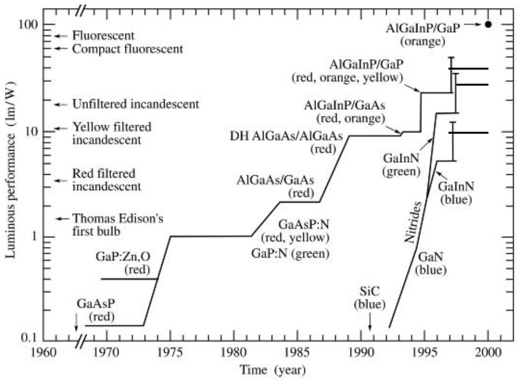
Outline

- Introduction and history
- Spontaneous emission from resonant cavities
  - modification of spontaneous emission
  - reflectors
  - optical mode density in a one-dimensionsl resonator
  - spectral and integrated emission enhancement
- Resonant cavity light emitting diodes
  - RCLED design rules
  - AlGaInP/GaAs RCLED (650nm)
  - GaN/AlGaN RCLED (510-570 nm)
- Conclusion
- Acknowledgements

Improvement in visible LED efficiency over the last forty years



efficiency improvements of 10x/decade over this timeframe

LED and RCLEDs

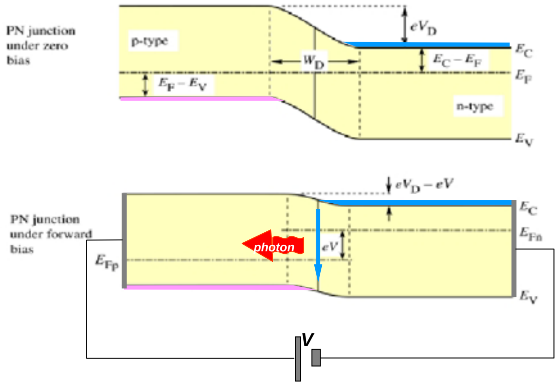
LED

RCLED

Resonant cavity LED (RCLED)
Vertical cavity LED (VCLED)
Microcavity LED (MCLED)

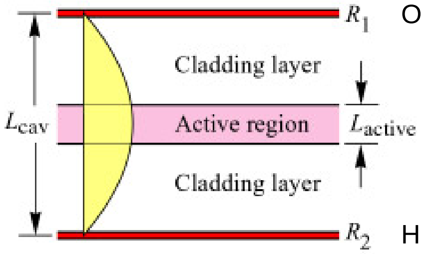
→ **Surface emitter with forward-directed radiation**

LED – basic electrical properties



What´s a Resonant Cavity LED?

Schematic illustration of a resonant cavity



Output mirror

High reflecting mirror

The cavity length L_{cav} is equal to $\lambda/2$

Advantages of RCLEDs

Resonators provide LEDs with laser-like performance

Superior to conventinal LEDs in :

- **luminous intensity**
- **high directionality**
- **spatial coherence**
- **spectral purity (less chromatic dispersion)**
- **modulation capabilities**

in comparison to laser light sources

- **less temperature sensitive**
- **longer life time (~ 30 000 h)**

Applications

Key technology for next generation of data communication via polymethyl methacrylate (PMMA) plastic optical fiber (POF) in local networks for in-home multimedia

- narrow-band services like phone or home automation

- broadband services based on the POF IEEE1394b standard known as “Firewire” or “i-link” or digital TV, PCs, DVD and Internet

- automotive applications (media orientated system transport (MOST))

Plastic optical fiber (POF)

POF advantages over copper cables (22.5 Mbit/s):
- Immunity to EM and RF interference
- Absence of crosstalk between fibres
- Complete electronic isolation
- Higher data transmission capability (500 Mbit/s)
- Small size and light weight

POF compared to glass fibers:
- Lower costs
- More reliable and vibration tolerant fibre connectors
  (core diameter typically 0.5 - 1 mm)
- Easier installation and handling

POF – large core with good flexibility

Plastic Optical Fiber

- Large Core: Up to 1mm
- Large Connecterization Tolerance
- Polishing-Free
- Flexible
- High N.A.

Glass Optical Fiber

- Small Core: Up to 62.5µm
- Small Connecterization Tolerance
- Polishing
- Brittle & Fragile
- Low N.A.

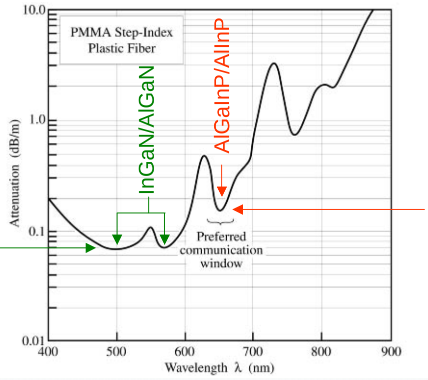

POF
Polymer Core
Polymer Clad

GOF
Silica Core
Silica Clad

Attenuation of a PMMA step-index plastic optical fiber

(PMMA polymethyl methacrylate)

Silica fiber:
0.15 dB/km
(1.55 µm)



70 dB/km
(510 nm, 570 nm)

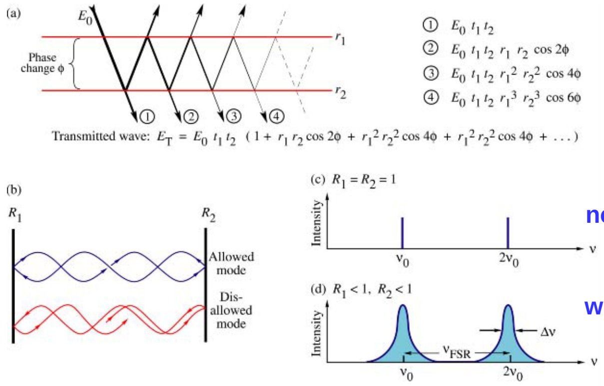
150 dB/km
(650 nm)

Wavelength	525 nm	560 nm	650 nm
Material dispersion	700 ps / (nm km)	500 ps / (nm km	320 ps / (nm km)

Spontaneous emission from resonant cavities

Fabry-Perot resonator

(for the electric field amplitude E_0)



ϕ...change of phase for single pass

no mirror losses

with mirror losses

Fabry-Perot cavities

T **transmittance through FP-cavity:**

$$T = \frac{T_1\, T_2}{1 + R_1 R_2 - 2\sqrt{R_1 R_2}\cos 2\phi}$$

F **finess of FP cavity:**

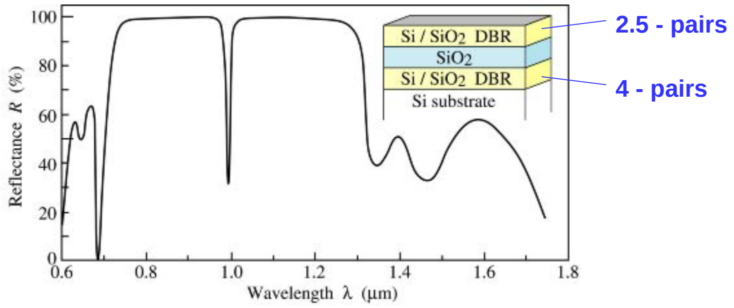
$$F = \frac{\text{Peak separation}}{\text{Peak width}} = \frac{\pi}{2\,\phi_{1/2}} = \frac{\pi\,\sqrt[4]{R_1 R_2}}{1-\sqrt{R_1 R_2}} \approx \frac{\pi}{1-\sqrt{R_1 R_2}}$$

Q **quality factor of FP cavity:**

$$Q = \frac{\text{Peak frequency}}{\text{Peak width}} = \frac{2nL_c}{\lambda}\,\frac{\pi\,\sqrt[4]{R_1 R_2}}{1-\sqrt{R_1 R_2}} \approx \frac{2nL_c}{\lambda}\,\frac{\pi}{1-\sqrt{R_1 R_2}}$$

$$\boxed{Q = \frac{2nL_c}{\lambda}\,F}$$

Reflectance of a microcavity of two Si/SiO_2 reflectors and a SiO_2 center region

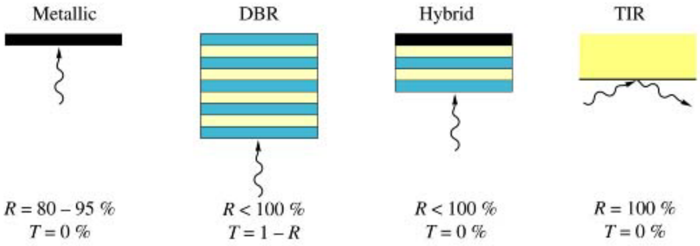


2.5 - pairs

4 - pairs

- **the resonance wavelength of the cavity is ~ 1.0 µm**
- **R > 0 at resonance due to unequalness of the reflectivities of mirrors**

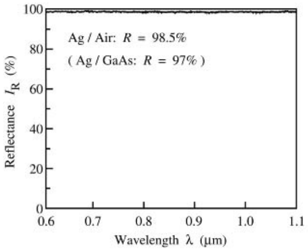
Reflectors



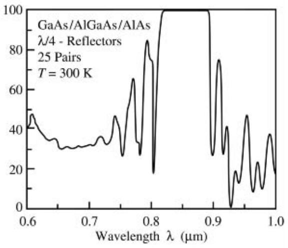
TIR ... Total internal refector

Metallic and distributed Bragg reflectors

Metallic mirror



Bragg reflector (DBR)



$$R_{DBR} = |r_{DBR}|^2 = \left(\frac{1 - \left(\frac{n_1}{n_2}\right)^{2m}}{1 + \left(\frac{n_1}{n_2}\right)^{2m}} \right)^2$$

$$\Delta\lambda_{stop\,band} = \frac{2\,\lambda_{Bragg}\,\Delta n}{\pi\, n_{eff}}$$

Distributed Bragg Reflector (DBR)

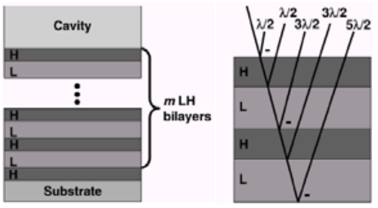


Figure 1. (a) Distributed Bragg reflector (DBR) structure using a high-refractive-index quarter-wave layer on the substrate followed by m low-index/high-index (LH) quarter-wave bilayers. (b) Relative phases at the DBR surface of light rays reflected from each interface within the DBR structure. The minus sign indicates the 180° phase shift that occurs upon reflection from a low- to high-index surface. A round-trip pass through each quarter-wave layer results in a half-wave phase shift. Every reflected ray returns to the DBR surface shifted by exactly 180° in phase. All reflected electric fields thus add constructively to give a high net reflectance for the DBR, even if individual interface reflectances are small.

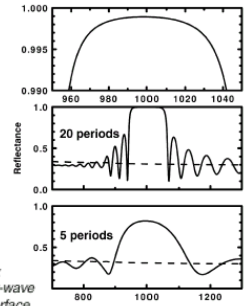
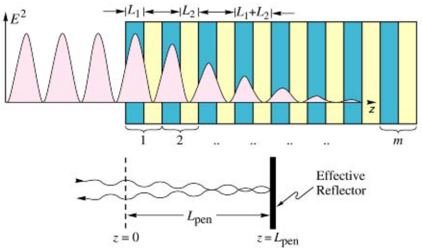


Figure 2. Reflectance spectrum in air of a 1000-nm GaAs/AlAs DBR for 20 periods and 5 periods (lower two plots). Dashed lines show the reflectance from a bare GaAs substrate. Top plot shows the high-reflectance region of the 20-period mirror near the design wavelength.

DBR penetration depth L_{pen}

in DBRs the opt. wave penetrates into the reflector by one or several quarter-wave pairs



$$r_{DBR} \approx |r_{DBR}| e^{-2i(\beta-\beta_{Bragg})L_{pen}}$$

$$r_{metal}(z=0) = |r_{metal}| e^{2i(2\pi/\lambda)L_{pen}}$$

$$L_1 = \frac{\lambda_{Bragg}}{4n_1} \qquad L_2 = \frac{\lambda_{Bragg}}{4n_2} \qquad L_{pen} \approx \frac{L_1+L_2}{4}\,\frac{n_1-n_2}{n_1+n_2}$$

Optical mode density in a one - dimensional resonator

spontaneous recombination probability:

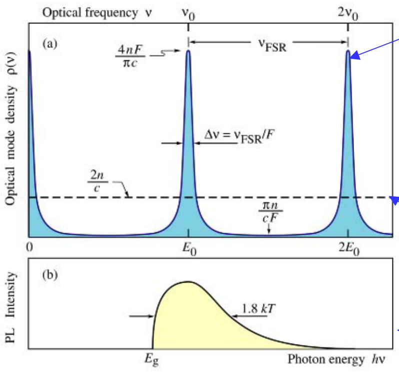
$$W_{spont} = \tau_{spont}^{-1} = \int_0^\infty W_{spont}^{(l)}\,\rho(\nu_l)\,d\nu_l$$

optical mode density:

$$\rho^{1D}(\nu) = \frac{2n}{c} \qquad \text{(1D space)}$$

$$\rho(\nu) = \frac{(R_1R_2)^{3/4}}{T_1T_2}\,\frac{4n}{c}\left(1-\sqrt{R_1R_2}\right)T(\nu) \qquad \text{(FP cavity)}$$

Optical mode density



One-dimensional planar microcavity

$$\nu_0 = \frac{c}{2n\,L_{cav}}$$

$$\rho_{\max} \approx \frac{4}{\pi}\frac{n}{c}F$$

$$\rho_{\min} \approx \frac{cn}{\pi}\frac{1}{F}$$

homogeneous one-dimensional space

luminescence spectrum of bulk semiconductor

Spectral emission enhancement at λ_{res}

average emission rate enhancement at the λ_{res} out of both reflectors:

$$G_e = \frac{\rho_{\max}}{\rho^{1D}} \approx \frac{2}{\pi}F \approx \left(\frac{2}{\pi}\right)\frac{\pi\left(R_1R_2\right)^{1/4}}{1-\sqrt{R_1R_2}}$$

emission rate enhancement out of one single reflector R_1:

$$G_e \approx \frac{2(1-R_1)}{2-R_1-R_2}\frac{2F}{\pi} \approx \frac{1-R_1}{1-\sqrt{R_1R_2}}\frac{2F}{\pi} \approx \left(\frac{2}{\pi}\right)\frac{\pi(R_1R_2)^{1/4}(1-R_1)}{\left(1-\sqrt{R_1R_2}\right)^2}$$

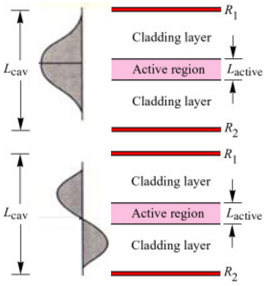
standing wave effect – distribution:

$$\boxed{G_e = \frac{\xi}{2}\left(\frac{2}{\pi}\right)\frac{\pi(R_1R_2)^{1/4}(1-R_1)}{\left(1-\sqrt{R_1R_2}\right)^2}\frac{\tau_{cav}}{\tau}}$$

$\frac{\tau_{cav}}{\tau} \geq 0.9$ **....ratio of lifetime with cavity to lifetime without cavity**

standing wave effect – distribution:

ξ ...antinode enhancement factor



ξ = 2 if the active region is located exactly at an antinode

ξ = 0 if the active mode is located at a node

ξ= 1 if the active mode is smeared out over many periodes of the standing wave

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Integral emission enhancement

***On resonance*, the emission is enhanced along the axis of the cavity. However, sufficiently far *off resonance*, the emission is suppressed.**

The integrated enhancement ratio (or suppression ratio) can be calculated analytically by assuming a gaussian natural emission

$$\boxed{G_{\text{int}} = G_e \sqrt{\pi \ln 2}\, \frac{\Delta\lambda}{\Delta\lambda_n}}$$

Example: R_1=90%, R_2=97%, $\xi=1.5, \frac{\tau_{cav}}{\tau} \sim 1$ ⟶ F=46, G_e=68

with $\Delta\lambda_{cav}$ =6.5 nm, $\Delta\lambda$ = 31 nm ⟶ G_{int}= 13

Experimental enhancement factor ~ 5

RCLED design rules

First design rule

Light-exit mirror should have lower reflectivity than back mirror

$$R_1 << R_2$$

Second design rule

Use shortest possible cavity length L_{cav}, typical,

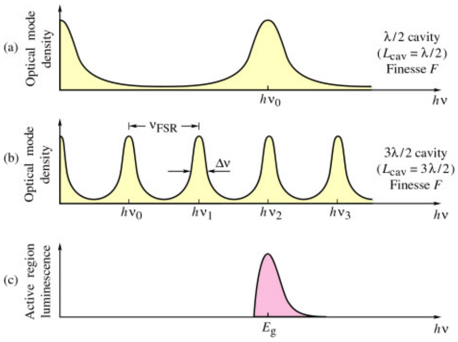
$$L_{cav} = \frac{\lambda}{2}$$

Third design rule

Absorption loss in active region should be smaller than the mirror loss of the light-exit mirror

$$2\,\xi\,\alpha\,L_{cav} < (1 - R_1)$$

Second design rule



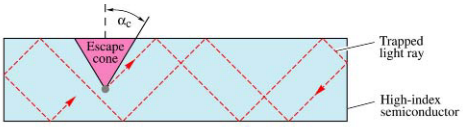
short cavity

long cavity

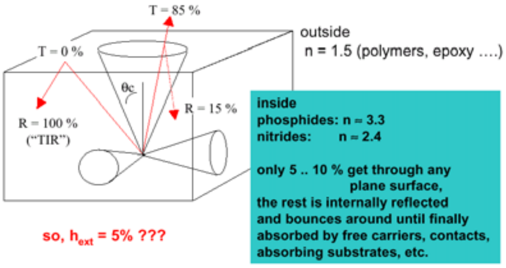
spontaneous emission of an LED

$$G_{\text{int}} = \frac{\xi}{2}\frac{2}{\pi}\frac{1-R_1}{1-\sqrt{R_1R_2}}\sqrt{\pi\ln 2}\,\frac{\lambda}{\Delta\lambda_n}\frac{\lambda_{cav}}{L_{cav}}\frac{\tau_{cav}}{\tau}$$

Extraction cone



slabs of high refractive index material act as ***photon traps***



outside
n = 1.5 (polymers, epoxy ….)

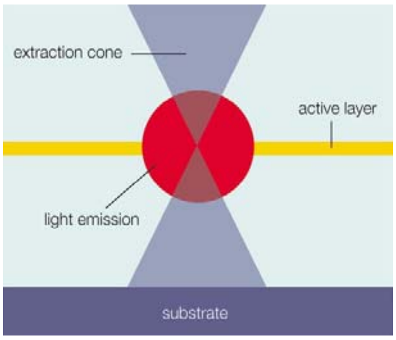
inside
phosphides: n ≈ 3.3
nitrides: n ≈ 2.4

only 5 .. 10 % get through any plane surface,
the rest is internally reflected and bounces around until finally absorbed by free carriers, contacts, absorbing substrates, etc.

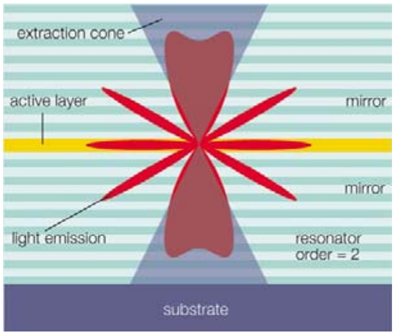
so, h_{ext} = 5% ???

Spontaneous emission in LEDs and RCLEDs

isotropic spontaneous emission



tailored spontaneous emission



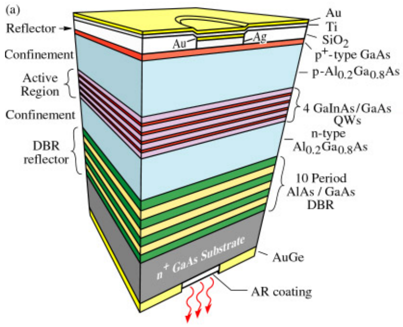
GaInAs/GaAs RCLEDs

(~ 910 nm)

GaInAs/GaAs RCLED

(AlAs/GaAs DBR and Ag top reflector)

Schematic structure

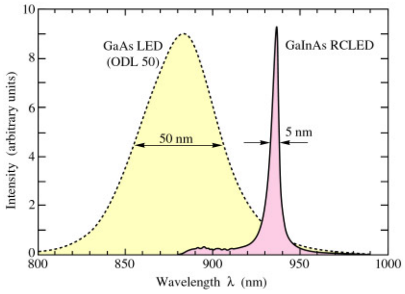


Picture of the first RCLED

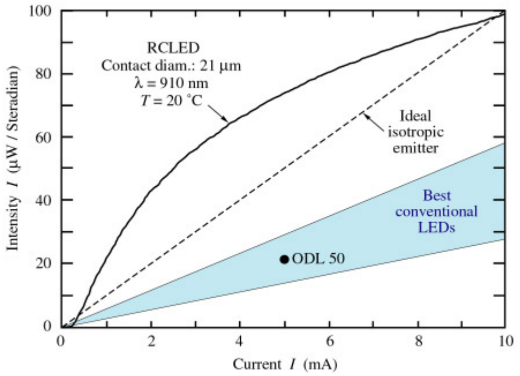
E.F. Schubert et al. (1994)

Comparison of emission spectra

GaAs LED emitting at 870 nm (AT&T ODL 50) and an GaInAs RCLED emitting at 930 nm



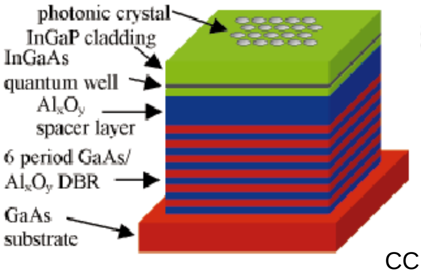
Light versus current curves of GaInAs/GaAs LEDs

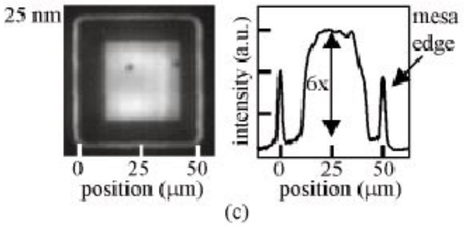


RCLED: saturation effects due to carrier overflow and heating

Photonic crystals

LED mesa containing a triangular photonic crystal schematic!.





CCD images of a photonic crystal centered within a LED mesa at various wavelengths.

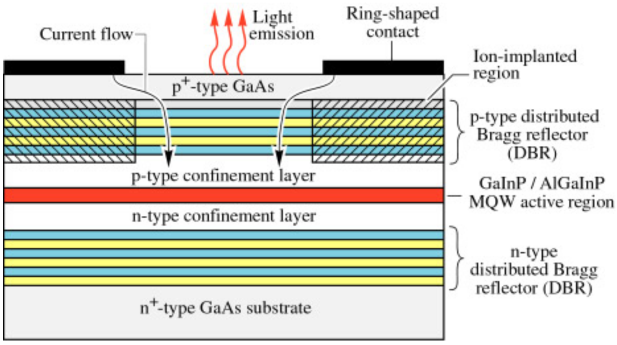
Sixfold intensity enhancement near λ ~ 925 nm.

AlGaInP/GaInP RCLED

(~ 650 nm)

GaInP/AlGaInP/GaAs MQW RCLED emitting at 650 nm

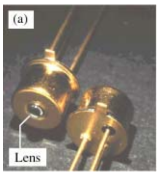
Schematic structure



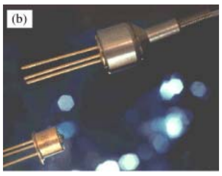
AlGaInP/GaAs RCLED emitting at 650 nm

(Mitel Corp., Sweden)

TO packaged RCLED

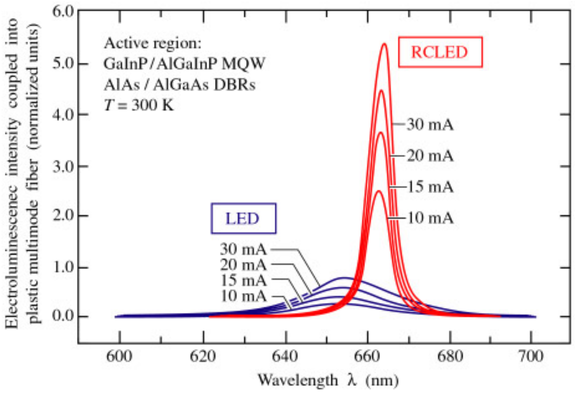


pigtailed RCLED



forward-directed emission pattern

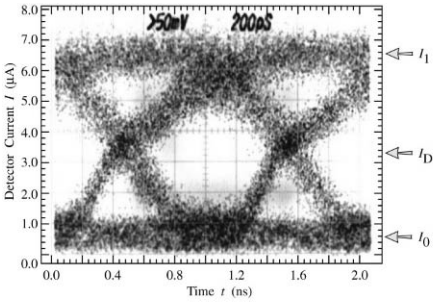
Spectra of a conventional LED and an RCLED coupled into POF



Streubel at al., 1998

Eye diagram of the received optical signal of an RCLED

data rate 622 Mbit/s (SONET)



“1“ state

decision current

“0“ state

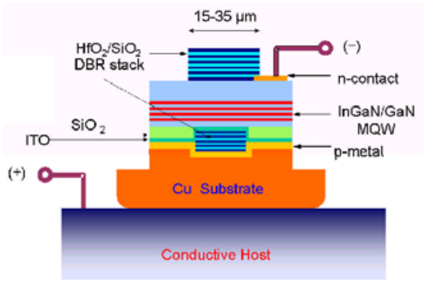
InGaN/GaN RCLED

(~ 510 nm)

Nitride Vertical Cavity QW light emitter

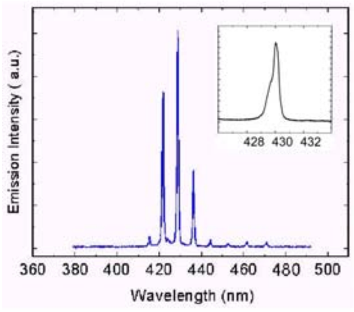
(with two dielectric mirrors)

Electrical injected VC InGaN/GaN LED



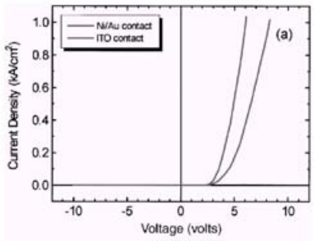
Y.-K. Song et al., APL **77**(12), 1744 (2000)

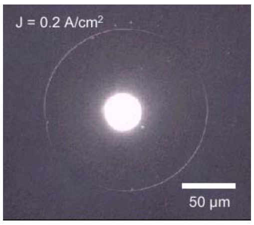
Emission spectrum of blue RCLED



- modal linewidth ≈ 0.7 nm, Q~ 700
- shorter cavities by ECR etching
- directional emission (~10º cone)

I-V and emission pattern

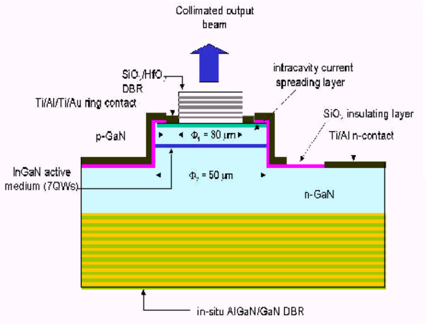




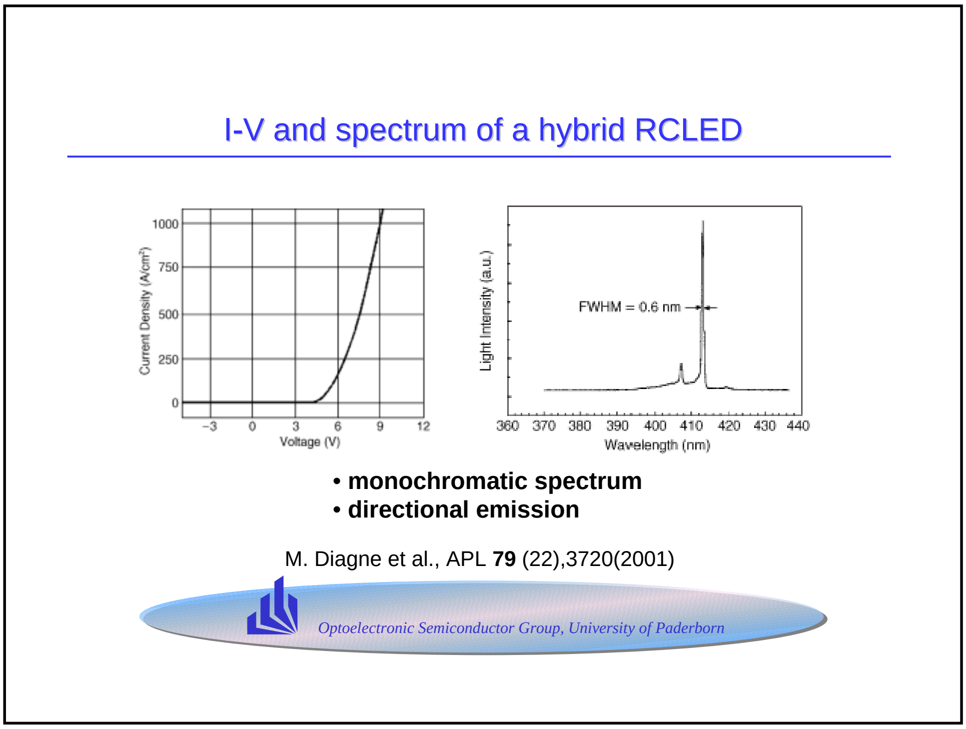
Y.-K. Song et al., APL **77**(12), 1744 (2000)

Nitride RCLED

(with one in-situ AlGaN DBR and one dielectric mirror)



M. Diagne et al., APL **79** (22),3720(2001)

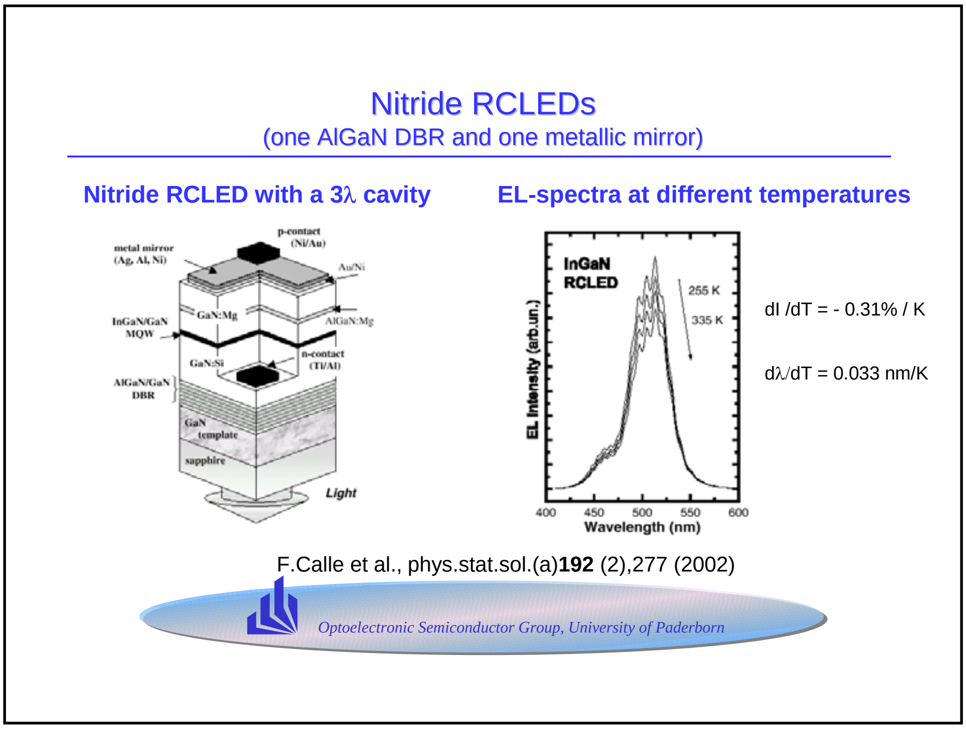


I-V and spectrum of a hybrid RCLED

- **monochromatic spectrum**
- **directional emission**

M. Diagne et al., APL **79** (22),3720(2001)

Optoelectronic Semiconductor Group, University of Paderborn



Nitride RCLEDs
(one AlGaN DBR and one metallic mirror)

Nitride RCLED with a 3λ cavity

EL-spectra at different temperatures

dI /dT = - 0.31% / K

dλ/dT = 0.033 nm/K

F.Calle et al., phys.stat.sol.(a)**192** (2),277 (2002)

Optoelectronic Semiconductor Group, University of Paderborn

Conclusion

Resonant-cavity light emitting diode – LED inside an optical cavity

Advantages of RCLEDs:

- light intensity is higher (enhancement factor 2-10)
- higher spectral purity (determined by Q factor)
- emission far-field pattern more directed
- less chromatic dispersion -> higher bit rates (622 Mbit/s SONET)
- less expensive, reliable and less temperature sensitive than Lasers
- lower manufacturing cost as compared to VCSEL

Realization of RCLEDs:

- InGaAs/GaAs (~900 nm)
- AlGaInP/GaAs (~650nm) → Communication via POF
- InGaN/GaN (~510nm)

Muster

Internal, extration, external, and power efficiency

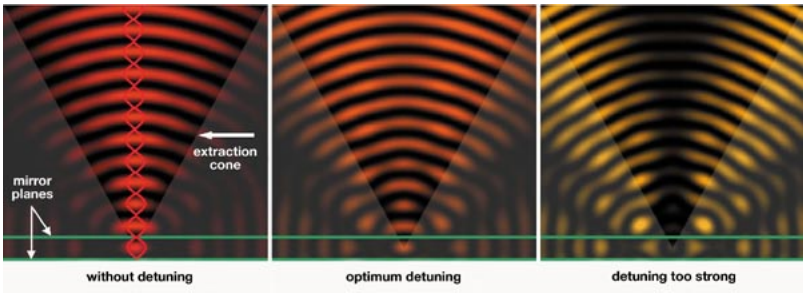
$$\eta_{\text{int}} = \frac{\#\text{ of photons emitted from active region per second}}{\#\text{ of electrons injected into LED per second}} = \frac{P_{\text{int}} / (h\nu)}{I / e}$$

$$\eta_{\text{extraction}} = \frac{\#\text{ of photons emitted into free space per second}}{\#\text{ of photons emitted from active region per second}}$$

$$\eta_{\text{ext}} = \frac{\#\text{ of photons emitted into free space per sec.}}{\#\text{ of electrons injected into LED per sec.}} = \frac{P / (h\nu)}{I / e} = \eta_{\text{int}}\,\eta_{\text{extraction}}$$

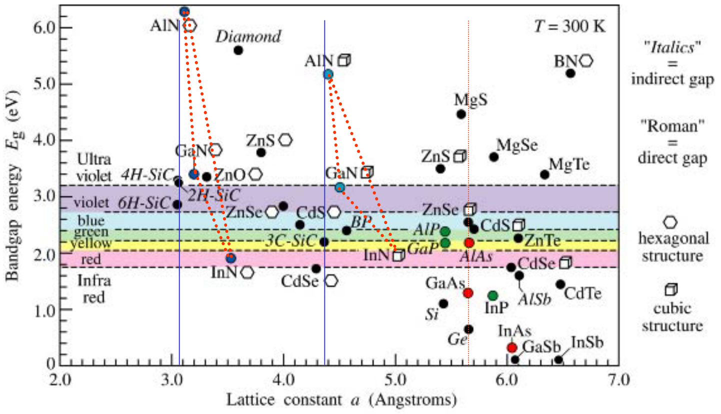
$$\eta_{\text{power}} = \frac{P}{IV}$$

Wavefield of an RCLED



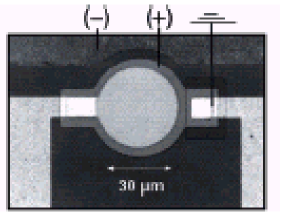
Light extraction is maximized at optimum detuning, where the wavelength of the emission is slightly shorter than the vertical resonance wavelength.

E_{gap} vs. Lattice constant

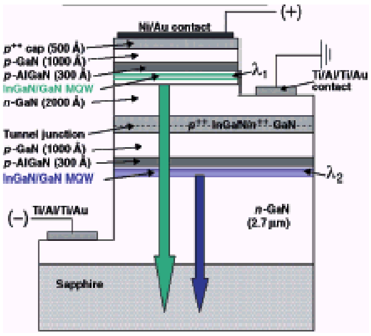


two-wavelength blue - green LED

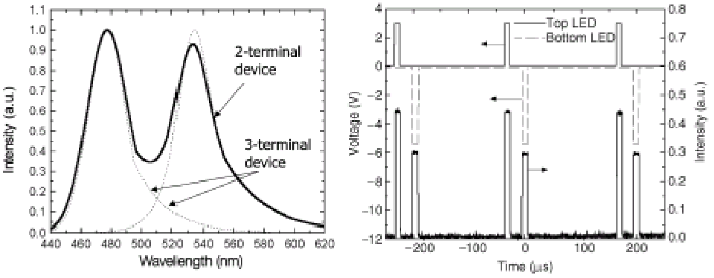
Planview photograph



Schematic illustration



Blue and green two-terminal LED



Emission spectra from blue and green LEDs when the devices are activated independently in a three-terminal case (dashed curve, and their simultaneous activation as a two-terminal LED (solid Curve). (b) Time sequenced activation of the two LEDs (amplitudes and duty cycle chosen arbiturily)

Optical mode density (mathematical considerations)

$$\rho(\nu) = \frac{(R_1R_2)^{3/4}}{T_1T_2}\frac{4n}{c}\left(1-\sqrt{R_1R_2}\right)T(\nu)$$

$$T(\nu) = \frac{T_1T_2}{1+R_1R_2-2\sqrt{R_1R_2}\cos\left(4\pi\, n\, L_{cav}\nu/c\right)}$$

$$\rho_{\max} \approx \frac{4}{\pi}\frac{n}{c}F = \frac{2}{\pi}\frac{\lambda}{c\,L_{cav}}Q$$

The mode density at the maximum is proportional to the finesse F or qualtiy factor Q of the cavity

$$\rho_{\min} \approx \frac{\pi\, n}{c}\frac{1}{F} = \frac{2\pi\, n^2}{\lambda\, c}\frac{L_{cav}}{Q}$$

The mode density at the minima is *inversely* proportional to the finesse F or qualtiy factor Q of the cavity

Mode density is conserved, i.e. the area below the 1D mode density and the 1D cavity mode density is the same

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Formeln 1

$$L_1 = \frac{\lambda_{Bragg}}{4n_1} \qquad L_{pen} \approx \frac{L_1+L_2}{4}\frac{n_1-n_2}{n_1+n_2}$$

$$L_2 = \frac{\lambda_{Bragg}}{4n_2}$$

$$r = \frac{n_1-n_2}{n_1+n_2}$$

$$n_{eff} = 2\left(\frac{1}{n_1}+\frac{1}{n_2}\right)^{-1}$$

$$\rho_{\max} \approx \frac{4}{\pi}\frac{n}{c}F = \frac{2}{\pi}\frac{\lambda}{c\,L_{cav}}Q$$

$$R_{DBR} = \left|r_{DBR}\right|^2 = \left(\frac{1-\left(\frac{n_1}{n_2}\right)^{2m}}{1+\left(\frac{n_1}{n_2}\right)^{2m}}\right)^2$$

$$r_{DBR} \approx \left|r_{DBR}\right| e^{-2i\left(\beta-\beta_{Bragg}\right)L_{pen}}$$

$$r_{metal}(z=0) = \left|r_{metal}\right| e^{2i(2\pi/\lambda)L_{pen}}$$

$$\Delta\lambda_{stop\,band} = \frac{2\,\lambda_{Bragg}\,\Delta n}{\pi\, n_{eff}}$$

Formeln 2

$$\rho(\nu) = \frac{(R_1R_2)^{3/4}}{T_1T_2}\frac{4n}{c}\left(1-\sqrt{R_1R_2}\right)T(\nu)$$

$$\rho_{\max} \approx \frac{4}{\pi}\frac{n}{c}F = \frac{2}{\pi}\frac{\lambda}{c\,L_{cav}}Q$$

$$T(\nu) = \frac{T_1T_2}{1+R_1R_2-2\sqrt{R_1R_2}\cos\left(4\pi\,n\,L_{cav}\nu/c\right)}$$

$$\rho_{\min} \approx \frac{\pi\,n}{c}\frac{1}{F} = \frac{2\pi\,n^2}{\lambda\,c}\frac{L_{cav}}{Q}$$

$$G_e = \frac{\rho_{\max}}{\rho_{1D}} \approx \frac{2}{\pi}F \approx \left(\frac{2}{\pi}\right)\frac{\pi\,(R_1R_2)^{1/4}}{1-\sqrt{R_1R_2}}$$

$$G_e \approx \frac{2(1-R_1)}{2-R_1-R_2}\frac{2F}{\pi} \approx \frac{1-R_1}{1-\sqrt{R_1R_2}}\frac{2F}{\pi} \approx \left(\frac{2}{\pi}\right)\frac{\pi(R_1R_2)^{1/4}(1-R_1)}{\left(1-\sqrt{R_1R_2}\right)^2}$$

$$G_e = \frac{\xi}{2}\left(\frac{2}{\pi}\right)\frac{\pi(R_1R_2)^{1/4}(1-R_1)}{\left(1-\sqrt{R_1R_2}\right)^2}\frac{\tau_{cav}}{\tau}$$