Optoelectronică, structuri şi tehnologii

Curs 7

2017/2013

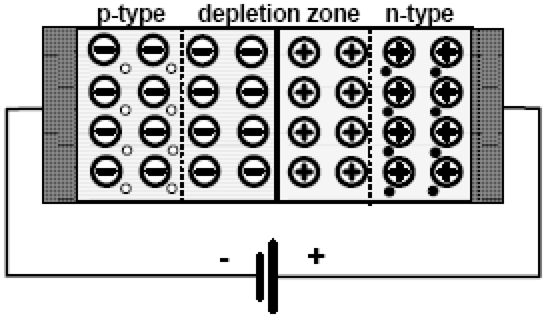
LED

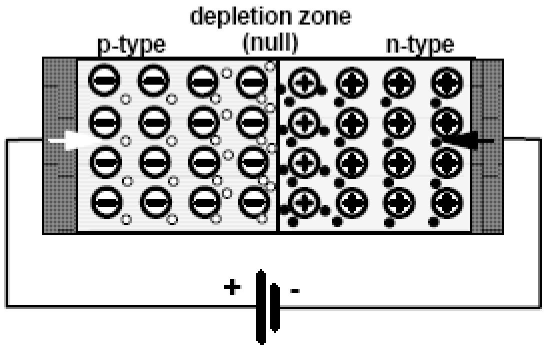
Dioda electroluminescenta
Capitolul 8

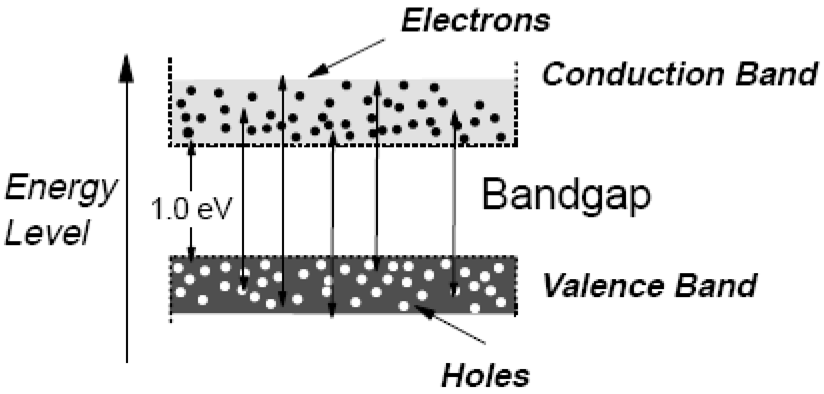
Caracteristici LED

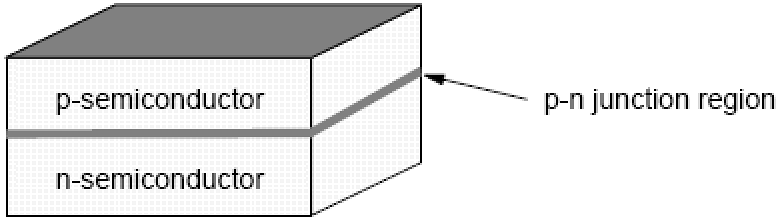
- Dezavantaje
  - Putere redusa (cuplata in fibra) ~ 100μW
  - Banda (viteza) reduse ~ 150MHz (300Mb/s)
  - Spectru larg ~ 0.05 λ
  - Lumina necoerenta si nedirectiva
- Avantaje
  - Structura interna mult mai simpla (fara suprafete reflective, straturi planare)
  - Cost (dispozitiv si circuit de comanda)
  - Durata de viata
  - Insenzitivitate la temperatura
  - Liniaritate (modulatie analogica)

LED – Principiul de operare









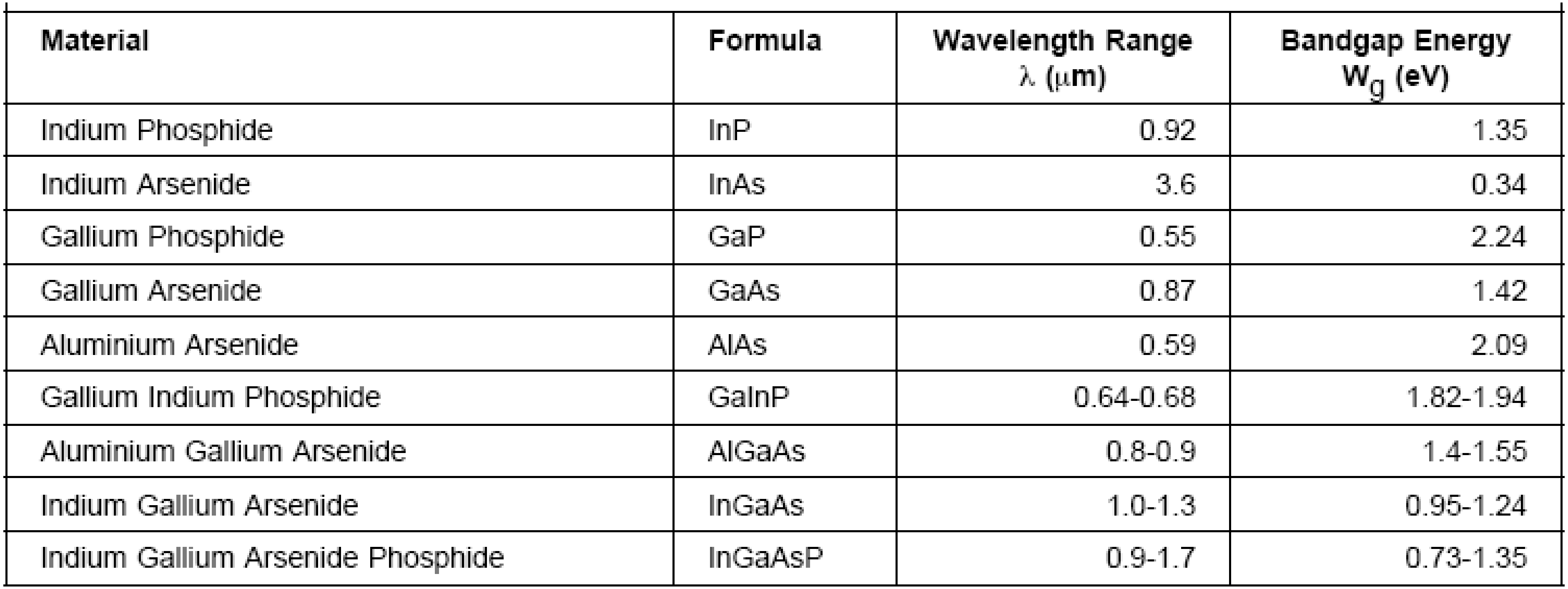
LED – Principiul de operare

- Lumina este generata de o recombinare radiativa dintre un electron si un gol
- Recombinarea neradiativa transforma energia in caldura
- Eficienta cuantica $\eta = \frac{R_r}{R_r + R_{nr}}$
- La recombinarea radiativa $E_g = h\nu; \quad \lambda = \frac{hc}{E_g}$
- Recombinare eficienta:
  - alegerea judicioasa a materialului
  - concentrarea purtatorilor in zona jonctiunii
- Lungimea de unda depinde de temperatura de functionare a dispozitivului: 0.6nm/°C

Aplicatii majore LED

- Comunicatii
  - Infrarosu (InGaAsP)
- Vizibil
  - Spectru vizibil (GaAlAs)
- Iluminare
  - Putere ridicata, lumina alba (GaInN)

Lăţimea benzii interzise/lungime de undă pentru materialele uzuale



Material	Formula	Wavelength Range λ (μm)	Bandgap Energy W_g (eV)
Indium Phosphide	InP	0.92	1.35
Indium Arsenide	InAs	3.6	0.34
Gallium Phosphide	GaP	0.55	2.24
Gallium Arsenide	GaAs	0.87	1.42
Aluminium Arsenide	AlAs	0.59	2.09
Gallium Indium Phosphide	GaInP	0.64-0.68	1.82-1.94
Aluminium Gallium Arsenide	AlGaAs	0.8-0.9	1.4-1.55
Indium Gallium Arsenide	InGaAs	1.0-1.3	0.95-1.24
Indium Gallium Arsenide Phosphide	InGaAsP	0.9-1.7	0.73-1.35

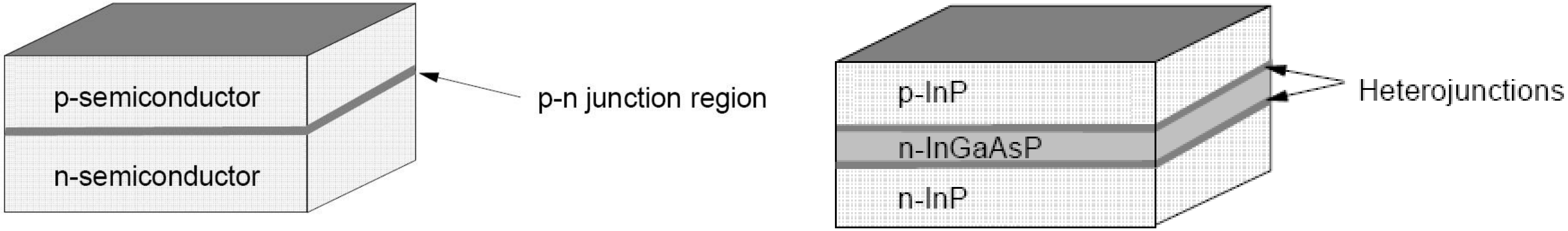
$$E_g = h\nu; \quad \lambda = \frac{hc}{E_g}; \quad \lambda[\mu\mathrm{m}] = \frac{1.240}{E_g[\mathrm{eV}]}$$

- h constanta lui Plank $6.62 \cdot 10^{-32}\ \mathrm{Ws}^2$
- c viteza luminii in vid $2.998 \cdot 10^{8}\ \mathrm{m/s}$
- benzi energetice: λ_0, $\Delta\lambda$

Detalii constructive - 1

- Recombinarea unei perechi electron-gol necesita conservarea "impulsului retelei" (cvasiimpuls)
  - In Si si Ge aceasta conditie presupune aparitia unui fonon intermediar (tranzitie indirecta) a carui energie se transforma in caldura
  - Majoritatea aliajelor de aluminiu Al de asemenea au tranzitie indirecta
- Se utilizeaza aliaje de Ga Al As sau In Ga As P
- Materialele utilizate trebuie sa fie "transparente" la lungimile de unda emise

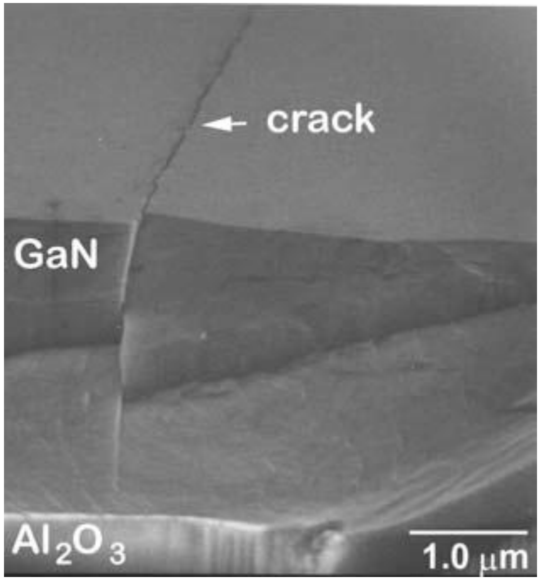
LED cu heterojuncţiuni – principiu



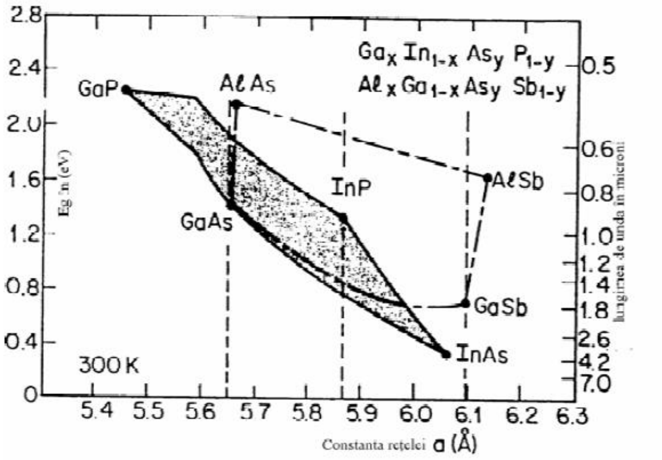
- **Orice** jonctiune p-n emite lumina
- O jonctiune p-n obisnuita este foarte subtire
  - volumul in care apar recombinari este foarte mic
  - eficienta luminoasa, redusa
- lumina este emisa in toate directiile
  - cantitatea de lumina utilizabila (intr-o anumita directie) este redusa

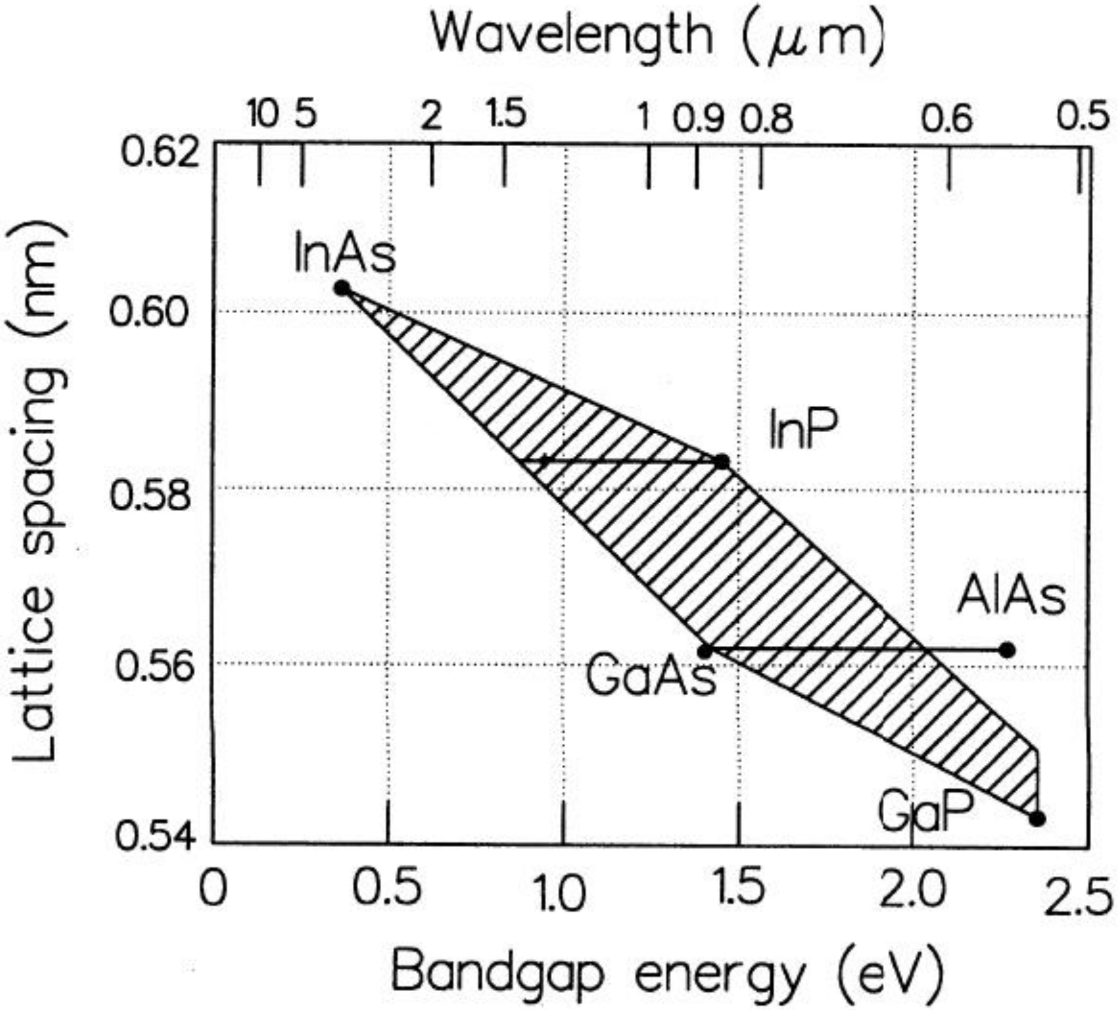
Detalii constructive – 2

- Spatierea atomilor in diferitele straturi trebuie sa fie egala (toleranta 0.1%) pentru a nu se introduce defecte mecanice la jonctiune
  - limitare a aliajelor utilizabile
  - aparitia defectelor
    - creste ineficienta (recombinari neradiative)
    - scade durata de viata a dispozitivului



Dependenţa benzii interzise de constanta reţelei





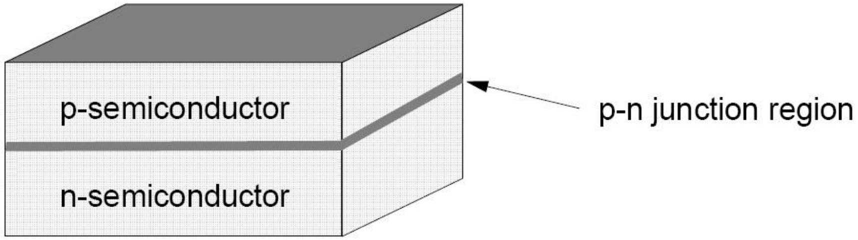
Materiale

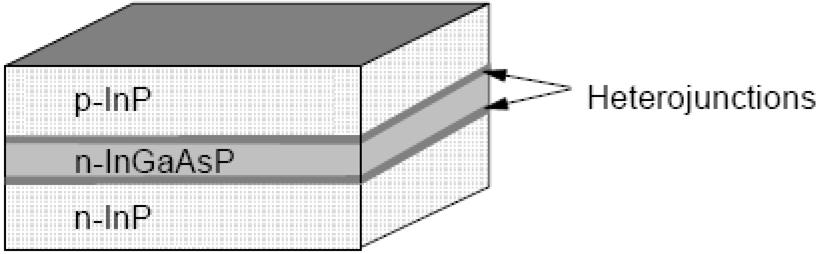
- Lungimi de unda mici (spectru vizibil – 1000nm)
  - GaP (665nm), $GaAs_yP_{1-y}$
  - GaAs (900nm), $Ga_{1-x}Al_xAs$ (AlAs – 550nm)
- Lungimi de unda mari (1000÷1700nm)
  - $In_xGa_{1-x}As_yP_{1-y}$
  - x,y concentratii relative in aliaj a materialelor corespunzatoare
  - x,y alese din considerente privind
    - lungimea de unda
    - spatierea atomilor
- Ultraviolet – Albastru: GaInN

Materiale

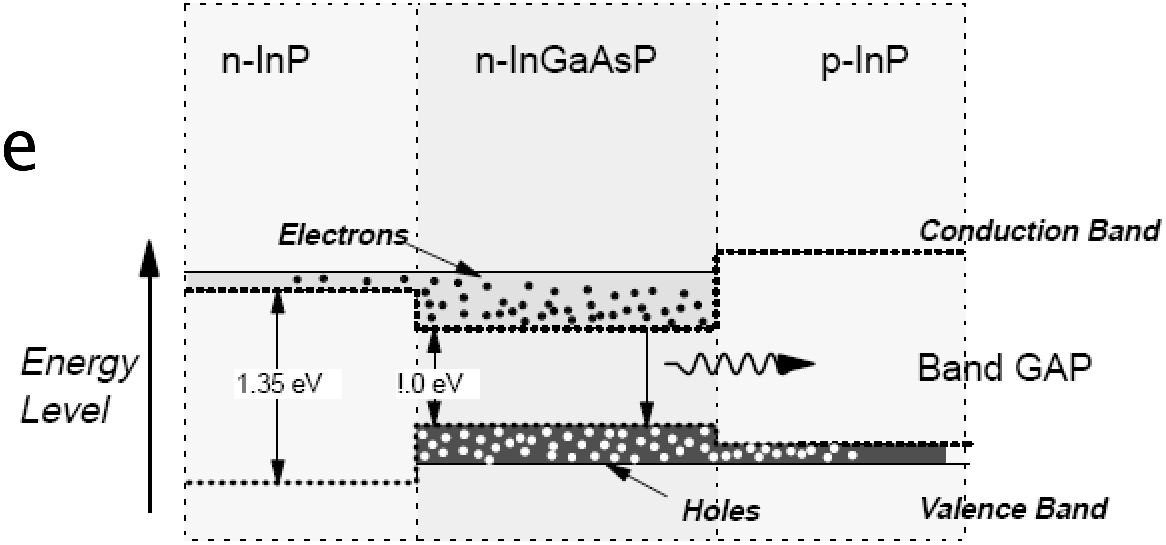
- Lungimi de unda mici
  - $Ga_{1-x}Al_xAs$
  - E_g (in eV) $E_g = 1.424 + 1.266 \cdot x + 0.266 \cdot x^2$
  - limitare pentru tranzitie directa $0 < x < 0.37$
- Lungimi de unda mari
  - $In_xGa_{1-x}As_yP_{1-y}$
  - E_g (in eV) $E_g = 1.35 - 0.72 \cdot y + 0.12 \cdot y^2$
  - Tipic substratul este InP
    - Spatierea atomilor (lattice spacing) corespunzatoare InP $x = \dfrac{0.4526}{1 - 0.031 \cdot y}$
  - Exemplu: 1300nm se obtine cu y=0.589 si x=0.461,
    - $In_{0.461}Ga_{0.539}As_{0.589}P_{0.411}$

LED cu heterojuncţiuni – principiu

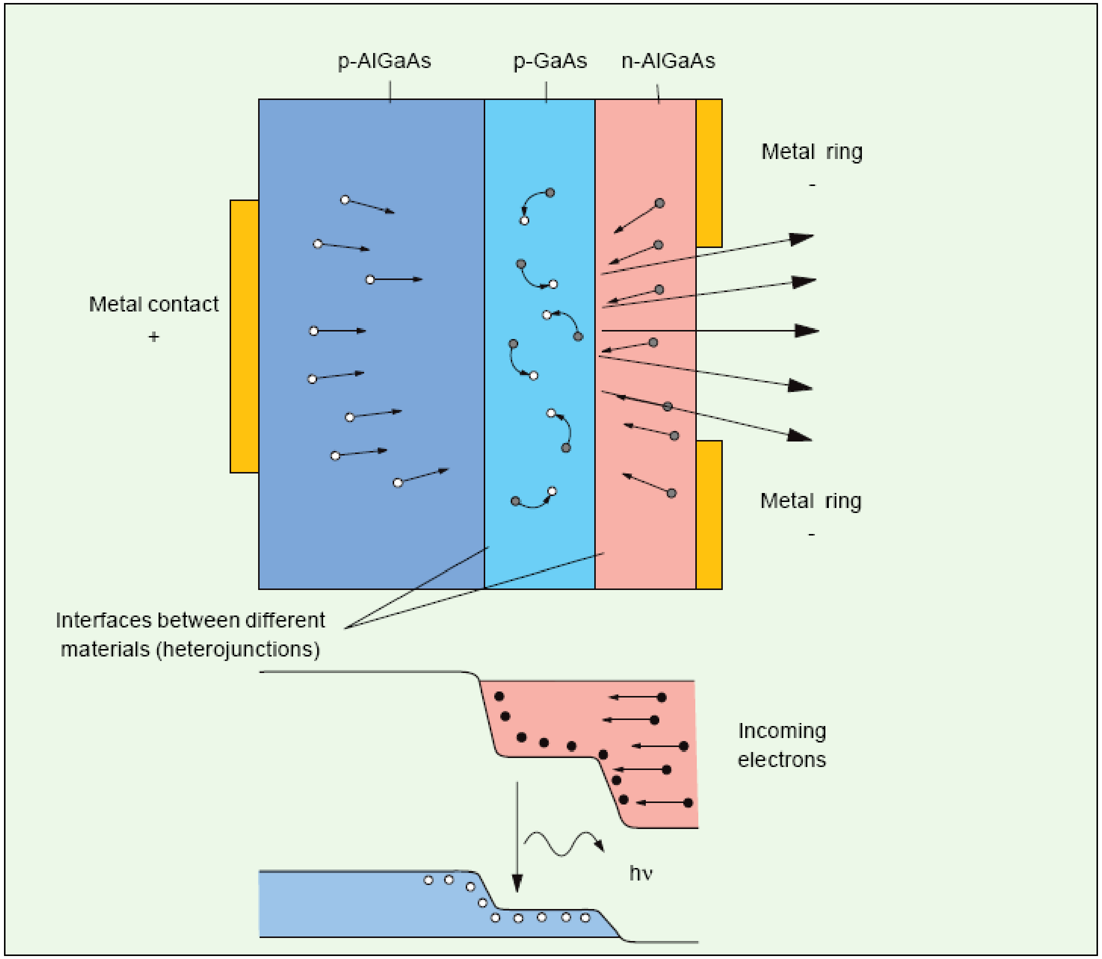




- Structura de nivele energetice permite capturarea purtatorilor intre cele doua heterojonctiuni

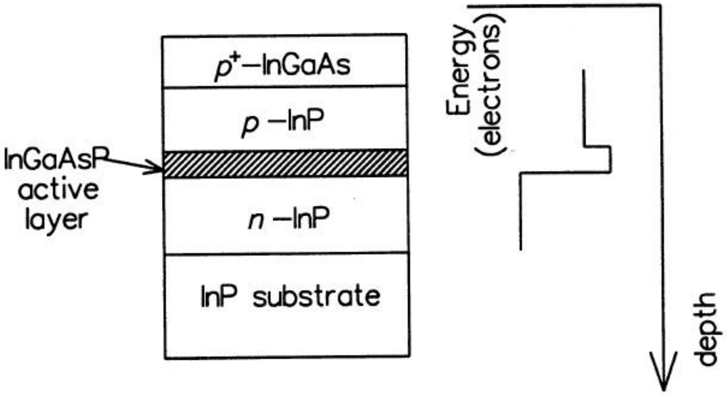


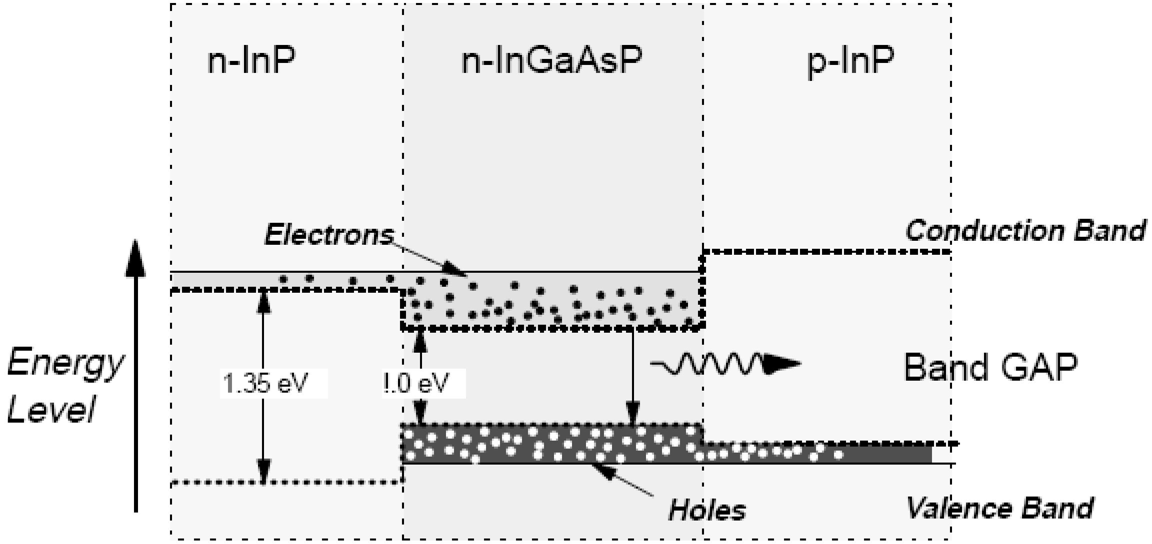
LED cu heterojuncţiuni – principiu



LED cu heterojuncţiuni – principiu

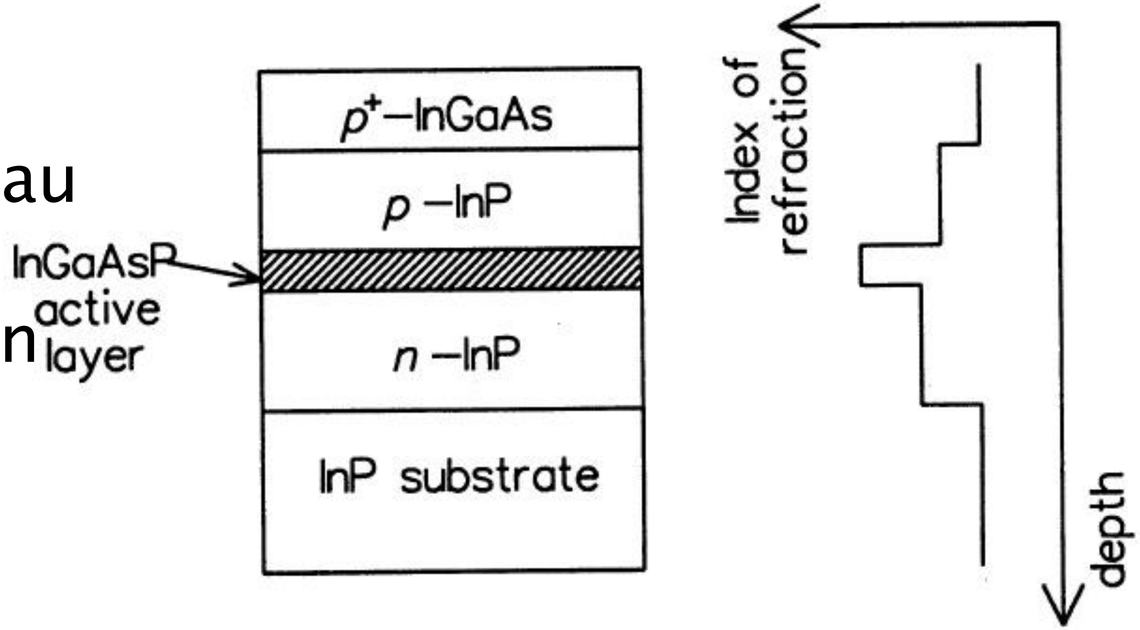
- Concentrare verticala a purtatorilor
  - Electronii sunt atrasi din zona n in zona activa
  - O bariera energetica existenta intre zona activa si zona n concentreaza electronii in zona activa
  - Situatie similara corespunzatoare golurilor
  - Purtatorii sunt concentrati in zona activa, crescand eficienta





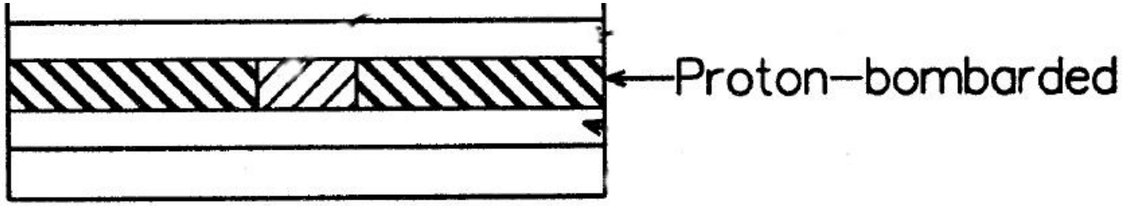
LED cu heterojuncţiuni – principiu

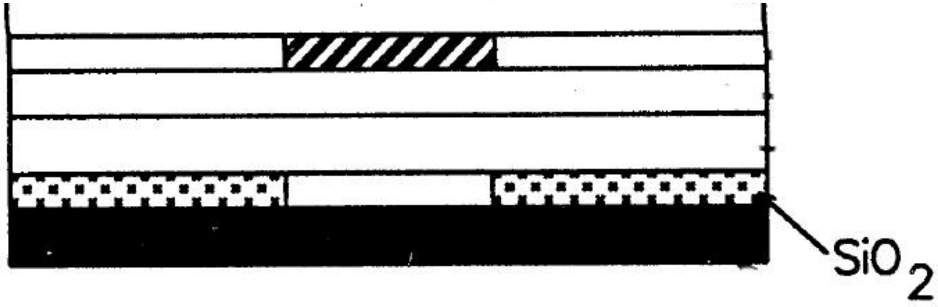
- Concentrare verticala a luminii
  - in general la diode laser (eficienta procesului LASER depinde de intensitatea luminoasa)
  - prezenta si la LED pentru cresterea eficientei luminoase: dirijarea luminii spre exterior si evitarea absorbtiei interne
- Straturile din materiale diferite au indici de refractie diferiti formand un ghid dielectric



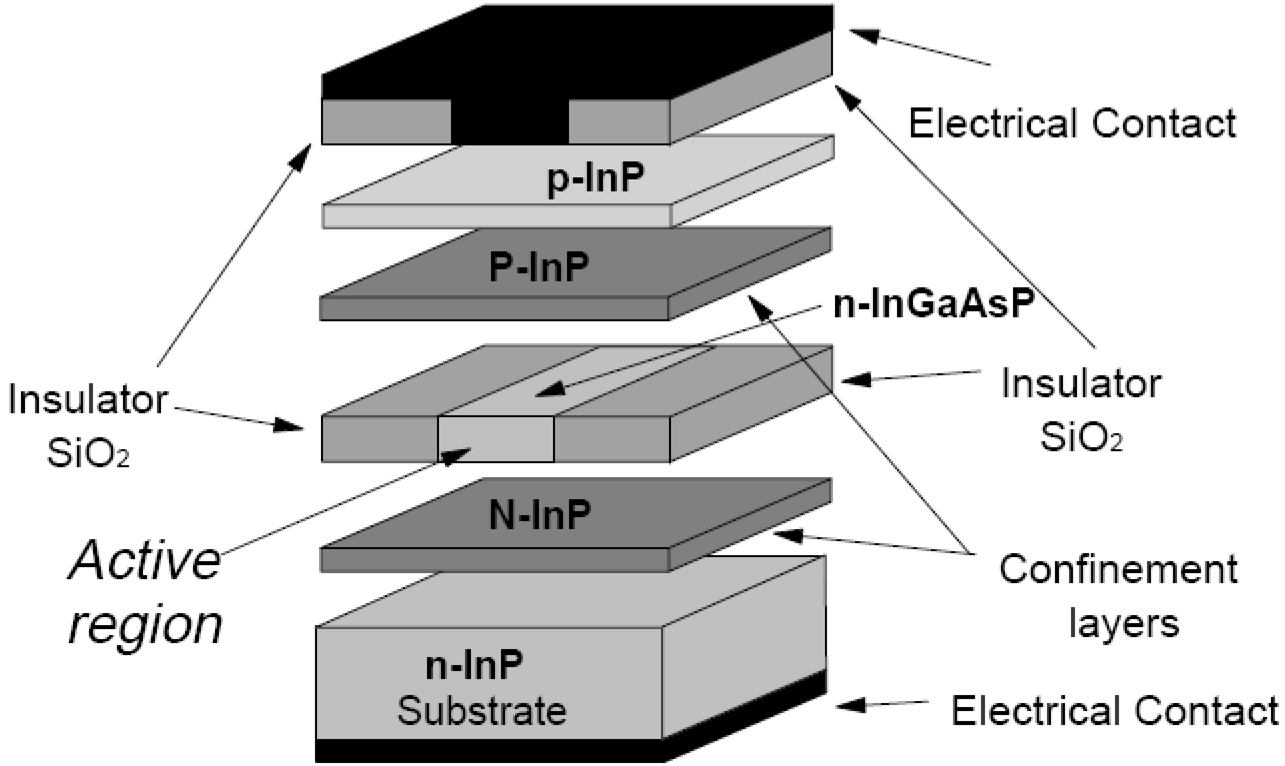
LED cu heterojuncţiuni – principiu

- Concentrare orizontala a curentului
  - Eficienta conversiei depinde de concentratia de purtatori, deci e necesara cresterea densitatii de curent in zona activa (20–50μm)
  - Se utilizeaza:
    - strat izolator (tipic SiO_2) cu o deschidere in dreptul zonei active
    - Bombardarea cu protoni a regiunii din jurul zonei active
    - Alte metode:
      - eliminarea materialului in jurul zonei active (mesa structure)
      - difuzie de Zn in zona centrala

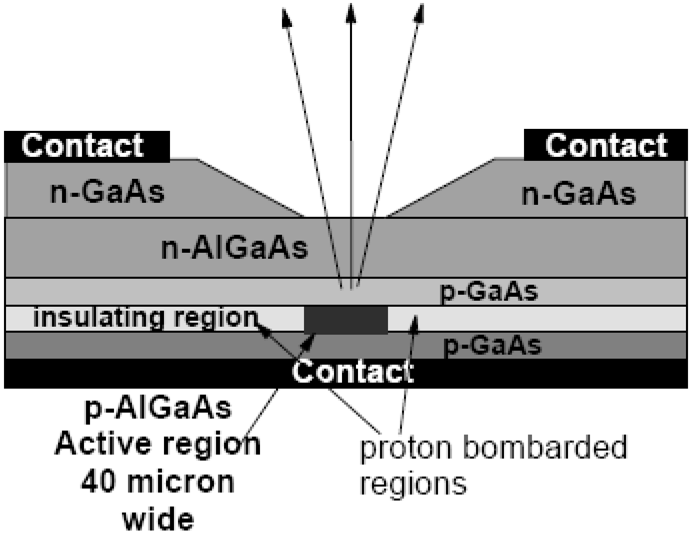




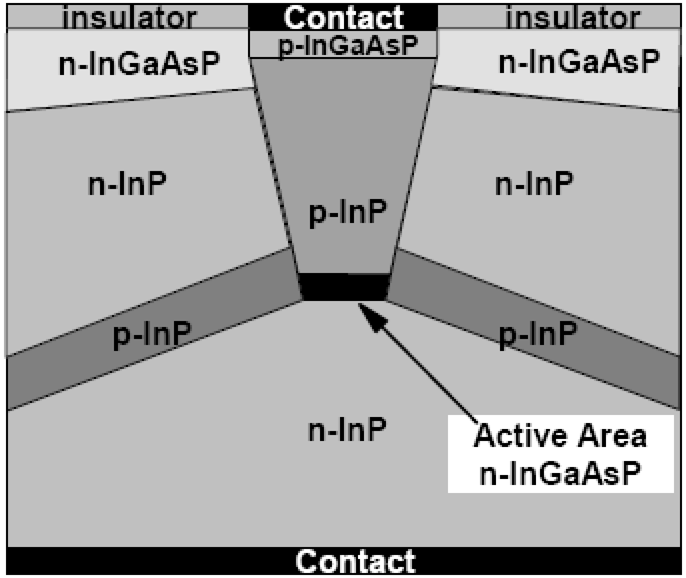
LED cu heterojuncţiuni – detalii



Structuri constructive pentru LED

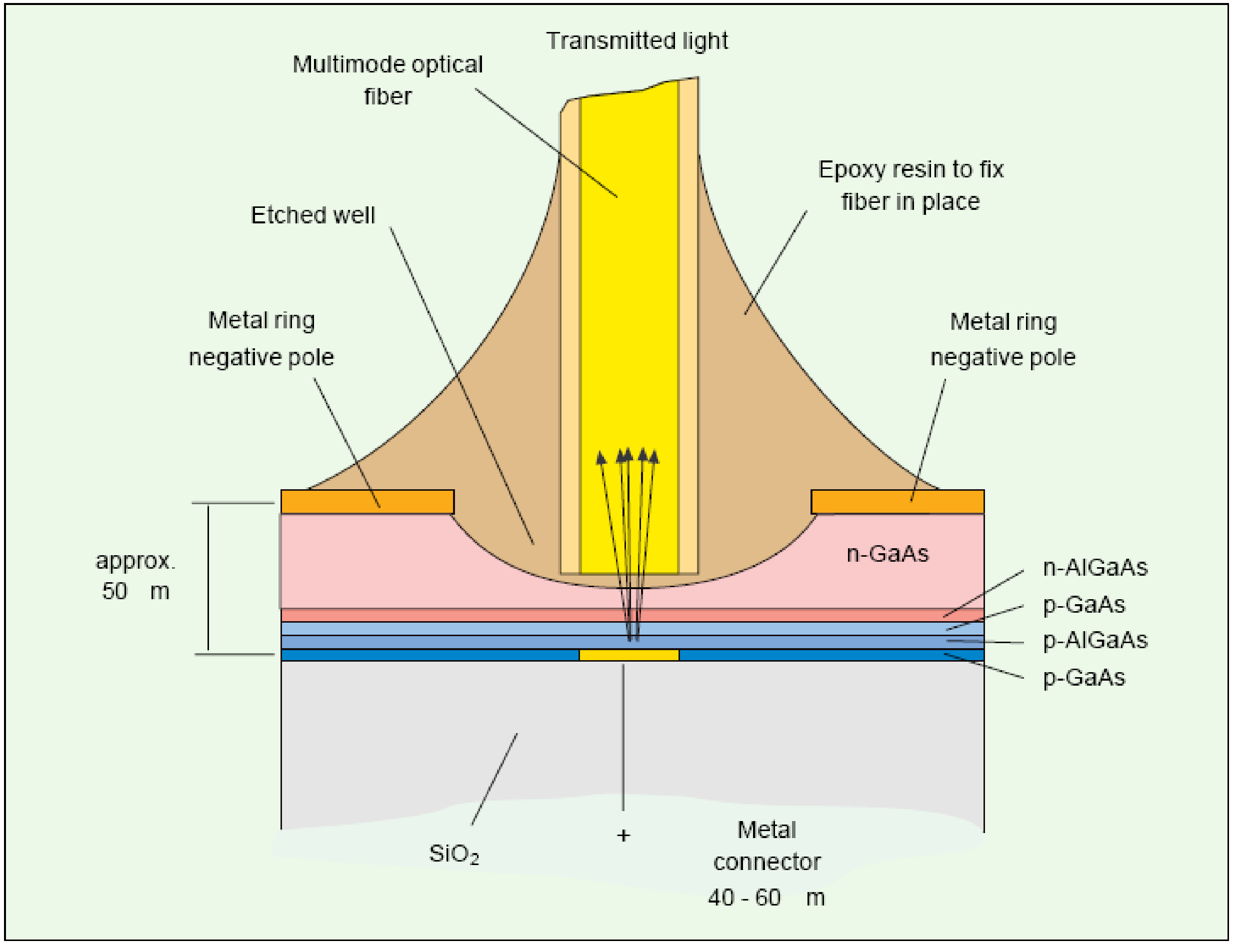


Burrus Surface Emitting LED (SLED)



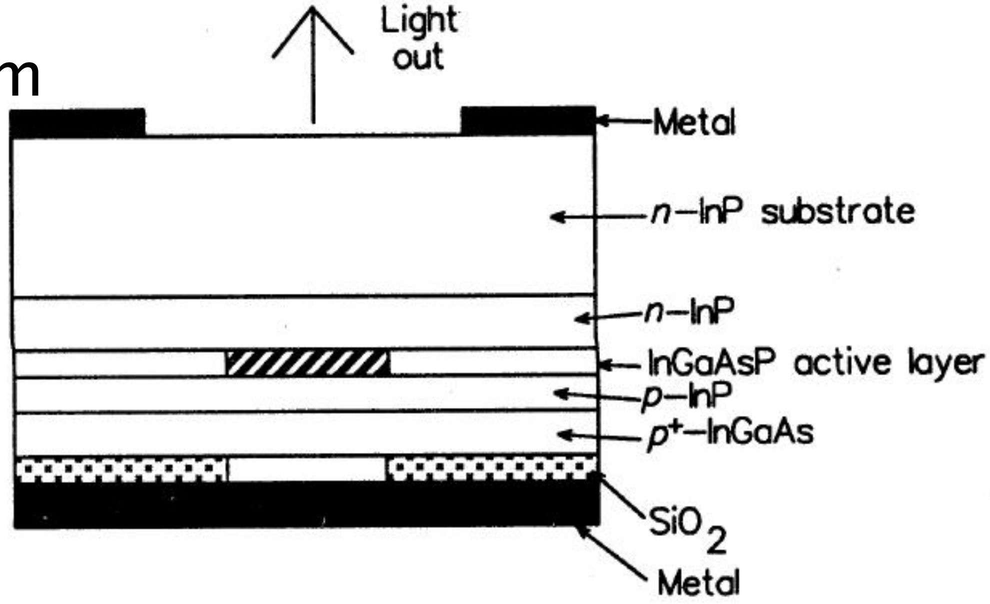
Edge Emitting LED (ELED)

LED cu emisie de suprafaţă



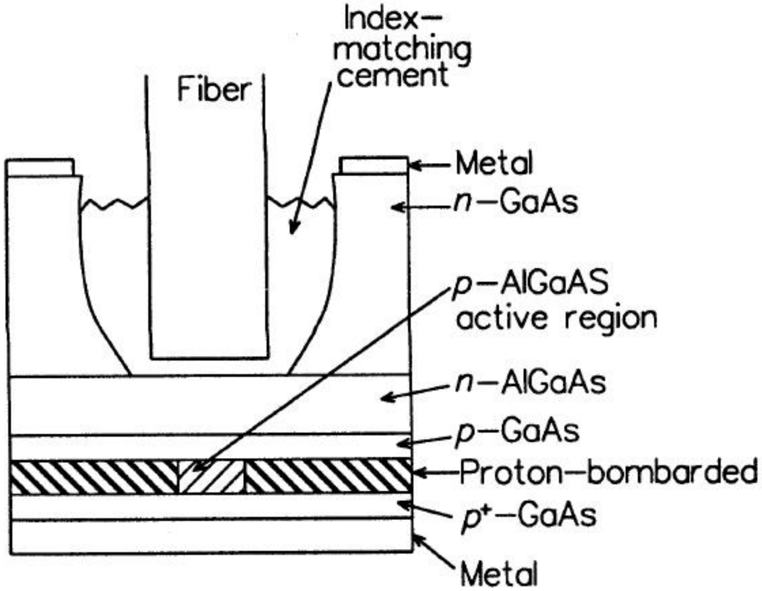
SLED InGaAsP – constructie

- InGaAsP
- 4 straturi
  - n InP ~2÷5µm
  - p InGaAsP ~0.4÷1.5µm
  - p InP ~1÷2µm
  - p^+ InGaAs ~0.2µm
- Latimea zonei active
  - ~20÷50µm diametru

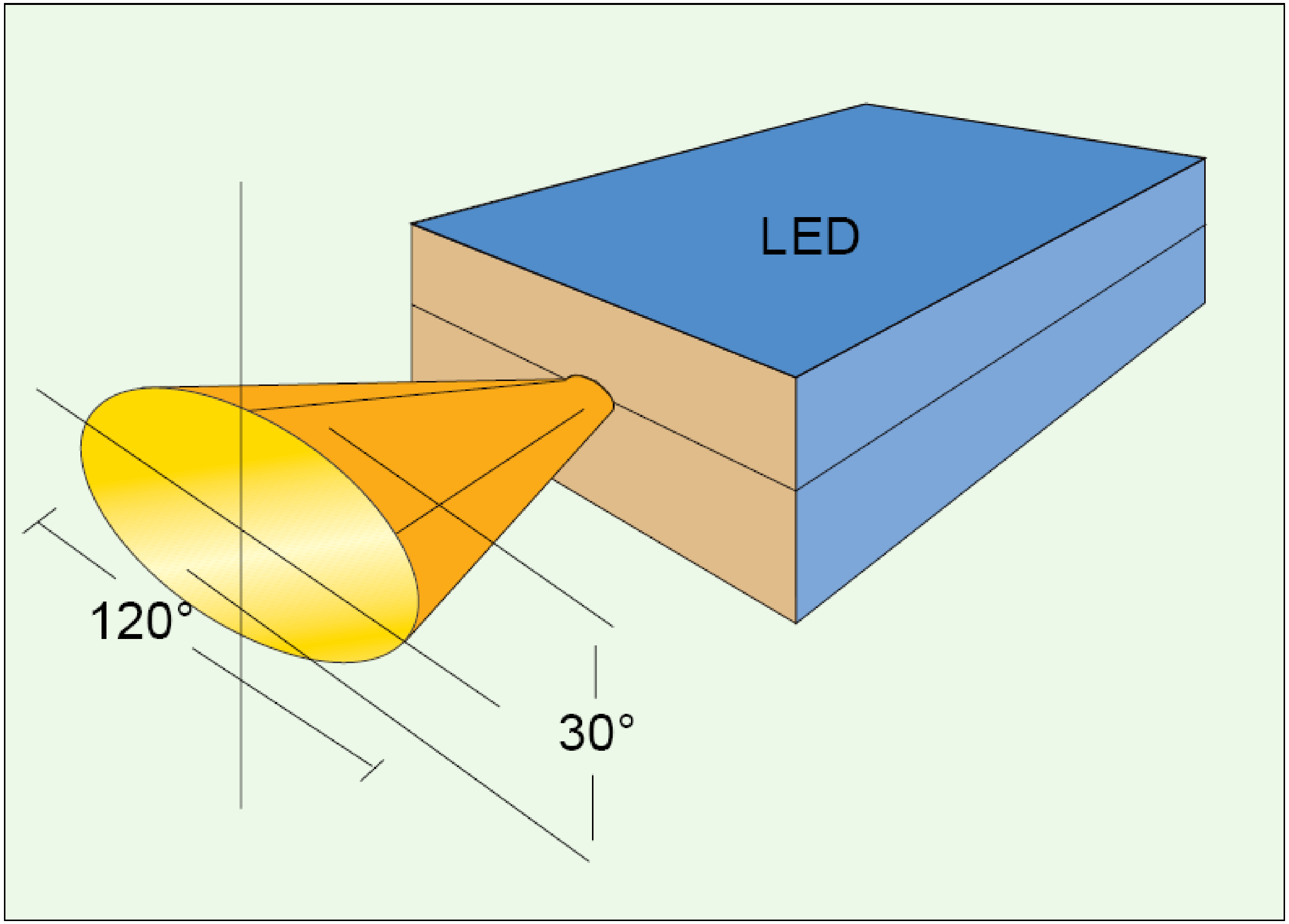


SLED GaAlAs – constructie

- GaAlAs
- diferenta principala e data de absorbtia crescuta a substratului GaAs, care este eliminat partial pentru a permite accesul luminii spre exterior



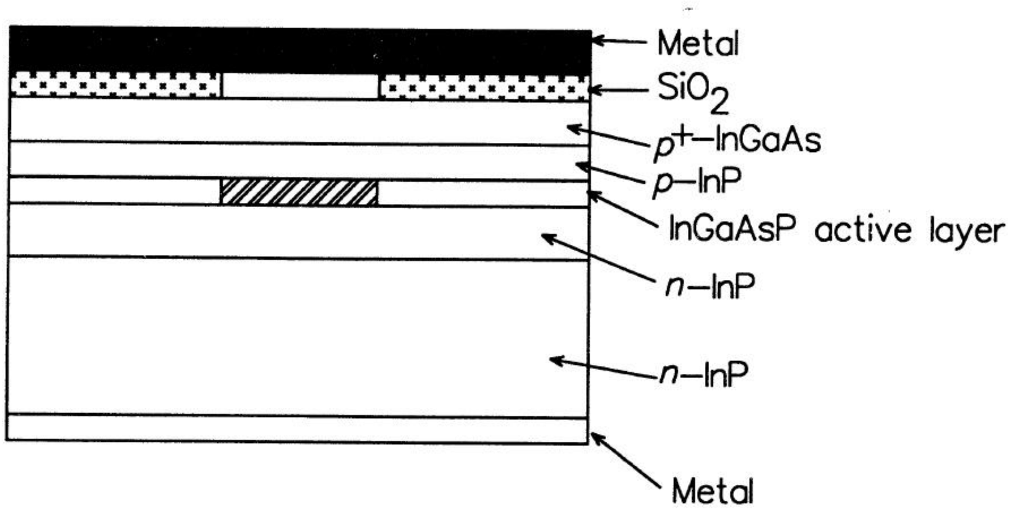
LED cu emisie laterală



ELED – constructie

- InGaAsP
- strict pentru comunicatii
- Cele patru straturi sunt in general similare
- Stratul activ este mult mai subtire decat la SLED ~0.05÷0.25μm

- Regiunea activa
  - latime 50÷70μm
  - lungime 100÷150μm
  - p InP ~1÷2μm
  - p^{+} InGaAs ~0.2μm
- Apare concentrarea verticala a luminii



Emisia luminii spre exterior

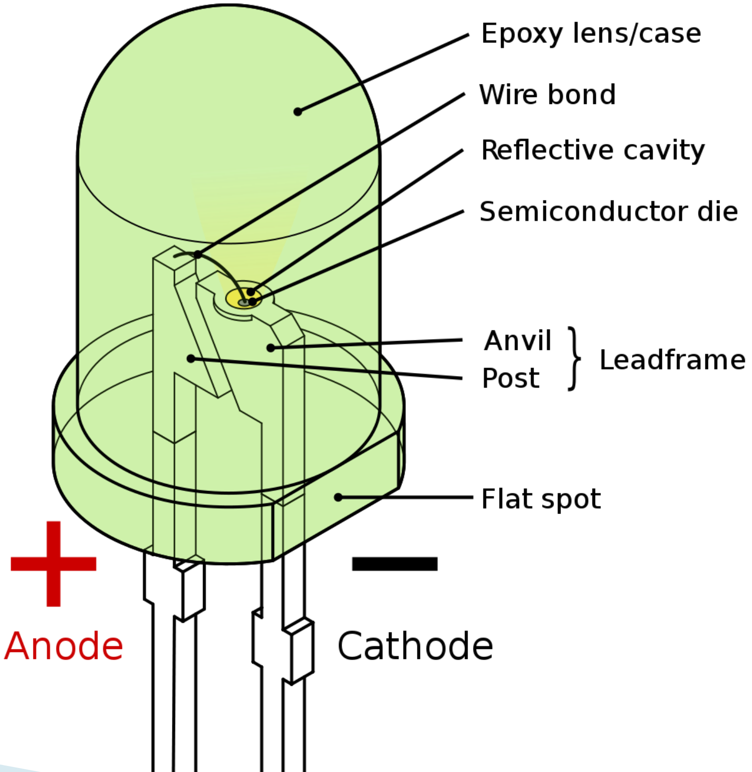
- Indici de refractie ridicati
    - InP n=3.4
    - GaAs n=3.6
- Doua probleme generate
    - pierderi prin reflexie ridicate
    - unghi critic de numai 15°

Emisia luminii spre exterior

- Solutii
  - utilizarea unui material intermediar pentru adaptarea indicelui de refractie (rasina epoxidica)
  - adaptarea formei de iesire din dispozitiv – forma de dom
    - eficienta de cuplaj

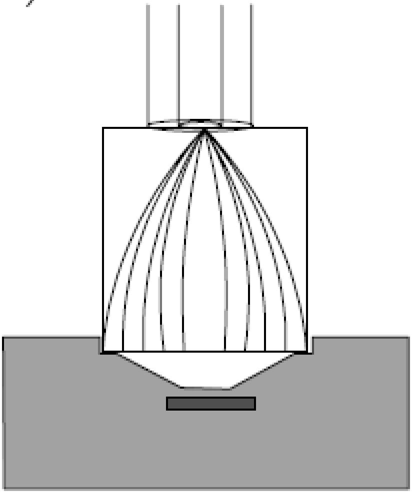
interfata plana semiconductor aer $\dfrac{1}{n\cdot(n+1)^2}$

dom $\dfrac{2n}{(n+1)^2}$

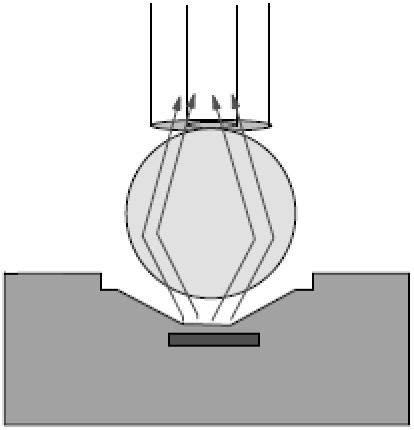


Cuplarea luminii în fibră

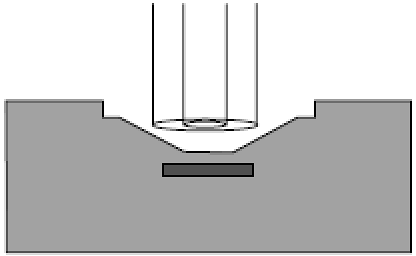
(a) Grin Lens



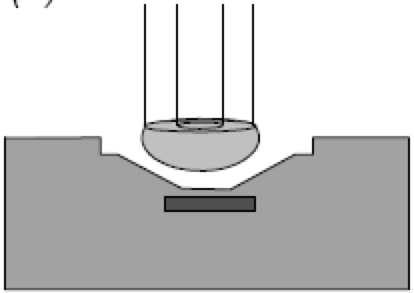
(b) Ball Lens



(c) Direct coupling



(d) Lensed fibre end



numai pentru fibre multimod cu salt de indice

Directivitatea radiatiei exterioare

- SLED
  - radiatia este emisa cu simetrie circulara, in interiorul unui con cu unghi la varf tipic de 60°
  - Viewing Half Angle ~ 10÷15°
- ELED
  - radiatia emisa nesimetric in forma de con eliptic
    - perpendicular pe jonctiune ~60°
    - paralel cu jonctiunea ~30°

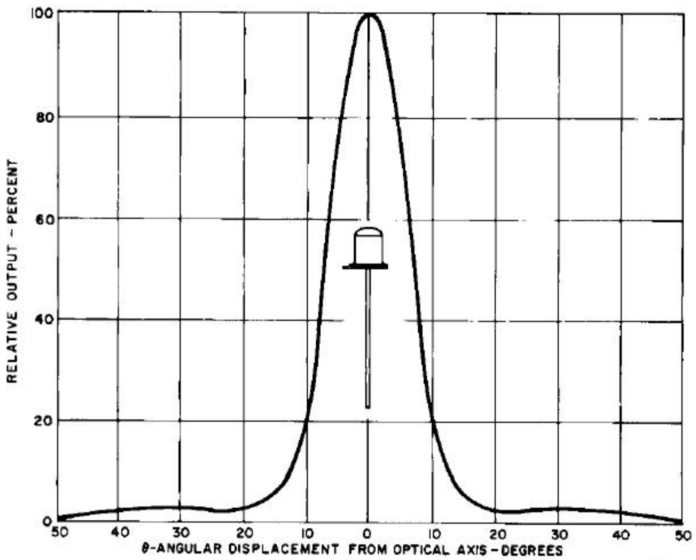
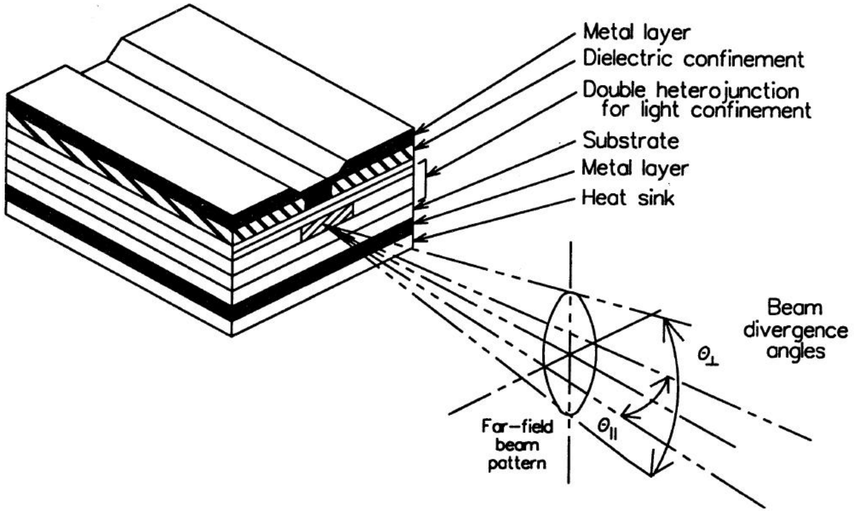


Fig. 5. Typical Radiation Pattern

ST1054



Directivitatea radiatiei exterioare

- Sursa lambertiana

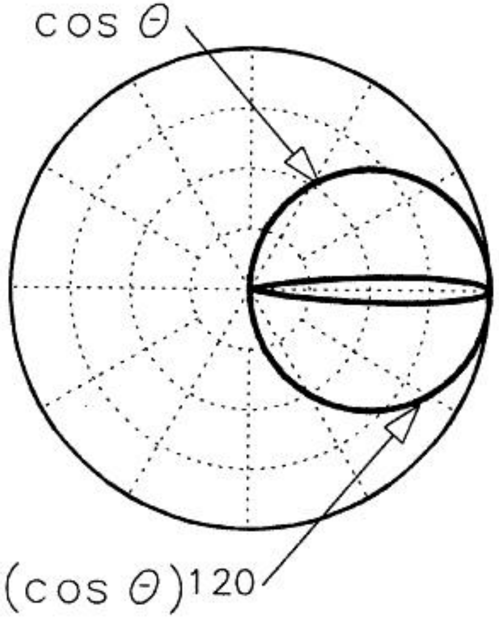
$$P(\theta) = P_0 \cdot \cos\theta$$

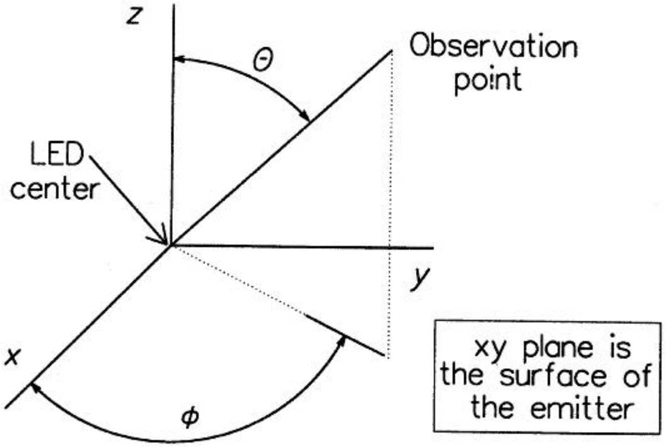
- Aproximatie Lambertiana pentru surse cu directivitate crescuta

$$P(\theta) = P_0 \cdot \cos^n \theta$$

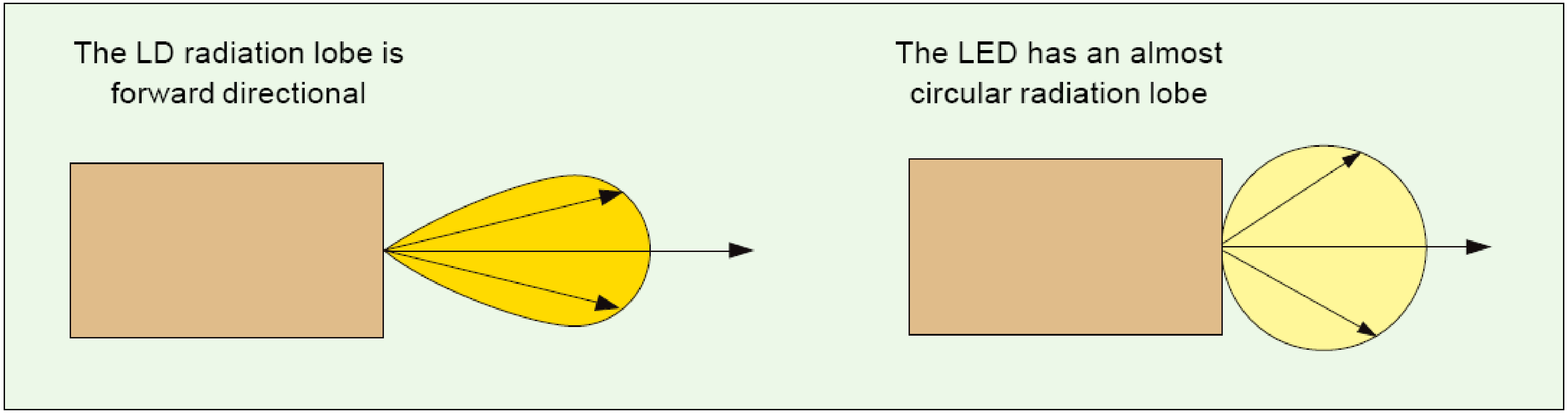
- Surse cu emisie asimetrica

$$P(\theta) = \frac{P_0}{\dfrac{\sin^2\phi}{\cos^T\theta} + \dfrac{\cos^2\phi}{\cos^L\theta}}$$



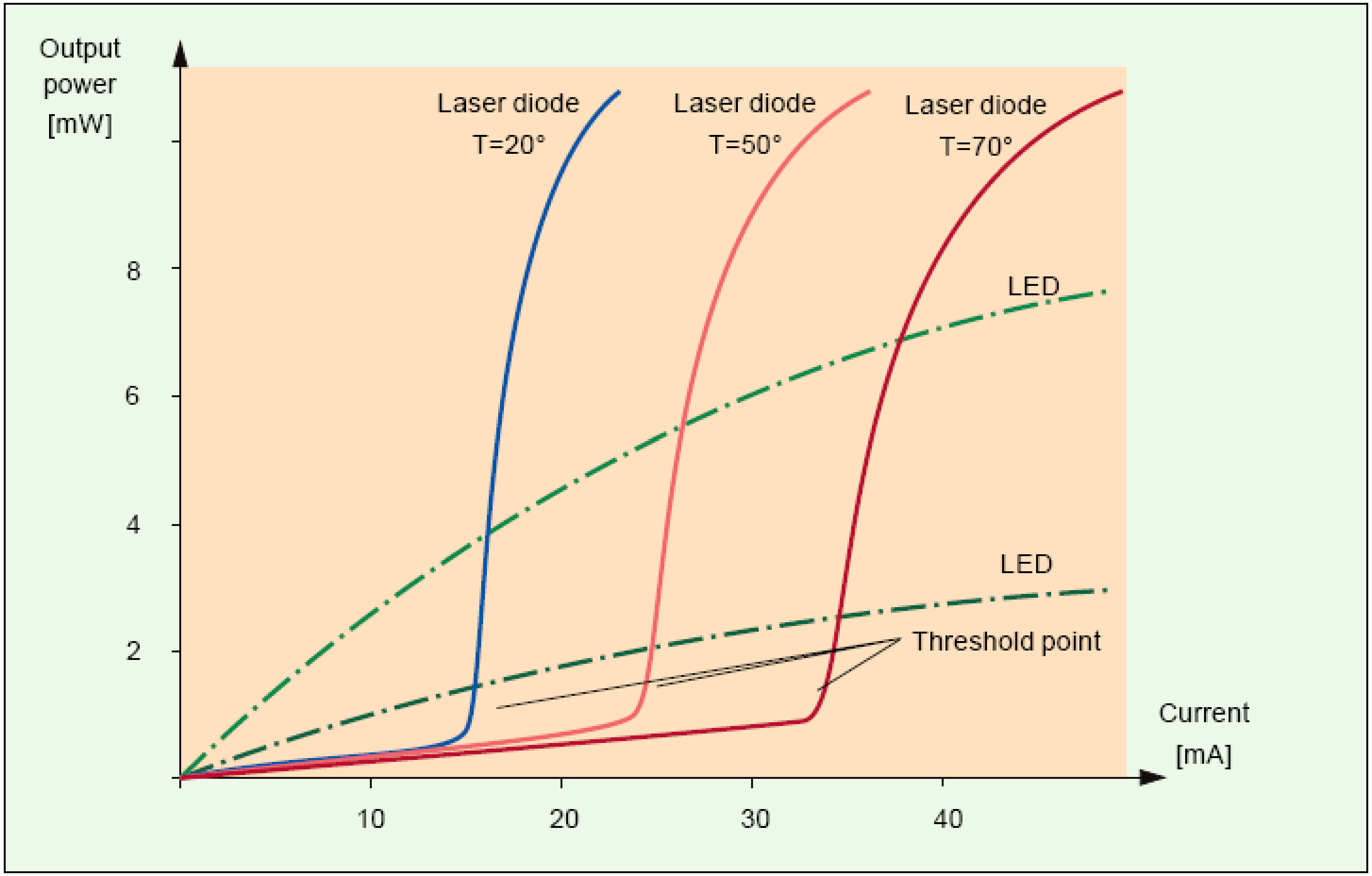


Profil de radiaţie a emiţătorilor optici



- Apertura numerică poate varia de la 0.9 pentru un LED de unghi foarte larg, la 0.2 pentru un LED prevăzut cu lentilă.
- Chiar şi pentru un NA de 0.2, aria emisivă este mare comparativ cu a unui laser. În consecinţă, densitatea de putere emisă este mică astfel încît se reduce drastic puterea care poate fi cuplată într-o fibră cu indice gradat, şi devine practic imposibilă cuplarea cu o fibră monomod.

Caracteristici putere optică/curent a emiţătorilor optici

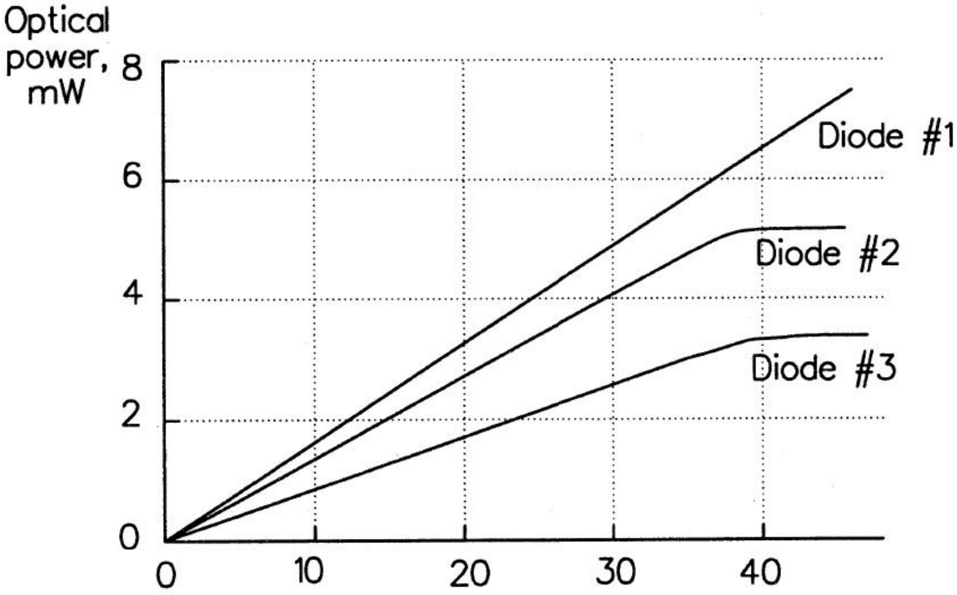


Caracteristica de raspuns a LED-urilor

- Caracteristica putere optica emisa functie de curentul direct prin LED este liniara la nivele mici ale curentului.
- Nu exista curent de prag
- La nivele foarte mari puterea optica se satureaza
- Responzivitatea

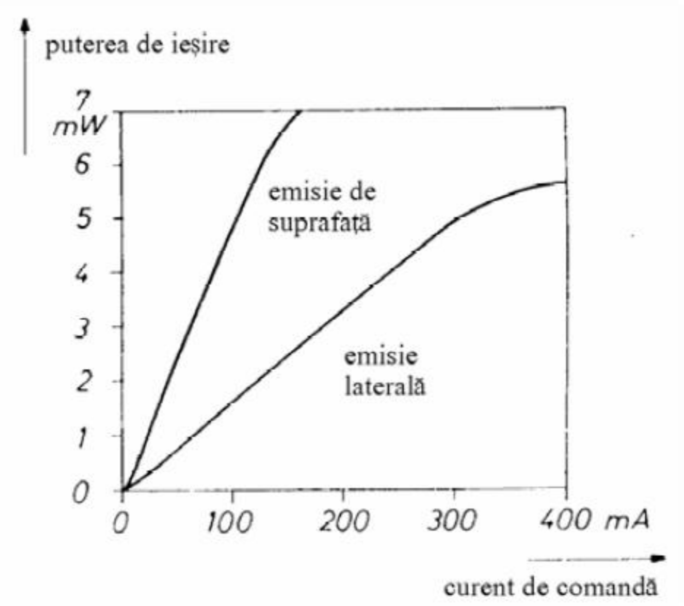
$$r = \frac{P_o}{I} \quad \left[\frac{W}{A}\right]$$

- Tipic r=50μW/mA



Caracteristica de raspuns a LED-urilor

- Tipic SLED au eficienta mai buna decat ELED



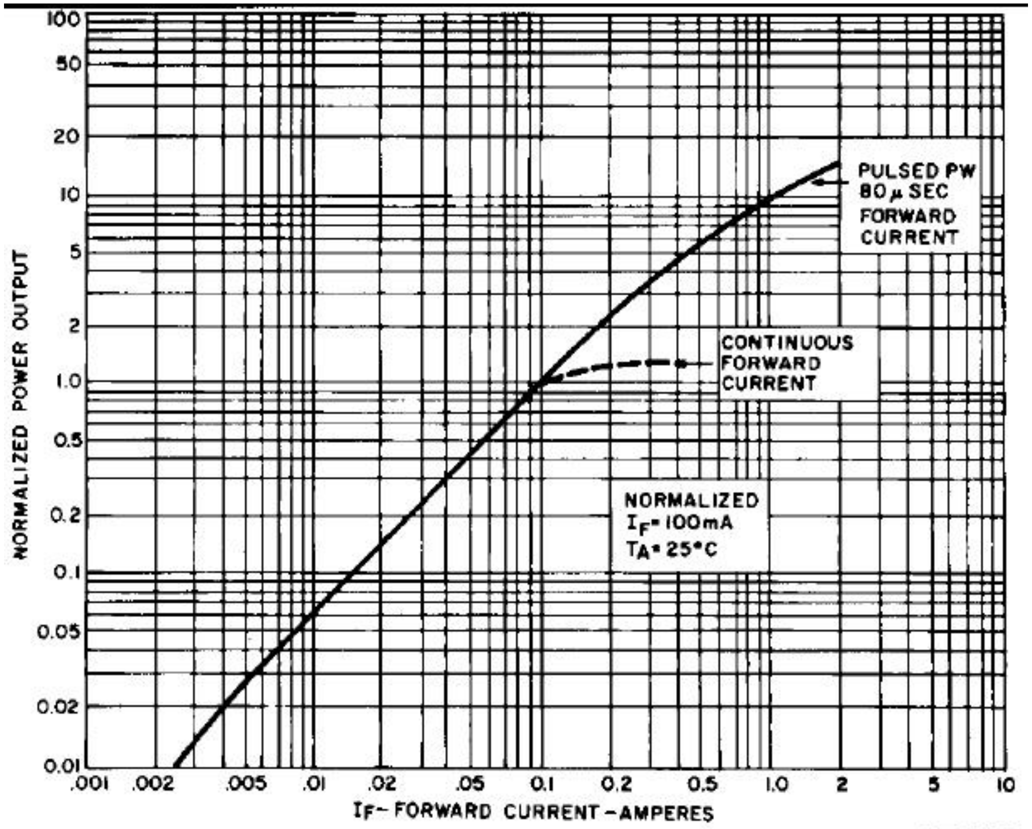
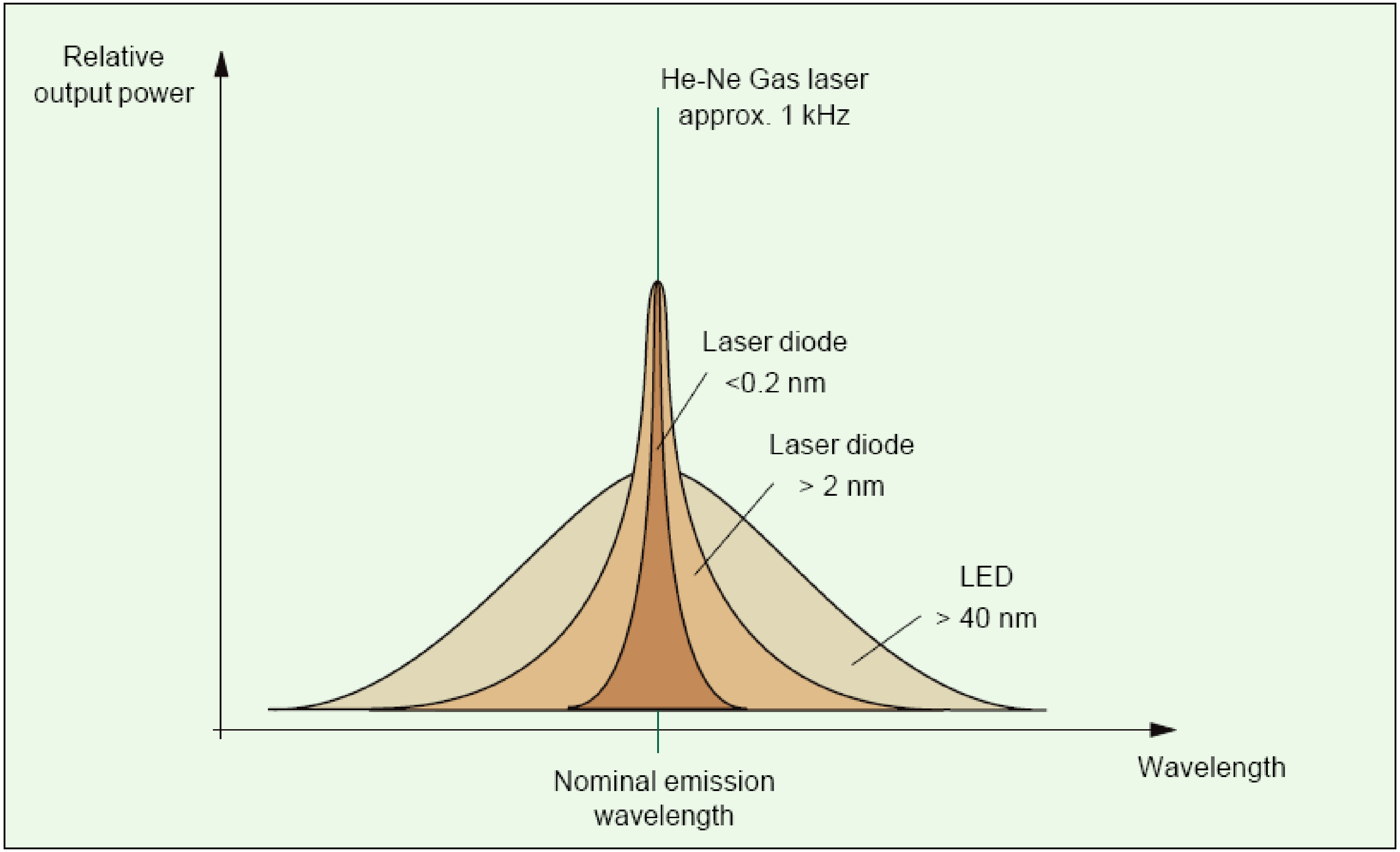


Fig. 1. Power Output vs. Input Current

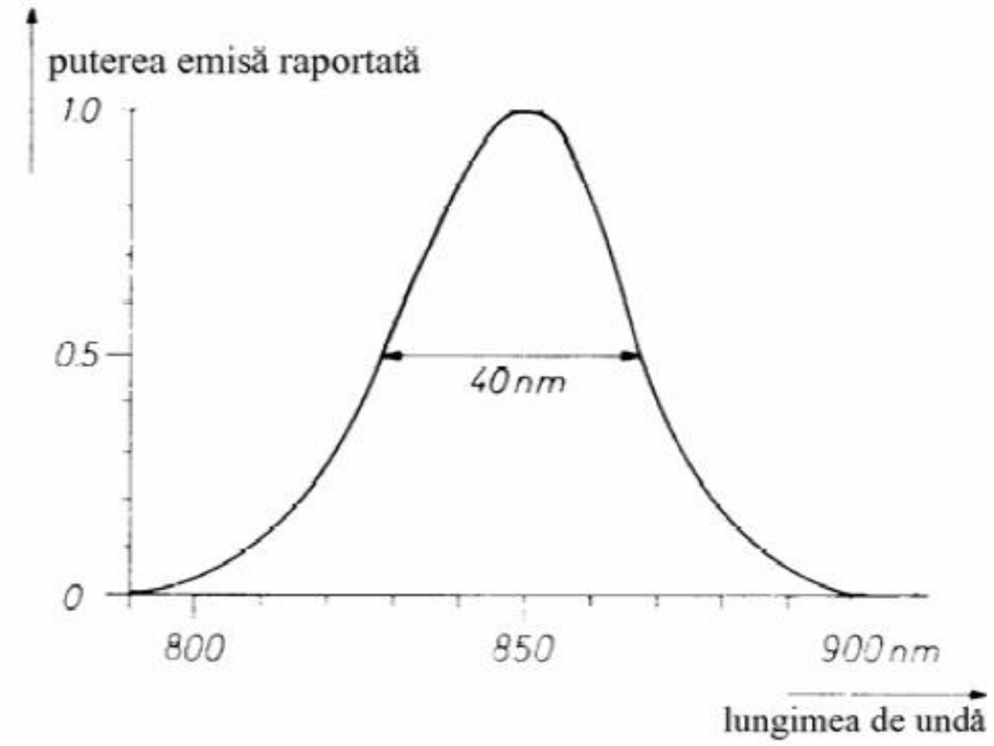
ST1052

Calitatea spectrală a emiţătorilor optici



Latimea spectrala a LED-urilor

- Aproximativ $\Delta\lambda \approx 0.05\lambda$
- Relatie empirica $\Delta\lambda[\mu m] \approx 1.45\lambda^2[\mu m](kT)[eV]$
- Tipic
  - GaAlAs – 20-40 nm
  - InGaAsP
    - SLED – 100 nm
    - ELED – 60-80 nm
  - GaInN – 30-40 nm (10%)



Comportare dinamica a LED

- Puterea de iesire la modulatia cu un semnal sinusoidal cu ω

$$P_{out} = \frac{P_o}{1+\omega^2\tau_{lf}^2}$$

  - Puterea electrica variaza proportional cu patratul curentului
  - Puterea optica variaza proportional cu curentul
- Banda la 3 dB electrica

$$\frac{P_{out}^2}{P_o^2} = \frac{1}{2} \qquad f_{3dB-el} = \frac{1}{2\cdot\pi\cdot\tau_{lf}}$$

  - Banda la 3 dB optic

$$\frac{P_{out}}{P_o} = \frac{1}{2}$$

Comportare dinamica a LED

- Cand curentul care trece prin dispozitiv e mic timpul de viata al purtatorilor e independent de curent si este dependent liniar de nivelul de dopare in regiunea activa
- Cand curentul este mare timpul de viata al purtatorilor este proportional cu $\sqrt{d}$ si invers proportional cu $\sqrt{J}$
- Banda poate fi crescuta
  - Crescand nivelul de dopare
  - Reducand inaltimea zonei active
  - Crescand densitatea de curent

Comportare dinamica a LED

- In domeniul timp
- Timpul de crestere (rise time)

$$t_r = 2.20 \cdot \left(\frac{2 \cdot k \cdot T \cdot C_s}{e \cdot I_p} + \tau_{lf} \right)$$

- Capacitatea asociata sarcinilor in regiunea activa: 350÷1000pF
- Produs Putere × Banda

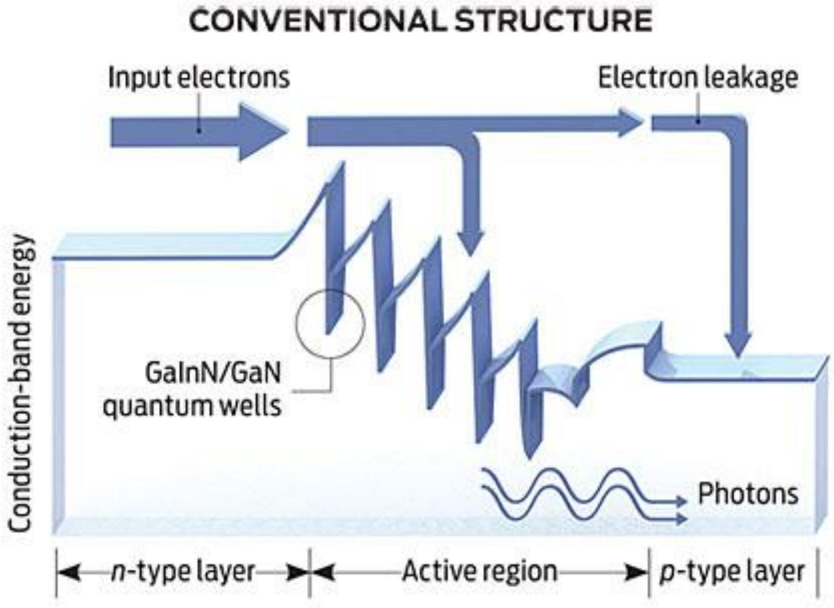
$$P \times \Delta f = \frac{h \cdot c}{2 \cdot \pi \cdot e \cdot \lambda} \cdot \frac{J}{\tau_{lf}}$$

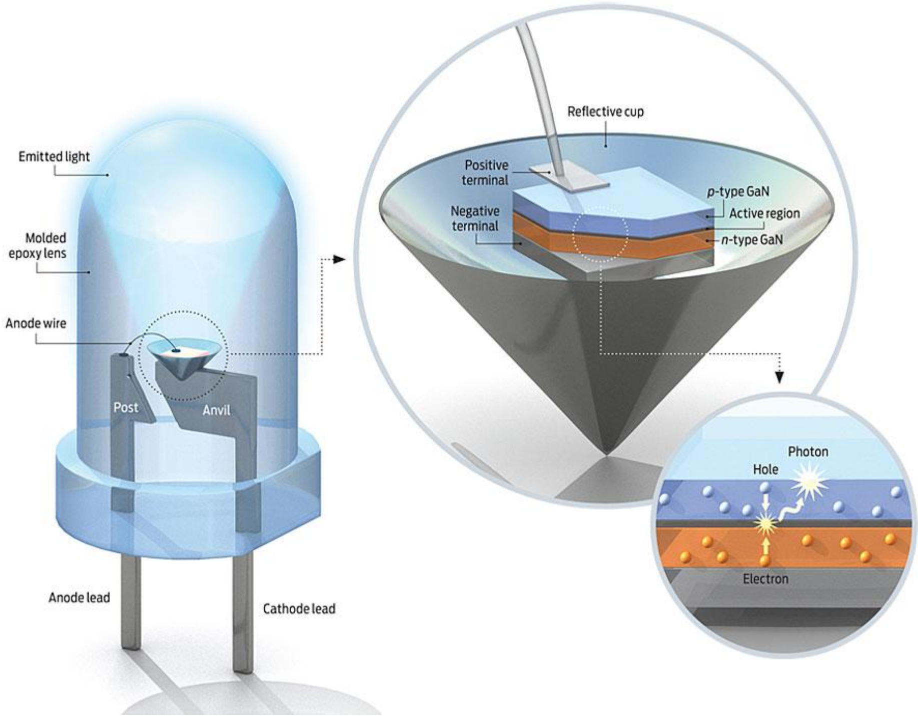
Aplicatii majore LED

- Comunicatii
  - Infrarosu (InGaAsP)
- Vizibil
  - Spectru vizibil (GaAlAs)
- Iluminare
  - Putere ridicata, lumina alba (GaInN)

LED albastru

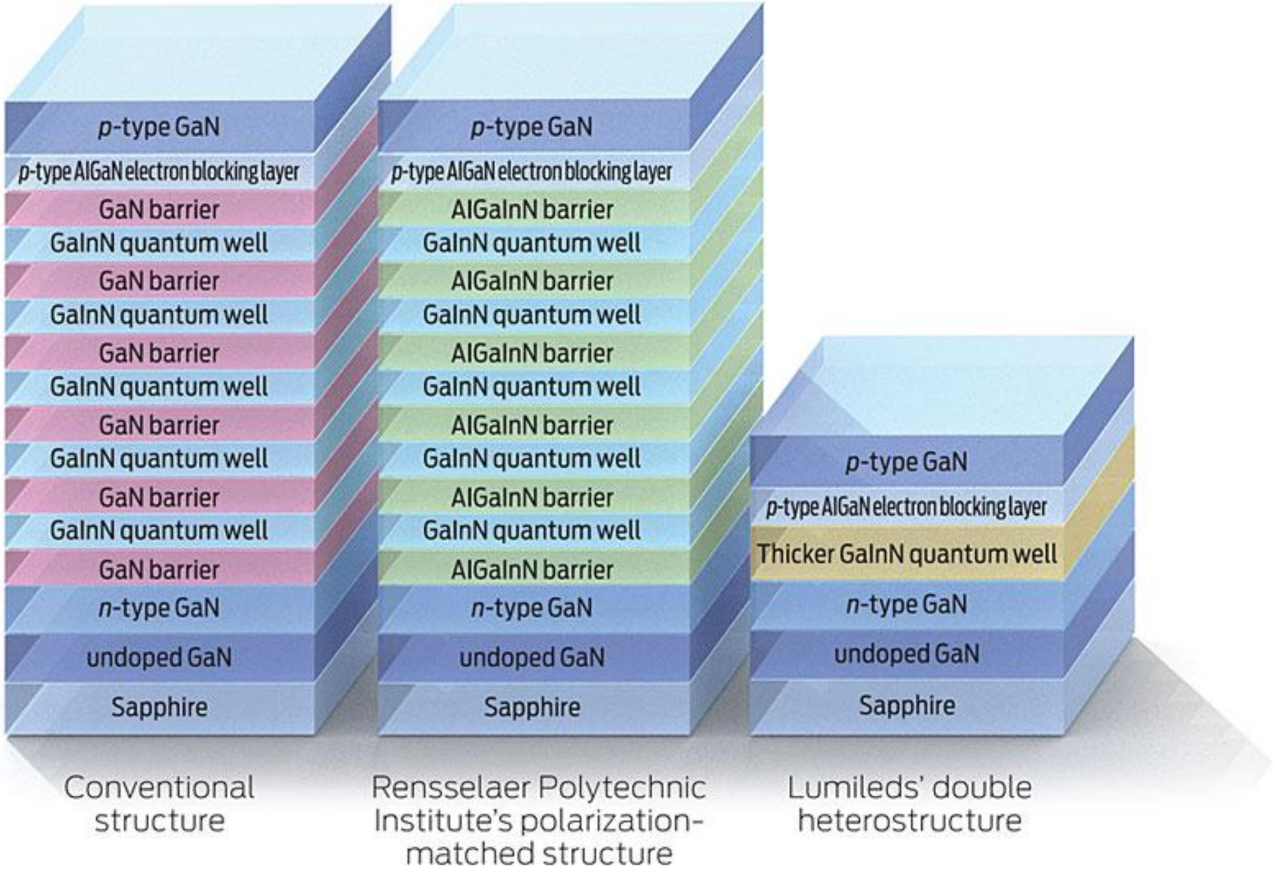
- bazat pe GaInAs
- dezvoltare tardiva (GaN)





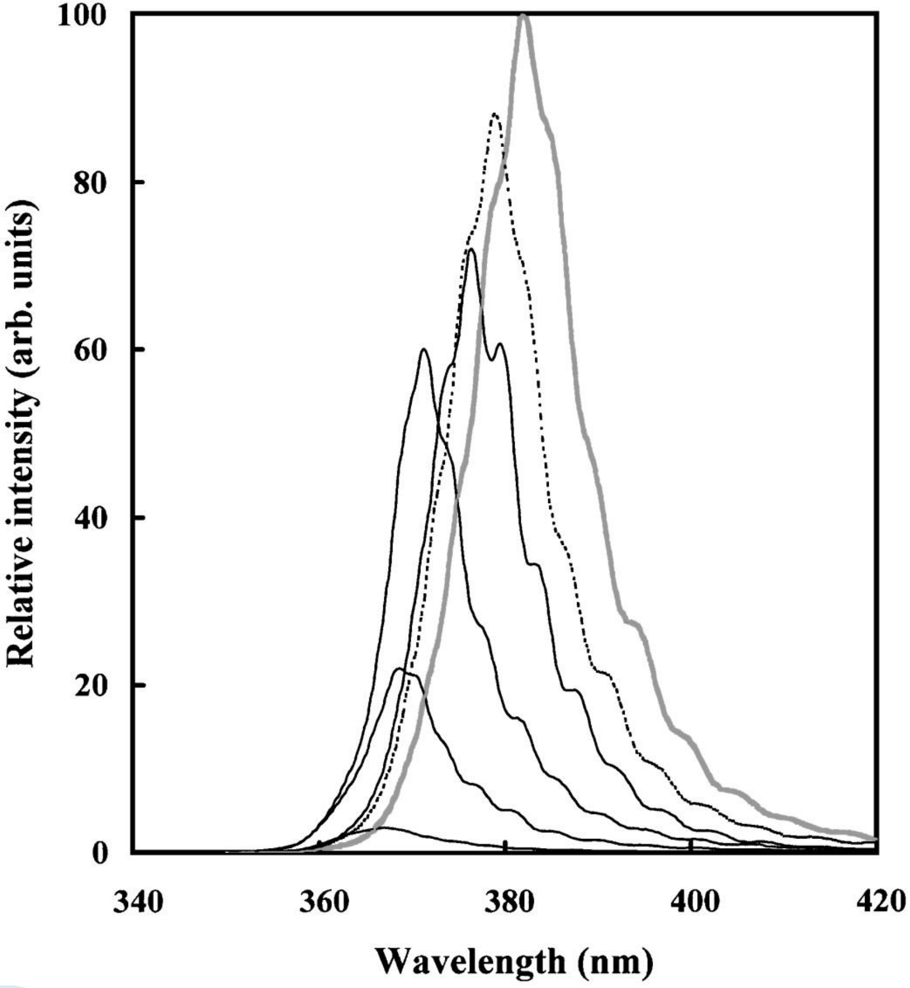
LED albastru

- realizare: Quantum Well/GaN

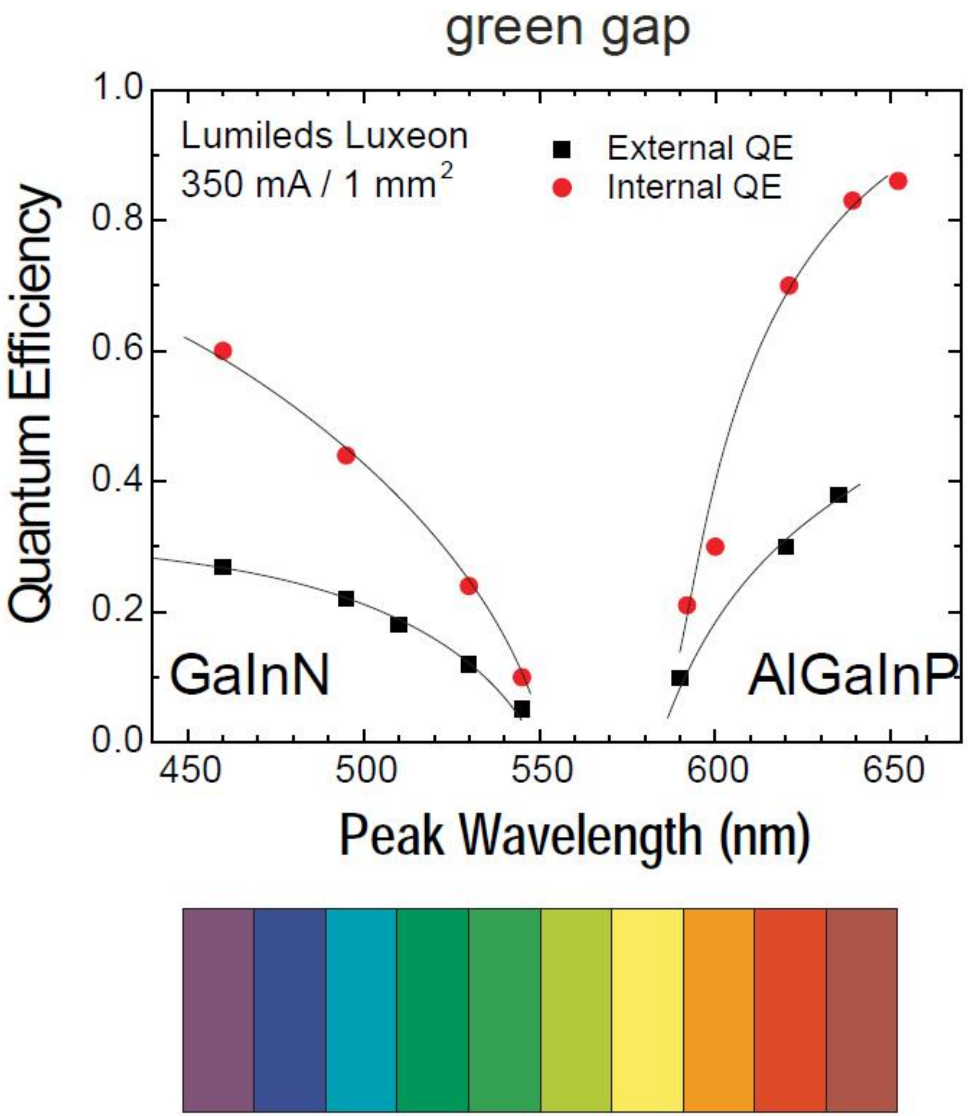


Spectru LED albastru

- Δλ relativ la λ mai mare



Eficienta cuantica



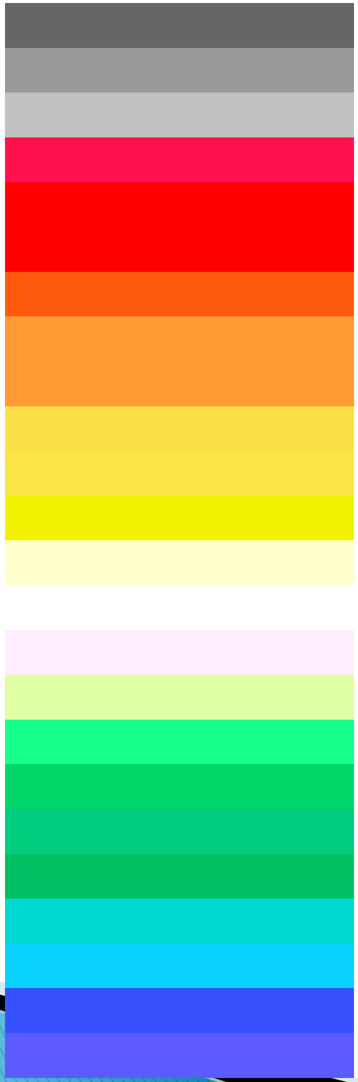
Culori/materiale – 1

	Color	**Wavelength (nm)**	**Voltage (V)**	**Semiconductor Material**
⬛	Infrared	$\lambda > 760$	$\Delta V < 1.9$	Gallium arsenide (GaAs) Aluminium gallium arsenide (AlGaAs)
🟥	Red	$610 < \lambda < 760$	$1.63 < \Delta V < 2.03$	Aluminium gallium arsenide (AlGaAs) Gallium arsenide phosphide (GaAsP) Aluminium gallium indium phosphide (AlGaInP) Gallium(III) phosphide (GaP)
🟧	Orange	$590 < \lambda < 610$	$2.03 < \Delta V < 2.10$	Gallium arsenide phosphide (GaAsP) Aluminium gallium indium phosphide (AlGaInP) Gallium(III) phosphide (GaP)
🟨	Yellow	$570 < \lambda < 590$	$2.10 < \Delta V < 2.18$	Gallium arsenide phosphide (GaAsP) Aluminium gallium indium phosphide (AlGaInP) Gallium(III) phosphide (GaP)
🟩	Green	$500 < \lambda < 570$	$1.9 < \Delta V < 4.0$	Indium gallium nitride (InGaN) / Gallium(III) nitride (GaN) Gallium(III) phosphide (GaP) Aluminium gallium indium phosphide (AlGaInP) Aluminium gallium phosphide (AlGaP)

Culori/materiale – 2

Color		Wavelength (nm)	Voltage (V)	Semiconductor Material
🟦	Blue	$450 < \lambda < 500$	$2.48 < \Delta V < 3.7$	Zinc selenide (ZnSe) Indium gallium nitride (InGaN) Silicon carbide (SiC) as substrate Silicon (Si) as substrate — (under development)
🟪	Violet	$400 < \lambda < 450$	$2.76 < \Delta V < 4.0$	Indium gallium nitride (InGaN)
🟪	Purple	multiple types	$2.48 < \Delta V < 3.7$	Dual blue/red LEDs, blue with red phosphor, or white with purple plastic
⬛	Ultraviolet	$\lambda < 400$	$3.1 < \Delta V < 4.4$	Diamond (235 nm) Boron nitride (215 nm) Aluminium nitride (AlN) (210 nm) Aluminium gallium nitride (AlGaN) Aluminium gallium indium nitride (AlGaInN) — (down to 210 nm)
	White	Broad spectrum	$\Delta V = 3.5$	Blue/UV diode with yellow phosphor

Denumiri tipice – LED



Wavelength (nm)	Color Name
940	Infrared
880	Infrared
850	Infrared
660	Ultra Red
635	High Eff. Red
633	Super Red
620	Super Orange
612	Super Orange
605	Orange
595	Super Yellow
592	Super Pure Yellow
585	Yellow
4500K	"Incandescent” White
6500K	Pale White
8000K	Cool White
574	Super Lime Yellow
570	Super Lime Green
565	High Efficiency Green
560	Super Pure Green
555	Pure Green
525	Aqua Green
505	Blue Green
470	Super Blue
430	Ultra Blue

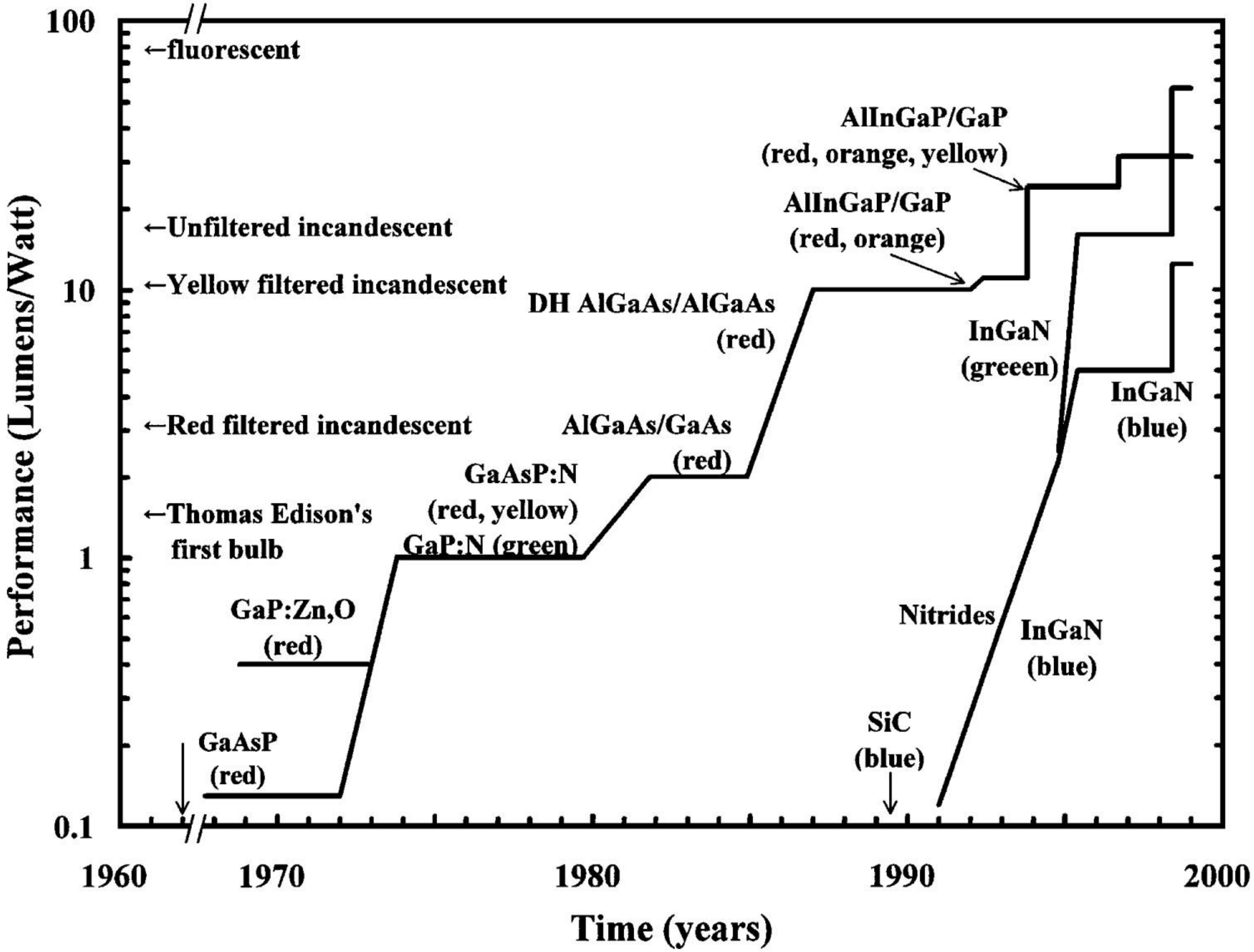
Aplicatii majore LED

- Comunicatii
  - Infrarosu (InGaAsP)
- Vizibil
  - Spectru vizibil (GaAlAs)
- Iluminare
  - Putere ridicata, lumina alba (GaInN)

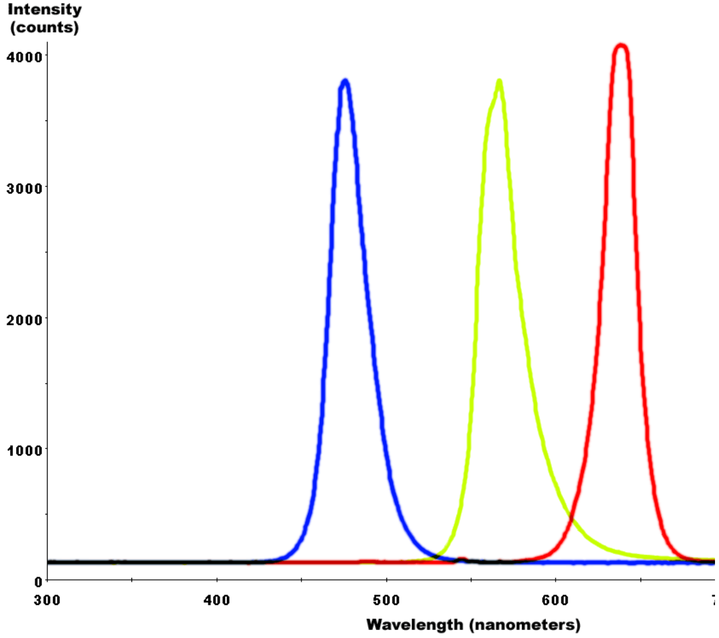
Eficienta

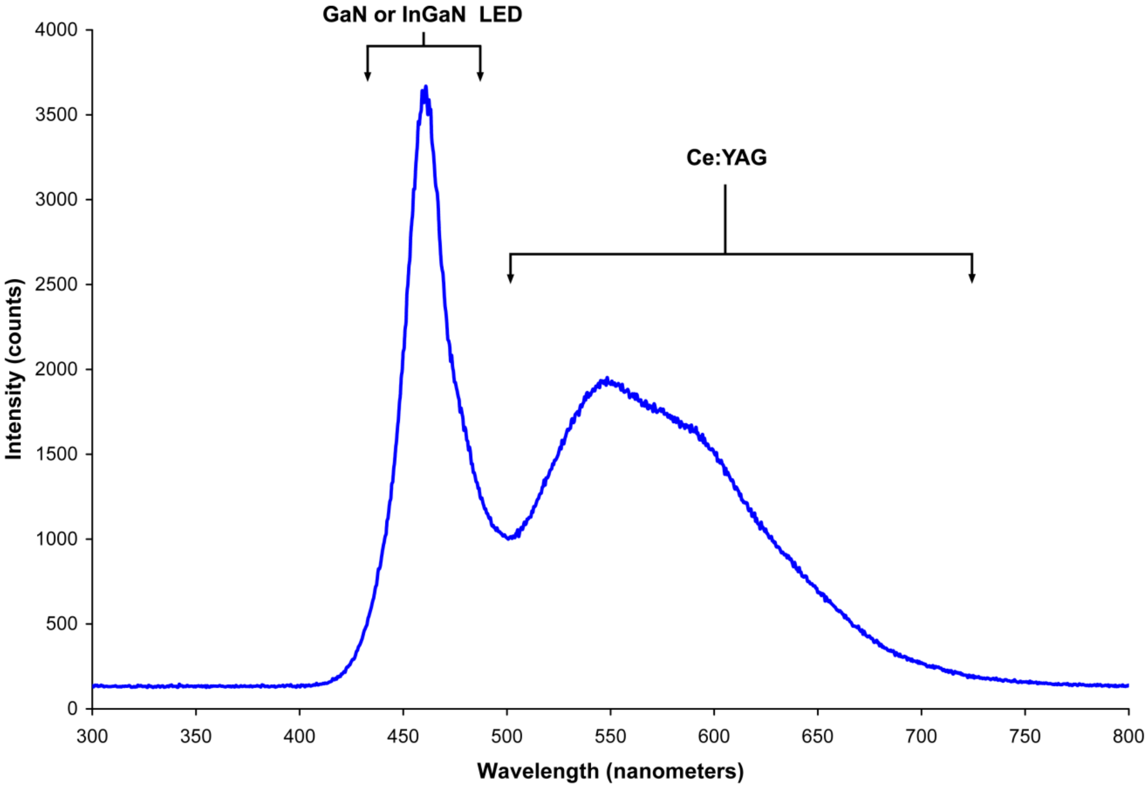
- Bec cu incadescenta
  - 16 lm/W
- Tub fluorescent
  - 100 lm/W
- LED
  - curent: 250 lm/W
  - curand: 300 lm/W

Eficienta in timp

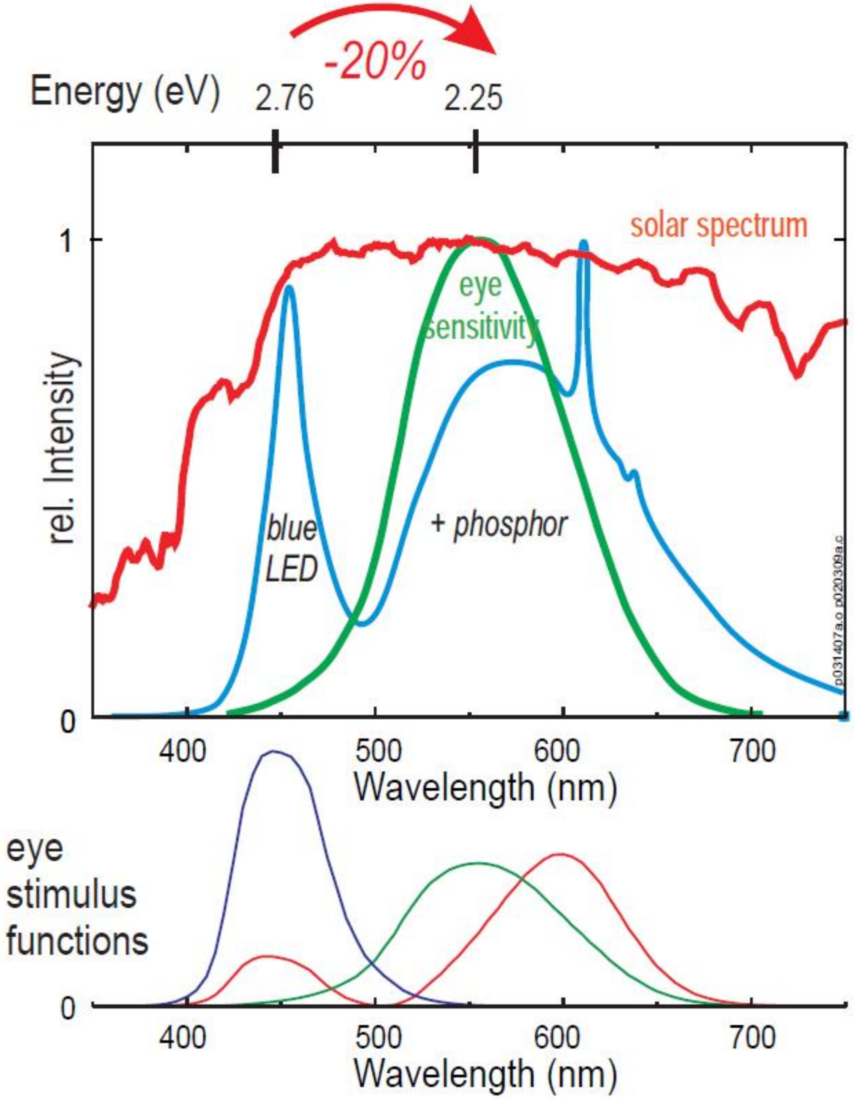


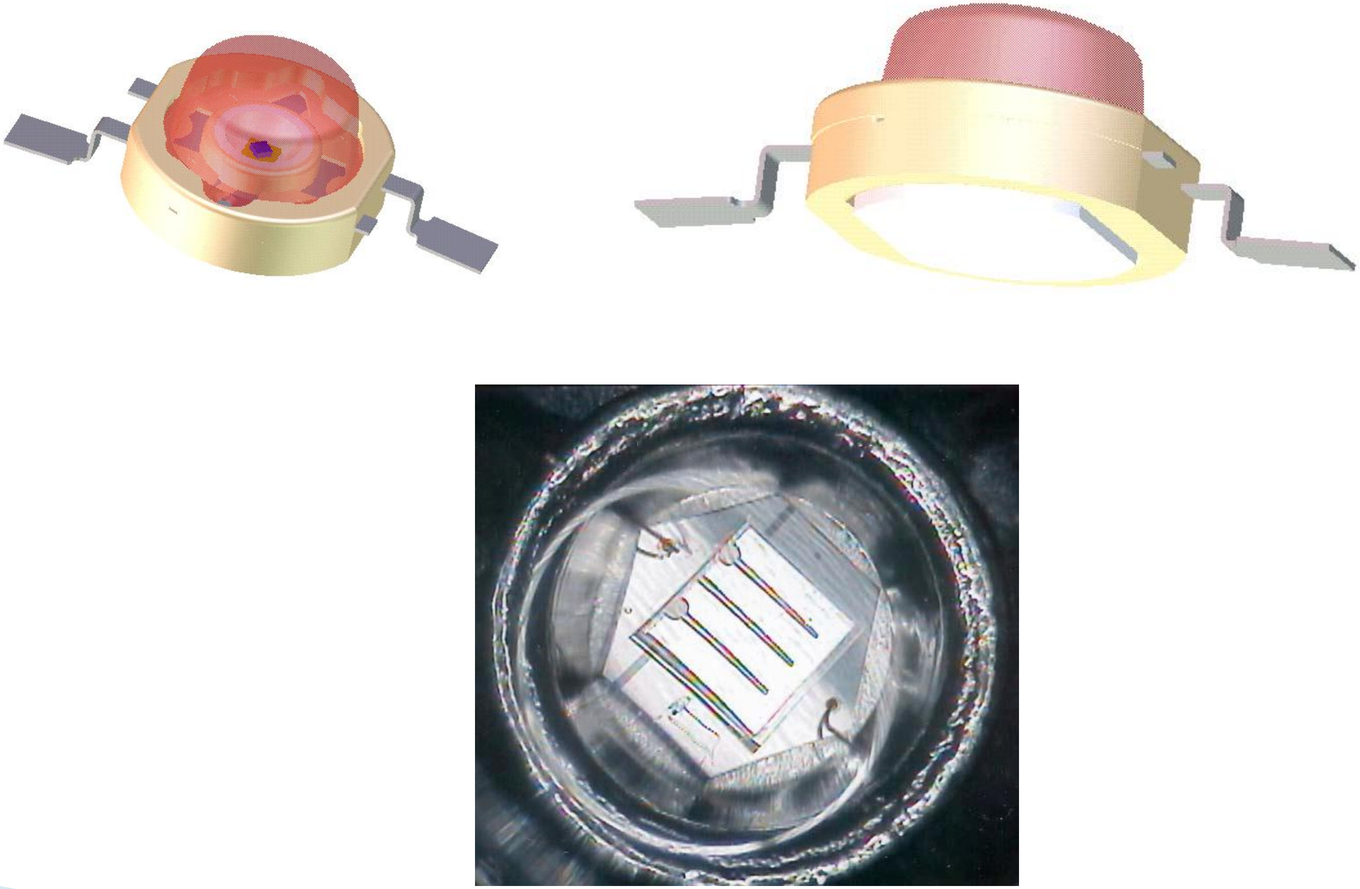
Culoare alba



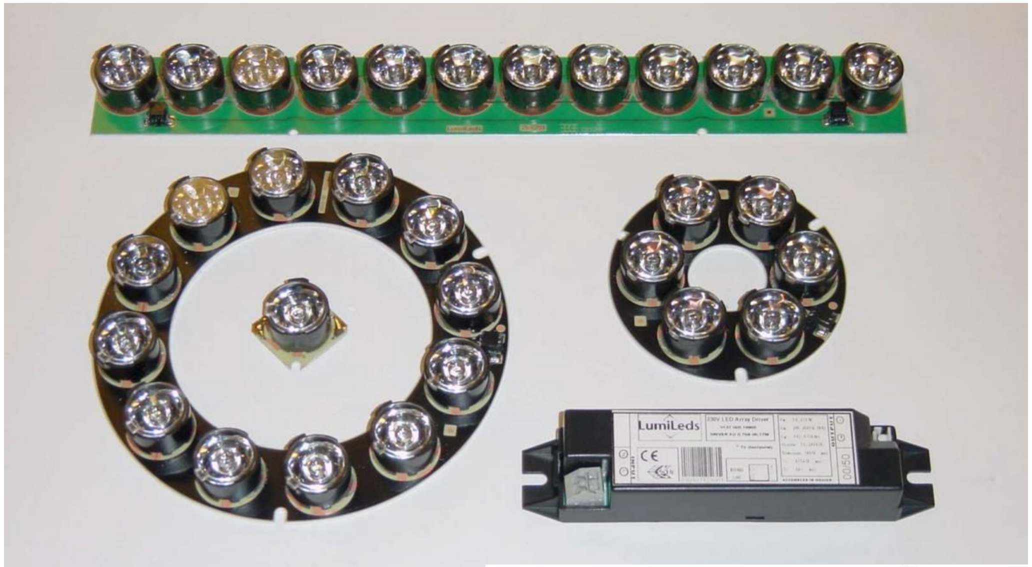


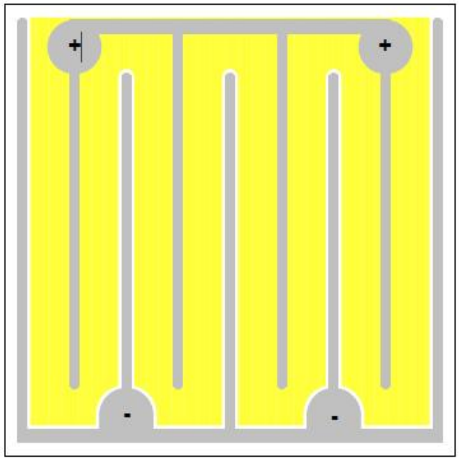
Fosfor activat de LED albastru/UV



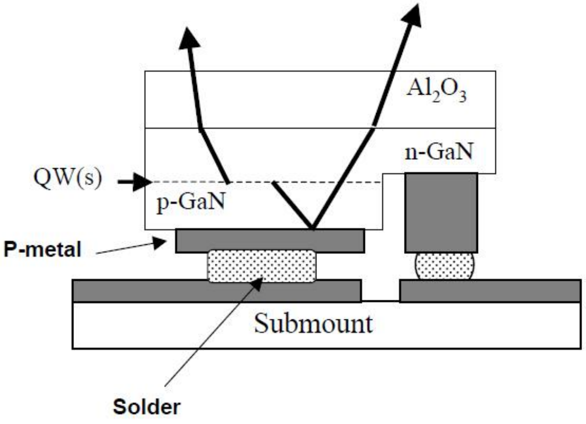


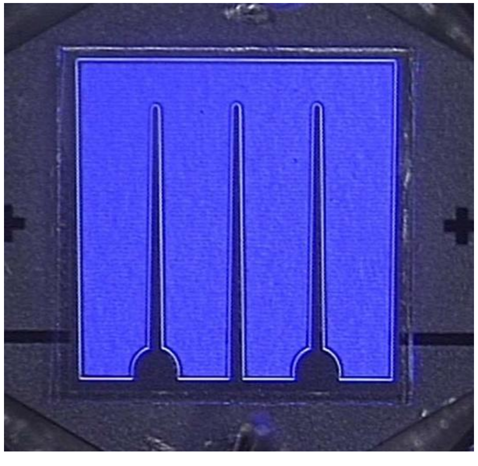
Realizare LED de putere



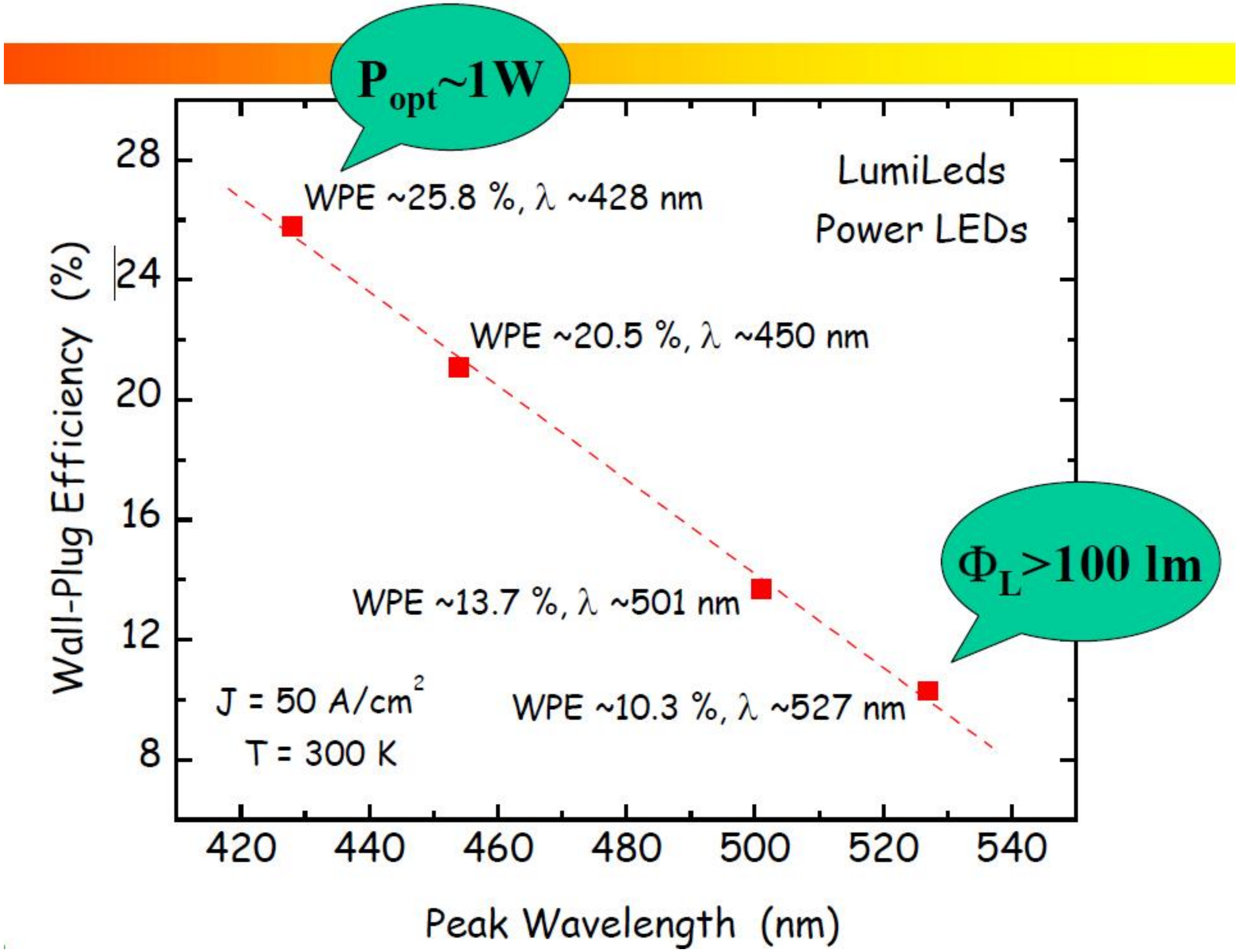


$A_{chip} \sim 1 \times 1\ mm^2$; $N = 4$



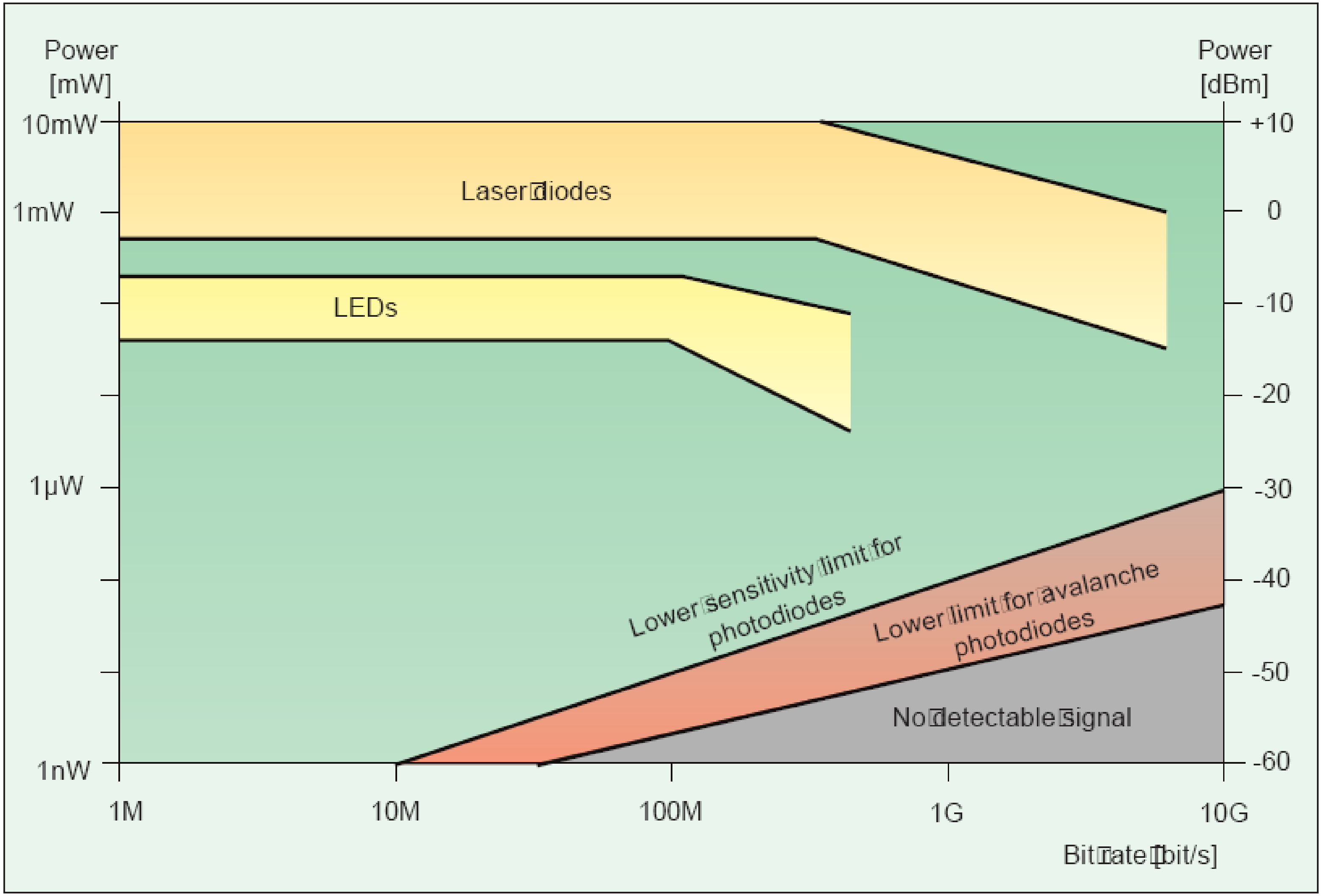


Performanta



OLED

Limite putere/bandă a dispozitivelor optoelectronice



Contact

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