Optoelectronică, structuri şi tehnologii

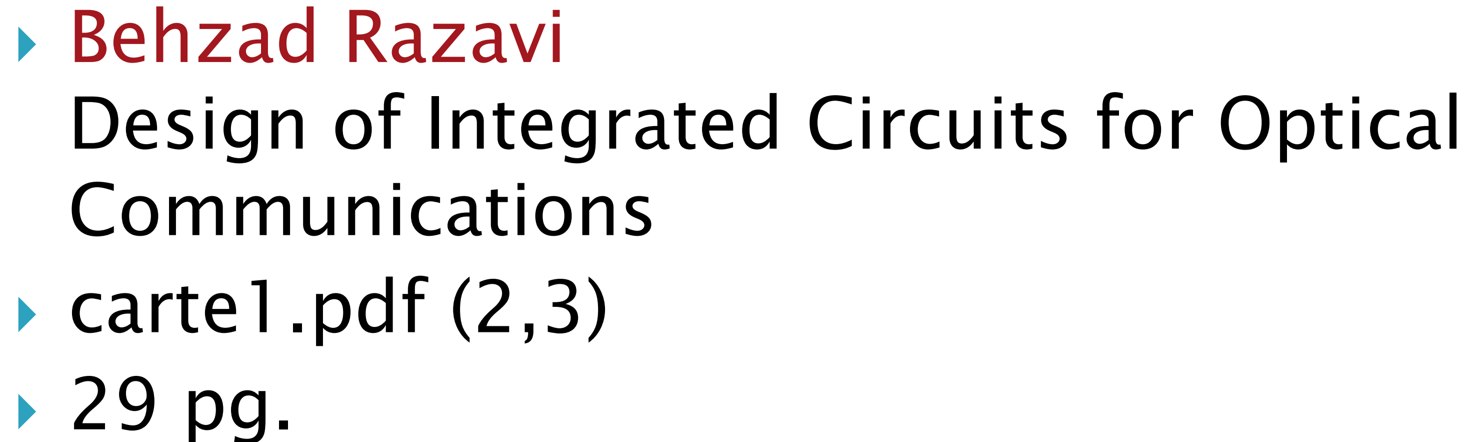
Curs 11

2014/2015

Orar

- Examen
  - 10.12.2013, P7

Capitolul 12



Lista subiecte

- Amplificatoare transimpedanţă
  - 4.1
  - 4.1.1
  - 4.2
  - 4.2.1
  - 4.3
  - 4.3.1
- Circuite pentru controlul emiţătoarelor optice
  - 10.3
  - 10.3.1
  - 10.4
  - 10.4.1

Dioda Laser

Capitolul 9

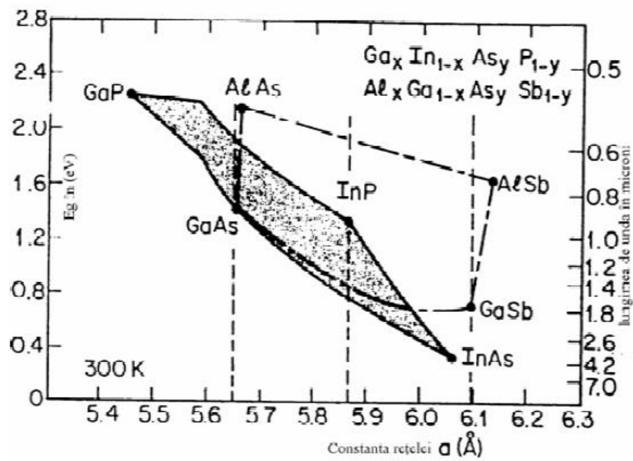
Lăţimea benzii interzise/lungime de undă pentru materialele uzuale

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

$$E_g = h\nu; \quad \lambda = \frac{hc}{E_g}$$

- h constanta lui Plank $6.62 \cdot 10^{-32}$ Ws^2
- c viteza luminii in vid $2.998 \cdot 10^8$ m/s

Dependenţa benzii interzise de constanta reţelei



Wavelength (μm)

10 5 2 1.5 1 0.9 0.8 0.6 0.5

Lattice spacing (nm)

0.62
0.60
0.58
0.56
0.54

InAs

InP

AlAs

GaAs

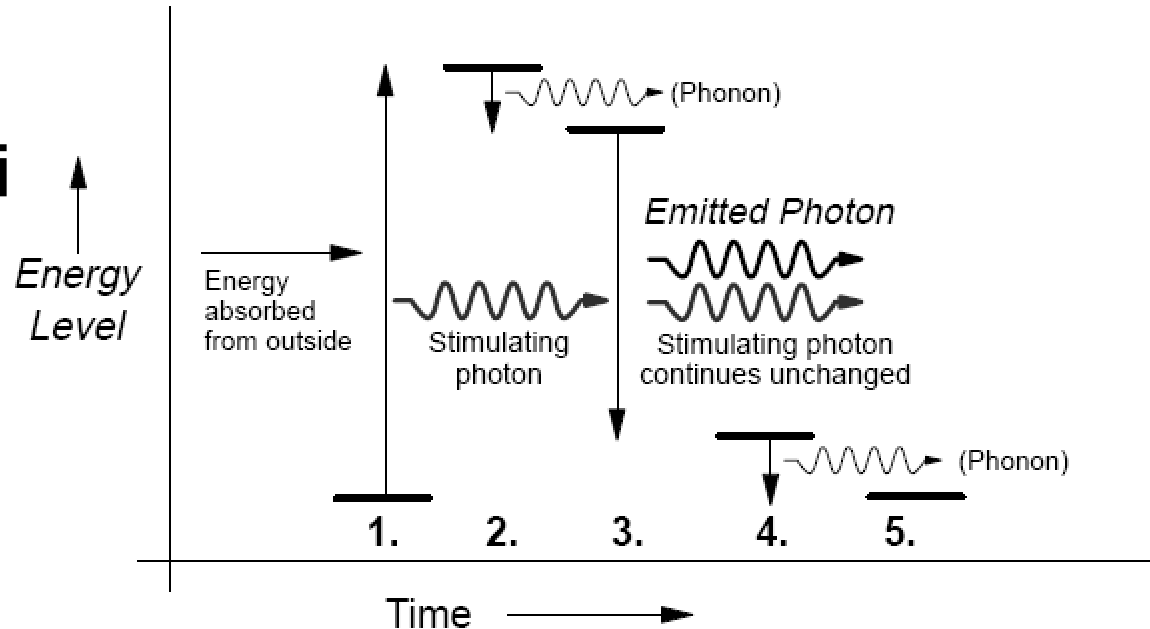
GaP

0 0.5 1.0 1.5 2.0 2.5

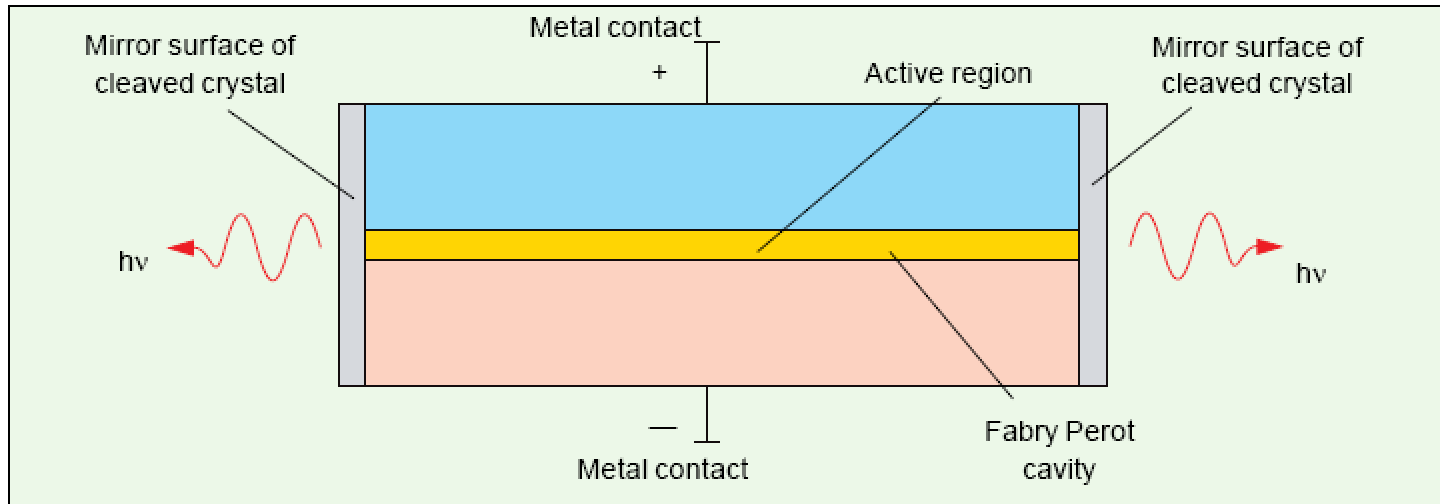
Bandgap energy (eV)

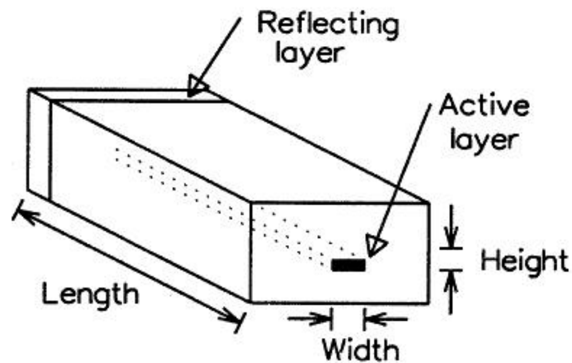
Materiale cu 4 nivele energetice

- La un material cu 4 nivele energetice tranzitia radianta a electronului (3) se termina intr-o stare instabila, starea de echilibru obtinandu-se prin emisia unui fonon
- Inversiunea de populatie se obtine mult mai usor datorita electronilor din starea intermediara

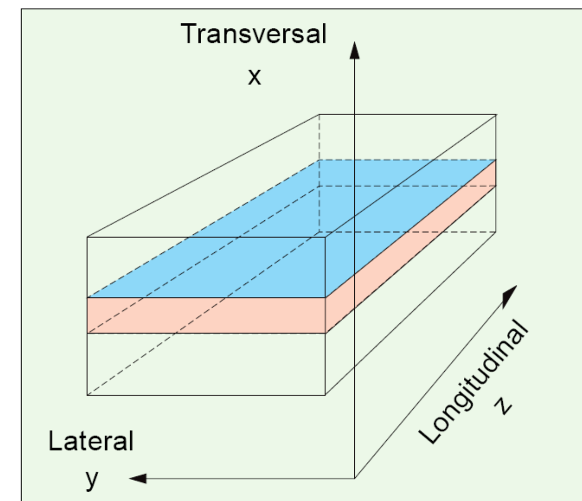


Dioda LASER Fabry Perot



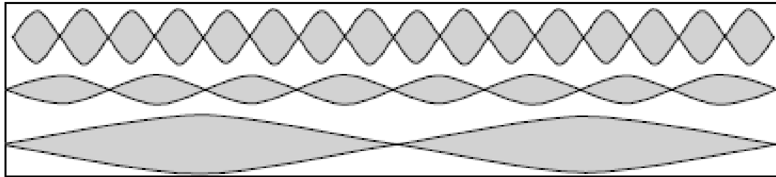


Height: 0.1 – 0.2 μm
Length: 250 – 500 μm
Width: 5 – 15 μm
Sides: rough–cut
Front: cleaved
Back: 100% reflector

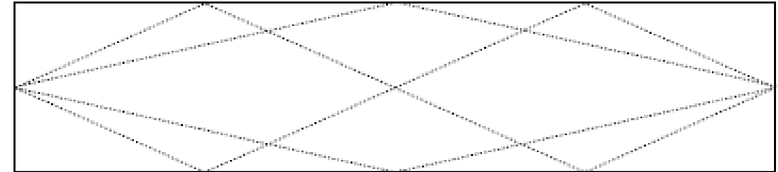


Definirea directiilor in dioda LASER

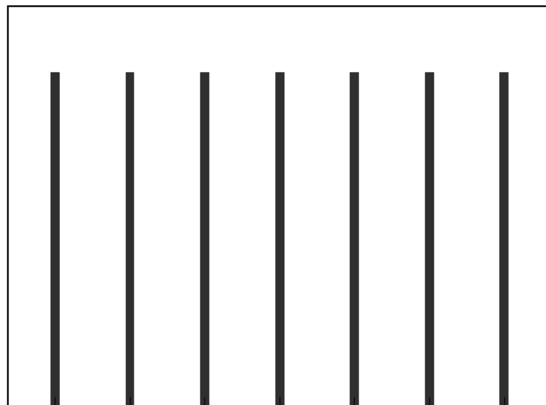
Spectrul diodei LASER



Longitudinal Modes

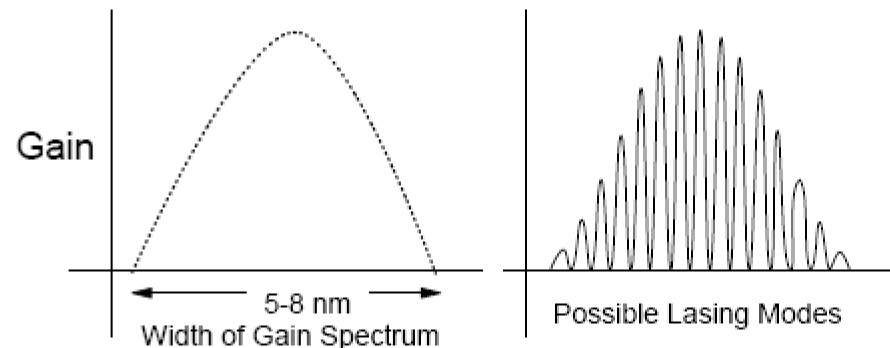


Lateral Modes



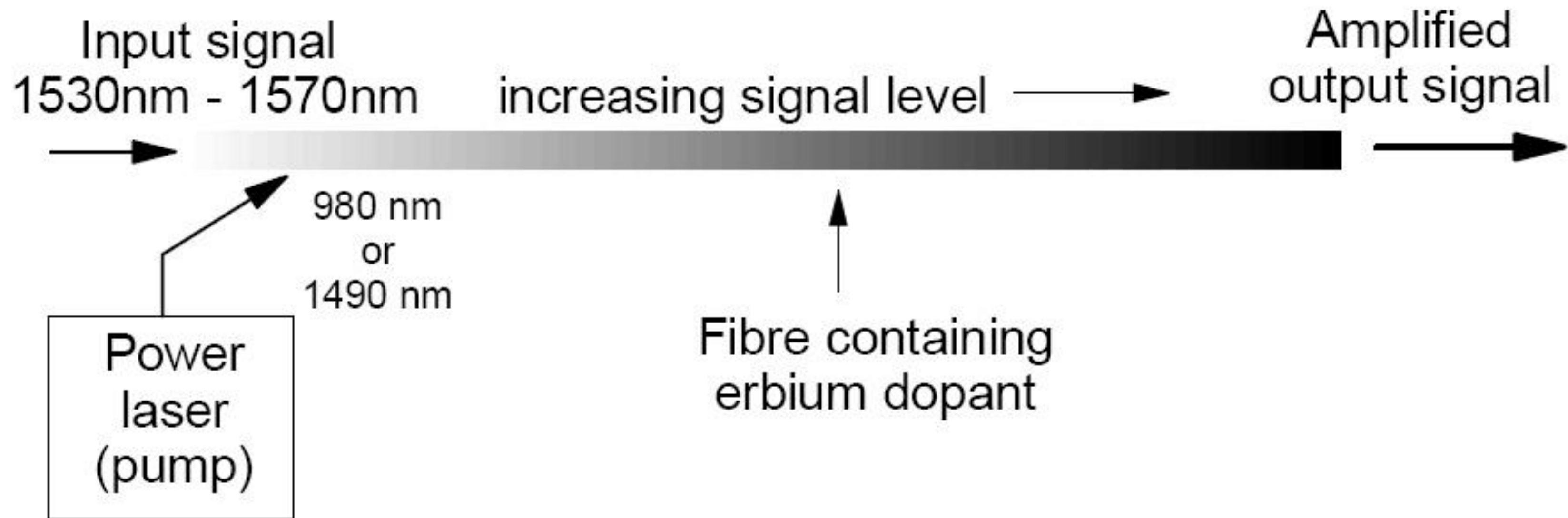
$$f_k = k \cdot \frac{c_0}{2 \cdot n \cdot L} \qquad \Delta f = \frac{c_0}{2 \cdot n \cdot L}$$

$$\Delta\lambda \cong \frac{\lambda_0^2}{2 \cdot n \cdot L}$$

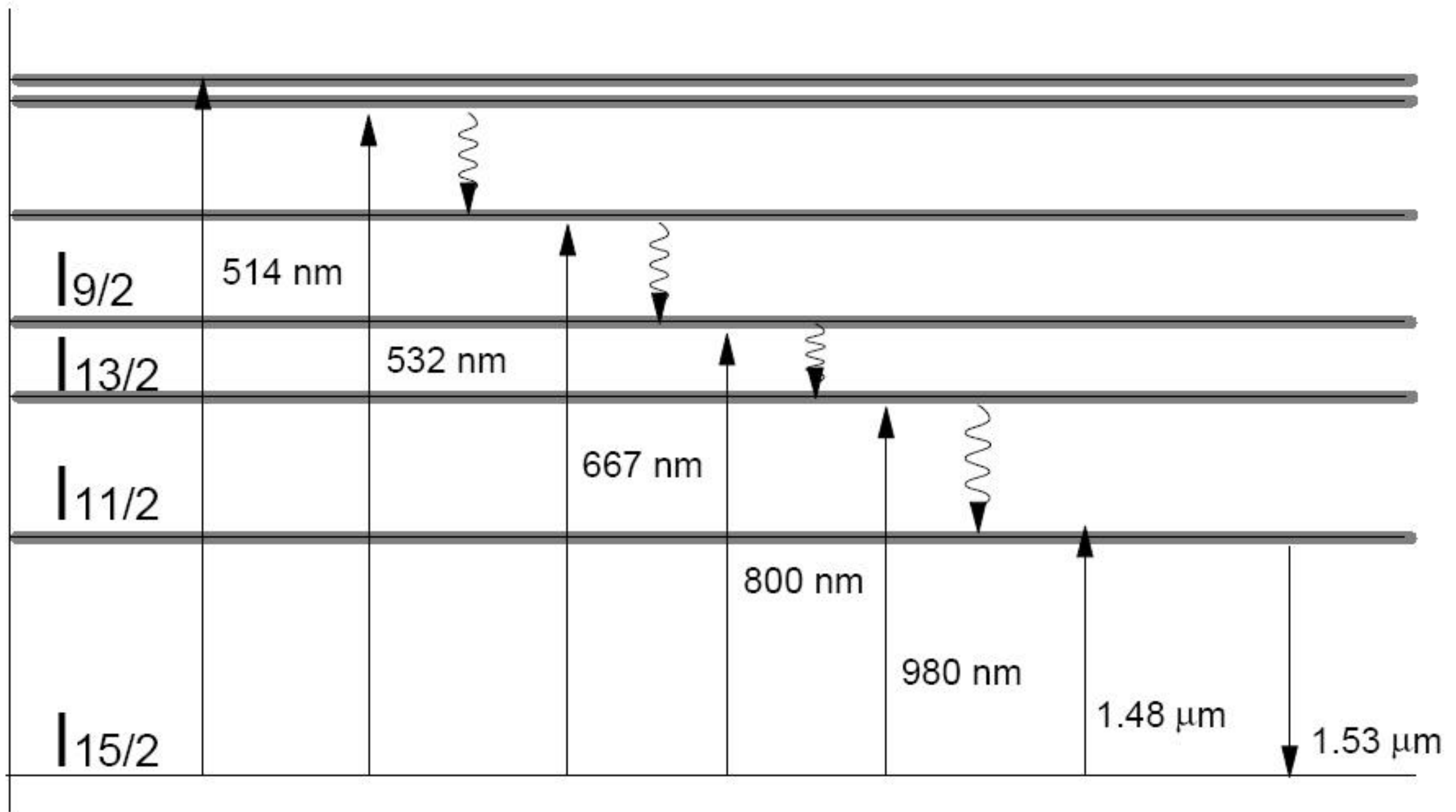


EDFA

- Erbidium Dopped Fiber Amplifier



EDFA



Fotodioda

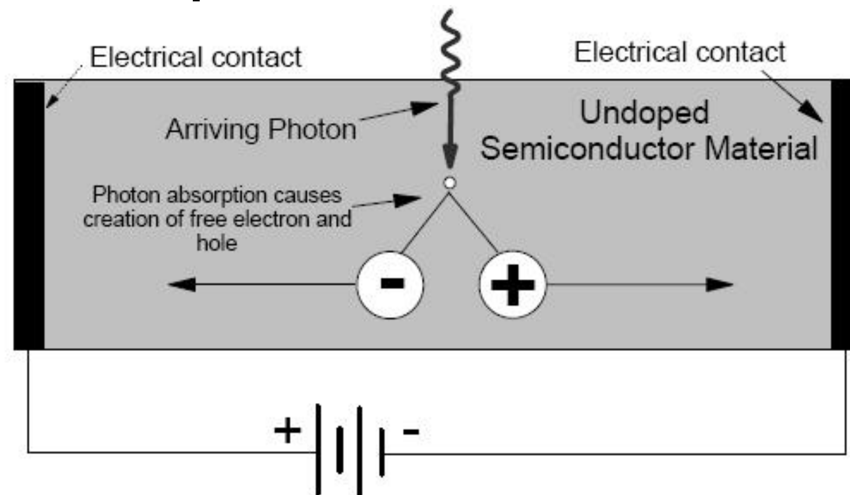
Capitolul 10

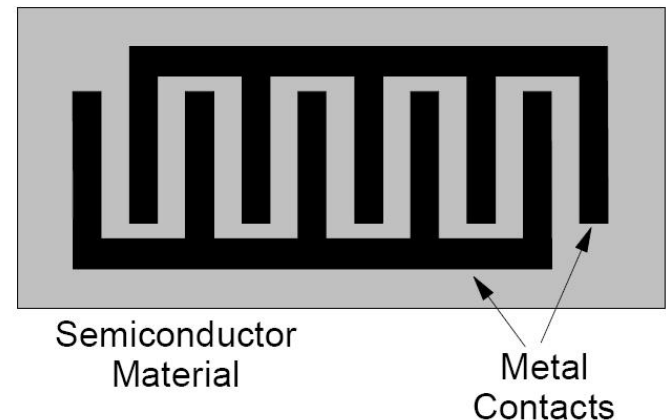
Detectori optici

- Cerinte
  - eficienta crescuta a conversiei optic/electric
  - zgomot redus
  - raspuns uniform la diferite lungimi de unda
  - viteza de raspuns ridicata
  - liniaritate
- Principii de operare
  - fotoconductori $R = R(P_o)$
  - fototranzistori $I_B = I_B(P_o)$
  - fotodiode $I = I(P_o)$
    - pn
    - pin
    - pin cu multiplicare in avalansa
    - Schottky

Fotoconductori

- Principiu

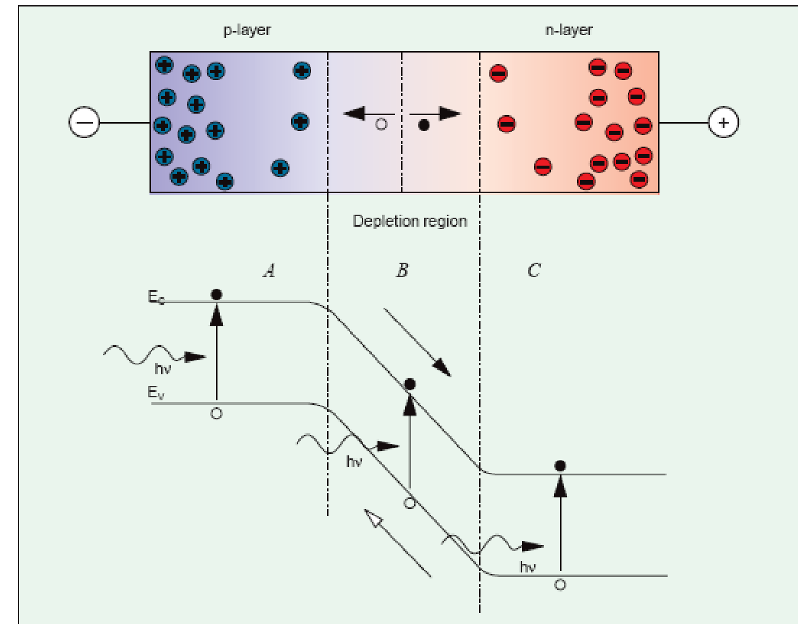


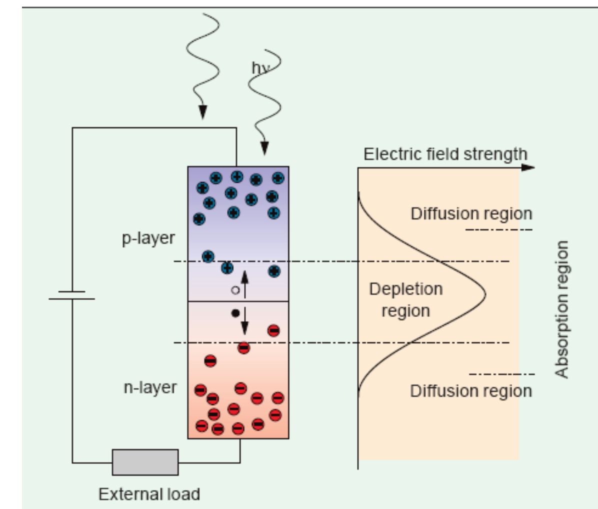


- Recent dispozitive Metal Semiconductor Metal (filtru interdigital) au inceput sa fie utilizate pentru usurinta de fabricare si integrare in aplicatii mai putin pretentioase

Fotodioda – Principiul de operare

- Jonctiunea pn este polarizata invers
- Lumina este absorbita in regiunea golita de purtatori, un foton absorbit generand o pereche electron-gol
- Sarcinile sunt separate de campul electric existent in regiunea golita si genereaza un curent in circuitul exterior





Fotodioda – Principiul de operare

- Energia necesara pentru eliberarea unei perechi electron gol

$$h\nu = \frac{hc}{\lambda} \geq E_g$$

- Lungime de unda de taiere

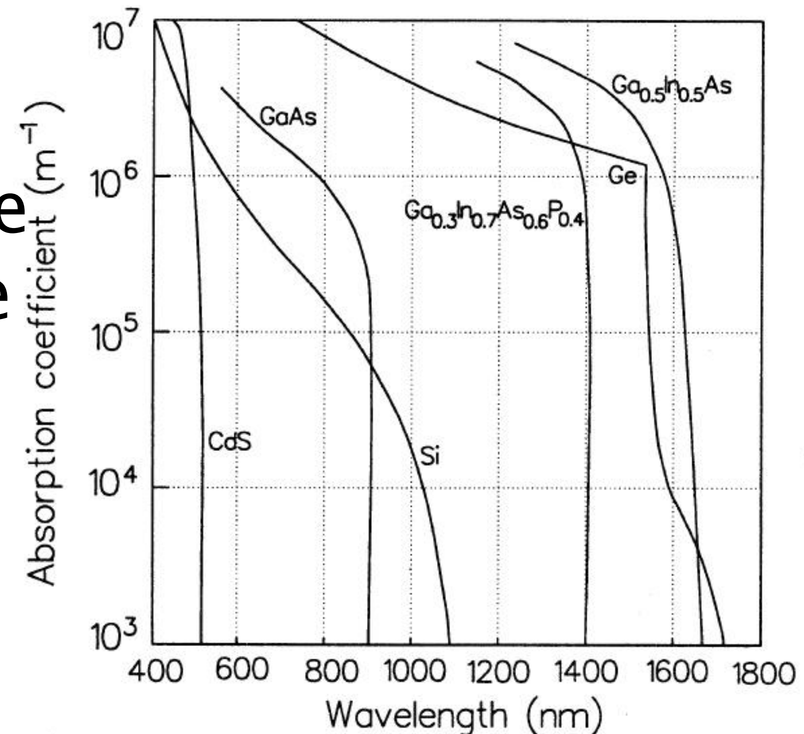
$$\lambda_{\max} = \frac{hc}{E_g}$$

- Puterea optica absorbita in zona golita de purtatori (w) aflata la o adincime d in interiorul dispozitivului

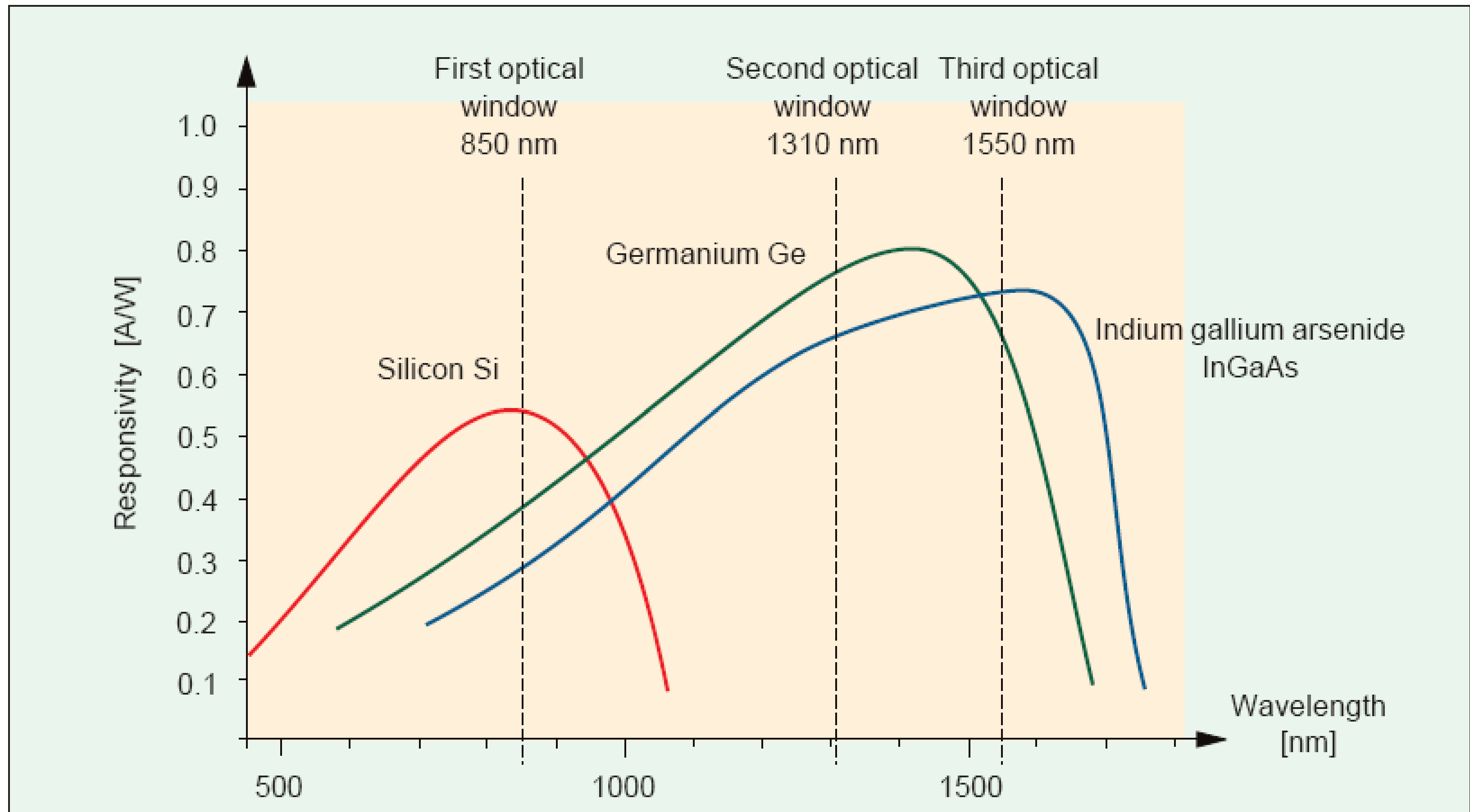
$$P(w) = P_i \cdot e^{-\alpha \cdot d} \cdot \left(1 - e^{-\alpha \cdot w}\right) \cdot \left(1 - R_f\right)$$

Fotodioda – Principiul de operare

- Coeficientul de absorbtie pentru materialele uzuale
- Valoarea mare a coeficientului de absorbtie la lungimi de unda reduse implica scaderea responzivitatii
- Ca urmare comportarea **tuturor** materialelor este de tip trece banda



Materiale utilizate pentru fotodiode



Fotodioda – Marimi caracteristice

- Eficienta cuantica – raportul dintre numărul de perechi electron–gol generate şi numărul de fotoni incidenţi

$$\eta = \frac{n_e}{n_f}$$

- In unitatea de timp numarul de fotoni depinde de puterea optica, iar numarul de electroni impune curentul generat

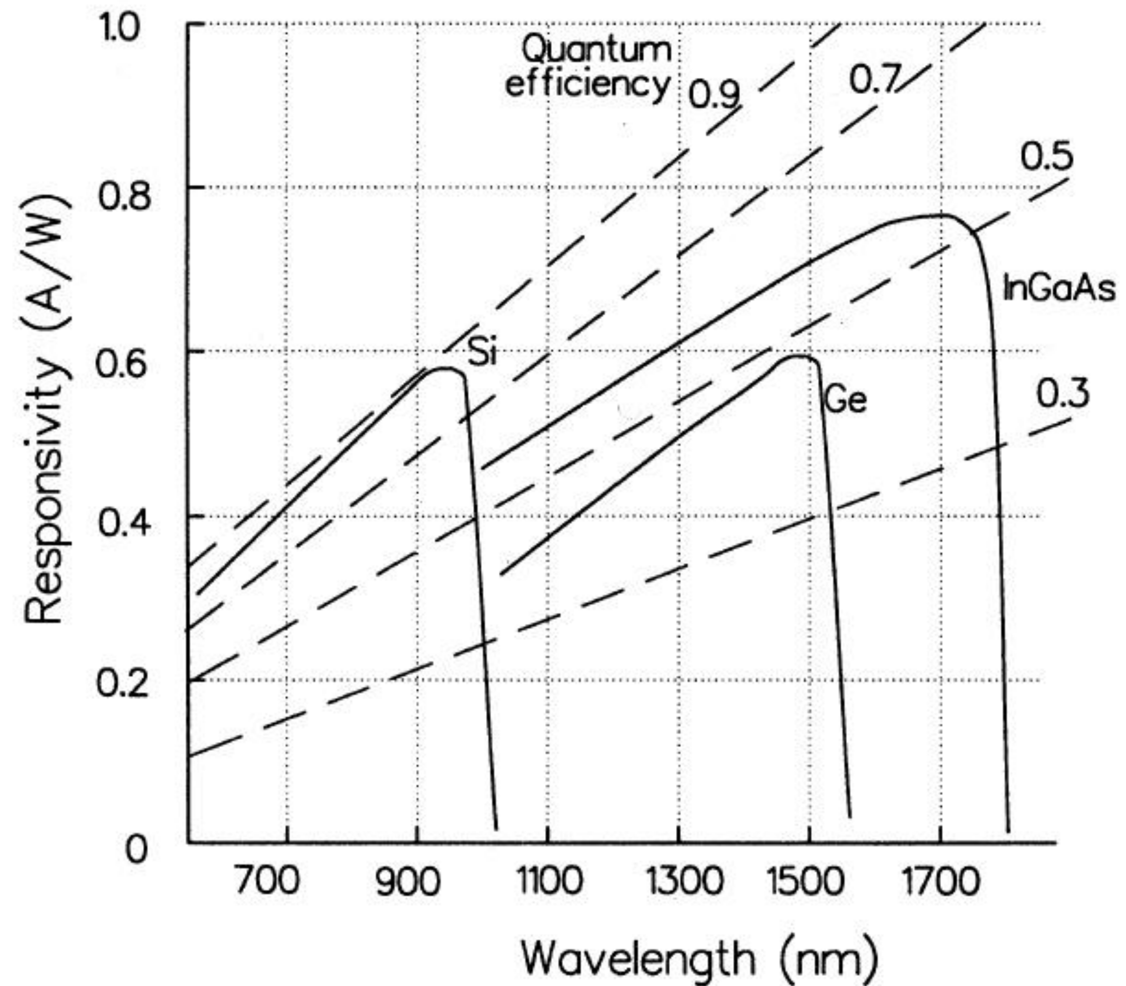
$$\eta = \frac{I/e}{P/h\nu}$$

- Responzivitatea

$$R = \frac{I}{P_o} = \frac{\eta \cdot e \cdot \lambda}{hc} \qquad R = 0.8 \cdot \eta \cdot \lambda[\mu m] \qquad \left[\frac{A}{W}\right]$$

Fotodiode – marimi caracteristice

$$R = \frac{I}{P_o} = \eta \cdot \frac{e}{hc} \cdot \lambda$$



Materiale utilizate pentru fotodiode

Material	λ [μm]	Responsivitate [A/W]	Viteza [ns]	Curent de intuneric
Si	0.85	0.55	3	1
Si	0.65	0.4	3	1
InGaAs	1.3-1.6	0.95	0.2	3
Ge	1.55	0.9	3	66

- Dezavantajul major pentru Ge este curentul de intuneric mare

Material	Eg (eV)
GaAs	1.43
GaSb	0.73
$GaAs_{0.88}Sb_{0.12}$	1.15
Ge	0.67
InAs	0.35
InP	1.35
$In_{0.53}Ga_{0.47}As$	0.75
$In_{0.14}Ga_{0.86}As$	1.15
Si	1.14

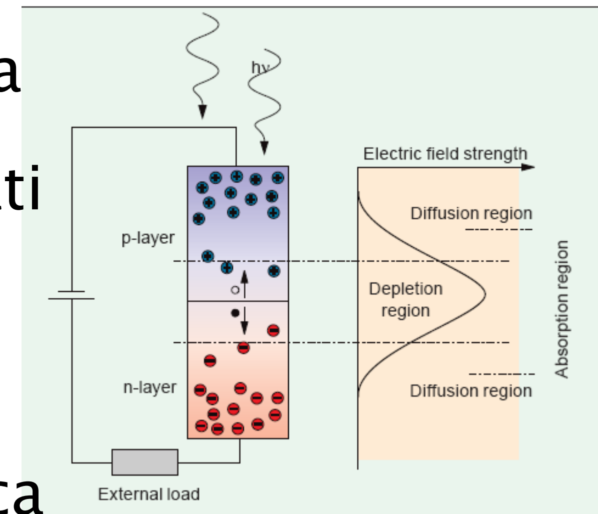
Curent de intuneric

- Curentul invers al jonctiunii p–n, datorat agitatiei termice, prezent in absenta iluminarii
- Constituie o importanta sursa de zgomot (limiteaza aplicatiile Ge)

$$I_D = I_S \approx \frac{\beta \cdot kT}{eR_0}$$

  - β – coeficient de idealitate $\beta = 1 \div 2$
  - R_0 – rezistenta la intuneric a diodei (invers proportionala cu aria diodei)

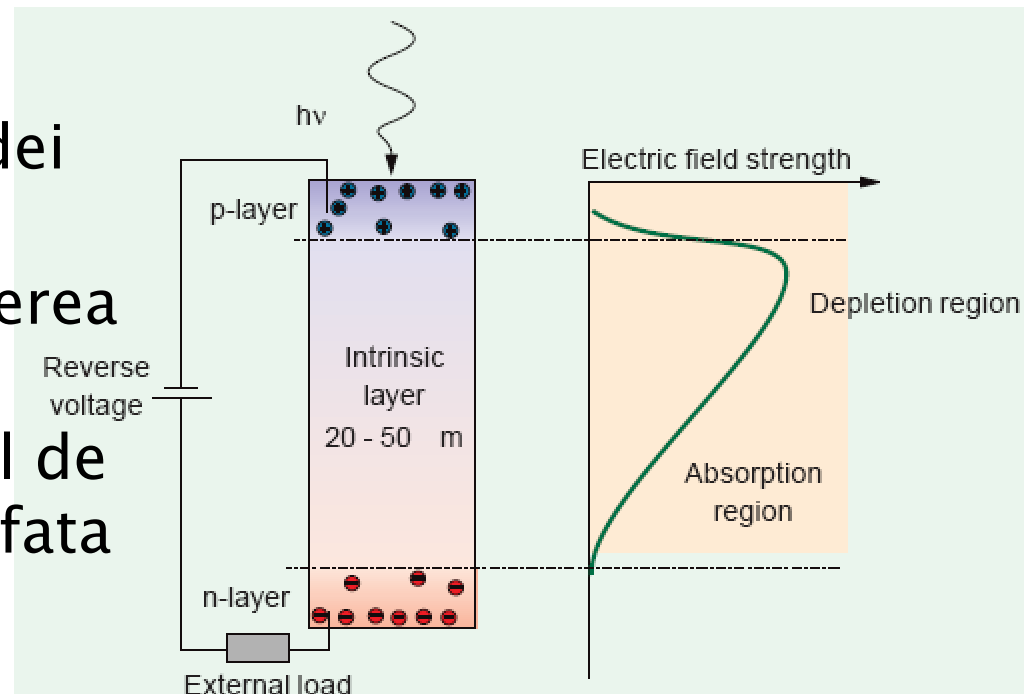
Fotodioda PIN



- Existenta campului electric in regiunea golita de purtatori face ca eventualii purtatori generati optic sa fie accelerati spre terminale pentru constituirea fotocurentului
- Problemele utilizarii diodei pn polarizate invers ca fotodetector sunt generate de adancimea extrem de mica a zonei golite (w)
- Puterea optica absorbita in interiorul acestei zone e in consecinta redusa
- Puratorii generati inafara zonei de golire ajung eventual in zona golita si vor fi accelerati spre terminale, dar viteza fenomenului este prea redusa pentru aplicatii in comunicatii

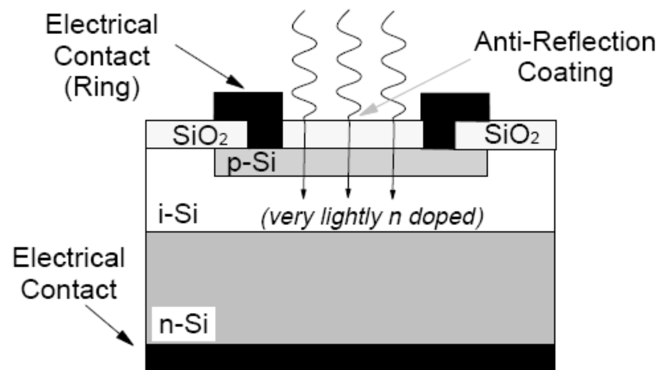
Fotodioda PIN

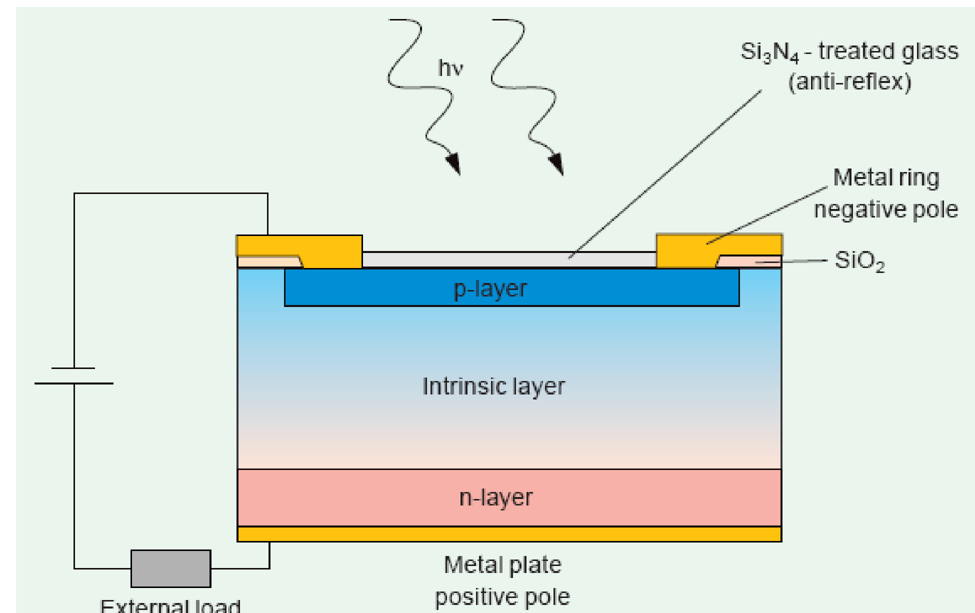
- Solutia consta in introducerea unui strat foarte slab dopat (intrinsec) intre cele doua zone ale diodei
  - creste volumul de absorbtie deci creste sensibilitatea fotodiodei
  - capacitatea jonctiunii scade ducand la cresterea vitezei
  - este favorizat curentul de conductie (mai rapid) fata de cel de difuzie



Structura fotodiodei PIN

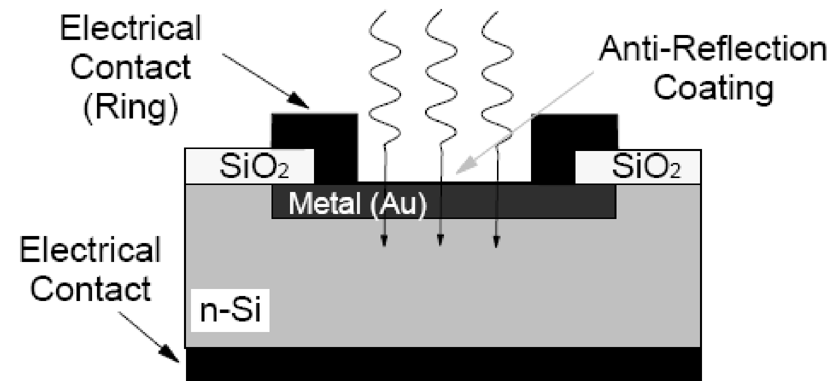
- tipic, adancimea stratului intrinsec este de 20-50μm
- cresterea suplimentara a adancimii ar duce la creterea timpului de tranzit
  - w=20μm -> $T_{tr} \cong 0.2$ns





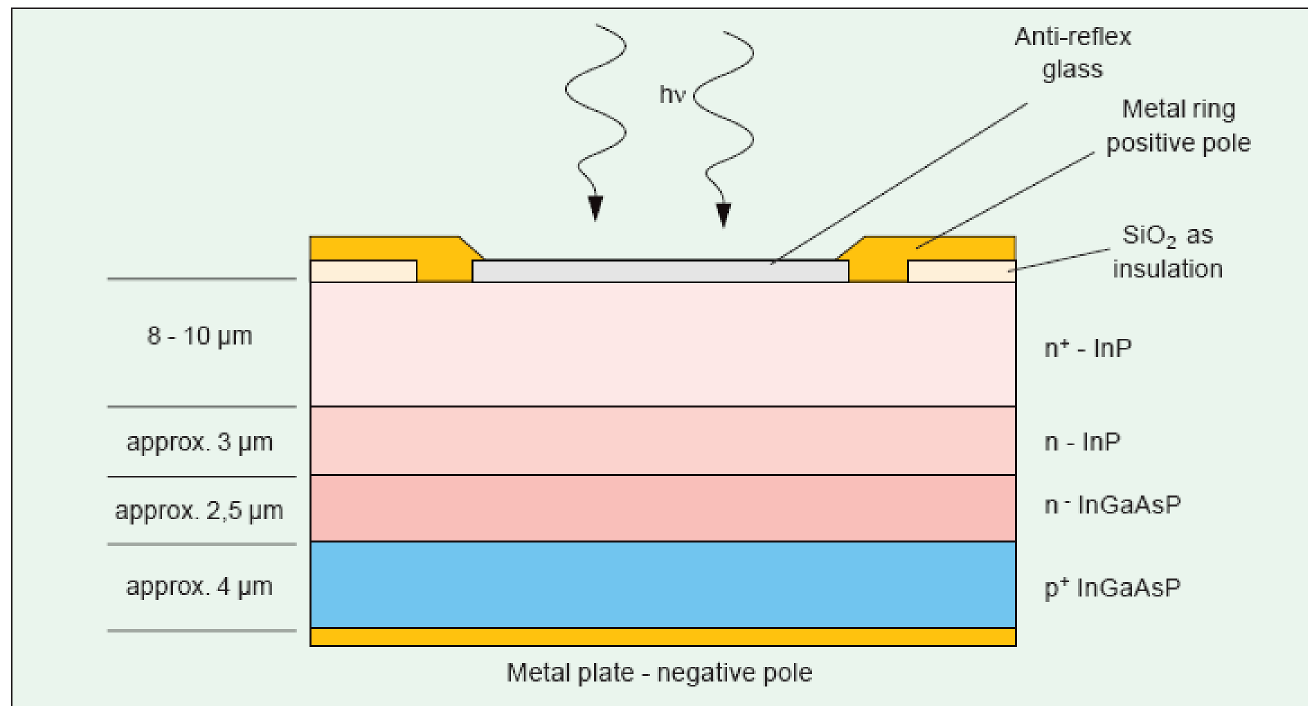
Structura fotodiodelor Schottky

- se bazeaza pe jonctiunea metal semiconductor
- vitezele de lucru sunt mult mai mari, metalul fiind un bun conductor realizeaza evacuarea mult mai rapida a purtatorilor din jonctiune
- permite utilizarea unor materiale cu eficienta mai mare dar care nu pot fi dopate simultan p si n pentru utilizare in PIN
- modulatie cu 100GHz posibila

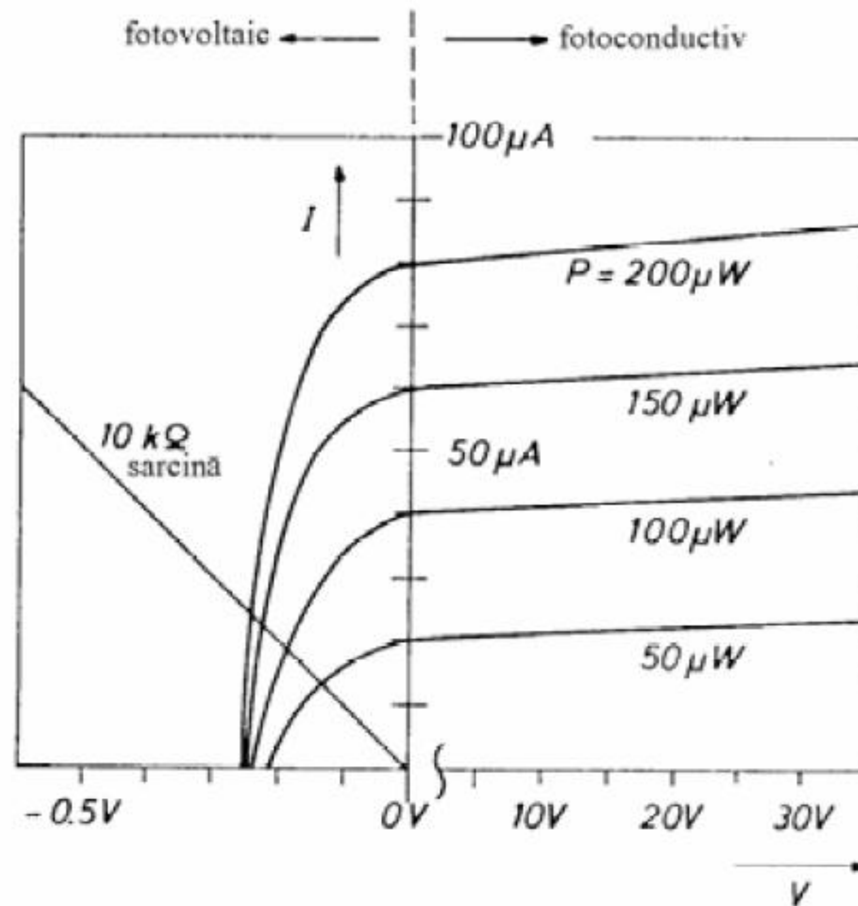


Fotodioda PIN pentru lungimi de unda crescute (1550nm)

- se utilizeaza tipic
  - InGaAsP pe substrat InP
  - GaAlAsSb pe substrat GaSb

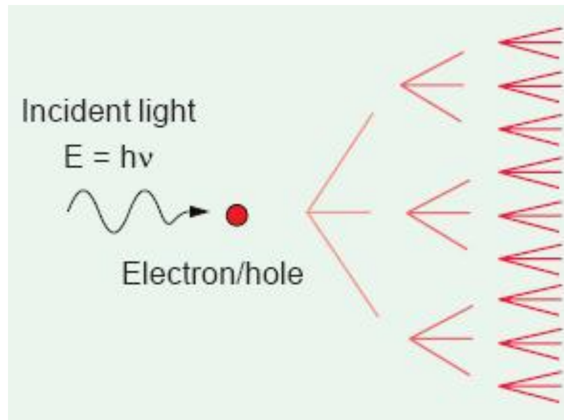


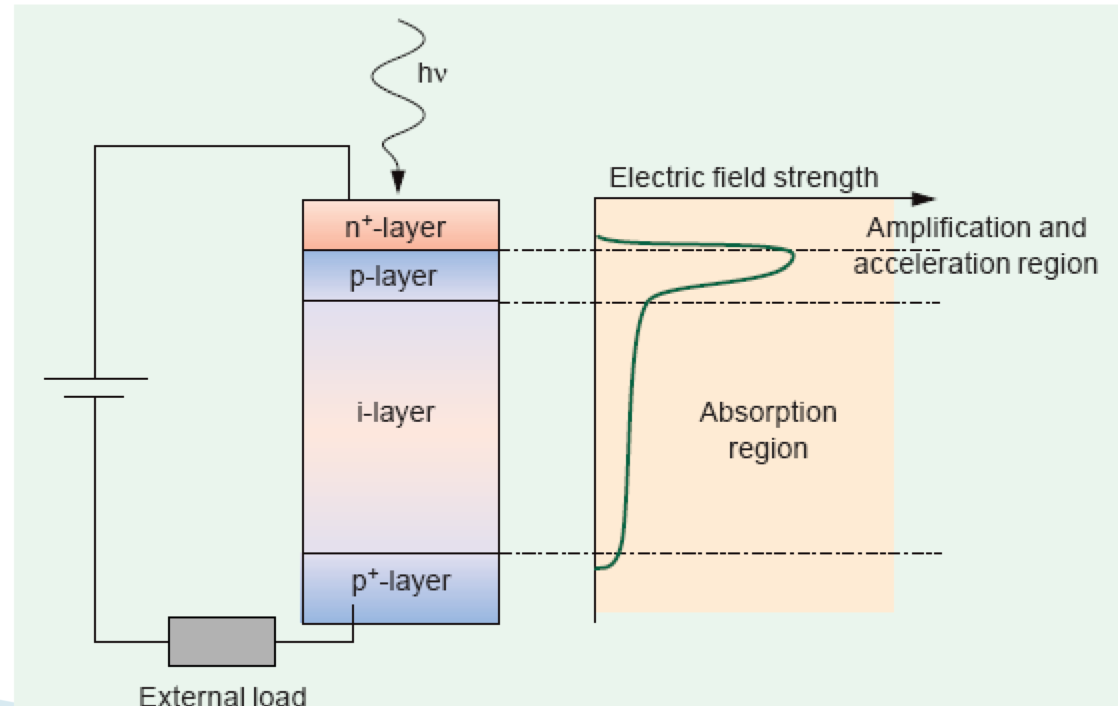
Caracteristici curent/tensiune



Fotodioda PIN cu multiplicare in avalansa

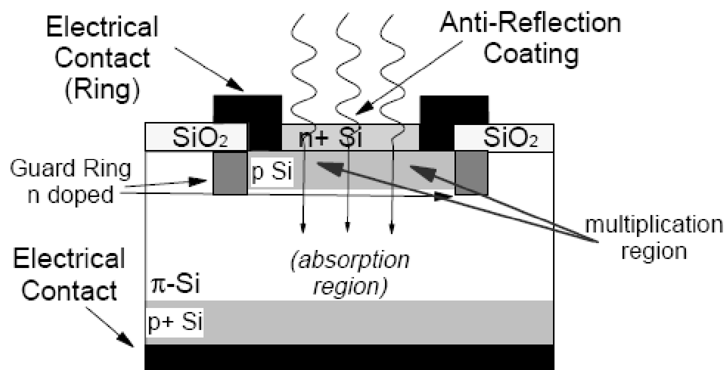
- daca viteza purtatorilor este suficient de mare genereaza noi perechi electron/gol prin ionizare de impact
- amplificarea are loc in acelasi timp cu detectia

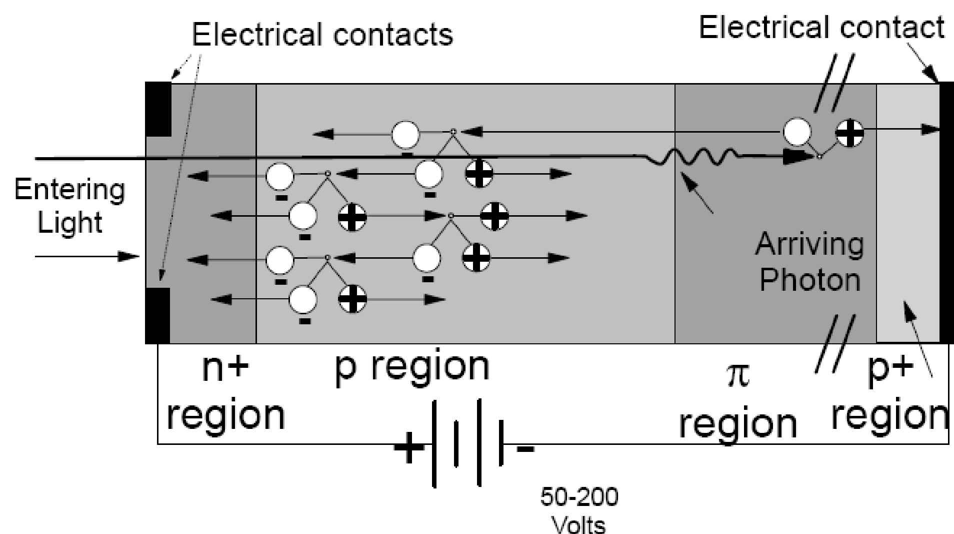




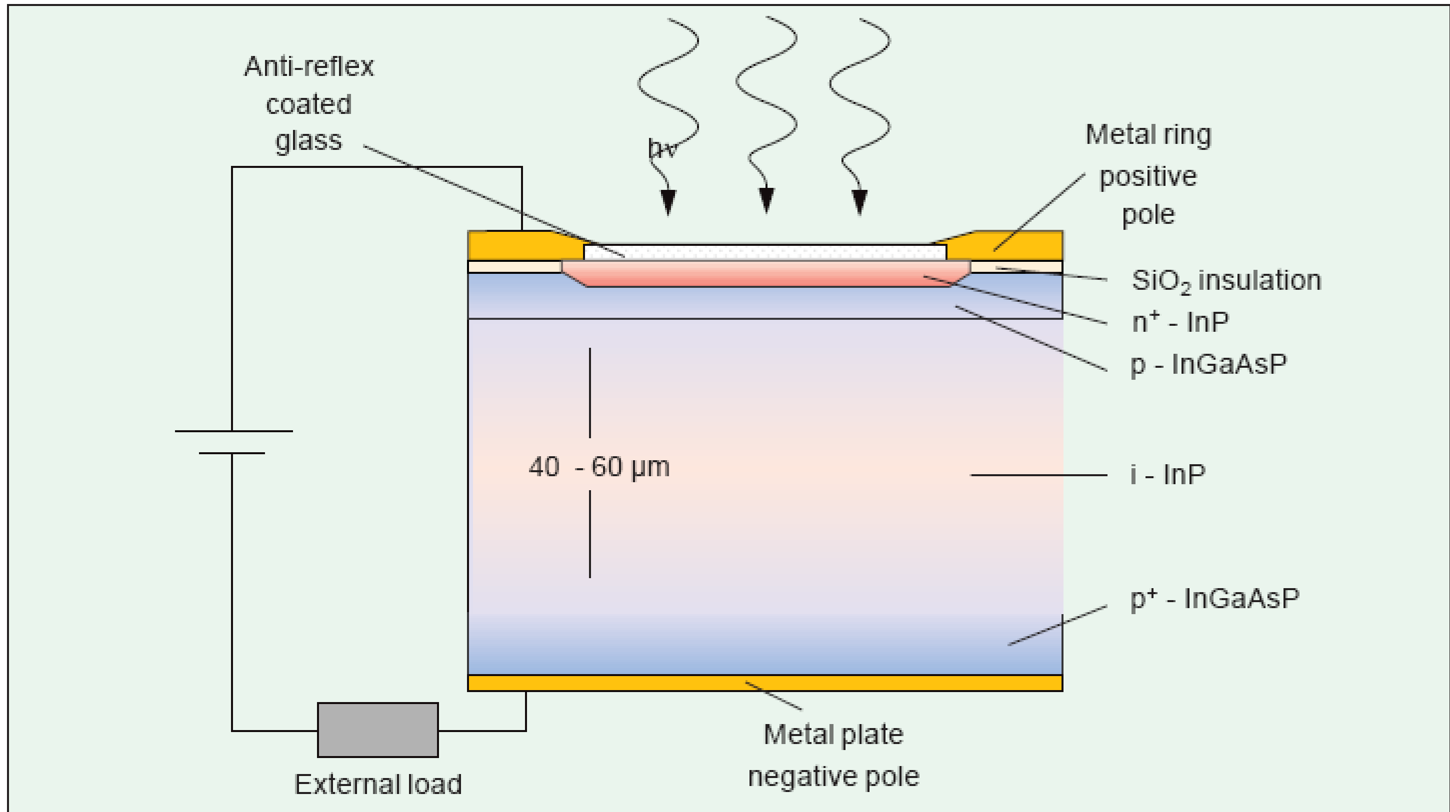
Functionarea fotodiodei cu multiplicare in avalansa

- campuri electrice de ordinul minim: $3x10^5$ V/m, tipic: 10^6 V/m sunt necesare
- aceste campuri sunt generate de tensiuni inverse de polarizare de ordinul 50-300V
- structura este modificata pentru concentrarea campului in zona de accelerare





Structura fotodiodei cu multiplicare in avalansa



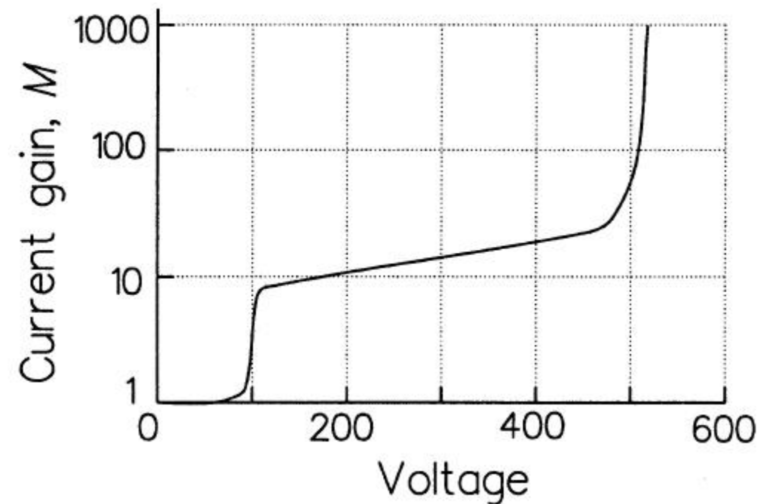
Caracteristicile fotodiodei cu multiplicare in avalansa

- factorul de multiplicare caracterizeaza amplificarea fotocurentului generat

$$M = \frac{I_M}{I}$$

- Responzivitatea

$$R = \frac{I}{P_o} = \frac{\eta \cdot e \cdot \lambda}{hc} \cdot M$$



Dezavantaje

- tensiuni inverse de polarizare mari cresc complexitatea circuitului
- diodele cu multiplicare in avalansa sunt intrinsec mai zgomotoase (curentul de zgomot este amplificat de asemenea)
- factorul de multiplicitate are o componenta aleatorie (zgomot suplimentar)
- viteza mai redusa (timp de generare al avalansei)

Zgomotul traductorilor electro-optici

Capitolul 11

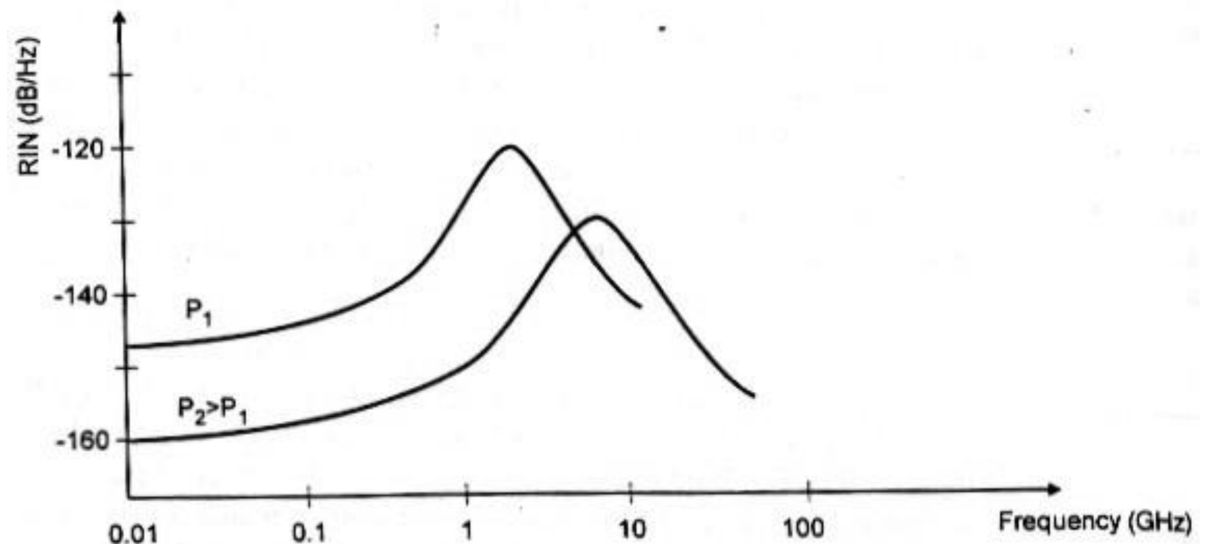
Zgomotul emitatorilor optici

- LED
  - este considerat o sursa lipsita de zgomot
  - nu contamineaza semnalul cu zgomot suplimentar
- Dioda LASER
  - fluctuatii de faza, determina o largire a spectrului emis
  - fluctuatii de intensitate, determina zgomotul de intensitate introdus de dioda
  - RIN – Relative Intensity Noise

$$RIN[1/Hz] = \frac{\left\langle P_n^2 \right\rangle}{\left\langle P^2 \right\rangle \cdot BW}$$

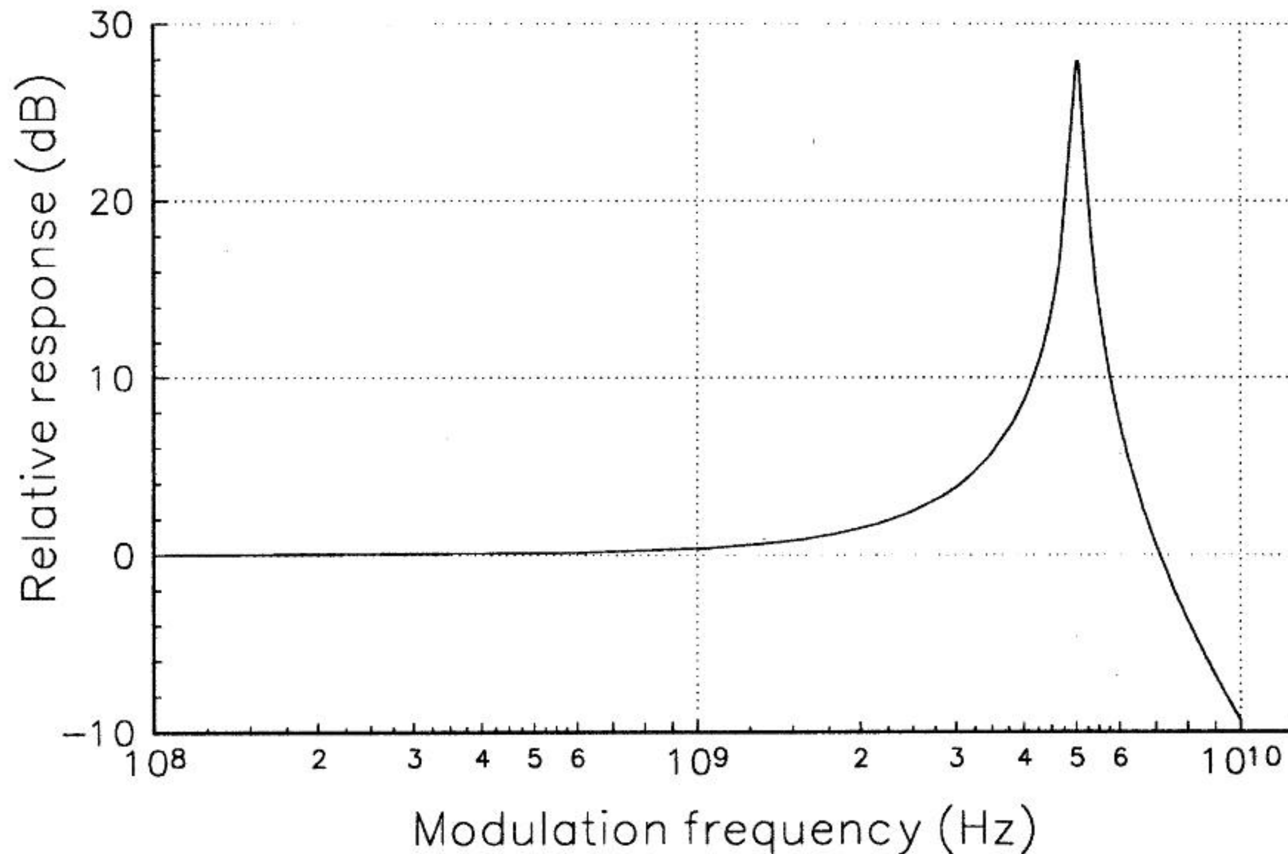
RIN

- reprezinta o densitate spectrala de zgomot
  - puterea de zgomot depinde de RIN si de banda semnalului
- Depinde de puterea semnalului
  - P^{-3} la puteri mici, P^{-1} la puteri mari



Raspunsul unei diode laser

- oscilatii de relaxare – x GHz



EIN

- Equivalent Input Noise
  - Ri – rezistenta de intrare in circuitul de modulatie a diodei
  - Variatiile de putere (zgomot) echivalente unor variatii de curent (zgomot) prin dioda

$$\left\langle P_n^2 \right\rangle = r \cdot \left\langle I_n^2 \right\rangle$$

$$EIN[W] = R_i \cdot \left\langle I_n^2 \right\rangle$$ 1 Hz banda

$$EIN[W/Hz] = RIN \cdot \left(I_0 - I_{th}\right)^2 \cdot R_i$$

Zgomotul fotodiodei

- NEP
  - Noise Equivalent Power
  - r – responzivitatea diodei

$$NEP[W] = \frac{\int \sqrt{\left\langle i_n^2 \right\rangle} df}{r}$$

  - r depinde de λ, implica NEP depinde de λ
  - In cataloage apare de obicei densitatea spectrala

$$NEP[W/\sqrt{Hz}] = \frac{\sqrt{\left\langle i_n^2 \right\rangle}}{r} = \frac{NEP}{\sqrt{BW_{PD}}}$$

Zgomotul fotodiodei

- NEP
  - cea mai mica putere detectabila

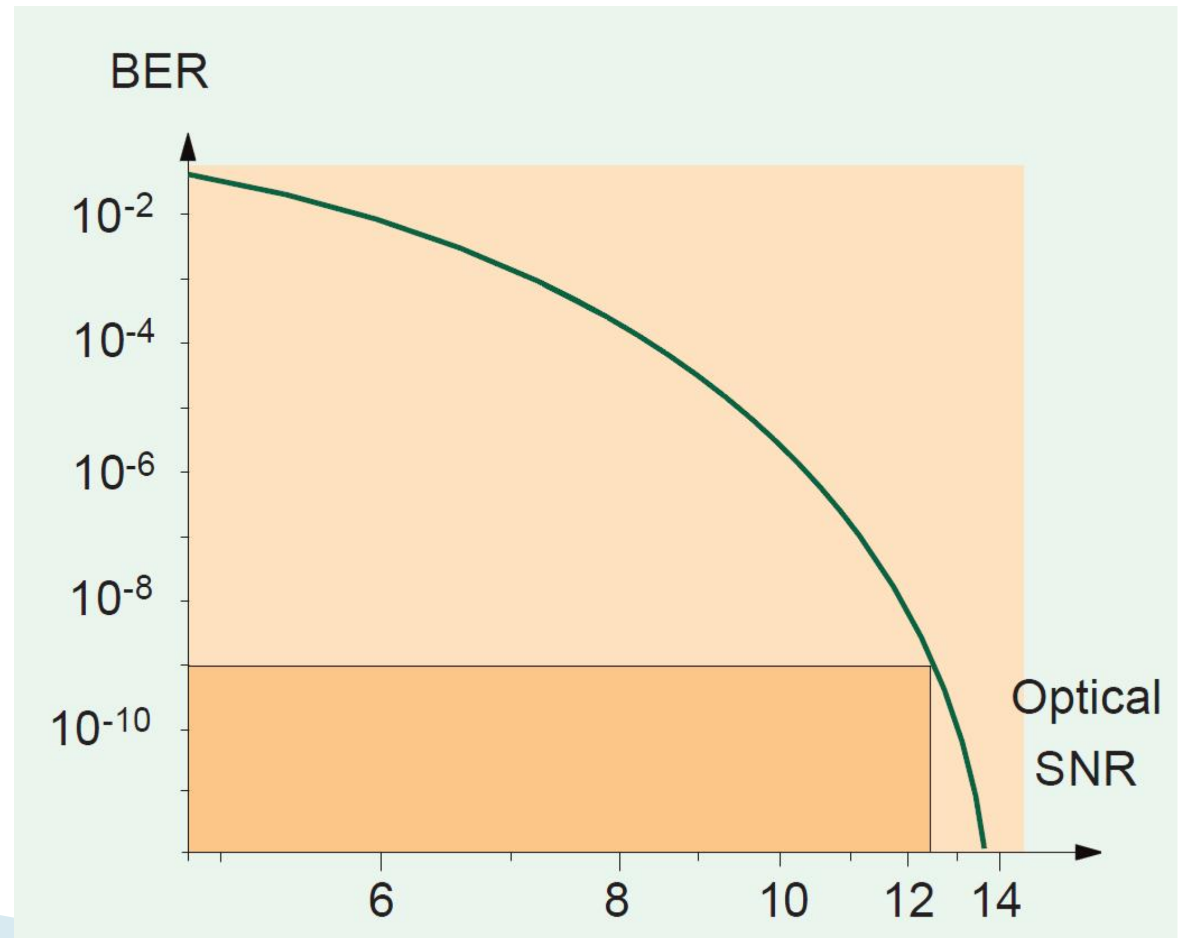
$$\left\langle i_n^2 \right\rangle = 2 \cdot e \cdot I \cdot BW_{PD} = 2 \cdot e \cdot \left(I_S + I_{dark} \right) \cdot BW_{PD}$$

$$P_{\min} = \frac{\sqrt{\left\langle i_n^2 \right\rangle_{\min}}}{r} = \frac{1}{r} \cdot \sqrt{2 \cdot e \cdot I_{dark} \cdot BW_{PD}}$$

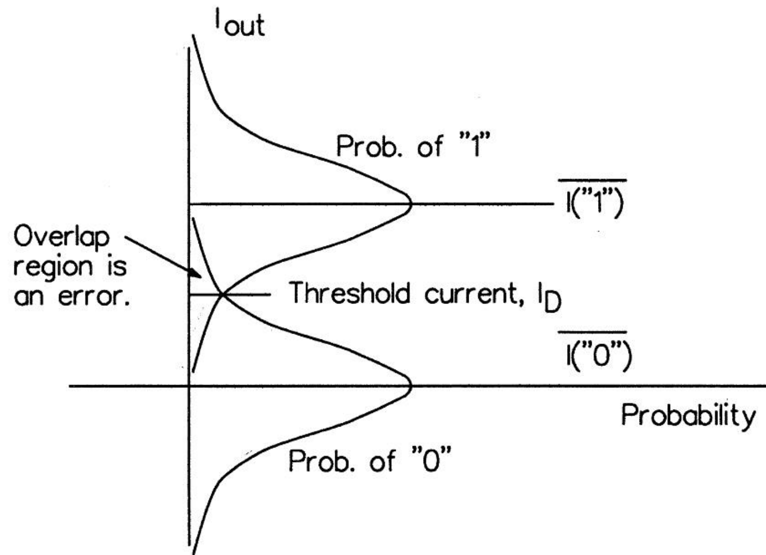
$$NEP[W / \sqrt{Hz}] == \frac{1}{r} \cdot \sqrt{2 \cdot e \cdot I_{dark}}$$

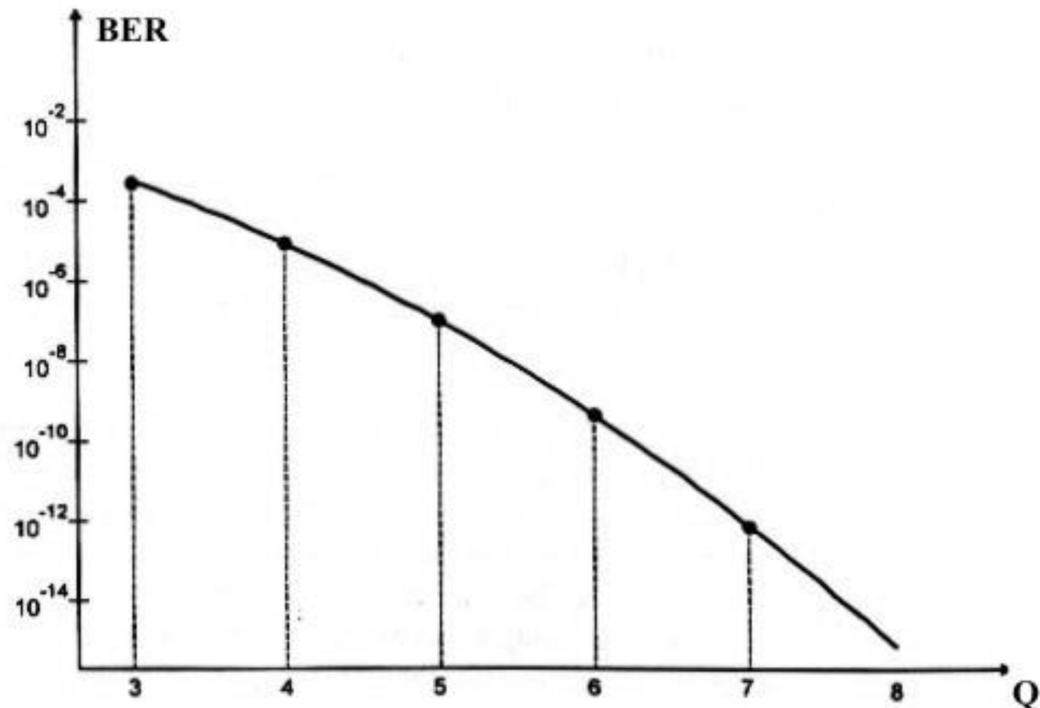
BER

- Bit Error Rate



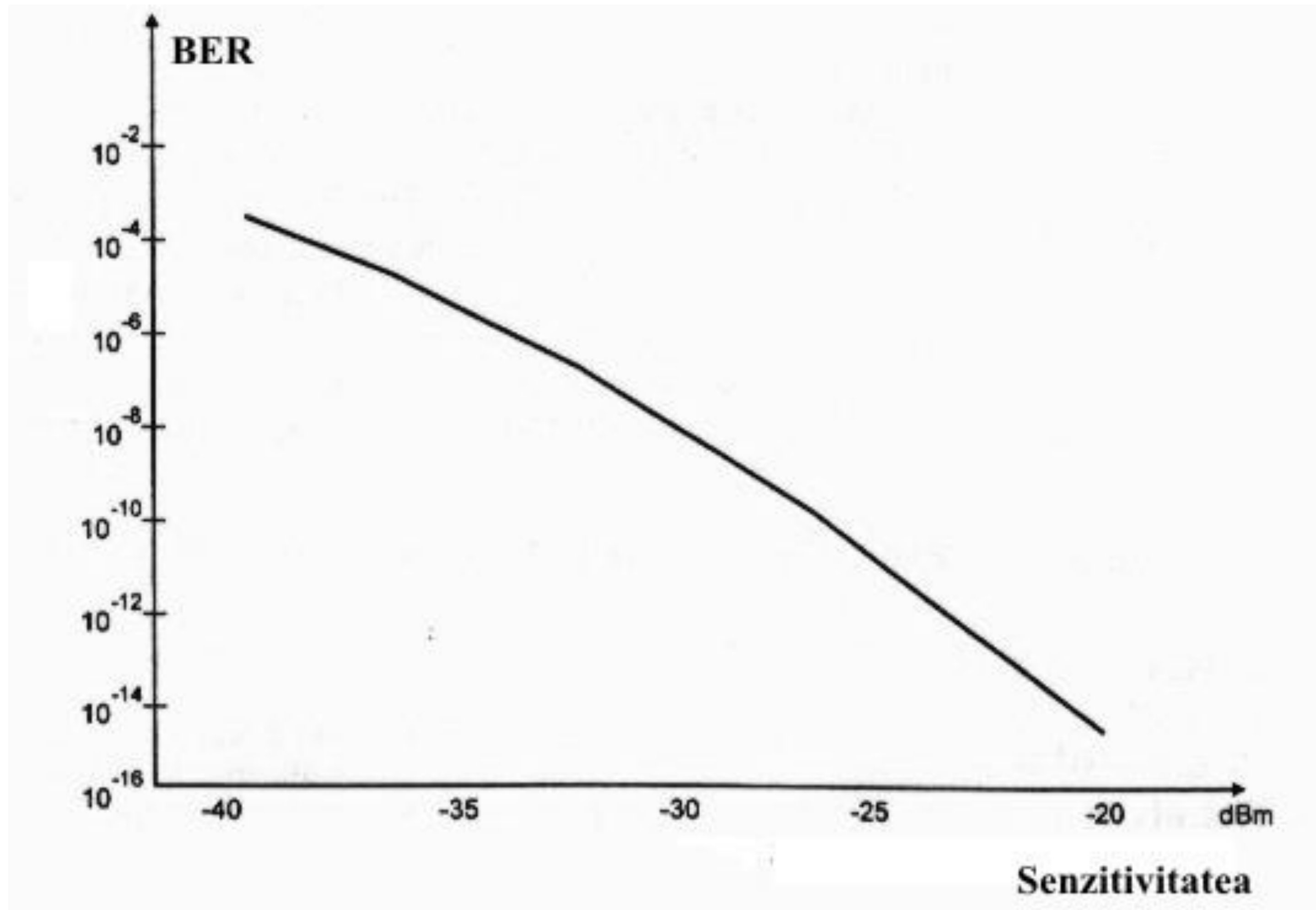
Probabilitate de eroare



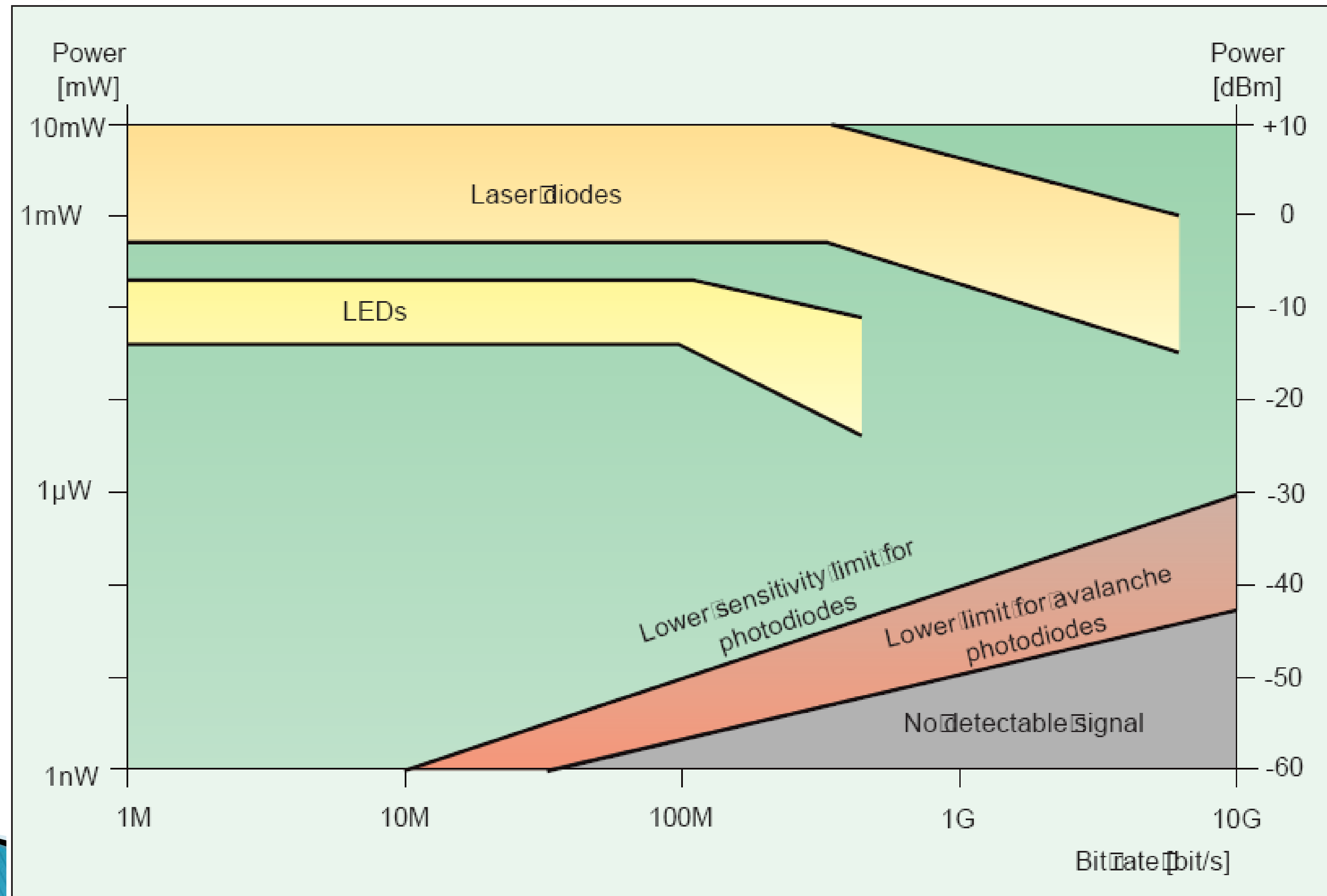


$$Q = \frac{\overline{i(1)} - I_D}{\sigma_1} = \frac{I_D - \overline{i(0)}}{\sigma_0}$$

Senzitivitatea unei diode



Limite putere/bandă a dispozitivelor optoelectronice



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