

Optoelectronică

Curs 9

2017/2018

Disciplina 2017/2018

- ▶ 2C/1L Optoelectronică **OPTO**
- ▶ **Minim 7** prezente curs + laborator
- ▶ Curs – **conf. Radu Damian**
 - an IV μ E
 - Vineri 8–11, P5
 - E – 70% din nota
 - **20% test la curs**, saptamana 4–5?
 - probleme + (? 1 subiect teorie) + (2p prez. curs)
 - toate materialele permise
- ▶ Laborator – **sl. Daniel Matasaru**
 - an IV μ E, an IV Tc
 - Joi 14-16 par/impar
 - L – 15% din nota
 - C – 15% din nota

Orar 2017/2018

▶ Curs

- Vineri 8–11, P5
- **2C ⇒ 3C**
 - $14 * 2/3 \approx 9.33$
 - $9 \div 10$ C

Recapitulare

Reprezentare logaritmică!!!

$$\text{dB} = 10 \cdot \log_{10} (P_2 / P_1)$$

$$\text{dBm} = 10 \cdot \log_{10} (P / 1 \text{ mW})$$

$$0 \text{ dB} = 1$$

$$+ 0.1 \text{ dB} = 1.023 (+2.3\%)$$

$$+ 3 \text{ dB} = 2$$

$$+ 5 \text{ dB} = 3$$

$$+ 10 \text{ dB} = 10$$

$$-3 \text{ dB} = 0.5$$

$$-10 \text{ dB} = 0.1$$

$$-20 \text{ dB} = 0.01$$

$$-30 \text{ dB} = 0.001$$

$$0 \text{ dBm} = 1 \text{ mW}$$

$$3 \text{ dBm} = 2 \text{ mW}$$

$$5 \text{ dBm} = 3 \text{ mW}$$

$$10 \text{ dBm} = 10 \text{ mW}$$

$$20 \text{ dBm} = 100 \text{ mW}$$

$$-3 \text{ dBm} = 0.5 \text{ mW}$$

$$-10 \text{ dBm} = 100 \mu\text{W}$$

$$-30 \text{ dBm} = 1 \mu\text{W}$$

$$-60 \text{ dBm} = 1 \text{ nW}$$

$$[\text{dBm}] + [\text{dB}] = [\text{dBm}]$$

$$[\text{dBm/Hz}] + [\text{dB}] = [\text{dBm/Hz}]$$

$$[\text{x}] + [\text{dB}] = [\text{x}]$$

Recapitulare

Curs 8

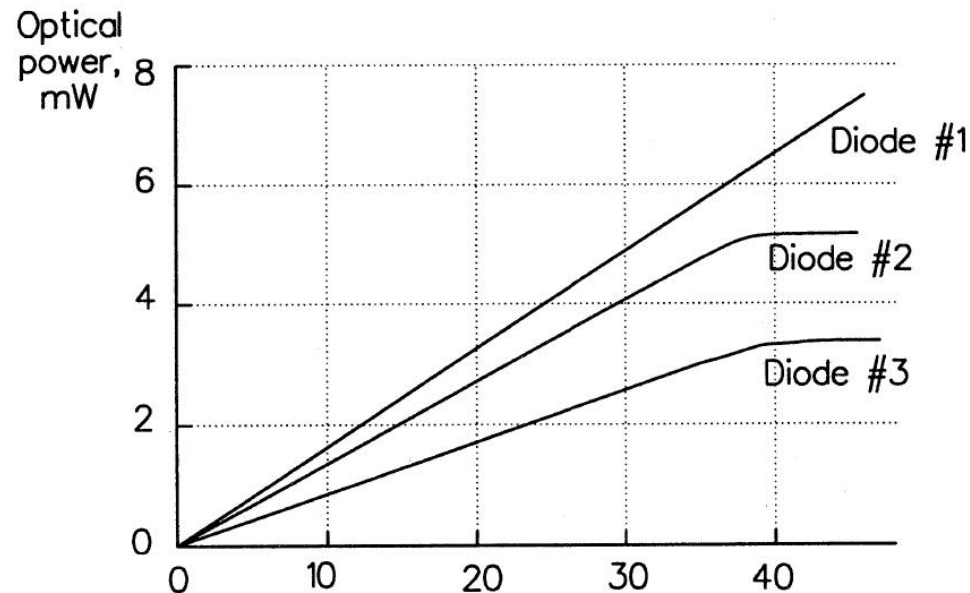
Caracteristica de raspuns a LED-urilor

- ▶ 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

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

- ▶ Tipic $r = 50 \mu\text{W}/\text{mA}$



Caracteristica de raspuns a DL

- ▶ Amorsarea emisiei stimulate necesita pomparea unei anumite cantitati de energie - curent de prag

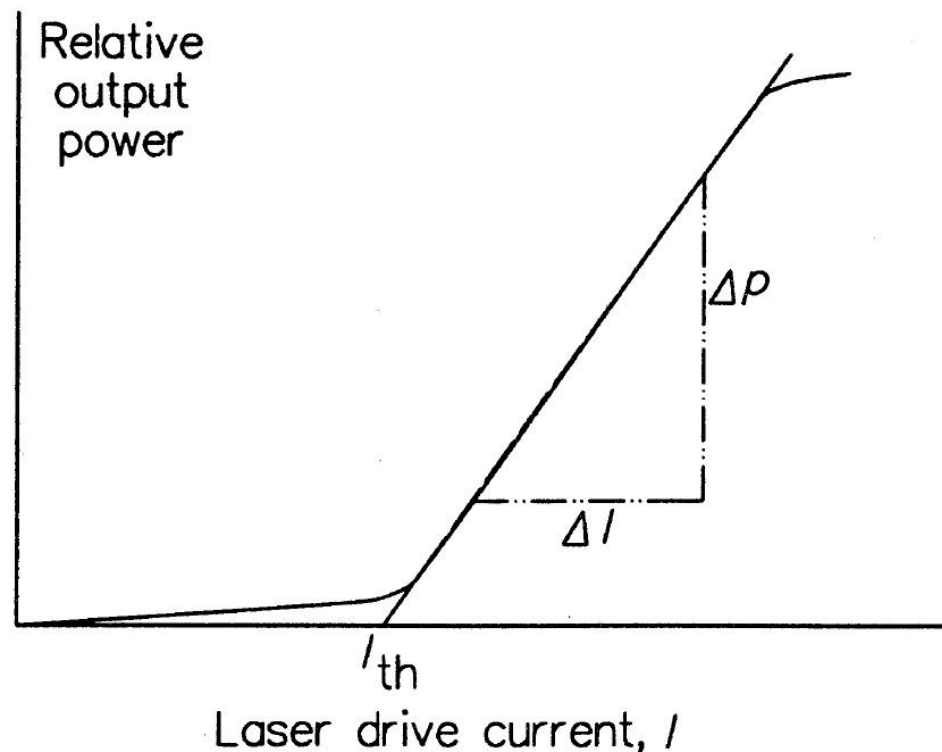
$I < I_{th}$ regim LED
ineficient!, $P_o \cong 0$

$I > I_{th}$ regim LASER

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

$$P_o = r \cdot (I - I_{th})$$

Apare saturare la nivele mari de curent



Fotodioda

Capitolul 9

Detectori optici

▶ Cerinte

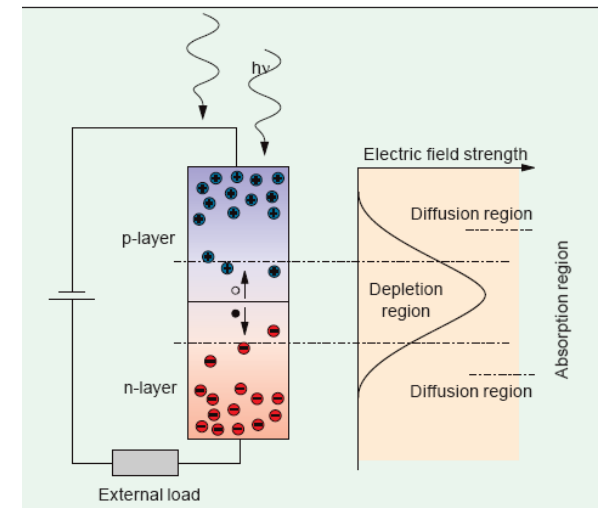
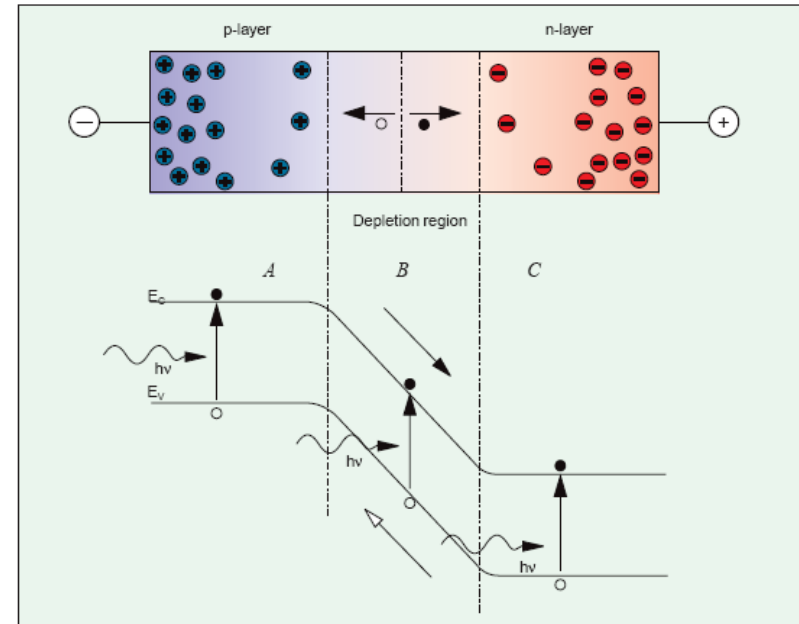
- eficienta crescuta a conversiei optic/electric
- zgomot redus
- raspuns uniform la diferite lungimi de unda
- viteza de raspuns ridicata
- liniaritate

▶ 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

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

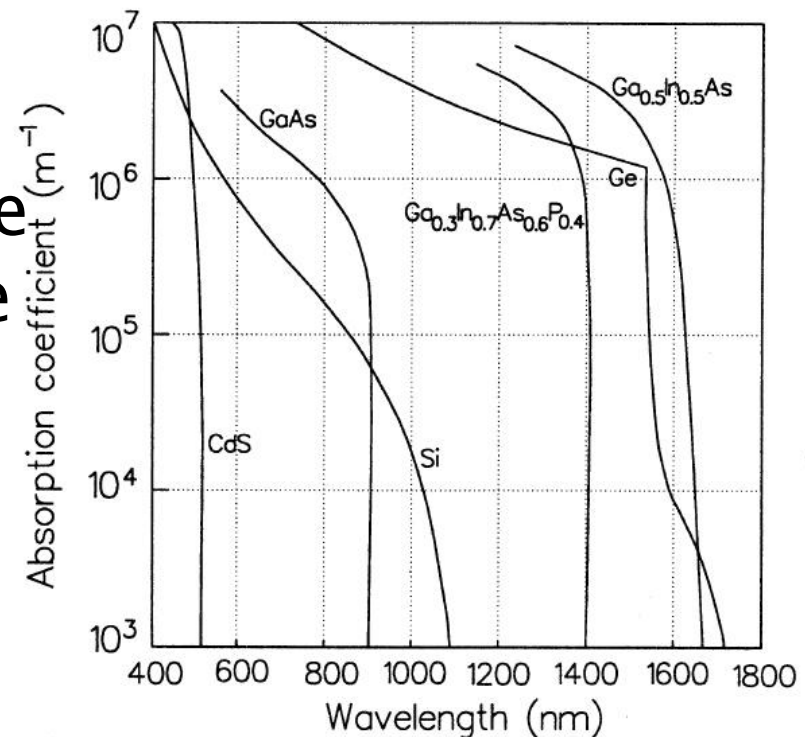
$$\lambda_{\max} = \frac{hc}{E_g}$$

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

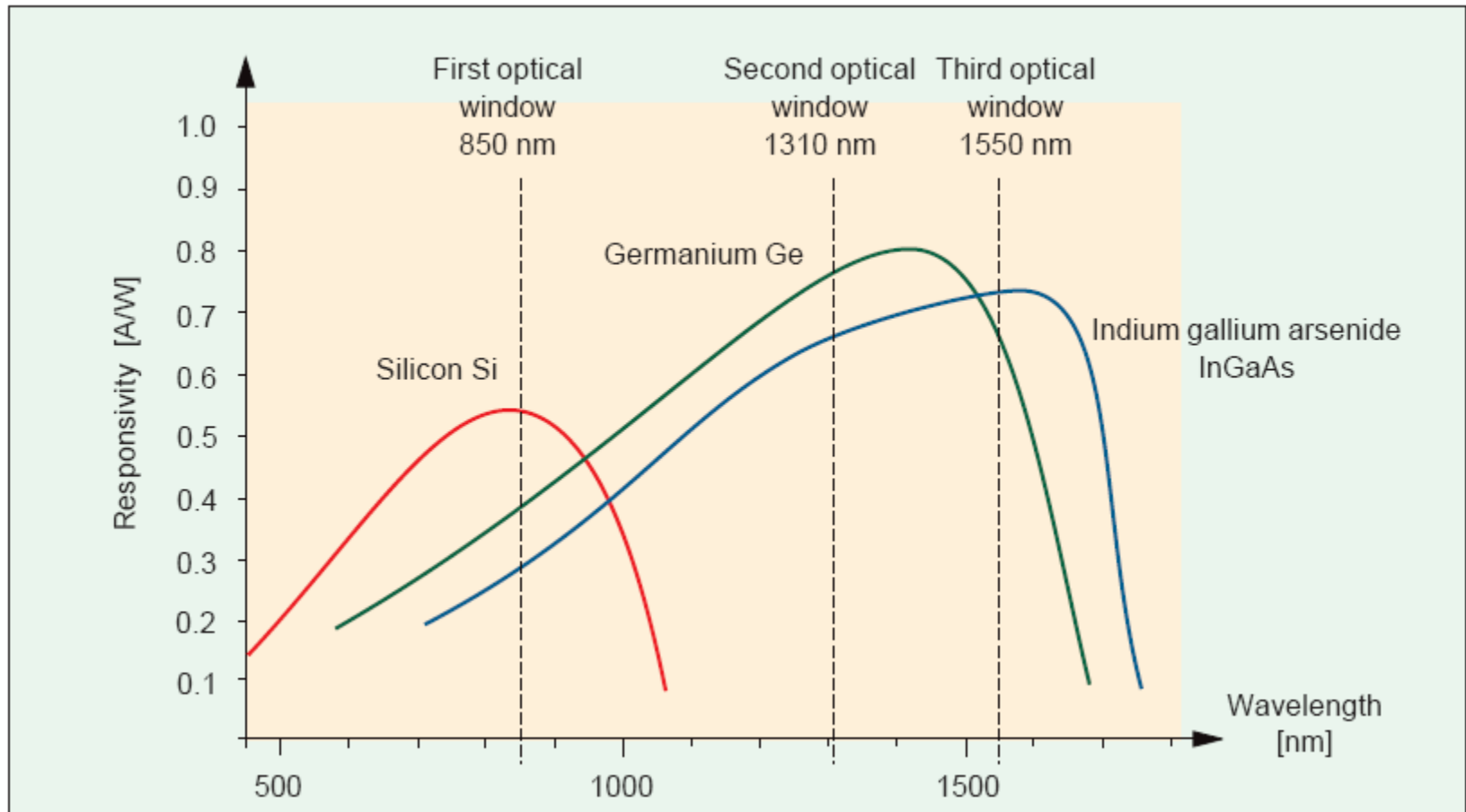
$$P(w) = P_i \cdot e^{-\alpha \cdot d} \cdot (1 - e^{-\alpha \cdot w}) \cdot (1 - R_f)$$

Fotodioda – Principiul de operare

- ▶ Coeficientul de absorbtie pentru materialele uzuale
- ▶ Valoarea mare a coeficientului de absorbtie la lungimi de unda reduse implica scaderea rezponzivitatii
- ▶ 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 și numărul de fotoni incidenti

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

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

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

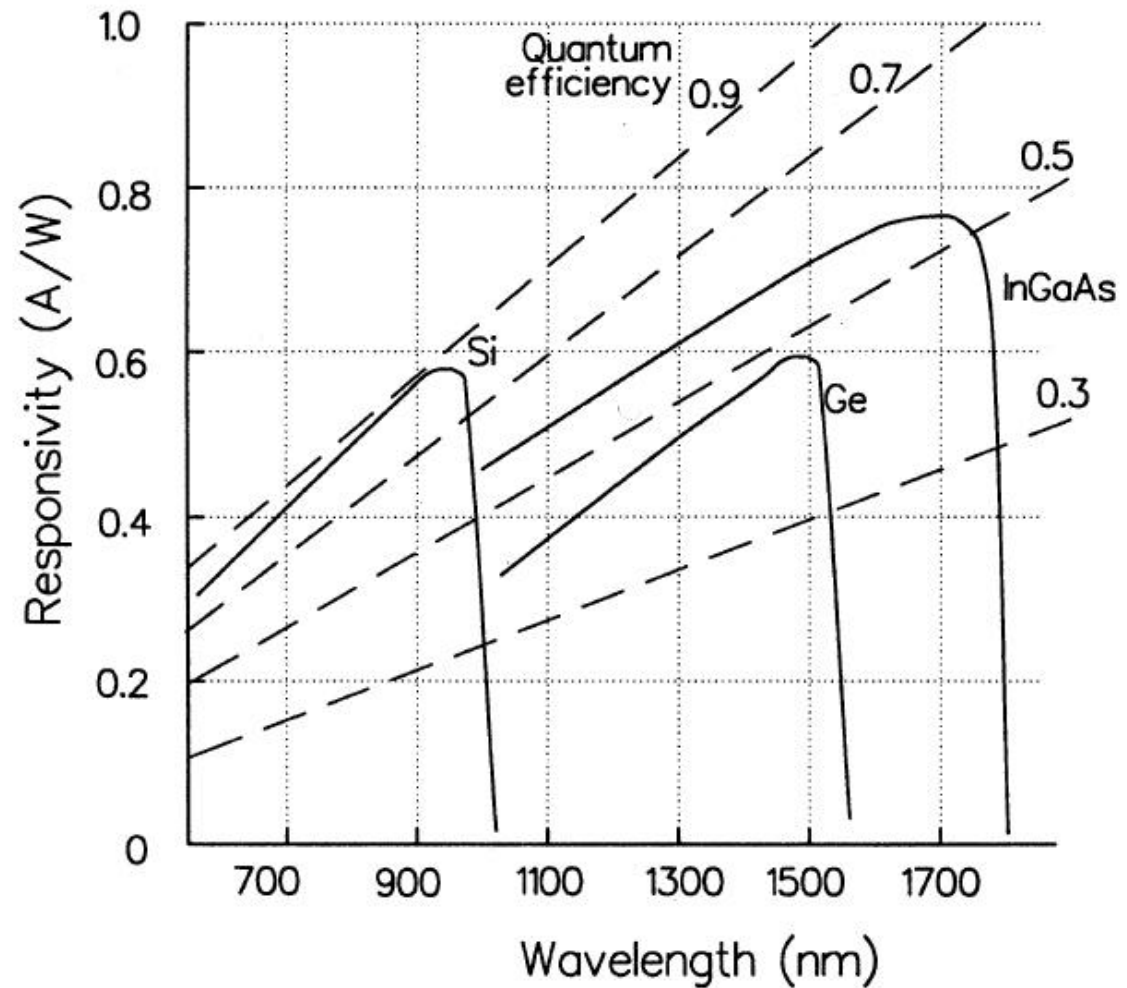
- ▶ Responzivitatea

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

$$R = 0.8 \cdot \eta \cdot \lambda [\mu m] \left[\frac{A}{W} \right]$$

Fotodiode - marimi caractéristice

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



Material 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	E_g (eV)
GaAs	1.43
GaSb	0.73
$\text{GaAs}_{0.88}\text{Sb}_{0.12}$	1.15
Ge	0.67
InAs	0.35
InP	1.35
$\text{In}_{0.53}\text{Ga}_{0.47}\text{As}$	0.75
$\text{In}_{0.14}\text{Ga}_{0.86}\text{As}$	1.15
Si	1.14

Curent de intuneric

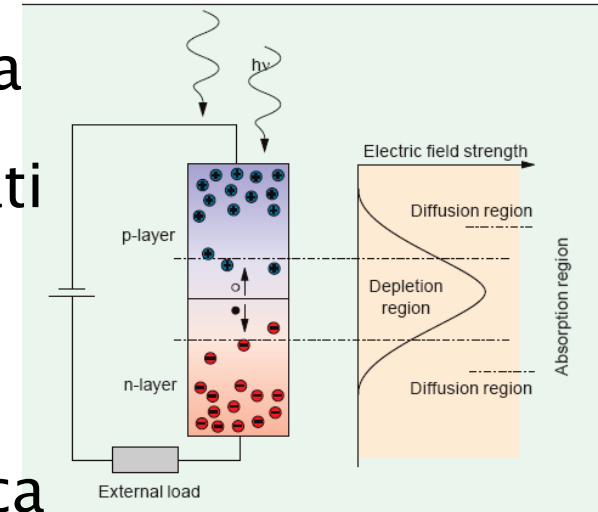
- ▶ Curentul invers al jonctiunii p-n, datorat agitatiei termice, prezent in absenta iluminarii
- ▶ Constitutie o importanta sursa de zgomot (limiteaza aplicatiile Ge)

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

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

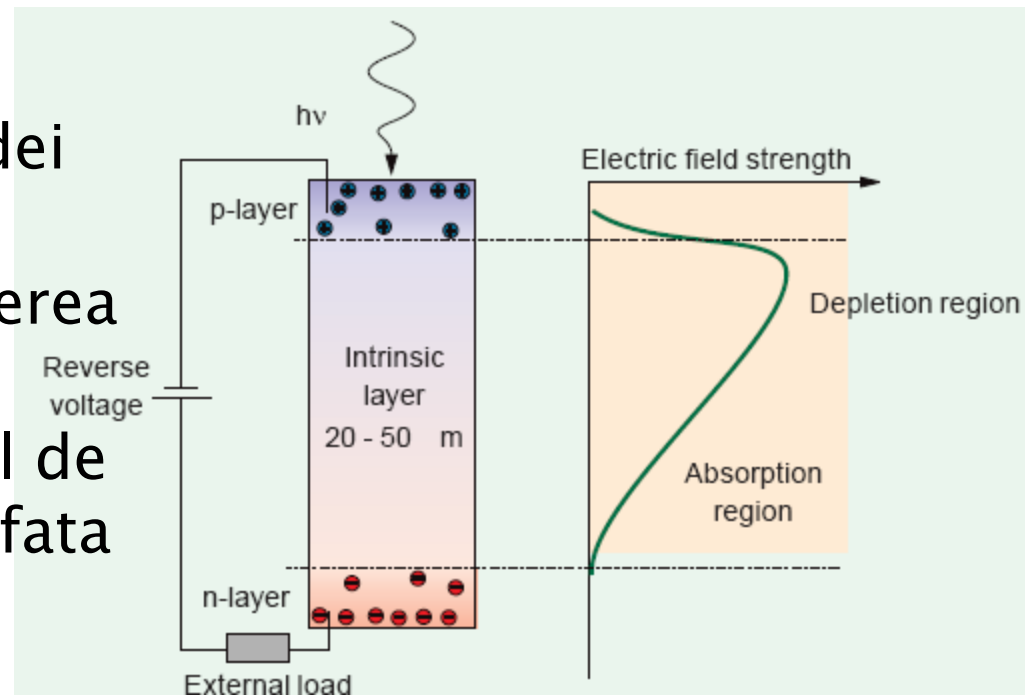
Fotodioda PIN

- ▶ 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
- ▶ Purtatorii 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



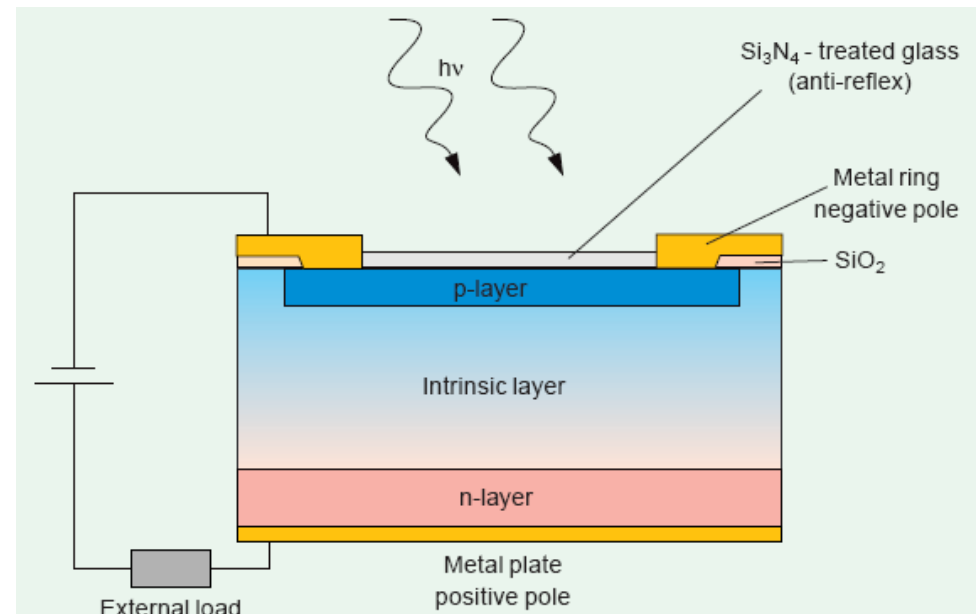
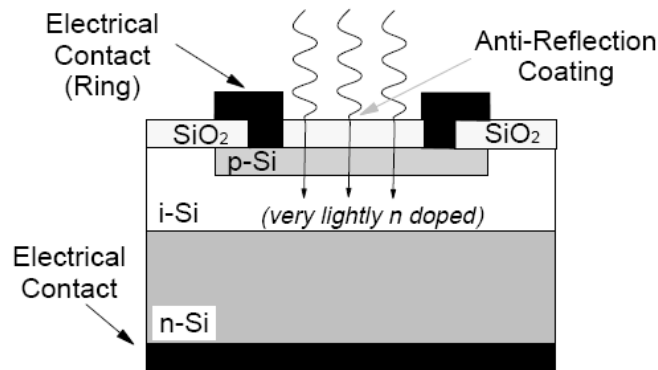
Fotodioda PIN

- ▶ 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



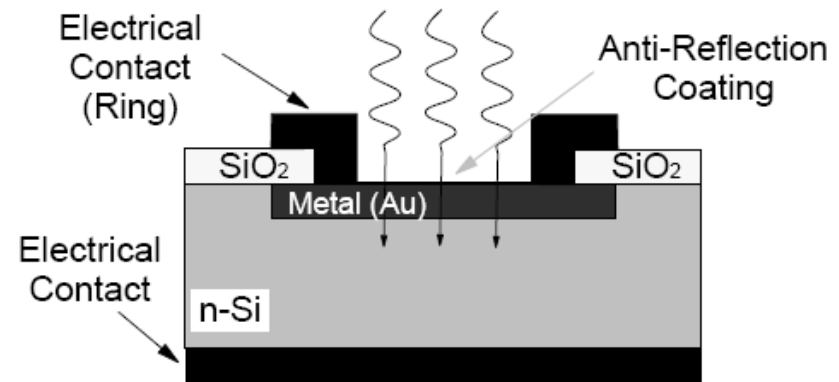
Structura fotodiodei PIN

- ▶ tipic, adancimea stratului intrinsec este de 20–50 μm
- ▶ cresterea suplimentara a adancimii ar duce la cresterea timpului de tranzit
 - $w=20\mu\text{m} \rightarrow T_{tr} \cong 0.2\text{ns}$



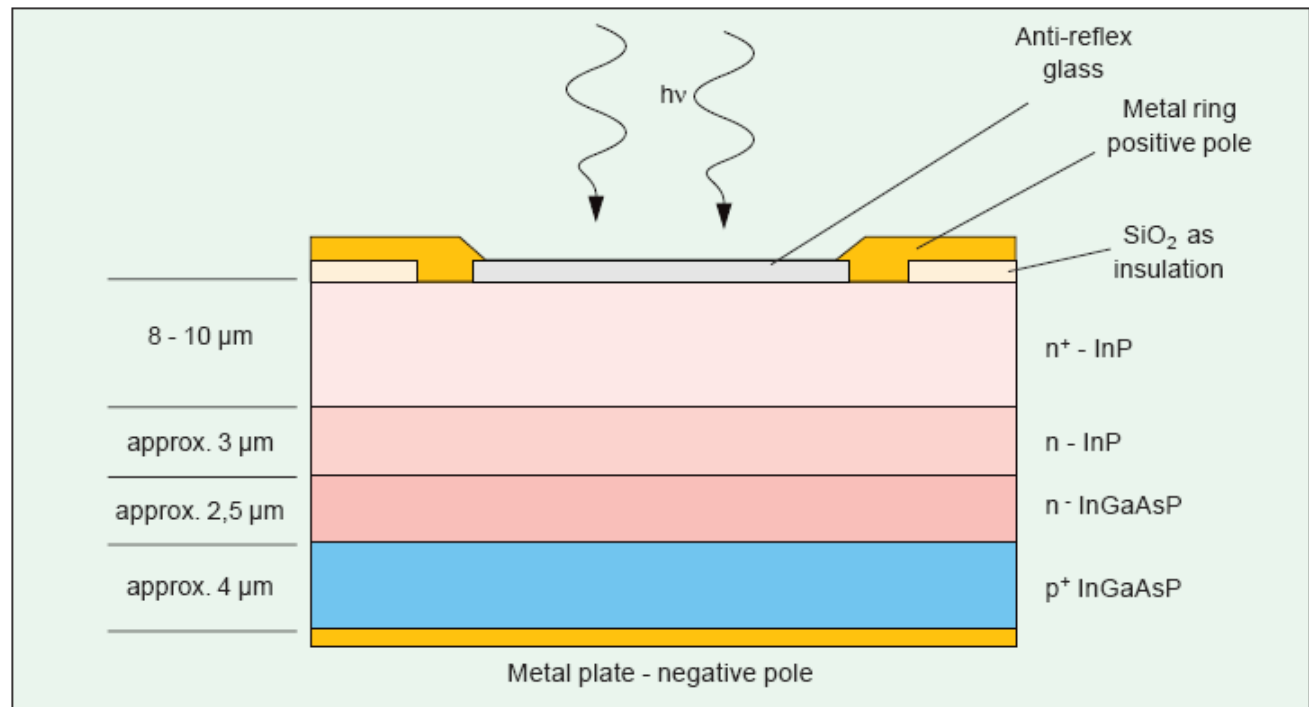
Structura fotodiodelor Schottky

- ▶ 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



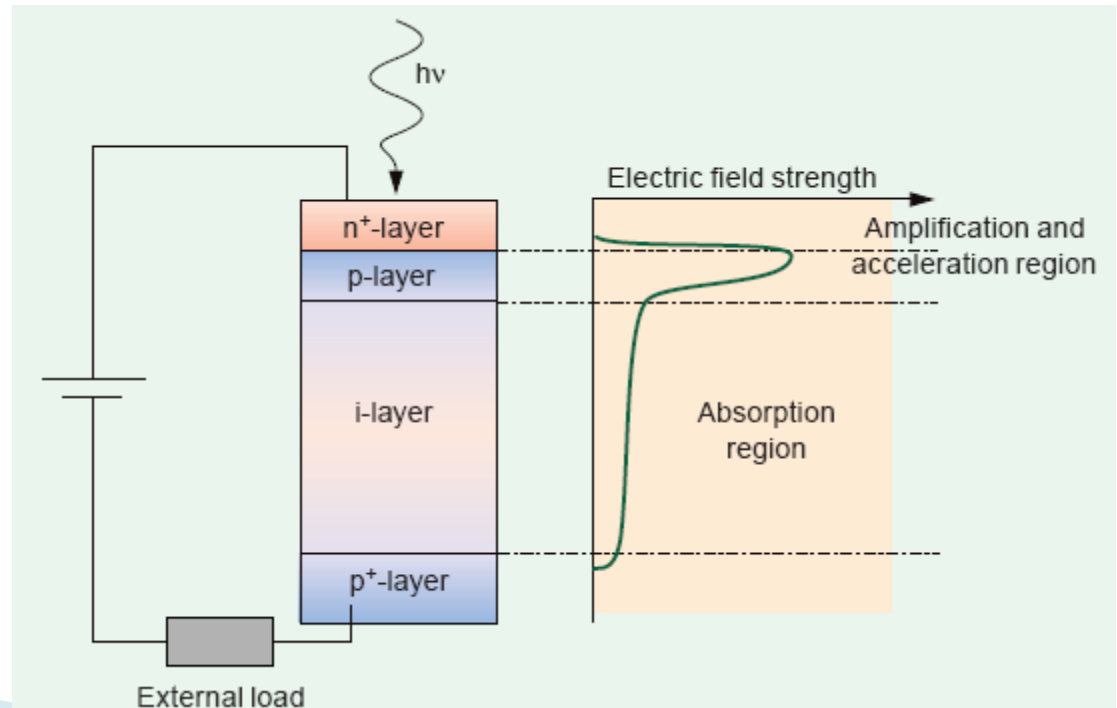
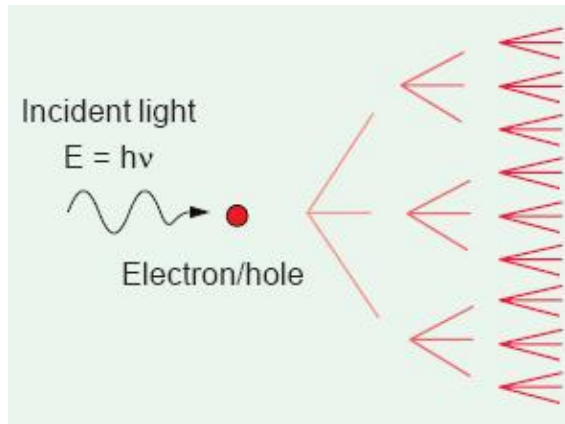
Fotodioda PIN pentru lungimi de unda crescute (1550nm)

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



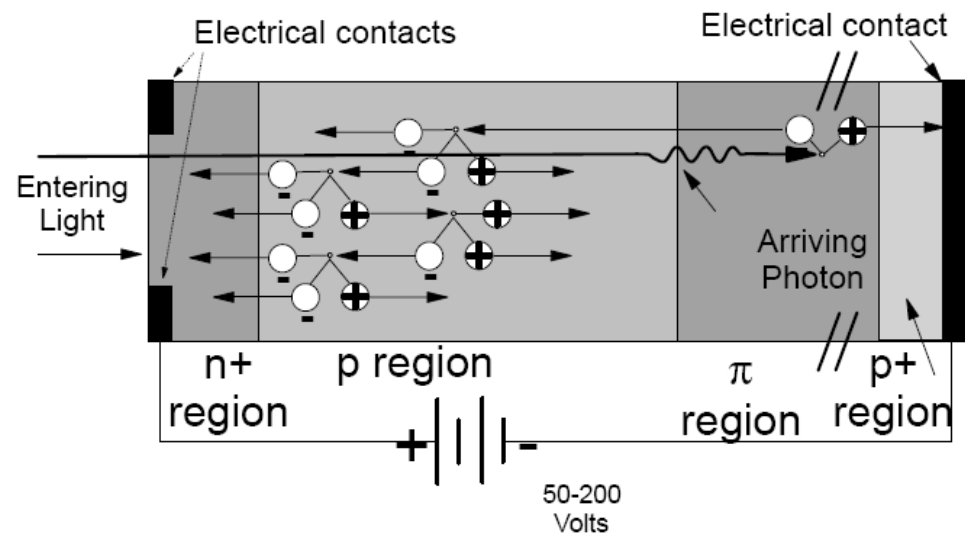
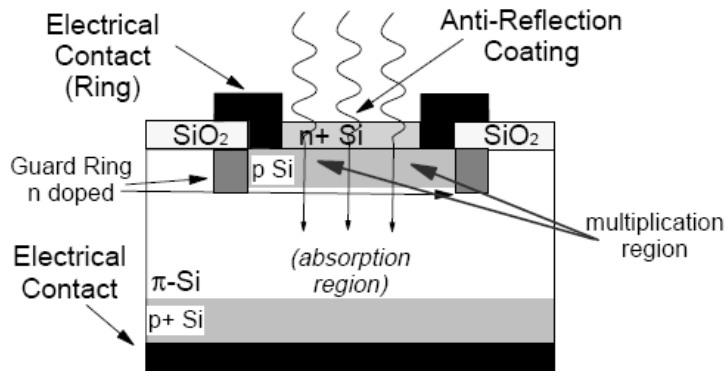
Fotodioda PIN cu multiplicare in avalansa

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

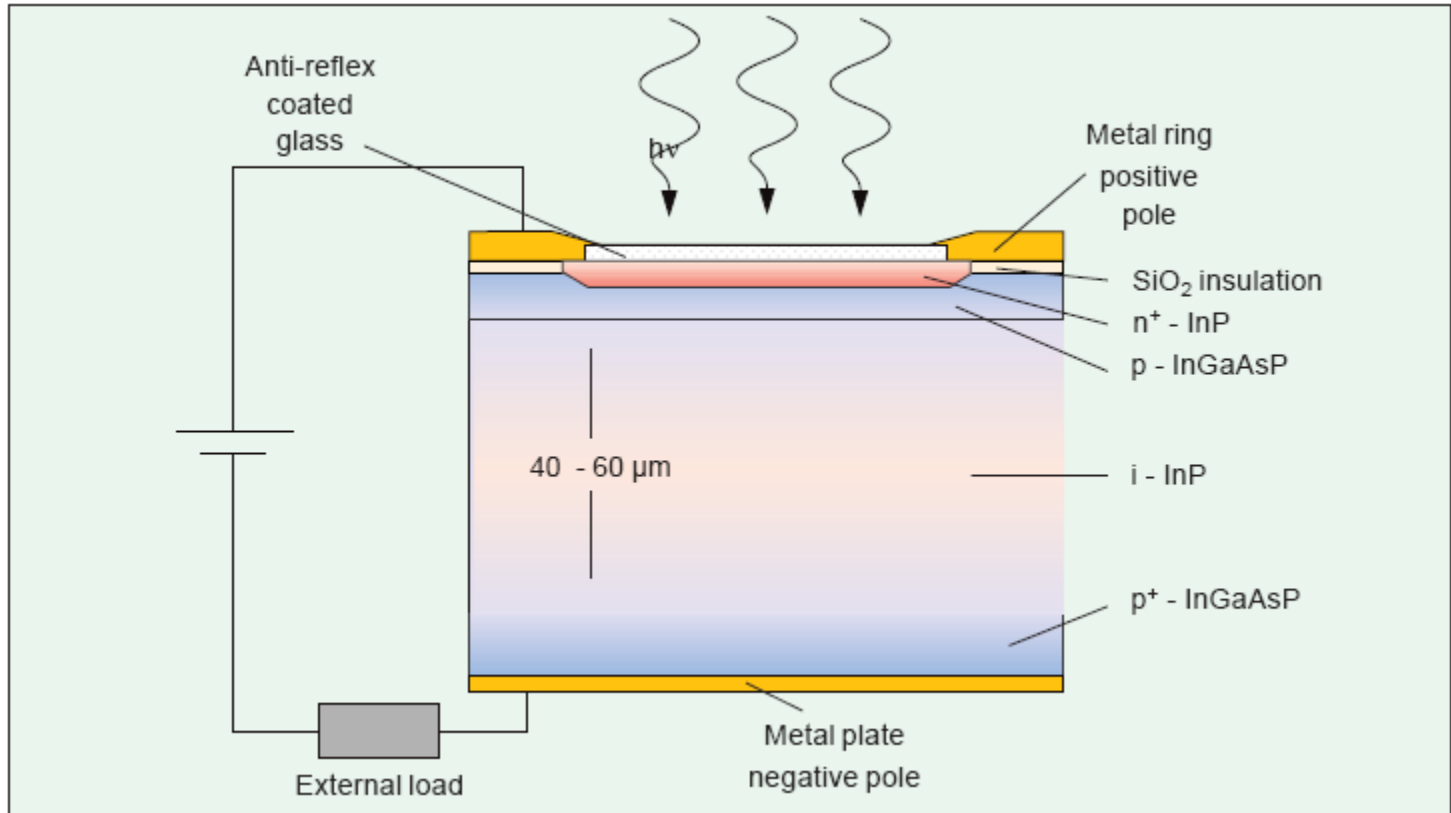


Functionarea fotodiodei cu multiplicare in avalansa

- ▶ campuri electrice de ordinul minim: 3×10^5 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



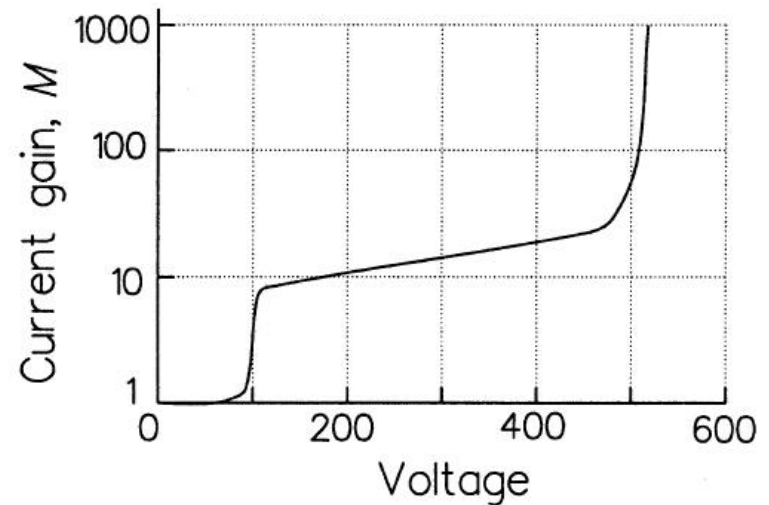
Caracteristicile fotodiodei cu multiplicare in avalansa

- ▶ factorul de multiplicare caracterizeaza amplificarea fotocurentului generat

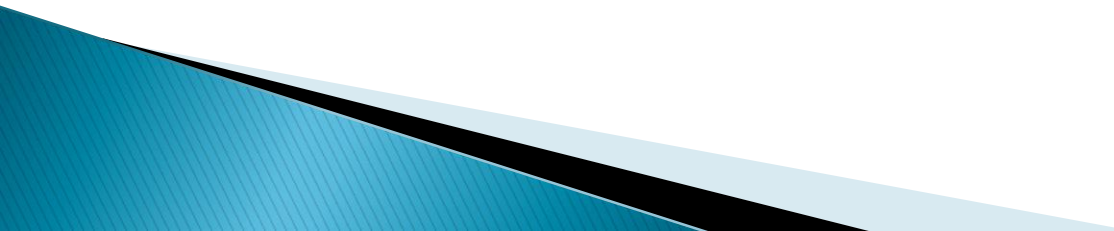
$$M = \frac{I_M}{I}$$

- ▶ Responzivitatea

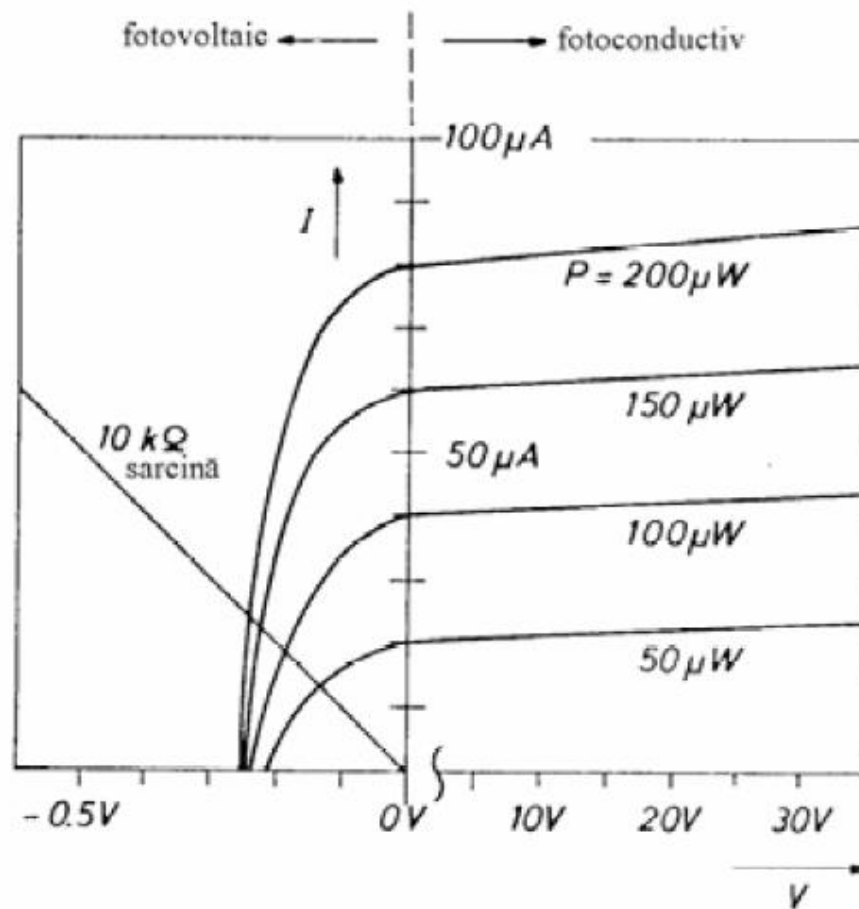
$$R = \frac{I}{P_o} = \frac{\eta \cdot e \cdot \lambda}{hc} \cdot M$$



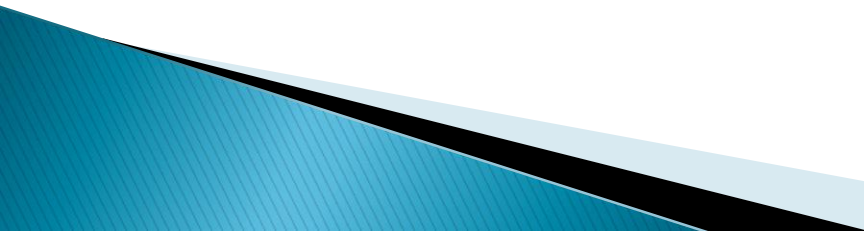
Dezavantaje

- ▶ 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 multiplicatie are o componenta aleatorie (zgomot suplimentar)
 - ▶ viteza mai redusa (timp de generare al avalansei)
- 

Caracteristici curent/tensiune Fotodioda

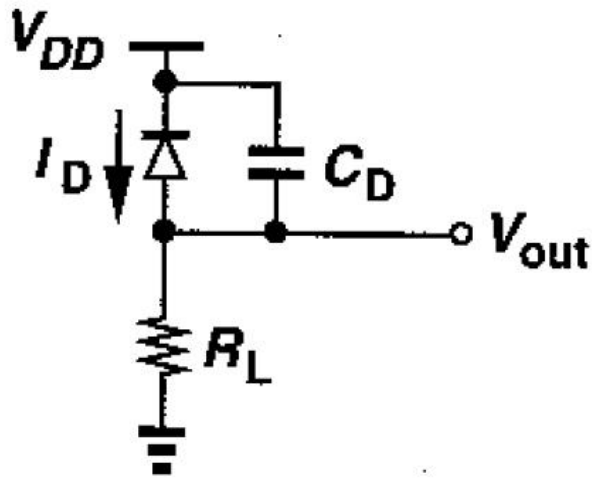


Amplificatoare transimpedanta

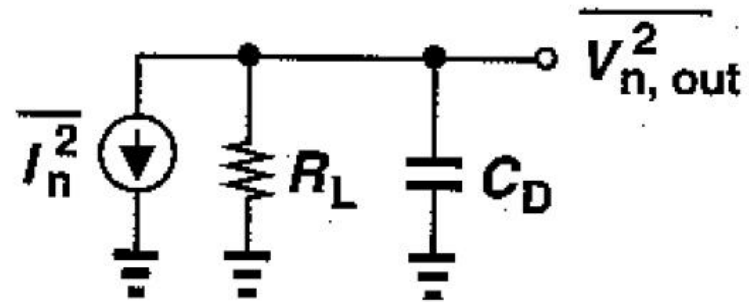
- ▶ Fotodiodele genereaza un curent proportional cu puterea optica receptionata
 - ▶ Primul pas necesar este conversia acestui curent la o tensiune
 - ▶ Amplificatoarele transimpedanta sunt amplificatoarele atacate in curent si care ofera la iesire o tensiune proportionala cu acesta
 - ▶ Amplificarea este masurata in Ω ($k\Omega$)
- 

Amplificatoare transimpedanta

- ▶ Cel mai simplu amplificator transimpedanta este un rezistor



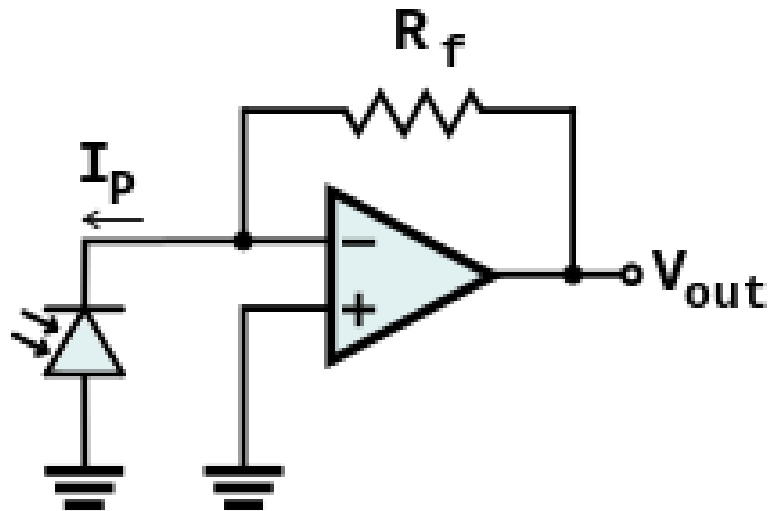
(a)



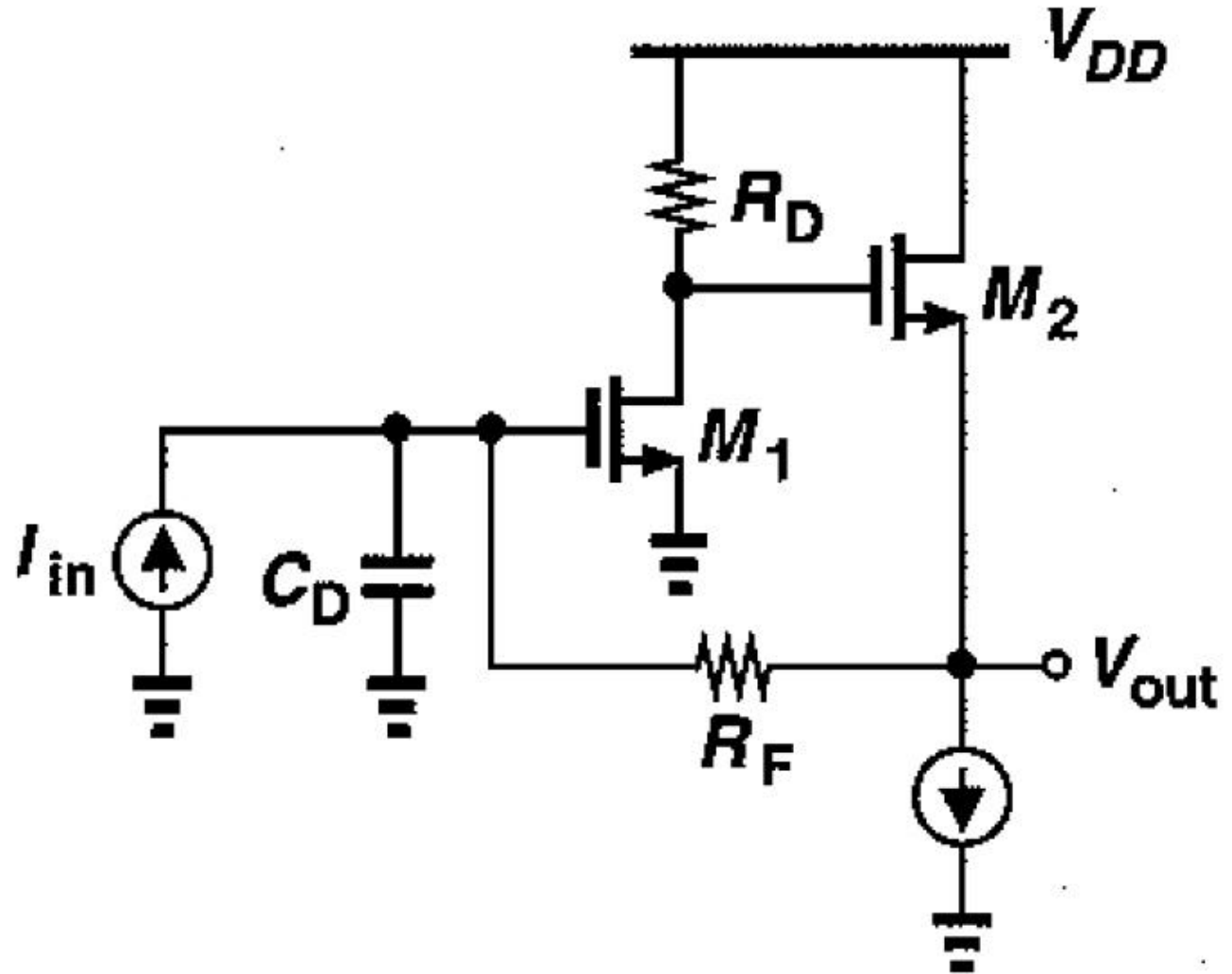
(b)

Amplificatoare transimpedanta

- ▶ Trebuie realizat un compromis intre
 - zgomot
 - castig
 - viteza
- ▶ De obicei sunt realizate cu reactie



Amplificatoare transimpedanta



Zgomotul traductorilor electro-optici

Zgomotul emitatorilor optici

▶ LED

- este considerat o sursa lipsita de zgomot
- nu contamineaza semnalul cu zgomot suplimentar

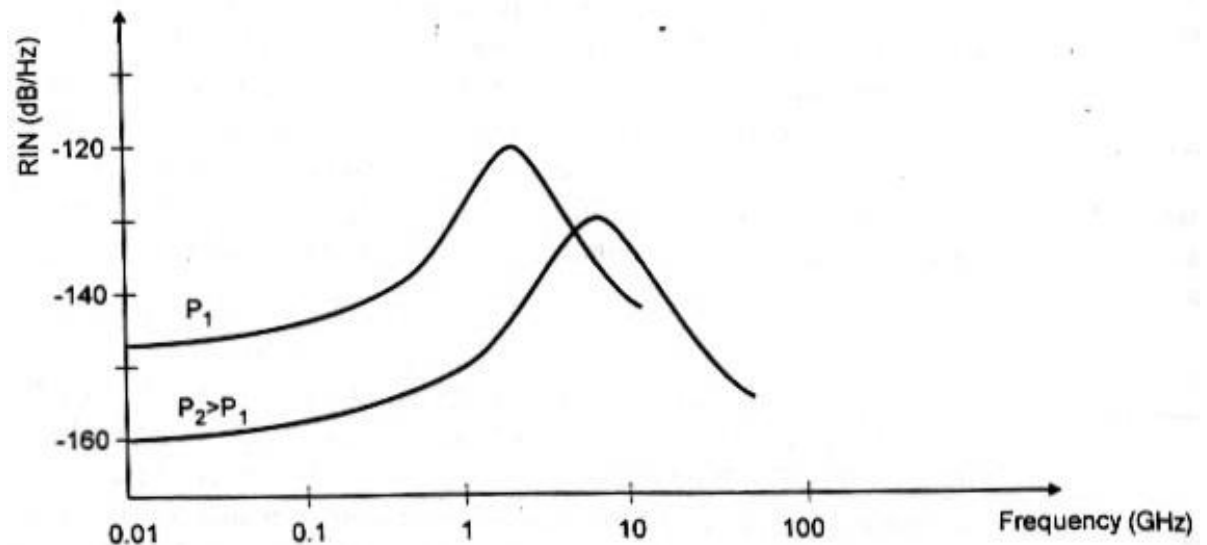
▶ Dioda LASER

- fluctuatii de faza, determina o largire a spectrului emis
- fluctuatii de intensitate, determina zgomotul de intensitate introdus de dioda
- RIN – Relative Intensity Noise

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

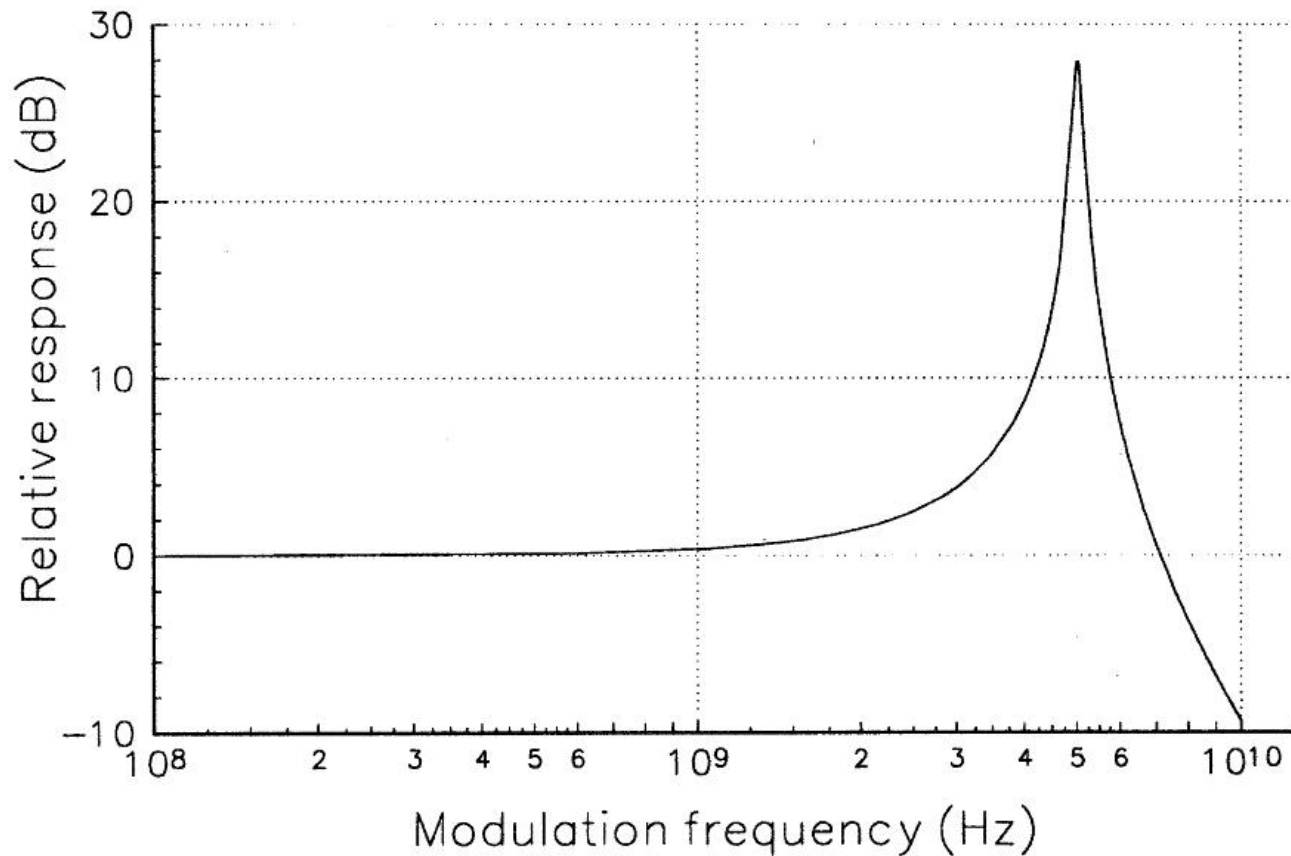
RIN

- ▶ 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

- R_i – rezistenta de intrare in circuitul de modulare a diodei
- Variatiile de putere (zgomot) echivalente unor variatii de curent (zgomot) prin dioda

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

$$EIN[W] = R_i \cdot \langle I_n^2 \rangle \quad 1 \text{ Hz banda}$$

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

Zgomotul fotodiodei

▶ NEP

- Noise Equivalent Power
- r – rezonvizitatea diodei

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

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

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

Zgomotul fotodiodei

▶ NEP

- cea mai mica putere detectabila

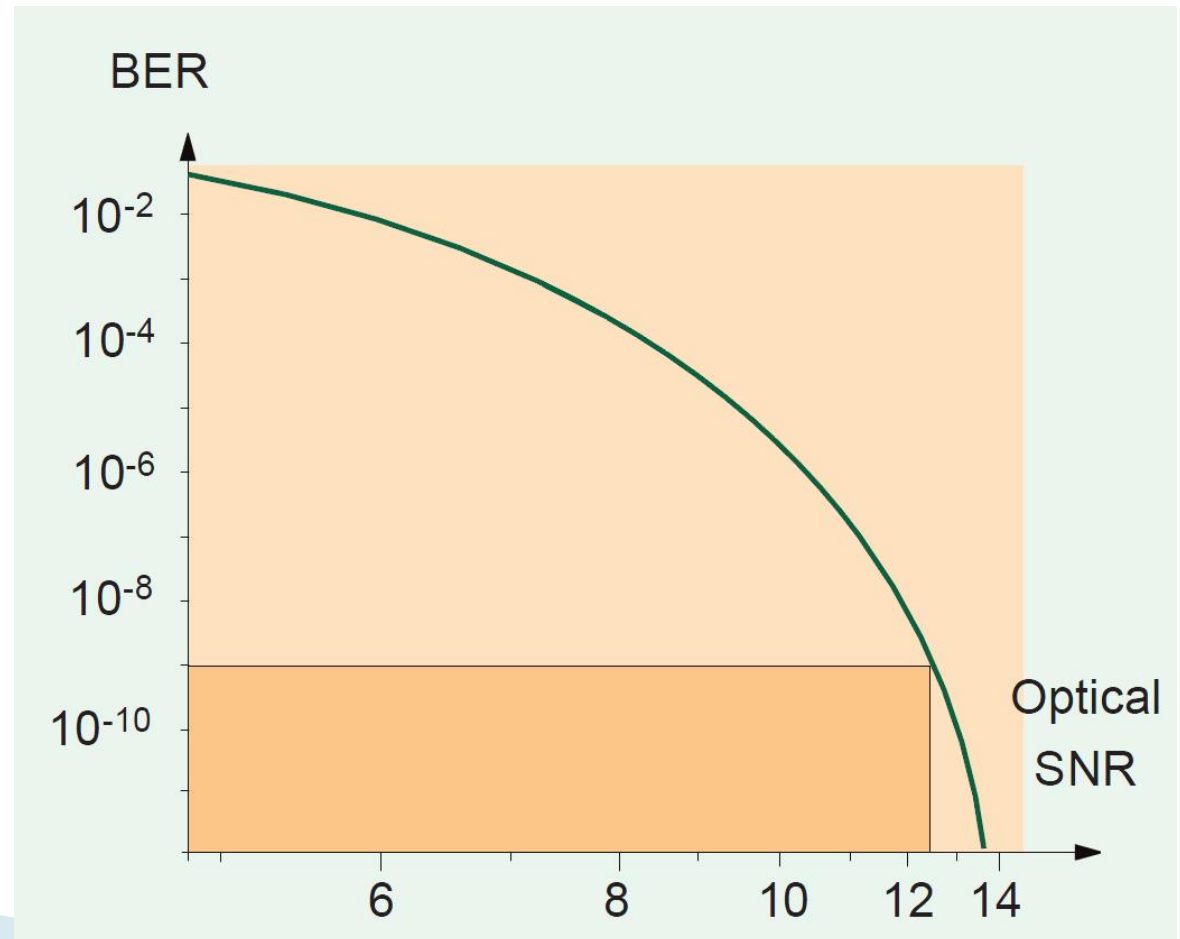
$$\langle i_n^2 \rangle = 2 \cdot e \cdot I \cdot BW_{PD} = 2 \cdot e \cdot (I_S + I_{dark}) \cdot BW_{PD}$$

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

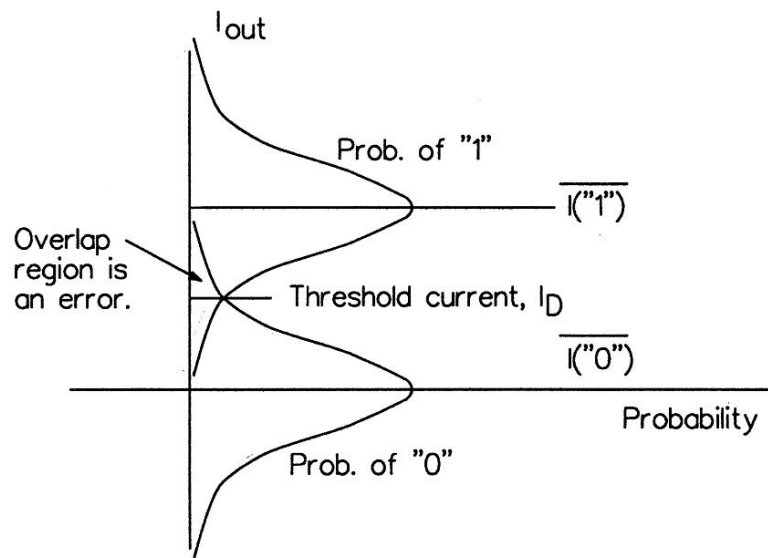
$$NEP[W / \sqrt{Hz}] = \frac{1}{r} \cdot \sqrt{2 \cdot e \cdot I_{dark}}$$

BER

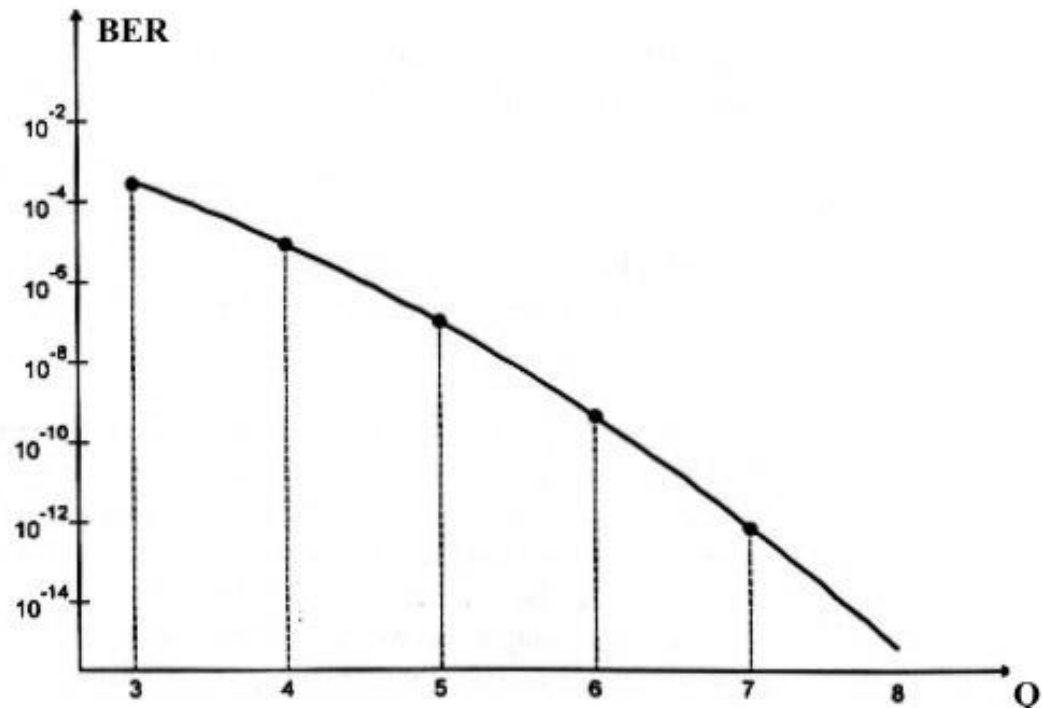
▶ Bit Error Rate



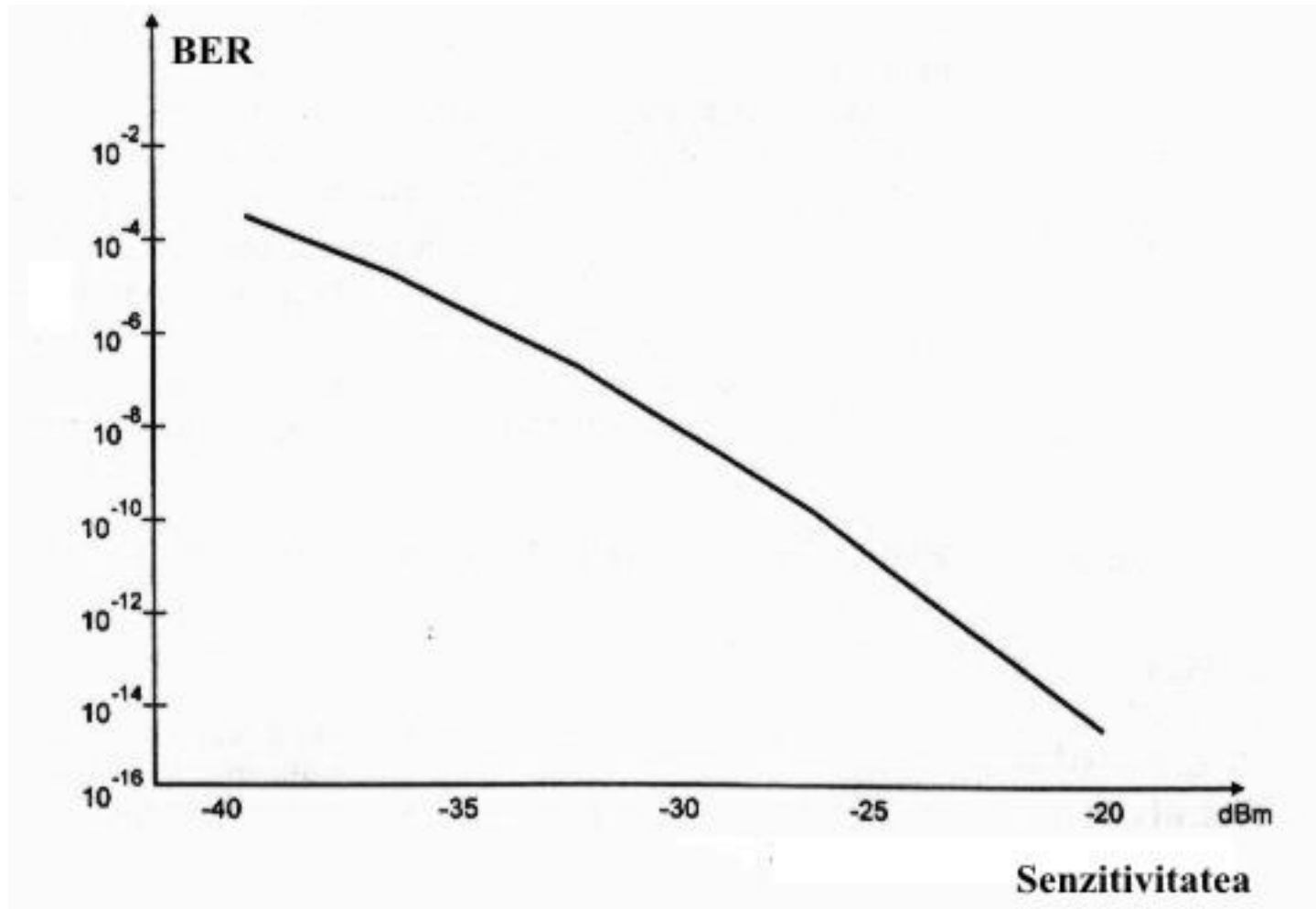
Probabilitate de eroare



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



Senzitivitatea unei diode



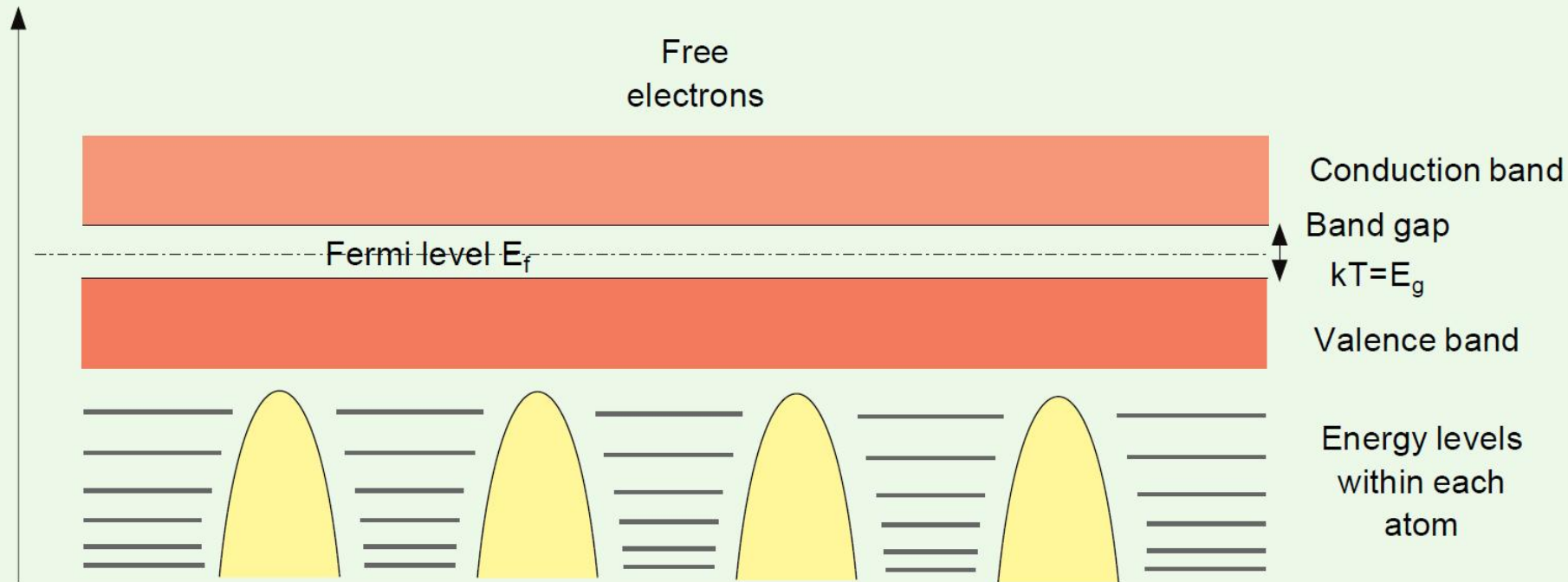
Utilizare celule solare

Capitolul 9

Efect fotovoltaic

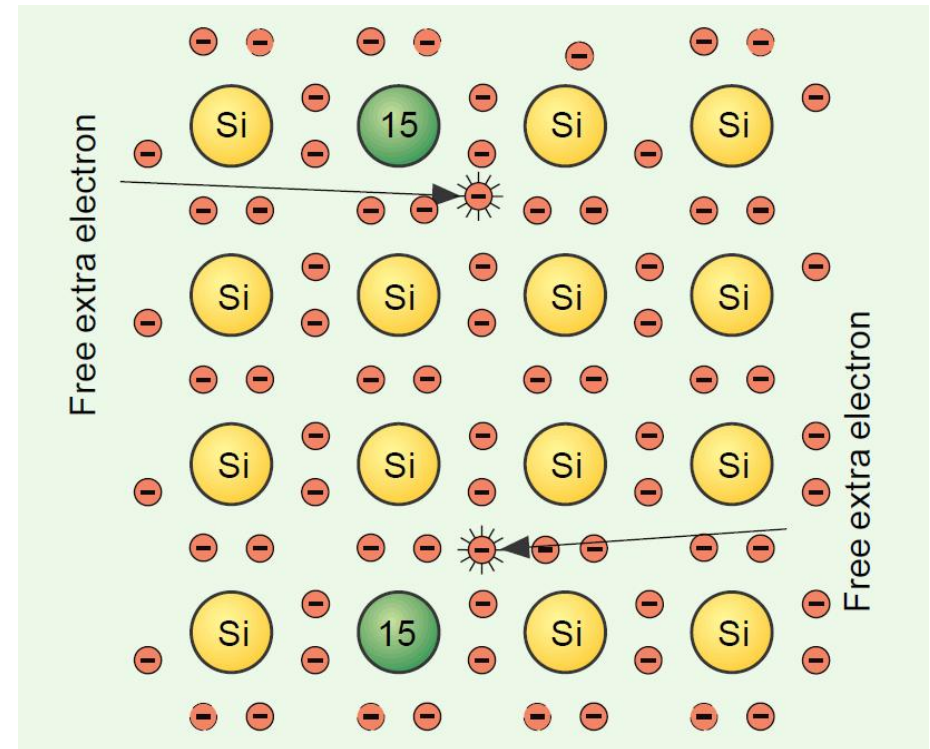
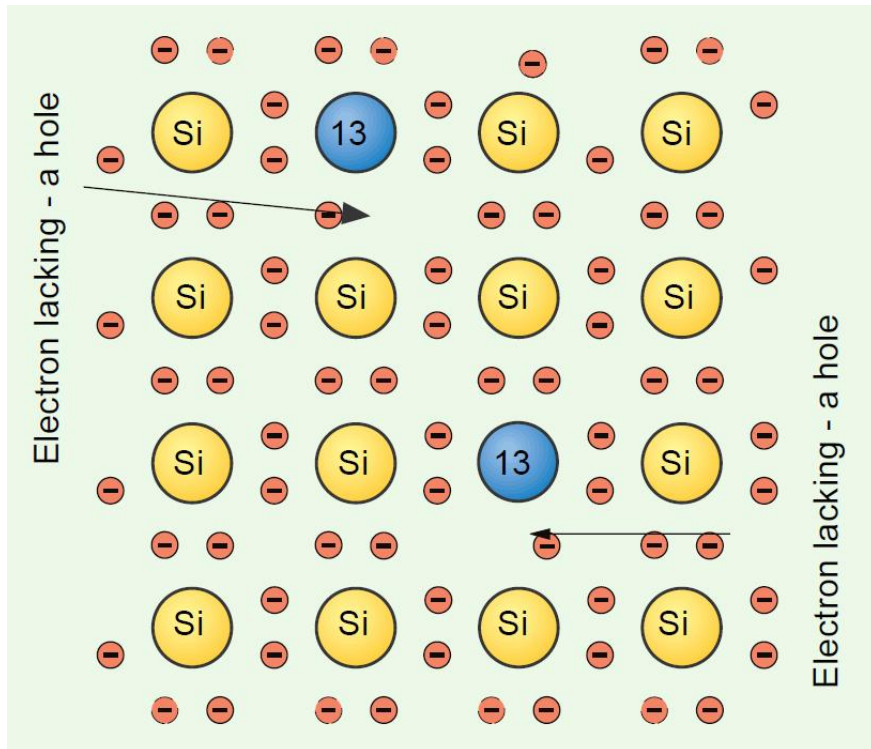
▶ joncțiunea pn

Energy level



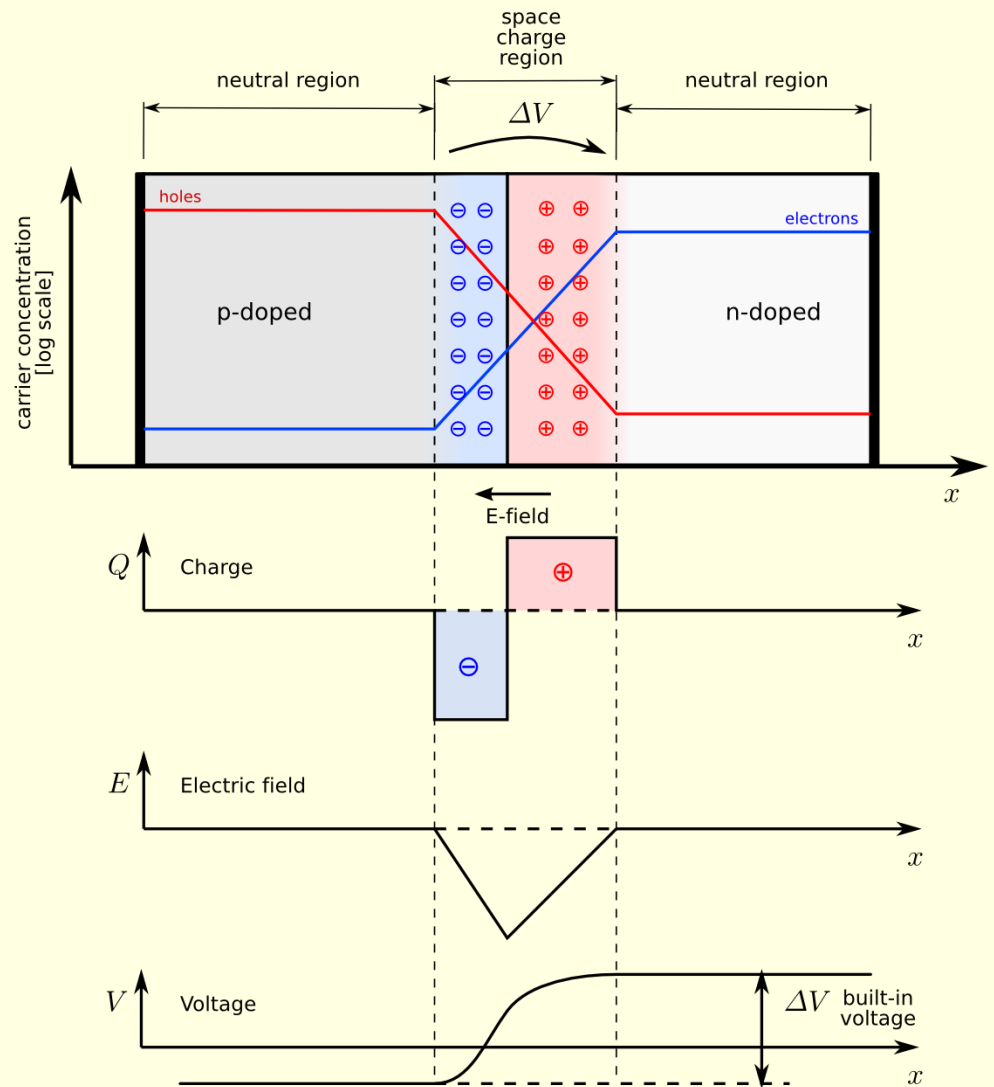
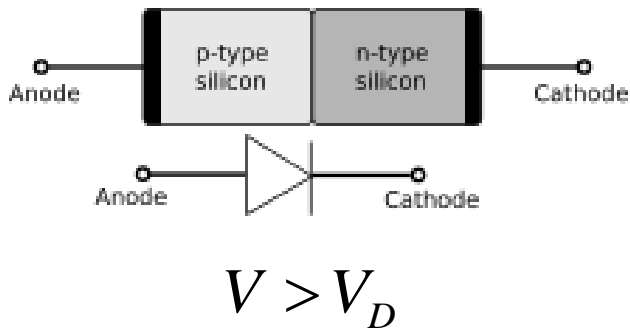
Efect fotovoltaic

▶ joncțiunea pn



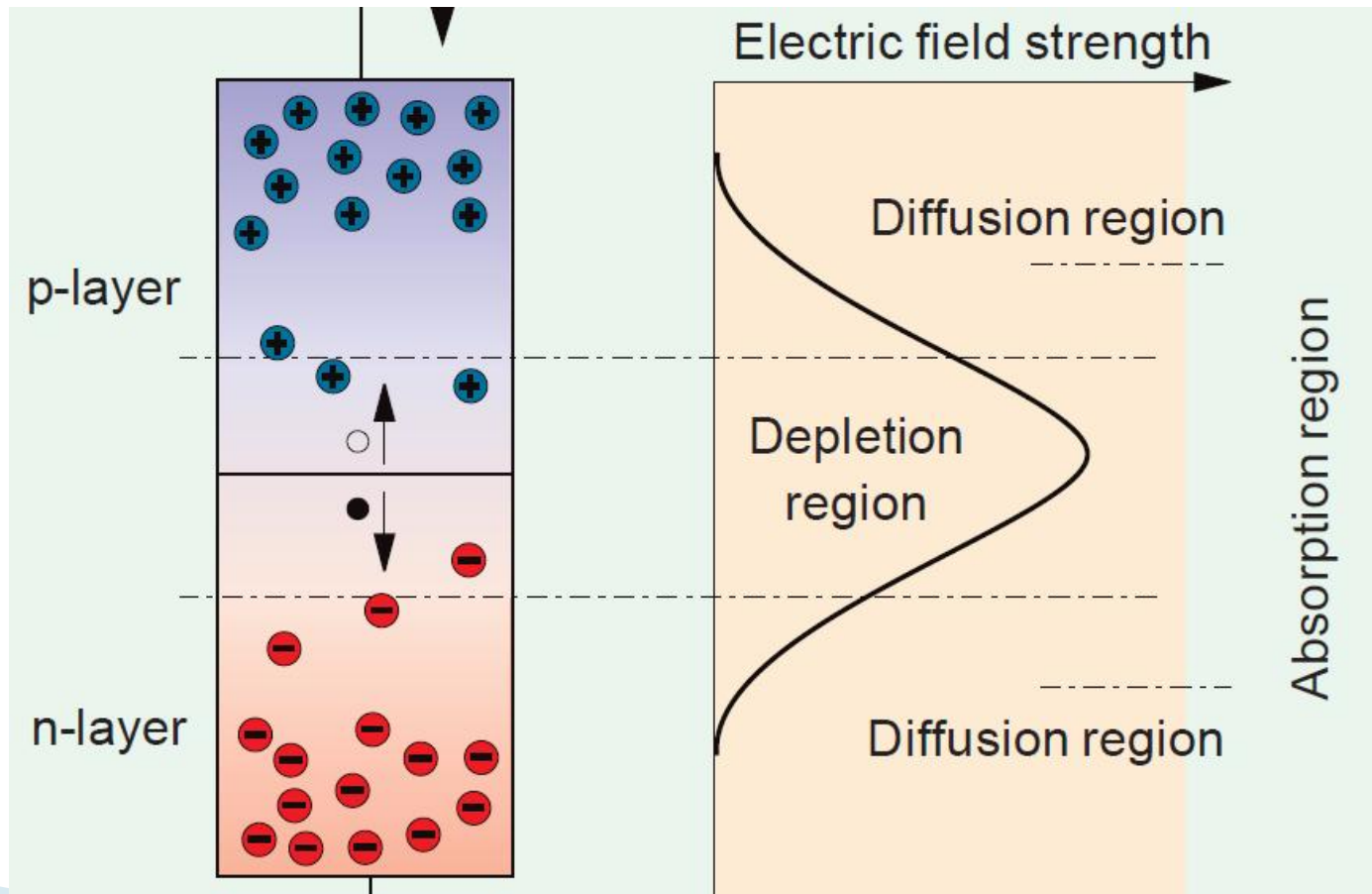
Efect fotovoltaic

▶ joncțiunea pn



Efect fotovoltaic

- ▶ joncțiunea pn / Fotodioda

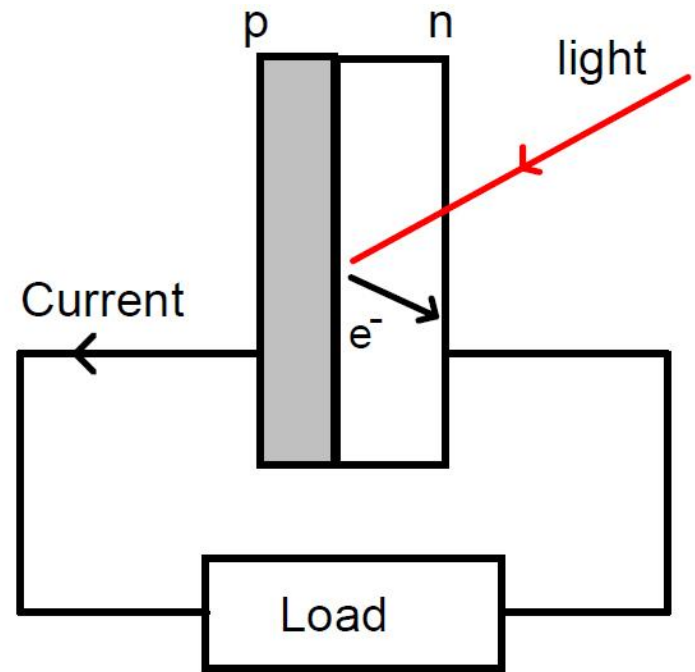
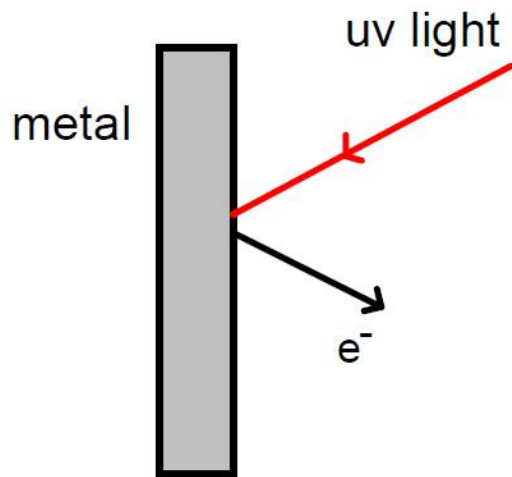


Efect fotovoltaic

- ▶ generarea unei perechi electron/gol in interiorul unui material prin absorbtia energiei fotonilor incidenti si cresterea energiei potentiale a electronilor
 - urmat de posibilitatea separarii sarcinilor
- ▶ deosebit de conversia:
 - fototermica (energia fotonilor este convertita in caldura – energie cinetica a electronilor)
 - fotochimica (fotosinteza energie potentiala utilizata chimic)
- ▶ duce la aparitia unei tensiuni electromotoare si a unui curent intr-un circuit inchis

Efect fotovoltaic

- ▶ diferit de efectul fotoelectric (cu toate ca este asemanator ca principiu)

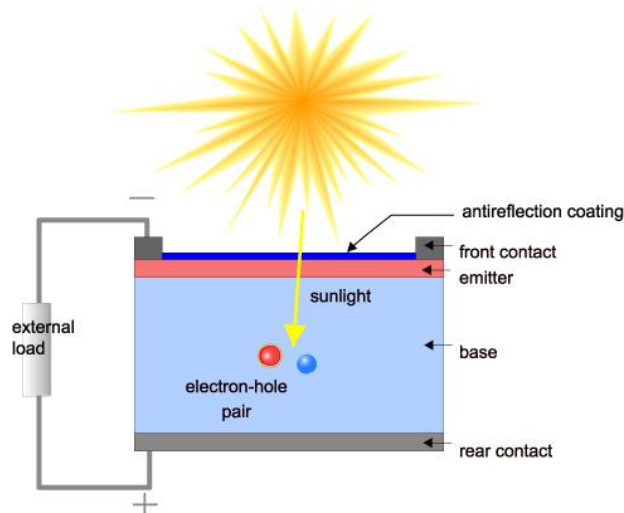


Efect fotovoltaic

- ▶ Separarea fizica a sarcinilor este de obicei realizata prin utilizarea unei jonctiuni pn:
 - campul electric generat de distributia sarcinilor in zona golita de purtatori a jonctiunii
- ▶ In principiu o **celula solara** este o **fotodioda** in care:
 - nivelul de semnal optic este ridicat (fortarea prin polarizare inversa externa a extragerii tuturor electronilor generati nu e necesara)
 - viteza de lucru nu e importanta (accelerarea iesirii din dispozitiv a electronilor generati nu e necesara)

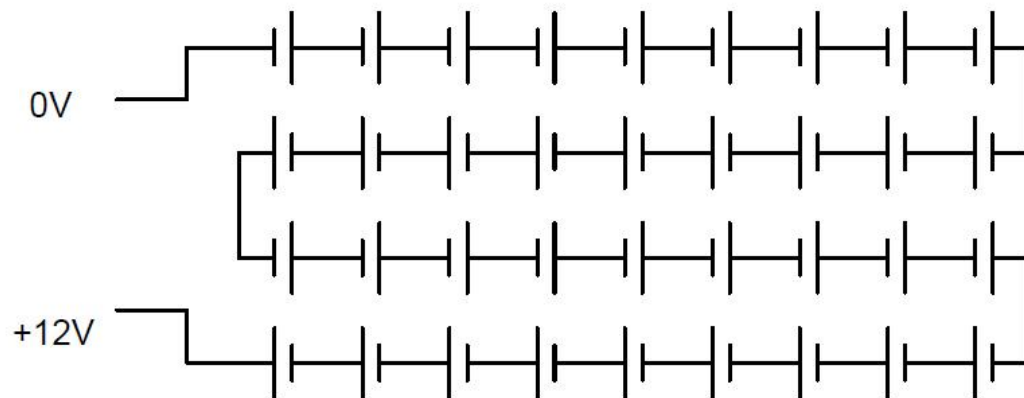
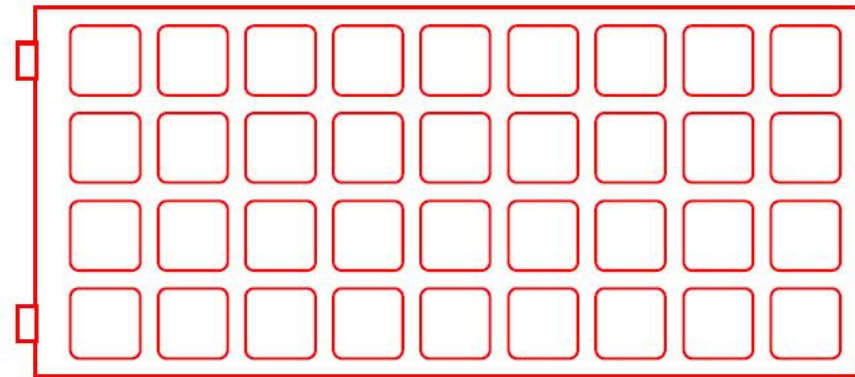
Celula solara (fotovoltaica)

- ▶ in principiu o dioda
 - cu arie mare ($\sim 100\text{cm}^2$)
 - cu suprafata tratata antireflectorizant
 - genereaza o tensiune electromotoare de $0.5\div 1\text{V}$
 - genereaza curenti de scurtcircuit de $x0\text{ mA/cm}^2$



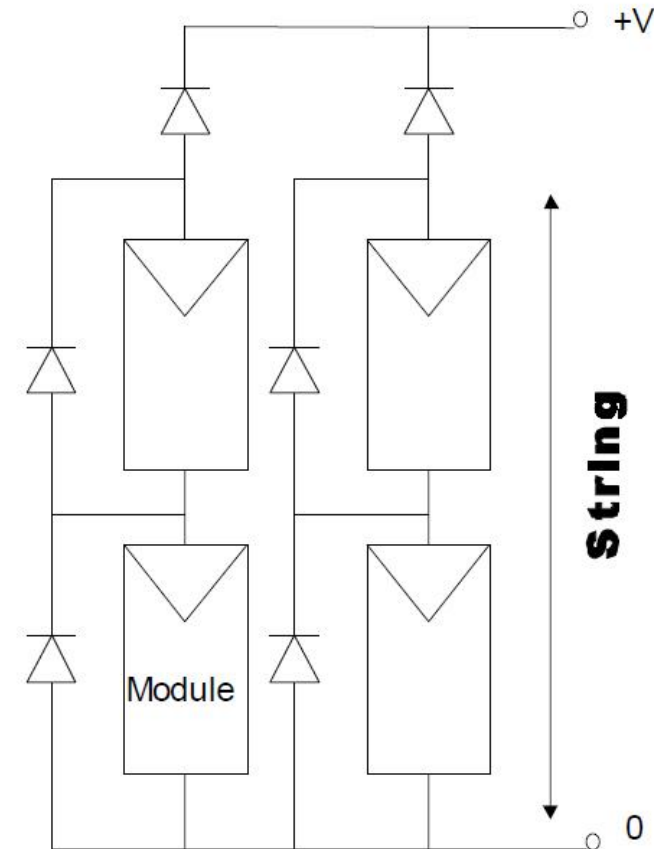
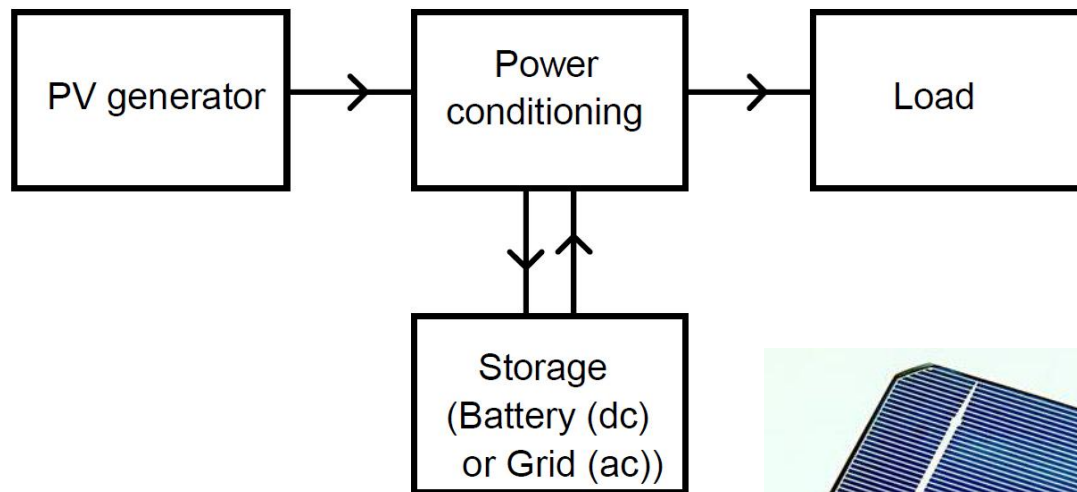
Celula solara (fotovoltaica)

- ▶ pentru utilizare in practica
 - module de 28 – 36 de celule conectate in serie
 - creste tensiunea la 12V (tipic)



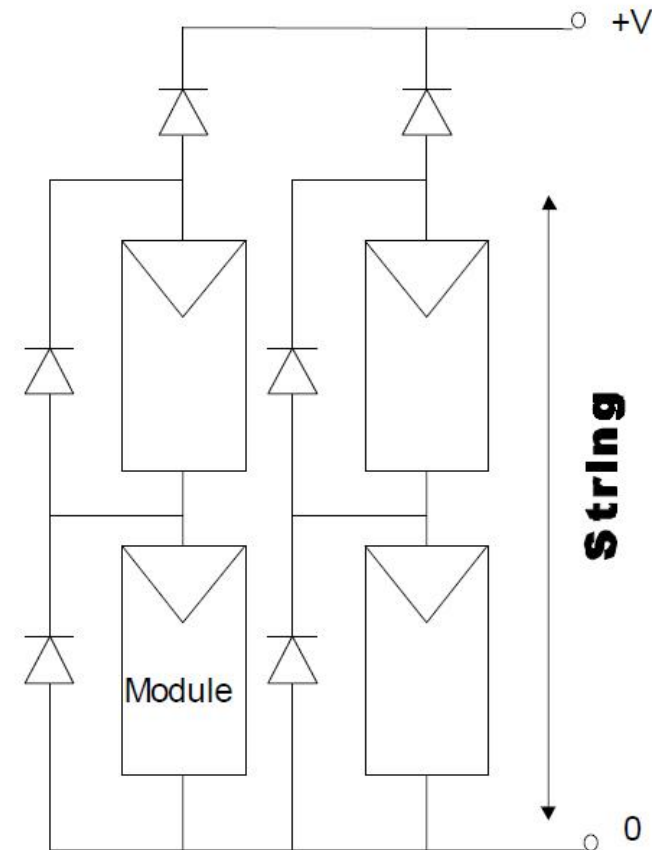
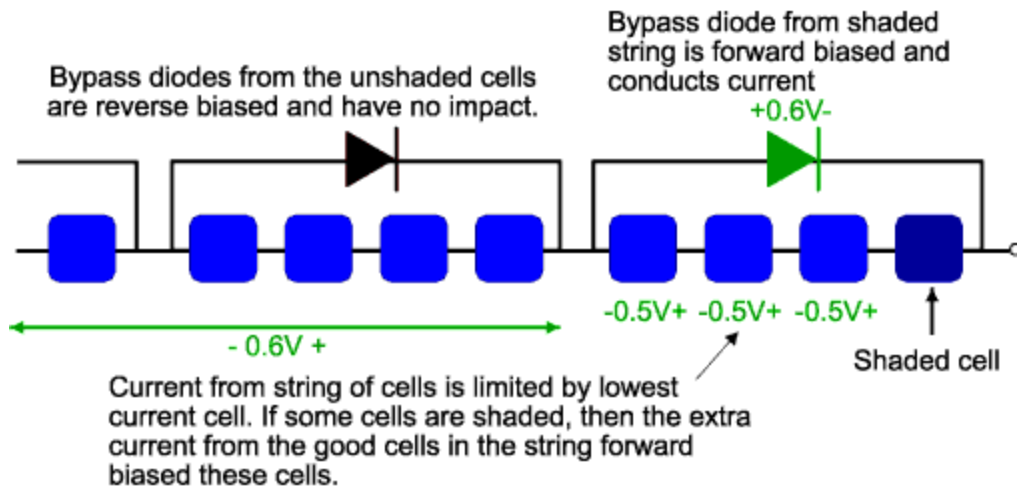
Celula solara (fotovoltaica)

- ▶ pentru utilizare in practica
 - modulele sunt conectate in serie si/sau paralel pentru obtinerea tensiunilor/curentilor necesari pentru aplicatie



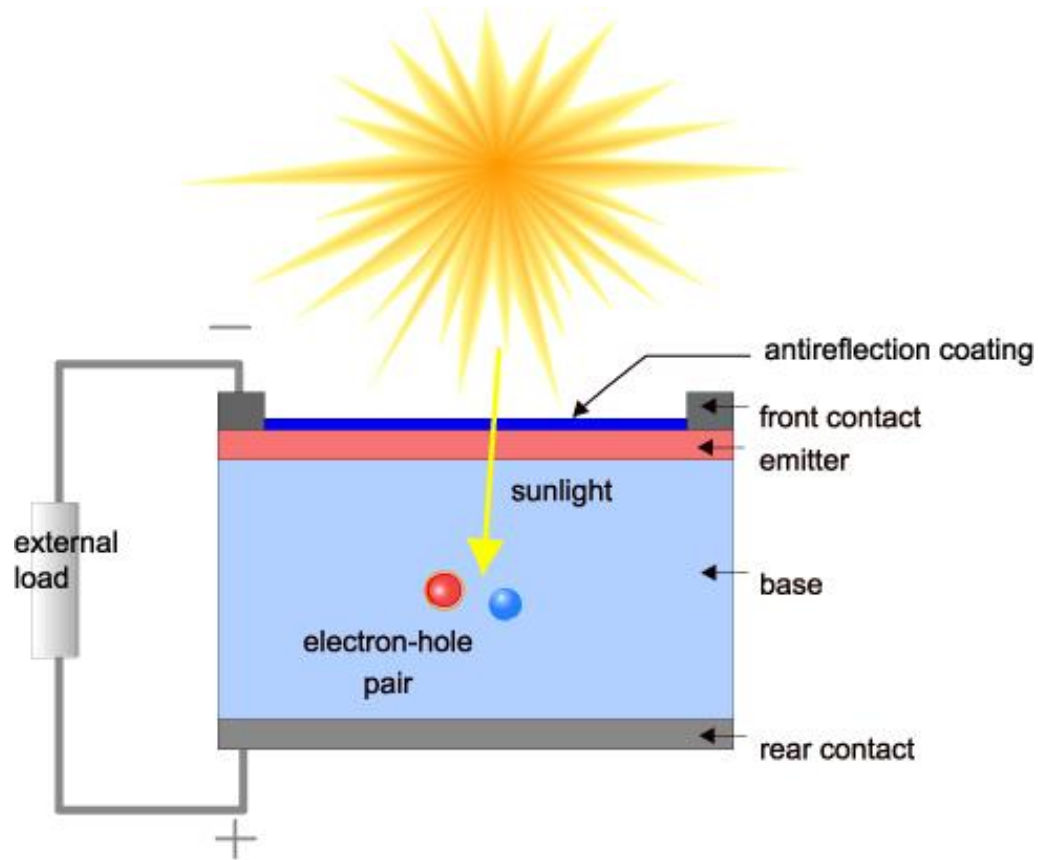
Celula solara (fotovoltaica)

- ▶ pentru utilizare in practica
 - diode pentru flexibilitate



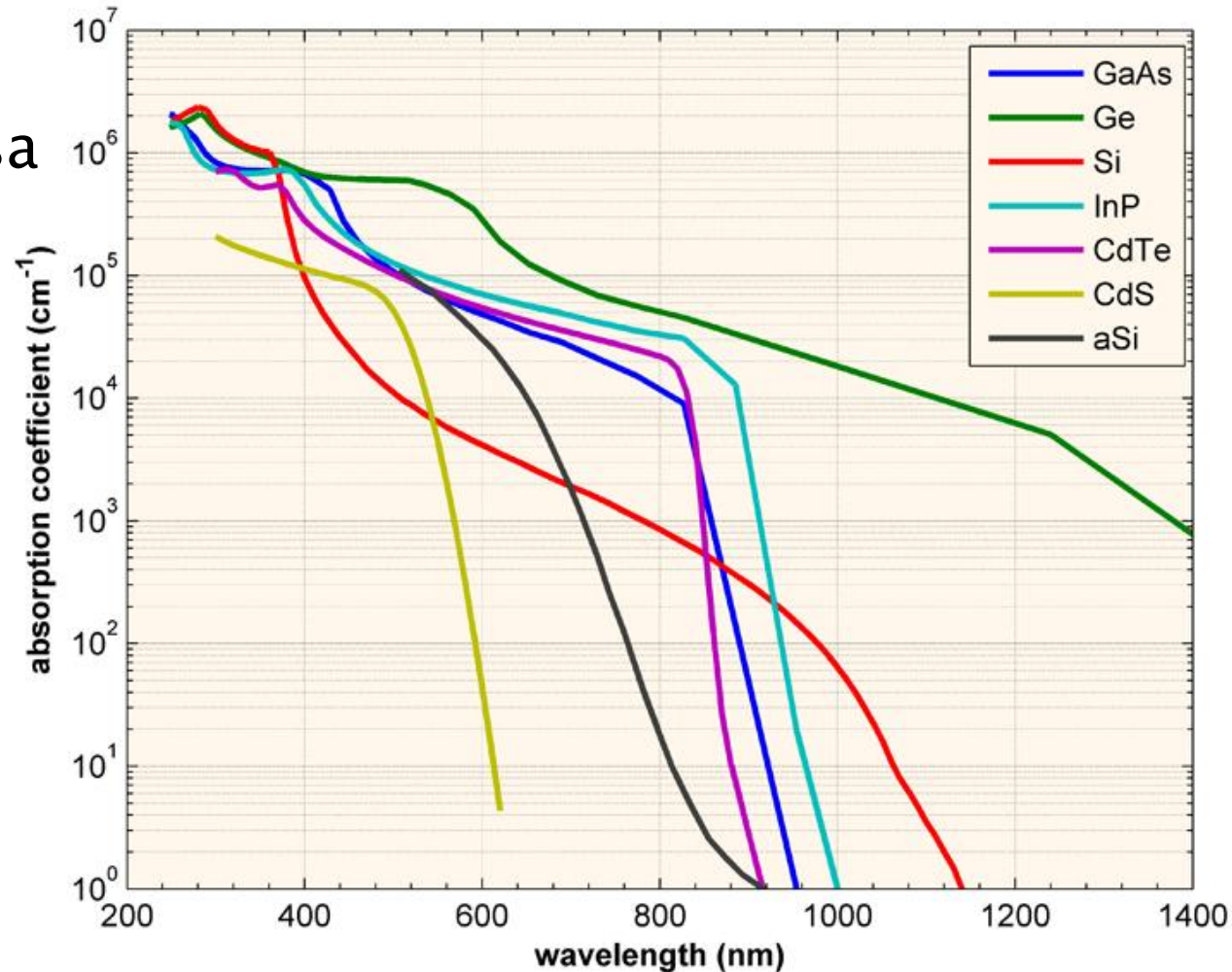
Celula solara (fotovoltaica)

- ▶ in principiu o dioda



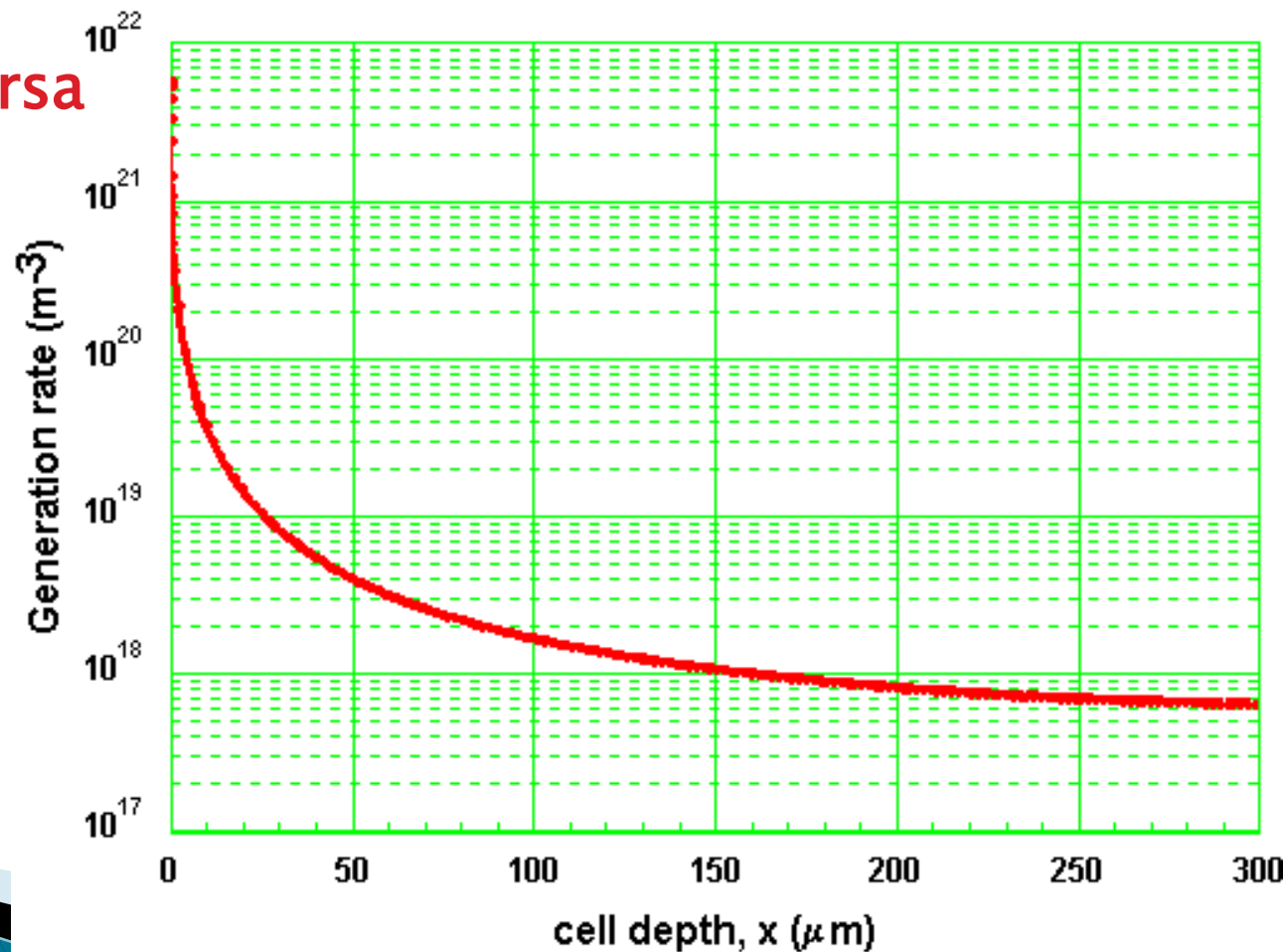
Celula solara

- ▶ probabilitate de generare a purtatorilor depinde de
 - **material**
 - distanta parcursa



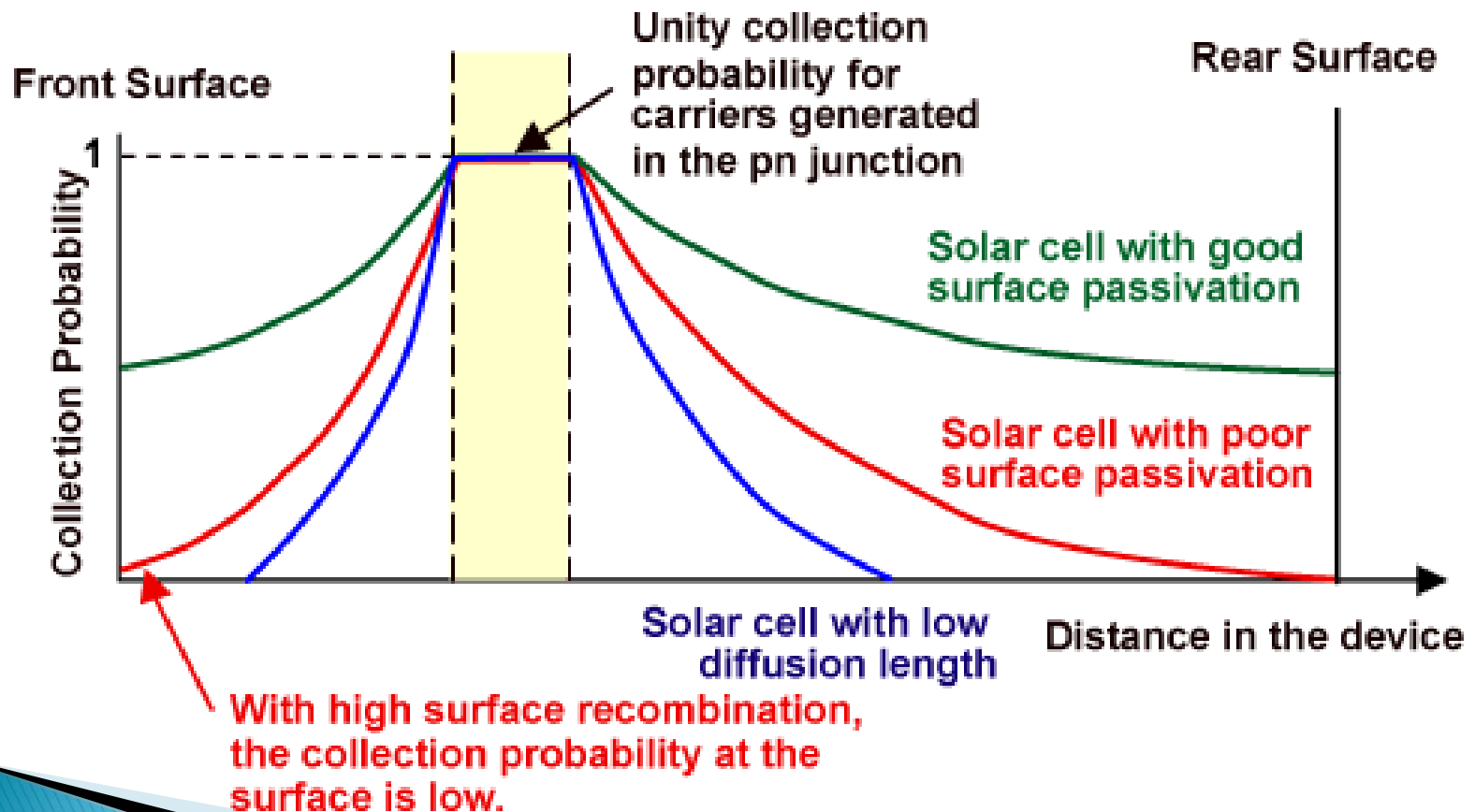
Celula solara

- ▶ probabilitate de generare a purtatorilor depinde de
 - material
 - **distanța parcursă**



Celula solara

- ▶ probabilitate de captura a purtatorilor



Celula solara/Fotodioda

- ▶ Energia necesara pentru eliberarea unei perechi electron gol

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

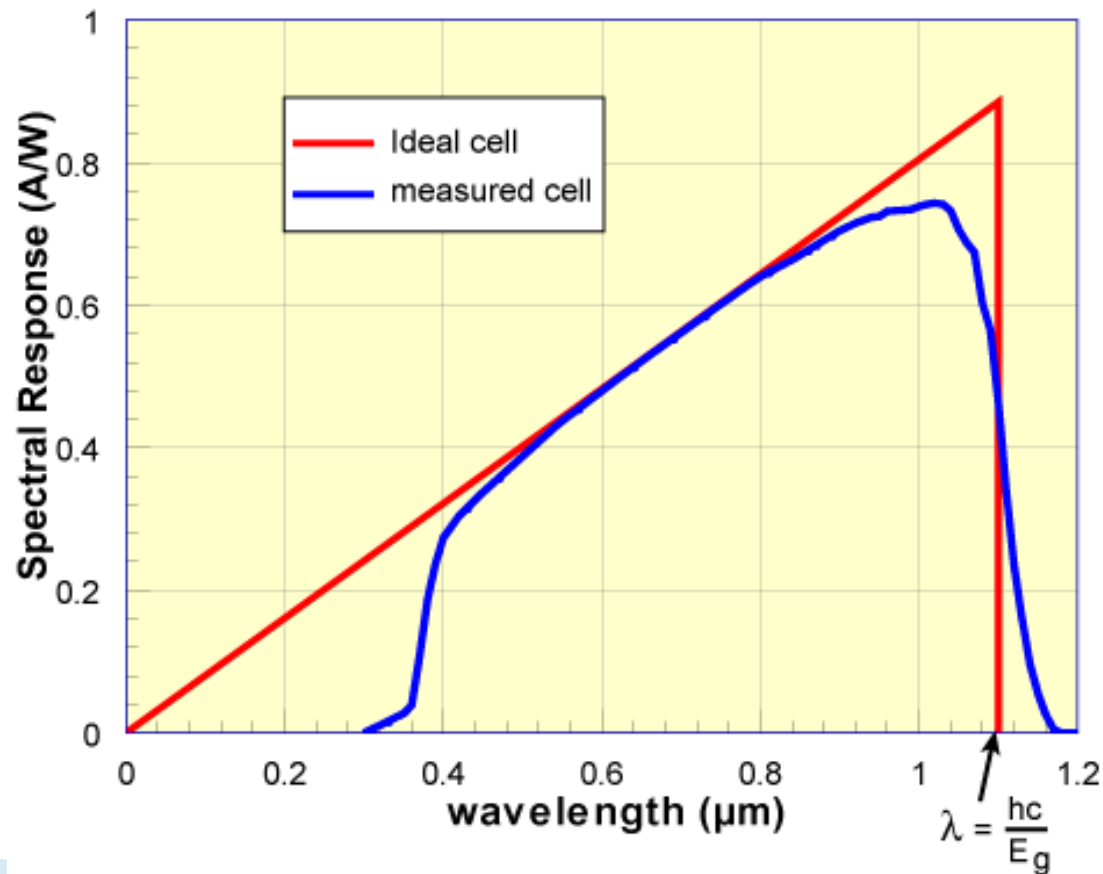
- ▶ Lungime de unda de taiere

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

- ▶ Coeficientul de absorbtie are valoare mare la lungimi de unda reduse
- ▶ Ca urmare comportarea **tuturor** materialelor este de tip trece banda

Celula solara

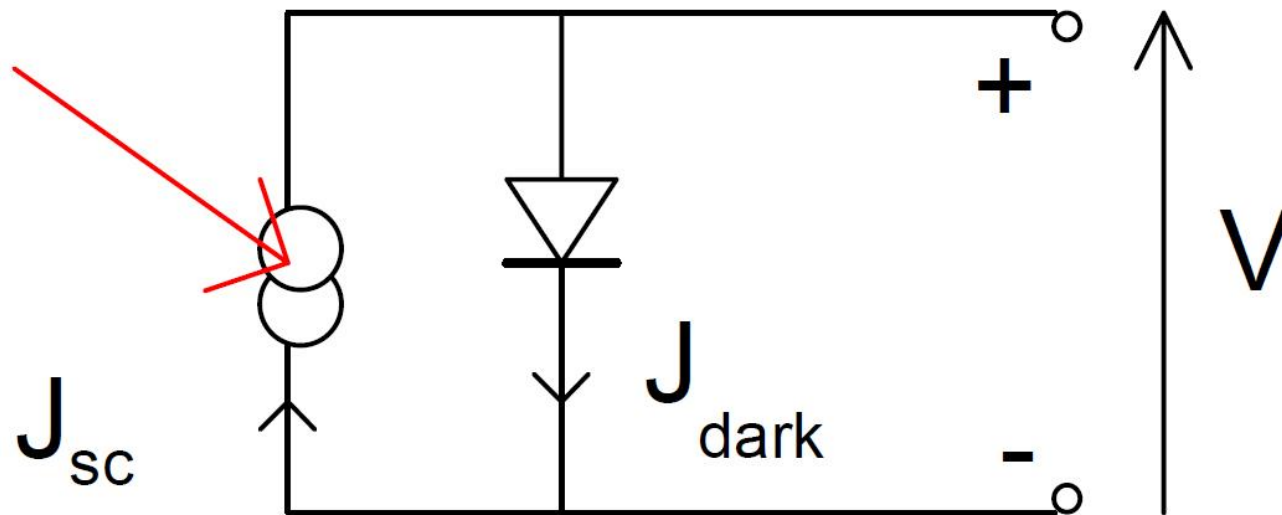
- ▶ raspuns spectral



Celula solara

- ▶ Schema echivalenta

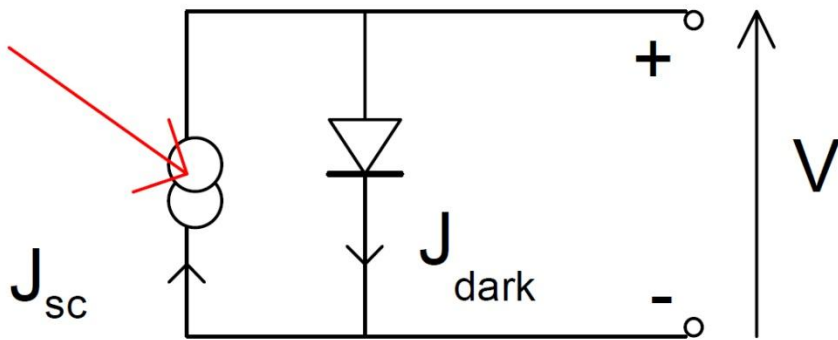
- dioda
- sursa de curent generat de fluxul de fotoni incident



Celula solara

▶ Schema echivalenta

- dioda
- sursa de curent generat de iluminarea energetica incidenta



- curent de intuneric

$$I_d(V) = I_0 \cdot (e^{eV/KT} - 1)$$

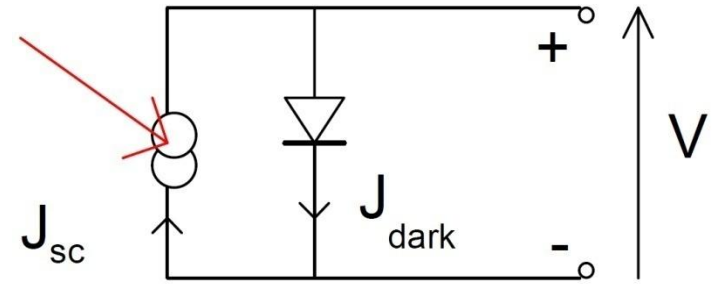
- adaugarea curentului generat de fotoni

$$I(E_e, V) = I_{sc}(E_e) - I_d(V)$$

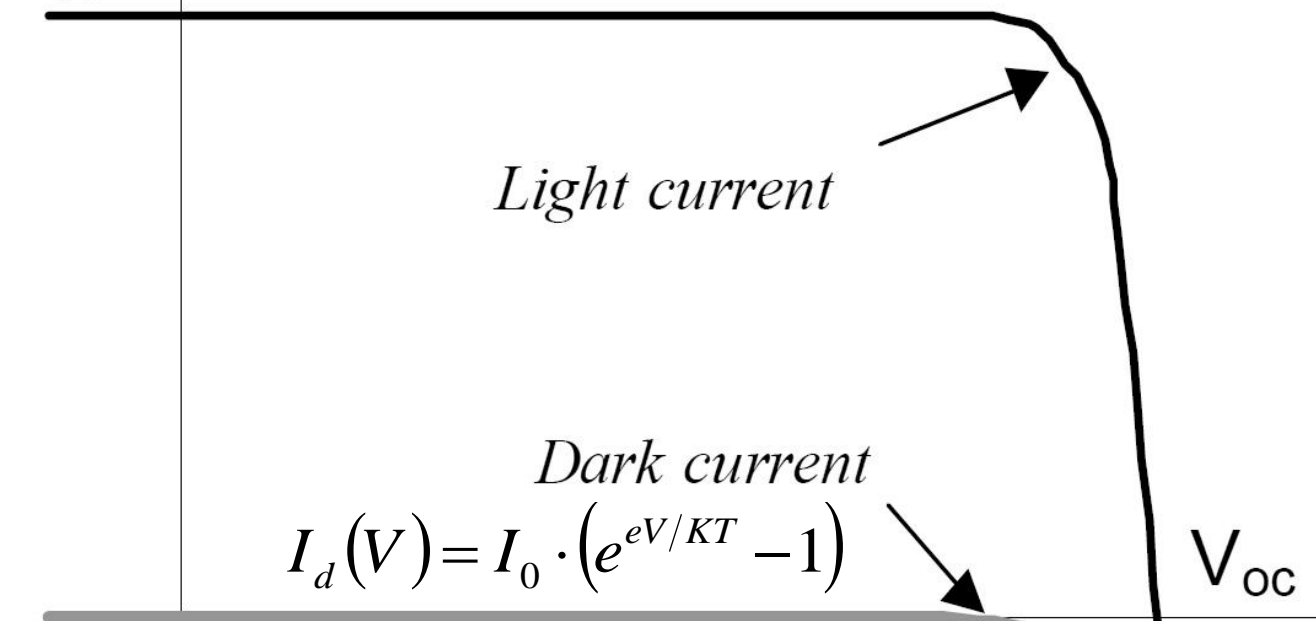
- tensiunea in gol

$$V_{oc} = \frac{k \cdot T}{e} \cdot \ln \left(\frac{I_{sc}(E_e)}{I_0} - 1 \right)$$

Celula solara



$$I(E_e, V) = I_{sc}(E_e) - I_d(V)$$



Light current

Dark current

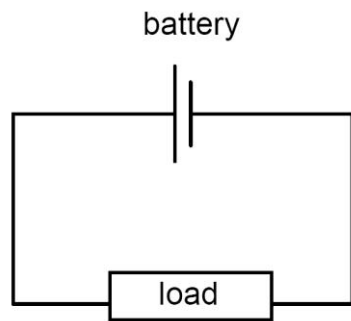
$$I_d(V) = I_0 \cdot (e^{eV/KT} - 1)$$

Bias voltage, V

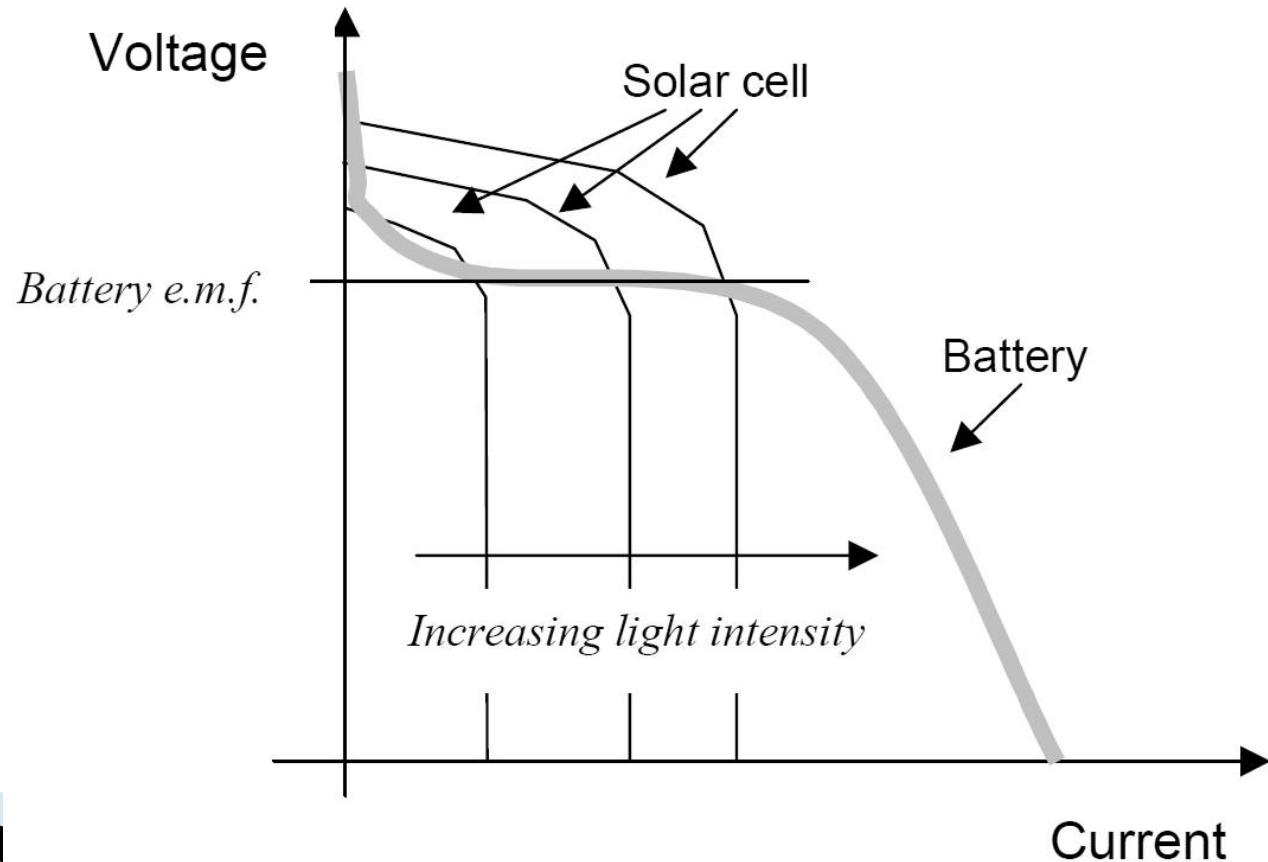
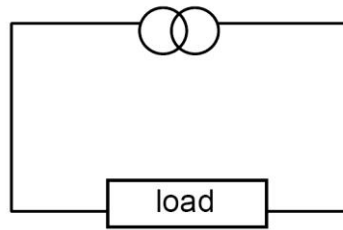
$$V_{oc} = \frac{k \cdot T}{e} \cdot \ln \left(\frac{I_{sc}(E_e)}{I_0} - 1 \right)$$

Celula solara

- ▶ poate fi folosita in loc de baterie intr-un circuit electric
 - cu anumite diferente



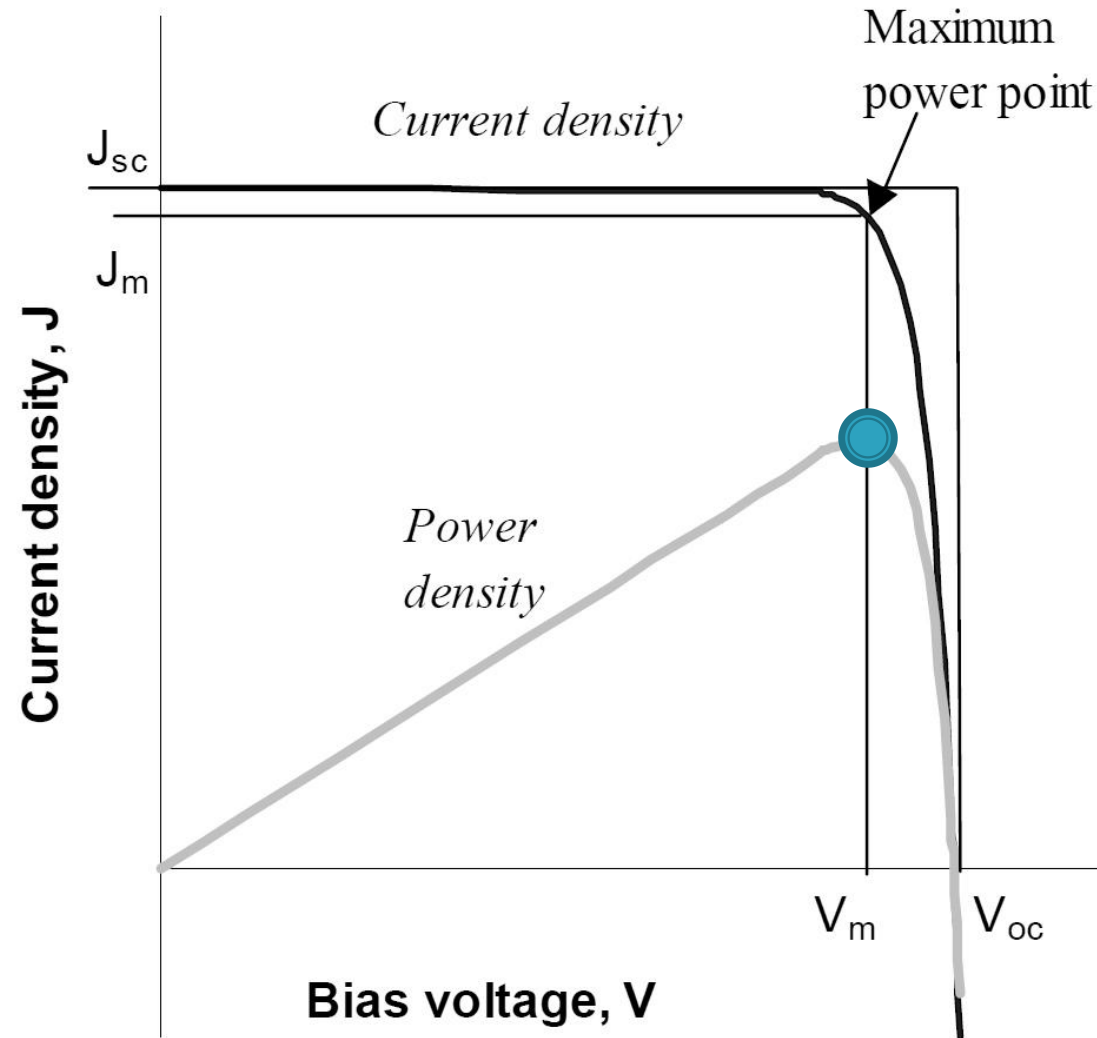
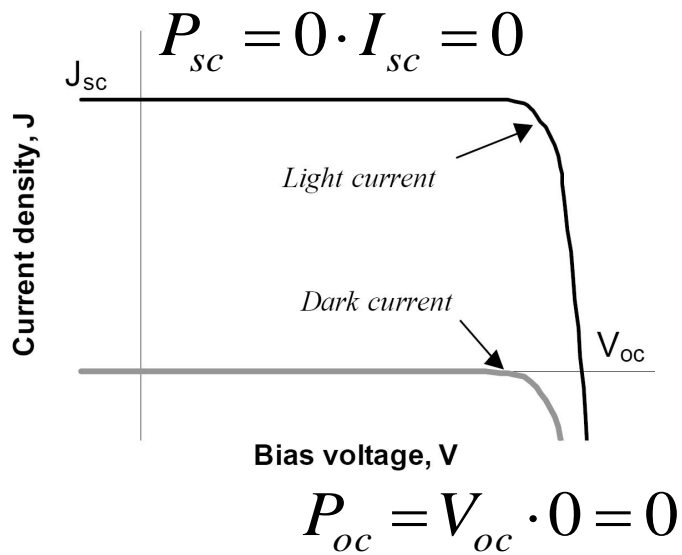
solar cell



Celula solara

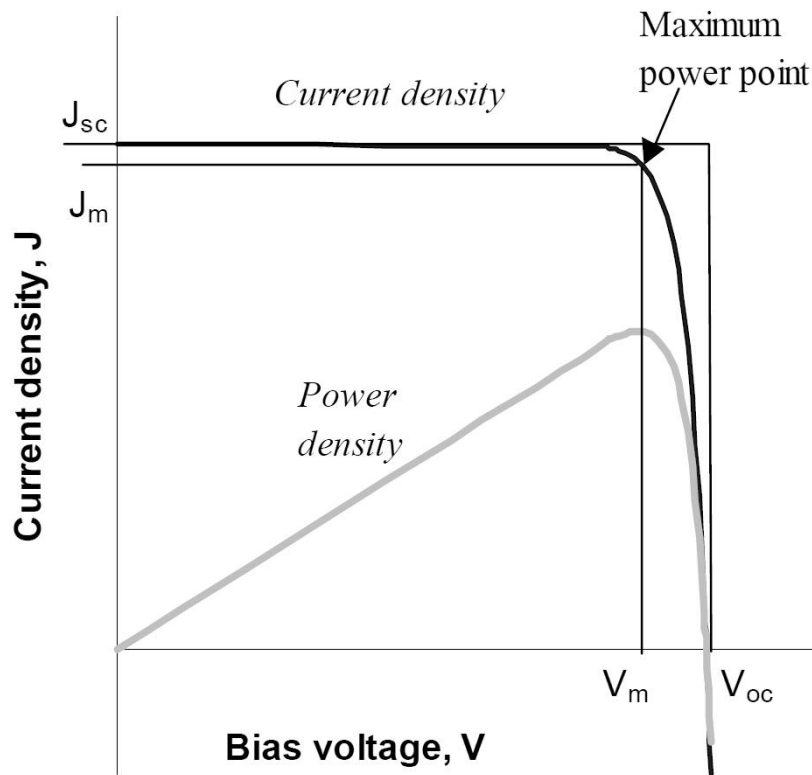
- ▶ Putere generata

$$P = V \cdot I$$



Celula solara

▶ Putere generata



$$P_m = V_{pm} \cdot I_{pm}$$

- ▶ Valorile de curent si tensiune pentru putere maxima sunt date de catalog, circuitul de conditionare care urmeaza dupa celule poate fi **optimizat** sa functioneze la aceste valori

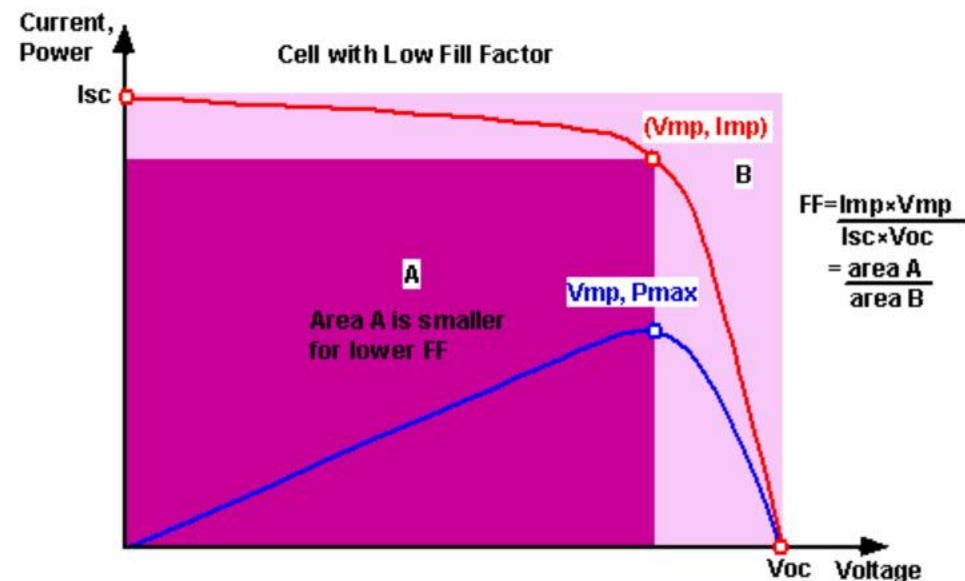
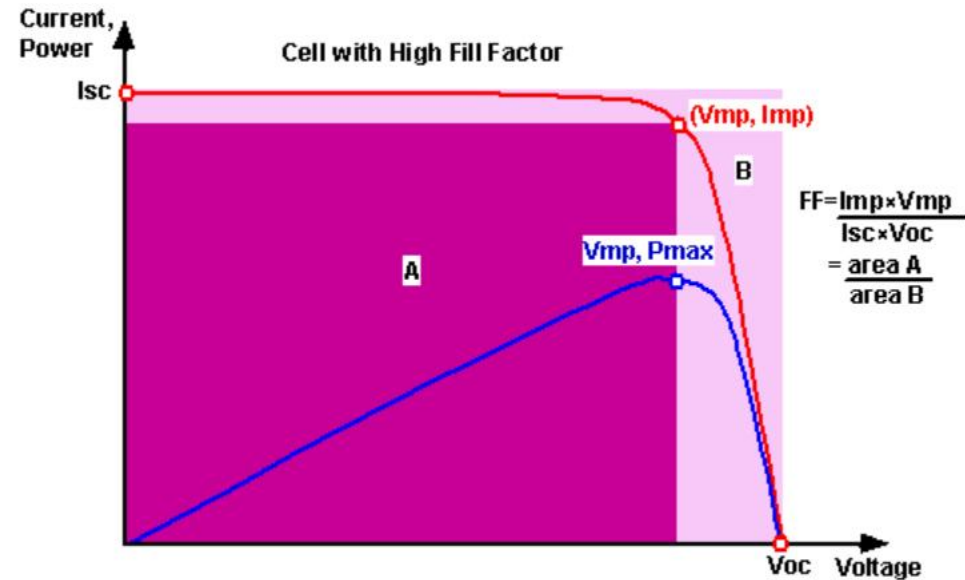
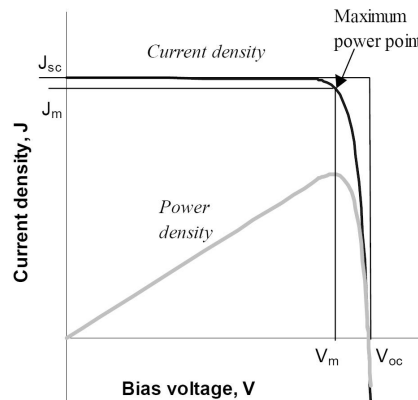
Celula solara

- ▶ Factor de umplere

$$FF = \frac{V_{pm} \cdot I_{pm}}{V_{oc} \cdot I_{sc}}$$

- ▶ o masura a calitatii celulei
 - dependent de material

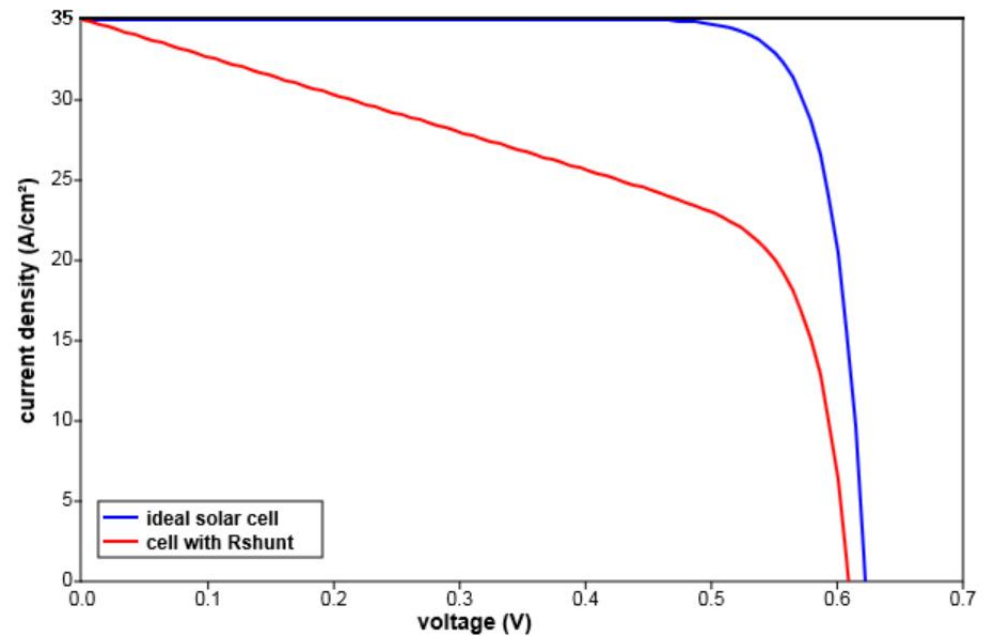
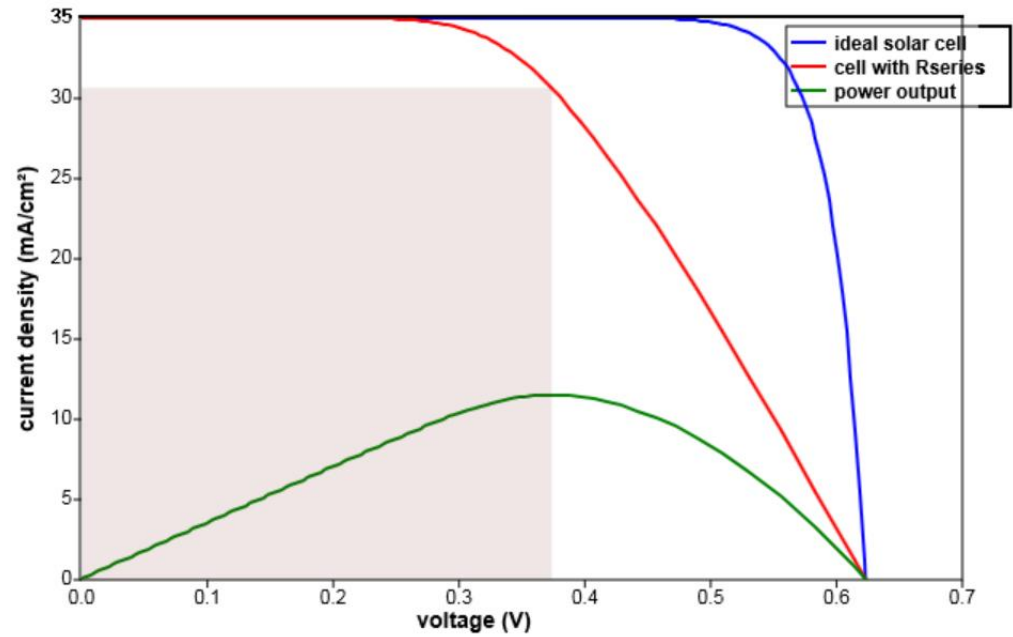
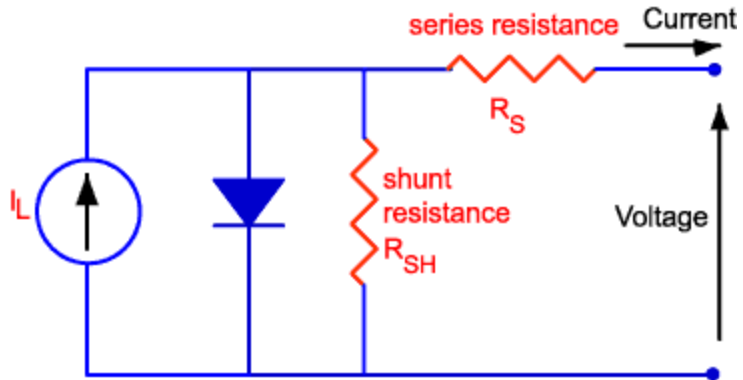
$$P_m = V_{pm} \cdot I_{pm}$$



Efect pierderi

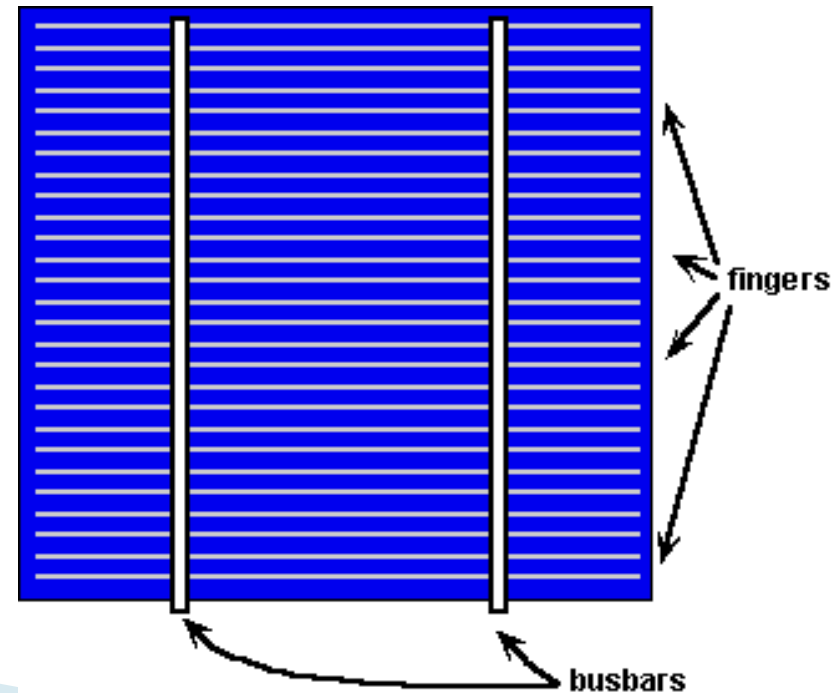
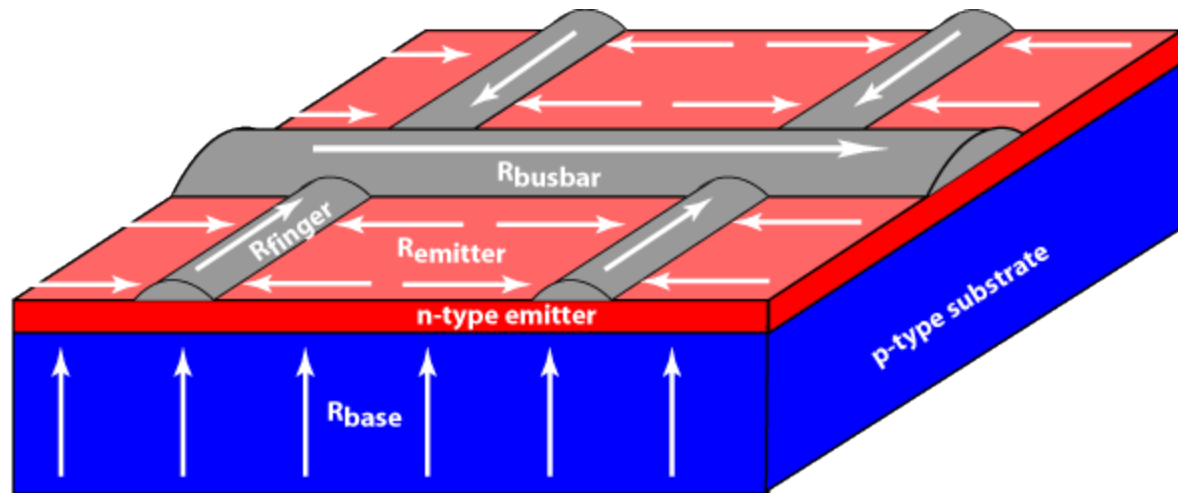
- ▶ Rezistenta serie
 - rezistenta echivalenta a semiconductorului utilizat
 - rezistenta jonctiunilor metal/semiconductor
 - rezistenta contactului metalic al anodului si colectorului
- ▶ Rezistenta paralel
 - generata de defecte de fabricatie

Efect pierderi



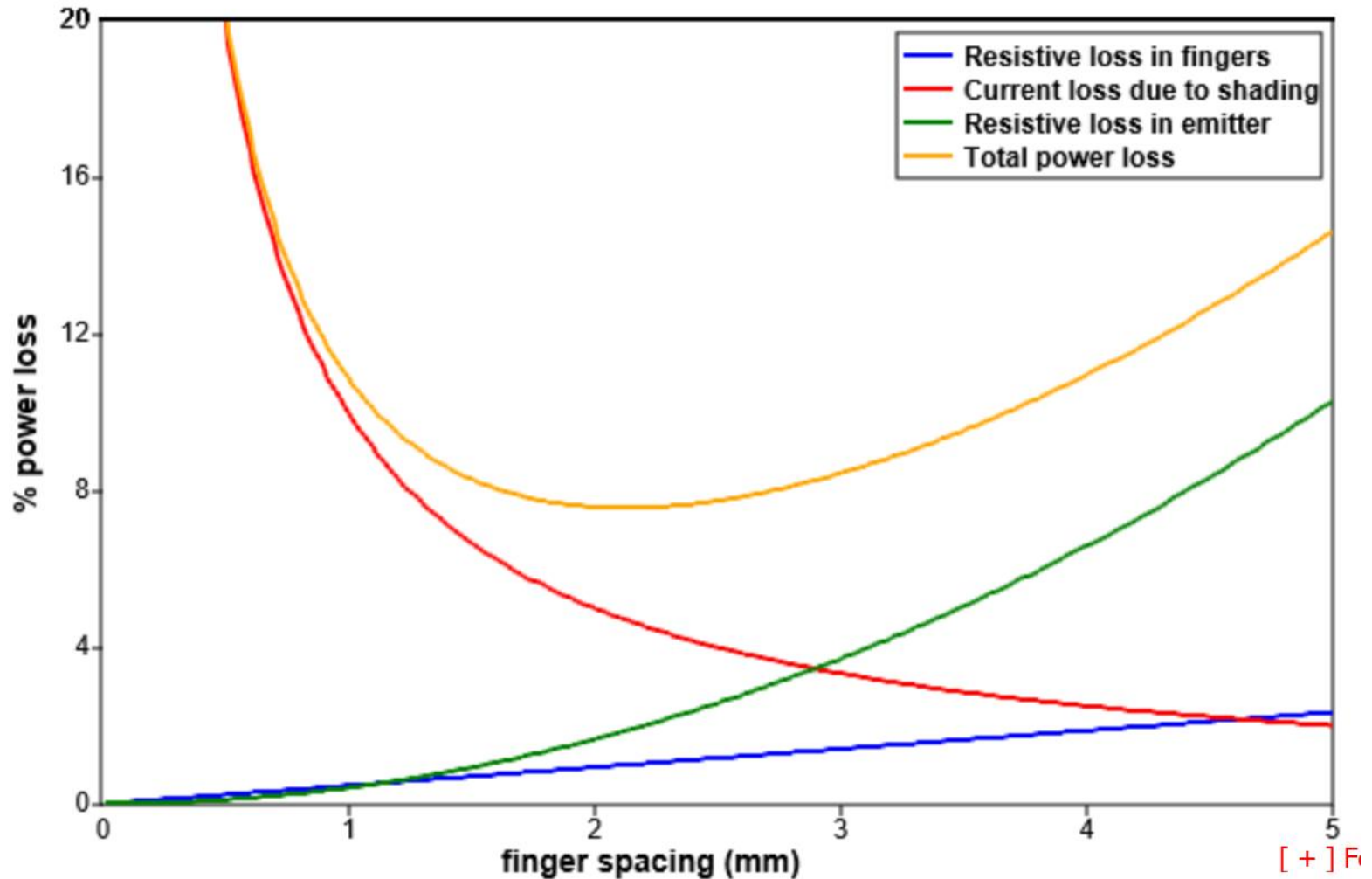
Rezistenta serie

- ▶ Minimizare R_s
 - bare colectoare
 - “degete”
- ▶ Comprimis
 - rezistenta
 - suprafata metalica reflectorizanta



Rezistenta serie

- ▶ Comprimis rezistenta/suprafata metalica



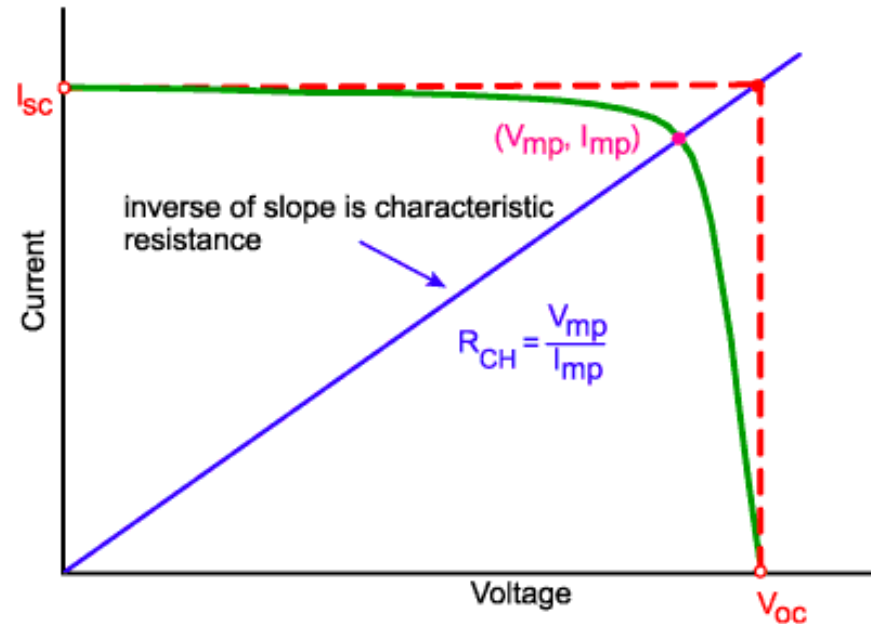
Rezistenta caracteristica

- ▶ Raportul intre V si I cand celula lucreaza la eficienta maxima

$$R_C = \frac{V_{pm}}{I_{pm}} \approx \frac{V_{OC}}{I_{SC}}$$

- ▶ Daca sarcina este egala cu RC , celula lucreaza la eficienta maxima

- ▶ Tipic, celulele comerciale opereaza la tensiune mica si curent mare
 - ▶ conexiunile la celule trebuie sa aiba rezistente de ordinul $m\Omega$



$$R_C = \frac{0.6V}{9A} \approx 0.067\Omega$$

Eficiența celulei solare

- ▶ raportul dintre puterea electrică generată și puterea optică incidentă

$$\eta = \frac{P_m}{P_o} = \frac{V_{pm} \cdot I_{pm}}{P_o}$$

$$\eta = \frac{P_m}{P_o} = \frac{V_{oc} \cdot I_{sc} \cdot FF}{P_o}$$

- ▶ Puterea optică depinde de fluxul energetic al luminii incidente și suprafața celulei

$$P_o = S \cdot \int_0^{\infty} \Phi_e(\lambda) d\lambda$$

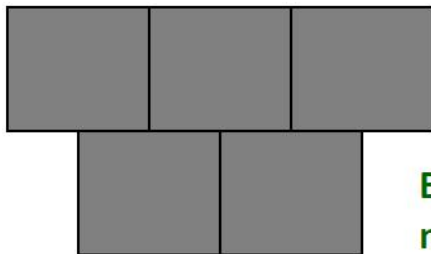
Eficiența celulei solare

- ▶ determina suprafața necesară pentru obținerea unei puteri dorite

100% efficiency
(impossible to achieve)

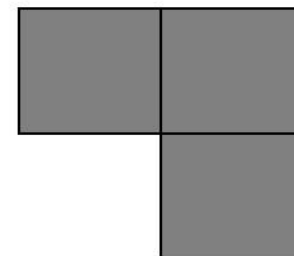


20% efficiency
(monocrystalline silicon solar cells)



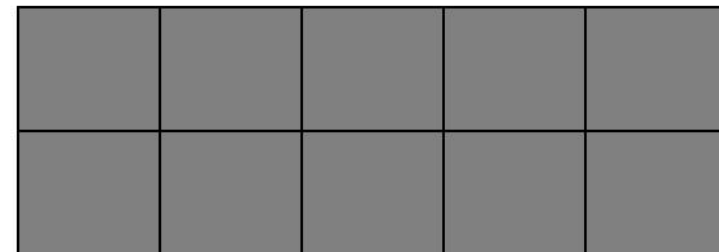
Expensive material

33% efficiency
(space-grade solar cells)



Very Expensive material

10% efficiency
(thin film material)



Relatively Inexpensive material

Eficiența celulei solare

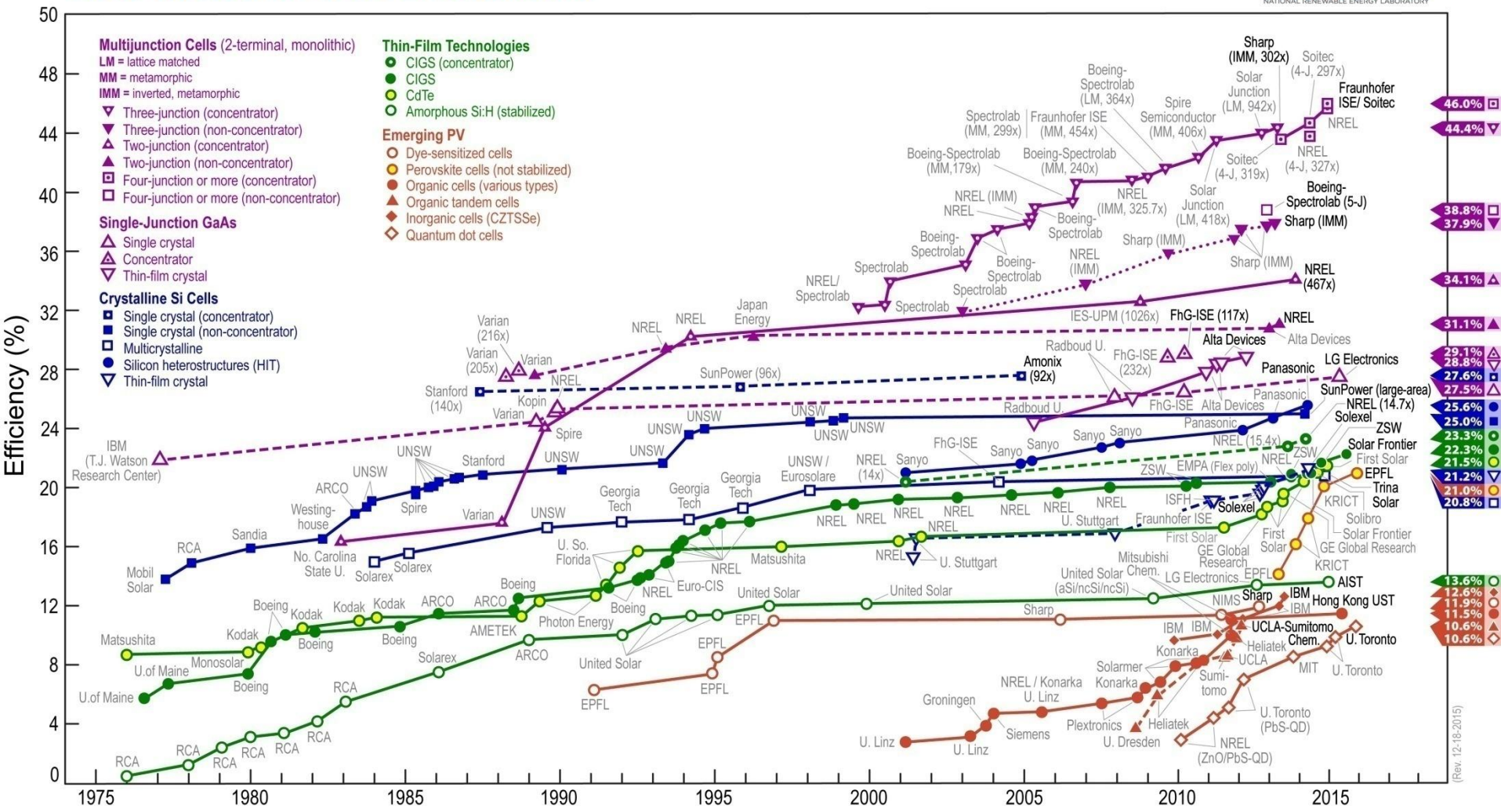
- ▶ Există o limită maximă teoretică pentru fiecare material semiconductor
 - fiecare material are o bandă spectrală proprie, **mai mica** decât banda spectrală a soarelui
- ▶ valorile nu sunt foarte mari
 - din motive economice, recordurile nu sunt repetate în practică

Table 1.1. Performance of some types of PV cell [Green *et al.*, 2001].

Cell Type	Area (cm ²)	V _{oc} (V)	J _{sc} (mA/cm ²)	FF	Efficiency (%)
crystalline Si	4.0	0.706	42.2	82.8	24.7
crystalline GaAs	3.9	1.022	28.2	87.1	25.1
poly-Si	1.1	0.654	38.1	79.5	19.8
a-Si	1.0	0.887	19.4	74.1	12.7
CuInGaSe ₂	1.0	0.669	35.7	77.0	18.4
CdTe	1.1	0.848	25.9	74.5	16.4

Eficiența maximă a celulei solare

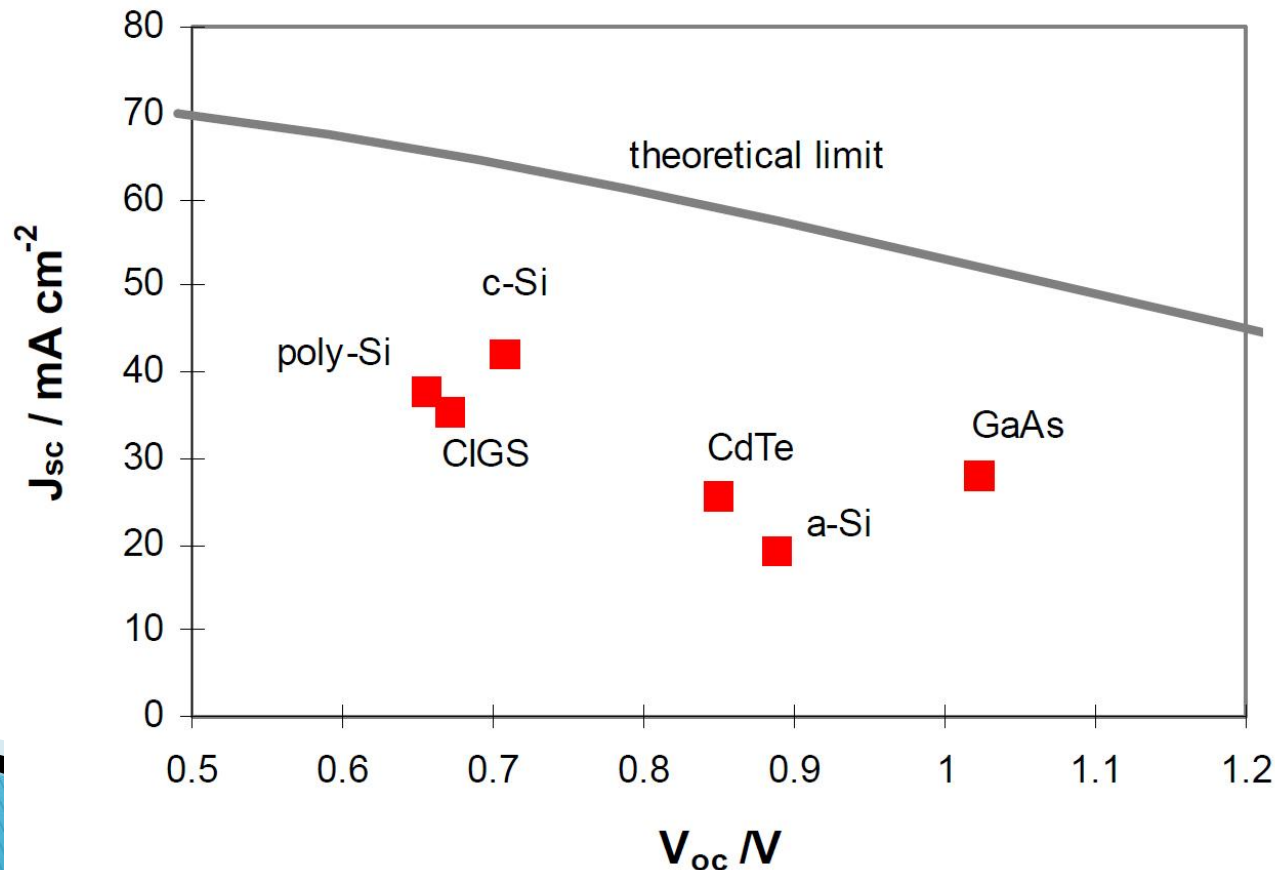
Best Research-Cell Efficiencies



(Rev. 12-16-2015)

Dependenta de material

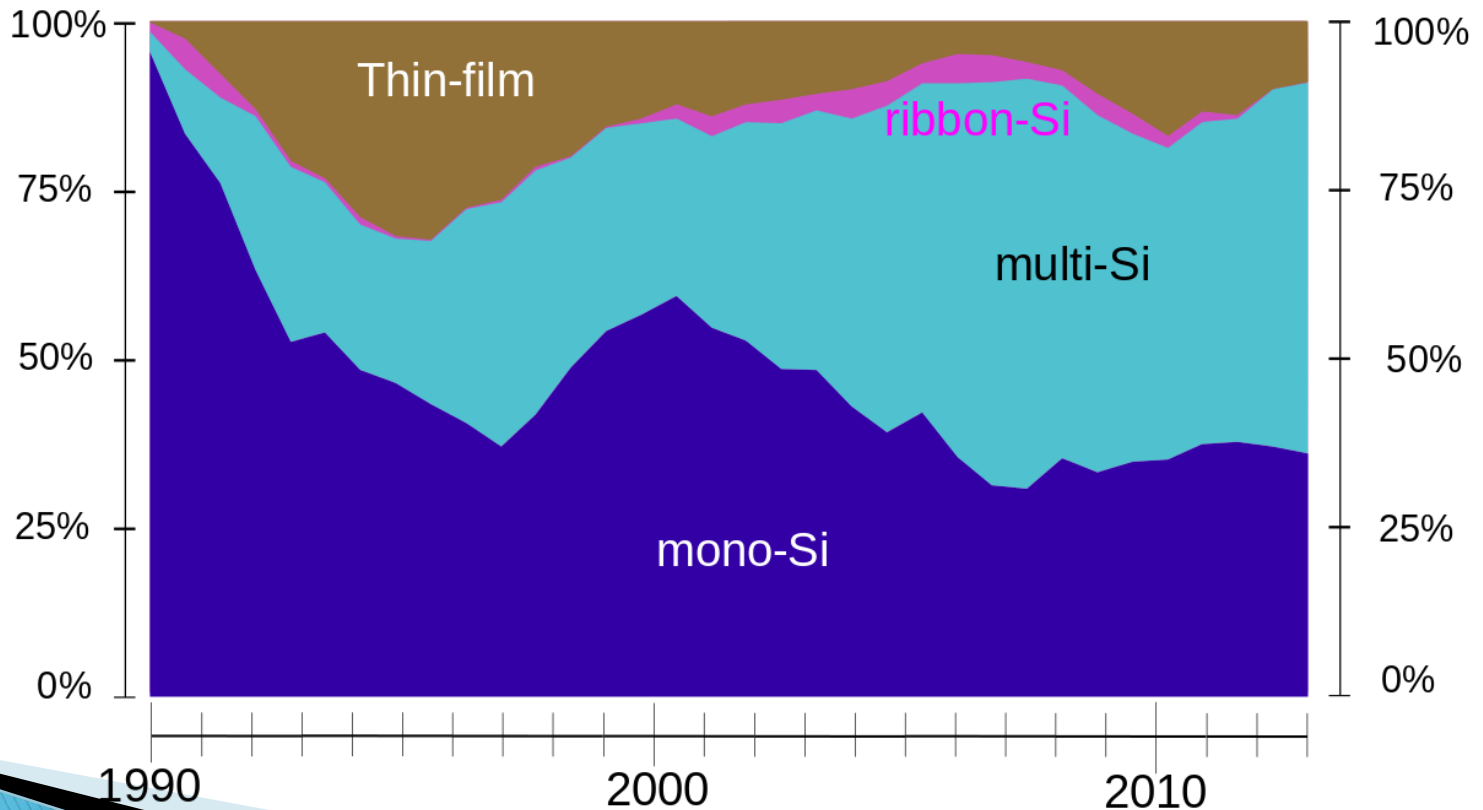
- ▶ materialele care ofera tensiuni mari au de obicei curenti mai mici
 - dependent de latimea benzii interzise



Realizari practice

- ▶ materialul preferat este Si

Global Market Share by PV Technology
from 1990 to 2013



Tipic

80 WATT

POWERFUL PERFORMANCE. SHARP RELIABILITY.

POLY-CRYSTALLINE SILICON PHOTOVOLTAIC MODULE WITH 80W MAXIMUM POWER

Sharp's NE-80EJA photovoltaic modules offer industry-leading performance, durability, and reliability for a variety of electrical power requirements. Using breakthrough technology perfected by Sharp's 45 years of research and development, these modules incorporate an advanced surface texturing process to increase light absorption and improve efficiency. Common applications include cabins, solar power stations, pumps, beacons,



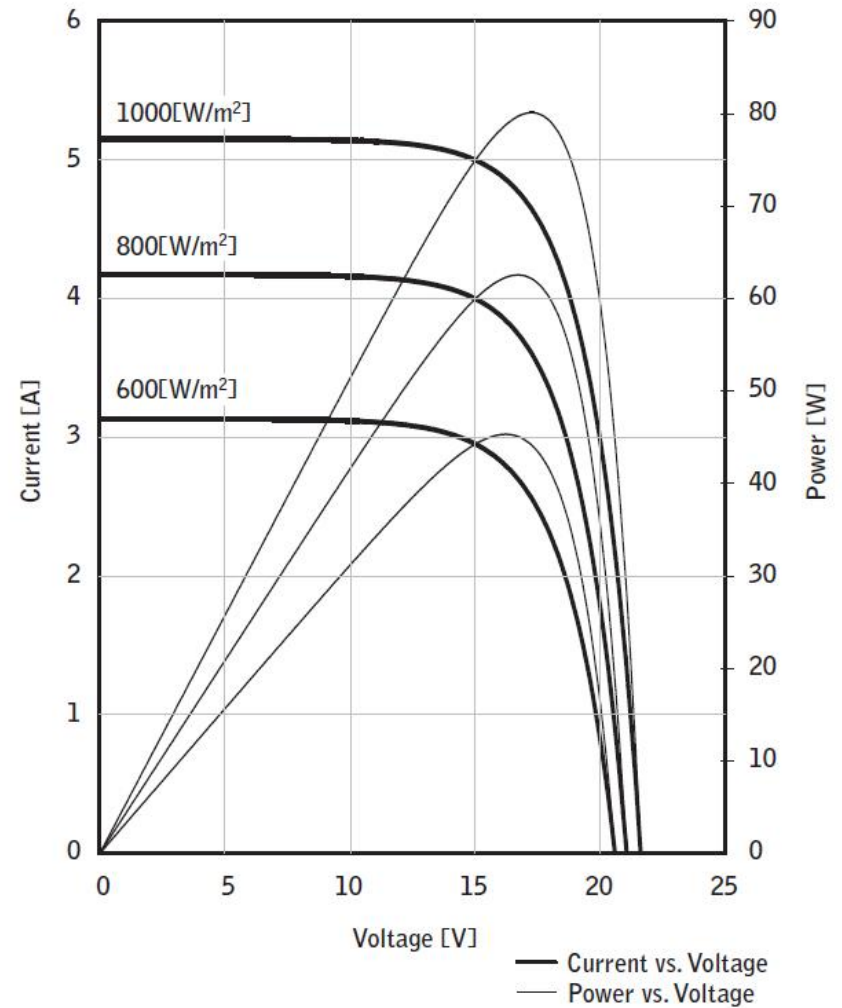
Tipic

ELECTRICAL CHARACTERISTICS

Cell	Poly-crystalline silicon
No. of Cells and Connections	36 in series
Open Circuit Voltage (Voc)	21.6V
Maximum Power Voltage (Vpm)	17.3V
Short Circuit Current (Isc)	5.16A
Maximum Power Current (Ipm)	4.63A
Maximum Power (Pmax)*	80W (+10% / -5%)
Module Efficiency (η_m)	12.40%
Maximum System Voltage	600VDC
Series Fuse Rating	10A
Type of Output Terminal	Junction Box

IV CURVES

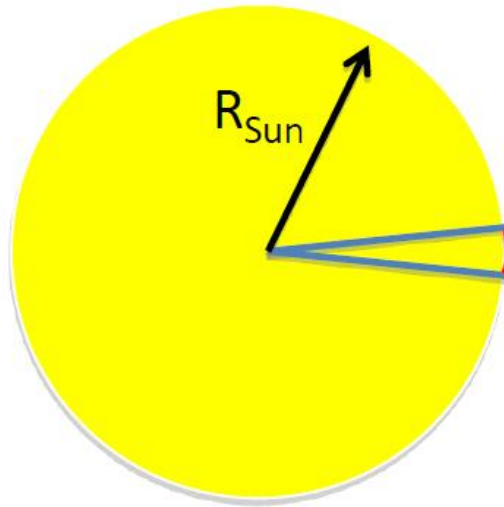
Cell Temperature: 25°C



Current, Power vs. Voltage Characteristics

Energia solara disponibila

Sun



Total Radiative Power of Sun (from Stefan-Boltzman law, $T = 5762 \pm 50K$)

$$P_o = \sigma \cdot T^4$$

Power radiated per unit area
 6.250×10^7
 W/m^2

Assumes Sun is a "black body."

Energia solara disponibila

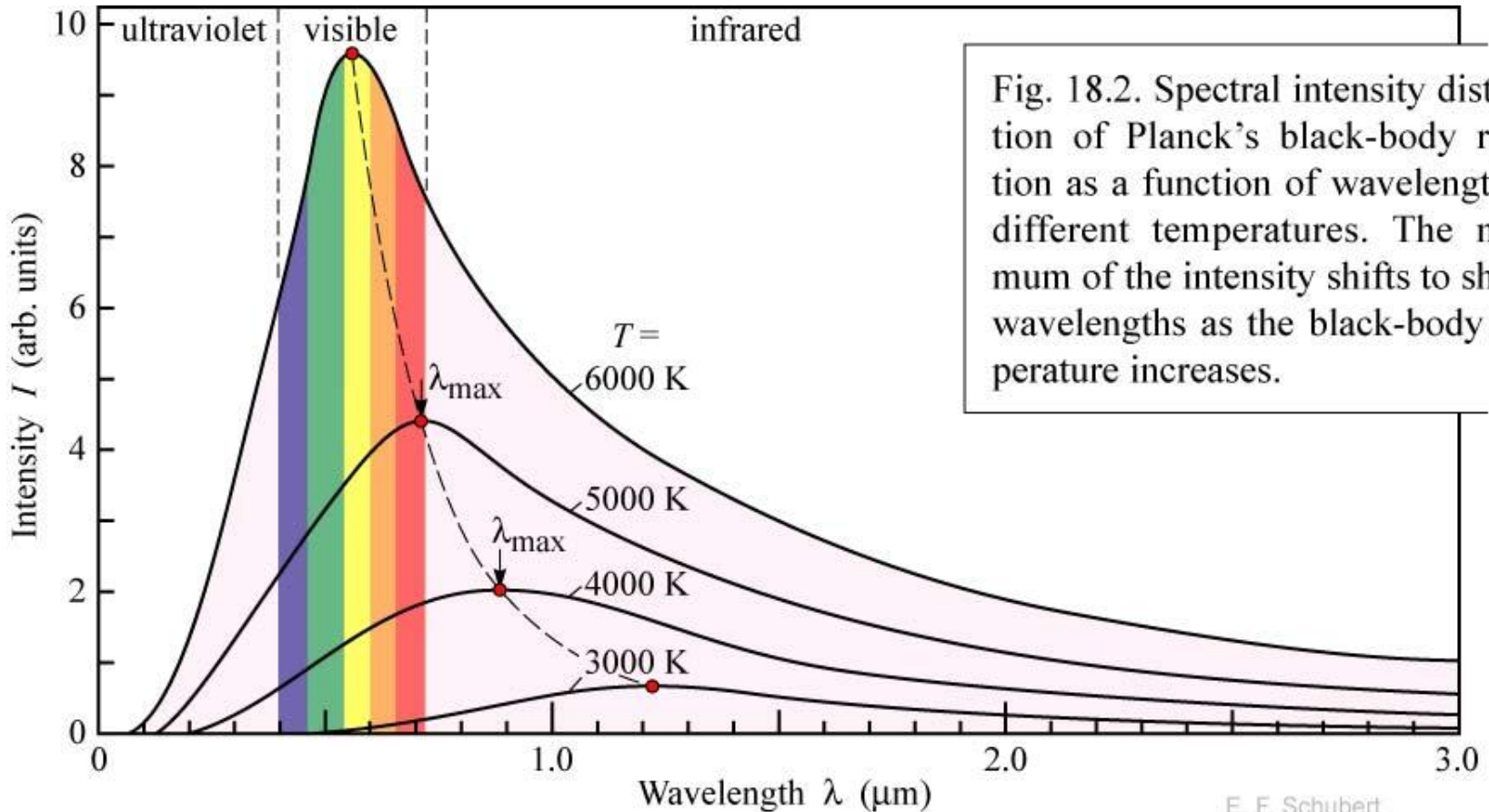
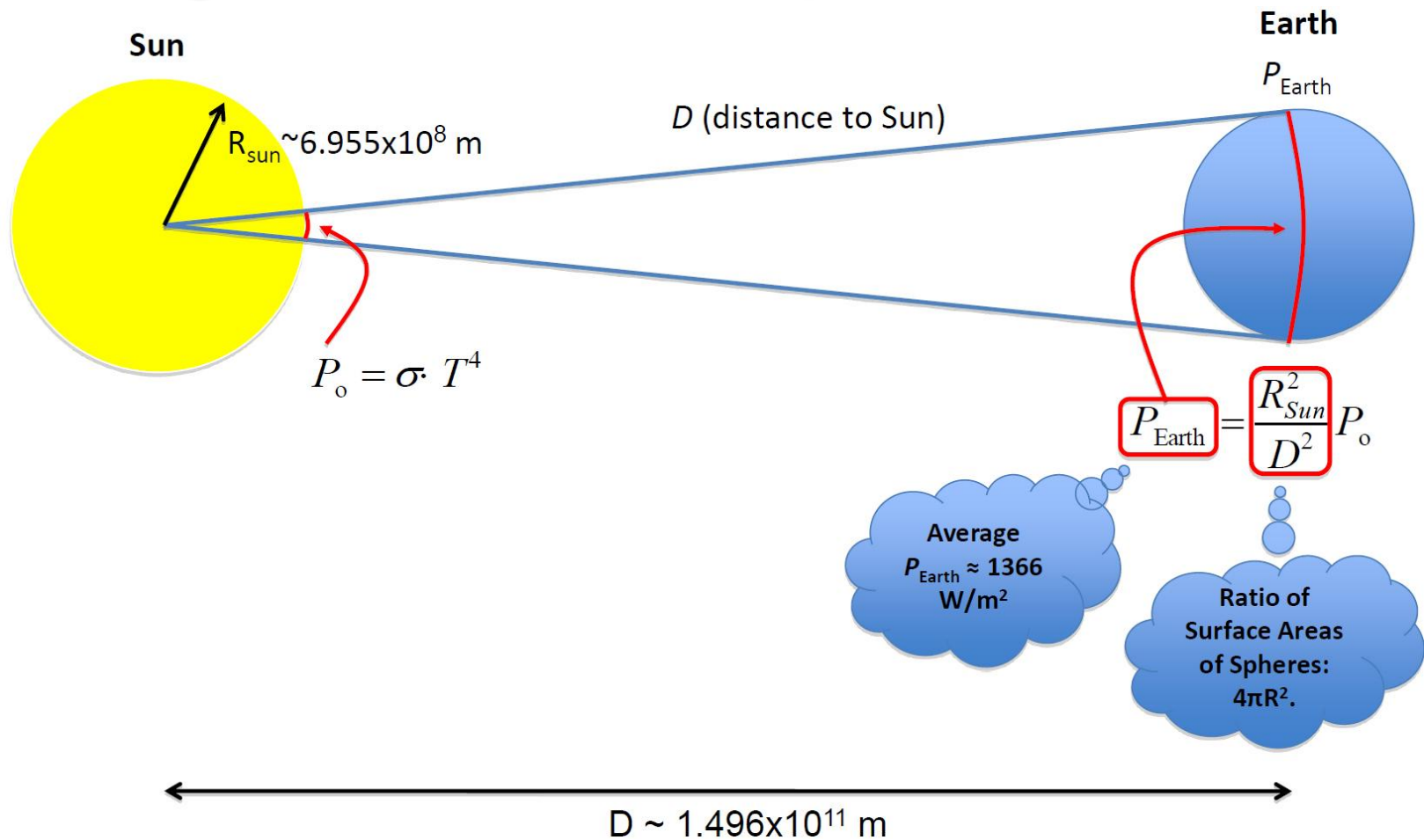


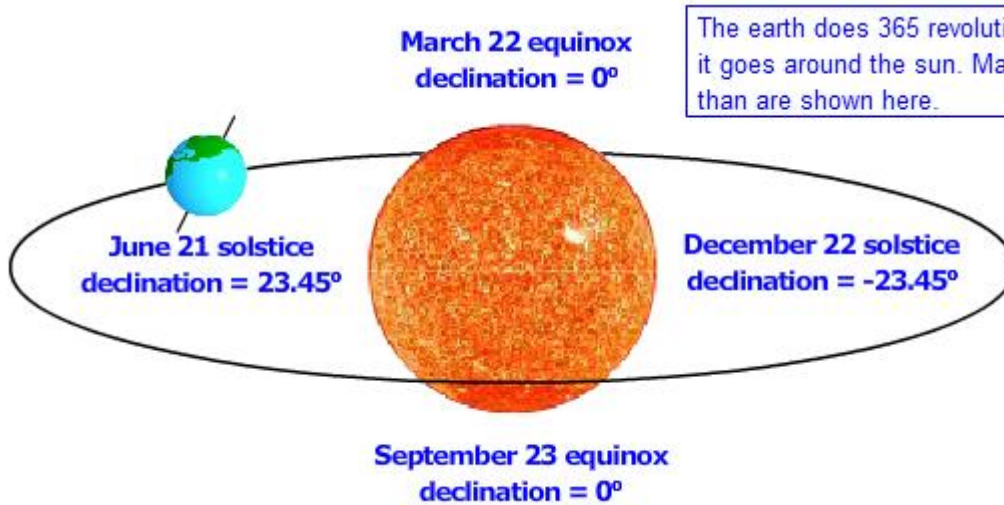
Fig. 18.2. Spectral intensity distribution of Planck's black-body radiation as a function of wavelength for different temperatures. The maximum of the intensity shifts to shorter wavelengths as the black-body temperature increases.

Energia solara disponibila



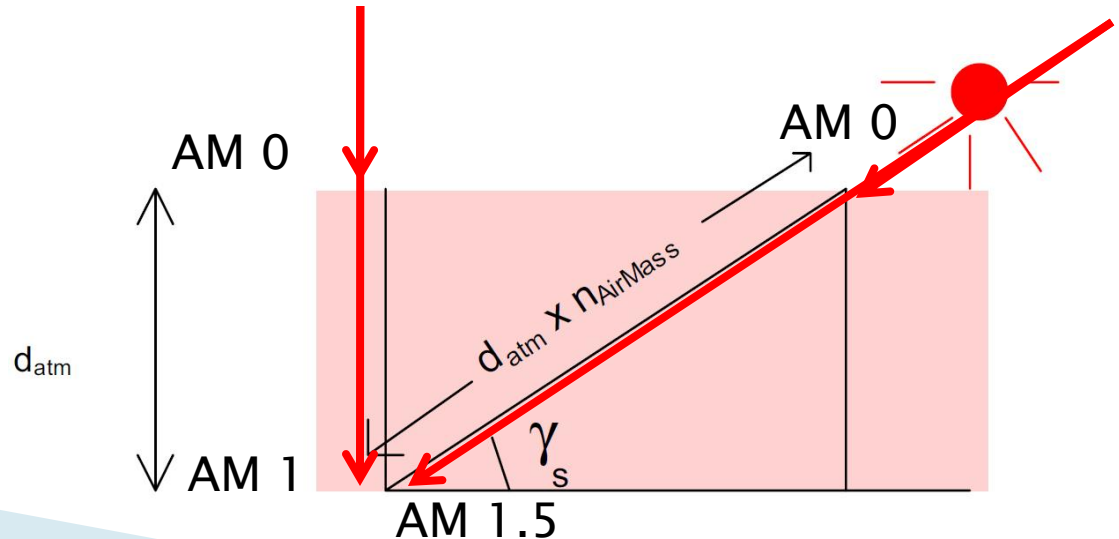
Energia receptionata pe toata suprafata Pamantului intr-**o ora** mai mare decat toata energia consumata de intreaga populatie intr-**un an**

Energia solara disponibila

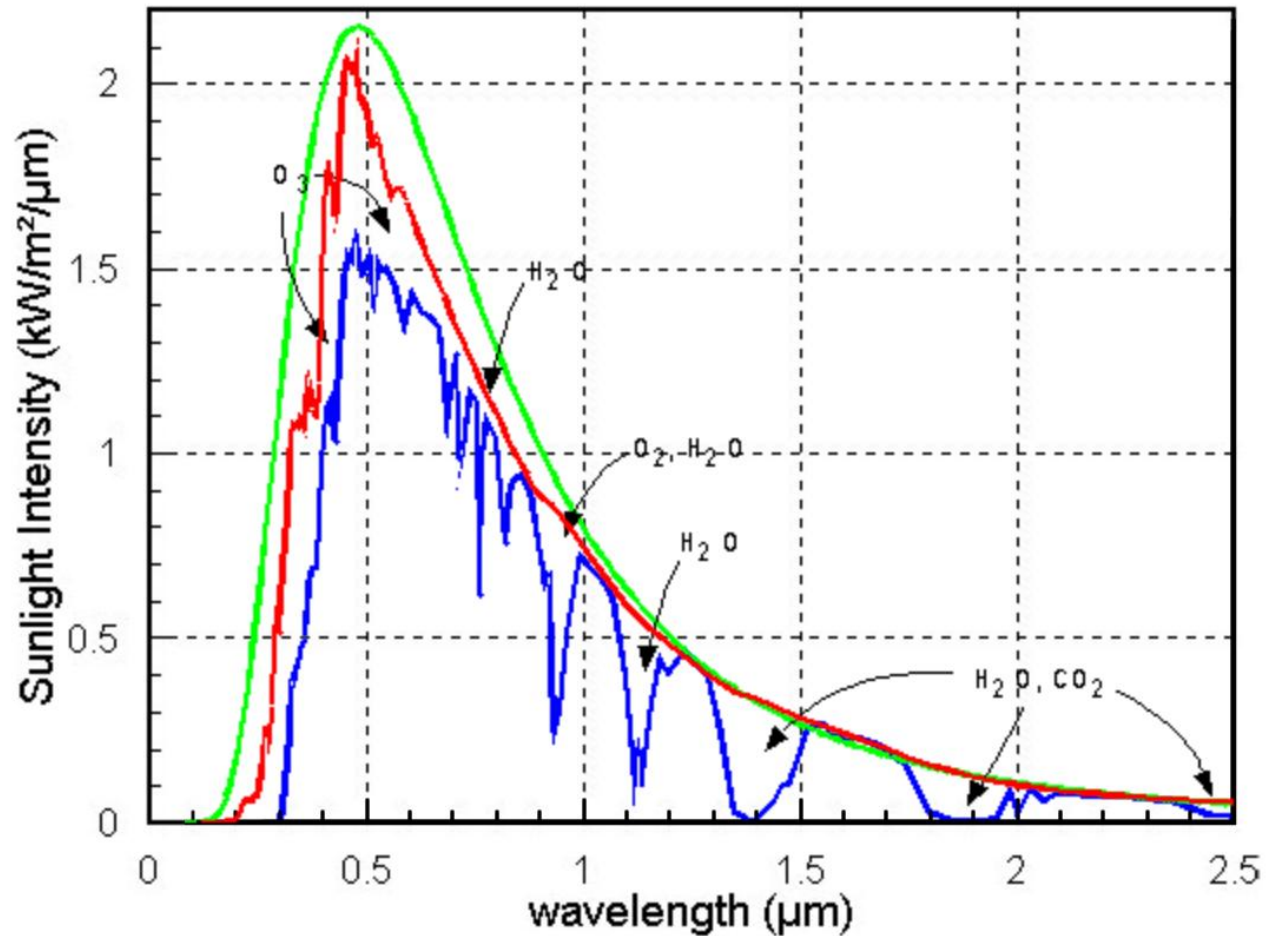


The earth does 365 revolutions as it goes around the sun. Many more than are shown here.

AM 0 = radiatia in afara atmosferei terestre
AM 1 = radiatia la suprafata terestra, incidenta normala
AM 1.5 = radiatia la suprafata terestra, incidenta corespunzatoare latitudinii de 48° (**standard**)

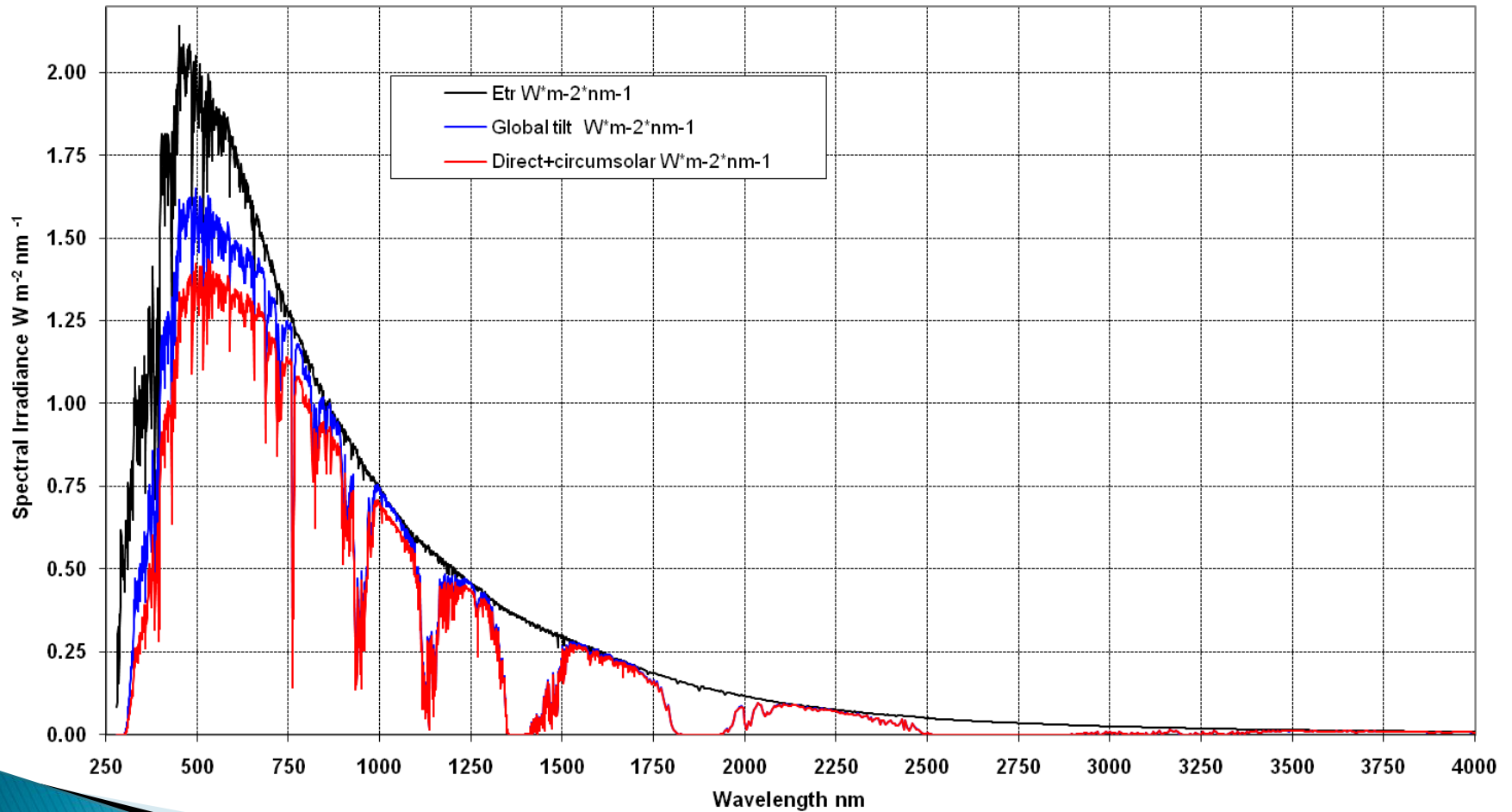


Energia solara disponibila

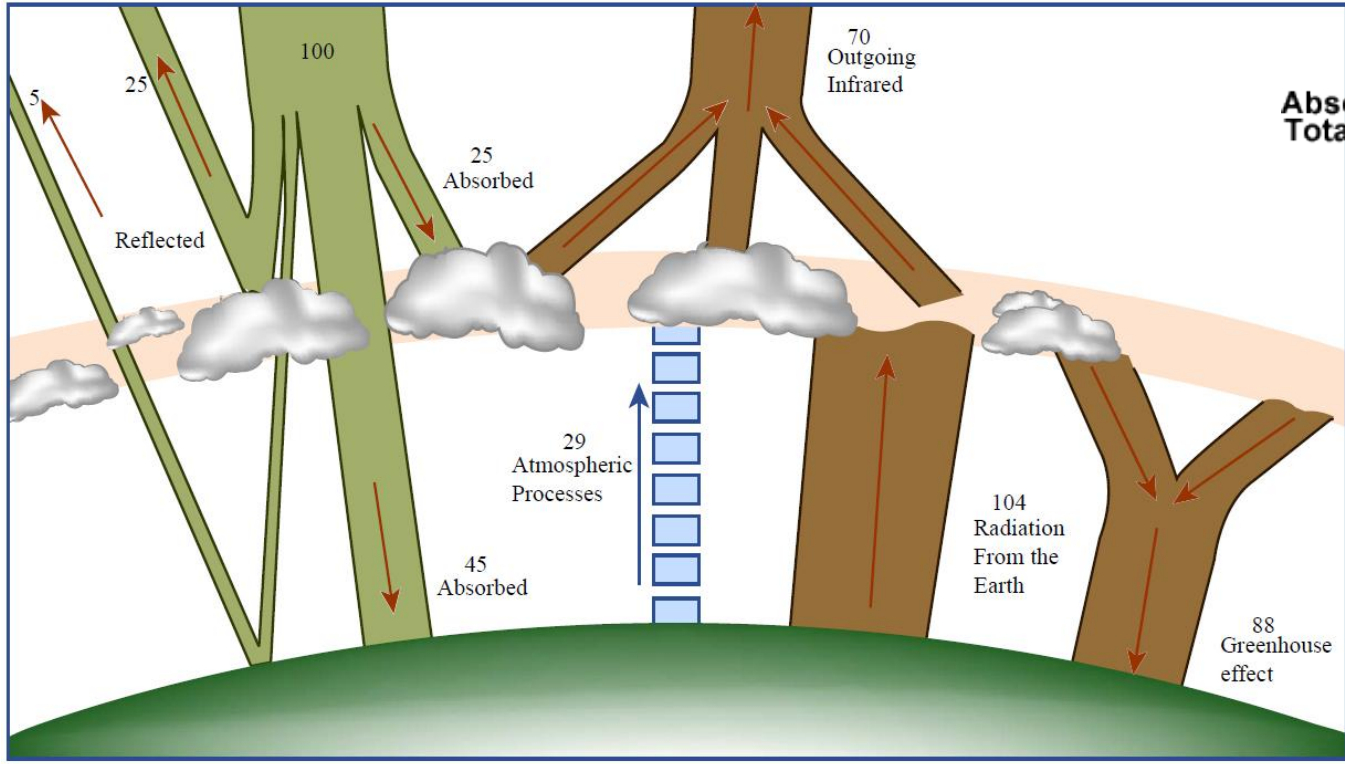


Energia solara disponibila

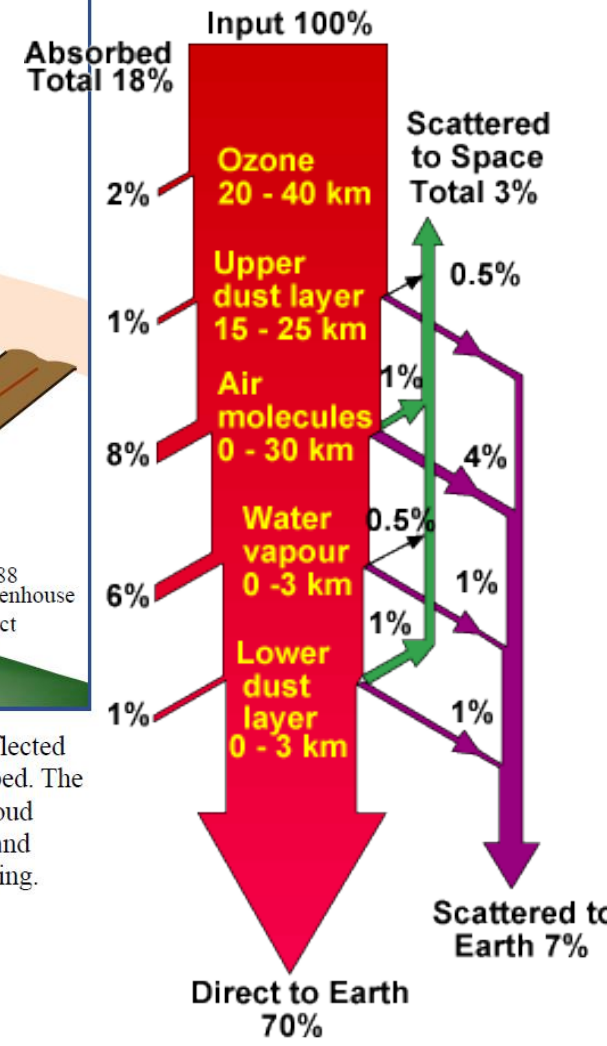
ASTM G173-03 Reference Spectra



Energia solara disponibile



Heat trapping in the atmosphere dominates the earth's energy balance. Some 30% of incoming solar energy is reflected (left), either from clouds and particles in the atmosphere or from the earth's surface; the remaining 70% is absorbed. The absorbed energy is reemitted at infrared wavelengths by the atmosphere (which is also heated by updrafts and cloud formation) and by the surface. Because most of the surface radiation is trapped by clouds and greenhouse gases and returned to the earth, the surface is currently about 33 degrees Celsius warmer than it would be without the trapping.



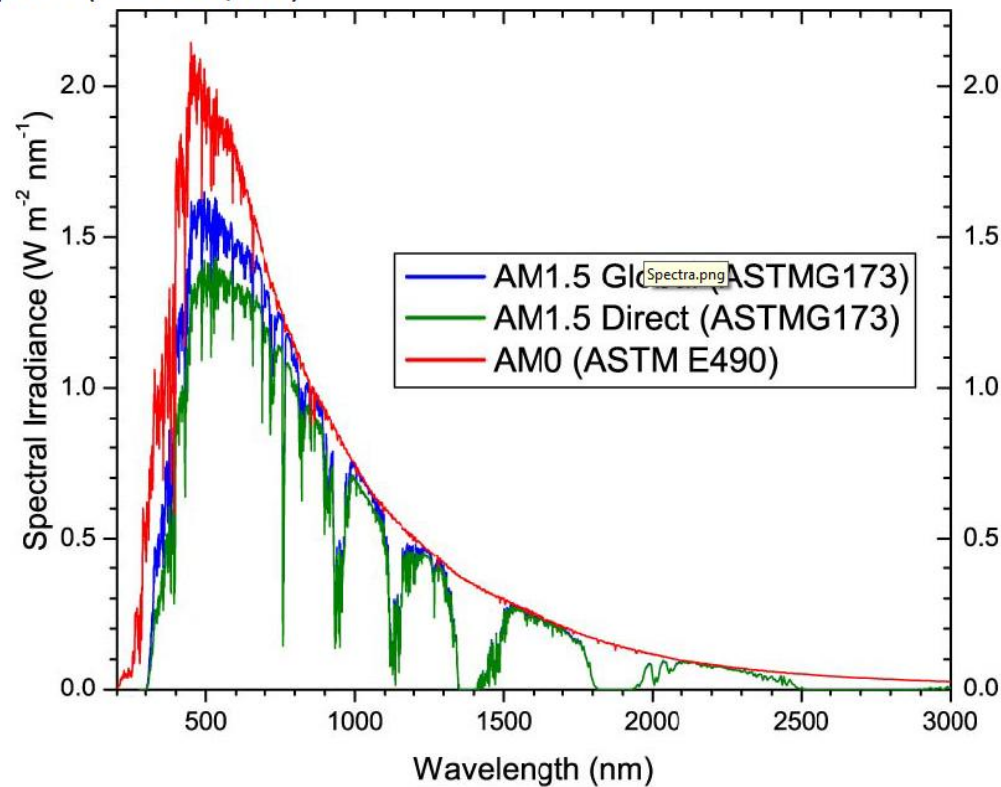
Energia solara disponibila

SOLAR SPECTRUM

AM1.5 Global: Used for testing of Flat Panels (Integrated power intensity: 1000 W/m²)

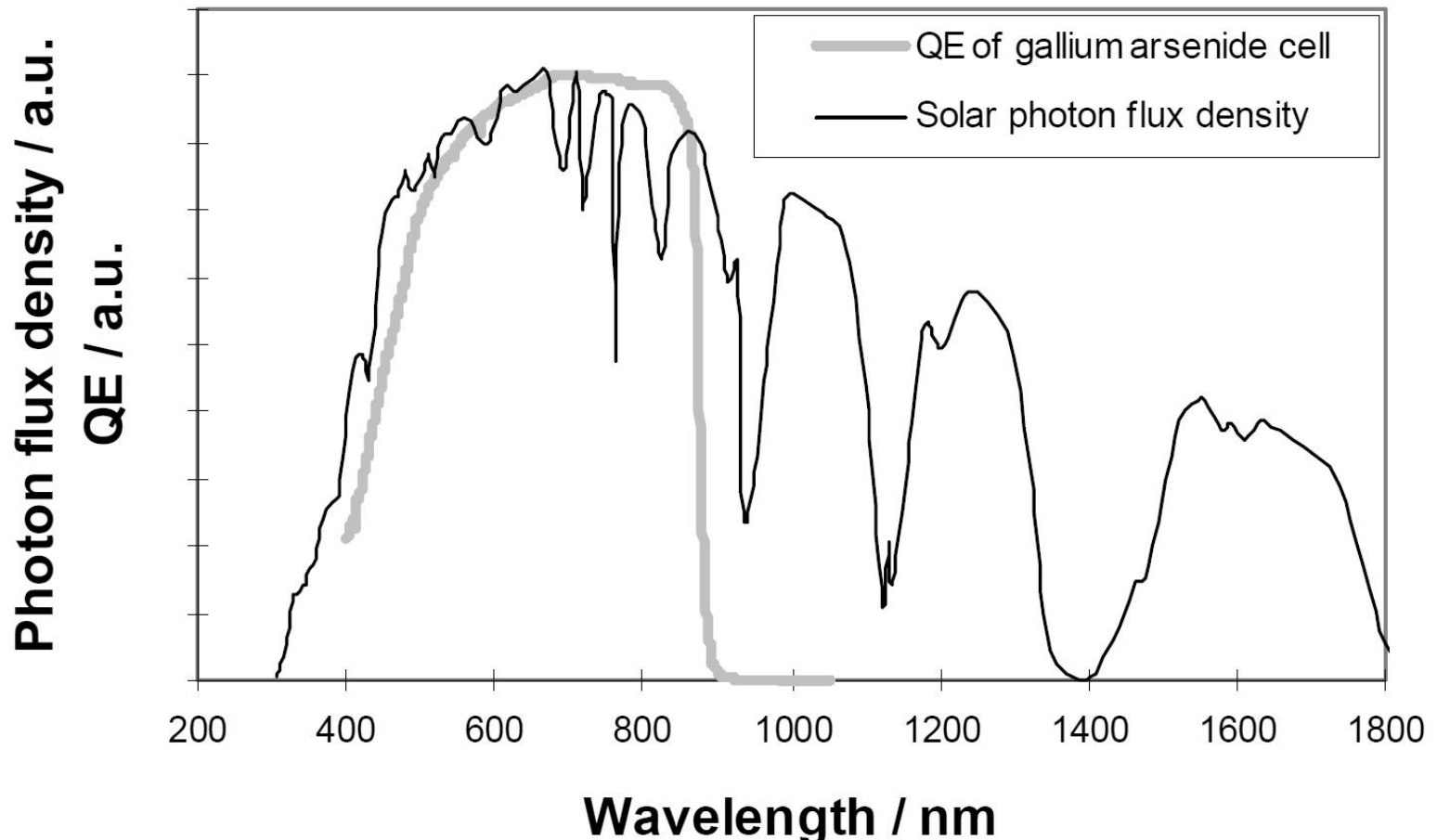
AM1.5 Direct: Used for testing of concentrators (900 W/m²)

AM0: Outer space (1366 W/m²)



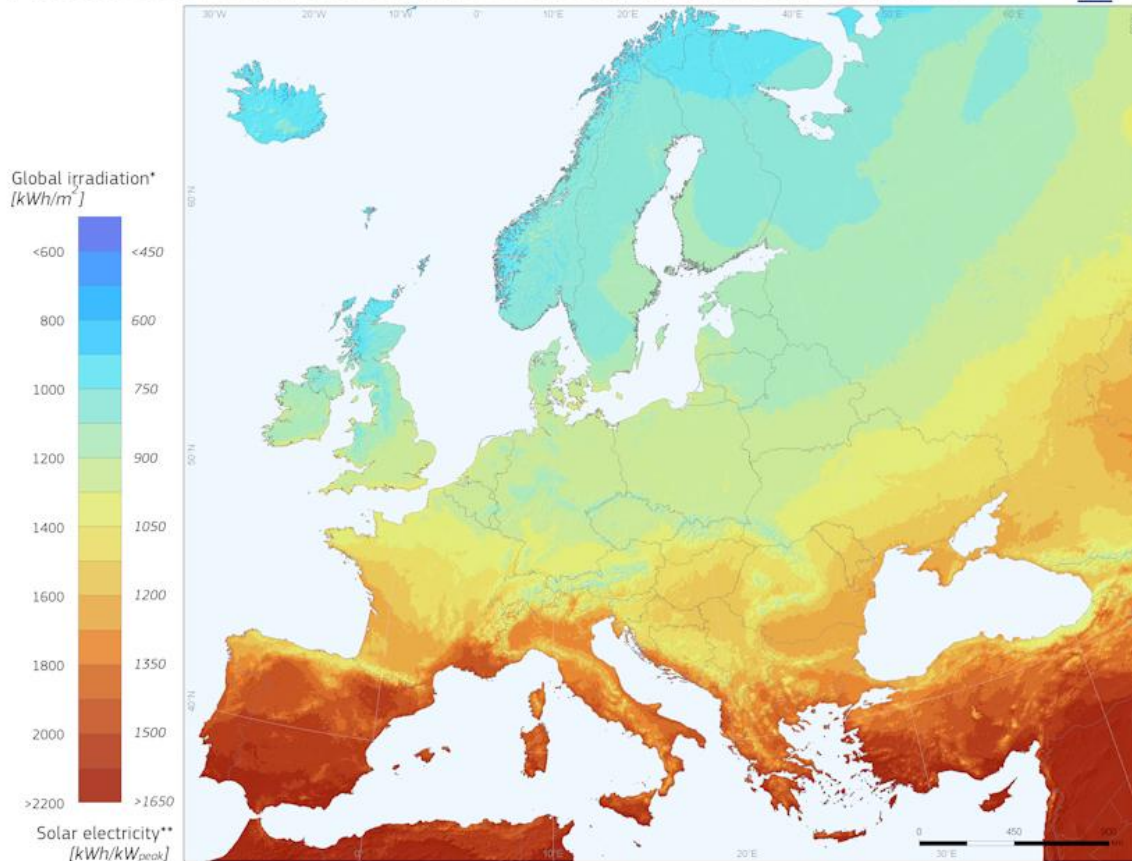
Motivatie eficienta limitata

- ▶ Toate materialele utilizate au o banda care acopera **doar** partial spectrul solar (ex. GaAs)



Energia solara disponibile

Photovoltaic Solar Electricity Potential in European Countries



* Yearly sum of global irradiation incident on optimally-inclined south-oriented photovoltaic modules

** Yearly sum of solar electricity generated by optimally-inclined 1kW_p system with a performance ratio of 0.75

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PVGIS <http://re.jrc.ec.europa.eu/pvgis/>

Authors: Thomas Huld, Irene Pinedo-Pascua
EC - Joint Research Centre
In collaboration with: CM SAF, www.cmsaf.eu

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<http://re.jrc.ec.europa.eu/pvgis/>

Energia solara disponibila



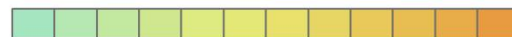
Global irradiation and solar electricity potential
Optimally-inclined photovoltaic modules

ROMANIA / ROMÂNIA



Yearly sum of global irradiation
[kWh/m²]




1100 1200 1300 1400 1500 1600 1700



825 900 975 1050 1125 1200 1275

Projection: Lambert Azimuthal Equal Area, WGS84, lat 52° 10' 10"
Source of ancillary data: CORINE Land Cover
DTM SRTM-30
GISC0 database
Geonames
Natural Earth

Energia solara disponibila


  **Photovoltaic Geographical Information System - Interactive Maps** 

EUROPA > EC > JRC > IE > RE > SOLAREC > PVGIS > Interactive maps > europe [Contact](#) [Important legal notice](#)

e.g., "Ispra, Italy" or "45.256N, 16.9589E"
Iasi

cursor position: 46.725, 31.882
selected position: 47.158, 27.601

Latitude: Longitude:



Ukraine
Vinnitsia
Chernivtsi
Iasi
Chişinău
Odessa
Bucharest
Cluj-Napoca
Constanța
Varna

Romania

Map data ©2016 GeoBasis-DE/BKG (©2009), Google, Mapa GISrael, ORION-ME Terms of Use

[Solar radiation](#) [Temperature](#) [Other maps](#)

PV Estimation **Monthly radiation** Daily radiation Stand-alone PV

Monthly global irradiation data

Radiation database:

- Horizontal irradiation
- Irradiation at opt. angle
- Direct normal irradiation
- Irradiation at chosen angle: deg.
- Linke turbidity
- Dif. / global radiation
- Optimal inclination angle

Monthly ambient temperature data

- Average daytime temperature
- Daily average of temperature
- Number of heating degree days

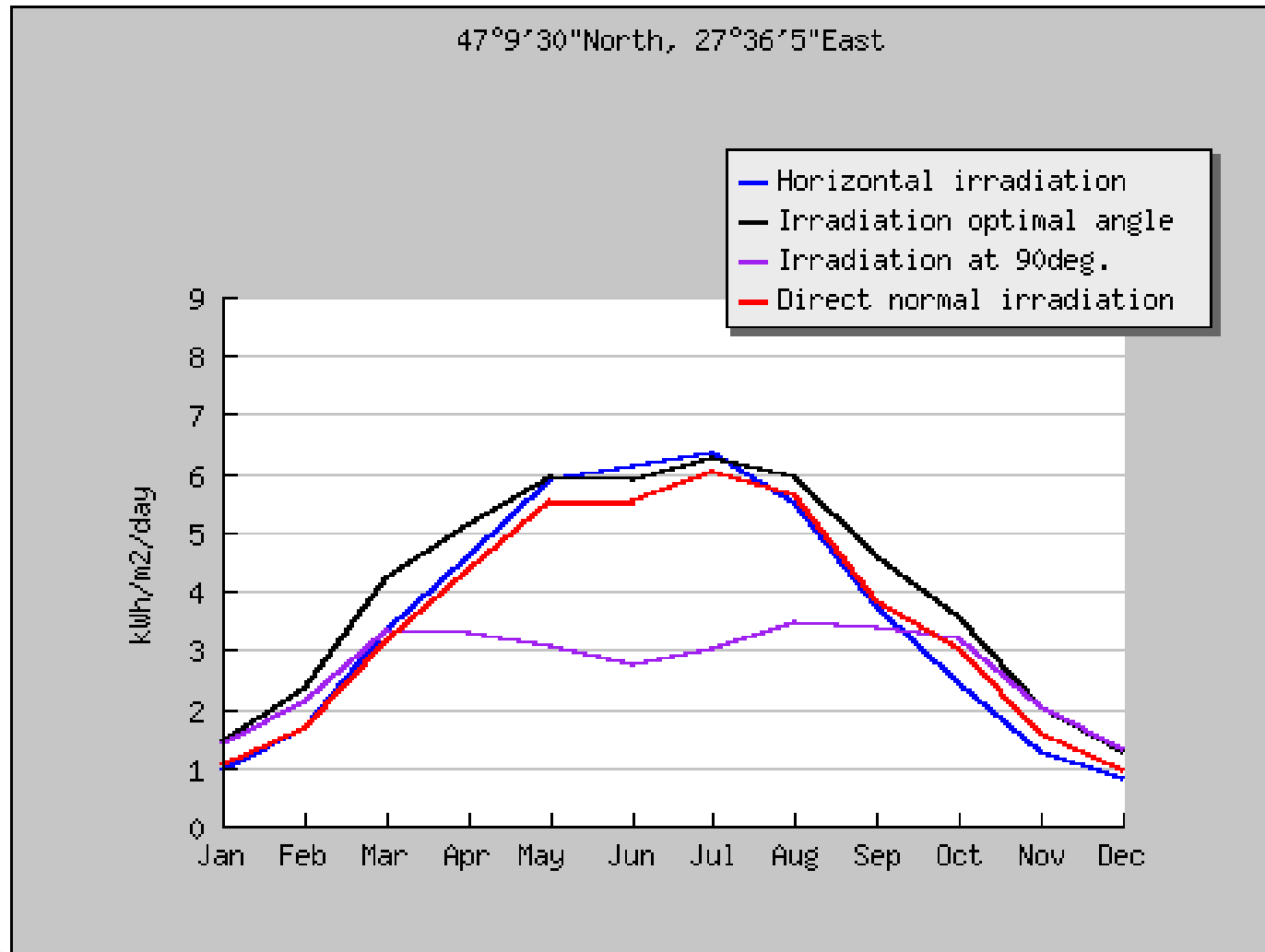
Output options

- Show graphs Show horizon
- Web page Text file PDF

[\[help\]](#)

<http://re.jrc.ec.europa.eu/pvgis/>

Energia solara disponibila – lasi



Unghi optim de inclinare

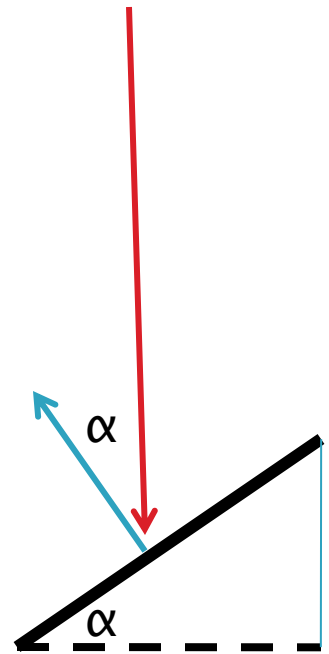
- ▶ Puterea optica depinde de fluxul energetic al luminii incidente si suprafata celulei
 - la **incidenta normala**

$$P_o = S \cdot \int_0^{\infty} \Phi_e(\lambda) d\lambda$$

- la **incidenta oarecare**

$$\Phi_e(\lambda) = \int_{\Sigma} \vec{S} \cdot \vec{n} dA = |S| \cdot A \cdot \cos \alpha$$

$$\vec{S} = \vec{E} \times \vec{H}$$



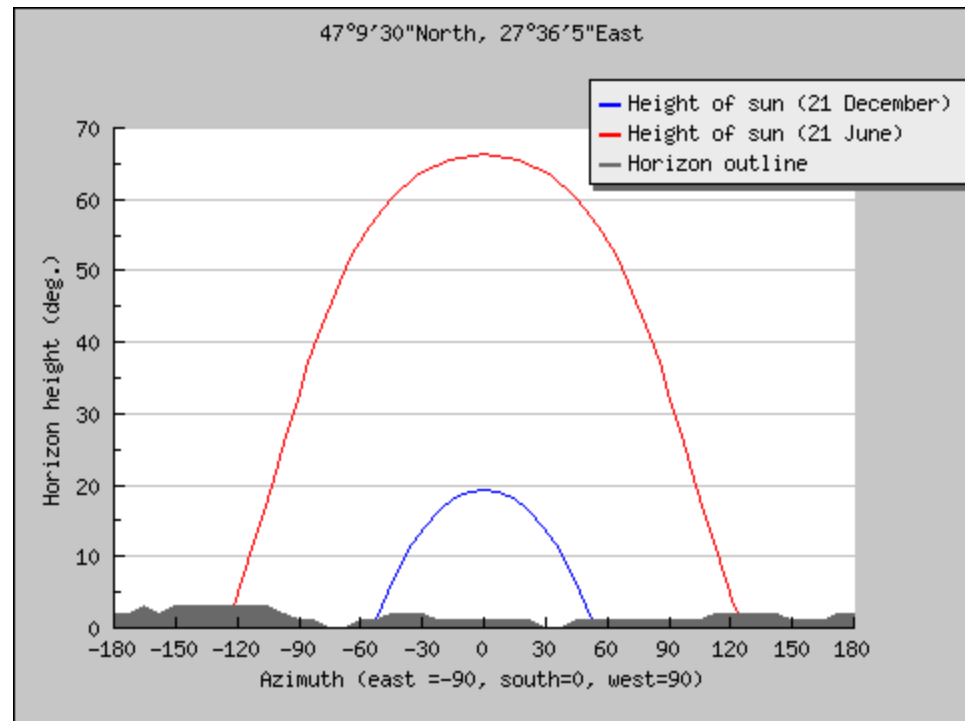
Unghi optim de inclinare

- ▶ Pozitia soarelui este diferita
 - in functie de ora
 - in functie de anotimp

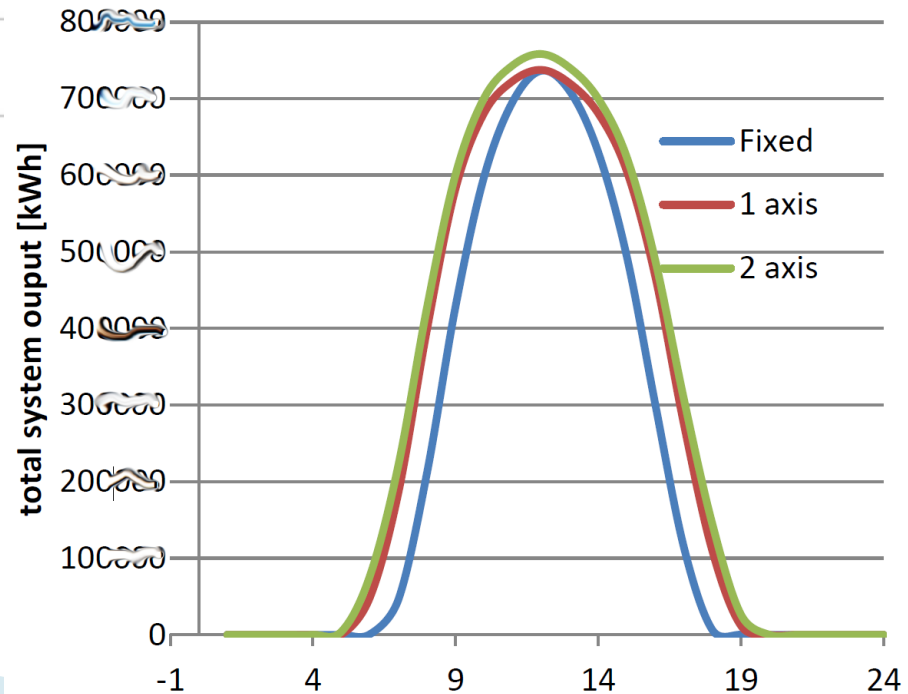
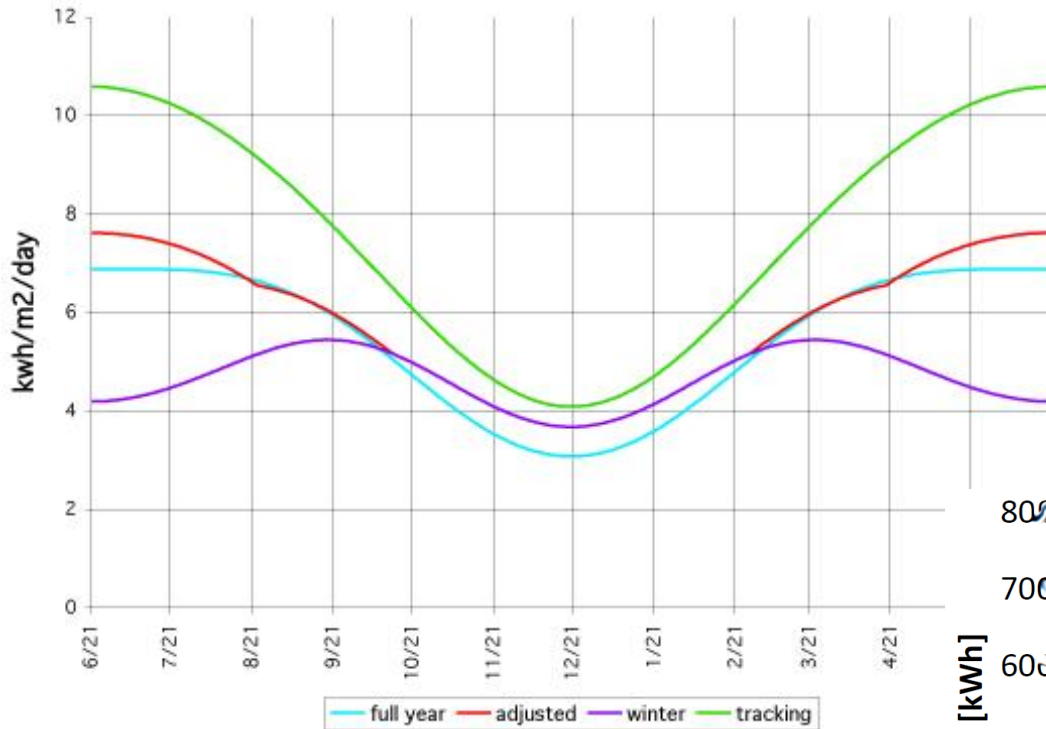


Sisteme de urmarire

- ▶ Sisteme motorizate de urmarire a soarelui
 - o axa
 - doua axe
- ▶ Reglaj
 - fix (optim an)
 - doua pozitii (anotimp)

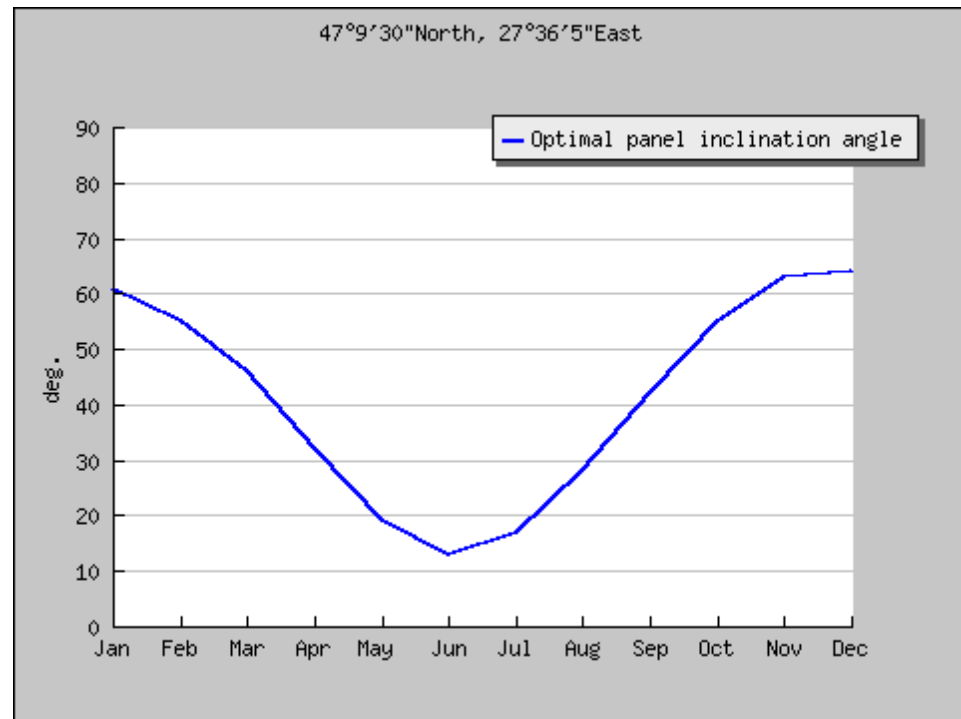


Sisteme de urmarire

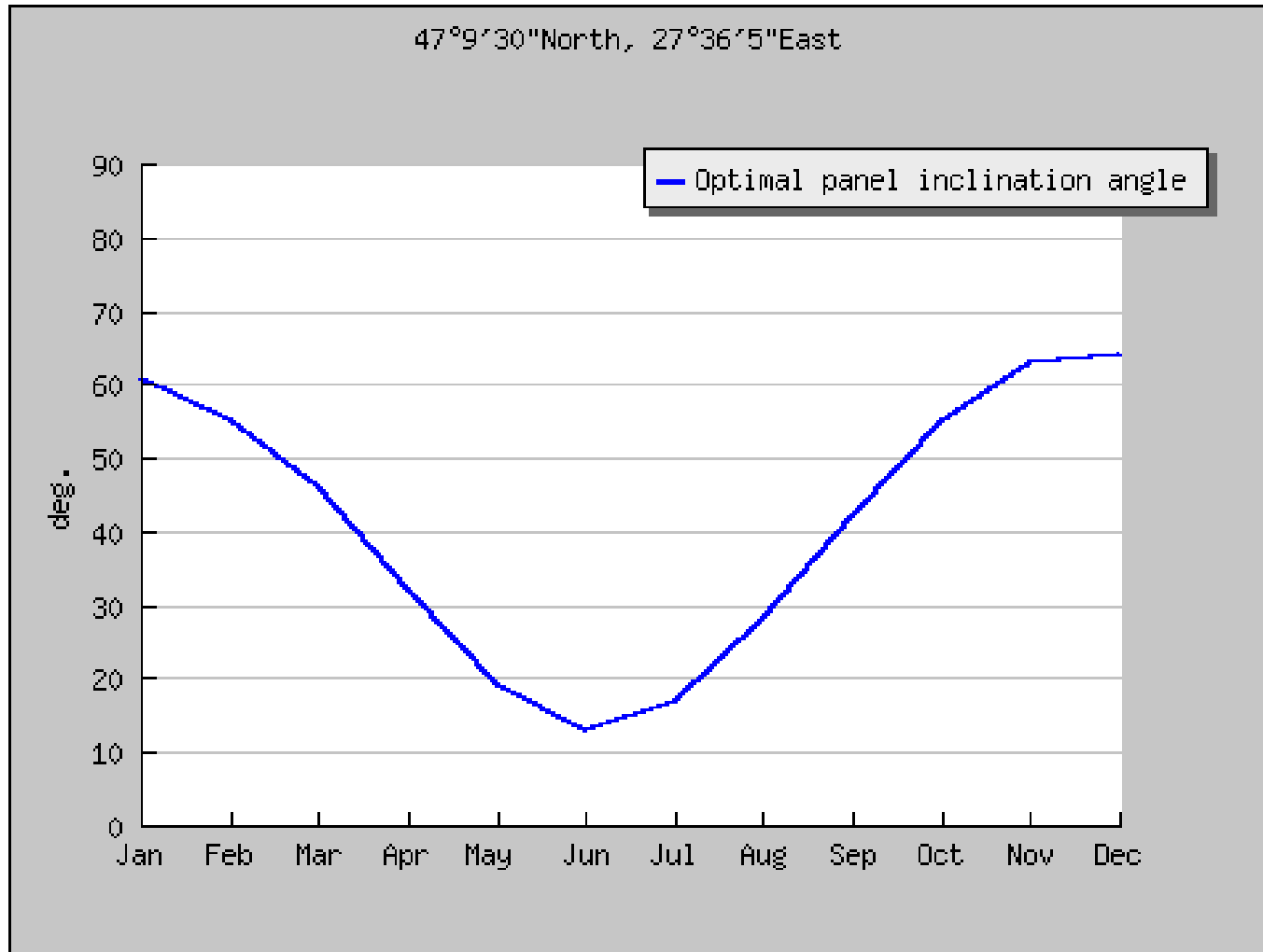


Unghi optim de inclinare

- ▶ Panourile se orienteaza spre sud (**geografic**)
- ▶ Inclinarea pe verticala se poate calcula din considerente
 - geometrice
 - astronomice



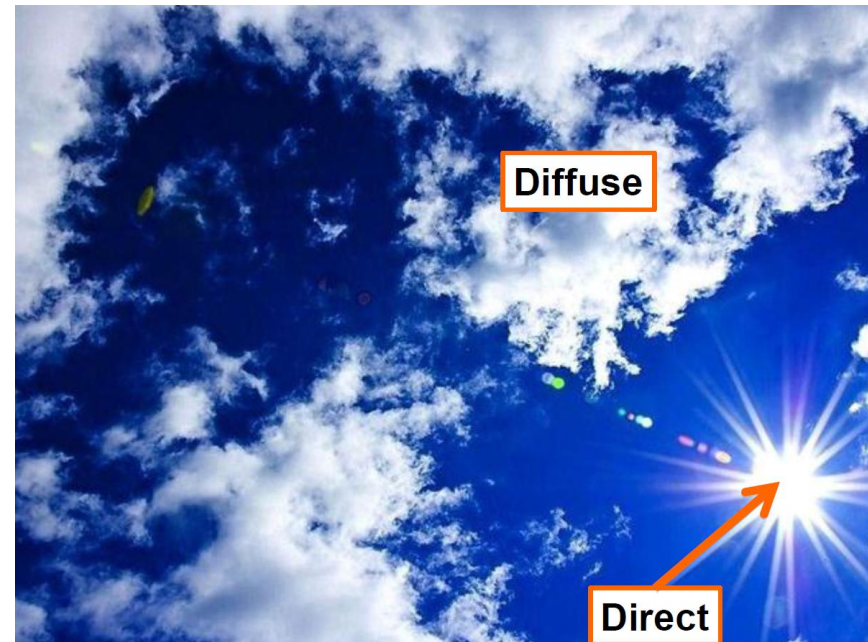
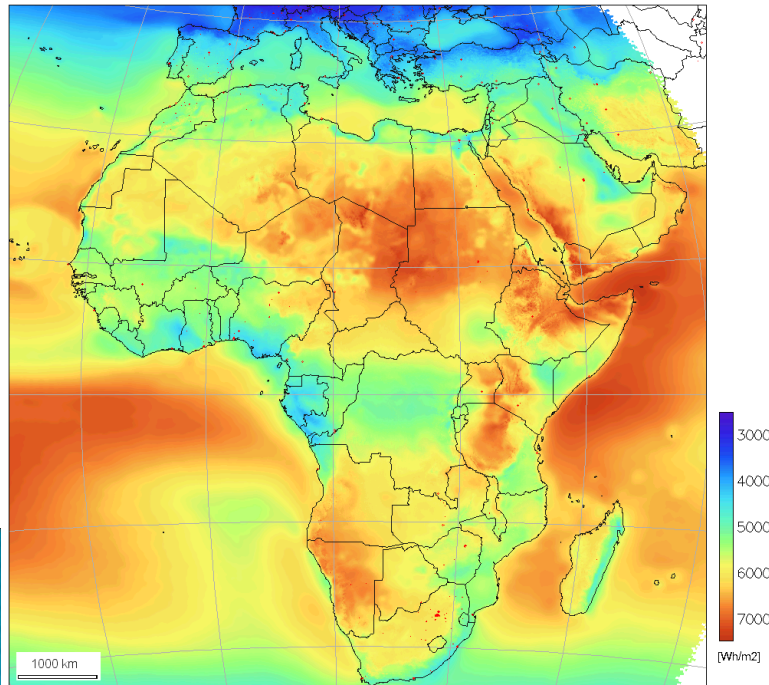
lasi



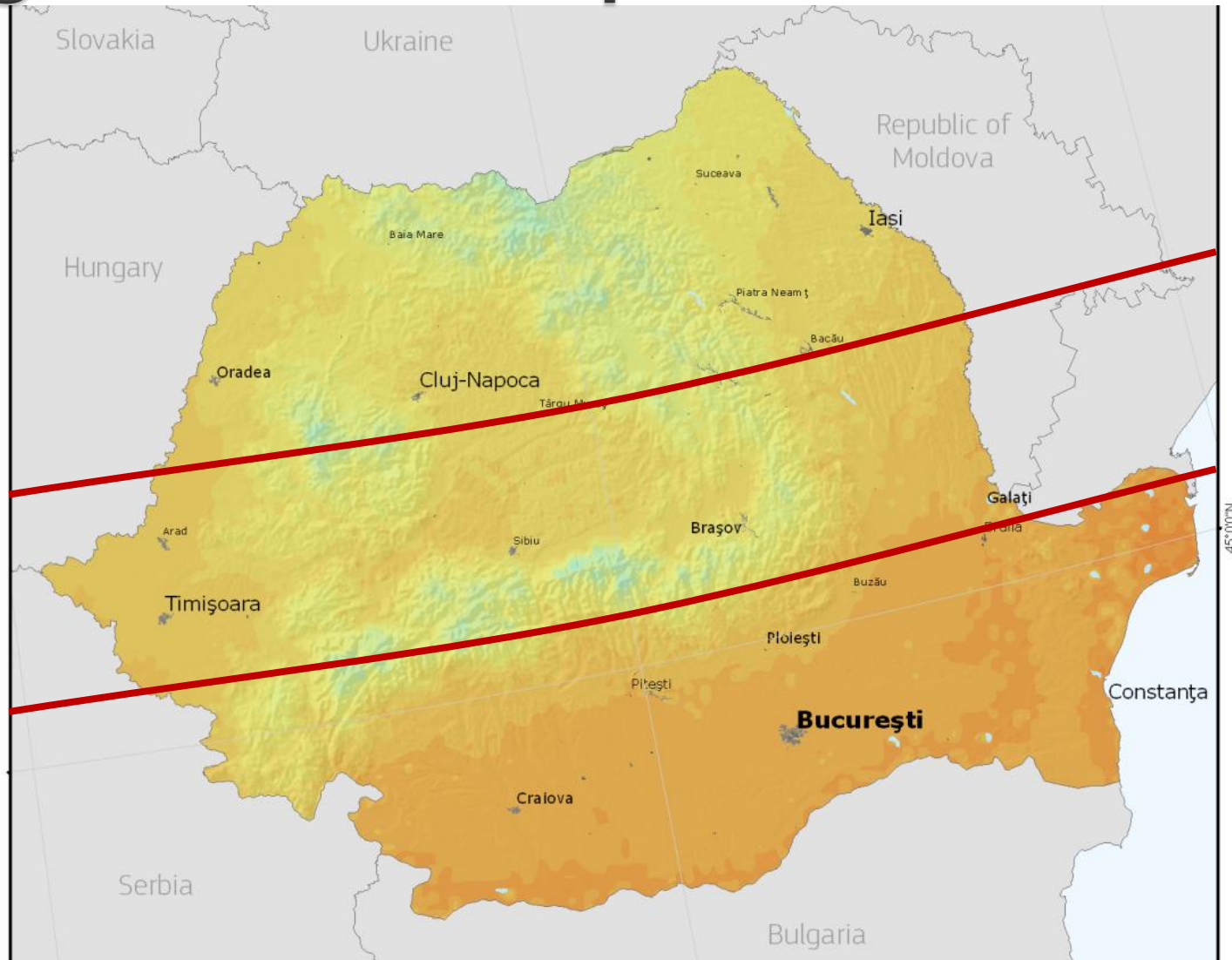
Tip de sistem de urmarire

- ▶ depinde de tipul de sistem solar
 - cu concentrare
 - fara concentrare
- ▶ depinde de conditii meteorologice

Global horizontal irradiation (1985-2004)
(annual average of daily sums, Gh)



Energia solara disponibila



lasi

Month	H_h	H_{opt}	H(90)	DNI	I_{opt}	T_{24h}
Jan	956	1440	1410	1020	61	-2.5
Feb	1680	2350	2130	1670	55	-1.4
Mar	3310	4210	3330	3150	46	4.0
Apr	4580	5150	3280	4380	32	10.6
May	5900	5960	3070	5530	19	16.7
Jun	6140	5900	2760	5530	13	20.0
Jul	6320	6240	3010	6010	17	22.3
Aug	5470	5960	3460	5630	28	21.4
Sep	3720	4600	3390	3820	42	16.1
Oct	2450	3570	3210	3000	55	10.2
Nov	1260	2000	2010	1600	63	5.5
Dec	802	1280	1310	959	64	-0.8
Year	3560	4070	2700	3540	35	10.2

Iasi

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H_h : Irradiation on horizontal plane (Wh/m²/day)

H_{opt} : Irradiation on optimally inclined plane (Wh/m²/day)

$H(90)$: Irradiation on plane at angle: 90deg. (Wh/m²/day)

DNI : Direct normal irradiation (Wh/m²/day)

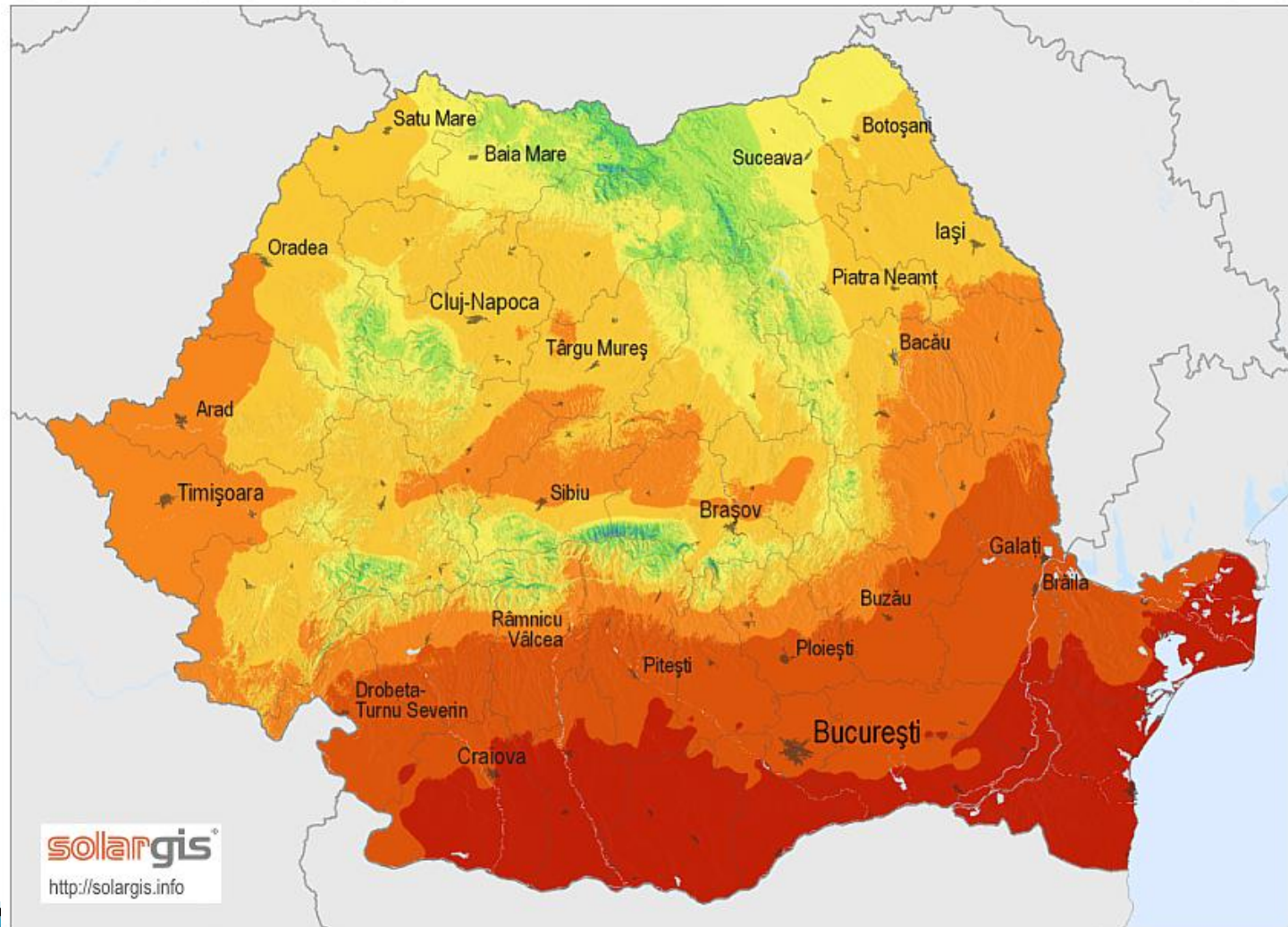
I_{opt} : Optimal inclination (deg.)

T_{24h} : 24 hour average of temperature (°C)

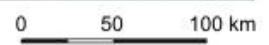
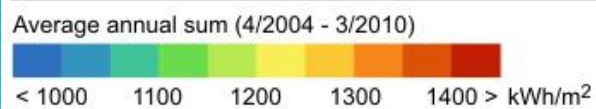
Romania

Global horizontal irradiation

Romania



solargis
<http://solargis.info>



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- ▶ rdamian@etti.tuiasi.ro

- ▶ <http://ocw.mit.edu/>
- ▶ MIT Course Number 2.627
- ▶ Fundamentals of Photovoltaics

- ▶ <http://re.jrc.ec.europa.eu/pvgis/>
- ▶ <http://www.pveducation.org/>