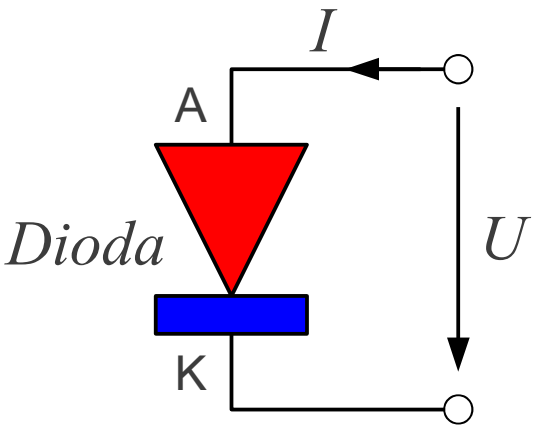
Optične komunikacije

Predavanje 13:

Svetlobni sprejemniki



Enačba diode :

$$I \approx I_S \left(e^{\frac{U|Q_e|}{n k_B T}} - 1 \right)$$

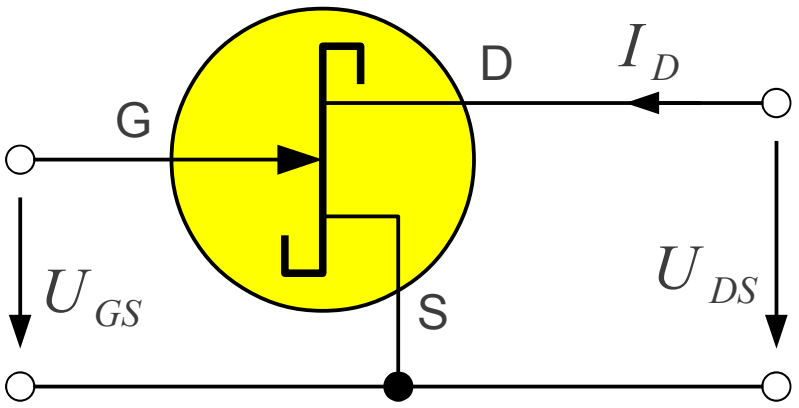
PN spoj → $f < 10\text{GHz}$
(manjšinski nosilci)

Schottky spoj → $f < 1\text{THz}$
(back / tunelska dioda)

Frekvenčna meja nelinearnosti polprevodnikov

Optika → $f \gg 10\text{THz}$

Spojni FET



$$I_D \approx I_{DSS} \left(\frac{U_{GS} - U_P}{U_P} \right)^2$$

InP spojni FET → $f < 1\text{THz}$

V svetlobnem sprejemniku pride do izraza zrnati (kvantni) značaj elektromagnetnega valovanja:

$$f\,[\mathrm{Hz}]=\nu\,[\mathrm{Hz}]\equiv \textit{frekvenca svetlobe}$$

$$W_f = h\,f = \frac{h\,c_0}{\lambda}\equiv \textit{energija fotona}$$

$$h\approx 6.626\cdot 10^{-34}\,\mathrm{Js}\equiv \textit{Planckova konstanta}$$

V področju svetlobnih frekvenc je praktična merska enota za energijo fotona elektronski volt [eV]:

$$W\,[\mathrm{eV}]=\frac{1}{|Q_e|}\cdot W\,[\mathrm{J}] \qquad Q_e\approx -1.6\cdot 10^{-19}\,\mathrm{As}$$

$$W_f\,[\mathrm{eV}]=\frac{h\,c_0}{\lambda\,|Q_e|} \qquad \frac{h\cdot c_0}{|Q_e|}\approx 1.24\mathrm{eV}\cdot\mu\mathrm{m}$$

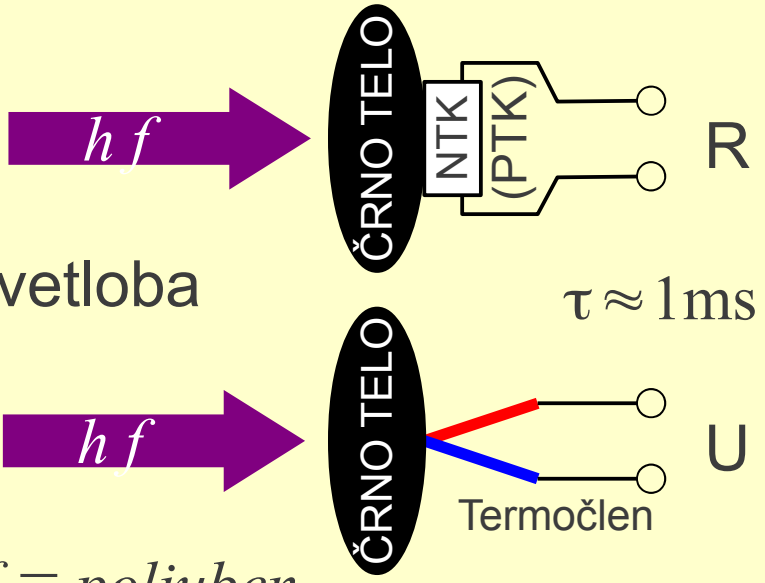
Toplotna energija:

$$k_B\approx 1.38\cdot 10^{-23}\,\mathrm{J/K} \qquad T\approx 293\mathrm{K}$$

$$W_T = k_B\,T\approx 4\cdot 10^{-21}\,\mathrm{J}\approx 0.025\mathrm{eV}$$

Svetloba	Območje λ	Območje W_f	Primerjava W
Vidna	400nm...700nm	3.1eV...1.7eV	$W_f >> W_T$
Bližnja IR	800nm...2μm	1.5eV...0.6eV	$W_f > W_T$
Toplotna IR	3μm...100μm	0.4eV...0.012eV	$W_f \approx W_T$

Toplotni sprejemnik



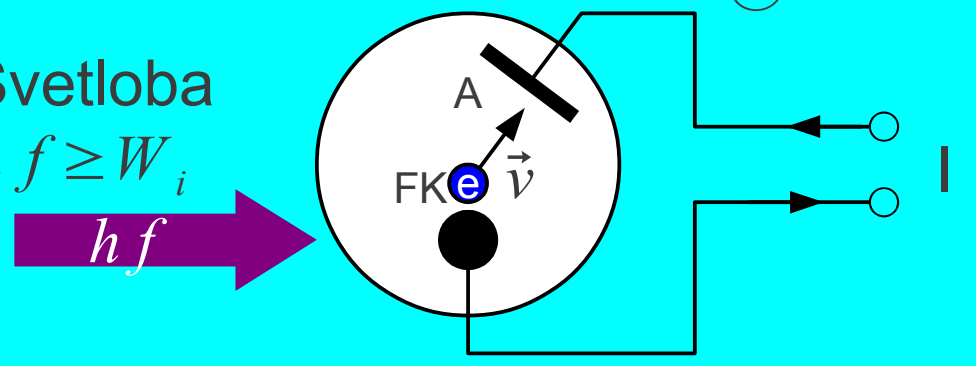
$h f \equiv poljuben$

→ *merilna oprema , termovizija*

Vakuumska fotodioda

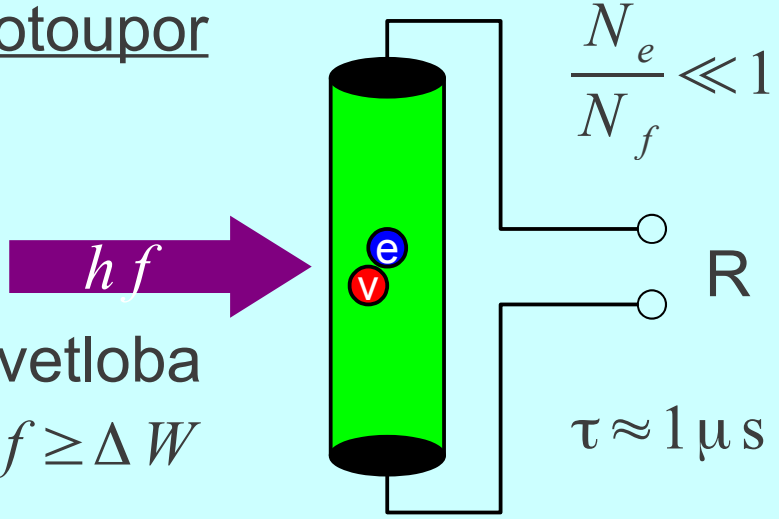
$$\frac{N_e}{N_f} = \eta \approx 0.2$$

@ 650nm



Fotoupor

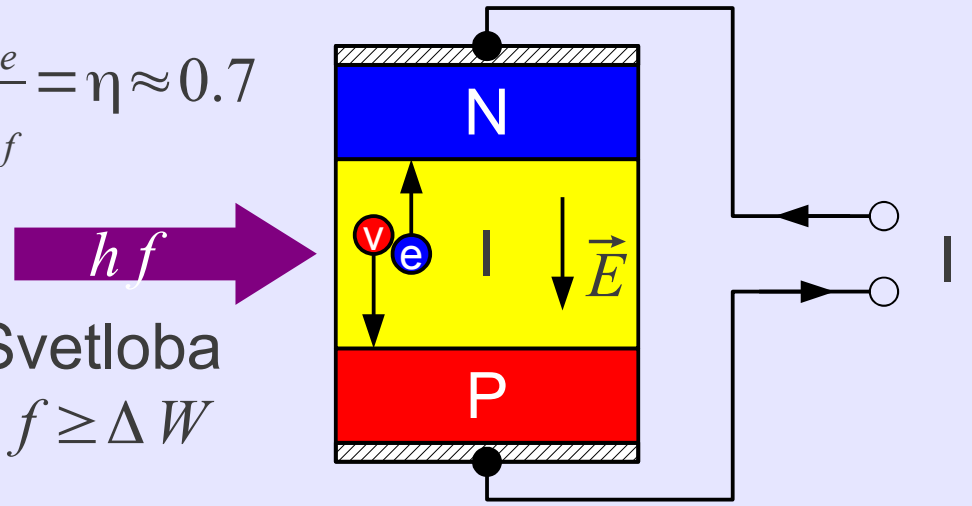
$$\frac{N_e}{N_f} \ll 1$$



Selen, Willoughby Smith 1873

Polprevodniška fotodioda

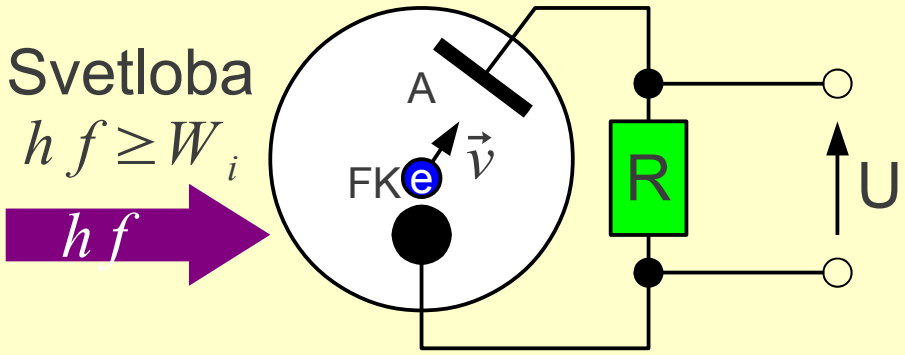
$$\frac{N_e}{N_f} = \eta \approx 0.7$$



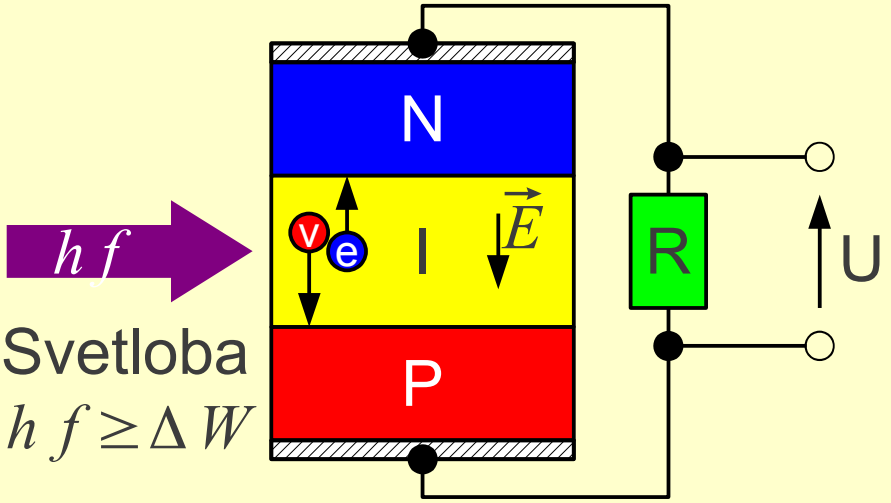
Zvrsti svetlobnih sprejemnikov

Režim delovanja fotodiode

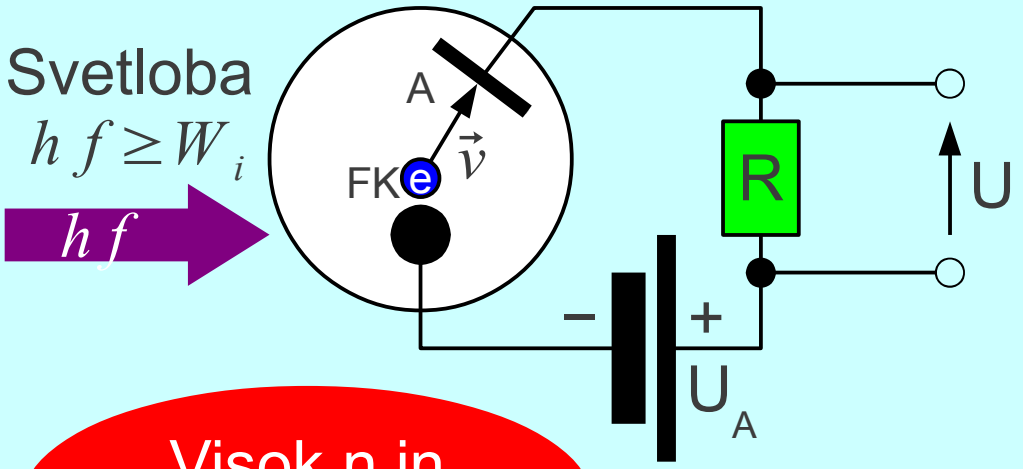
Fotovoltaični režim



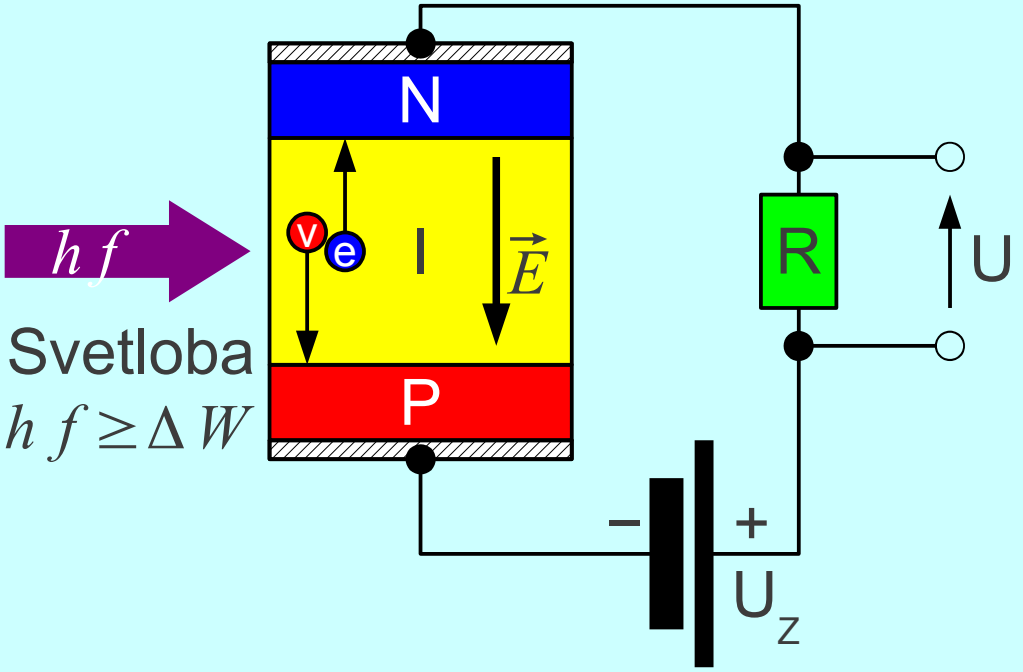
Pretvorba svetlobne moči v električno DC...



Fotouporovni režim

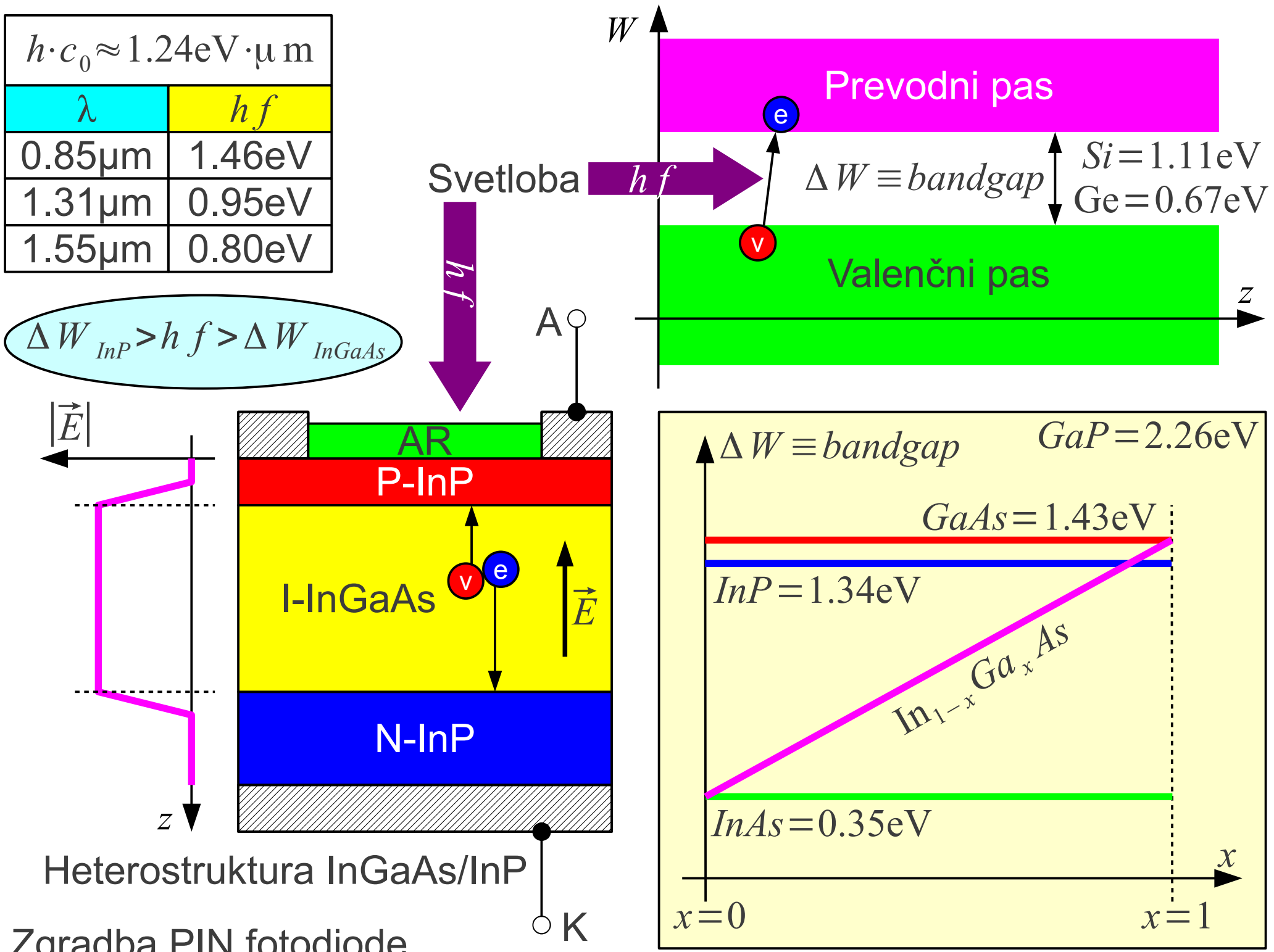


Visok η in hiter odziv...



$h \cdot c_0 \approx 1.24\text{eV} \cdot \mu\text{m}$

λ	hf
0.85μm	1.46eV
1.31μm	0.95eV
1.55μm	0.80eV



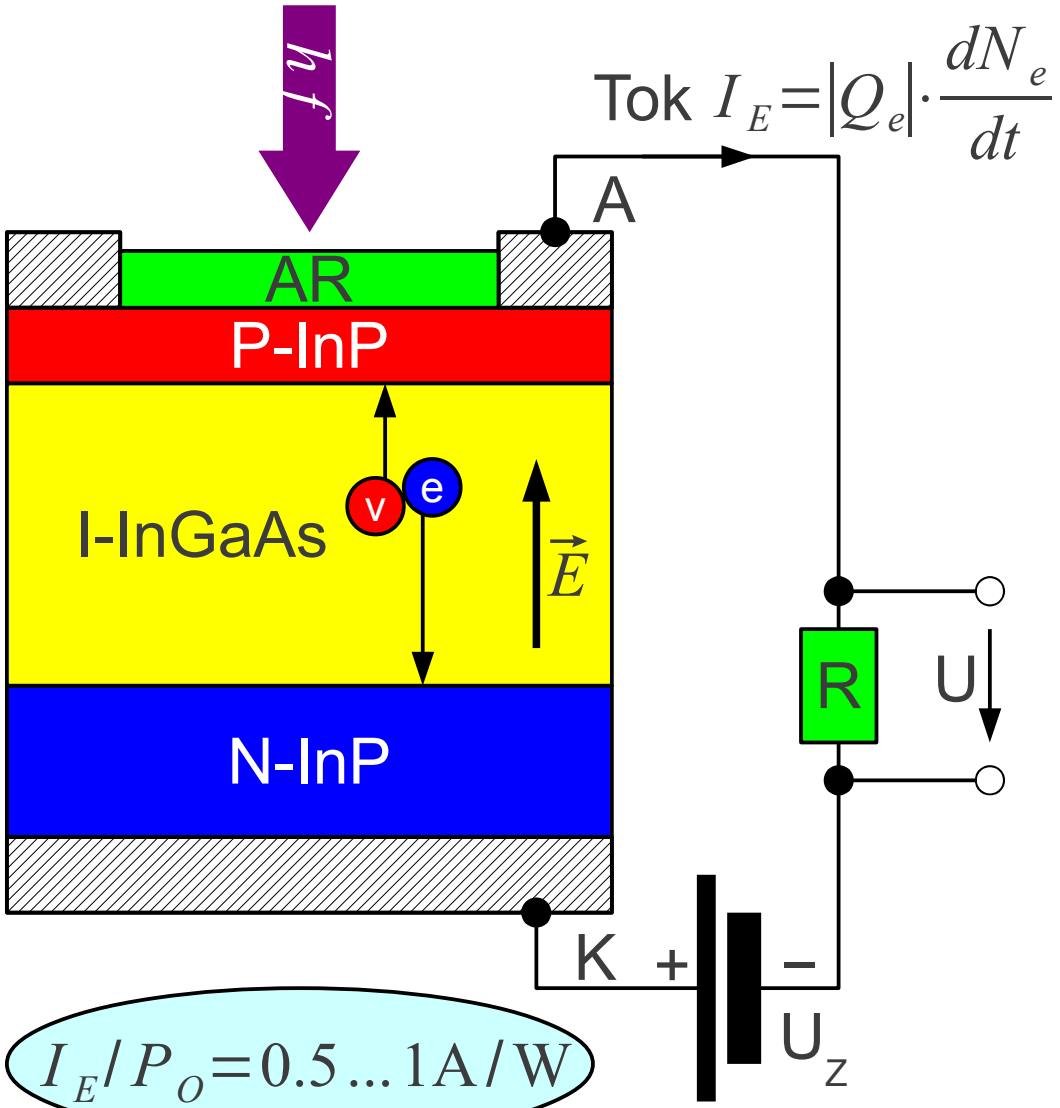
Zgradba PIN fotodiode

Svetlobna moč

$$P_O = h f \cdot \frac{dN_f}{dt}$$

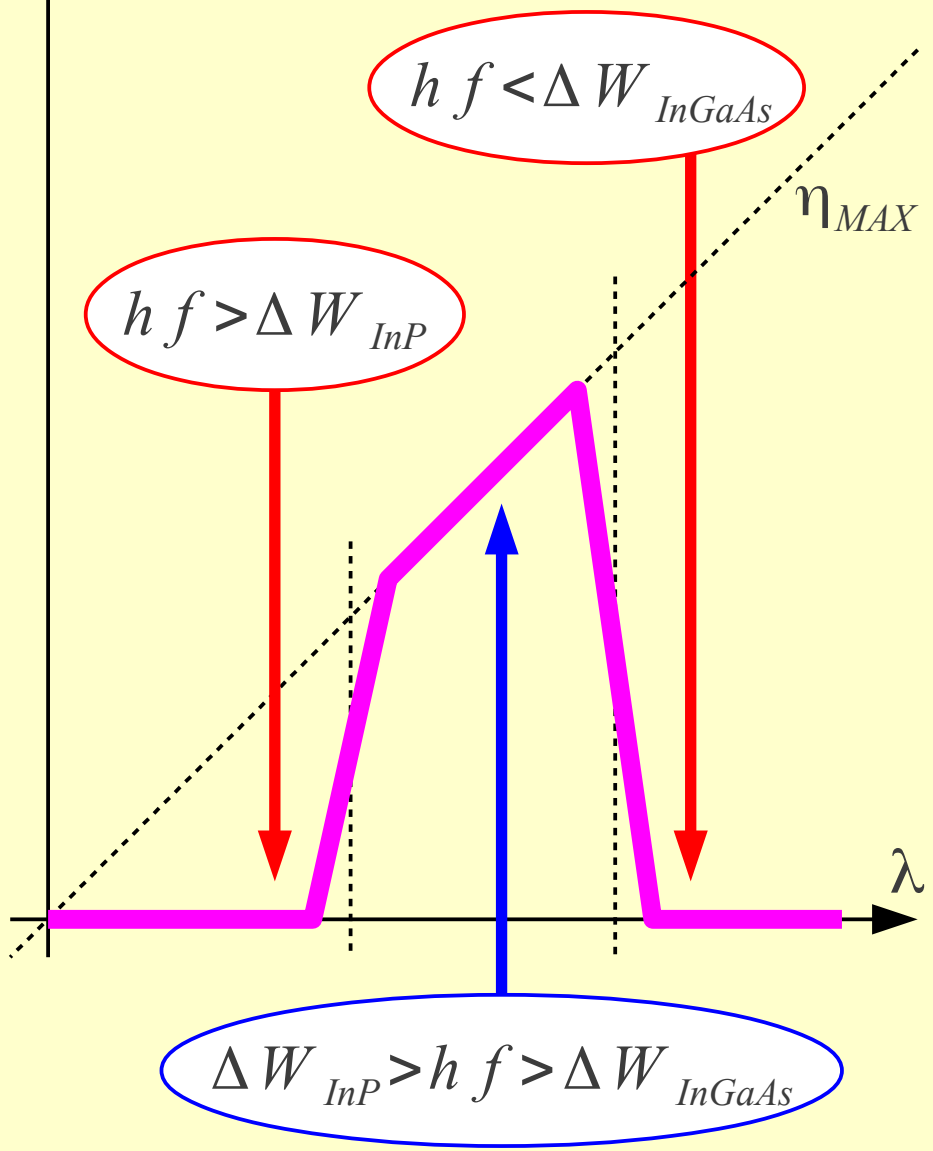
Kvantni izkoristek

$$\eta(\lambda) = \frac{N_e}{N_f} \approx 0.7$$

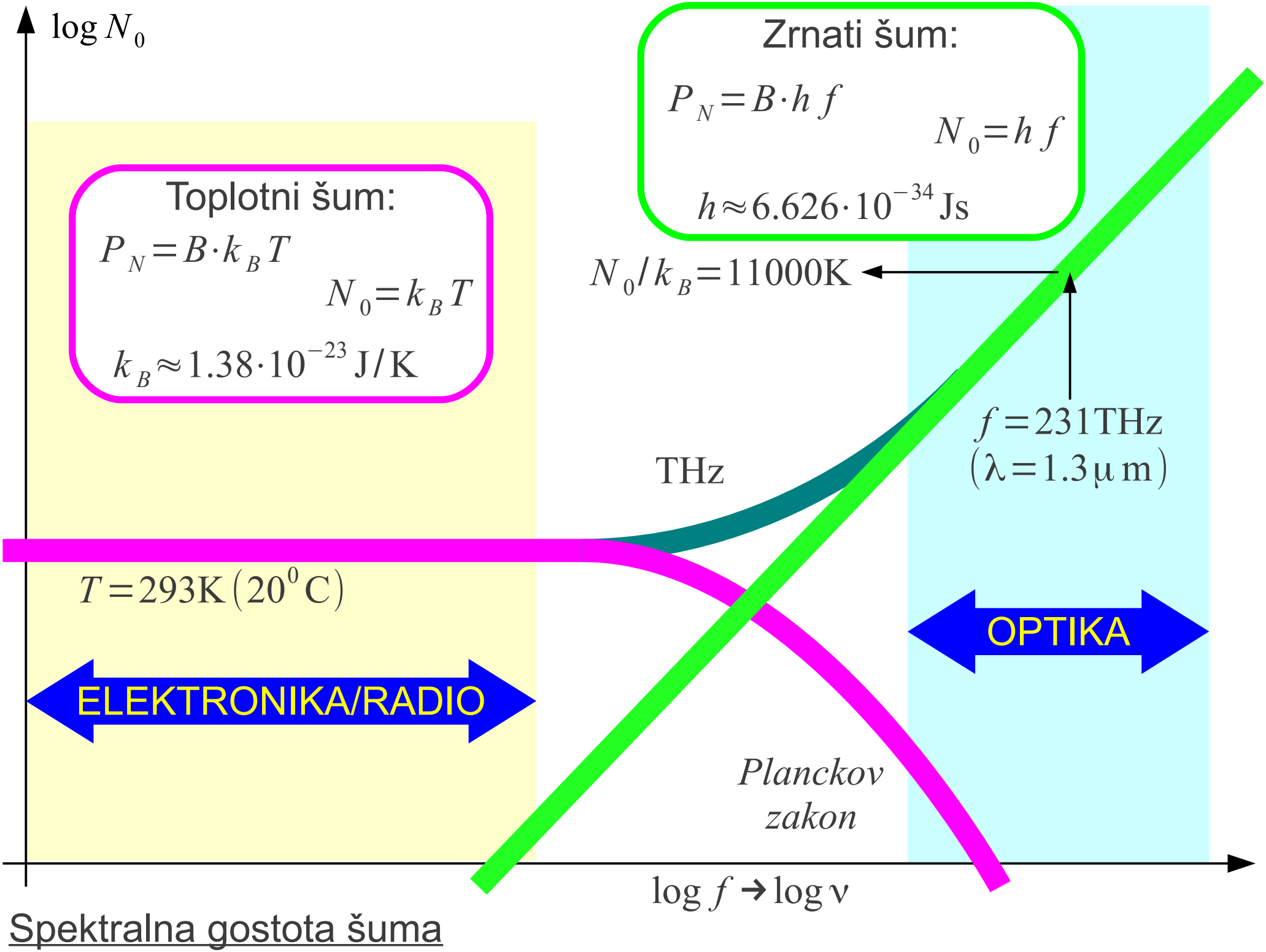


Odzivnost

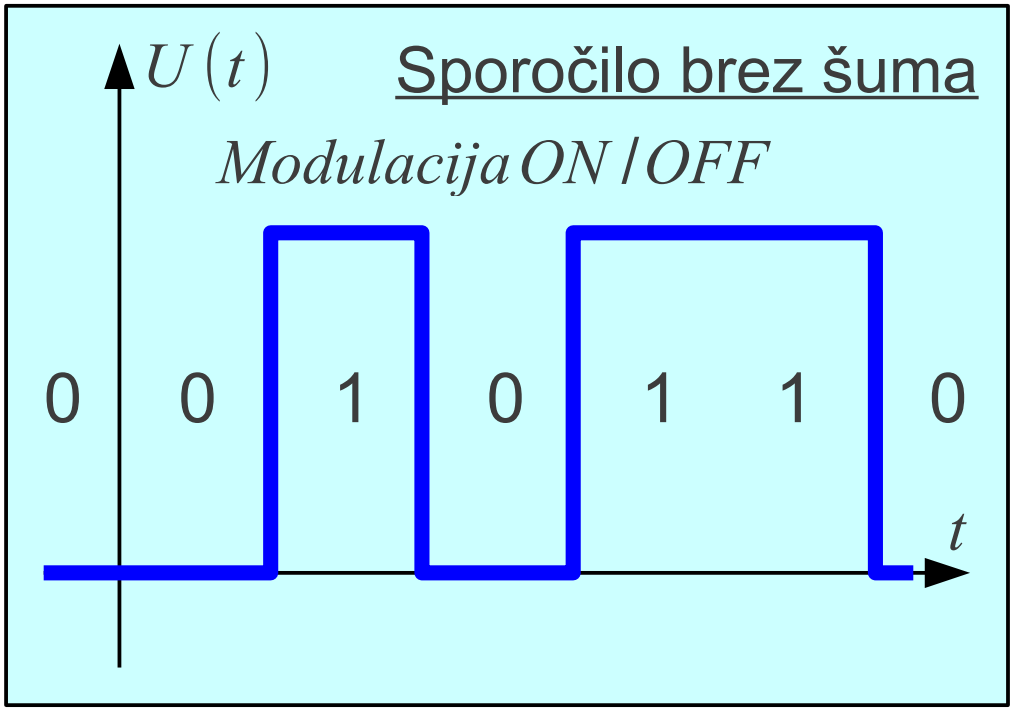
$$I_E / P_O \left[\frac{A}{W}\right] = \frac{N_e |Q_e|}{N_f h f} = \frac{\eta(\lambda)}{W_f [eV]}$$

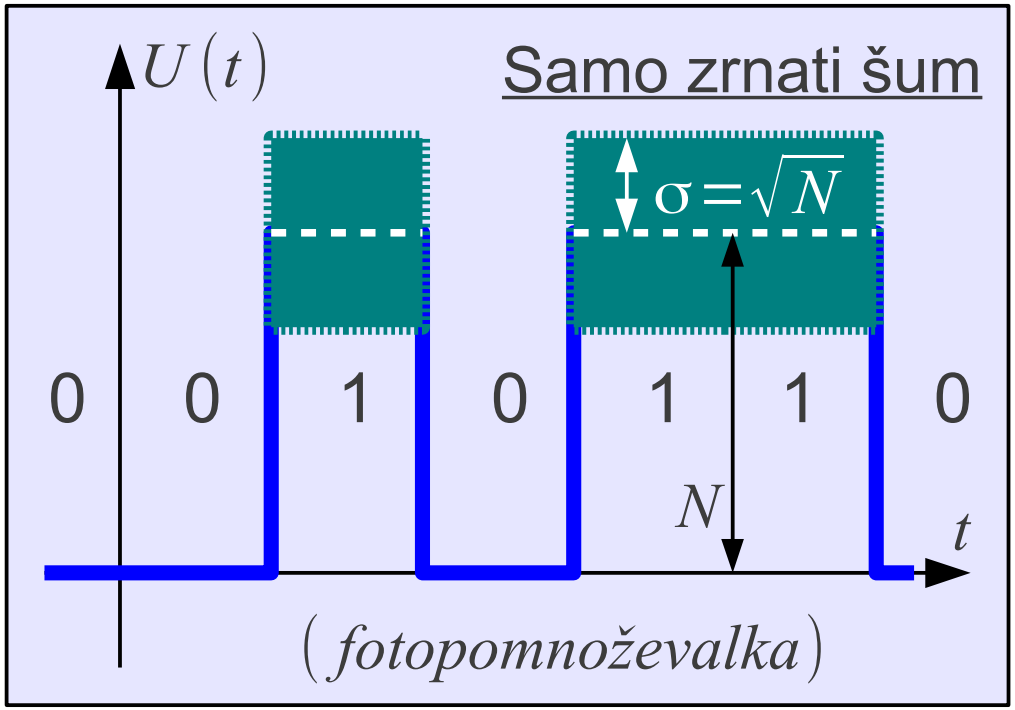


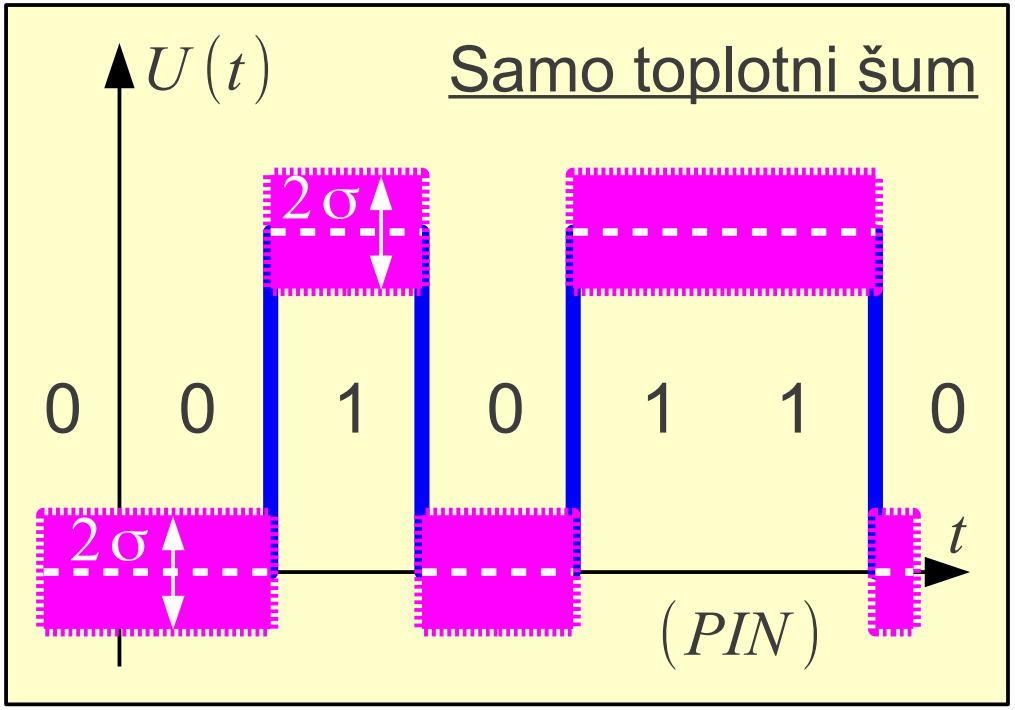
Odzivnost PIN fotodiode

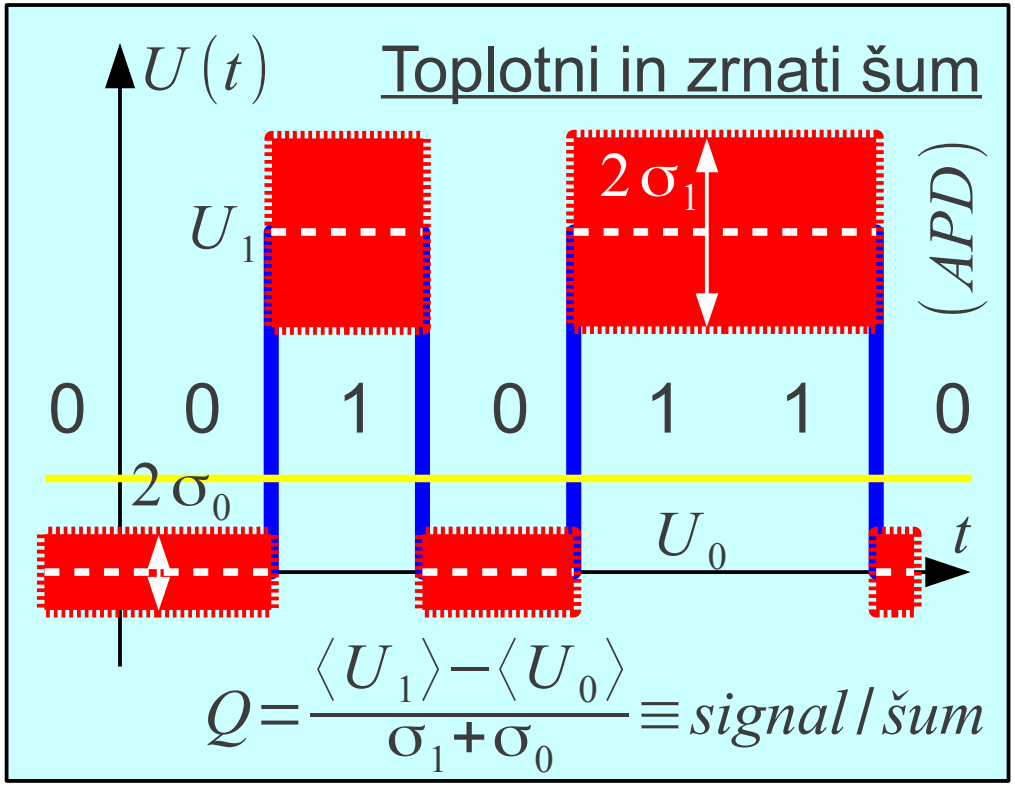


Spektralna gostota šuma

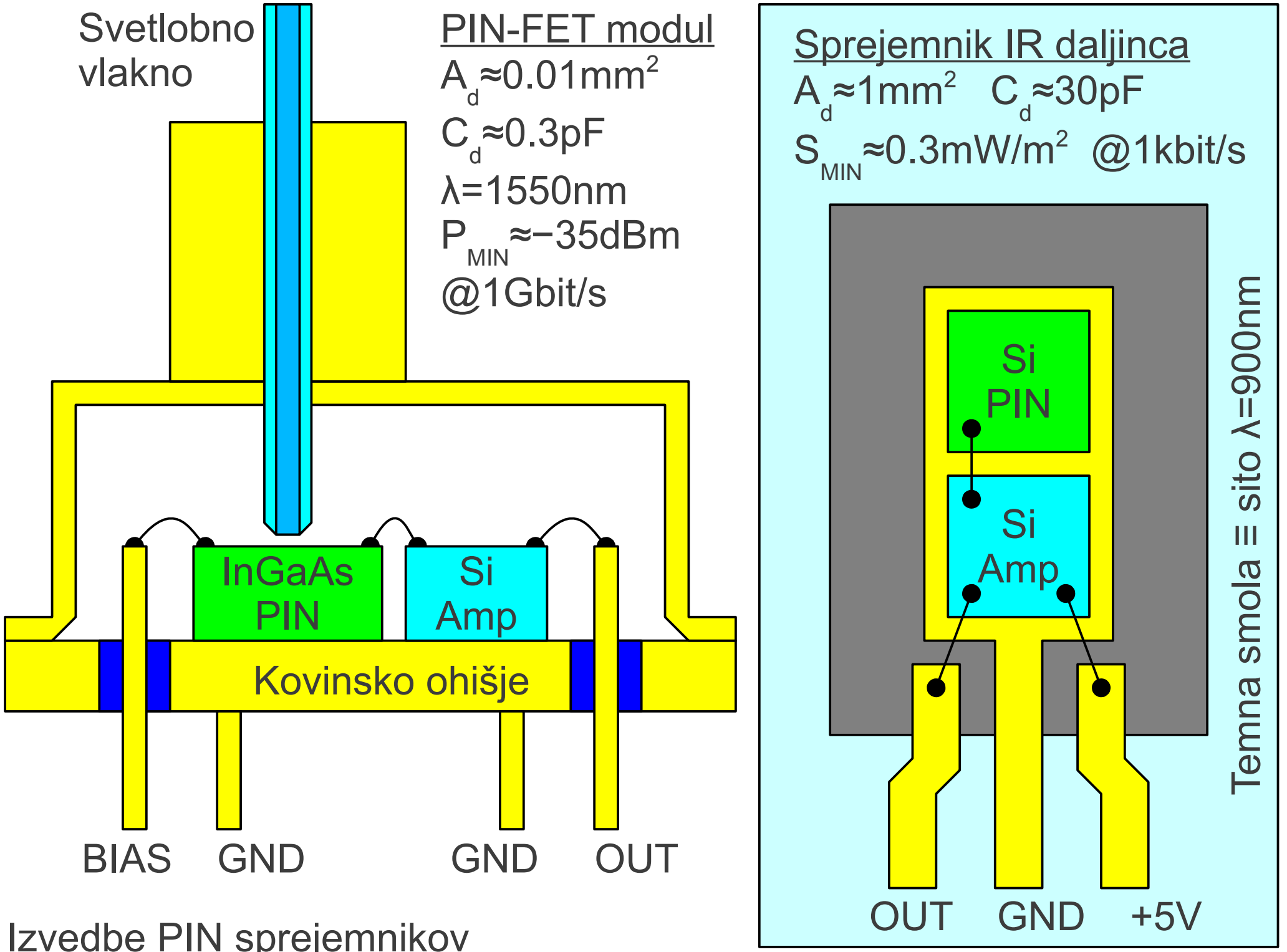


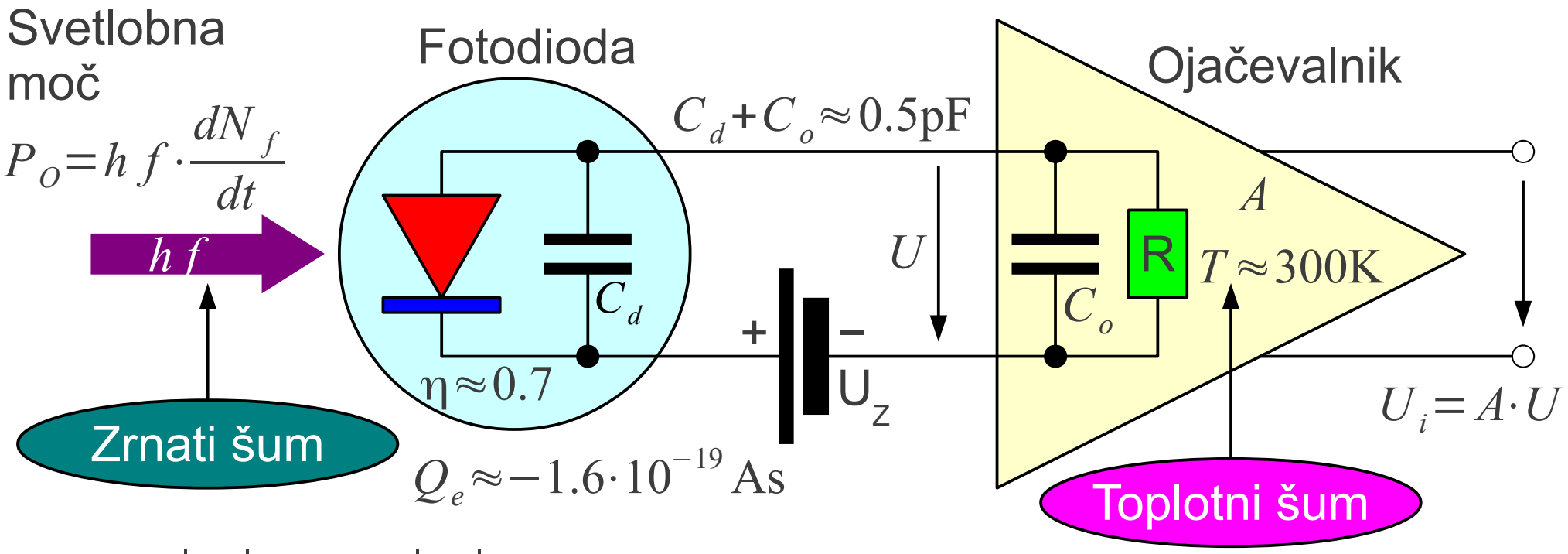






Toplotni in zrnati šum


Svetlobno vlakno
PIN-FET modul
$A_d \approx 0.01 mm^2$
$C_d \approx 0.3 pF$
λ=1550nm
$P_{MIN} \approx -35 dBm$
@1Gbit/s
InGaAs PIN
Si Amp
Kovinsko ohišje
BIAS
GND
GND
OUT
Izvedbe PIN sprejemnikov
Sprejemnik IR daljinca
$A_d \approx 1 mm^2$ $C_d \approx 30 pF$
$S_{MIN} \approx 0.3 mW/m^2$ @1kbit/s
Si PIN
Si Amp
Temna smola ≡ sito λ=900nm
OUT
GND
+5V



$$U_S = \frac{N_e |Q_e|}{C_d + C_o} = \frac{\eta N_f |Q_e|}{C_d + C_o} \approx N_e \cdot 0.32\,\mu\text{V}$$

$$U_{ZRNATI} \approx 0.32\,\mu\text{V}_{\text{eff}} \cdot \sqrt{N_e}$$

$$U_{ŠUMA1} = \sigma_1 = \sqrt{U_{ZRNATI}^2 + U_{TOPLOTNI}^2} \approx 38\,\mu\text{V}_{\text{eff}}$$

Toplotni šum ojačevalnika je dosti večji od zrnatega šuma elektronov:

$$B \approx \frac{1}{2\pi R (C_d + C_o)}$$

$$U_{TOPLOTNI} = \sqrt{P_N R} = \sqrt{B k_B T R} \approx \sqrt{\frac{k_b T}{2\pi (C_d + C_o)}} \approx 36\,\mu\text{V}_{\text{eff}}$$

Šum sprejemnika s PIN diodo

Razmerje signal/šum

$$Q=\frac{\langle U_1\rangle-\langle U_0\rangle}{\sigma_1+\sigma_0}$$

$$Q_{dB}=20\cdot\log_{10}Q$$

$$\sigma_1\approx\sigma_0\approx 36\,\mu\,\mathrm{V_{eff}}$$

$$Q\approx 6\ldots 7\rightarrow U_S\approx 450\,\mu\,\mathrm{V}$$

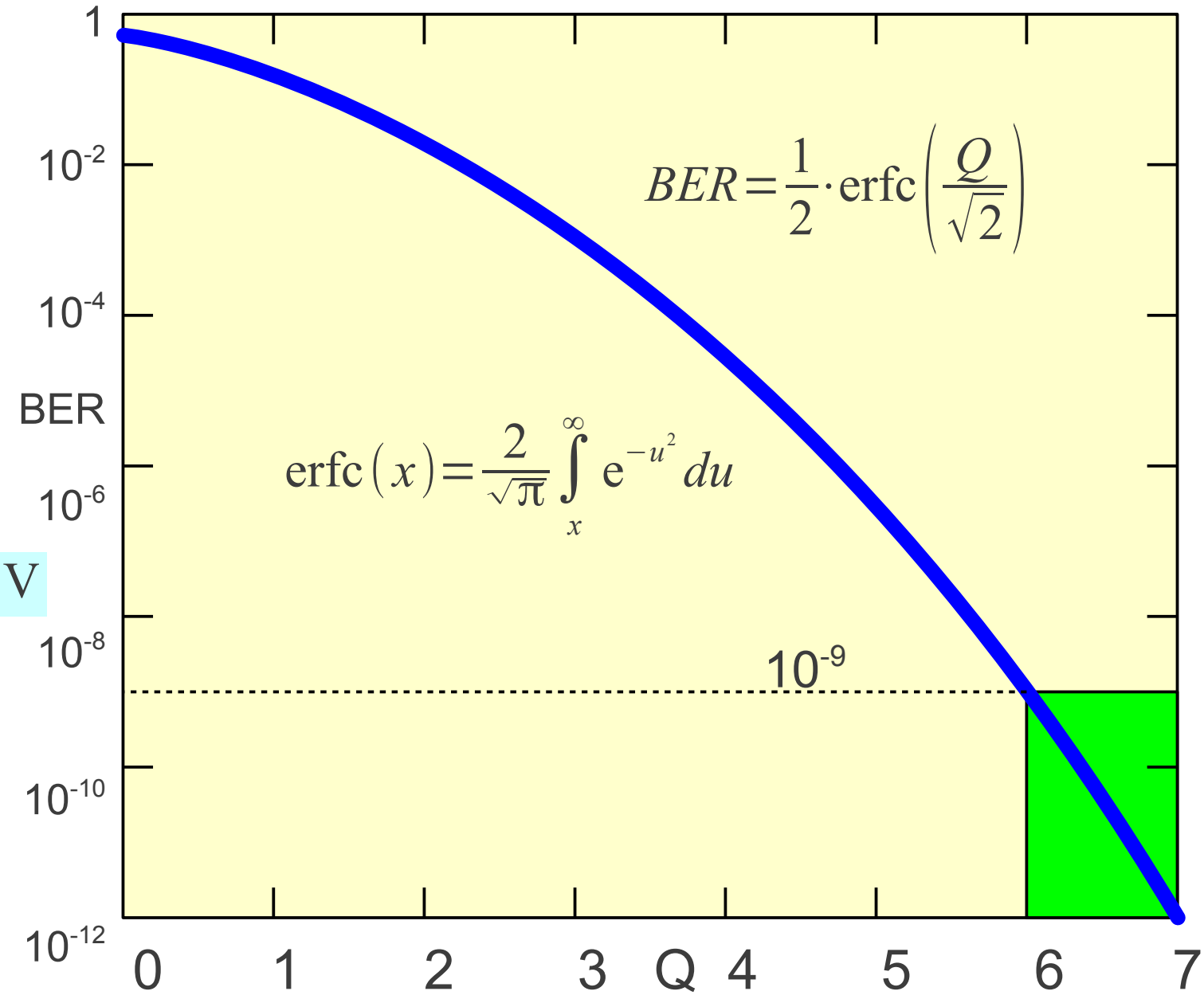
$$enica\rightarrow N_e\approx 1400$$

$$(ničla\rightarrow N_e=0)$$

$$U_{ZRNATI}\approx 12\,\mu\,\mathrm{V_{eff}}$$

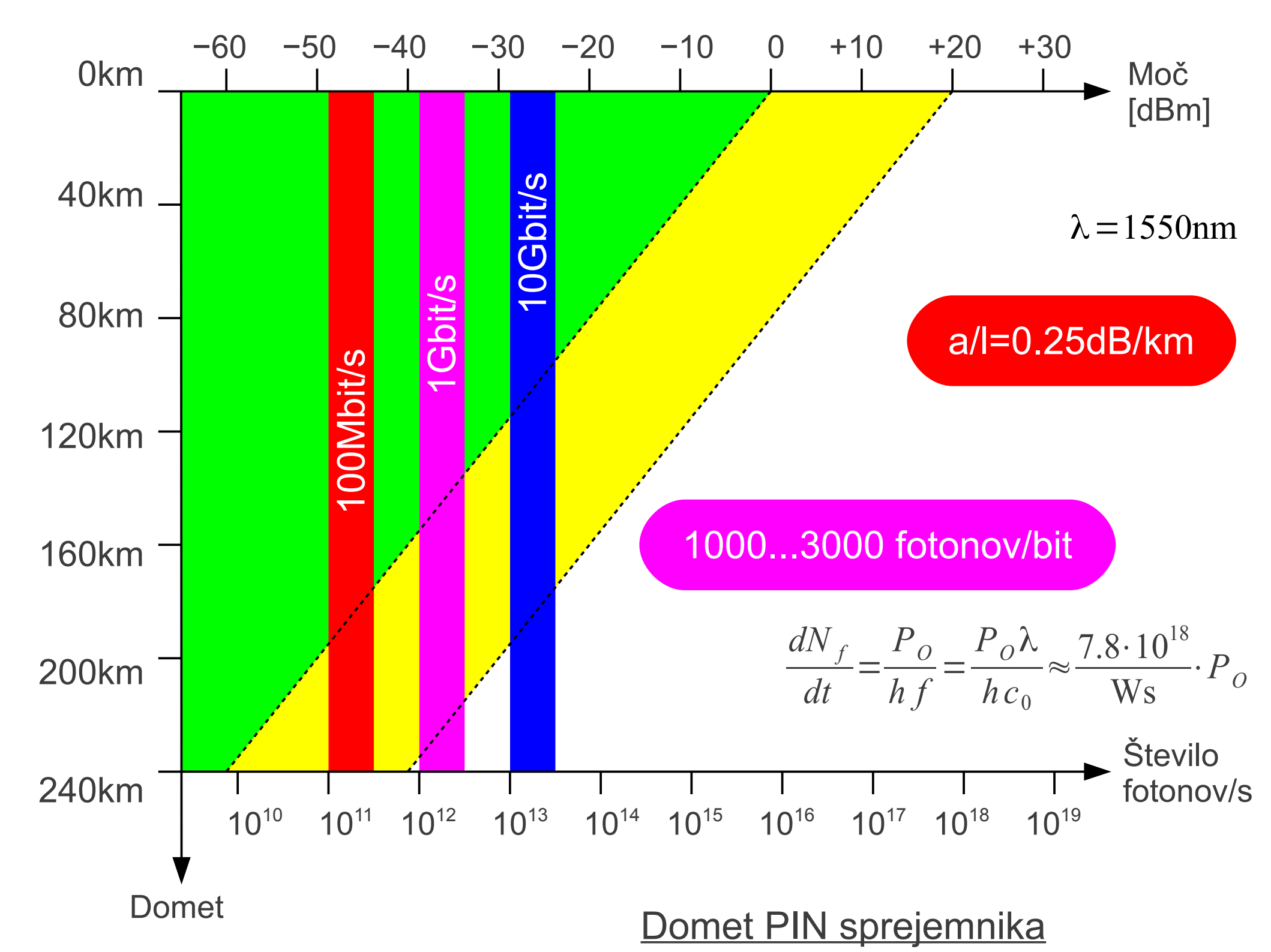
$$\eta\approx 0.7$$

$$enica\rightarrow N_f=\frac{N_e}{\eta}\approx 2000$$

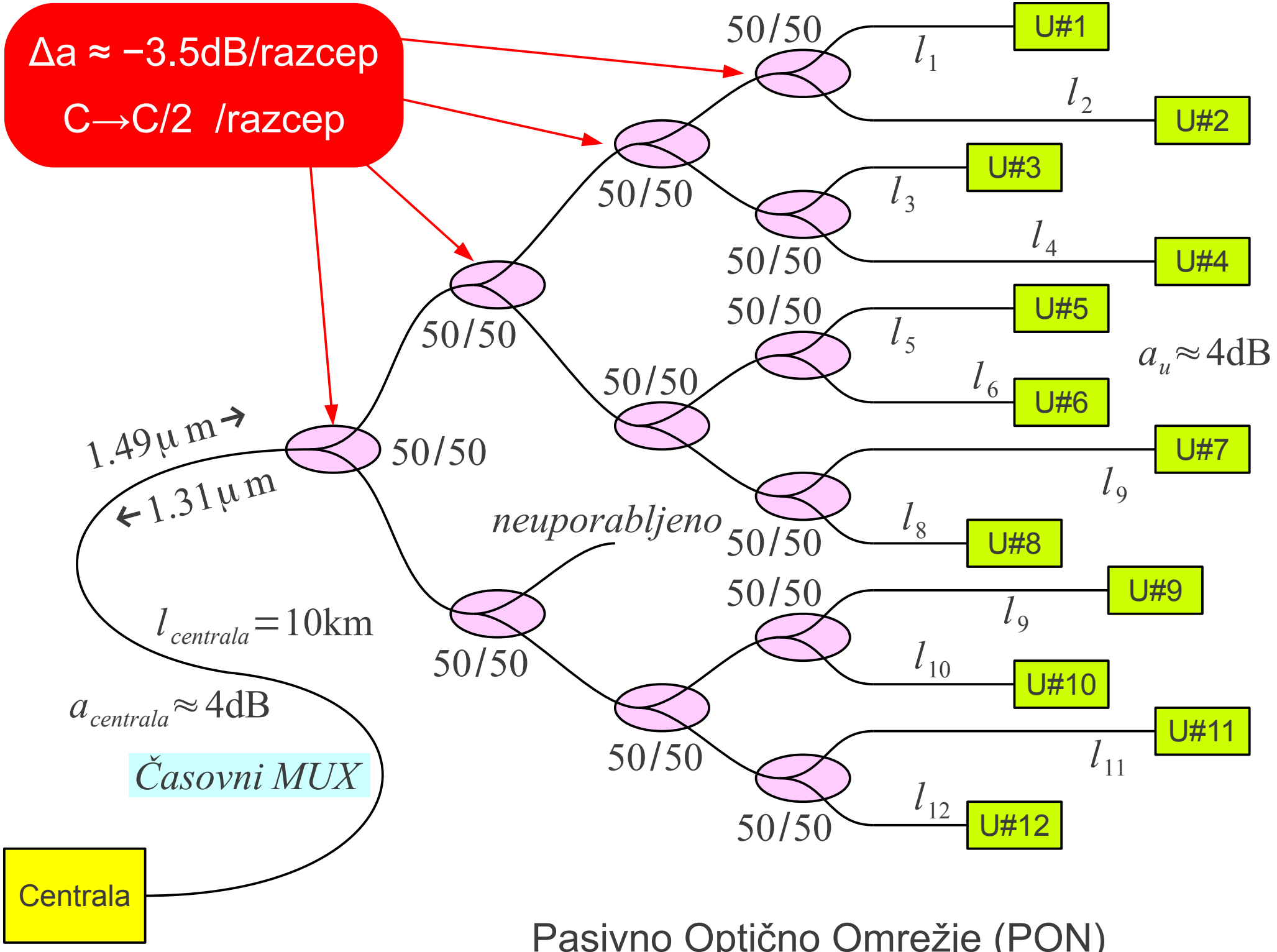


$50\,\%$ $enic\rightarrow$ N_f/bit ≈ 1000 fotonov/bit

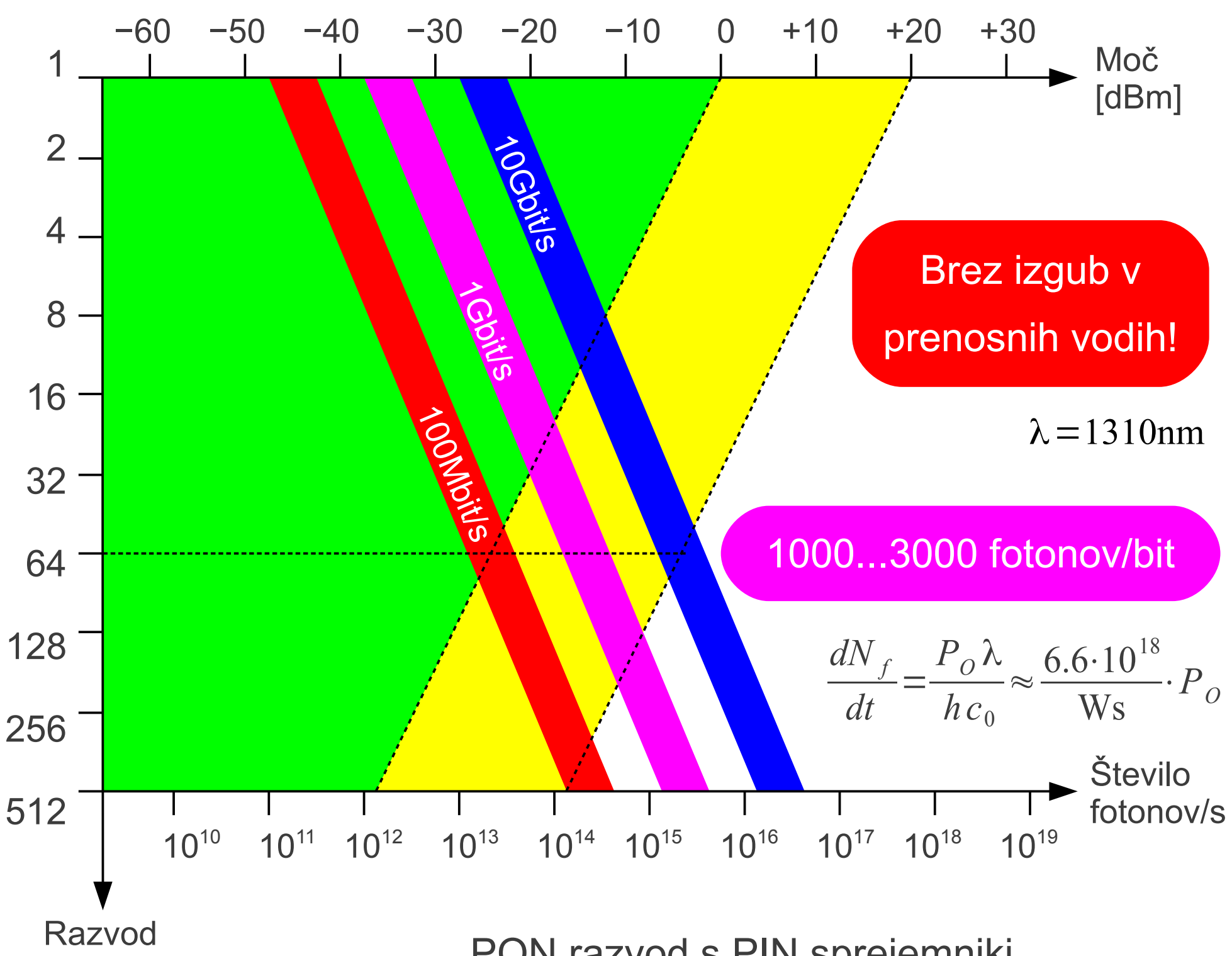
Razmerje Q in pogostnost napak



Domet PIN sprejemnika



Pasivno Optično Omrežje (PON)



PON razvod s PIN sprejemniki

Fotopomnoževalka

$I_A = I_{FK} \cdot M^N$

$U_B \approx 100\,\mathrm{V}$

$M \approx 3 \ldots 5$

$N = 3$

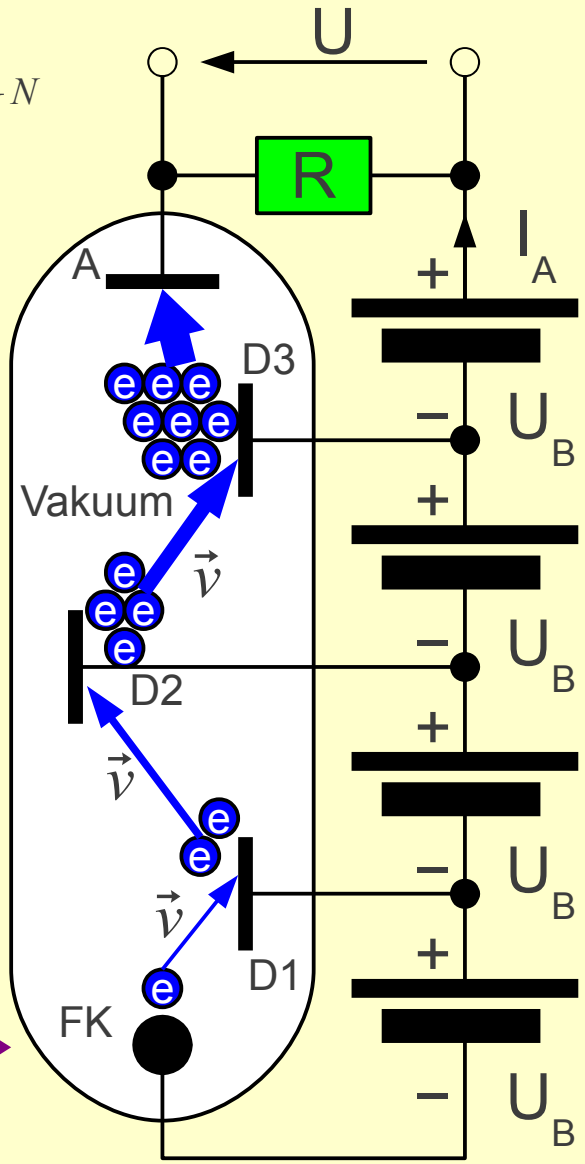
$(N = 8 \ldots 14)$

$\tau \approx 1\,\mu\mathrm{s}$

Svetloba

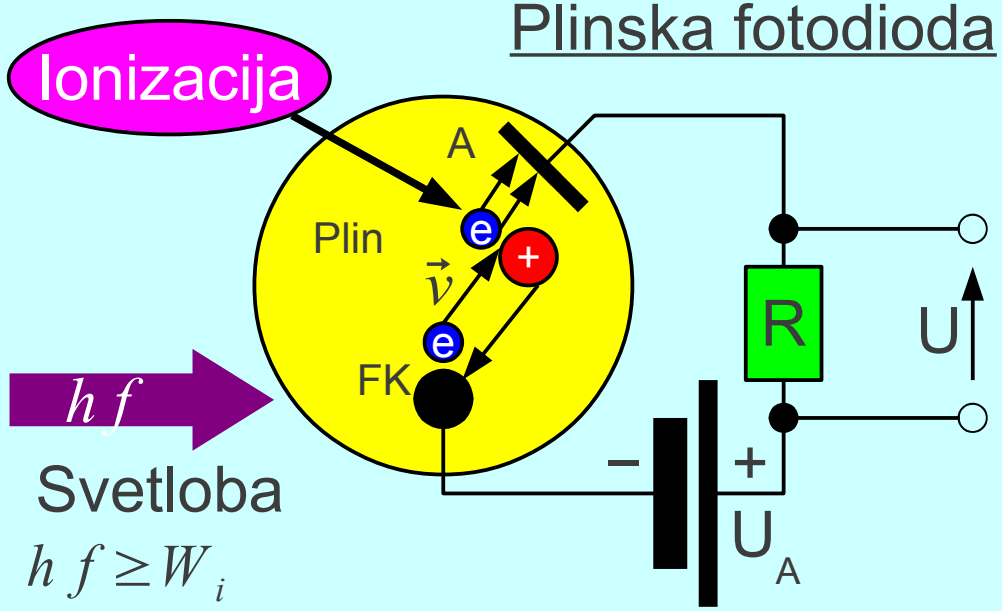
$h f \geq W_i$

$h f$

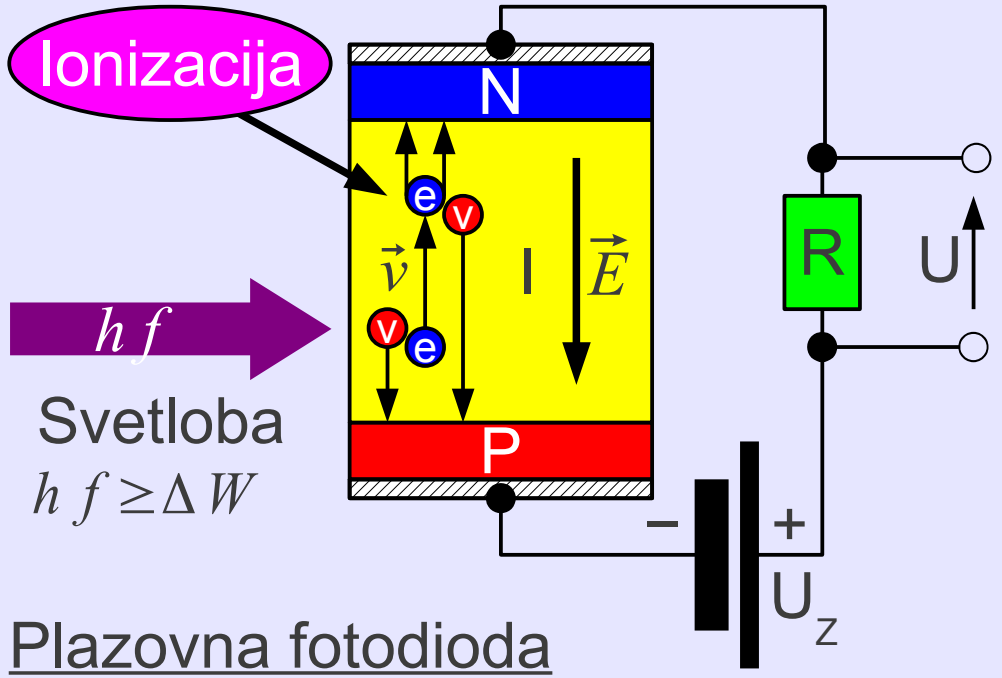


$$\frac{N_{eFK}}{N_f} = \eta_{FK} \approx \begin{Bmatrix} 50\,\% & @\,500\mathrm{nm} \\ 10^{-6} & @\,1550\mathrm{nm} \end{Bmatrix}$$

Plinska fotodioda

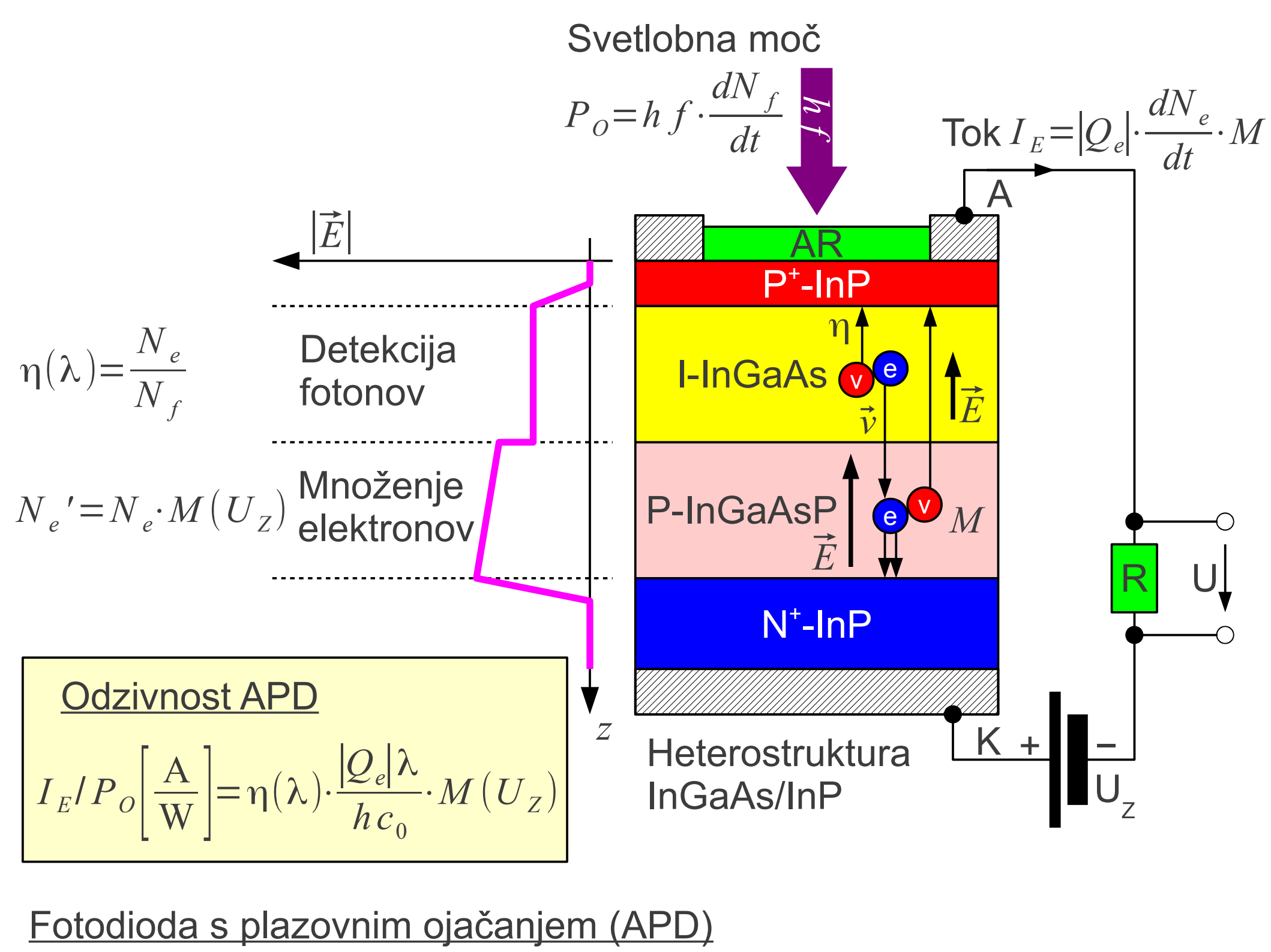


Plazovna fotodioda

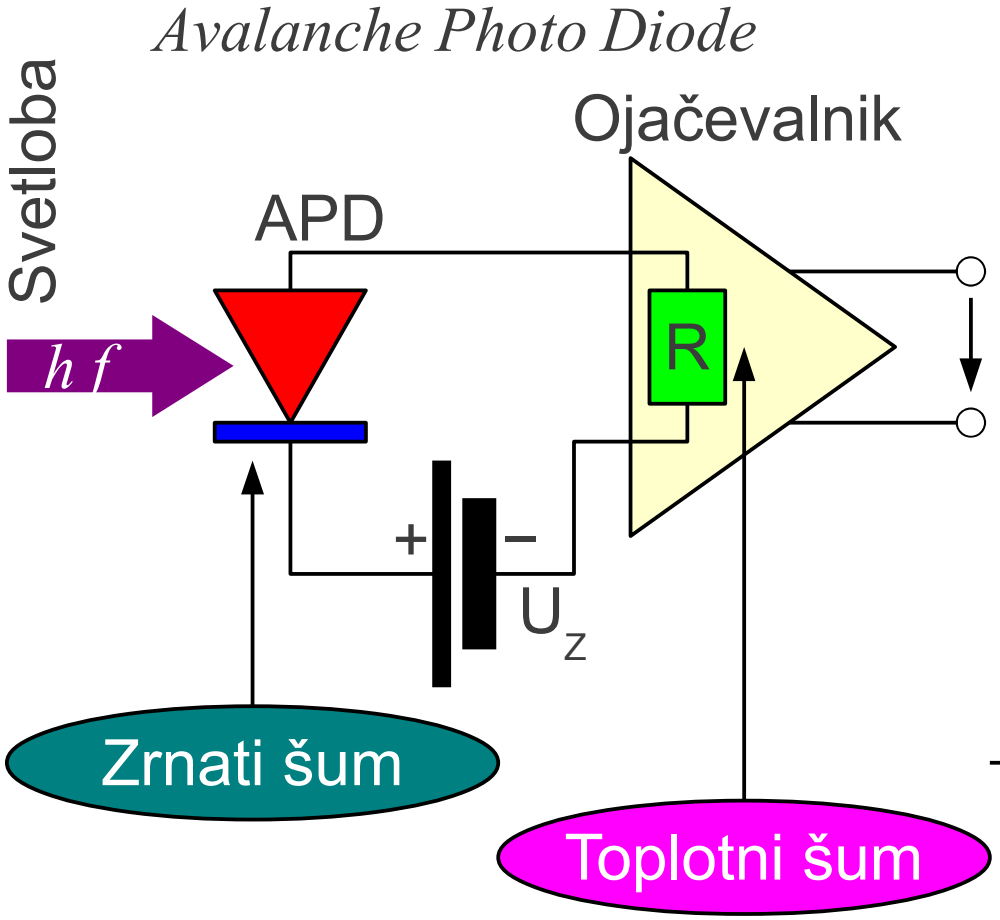


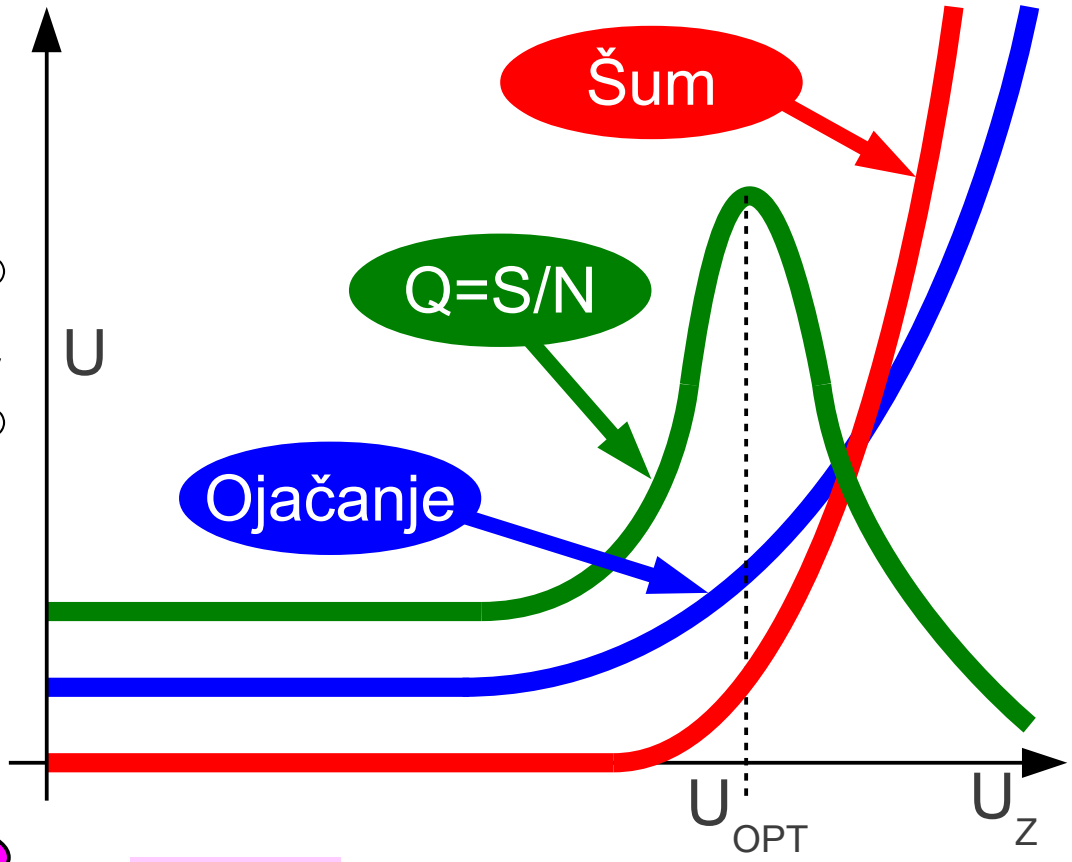
Svetlobni sprejemniki z ojačanjem

Fotopomnoževalke



Fotodioda s plazovnim ojačanjem (APD)

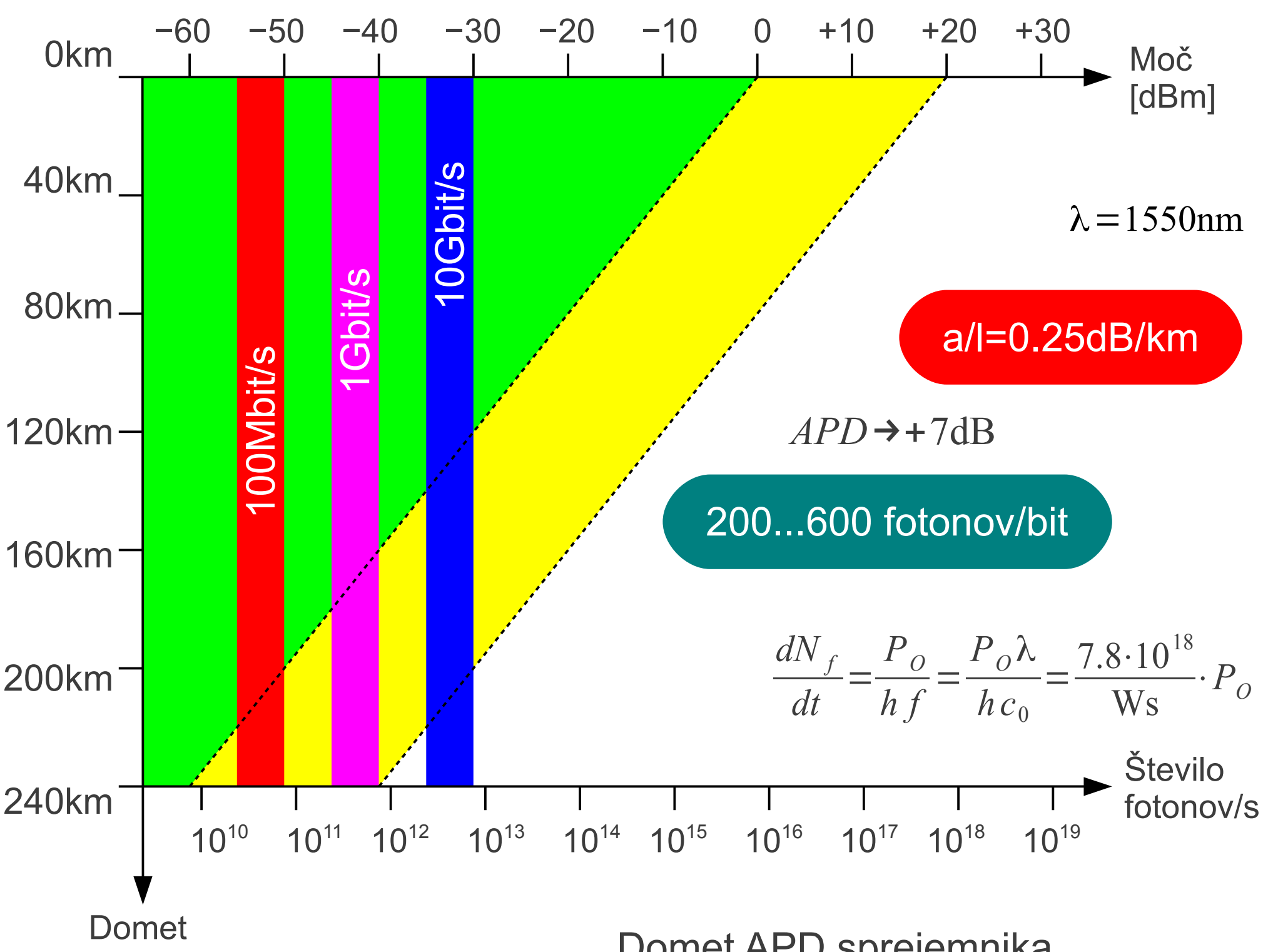




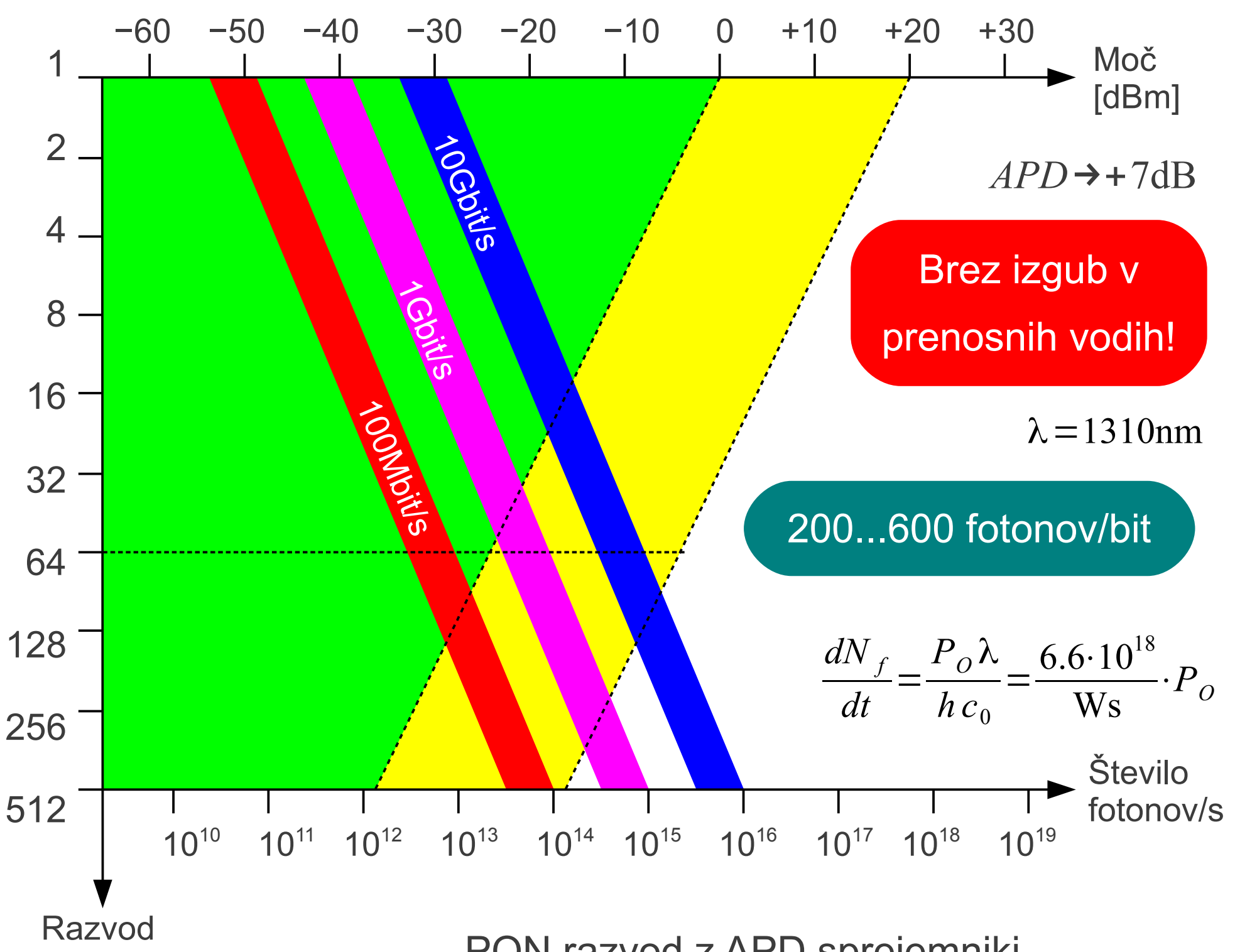
$TK_U > 0$

APD	ΔW	λ	W_f	U_{OPT}	M_{OPT}	Občutljivost
Si	1.11eV	850nm	1.46eV	~150V	~100	~60 fotonov/bit
Ge	0.67eV	1310nm	0.95eV	~30V	~10	~500 fotonov/bit
InGaAsP	~0.75eV	1550nm	0.80eV	~70V	~20	~200 fotonov/bit

Lastnosti APD sprejemnika



Domet APD sprejemnika



PON razvod z APD sprejemniki