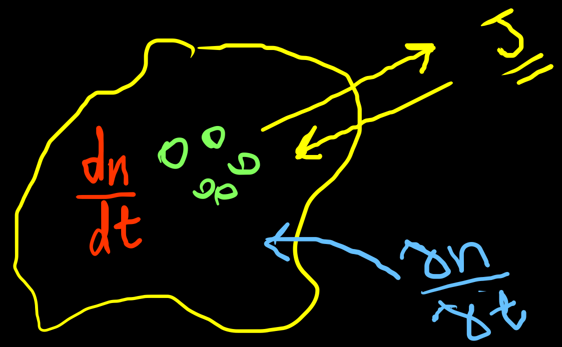
دینامیک بارها: حرکت، تولید، بازترکیب

روابط پیوستگی



$$\frac{dn}{dt} \quad , \quad \frac{dp}{dt}$$

$$n(x, y, z, t)$$

$$\frac{dn}{dt} = \frac{\partial n}{\partial t} \cdot \frac{dt}{dt} + \frac{\partial n}{\partial x} \cdot \frac{dx}{dt} + \frac{\partial n}{\partial y} \cdot \frac{dy}{dt} + \frac{\partial n}{\partial z} \cdot \frac{dz}{dt}$$

$$= \frac{\partial n}{\partial t} + \frac{\partial n}{\partial x} \cdot v_x + \frac{\partial n}{\partial y} \cdot v_y + \frac{\partial n}{\partial z} \cdot v_z$$

$$\vec{\nabla} = \frac{\partial n}{\partial x} \hat{i} + \frac{\partial n}{\partial y} \hat{j} + \frac{\partial n}{\partial z} \hat{k}$$

تولید - بازترکیب

$$\boxed{\frac{dn}{dt} = \frac{\partial n}{\partial t} + \vec{V} \circ \overrightarrow{\nabla n}}$$

معادله پیوستگی

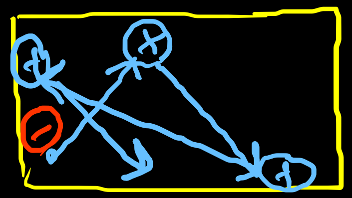
محلی

ورود و خروج بارها

$J = ۲ . e = \sum \vec{v_i} \times e$

$\sum \vec{v_i} = 0$

بدون میدان



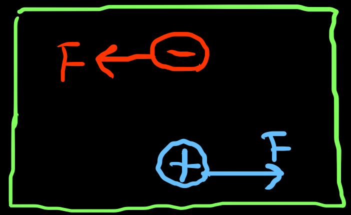
$\langle \vec{v} \rangle = 0 \qquad J = 0$

$E_f ,\ E_i ,\ P_0 ,\ n_0$

جریان و رسانایی

حرکت بارها →
- رسانایی $\quad \sigma \quad \times$
- قابلیت تحرک $\quad \mu \quad \times$
- نفوذ $\quad D$

میدان الکتریکی $\xrightarrow{\mathcal{E}}$



$\langle v_n \rangle \neq 0 \qquad J_n \neq 0$

$\langle v_p \rangle \neq 0 \qquad J_p \neq 0$

اصل بقای تکانه

$$F = ma = m\frac{dv}{dt} = \frac{d(mv)}{dt} = \frac{dP}{dt}$$

$$F = \mathcal{E} q$$

$$\frac{d}{dt}P = \frac{d}{dt}P_{gain} + \frac{d}{dt}P_{loss}$$

$$0 = \mathcal{E} q + \frac{-\langle P \rangle}{\tau} \rightarrow \langle P \rangle = \mathcal{E} q \tau \qquad \mu$$

τ ← زمان متوسط برخورد

$$\langle P \rangle = m^* \langle v \rangle = \mathcal{E} q \tau \rightarrow \langle v \rangle = \frac{q\tau}{m^*}\mathcal{E}$$

ورودی → نیمه رسانا → خروجی

میدان $\mathcal{E}$

سرعت بارها

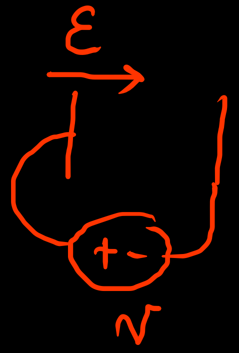
جریان بارها

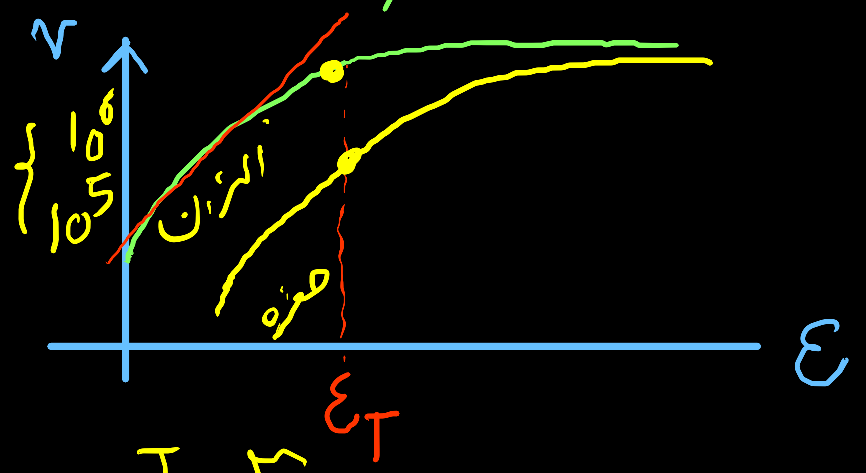
$$\frac{v}{\mathcal{E}} = \frac{\text{سرعت}}{\text{میدان}} = \mu \qquad \frac{J}{\mathcal{E}} = \sigma$$

$$\begin{cases} \mu_n = \dfrac{|q|\tau}{m_n^*} \\ \mu_p = \dfrac{|q|\tau}{m_p^*} \end{cases}$$

ثابت

$$\mu = \frac{v \uparrow}{\mathcal{E} \uparrow} \rightarrow v = \mu \mathcal{E}$$





① جرم موثر

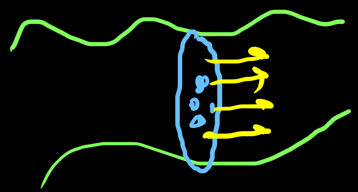
② $\downarrow \mu \leftarrow \downarrow \tau \leftarrow \uparrow$ دما

③ $\downarrow \mu \leftarrow \downarrow \tau \leftarrow \uparrow$ ناخالصی

④

$$\frac{\langle v \rangle}{\mathcal{E}} = \mu$$

جریان :



$$\Gamma = \sum_{i=1}^{n} v_i \qquad J = \Gamma e$$

$$\Gamma = n \times \sum_{i=1}^{n} \frac{v_i}{n} = n \langle v \rangle$$

$$J = nq\langle v \rangle \quad , \quad \langle v \rangle = \mathcal{E}\mu$$

$$J = nq\mu$$

$$\begin{cases} J_n = nq\mu_n \\ J_p = pq\mu_p \end{cases}$$

$$J = J_n + J_p = q(n_0\mu_n + p_0\mu_p)\mathcal{E}$$

$$J = \sigma \mathcal{E} \rightarrow \boxed{\sigma = q(n_0\mu_n + p_0\mu_p)}$$

$$J_{drift} = J_n + J_p$$

$$J_n = n_0 q \mu_n \mathcal{E}$$

$$J_p = p_0 q \mu_p \mathcal{E}$$

$$\mu = \frac{v}{\mathcal{E}}$$

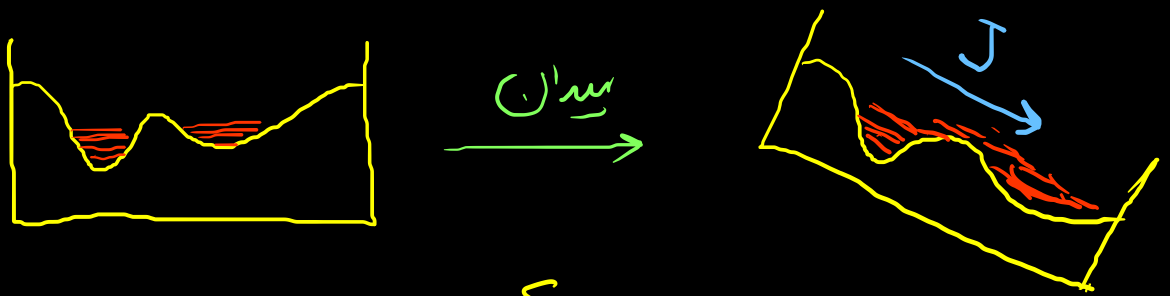
$$\sigma = \frac{J}{\mathcal{E}}$$

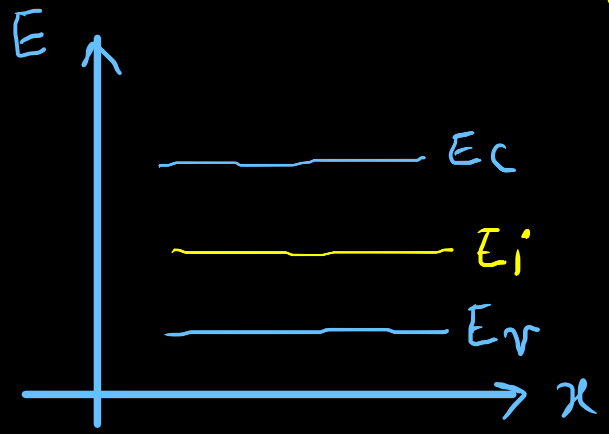
$$\sigma = n_0 q \mu_n + p_0 q \mu_p$$

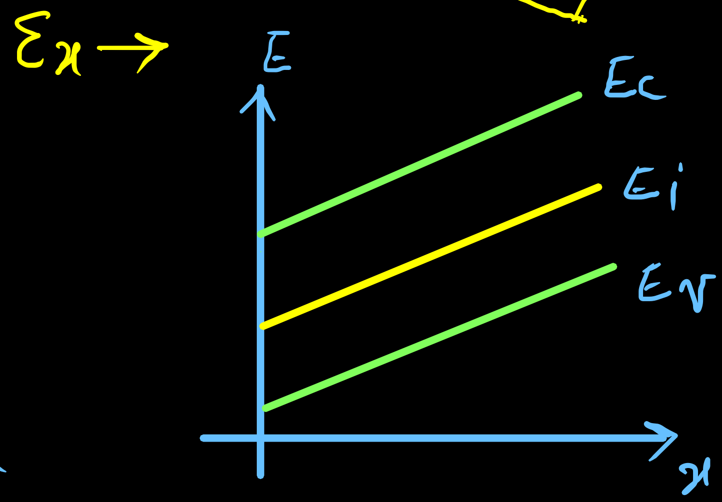
$$R = \rho \frac{l}{A} \quad , \quad \sigma = \frac{1}{\rho}$$

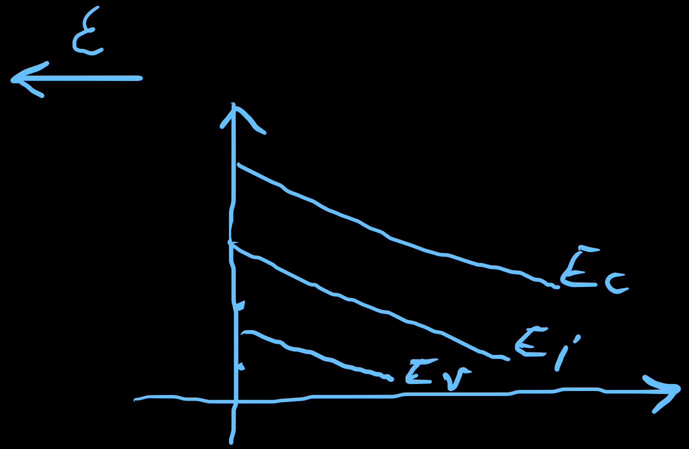
$$\boxed{n_0 , p_0 , \mu_n \; \mu_p} \longrightarrow \sigma \quad l \quad \rho$$

به نام خدا









$$\mathcal{E} = -\nabla V = -\frac{\partial}{\partial x} V$$

$$PE = E_{ref} - E_v$$

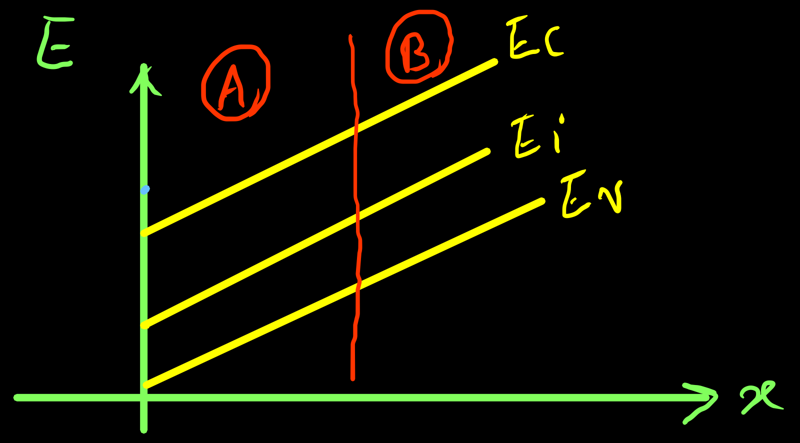
$$PE = E_c - E_{ref} = -qV_x$$

$$V_x = -\frac{1}{q}(E_c - E_{ref})$$

$$\mathcal{E}_x = -\frac{\partial}{\partial x}\left[-\frac{1}{q}(E_c - E_{ref})\right]$$

$$\begin{cases} \mathcal{E}_x = \frac{1}{q}\frac{\partial}{\partial x} E_c \\ \mathcal{E}_x = \frac{1}{q}\frac{\partial}{\partial x} E_v \end{cases}$$

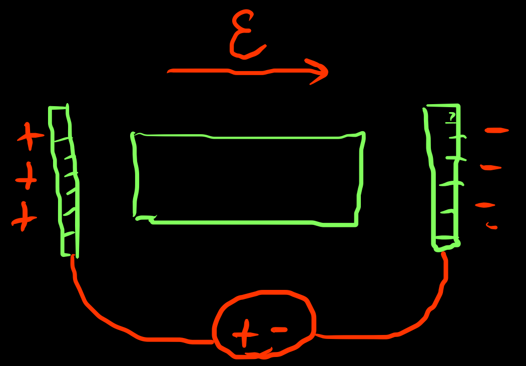
← اعمال میدان الکتریکی باعث خم شدن نوارهای انرژی می‌شود E_i, E_v, E_c



تراز فرمی ؟

$$R_{AB} = N_A f_A(E) \times N_B(1 - f_B(E))$$

$$R_{BA} = N_B f_B(E) \times N_A(1 - f_A(E))$$

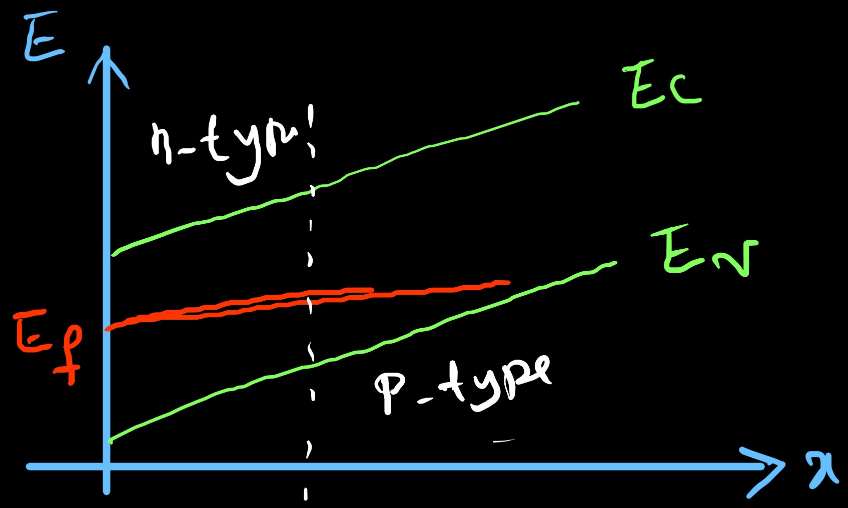


$$J = 0 \longrightarrow R_{AB} = R_{BA}$$

$$N_A N_B f_A - N_A N_B f_A f_B = N_A N_B f_B - N_A N_B f_A f_B$$

$$f_A(E) = f_B(E)$$

$$\frac{1}{1 + e^{\frac{E - E_{fA}}{k_B T}}} = \frac{1}{1 + e^{\frac{E - E_{fb}}{k_B T}}}$$



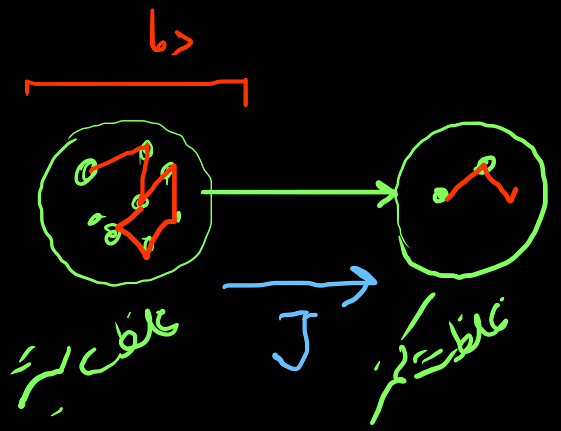
$$\boxed{E_{fA} = E_{fB}}$$

تراز فرمی ثابت باقی میماند

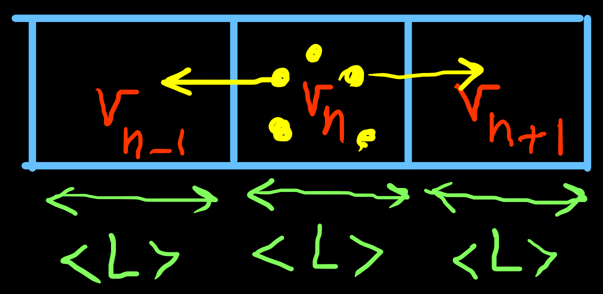
$$J_{drift} = J_{N\,drift} + J_{p\,drift}$$

$$J_N = n_0 q \mu_n \mathcal{E}$$
$$J_p = p_0 q \mu_p \mathcal{E}$$

Diffusion نفوذ -



$$J_{diffusion} = ? \qquad J = \Gamma e$$



تعداد ذرات

$$\text{شار} = \frac{\frac{1}{2} n \times A_n \times \langle L\rangle}{\tau}$$

تعداد شار

$$\Gamma_{v_n \to v_{n+1}} = \frac{1}{2} n_n \frac{\langle L\rangle}{\tau}$$

$$\frac{\partial n}{\partial x} \simeq \frac{n_{n+1} - n_n}{\langle L\rangle} = -\frac{n_n - n_{n+1}}{\langle L\rangle} \rightarrow n_n - n_{n+1} = -\langle L\rangle \frac{\partial n}{\partial x}$$

$$\Gamma_{v_n \rightleftarrows v_{n+1}} = \frac{1}{2} n_n \frac{\langle L\rangle}{\tau} - \frac{1}{2} n_{n+1} \frac{\langle L\rangle}{\tau} = \frac{1}{2} (n_n - n_{n+1}) \frac{\langle L\rangle}{\tau} = \frac{1}{2}\left[-\langle L\rangle \frac{\partial n}{\partial x}\right] \frac{\langle L\rangle}{\tau} =$$

$$\Gamma = -\boxed{\frac{1}{2} \frac{\langle L\rangle^2}{\tau}} \nabla n = -D \nabla n$$

$$\Gamma_n = -D_n \nabla n \qquad J_n = -q\Gamma_n = qD_n \nabla n$$

$$\Gamma_p = -D_p \nabla p \qquad J_p = +q\Gamma_p = -qD_p\nabla p$$

$$\begin{cases} J_{diffusion} = J_{n\,diff} + J_{p\,diff} \\ J_{n\,diff} = qD_n\nabla n \qquad J_{p\,diff} = -qD_p\nabla p \end{cases}$$

$$J_{drift} = J_{n\,drift} + J_{p\,drift}$$

$$J_{diff} = J_{n\,diff} + J_{p\,diff}$$

$$\boxed{J = J_{drift} + J_{diff}}$$

رابطه اینشتین:

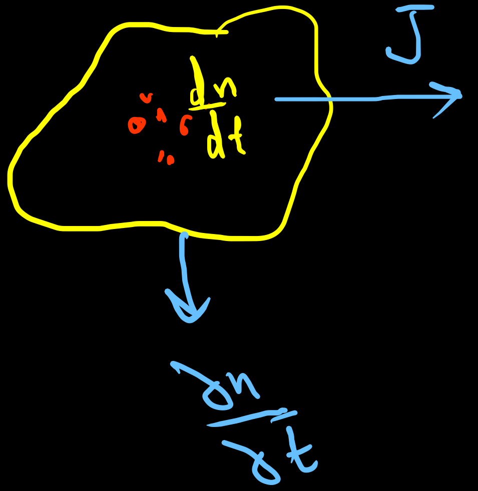
$$J_p = 0 \qquad J_n = 0$$

$$J_n = J_{n\,drift} + J_{n\,diff} = nq\mu_n\mathcal{E} + qD_n\nabla n = 0$$

$$\rightarrow \mathcal{E} = \frac{-D_n\nabla n}{n\mu_n} \qquad \mathcal{E} = \frac{D_p\nabla p}{p\mu_p}$$

$$\nabla n = \nabla\left(n_i e^{\frac{E_f - E_i}{k_B T}}\right) = \frac{n_i}{k_B T}\nabla(E_f - E_i)\, e^{\frac{E_f-E_i}{k_BT}} = \frac{n}{k_BT}\overbrace{\nabla(-E_i)}^{\mathcal{E}q} = \frac{-n}{k_BT}\mathcal{E}q$$

$$\begin{cases} \mathcal{E} = \frac{-D_n\nabla n}{n\mu_n} \\ \nabla n = \frac{-n}{k_BT}\mathcal{E}q \end{cases} \longrightarrow \boxed{\frac{D_n}{\mu_n} = \frac{k_BT}{q}} \qquad \boxed{\frac{D_p}{\mu_p} = \frac{k_BT}{q}}$$



$$\frac{dn}{dt} = \frac{\partial n}{\partial t} + \frac{1}{q}\vec{\nabla}\cdot\vec{J}$$

$$\frac{dn}{dt} = \frac{\partial n}{\partial t} + \vec{\nabla}\cdot\overrightarrow{\nabla n}$$

روابط پیوستگی

$$\Gamma = \sum v_i = n\langle v\rangle$$

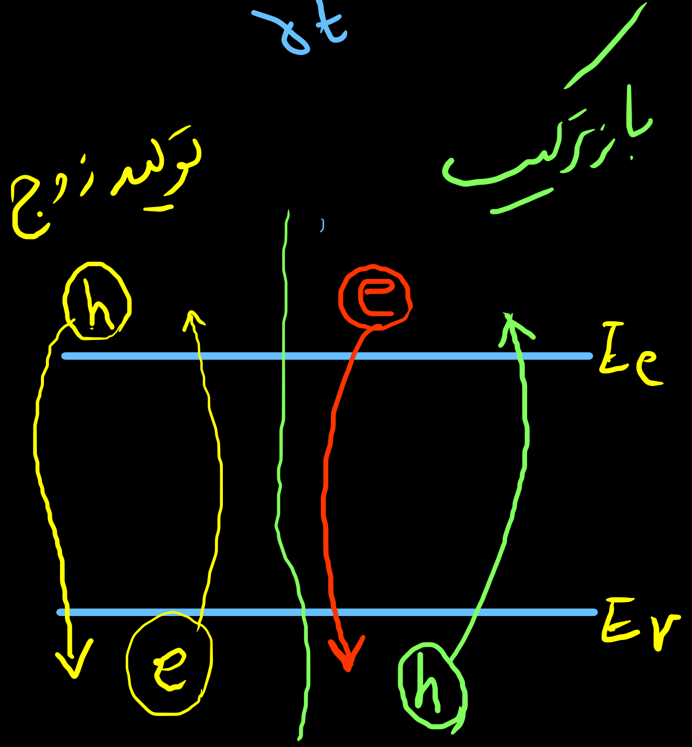
$$J = q\Gamma$$

$$J = nq\langle v\rangle$$

$$\frac{1}{q}\left(\nabla n q \vec{v}\right)$$

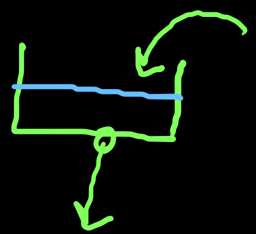
$$\frac{1}{q}\left(\nabla\cdot J\right)$$

$$\vec{\nabla} = \frac{\partial}{\partial x} i + \frac{\partial}{\partial y} j + \frac{\partial}{\partial z} k$$



$$\begin{cases} r = \alpha_r n_0 p_0 = \alpha_r n_i^2 \\ g_{thermal} = r = \alpha_r n_0 p_0 = \alpha_r n_i^2 \end{cases}$$

تولید و نابودی بارها



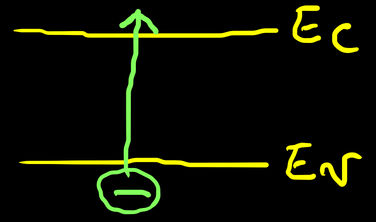
به نام خدا

$$\left\{\begin{aligned} \frac{dn}{dt} &= \frac{\partial n}{\partial t} - \frac{1}{q}\nabla\cdot J_n \\ \frac{dp}{dt} &= \frac{\partial p}{\partial t} + \frac{1}{q}\nabla\cdot J_p \end{aligned}\right.$$

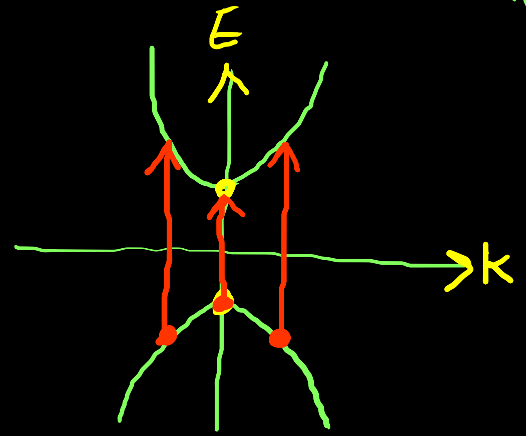
$$\frac{dn}{dt} = g_{thermal} = r = \alpha_r n_0 p_0 = \alpha_r n_i^2$$

$$\frac{dp}{dt} = g_{thermal} = r$$

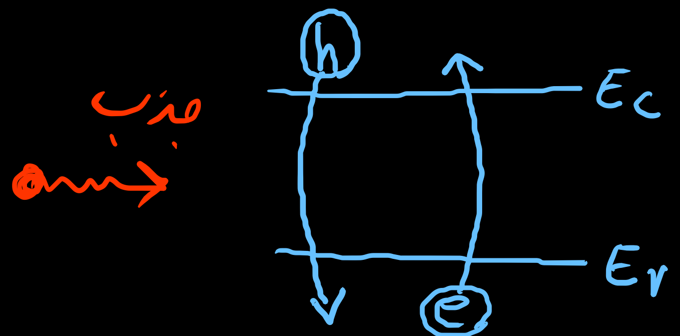
با ازدیاد n_i : $\uparrow T \rightarrow \uparrow n_i \rightarrow \uparrow r = \uparrow g$

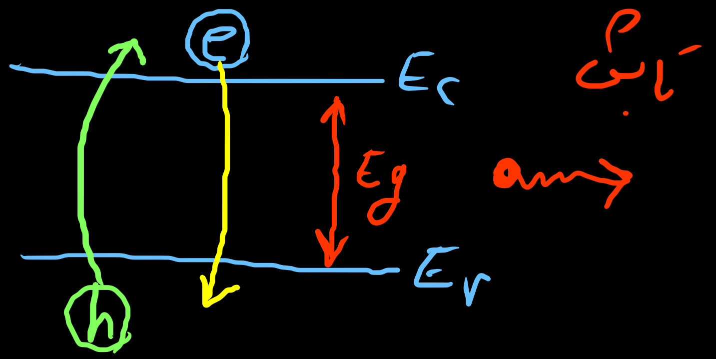


$$f(E) = \frac{1}{1+e^{\frac{E-E_f}{k_B T}}}$$

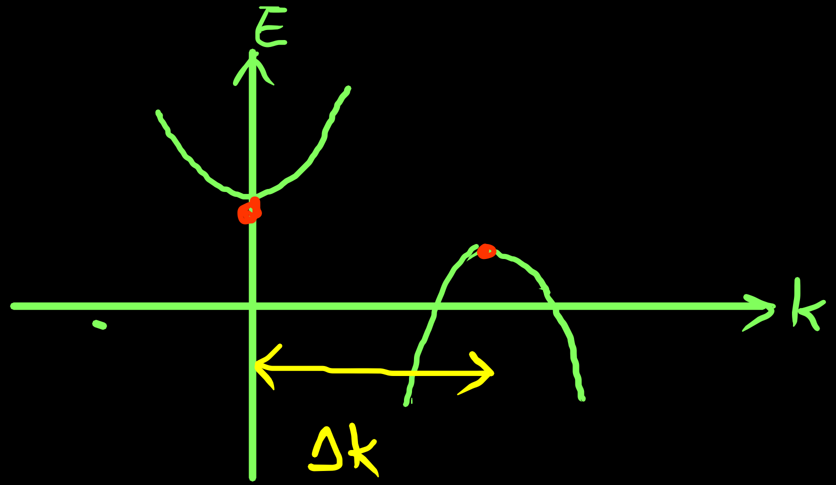


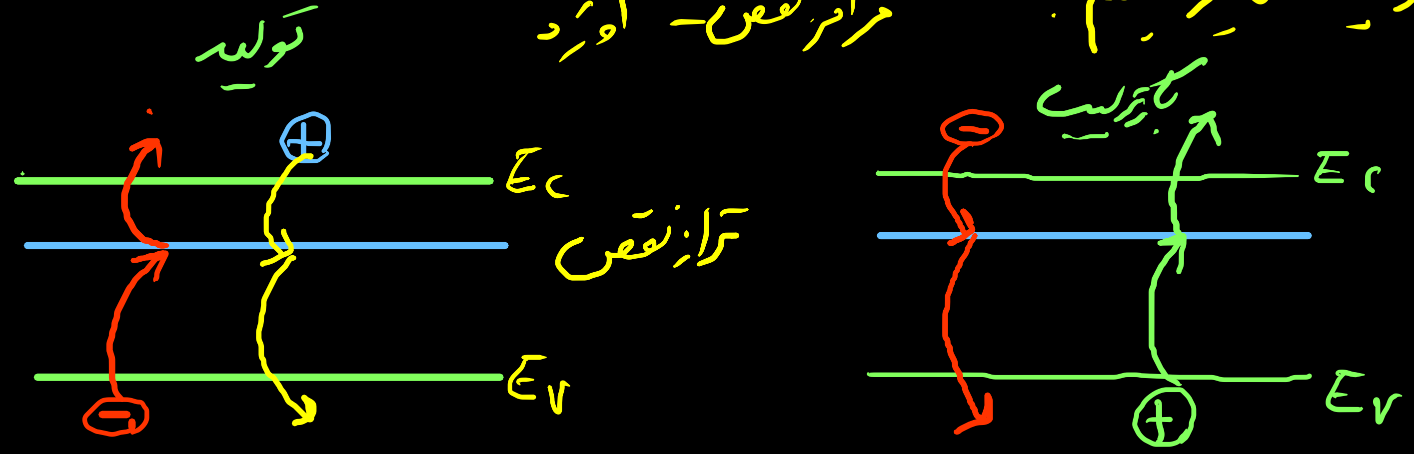
① فرایندهای مستقیم (باند به باند)

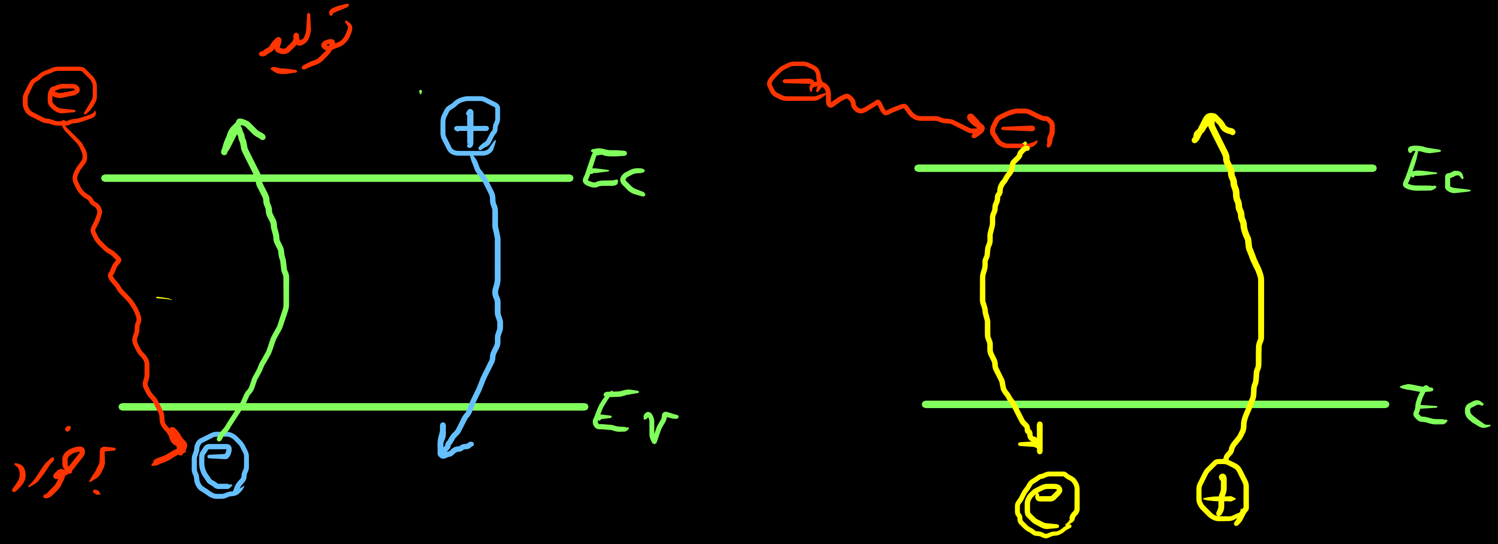




۲) فرآیندهای غیرمستقیم : مراکز نقص - اوژه



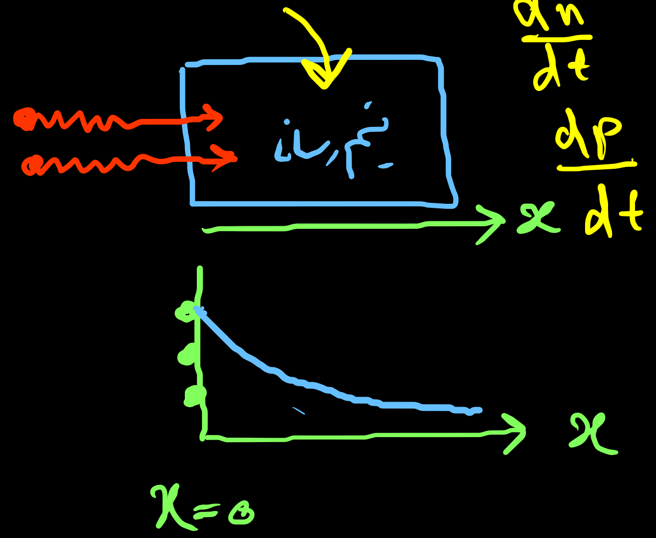




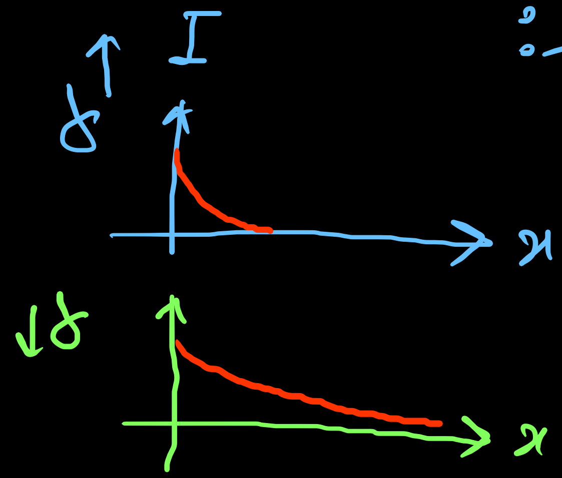
$$I = I_0 e^{-\gamma x}$$

شدت فوتون ها

شدت فوتون های اولیه



جذب نوری



$$\frac{dn}{dt} , \frac{dp}{dt} \qquad h^+ + e^- \longleftarrow \text{هر فوتون}$$

$$\frac{dn}{dt} = \frac{dp}{dt} = \text{نرخ تولید} - \text{نرخ بازترکیب} = g - r$$

$$g = g_{thermal} + g_{optical}$$

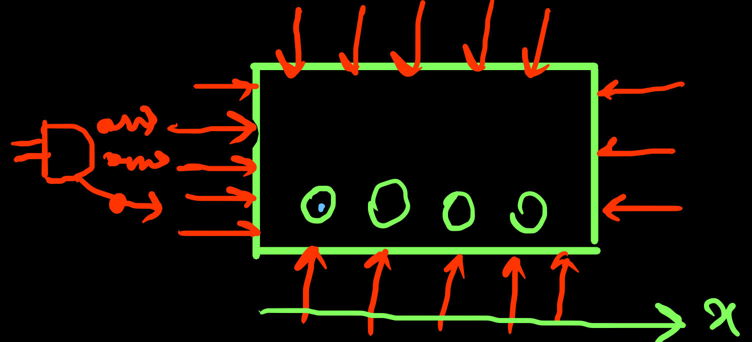
$$\begin{cases} g - r = \frac{dn}{dt} = \frac{\partial n}{\partial t} - \frac{1}{q} \nabla \cdot J_n \\ g - r = \frac{dp}{dt} = \frac{\partial p}{\partial t} + \frac{1}{q} \nabla \cdot J_p \end{cases}$$

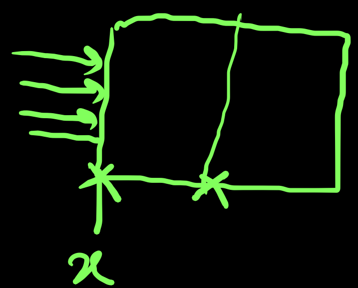
$$\begin{cases} J_n = J_{n,\,diff} + J_{n,\,drift} \\ J_p = J_{p,\,diff} + J_{p,\,drift} \end{cases}$$

① حالت

$n(x,y,z,t) \longrightarrow n(x,t)$

$p(x,y,z,t) \longrightarrow p(x,t)$





$$\frac{dn}{dt} = \frac{dp}{dt} = \frac{\partial n}{\partial t} - \frac{1}{q}\cancel{\nabla \cdot J}$$

$\overbrace{\quad}^{\text{inj}}$

$$\rightarrow \begin{cases} n(t) = n_0 + \delta n(t) \\ p(t) = p_0 + \delta p(t) \end{cases}$$

$$\delta n(t) = \delta p(t)$$

$$\frac{dn}{dt} = \frac{d}{dt}\left(n_0 + \delta n(t)\right) = \frac{\partial n}{\partial t} = g - r$$

$g_{thermal} + \cancel{g_{opt}}$

$$\frac{d}{dt}\delta n(t) = \alpha_r n_i^2 - \alpha_r n p$$

$$\frac{d}{dt}\delta n(t) = \alpha_r n_i^2 - \alpha_r \left(n_0 + \delta n(t)\right)\left(p_0 + \delta p(t)\right)$$

$$= \cancel{\alpha_r n_i^2} - \cancel{\alpha_r n_0 p_0} - \alpha_r n_0 \delta p(t) - \alpha_r p_0 \delta n(t) - \alpha_r \delta n(t)\delta p(t)$$

$$= -\alpha_r n_0 \delta n(t) - \alpha_r p_0 \delta n(t) - \alpha_r \delta n^2(t)$$

$$\frac{d}{dt}\delta n(t) = -\alpha_r\left((n_0 + p_0)\delta n(t) + \cancel{\delta n^2(t)}\right)$$

$\underline{(n_0 + p_0)}\,\delta n \qquad \delta n \cdot \delta n$

low-level inj. فرض تزریق کم

$\rightarrow \delta n, \delta p \ll n_0 + p_0$

$\delta n^2, \delta p^2 \ll \delta n (n_0 + p_0)$

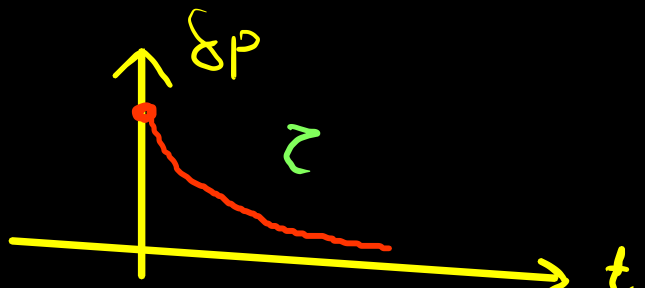
$$\begin{cases} \dfrac{d\,\delta n(t)}{dt} = -\alpha_r(n_0+p_0)\,\delta n(t) \\[2ex] \dfrac{d\,\delta p(t)}{dt} = -\alpha_r(n_0+p_0)\,\delta p(t) \end{cases} \longrightarrow \quad \begin{aligned} \delta n(t) &= \delta n(t=0)\, e^{-\frac{t}{\tau}} \\ \delta p(t) &= \delta p(t=0)\, e^{-\frac{t}{\tau}} \end{aligned} \qquad \tau = \frac{1}{\alpha_r(n_0+p_0)}$$

$$n(t) = n_0 + \cancel{\delta n(t)}^{\,0} \simeq n_0$$

$$p(t) = \cancel{p_0} + \delta p(t) \simeq \delta p(t)$$

$$\leftarrow \quad \tau_p = \frac{1}{\alpha_r n_0} \quad \leftarrow \quad n_0 \gg p_0 \quad : \text{نوع } n$$

$$\delta p(t) = \delta p(t=0)\, e^{-\frac{t}{\tau_p}}$$

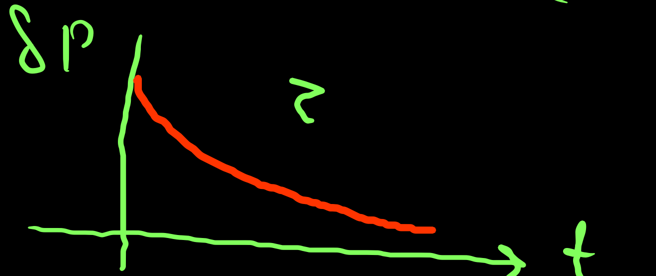


$$n(t) = n_0 + \delta n(t) \simeq \delta n(t)$$

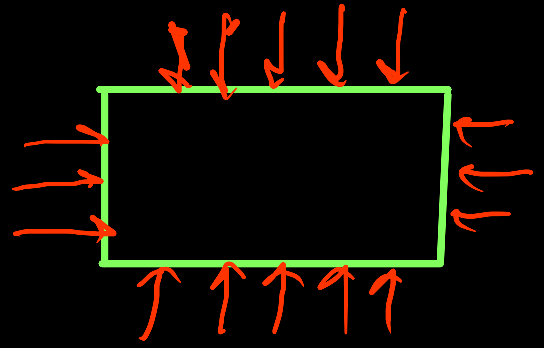
$$p(t) = p_0 + \delta p(t) \simeq p_0$$

$$\tau_n = \frac{1}{\alpha_r p_0}$$

$$p_0 \gg n_0 \quad : \text{نوع } p$$



$$4\tau \longrightarrow \begin{aligned} \delta n(t) &= 0 \\ \delta p(t) &= 0 \end{aligned}$$



شکل ۲ حالت پایا (Steady state)

$\frac{dn}{dt}=0 \qquad \frac{dp}{dt}=0$ پا

$$\frac{dn}{dt} = g - r = g_{opt} + g_{th} - r$$

$$0 = g_{opt} + \alpha_r n_i^2 - \alpha_r n(t)p(t)$$

$$0 = g_{opt} + \alpha_r n_i^2 - \alpha_r (n_0 + \delta n(t))(P_0 + \delta p(t))$$

$$0 = g_{opt} - \alpha_r \left[(n_0 + p_0)\delta n(t) + \cancel{\delta^2 n(t)} \right]$$

low inj

$$0 = g_{opt} - \alpha_r (n_0 + p_0)\delta n(t) \rightarrow \delta n(t) = \frac{g_{opt}}{\alpha_r (n_0 + p_0)} = g_{opt}\tau$$

$$\tau = \frac{1}{\alpha_r (n_0 + p_0)}$$

$$\boxed{\delta n(t) = \delta p(t) = g_{opt}\tau}$$

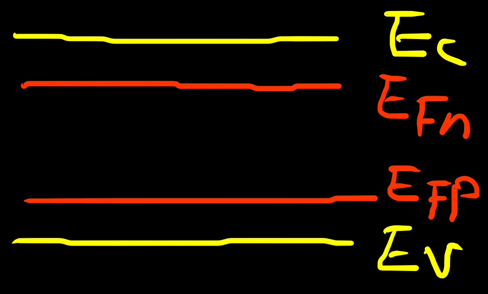
بنام خدا

Equilibrium → تعادل حرارتی : بدون نور بدون میدان بدون تغییر دما → اندیس ۰ n_0, p_0

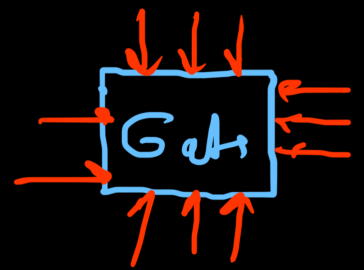
Steady State → نور یا میدان تعداد بارها ثابت

$$\longrightarrow \quad n = n_0 + \delta n, \qquad p = p_0 + \delta p$$

$$\begin{cases} n_0, p_0, E_f \\ p_0 = n_i e^{\frac{E_i - E_f}{k_B T}} \\ n_0 = n_i e^{\frac{E_f - E_i}{k_B T}} \end{cases} \longrightarrow \begin{aligned} p &= p_0 + \delta p = n_i e^{\frac{E_i - E_f}{k_B T}} + \delta p = n_i e^{\frac{E_i - E_{Fp}}{k_B T}} \\ n &= n_0 + \delta n = n_i e^{\frac{E_f - E_i}{k_B T}} + \delta n = n_i e^{\frac{E_{Fn} - E_i}{k_B T}} \end{aligned}$$



مثال: GaAs: $g_{opt} = 10^{20}$ EHP $cm^{-3} s^{-1}$ ، $n_i = 10^6 \, cm^{-3}$ ، $\tau_n \simeq 10^{-8}$ sec ، $N_a = 10^{14} \, cm^{-3}$ ، $E_g = 1.43$ eV



آ) p_0, n_0

ب) $\delta p, \delta n$

پ) F_p, F_n

ت) نور سوونیاز - چه اتفاقی 100 W

آ) p-type $\quad N_a = 10^{14} \gg 10^6 \longrightarrow p_0 = N_a = 10^{14} \, cm^{-3}$

$$n_0 = \frac{n_i^2}{p_0} = \frac{(10^6)^2}{10^{14}} = 10^{-2} \, cm^{-3}$$

ب) $\tau = \dfrac{1}{\alpha_r (n_0 + p_0)} \longrightarrow \alpha_r = \dfrac{1}{\tau (n_0 + p_0)} = \dfrac{1}{10^{-8} (10^{14} + 10^{-2})} \simeq 10^{-6} \, cm^{3} s^{-1}$

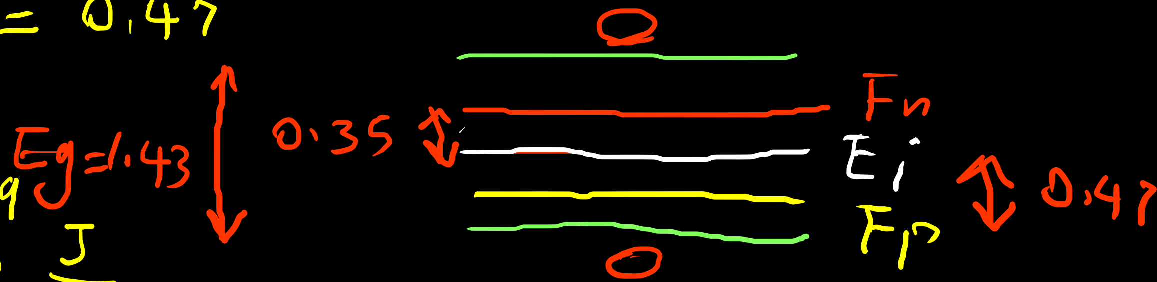
$$g_{opt} = \alpha_r (\delta n (n_0 + p_0) + \delta n^2) \longrightarrow \alpha_r \delta n^2 + \alpha_r (n_0 + p_0) - g_{opt} = 0$$

$$\longrightarrow \alpha_r \delta n^2 + \frac{1}{\tau} \delta n - g_{opt} = 0 \qquad 10^{-6} \delta n^2 + 10^{8} \delta n - 10^{20} = 0 \qquad \delta n = \delta p = 10^{12} \, cm^{-3}$$

$\delta n = 10^{12}\ cm^{-3} << n_0 + p_0 = 10^{14} \longrightarrow$ فرض تزریق کم برقرار $\qquad \delta n = g_{opt}\,\tau = 10^{20} \times 10^{-8} = 10^{12}$

پ) $n = n_i\, e^{\frac{F_n - E_i}{k_B T}} \longrightarrow F_n - E_i = -k_B T \ln\left(\frac{n_i}{n}\right) = -k_B T \ln\left(\frac{10^6}{10^{-2} + 10^{12}}\right) = 0.35\ eV$

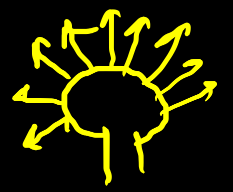
$p = n_i\, e^{\frac{E_i - F_p}{k_B T}} \longrightarrow E_i - F_p = k_B T \ln\left(\frac{10^{14} + 10^{12}}{10^6}\right) = 0.47\ eV$



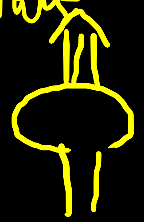
ت) $g_{opt} = 10^{20}\ cm^{-3} s^{-1} \Rightarrow 10^{20}\ \frac{EHP}{cm^3 \cdot s} \times \frac{1.43\ eV}{EHP} \times 1.6 \times 10^{-19}\ \frac{J}{eV}$

$power = 23\ \frac{Watt}{cm^{-3}}$

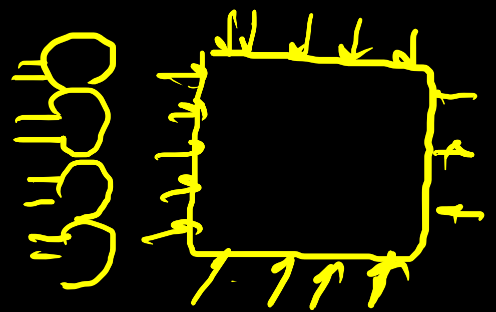
100W لامپ



5watt



$\frac{23}{5} \simeq 5$ لامپ



معادلات پیوستگی

$$g-r=\frac{dn}{dt}=\frac{\partial n}{\partial t}-\frac{1}{q}\nabla\cdot\vec{J}_n$$

$$g-r=\frac{dp}{dt}=\frac{\partial p}{\partial t}+\frac{1}{q}\nabla\cdot J_p$$

$\frac{dn}{dt}$ $\vec{J}$

$\frac{\partial n}{\partial t}$

$\frac{dn}{dt}=g-r$

$$\begin{cases}\frac{\partial n}{\partial t}=\frac{dn}{dt}+\frac{1}{q}\nabla\cdot J_N=\underbrace{\alpha_r n_i^2+g_{opt}}_{g}-\underbrace{\alpha_r n(x,t)p(x,t)}_{r}+\frac{1}{q}\nabla\cdot J_n\\ \frac{\partial p}{\partial t}=\frac{dp}{dt}-\frac{1}{q}\nabla\cdot J_p=\underbrace{\alpha_r n_i^2+g_{opt}-\alpha_r n(x,t)p(x,t)}_{\frac{dp}{dt}}-\frac{1}{q}\nabla\cdot J_p\end{cases}$$

(فرض تزریق) $\rightarrow$

$$g-r=\alpha_r n_i^2+g_{opt}-\alpha_r(n_0+\delta n)(p_0+\delta p)$$

$$g-r=g_{opt}-\alpha_r(n_0+p_0)\delta n=g_{opt}-\frac{\delta n}{\tau}$$

$$\boxed{\begin{aligned}\frac{dn}{dt}&=g-r=g_{opt}-\frac{\delta n}{\tau}\\ \frac{dp}{dt}&=g-r=g_{op}-\frac{\delta p}{\tau}\end{aligned}}$$

$$\begin{cases} \dfrac{\partial n}{\partial t} = g_{opt} - \dfrac{\delta n}{\tau} + \dfrac{1}{q} \nabla \cdot J_n \\ \dfrac{\partial p}{\partial t} = g_{opt} - \dfrac{\delta p}{\tau} - \dfrac{1}{q} \nabla \cdot J_p \end{cases}$$

$$\begin{cases} J_n = n q \mu_n \mathcal{E} + q D_n \nabla n \\ J_p = p q \mu_p \mathcal{E} - q D_p \nabla p \end{cases}$$

با فرض تزریق کم :

$$\frac{\partial n}{\partial t} = g_{opt} - \frac{\delta n}{\tau} + \frac{1}{q} \nabla \cdot \left(n q \mu_n \mathcal{E} + q D_n \nabla n \right)$$

$$\begin{cases} \nabla = \dfrac{\partial}{\partial x} \hat{i} + \dfrac{\partial}{\partial y} \hat{j} + \dfrac{\partial}{\partial z} \hat{k} \\ \nabla^2 = \dfrac{\partial^2}{\partial x^2} + \dfrac{\partial^2}{\partial y^2} + \dfrac{\partial^2}{\partial z^2} \end{cases}$$

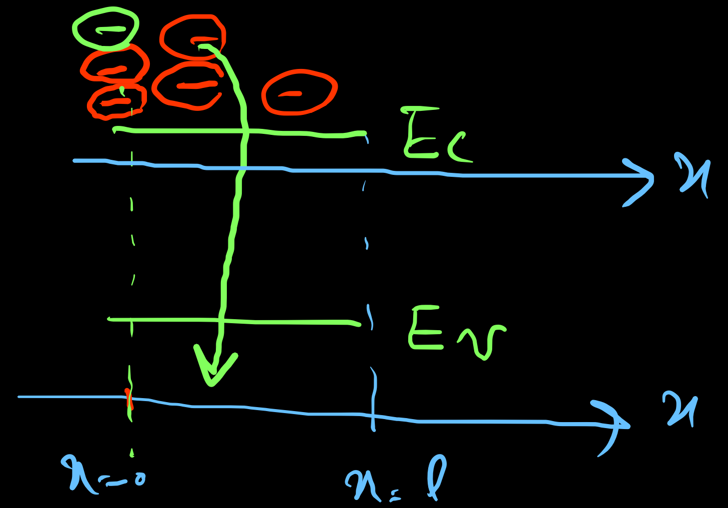
$$\begin{cases} \dfrac{\partial n}{\partial t} = g_{opt} - \dfrac{\delta n}{\tau} + n \mu_n \nabla \cdot \mathcal{E} + D_n \nabla^2 n \\ \dfrac{\partial p}{\partial t} = g_{opt} - \dfrac{\delta p}{\tau} - p \mu_p \nabla \cdot \mathcal{E} + D_p \nabla^2 p \end{cases}$$

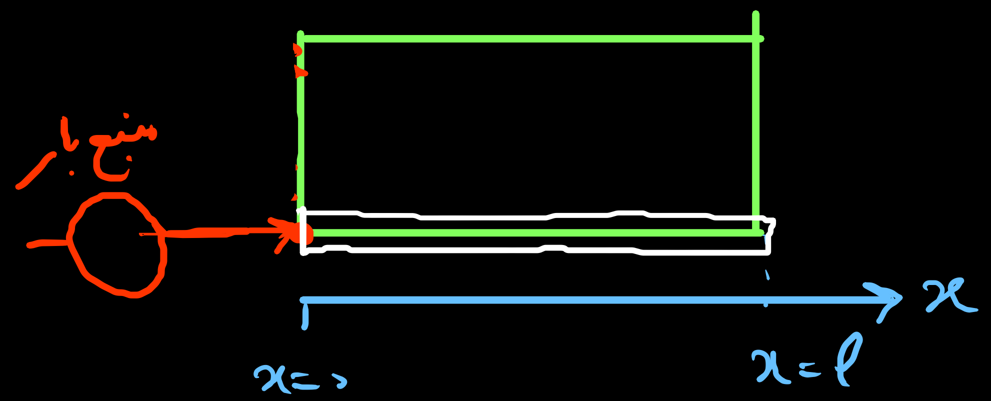
$$\rightarrow \begin{aligned} n &= n_0 + \delta n(x,t) \\ p &= p_0 + \delta p(x,t) \end{aligned}$$

$$\begin{cases} \dfrac{\partial \, \delta n}{\partial t} = g_{opt} - \dfrac{\delta n}{\tau} + n \mu_n \nabla \mathcal{E} + D_n \nabla^2 \delta n \\ \dfrac{\partial \, \delta p}{\partial t} = g_{opt} - \dfrac{\delta p}{\tau} - p \mu_p \nabla \cdot \mathcal{E} + D_p \nabla^2 \delta p \end{cases}$$

$$\rightarrow \begin{matrix} \delta n(x,t) \\ \delta p(x,t) \end{matrix} \rightarrow n, p \rightarrow \begin{matrix} J_n \\ J_p \end{matrix}$$

مثال : تزریق بار در حالت مانا





ثابت

$$n = n_0 + \delta n(x, \cancel{t}) \qquad \frac{\partial n}{\partial t} = 0$$

$$\begin{cases} \dfrac{\partial\, \delta n}{\partial t} = 0 - \dfrac{\delta n}{\tau} + D_n \nabla^2 \delta n \\[2ex] \dfrac{\partial\, \delta p}{\partial t} = 0 - \dfrac{\delta p}{\tau} + D_p \nabla^2 \delta p \end{cases}$$

$$0 = D_n \frac{\partial^2}{\partial x^2} \delta n(x) - \frac{1}{\tau} \delta n(x)$$

$$0 = D_p \frac{\partial^2}{\partial x^2} \delta p(x) - \frac{1}{\tau} \delta p(x)$$

$$D_n s^2 - \frac{1}{\tau} = 0 \rightarrow s^2 = \pm \frac{1}{D_n \tau}$$

$$s_{1,2} = \pm \frac{1}{\sqrt{D_n \tau}}$$

$$\delta n(x) = C_1 e^{\frac{1}{\sqrt{D_n \tau}} x} + C_2 e^{-\frac{1}{\sqrt{D_n \tau}} x}$$

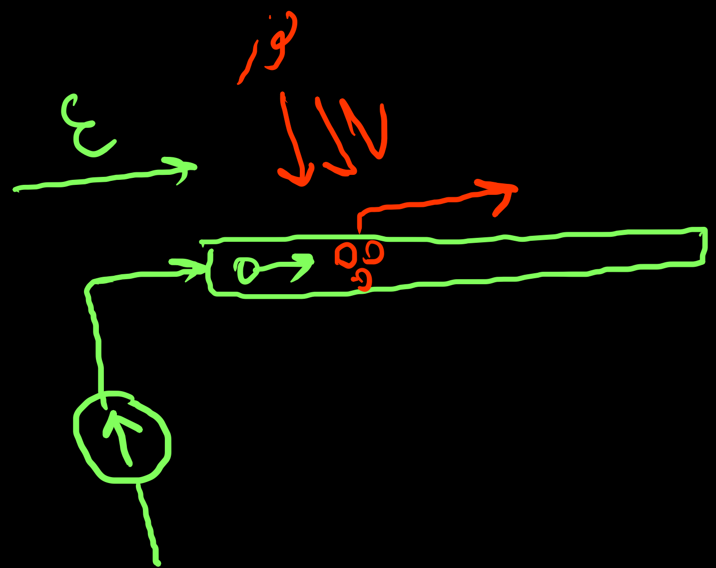
$$\delta p(x) = C_3 e^{\frac{1}{\sqrt{D_p \tau}} x} + C_4 e^{-\frac{1}{\sqrt{D_p \tau}} x}$$

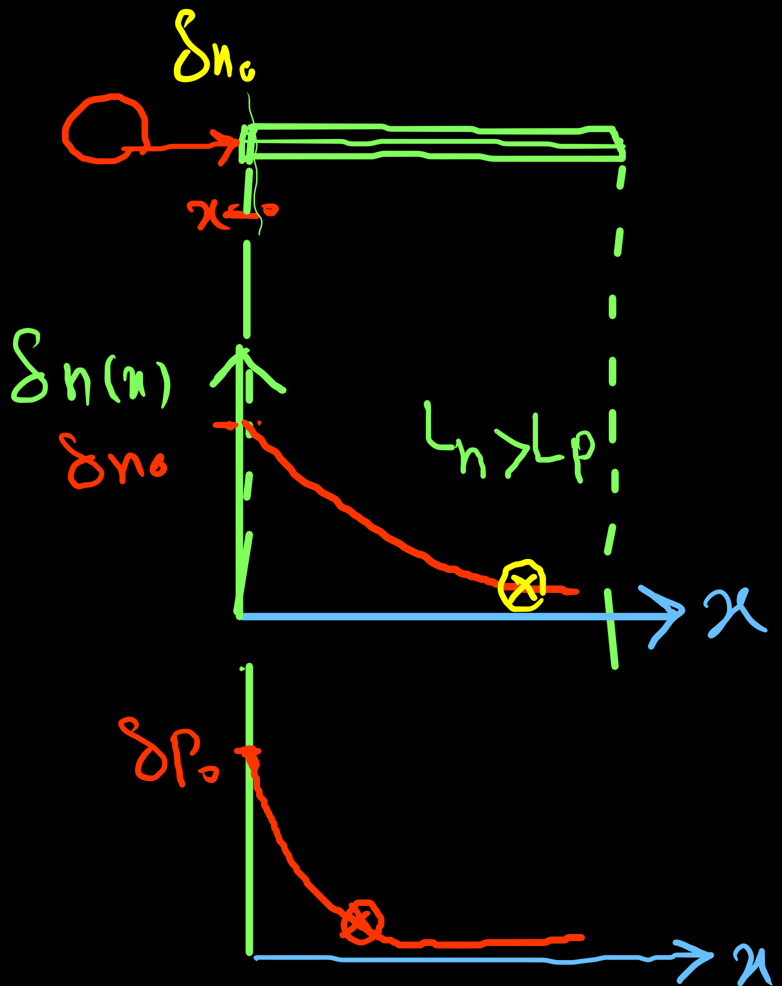
$$\sqrt{D_n \tau} = L_n \qquad \sqrt{D_p \tau} = L_p$$

$$\delta n(x) = c_1 e^{\frac{x}{L_n}} + c_2 e^{\frac{-x}{L_n}}$$

$$\delta p(x) = c_3 e^{\frac{x}{L_p}} + c_4 e^{\frac{-x}{L_p}}$$

$\tau \rightarrow$ طول عمر بار





$$\delta n(x=0) = \cancel{c_1}^{\,0} + c_2 = \delta n_0$$

$$\delta n(x \to \infty) = 0 \rightarrow c_1 = 0$$

$$\delta n(x) = \delta n_0 \, e^{\frac{-x}{L_n}}$$

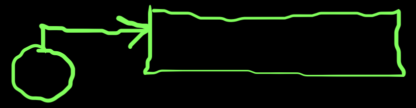
$$\delta p(x) = \delta p_0 \, e^{\frac{-x}{L_p}}$$

$$L_n = \sqrt{D_n \tau}$$

$$L_p = \sqrt{D_p \tau}$$

$L_p \uparrow \longrightarrow$

بنام خدا



محاسبه جریان برای شکل مقابل

$$J_n = qD_n \nabla n = qD_n \nabla\left(n_0 + \delta n_0 e^{-\frac{x}{L_n}}\right)$$

$$= \frac{-q}{L_n} D_n \delta n_0 e^{-\frac{x}{L_n}}$$

$$J_n = \frac{-q}{L_n} D_n \delta n(x)$$

$$J_p = -qD_p \nabla p = -qD_p \nabla\left(P_0 + \delta P_0 e^{-\frac{x}{L_p}}\right) = \frac{-q}{-L_p} D_p \delta p_0 e^{-\frac{x}{L_p}}$$

$$J_p = \frac{q}{L_p} D_p \delta p(x)$$

رابطه جریان با سطوح شبه فرمی

$$p = n_i e^{\frac{E_i - F_p}{k_B T}} \qquad n = n_i e^{\frac{F_n - E_i}{k_B T}}$$

$$\frac{D_n}{\mu_n} = \frac{k_B T}{q}$$

$$J_n = nq\mu_n \mathcal{E} + qD_n \nabla n$$

$$nq\mu_n \mathcal{E} + qD_n \nabla\left(n_i e^{\frac{F_n - E_i}{k_B T}}\right) = nq\mu_n \mathcal{E} + \frac{q D_n}{k_B T} \nabla(F_n - E_i) \cdot n$$

$$\frac{D_n}{k_B T} \to \frac{\mu_n}{q}$$

$$= nq\mu_n \mathcal{E} + n\mu_n \nabla F_n - n\mu_n \nabla E_i$$

$$\nabla E_i \to \mathcal{E} q$$

$$\boxed{\begin{aligned} J_n &= n\mu_n \nabla F_n \\ J_p &= p\mu_p \nabla F_p \end{aligned}}$$