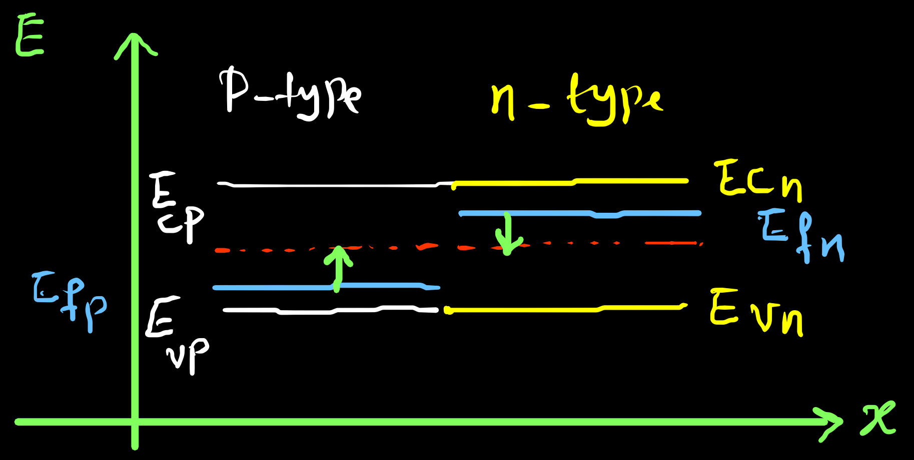
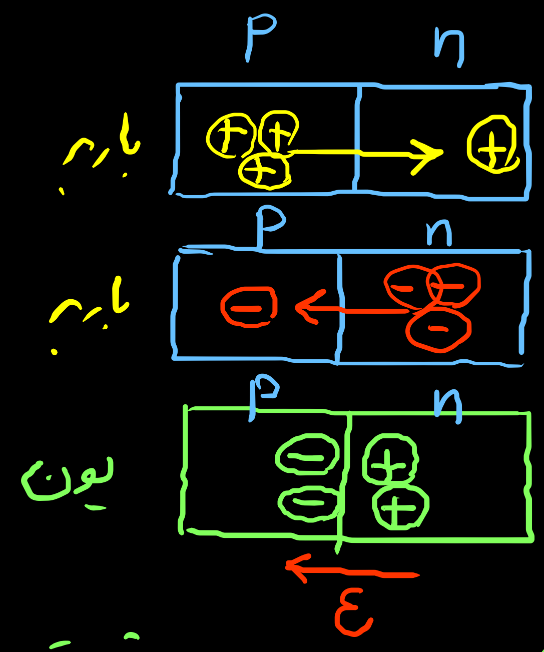
پیوند P-n



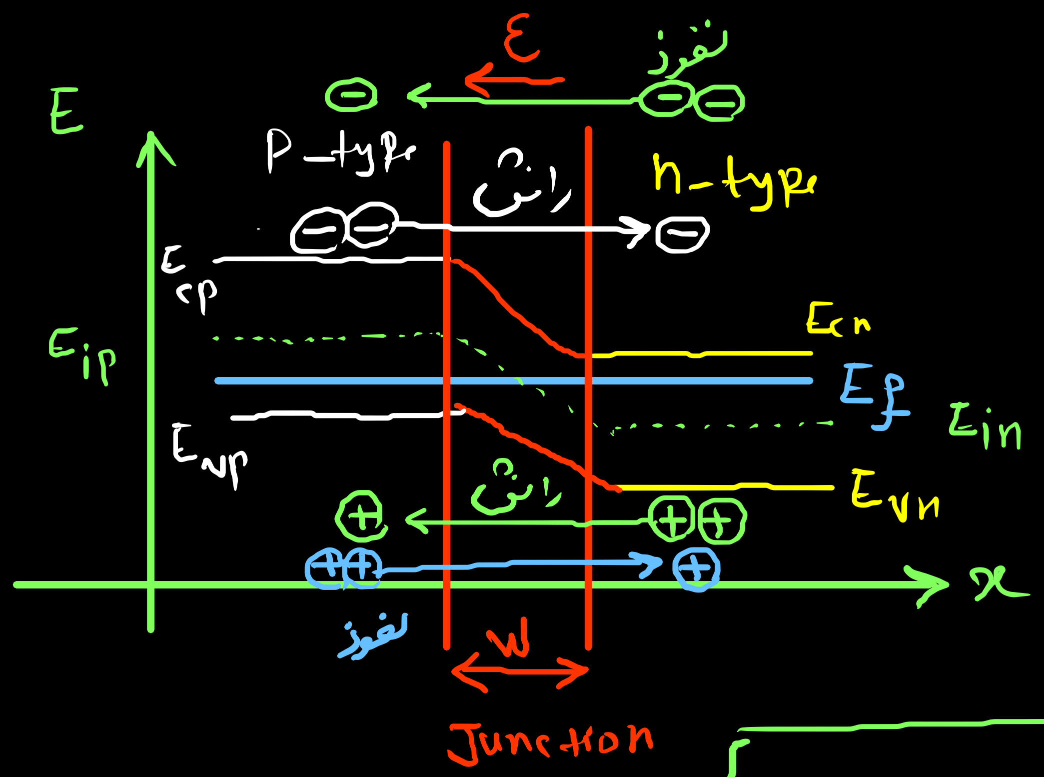
$J = q.\mu$

آنچه رخ می‌دهد:



① ② ③

④ خم شدن ترازهای E_c, E_v, E_i , ثابت بودن E_f

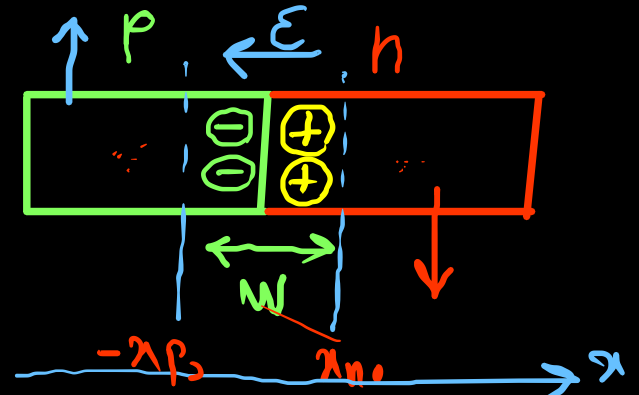


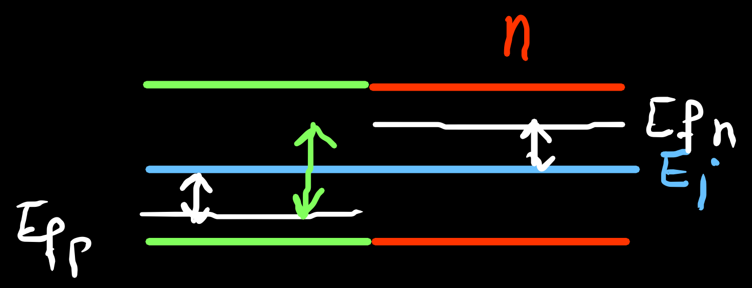
مکانیسم	حامل	J
رانش p	$p \leftarrow n$	$p \leftarrow n$
نفوذ p	$p \rightarrow n$	$p \rightarrow n$
رانش n	$p \rightarrow n$	$p \leftarrow n$
نفوذ n	$p \leftarrow n$	$p \rightarrow n$

رانش p, n	$p \leftarrow n$
نفوذ p, n	$p \rightarrow n$

تابع: V_{bi} ، میدان الکتریکی داخلی پیوند $\mathcal{E}$ ، عرض پیوند W

① تابع V_{bi}:





انرژی

$$\Delta = E_{fn} - E_{fp}$$

$$= \underbrace{E_{fn} - E_i} + \underbrace{E_i - E_{fp}}$$

$$= k_BT \ln \frac{n_0}{n_i} + k_BT \ln \frac{p_0}{n_i}$$

$$= k_BT \ln \frac{n_0(x \geq x_{n_0}) \times p_0(x \leq -x_{p_0})}{n_i^2} = k_BT \ln \frac{N_D \times N_A}{n_i^2}$$

$$n_0 = n_i e^{\frac{E_{fn} - E_i}{k_BT}} \rightarrow E_{fn} - E_i = k_BT \ln \frac{n_0}{n_i}$$

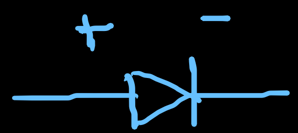
$x \geq x_{n_0}$

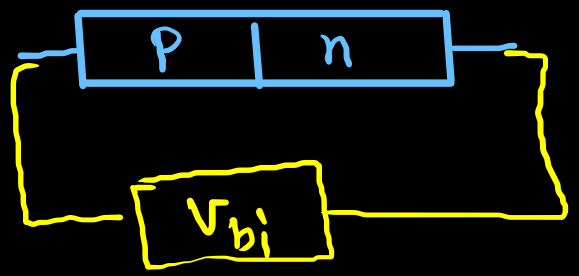
$$p_0 = n_i e^{\frac{E_i - E_{fp}}{k_BT}} \rightarrow E_i - E_{fp} = k_BT \ln \frac{p_0}{n_i}$$

$$\boxed{V_{bi} = \frac{k_BT}{q} \ln \frac{N_A N_D}{n_i^2}}$$

انرژی ولتاژ

$$W = Vq$$





$$\frac{p(x_{n0})}{1} = \frac{n_i^2}{n(x_{n0})} \qquad \frac{n(-x_{p0})}{1} = \frac{n_i^2}{p(-x_0)}$$

بار اقلیت — بار اکثریت

$$qV_{bi} = k_BT \ln \frac{n(x_{n0})\,p(-x_{p0})}{n_i^2} = k_BT \ln \frac{\frac{\cancel{n_i^2}}{p(x_{n0})} \times \frac{n_i^2}{n(-x_{p0})}}{\cancel{n_i^2}} = k_BT \ln \frac{1}{p(x_{n0})\,n(-x_{p0})}$$

$$qV_{bi} = k_BT \ln \frac{n(x_{n0}) \times \frac{\cancel{n_i^2}}{n(-x_{p0})}}{\cancel{n_i^2}} = k_BT \ln \frac{n(x_{n0})}{n(-x_{p0})}$$

اکثریت / اقلیت

$$qV_{bi} = k_BT \ln \frac{\frac{\cancel{n_i^2}}{p(x_{n0})} \times p(-x_{p0})}{\cancel{n_i^2}} = k_BT \ln \frac{p(-x_{p0})}{p(x_{n0})}$$

اکثریت / اقلیت

$$\boxed{\frac{p(-x_{p0})}{p(x_{n0})} = \frac{n(x_{n0})}{n(-x_{p0})} = e^{\frac{qV_{bi}}{k_BT}}}$$

اکثریت / اقلیت — اکثریت / اقلیت

$$\boxed{\frac{\text{اکثریت}}{\text{اقلیت}} = e^{\frac{qV_{bi}}{k_BT}}}$$

برای دو طرف پیوند

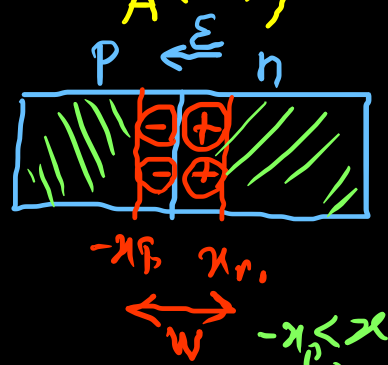
بنام خدا

محاسبه میدان الکتریکی

$$\nabla \cdot \mathcal{E} = \frac{\rho}{\varepsilon}$$

$$\rho(x, \mathcal{E})$$

$$\frac{\partial \mathcal{E}_x}{\partial x} = \frac{\rho}{\varepsilon} = \frac{1}{\varepsilon}\left(p(x) - n(x) + N_D^{+}(x) + N_A^{-}(x)\right)$$

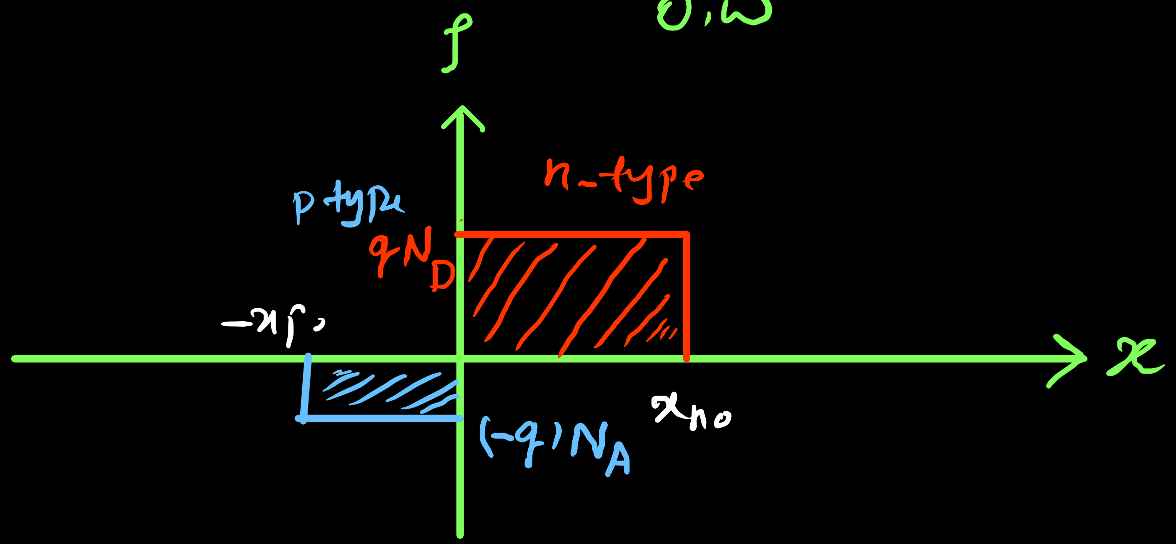


فرض اول: خارج از ناحیه پیوند چگالی بار صفر است.

فرض دوم: در ناحیه پیوند باربر نداریم.

فرض سوم: در ناحیه پیوند N_D, N_A ثابت هستند

$$\frac{d\mathcal{E}_x}{dx} = \frac{\rho}{\varepsilon} = \begin{cases} \frac{1}{\varepsilon}\left(N_D(x) - N_A(x)\right) & -x_{p0} < x < x_{n0} \\ 0 & \text{O.W} \end{cases}$$



میدان الکتریکی

$$\mathcal{E} = \int \frac{\rho(x)}{\varepsilon}\, dx$$

p-type

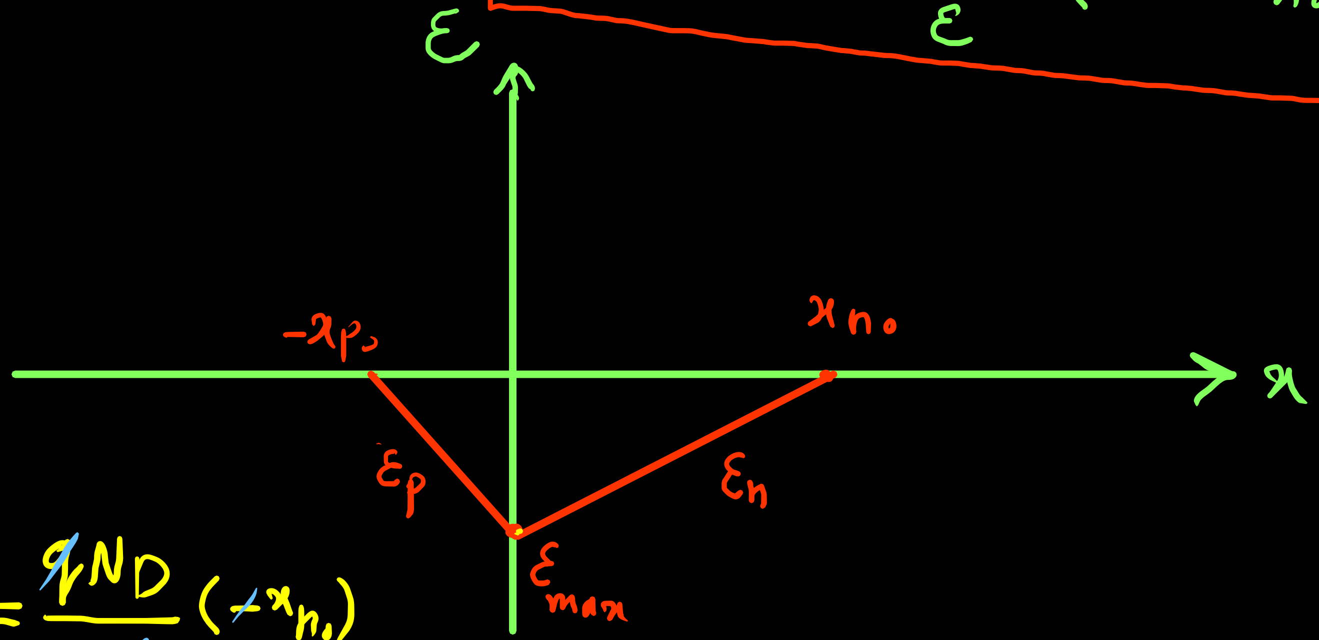
$-x_{p_0} \leq x \leq 0$ $\quad \mathcal{E}_p(x) = \int -\frac{qN_A}{\varepsilon}\, dx = \frac{-qN_A}{\varepsilon} x + c_1$

شرایط مرزی $\quad \mathcal{E}_p(-x_{p_0}) = 0 \rightarrow \boxed{\mathcal{E}_p(x) = \frac{-qN_A}{\varepsilon}(x + x_{p_0})}$

n-type

$0 \leq x \leq x_{n_0}$ $\quad \mathcal{E}_n(x) = \int \frac{qN_D}{\varepsilon}\, dx \rightarrow \mathcal{E}_n(x) = \frac{qN_D}{\varepsilon} x + c_2$

شرایط مرزی $\quad \mathcal{E}_n(x_{n_0}) = 0 \rightarrow \boxed{\mathcal{E}_n(x) = \frac{qN_D}{\varepsilon}(x - x_{n_0})}$

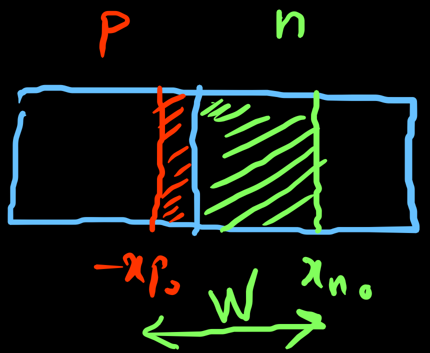


$\mathcal{E}$ ، V_{bi}

W , x_{p_0} , x_{n_0}

$\mathcal{E}_{max} = -\frac{\cancel{q}N_A}{\cancel{\varepsilon}} x_{p_0} = \frac{\cancel{q}N_D}{\cancel{\varepsilon}}(-x_{n_0})$

$N_A x_{p_0} = N_D x_{n_0}$ $\quad N_A > N_D$



میزان پیشرفتگی پیوند در ناحیه p , n

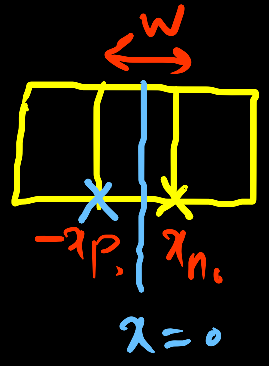
محاسبه پتانسیل

$$\varepsilon = -\nabla V$$

میدان الکتریکی ⟷ پتانسیل

ρ توزیع بار الکتریکی ⟷ میدان ε

قانون گوس $\quad \nabla \cdot \varepsilon = \dfrac{\rho}{\varepsilon}$



$$V(x) = -\int \varepsilon(x)\,dx$$

ناحیه p:

$-x_{p_0} < x < 0 \qquad V_p(x) = \int \dfrac{qN_A}{\varepsilon}(x + x_{p_0})\,dx = \dfrac{qN_A}{2\varepsilon}(x + x_{p_0})^2 + C_1$

شرط مرزی

$V_p(-x_{p_0}) = 0 \rightarrow C_1 = 0$

$$\boxed{V_p(x) = \frac{qN_A}{2\varepsilon}(x + x_{p_0})^2 \qquad -x_{p_0} \leq x \leq 0}$$

$0 \leq x \leq x_{n_0} \qquad V_n(x) = \int \dfrac{-qN_D}{\varepsilon}(x - x_{n_0})\,dx = \dfrac{-qN_D}{2\varepsilon}(x - x_{n_0})^2 + C_2$

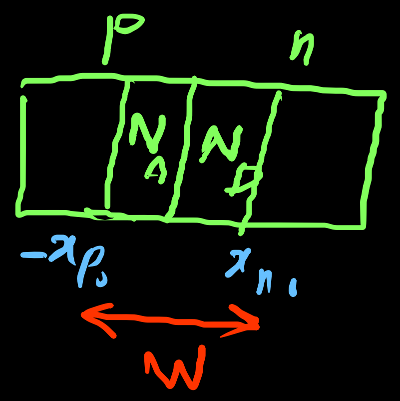
شرط مرزی

$V_n(x_{n_0}) = V_{bi} \rightarrow C_2 = V_{bi}$

ناحیه n:

$$\boxed{V_n(x) = \frac{-qN_D}{2\varepsilon}(x - x_{n_0})^2 + V_{bi}}$$

شرط پیوستگی پتانسیل $\quad x=0 \quad V_p(x=0) = V_n(x=0)$



$$\frac{qN_A}{2\varepsilon} x_{p_0}^2 = -\frac{qN_D}{2\varepsilon} x_{n_0}^2 + V_{bi}$$

1 $$V_{bi} = \frac{qN_A}{2\varepsilon} x_{p_0}^2 + \frac{qN_D}{2\varepsilon} x_{n_0}^2$$

2 $$N_A x_{p_0} = N_D x_{n_0} \rightarrow x_{p_0} = \frac{N_D}{N_A} x_{n_0}$$

$$V_{bi} = \frac{qN_A}{2\varepsilon}\left(\frac{N_D}{N_A}\right)^2 x_{n_0}^2 + \frac{qN_D}{2\varepsilon} x_{n_0}^2 = \left[\frac{qN_D^2}{2\varepsilon N_A} + \frac{qN_D}{2\varepsilon}\right] x_{n_0}^2 = \left[\frac{qN_D}{2\varepsilon}\left(1+\frac{N_D}{N_A}\right)\right] x_{n_0}^2$$

$$V_{bi} = \left[\frac{q\cancel{N_D}}{2\varepsilon} \times \frac{N_A+N_D}{N_A \cancel{N_D}}\right] x_{n_0}^2 \rightarrow x_{n_0} = \left[\frac{2\varepsilon V_{bi}}{qN_D\left(1+\frac{N_D}{N_A}\right)}\right]^{\frac{1}{2}} = \left[\frac{2\varepsilon V_{bi} \cdot N_A}{qN_D(N_A+N_D)}\right]^{\frac{1}{2}}$$

$$x_{n_0} = \left[\frac{2\varepsilon V_{bi} N_A}{qN_D(N_A+N_D)}\right]^{\frac{1}{2}}$$

$$x_{p_0} = \left[\frac{2\varepsilon V_{bi} N_D}{qN_A(N_A+N_D)}\right]^{\frac{1}{2}}$$

$$W = x_{n_0} + x_{p_0} = \left[\frac{2\varepsilon V_{bi}}{q}\left(\frac{1}{N_A}+\frac{1}{N_D}\right)\right]^{\frac{1}{2}}$$

1) $x_{n_0} + x_{p_0} = W$

2) $x_{n_0} = \frac{N_A}{N_D} x_{p_0}$, $x_{p_0} = \frac{N_D}{N_A} x_{n_0}$

3) $x_{n_0} = W \times \frac{N_A}{N_A + N_D}$

$x_{p_0} = W \times \frac{N_D}{N_A + N_D}$

4) $V_{bi} = \frac{q}{2\varepsilon} \frac{N_A N_D}{N_A + N_D} \times W^2$

5) $V_{bi} = \frac{k_B T}{q} \ln \frac{N_A N_D}{n_i^2}$

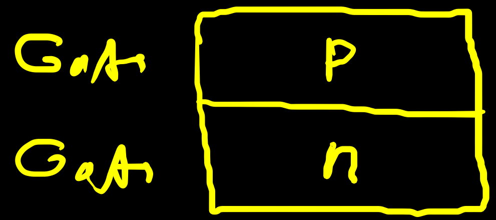
۱) V_{bi} :

۲) $\nabla \cdot \mathcal{E} = \frac{\rho}{\varepsilon}$ ← میدان الکتریکی

۳) $\mathcal{E} = -\nabla V$ ← پتانسیل

۴) W ← عرض پیوند

شکل:



$n_i = 2\times10^{6}\ cm^{-3}$ $\quad N_D = 10^{14}\ cm^{-3}$

$\varepsilon_r = 13.2$ $\quad N_A = 2\times10^{15}\ cm^{-3}$

$\varepsilon = \varepsilon_0 \varepsilon_r$

آ) ولتاژ داخلی پیوند

ب) عرض پیوند

پ) شدت بیشینه میدان

ت) x_{p_0}, x_{n_0}

ث) چگالی بار سطحی

آ) $$V_{bi} = \frac{kT}{q} \ln\left[\frac{N_A N_D}{n_i^2}\right] = 0.025 \ln\left[\frac{10^{14}\times 2\times10^{15}}{(2\times10^{6})^2}\right] = 0.996\ V$$

ب) $$W = \left[\frac{2\varepsilon V_{bi}(N_A+N_D)}{q N_A N_D}\right]^{\frac{1}{2}} = \left[\frac{2\times 8.85\times10^{-14}\times13.2\times0.996\times(10^{14}+2\times10^{15})}{1.6\times10^{-19}\times2\times10^{15}\times10^{14}}\right]^{1/2}$$

$$W = 3.9\ \mu m$$ تقریب!

ت) $$x_{n_0} = W\cdot\frac{N_A}{N_A+N_D} = 3.9^{\mu}\times\frac{2\times10^{15}}{2\times10^{15}+10^{14}} = 3.72\ \mu m$$

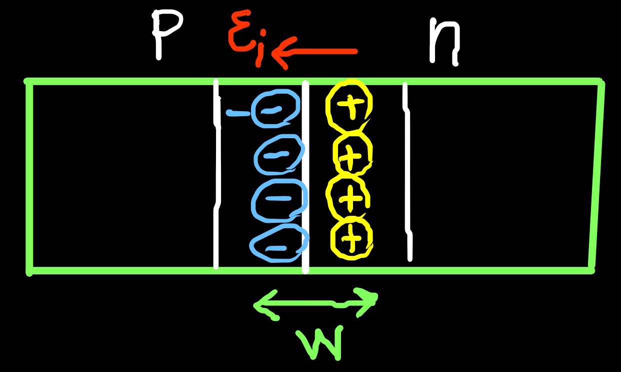
$$x_{p_0} = W\,\frac{N_D}{N_A+N_D} = 3.9\times\frac{10^{14}}{2\times10^{15}+10^{14}} = 0.19\ \mu m$$

پ) $$\mathcal{E}_{max} = \frac{qN_D}{\varepsilon}x_{n_0} = \frac{1.6\times10^{-19}\times10^{14}\times3.72\times10^{4}}{8.85\times10^{-14}\times13.2} \approx 8\ \frac{kN}{m}$$

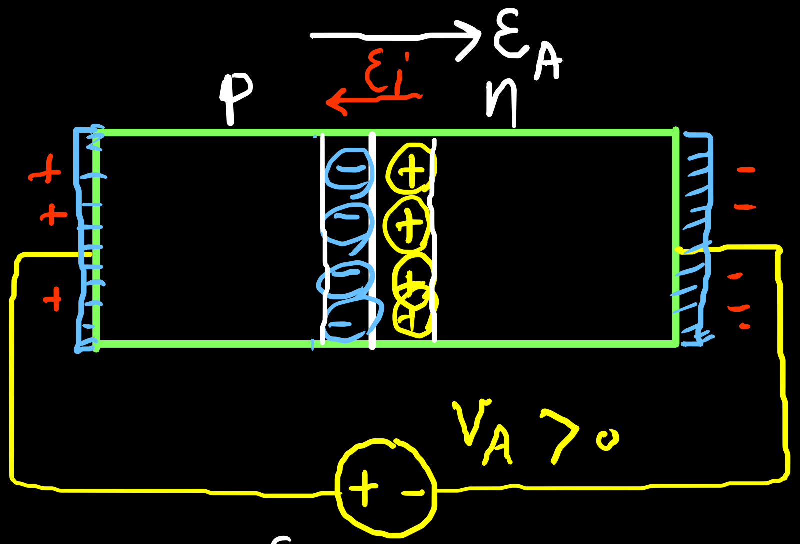
ث) $$\frac{Q}{A} = q x_{p_0} N_A = q x_{n_0} N_D = 2.098\times10^{-8}\ C.cm^{-2}$$

بنام خدا

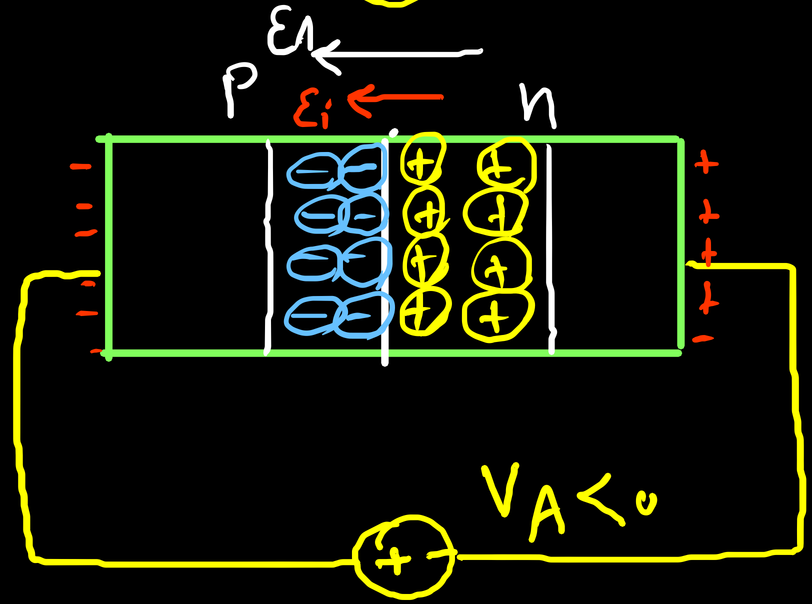
بایاس پیوند



بدون بایاس

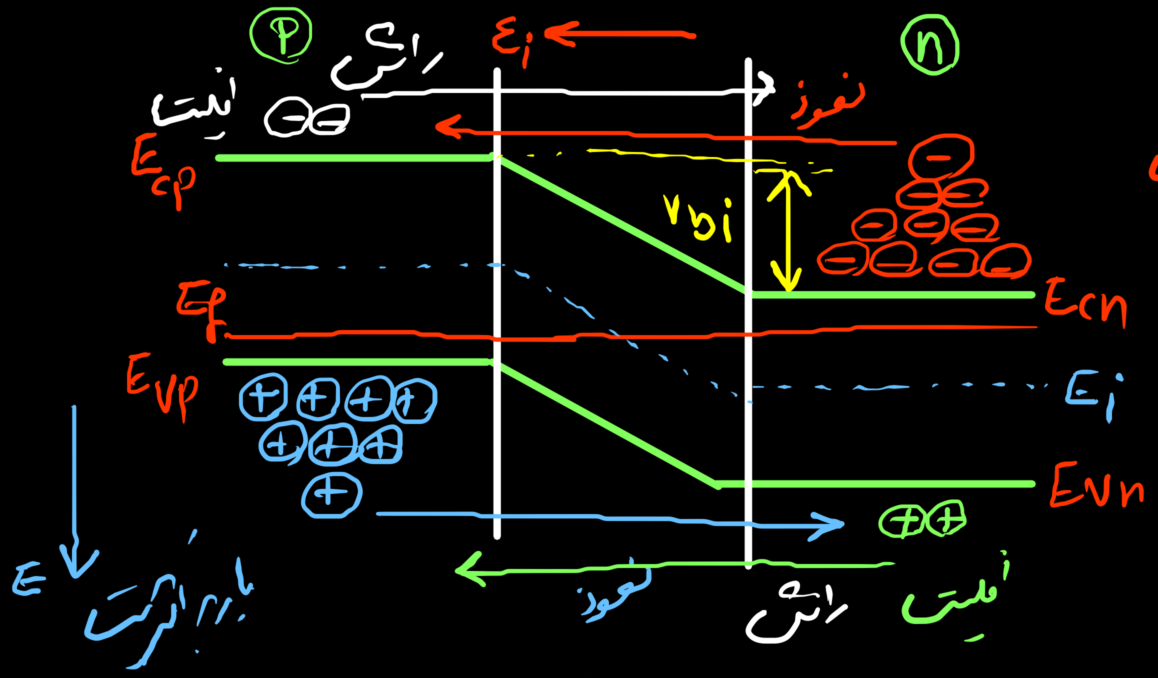


بایاس مستقیم



بایاس معکوس

تحلیل کیفی جریان

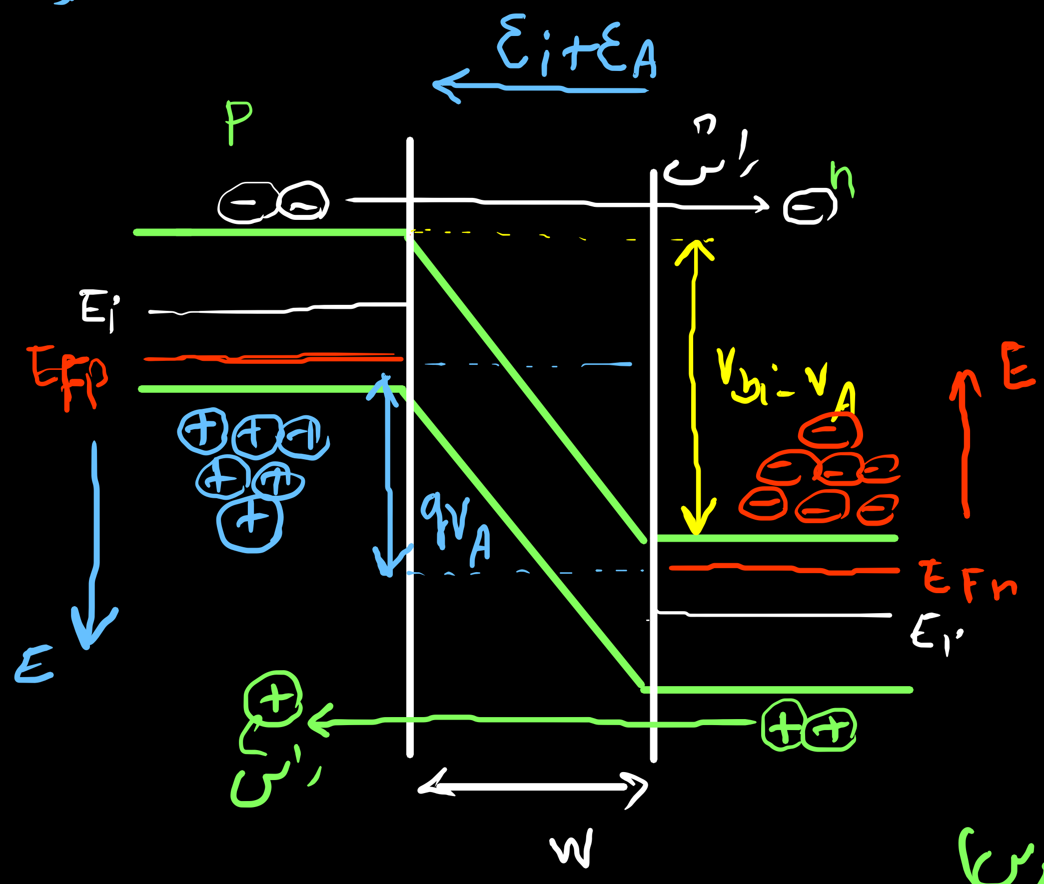


بار اکثریت $\uparrow E$

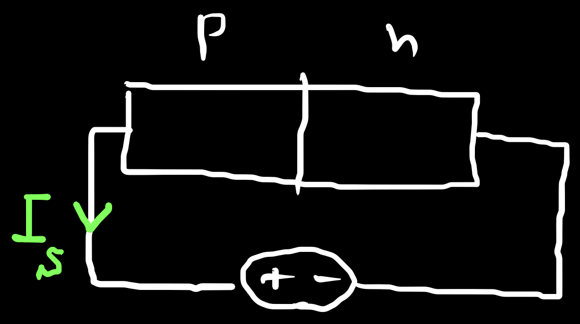
V_{bi} بدون بایاس

بایاس معکوس

$V_A < 0$



$V_{bi} - V_A$



$V_A < 0$

رانش بارهای اقلیت

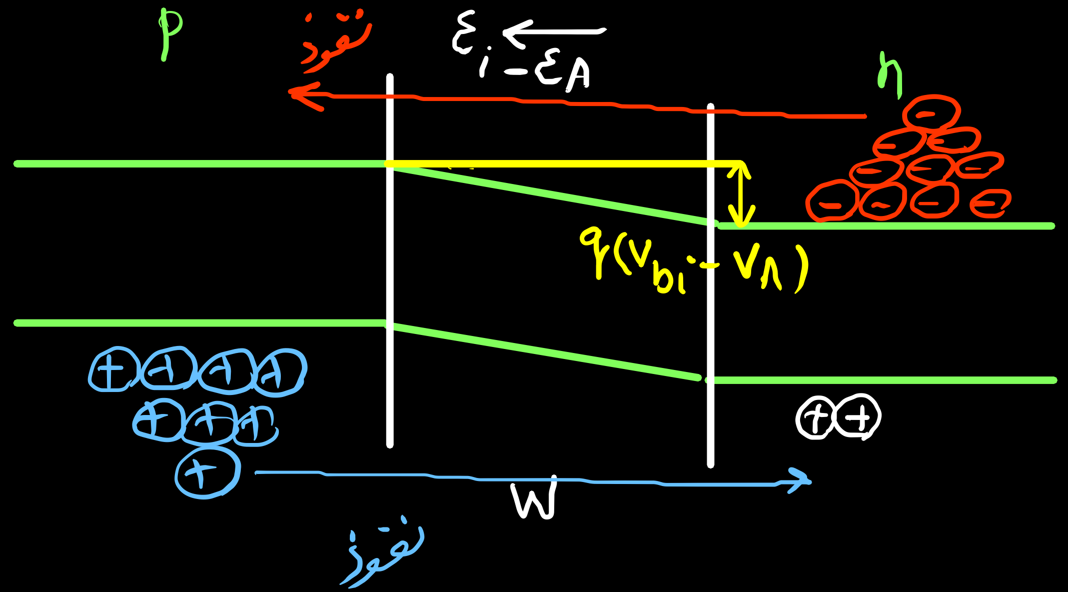
$\downarrow$

جریان کم (جریان اشباع معکوس)

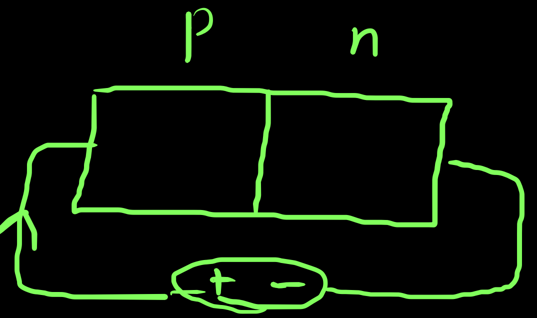
$n \propto e^{-\frac{(E-E_{Fn})}{k_BT}}$

$\frac{1}{1+e^{\frac{E-E_F}{k_BT}}}$

بایاس مستقیم



کم
بارهای اکثریت
↓
نفوذ

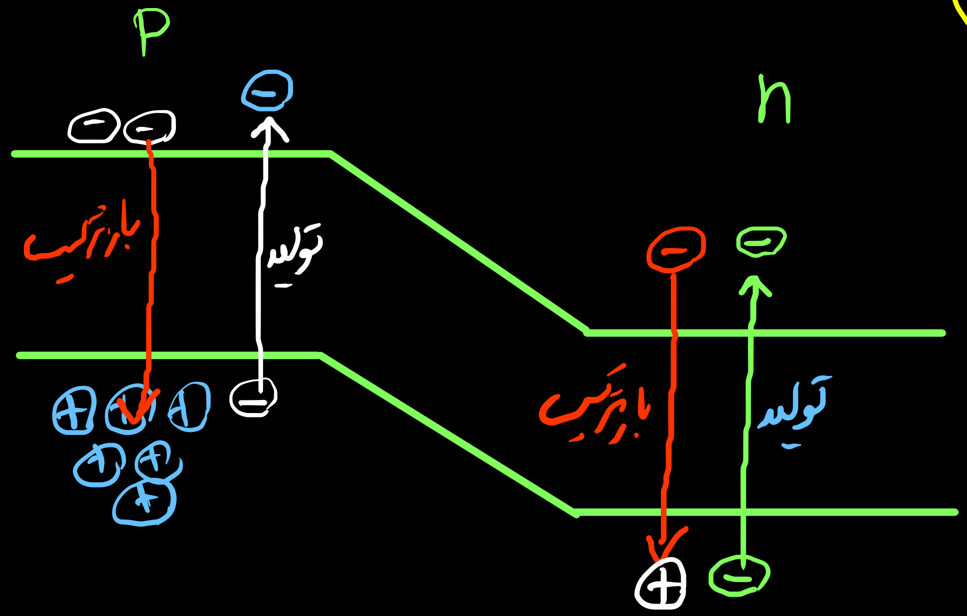


$V_A > 0$

روابط قبل بدون بایاس ← اعمال بایاس

$V_{bi} \to V_{bi}+V_A$

$\left\{ \begin{array}{l} W \\ x_{n0} \\ \vdots \end{array} \right.$



نفوذ
رانش
تولید
بازترکیب

تحلیل کمی جریان :

① شرایط ها : $\frac{\partial n}{\partial t} = 0$ ، جریان ثابت نسبت به زمان

② پیوند پله‌ای

③ یک بعدی

④ تزریق کم

⑤ فرایندها : رانش - نفوذ - تولید حرارتی - بازترکیب

⑥ $V_{bi} \rightarrow V_{bi} - V_A$

چگالی جریان ، سطح مقطع

$$I = J \cdot A$$

① شرایط ها

$$J = J_n(x) + J_p(x) = \text{ثابت}$$

② جریان

$$J_n(x) = q\mu_n n(x)\mathcal{E}(x) + qD_n \frac{d}{dx} n(x)$$

$$J_p(x) = q\mu_p p(x)\mathcal{E}(x) - qD_p \frac{d}{dx} p(x)$$

$$n(x) = n_0 + \delta n(x) \qquad p(x) = p_0 + \delta p(x)$$

③ روابط پیوستگی

شرایط ① ② ③ ④ ⑤

$$0 = \frac{\partial n(x)}{\partial t} = \frac{1}{q}\frac{d}{dx}J_n(x) - \frac{\delta n(x)}{\tau}$$

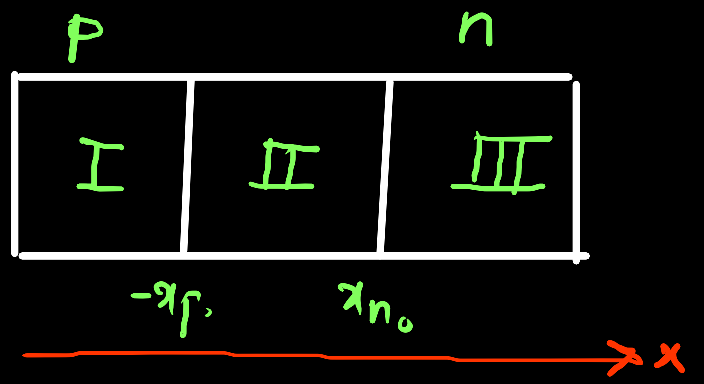
$$0 = \frac{\partial p(x)}{\partial t} = \frac{-1}{q}\frac{d}{dx}J_p(x) - \frac{\delta p(x)}{\tau}$$

④ میدان ، پتانسیل

$$\frac{\partial}{\partial x}\mathcal{E}(x) = \frac{1}{\varepsilon}\left(N_D(x) - N_A(x)\right)$$

$$\mathcal{E}(x) = -\frac{d}{dx}V(x)$$

دردو طرف پیوند I, III



I, III: $\mathcal{E} = 0$

$\frac{\partial}{\partial t} n = \frac{\partial}{\partial t} = 0$

$$0 = n \mu_n \cancel{\frac{d}{dx}\mathcal{E}} + D_n \frac{d^2}{dx^2} \delta n(x) - \frac{\delta n(x)}{\tau}$$

$$0 = -p \mu_p \cancel{\frac{d}{dx}\mathcal{E}} + D_p \frac{d^2}{dx^2} \delta p(x) - \frac{\delta p(x)}{\tau}$$

I

$$D_n \frac{d^2}{dx^2} \delta n(x) - \frac{\delta n(x)}{\tau} = 0 \qquad \delta n(x) = A_1 e^{\frac{x}{L_n}} + A_2 e^{-\frac{x}{L_n}} \qquad L_n = \sqrt{D_n \tau}$$

$$\delta n(x)\Big|_{x \to -\infty} = 0 \quad (A_2 = 0) \quad \boxed{\delta n(x) = A_1 e^{\frac{x}{L_n}}} \qquad n(x) = n_0 + \delta n(x)$$

III

$$D_p \frac{d^2}{dx^2} \delta p(x) - \frac{\delta p(x)}{\tau} = 0 \qquad \delta p(x) = B_1 e^{\frac{x}{L_p}} + B_2 e^{-\frac{x}{L_p}}$$

$$\delta p(x)\Big|_{x \to +\infty} = 0 \quad B_1 = 0 \rightarrow \boxed{\delta p(x) = B_2 e^{-\frac{x}{L_p}}} \qquad p(x) = p_0 + \delta p(x)$$

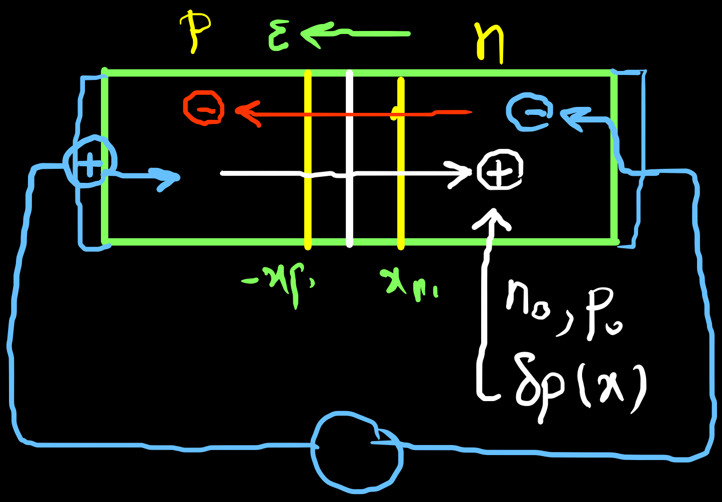
II در ناحیه تخلیه

$$\frac{\partial \delta n}{\partial t} = 0 = \frac{1}{q} \frac{d}{dx} J_n(x) \longrightarrow J_n(x) = \text{Constant} \qquad -x_{p_0} \leq x < x_{n_0}$$

$$\longrightarrow J = J_n(x) + J_p(x) = \text{مقدار ثابت}$$

$$\frac{\partial \delta p}{\partial t} = 0 = -\frac{1}{q} \frac{d}{dx} J_p(x) \longrightarrow J_p(x) = \text{Constan} \qquad -x_{p_0} \leq x \leq x_{n_0}$$

ادامه



$$\begin{cases} \delta n(x) = A_1 e^{\frac{x}{L_n}} & L_n = \sqrt{D_n \tau_n} \quad ۱ \\ \delta p(x) = B_1 e^{\frac{-x}{L_p}} & L_p = \sqrt{D_p \tau_p} \quad ۲ \\ J_n(x) + J_p(x) = \text{Constant} \quad ۵ \end{cases}$$

$$n(x)p(x) = n_i e^{\frac{F_n - E_i}{k_B T}} \times n_i e^{\frac{E_i - F_p}{k_B T}} = n_i^2 e^{\frac{F_n - F_p}{k_B T}} = n_i^2 e^{\frac{qV_A}{k_B T}} \qquad x \geq x_{n_0}, \; x \leq -x_{p_0}$$

$x = -x_{p_0}$:

$$n(-x_{p_0}) \times p(-x_{p_0}) = n_i^2 e^{\frac{qV_A}{k_B T}} \qquad [n_0(-x_{p_0}) + \delta n(-x_{p_0})] \times N_A = n_i^2 e^{\frac{qV_A}{k_B T}}$$

$$\left[\frac{n_i^2}{N_A} + \delta n(-x_{p_0})\right] N_A = n_i^2 e^{\frac{qV_A}{k_B T}} \qquad \boxed{\delta n(-x_{p_0}) = \frac{n_i^2}{N_A}\left(e^{\frac{qV_A}{k_B T}} - 1\right)} \quad ۳$$

$x = x_{n_0}$

$$N_D\left[\frac{n_i^2}{N_D} + \delta p(x_{n_0})\right] = n_i^2 e^{\frac{qV_A}{k_B T}} \qquad \boxed{\delta p(x_{n_0}) = \frac{n_i^2}{N_D}\left(e^{\frac{qV_A}{k_B T}} - 1\right)} \quad ۴$$

۱ ۳

$$\delta n(-x_{p_0}) = A_1 e^{\frac{-x_{p_0}}{L_n}} = \frac{n_i^2}{N_A}\left(e^{\frac{qV_A}{k_B T}} - 1\right) \rightarrow A_1 = \frac{n_i^2}{N_A}\left(e^{\frac{qV_A}{kT}} - 1\right) e^{\frac{x_{p_0}}{L_n}}$$

$$\boxed{\delta n(x) = \frac{n_i^2}{N_A}\left(e^{\frac{qV_A}{kT}} - 1\right) e^{\frac{x + x_{p_0}}{L_n}}}$$

۲ ۴

$$\delta p(x_{n_0}) = B_1 e^{\frac{-x_{n_0}}{L_p}} = \frac{n_i^2}{N_D}\left(e^{\frac{qV_A}{kT}} - 1\right) \rightarrow B_1 = \frac{n_i^2}{N_D}\left(e^{\frac{qV_A}{kT}} - 1\right) e^{\frac{x_{n_0}}{L_p}}$$

$$\boxed{\delta p(x) = \frac{n_i^2}{N_D}\left(e^{\frac{qV_A}{kT}} - 1\right) e^{\frac{-x + x_{n_0}}{L_p}}}$$

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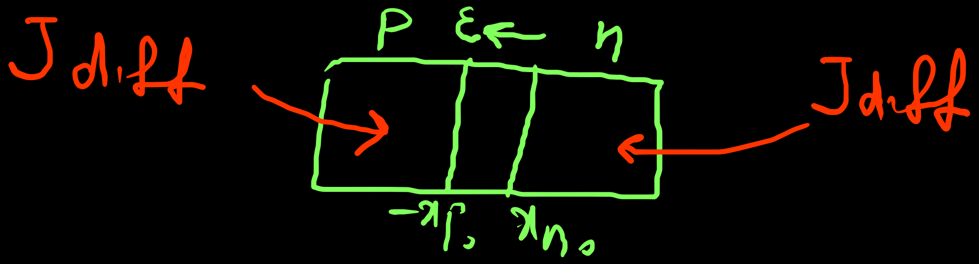
$$J_n(x) + J_p(x) = \text{Constant} \qquad J_n(x) = \text{Const} \qquad J_p(x) = \text{Const} \rightarrow J_n(x_1) + J_p(x_2) = \text{Constant}$$



$$J = J_n(-x_{p_0}) + J_p(x_{n_0})$$

$$J_n(x) = qD_n \frac{d}{dx} \delta_n(x)$$

$$\boxed{J_n(x) = q\frac{D_n}{L_n}\delta_n(x)}$$

$$\boxed{J_p(x) = +q\frac{D_p}{+L_p}\delta_p(x)}$$

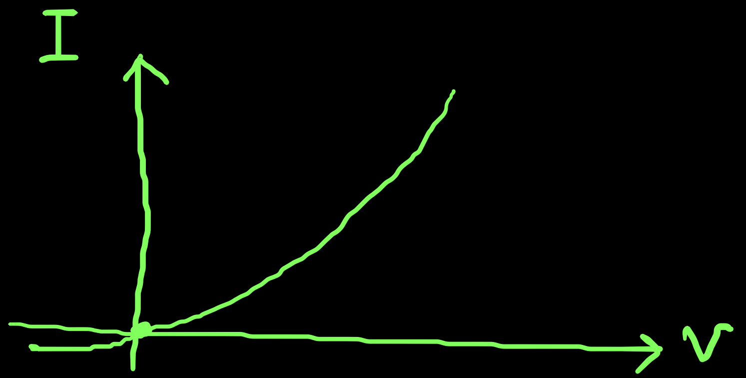
$$J = J_n(-x_{p_0}) + J_p(x_{n_0})$$

$$= \frac{qD_n}{L_n}\frac{n_i^2}{N_A}\left(e^{\frac{qV_A}{kT}} - 1\right) + q\frac{D_p}{L_p} \times \frac{n_i^2}{N_D}\left(e^{\frac{qV_A}{kT}} - 1\right)$$

$$I = J.A$$

$$J = q\left(\frac{D_n}{L_n}\frac{n_i^2}{N_A} + \frac{D_p}{L_p}\frac{n_i^2}{N_D}\right)\left(e^{\frac{qV_A}{kT}} - 1\right)$$

$$\boxed{I = qA\left(\overbrace{\frac{D_n}{L_n} n_p}^{\text{ناحیه } P} + \overbrace{\frac{D_p}{L_p} P_n}^{\text{ناحیه } n}\right)\left(e^{\frac{qV_A}{kT}} - 1\right)}$$



$$I = I_s\left(e^{\frac{qV_A}{kT}} - 1\right)$$

$D_n \leftarrow$ ثابت نفوذ الکترون در ناحیه P

$L_n \leftarrow$ طول نفوذ الکترون در ناحیه P

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

$D_p \leftarrow$ ثابت نفوذ حفره در ناحیه n

$L_p \leftarrow$ طول نفوذ حفره در ناحیه n

جنس دیود :

$$I = I_s \left(e^{\frac{qV_A}{kT}} - 1 \right)$$

$$\frac{D}{\mu} = \frac{kT}{q}$$

$$I_s = qAn_i^2 \left[\frac{D_n}{L_n \cdot N_A} + \frac{D_p}{L_p \cdot N_D} \right]$$

$$I_s = qAn_i^2 \left[\frac{\sqrt{D_n/\tau_n}}{N_A} + \frac{\sqrt{D_p/\tau_p}}{N_D} \right]$$

1. معادلات پیوستگی
2. محاسبه میدان با قانون گوس
3. محاسبه پتانسیل الکتریکی
4. معادلات جریان

$p - n^+$ $\quad N_D \gg N_A \quad$ $I_s = qn_i^2 A \left[\frac{\sqrt{D_n/\tau_n}}{N_A} \right]$

$p^+ - n$ $\quad N_A \gg N_D \quad$ $I_s = qn_i^2 A \left[\frac{\sqrt{D_p/\tau_p}}{N_D} \right]$

$p - n$