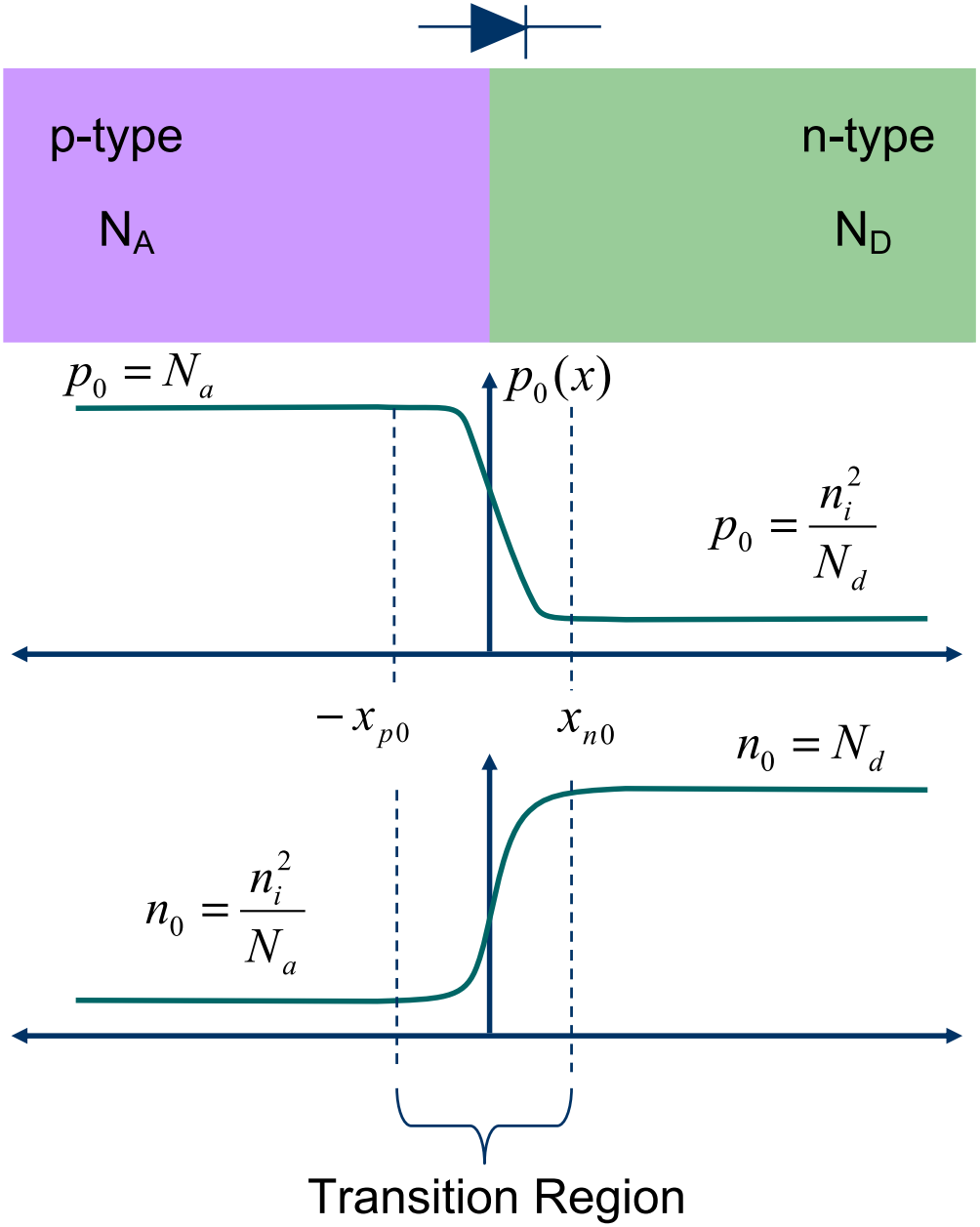
# Slide 2


p-type
$N_A$
n-type
$N_D$
$p_0 = N_a$
$p_0(x)$
$p_0 = \frac{n_i^2}{N_d}$
$-x_{p0}$
$x_{n0}$
$n_0 = N_d$
$n_0 = \frac{n_i^2}{N_a}$
Transition Region

# Slide 4)

$$J_n = 0 = q n_0 \mu_n E_0 + q D_n \frac{dn_o}{dx}$$

$$\frac{dn_o}{dx} = -\left(\frac{\mu_n}{D_n}\right) n_o E_0 = \left(\frac{q}{kT}\right) n_o \frac{d\varphi_0}{dx}$$

$$d\varphi_0 = \left(\frac{kT}{q}\right) \frac{dn_o}{n_0} = V_{th} \frac{dn_0}{n_0}$$

# Slide 5

$$d\varphi_0 = \left(\frac{kT}{q}\right)\frac{dn_o}{n_0} = V_{th}\frac{dn_0}{n_0}$$

$$\varphi_0(x) - \varphi_0(x_0) = V_{th}\ln\frac{n_0(x)}{n_0(x_0)}$$

$$\varphi_0(x_0) = 0 \; n_0(x_0) = n_i$$

# Slide 6)

$$n_0(x) = n_i e^{\varphi_0(x)/V_{th}}$$
$$p_0(x) = n_i e^{-\varphi_0(x)/V_{th}}$$
$$n_0(x)p_0(x) = n_i^2 e^{-\varphi_0(x)/V_{th}} e^{\varphi_0(x)/V_{th}} = n_i^2$$

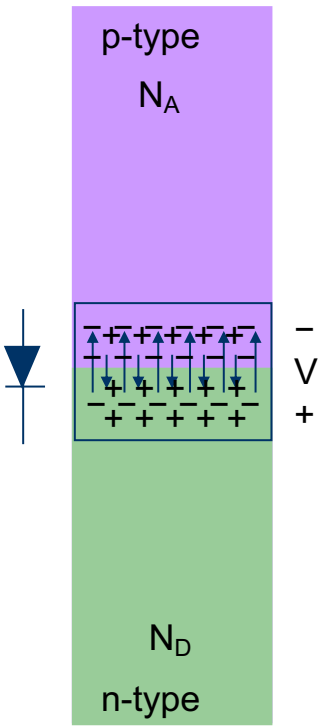
# Slide 7)

$$\varphi_0(x) = V_{th} \ln \frac{n_0(x)}{n_i(x_0)} = 26\mathrm{mV} \ln \frac{n_0(x)}{n_i(x_0)} \approx 26\mathrm{mV} \ln 10 \log \frac{n_0(x)}{10^{10}}$$

$$\varphi_0(x) \approx 60\mathrm{mV} \log \frac{n_0(x)}{10^{10}}$$

$$\varphi_0(x) \approx -60\mathrm{mV} \log \frac{p_0(x)}{10^{10}}$$

# Slide 9)



# Slide 10)

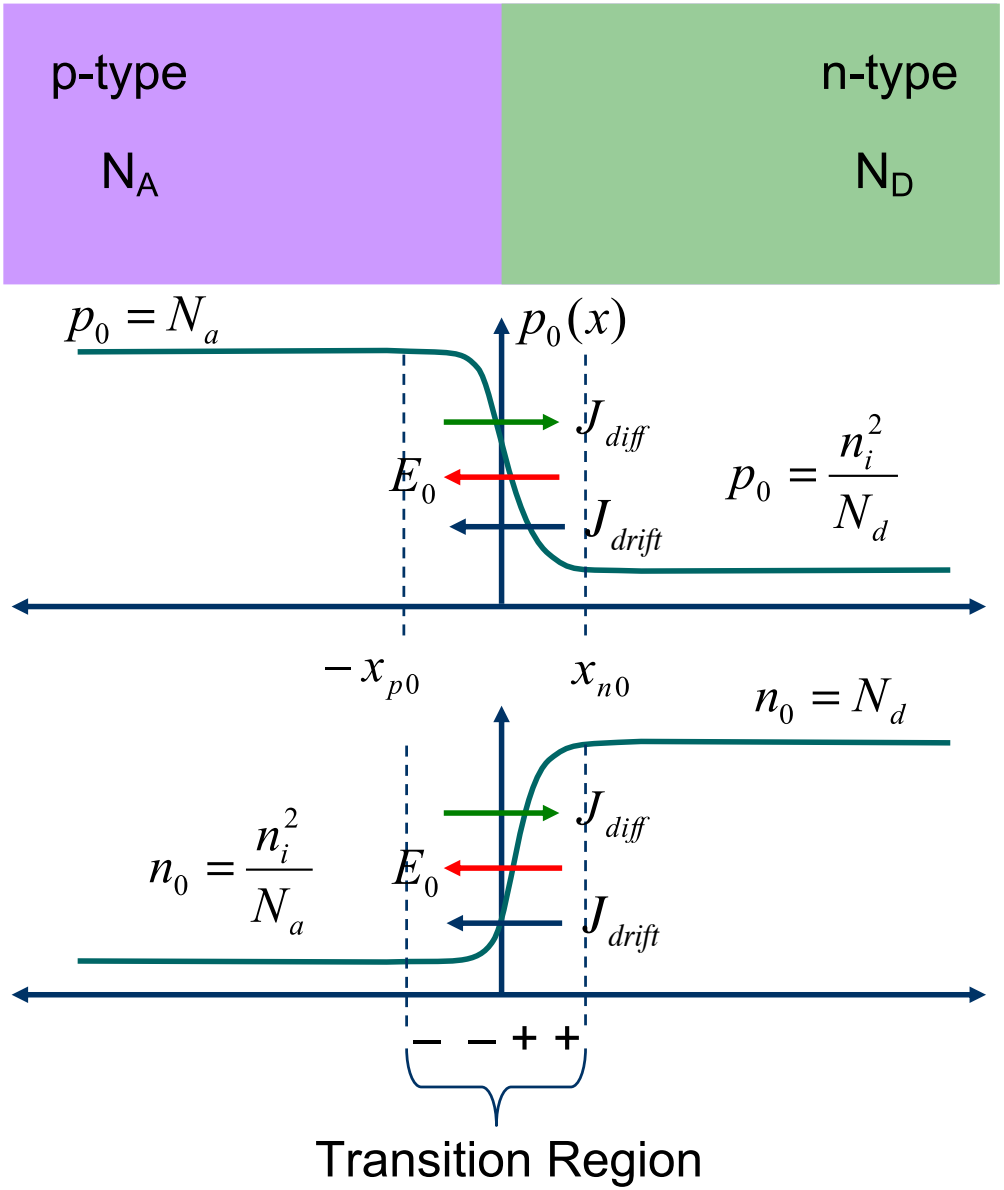
$$J_n = 0 = qn_0\mu_n E_0 + qD_n \frac{dn_o}{dx}$$

$$qn_0\mu_n E_0 = -qD_n \frac{dn_o}{dx}$$

$$E_0 = \frac{-D_n \frac{dn_o}{dx}}{n_0\mu_n} = -\frac{kT}{q}\frac{1}{n_0}\frac{dn_0}{dx}$$

$$E_0 = \frac{D_p \frac{dp_o}{dx}}{n_0\mu_p} = -\frac{kT}{q}\frac{1}{p_0}\frac{dp_0}{dx}$$

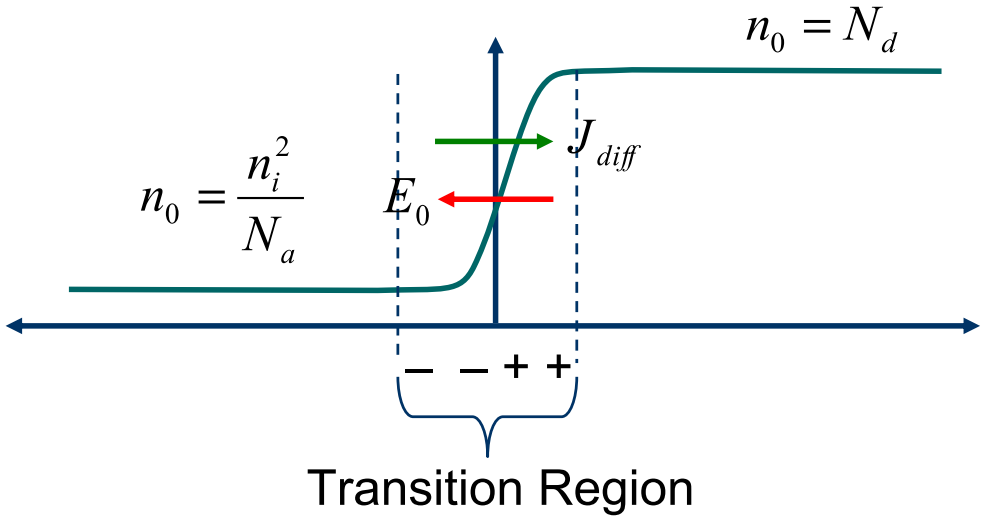
# Slide 11)


p-type
$N_A$
n-type
$N_D$
$p_0 = N_a$
$p_0(x)$
$J_{diff}$
$E_0$
$J_{drift}$
$p_0 = \frac{n_i^2}{N_d}$
$-x_{p0}$
$x_{n0}$
$n_0 = N_d$
$n_0 = \frac{n_i^2}{N_a}$
$J_{diff}$
$E_0$
$J_{drift}$
– – + +
Transition Region

# Slide 12)

$$\rho_0(x) = q(p_0 - n_0 + N_d - N_a)$$
$$\rho_0(x) \approx q(p_0 - N_a) \; -x_{p0} < x < 0$$
$$N_a > p_0 \; \rho_0(x) < 0$$

# Slide 13)




$\rho_0(x) \approx q(-n_0 + N_d)\ 0 < x < x_{n0}$
$N_d > n_0\ \rho_0(x) > 0$

# Slide 14)

$$\rho_0(x) \cong \begin{cases} q(n_i e^{-\varphi_0(x)/V_{th}} - N_a) & -x_{po} < x < 0 \\ q(N_d - n_i e^{\varphi_0(x)/V_{th}}) & 0 < x < x_{n0} \end{cases}$$

$$\frac{dE_0}{dx} = -\frac{d^2\varphi}{dx^2} = \frac{\rho_0(x)}{\varepsilon_s}$$

# Slide 15)

$$\rho_0(x) \cong \begin{cases} -qN_a & -x_{po} < x < 0 \\ +qN_d & 0 < x < x_{n0} \end{cases}$$

$$\frac{dE_0}{dx} = \frac{\rho_0(x)}{\varepsilon_s}$$

$$E_0(x) = \int_{-x_{p0}}^{x} \frac{\rho_0(x')}{\varepsilon_s} dx' + E_0(-x_{p0})$$

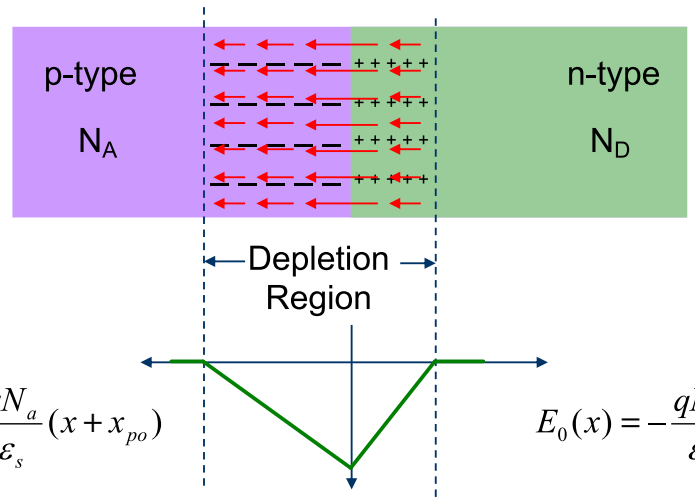
# Slide 17)

$$E_0(x) = \int_{-x_{p0}}^{x} \frac{\rho_0(x')}{\varepsilon_s} dx' = -\frac{qN_a}{\varepsilon_s}(x + x_{po})$$

$$E_0(x_{n0}) = \int_{x}^{x_{n0}} \frac{\rho_0(x')}{\varepsilon_s} dx' + E_0(x) = \frac{qN_d}{\varepsilon_s}(x_{n0} - x) + E_0(x)$$

$$E_0(x) = -\frac{qN_d}{\varepsilon_s}(x_{n0} - x)$$

# Slide 18)




$$E_0(x) = -\frac{qN_a}{\varepsilon_s}(x + x_{po})$$

$$E_0(x) = -\frac{qN_d}{\varepsilon_s}(x_{n0} - x)$$

# Slide 19)

$$E_0^n(x=0) = -\frac{qN_a}{\varepsilon_s}x_{po} = -\frac{qN_d}{\varepsilon_s}x_{no} = E_0^p(x=0)\ qN_a x_{po} = qN_d x_{no}$$

# Slide 20)

$$\varphi(x) = \varphi(-x_{po}) + \int_{-x_{p0}}^{x} \frac{qN_a}{\varepsilon_s}(x' + x_{po})dx'$$

$$\varphi(x) = \varphi_p + \frac{qN_a}{\varepsilon_s}\left(\frac{x'^2}{2} + x'x_{po}\right)\Bigg|_{-x_{p0}}^{x}$$

# Slide 21)

$\varphi_o^p(x) = \varphi_p + \frac{qN_a}{2\varepsilon_s}(x + x_{p0})^2$

Two equations are pictures and cannot be opened

# Slide 22)

$$\varphi_n - \frac{qN_d}{2\varepsilon_s} x_{n0}^2 = \varphi_p + \frac{qN_a}{2\varepsilon_s} x_{p0}^2$$

$$qN_a x_{po} = qN_d x_{no}$$

$$x_{no} = \sqrt{\frac{2\varepsilon_s \varphi_{bi}}{qN_d} \left( \frac{N_a}{N_a + N_d} \right)}$$

$$x_{po} = \sqrt{\frac{2\varepsilon_s \varphi_{bi}}{qN_a} \left( \frac{N_d}{N_d + N_a} \right)}$$

$$\varphi_{bi} \equiv \varphi_n - \varphi_p > 0$$

# Slide 23)

$$x_{n0} = \lim_{N_d \to \infty} \sqrt{\frac{2\varepsilon_s \varphi_{bi}}{qN_d} \frac{N_d}{N_d + N_a}} = 0$$

$$x_{p0} = \lim_{N_d \to \infty} \sqrt{\frac{2\varepsilon_s \varphi_{bi}}{qN_a} \left( \frac{N_d}{N_d + N_a} \right)} = \sqrt{\frac{2\varepsilon_s \varphi_{bi}}{qN_a}}$$

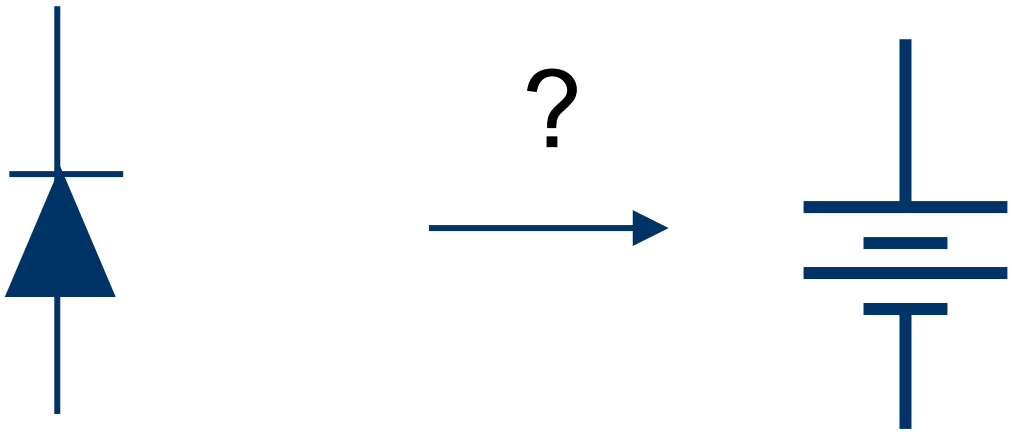
# Slide 24)

$$X_{d0} = x_{p0} + x_{n0} = \sqrt{\frac{2\varepsilon_s \varphi_{bi}}{q}\left(\frac{1}{N_a} + \frac{1}{N_d}\right)}$$

$$X_{d0} = \sqrt{\frac{2\varepsilon_s \varphi_{bi}}{q}\left(\frac{1}{10^{15}}\right)} \approx 1\mu$$

$$E_{pn} \approx \frac{1\mathrm{V}}{1\mu} = 10^4 \frac{\mathrm{V}}{\mathrm{cm}}$$

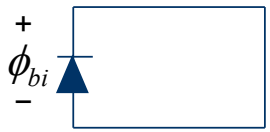
# Slide 25)

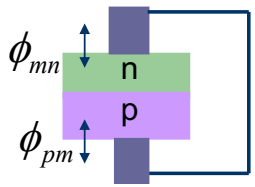



$$\varphi_{bi} \equiv \varphi_n - \varphi_p = V_{th}\left(\ln\frac{N_D}{n_i} + \ln\frac{N_A}{n_i}\right) = V_{th}\ln\frac{N_D N_A}{n_i^2}$$

$$\varphi_{bi} = 26\mathrm{mV}\ln\frac{N_D N_A}{n_i^2} = 60\mathrm{mV}\times\log\frac{10^{15}10^{15}}{10^{20}} = 600\mathrm{mV}$$

# Slide 26)




$$0 = \phi_{bi} + \phi_{pm} + \phi_{mn}$$

$$\phi_{bi} = -(\phi_{pm} + \phi_{mn})$$

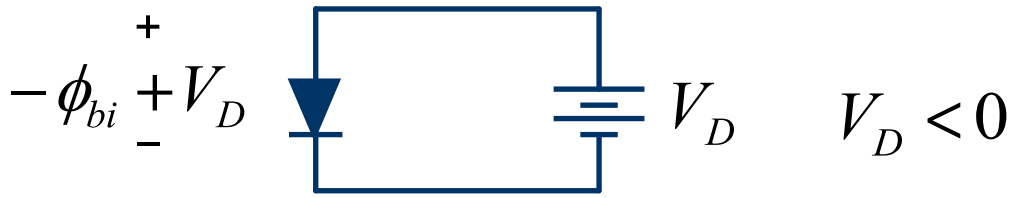
$$0 = \varphi_{bi} + \varphi_{pm} + \varphi_{mn}$$

$$\varphi_{bi} = -(\varphi_{pm} + \varphi_{mn})$$

# Slide 27)

$$qN_a x_{po} = qN_d x_{no}$$

# Slide 28)




$V_D < 0$

# Slide 29)

$$x_n(V_D) = \sqrt{\frac{2\varepsilon_s(\varphi_{bi}-V_D)}{qN_d}\left(\frac{N_a}{N_a+N_d}\right)} = x_{n0}\sqrt{1-\frac{V_D}{\varphi_{bi}}}$$

$$x_p(V_D) = \sqrt{\frac{2\varepsilon_s(\varphi_{bi}-V_D)}{qN_a}\left(\frac{N_d}{N_a+N_d}\right)} = x_{p0}\sqrt{1-\frac{V_D}{\varphi_{bi}}}$$

$$X_d(V_D) = x_p(V_D) + x_n(V_D) = \sqrt{\frac{2\varepsilon_s(\varphi_{bi}-V_D)}{q}\left(\frac{1}{N_a}+\frac{1}{N_d}\right)}$$

$$X_d(V_D) = X_{d0}\sqrt{1-\frac{V_D}{\varphi_{bi}}}$$

# Slide 30)

$$Q_J(V_D) = -qN_a x_p(V_D) = -qN_a\sqrt{1-\frac{V_D}{\varphi_{bi}}}$$
$$Q_J(V_D + v_D) = Q_J(V_D) + q(v_D)$$

# Slide 31)

$$Q_J(V_D + v_D) = Q_J(V_D) + \left.\frac{dQ_D}{dV}\right|_{V_D} v_D + \cdots$$

$$C_j = C_j(V_D) = \left.\frac{dQ_j}{dV}\right|_{V=V_D} = \frac{d}{dV}\left(-qN_a x_{p0}\sqrt{1-\frac{V}{\varphi_{bi}}}\right)\Bigg]_{V=V_R}$$

$$C_j = \frac{qN_a x_{p0}}{2\varphi_{bi}\sqrt{1-\frac{V_D}{\varphi_{bi}}}} = \frac{C_{j0}}{\sqrt{1-\frac{V_D}{\varphi_{bi}}}}$$

$$C_{j0} = \frac{qN_a x_{p0}}{2\varphi_{bi}} = \frac{qN_a}{2\varphi_{bi}}\sqrt{\left(\frac{2\varepsilon_s\varphi_{bi}}{qN_a}\right)\left(\frac{N_d}{N_a+N_d}\right)} = \sqrt{\frac{q\varepsilon_s}{2\varphi_{bi}}\frac{N_a N_d}{N_a+N_d}}$$

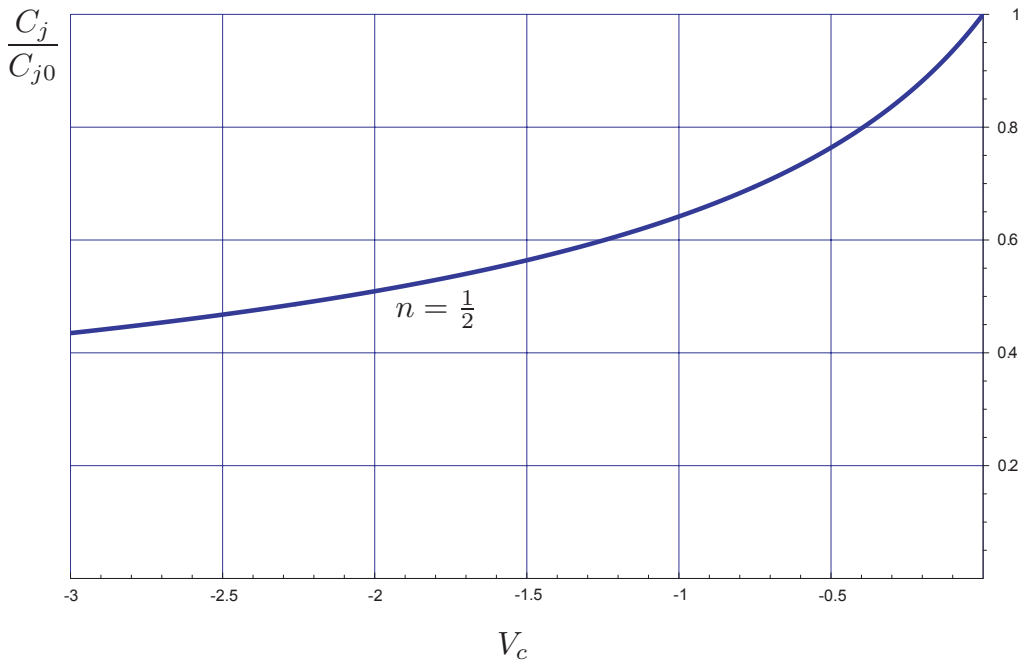
# Slide 32)

$$C_{j0} = \sqrt{\frac{q\varepsilon_s}{2\varphi_{bi}} \frac{N_a N_d}{N_a + N_d}}$$

$$C_{j0} = \varepsilon_s \sqrt{\frac{q}{2\varepsilon_s \varphi_{bi}} \left( \frac{1}{N_a} + \frac{1}{N_d} \right)^{-1}} = \frac{\varepsilon_s}{X_{d0}}$$

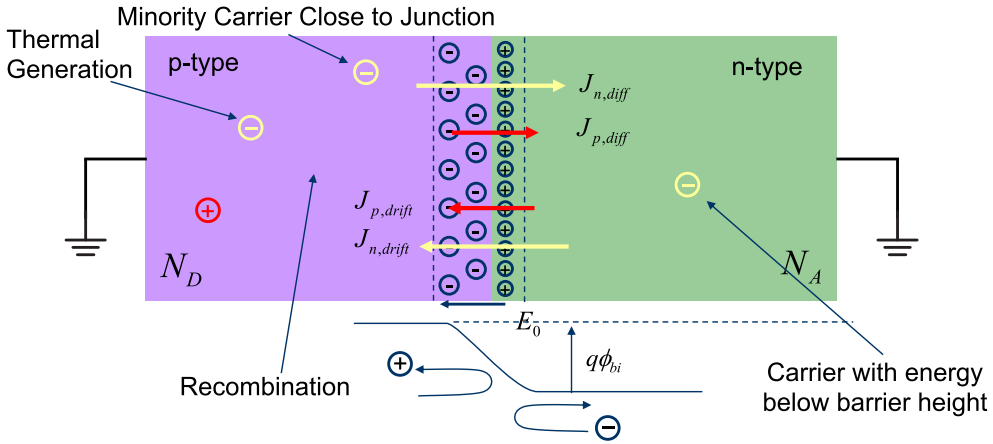
$$C_j(V_D) = \frac{\varepsilon_s}{X_d(V_D)}$$

# Slide 33)

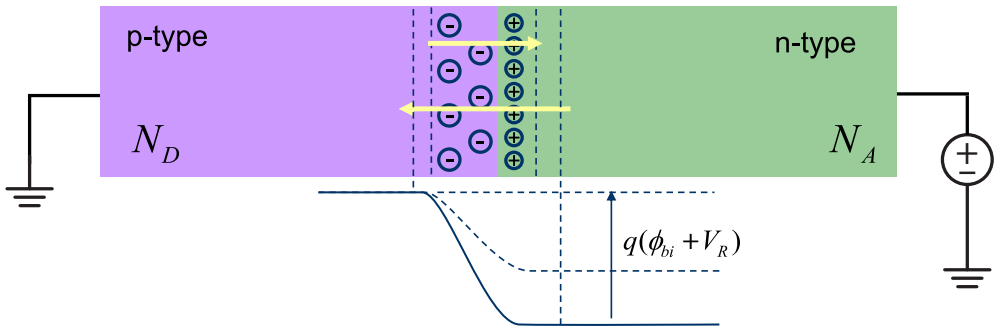


# Slide 34)

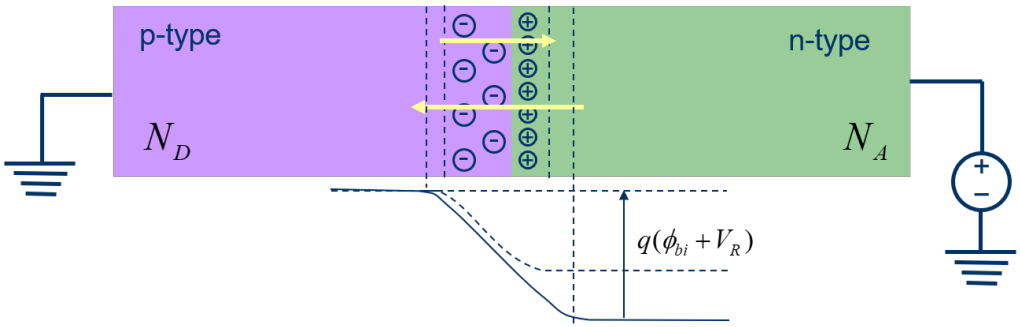
# Slide 35)


Minority Carrier Close to Junction
Thermal Generation
p-type
n-type
$J_{n,diff}$
$J_{p,diff}$
$J_{p,drift}$
$J_{n,drift}$
$N_D$
$N_A$
$E_0$
$q\phi_{bi}$
Recombination
Carrier with energy below barrier height

# Slide 36)

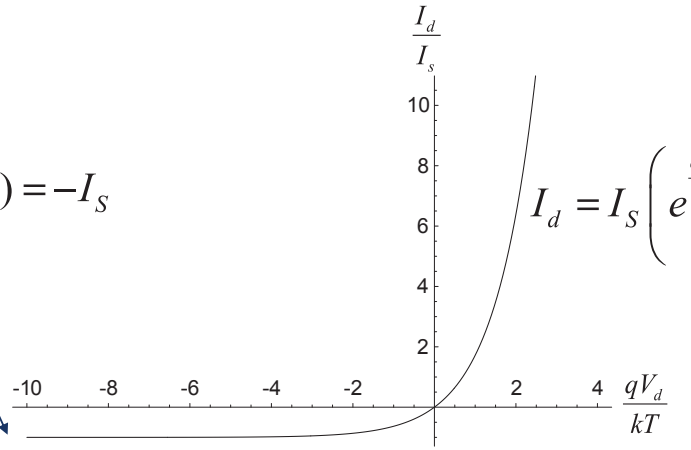


# Slide 37)



# Slide 38)

$$I_d(V_d \to -\infty) = -I_S$$




$$I_d = I_S\left(e^{\frac{qV_d}{kT}} - 1\right)$$

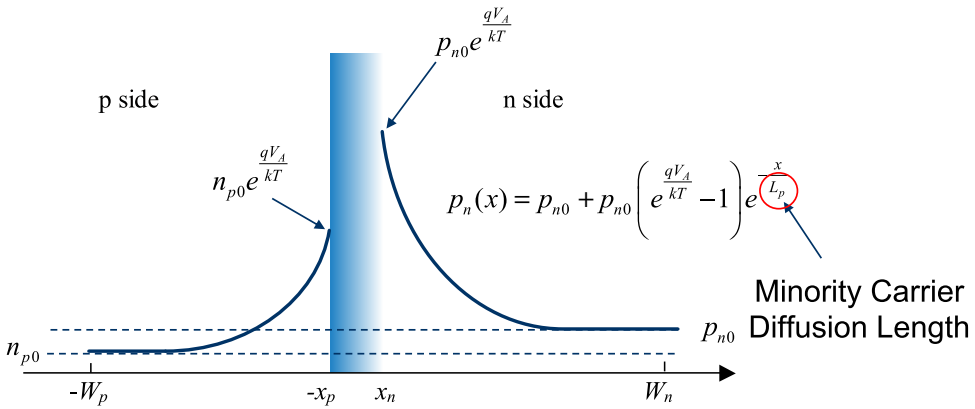
# Slide 39)

$$\frac{p_n(x{=}x_n)}{p_p(x{=}{-}x_p)} = = e^{-(Barrier\ Energy)/kT} \quad \frac{p_n(x{=}x_n)}{N_A} = e^{-q(\varphi_B - V_D)/kT}$$

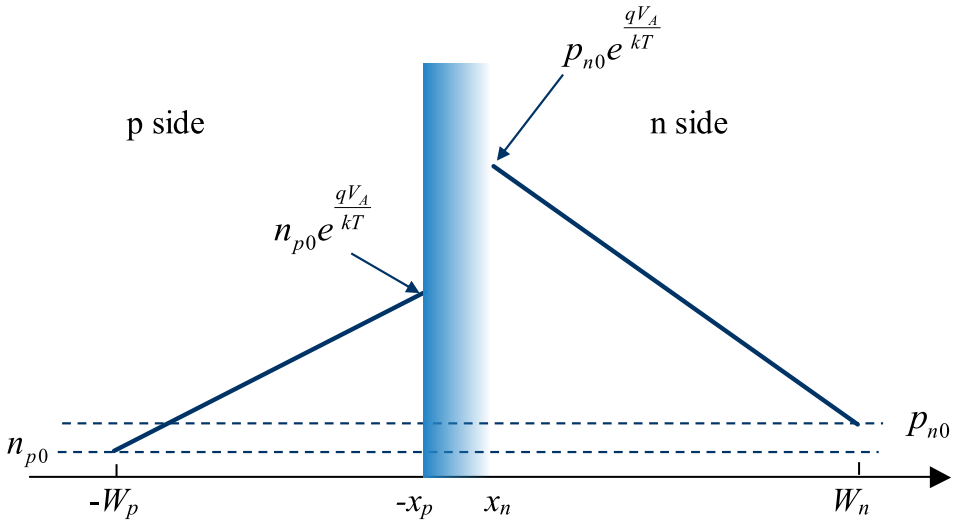
# Slide 40)

$$p_n(x = x_n) = N_A e^{-q(\varphi_B - V_D)/kT} \quad n_p(x = -x_p) = N_D e^{-q(\varphi_B - V_D)/kT}$$

# Slide 41)

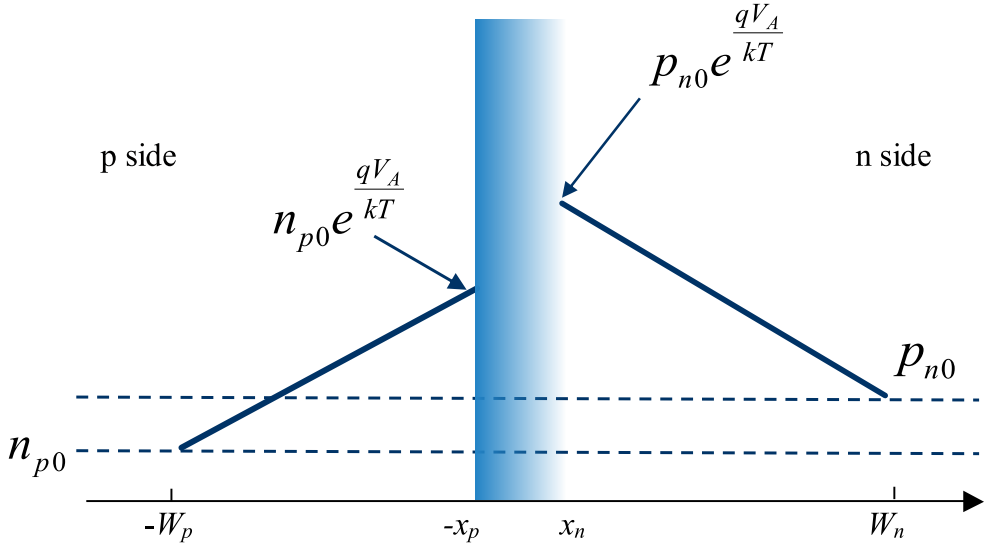

$p_{n0}e^{\frac{qV_A}{kT}}$
p side
n side
$n_{p0}e^{\frac{qV_A}{kT}}$
$p_n(x) = p_{n0} + p_{n0}\left(e^{\frac{qV_A}{kT}} - 1\right)e^{-\frac{x}{L_p}}$
Minority Carrier
Diffusion Length
$p_{n0}$
$n_{p0}$
$-W_p$
$-x_p$
$x_n$
$W_n$

# Slide 42)




$$L_{n,p} >> W_{n,p}$$

# Slide 43)



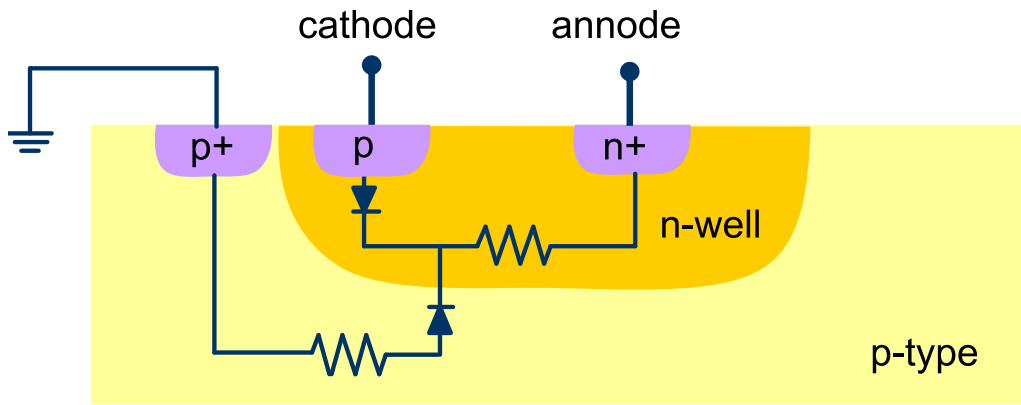

$$\frac{dn_p}{dx}(x) \approx \frac{n_{p0}e^{\frac{qV_A}{kT}} - n_{p0}}{-x_p - (-W_p)}$$

$$n_{p0} = \frac{n_i^2}{N_a}$$

$$J_n^{diff} = qD_n \frac{dn_p}{dx}\bigg|_{x=-x_p} \approx q\frac{D_n}{W_p} n_{p0}\left(e^{\frac{qV_A}{kT}} - 1\right)$$

$$J_p^{diff} = -qD_p \frac{dp_n}{dx}\bigg|_{x=x_n} \approx -q\frac{D_p}{W_n} p_{n0}\left(1 - e^{\frac{qV_A}{kT}}\right)$$

# Slide 44)



# Slide 45)

$$I_D + i_D = I_S \left( e^{\frac{q(V_d + v_d)}{kT}} - 1 \right) \approx I_S e^{\frac{qV_d}{kT}} e^{\frac{qv_d}{kT}}$$

$$e^x = 1 + x + \frac{x^2}{2!} + \frac{x^3}{3!} + \cdots$$

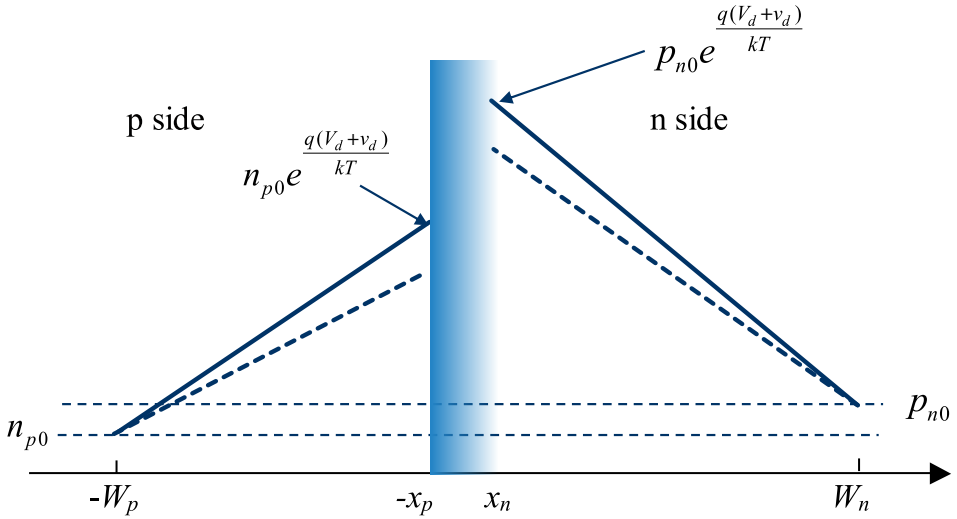
$$I_D + i_D \approx I_D \left( 1 + \frac{q(V_d + v_d)}{kT} + \cdots \right)$$

$$i_D \approx \frac{qv_d}{kT} = g_d v_d$$

# Slide 46)

$$C_j = A\frac{\varepsilon_S}{X_{dep}} \approx 1.4 C_{j0}$$

# Slide 47)




$$C_d = \frac{1}{2}\frac{qI_d}{kT}\tau$$