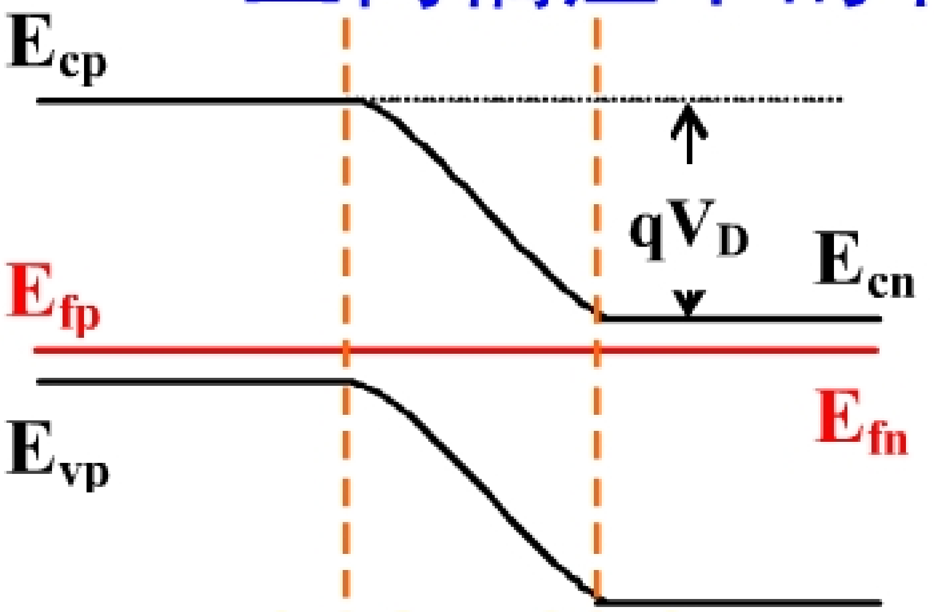
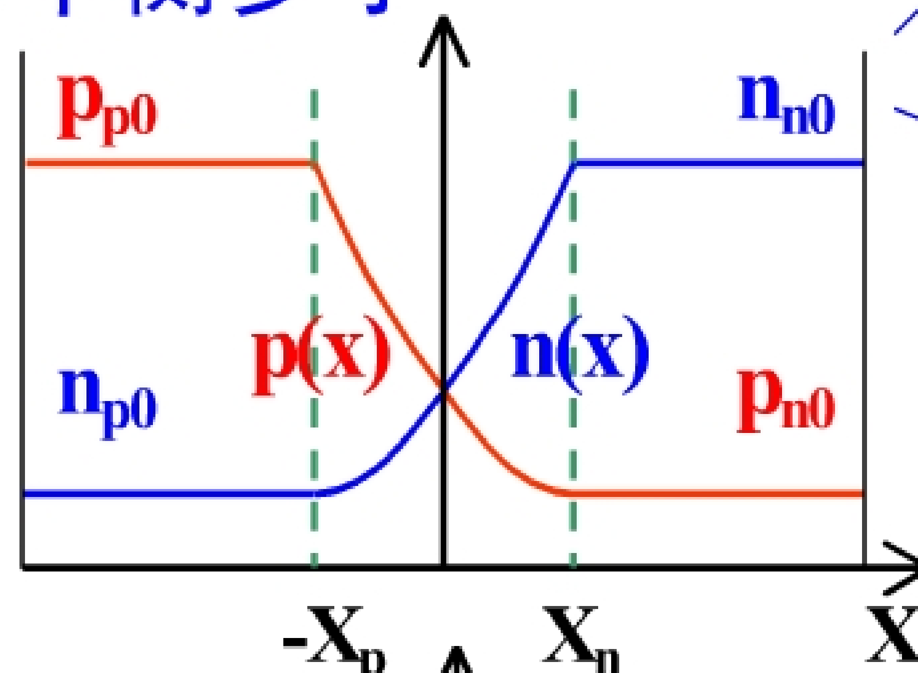
8.2 p-n结电流电压特性8

8.2.2 非平衡p-n结的能带图

—正向偏压下的非平衡少子





$$n(-x_p)=n_{p0}=n_{n0}\exp\left(-\frac{qV_D}{kT}\right)$$

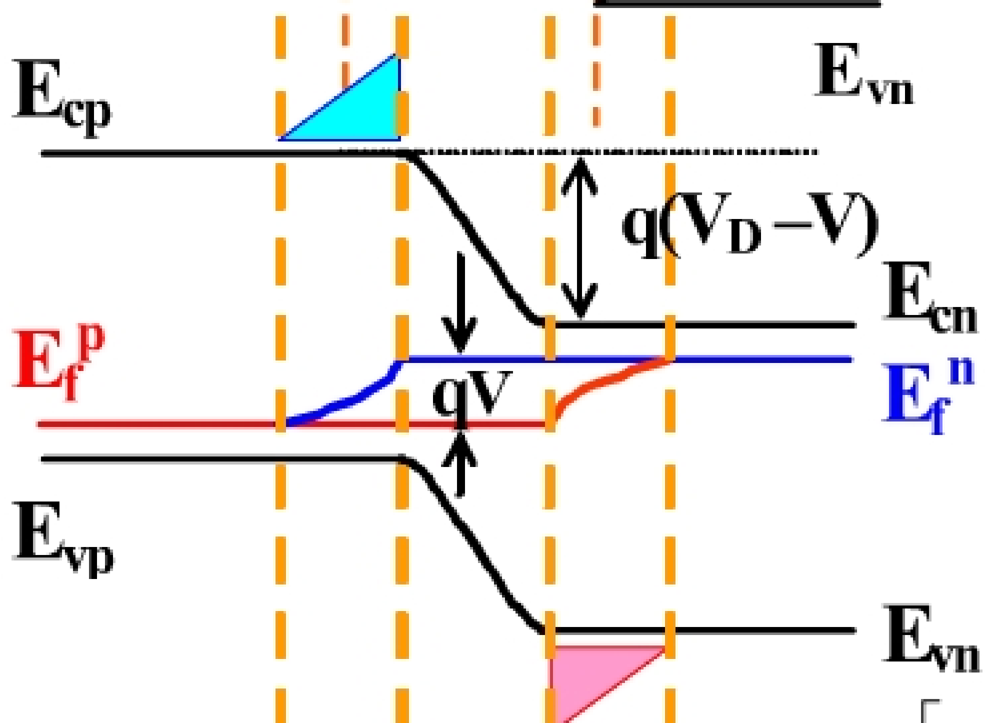
$$p(x_n)=p_{n0}=p_{p0}\exp\left(-\frac{qV_D}{kT}\right)$$

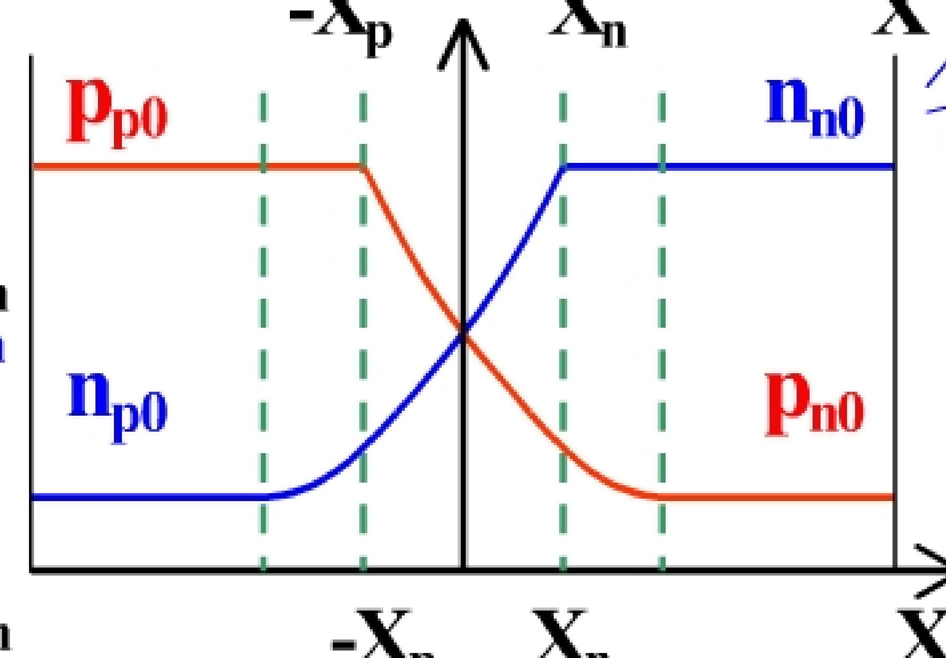
$$p(x_n)=p_{p0}\exp\left(-\frac{q(V_D-V)}{kT}\right)$$

$$p(x_n)=p_{n0}\exp\left(\frac{qV}{kT}\right)$$

$$\Delta p(x_n)=p_{n0}\left[\exp\left(\frac{qV}{kT}\right)-1\right]$$

$x > x_n$ $\Delta p(x)=p(x)-p_{n0}$





$$\Delta n(-x_p)=n_{p0}\left[\exp\left(\frac{qV}{kT}\right)-1\right]$$

注入到P区的非平衡电子

$$\boxed{\Delta n(x)=\Delta n(-x_p)\exp\left(\frac{x+x_p}{L_n}\right)}$$

注入到N区的非平衡空穴

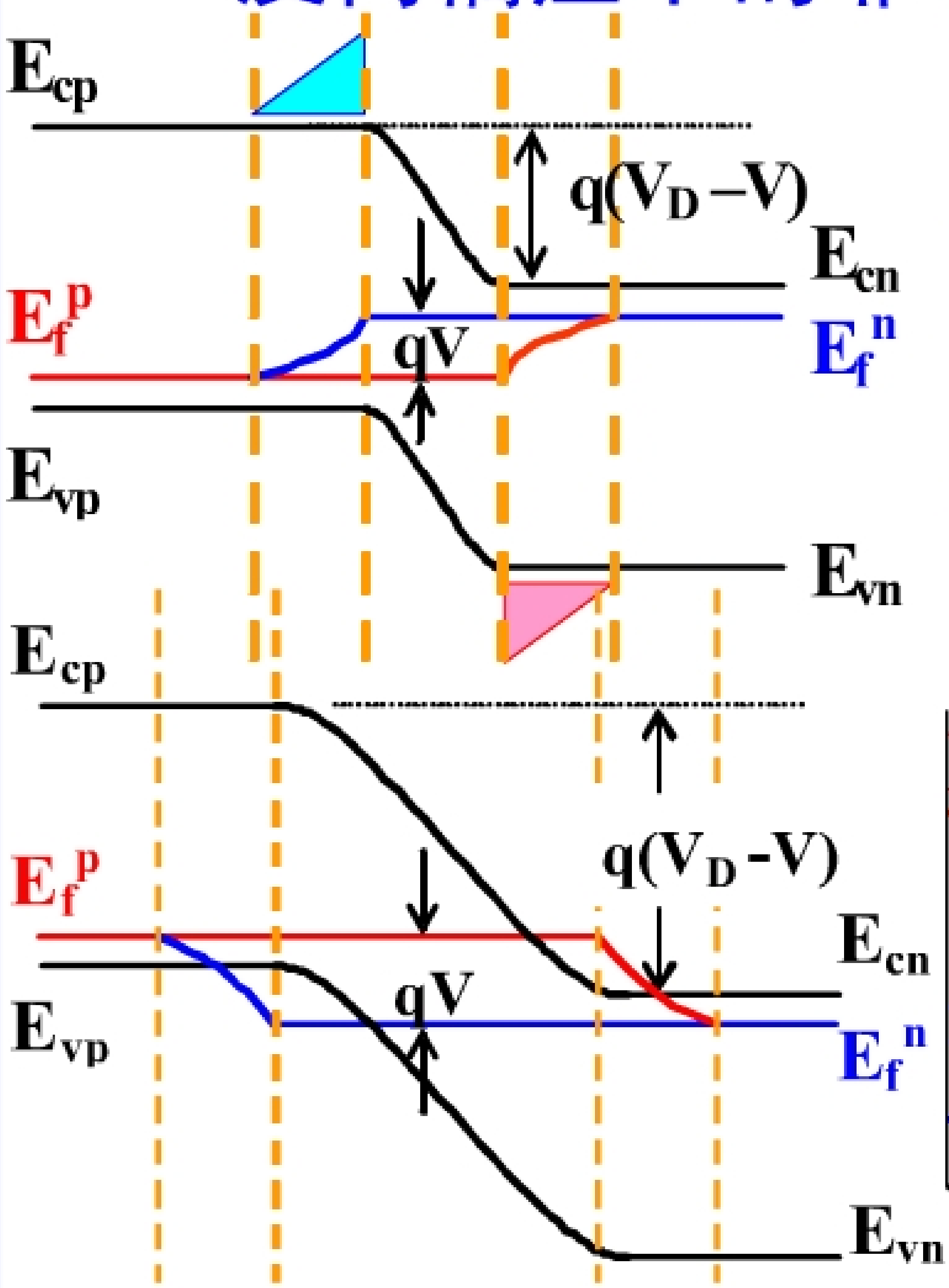
无限厚样品的稳态扩散解

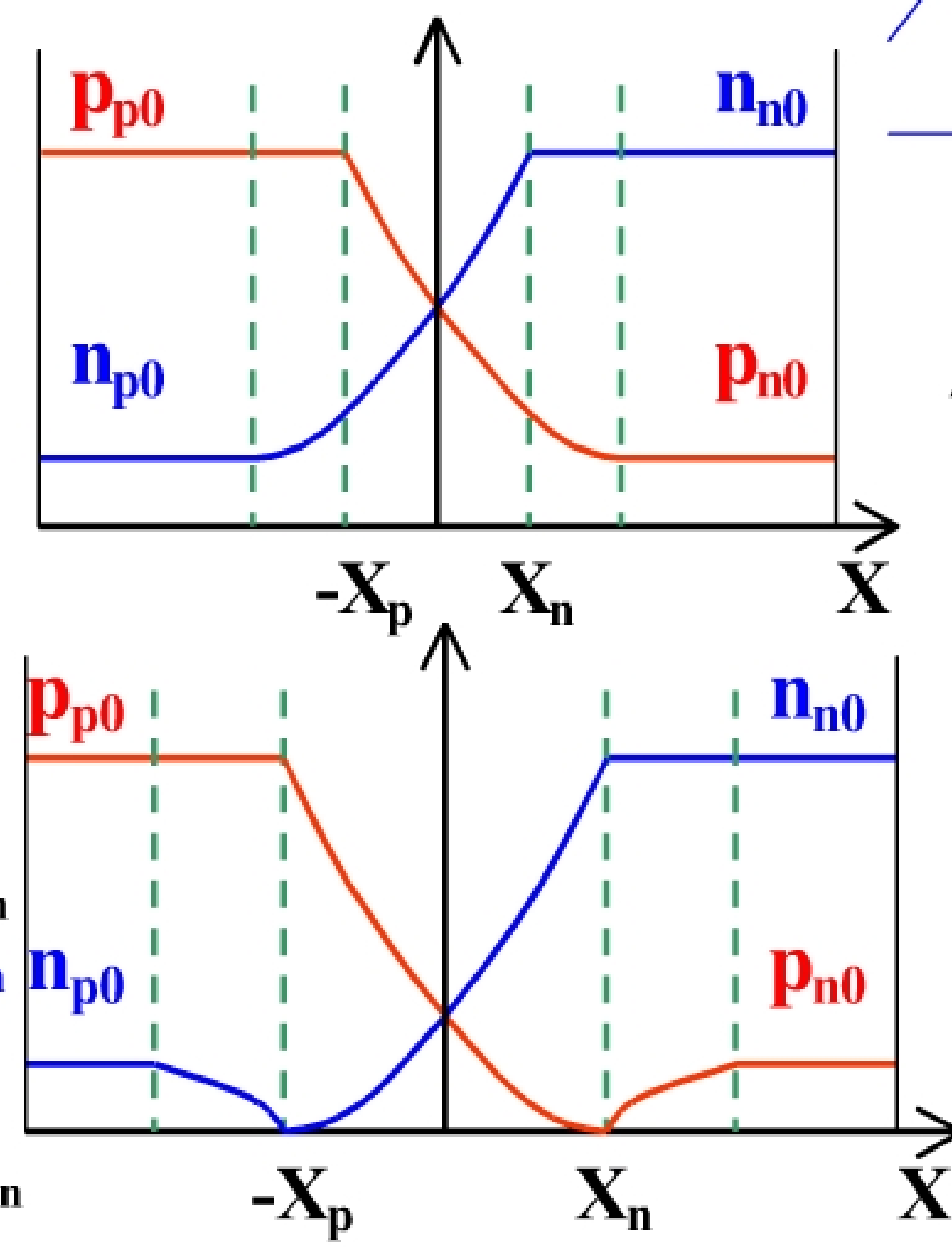
$$\boxed{\Delta p(x)=\Delta p(x_n)\exp\left(-\frac{x-x_n}{L_p}\right)}$$

8.2 p-n结电流电压特性9

8.2.2 非平衡p-n结的能带图

—反向偏压下的非平衡少子





$$\Delta p(x_n) = p_{n0}\left[\exp\left(\frac{qV}{kT}\right)-1\right]$$

$$\Delta n(-x_p) = n_{p0}\left[\exp\left(\frac{qV}{kT}\right)-1\right]$$

$$\Delta p(x) = \Delta p(x_n)\exp\left(-\frac{x-x_n}{L_p}\right)$$

$$\Delta n(x) = \Delta n(-x_p)\exp\left(\frac{x+x_p}{L_n}\right)$$

$V<0$ $\quad q|V| >> kT$

=0

抽取

$$\Delta p(x_n) = p(x_n) - p_{n0} = -p_{n0}$$

$$\Delta n(-x_p) = n(-x_p) - n_{p0} = -n_{p0}$$

$$\boxed{\Delta n(x) = -n_{p0}\exp\left(\frac{x+x_p}{L_n}\right)}$$

$$\boxed{\Delta p(x) = -p_{n0}\exp\left(-\frac{x-x_n}{L_p}\right)}$$

8.2 p-n结电流电压特性10

8.2.3 理想p-n结的J-V关系

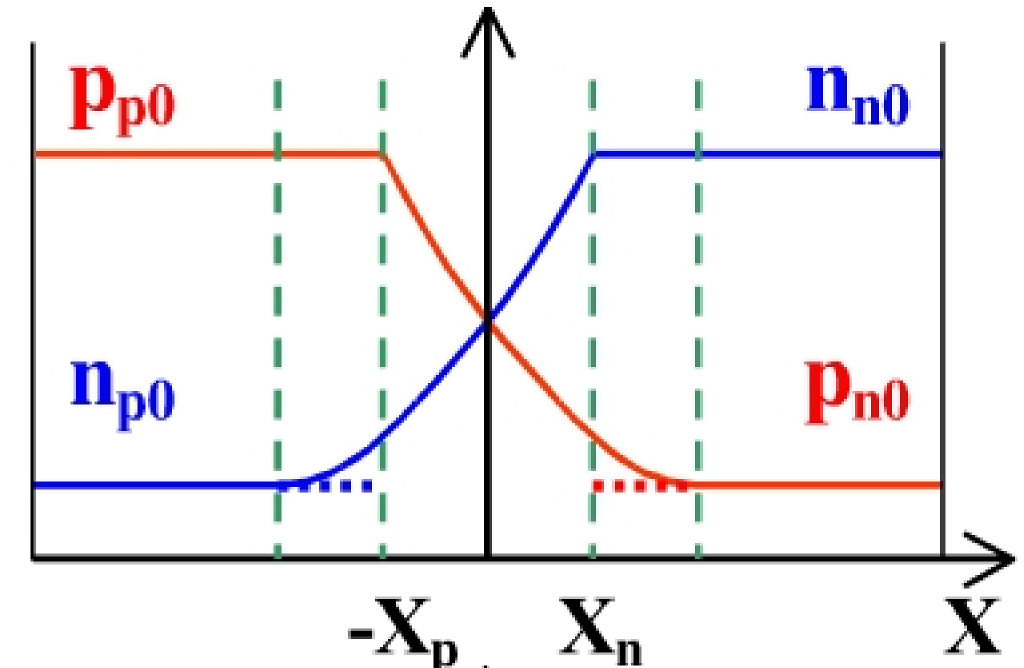
前提：

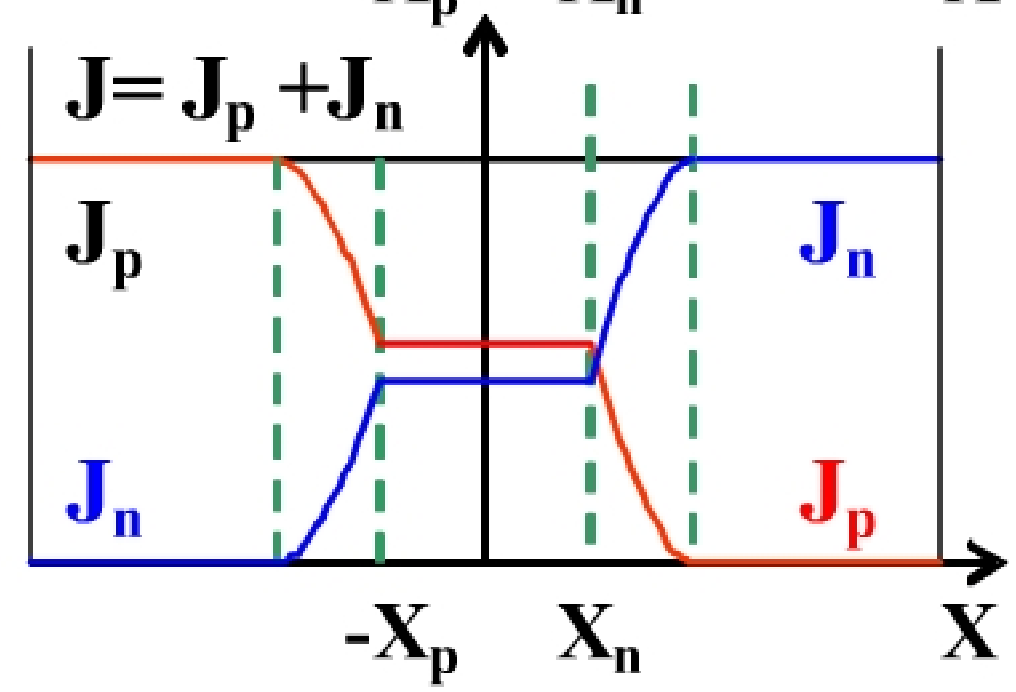
—小注入 $\Delta n_p << p_{p0} \qquad \Delta p_n << n_{n0}$

—突变耗尽层条件 （耗尽层外电中性）

—忽略势垒区中载流子的产生、复合

—非简并





扩散电流组成

$\boxed{\text{电流密度}}$ $\longrightarrow$ $J = J_p(x_n) + J_n(x_n)$

$$J = J_p + J_n \qquad\qquad = J_p(x_n) + J_n(-x_p)$$

$$\Delta p(x) = \Delta p(x_n)\exp\left(-\frac{x-x_n}{L_p}\right) \leftarrow \Delta p(x_n) = p_{n0}\left[\exp\left(\frac{qV}{kT}\right)-1\right]$$

$$\downarrow$$

$$J_p(x_n) = -qD_p\frac{d\Delta p}{dx}\Big|_{x=x_n} = \frac{qD_p}{L_p}p_{n0}\left[\exp\left(\frac{qV}{kT}\right)-1\right] \leftrightarrow J_n(-x_p) = \frac{qD_n}{L_n}n_{p0}\left[\exp\left(\frac{qV}{kT}\right)-1\right]$$

$$\boxed{J_s = \left(\frac{qD_p n_i^2}{L_p N_D} + \frac{qD_n n_i^2}{L_n N_A}\right) \quad p_{n0} = \frac{n_i^2}{N_D} \quad n_{p0} = \frac{n_i^2}{N_A}} \rightarrow \boxed{J = J_s\left[\exp\left(\frac{qV}{kT}\right)-1\right]}$$

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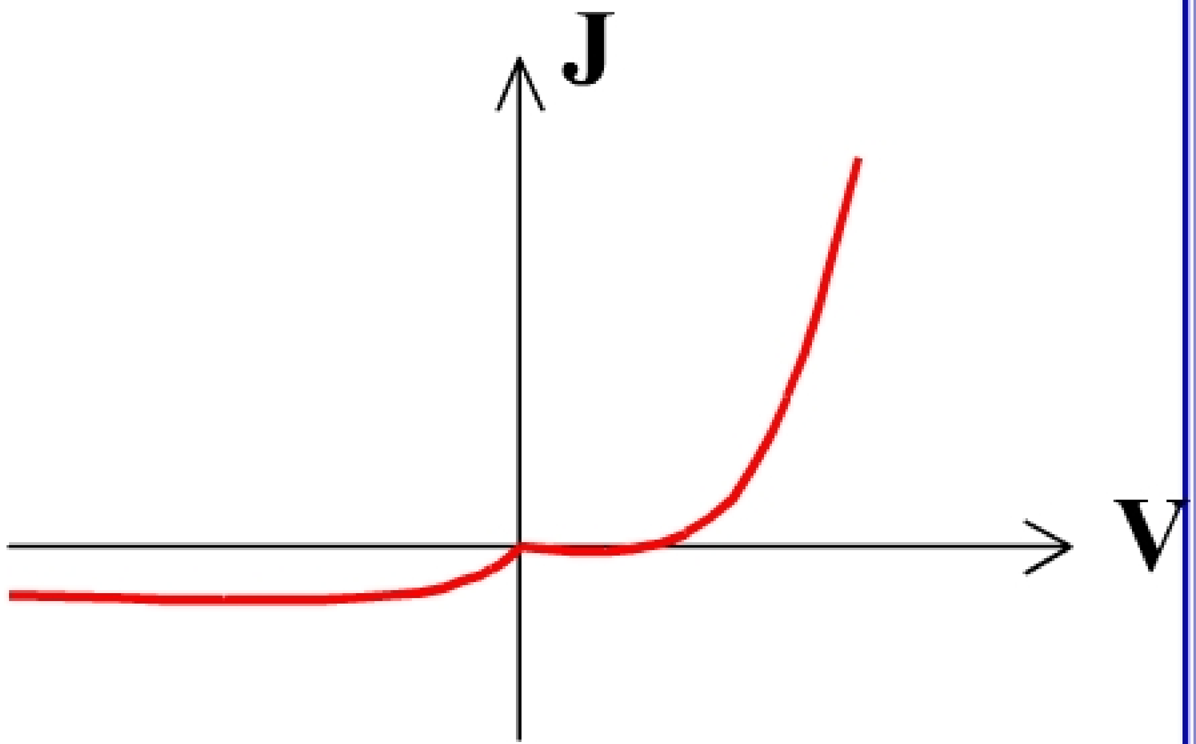
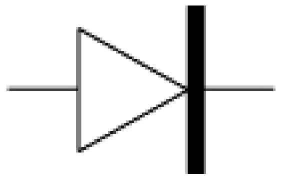
8.2.4 理想p-n结J-V关系的特性

$$\boxed{J = J_s\left[\exp\left(\frac{qV}{kT}\right) - 1\right]} \quad J_s = \left(\frac{qD_p n_i^2}{L_p N_D} + \frac{qD_n n_i^2}{L_n N_A}\right)$$



—整流特性



$$J = J_s \exp\left(\frac{qV}{kT}\right) \quad qV/kT >> 1$$

$$J = -J_s \quad -qV/kT >> 1$$

Js：反向饱和电流密度

—强烈依赖温度

$$J_s \propto T^{3+\frac{\gamma}{2}} \exp\left(-\frac{E_g}{kT}\right)$$

$$J \propto T^{3+\frac{\gamma}{2}} \exp\left[\frac{q(V - V_{g0})}{kT}\right]$$

8.2 p-n结电流电压特性12

8.2.5 理想p-n结J-V关系的修正

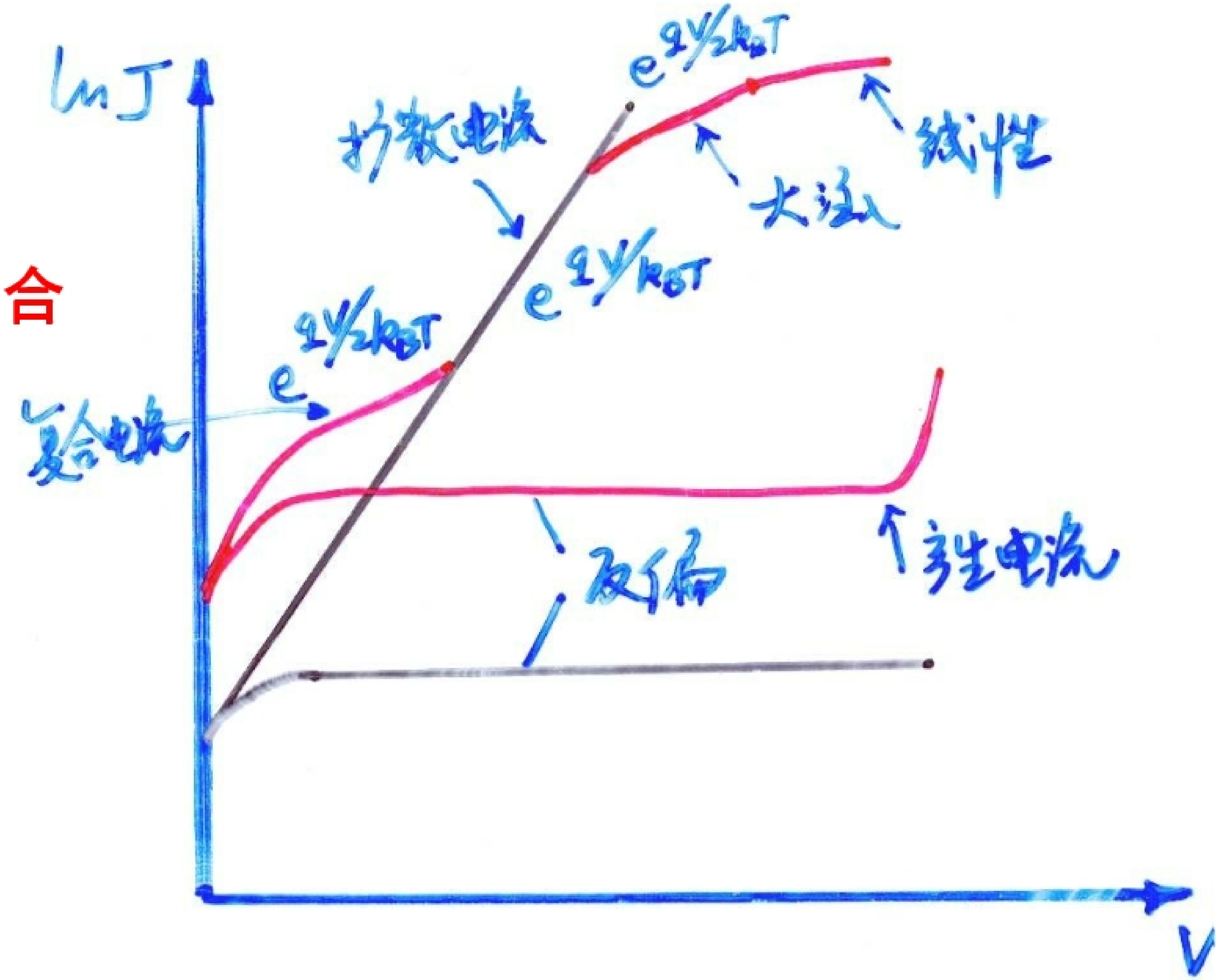
可能因素：

—表面效应

—势垒区中的产生和复合

—大注入条件

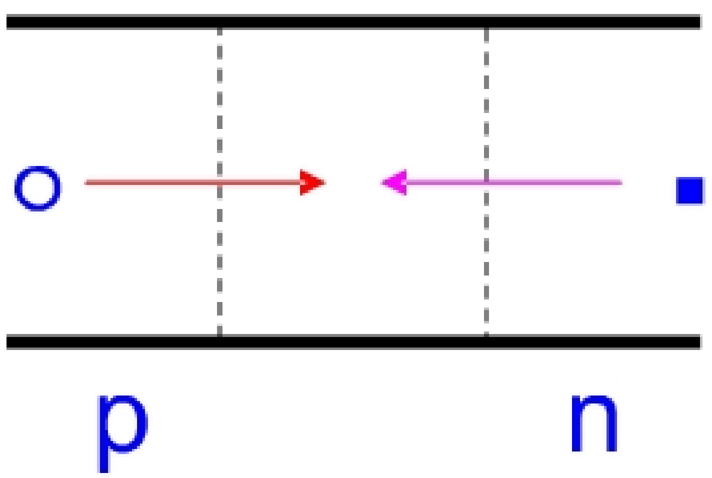
—串联电阻



8.2 p-n结电流电压特性13

8.2.5 理想p-n结J-V关系的修正

一复合电流(正向偏压)



假设$E_t = E_i$, $n_1 = p_1 = n_i, r_n = r_p = r$

$$U = \frac{N_t r_n r_p \left(np - n_i^2\right)}{r_n\left(n + n_1\right) + r_p\left(p + p_1\right)} = \frac{N_t r\left(np - n_i^2\right)}{n + p + 2n_i}$$

$$n = n_i \exp\left(\frac{E_F^n - E_i}{kT}\right)$$

$$p = n_i \exp\left(\frac{E_i - E_F^p}{kT}\right)$$

$$\Rightarrow \quad np = n_i^2 \exp\left(\frac{E_F^n - E_F^p}{kT}\right) = n_i^2 \exp\left(qV_f / kT\right)$$

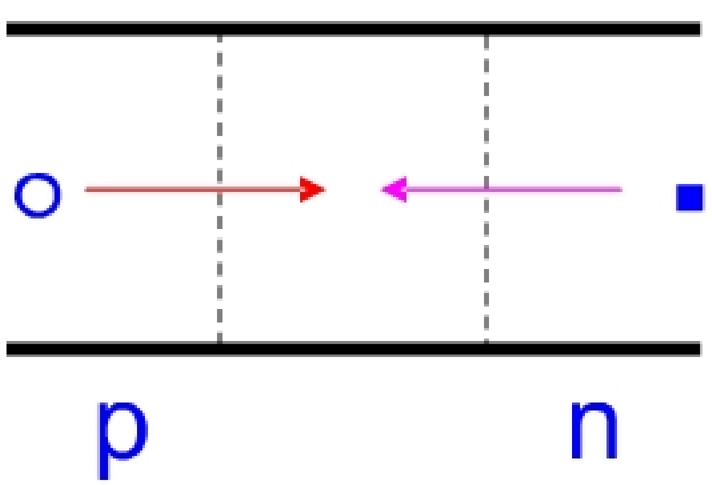
$n = p$时

$$U_{\max} = \frac{1}{2}\frac{n_i}{\tau}\exp\left(qV_f / \boxed{2}kT\right) \qquad \left(qV_f >> kT\right)$$

8.2 p-n结电流电压特性14

8.2.5 理想p-n结J-V关系的修正

一复合电流(正向偏压)



$$U_{\max}=\frac{1}{2}\frac{n_i}{\tau}\exp\left(qV_f/2kT\right)\qquad\left(qV_f>>kT\right)$$

$$J_r=\int_{-x_p}^{x_n}qU_{\max}dx=qU_{\max}X_D=\frac{qn_iX_D}{2\tau}\exp\left(qV_f/\boxed{2}kT\right)$$

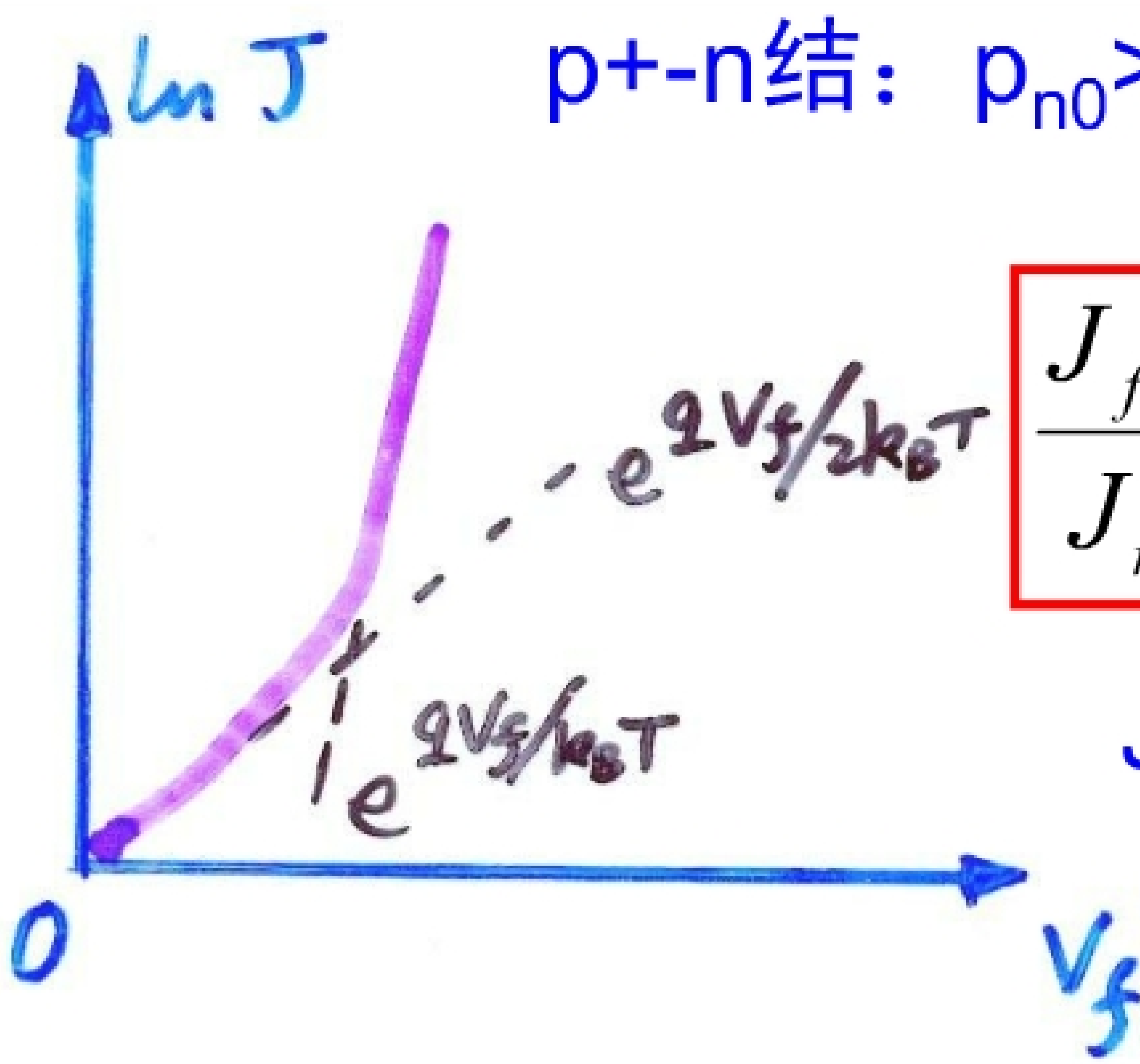
p+-n结：$p_{n0}>>n_{p0}$ & qV>>kT

$$J_{fd}=\frac{qD_pn_i^2}{L_pN_D}\exp\left(\frac{qV}{kT}\right)$$

$$\boxed{\frac{J_{fd}}{J_r}\propto\frac{2n_iL_p}{N_DX_D}\exp\left(qV/\boxed{2}kT\right)}$$

$\rightarrow$ $J_r>J_{fd}\quad(\mathrm{V}<<1)$

$J_{fd}>J_r\quad(\mathrm{V}>>1)$



J-V经验公式

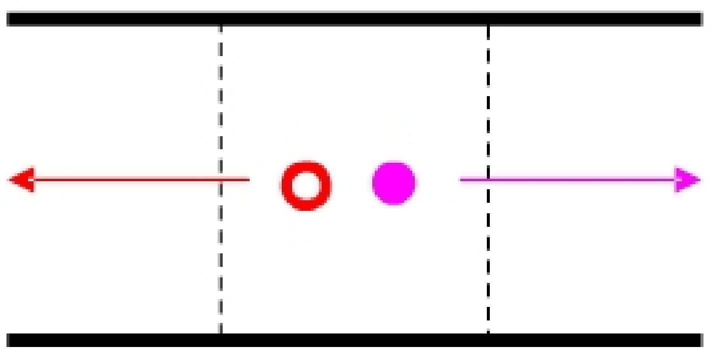
$$J_f\propto\exp\left(qV_f/mkT\right)$$

理想因子 $m:1\sim2$

8.2 p-n结电流电压特性15

8.2.5 理想p-n结J-V关系的修正

—产生电流(反向偏压)



$$n_i >> n, p; E_t = E_i; r_n = r_p = r$$

$$\downarrow$$

$$U = \frac{N_t r_n r_p \left(np - n_i^2\right)}{r_n\left(n + n_1\right) + r_p\left(p + p_1\right)} = -\frac{n_i}{2\tau}$$

$$\downarrow$$

$$\boxed{J_G = qGX_D = q\frac{n_i}{2\tau}X_D} \quad G = -U = \frac{n_i}{2\tau}$$

$$\downarrow$$

$$\boxed{\frac{J_{rd}}{J_G} = 2\frac{n_i}{N_D}\frac{L_p}{X_D}}$$

p+-n结

$$J_{rd} = J_s = \frac{qD_p n_i^2}{L_p N_D}$$

—J_s与反向偏压无关,J_G随反向偏压增加而增加

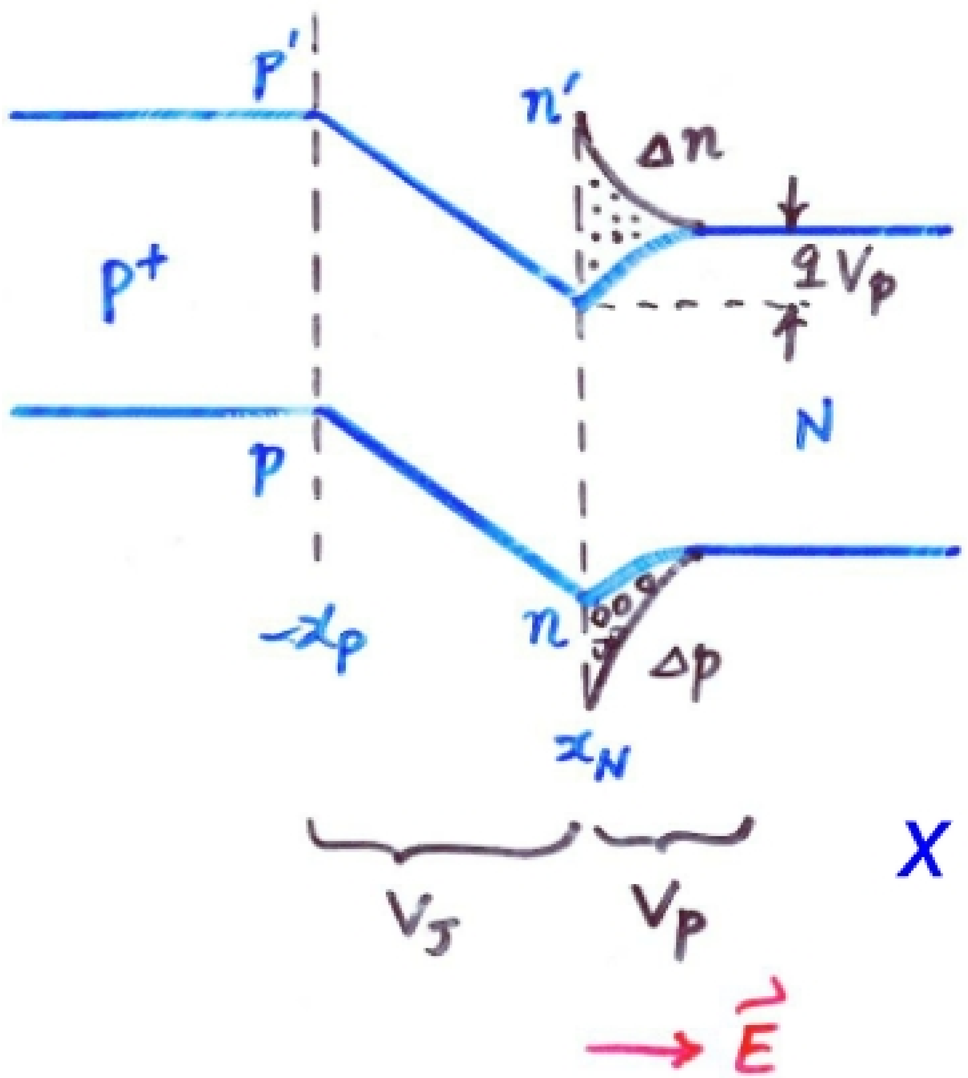
—禁带宽度小的半导体,反向漏电流将明显增加

—温度升高,反向漏电流将增加

—少子寿命越小,反向漏电流也就越大

8.2.5 理想p-n结J-V关系的修正

一大注入条件(正向大偏压)



p⁺n 结 $\Delta p_n(x_n) \geq n_{n0} = N_D$

电中性条件 $\Delta p_n(x) = \Delta n_n(x)$

$$\frac{d\Delta p_n(x)}{dx} = \frac{d\Delta n_n(x)}{dx}$$

内建电场 $J_n = 0$ $\quad V = V_J + V_p$

$x = x_n$ $$J_p = q\mu_p p_n(x_n)E(x_n) - qD_p \left.\frac{d\Delta p_n(x)}{dx}\right|_{x=x_n}$$

$$J_n = q\mu_n n_n(x_n)E(x_n) + qD_n \left.\frac{d\Delta n_n(x)}{dx}\right|_{x=x_n} = 0$$

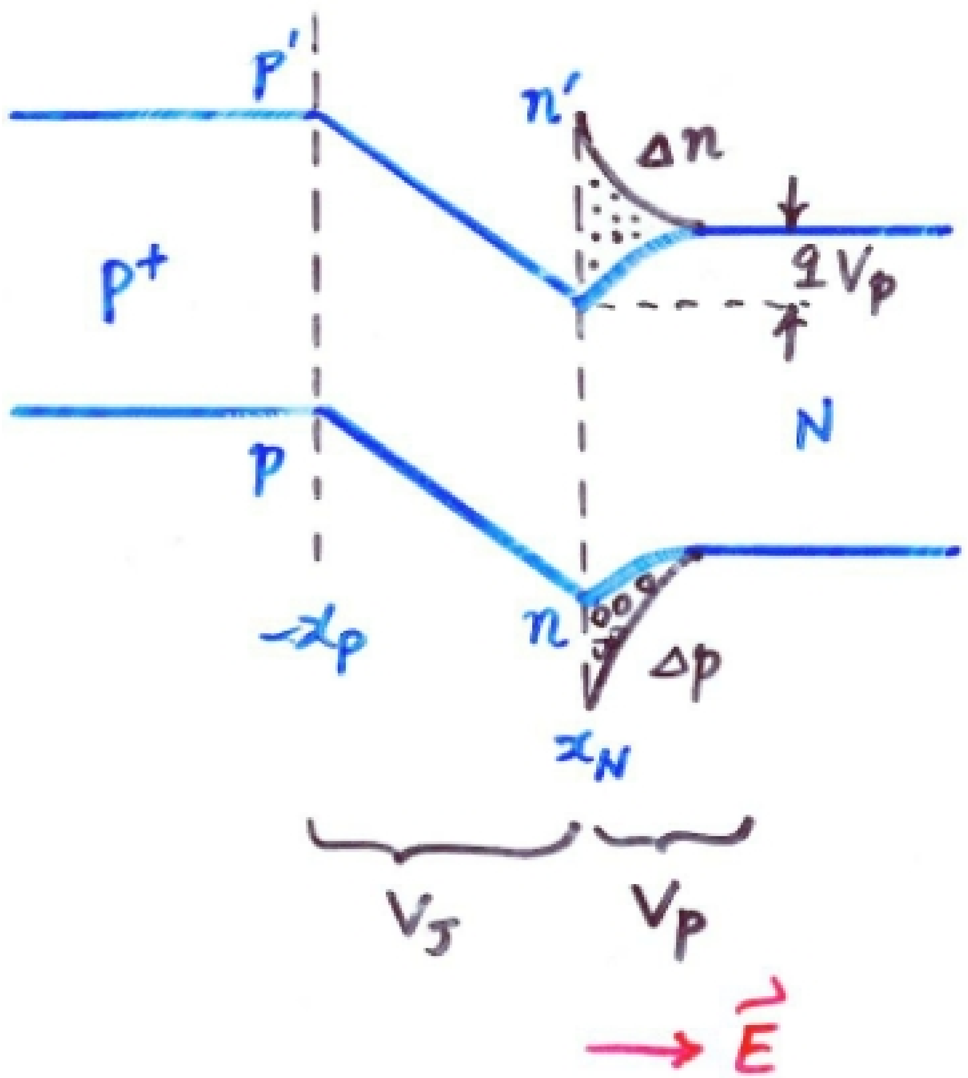
$$\downarrow$$

$$\boxed{E(x_n) = -\frac{D_n}{\mu_n}\frac{1}{n_n(x_n)}\left.\frac{d\Delta n_n(x)}{dx}\right|_{x=x_n}}$$

8.2 p-n结电流电压特性17

8.2.5 理想p-n结J-V关系的修正

一大注入条件(正向大偏压)



$$\longrightarrow J_p = -qD_p\left[1+\frac{p_n(x_n)}{n_n(x_n)}\right]\frac{d\Delta p_n(x)}{dx}\bigg|_{x=x_n}$$

$\Delta p_n >> n_{n0}$

$$D = 2D_p \longleftarrow = -2qD_p\frac{d\Delta p_n(x)}{dx}\bigg|_{x=x_n}$$

$$p_n(x_n) = p_{p0}\exp\left[-\frac{q(V_D - V_J)}{kT}\right] = p_{n0}\exp(qV_J/kT)$$

$$n_n(x_n) = n_{n0}\exp(qV_p/kT)$$

$$p_n(x_n)n_n(x_n) = n_{n0}p_{n0}\exp\left[\frac{q(V_p+V_J)}{kT}\right] = n_i^2\exp(qV/kT)$$

$$p_n(x_n) \approx n_n(x_n)$$

$$\boxed{p_n(x_n) = n_i\exp(qV/2kT)}$$

8.2 p-n结电流电压特性17

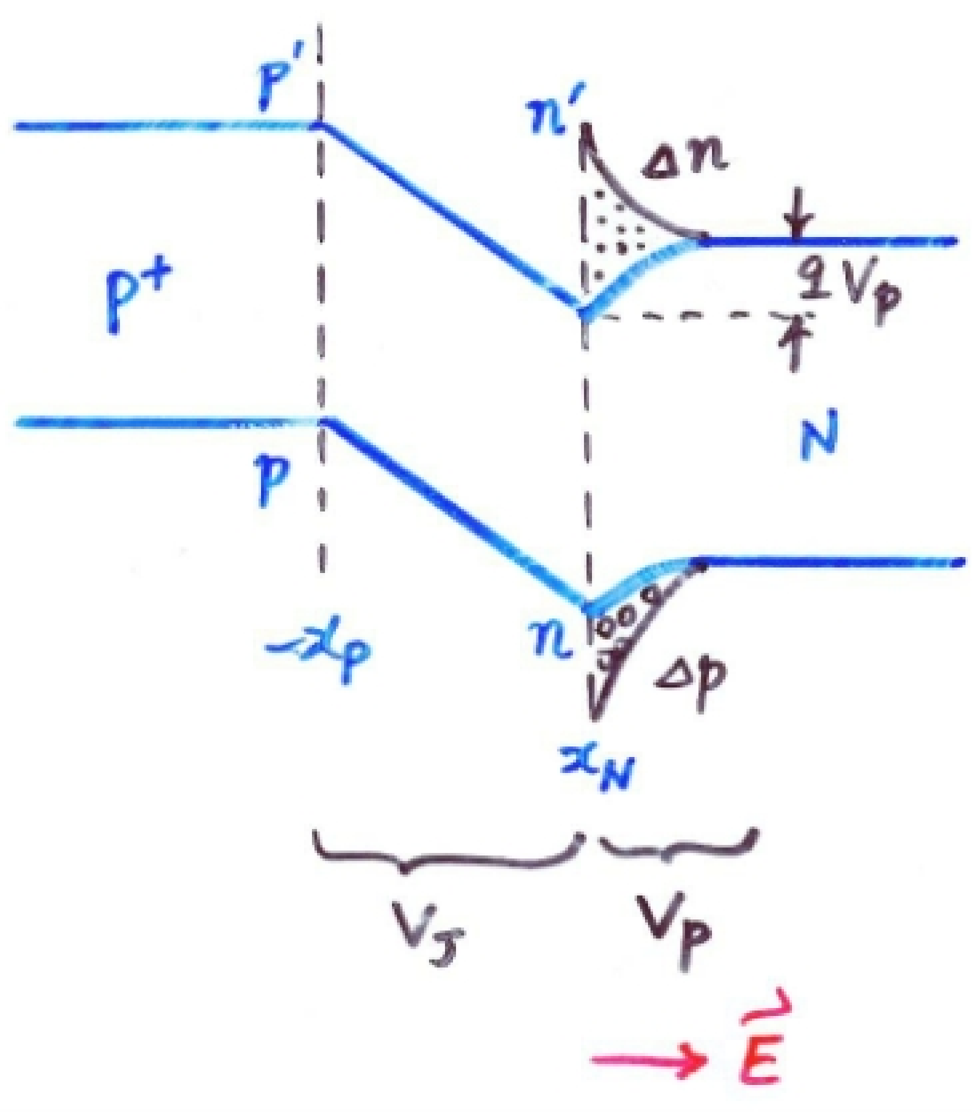
8.2.5 理想p-n结J-V关系的修正

—大注入条件(正向大偏压)

$$p_n(x_n) = n_i \exp(qV/2kT) \longrightarrow J_p = -2qD_p \left.\frac{d\Delta p_n(x)}{dx}\right|_{x=x_n}$$

线性分布近似

$$\left.\frac{d\Delta p_n(x)}{dx}\right|_{x=x_n} \approx -\frac{p_n(x_n) - p_{n0}}{L_p} \approx -\frac{n_i}{L_p}\exp(qV/2kT)$$



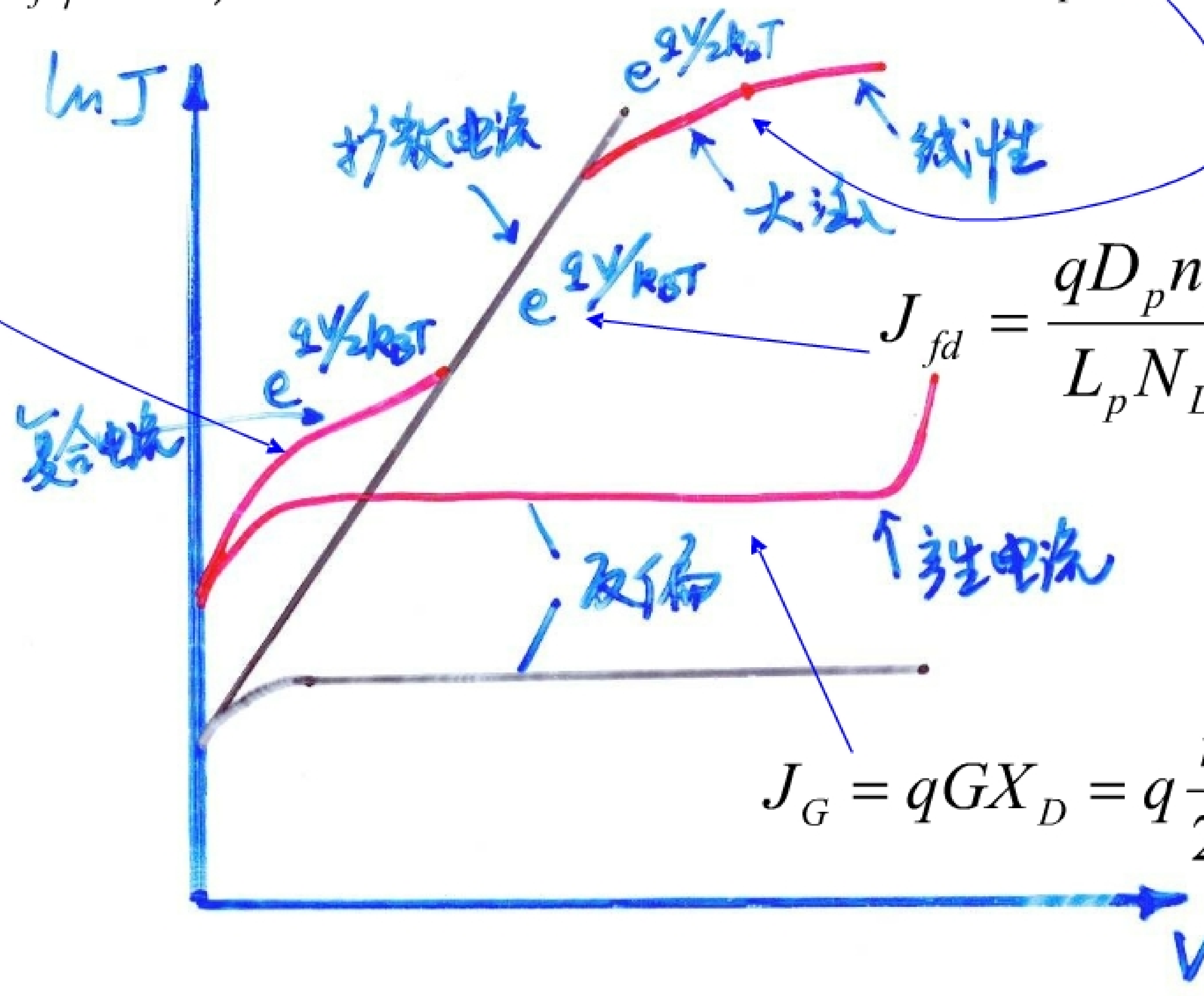
$$J_f = q(2D_p)\frac{n_i}{L_p}\exp(qV/\boxed{2}kT)$$

8.2.5 理想p-n结J-V关系的修正

—总结

$$J_r = \frac{q n_i X_D}{2\tau} \exp\left(qV_f / 2kT\right)$$

$$J_f = q\left(2D_p\right)\frac{n_i}{L_p}\exp\left(qV/2kT\right)$$



$$J_{fd} = \frac{q D_p n_i^2}{L_p N_D}\exp\left(\frac{qV}{kT}\right)$$

$$J_G = qGX_D = q\frac{n_i}{2\tau}X_D$$