二極體原理

1.二極體之基本結構---pn 接面

2.二極體的電流電壓特性--- $I = I_S\left(e^{\frac{v_D}{\eta V_T}} - 1\right)$

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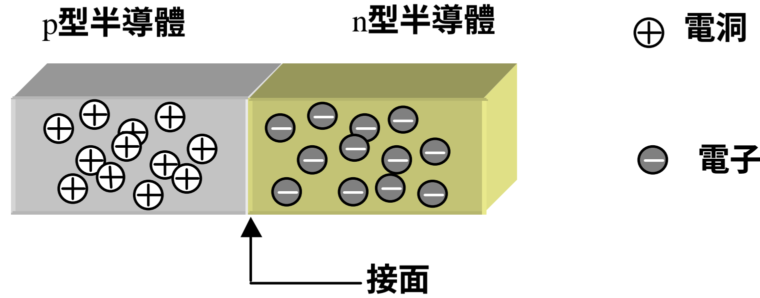
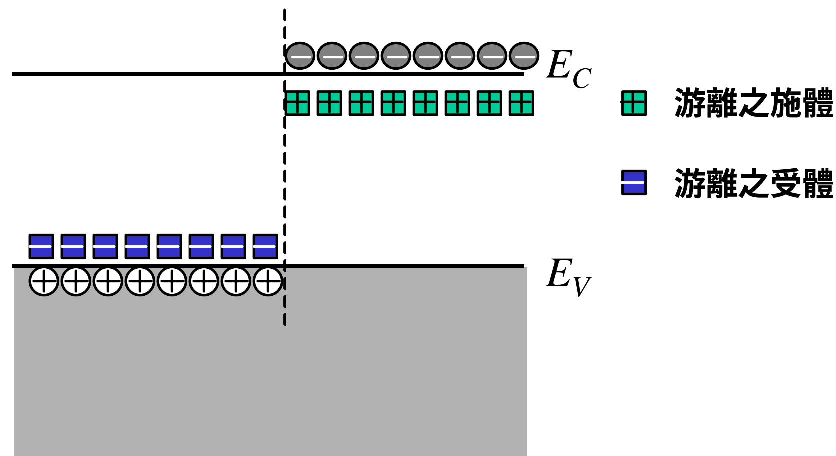
1. 二極體之基本結構---pn 接面

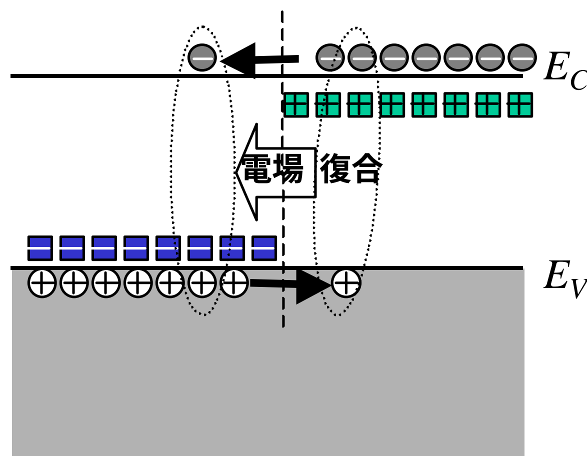
A. 接面與空乏區(Junction and depletion region)

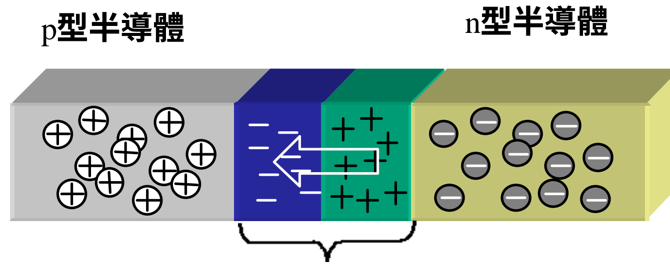


能帶圖（電中性）

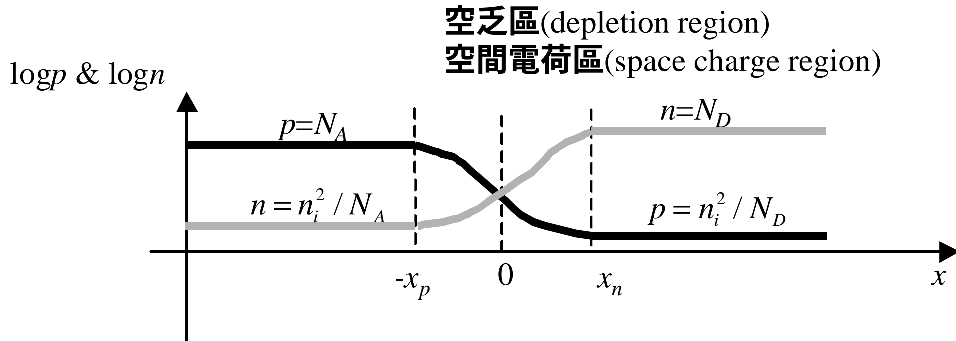


由於電子與電洞之分布不均勻產生擴散，
擴散後電中性被破壞，產生電場。





空乏區(depletion region)
空間電荷區(space charge region)



ρ(x) charge density

由全域之電中性

$x_n N_D = x_p N_A$

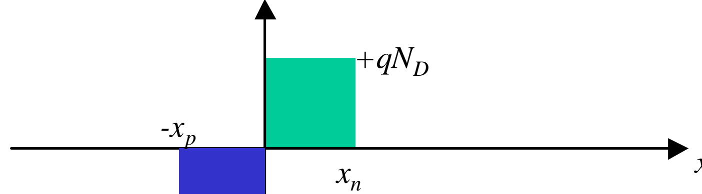
即

$$x_n = \frac{N_A}{N_A + N_D} x_d$$

$$x_p = \frac{N_D}{N_A + N_D} x_d$$

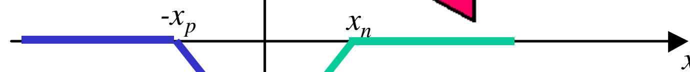
$$x_d = x_n + x_p$$

x_d **空乏區寬度**



$$\frac{dE}{dx} = \frac{\rho}{\varepsilon_{Si}}$$

E(x) electric field

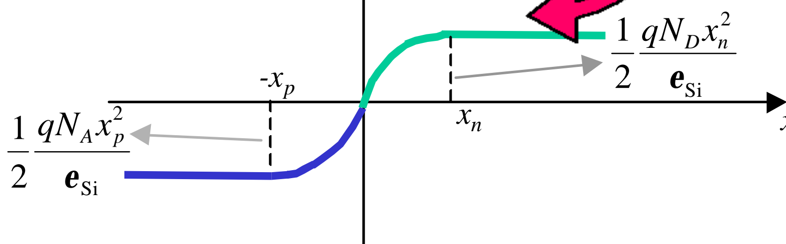


$$|E_{max}| = \frac{qN_D x_n}{\varepsilon_{Si}} = \frac{qN_A x_p}{\varepsilon_{Si}}$$

-/E_max/

$$\frac{dV}{dx} = -E$$

V(x) electric potential

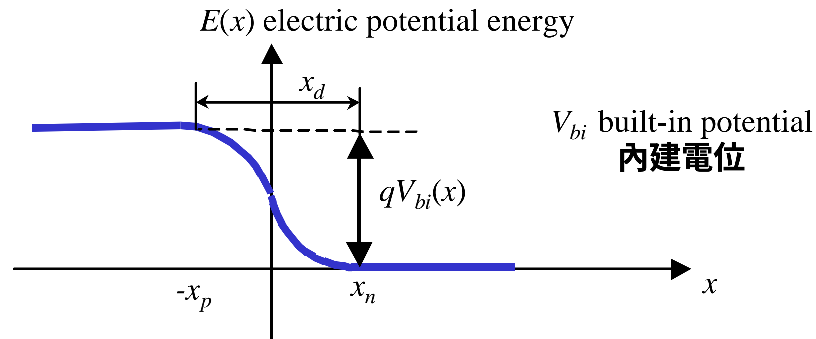


$$\frac{1}{2}\frac{qN_D x_n^2}{\varepsilon_{Si}}$$

$$\frac{1}{2}\frac{qN_A x_p^2}{\varepsilon_{Si}}$$

對電子而言，電位能 $E = -qV$

$E \downarrow \quad V \uparrow$



$$V_{bi} = \frac{1}{2}\frac{qN_A x_p^2}{\varepsilon_{Si}} + \frac{1}{2}\frac{qN_D x_n^2}{\varepsilon_{Si}}$$

$$= \frac{1}{2}\frac{q}{\varepsilon_{Si}}\left(N_A x_p^2 + N_D x_n^2\right)$$

$$= \frac{1}{2}\frac{q}{\varepsilon_{Si}}\left(N_A\left(\frac{N_D}{N_A+N_D}\right)^2 x_d^2 + N_D\left(\frac{N_A}{N_A+N_D}\right)^2 x_d^2\right)$$

$$= \frac{1}{2}\frac{q}{\varepsilon_{Si}}\left(\frac{N_A N_D}{N_A+N_D}\right)x_d^2$$

$$x_d = \sqrt{\frac{2\varepsilon_{Si}V_{bi}}{q}\left(\frac{N_A+N_D}{N_A N_D}\right)}$$

對one-sided abrupt junction:

- n^+-p ($N_D >> N_A$) $x_d \sim x_p$ $\quad V_{bi} = \frac{1}{2}\frac{qN_A x_d^2}{\varepsilon_{Si}}$
- n-p^+ ($N_A >> N_D$) $x_d \sim x_n$ $\quad V_{bi} = \frac{1}{2}\frac{qN_D x_d^2}{\varepsilon_{Si}}$

求內建電位 V_{bi}

這裡我們用到在平衡時電洞(電子)流為零，即擴散電流和漂移電流底消。

$$J_p = qp\mu_p E - qD_p \frac{dp}{dx} = 0$$

$$E = \frac{D_p}{\mu_p}\frac{dp}{pdx} = -\frac{dV}{dx}$$

$=kT/q$ Einstein Relationship

$$dV = -\frac{kT}{q}\frac{dp}{p}$$

積分範圍由空乏區的一端 $-x_p$ **積分到另一端**x_n

$$V_{bi} = \int_{-x_p}^{x_n} dV = -\frac{kT}{q}\int_{p(-x_p)}^{p(x_n)}\frac{dp}{p} = -\frac{kT}{q}\ln p\Big|_{p(-x_p)}^{p(x_n)}$$

$$= -\frac{kT}{q}\ln p\Big|_{N_A}^{n_i^2/N_D} = -\frac{kT}{q}\left(\ln\frac{n_i^2}{N_D} - \ln N_A\right)$$

$$V_{bi} = \frac{kT}{q}\ln\frac{N_A N_D}{n_i^2} = \frac{kT}{q}\left(\ln\frac{N_A}{n_i} + \ln\frac{N_D}{n_i}\right)$$

給定 N_A**及**N_D

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

計算內建電位 V_{bi}

$$x_d = \sqrt{\frac{2\varepsilon_{Si}V_{bi}}{q}\left(\frac{N_A + N_D}{N_A N_D}\right)}$$

計算空乏區寬度 x_d

例題 300K的Si，n_i=1.45×10^10 cm^-3

(A) $N_A = N_D = 10^{19}$ cm^{-3}

$$V_{bi} = \frac{kT}{q}\ln\frac{N_A N_D}{n_i^2} = 25.8\text{mV}\ln\frac{10^{19}\times 10^{19}}{\left(1.45\times 10^{10}\right)^2}$$

$$= 1050\text{mV} = 1.05\text{V}$$

$$x_d = \sqrt{\frac{2\varepsilon_{\text{Si}} V_{bi}}{q}\left(\frac{N_A + N_D}{N_A N_D}\right)}$$

$$= \sqrt{\frac{2\times 1.05\times 10^{-12}(\text{F/cm})1.05\text{V}}{1.6\times 10^{-19}\text{C}}\left(\frac{10^{19}+10^{19}}{10^{19}\times 10^{19}}\left(\text{cm}^3\right)\right)}$$

$$= 1.66\times 10^{-6}\text{cm} = 16.6\text{nm}$$

(B) $N_A = 10^{17}$ cm^{-3}，$N_D = 10^{19}$ cm^{-3}

$$V_{bi} = \frac{kT}{q}\ln\frac{N_A N_D}{n_i^2} = 25.8\text{mV}\ln\frac{10^{17}\times 10^{19}}{\left(1.45\times 10^{10}\right)^2}$$

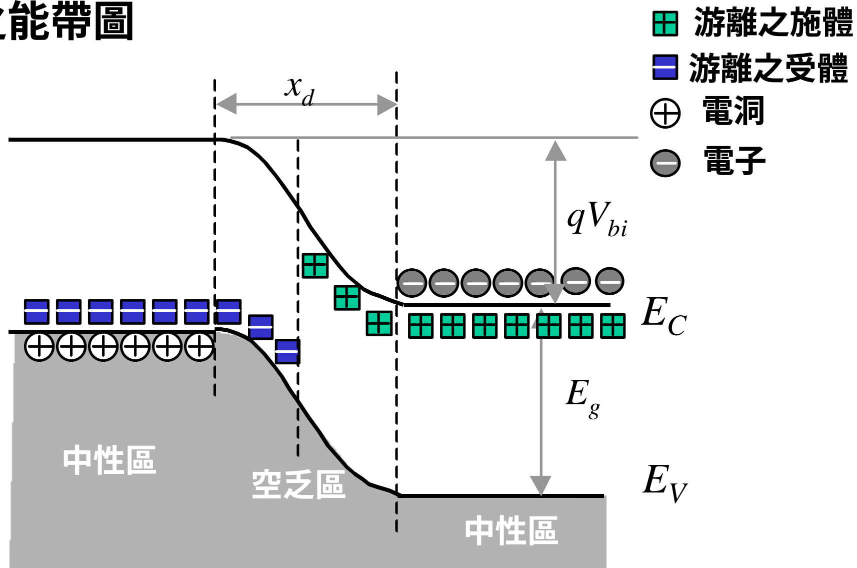
$$= 931\text{mV} = 0.93\text{V}$$

$$x_d = \sqrt{\frac{2\varepsilon_{\text{Si}} V_{bi}}{q}\left(\frac{N_A + N_D}{N_A N_D}\right)}$$

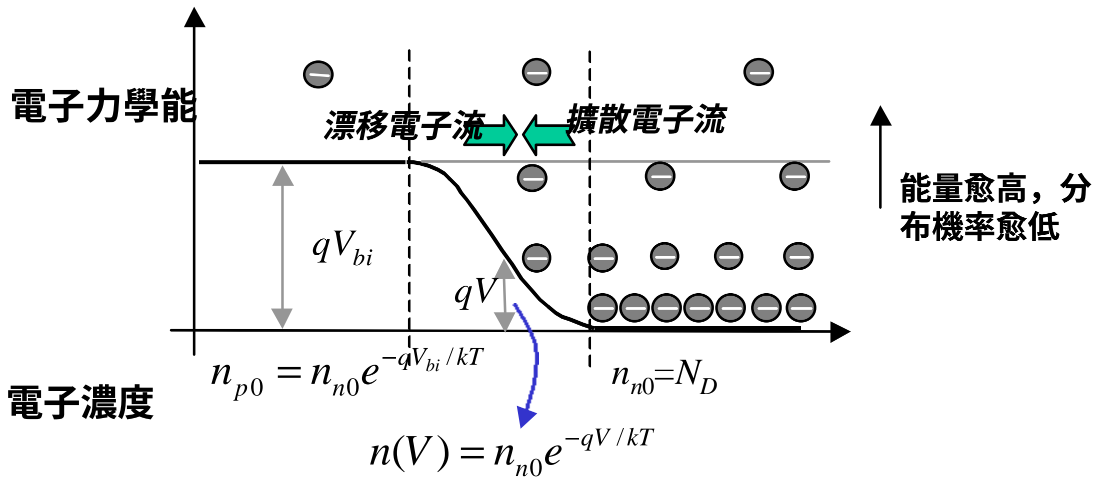
$$= \sqrt{\frac{2\times 1.05\times 10^{-12}(\text{F/cm})0.93\text{V}}{1.6\times 10^{-19}\text{C}}\left(\frac{10^{17}+10^{19}}{10^{17}\times 10^{19}}\left(\text{cm}^3\right)\right)}$$

$$= 1.11\times 10^{-5}\text{cm} = 111\text{nm}$$

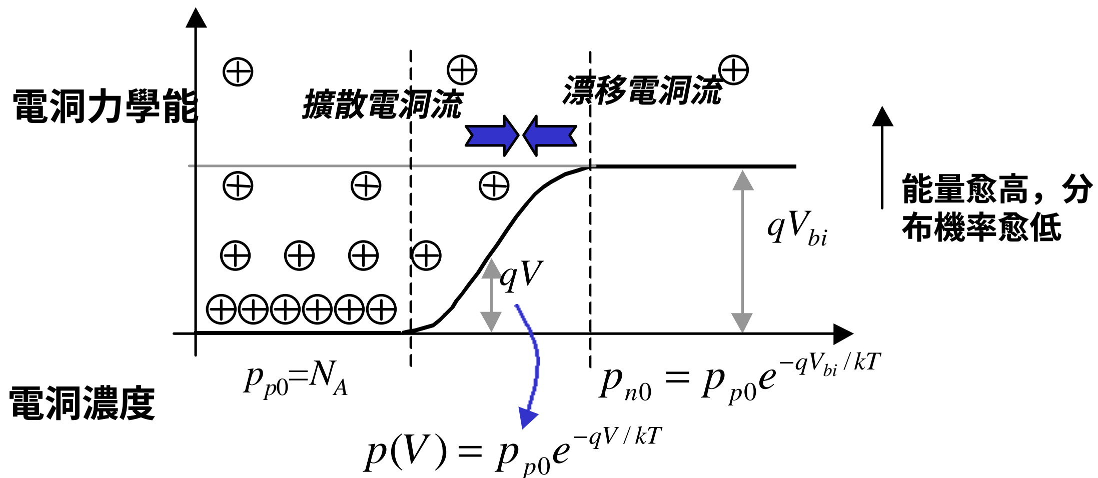
平衡時之能帶圖



電子所見到之位能分布及電子分布示意圖

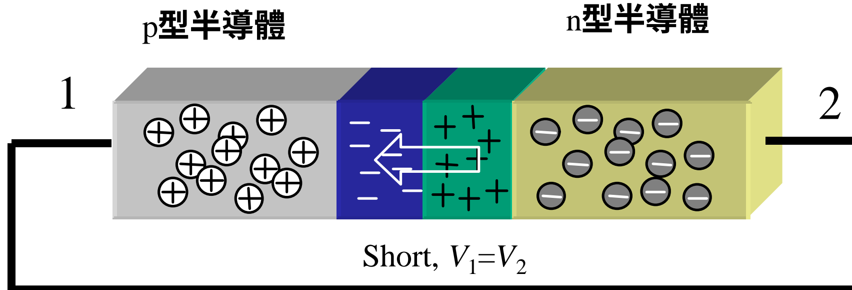


電洞所見到之位能分布及電洞分布示意圖

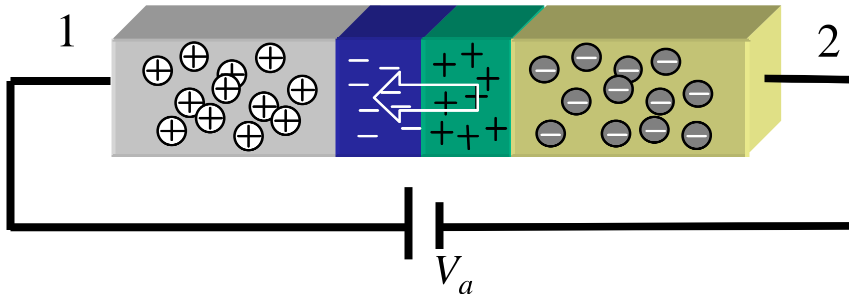


B. 加偏壓後之pn接面

上節所討論的接面，p及n兩極並沒有加電壓，即

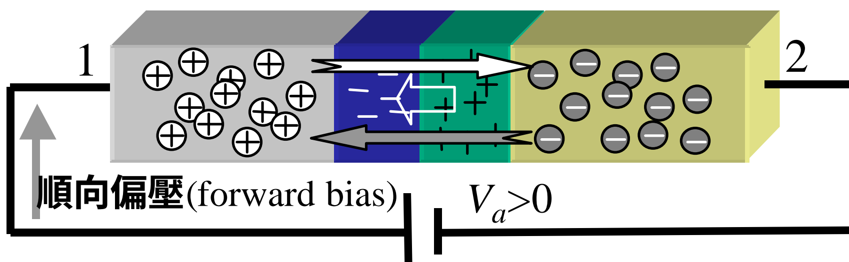


假如有加電壓，即V_1-V_2= V_a≠0，結果如何？

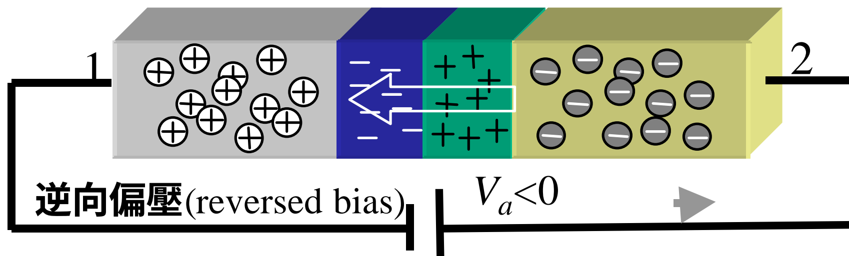


直覺圖像

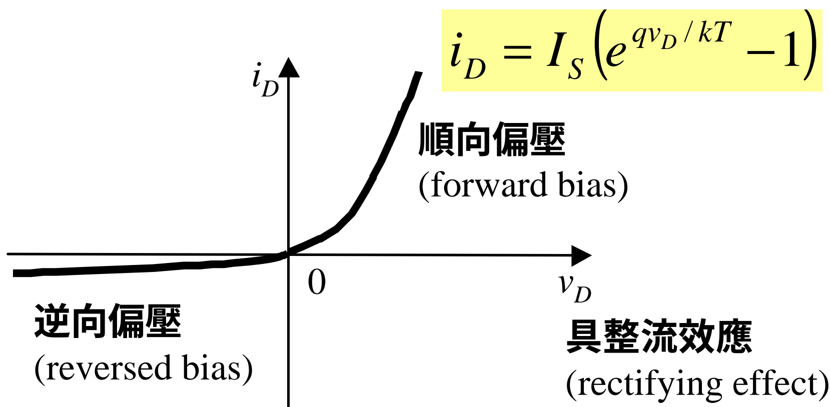
假如V_1-V_2= V_a>0，外加電場方向和內建電場相反，結果電場變小



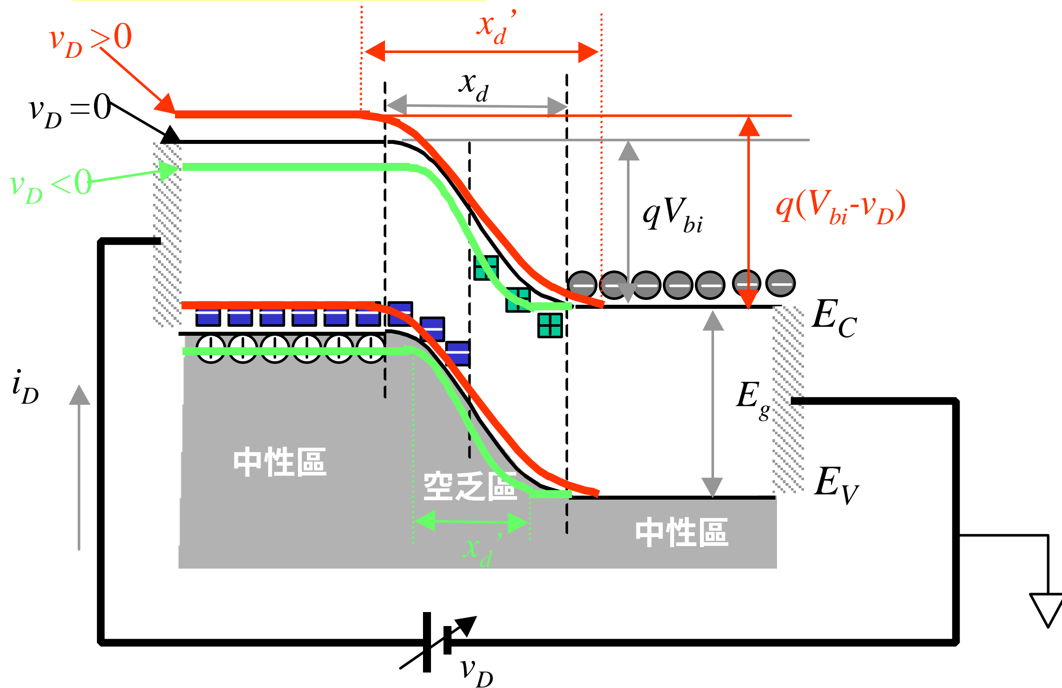
假如V_1-V_2= V_a<0，外加電場方向和內建電場相同，結果電場變大



$$i_D = I_S\left(e^{qv_D/kT} - 1\right)$$



加偏壓對空乏區之影響

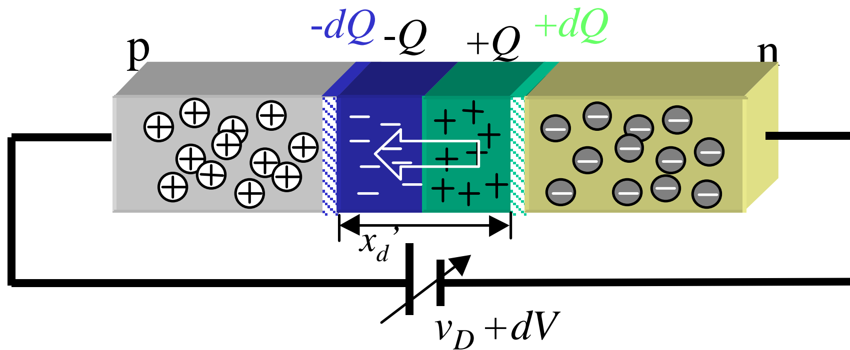


空乏區之寬度

$$x_d = \sqrt{\frac{2\varepsilon_{Si}V_{bi}}{q}\left(\frac{N_A + N_D}{N_A N_D}\right)}$$

$$x_d' = \sqrt{\frac{2\varepsilon_{Si}(V_{bi} - v_D)}{q}\left(\frac{N_A + N_D}{N_A N_D}\right)}$$

C. **接面電容**(Junction Capacitance)



偏壓改變dV**時，**x_d**改變，同時產生儲存電荷的改變**$\pm dQ$**。**

dV → $\pm dQ$　　**電容的效應**

電容有多大？

$$C_j = \frac{\varepsilon_{\mathrm{Si}}}{x_d}$$

電容/單位面積

(**和平行板電容相同**)

x_d**是偏壓**v_D**的函數，接面電容**C_j**也是**v_D**的函數。**

$$C_j = \frac{\varepsilon_{\mathrm{Si}}}{x_d} = \left[\frac{q\varepsilon_{\mathrm{Si}}}{2(V_{bi} - v_D)} \frac{N_A N_D}{N_A + N_D}\right]^{1/2}$$

Only for abrupt junction!!

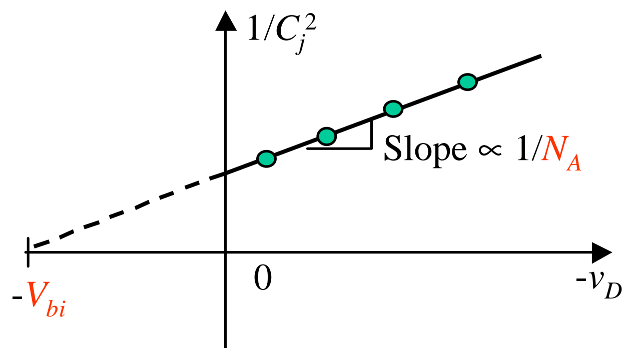
假如只考慮one-sided abrupt junction，**例如**n^+-p，$N_D >> N_A$

$$C_j = \frac{\varepsilon_{\mathrm{Si}}}{x_d} \approx \left[\frac{q\varepsilon_{\mathrm{Si}} N_A}{2(V_{bi} - v_D)}\right]^{1/2}$$

$$C_j \propto (V_{bi} - v_D)^{-1/2}$$

$$\frac{1}{C_j^2} \approx \frac{2(V_{bi} - v_D)}{q\varepsilon_{\mathrm{Si}} N_A}$$

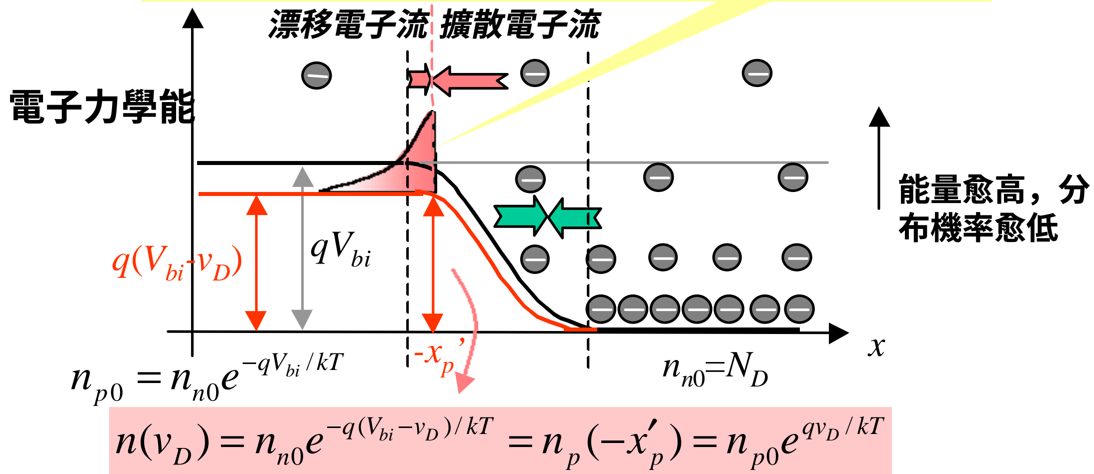
取$1/C_j^2$對$-v_D$作圖



逆向偏壓的pn接面可用作偏壓調變的可變電容。

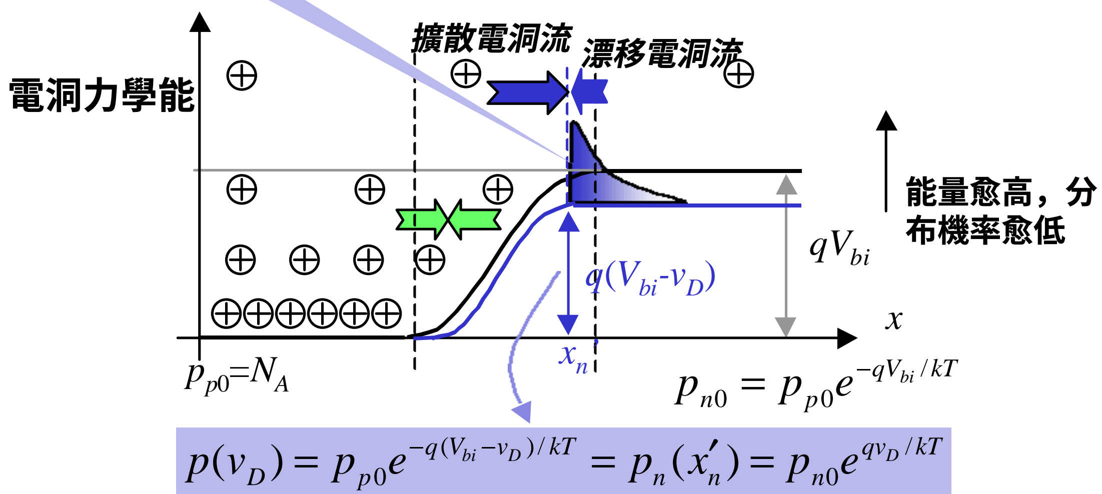
2. 二極體的電流電壓特性--- $I = I_S\left(e^{\frac{v_D}{\eta V_T}} - 1\right)$

順向偏壓時多出電子在$-x_p$'處注入(injection) p型半導體中，並向p型半導體中擴散，同時和電洞復合。



$$n(v_D) = n_{n0}e^{-q(V_{bi}-v_D)/kT} = n_p(-x_p') = n_{p0}e^{qv_D/kT}$$

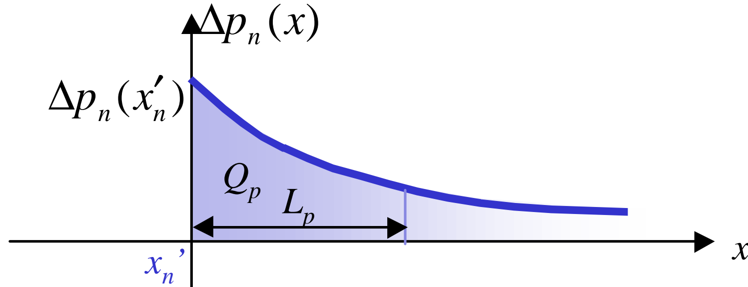
順向偏壓時多出電洞在x_n'處注入(injection) n型半導體中，並向n型半導體中擴散，同時和電子復合。



$$p(v_D) = p_{p0}e^{-q(V_{bi}-v_D)/kT} = p_n(x_n') = p_{n0}e^{qv_D/kT}$$

計算多出載體擴散電流

以電洞為例：



$$p_n(x_n') = p_{p0} e^{-q(V_{bi}-v_D)/kT} = p_{n0} e^{qv_D/kT}$$

$$\Delta p_n(x_n') = p_n(x_n') - p_{n0} = p_{n0}\left(e^{qv_D/kT} - 1\right)$$

$$\Delta p_n(x) = \Delta p_n(x_n') e^{-\frac{x-x_n'}{L_p}} = p_{n0}\left(e^{qv_D/kT} - 1\right) e^{-\frac{x-x_n'}{L_p}}$$

$$i_{D,p} = -AqD_p \frac{\partial \Delta p_n(x)}{\partial x} = \frac{AqD_p p_{n0}}{L_p}\left(e^{qv_D/kT} - 1\right) e^{-\frac{x-x_n'}{L_p}}$$

$$i_{D,p}(x_n') = \frac{AqD_p p_{n0}}{L_p}\left(e^{qv_D/kT} - 1\right) = \frac{AqD_p n_i^2}{L_p N_D}\left(e^{qv_D/kT} - 1\right)$$

在n型區之多出電洞之總電荷為

$$Q_p = Aq\int_{x_n'}^{\infty} \Delta p_n(x)dx = Aq\Delta p_n(x_n')\int_{x_n'}^{\infty} e^{-\frac{x-x_n'}{L_p}} dx = Aq\Delta p_n(x_n')L_p$$

$$= AqL_p p_{n0}\left(e^{qv_D/kT} - 1\right)$$

$$L_p = \sqrt{D_p \tau_p} \Rightarrow L_p^2 = D_p \tau_p$$

$$i_{D,p}(x_n') = \frac{AqD_p p_{n0}}{L_p}\left(e^{qv_D/kT} - 1\right) = \frac{AqL_p p_{n0}}{\tau_p}\left(e^{qv_D/kT} - 1\right) = \frac{Q_p}{\tau_p}$$

τ_p為在n型區之多出電洞之生命期

同理可得電子之擴散電流

$$\Delta n_p(x)=\Delta n_p(-x'_p)e^{\frac{x+x'_p}{L_n}}=n_{p0}\left(e^{qv_D/kT}-1\right)e^{\frac{x+x'_p}{L_n}}$$

$$i_{D,n}=AqD_n\frac{\partial\Delta n_p(x)}{\partial x}=\frac{AqD_n n_{p0}}{L_n}\left(e^{qv_D/kT}-1\right)e^{\frac{x+x'_p}{L_n}}$$

$$i_{D,n}(-x'_p)=\frac{AqD_n n_{p0}}{L_n}\left(e^{qv_D/kT}-1\right)=\frac{AqD_n n_i^2}{L_n N_A}\left(e^{qv_D/kT}-1\right)$$

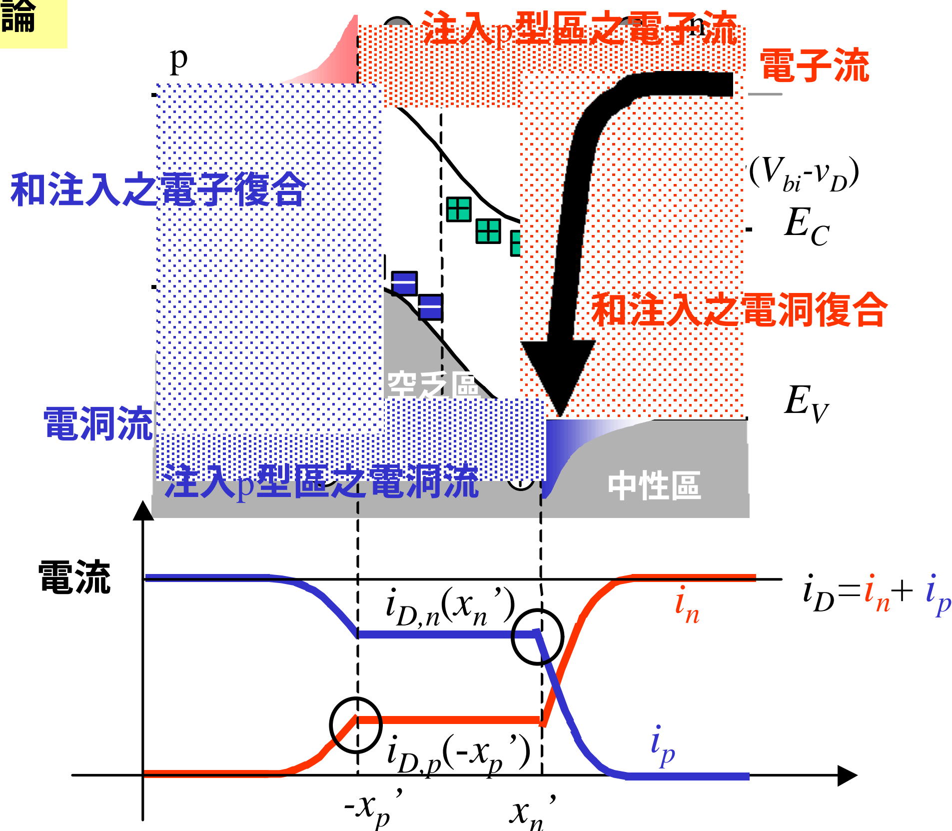
$$Q_n=Aq\int_{-\infty}^{-x'_p}\Delta n_p(x)dx=Aq\Delta n_p(-x'_p)\int_{x'_n}^{\infty}e^{\frac{x+x'_p}{L_n}}dx=Aq\Delta n_p(-x'_p)L_n$$

$$=AqL_n n_{p0}\left(e^{qv_D/kT}-1\right)$$

$$L_n=\sqrt{D_n\tau_n}\Rightarrow L_n^2=D_n\tau_n$$

$$i_{D,n}(-x'_p)=\frac{AqD_n n_{p0}}{L_n}\left(e^{qv_D/kT}-1\right)=\frac{AqL_n n_{p0}}{\tau_n}\left(e^{qv_D/kT}-1\right)=\frac{Q_n}{\tau_n}$$

結論



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$$i_D = i_{D,n}(-x'_p) + i_{D,p}(x'_n) = \frac{Q_n}{\tau_n} + \frac{Q_p}{\tau_p}$$

$$i_D = \underbrace{\left(\frac{AqD_n n_i^2}{L_n N_A} + \frac{AqD_p n_i^2}{L_p N_D}\right)}_{I_S}\left(e^{qv_D/kT} - 1\right)$$

$$i_D = I_S\left(e^{qv_D/kT} - 1\right)$$ 理想二極體方程式

I_S :反向飽和電流，是溫度的函數。

我們假設了：
- 空乏區中沒有產生和復合
- 低注入

實際二極體方程式 $$i_D = I_S\left(e^{qv_D/\eta kT} - 1\right)$$

η 在1與2之間

和空乏區或邊界之復合有關

η:理想因子(ideality factor)

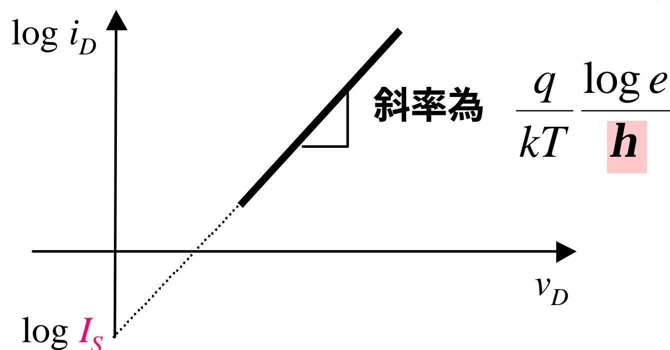
emission coefficient

有些人用n表示

實如何測量η及I_S？

在順向偏壓時，假如 $e^{qv_D/\eta kT} >> 1$

$$i_D \approx I_S e^{qv_D/\eta kT} \Rightarrow \log i_D = \log I_S + \frac{qv_D}{\eta kT}\log e$$



斜率為 $\dfrac{q}{kT}\dfrac{\log e}{\eta}$