半導體元件與物理
Semiconductor Devices and physics

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- 2. Quantum Theory of Solids
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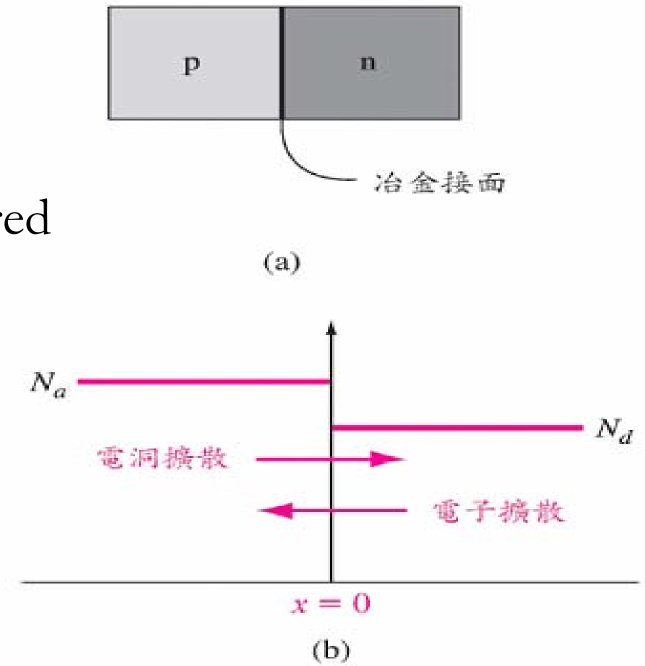
PN Junction

Most semiconductor device contain at least one junction between p-type and n-type semiconductor regions. Semiconductor device characteristics and operation are intimately connected to these pn junctions, so considerable attention is devoted initially connected this basic device. → The pn junction diode itself provides characteristics that are used in rectifiers and switching circuits. ; In addition, the analysis of the pn junction device establishes some basic terminology and concepts that are used in the discussion of other semiconductor devices.

Basic Structure of the pn junction

The interface separating the n and p regions is referred to as the metallurgical junction.

Majority carrier electrons in the n region will begin diffusing into the p region and majority carrier holes in p region will begin diffusing into the n region. → the net positive and negative charges in the n and p regions induce an electric field in the region near the metallurgical junction, in the direction from the positive to the negative charge, or from the n to p region.

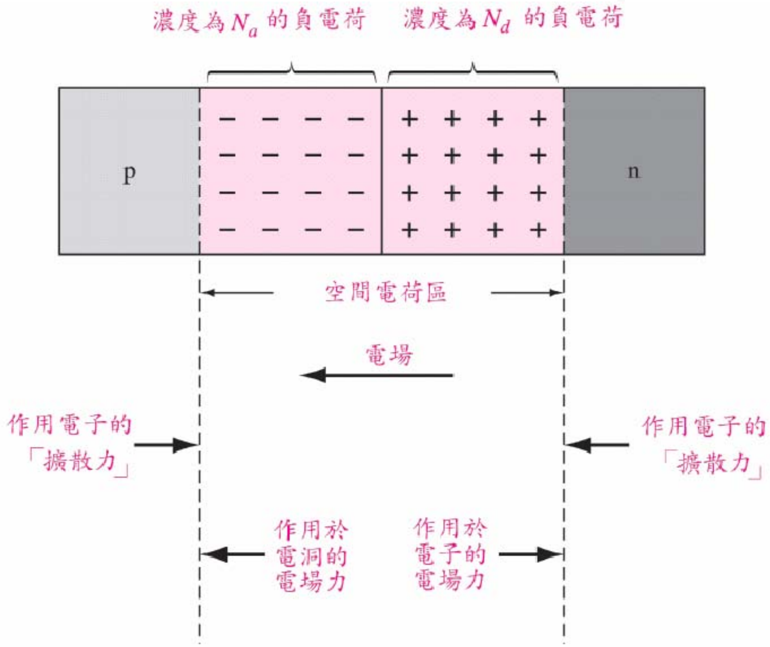


(a)簡化的 pn 接面的幾何結構；及
(b)理想化的摻雜均勻的 pn 接面之雜質濃度分佈。

The net positively and negatively charged regions are shown in figure. These two regions are referred to as the space charge region. → all electrons and holes are swept out of the space charge region by the electric field. → since the space charge region is depleted of any mobile charge, this region is also referred to as the depletion region.

=> A “diffusion force” that acts on the majority carriers → these diffusion forces, acting on the electrons and holes at the edges of the space charge region. <the electric field in the space charge region produces another force on the electrons and holes which is in the opposite direction to the diffusion force for each type of particle.>

In thermal equilibrium, the diffusion force and the E-field force exactly balance each other.



空間電荷區、電場及電荷載子所受的作用力。

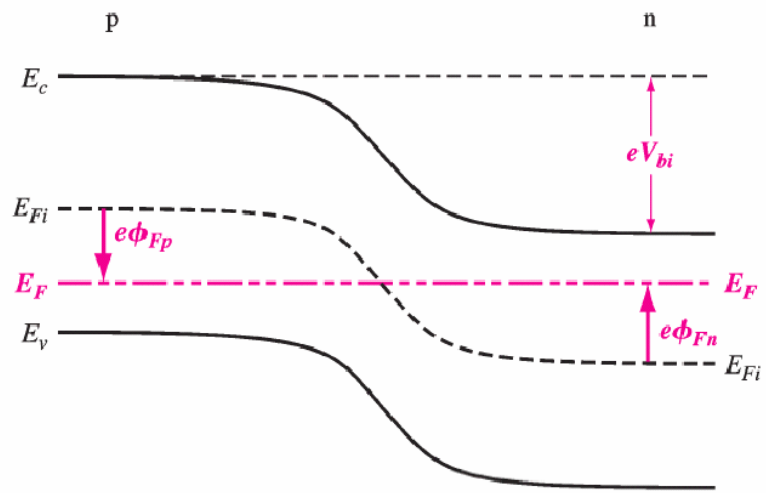
Zero Applied Bias

Determine the space charge region width, electric field, and potential through the depletion region, where no currents exist and no external excitation is applied in thermal equilibrium.

Built-in Potential barrier

If we assume that no voltage is applied across the pn junction, then the junction is in thermal equilibrium –the Fermi energy level is constant throughout the entire system. The conduction and valence band energies must bend as we go through the space charge region, since the relative position of the conduction and valence bands with respect to Fermi energy charges between p and n regions.

Electrons in the conduction band of the n region see a potential barrier in trying to move into the conduction band of the p region. → this potential barrier is referred to as the built-in potential barrier and is denoted as V_{bi}.



熱平衡時，pn 接面的能帶圖。

The built-in potential barrier maintains equilibrium between majority carrier electrons in the n region and minority carrier electrons in the p region, and also between majority carrier holes in the p region and minority carrier holes in the n region. → this potential difference across the junction cannot be measured with a voltmeter because new potential barriers will be formed between the probes and the semiconductor hat will be cancer V_{bi}.

The intrinsic Fermi level is equidistant from the conduction band edge through the junction, thus the built-in potential barrier can be determined as the difference between the intrinsic Fermi levels in the p and n region. → $V_{bi} = |\phi_{Fn}| + |\phi_{Fp}|$

In the n region, the electron concentration in the conduction band is given by

$n_0 = N_c \exp\left[\frac{-(E_c - E_F)}{kT}\right]$ which can also be written in the form $n_0 = n_i \exp\left[\frac{E_F - E_{Fi}}{kT}\right]$

where n_i and E_{Fi} are the intrinsic carrier concentration and the intrinsic Fermi energy

We may define the potential ϕ_{Fn} in the n region as $e\phi_{Fn} = E_{Fi} - E_F$

→ then $n_0 = n_i \exp\left[\frac{-(e\phi_{Fn})}{kT}\right]$

Taking the natural log of both sides and setting $n_o = N_d$ → $\phi_{Fn} = \frac{-kT}{e} \ln\left(\frac{N_d}{n_i}\right)$

Similarly, in the p region, the hole concentration is given by $p_0 = N_a = n_i \exp\left[\frac{E_{Fi} - E_F}{kT}\right]$

where N_a is the acceptor concentration. We can define the potential ϕ_{Fp} in the p region as

$$\phi_{Fp} = +\frac{kT}{e} \ln\left(\frac{N_a}{n_i}\right)$$

Finally, the built-in potential barrier for the step junction is found by substituting above equation and solving → $V_{bi} = \frac{kT}{e} \ln\left(\frac{N_a N_d}{n_i^2}\right) = V_t \ln\left(\frac{N_a N_d}{n_i^2}\right)$ where Vt = kT/e (thermal voltage)

Electric Field

An electric field is created in the depletion region by the separation of positive and negative space charge densities.

Figure shows the volume charge density distribution in the pn junction assuming uniform doping and assuming an abrupt junction approximation.

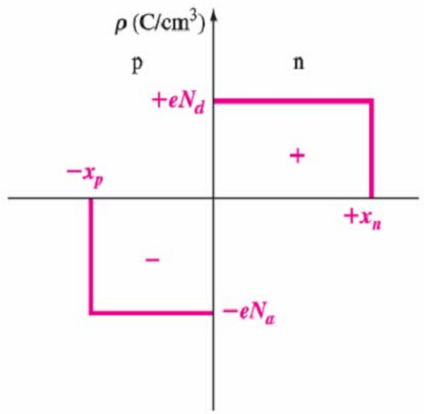
We will assume that the space charge region abruptly ends in the n region at $x = +x_n$ and abruptly ends in the p region at $x = -x_p$. → the electric field is determined from Poisson's equation which, for a 1D analysis is

$$\frac{d^2\phi(x)}{dx^2} = \frac{-\rho(x)}{\epsilon_s} = -\frac{d\mathrm{E}(x)}{dx}$$

where $\phi(x)$ is the electric potential, E(x) is the electric field, $\rho(x)$ is the volume charge density, and ε_s is the permittivity of the semiconductor. → the charge densities are

$$\rho(x) = -eN_a \qquad -x_p < x < 0$$

$$\rho(x) = eN_d \qquad 0 < x < x_n$$



均勻摻雜的 pn 接面空間電荷密度圖。假設其為陡峭式的接面。

The electrical field in the p region is found by integrating above equation →

$$E = \int \frac{\rho(x)}{\epsilon_s} dx = -\int \frac{eN_a}{\epsilon_s} dx = \frac{-eN_a}{\epsilon_s} x + C_1$$

where C_1 is a constant of integration. The electric field is assumed to be zero in the neutral p region for $x < -x_p$ since the currents are zero in the thermal equilibrium. → As there are no surface charge densities within the pn junction structure, the electric field is a continuous function. → the constant of integration is determined by setting $E = 0$ at $x = -x_p$. The electric field in p region is then given by

$$E = \frac{-eN_a}{\epsilon_s}(x + x_p) \qquad -x_p \le x \le 0$$

In the n region, the electric field is determined from $E = \int \frac{(eN_d)}{\epsilon_s} dx = \frac{eN_d}{\epsilon_s} x + C_2$

where C_2 is again a constant of integration. The C_2 is determined by setting $E = 0$ at $x = x_n$, since the E-field is assumed to be zero in the n region and is a continuous function. Then

$$E = \frac{-eN_d}{\epsilon_s}(x_n - x) \qquad 0 \le x \le x_n$$

The electric field is also continuous at the metallurgical junction, or at $x = 0$. Setting above two equations equal to each other at $x = 0$ gives → $N_a x_p = N_d x_n$

→ The number of negative charges per unit area in the p region is equal to the number of positive charges per unit area in the n region.

Figure is a plot of the electric field in the depletion region. The electric field direction is from the n to the p region, or in the negative x direction for this geometry. For the uniformly doped pn junction, the E-field is a linear function of distance through the junction, the maximum (magnitude) electric field occurs at the metallurgical junction. An electric field exists in the depletion region even when no voltage is applied between the p and n region.

The potential in the junction is found by integrating the electric field. → in the p region then, we have

$$\phi(x) = -\int E(x)\,dx = \int \frac{eN_a}{\epsilon_s}(x + x_p)\,dx$$

or

$$\phi(x) = \frac{eN_a}{\epsilon_s}\left(\frac{x^2}{2} + x_p \cdot x\right) + C_1'$$

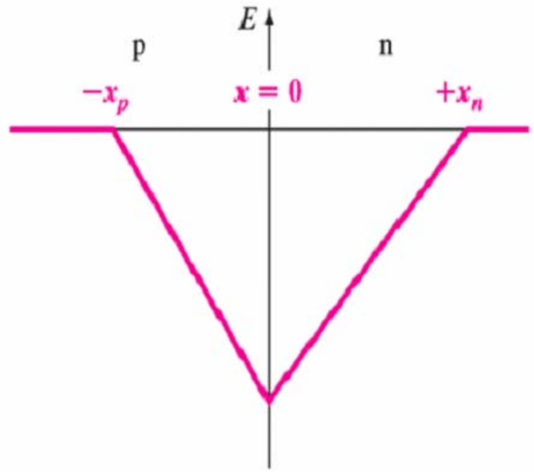
where C'_1 is again a constant of integration

The potential difference through the pn junction is the important parameter, rather than the absolute potential, so we may arbitrarily set the potential equal to zero at $x = -x_p$. *The constant of integration is*

$$C_1' = \frac{eN_a}{2\epsilon_s}x_p^2$$

so that the potential in the p region can now be written as

$$\phi(x) = \frac{eN_a}{2\epsilon_s}(x + x_p)^2 \qquad (-x_p \le x \le 0)$$



均勻摻雜 pn 的接面在空間電荷區的電場。

The potential in the n region is determined by integrating the electric field in the n region, or $\phi(x) = \int \frac{eN_d}{\epsilon_s}(x_n - x)\,dx$ then $\phi(x) = \frac{eN_d}{\epsilon_s}\left(x_n \cdot x - \frac{x^2}{2}\right) + C_2'$

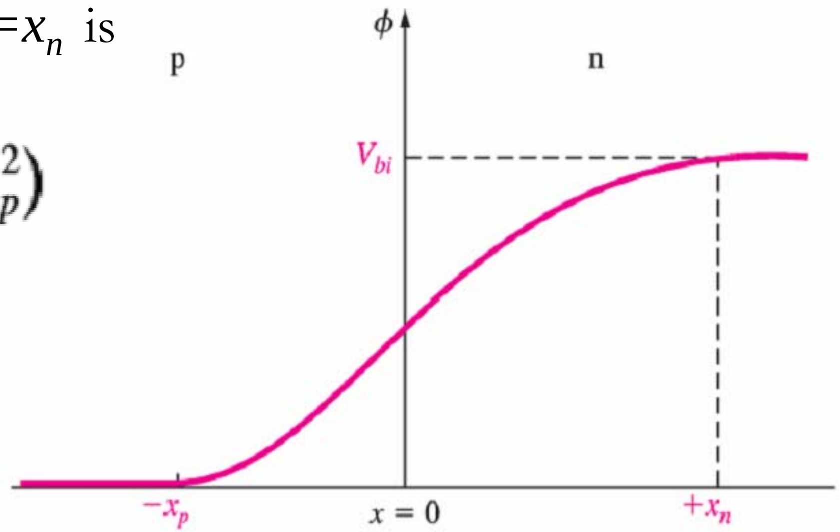
Where C'$_2$ is another constant of integration. The potential is a continuous function, so setting above two equation equal to each other at the metallurgical junction, or at x = 0, gives $C_2' = \frac{eN_a}{2\epsilon_s}x_p^2$

The potential in the n region can thus be written as $\phi(x) = \frac{eN_d}{\epsilon_s}\left(x_n \cdot x - \frac{x^2}{2}\right) + \frac{eN_a}{2\epsilon_s}x_p^2 \qquad (0 \le x \le x_n)$

Figure show a plot of the potential through the junction and shows the quadratic dependence on distance. The magnitude of the potential at $x=x_n$ is equal to the built-in potential barrier. →

$$V_{bi} = |\phi(x = x_n)| = \frac{e}{2\epsilon_s}\left(N_d x_n^2 + N_a x_p^2\right)$$

The potential energy of an electron is given by $E=-e\phi$, which means that the electron potential energy also varies as a quadratic function of distance through the space charge region.



均勻摻雜 pn 的接面在整個空間中的電位變化。

Space charge width

We can determine the distance that the space charge region extends into the p and n regions from the metallurgical junction. This distance is known as the space charge width. → we may write

$$x_p = \frac{N_d x_n}{N_a}$$

Then, substituting above equation into built-in potential barrier and solving for x_n →

$$x_n = \left\{ \frac{2\epsilon_s V_{bi}}{e} \left[\frac{N_a}{N_d} \right] \left[\frac{1}{N_a + N_d} \right] \right\}^{1/2}$$

→gives the space charge width, or the width of the depletion region, x_n extending into the n-type for the case zero applied voltage.

Similarly, solving x_p → $x_p = \left\{ \frac{2\epsilon_s V_{bi}}{e} \left[\frac{N_d}{N_a} \right] \left[\frac{1}{N_a + N_d} \right] \right\}^{1/2}$

where x_p is the width of the depletion region extending into the p region for the case of zero applied voltage.

The total depletion or space charge width W is the sum of the two components, or

$$W = x_n + x_p$$

→ $W = \left\{ \frac{2\epsilon_s V_{bi}}{e} \left[\frac{N_a + N_d}{N_a N_d} \right] \right\}^{1/2}$

Reverse Applied Bias

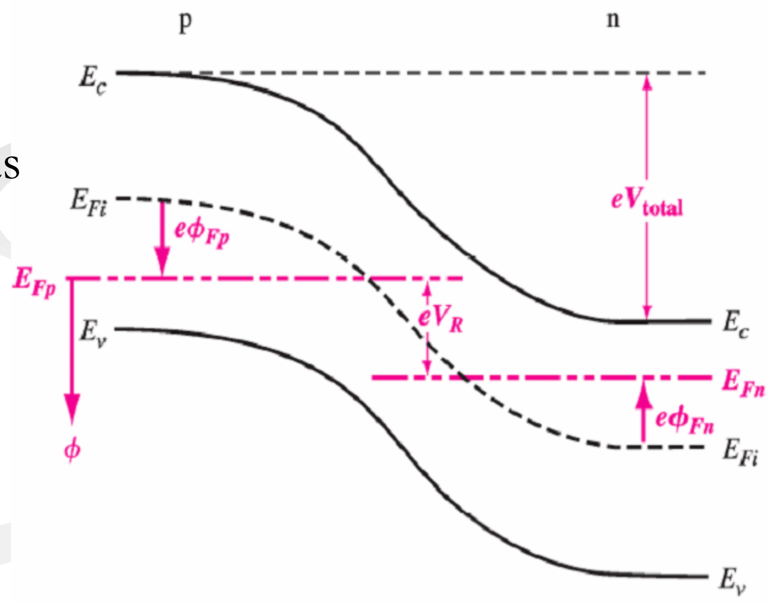
If we apply a potential between the p and n regions, we will no longer be in an equilibrium condition – the Fermi energy level will no longer be constant through the system. For figure, when a positive voltage is applied to the n region with respect to the p region. → for the positive potential is downward, the Fermi level on the n side is below the Fermi level on the p side. The difference between the two is equal to the applied voltage in units of energy.

→ The total potential barrier, indicated by V_{total}, has increased. The applied potential is the reverse-bias condition. The total potential barrier is now given by

$$V_{\text{total}} = |\phi_{Fn}| + |\phi_{Fp}| + V_R$$

where V_R is the magnitude of the applied reverse-bias voltage. → $V_{\text{total}} = V_{bi} + V_R$

where V_{bi} is the same built-in potential barrier we had defined in thermal equilibrium.

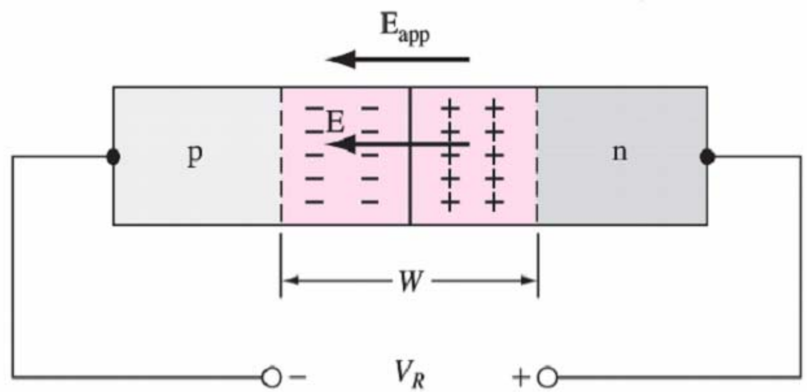


逆向偏壓 pn 接面的能帶圖。

Space Charge Width and Electric Field

Figure shows a pn junction with an applied reverse-bias voltage V_R, and also indicated in the figure are the electric field in the space charge region and the electric field E_{app}, induced by the applied voltage. → The electric fields in the neutral p and n regions are essentially zero, or at least very small, which means that the magnitude of the electric field in the space charge region must increase above the thermal equilibrium value due to the applied voltage. => if electric field increase → number of positive and negative charges must increase ; for given impurity doping concentrations, the number of positive and negative charges in the depletion region can be increased only if the space charge width W increases. => V_R increases → W increases

The total space charge width can be written as $W = \left\{ \frac{2\epsilon_s (V_{bi} + V_R)}{e} \left[\frac{N_a + N_d}{N_a N_d} \right] \right\}^{1/2}$



逆向偏壓的 pn 接面，圖中標示出 V_R 所引導出的電場之方向及空間電荷的電場方向。

The magnitude of electric field in the depletion region increases with an applied reverse-bias voltage. And the electric field is still a linear function of distance through the space charge region. → since x_n and x_p increase with reverse-bias voltage, the magnitude of the electric field also increases. → max. electric field occurs at the metallurgical junction.

=> $$E_{max} = \frac{-eN_d x_n}{\epsilon_s} = \frac{-eN_a x_p}{\epsilon_s}$$

→If we above equation in conjunction with the total potential barrier, $V_{bi}+V_R$,

then $$E_{max} = -\left\{\frac{2e(V_{bi}+V_R)}{\epsilon_s}\left(\frac{N_a N_d}{N_a+N_d}\right)\right\}^{1/2}$$

⇒ We can show that the maximum electric field in the pn junction can also be written as

$$E_{max} = \frac{-2(V_{bi}+V_R)}{W}$$

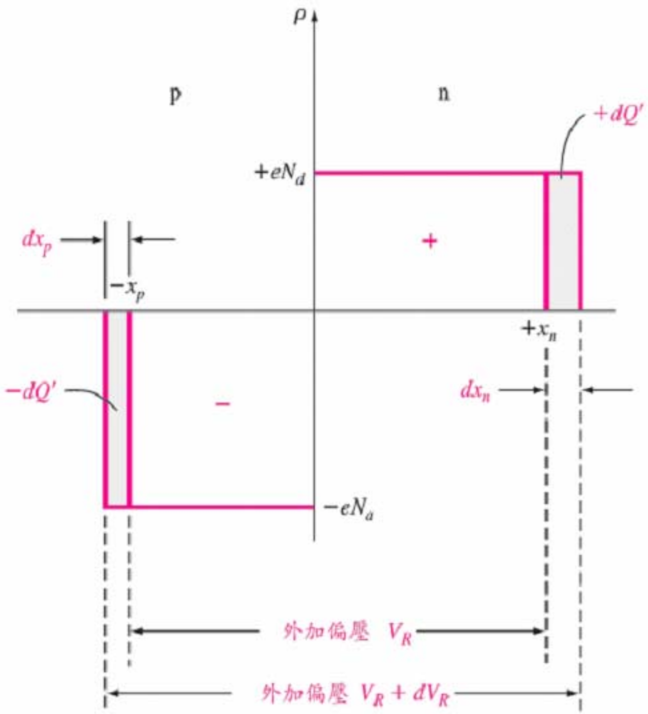
where W is the total space charge width

Junction Capacitance

Since we have a separation of positive and negative charges in the depletion region, a capacitance is associated with the pn junction. Figure shows the charge densities in the depletion region for applied reverse-bias voltage of V_R and V_R+dV_R. An increase in the reverse-bias voltage dV_R will uncover additional positive charges in the n region and additional negative charges in the p region. → the junction capacitance is defined as $C' = \dfrac{dQ'}{dV_R}$ where $dQ' = eN_d\,dx_n = eN_a\,dx_p$

The differential charge dQ' is in units of C/cm^2 so that the capacitance C' is in units of farads per square centimeter (F/cm^2), or capacitance per unit area. → For the total potential barrier,

$$x_n = \left\{ \frac{2\epsilon_s(V_{bi}+V_R)}{e}\left[\frac{N_a}{N_d}\right]\left[\frac{1}{N_a+N_d}\right]\right\}^{1/2}$$



在均勻摻雜 pn 接面中，微量的逆向偏壓變化，造成微量的空間電荷寬度變化。

The junction capacitance can be written as $$C' = \frac{dQ'}{dV_R} = eN_d \frac{dx_n}{dV_R}$$

$$\rightarrow C' = \left\{ \frac{e\epsilon_s N_a N_d}{2(V_{bi} + V_R)(N_a + N_d)} \right\}^{1/2}$$

Exactly the same capacitance expression is obtained by considering the space charge region extending into the p region x_p. The junction capacitance is also referred to as the depletion layer capacitance. → if we compare above total space charge width equation for the total depletion width W of the space charge region under reverse bias and above equation for the junction capacitance C' → $C' = \frac{\epsilon_s}{W}$

→ the same as the capacitance per unit area of a parallel plate capacitor.

Keep in mind that the space charge width is a function of the reverse bias voltage so that the junction capacitance is also a function of the reverse bias voltage applied to the pn junction.

One-sided Junctions

Consider a special pn junction called the one-sided junction. → for $N_a >> N_d$, this junction is referred to as a p^+n junction. The total space charge width reduces to

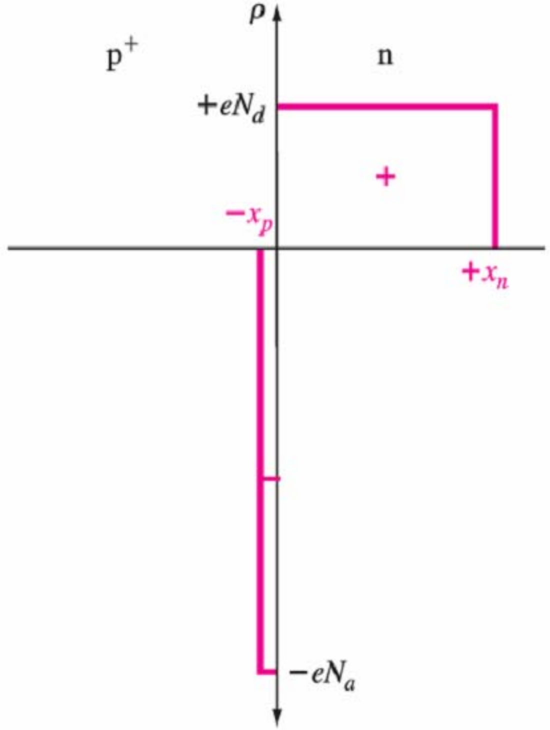
$$W \approx \left\{ \frac{2\epsilon_s (V_{bi} + V_R)}{eN_d} \right\}^{1/2}$$

Considering the expressions for x_n and x_p, we have for the p^+n junction $x_p << x_n$ and $W \approx x_n$.

Almost the entire space charge layer extends into the low-doped region of the junction. (see the figure)

The junction capacitance of the p^+n junction reduces to

$$C' \approx \left\{ \frac{e\epsilon_s N_d}{2(V_{bi} + V_R)} \right\}^{1/2}$$



單邊 p⁺n 接面的空間電荷密度。

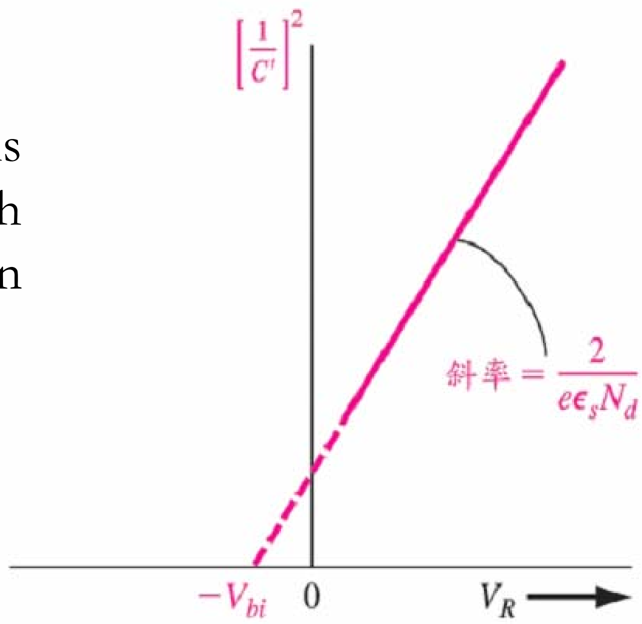
The depletion layer capacitance of a one-sided junction is a function of the doping concentration in the low-doped region. → then

$$\left(\frac{1}{C'}\right)^2 = \frac{2(V_{bi} + V_R)}{e\epsilon_s N_d}$$

Shows that the inverse capacitance squared is a linear function of applied reverse-bias voltage.

Figure show the bulit-in potential of the junction can be determined by extrapolating the curve to the point where $(1/C')^2 = 0$.

The assumptions used in the derivation of this capacitance include uniform doping in both semiconductor regions, the abrupt junction approximation, and a planar junction.

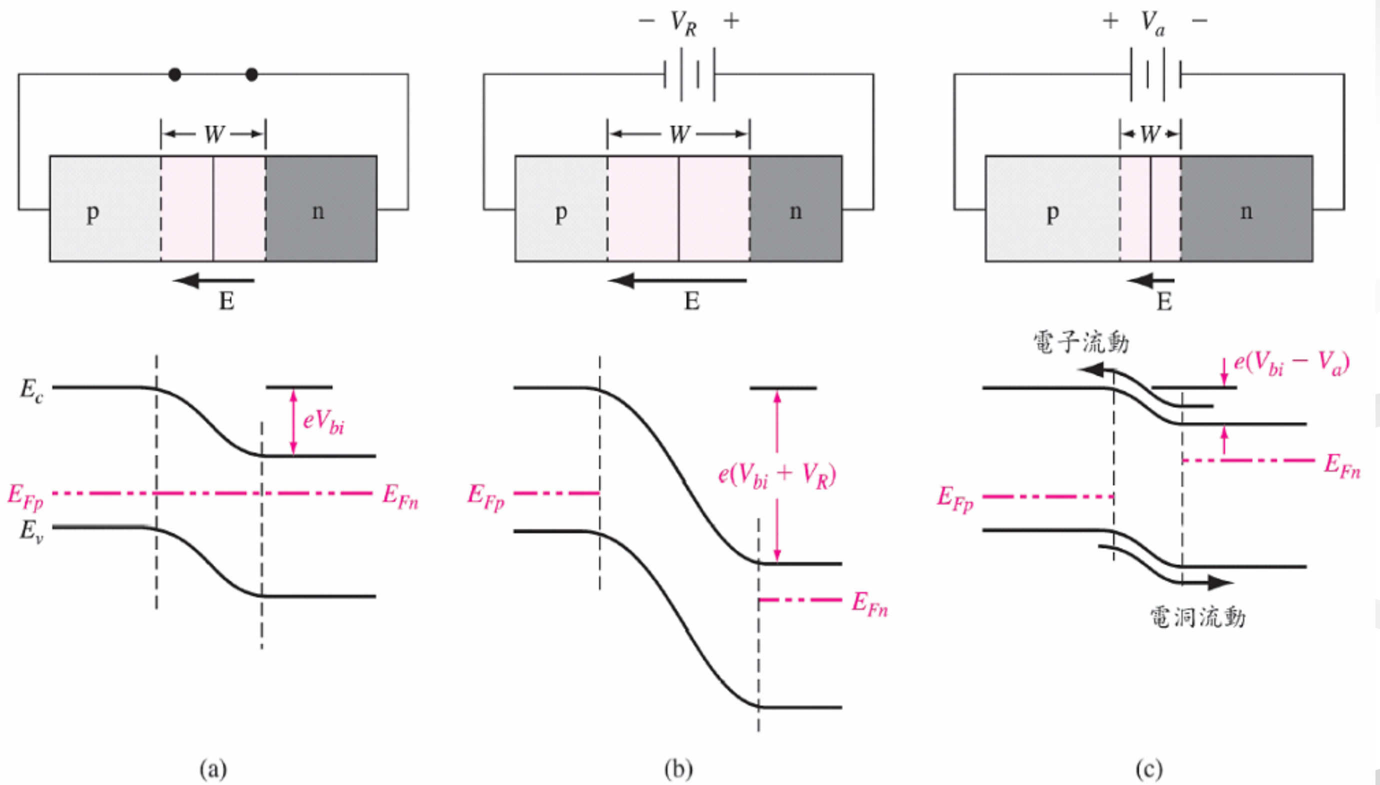


均勻摻雜 pn 接面的$(1/C')^2$對 V_R 圖

PN Junction Current

When a forward-bias voltage is applied to a pn junction, a current will be induced in the device.

Qualitative description of charge flow in a pn junction



在(a)零偏壓；(b)逆向偏壓及(c)順向偏壓下的 pn 接面及其能帶圖。

Ideal current-voltage relationship

The ideal current-voltage relationship of a pn junction is derived on the basis of four assumptions.

1. The abrupt depletion layer approximation applies. The space charge regions have abrupt boundaries and the semiconductor is neutral outside of the depletion region.
2. The Maxwell-Boltzmann approximation applies to carrier statistics.
3. The concept of low injection applies.

4a. The total current is a constant throughout the entire pn structure.

4b. The individual electron and hole currents are continues functions through the pn structure.

4c. The individual electron and hole currents are constant throughout the depletion region.

表 8.1｜本章常用的項目與記號。

項目	意義
N_a	pn 接面中 p 型區的受體濃度
N_d	pn 接面中 n 型區的施體濃度
$n_{n0} = N_d$	熱平衡時 n 型區的多數載子電子的濃度
$p_{p0} = N_a$	熱平衡時 p 型區的多數載子電洞的濃度
$n_{p0} = n_i^2/N_a$	熱平衡時 p 型區的少數載子電子的濃度
$p_{n0} = n_i^2/N_d$	熱平衡時 n 型區的少數載子電洞的濃度
n_p	p 型區的少數載子電子的總濃度
p_n	n 型區的少數載子電洞的總濃度
$n_p(-x_p)$	空間電荷區靠近 p 型區邊緣處的少數載子電子的濃度
$p_n(x_n)$	空間電荷區靠近 n 型區邊緣處的少數載子電洞的濃度
$\delta n_p = n_p - n_{p0}$	p 型區的過量少數載子電子的濃度
$\delta p_n = p_n - p_{n0}$	n 型區的過量少數載子電洞的濃度