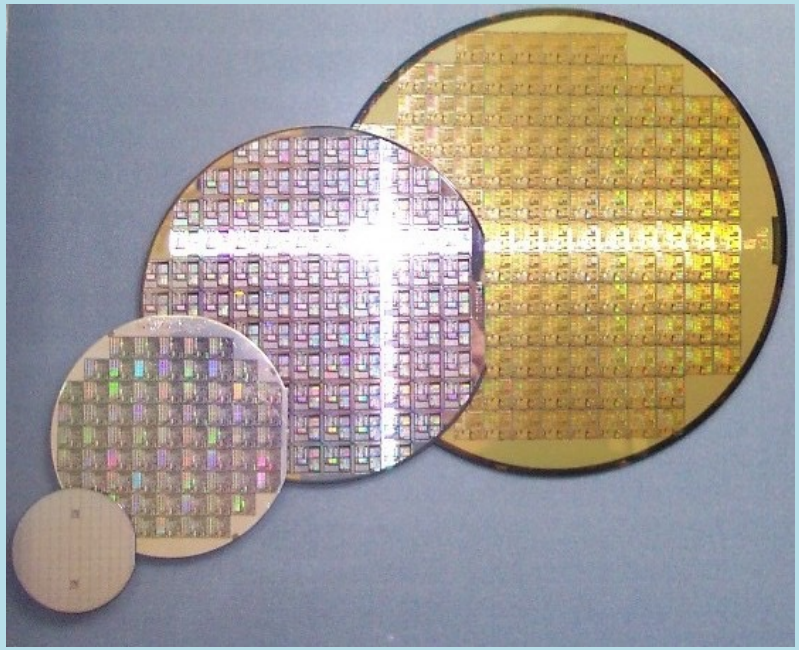
半導體 Semiconductor



固體是原子組成的晶格 Lattice

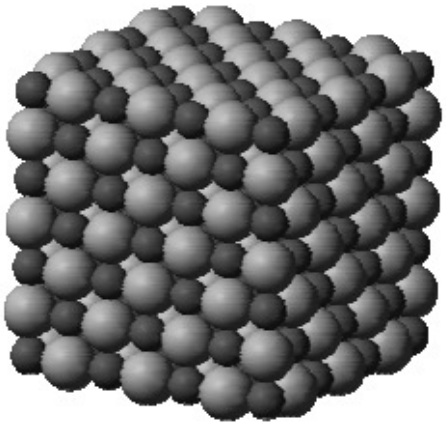
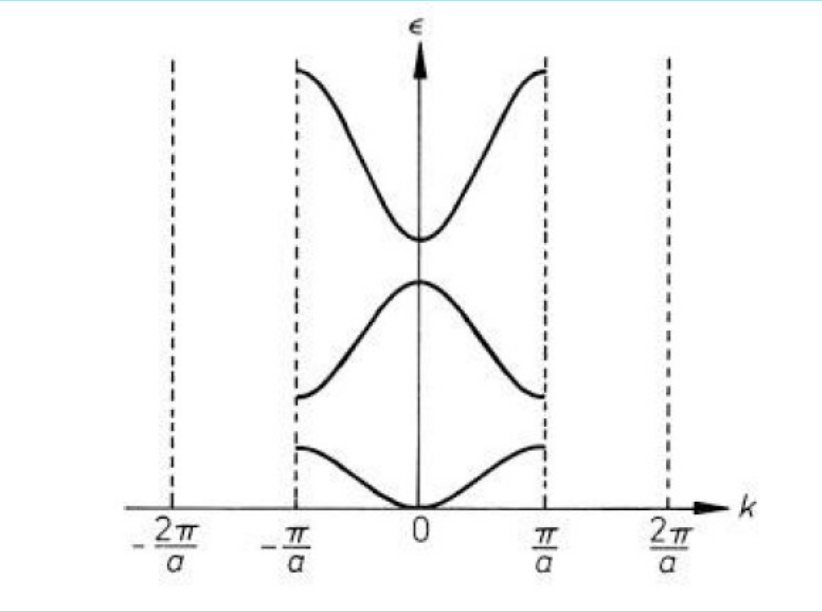
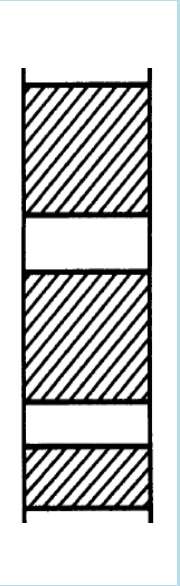


Fig. 7.1: **Left:** Small units reproduced periodically to form a crystal. This particular figure depicts NaCl (table salt), with the larger spheres being Cl^- ions and the smaller spheres being Na^+ ions. **Right:** The macroscopic morphology of a crystal often will reflect the underlying microscopic structure. These are large crystals of salt (also known as halite). Photograph by Piotr Włodarczyk, used by kind permission.

週期性晶格位能中電子的能帶 Energy Band



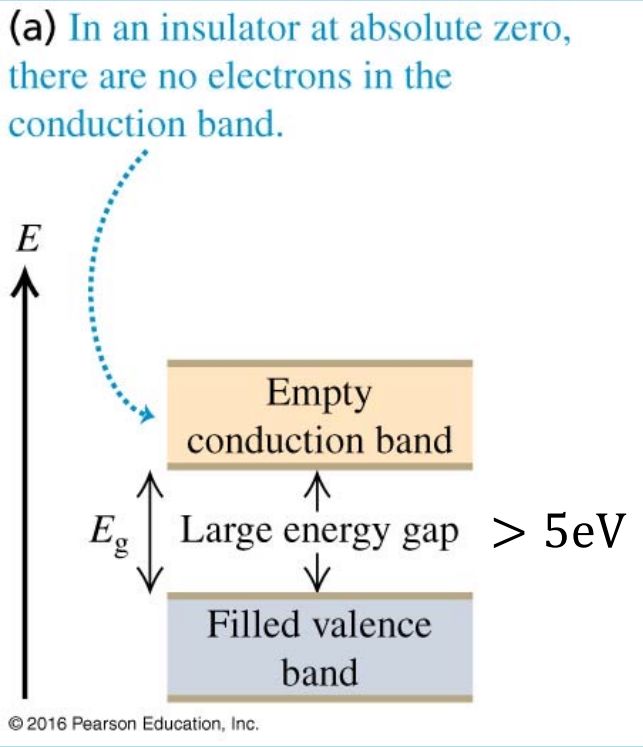


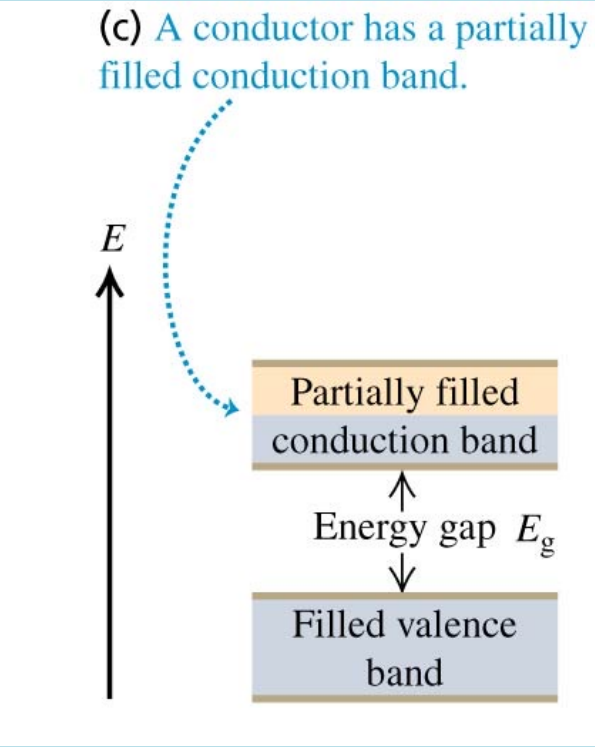
電子會一個一個填入能帶中的狀態，不能有兩個電子佔據同一狀態。

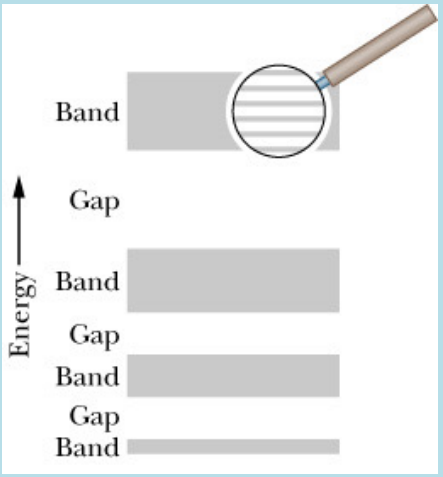
如果電子恰好填滿一個能帶（稱Valence），這些能帶中的電子無處可去！

需要很大能量才能克服間隙，改變狀態。

這樣的固體無法導電，是絕緣體。







如果電子未填滿能帶（稱Conduction），未滿能帶內的電子很容易改變狀態。

只要些許能量就能讓它激發到其他能態。

這些電子非常自由，這樣的固體就可以導電，就是導體。

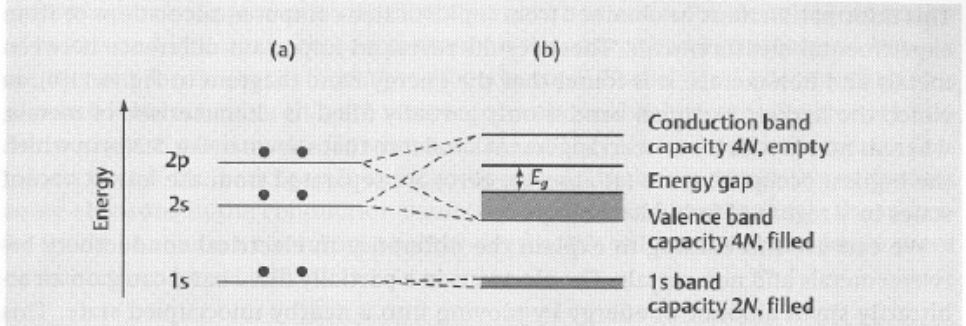
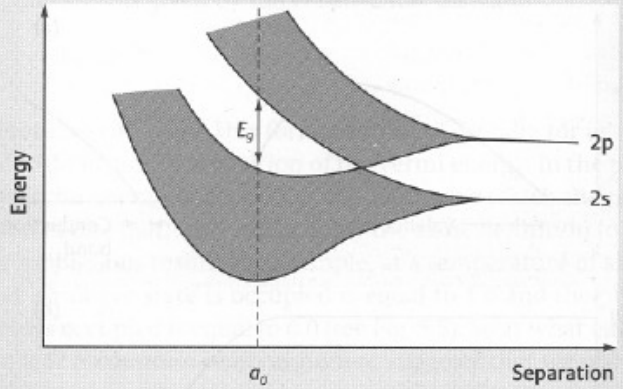
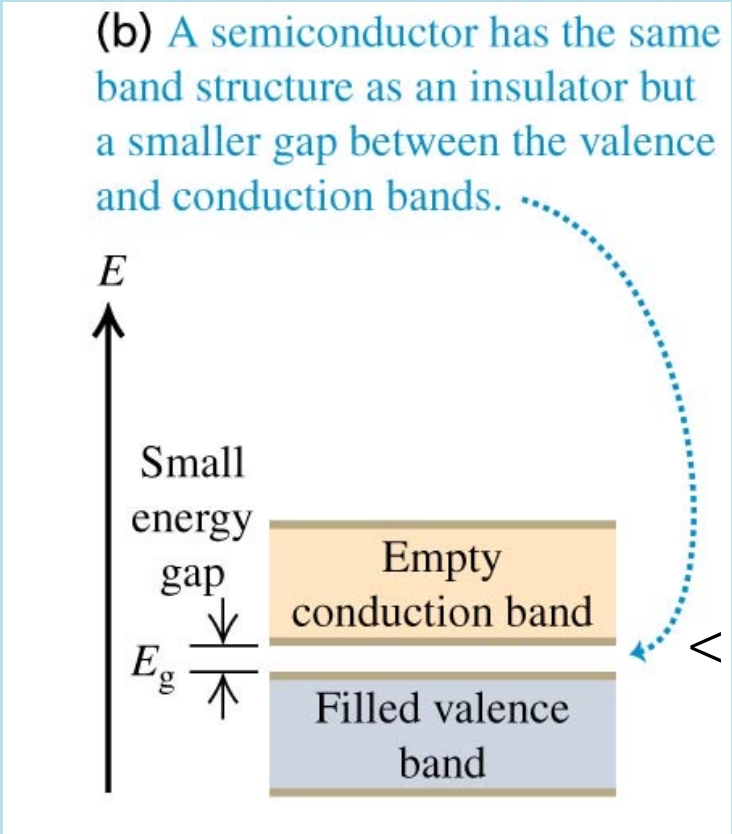


Figure 5.2 The occupation of (a) the energy levels in an isolated carbon atom, and (b) the energy bands in a diamond crystal. Notice that there is an energy range E_g separating the highest occupied states (in the valence band) from the lowest vacant states (in the conduction band). This is a characteristic feature of all insulators.



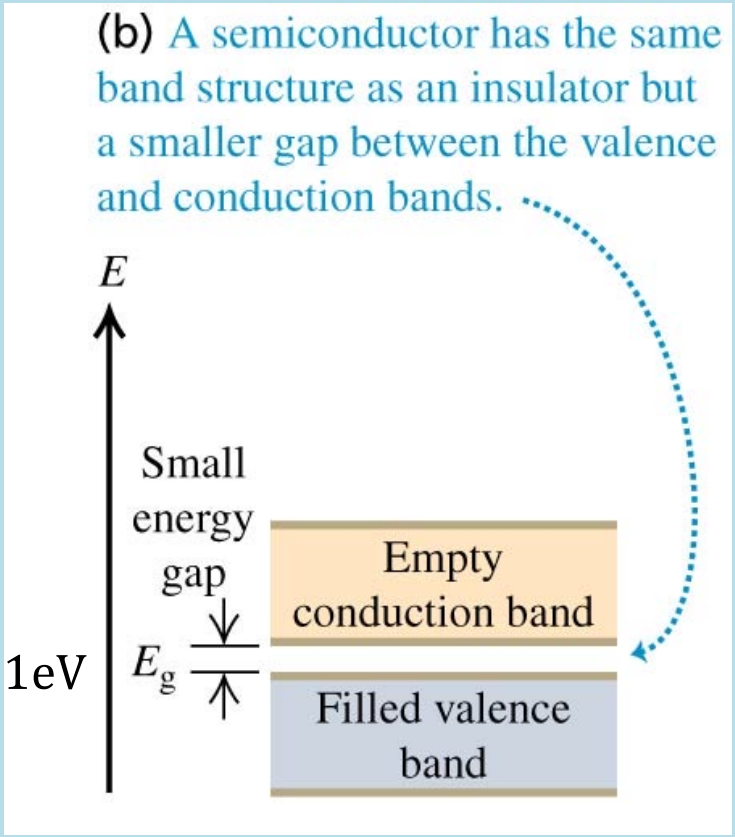
碳

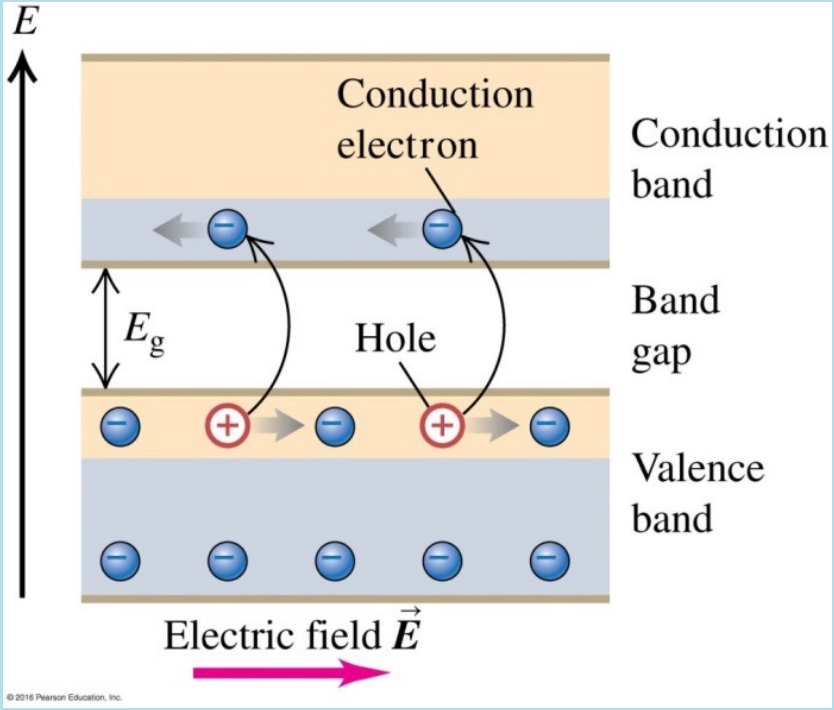
Figure 5.3 The energy levels of the 2s and 2p states for a group of N carbon atoms as a function of the separation of the atoms.



若全滿的Valence能帶與全空的Conduction能帶間隙很小時，情況與絕緣體很不一樣！

半導體 Semiconductor



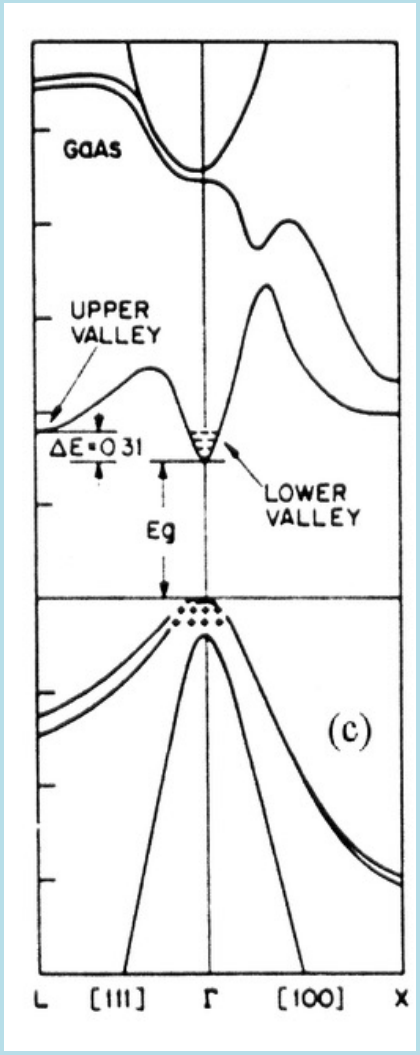


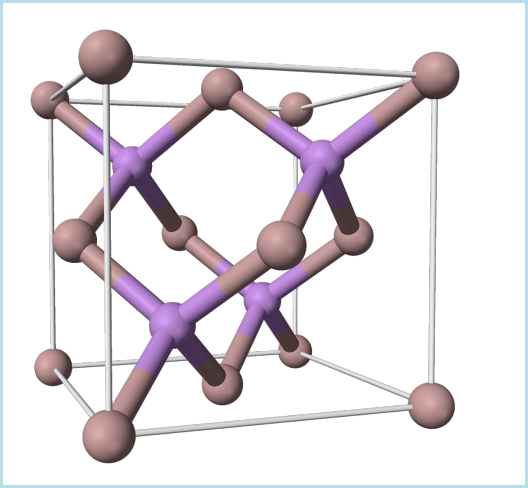
半導體的能帶間隙小，在室溫時即可以有電子由Valence跳上Conduction。

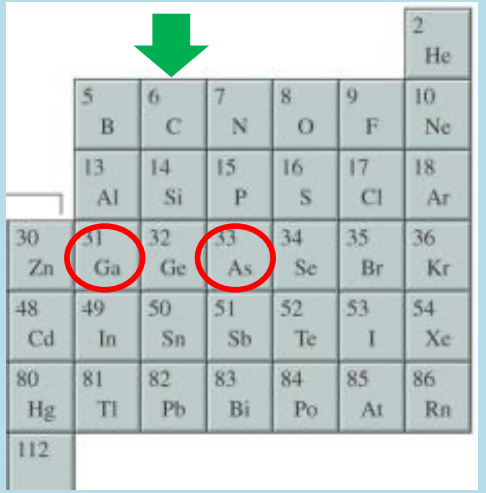
Conduction帶內的電子及Valence帶內的電洞形成導電的載體carrier。

砷化鎵

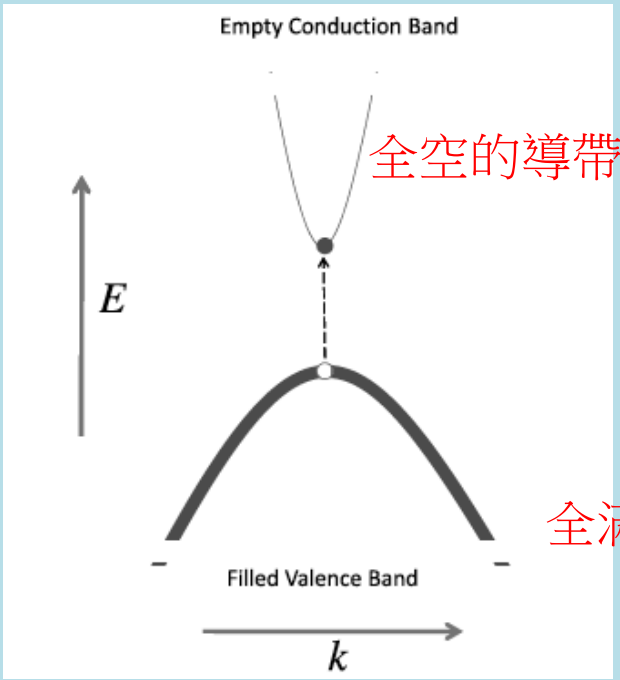
Gallium arsenide

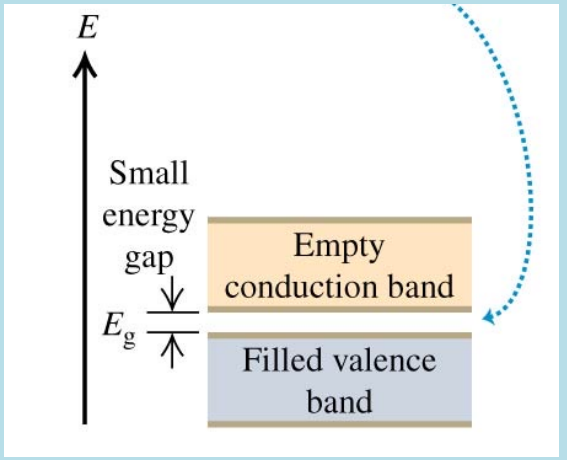




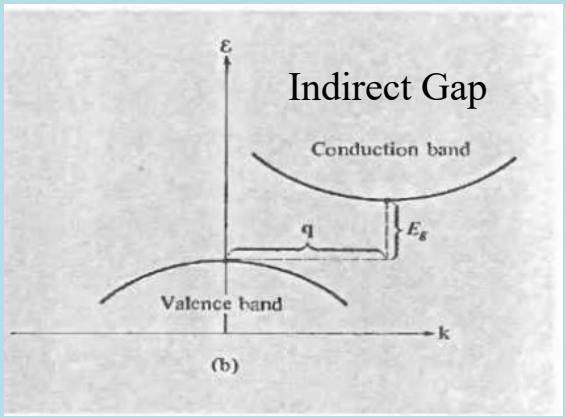


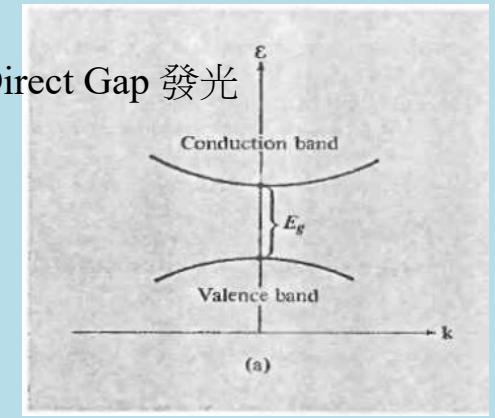
以下是一個典型半導體的能帶圖：



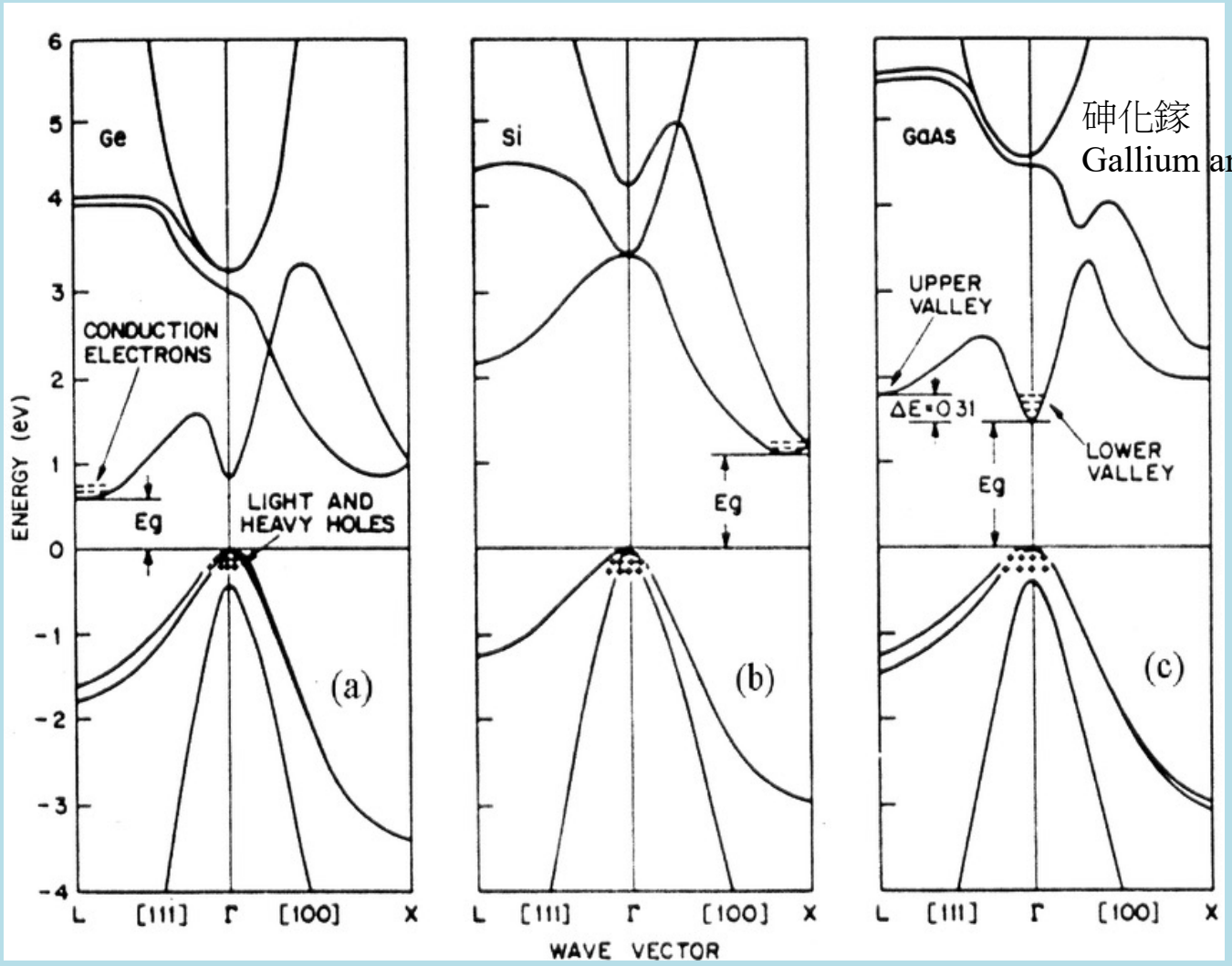


橫軸是能態波函數的晶體動量k。

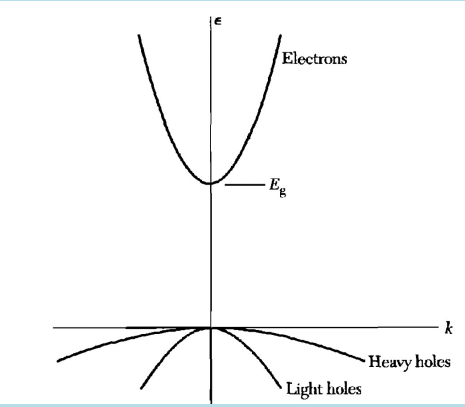


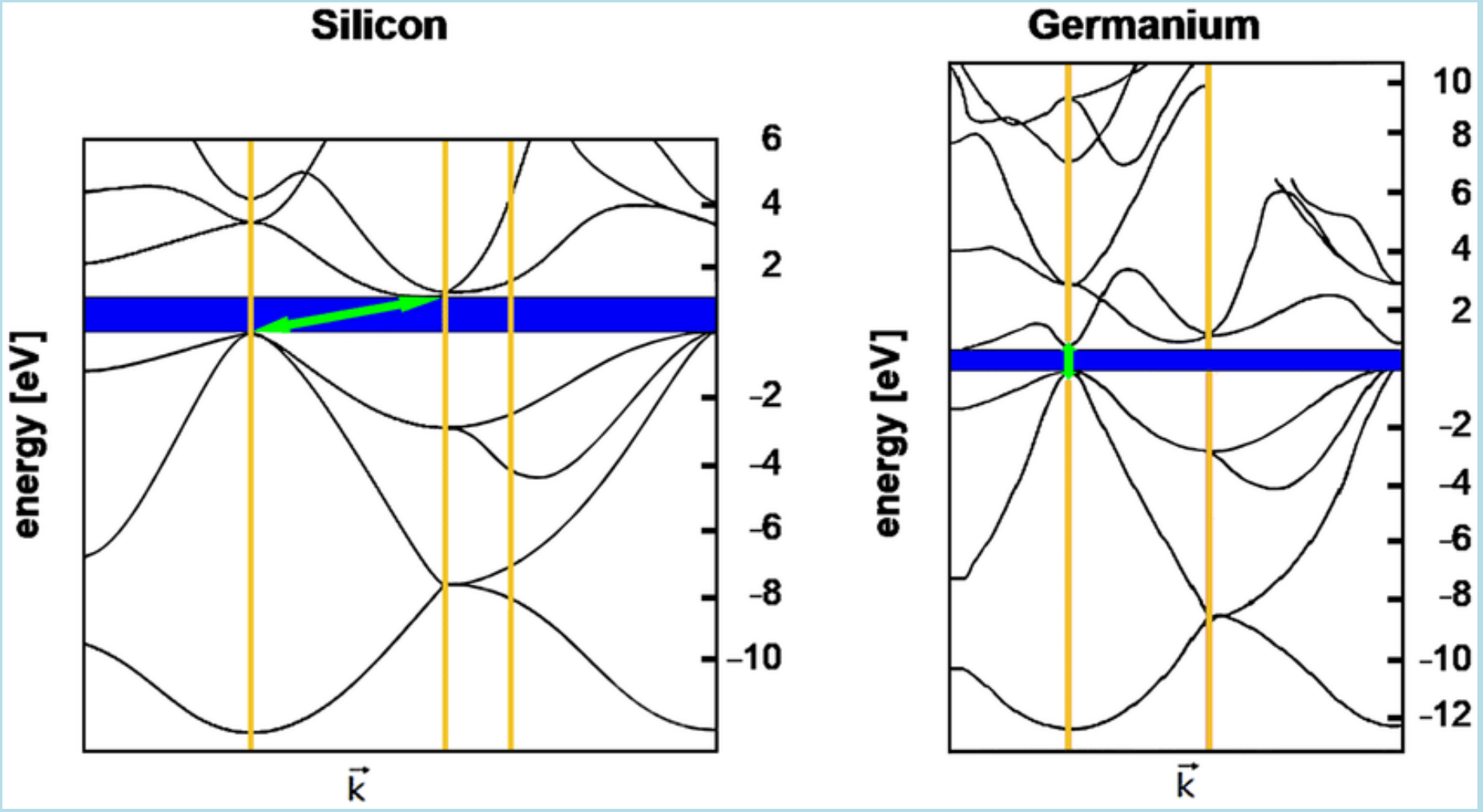


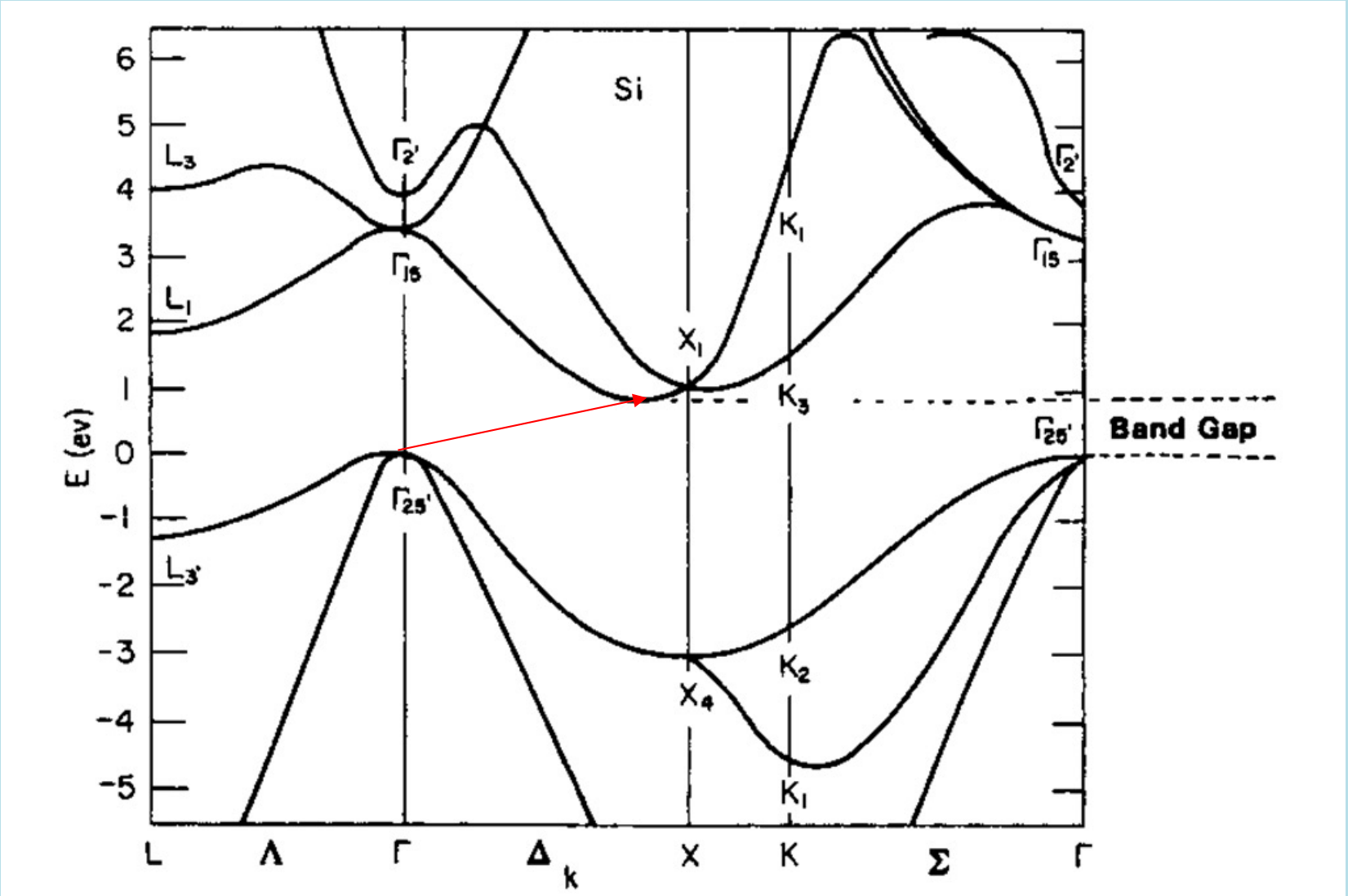
						2 He
	5 B	6 C	7 N	8 O	9 F	10 Ne
	13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr
48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe
80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn
112						

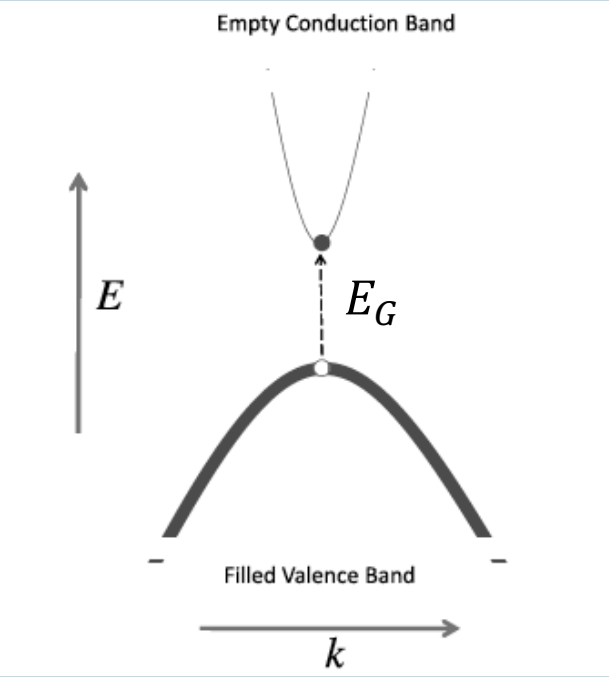


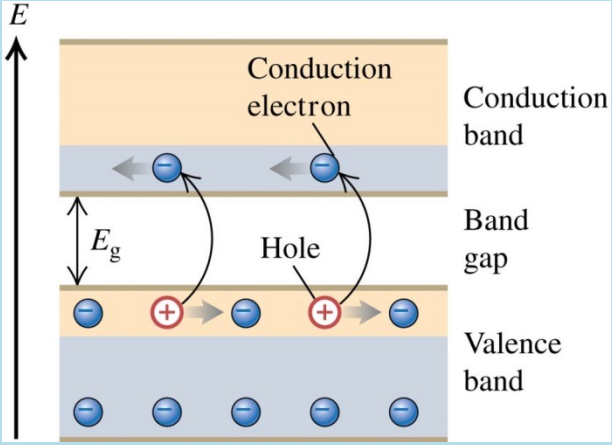
砷化鎵
Gallium arsenide




Silicon
energy [eV]
6
4
2
-2
-4
-6
-8
-10
$\vec{k}$
Germanium
energy [eV]
10
8
6
4
2
-2
-4
-6
-8
-10
-12
$\vec{k}$


Si
E (ev)
6
5
4
3
2
1
0
-1
-2
-3
-4
-5
L
Λ
Γ
Δ
k
X
K
Σ
Γ
L3
L1
L3'
Γ2'
Γ15
Γ25'
X1
X4
K1
K3
K2
K1
Γ2'
Γ15
Γ25'
Band Gap





由全滿價能帶跳上全空導帶的傳導電子，數量不足以到達導帶的高能階，

在能量最低點E_G（$k_{\min}$設為零）附近，能量是一個二次曲線，可寫成：

$$E \sim E_G + \alpha k^2 = E_G + \frac{\hbar^2 k^2}{2m_e^*}$$

以價帶的頂點能量為零。

m_e^*稱為電子有效質量。就是若將m_e^*代入動能公式就得到電子在導帶的能量。

電子組成的波包，群速度為動量為$\hbar k$的電子波包的群速度：

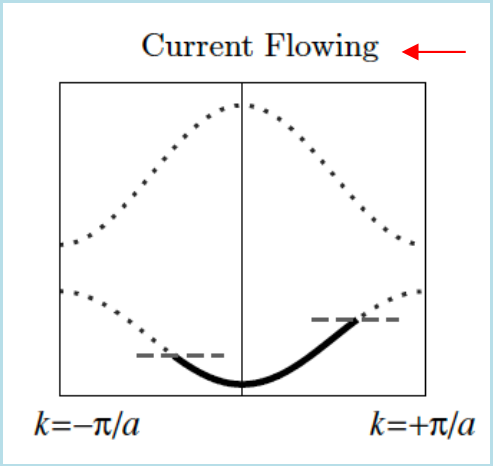
$$v_g = \frac{\partial \omega}{\partial k} = \frac{1}{\hbar}\frac{\partial E}{\partial k} = \frac{\hbar k}{m_e^*}$$

能量最低點附近，傳導電子完全像質量為m_e^*、動量$\hbar k$的自由電子！

在外加均勻電場下，所有電子態的k會以均勻變化率變化：

$$\hbar \frac{dk}{dt} = -eE$$

而傳導電子的性質就如帶負電，質量為m_e^*電子有效質量的自由粒子！



At any rate, in the semiclassical picture, we can write a simple Drude transport equation (really Newton's equations!) for electrons in the conduction band

$$m_e^* \, d\mathbf{v}/dt = -e(\mathbf{E} + \mathbf{v} \times \mathbf{B}) - m_e^* \, \mathbf{v}/\tau$$

with m_e^* the electron effective mass. Here the first term on the right-hand side is the Lorentz force on the electron, and the second term is a drag force with an appropriate scattering time τ. The scattering time

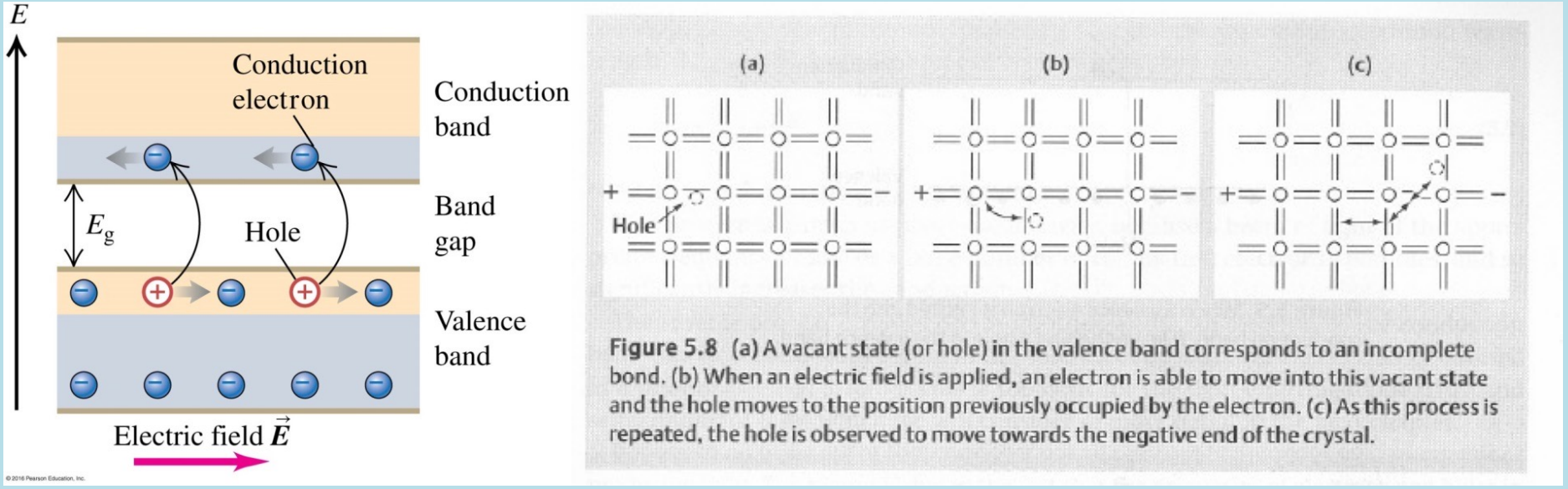
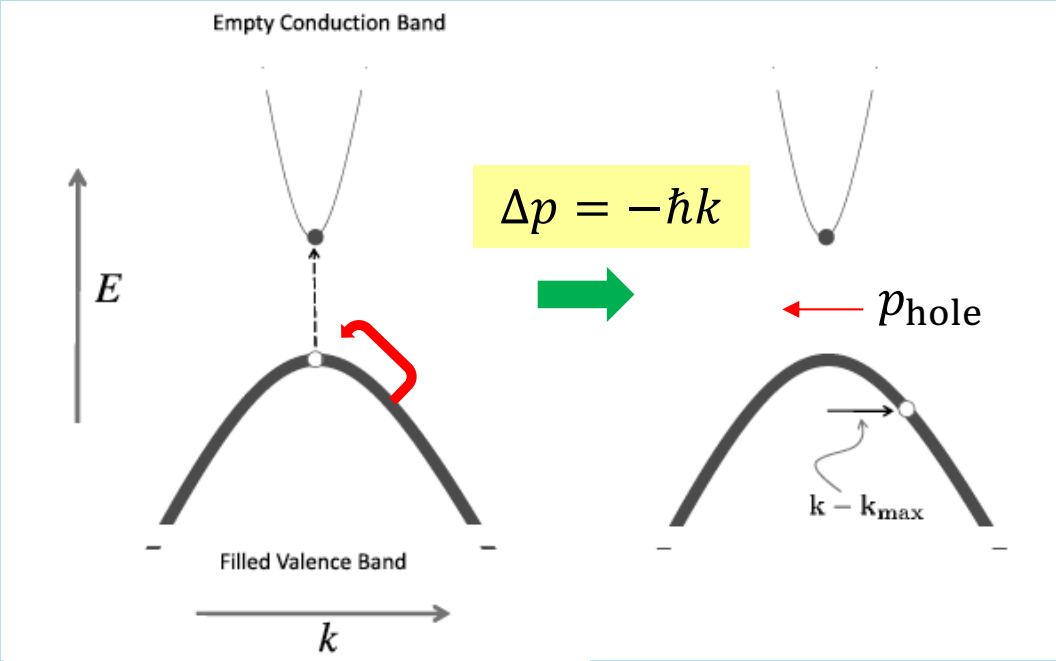


Figure 5.8 (a) A vacant state (or hole) in the valence band corresponds to an incomplete bond. (b) When an electric field is applied, an electron is able to move into this vacant state and the hole moves to the position previously occupied by the electron. (c) As this process is repeated, the hole is observed to move towards the negative end of the crystal.

電洞也能導電！



價能帶的能量：設$k_{\max} = 0$

$$E \sim -\beta k^2 \equiv -\frac{\hbar^2 k^2}{2m^*_{\text{hole}}}$$

m^*_{hole}稱為電洞的有效質量

當價帶頂點電子躍上導帶，

價帶頂點有一靜止$k = 0$電洞。

左圖狀態動量、能量為零。

電洞移至$k \neq 0$如右圖，此狀態等同左圖將$k \neq 0$態電子移入頂點$k = 0$電洞。

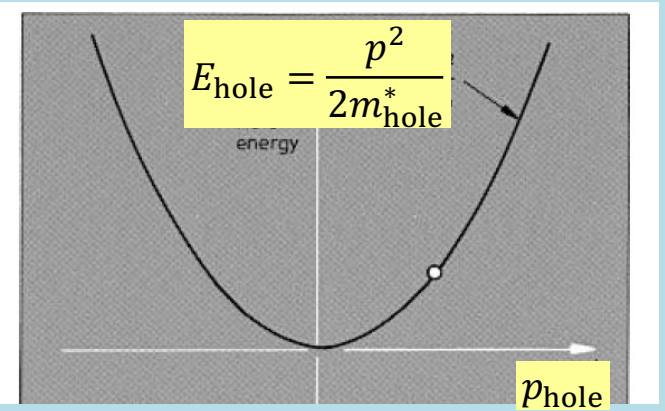
右圖相對於左圖，動量為實體移動的電子原來的動量的負號$-\hbar k$ ：

因此$-\hbar k$即為右圖此電洞的動量p_{hole}！ $p_{\text{hole}} = -\hbar k$

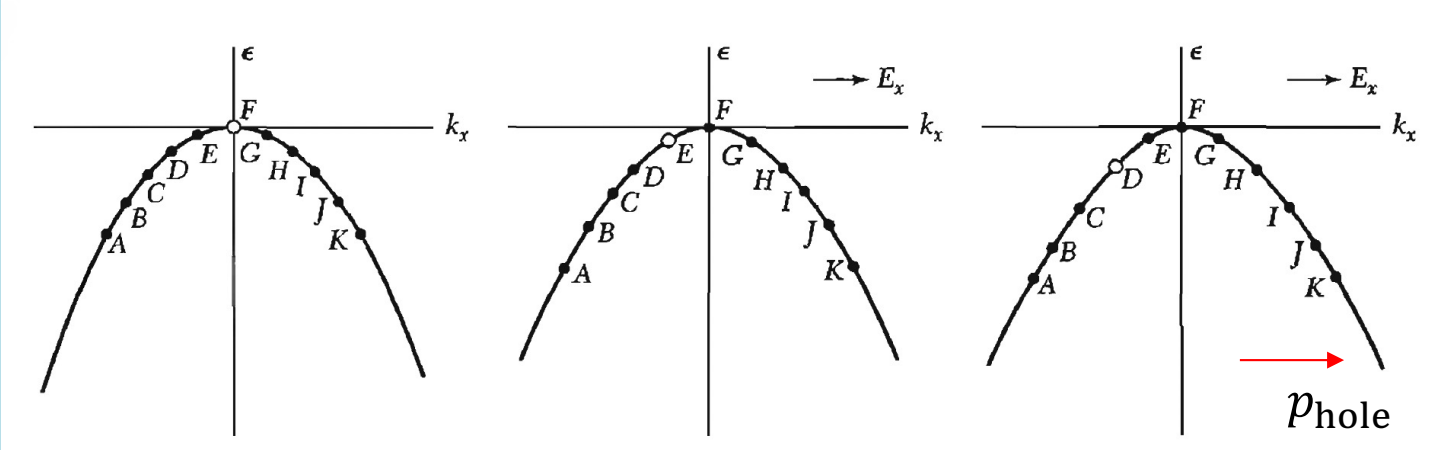
而此實體移動的電子，能量增加$\frac{\hbar^2 k^2}{2m^*_{\text{hole}}}$(兩狀態能差)

右圖狀態的能量即為：如右圖：

$$E_{\text{hole}} \sim \frac{\hbar^2 k^2}{2m^*_{\text{hole}}} = \frac{p^2}{2m^*_{\text{hole}}}$$



電洞的行為完全像質量為m^*_{hole}、動量為$p_{\text{hole}} = -\hbar k$的自由粒子！



在外加沿$+x$均勻電場下，電子態的k會向$-x$以均勻變化率變化：

$$\hbar\frac{dk}{dt} = -eE$$

上圖原來在原點的電洞位置，也跟著其他電子如一條chain向左移動至$-x$，若以$p_{\text{hole}} = -\hbar k$表示，此狀態的動量$p_{\text{hole}}$為$+x$方向：

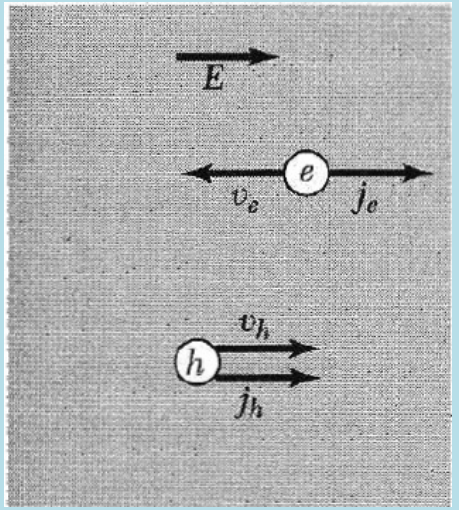
$$\hbar\frac{dp_{\text{hole}}}{dt} = +eE$$

可見電洞的性質如帶正電，向$+x$方向加速！

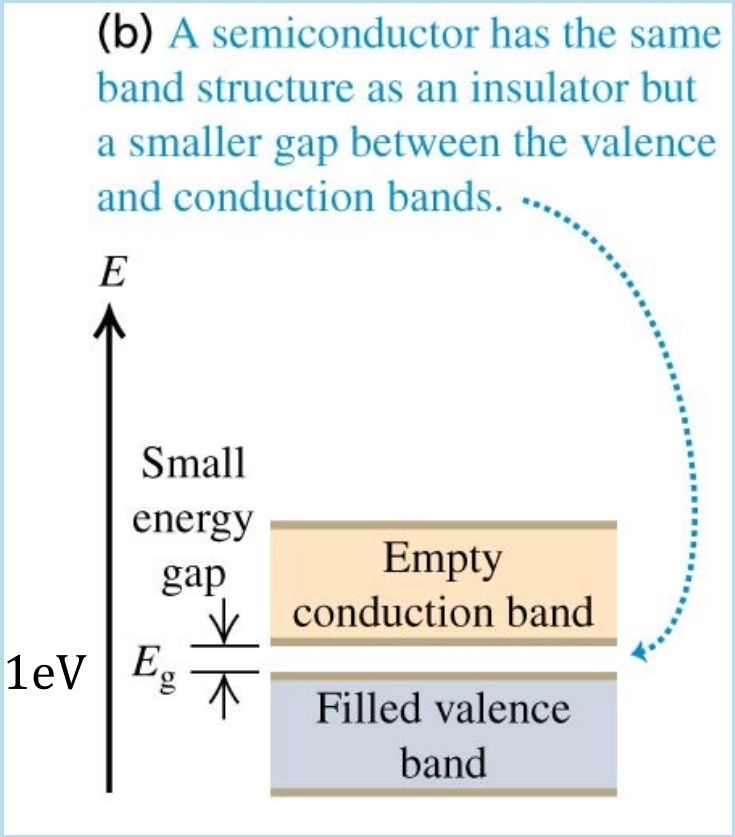
Similarly, we can write equations of motion for holes in the valence band

$$m_h^* \, d\mathbf{v}/dt = e(\mathbf{E} + \mathbf{v} \times \mathbf{B}) - m_h^* \, \mathbf{v}/\tau$$

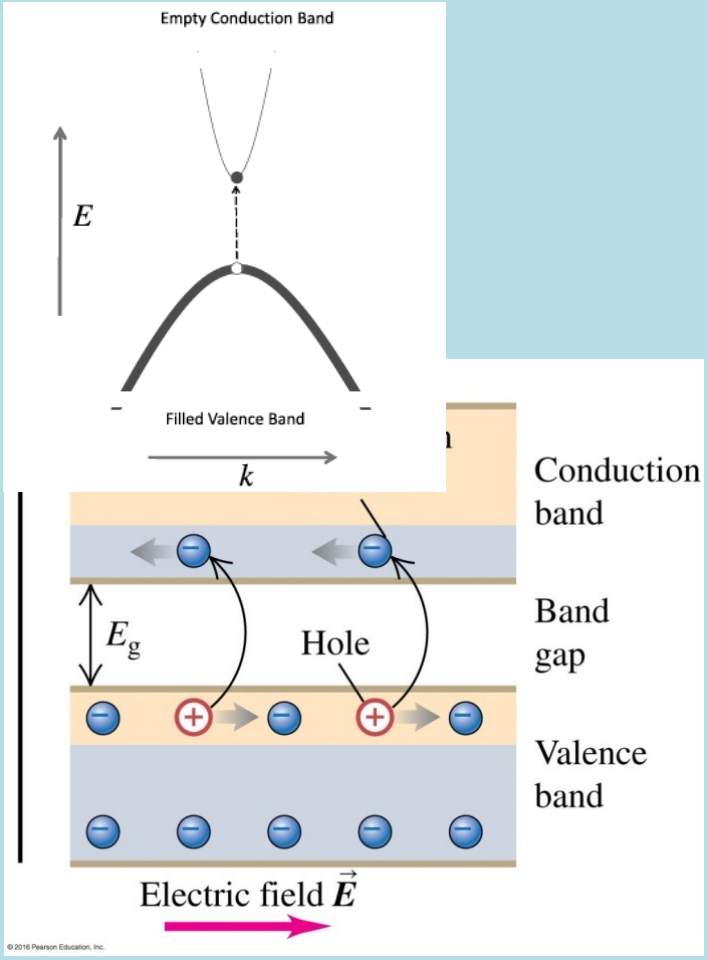
where m_h^* is the hole effective mass. Note again that here the charge on the hole is *positive*. This should make sense—the electric field pulls on an electron in a direction opposite to the direction that it pulls on the absence of an electron!



半導體 Semiconductor



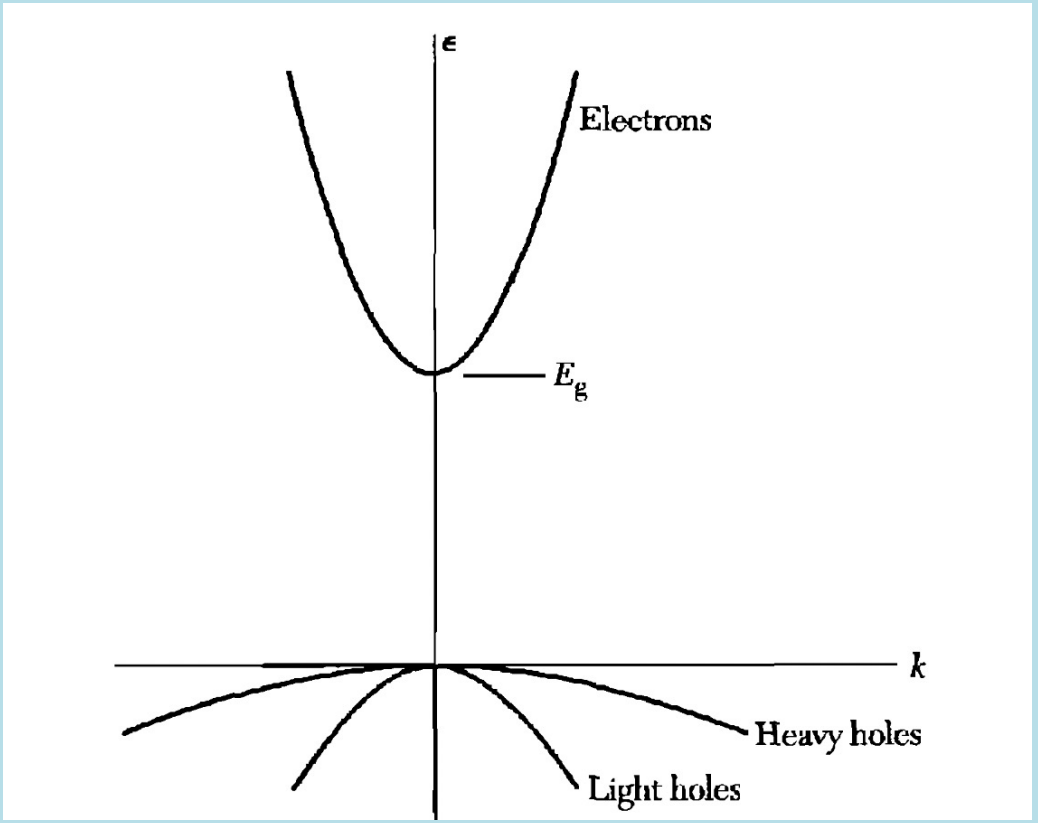
< 1eV



Conduction帶內的電子及Valence帶內的電洞形成導電的載體carrier。

而且兩者都是自由自在、如同沒有交互作用，而且機動。

從這個事實的基礎就能建立整個半導體理論，幾乎無需再回到能帶等等概念！



Crystal	Electron m_e/m	Heavy hole m_{hh}/m	Light hole m_{lh}/m
InSb	0.015	0.39	0.021
InAs	0.026	0.41	0.025
InP	0.073	0.4	(0.078)
GaSb	0.047	0.3	0.06
GaAs	0.066	0.5	0.082
Cu_2O	0.99	—	0.58
	$\frac{m_e^*}{m}$	$\frac{m_{hole}^*}{m}$	

The valence band edges are not simple. Holes near the band edge are characterized by two effective masses, light and heavy. These arise from the two bands formed from the $p_{3/2}$ level of the atom. There is also a band formed from the $p_{1/2}$ level, split off from the $p_{3/2}$ level by the spin-orbit interaction. The energy surfaces are not spherical, but warped (*QTS*, p. 271):

$$\epsilon(\mathbf{k}) = Ak^2 \pm [B^2k^4 + C^2(k_x^2k_y^2 + k_y^2k_z^2 + k_z^2k_x^2)]^{1/2} \tag{33}$$

The choice of sign distinguishes the two masses. The split-off band has $\epsilon(k) = -\Delta + Ak^2$. The experiments give, in units $\hbar^2/2m$,

Si:	$A = -4.29$;	$\lvert B\rvert = 0.68$;	$\lvert C\rvert = 4.87$;	$\Delta = 0.044$ eV
Ge:	$A = -13.38$;	$\lvert B\rvert = 8.48$;	$\lvert C\rvert = 13.15$;	$\Delta = 0.29$ eV

Roughly, the light and heavy holes in germanium have masses 0.043 m and 0.34 m; in silicon 0.16 m and 0.52 m; in diamond 0.7 m and 2.12 m.

The conduction band edges in Ge are at the equivalent points L of the Brillouin zone, Fig. 15a. Each band edge has a spheroidal energy surface oriented along a ⟨111⟩ crystal axis, with a longitudinal mass $m_l = 1.59\ m$ and a transverse mass $m_t = 0.082\ m$. For a static magnetic field at an angle θ with the longitudinal axis of a spheroid, the effective cyclotron mass m_c is

$$\frac{1}{m_c^2} = \frac{\cos^2\theta}{m_t^2} + \frac{\sin^2\theta}{m_t m_l} \tag{34}$$

Results for Ge are shown in Fig. 16.

In silicon the conduction band edges are spheroids oriented along the equivalent ⟨100⟩ directions in the Brillouin zone, with mass parameters $m_l = 0.92\ m$ and $m_t = 0.19\ m$, as in Fig. 17a. The band edges lie along the lines labeled Δ in the zone of Fig. 15a, a little way in from the boundary points X.

In GaAs we have $A = -6.98$, $B = -4.5$, $\lvert C\rvert = 6.2$, $\Delta = 0.341$ eV. The band structure is shown in Fig. 17b. It has a direct band gap with an isotropic conduction mass of 0.067 m.

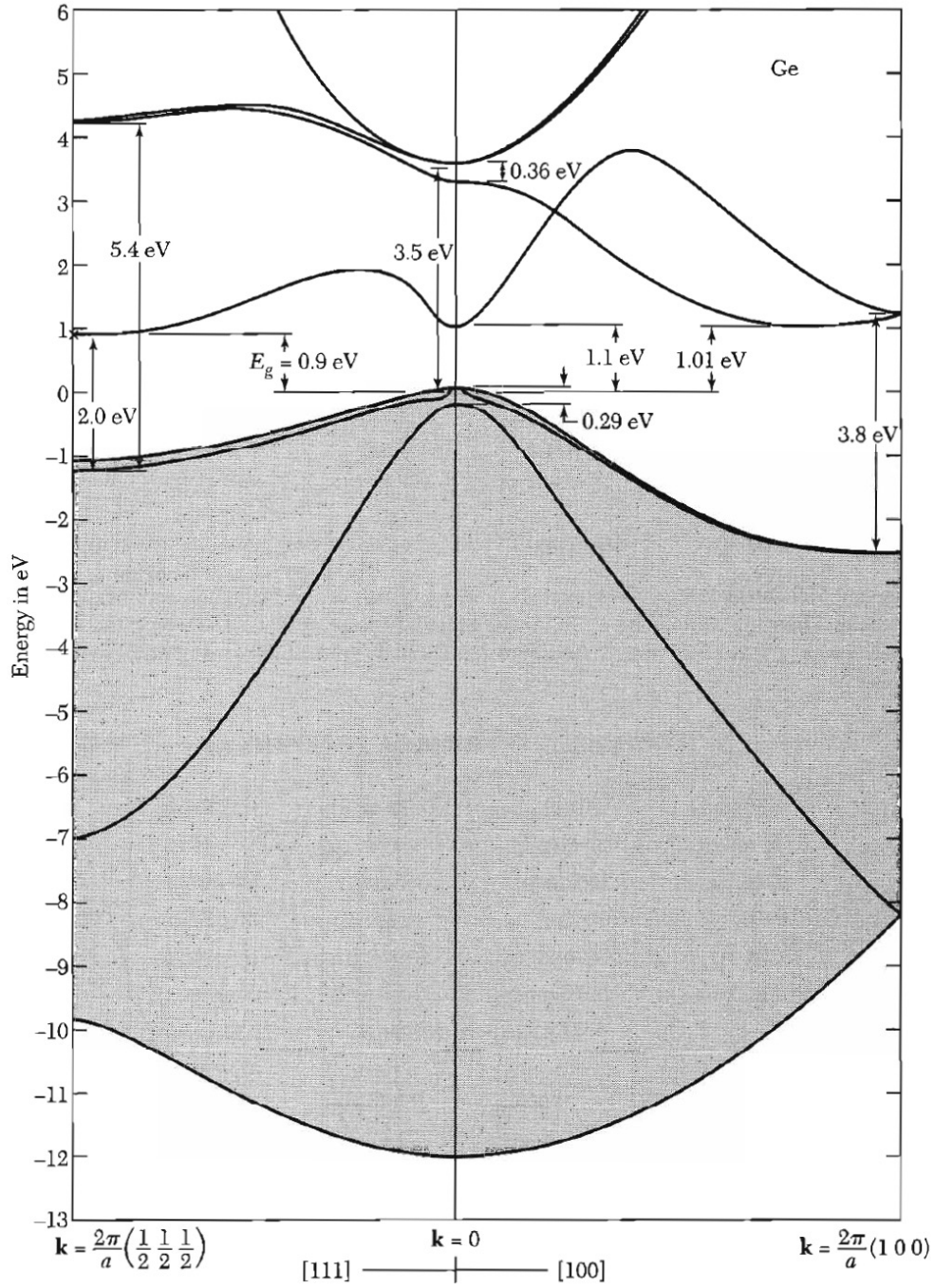


Figure 14 Calculated band structure of germanium, after C. Y. Fong. The general features are in good agreement with experiment. The four valence bands are shown in gray. The fine structure of the valence band edge is caused by spin-orbit splitting. The energy gap is indirect; the conduction band edge is at the point $(2\pi/a)(\frac{1}{2}\,\frac{1}{2}\,\frac{1}{2})$. The constant energy surfaces around this point are ellipsoidal.

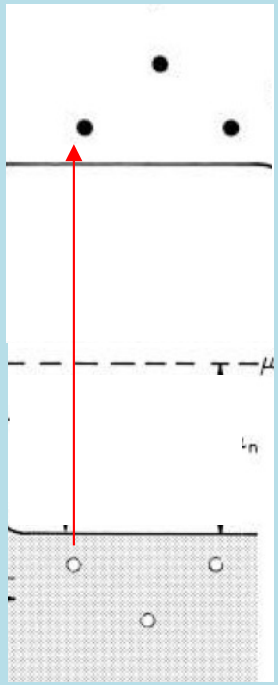
由價帶跳上導帶的電子密度n，就是價帶的電洞密度，決定了導電性：

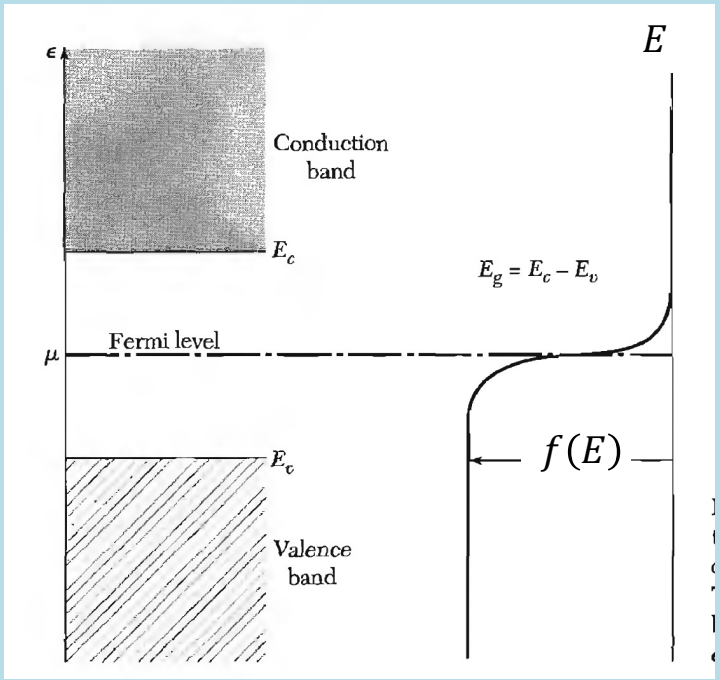
$$\rho = \frac{m}{e^2 n \tau}$$

溫度為T時，電子密度n可以以狀態機率Fermi-Dirac Factor$f(E)$決定：

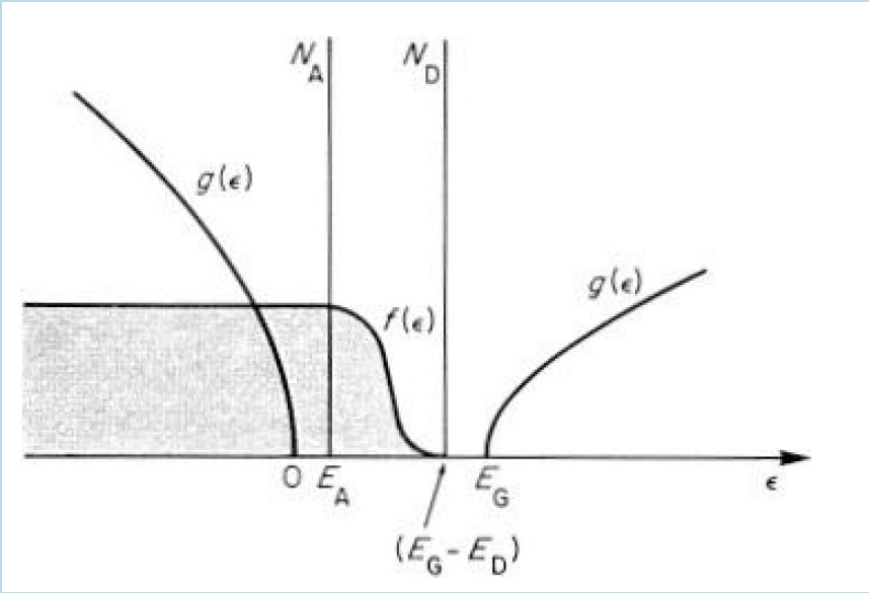
$$f(E) = \frac{1}{e^{\frac{1}{kT}(E-\mu)} + 1}$$

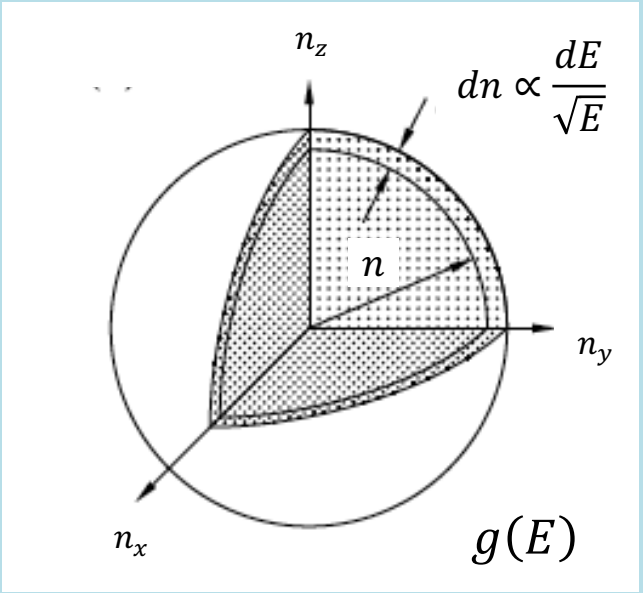
μ是化學能，由導電電子總數決定。





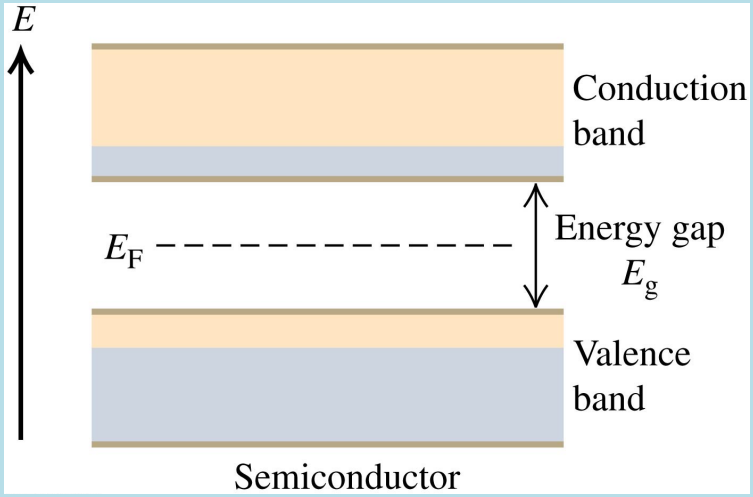
嚴格來說，電子密度n等於狀態發生機率$f(E)$，乘狀態數密度$g(E)$計算：





$$n = \int_{E_G}^{\infty} dE \cdot g(E) \cdot f(E)$$

$$= \frac{1}{\sqrt{2}} \left(\frac{kT}{\pi\hbar^2}\right)^{\frac{3}{2}} (m_e^* m_h^*)^{\frac{3}{4}} \cdot e^{-\frac{E_G}{2kT}}$$

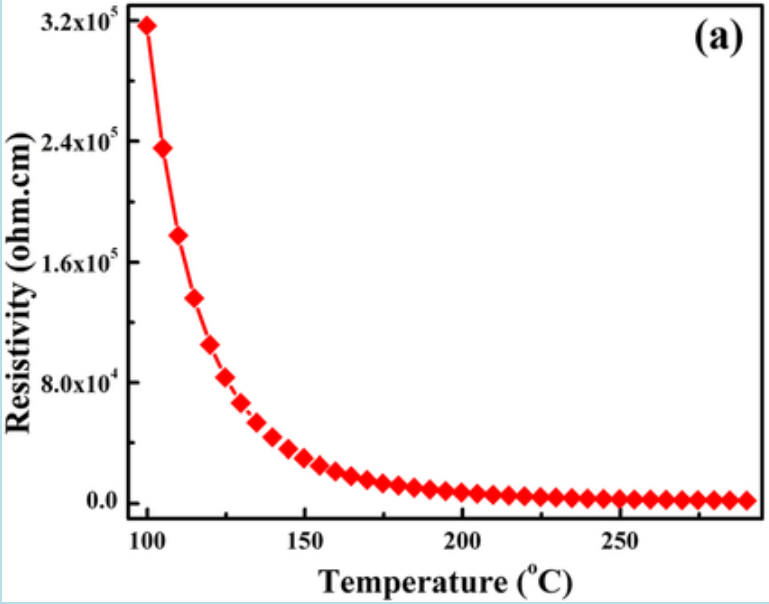


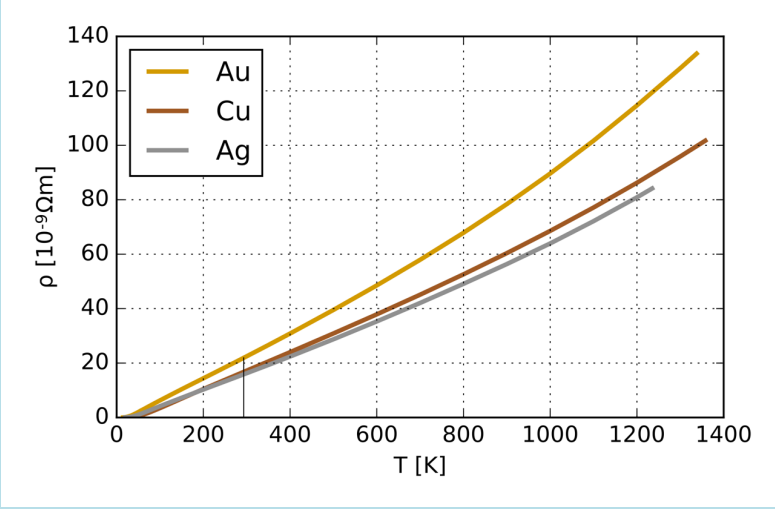
導電電子密度大約可以以波茲曼factor估計：

$n \propto e^{-\frac{E_G}{2kT}}$ 導電電子密度由能隙決定！

$$\frac{E_g}{kT} \sim \frac{0.2\text{eV}}{8.617\times10^{-5}\text{eV/K}\cdot 300\text{K}} \sim 7.736$$

$$n \propto 2.00\times10^{-2} \sim 9.22\times10^{15}\text{m}^{-3}$$





半導體的電阻率隨溫度增加快速降低。

相對的、導體的電阻率隨溫度增加而增加。

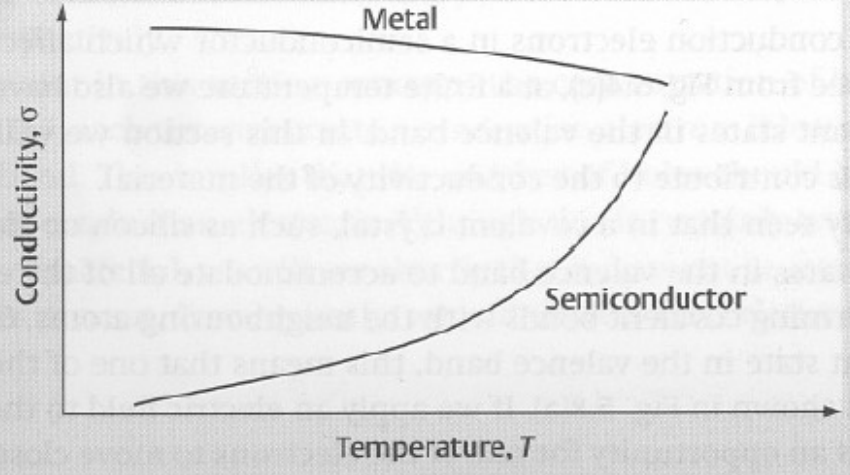


Figure 5.6 Variation of conductivity with temperature for a typical metal and semiconductor.

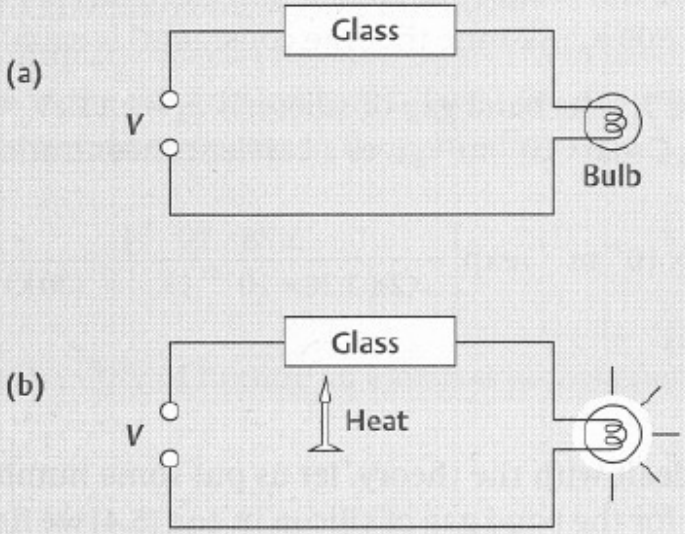


Figure 5.7 (a) A simple circuit consisting of a glass bar in series with a light bulb. At room temperature the bulb does not light because glass is an insulator. (b) But if the glass bar is heated (e.g. using a Bunsen burner), the conductivity of the glass increases and the bulb lights.

但E_g~1.0eV能跳上導帶的電子數量還是遠少於導體，

電阻率比起導體還是來得大！

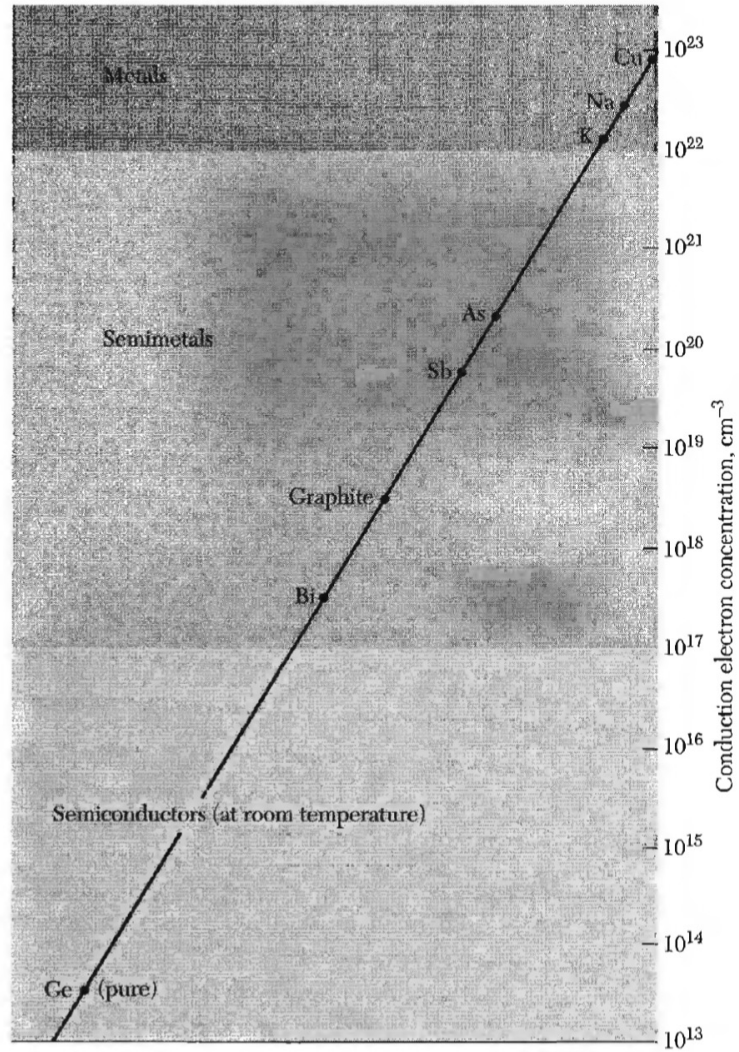


Figure 1 Carrier concentrations for metals, semimetals, and semiconductors. The semiconductor range may [Screenshot] ward by increasing the impurity concentration, and the range can be extended downward to merge eventually with the insulator range.

17.1 Electrons and Holes

Suppose we start with an insulator or semiconductor and we excite one electron from the valence band to the conduction band, as shown in the left of Fig. 17.1. This excitation may be due to absorbing a photon, or it might be a thermal excitation. (For simplicity in the figure we have shown a direct band gap. For generality we have not assumed that the curvature of the two bands are the same.) When the electron has been moved up to the conduction band, there is an absence of an electron in the valence band known as a *hole*. Since a completely filled band is inert, it is very convenient to only keep track of the few holes in the valence band (assuming there are only a few) and to treat these holes as individual elementary particles. The electron can fall back into the empty state that is the hole, emitting energy (a photon, say) and "annihilating" both the electron from the conduction band and the hole from the valence band.[1] Note that while the electrical charge of an electron is negative the electrical charge of a hole (the absence of an electron) is positive—equal and opposite to that of the electron.[2]

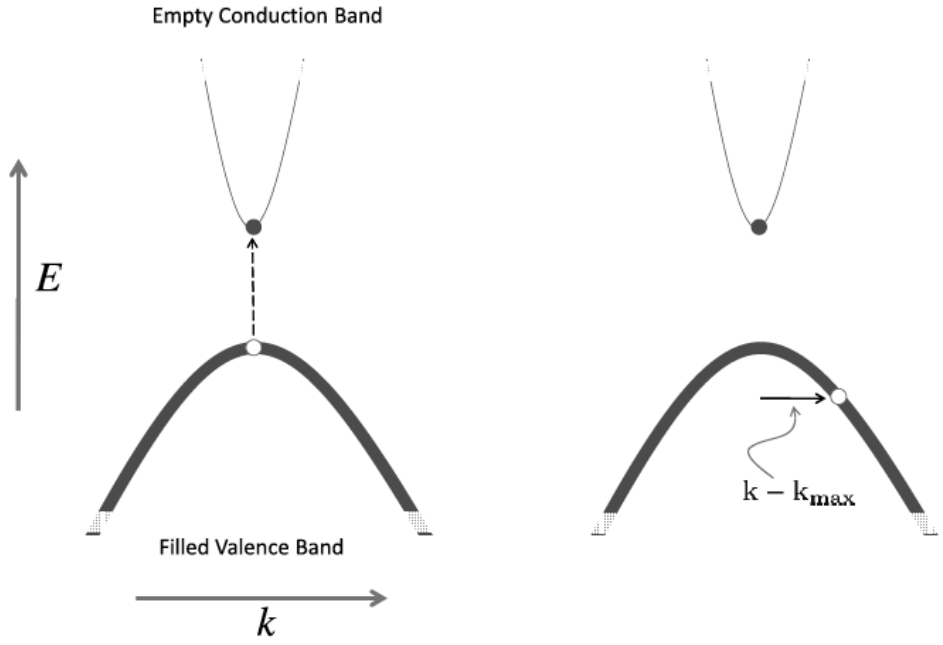


Fig. 17.1 Electrons and holes in a semiconductor. **Left:** A single hole in the valence band and a single electron in the conduction band. **Right:** Moving the hole to a momentum away from the top of the valence band costs *positive* energy—like pushing a balloon under water. As such, the effective mass of the hole is defined to be positive. The energy of the configuration on the right is greater than that on the left by $E = \hbar^2|\mathbf{k} - \mathbf{k_{max}}|^2/(2m^*)$

[1] This is equivalent to pair annihilation of an electron with a positron. In fact, the analogy between electron–hole and electron–positron is fairly precise. As soon as Dirac constructed his equation (in 1928) describing the relativistic motion of electrons, and predicting positrons, it was understood that the positron could be thought of as an absence of an electron in a filled sea of states. The filled sea of electron states with a gap to exciting electron–positron pairs is the inert vacuum, which is analogous to an inert filled valence band.

[2] If this does not make intuitive sense consider the process of creating an electron–hole pair as described in Fig. 17.1. Initially (without the excited electron–hole pair) the system is charge neutral. We excite the system with a photon to create the pair, and we have not moved any additional net charge into the system. Thus if the electron is negative, the hole must be positive to preserve overall charge neutrality.

Effective Mass of Electrons

As mentioned in Sections 11.2 and 15.1.1, it is useful to describe the curvature at the bottom of a band in terms of an effective mass. Let us assume that near the bottom of the conduction band (assumed to be at $\mathbf{k} = \mathbf{k_{min}}$) the energy is given by[3,4,5,6]

$$E = E_{min} + \alpha|\mathbf{k} - \mathbf{k_{min}}|^2 + \dots$$

with $\alpha > 0$, where the dots mean higher-order term in the deviation from $\mathbf{k_{min}}$. We then *define* the *effective mass* to be given by

$$\frac{\hbar^2}{m^*} = \frac{\partial^2 E}{\partial k^2} = 2\alpha \tag{17.1}$$

at the bottom of the band (with the derivative being taken in any direction for an isotropic system). Correspondingly, the (group) velocity is given by[7]

$$\mathbf{v} = \frac{\nabla_{\mathbf{k}} E}{\hbar} = \frac{\hbar(\mathbf{k} - \mathbf{k_{min}})}{m^*} \,. \tag{17.2}$$

This definition is chosen to be in analogy with the free electron behavior $E = \hbar^2|\mathbf{k}|^2/(2m)$ with corresponding velocity $\mathbf{v} = \nabla_{\mathbf{k}} E/\hbar = \hbar\mathbf{k}/m$.

Effective Mass of Holes

Analogously we can define an effective mass for holes. Here things get a bit more complicated. For the top of the valence band, the energy dispersion for electrons would be

$$E = E_{\max} - \alpha|\mathbf{k} - \mathbf{k_{max}}|^2 + \dots \tag{17.3}$$

with $\alpha > 0$. The modern convention is to *define the effective mass for holes at the top of a valence band to be always positive*[8]

$$\frac{\hbar^2}{m^*_{\text{hole}}} = -\frac{\partial^2 E}{\partial k^2} = 2\alpha. \tag{17.4}$$

The convention of the effective mass being positive makes sense because the energy to boost the hole from zero velocity ($\mathbf{k} = \mathbf{k_{max}}$ at the top of the valence band) to finite velocity is positive. This energy is naturally given by

$$E_{\text{hole}} = \text{constant} + \frac{\hbar^2|\mathbf{k} - \mathbf{k_{max}}|^2}{2m^*_{\text{hole}}} \,.$$

The fact that boosting the hole away from the top of the valence band is positive energy may seem a bit counter-intuitive being that the dispersion of the hole band is an upside-down parabola. However, one should think of this as being like pushing a balloon under water. The lowest energy configuration is with the *electrons* at the lowest energy possible and the hole at the highest energy possible. So pushing the hole under the electrons costs positive energy. (This is depicted in the right-hand side of Fig. 17.1.) A good way to handle this bookkeeping is to remember

$$E(\text{absence of electron in state } \mathbf{k}) = -E(\text{electron in state } \mathbf{k}). \tag{17.5}$$

[3] It is an important principle that near a minimum or a maximum one can always expand and get something quadratic plus higher order corrections.

[4] For simplicity we have assumed the system to be isotropic. In the more general case we would have

$$\begin{aligned} E = E_{min} \quad &+ \quad \alpha_x(k_x - k_x^{min})^2 \\ &+ \quad \alpha_y(k_y - k_y^{min})^2 \\ &+ \quad \alpha_z(k_z - k_z^{min})^2 + \dots \end{aligned}$$

for some orthogonal set of axes (the "principal axes") x, y, z. In this case we would have an effective mass which can be different in the three different principal directions.

[5] For simplicity we also neglect the spin of the electron here. In general, spin–orbit coupling can make the dispersion depend on the spin state of the electron. Among other things, this can modify the effective electron g-factor.

[6] It often occurs that the bottom of conduction band has more than one minimum at different points $\mathbf{k}^{(n)}_{\mathbf{min}}$ in the Brillouin zone with exactly the same energy. We then say that there are multiple "valleys" in the band structure. Such a situation occurs due to the symmetry of the crystal. For example, in silicon (an fcc structure with a basis, see Fig. 12.21), six conduction band minima with the same energy occur approximately at the k-points $(\pm 5.3/a, 0, 0)$, $(0, \pm 5.3/a, 0)$, and $(0, 0, \pm 5.3/a)$.

[7] More accurately, $\mathbf{v} = \nabla_{\mathbf{k}} E(\mathbf{k})/\hbar + \mathbf{K}$ where the additional term $\mathbf{K}$ is known as the "Karplus–Luttinger" anomalous velocity and is proportional to applied electric field. This correction, resulting from subtle quantum-mechanical effects, is almost always neglected in solid state texts and rarely causes trouble (this is related to footnote 9 in Chapter 11). Only recently has research focused more on systems where such terms do matter. Proper treatment of this effect is beyond the scope of this book.

[8] Be warned: a few books define the mass of holes to be negative. This is a bit annoying but not inconsistent as long as the negative sign shows up somewhere else as well!

The momentum and velocity of a hole

There is a bit of complication with signs in keeping track of the momentum of a hole. If an electron is added to a band in a state $\mathbf{k}$ then the crystal momentum contained in the band increases by $\hbar\mathbf{k}$. Likewise, if an electron in state $\mathbf{k}$ is *removed* from an otherwise filled band, then the crystal momentum in the band must decrease by $\hbar\mathbf{k}$. Then, since a fully filled band carries no net crystal momentum the absence of an electron in state $\mathbf{k}$ should be a hole whose crystal momentum is $-\hbar\mathbf{k}$. It is thus convenient to *define* the wavevector $\mathbf{k}_{\text{hole}}$ of a hole to be the negative of the wavevector $\mathbf{k}_{\text{electron}}$ of the corresponding absent electron.[9]

This definition of wavevector is quite sensible when we try to calculate the group velocity of a hole. Analogous to the electron, we write the hole group velocity as the derivative of the hole energy

$$\mathbf{v}_{\text{hole}} = \frac{\nabla_{\mathbf{k}_{\text{hole}}} E_{\text{hole}}}{\hbar}. \tag{17.6}$$

Now, using Eq. 17.5, and also the fact that that the wavevector of the hole is minus the wavevector of the missing electron, we get two canceling minus signs and we find that

$$\mathbf{v}_{\text{hole}} = \mathbf{v}_{\text{missing electron.}}$$

This is a rather fundamental principle. The time evolution of a quantum state is independent of whether that state is occupied with a particle or not!

Effective Mass and Equations of Motion

We have defined the effective masses above in analogy with that of free electrons, by looking at the curvature of the dispersion. An equivalent definition (equivalent at least at the top or bottom of the band) is to define the effective mass m^* as being the quantity that satisfies Newton's second law, $F = m^*a$ for the particle in question. To demonstrate this, our strategy is to imagine applying a force to an electron in the system and then equate the work done on the electron to its change in energy. Let us start with an electron in momentum state $\mathbf{k}$. Its group velocity is $\mathbf{v} = \nabla_k E(\mathbf{k})/\hbar$. If we apply a force,[10] the work done per unit time is

$$dW/dt = \mathbf{F} \cdot \mathbf{v} = \mathbf{F} \cdot \nabla_k E(\mathbf{k})/\hbar.$$

On the other hand, the change in energy per unit time must also be (by the chain rule)

$$dE/dt = d\mathbf{k}/dt \cdot \nabla_k E(\mathbf{k}).$$

Setting these two expressions equal to each other we (unsurprisingly) obtain Newton's equation

$$\mathbf{F} = \hbar\frac{d\mathbf{k}}{dt} = \frac{d\mathbf{p}}{dt} \tag{17.7}$$

where we have used $\mathbf{p} = \hbar\mathbf{k}$.

[9] Other conventions are possible but this is probably the simplest.

[10] For example, if we apply an electric field $\mathbf{E}$ and it acts on an electron of charge $-e$, the force is $\mathbf{F} = -e\mathbf{E}$.

If we now consider electrons near the bottom of a band, we can plug in the expression Eq. 17.2 for the velocity, and this becomes

$$\mathbf{F} = m^* \frac{d\mathbf{v}}{dt}$$

exactly as Newton would have expected. In deriving this result recall that we have assumed that we are considering an electron near the bottom of a band so that we can expand the dispersion quadratically (or similarly we assumed that holes are near the top of a band). One might wonder how we should understand electrons when they are neither near the top nor the bottom of a band. More generally Eq. 17.7 always holds, as does the fact that the group velocity is $\mathbf{v} = \nabla_k E/\hbar$. It is then sometimes convenient to define an effective mass for an electron as a function of momentum to be given by[11]

$$\frac{\hbar^2}{m^*(k)} = \frac{\partial^2 E}{\partial k^2}$$

which agrees with our definition (Eq. 17.1) near the bottom of band. However, near the top of a band it is the *negative* of the corresponding hole mass (note the sign in Eq. 17.4). Note also that somewhere in the middle of the band the dispersion must reach an inflection point ($\partial^2 E/\partial k^2 = 0$), whereupon the effective mass actually becomes infinite as it changes sign.

[11] For simplicity we write this in its one-dimensional form.

Aside: It is useful to compare the time evolution of electrons and holes near the top of bands. If we think in terms of holes (the natural thing to do near the top of a band) we have $\mathbf{F} = +e\mathbf{E}$ and the holes have a positive mass. However, if we think in terms of electrons, we have $\mathbf{F} = -e\mathbf{E}$ but the mass is negative. Either way, the acceleration of the k-state is the same, whether we are describing the dynamics in terms of an electron in the state or in terms of a hole in the state. As mentioned below Eq. 17.6, this equivalence is expected, since the time evolution of an eigenstate is independent of whether that eigenstate is filled with an electron or not.

17.1.1 Drude Transport: Redux

Back in Chapter 3 we studied Drude theory—a simple kinetic theory of electron motion. The main failure of Drude theory was that it did not treat the Pauli exclusion principle properly: it neglected the fact that in metals the high density of electrons makes the Fermi energy extremely high. However, in semiconductors or band insulators, when only a few electrons are in the conduction band and/or only a few holes are in the valence band, then we can consider this to be a low-density situation, and to a very good approximation, we can ignore Fermi statistics. (For example, if only a single electron is excited into the conduction band, then we can completely ignore the Pauli principle, since it is the only electron around—there is no chance that any state it wants to sit in will already be filled!) As a result, when there is a low density of conduction electrons or valence holes, it turns out that Drude theory works

extremely well! We will come back to this issue later in Section 17.3, and make this statement much more precise.

At any rate, in the semiclassical picture, we can write a simple Drude transport equation (really Newton's equations!) for electrons in the conduction band

$$m_e^* \, d\mathbf{v}/dt = -e(\mathbf{E} + \mathbf{v} \times \mathbf{B}) - m_e^* \, \mathbf{v}/\tau$$

with m_e^* the electron effective mass. Here the first term on the right-hand side is the Lorentz force on the electron, and the second term is a drag force with an appropriate scattering time τ. The scattering time determines the so-called *mobility* μ which measures the ease with which the particle moves. The mobility is generally defined as the ratio of the velocity to the electric field.[12] In this Drude approach we then obtain

$$\mu = |\mathbf{v}|/|\mathbf{E}| = |e\tau/m^*|.$$

Similarly, we can write equations of motion for holes in the valence band

$$m_h^* \, d\mathbf{v}/dt = e(\mathbf{E} + \mathbf{v} \times \mathbf{B}) - m_h^* \, \mathbf{v}/\tau$$

where m_h^* is the hole effective mass. Note again that here the charge on the hole is *positive*. This should make sense—the electric field pulls on an electron in a direction opposite to the direction that it pulls on the absence of an electron!

If we think back all the way to Chapters 3 and 4, one of the physical puzzles that we could not understand is why the Hall coefficient sometimes changes sign (see Table 3.1). In some cases it looked as if the charge carrier had positive charge. Now we understand why this is true. In some materials the main charge carrier is the hole!

17.2 Adding Electrons or Holes with Impurities: Doping

In a pure band insulator or semiconductor, if we excite electrons from the valence to the conduction band (either with photons or thermally) we can be assured that the density of electrons in the conduction band (typically called n, which stands for "negative" charges) is precisely equal to the density of holes left behind in the valence band (typically called p, which stands for "positive" charges). However, in an impure semiconductor or band insulator this is not the case.

Without impurities, a semiconductor is known as *intrinsic*. The opposite of intrinsic, the case where there are impurities present, is sometimes known as *extrinsic*.

Let us now examine the extrinsic case more carefully. Consider for example, silicon (Si), which is a semiconductor with a band gap of about 1.1 eV. Now imagine that a phosphorus (P) atom replaces one of the Si atoms in the lattice as shown on the top of Fig. 17.2. This P atom, being directly to the right of Si on the periodic table, can be thought

[12] Mobility is defined to be positive for both electrons and holes.

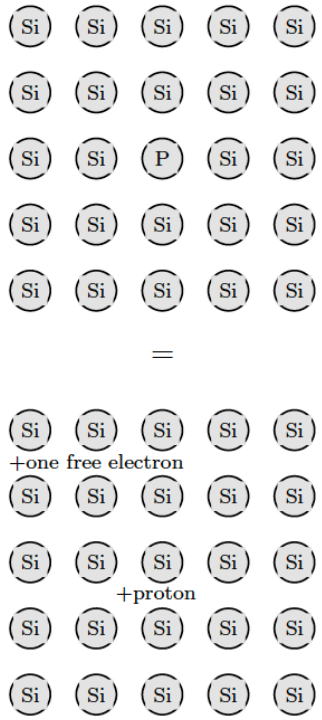


Fig. 17.2 Cartoon of doping a semiconductor. Doping Si with P adds one free electron to wander freely in the conduction band and leaves behind a positive charge on the nucleus.

of as nothing more than a Si atom plus an extra proton and an extra electron,[13] as shown in the bottom of Fig. 17.2. Since the valence band is already filled this additional electron must go into the conduction band. The P atom is known as a *donor* (or *electron donor*) in silicon since it donates an electron to the conduction band. It is also sometimes known as an *n-dopant*,[14] since n is the symbol for the density of electrons in the conduction band.

Analogously, we can consider aluminum, the element directly to the left of Si on the periodic table. In this case, the aluminum dopant provides one fewer electron than Si, so there will be one electron missing from the valence band. In this case Al is known as an electron *acceptor*, or equivalently as a *p-dopant*, since p is the symbol for the density of holes.[15,16]

In a more chemistry-oriented language, we can depict the donors and acceptors as shown in Fig. 17.3. In the intrinsic case, all of the electrons are tied up in covalent bonds of two electrons. With the n-dopant, there is an extra unbound electron, whereas with the p-dopant there is an extra unbound hole (one electron too few).

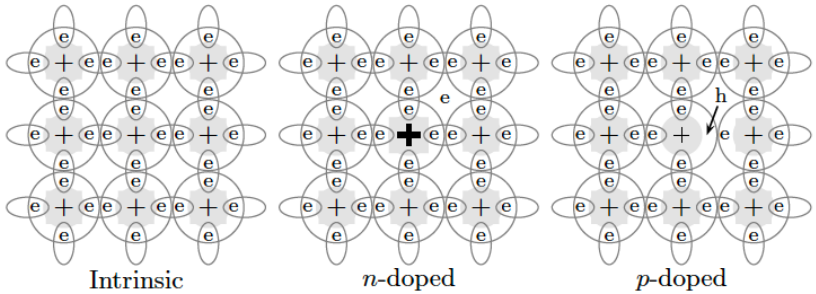


Fig.17.3 Cartoon of doping a semiconductor. **Left:** In the intrinsic case, all of the electrons are tied up in covalent bonds of two electrons. **Middle:** In the n-dopant case there is an extra unbound electron, and the dopant carries an extra nuclear charge. **Right:** In the p-dopant case there is one electron too few to complete all the bonds so there is an extra hole (denoted h) and the nuclear charge has one less positive charge than in the intrinsic case (the + sign is supposed to look slightly less large).

17.2.1 Impurity States

Let us consider even more carefully what happens when we add dopants. For definiteness let us consider adding an n-dopant such as P to a semiconductor such as Si. Once we add a single n-dopant to an otherwise intrinsic sample of Si, we get a single electron above the gap in the conduction band. This electron behaves like a free particle with mass m_e^*. However, in addition, we have a single extra positive charge $+e$ at some point in the crystal due to the P nucleus. The free electron is attracted back to this positive charge and forms a bound state that is similar to a hydrogen atom. There are two main differences between a real hydrogen atom and this bound state of an electron in the conduction band and the impurity nucleus. First of all, the electron has effective mass m_e^* which can be very different from the real (bare) mass of the electron (and is typically smaller than the bare mass of the electron). Secondly, instead of the two charges attracting each other with a potential $V = e^2/(4\pi\epsilon_0 r)$ they attract each other with a potential $V = e^2/(4\pi\epsilon_r\epsilon_0 r)$, where ϵ_r is the relative permittivity (or relative dielectric constant) of the material.

[13] There are extra neutrons as well, but they don't do much in this context.

[14] "Dopant" generally means a chemical inserted into an object to alter its properties. This definition is true more broadly than the field of physics (e.g. Lance Armstrong, Jerry Garcia).

[15] Yes, it is annoying that the common dopant phosphorus has the chemical symbol P, but it is not a p-dopant in Si, it is an n-dopant.

[16] More frequently than Al, boron (B) is used as a p-dopant in Si. Since B lies just above Al in the periodic table, it plays the same chemical role.

With these two small differences we can calculate the energies of the hydrogenic bound states exactly as we do for genuine hydrogen in our quantum mechanics courses.

We recall that the energy eigenstates of the hydrogen atom are given by $E_n^{H-atom} = -\text{Ry}/n^2$ where Ry is the Rydberg constant given by

$$\text{Ry} = \frac{me^2}{8\epsilon_0^2 h^2} \approx 13.6\text{eV}$$

with m the electron mass. The corresponding radius of this hydrogen atom wavefunction is $r_n \approx n^2 a_0$ with the Bohr radius given by

$$a_0 = \frac{4\pi\epsilon_0\hbar^2}{me^2} \approx .51 \times 10^{-10}\text{m}.$$

The analogous calculation for a hydrogenic impurity state in a semiconductor gives precisely the same expression, only ϵ_0 is replaced by $\epsilon_0\epsilon_r$ and m is replaced by m_e^*. One obtains

$$\text{Ry}^{\text{eff}} = \text{Ry}\left(\frac{m_e^*}{m}\frac{1}{\epsilon_r^2}\right)$$

and

$$a_0^{\text{eff}} = a_0\left(\epsilon_r\frac{m}{m_e^*}\right).$$

Because the dielectric constant of semiconductors is typically high (on the order of 10 for most common semiconductors) and because the effective mass is frequently low (a third of m or even smaller), the effective Rydberg Ry^{eff} can be tiny compared to the real Rydberg, and the effective Bohr radius a_0^{eff} can be huge compared to the real Bohr radius.[17] For example, in silicon[18] the effective Rydberg, Ry^{eff}, is much less than .1 eV and a_0^{eff} is above 30 Ångstroms! Thus this donor impurity forms an energy eigenstate with energy just below the bottom of the conduction band (Ry^{eff} below the band bottom only). At zero temperature this eigenstate will be filled, but it takes only a small temperature to excite a bound electron out of a hydrogenic orbital and into the conduction band.

A depiction of this physics is given in Fig. 17.4 where we have plotted an energy diagram for a semiconductor with donor or acceptor impurities. Here the energy eigenstates are plotted as a function of position. Between the valence and conduction band (which are uniform in position), there are many localized hydrogen-atom-like eigenstates. The energies of these states are not all exactly the same, since each impurity atom is perturbed by other impurity atoms in its environment. If the density of impurities is high enough, electrons (or holes) can hop from one impurity to the next, forming an *impurity band*.

Note that because the effective Rydberg is very small, the impurity eigenstates are only slightly below the conduction band or above the valence band respectively. With a small temperature, these donors or acceptors can be thermally excited into the band. Thus, except at low

[17] Note that the large Bohr Radius justifies *post facto* our use of a continuum approximation for the dielectric constant ϵ_r. On small length scales, the electric field is extremely inhomogeneous due to the microscopic structure of the atoms, but on large enough length scales we can use classical electromagnetism and simply model the material as a medium with a dielectric constant.

[18] Because silicon has an anisotropic band, and therefore an anisotropic mass, the actual formula is more complicated.

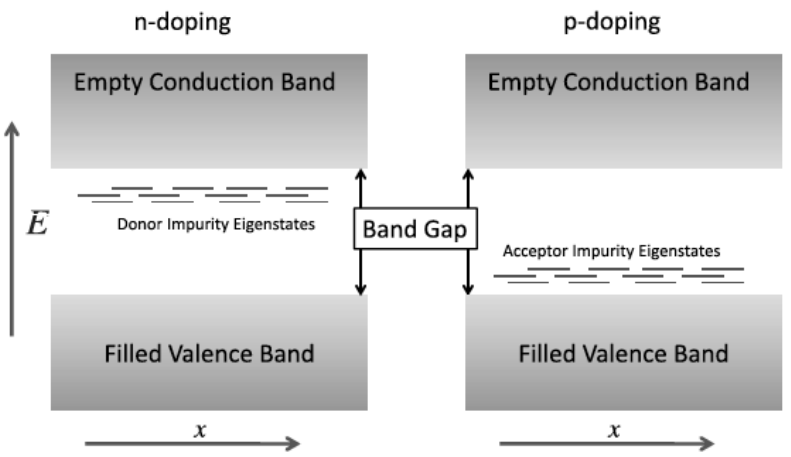


Fig. 17.4 Energy diagram of a doped semiconductor (left) with donor impurities, or (right) with acceptor impurities. The energy eigenstates of the hydrogenic orbitals tied to the impurities are not all the same because each impurity is perturbed by neighbor impurities. At low temperature, the donor impurity eigenstates are filled and the acceptor eigenstates are empty. But with increasing temperature, the electrons in the donor eigenstates are excited into the conduction band, and similarly the holes in the acceptor eigenstates are excited into the valence band.

enough temperature that the impurities bind the carrier, we can think of the impurities as simply adding carriers to the band. So the donor impurities donate free electrons to the conduction band, whereas the acceptor impurities give free holes to the valence band. However, at very low temperature these carriers get bound back to their respective nuclei so that they can no longer carry electricity—a phenomenon known as *carrier freeze out*. We will typically assume that we are at temperatures high enough (such as room temperature) such that freeze-out does not occur.

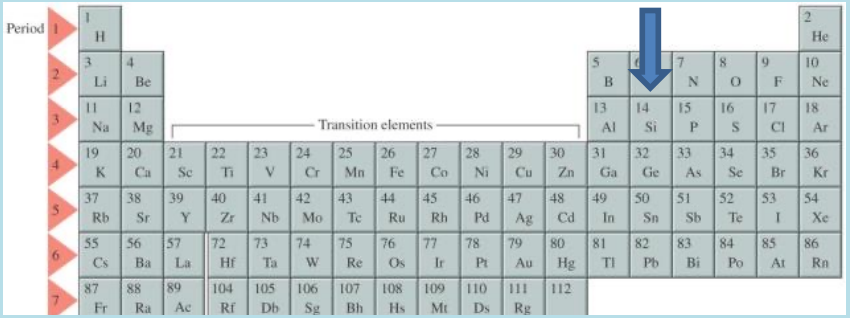
Note that in the absence of impurities, the Fermi energy (the chemical potential at zero temperature) is in the middle of the band gap. When donor impurities are added, at zero temperature, impurity states near the top of the band gap are filled. Thus the Fermi energy is moved up to the top of the band gap. On the other hand, when acceptors are added, the acceptor states near the bottom of the band gap are empty (remember it is a bound state of a hole to a nucleus!). Thus, the Fermi energy is moved down to the bottom of the band gap.

野生的半導體幾乎毫無用處！

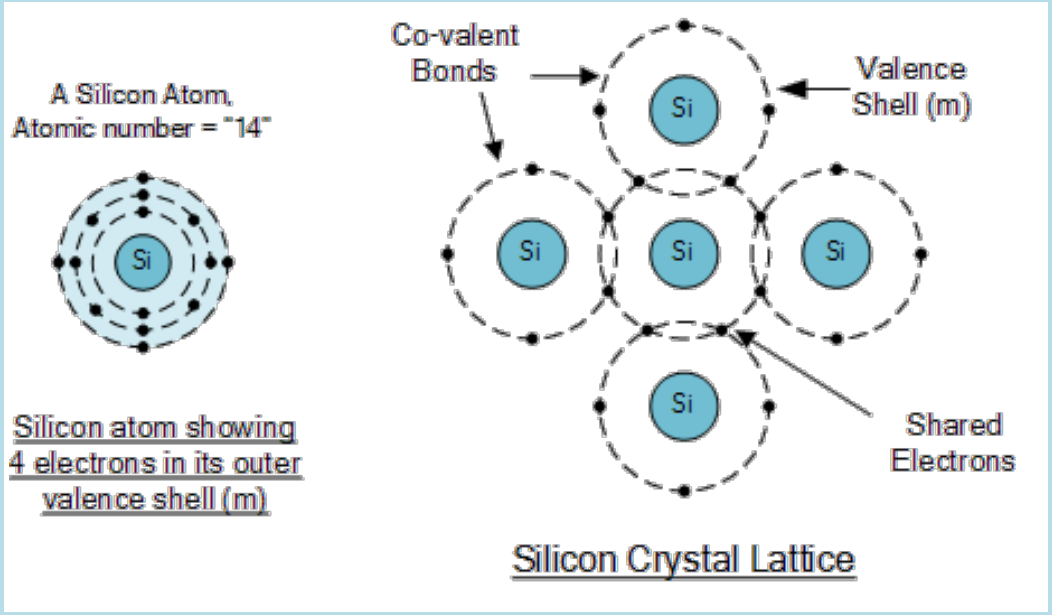
能跳上Conduction的電子數量還是少於導體，

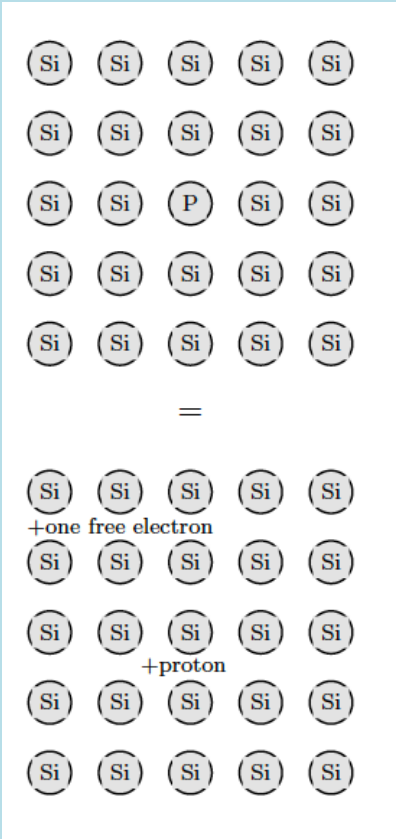
電阻率比起導體還是來得大！

但我們可以用雜質Doping來增加半導體的導電性：

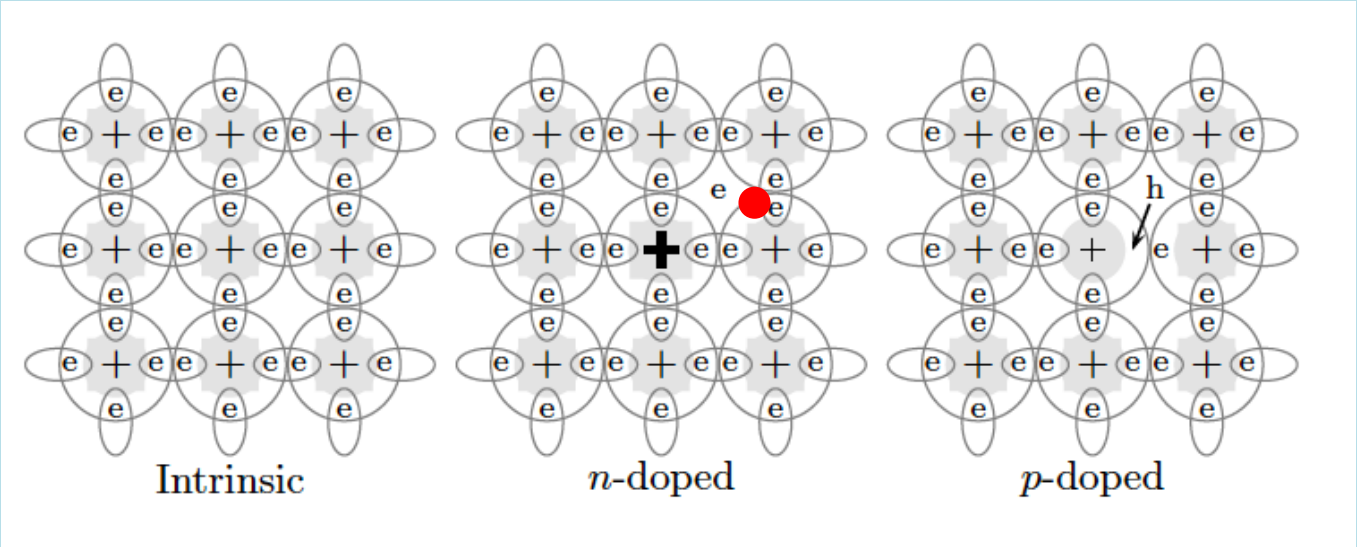


加入五個價電子的磷！

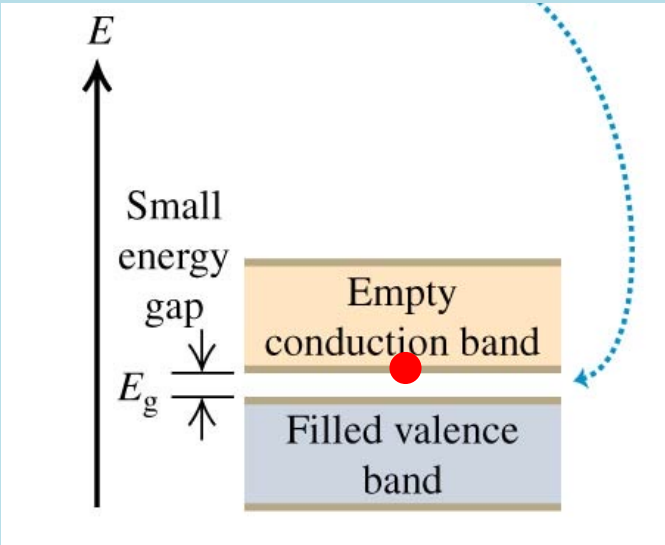




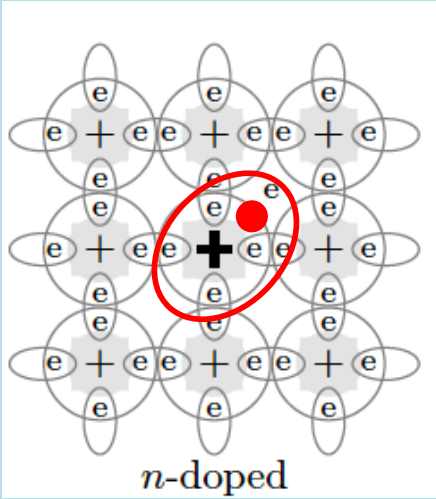
如此晶體結構幾乎不變，但電子會多出一個。



價能帶已填滿，多出來的電子，就會進入全空的傳導帶。



但不完全……



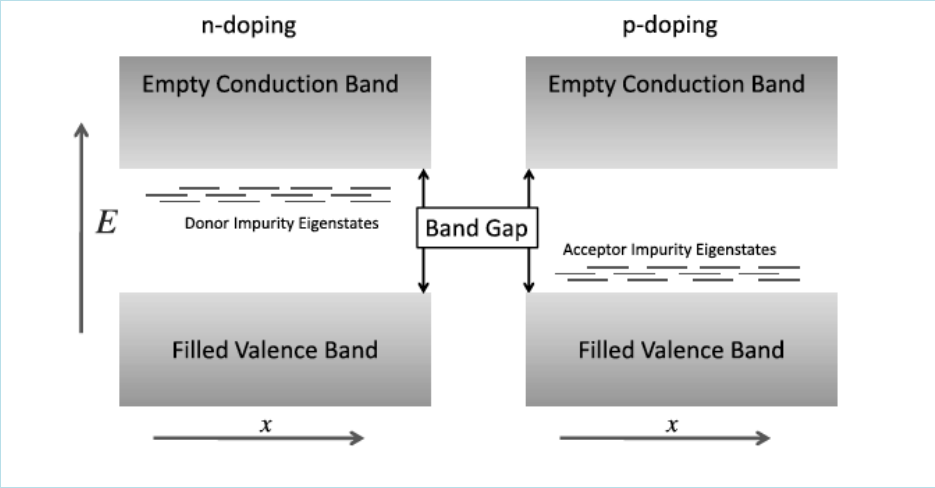
多出來的電子，與多出來的磷原子核正電荷，會如氫原子，形成束縛態。

但因此電子的有效質量一般小於電子質量，

而且必須考慮半導體內的介電性，一般極大。

因此束縛能~0.1 eV遠小於氫原子束縛能，以及能隙E_G，而半徑遠大~30Å。

這些束縛態的能量略低於傳導帶下端，與導帶的間隙E_D就是束縛能~0.1 eV 。



Escape of the electron to large distances leaves the impurity atom with a net positive charge; at finite separations the positive charge exerts an attractive force on the electron and leads to the existence of a bound state for the electron. The 'charged impurity plus electron' system is analogous to the 'proton plus electron' system and we can therefore estimate the strength of this binding by adapting the standard result for the energy levels of the hydrogen atom to allow for the fact that the electron is moving through a crystal rather than a vacuum. Thus we use m_e for the electron mass and assume that the crystal has a dielectric constant (relative permittivity) ε to obtain

$$E_n = -\frac{m_e e^4}{2\varepsilon^2 \hbar^2 n^2 (4\pi\varepsilon_0)^2}. \tag{5.10}$$

To estimate the spatial extent of the bound state wavefunctions we use the radii of the corresponding orbits as given by the Bohr theory,

$$r_n = \frac{\varepsilon n^2 \hbar^2}{m_e e^2} 4\pi\varepsilon_0. \tag{5.11}$$

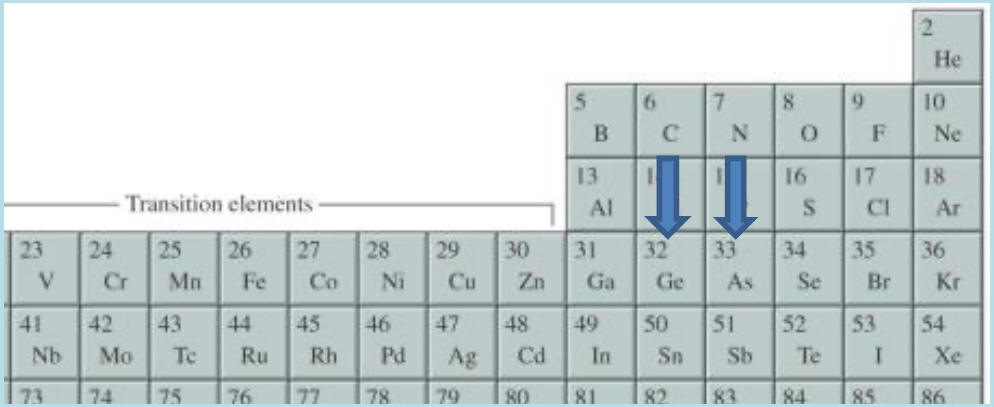
The effective mass of electrons in germanium is 0.2 electron masses and the dielectric constant is 15.8. Using these values in Eqs. (5.10) and (5.11) gives an estimate

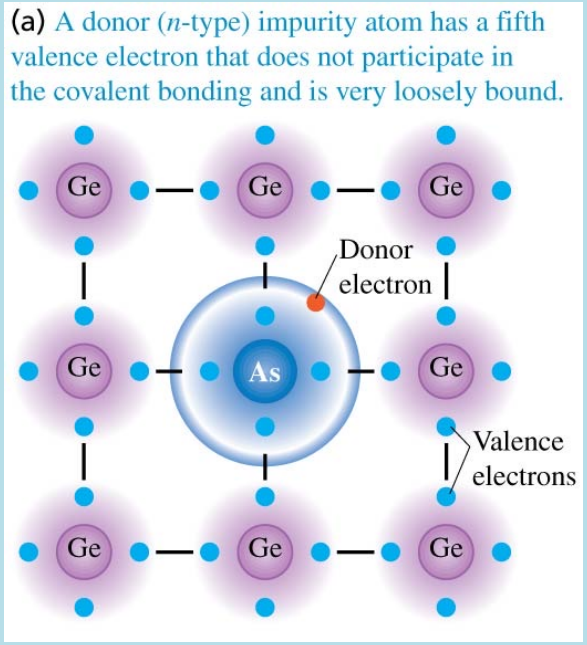
$$E_1 = -\left(\frac{m_e}{m\varepsilon^2}\right) \times 13.6\ \text{eV} \approx -0.01\ \text{eV} \tag{5.12}$$

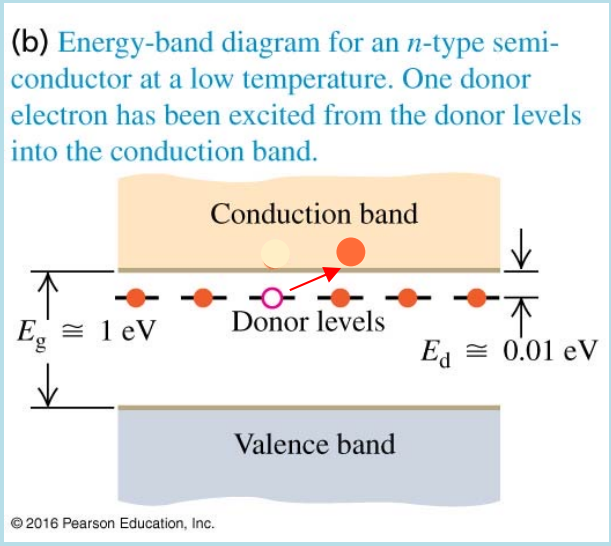
for the ground state binding energy of the extra electron and

$$r_1 = \left(\frac{\varepsilon m}{m_e}\right) \times 0.53\ \text{Å} \approx 40\ \text{Å} \tag{5.13}$$

for the radius of the corresponding orbit (−13.6 eV and 0.53 Å are the corresponding values for hydrogen). Thus the combination of small effective mass and large dielectric constant gives very weak binding of the extra electron to the impurity and a very extended wavefunction for the bound state. Since the bound state wavefunction extends over many







鍺 Ge

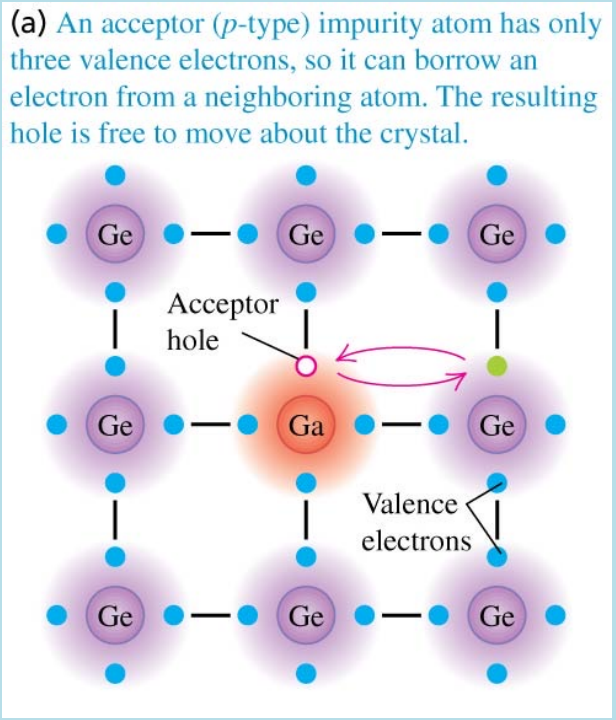
砷 As Arsenic

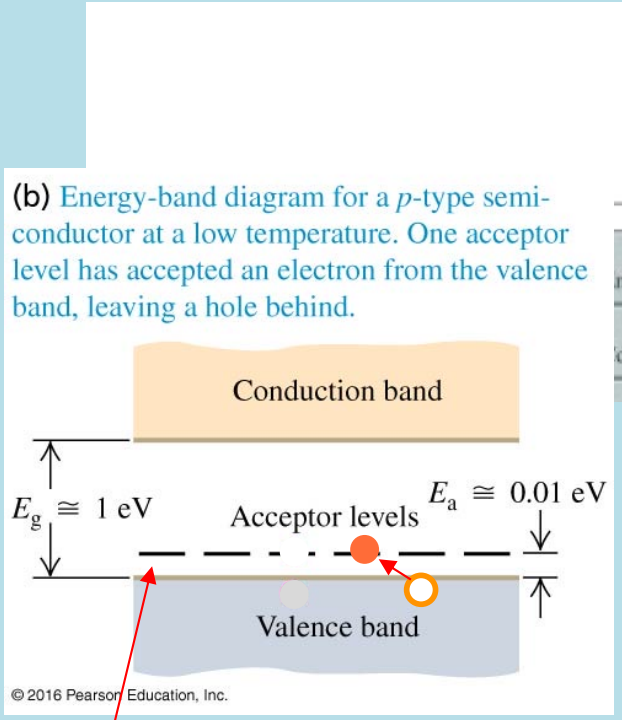
加入五價雜質提供鍵結以外多一顆電子。

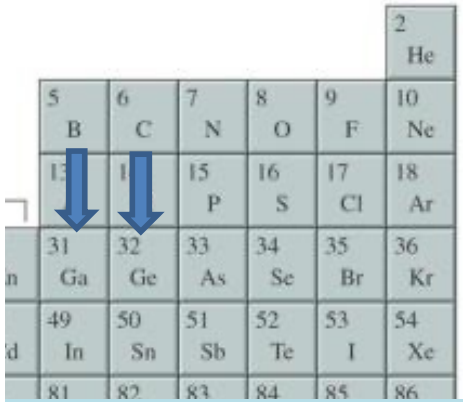
此電子的能態，在傳導帶之下，且間隙E_D極小，稱為Doner態。

因此室溫時即可以有大量電子跳上Conduction帶，可以導電。

作為載體的電子帶負電，此類固體稱為n type半導體。







Ga Gallium 鎵

反之，加入三價雜質使鍵結內少一顆電子，等於價帶出現一個電洞。

此電洞與帶負電原子核的束縛態，稱Acceptor態，在價帶上方，間隙E_A也極小，

因此室溫時即可以有電子由價帶跳上空的Acceptor態。

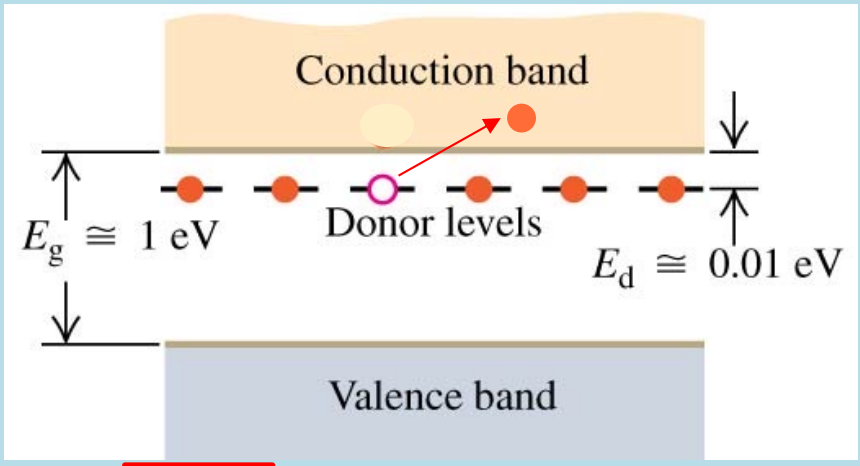
價帶出現電洞，電洞可以移動，就可以導電。

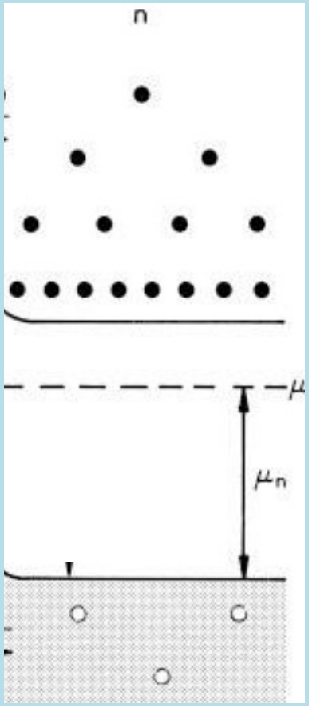
作為載體的電洞帶正電，此類固體稱為p type半導體。

以帶正電的粒子來導電的固態導體，在自然界是不存在的，

因此這是一種人類利用半導體所發明的新材料

雜質半導體導電性好嗎？ n type半導體，





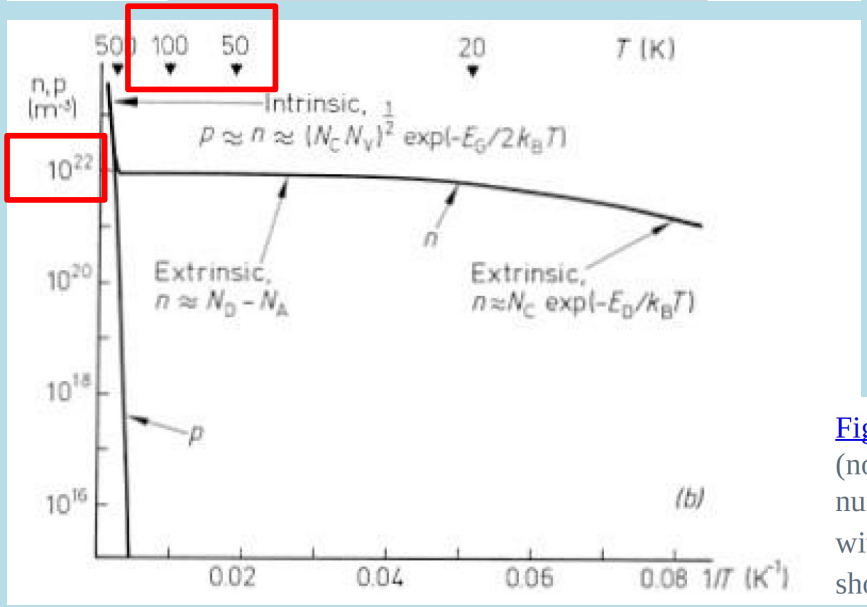
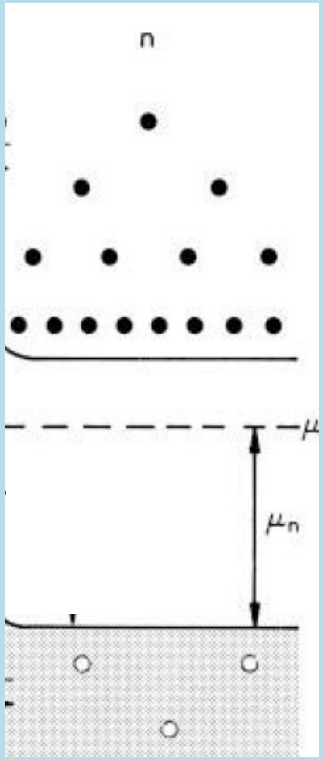
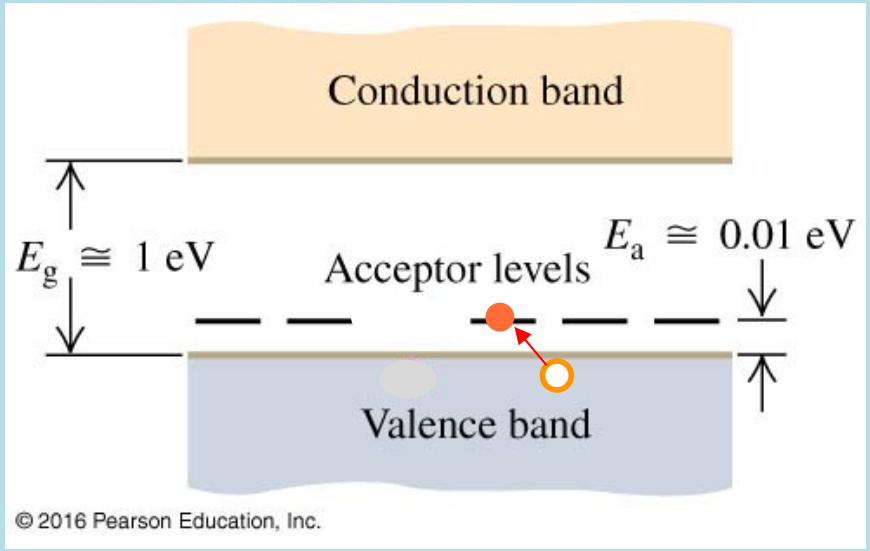


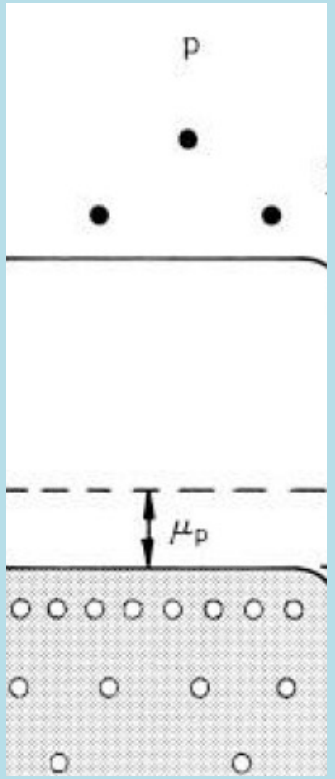
Fig. 5.6 Variations of (*a*) the Fermi level μ and (*b*) the electron and hole concentrations (note the logarithmic scale) with $1/T$ for an n-type semiconductor containing a significant number of acceptor impurities. The figure was calculated for a germanium semiconductor with, $N_D = 10^{22}$ m^{-3}, $E_D = 0.012$eV, $N_A = 10^{21}$ m^{-3} and $E_A = 0.010$ eV; the scale at the top shows temperature values for this case

因能量間隙E_d很小，可以設計使室溫下，幾乎所有Doner Level電子都上到傳導帶，

在導帶上電子的能量分佈是波茲曼分佈$\sim e^{-E/kT}$ 。







p type半導體內，電子從價帶跳上Acceptor Level，在價帶留下大量電洞的分佈。

同時，還是有比較少的電子會跳上導帶，

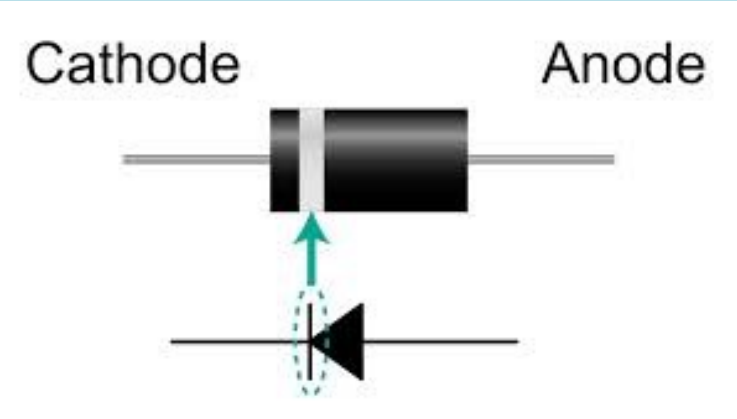
當溫度不高時，雜質貢獻的載體密度會比溫度產生的載體密度重要！

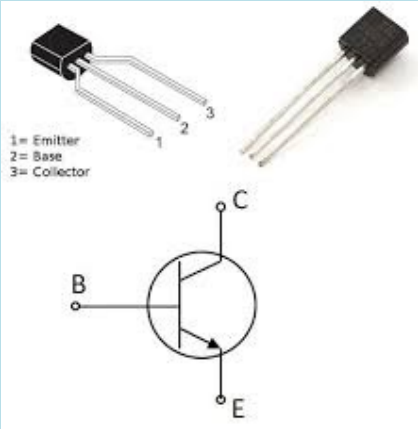
$$n - p = (\text{density of donors}) - (\text{density of acceptors}).$$

This, along with the law of mass action, gives us two equations with two unknowns which can be solved.[21] In short, the result is that if we are at a temperature where the undoped intrinsic carrier density is much greater than the dopant density, then the dopants do not matter much, and the chemical potential is roughly midgap as in Eq. 17.11 (this is the *intrinsic* regime). On the other hand, if we are at a temperature where the intrinsic undoped density is much smaller than the dopant density, then we can think of this as a low-temperature situation where the carrier concentration is mainly set by the dopant density (this is the *extrinsic* regime). In the n-doped case, the bottom of the conduction band gets filled with the density of electrons from the donors, and the chemical potential gets shifted up towards the conduction band. Correspondingly, in the p-doped case, holes fill the top of the valence band, and the chemical potential gets shifted down towards the valence band. Note that in this case of strong doping, the majority carrier concentration is obtained just from the doping, whereas the minority carrier concentration—which might be very small—is obtained via law of mass action. The ability to add carriers of either charge to semiconductors by doping is absolutely crucial to being able to construct semiconductor devices, as we will see in the next chapter.

利用雜質滲入的技術，在一塊半導體晶體內，可以自由製成兩種類似導體的材料。

將不同型的半導體組合在一起，可以製造出各式半導體元件，來控制電路中的電流：

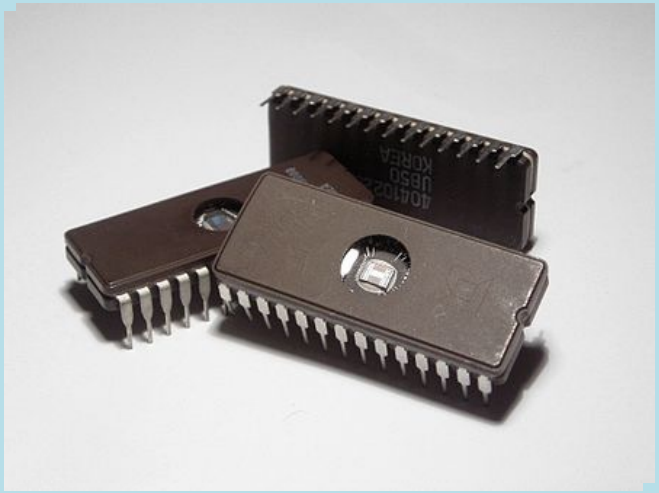


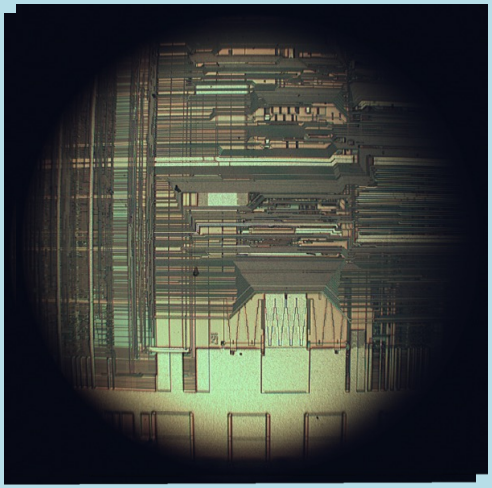


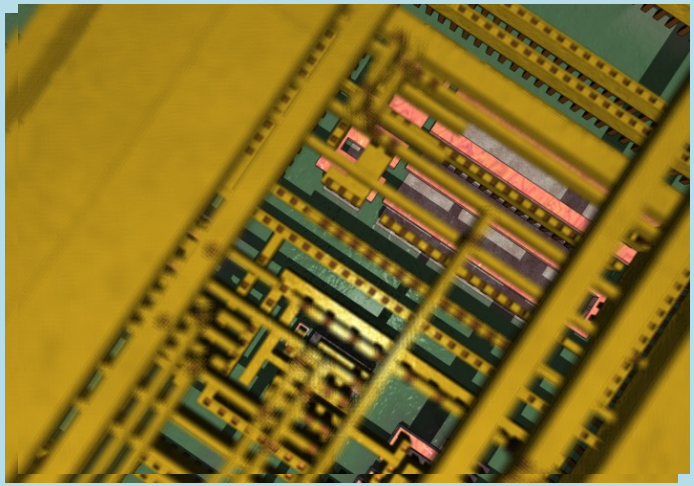
半導體元件非常不自然、完全人工，這是一個工程問題！

It is all about control. 控制！

control freak

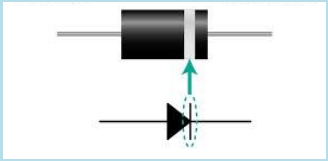






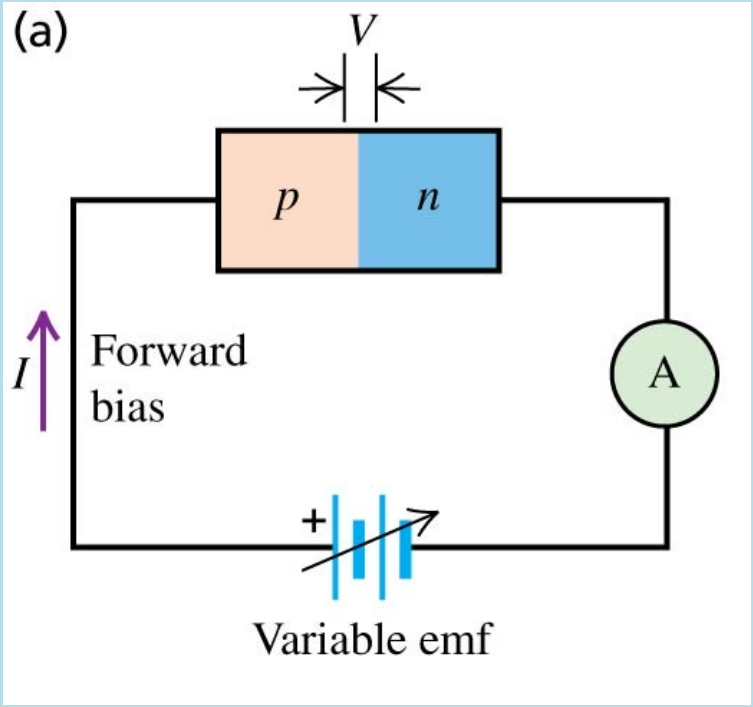
把元件與彼此的連接製作於一塊半導體板內，就稱Integrated Circuit IC 積體電路

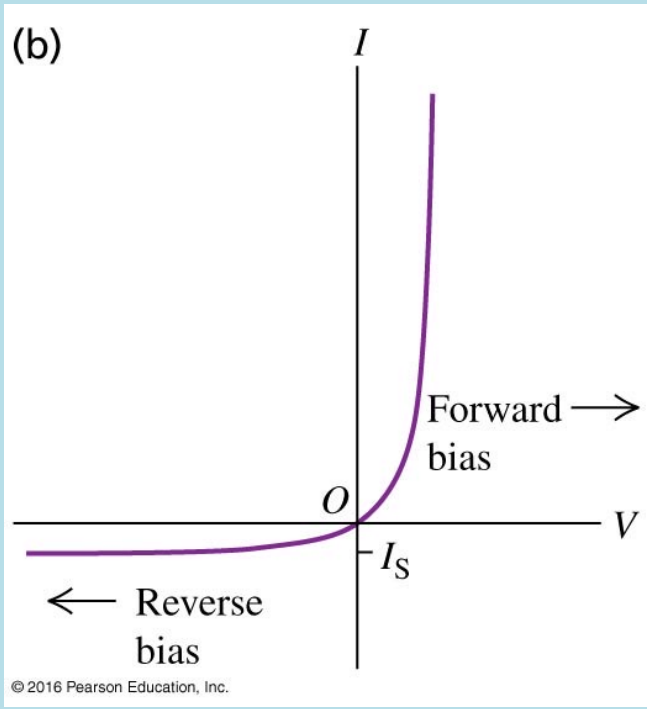
這是一個建築問題！元件就如微觀世界的歌德教堂！

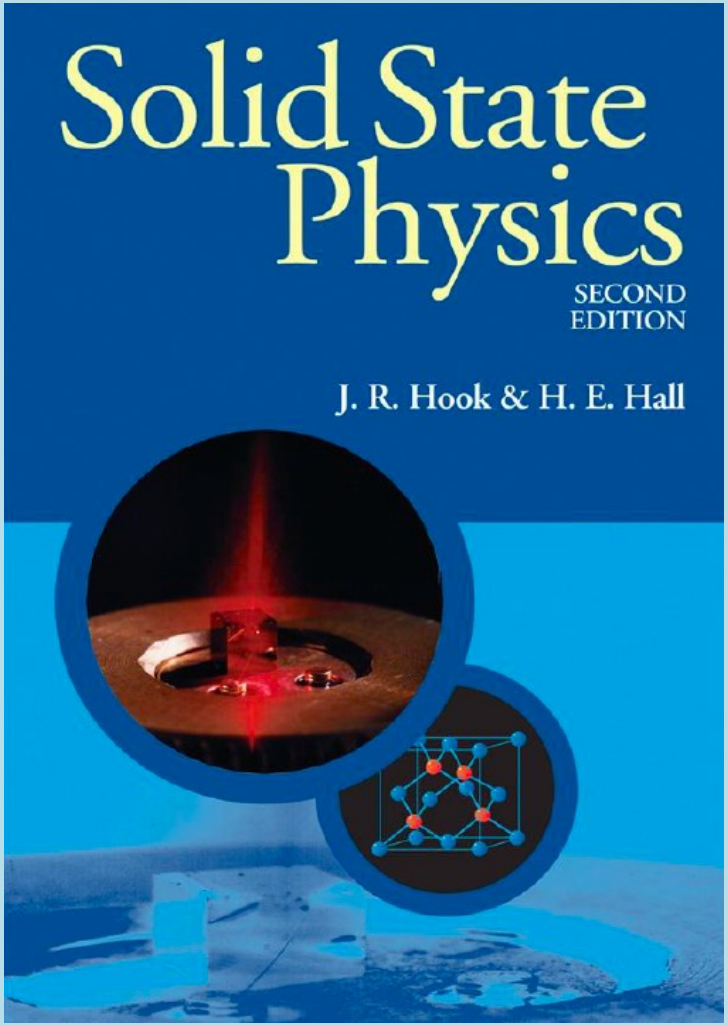


p-n Junction, Diode二極體：將一塊完整半導體兩邊製成p型及n型半導體。

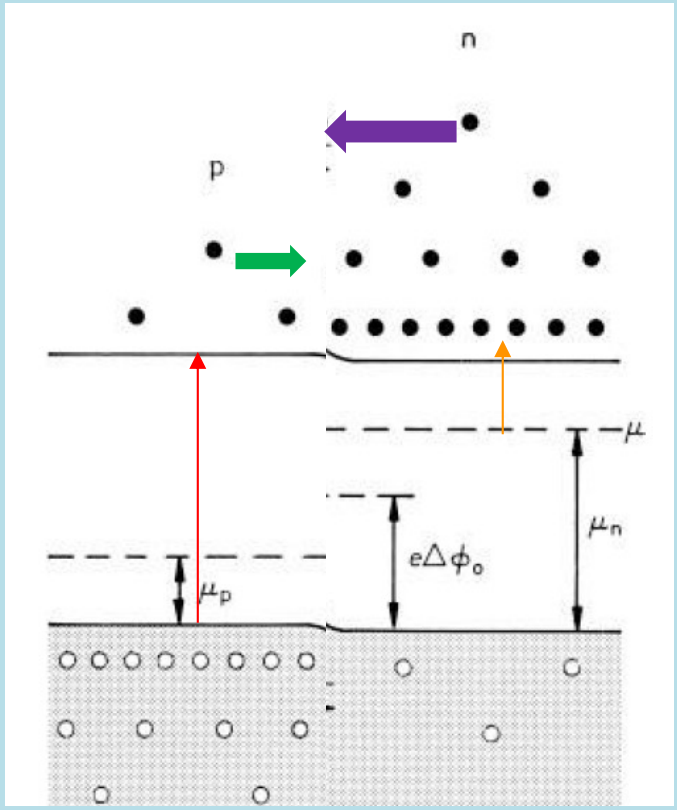
電流只能朝單一方向p→n流動！整流器

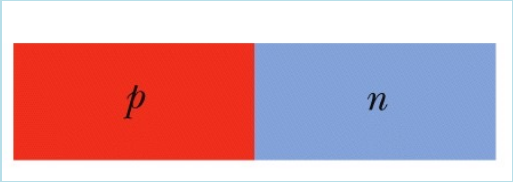





Solid State Physics
SECOND EDITION
J. R. Hook & H. E. Hall

二極體的關鍵在p-n介面Junction！



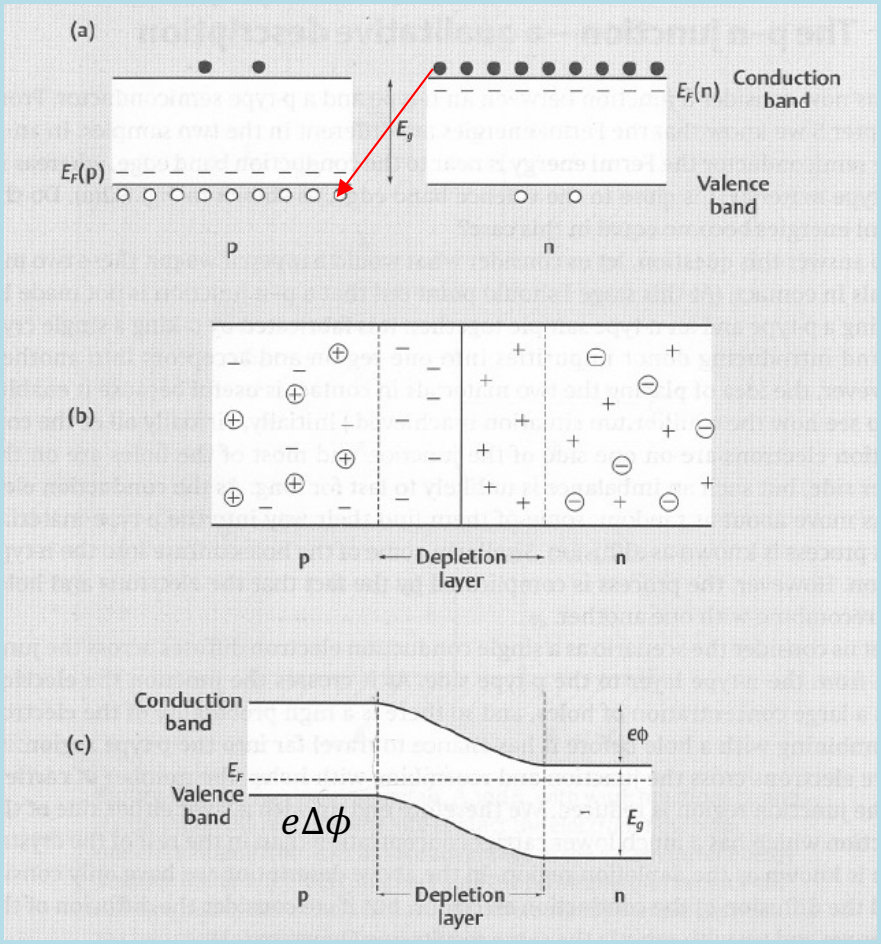


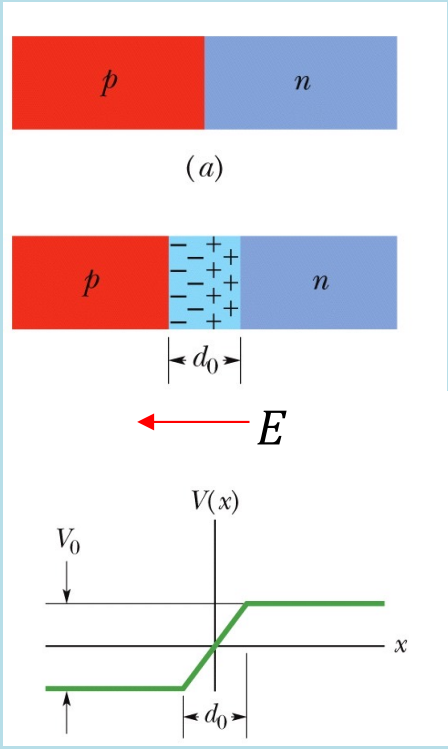
重點是兩種雜質半導體導帶之間沒有障礙，因此載體可以自由移動。

左端p，導帶上有少量因熱擾動跳上↑的電子，$\propto e^{\frac{E_G}{2kT}}$，可以向右流。

右端n，因間隙較小，則有大量自Doner因熱跳上↑導帶，可以向左流。

因此電子會淨向左流。



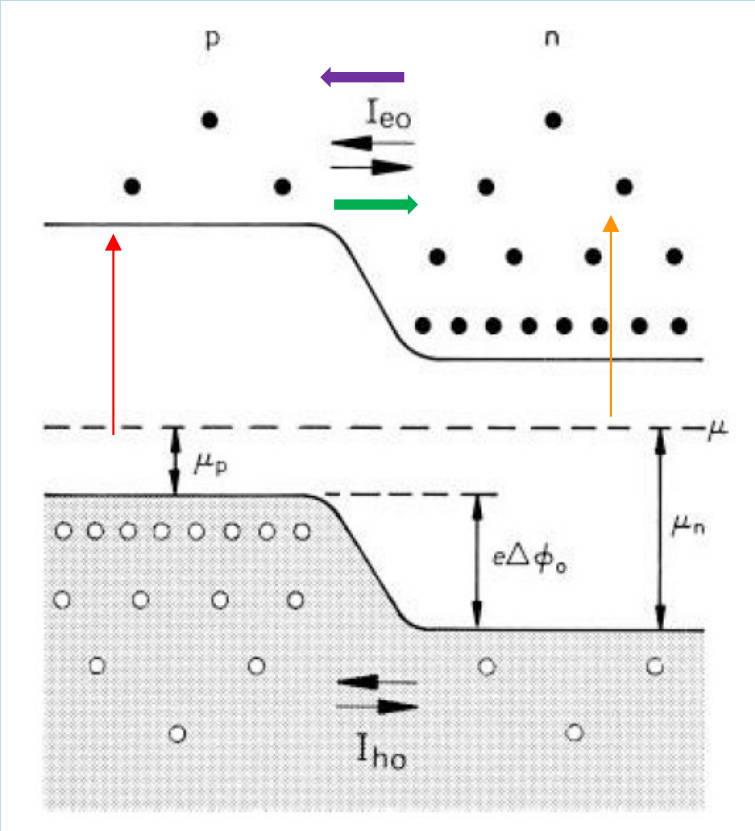


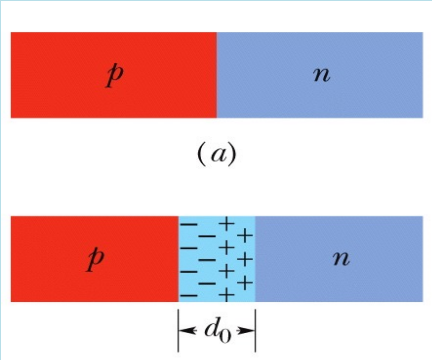
從右邊淨向左流的電子，因缺少載體，不會走遠，會填入價帶的電洞。

在介面附近形成一個帶電、薄層、但無載體區域，稱空乏層Depletion Zone。

Zone右側電子離開後留下正電離子，而左側則帶負電，薄層中會有一向左電場。

因此n會比p電位高！對電子則是左邊p電位能高$e\Delta\phi$。





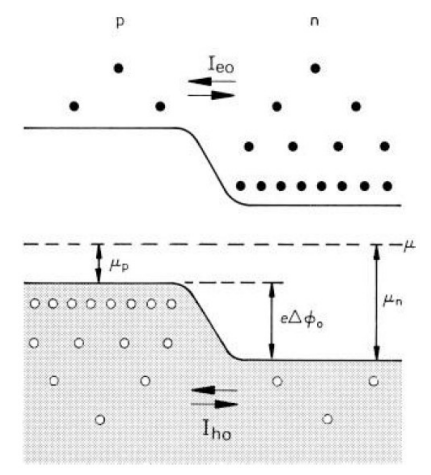
電位能差$e\Delta\phi$會將p中的能帶連同化學能μ一起提高，p的導帶會高於n的導帶。

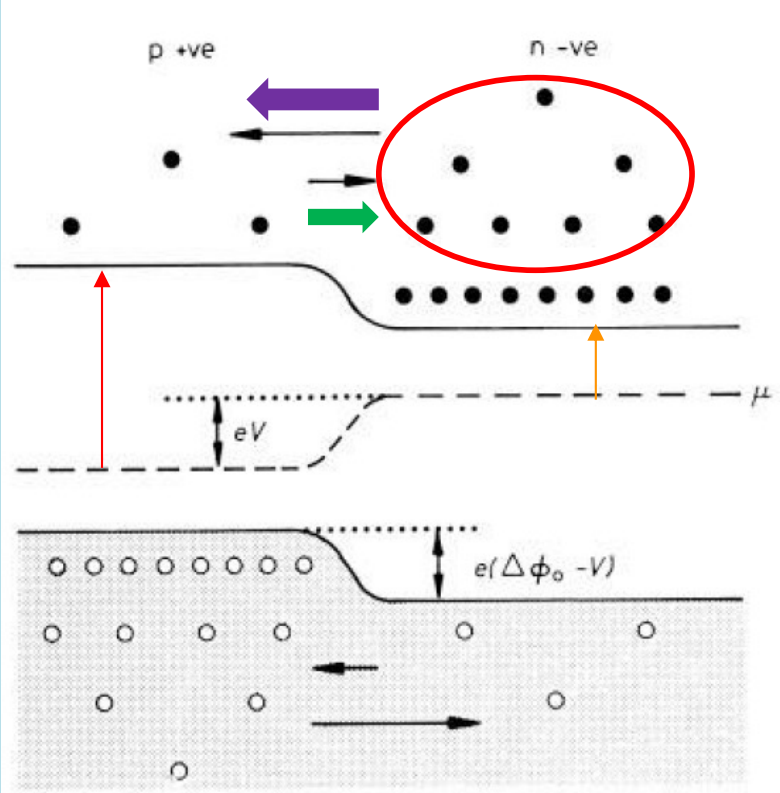
現在右端n的導帶電子，必須有足夠能量克服 $e\Delta\phi$，才能往左流。向左電流變小，但向右電流並不被影響。

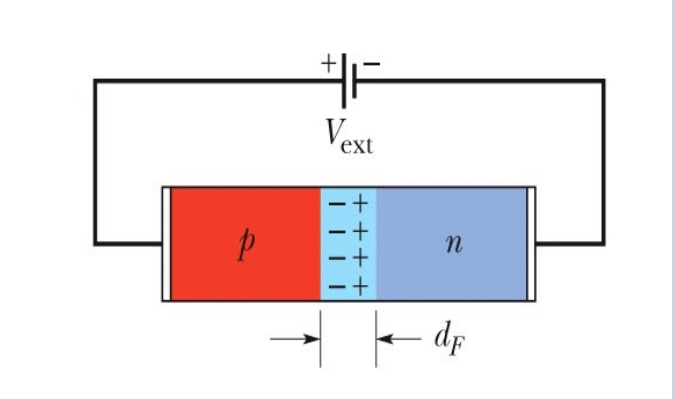
$\Delta\phi$會一直增加，兩邊化學能也漸漸接近，直到向右與向左的電流彼此抵消，

這就達到穩定。因為導帶電子可自由流動，熱力學平衡條件就是化學能μ相等。

現在p-n間加上一順向、正電位差V(對電子是負的），左右能量差又縮小：







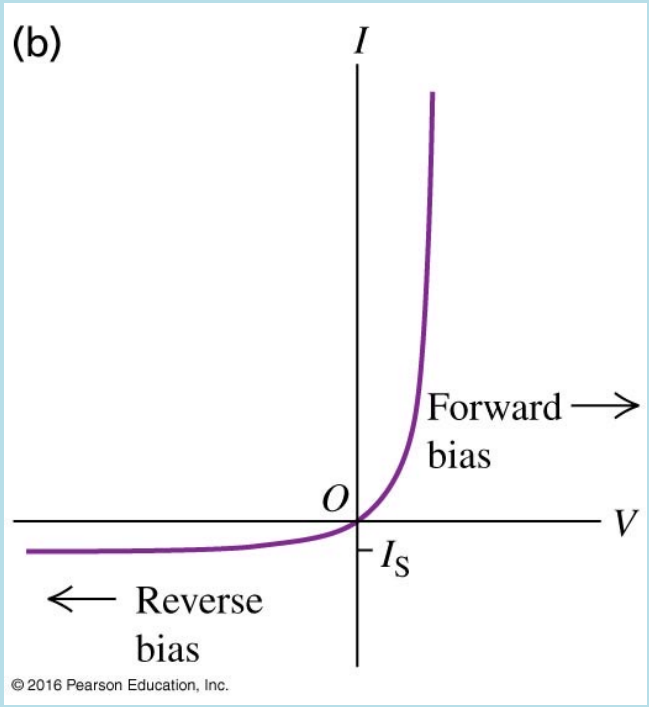
左端p的價帶上能向右流的電子，依舊不受所加電壓影響。➡

右端n的導帶下方，電子要跨越的門檻能差因加電壓變小，跨越電子增加！

因此電子會淨流向左，電流I向右。⬅

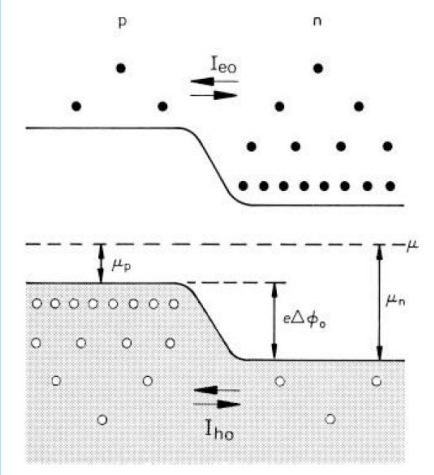
在導帶上電子的能量分佈是波茲曼分佈$\sim e^{-E/kT}$。

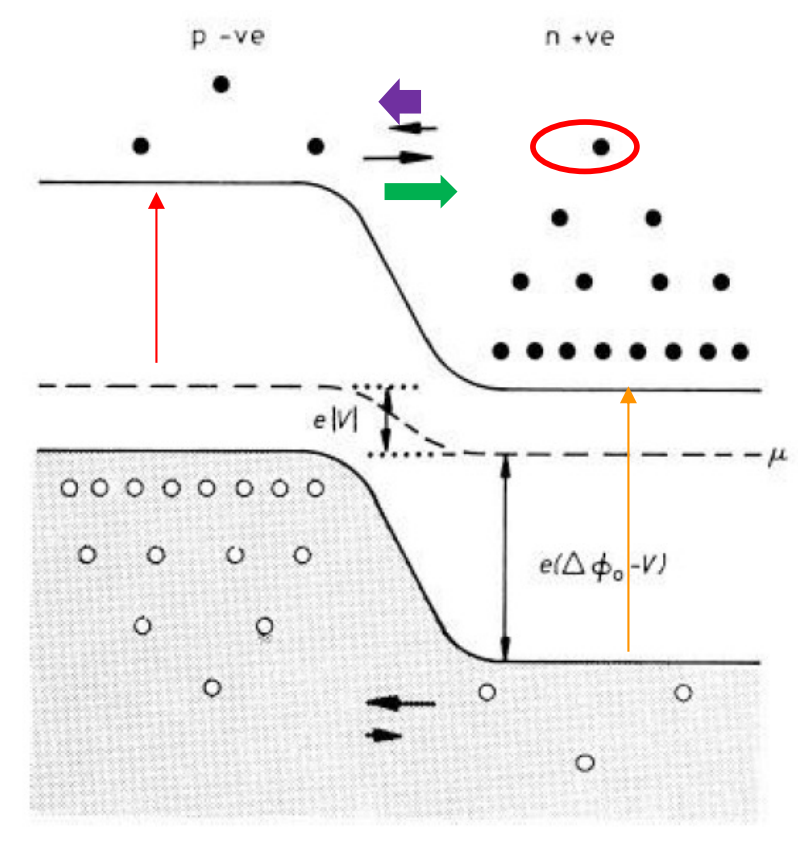
門檻降低V，跨越門檻的電子數就增加$\sim e^{V/kT}$！

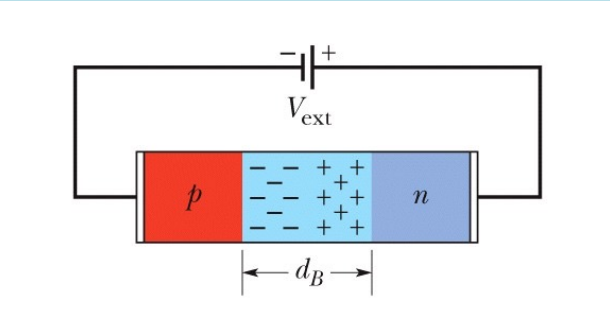


以順向電壓為正，順向向右電流為正，

電流會隨電壓依指數增加！ $I \sim e^{V/kT}$







若p-n間加上一負的反向電位差，左右能量差加大，

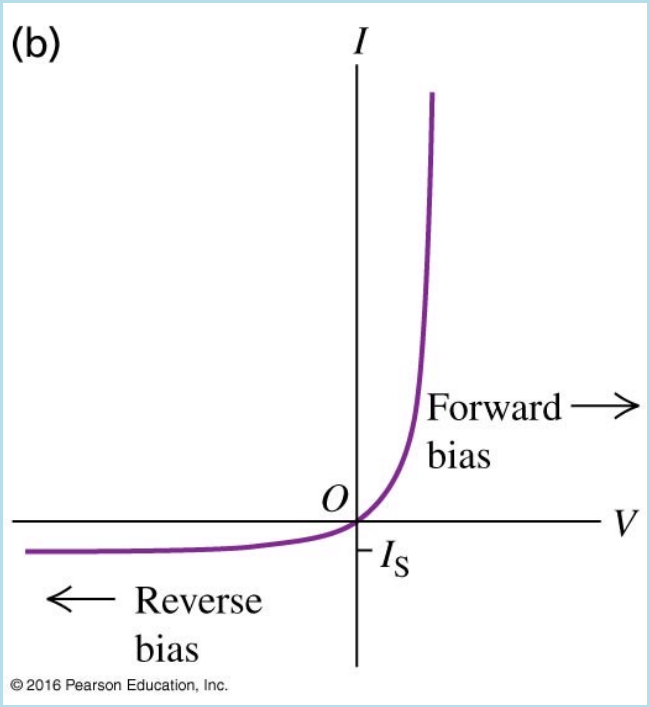
左端p的導帶上方電子，依舊不受所加電壓影響。但電子數量很小 $\propto e^{\frac{E_G}{2kT}}$ 。

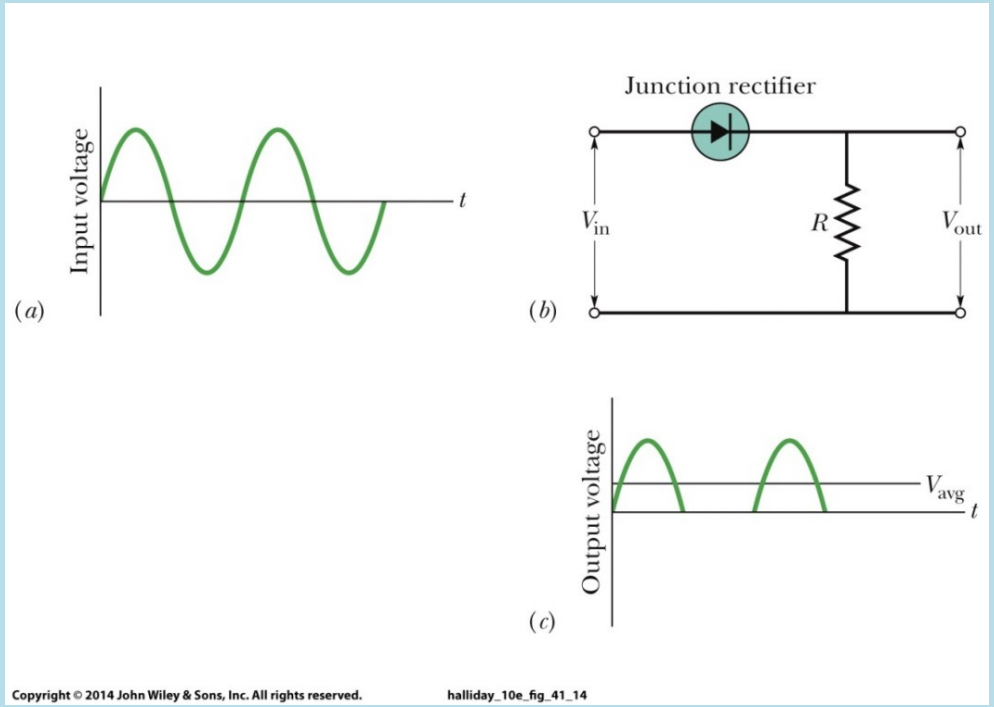
右端n的導帶上方，能有足夠能量向左流的電子，因門檻增加而劇烈減少！

因此電子會淨流向右，電流向左，但只剩下無雜質半導體本來就有很小的導電度。

若p-n間加上一負的反向電位差，電流為負。

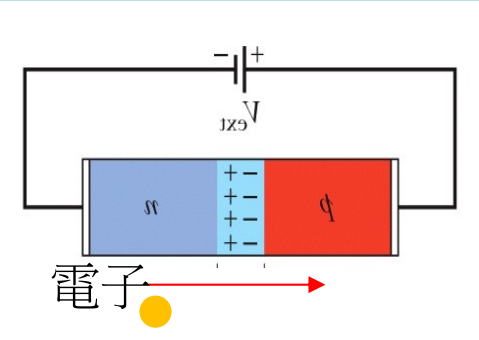
但因載體稀少，導電性差，電流很小，且很快飽和。

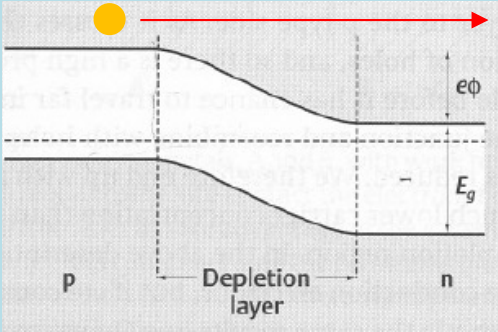


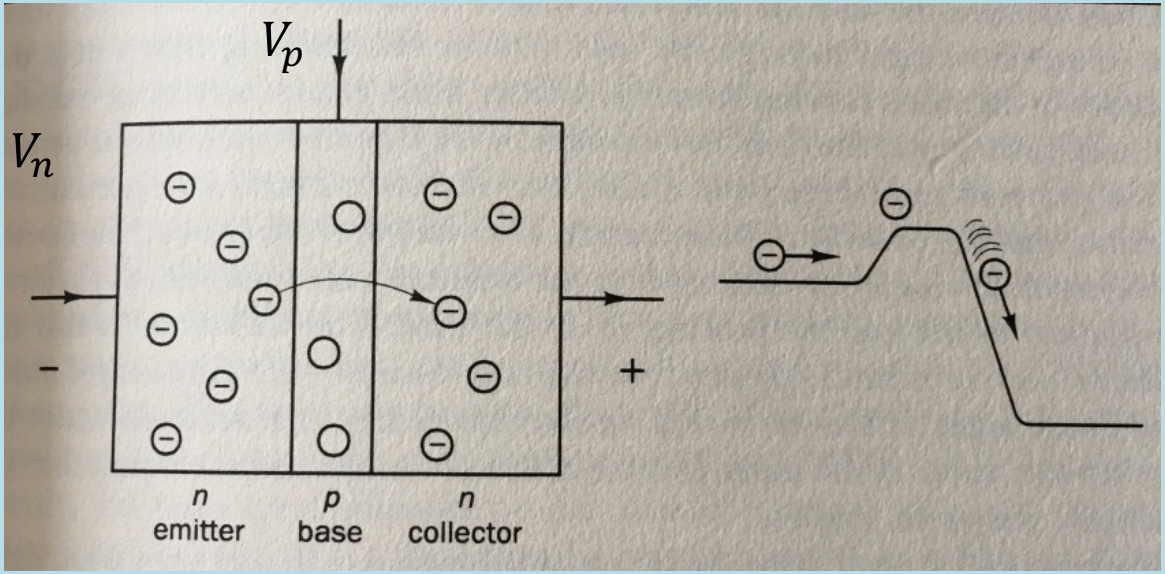


電流只能朝單一方向流動！ p-n介面提供了一個整流器。

三極體





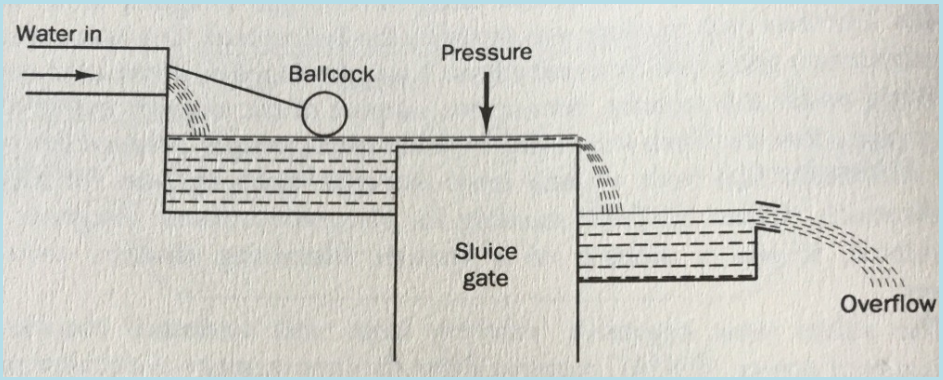


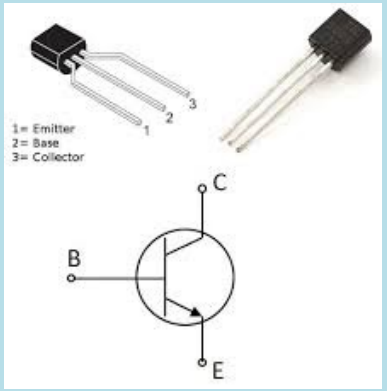
p-n介面中，p與n間有電位差，如有電子載體，電子可大量向右移動！

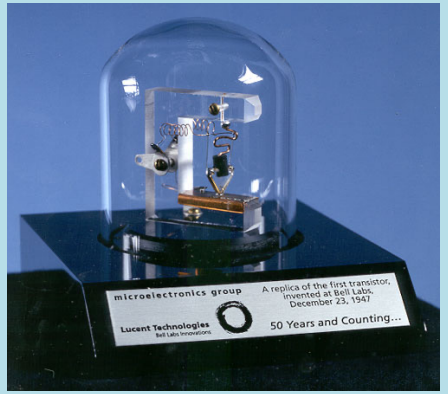
這正是n-p二極體整流器可以做的事！

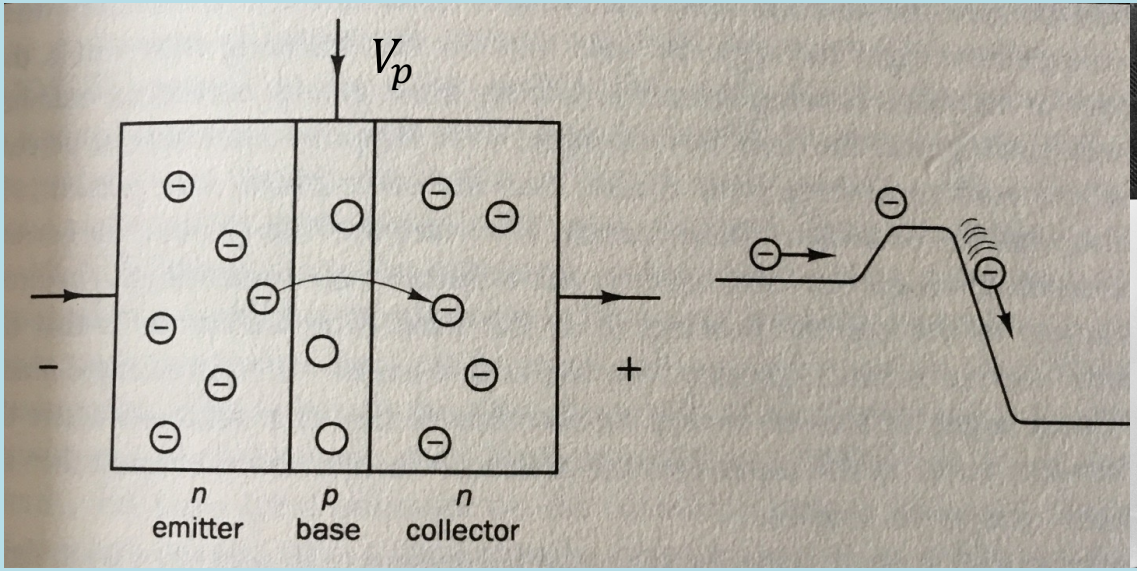
在p的左邊再放一個n，並施以可變的順向電壓$V_p > 0$，

傳導電子就可以由左邊的n被推動流入很薄一層p，順勢再流入右邊n。









Bardeen, Shockley and Brattain at Bell Labs in 1948

左邊的二極體的順向電壓 V_p 控制流到p的電子，也就控制了流到右邊n的電流大小。

Bipolar Transistor 雙極性電晶體

如果電壓V_p很小而且有訊號，電壓V_c很大，所產生的大I_c就會攜帶訊號。

這就是訊號放大器！

金屬氧化物半導體、場效型電晶體 MOSFET

Metal-Oxide-Semiconductor Field Effect Transistor

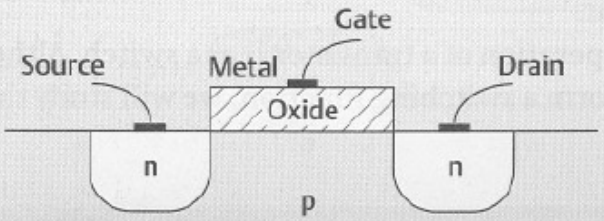
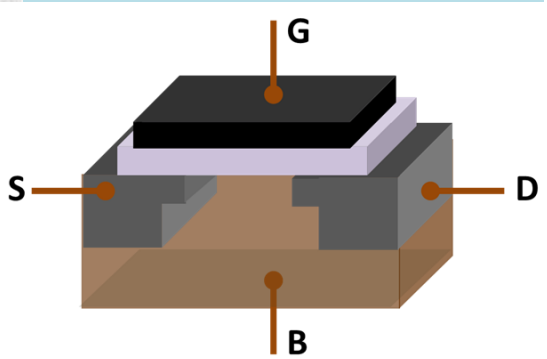


Figure 6.10 The structure of an n-channel MOSFET showing the source, gate and drain region. The electrical contact to the gate is separated from the semiconductor by a thin layer of insulator, typically silicon dioxide.



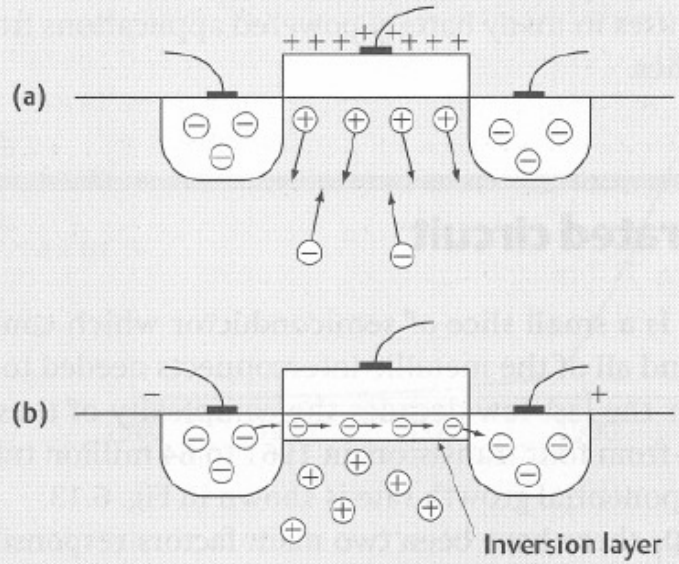
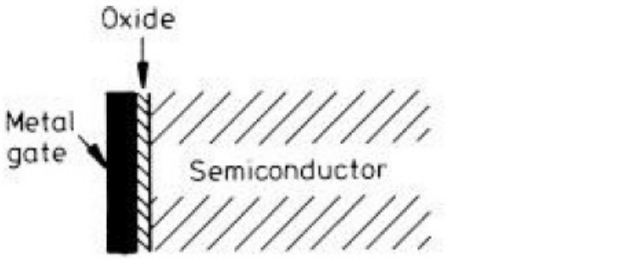
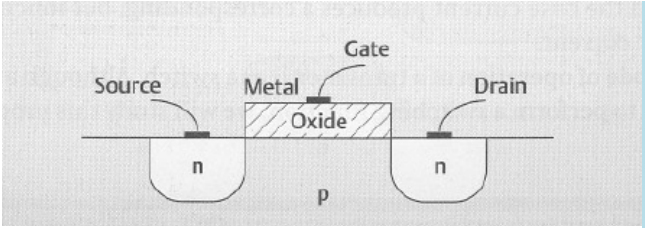
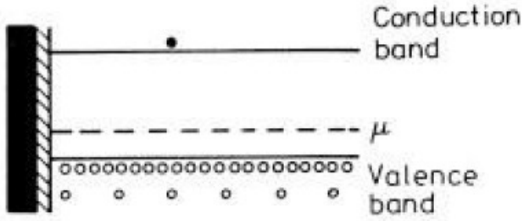


Figure 6.11 (a) When a positive voltage is applied to the gate the holes in the p-type semiconductor are repelled from the surface, and the minority carrier conduction electrons are attracted to the surface. (b) If the gate voltage exceeds the threshold value then an inversion layer is created near the surface. In this layer the material behaves as an n-type semiconductor and so provides a conducting channel between the source and the drain.



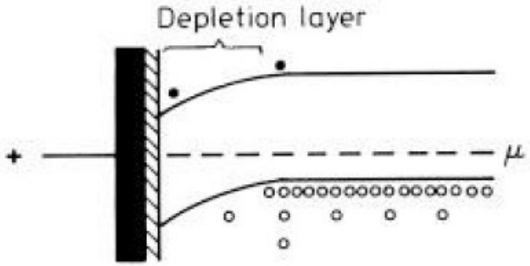


(*a*) Basic MOS structure



Gate未加電場

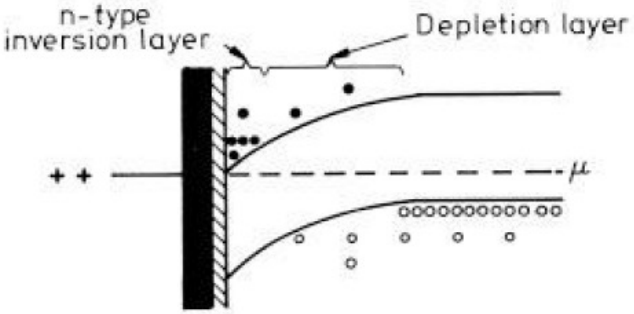
(*b*) Electron energy levels in the absence of an applied gate bias



Gate加電場，電洞離開。

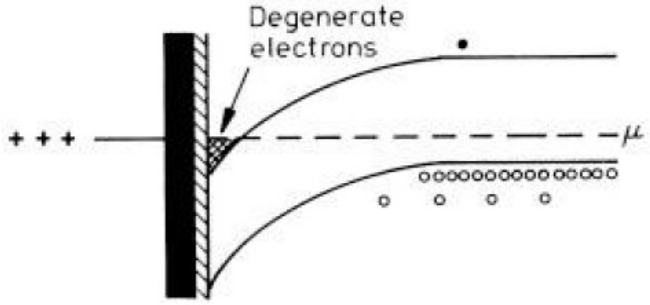
少量電子進入，產生空乏層。

(*c*) A small positive gate bias produces a depletion layer near the surface



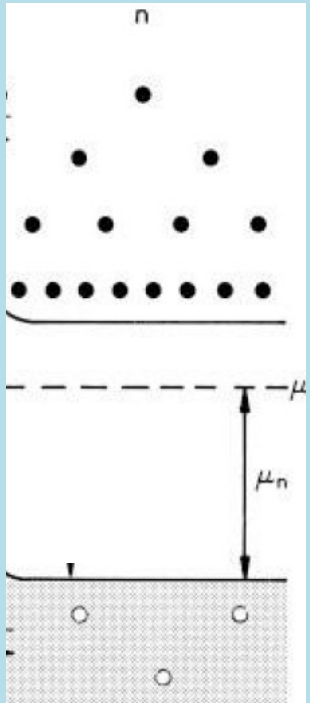
導帶在介面處能量降低
以致逼近於化學能。

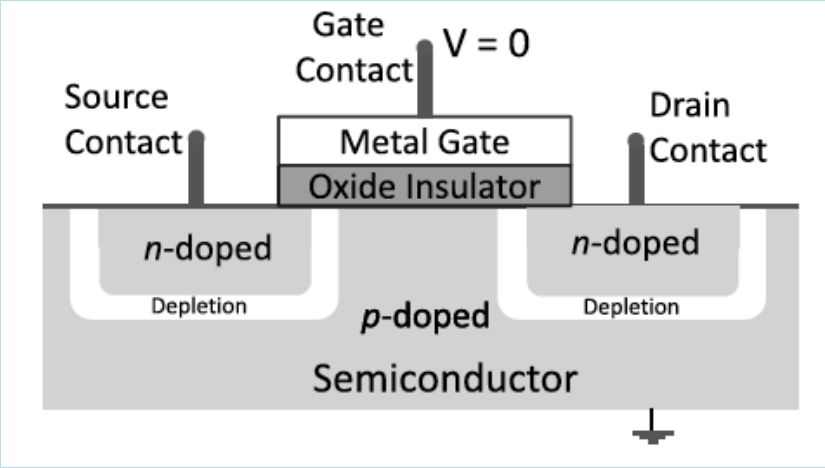
(*d*) With a larger positive bias, an n-type inversion layer is created

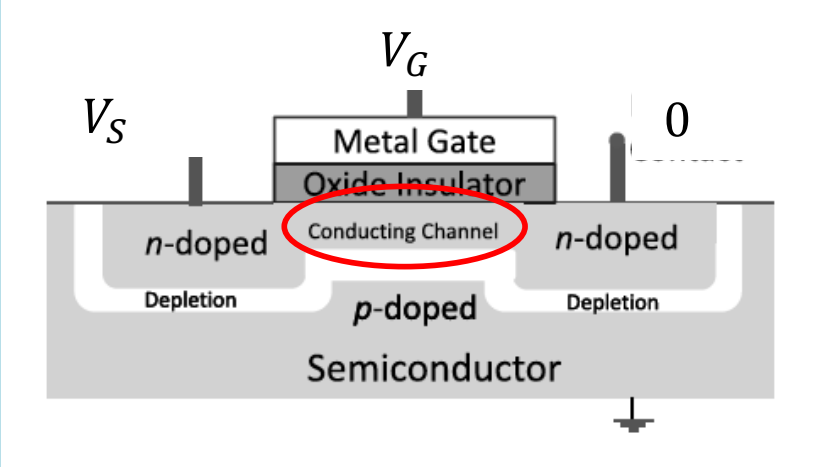


在空乏層與氧化物層間
形成n半導體薄層。

(*e*) For an even larger positive gate bias the electrons in the inversion layer become degenerate



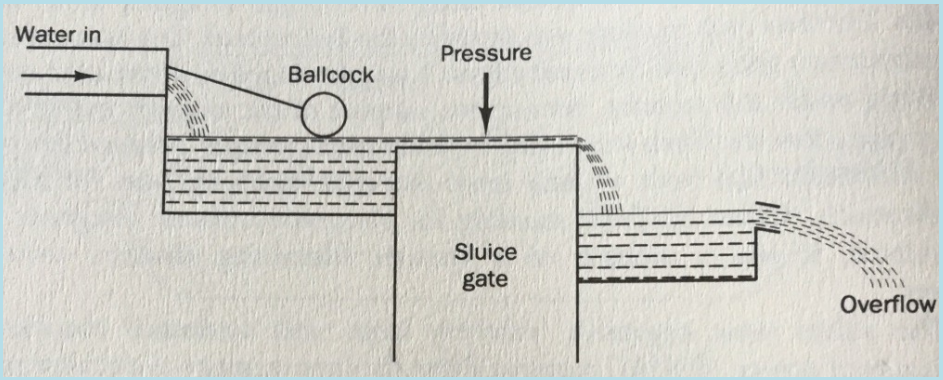


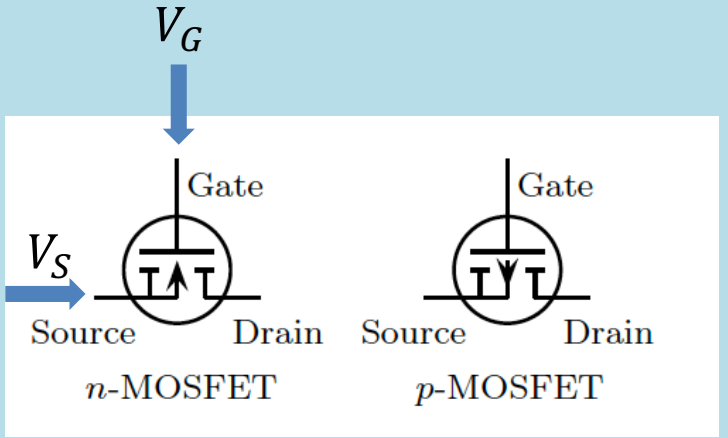


有gate閘電壓V_G，n半導體薄層才能形成，連接兩個n半導體電極。

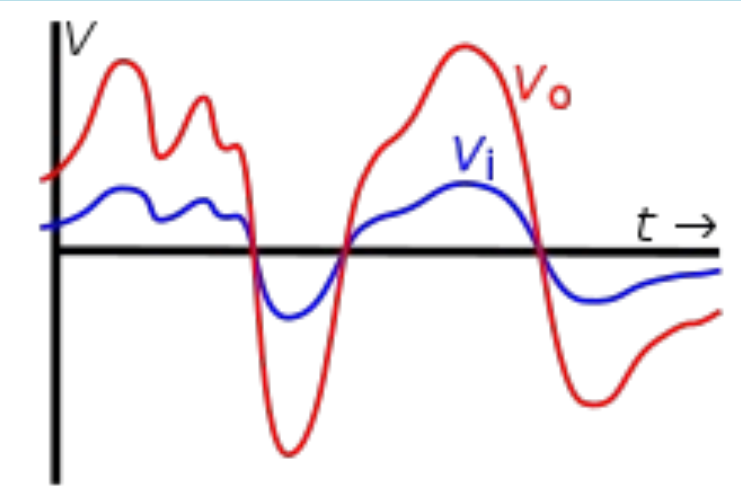
如此以閘電壓V_G做為條件，來控制電壓V_S是否能產生I_S，等同可以連續控制電阻。

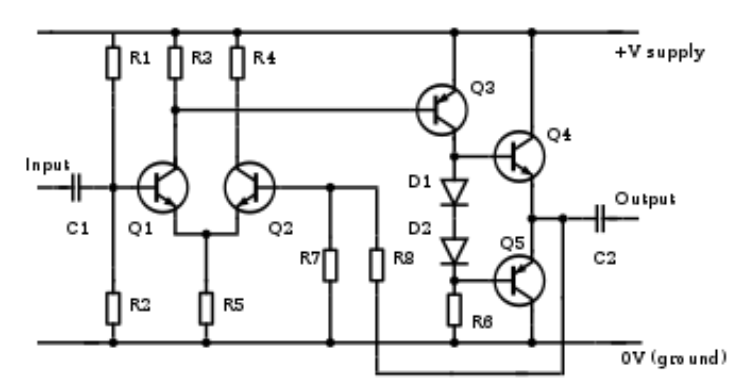
如果電壓V_G很小而且有訊號，電壓V_S很大，所產生的大I_S就會攜帶訊號。





audio amplifier 音響放大器





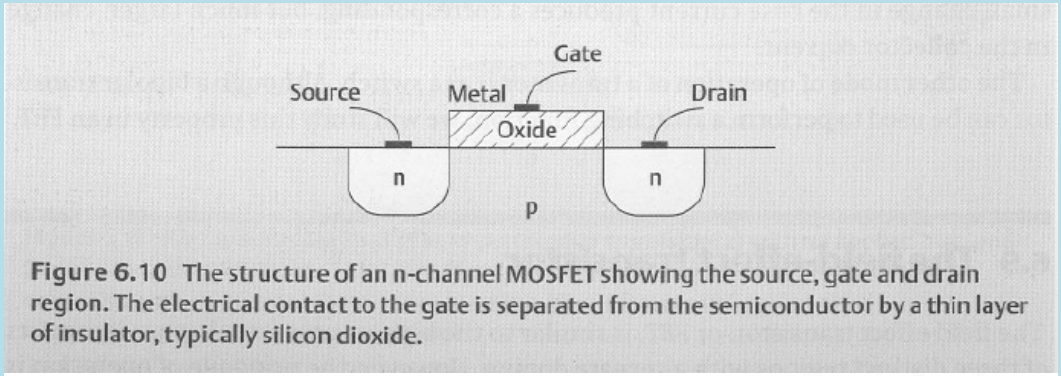
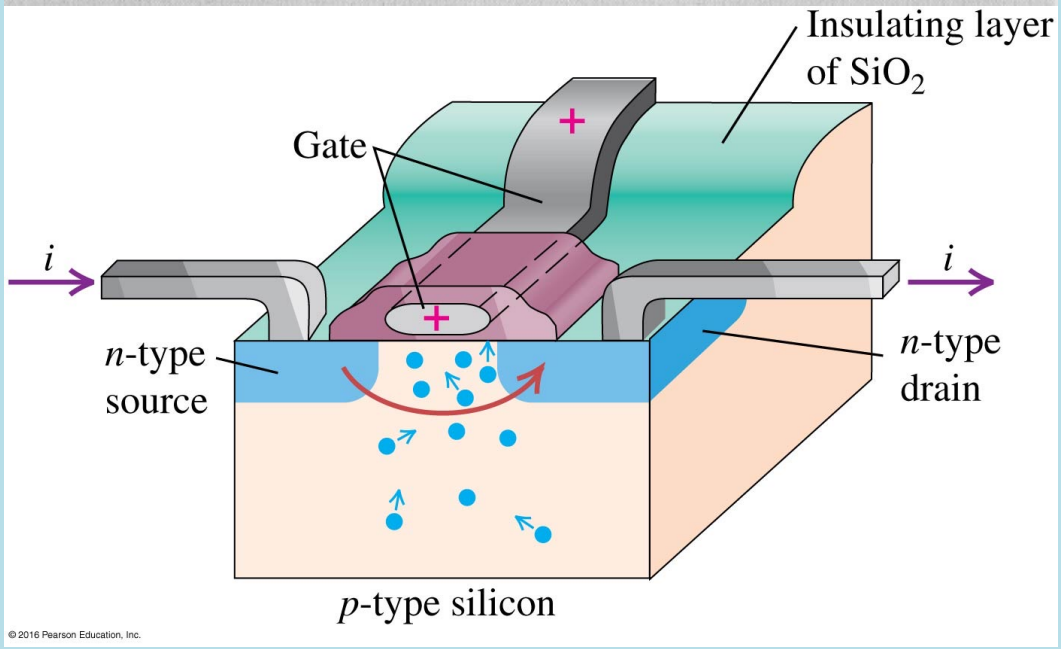
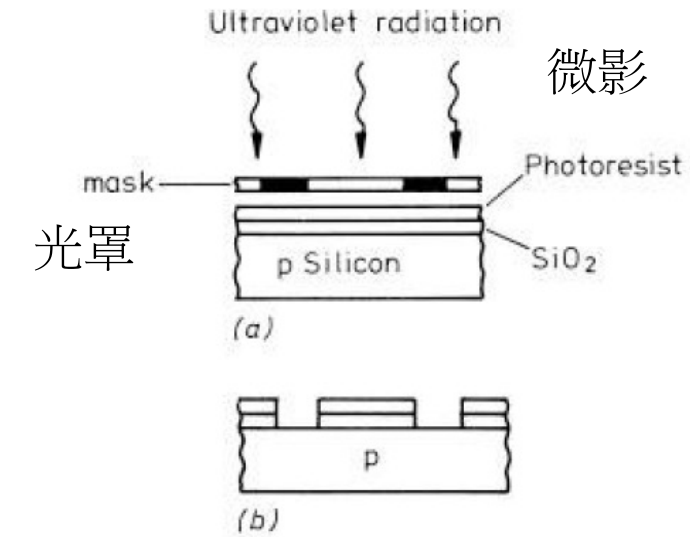


Figure 6.10 The structure of an n-channel MOSFET showing the source, gate and drain region. The electrical contact to the gate is separated from the semiconductor by a thin layer of insulator, typically silicon dioxide.



MOSFET 非常適合一層一層、積體電路的處理方式。

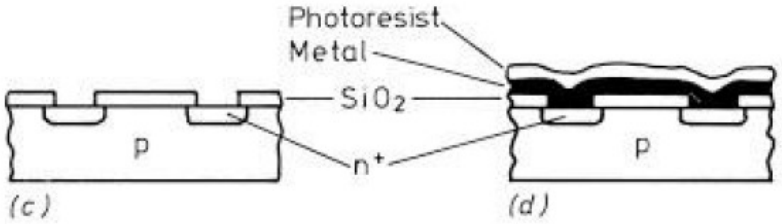


微影

光罩

以上所描述的電晶體配置有一個很長的名字：金屬氧化物半導體、場效型電晶體 MOSFET，比起傳統的雙極型電晶體，場效電晶體更適合於平面的半導體大量製造，而且體積可以極度縮小。如上所述，場效電晶體的主體是由p型與n型半導體分布組成，這個分布可以規劃在二維平面上，於是由電晶體所組成的電路就可以在一片平板上展開。製作時會以矽為晶片基板，第一步先全部摻雜為p型半導體。接著先設計好藍圖，在平面上安排出n型半導體的位置。第三步，在基板上塗一層感光的光阻劑，然後將設計畫在一片光罩上，當光罩放置於基板上時，光罩的圖案會遮蓋規劃為p型半導體的區域。接著以紫外線曝照，消除掉光罩圖案未遮蓋處的光阻劑，於是規劃為n型半導體區域的基板就曝露在外。最後，將此曝露的部分滲進適當雜質，就得到所設計的n型半導體分布，而光阻劑覆蓋的部分則維持原來的p型。利用這樣的製程就可以在晶片上建構出你所設計的分布，其他如絕緣層、導電線路與電極也可以用類似的方式往上堆疊建構。

上一段描述是不是讓你感覺很枯燥、很機械化？那就對了，一個接著一個的步驟，有條不紊，如此，就可以大量機械化生產。而且平面化的設計，可以將電路非常節省空間地集中在一塊小晶片上，這就稱為積體電路。它的最大好處在於，只要你的藍圖光罩夠精細，電晶體的大小幾乎可以無限地縮小。如此我們才能把驚人的計算能力，置於一個日常生活能夠輕鬆攜帶的裝置。積體電路在1960年代出現，大概從

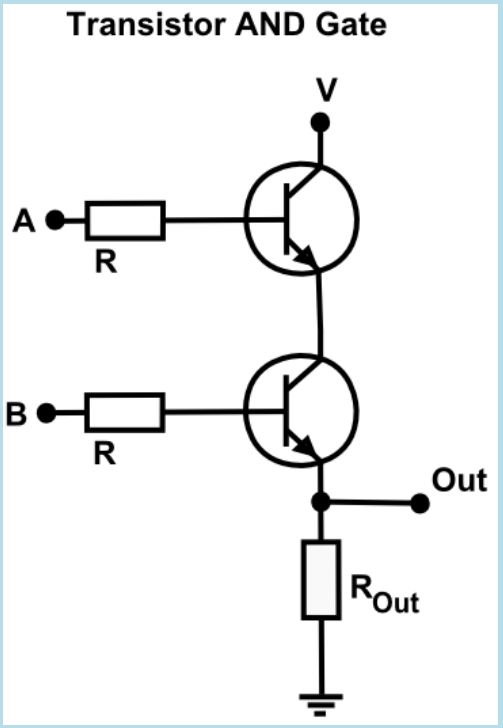


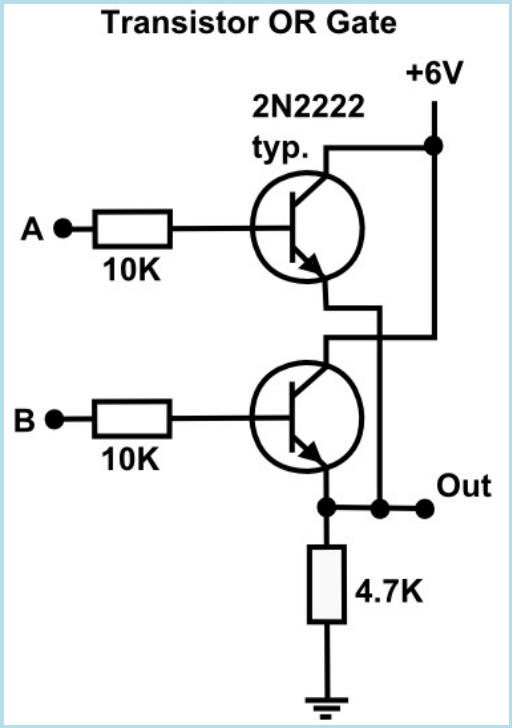
半導體製造是印刷業

is dissolved. Suitable donor atoms are diffused into the regions of Si from which the oxide layer has been removed; this creates the n^+ gate and source regions
(*d*) A thin metal film is evaporated over the whole surface and this is covered with another layer of photoresist. Exposure to ultraviolet radiation through a suitable mask enables regions of the metal film to be selectively removed by steps similar to those in (*a*) and (*b*). The electrode pattern of Fig. 6.11 is thus established

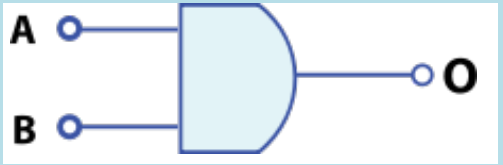
將不同型的半導體組合在一起，可以製造出各式半導體元件，來控制電路中的電流：

甚至可以設計出邏輯閘門！ Logical Gates



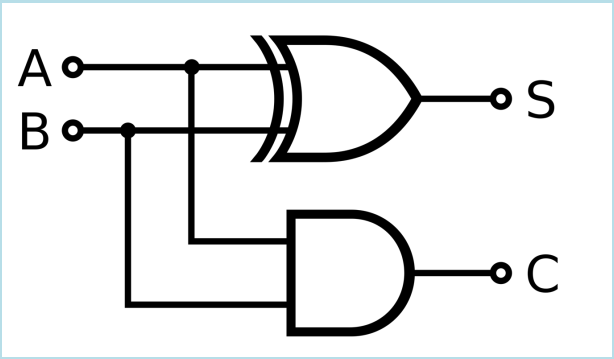


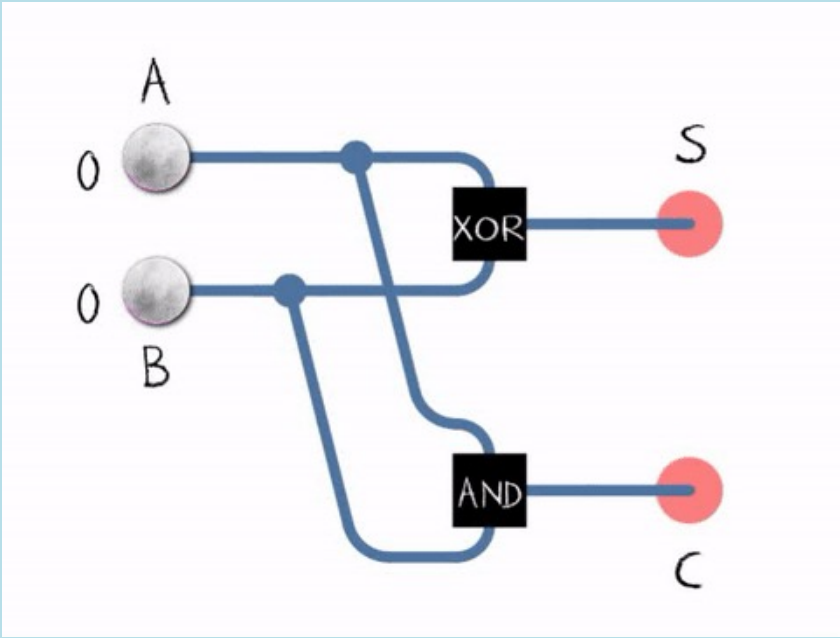
Input		Output
A	B	A XOR B
0	0	0
0	1	1
1	0	1
1	1	0

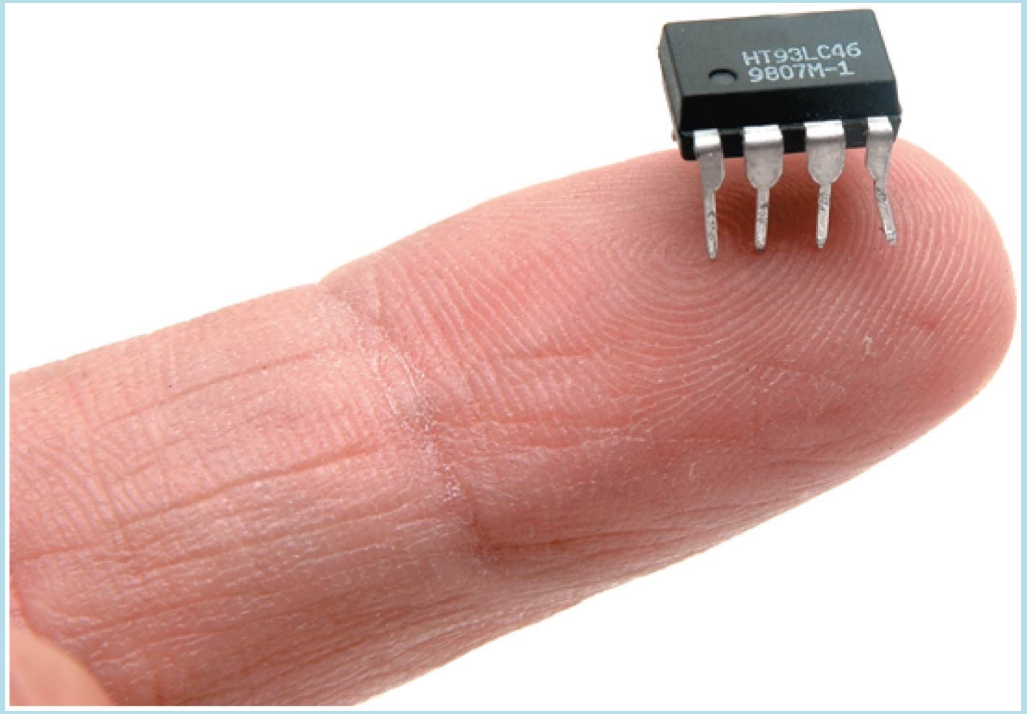


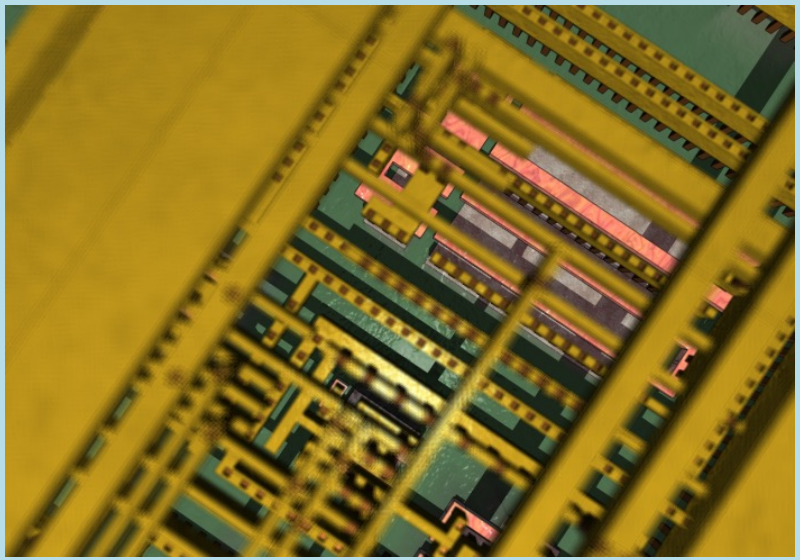
邏輯閘門可以組成演算電路！

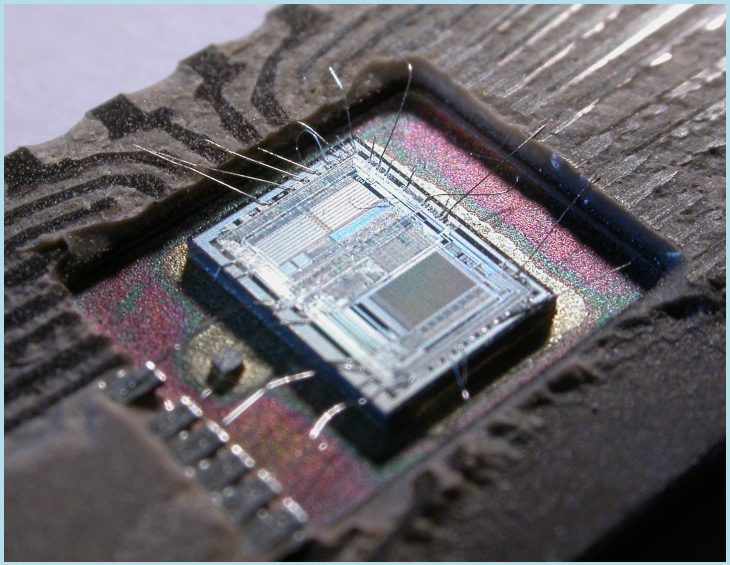
Half adder logic circuits

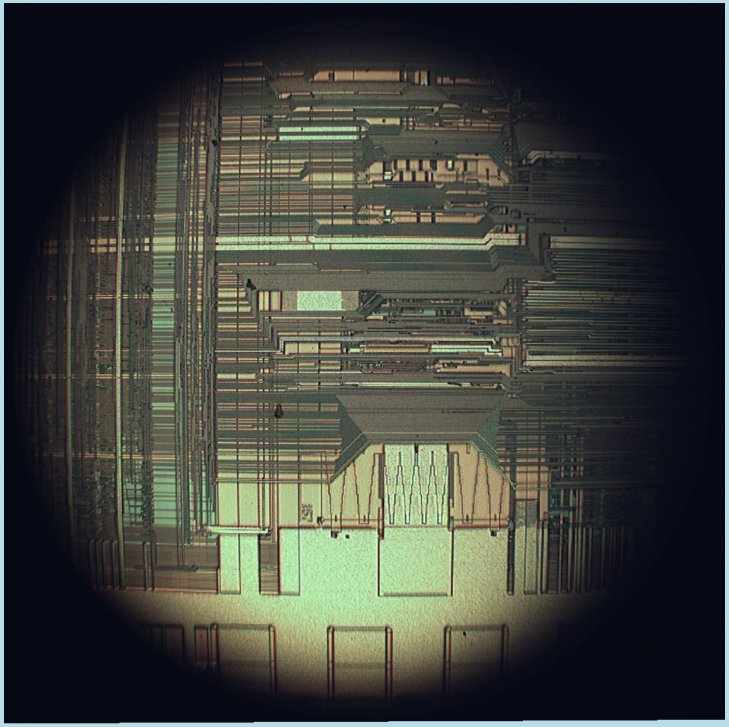





HT93LC46
9807M-1







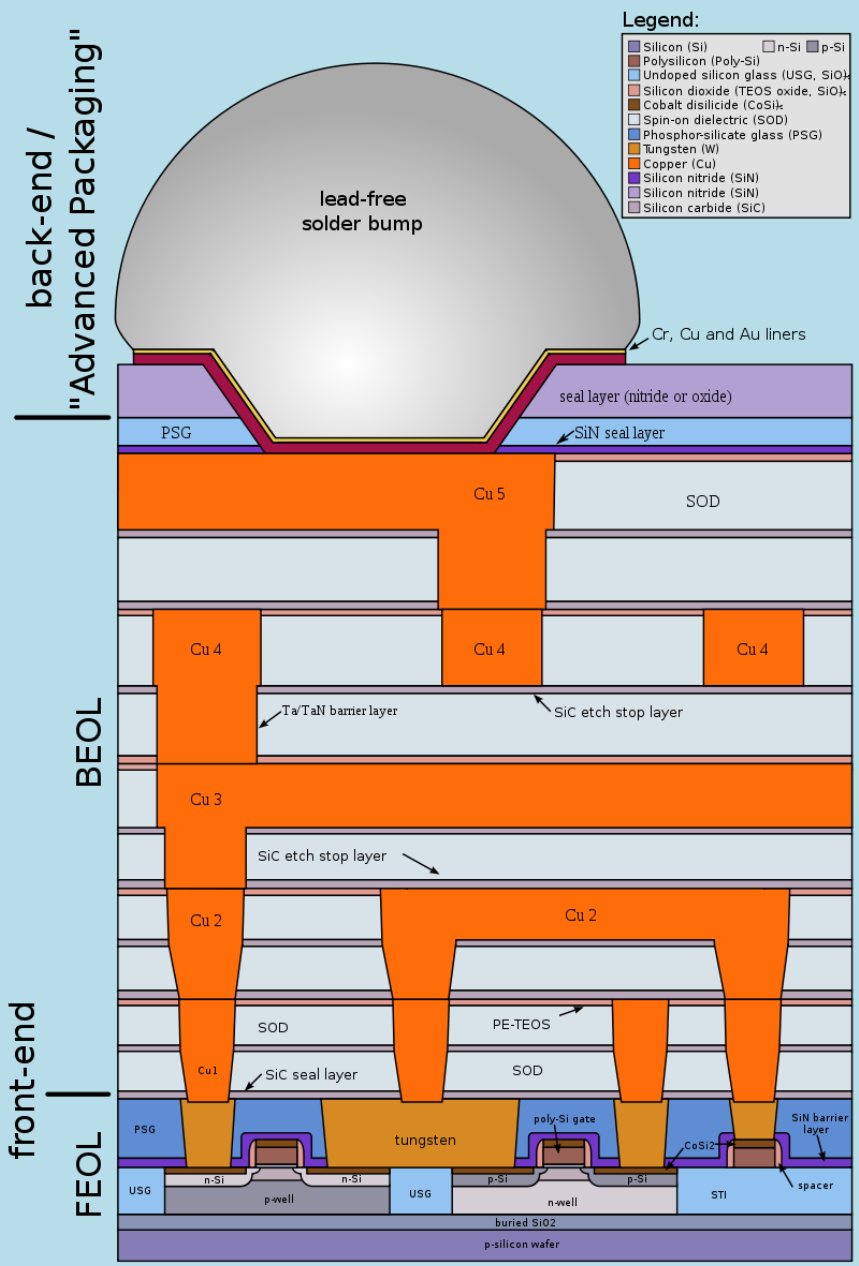
Integrated Circuit 積體電路

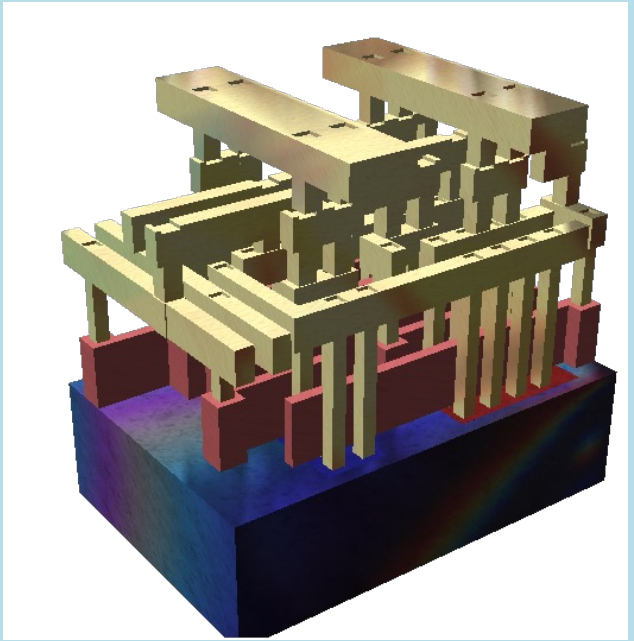

CIC0001
造山者
世紀的賭注
REC

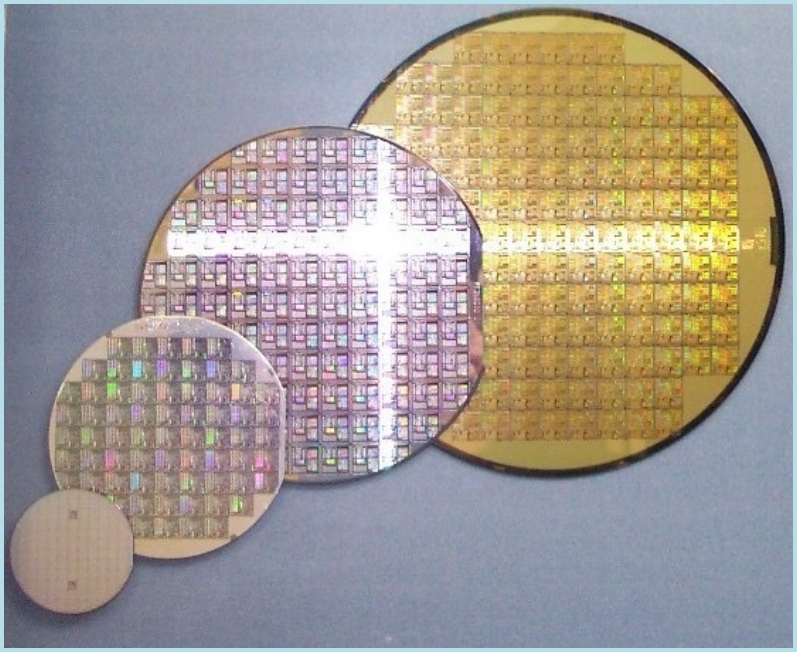
HISTORY

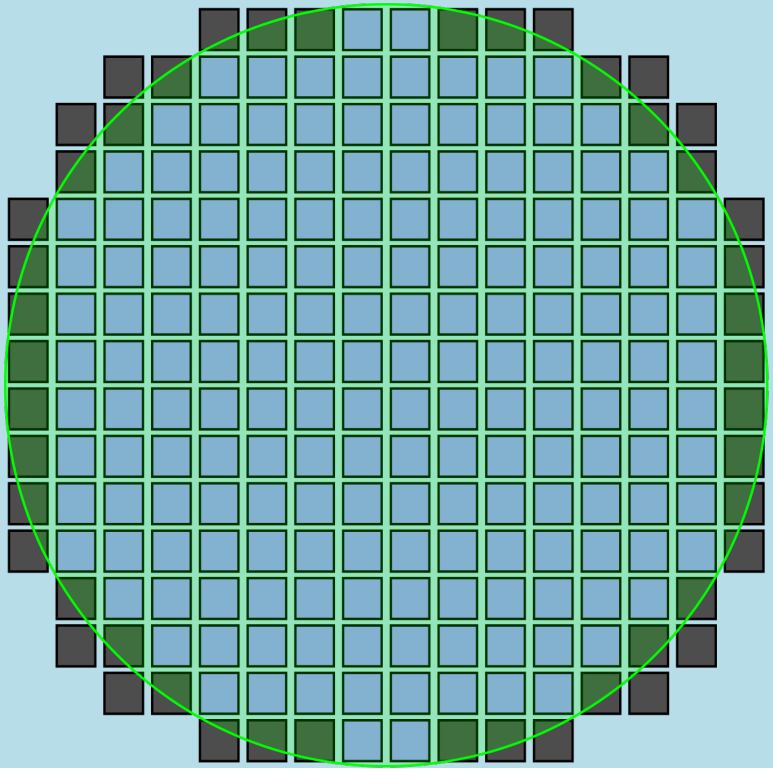
1976

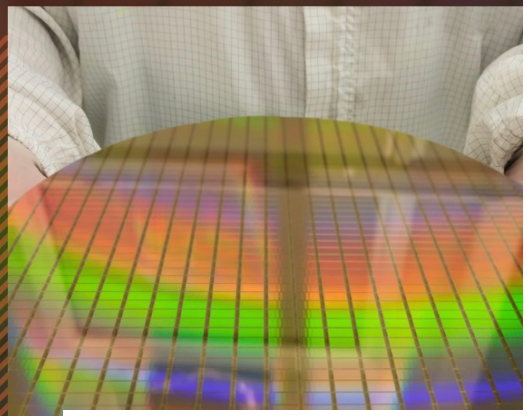
工研院派員赴美國RCA訓練。與RCA公關主任合影，左起曹興誠、倪其良、曾繁城、戴寶通、劉英達、陳碧灣、史欽泰。


Legend:
Silicon (Si)
n-Si
p-Si
Polysilicon (Poly-Si)
Undoped silicon glass (USG, SiO2)
Silicon dioxide (TEOS oxide, SiO2)
Cobalt disilicide (CoSi2)
Spin-on dielectric (SOD)
Phosphor-silicate glass (PSG)
Tungsten (W)
Copper (Cu)
Silicon nitride (SiN)
Silicon nitride (SiN)
Silicon carbide (SiC)
back-end / "Advanced Packaging"
BEOL
front-end
FEOL
lead-free solder bump
Cr, Cu and Au liners
seal layer (nitride or oxide)
PSG
SiN seal layer
Cu 5
SOD
Cu 4
Cu 4
Cu 4
Ta/TaN barrier layer
SiC etch stop layer
Cu 3
SiC etch stop layer
Cu 2
Cu 2
SOD
PE-TEOS
Cu1
SiC seal layer
SOD
PSG
tungsten
poly-Si gate
CoSi2
SiN barrier layer
USG
n-Si
n-Si
p-well
USG
p-Si
p-Si
n-well
STI
spacer
buried SiO2
p-silicon wafer









節目 知識好好玩

EP08｜台灣這美麗的矽島——聊一聊半導體物理

主持人 | 張嘉泓

單曲長度 | 00:25:46　發布時間 | 2021-08-03

查看節目資訊

開始播放

以上所描述的電晶體配置有一個很長的名字：金屬氧化物半導體、場效型電晶體 MOSFET，比起傳統的雙極型電晶體，場效電晶體更適合於平面的半導體大量製造，而且體積可以極度縮小。如上所述，場效電晶體的主體是由p型與n型半導體分布組成，這個分布可以規劃在二維平面上，於是由電晶體所組成的電路就可以在一片平板上展開。製作時會以矽為晶片基板，第一步先全部摻雜為p型半導體。接著先設計好藍圖，在平面上安排出n型半導體的位置。第三步，在基板上塗一層感光的光阻劑，然後將設計畫在一片光罩上，當光罩放置於基板上時，光罩的圖案會遮蓋規劃為p型半導體的區域。接著以紫外線曝照，消除掉光罩圖案未遮蓋處的光阻劑，於是規劃為n型半導體區域的基板就曝露在外。最後，將此曝露的部分滲進適當雜質，就得到所設計的n型半導體分布，而光阻劑覆蓋的部分則維持原來的p型。利用這樣的製程就可以在晶片上建構出你所設計的分布，其他如絕緣層、導電線路與電極也可以用類似的方式往上堆疊建構。

上一段描述是不是讓你感覺很枯燥、很機械化？那就對了，一個接著一個的步驟，有條不紊，如此，就可以大量機械化生產。而且平面化的設計，可以將電路非常節省空間地集中在一塊小晶片上，這就稱為積體電路。它的最大好處在於，只要你的藍圖光罩夠精細，電晶體的大小幾乎可以無限地縮小。如此我們才能把驚人的計算能力，置於一個日常生活能夠輕鬆攜帶的裝置。積體電路在1960年代出現，大概從