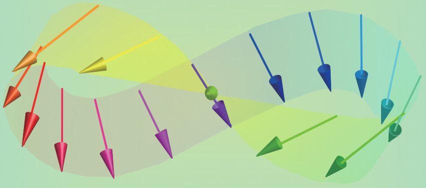
Semiconductor Devices

21



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Department of Electronics

THE UNIVERSITY *of York*

11:00 Thursday, 20/November/2014 (P/T 005)

Contents of Semiconductor Devices

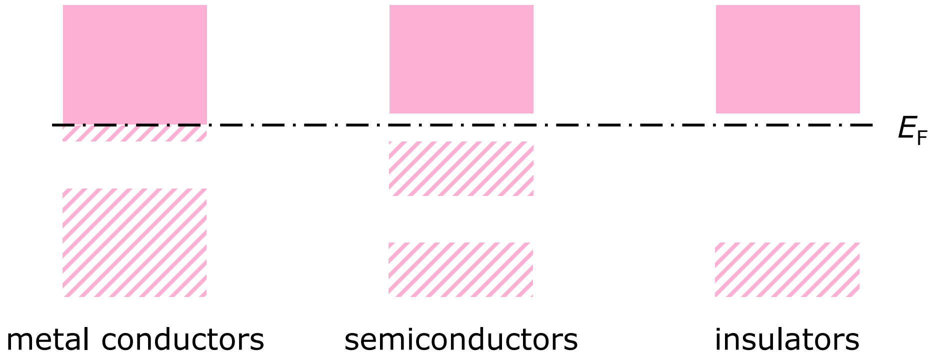
Lectures : Atsufumi Hirohata (atsufumi.hirohata@york.ac.uk, P/Z 019)
p-*n* junctions and Schottky diodes (Weeks 8 ~ 10)
[11:00 Mon. (P/L 005), Tue. (P/L 006) & Thu. (P/T 005)]

21. Intrinsic semiconductor
22. Extrinsic semiconductor
23. *p*-*n* junction
24. Bias application
25. Metal semiconductor junction
26. Schottky junction
27. Metal oxide semiconductor junction

Lecture notes / slides : http://www-users.york.ac.uk/~ah566/lectures/lectures.html

What is *semi*-conductor ?

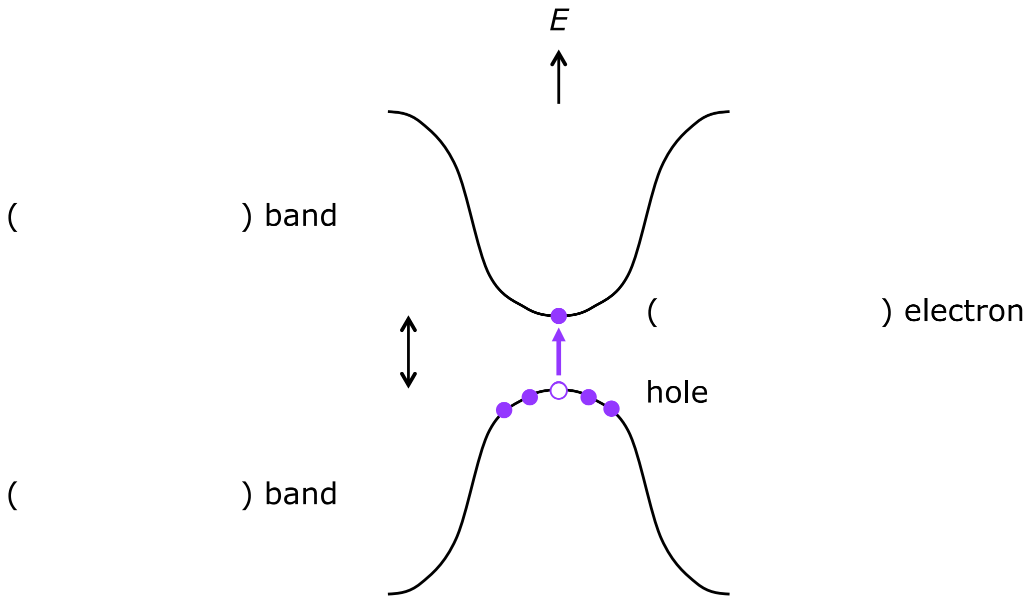
Band diagrams :



With (   ),
electrons can overcome
the (   ) band.

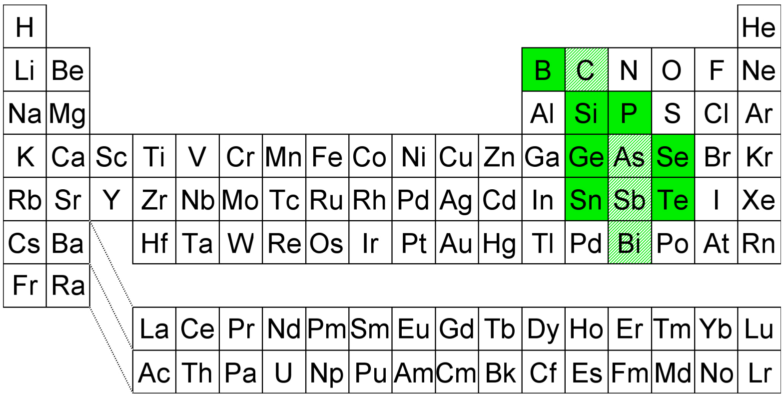
Energy Band of a semiconductor

Schematic energy band diagram :



Elemental Semiconductors

In the periodic table,



H																	He
Li	Be											B	C	N	O	F	Ne
Na	Mg											Al	Si	P	S	Cl	Ar
K	Ca	Sc	Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Zn	Ga	Ge	As	Se	Br	Kr
Rb	Sr	Y	Zr	Nb	Mo	Tc	Ru	Rh	Pd	Ag	Cd	In	Sn	Sb	Te	I	Xe
Cs	Ba		Hf	Ta	W	Re	Os	Ir	Pt	Au	Hg	Tl	Pd	Bi	Po	At	Rn
Fr	Ra																
			La	Ce	Pr	Nd	Pm	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu
			Ac	Th	Pa	U	Np	Pu	Am	Cm	Bk	Cf	Es	Fm	Md	No	Lr

Carrier density : Cu (metal) ~ 10^{23} cm $^{-3}$

Ge (semiconductor) ~ 10^{13} cm $^{-3}$

Semimetal : conduction and valence bands are slightly overlaped.

As (semimetal) ~ 10^{20} cm $^{-3}$

Sb (semimetal) ~ 10^{19} cm $^{-3}$

C (semimetal) ~ 10^{18} cm $^{-3}$

Bi (semimetal) ~ 10^{17} cm $^{-3}$

Si Substrate Manufacturing

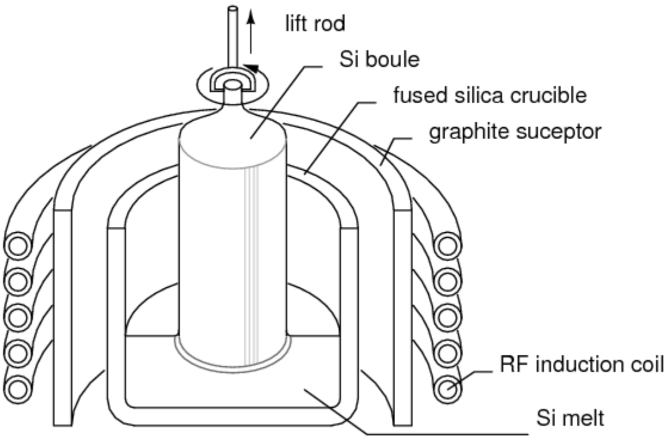
Czochralski process :

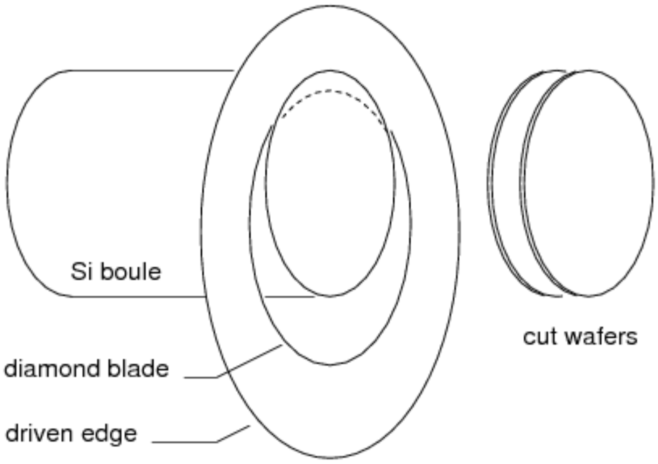
Silicon is the second most common element in the Earth crust.

A common form is Silicon dioxide, SiO_2 (Silica).

A Si single-crystal with a desired orientation is used.

The Si crystal is lifted at a certain rotation speed from melt Si pot.



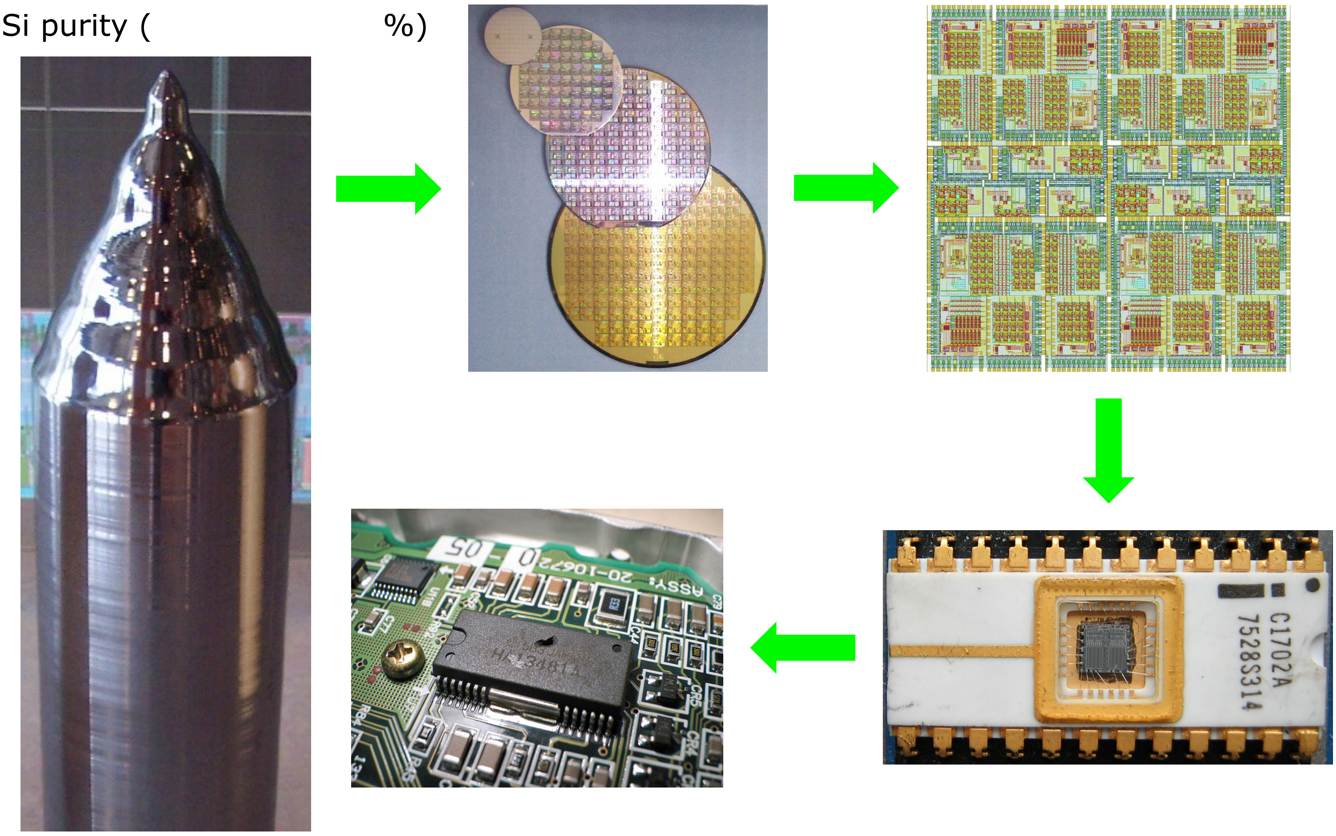


* http://www.allaboutcircuits.com/vol_3/chpt_2/12.html;
** http://www.homepower.com/articles/solar-electricity/equipment-products/peek-inside-pv

Fabrication of a Si-Based Integrated Circuit

Czochralski method :

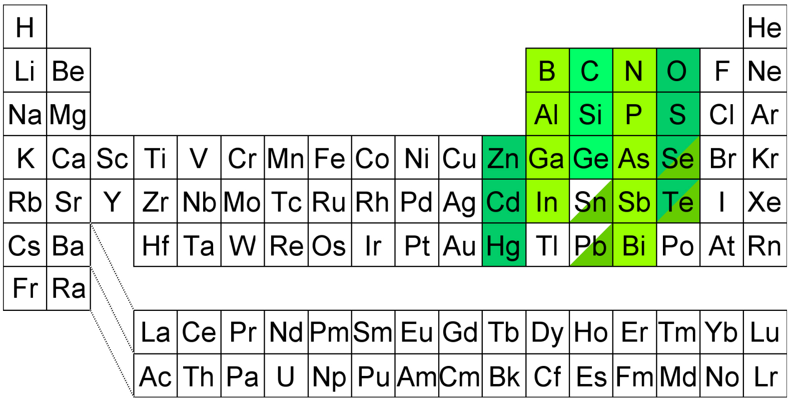
Si purity (%)



* http://www.wikipedia.org/

Compound Semiconductors

In the periodic table,



H																	He
Li	Be											B	C	N	O	F	Ne
Na	Mg											Al	Si	P	S	Cl	Ar
K	Ca	Sc	Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Zn	Ga	Ge	As	Se	Br	Kr
Rb	Sr	Y	Zr	Nb	Mo	Tc	Ru	Rh	Pd	Ag	Cd	In	Sn	Sb	Te	I	Xe
Cs	Ba		Hf	Ta	W	Re	Os	Ir	Pt	Au	Hg	Tl	Pb	Bi	Po	At	Rn
Fr	Ra																
			La	Ce	Pr	Nd	Pm	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu
			Ac	Th	Pa	U	Np	Pu	Am	Cm	Bk	Cf	Es	Fm	Md	No	Lr

III-V compounds : GaAs, InAs, InSb, AlP, BP, …

II-VI compounds : ZnO, CdS, CdTe, …

IV-IV compounds : SiC, GeSi

IV-VI compounds : PbSe, PbTe, SnTe, …

Semiconductor Band Gap in Si, Ge and GaAs

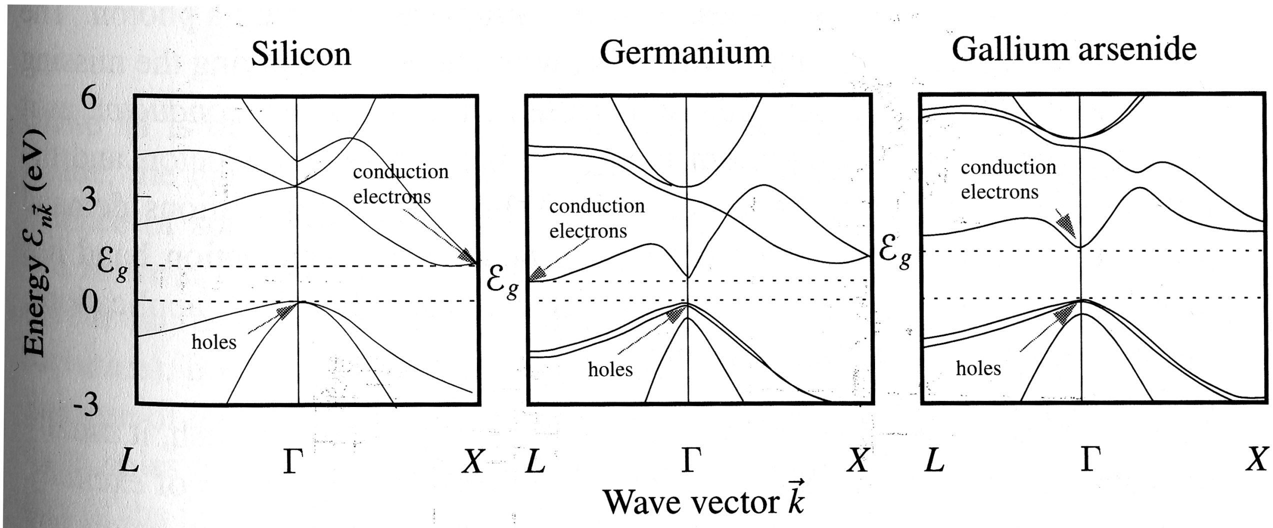


Figure 19.8. Essential features of band structures of silicon, germanium, and gallium arsenide. All have band gaps on the order of 1 eV. The bottom of the conduction band for silicon and germanium does not lie at Γ, so these materials have an indirect gap. Gallium arsenide, by contrast, has a direct gap. These diagrams are extracted from Figures 23.15 and 23.16, which contain information on how they were obtained.

* M. P. Marder, *Condensed Matter Physics* (John-Wiley, New York, 2000).

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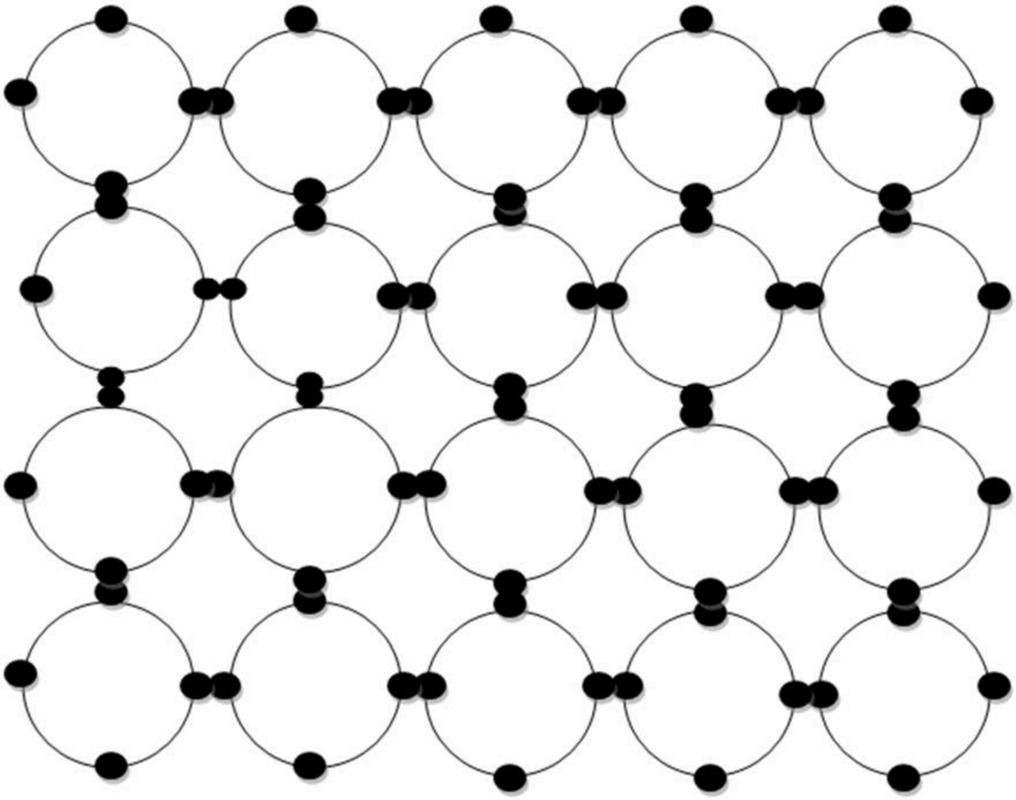
21 Intrinsic Semiconductor

- Bandgap
- Conduction band
- Valence band
- Fermi level
- Shockley Model
- Carrier density
- Ion implantation

Intrinsic Semiconductors

Atomic structures :



* http://chemwiki.ucdavis.edu/u_Materials/Semiconductors/Intrinsic_Semiconductors/Intrinsic_Semiconductors

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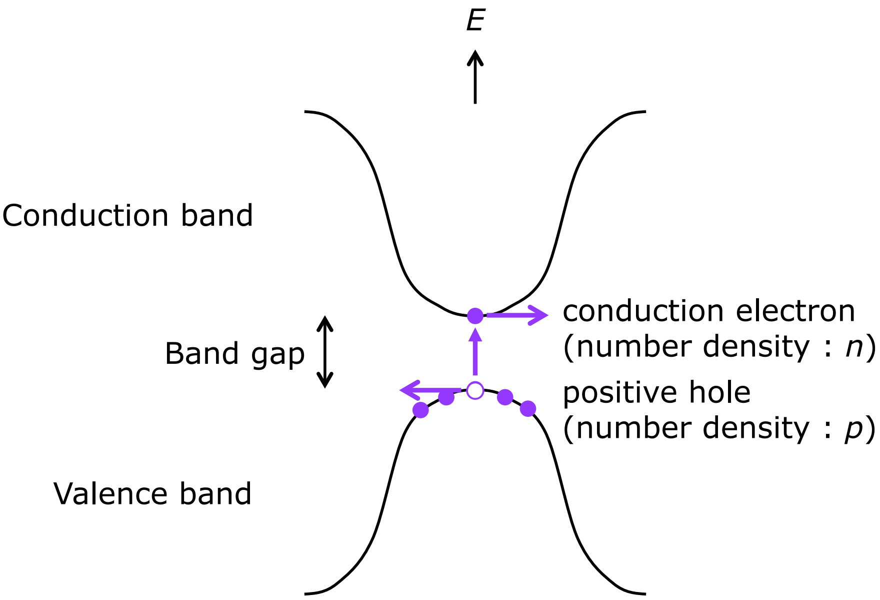
Shockley Model

Contributions for electrical transport :



E

Conduction band

Band gap

Valence band

conduction electron
(number density : *n*)

positive hole
(number density : *p*)

→ (   ) conduction

→ (   ) semiconductor

$$\sigma = \sigma_{\mathrm{e}} + \sigma_{\mathrm{h}} = nq\mu_{\mathrm{e}} + pq\mu_{\mathrm{h}} = n_{\mathrm{i}}q\left(\mu_{\mathrm{e}} + \mu_{\mathrm{h}}\right) \quad (\qquad\qquad)$$

* http://www.wikipedia.org/

Carrier Number Density of an Intrinsic Semiconductor

Carrier number density is defined as

Here, the Fermi distribution function is $f(E) = \dfrac{1}{\exp\left[(E - E_F)/k_B T\right] + 1}$

For the carriers like free electrons with m^*, the density of states is

$$g(E) = 2\frac{1}{(2\pi)^2}\left(\frac{2m^*}{\hbar^2}\right)^{3/2}\sqrt{E}$$

For electrons with effective mass m_e^*, $g(E)$ in the conduction band is written with respect to the energy level E_C,

$$g_C(E) = 2\frac{1}{(2\pi)^2}\left(\frac{2m_e^*}{\hbar^2}\right)^{3/2}\sqrt{E - E_C}$$

For holes with effective mass m_p^*, $g(E)$ in the valence band is written with respect to the energy level $E_V = 0$,

$$g_V(E) = 2\frac{1}{(2\pi)^2}\left(\frac{2m_p^*}{\hbar^2}\right)^{3/2}\sqrt{-E}$$

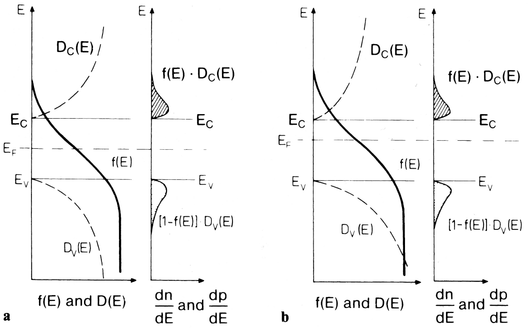


Fig. 12.5. (**a**) Fermi function $f(E)$, density of states $D(E)$ and electron (n) and hole (p) concentrations in the conduction and valence bands for the case of equal densities of states in the conduction and valence bands (schematic); (**b**) the same figure for the case of differing densities of states in the conduction and valence bands. The number of holes must again be equal to the number of electrons, and thus the Fermi level no longer lies in the middle of the gap between conduction and valence bands; its position then becomes temperature dependent

* H. Ibach and H. Lüth, *Solid-State Physics* (Springer, Berlin, 2003).

Carrier Number Density of an Intrinsic Semiconductor (Cont'd)

$f_p(E)$ for holes equals to the numbers of unoccupied states by electrons :

n is an integral in the conduction band from the bottom E_C to top E_{ct} :

$$n = \int_{E_C}^{E_{Ct}} f_e(E) g_e(E) dE = \int_{E_C}^{E_{Ct}} \frac{1}{2\pi^2}\left(\frac{2m_e^*}{\hbar^2}\right)^{3/2}\sqrt{E - E_C}\,\frac{1}{\exp\left[(E - E_F)/k_B T\right] + 1} dE$$

p is an integral in the valence band from the bottom $-E_{Vb}$ to top 0 :

$$p = \int_{-E_{Vb}}^{0} f_p(E) g_p(E) dE = \int_{-E_{vb}}^{0} \frac{1}{2\pi^2}\left(\frac{2m_p^*}{\hbar^2}\right)^{3/2}\sqrt{-E}\left\{1 - \frac{1}{\exp\left[(E - E_F)/k_B T\right] + 1}\right\} dE$$

$$= \int_{-E_{vb}}^{0} \frac{1}{2\pi^2}\left(\frac{2m_p^*}{\hbar^2}\right)^{3/2}\sqrt{-E}\,\frac{1}{\exp\left[-(E - E_F)/k_B T\right] + 1} dE$$

Here, E_C (= E_g = E_C - E_V) >> $k_B T$ → E - E_F ≥ E_C /2 for E_C ≤ E ≤ E_{ct} (E_F ~ E_C /2)

$$\boxed{f_e(E) \approx \exp\left[-(E - E_F)/k_B T\right]}$$

Similarly, E_C >> $k_B T$ → -(E - E_F) ≥ E_C /2 for E_{Vb} ≤ E ≤ 0

$$\boxed{f_p(E) \approx \exp\left[(E - E_F)/k_B T\right]}$$

Carrier Number Density of an Intrinsic Semiconductor (Cont'd)

For $E - E_F > 3k_BT$, $f_e(E_F + 3k_BT) < 0.05$ and hence $E_{Ct} \rightarrow \infty$

Similarly, $f_p(E_F - 3k_BT) < 0.05$ and hence $E_{Vb} \rightarrow -\infty$

$$n = \frac{1}{2\pi^2}\left(\frac{2m_e^*}{\hbar^2}\right)^{3/2}\int_{E_C}^{\infty}\sqrt{E - E_C}\,\exp\left[-(E - E_F)/k_BT\right]dE$$

$$p = \frac{1}{2\pi^2}\left(\frac{2m_p^*}{\hbar^2}\right)^{3/2}\int_{-\infty}^{0}\sqrt{-E}\,\exp\left[(E - E_F)/k_BT\right]dE$$

As a result,

$$n = N_C \exp\left[-(E_C - E_F)/k_BT\right] \approx N_C f_e(E_C) \quad \begin{cases} \boxed{N_C \equiv N_{Ce}T^{3/2}} \\ N_{Ce} \equiv 2\left(\dfrac{2\pi m_e^* k_B}{h^2}\right)^{3/2} \end{cases}$$

$$n = N_V \exp\left[-E_F/k_BT\right] \approx N_V f_p(0) \quad \begin{cases} \boxed{N_V \equiv N_{Vp}T^{3/2}} \\ N_{Vp} \equiv 2\left(\dfrac{2\pi m_p^* k_B}{h^2}\right)^{3/2} \end{cases}$$

Fermi Level of an Intrinsic Semiconductor

For an intrinsic semiconductor, $n = p \equiv n_i$

$$N_C \exp\left[-(E_C - E_F)/k_BT\right] = N_V \exp\left[-E_F/k_BT\right]$$

$$\therefore E_F = \frac{1}{2}E_C + \frac{3}{4}k_BT\ln\left(\frac{m_p^*}{m_e^*}\right)$$

Assuming, $m_e^* = m_p^* = m^*$

(   )

np product is calculated to be

$$np = n_i^2 = N_C N_V \exp\left[-E_C/k_BT\right] = 4\left(\frac{2\pi k_BT}{h^2}\right)^3\left(m_e^* m_p^*\right)^{3/2}\exp\left(-E_C/k_BT\right)$$

$\rightarrow \boxed{\qquad\qquad}$

→ can be applied for an $\boxed{\qquad\qquad \text{semiconductor}}$

Typical Bandgaps

Bandgaps between the conduction and valence bands :

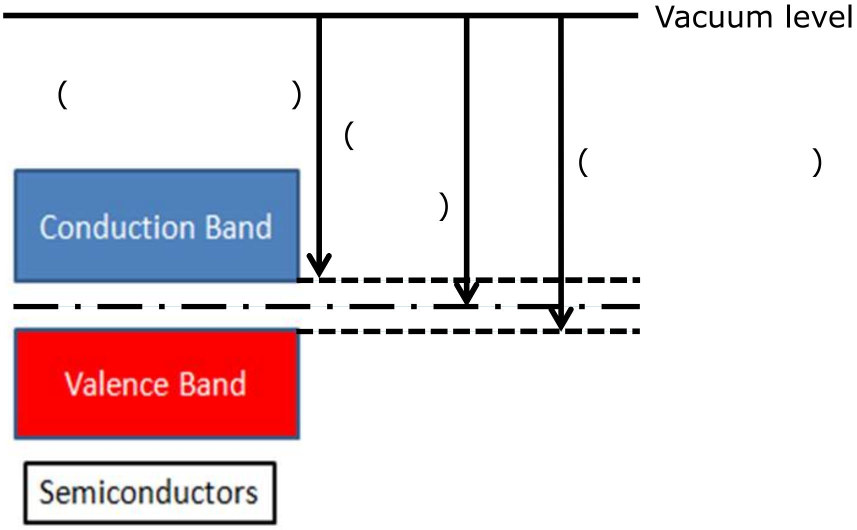
	Bandgap E_g [eV]	Resistivity ρ [Ω·cm]
Ge	0.66	0.5
Si	1.11	2.3×10^3
GaAs	1.43	$\sim 10^3$
C (diamond)	6 ~ 7	$\times 10^{12}$

$E_g \propto \rho$

Semiconductors : E_g ~ ( ) eV

Typical Bandgap

Bandgaps between the conduction and valence bands :



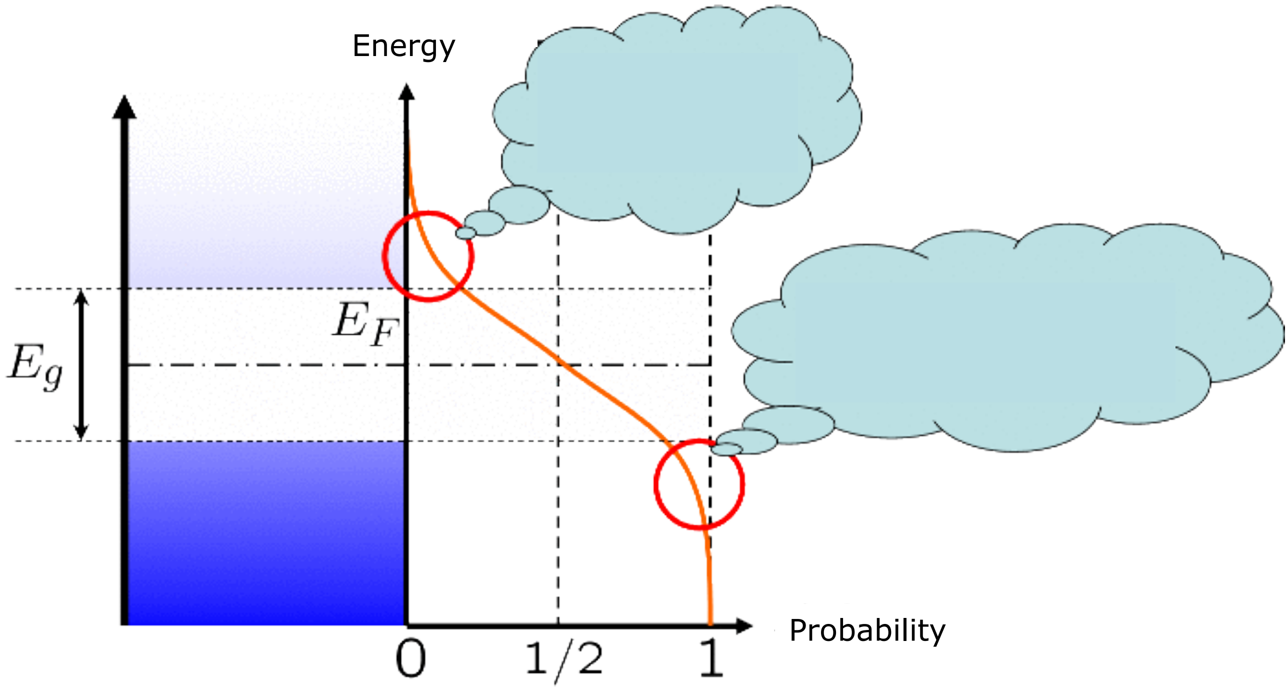
Electron / hole transport under a bias :

http://kccn.konan-u.ac.jp/physics/semiconductor/diagram/a05.html

* http://fhirose.yz.yamagata-u.ac.jp/text/kiso1.pdf

Intrinsic Semiconductors

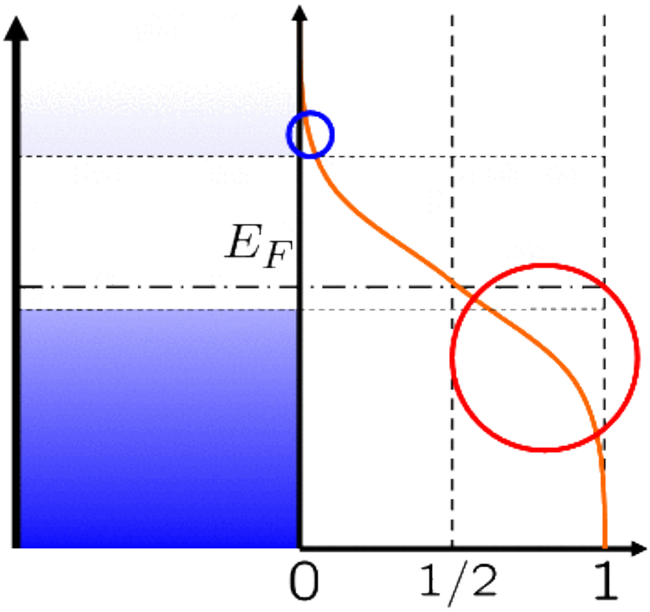
Band structures :



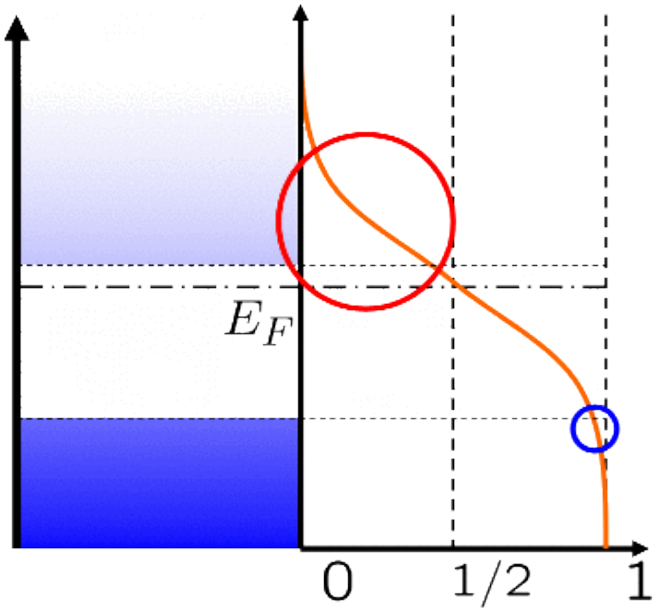
* http://hooktail.sub.jp/solid/shino-PNI-typeSemiconductor-upper/

Extrinsic Semiconductors

p-type band structures :



n-type band structures :



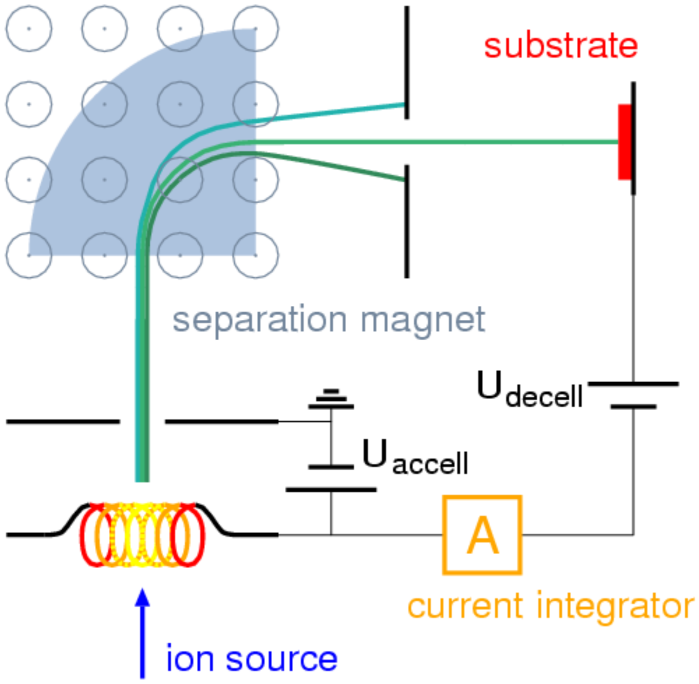
* http://hooktail.sub.jp/solid/shino-PNI-typeSemiconductor-upper/

Fabrication of Doped Semiconductor

Ion implantation :

Typical acceleration energy : 10 ~ 500 keV.

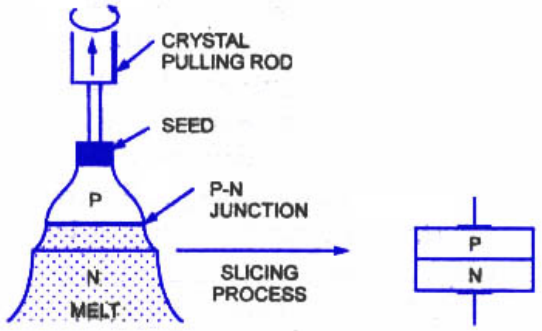
Annealing required to activate injected ions as (   ).

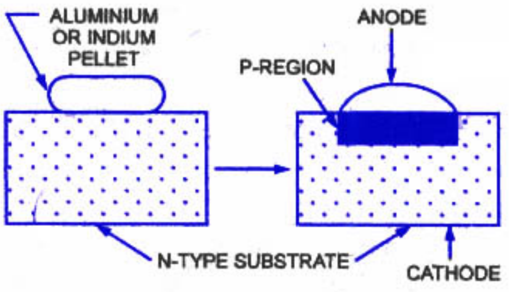


* http://www.wikipedia.org/

Fabrication of *p*-*n* Junctions 1

Alloy type or fused junction diodes :



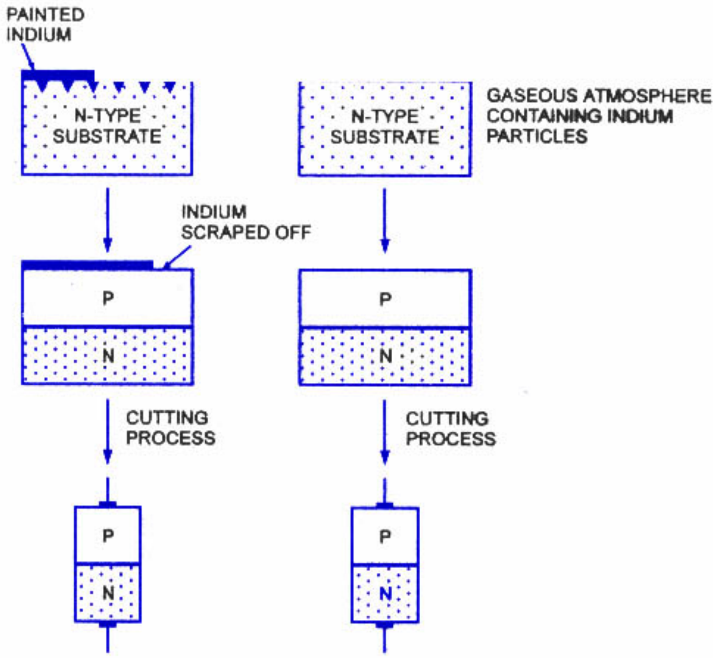


Alloy Type or Fused Junction Diode

* http://www.circuitstoday.com/semiconductor-diode-fabrication-types

Fabrication of *p-n* Junctions 2

Diffused junction diodes :



Solid Diffusion *Gaseous Diffusion*

Diffusion Process

* http://www.circuitstoday.com/semiconductor-diode-fabrication-types

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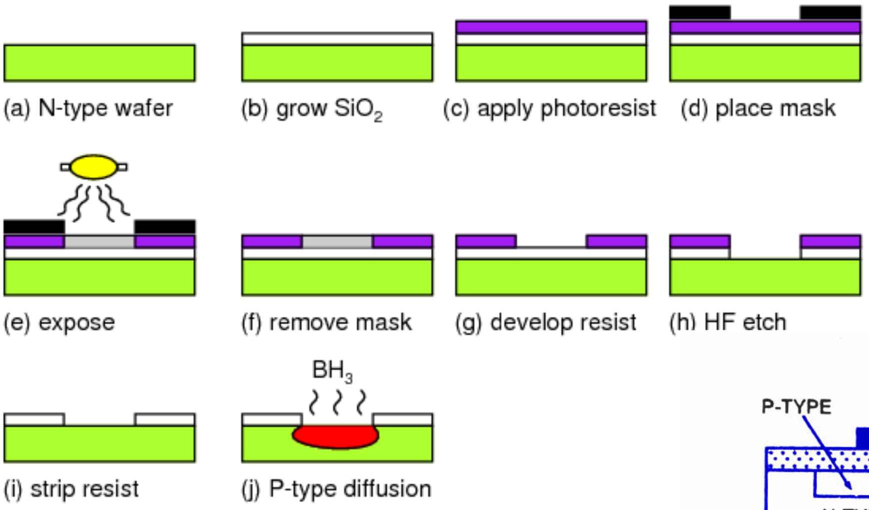
Fabrication of *p-n* Junctions 3

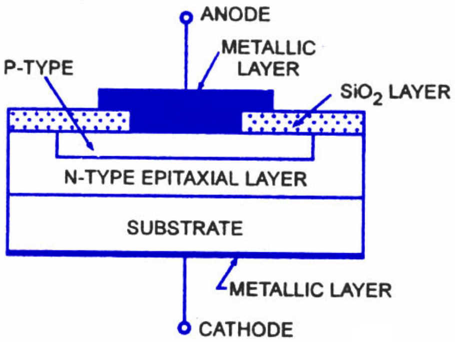
Epitaxial growth or planar diffused diodes :

epi = upon + *taxis* = arrangement.


(a) N-type wafer (b) grow SiO_2 (c) apply photoresist (d) place mask

(e) expose (f) remove mask (g) develop resist (h) HF etch

(i) strip resist (j) P-type diffusion



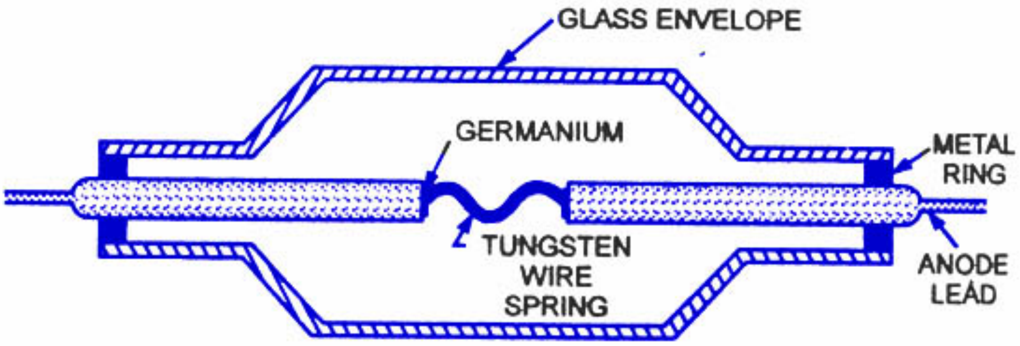
Epitaxially Grown or Planar Diffused Diode

* http://www.circuitstoday.com/semiconductor-diode-fabrication-types;
** http://www.allaboutcircuits.com/vol_3/chpt_2/12.html

Fabrication of *p*-*n* Junctions 4

Point contact diodes :

Bonded by radio frequency heating.



Germanium Point Contact Diode

* http://www.circuitstoday.com/semiconductor-diode-fabrication-types

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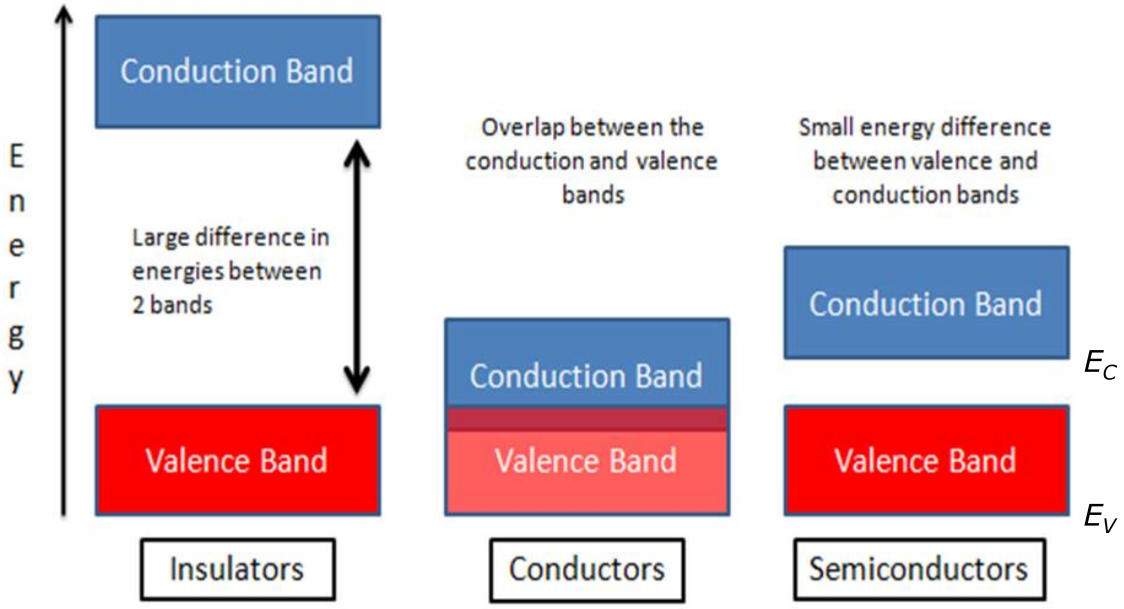
Intrinsic Semiconductors

Band structures :



N_V and N_C : carrier densities of the valence and conduction bands

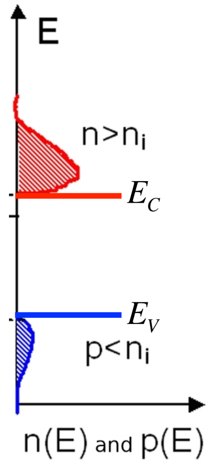
Fermi level : $E_i =$

$n = p =$ (n_i : intrinsic carrier density)

* http://chemwiki.ucdavis.edu/u_Materials/Semiconductors/Intrinsic_Semiconductors/Intrinsic_Semiconductors

Exercise 1

Find the probability of occupation of a level of 0.05 eV above the conduction band edge of a Silicon device if the Fermi level is 0.7 eV above the valence band edge.



Assume the bandgap (E_g) of Silicon is 1.1 eV and the effective mass of electron in Silicon is

$0.40 \times (0.91 \times 10^{-30}$ kg).

The Boltzmann constant (k_B) is 1.4×10^{-23} J/K,

the Planck constant is 6.6×10^{-34} J·s and

the temperature is 300K.

Use the conversion ratio: 1 eV = 1.6×10^{-19} J.