

# Semi-conductor Physics

**Semi-conductors**

|   | I A                | II A | 0  |    |    |    |    |    |    |    |     |     |     |     |  |
|---|--------------------|------|----|----|----|----|----|----|----|----|-----|-----|-----|-----|--|
| 1 | H                  | Be   | He |    |    |    |    |    |    |    |     |     |     |     |  |
| 2 | Li                 | Mg   | Ne |    |    |    |    |    |    |    |     |     |     |     |  |
| 3 | Na                 | Al   | Ar |    |    |    |    |    |    |    |     |     |     |     |  |
| 4 | K                  | Si   | Kr |    |    |    |    |    |    |    |     |     |     |     |  |
| 5 | Rb                 | Ge   | Xe |    |    |    |    |    |    |    |     |     |     |     |  |
| 6 | Cs                 | As   | At |    |    |    |    |    |    |    |     |     |     |     |  |
| 7 | Fr                 | Po   | Rn |    |    |    |    |    |    |    |     |     |     |     |  |
|   | *Lanthanide Series | Tl   | Lu |    |    |    |    |    |    |    |     |     |     |     |  |
|   | + Actinide Series  | Pb   | Lr |    |    |    |    |    |    |    |     |     |     |     |  |
|   | Rf                 | Bi   |    |    |    |    |    |    |    |    |     |     |     |     |  |
|   | Ha                 | Te   |    |    |    |    |    |    |    |    |     |     |     |     |  |
|   | 106                | In   |    |    |    |    |    |    |    |    |     |     |     |     |  |
|   | 107                | Sn   |    |    |    |    |    |    |    |    |     |     |     |     |  |
|   | 108                | Sb   |    |    |    |    |    |    |    |    |     |     |     |     |  |
|   | 109                | Pt   |    |    |    |    |    |    |    |    |     |     |     |     |  |
|   | 110                | Au   |    |    |    |    |    |    |    |    |     |     |     |     |  |
|   |                    | Hg   |    |    |    |    |    |    |    |    |     |     |     |     |  |
|   |                    | Tl   |    |    |    |    |    |    |    |    |     |     |     |     |  |
|   |                    | Pb   |    |    |    |    |    |    |    |    |     |     |     |     |  |
|   |                    | Bi   |    |    |    |    |    |    |    |    |     |     |     |     |  |
|   |                    | Po   |    |    |    |    |    |    |    |    |     |     |     |     |  |
|   |                    | At   |    |    |    |    |    |    |    |    |     |     |     |     |  |
|   |                    | Rn   |    |    |    |    |    |    |    |    |     |     |     |     |  |
|   |                    |      |    |    |    |    |    |    |    |    |     |     |     |     |  |
|   | 58                 | 59   | 60 | 61 | 62 | 63 | 64 | 65 | 66 | 67 | 68  | 69  | 70  | 71  |  |
|   | Ce                 | Pr   | Nd | Pm | Sm | Eu | Gd | Tb | Dy | Ho | Er  | Tm  | Yb  | Lu  |  |
|   | 90                 | 91   | 92 | 93 | 94 | 95 | 96 | 97 | 98 | 99 | 100 | 101 | 102 | 103 |  |
|   | Th                 | Pa   | U  | Np | Pu | Am | Cm | Bk | Cf | Es | Fm  | Md  | No  | Lr  |  |

**Tetravalent**  
e.g. Silicon

**Trivalent “Acceptor”**  
e.g. Gallium

**Pentavalent “Donor”**  
e.g. Arsenic

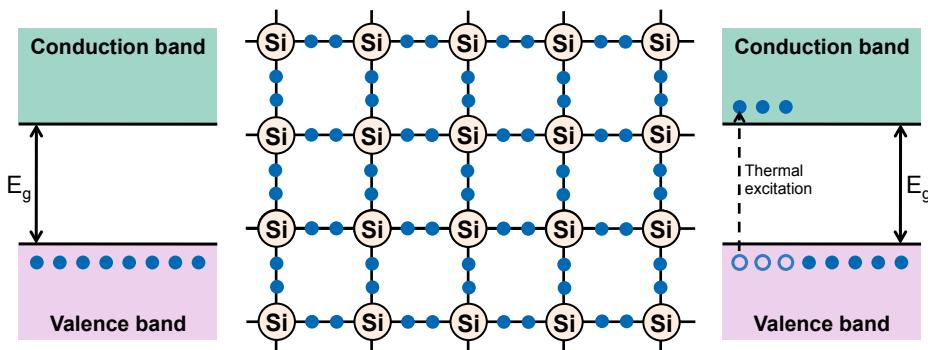
## Semiconductor band gap

**Table 6.2.** Forbidden energy gaps and long-wavelength photo-absorption limits for some common semiconductors

| Name                                   | Symbol                               | T (K)      | E <sub>G</sub> (eV)                  | λ <sub>c</sub> (μm) |
|--|--------------------------------------|------------|--------------------------------------|---------------------|
| Cadmium sulphide                       | CdS                                  | 295        | 2.4                                  | 0.5                 |
| Cadmium selenide                       | CdSe                                 | 295        | 1.8                                  | 0.7                 |
| Gallium arsenide                       | GaAs                                 | 295        | 1.35                                 | 0.92                |
| <b>Silicon</b>                         | <b>Si</b>                            | <b>295</b> | <b>1.12</b>                          | <b>1.11</b>         |
| Germanium                              | Ge                                   | 295        | 0.67                                 | 1.85                |
| Lead sulphide                          | PbS                                  | 295        | 0.42                                 | 2.95                |
| <b>Indium antimonide</b>               | <b>InSb</b>                          | <b>295</b> | <b>0.18</b>                          | <b>6.9</b>          |
| <b>Sensitive to optical photons →</b>  |                                      |            |                                      |                     |
| Mercury cadmium telluride              | Hg <sub>x</sub> Cd <sub>1-x</sub> Te | 77         | 0.1 ( $x=0.8$ )<br>0.5 ( $x=0.554$ ) | 12.4<br>2.5         |
| <b>Sensitive to infrared photons →</b> |                                      |            |                                      |                     |

## Pure Tetravalent Semi-conductors

E.g. Silicon ( $E_g=1.1\text{eV}$ ) and Germanium ( $E_g=0.67\text{eV}$ )



- T=0K

- Valence band is full
- Conduction band is empty
- Perfect insulator

- T>0K

- Mobile electrons in conduction band
- Mobile holes in valence band
- Conductivity is very low at room temperature:  $E_{th}=0.025\text{eV}$  at T=293K

# Holes

## Vacant electron states: positive mass and charge

Let us first take a completely filled band containing  $n$  electrons which have velocities  $v_1, v_2, \dots, v_n$ . Since the band is full there are as many electrons with velocity  $+v$  as there are with  $-v$  and so the total current flow is zero and we may write

$$-|e| \sum_n v_n = 0,$$

where we have written the electron charge as  $-|e|$  to make the presence of the negative sign completely unambiguous. Now let the  $i$ th electron be missing. There will be a net current equal to

$$\begin{aligned} & -|e| \sum_{n \neq i} v_n \\ \text{but } & -|e| \sum_{n \neq i} v_n + (-|e|v_i) = 0, \end{aligned}$$

and so the current is equal to  $+|e|v_i$ , i.e. the current could be considered to be due to a *positive* charge which has the same velocity as the  $i$ th electron state. It is important to note that this hole has the *same velocity* as an electron would have in state  $i$ . It does *not* move (as is sometimes stated) with a velocity which is opposite to that of the  $i$ th electron. This is because the hole itself is on the 'emptier' side of the electron distribution (Fig. 9.3), and so its velocity is already in a direction which is opposite to the net electron current flow.

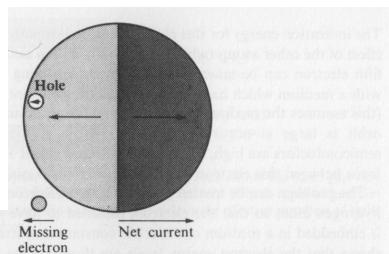
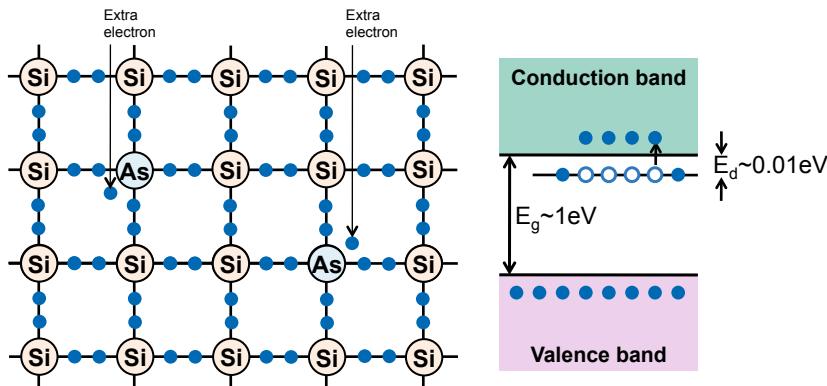


FIG. 9.3. Holes in the valence band. If there is an electron missing from the band the hole has the same velocity as the missing electron. This is in a direction which is *opposite* to the net electron current.

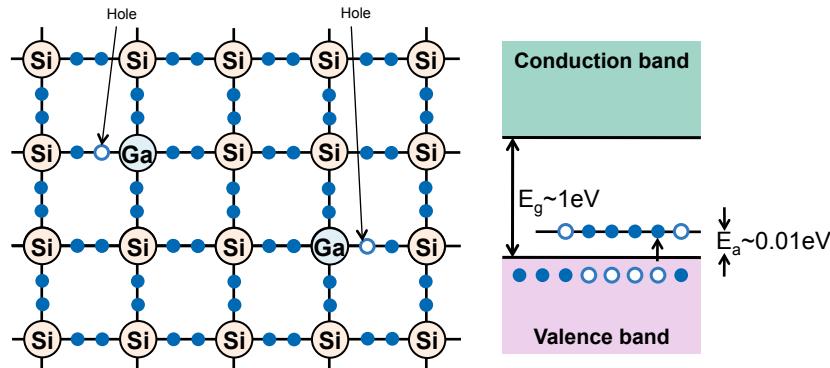
## Pentavalent Impurities: n-type doping E.g. Arsenic, Phosphorous



- The fifth electron:
  - occupies orbits several atomic radii in size
  - very low ionization energy
- All impurities ionized at room temperature
- Donor impurity level is just  $\sim 0.01\text{eV}$  below the conduction band
- Conductivity is strongly enhanced over pure tetravalent semi-conductor

## Trivalent Impurities: p-type doping

E.g. Gallium, Indium



- Impurity atoms can easily attract an electron from a host atom
- Results in a population of mobile holes in the valence band
- Acceptor impurity level is just  $\sim 0.01\text{eV}$  above the valence band
- Conductivity is strongly enhanced over pure tetravalent semi-conductor

## Number of charge carriers

intrinsic and extrinsic

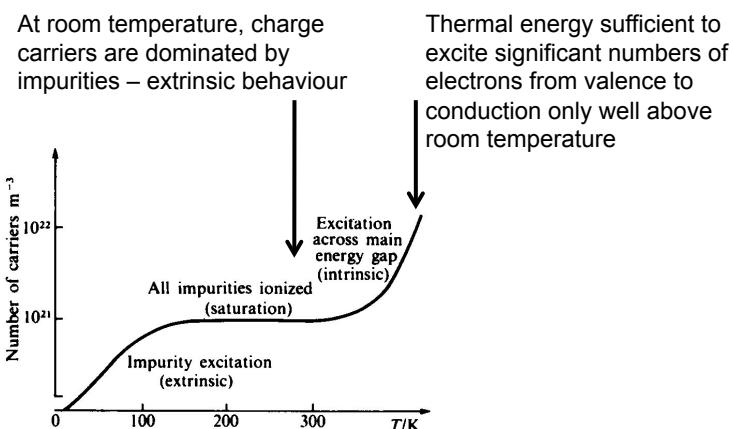


FIG. 9.5. The excitation of carriers in a semiconductor as a function of temperature.  
(Typical values for a specimen of doped germanium.)

## Fermi Energy: Pure Semi-conductor

Number of charge carriers = density of energy states X probability of occupation

$$N_e = \int_{E_g}^{\infty} g(E) f_{FD}(E) dE$$

Integrate from bottom of conduction band to infinity

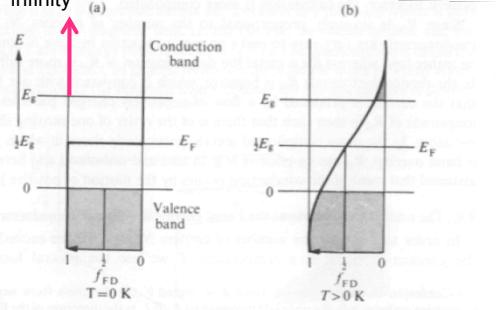


FIG. 9.7. The Fermi function  $f_{FD}$  for a pure semiconductor (a) at 0 K ; (b) above 0 K .  
The Fermi energy remains approximately at the centre of the band gap.

Fermi-Dirac function:

$$f_{FD}(E) = \frac{1}{\exp\left(\frac{(E - E_F)}{kT}\right) + 1}$$

Fermi Energy is defined as the energy of the state for which the probability of occupation is 0.5.

$$E_F = E_g / 2$$

## Fermi Energy: Doped Semi-conductor

Example: n-type with no acceptor impurities

T=0K

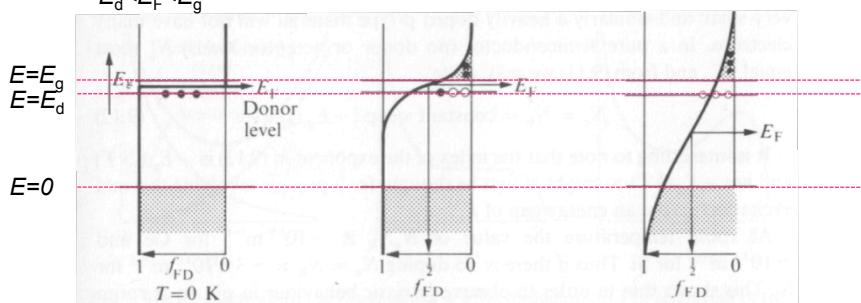
- Valence band full
- Donor levels full
- Conduction band empty
- $E_d < E_F < E_g$

T>0K

- Donor electrons excited into conduction band
- $E_d < E_F < E_g$

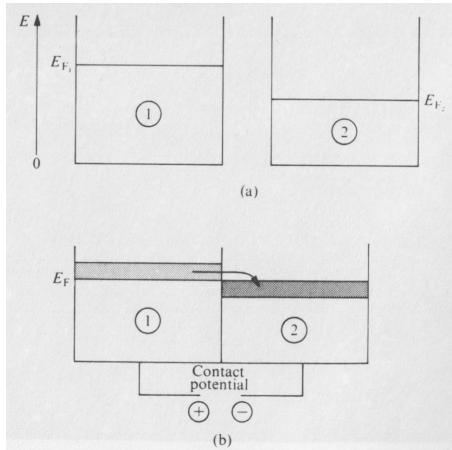
T>>0K

- Valence electrons excited into conduction band
- $E_F = 0.5E_g$



At room temperature:  $E_F(n\text{-type}) \approx E_d$  and:  $E_F(p\text{-type}) \approx E_a$

## Contact Potential of Conductors



In general the Fermi energy of two dissimilar conductors will not be coincident.

Electrons flow from one material to the other to minimize the energy of the system.

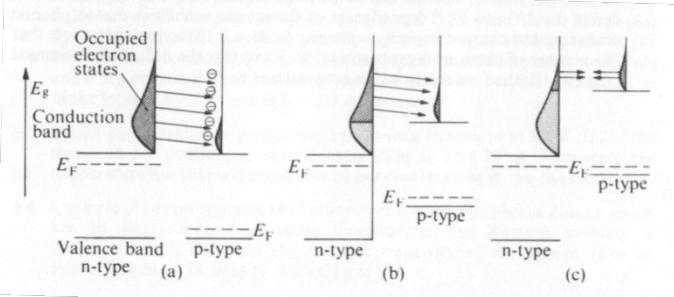
The Fermi energies become equalized when the combined system reaches equilibrium.

In equilibrium there is then a potential difference between the conductors.

$$V_{contact} = \frac{\phi_1 - \phi_2}{e} \quad \phi \text{ is the work function of the conductor}$$

## Equalization of Fermi Energies

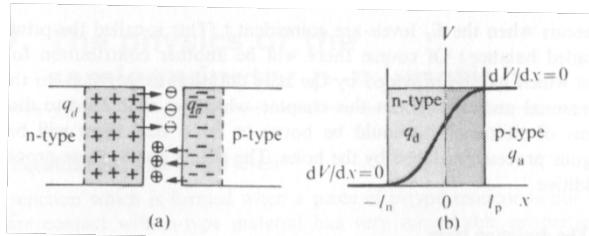
Consider two samples of semi-conductor, one n-type, the other p-type



- When the samples are brought into contact:
  - electrons diffuse from the n-type valence band into the p-type valence band
  - p-type sample becomes negatively charged
  - n-type sample becomes positively charged
  - the energy levels shift
- Dynamical equilibrium is achieved when the Fermi energies are equalized and the net flow of charge carriers is zero

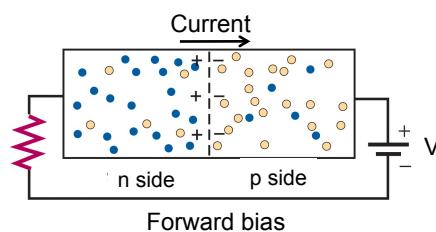
## Depletion Layer

p-n junction as a capacitor

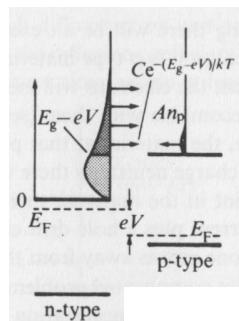


- Electrons diffuse from n-type to p-type, leaving positively charged ions behind
- Holes diffuse from p-type to n-type, leaving negatively charged ions behind
- Resulting two “depletion layers” have equal opposite charges and depths – they behave like a charged capacitor
- Solving Poisson’s equation, it can be shown that the potential difference across the depletion layer is  $\sim 0.5V$  and  $l_p \sim l_n \sim 1\mu m$

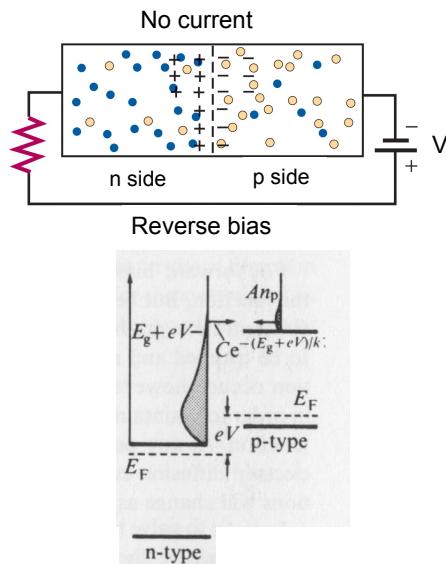
## Forward biased p-n junction



- $E_{F,p} = E_{F,n} - eV$
- Electrons diffuse from n-side to p-side
- Strong electron concentration gradient across p-side (decreasing left to right in figure)
- Current flows round circuit

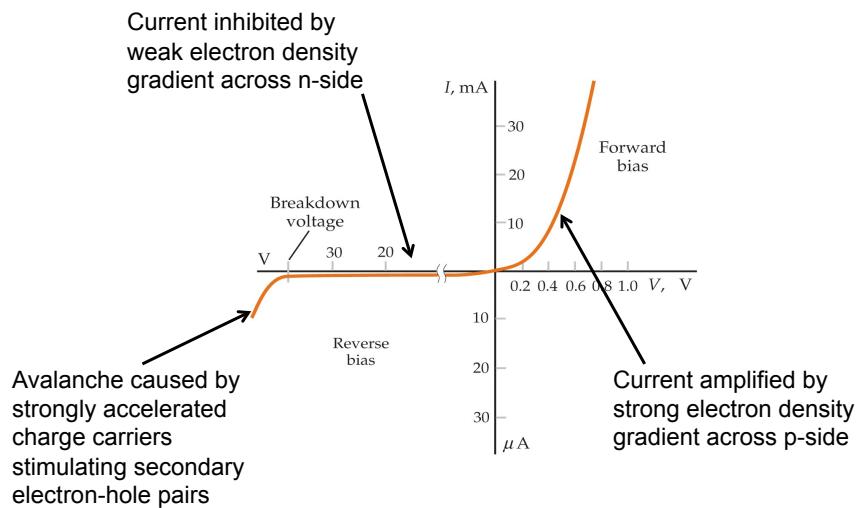


## Reverse biased p-n junction



- $E_{F,p} = E_{F,n} + eV$
- Electrons diffuse from p-side to n-side
- Very weak electron concentration gradient across n-side
- Negligible current flows round circuit

## Behaviour of biased p-n junction



## p-n junction as a photo-detector

- Incoming photons of energy  $< E_g$ :
  - Electron-hole pairs created in both sides of junction
  - Electrons in p-type depletion region attracted to n-side
  - Holes in n-type depletion region attracted to p-side
  - Current flows
- Note this is intrinsic behaviour that leads to a current thanks to doping
- Measured current is proportionality to light intensity
- E.g. photo-diode, photovoltaic cell, solar cells

