FoP 3B Part II

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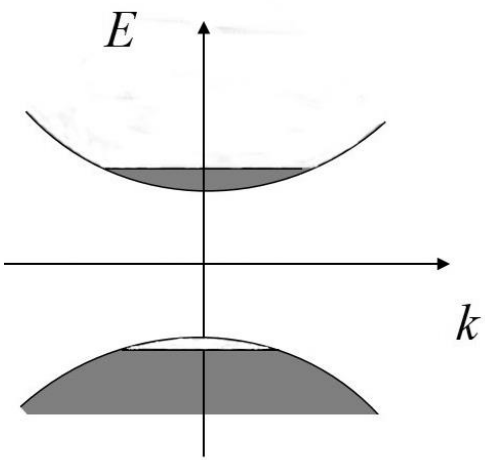
Room 151

Lecture 4: Extrinsic semiconductors

Durham University

Summary of Lecture 3

Electron/hole concentrations:



$$n = \int f(E) g_e(E) dE$$

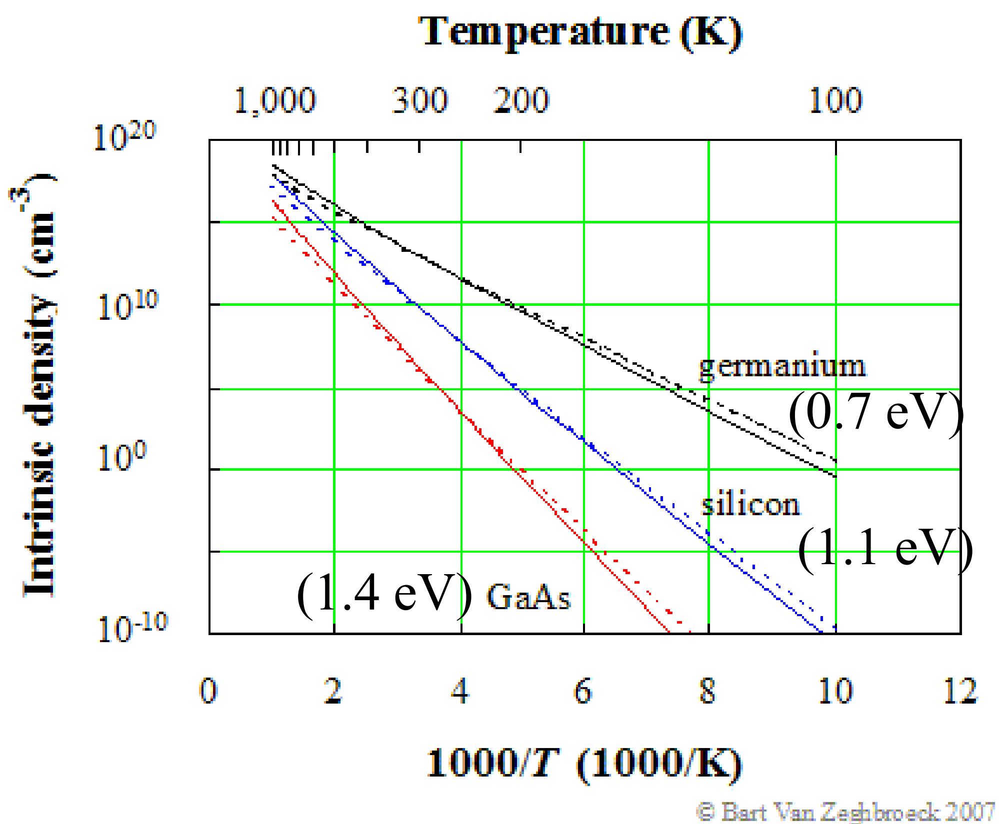
$$p = \int [1 - f(E)] g_h(E) dE$$

Law of mass action:

$$np = N_c N_v \exp\left(-\frac{E_g}{kT}\right)$$

Conductivity vs temp:

$$\mathbf{J} = (en\mu_e + ep\mu_h)\mathbf{E} = \sigma\mathbf{E}$$



Aim of today's lecture

Q: How can we manipulate conductivity at room temperature?

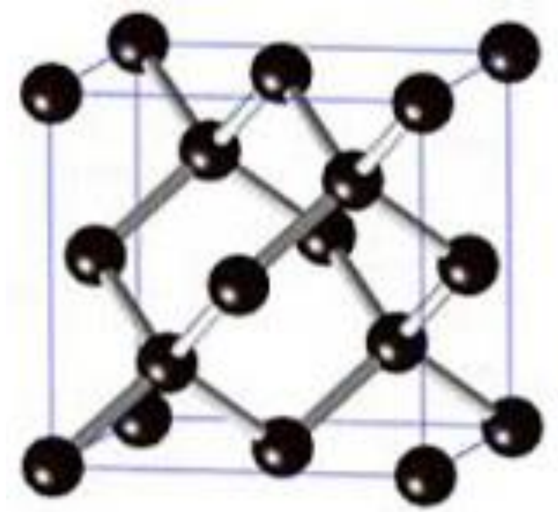
A: 'doping' with foreign atoms

Key concepts:

- -Donor and acceptor doping
- -Role of temperature on doping
- -Carrier concentrations and..
- -Chemical potential in extrinsic semiconductors

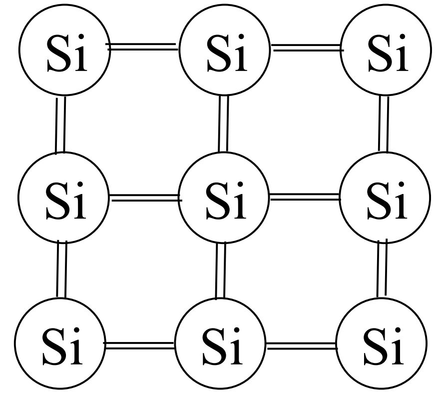
* See supplementary information for purification and doping methods (non-examinable).

Donor impurities

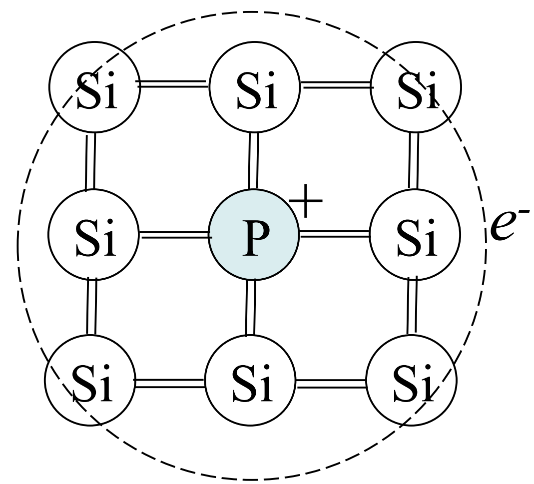


Diamond cubic crystal structure

	5 **B** boron 10.81 [10.806, 10.821]	6 **C** carbon 12.011 [12.009, 12.012]	7 **N** nitrogen 14.007 [14.006, 14.008]
12	13 **Al** aluminium 26.982	14 **Si** silicon 28.085 [28.084, 28.086]	15 **P** phosphorus 30.974
30 **Zn** zinc 65.38(2)	31 **Ga** gallium 69.723	32 **Ge** germanium 72.630(8)	33 **As** arsenic 74.922
48 **Cd** cadmium 112.41	49 **In** indium 114.82	50 **Sn** tin 118.71	51 **Sb** antimony 121.76



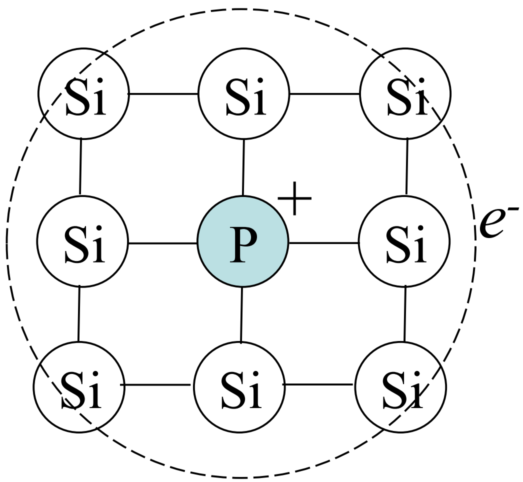
Perfect crystal



Group V substitutional atom (e.g. N, P)

Donor electron energy level

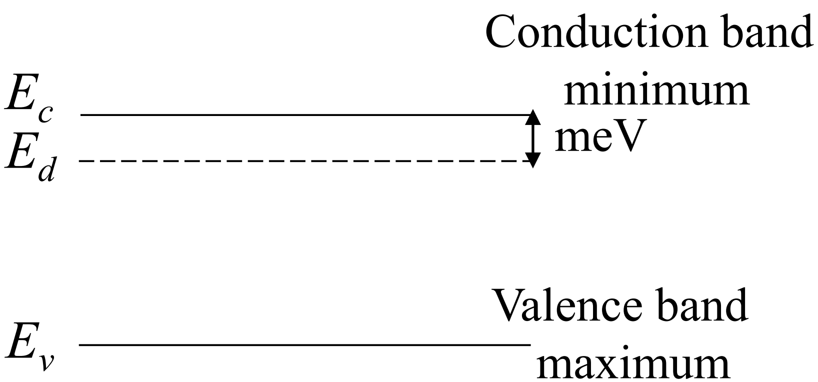
Adapt Bohr's atomic model:



Energy level:

$$E_D = \frac{e^4 m_e^*}{2(4\pi\varepsilon_r\varepsilon_0\hbar)^2} = \frac{m_e^*}{m{\varepsilon_r}^2}\underbrace{\left[\frac{e^4 m}{2(4\pi\varepsilon_0\hbar)^2}\right]}_{13.6\text{ eV}}$$

⇨ Typical energies meV



Energy level diagram

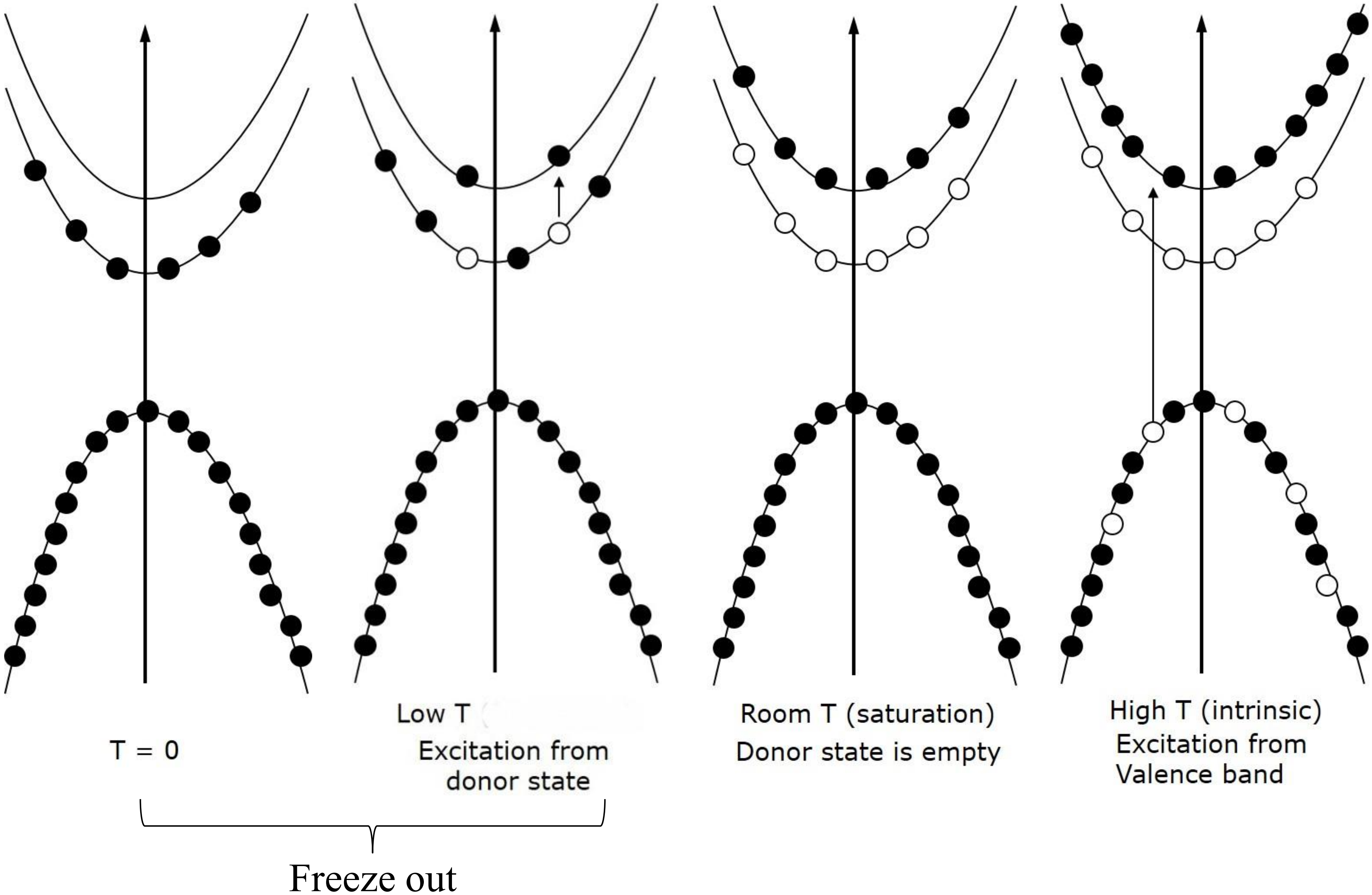
E_d: donor level

Orbit radius:

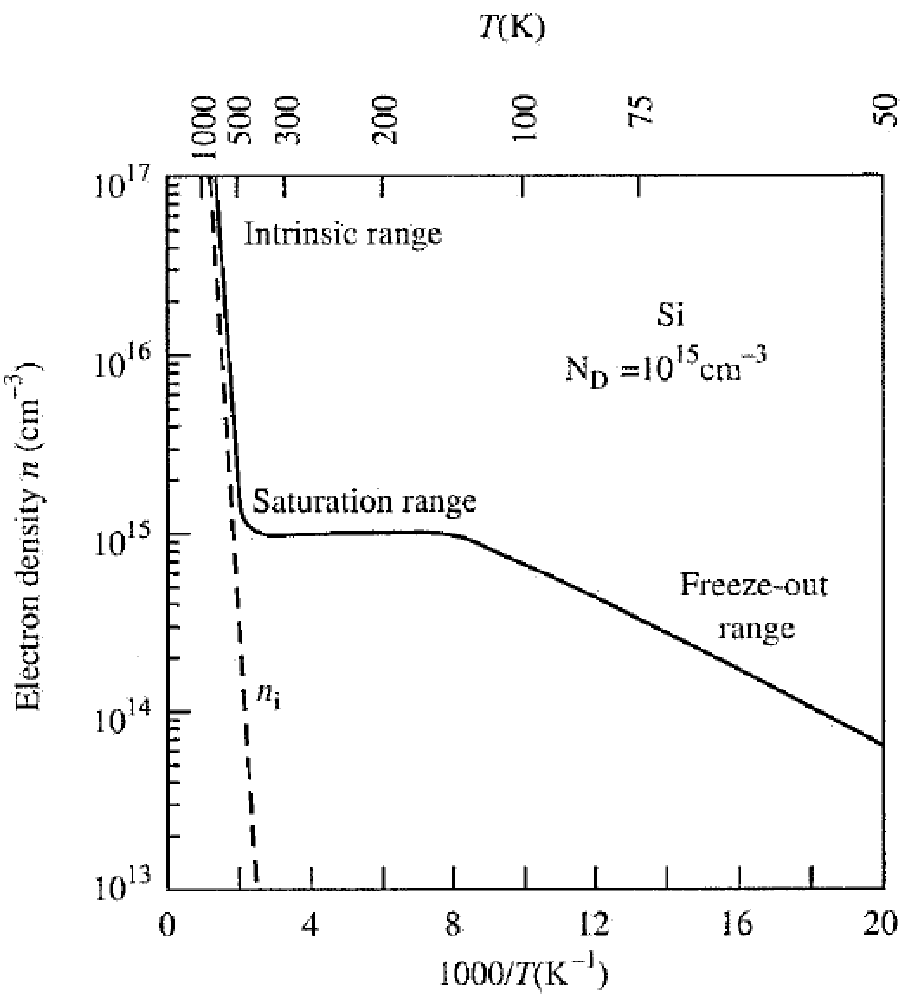
$$r = \frac{4\pi\varepsilon_r\varepsilon_0\hbar^2}{m_e^* e^2} = \frac{\varepsilon_r m}{m_e^*}\underbrace{\left(\frac{4\pi\varepsilon_0\hbar^2}{me^2}\right)}_{0.5\text{ Å}}$$

⇨ Typical radius nm

Temperature effects on donor ionisation



Electron, hole concentrations in saturation regime



Law of mass action:

$$np = N_c N_v \exp\left(-\frac{E_g}{kT}\right)$$

$$np = n_i(T)^2 \qquad \ldots (1)$$

$n_i(T)$ = electron/hole concentration for intrinsic semiconductor at temp T

Charge conservation:

$$n = p + N_D \qquad \ldots (2)$$

N_D = donor concentration

Combining (1) and (2):

$$n = \frac{N_D}{2} + \sqrt{\left(\frac{N_D}{2}\right)^2 + n_i^2}$$

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Electron, hole concentrations in saturation regime

$$n = \frac{N_D}{2} + \sqrt{\left(\frac{N_D}{2}\right)^2 + n_i^2}$$

Assuming $N_D >> n_i(T)$ then:

$$n \sim N_D$$
$$p \sim n_i^2/N_D \text{ (law of mass action)}$$

In other words $n > n_i$ and $p = n_i(n_i/N_D) < n_i$. Electrons are therefore the *majority* carriers and holes the *minority* carriers. The semiconductor is said to be doped *n*-type.

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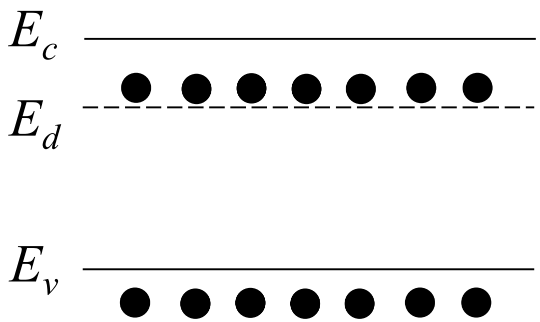
Chemical potential in *n*-type extrinsic semiconductor



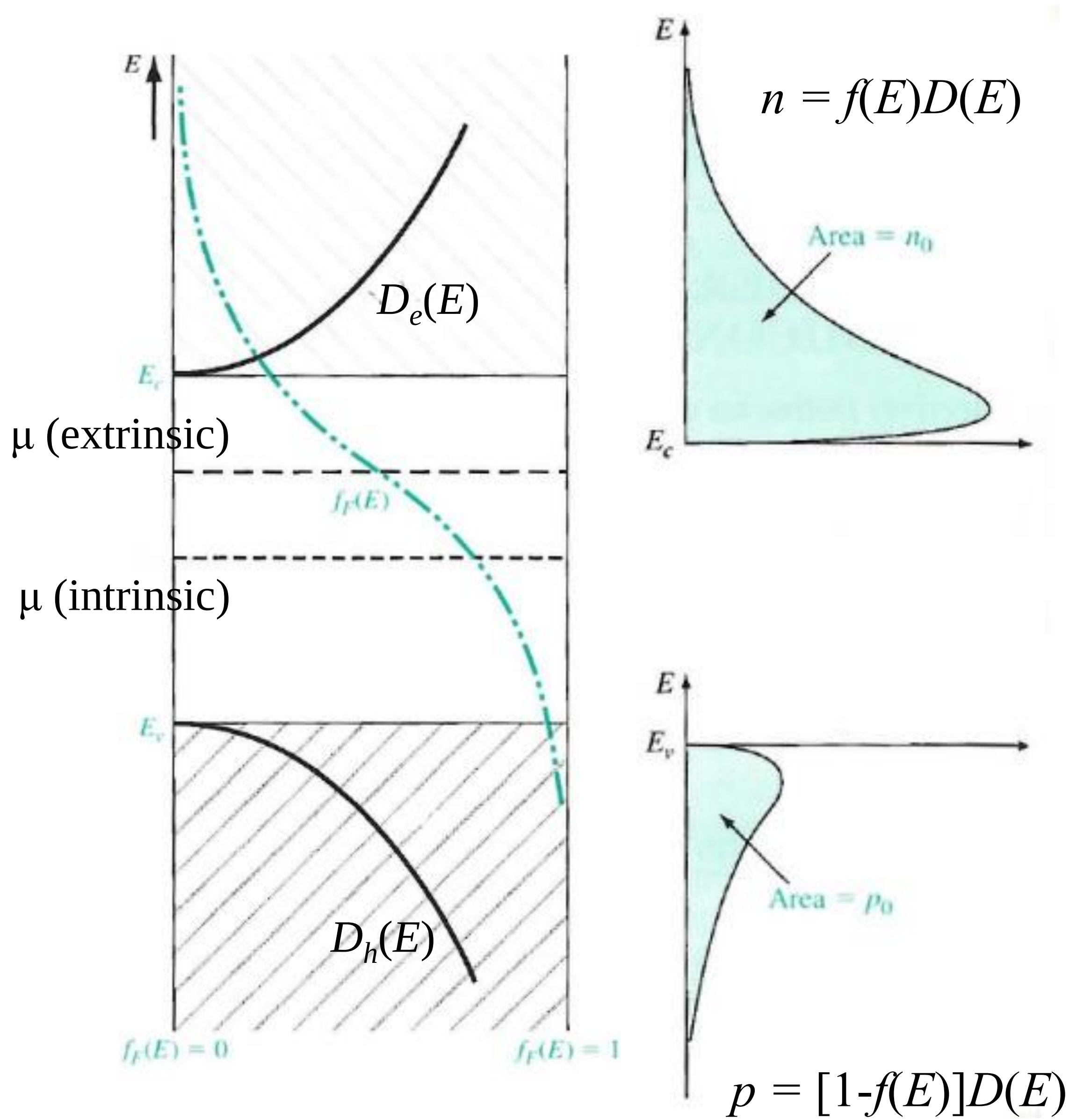
n-type semiconductor at 0K
(Fermi level above E_d)

From

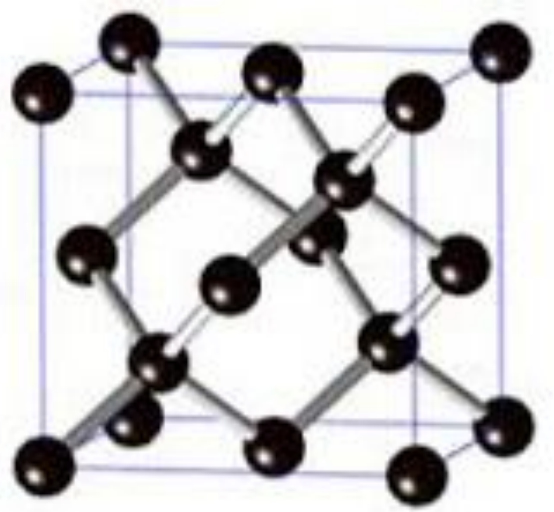
$$n = N_c \exp\left[-\frac{(E_c - \mu)}{kT}\right]$$

and substituting $n \sim N_D$

$$\mu = E_c - kT \ln\left(\frac{N_c}{N_D}\right)$$



Acceptor impurities



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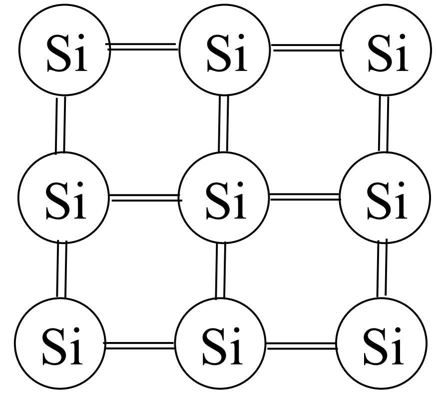
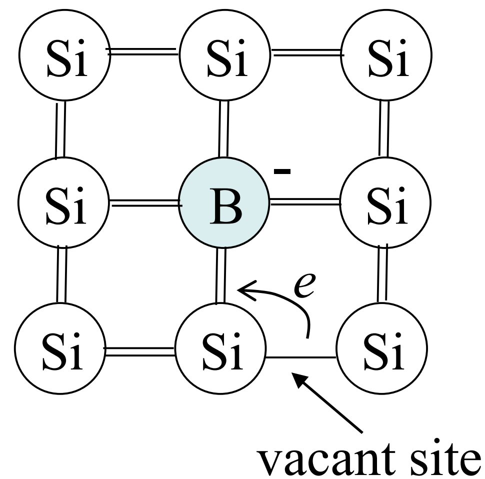
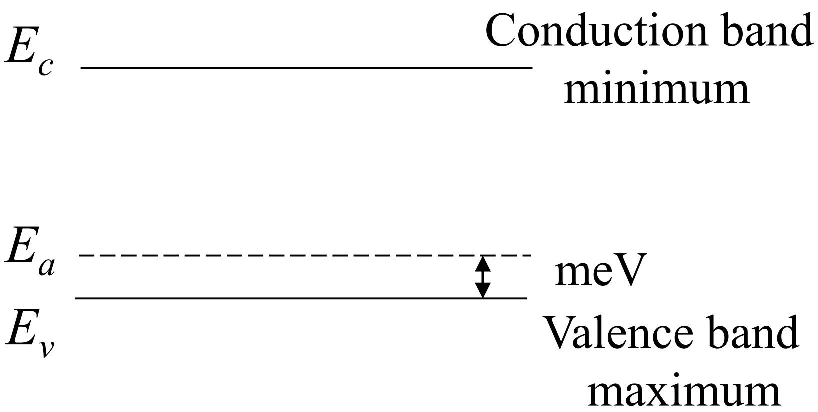


Perfect crystal



Group III substitutional atom (e.g. B, Al)

Acceptor energy level



Energy level diagram

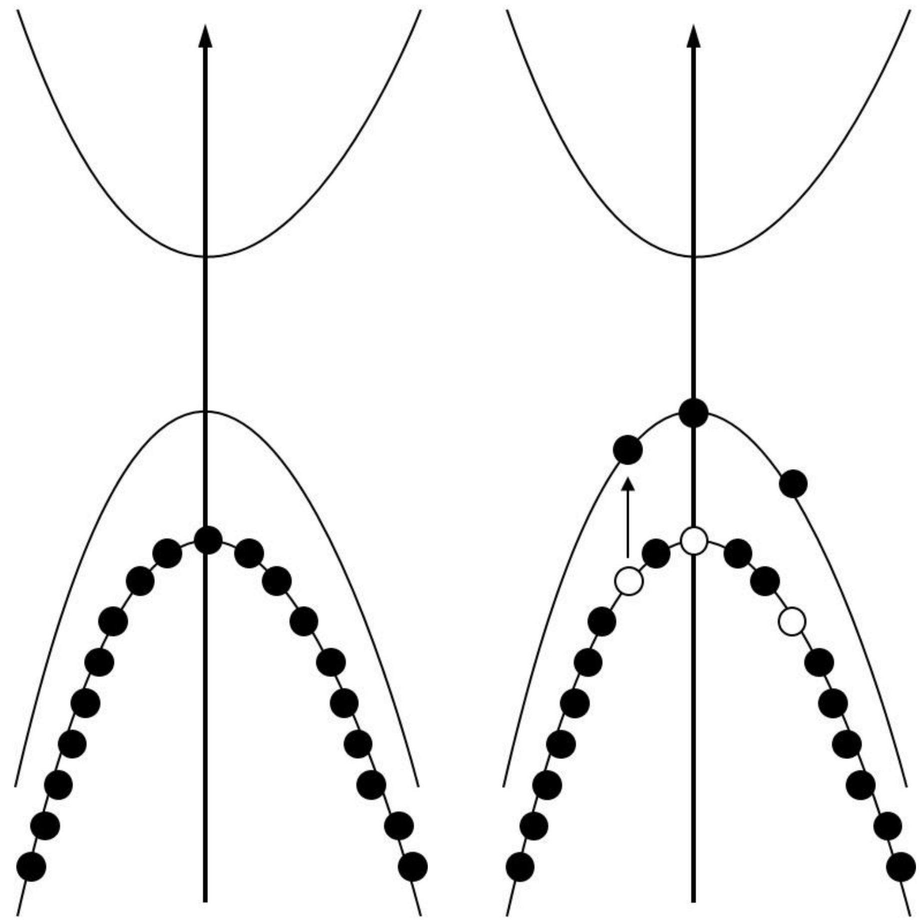
E_a : acceptor level

Saturation regime:

$p \sim N_A$ (acceptor concentration)

$n \sim n_i^2/N_A$

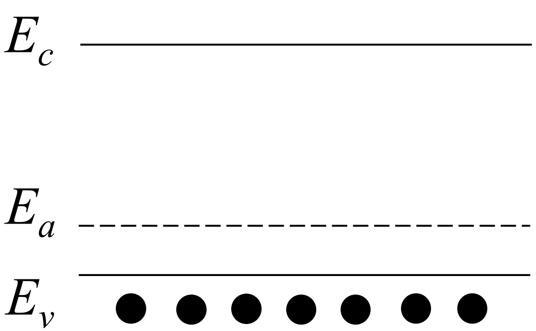
Holes are *majority* carriers,
electrons are *minority* carriers.
Semiconductor is *p*-type.



T = 0

Low T (freeze-out)

Chemical potential in *p*-type extrinsic semiconductor



p-type semiconductor at 0K
(Fermi level below E_a)

From

$$p = N_v \exp\left[-\frac{(\mu - E_v)}{kT}\right]$$

and substituting $p \sim N_A$

$$\mu = E_v + kT \ln\left(\frac{N_v}{N_A}\right)$$