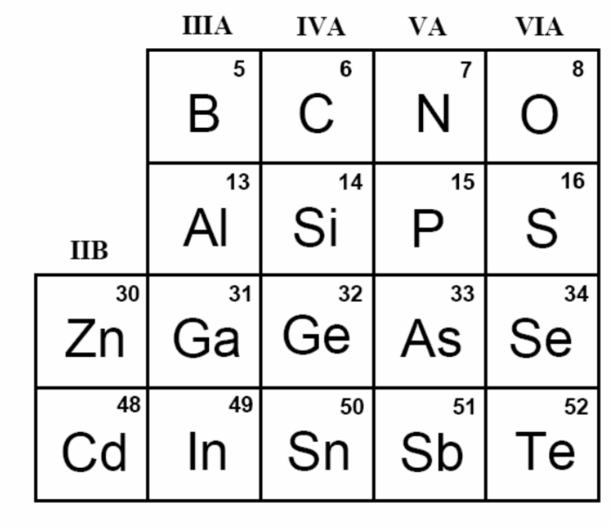
Extrinsic semiconductors

The introduction of impurity atoms that can and electrons or holes is called doping.

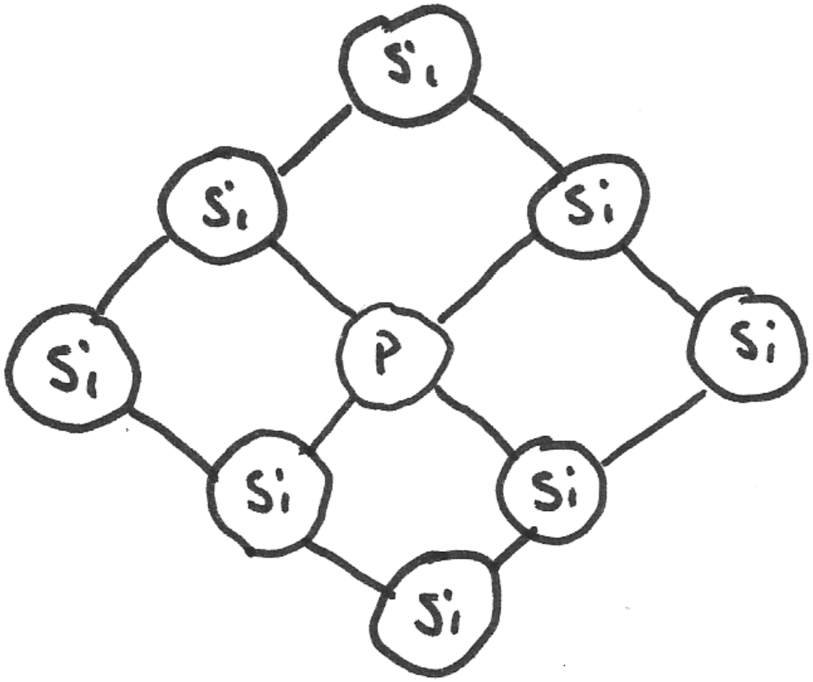
n-type : donor atoms contribute electrons to the conduction band. Examples: P, As in Si.

p-type : acceptor atoms contribute holes to the valence band. Examples: B, Ga, Al in Si.



IIB	IIIA	IVA	VA	VIA
	5 B	6 C	7 N	8 O
	13 Al	14 Si	15 P	16 S
30 Zn	31 Ga	32 Ge	33 As	34 Se
48 Cd	49 In	50 Sn	51 Sb	52 Te

Ionization of dopants



Easier to ionize a P atom in Si than a free P atom

$$E_n = -\frac{me^4}{8\varepsilon_0^2 h^2 n^2}$$

Ionization energy is smaller by a factor: $\frac{m^*}{m}\left(\frac{\varepsilon_0}{\varepsilon_r \varepsilon_0}\right)^2$

Ionization energy ~ 25 meV

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Direct Observation of Friedel Oscillations around Incorporated $\mathrm{Si_{Ga}}$ Dopants in GaAs by Low-Temperature Scanning Tunneling Microscopy

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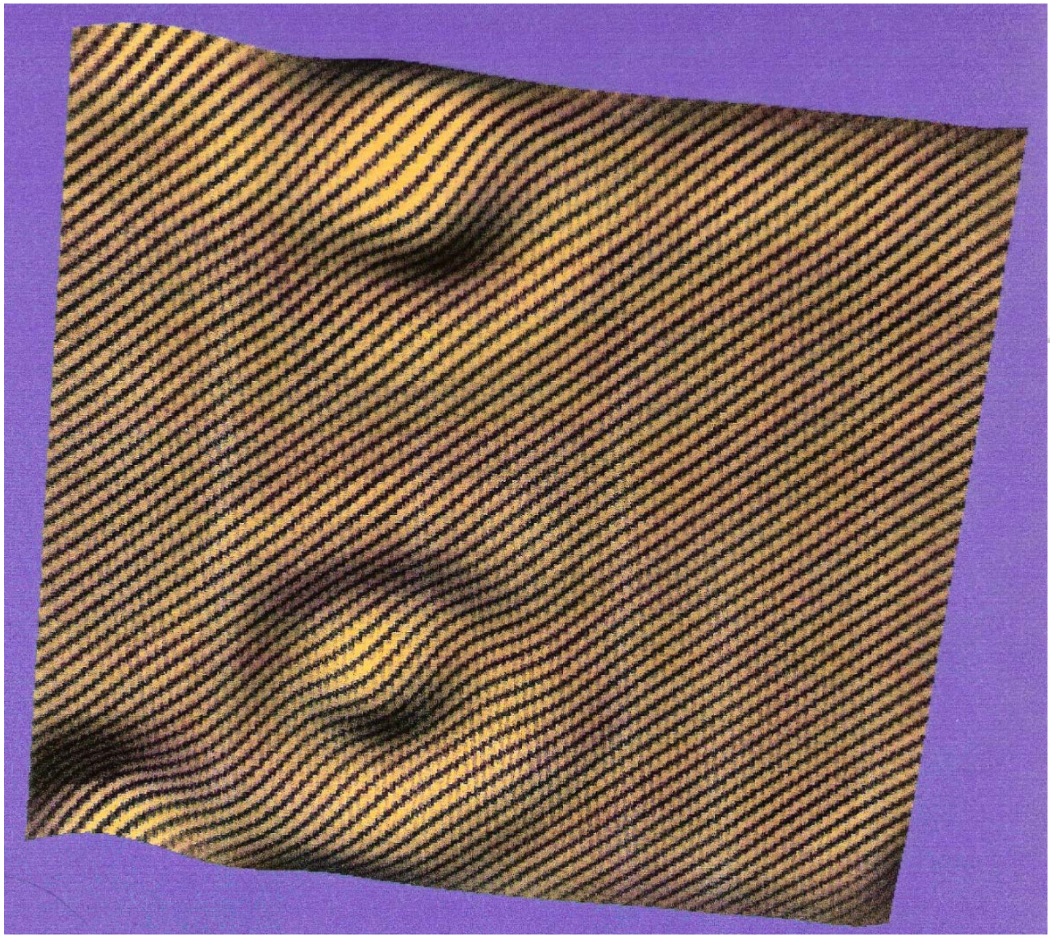
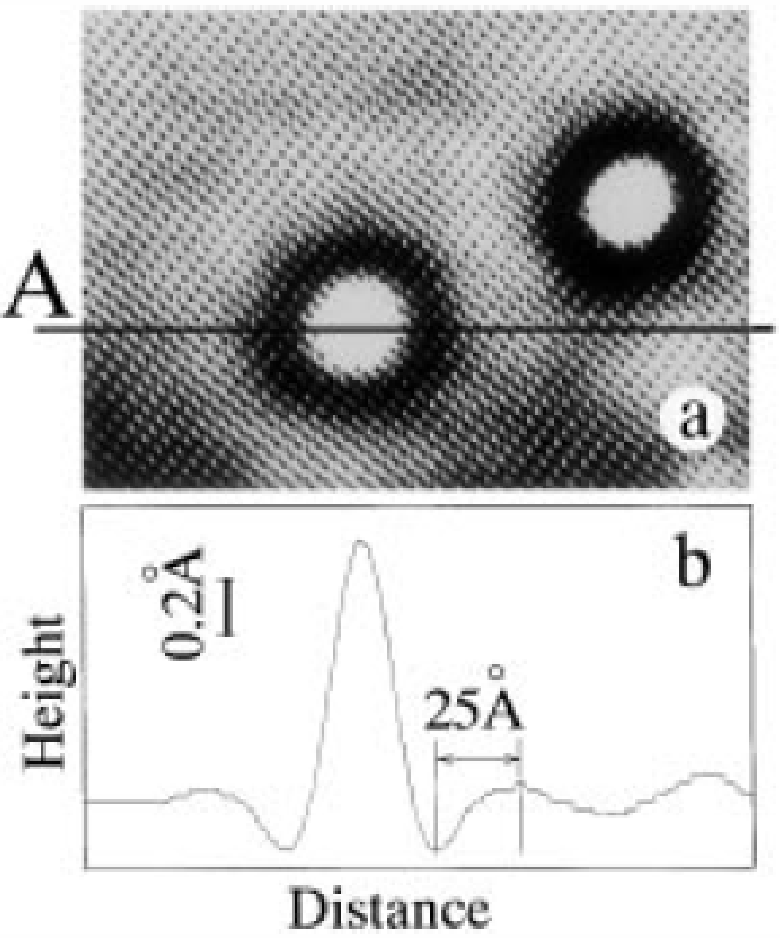
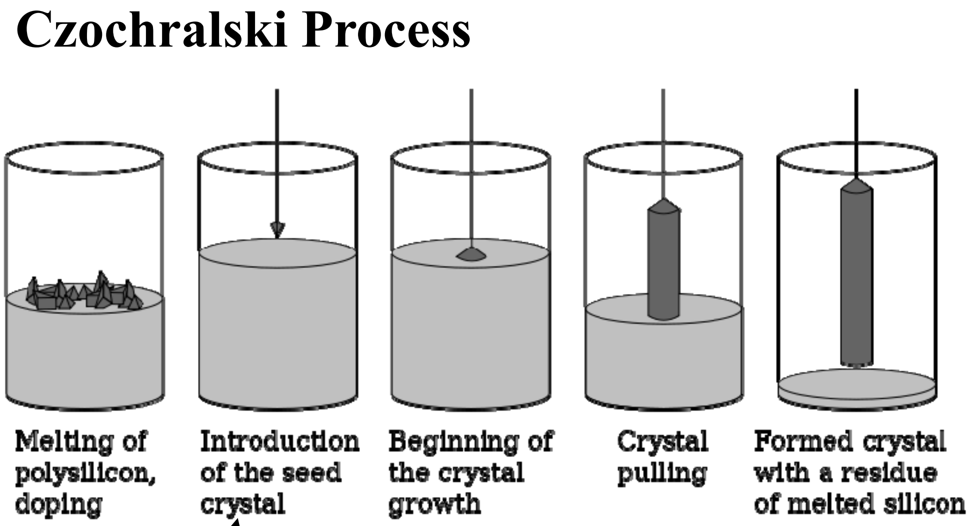
(Received 25 July 1995)





Crystal growth


Czochralski Process

add dopants to the melt

images from wikipedia

Crystal growth

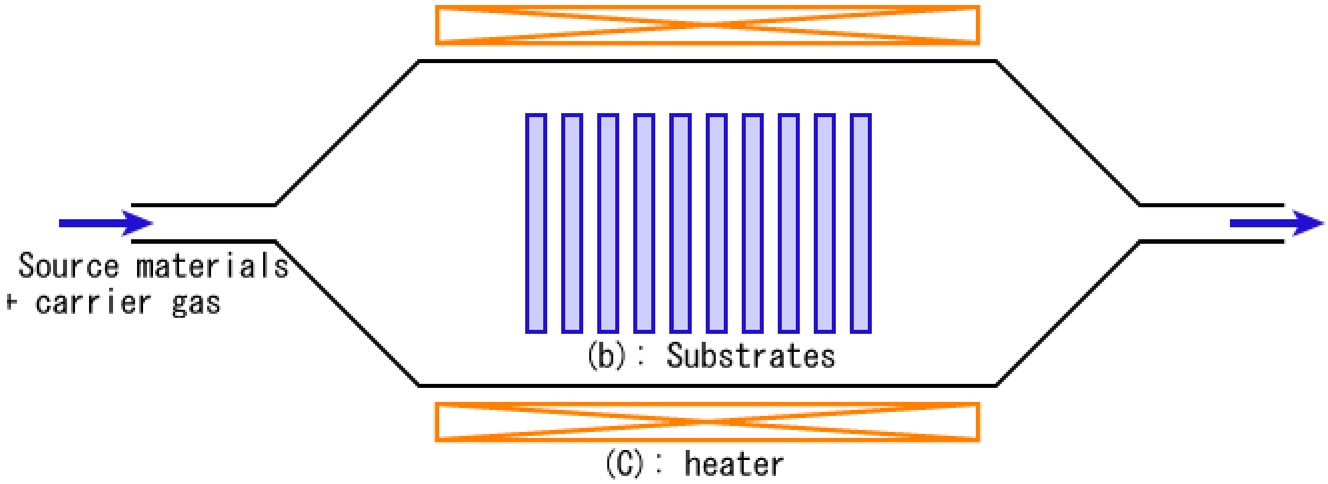
Float zone Process

image from wikipedia

Neutron transmutation

$^{30}\mathrm{Si} + \mathrm{n} \rightarrow\ ^{31}\mathrm{Si} + \gamma$
$^{31}\mathrm{Si} \rightarrow\ ^{31}\mathrm{P} + \beta$

Chemical vapor deposition



Epitaxial silicon CVD SiH_4 (silane) or SiH_2Cl_2 (dichlorosilane)
PH_3 (phosphine) for n-doping or B_2H_6 (diborane) for p-doping.

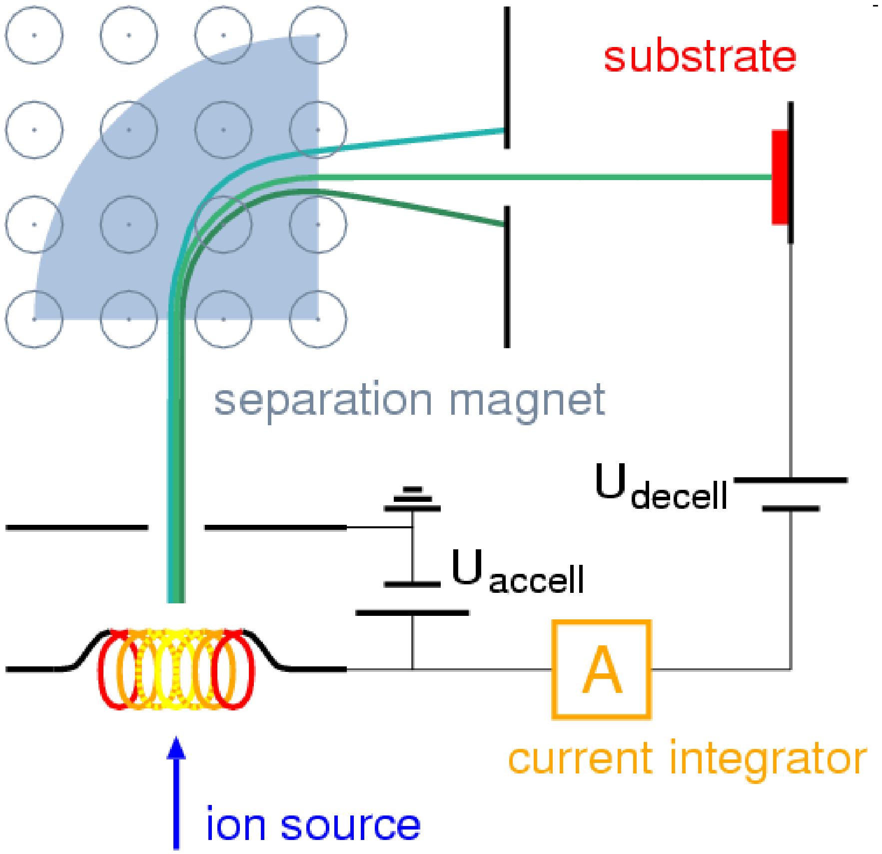
image from wikipedia

Gas phase diffusion

AsH_3 (Arsine) or PH_3 (phosphine) for n-doping
B_2H_6 (diborane) for p-doping.

http://www.microfab.de/foundry/services/diffusion/index.html

Ion implantation

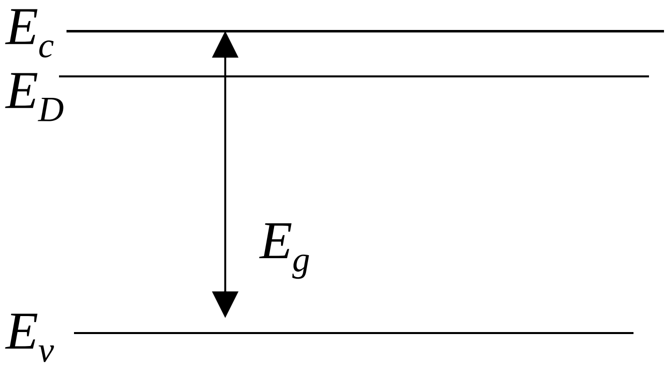


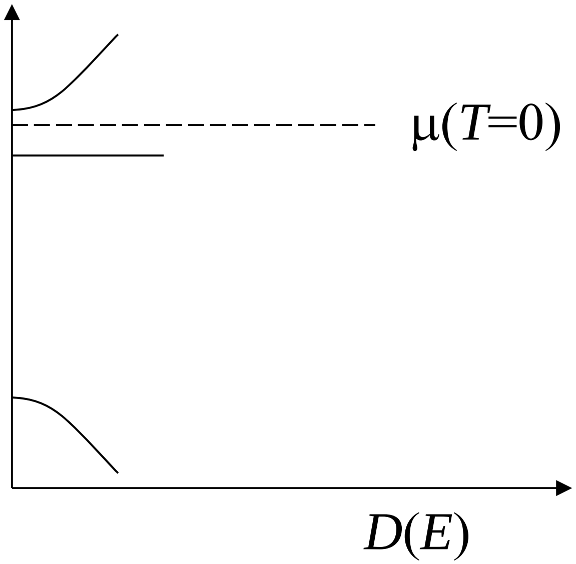
Implant at 7º to avoid channeling

Donors

Five valence electrons: P, As

States are added in the band gap just below the conduction band





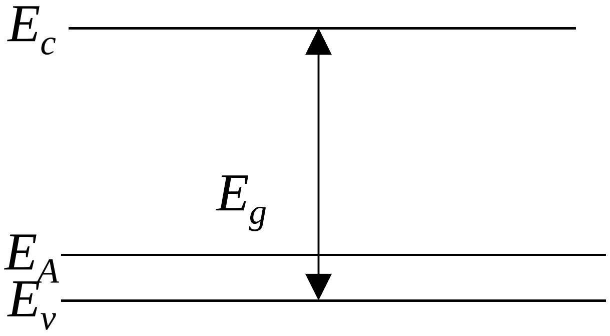
n-type: $n \sim N_D$ Many more electrons in the conduction band than holes in the valence band.

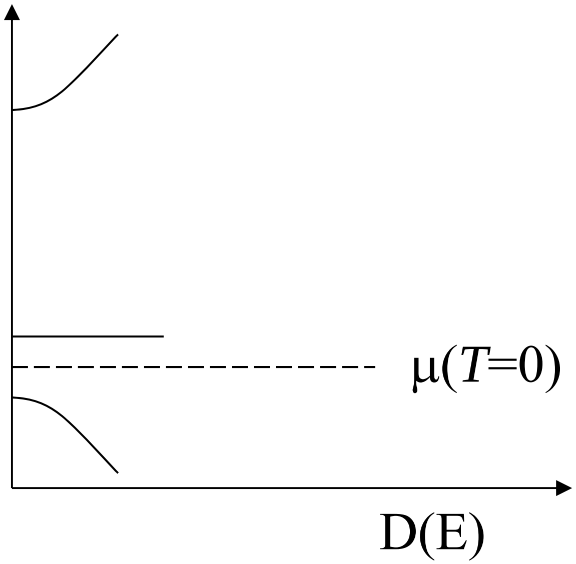
majority carriers: electrons; minority carriers: holes

Acceptors

Three valence electrons: B, Al, Ga

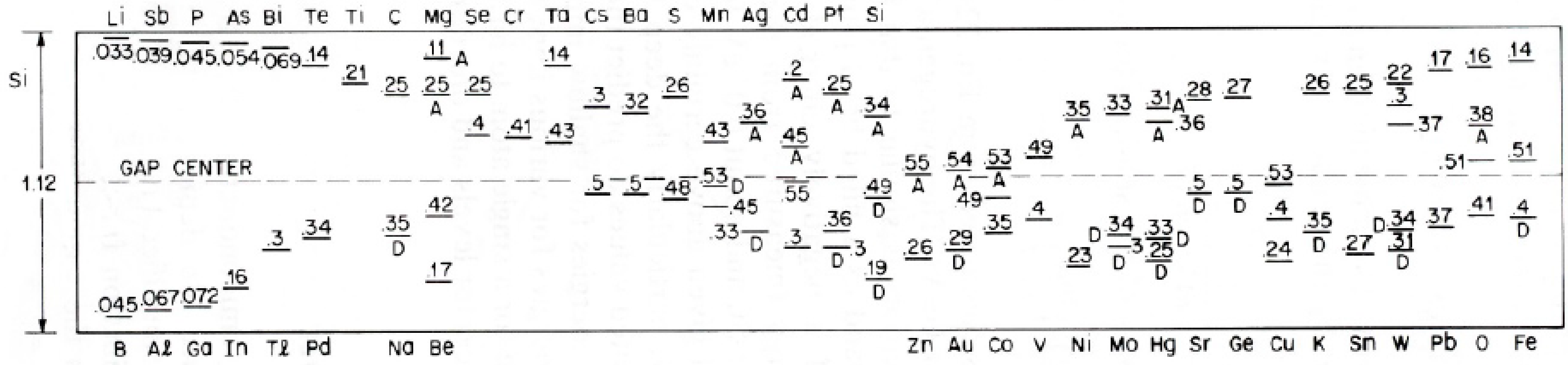
States are added in the band gap just above the valence band





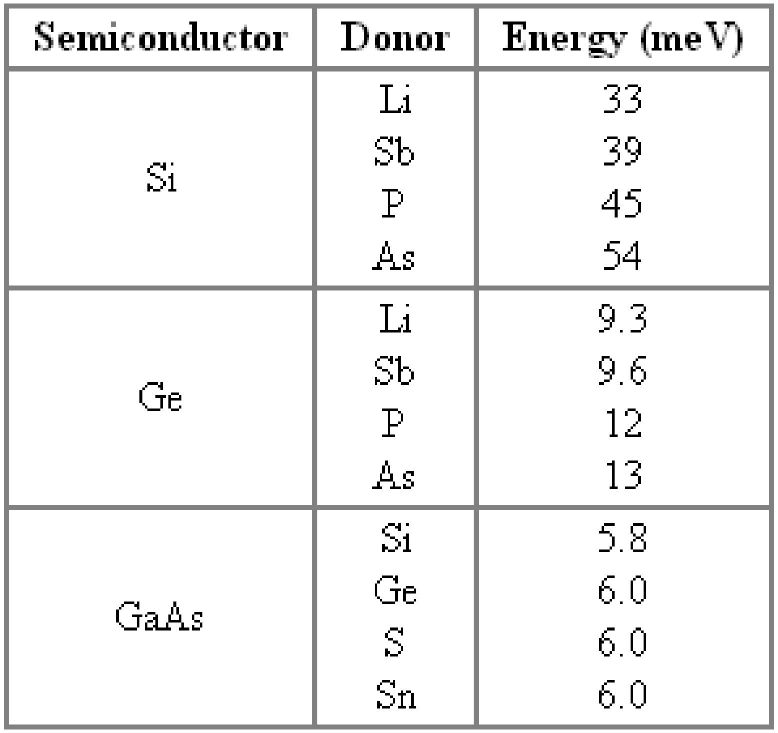
p-type: $p \sim N_A$ Many more holes in the valence band than electrons in the conduction band.

majority carriers: holes; minority carriers: electrons



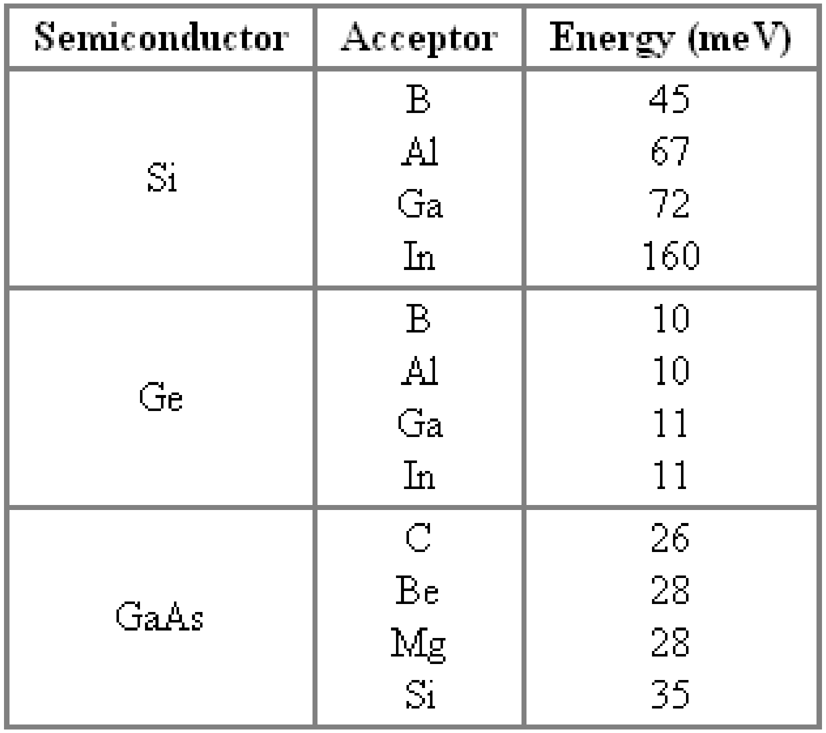
Source: Semiconductor Devices Physics and Technology, S.M. Sze, 1985

Donor and Acceptor Energies



Semiconductor	Donor	Energy (meV)
Si	Li	33
	Sb	39
	P	45
	As	54
Ge	Li	9.3
	Sb	9.6
	P	12
	As	13
GaAs	Si	5.8
	Ge	6.0
	S	6.0
	Sn	6.0

Energy below the conduction band



Semiconductor	Acceptor	Energy (meV)
Si	B	45
	Al	67
	Ga	72
	In	160
Ge	B	10
	Al	10
	Ga	11
	In	11
GaAs	C	26
	Be	28
	Mg	28
	Si	35

Energy above the valence band

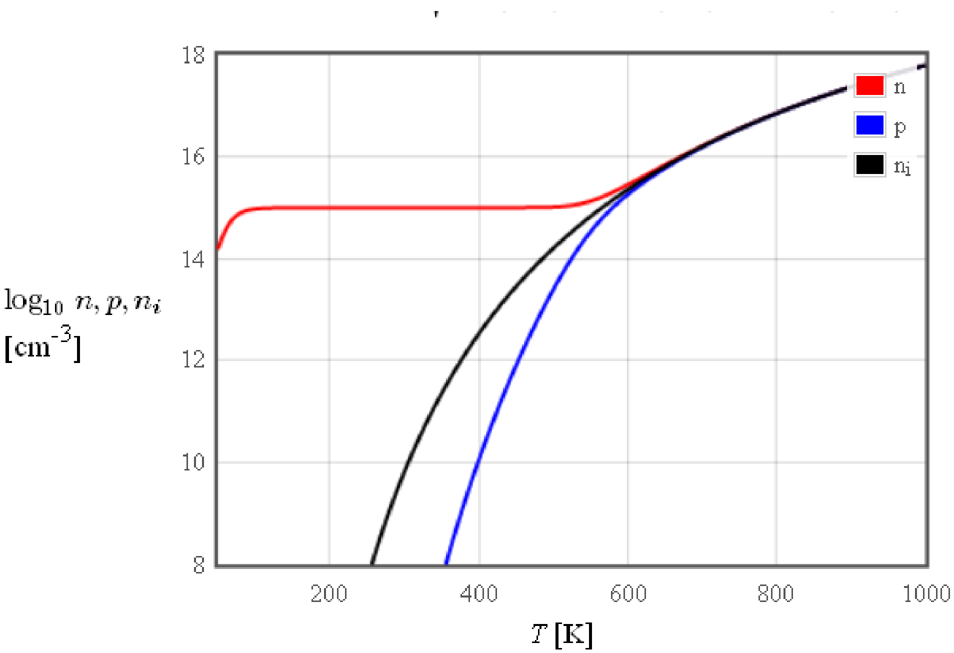
n-type

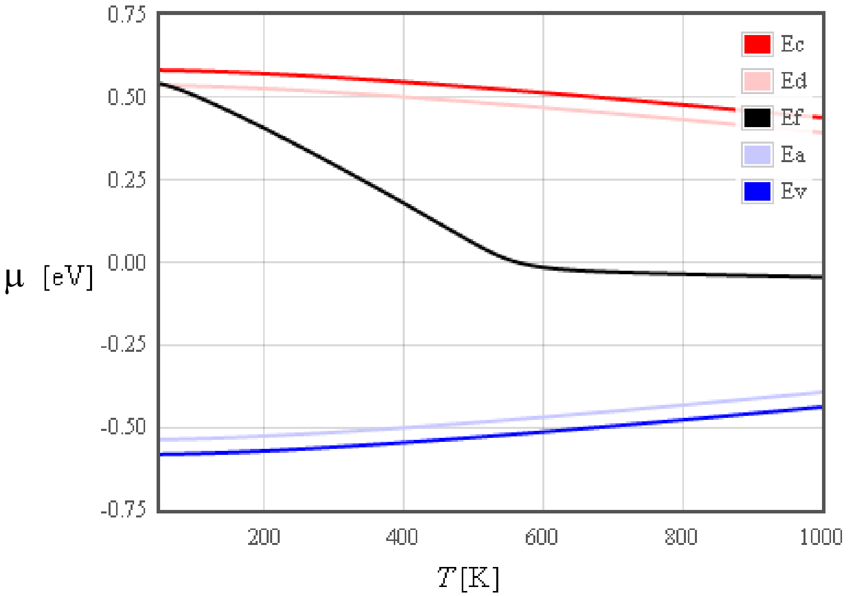
n-type $N_D > N_A$, $p \sim 0$

$$n = N_D = N_c \exp\left(\frac{\mu - E_c}{k_B T}\right)$$

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

For n-type, $n \sim$ density of donors, $p = n_i^2/n$





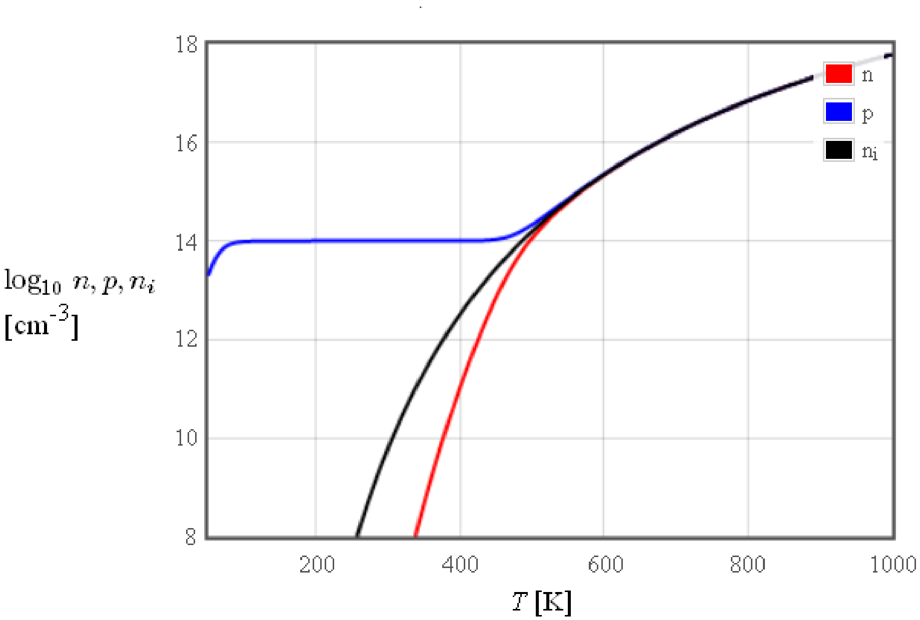
p-type

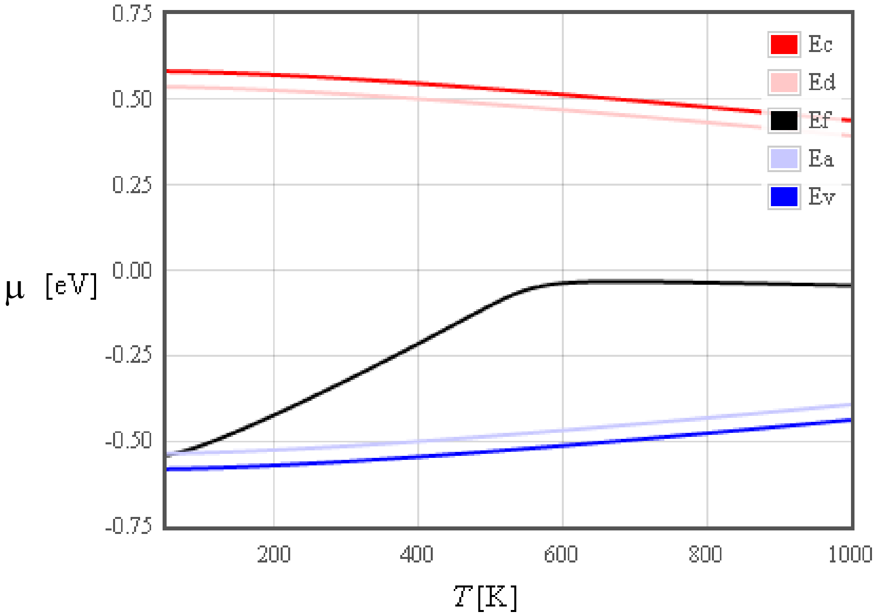
p-type $N_A > N_D$, $n \sim 0$

$$p = N_A = N_v \exp\left(\frac{E_v - \mu}{k_B T}\right)$$

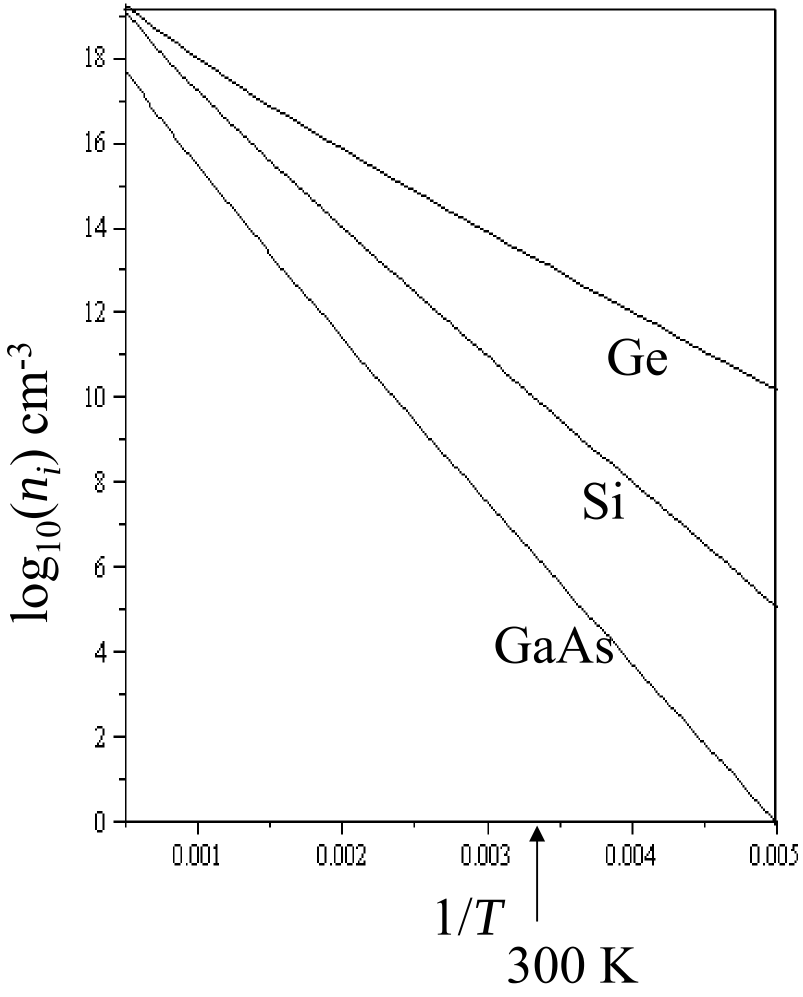
$$\boxed{\mu = E_v + k_B T \ln\left(\frac{N_v}{N_A}\right)}$$

For p-type, $p \sim$ density of acceptors,
$n = n_i^2/p$



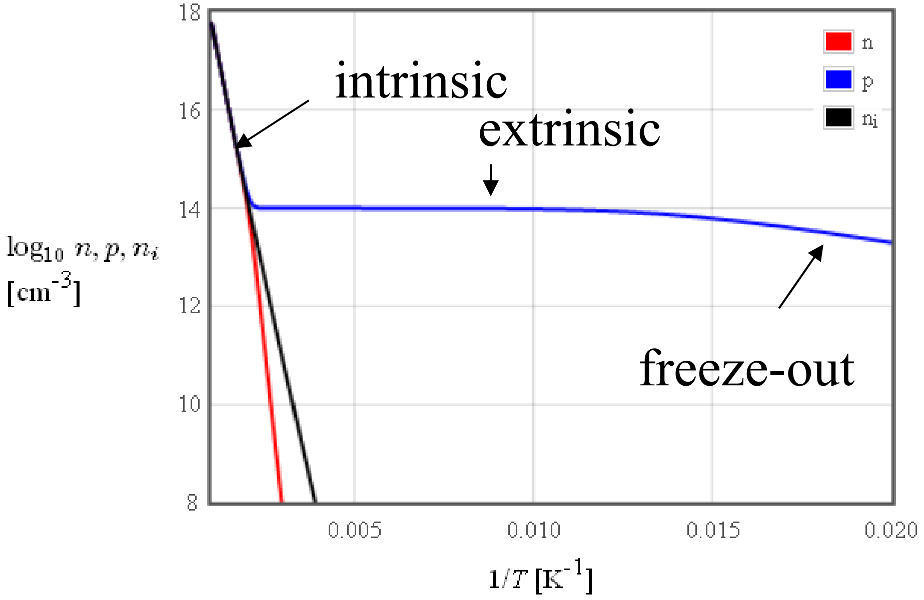


Intrinsic semiconductors



$$n_i = \sqrt{N_v N_c}\,\exp\left(-\frac{E_g}{2k_B T}\right)$$

Extrinsic semiconductors



At high temperatures, extrinsic semiconductors have the same temperature dependence as intrincic semiconductors.

Ionized donors and acceptors

For $E_v + 3k_BT < \mu < E_c - 3k_BT$ Boltzmann approximation

$$N_D^+ = \frac{N_D}{1 + 2\exp\left(\frac{\mu - E_D}{k_BT}\right)}$$

$$N_A^- = \frac{N_A}{1 + 4\exp\left(\frac{E_A - \mu}{k_BT}\right)}$$

4 for materials with light
holes and heavy holes (Si)
2 otherwise

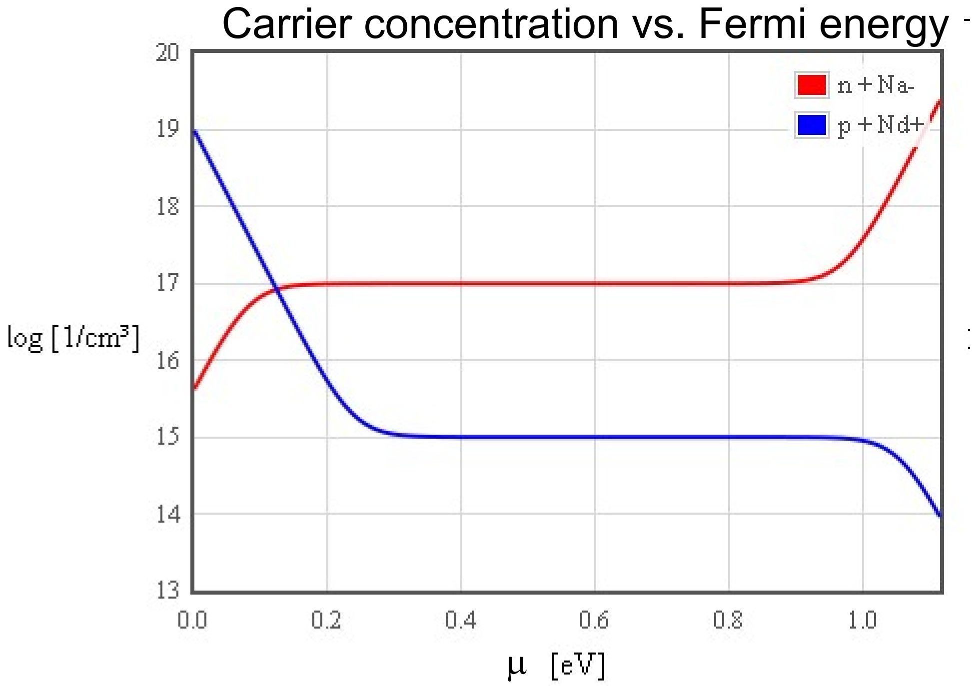
N_D = donor density cm^{-3} N_D^+ = ionized donor density cm^{-3}

N_A = donor density cm^{-3} N_A^- = ionized donor density cm^{-3}

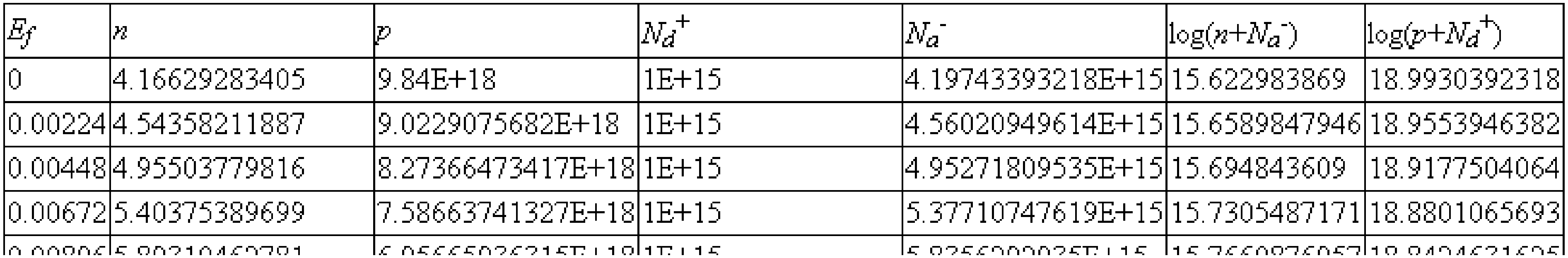
Mostly, $N_D^+ = N_D$ and $N_A^- = N_A$

Charge neutrality

$$n + N_A^- = p + N_D^+$$



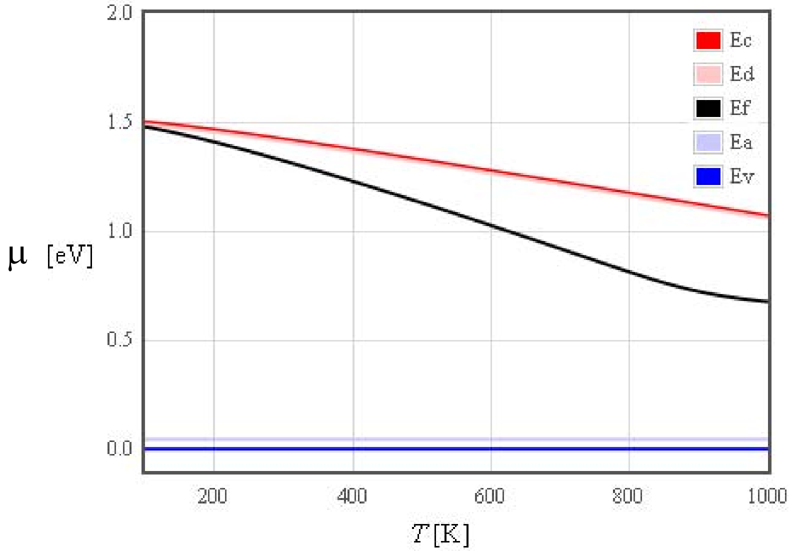
```
for ($i=0; $i<500; $i++) {
  $Ef = $i*$Eg/500;
  $n=$Nc*pow($T/300,1.5)*exp(1.6022E-19*($Ef-$Eg)/(1.38E-23*$T));
  $p=$Nv*pow($T/300,1.5)*exp(1.6022E-19*(-$Ef)/(1.38E-23*$T));
  $Namin = $Na/(1+4*exp(1.6022E-19*($Ea-$Ef)/(1.38E-23*$T)));
  $Ndplus = $Nd/(1+2*exp(1.6022E-19*($Ef-$Ed)/(1.38E-23*$T)));
}
```

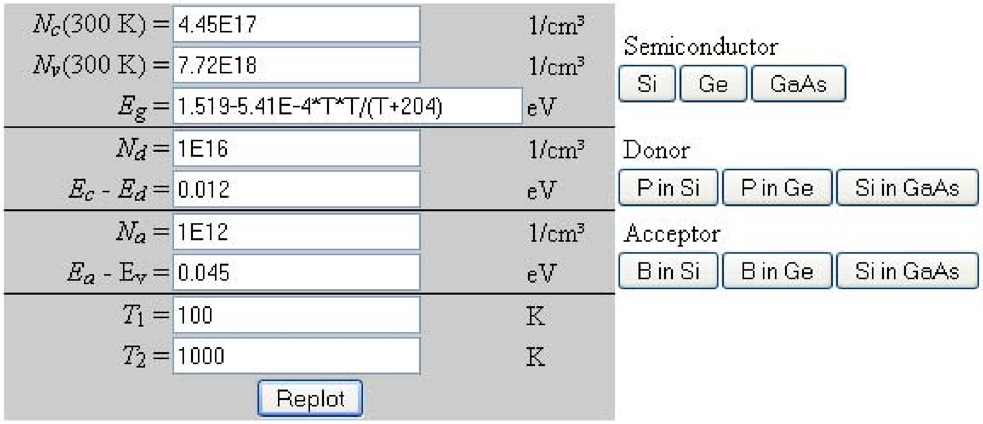


E_f	n	p	N_d^+	N_a^-	$\log(n+N_a^-)$	$\log(p+N_d^+)$
0	4.16629283405	9.84E+18	1E+15	4.19743393218E+15	15.622983869	18.9930392318
0.00224	4.54358211887	9.0229075682E+18	1E+15	4.56020949614E+15	15.6589847946	18.9553946382
0.00448	4.95503779816	8.27366473417E+18	1E+15	4.95271809535E+15	15.694843609	18.9177504064
0.00672	5.40375389699	7.58663741327E+18	1E+15	5.37710747619E+15	15.7305487171	18.8801065693

Fermi energy vs. temperature

Fermi energy of an extrinsic semiconductor is plotted as a function of temperature. At each temperature the Fermi energy was calculated by requiring that charge neutrality be satisfied.





N_c(300 K) = 4.45E17 1/cm³

N_v(300 K) = 7.72E18 1/cm³

E_g = 1.519-5.41E-4*T*T/(T+204) eV

N_d = 1E16 1/cm³

E_c - E_d = 0.012 eV

N_a = 1E12 1/cm³

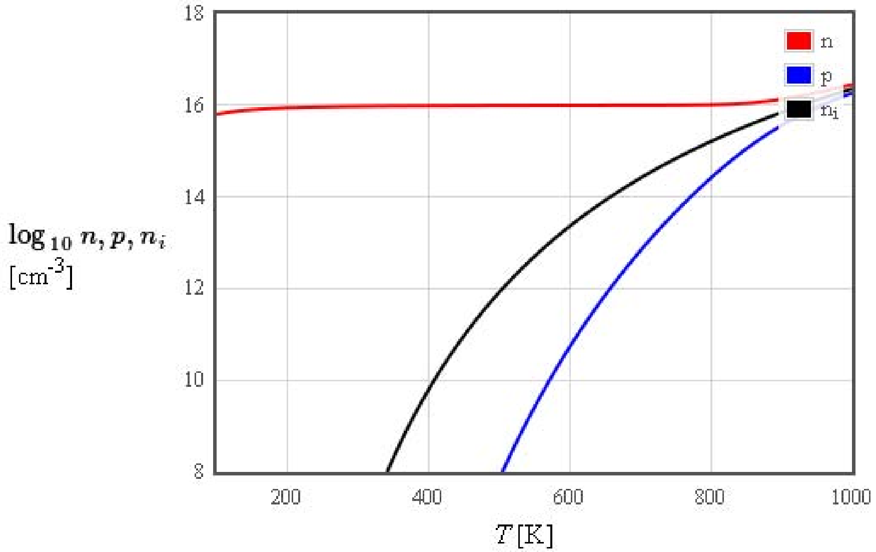
E_a - E$_v$ = 0.045 eV

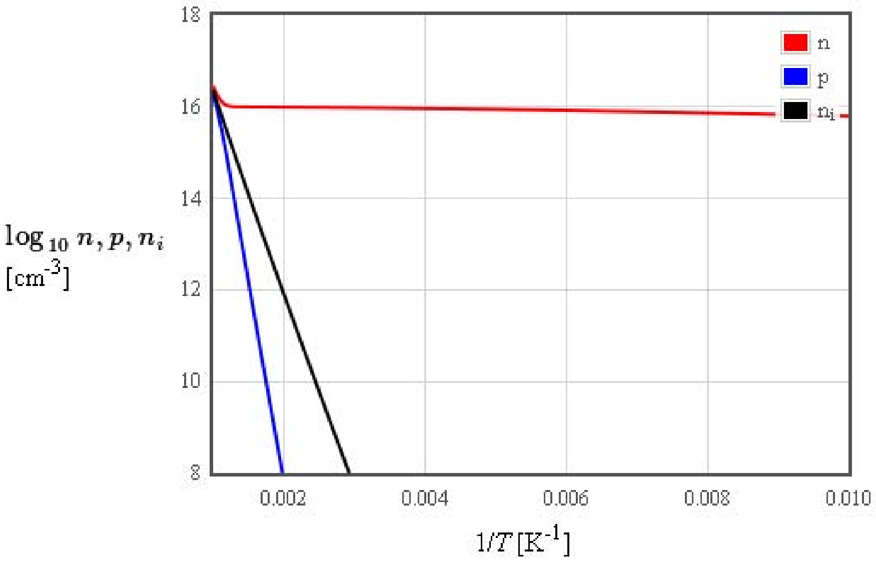
T_1 = 100 K

T_2 = 1000 K

Once the Fermi energy is known, the carrier densities n and p can be calculated from the formulas, $n = N_c\left(\frac{T}{300}\right)^{3/2}\exp\left(\frac{E_F-E_c}{k_BT}\right)$ and $p = N_v\left(\frac{T}{300}\right)^{3/2}\exp\left(\frac{E_v-E_F}{k_BT}\right)$.

The intrinsic carrier density is $n_i = \sqrt{N_c\left(\frac{T}{300}\right)^{3/2} N_v\left(\frac{T}{300}\right)^{3/2}}\exp\left(\frac{-E_g}{2k_BT}\right)$.



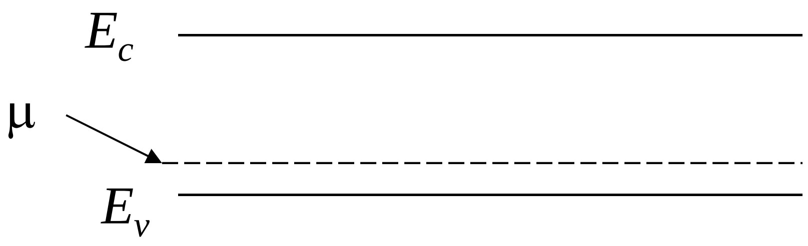


pn junction

under normal operation conditions

p-type

$N_A > N_D$ $\quad p = N_A - N_D$

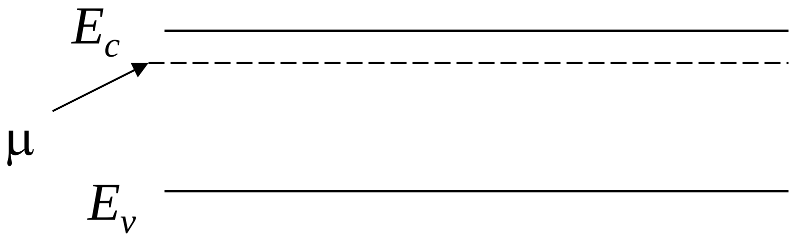


$$n = \frac{n_i^2}{p} = \frac{n_i^2}{N_A - N_D}$$

$$\mu = E_v + k_B T \ln\left(\frac{N_v}{N_A - N_D}\right)$$

n-type

$N_D > N_A$ $\quad n = N_D - N_A$

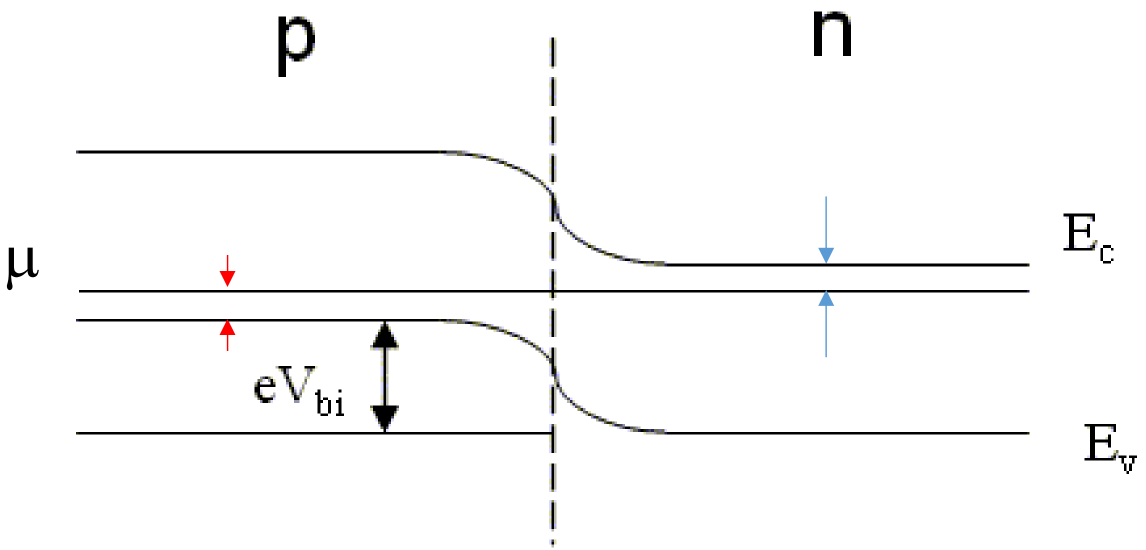


$$p = \frac{n_i^2}{n} = \frac{n_i^2}{N_D - N_A}$$

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

Semiconductor devices Kittel p. 503 - 512

V_{bi} built-in voltage



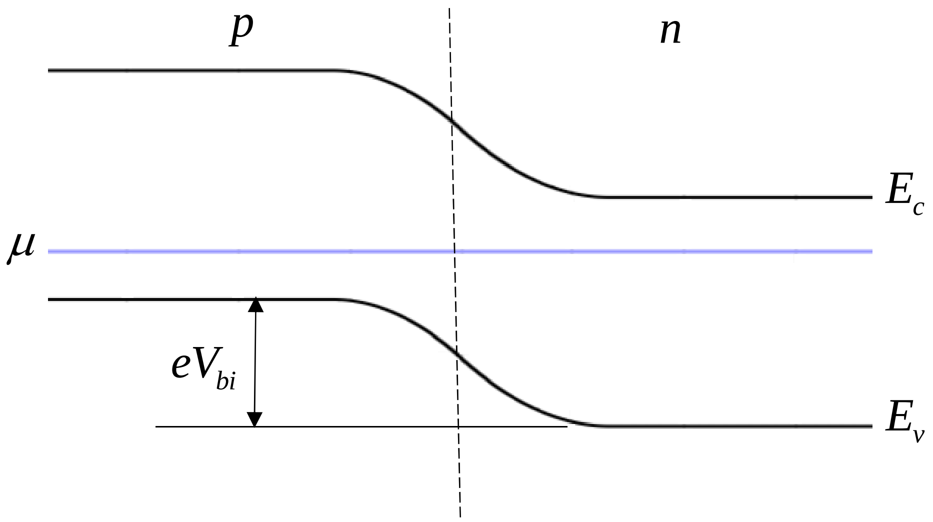
law of mass action

$$n_i^2 = N_c N_v \exp\left(\frac{-E_g}{k_B T}\right)$$

$$eV_{bi} = E_g \boxed{-k_B T \ln\left(\frac{N_c}{N_D}\right)}\boxed{-k_B T \ln\left(\frac{N_v}{N_A}\right)}$$

$$eV_{bi} = E_g - k_B T \ln\left(\frac{N_c N_v}{N_D N_A}\right) = k_B T \ln\left(\frac{N_D N_A}{n_i^2}\right)$$

p and n profiles



$V_{bi} \sim 1$ V

$W \sim 1$ μm

$E_{max} \sim 10^4$ V/cm

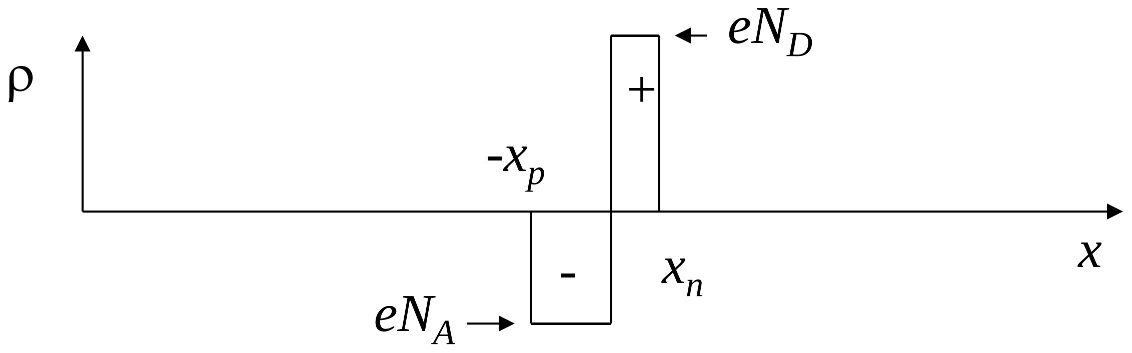
$$p = N_v \exp\left(\frac{E_v - \mu}{k_B T}\right)$$

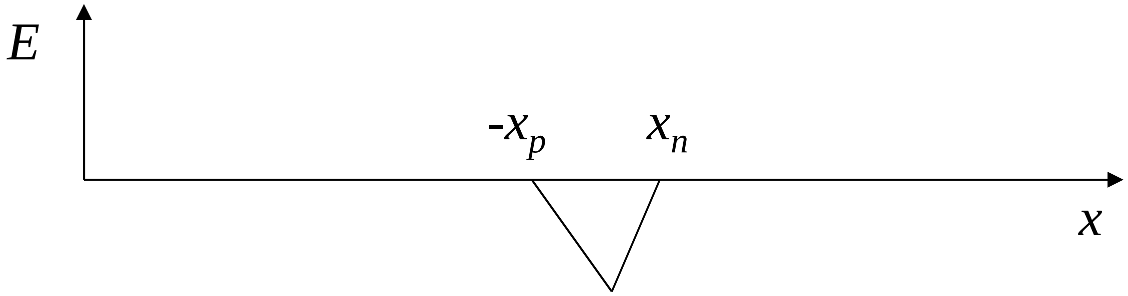
$$n = N_c \exp\left(\frac{\mu - E_c}{k_B T}\right)$$

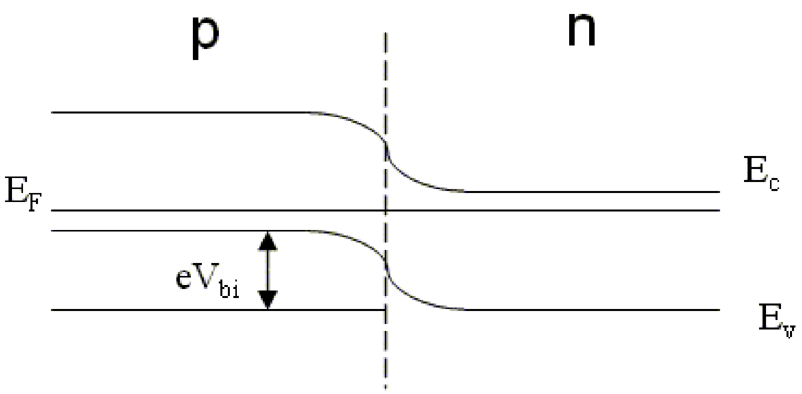
The electric field pushes the electrons towards the n-region and the holes towards the p-region.

Diffusion sends electrons towards the p-region and holes towards the n-region.

depletion approximation







$$eV_{bi} = k_B T \ln\left(\frac{N_D N_A}{n_i^2}\right)$$

$$E = -\frac{eN_A}{\varepsilon}\left(x + x_p\right) \qquad -x_p > x > 0$$

$$E = \frac{eN_D}{\varepsilon}\left(x - x_n\right) \qquad 0 > x > x_n$$

$$V = \frac{eN_A}{\varepsilon}\left(\frac{x^2}{2} + xx_p\right) \qquad -x_p > x > 0$$

$$V = \frac{-eN_D}{\varepsilon}\left(\frac{x^2}{2} - xx_n\right) \qquad 0 > x > x_n$$

Abrupt pn junctions in the depletion approximation

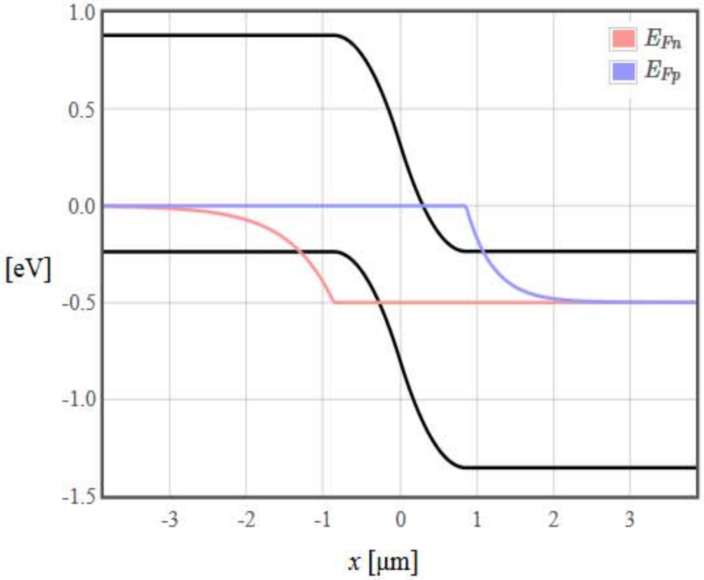
In an abrupt pn junction, the doping changes abruptly from p to n. It is common to solve for the band bending, the local electric field, the carrier concentration profiles, and the local conductivity in the depletion approximation. In this approximation it is assumed that there is a depletion width W around the transition from p to n where the charge carrier densities are negligible. Outside the depletion width the charge carrier densities are equal to the doping densities so that the semiconductor is electrically neutral outside the depletion width. Using this approximation it is possible to calculate the important properties of the pn junction.

$N_A =$ 1E15 1/cm³ $N_D =$ 1E15 1/cm³ $E_g =$ 1.166-4.73E-4*T*T/(T+636) eV
$N_v(300) =$ 9.84E18 1/cm³ $N_c(300) =$ 2.78E19 1/cm³ $\epsilon_r =$ 12 $T =$ 300 K
$\mu_p =$ 480 cm²/V s $\mu_n =$ 1350 cm²/V s $\tau_p =$ 1E-10 s $\tau_n =$ 1E-10 s
$V =$ -0.5 V Submit
V

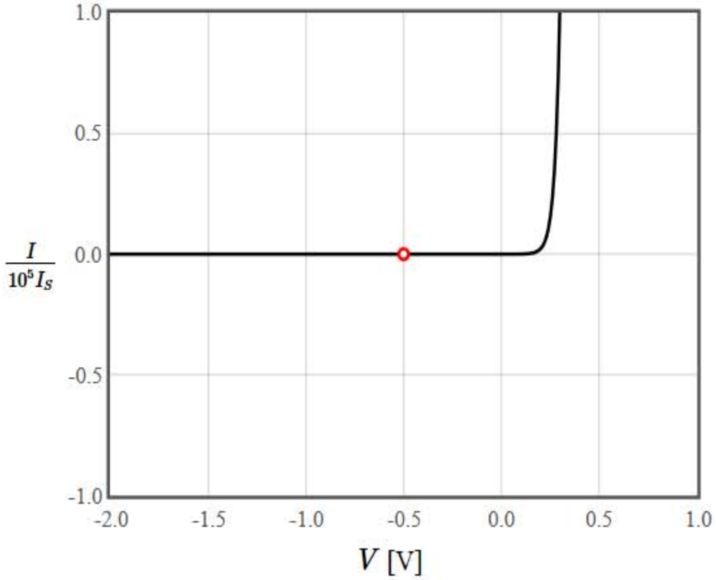
$E_g = 1.12$ eV $W = 1.72$ µm $x_p =$ -0.861 µm $x_n = 0.861$ µm $V_{bi} = 0.618$ V $C_j = 6.17$ nF/cm²

$D_p = 12.4$ cm²/s $D_n = 34.9$ cm²/s $L_p = 0.352$ µm $L_n = 0.591$ µm

Band diagram



Current-Voltage Characteristics



Charge density

Electric field