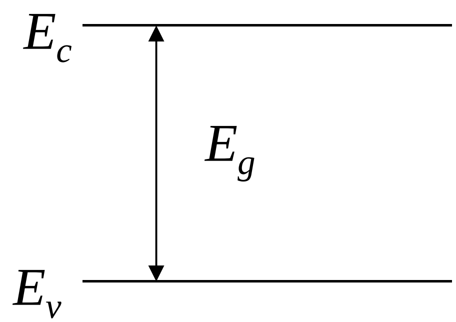
8. Semiconductors

Oct 25, 2018

Review

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



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

Intrinsic semiconductors

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

$$E_F = \frac{E_c + E_v}{2} + \frac{k_B T}{2} \ln\left(\frac{N_v}{N_c}\right)$$

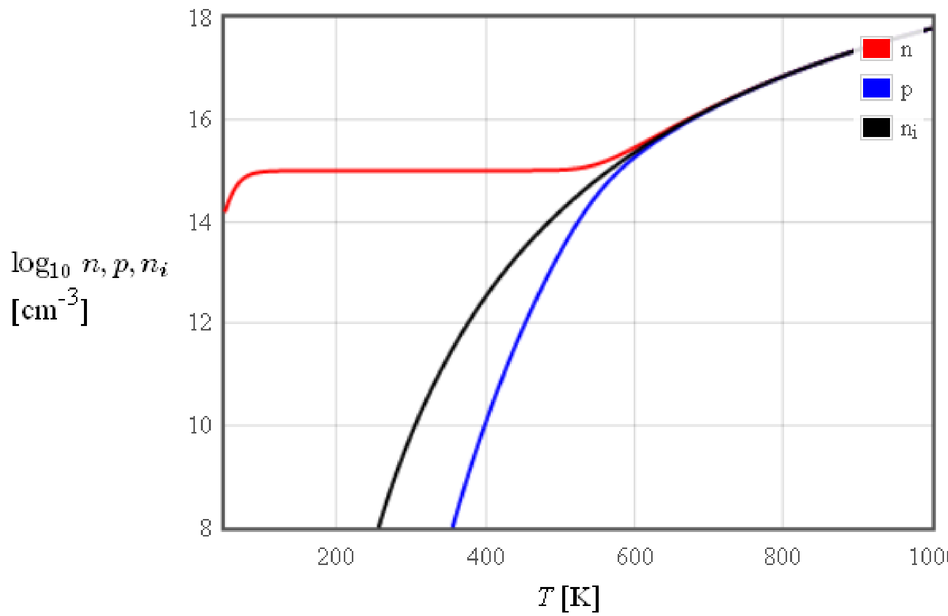
n-type

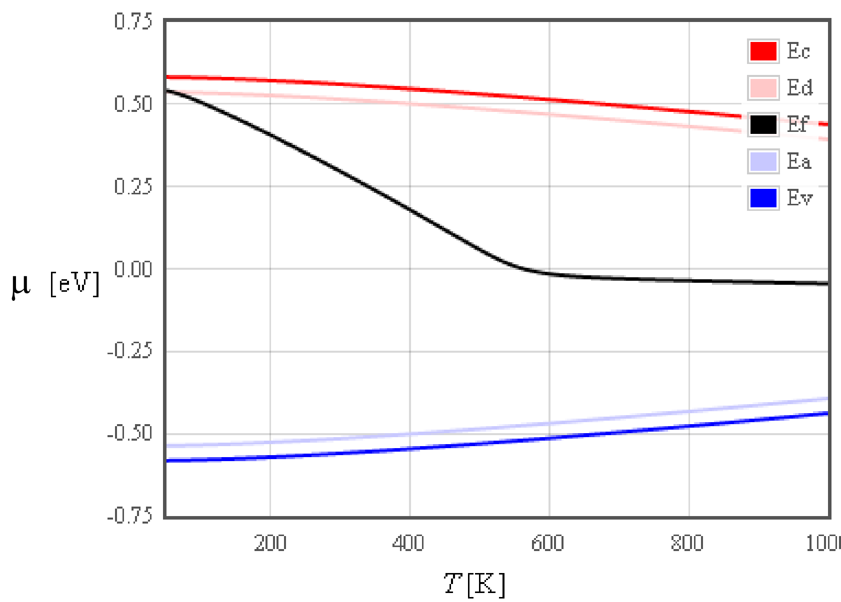
n-type $N_D > N_A$, $p \sim 0$

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

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

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





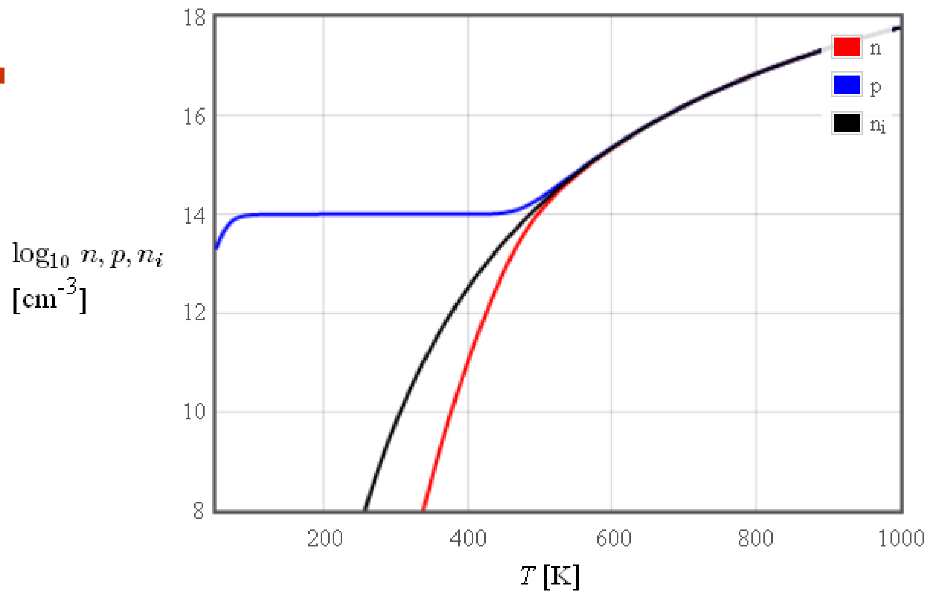
p-type

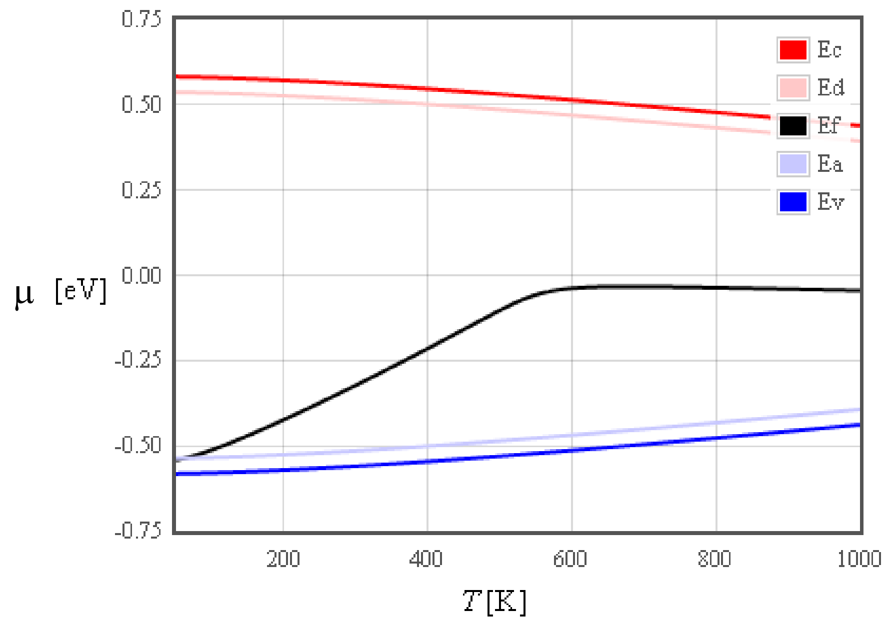
p-type $N_A > N_D$, $n \sim 0$

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

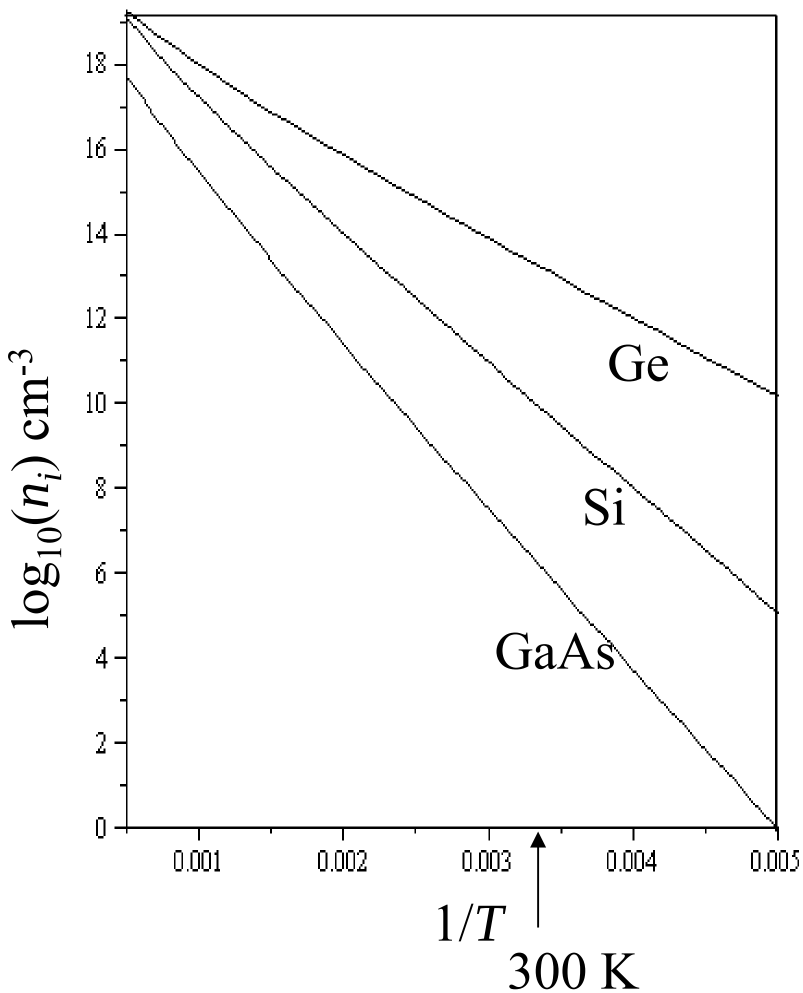
$$\mu = E_v + k_B T \ln\left(\frac{N_v}{N_A}\right)$$

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



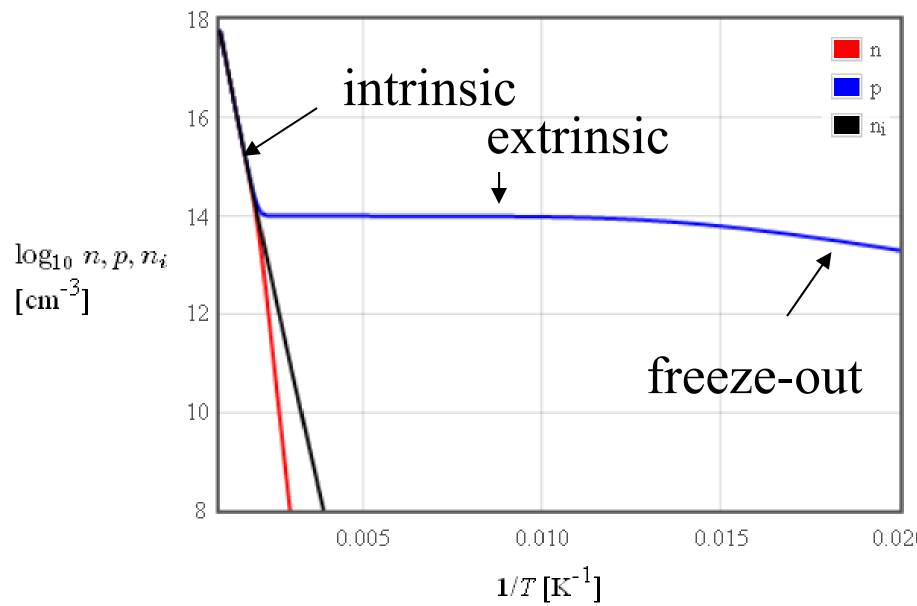


Intrinsic semiconductors



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

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

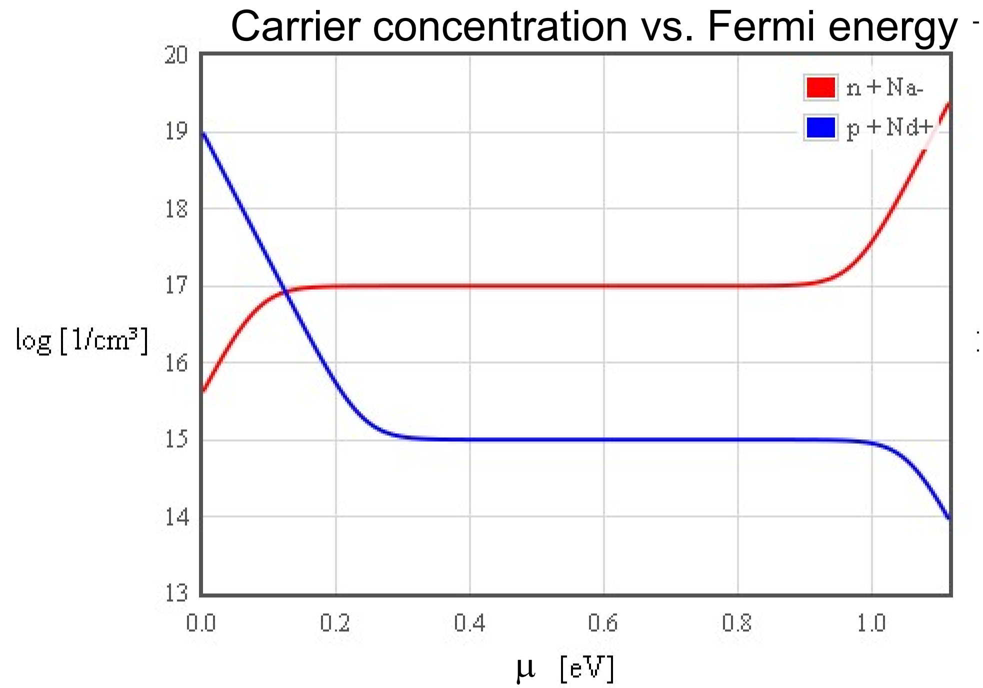
N_D = donor density cm^{-3} N_D^+ = ionized donor density cm^{-3}

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

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

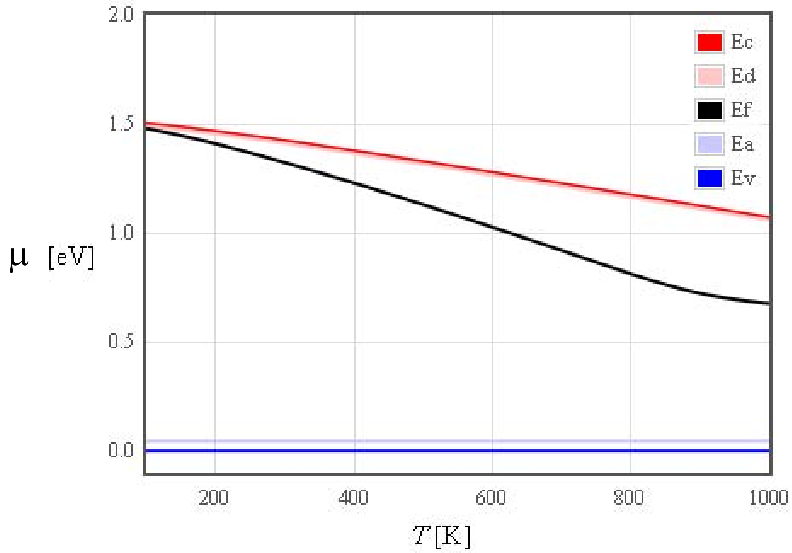



```
for ($i=0; $i<500; $i++) {
  $Ef = $i*$Eg/500;
  $n=$Nc*pow($T/300,1.5)*exp(1.6022E-19*($Ef-$Eg)/(1.38E-23*$T));
  $p=$Nv*pow($T/300,1.5)*exp(1.6022E-19*(-$Ef)/(1.38E-23*$T));
  $Namin = $Na/(1+4*exp(1.6022E-19*($Ea-$Ef)/(1.38E-23*$T)));
  $Ndplus = $Nd/(1+2*exp(1.6022E-19*($Ef-$Ed)/(1.38E-23*$T)));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

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
0.00896	[illegible]	[illegible]	1E+15	[illegible]	[illegible]	[illegible]

Fermi energy vs. temperature

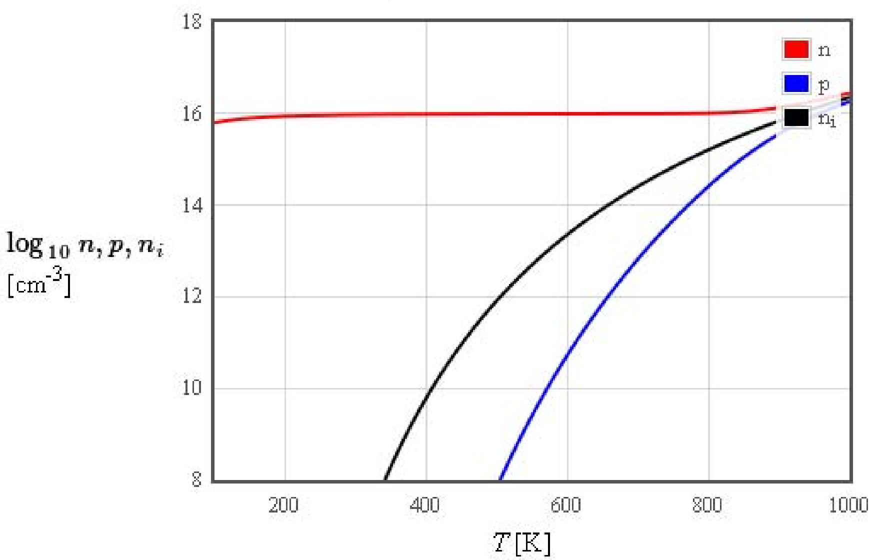
Fermi energy of an extrinsic semiconductor is plotted as a function of temperature. At each temperature the Fermi energy was calculated by requiring that charge neutrality be satisfied.

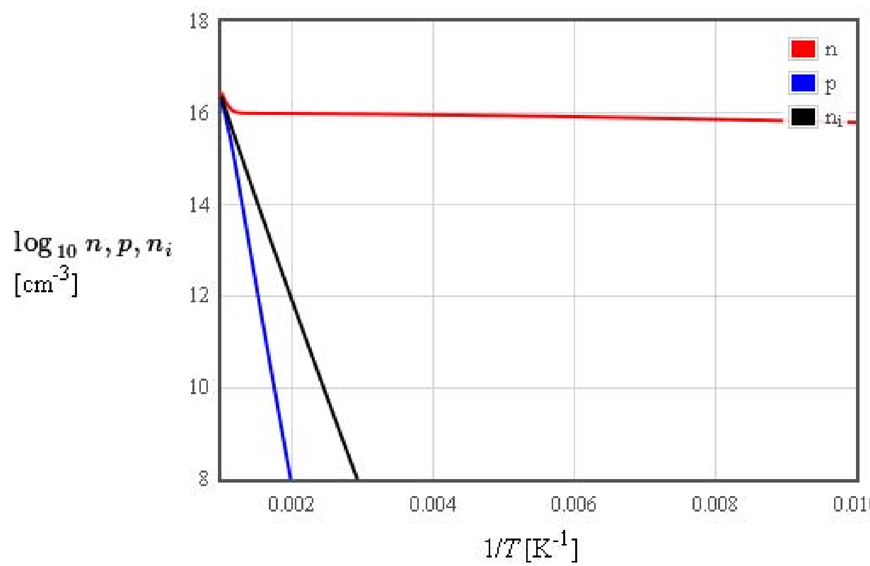


N_c(300 K) =	4.45E17	1/cm³	Semiconductor: Si, Ge, GaAs
N_v(300 K) =	7.72E18	1/cm³	
E_g =	1.519-5.41E-4*T*T/(T+204)	eV	
N_d =	1E16	1/cm³	Donor: P in Si, P in Ge, Si in GaAs
E_c - E_d =	0.012	eV	
N_a =	1E12	1/cm³	Acceptor: B in Si, B in Ge, Si in GaAs
E_a - E_v =	0.045	eV	
T_1 =	100	K	
T_2 =	1000	K	
	Replot		

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



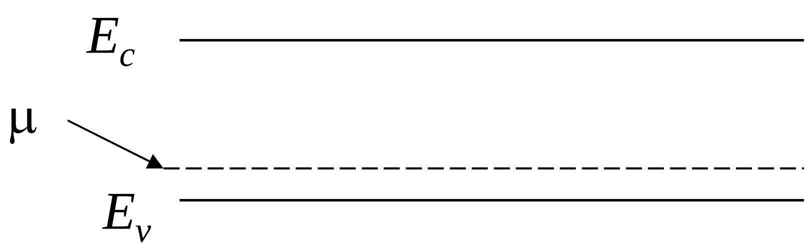


pn junction

under normal operation conditions

p-type

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

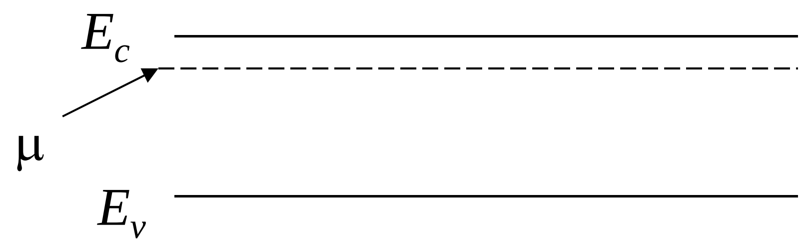


$$n = \frac{n_i^2}{p} = \frac{n_i^2}{N_A - N_D}$$

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

n-type

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

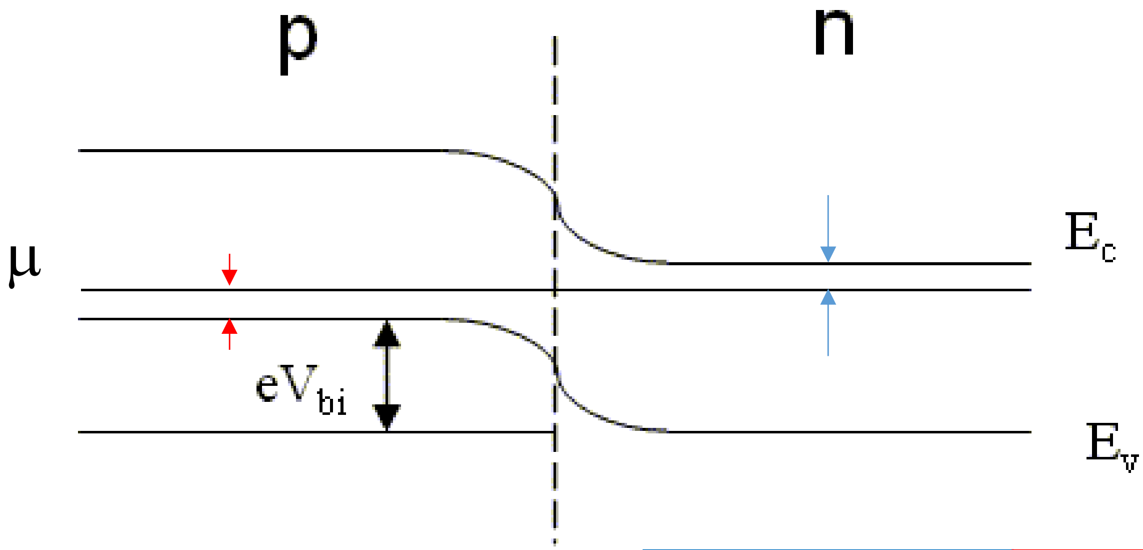


$$p = \frac{n_i^2}{n} = \frac{n_i^2}{N_D - N_A}$$

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

Semiconductor devices   Kittel p. 503 - 512

V_{bi} built-in voltage



law of mass action

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

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

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