

Extrinsic semiconductors

Extrinsic semiconductors

The introduction of impurity atoms that can add 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.

n and p

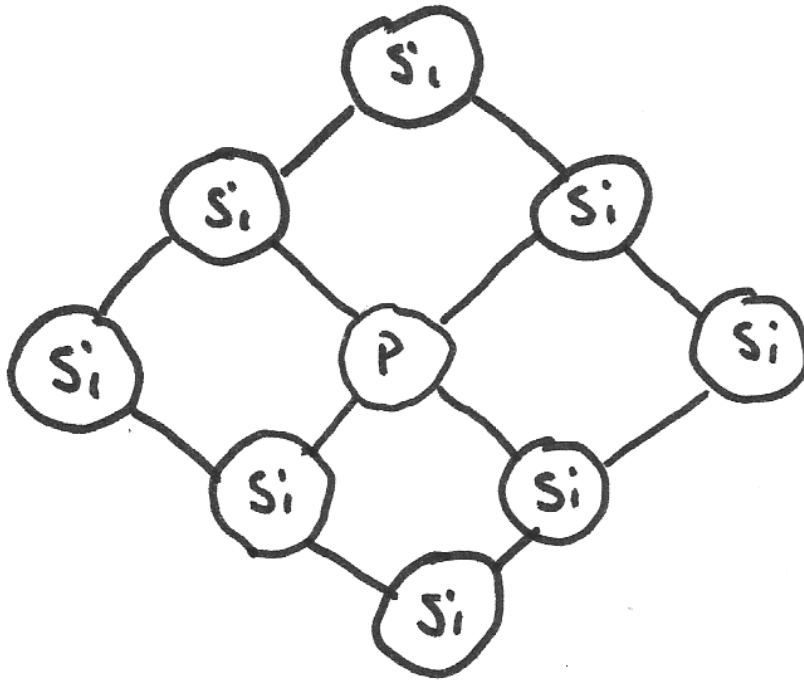
The electron density and hole density are:

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

The law of mass action:

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

Ionization of dopants



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

$$E_n = -\frac{me^4}{8\epsilon_0^2 h^2 n^2}$$

Ionization energy is smaller by a factor:

$$\frac{m^*}{m} \left(\frac{\epsilon_0}{\epsilon_r \epsilon_0} \right)^2$$

Ionization energy ~ 25 meV

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

acceptors in Si

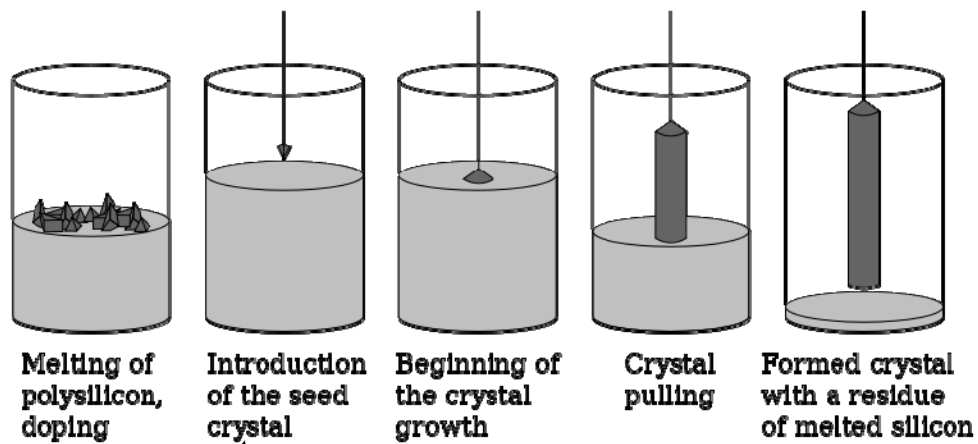


donors in Si



Crystal growth

Czochralski Process



add dopants to the melt



images from wikipedia

Crystal growth

Float zone Process

Neutron transmutation

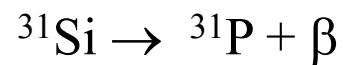
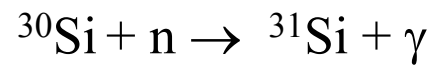


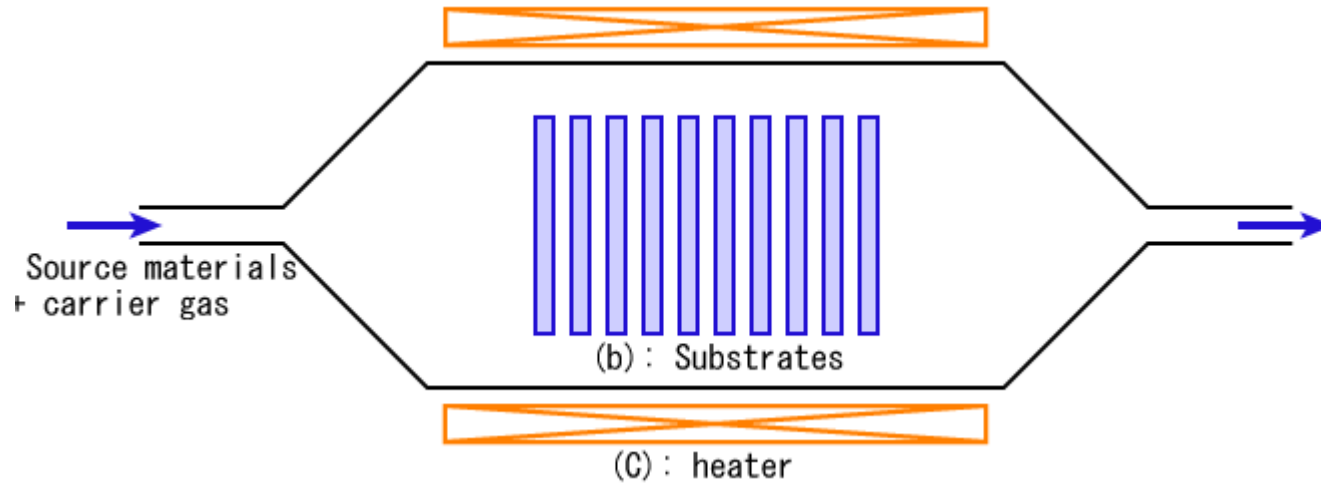
image from wikipedia

Gas phase diffusion



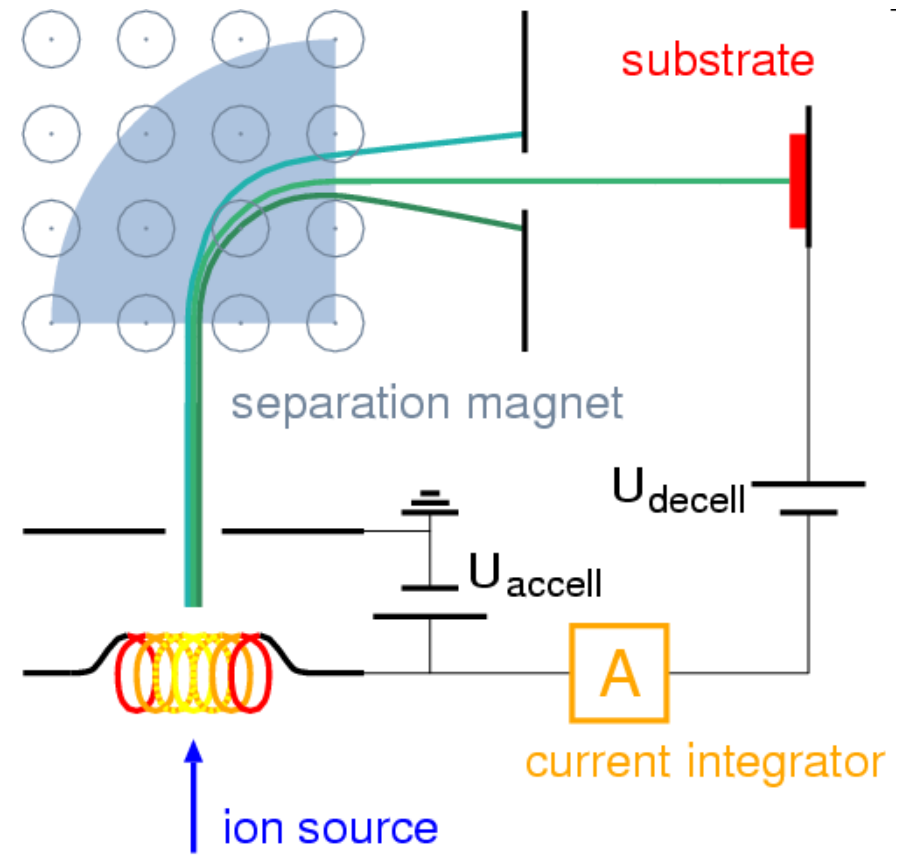
AsH_3 (Arsine) or PH_3 (phosphine) for n-doping
 B_2H_6 (diborane) for p-doping.

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.

Ion implantation



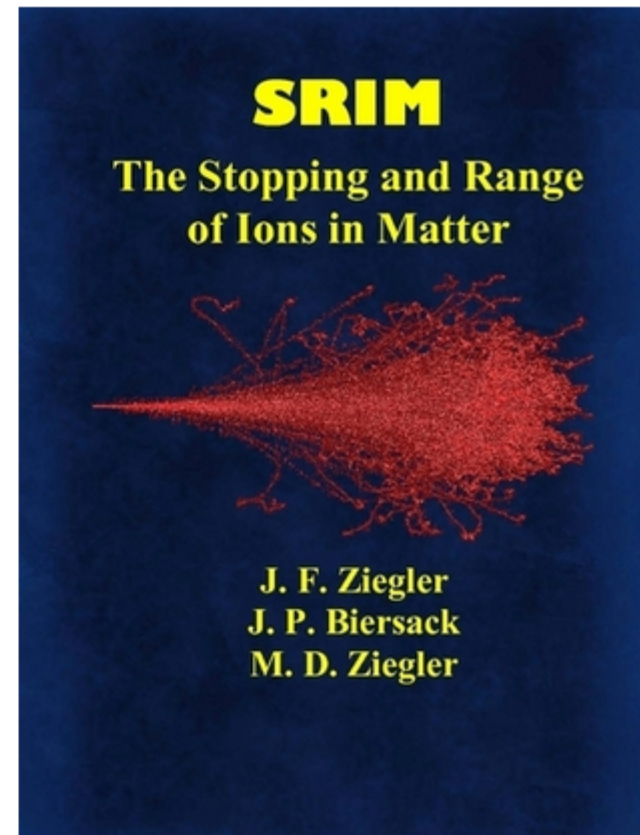
Implant at 7° to avoid channeling

SRIM

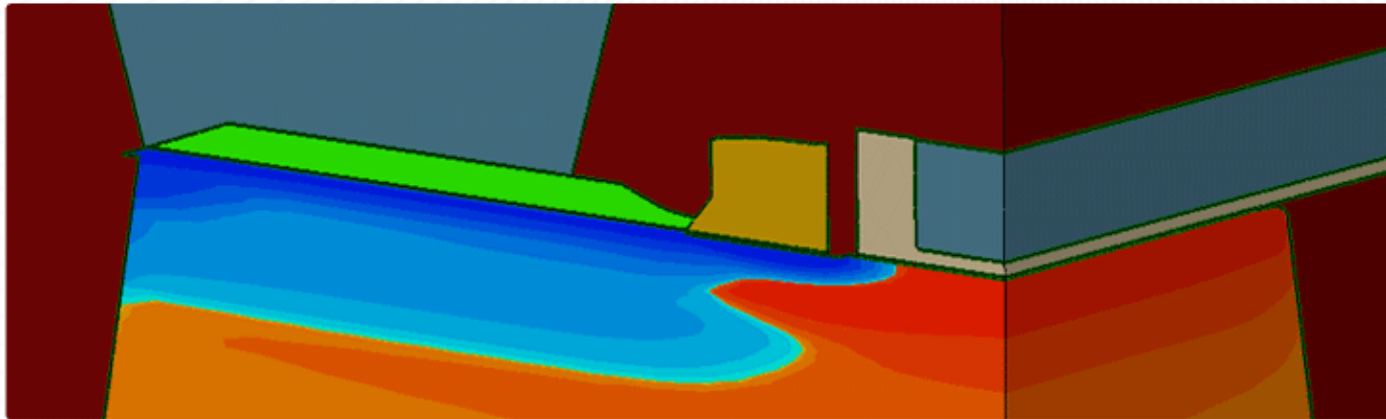
The Stopping and Range of Ions in Matter

James F. Ziegler, Jochen P. Biersack, Matthias D. Ziegler

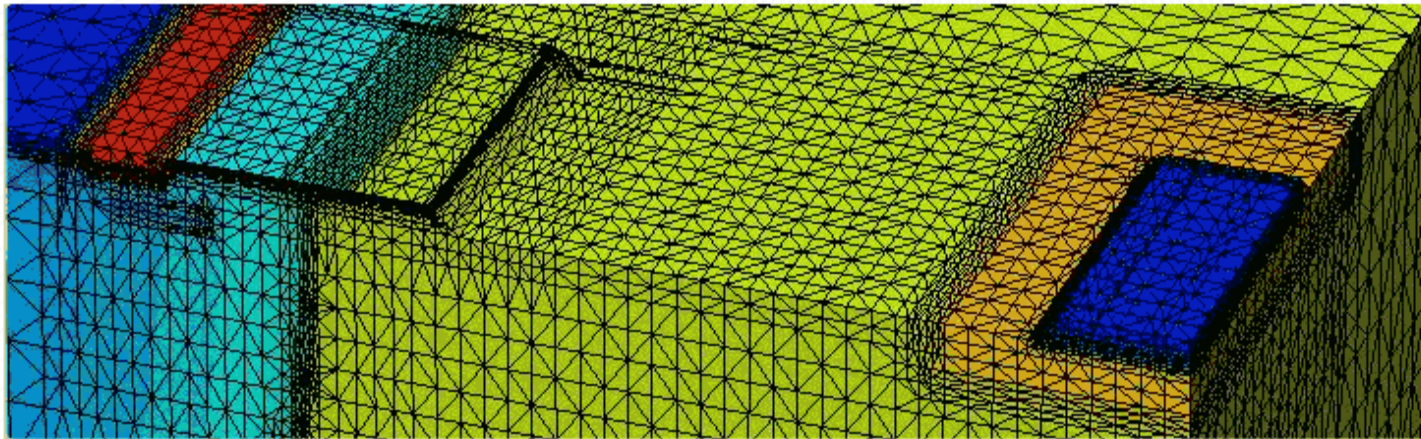
- Ch 1 - **Historical Review**
- Ch 2 - **Nuclear Stopping of Ions**
- Ch 3 - **Electronic Stopping of Ions**
- Ch 4 - **Stopping of Energetic Light Ions**
- Ch 5 - **Stopping of Ions in Compounds**
- Ch 6 - **Ion Straggling**
- Ch 7 - **TRIM : Scientific Background**
- Ch 8 - **TRIM : Setup and Input**
- Ch 9 - **TRIM : Output Files**
- Ch 10 - **Stopping and Range Tables**
- Ch 11 - **SRIM Tutorials**



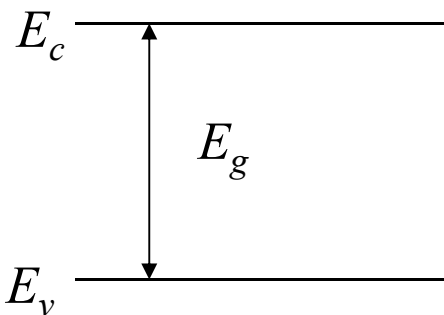
Process Simulation



Device Simulation



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

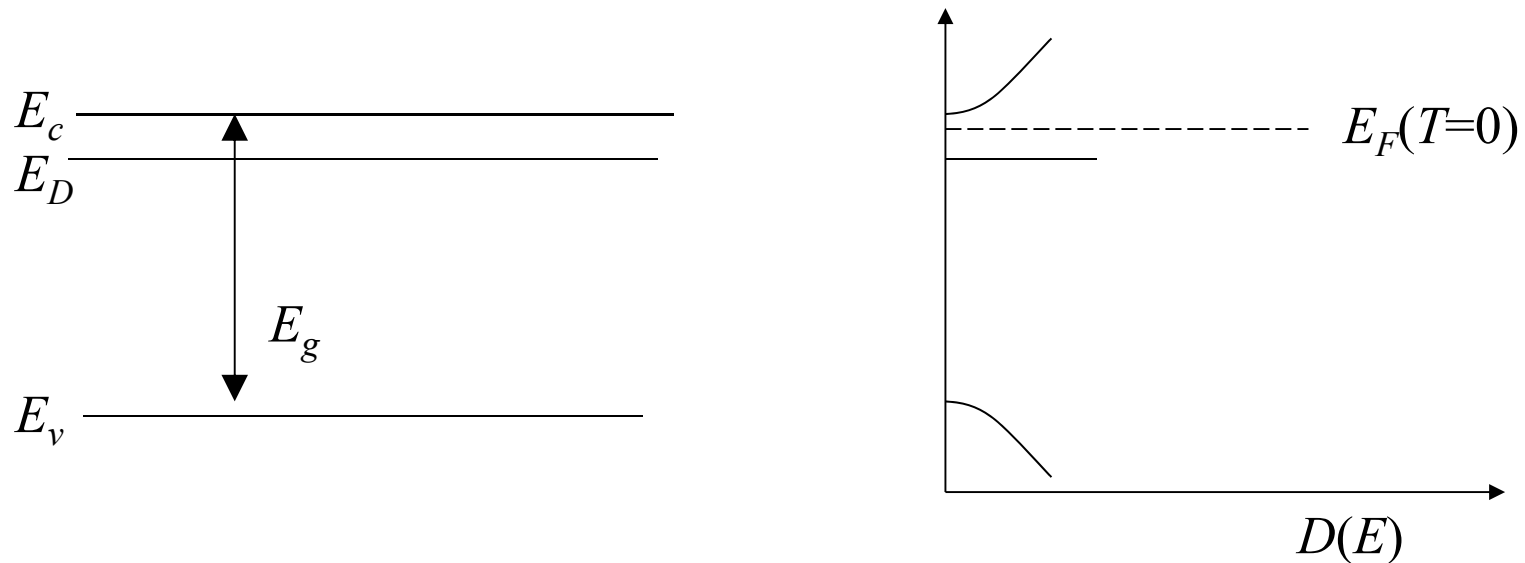
$$n = p = n_i = \sqrt{N_c N_v} \exp\left(\frac{-E_g}{2k_B T}\right)$$

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

Donors

Five valence electrons: P, As

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



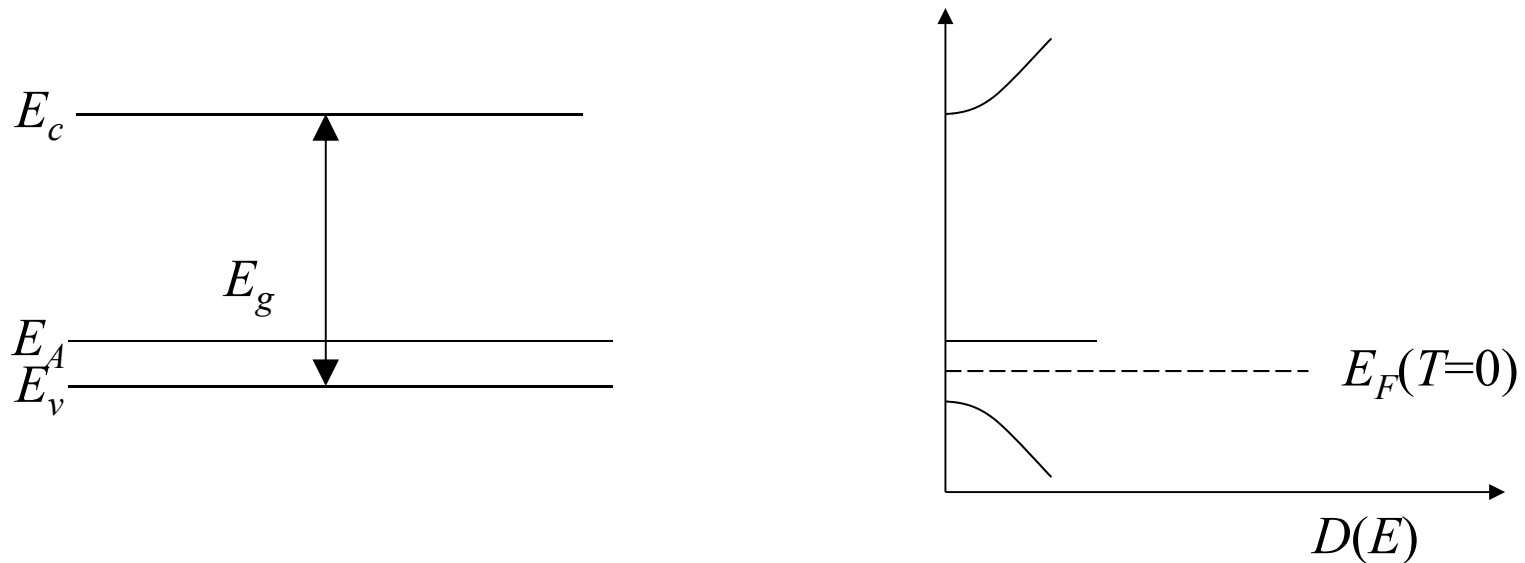
n-type: $n \sim N_D$ Many more electrons in the conduction band than holes in the valence band.

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

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

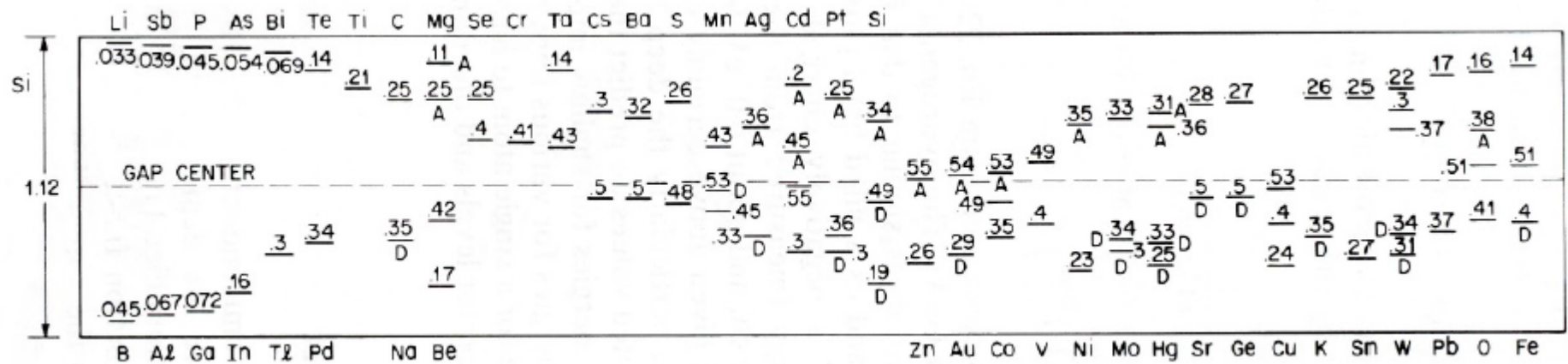
Energy below the conduction band



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





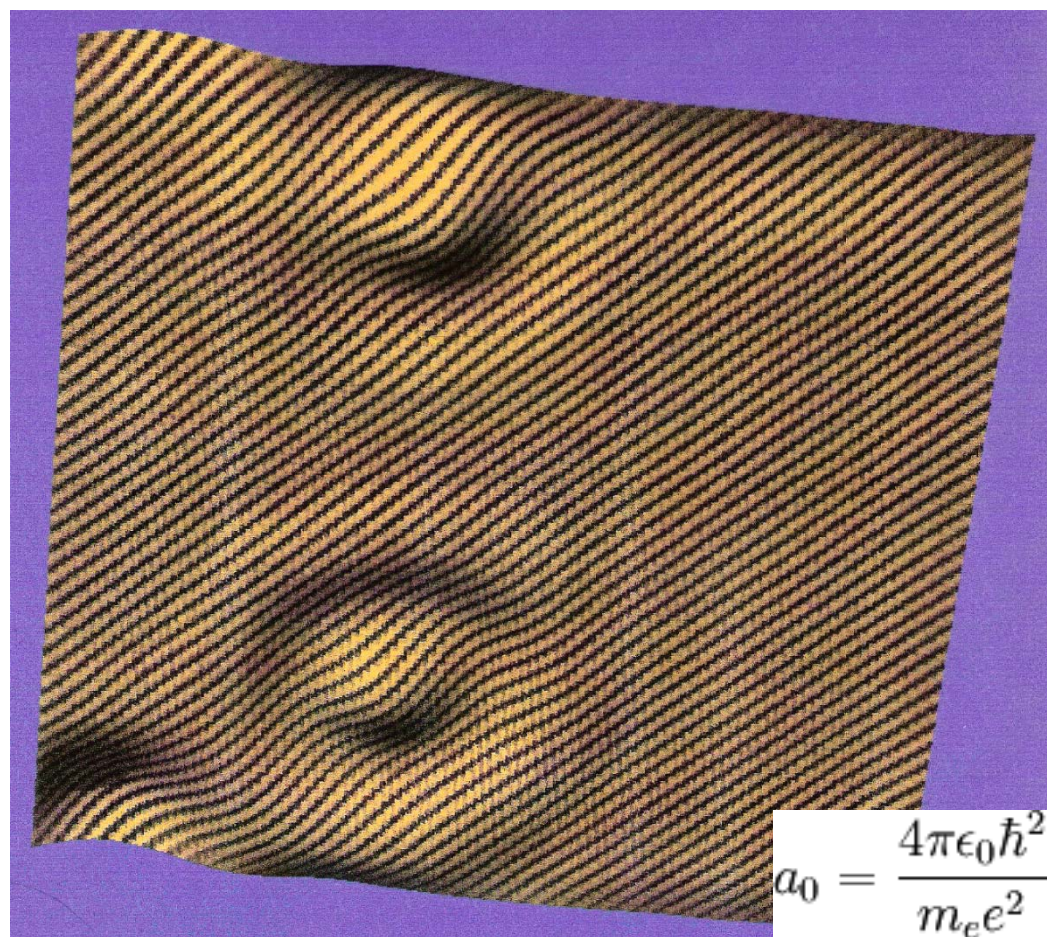
Source: Semiconductor Devices Physics and Technology, S.M. Sze, 1985

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

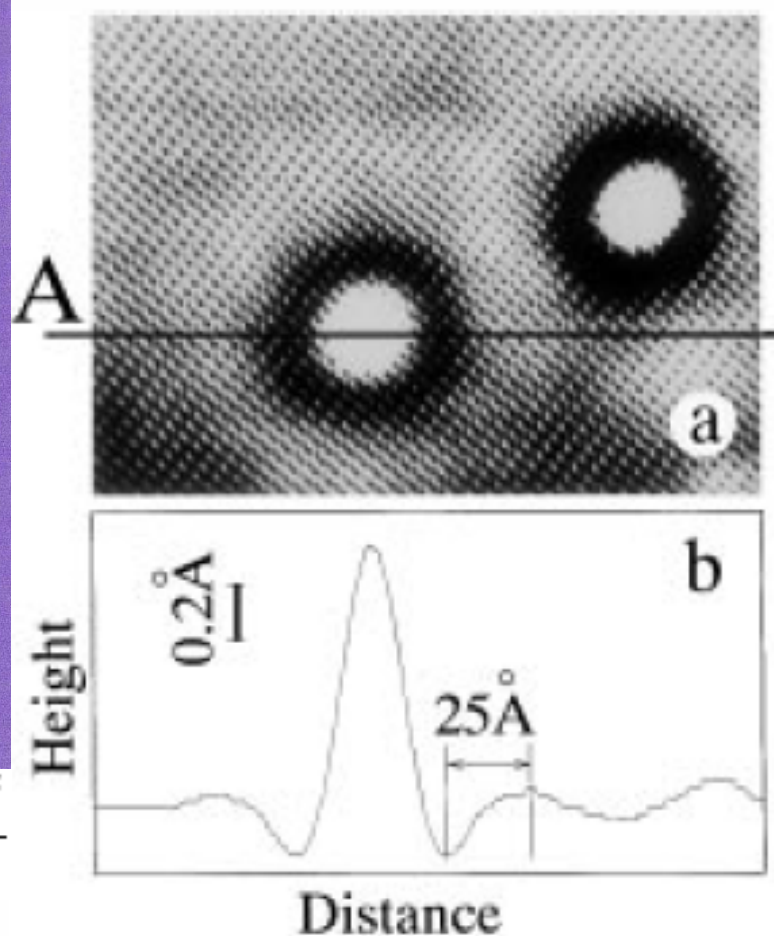
M. C. M. M. van der Wielen, A. J. A. van Roij, and H. van Kempen

Research Institute for Materials, University of Nijmegen, Toernooiveld 1, 6525 ED Nijmegen, The Netherlands

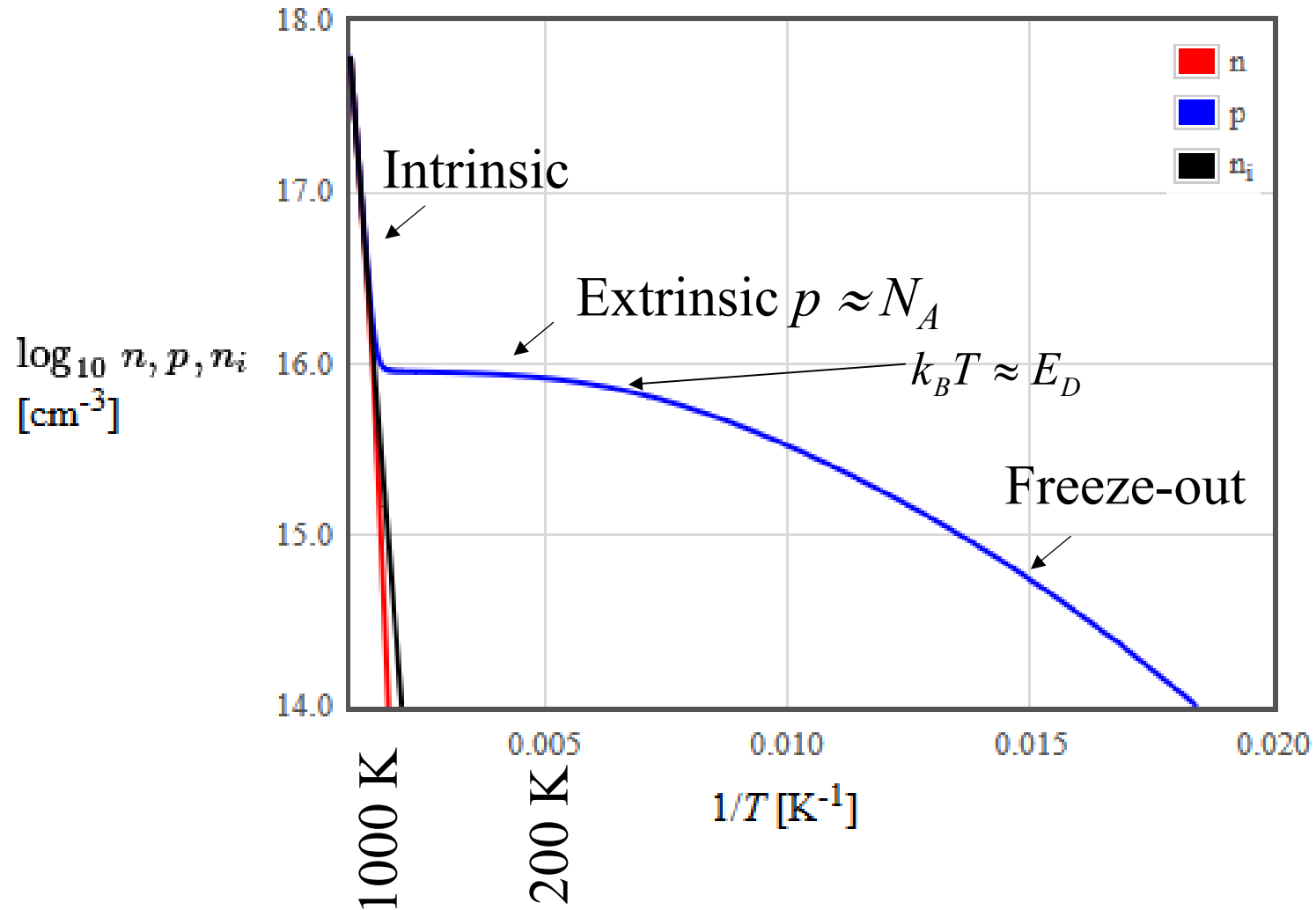
(Received 25 July 1995)



$$a_0 = \frac{4\pi\epsilon_0\hbar^2}{m_e e^2}$$



Temperature dependence



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problem
list

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Temperature dependent conductivity

A doped semiconductor makes a transition from extrinsic behavior to intrinsic behavior when number of thermally activated charge carriers equals the number of dopants. What is this temperature for silicon doped with boron at $4E+17 \text{ cm}^{-3}$?

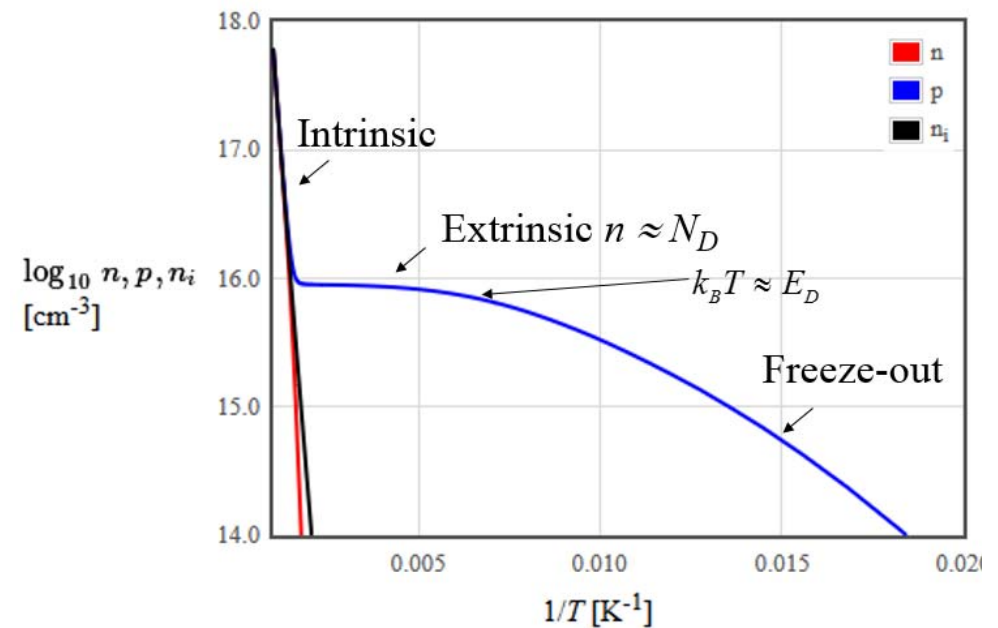
E_g is slightly temperature dependent but use $E_g = 1.12 \text{ eV}$, $N_c = 2.78 \times 10^{25} \text{ m}^{-3}$ and $N_v = 9.84 \times 10^{24} \text{ m}^{-3}$ to estimate the transition temperature.

$T =$ K

Submit answer

Clear

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



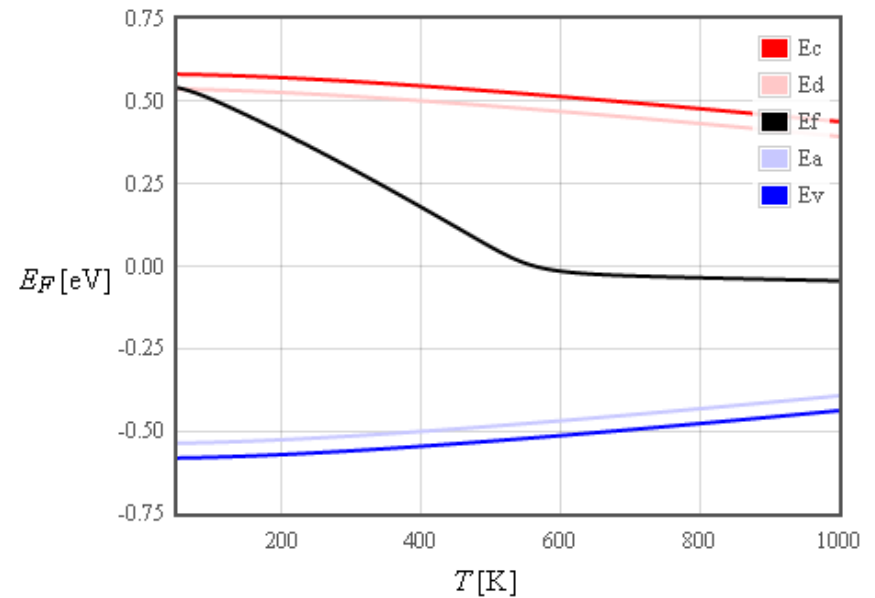
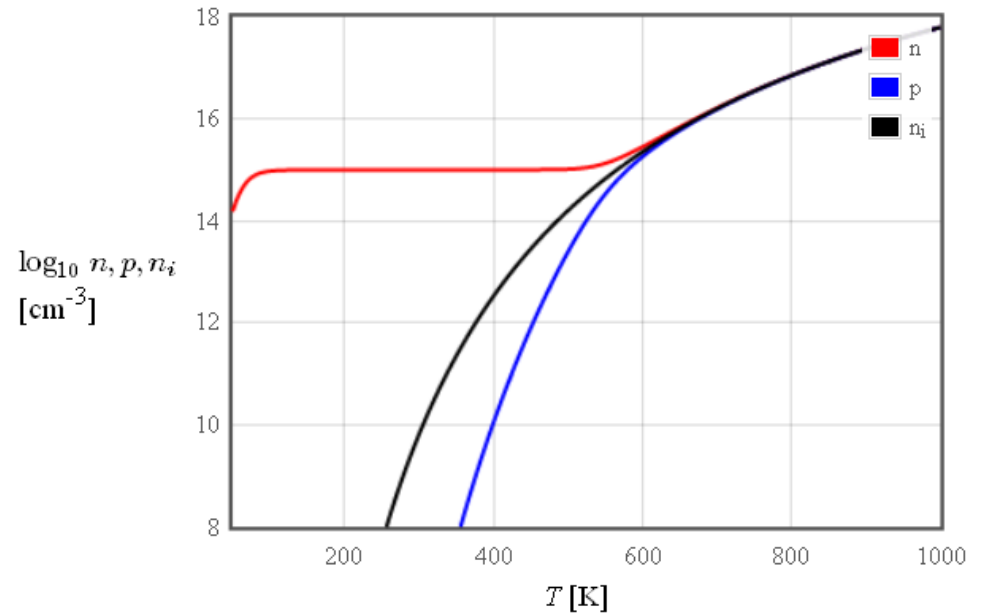
n-type

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

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

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

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



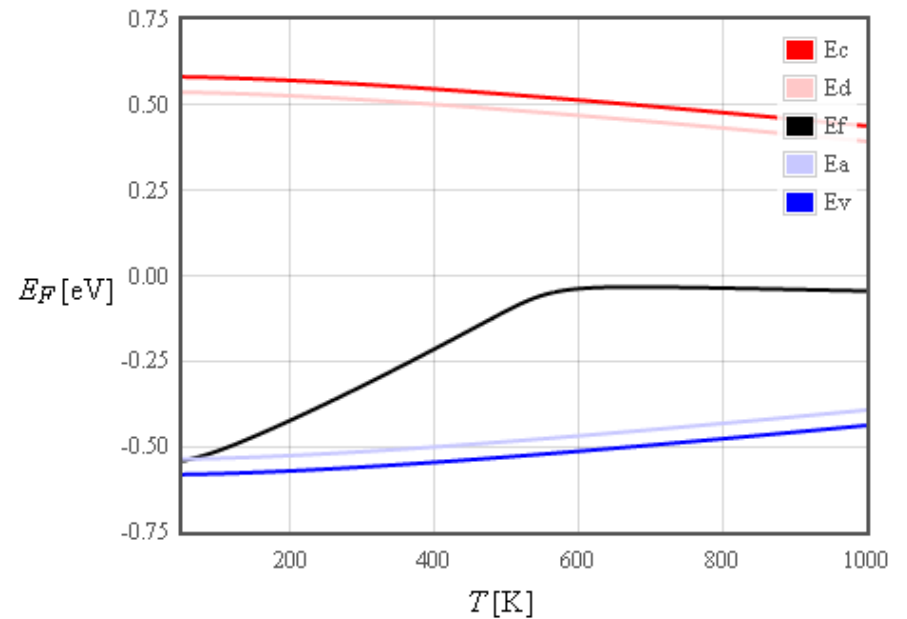
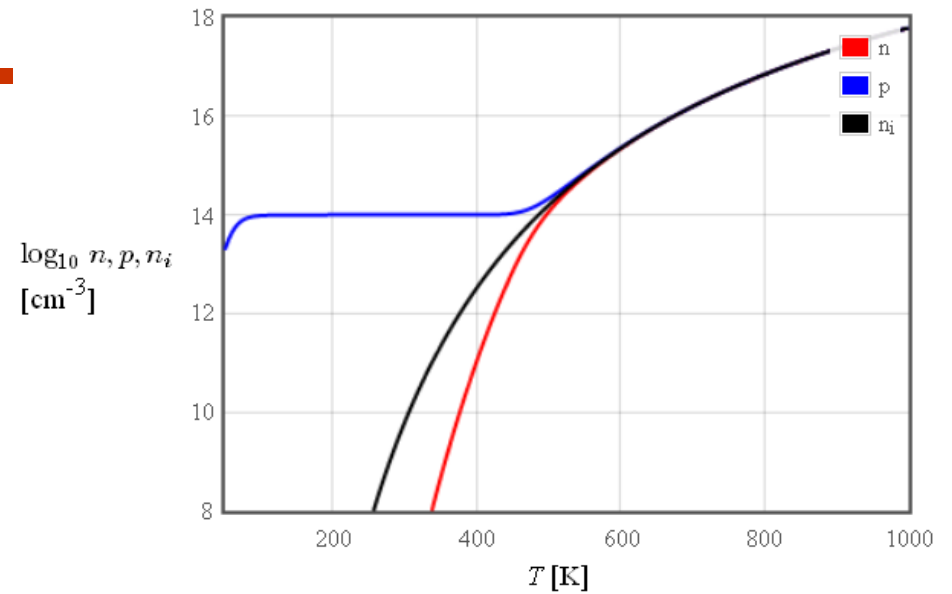
p-type

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

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

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

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



Intrinsic / Extrinsic

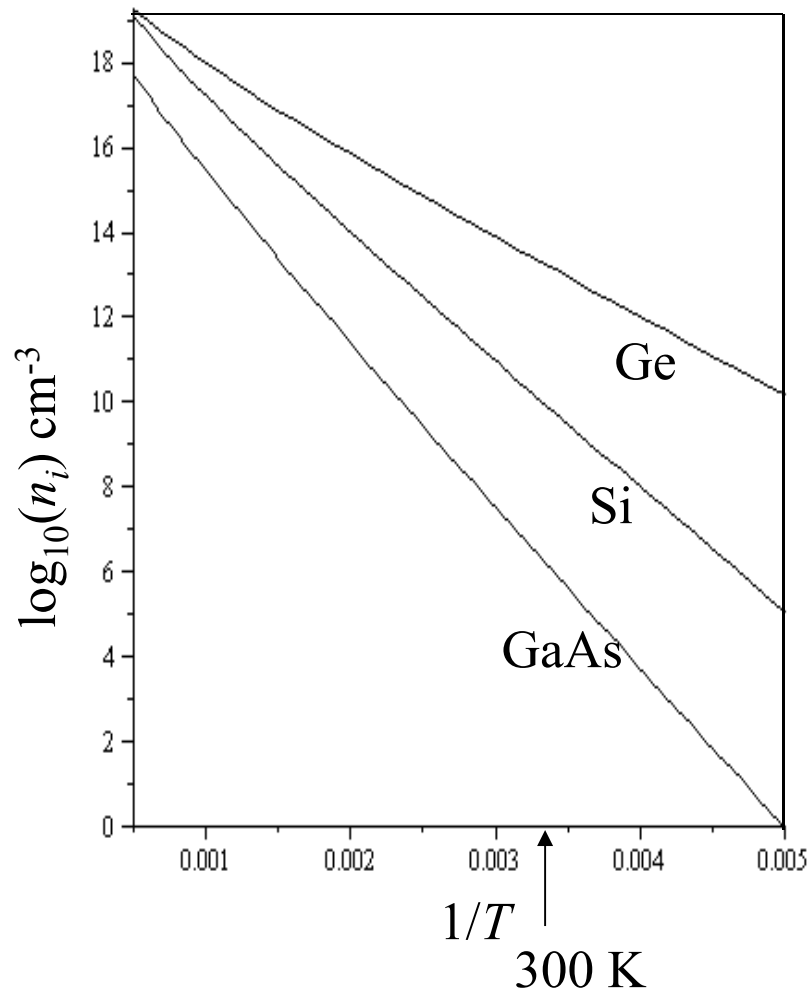
Intrinsic: $n = p$

Conductivity strongly temperature dependent near room temperature

Extrinsic: $n \neq p$

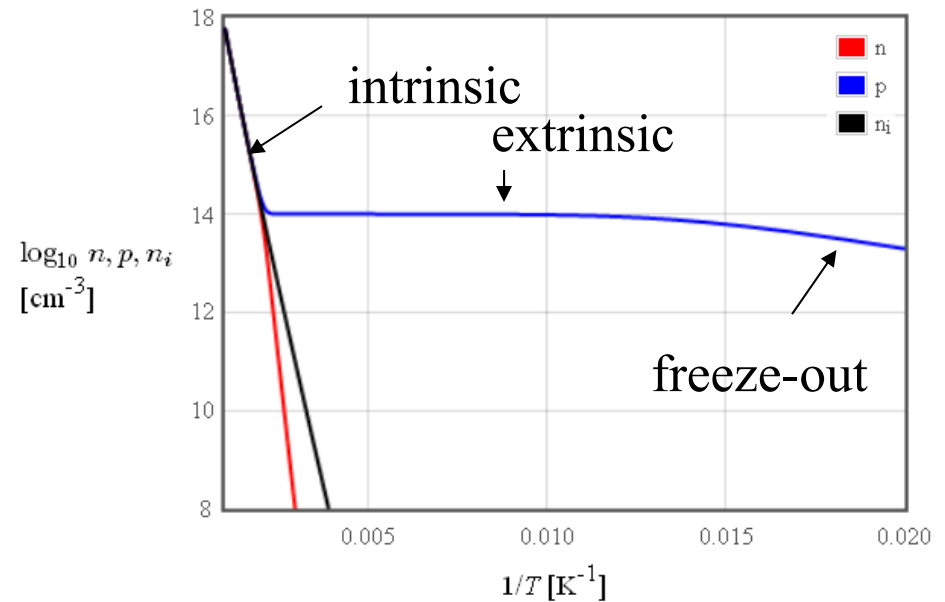
Conductivity almost temperature independent at room temperature

Intrinsic semiconductors



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

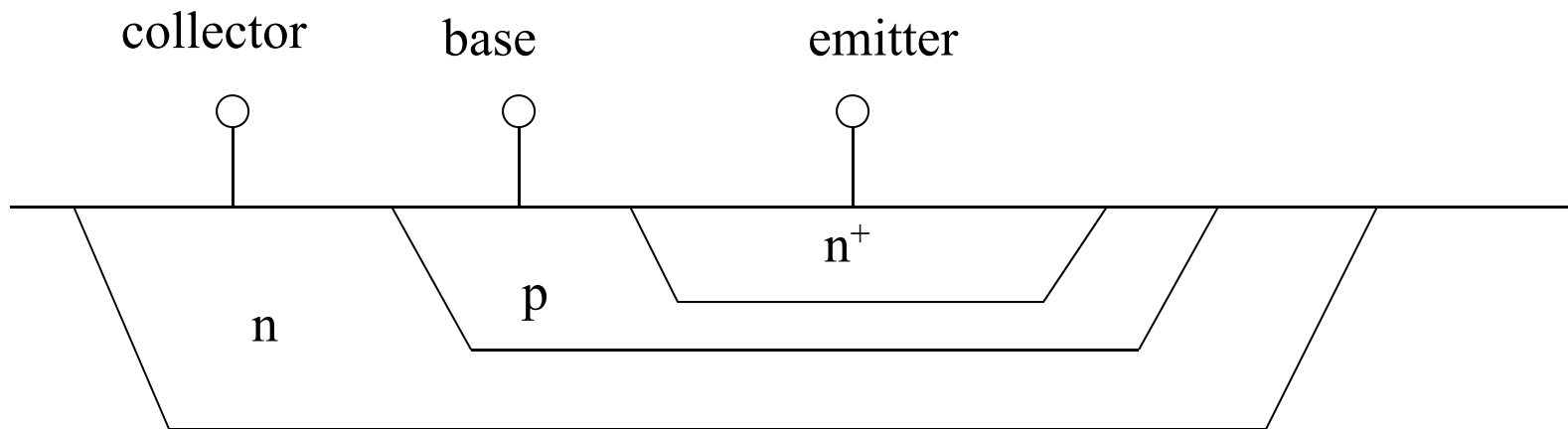
Extrinsic semiconductors



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

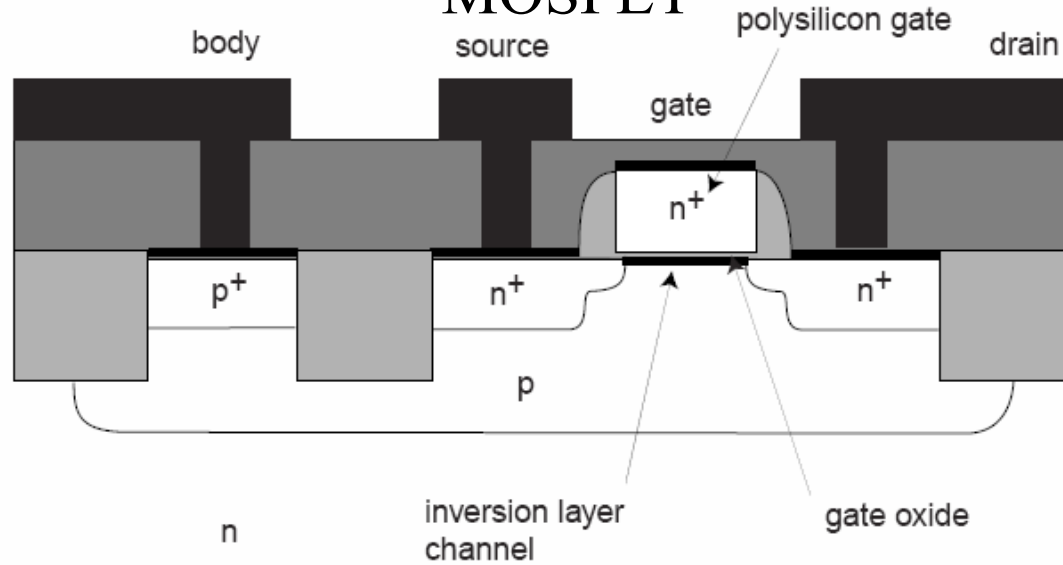
Why dope with donors AND acceptors?

Bipolar transistor

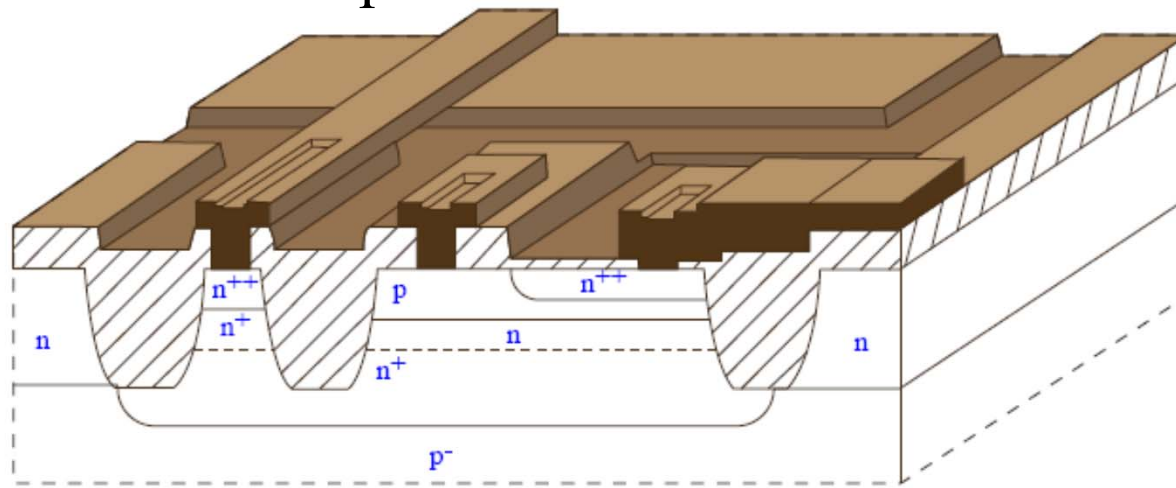


lightly doped p substrate

MOSFET



Bipolar Junction Transistor



Oxide isolated integrated BJT - a modern process

Ionized donors and acceptors

For $E_v + 3k_B T < E_F < E_c - 3k_B T$ Boltzmann approximation

$$N_D^+ = \frac{N_D}{1 + 2 \exp\left(\frac{E_F - E_D}{k_B T}\right)} \qquad N_A^- = \frac{N_A}{1 + 4 \exp\left(\frac{E_A - E_F}{k_B T}\right)}$$

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

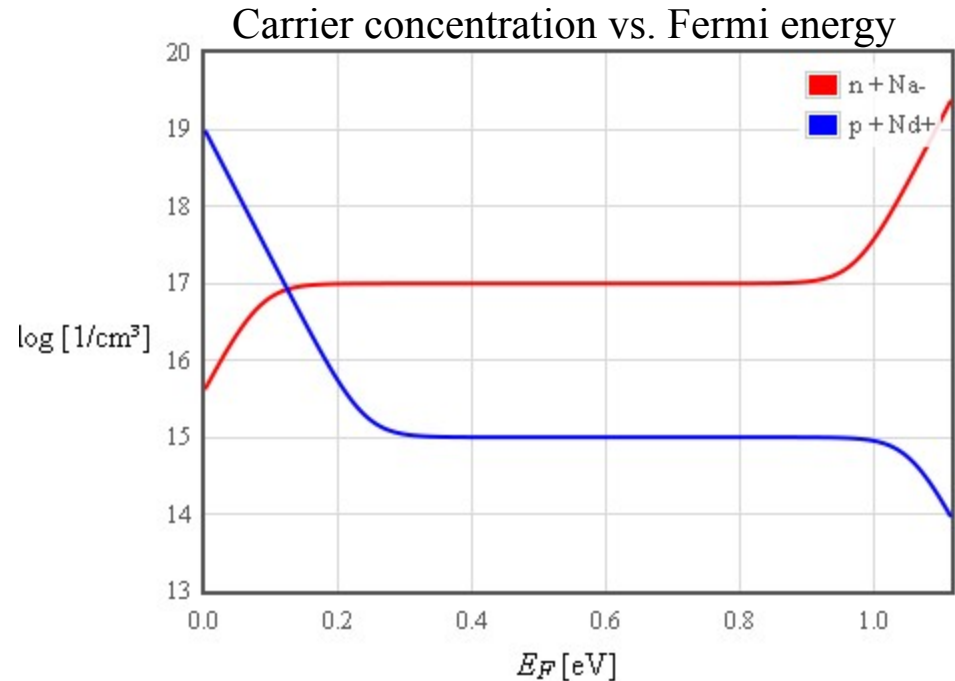
N_D = donor density cm^{-3} N_D^+ = ionized donor density cm^{-3}

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

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

Charge neutrality

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



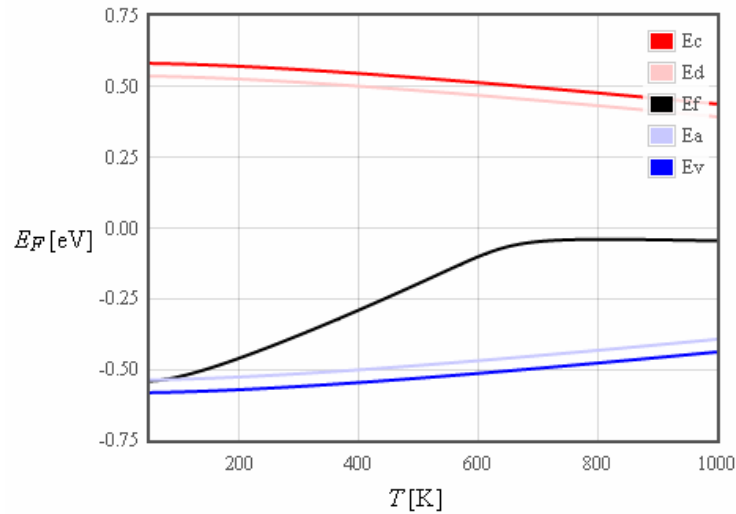
```

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	5.89210460791	6.95665026215E+18	1E+15	5.8256000025E+15	15.7660076057	18.8404621605

Calculating $E_F(T)$ numerically



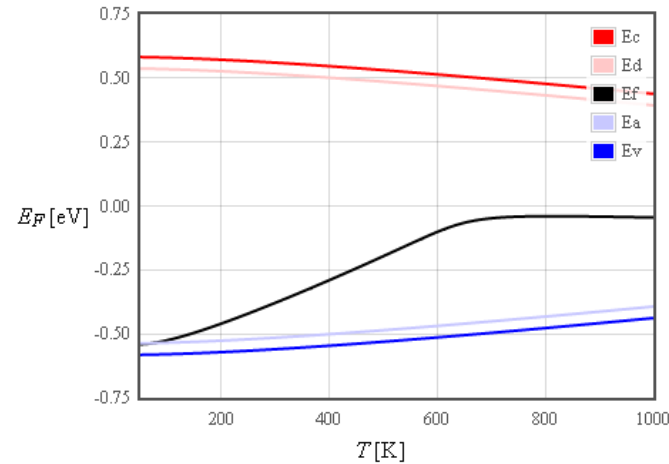
$N_c(300\text{ K}) = 2.78\text{E}19$	1/cm ³	Semiconductor <input type="button" value="Si"/> <input type="button" value="Ge"/> <input type="button" value="GaAs"/>
$N_v(300\text{ K}) = 9.84\text{E}18$	1/cm ³	
$E_g = 1.166 - 4.73\text{E-}4 * T * T / (T + 636)$	eV	
$N_d = 1\text{E}15$	1/cm ³	Donor <input type="button" value="P in Si"/> <input type="button" value="P in Ge"/> <input type="button" value="Si in GaAs"/>
$E_c - E_d = 0.045$	eV	
$N_a = 1\text{E}16$	1/cm ³	Acceptor <input type="button" value="B in Si"/> <input type="button" value="B in Ge"/> <input type="button" value="Si in GaAs"/>
$E_a - E_v = 0.045$	eV	
$T_1 = 50$	K	
$T_2 = 1000$	K	
<input type="button" value="Replot"/>		

[Source code](#)

E_f	n	p	N_d^+	N_a^-	T
0.0421442489848	2.40151024146E-36	1.42005993475E+16	1E+15	1.52148150693E+16	100
0.0432605499091	3.55188567934E-34	1.60496732529E+16	1E+15	1.70727565871E+16	104
0.0443992886238	3.6447725184E-32	1.79708501904E+16	1E+15	1.89867455992E+16	108
0.0455696761919	2.70091324524E-30	1.99342913907E+16	1E+15	2.0961617146E+16	112
0.046759290261	1.49291303432E-28	2.19530074854E+16	1E+15	2.29663635196E+16	116
0.0479826534344	6.34683409239E-27	2.39841986132E+16	1E+15	2.50167521691E+16	120
0.0492194372194	2.12451662366E-25	2.60634467518E+16	1E+15	2.70669670674E+16	124
0.0504951208621	5.73929239594E-24	2.81194143968E+16	1E+15	2.91550921724E+16	128

Fermi energy vs. temperature

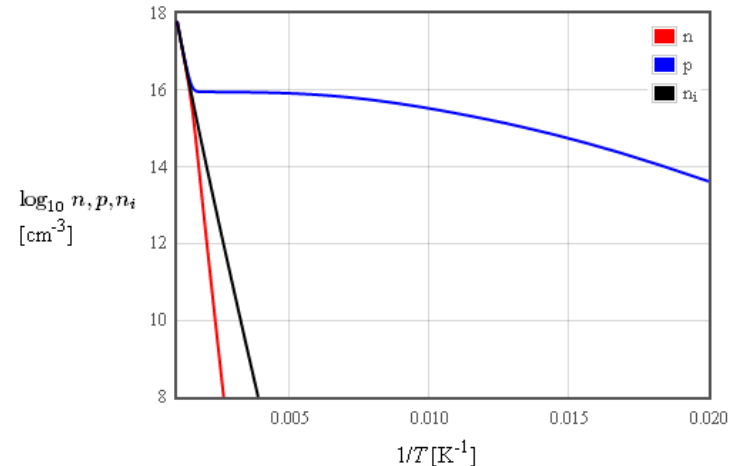
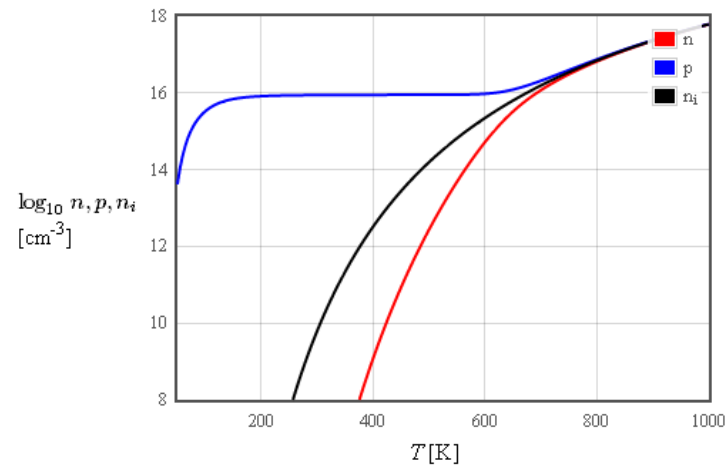
Fermi energy of an extrinsic semiconductor is plotted as a function of temperature. At each temperature the Fermi energy was calculated by requiring that [charge neutrality](#) be satisfied.



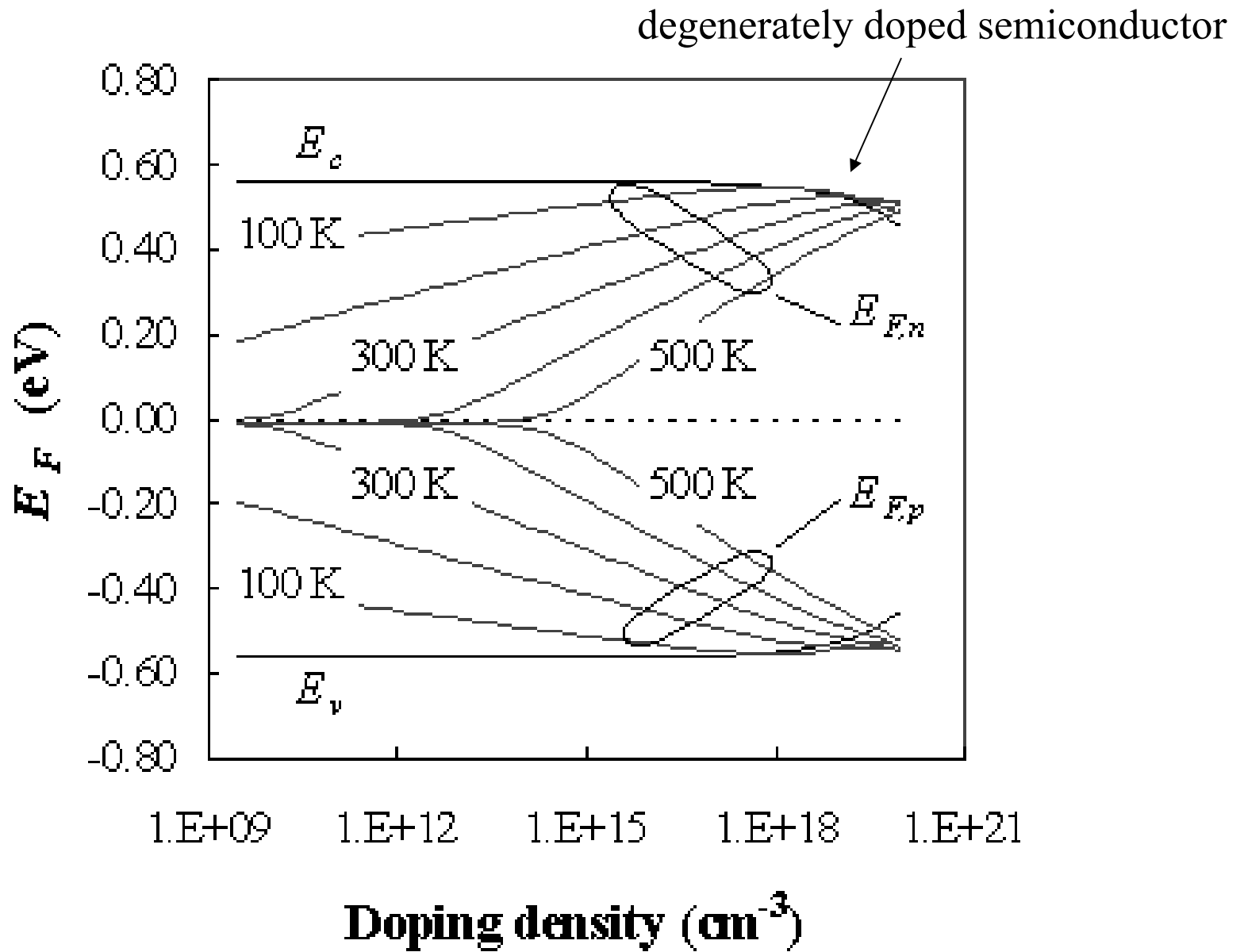
$N_c(300\text{ K}) = 2.78\text{E}19$	1/cm ³	Semiconductor <input type="button" value="Si"/> <input type="button" value="Ge"/> <input type="button" value="GaAs"/>
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$E_c - E_d = 0.045$	eV	
$N_a = 1\text{E}16$	1/cm ³	Acceptor <input type="button" value="B in Si"/> <input type="button" value="B in Ge"/> <input type="button" value="Si in GaAs"/>
$E_a - E_v = 0.045$	eV	
$T_1 = 50$	K	
$T_2 = 1000$	K	
<input type="button" value="Replot"/>		

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

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



<http://lamp.tu-graz.ac.at/~hadley/psd/L4/eftplot.html>



Degenerate semiconductor

Heavily doped semiconductors are called degenerately doped

$N_D > 0.1 N_c \rightarrow E_F$ in the conduction band

$N_A > 0.1 N_v \rightarrow E_F$ in the valence band

Heavy doping narrows the band gap

The Boltzmann approximation is not valid

Degenerate semiconductors = metal