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

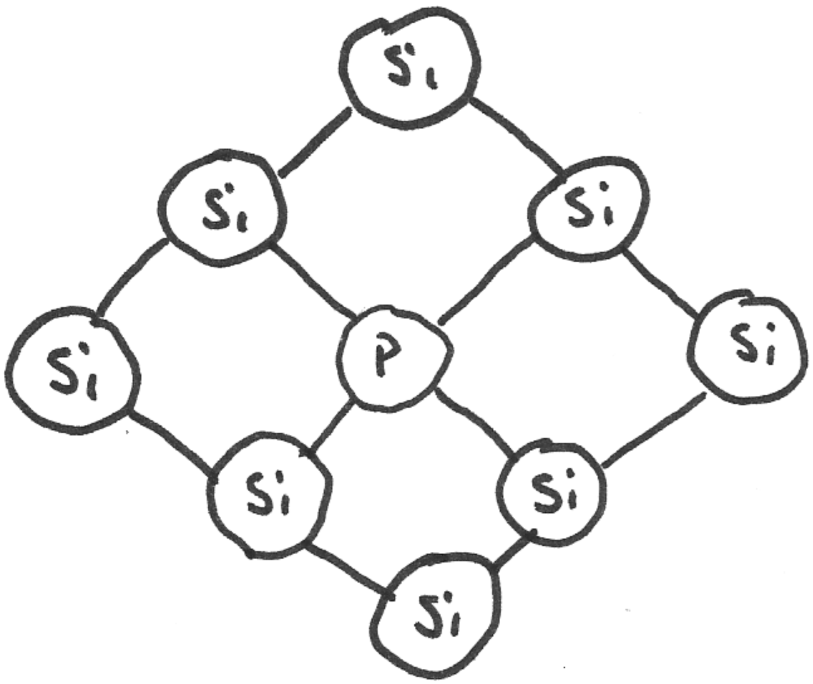
The electron density and hole density are:

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

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



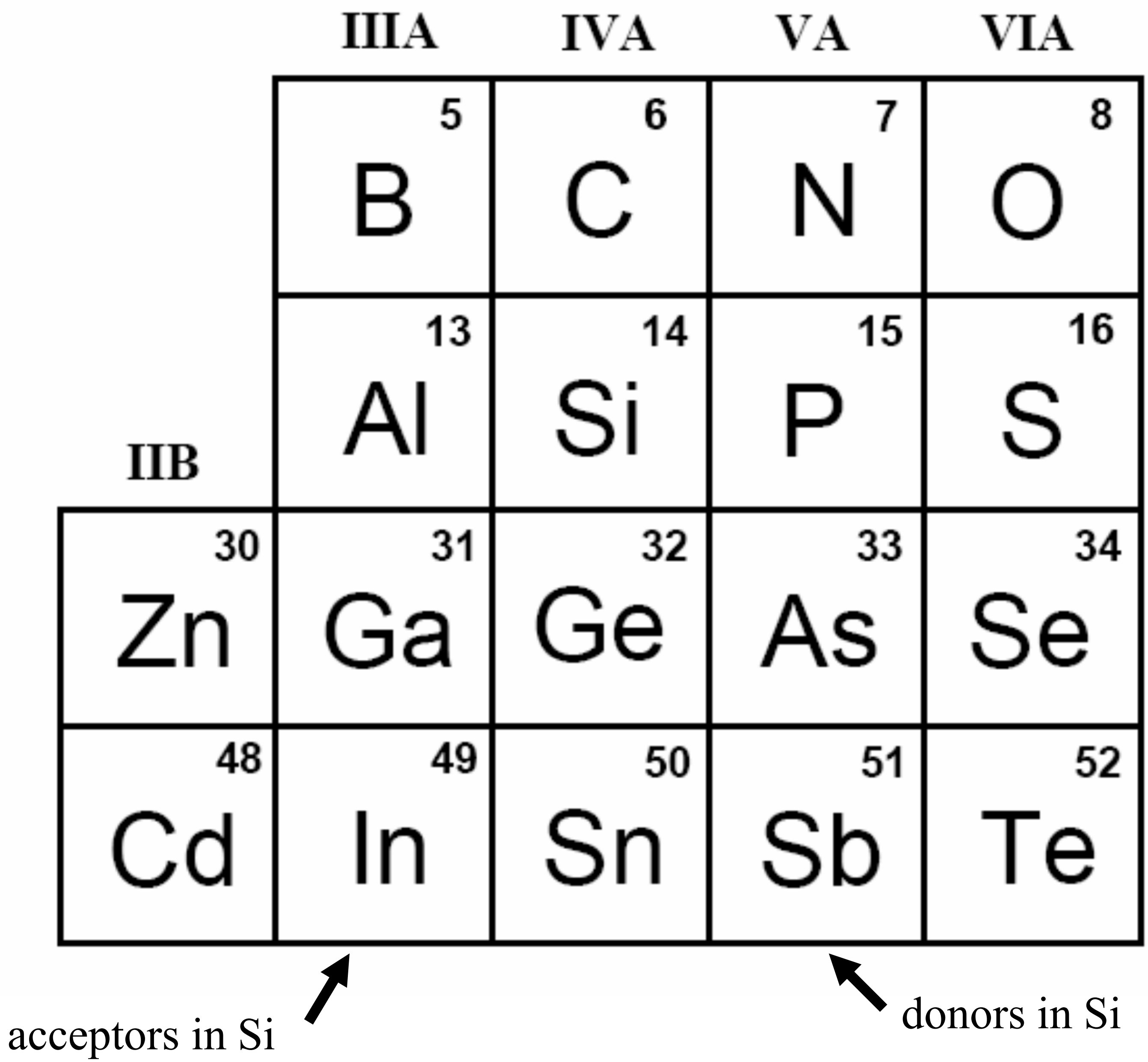
Easier to ionize a P atom in Si than a free P atom

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

Ionization energy is smaller by a factor:

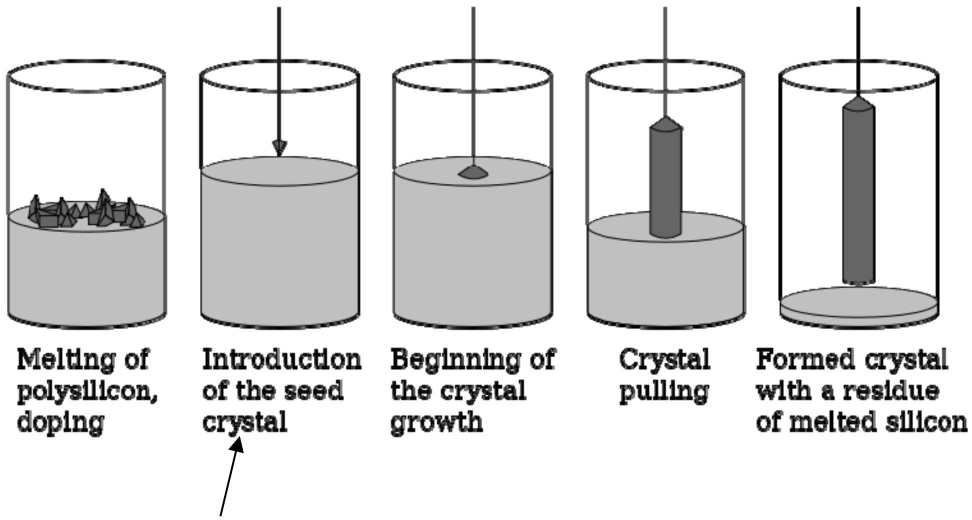
$$\frac{m^*}{m}\left(\frac{\varepsilon_0}{\varepsilon_r \varepsilon_0}\right)^2$$

Ionization energy ~ 25 meV


IIIA
IVA
VA
VIA
IIB
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
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

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

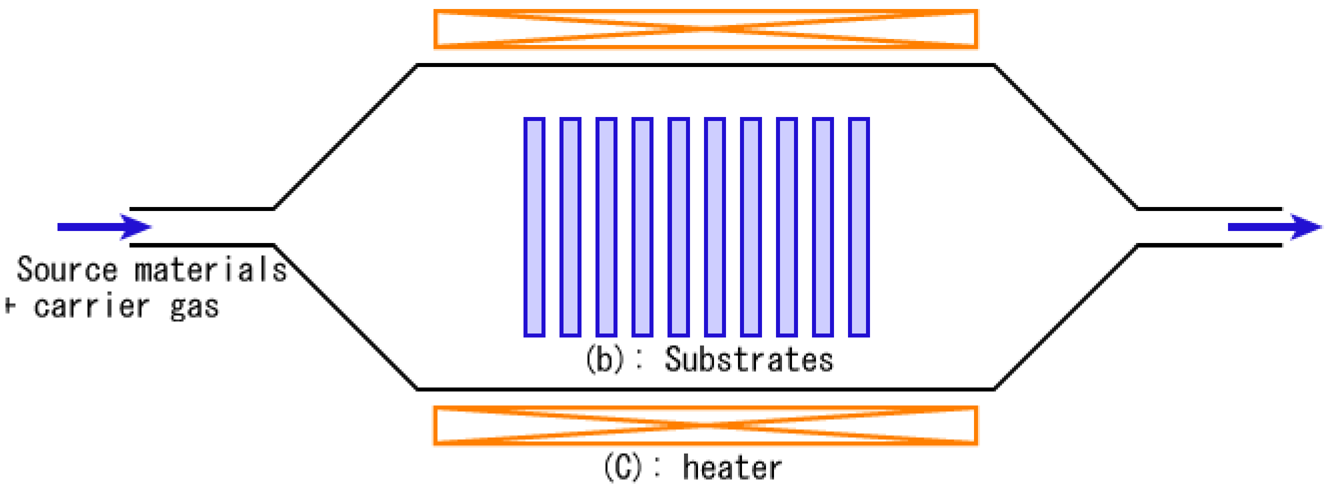
image from wikipedia

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

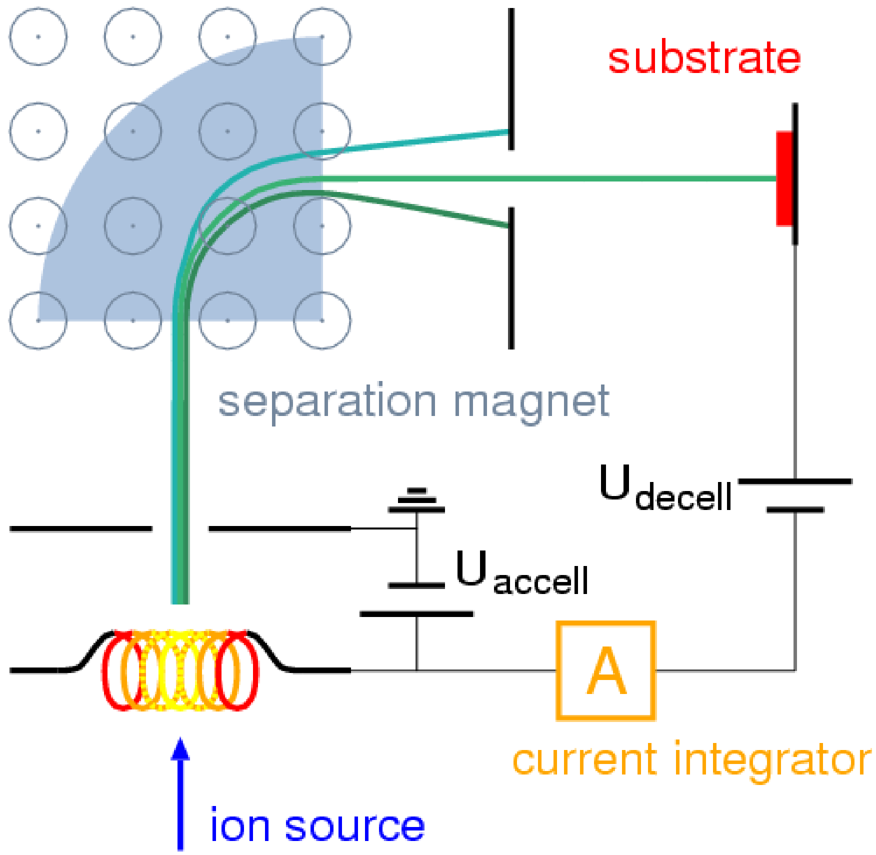
Chemical vapor deposition



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

Ion implantation

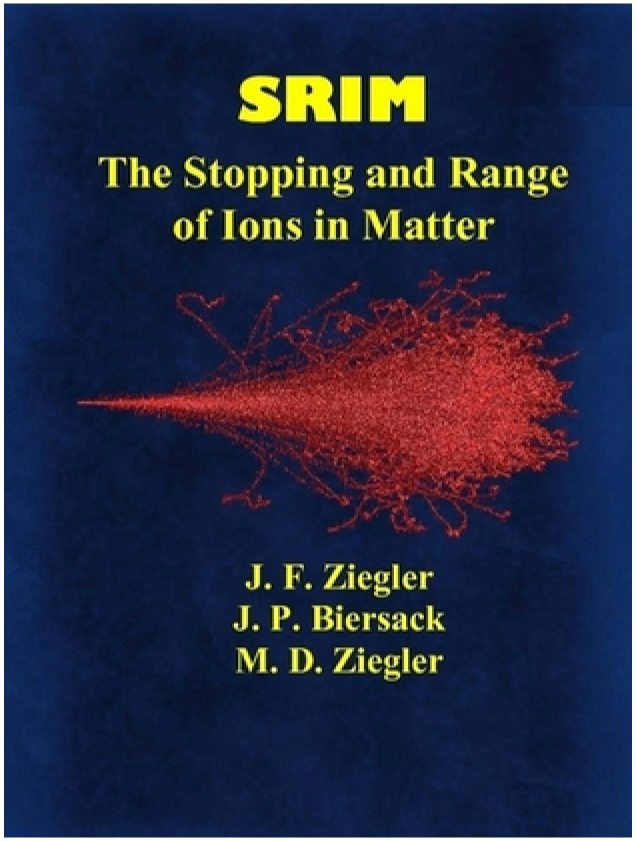


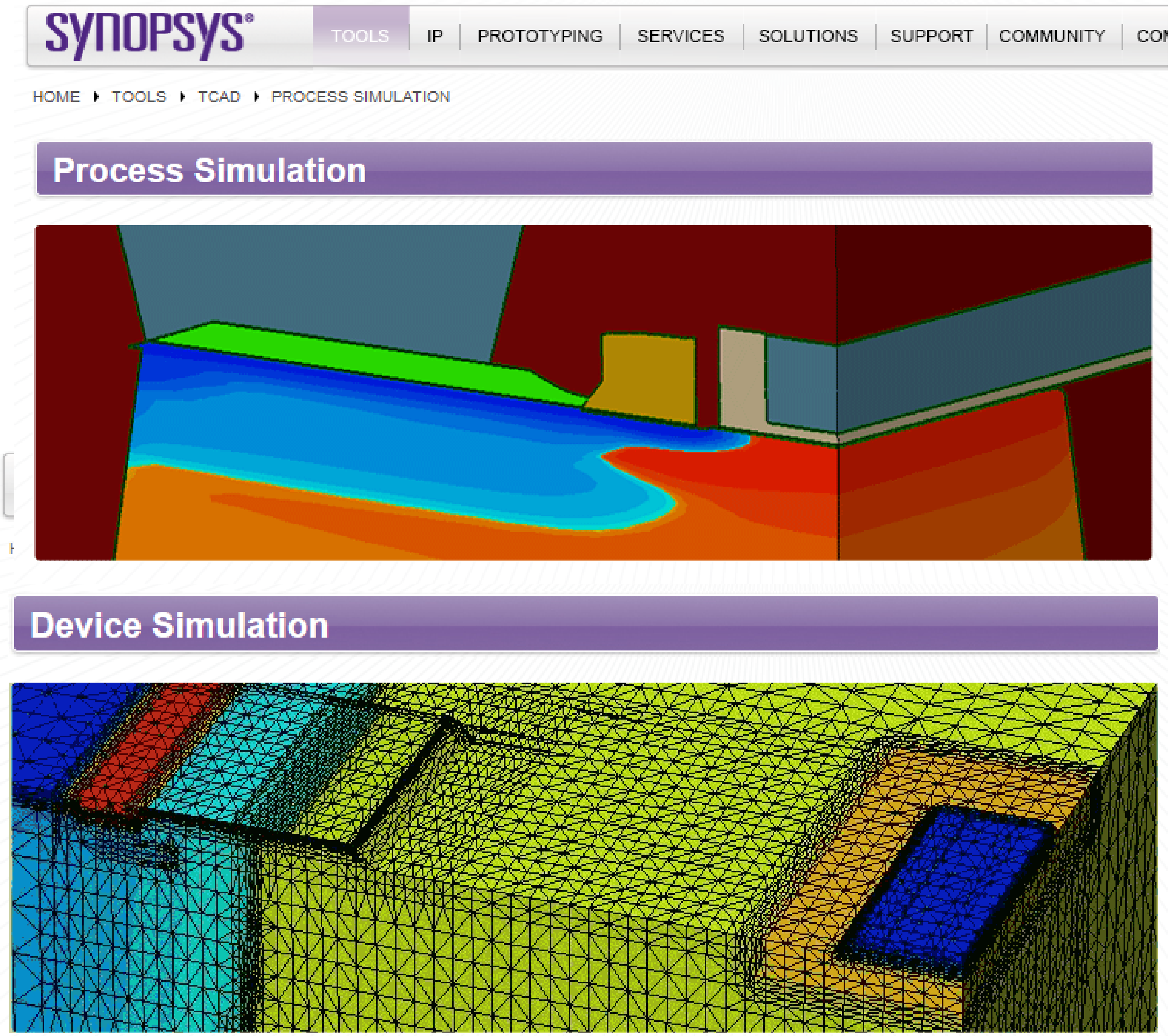
Implant at 7º to avoid channeling

SRIM

The Stopping and Range of Ions in Matter

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



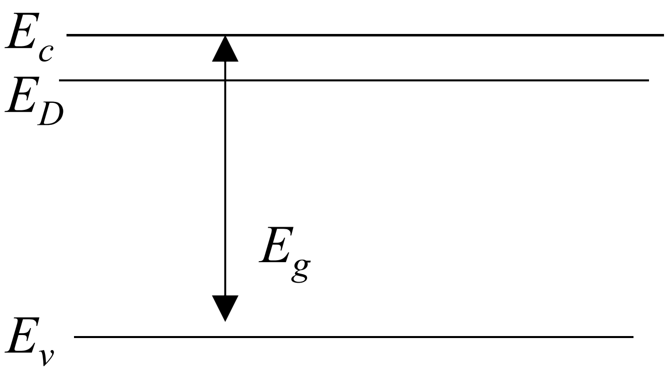


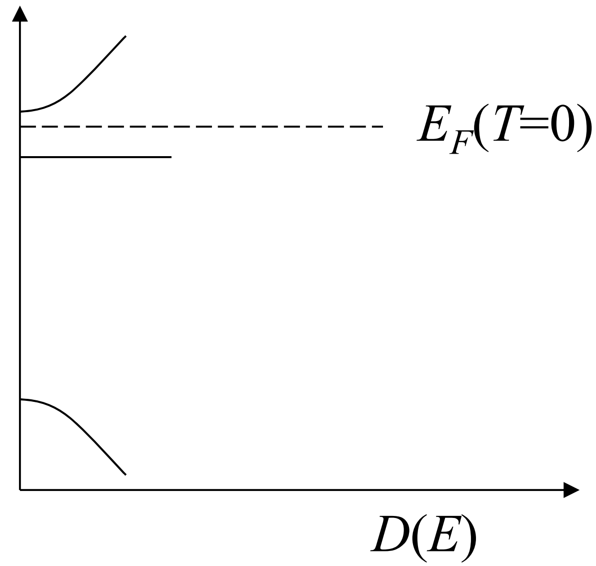
http://www.synopsys.com

Donors

Five valence electrons: P, As

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





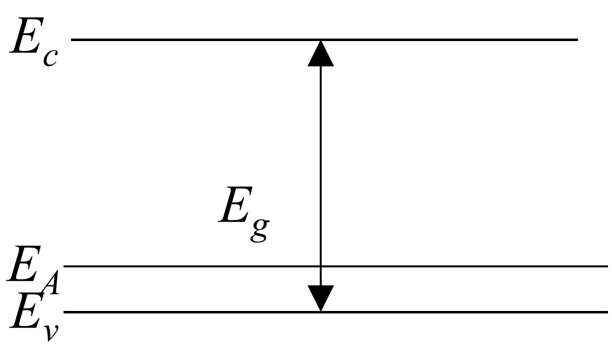
n-type: $n \sim N_D$ Many more electrons in the conduction band than holes in the valence band.

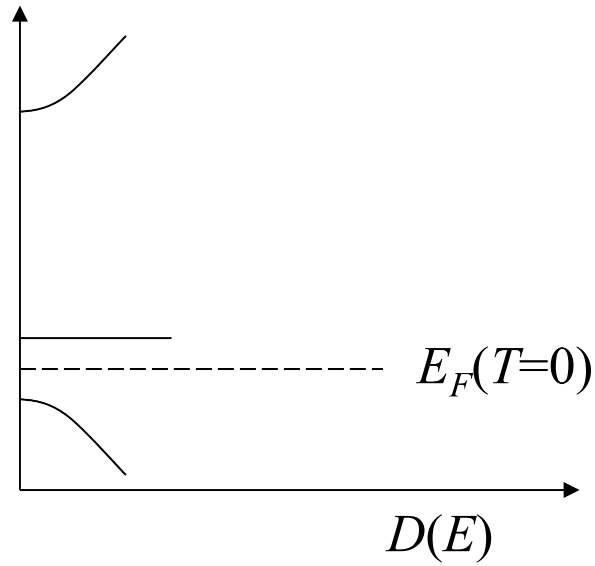
majority carriers: electrons; minority carriers: holes

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 Sb P As	33 39 45 54
Ge	Li Sb P As	9.3 9.6 12 13
GaAs	Si Ge S Sn	5.8 6.0 6.0 6.0

Energy below the conduction band

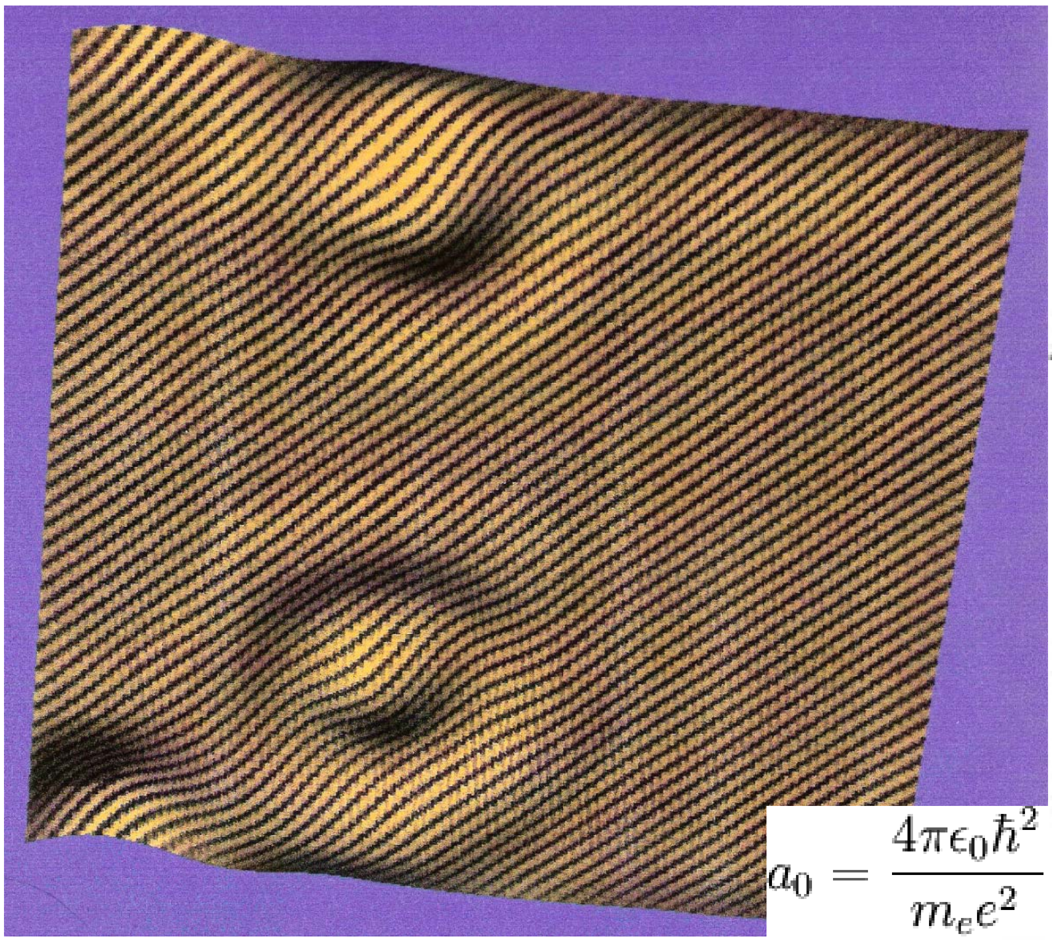
Semiconductor	Acceptor	Energy (meV)
Si	B Al Ga In	45 67 72 160
Ge	B Al Ga In	10 10 11 11
GaAs	C Be Mg Si	26 28 28 35

Energy above the valence band

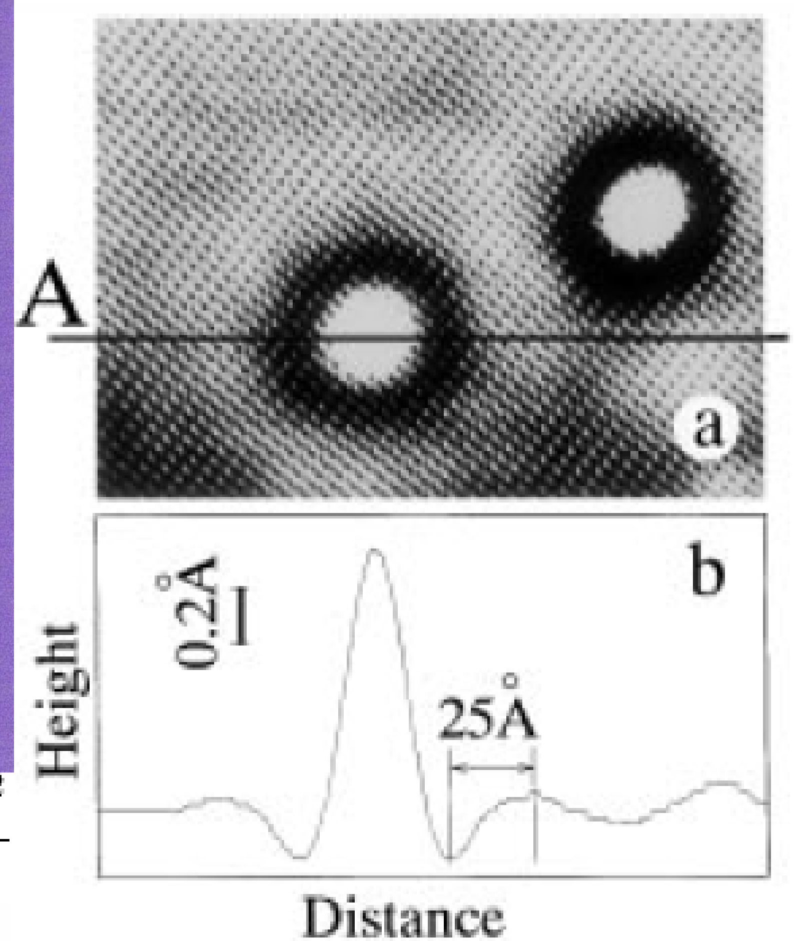
VOLUME 76, NUMBER 7 PHYSICAL REVIEW LETTERS 12 FEBRUARY 1996

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

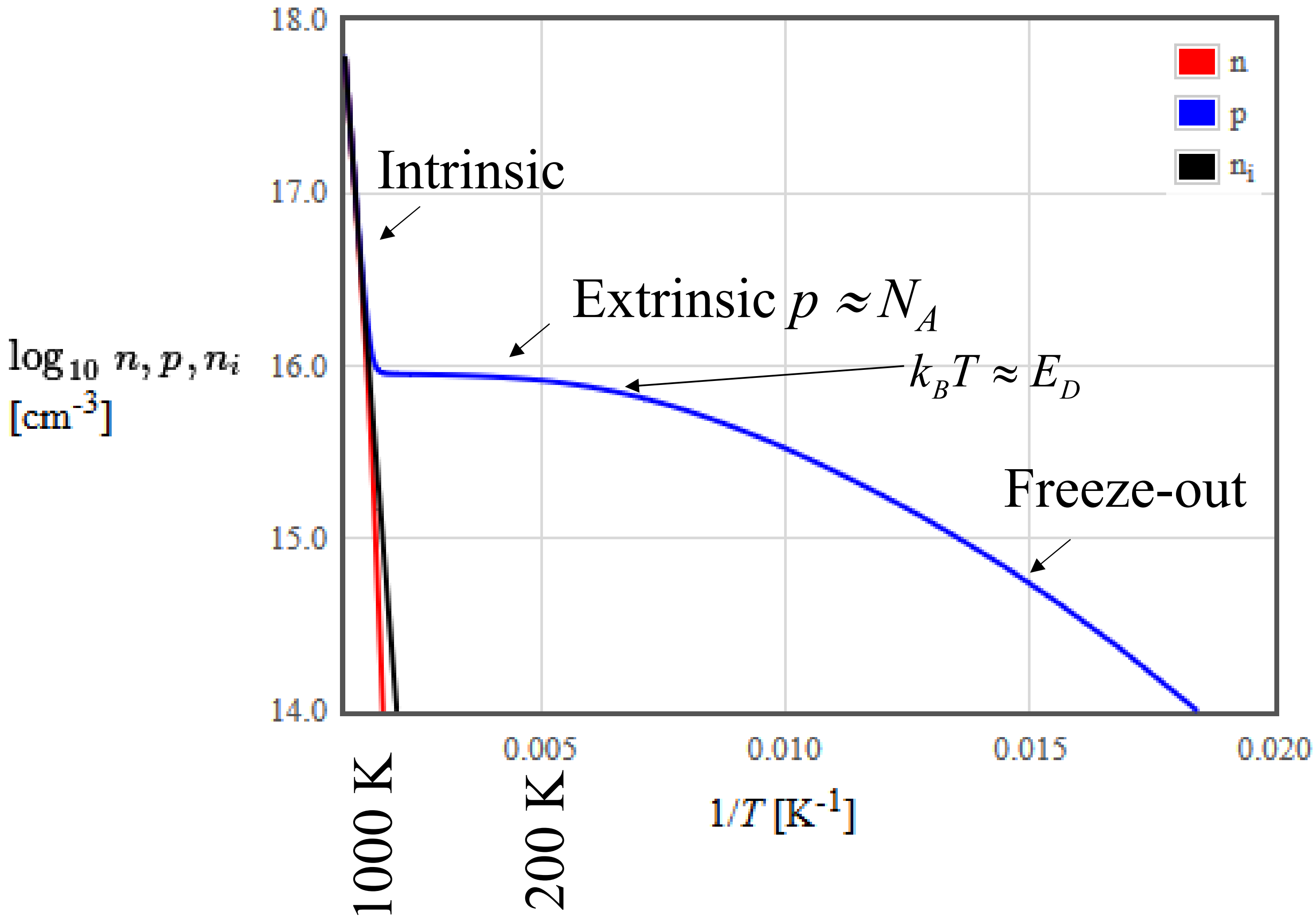
M. C. M. M. van der Wielen, A. J. A. van Roij, and H. van Kempen
Research Institute for Materials, University of Nijmegen, Toernooiveld 1, 6525 ED Nijmegen, The Netherlands
(Received 25 July 1995)



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



Temperature dependence



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Physics of Semiconductor Devices

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Temperature dependent conductivity

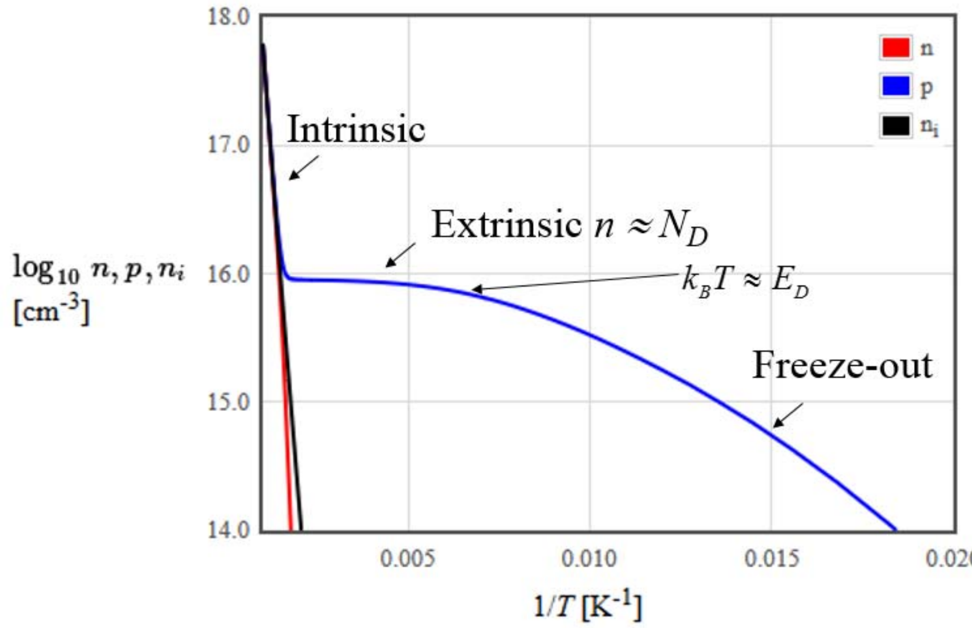
A doped semiconductor makes a transition from extrinsic behavior to intrinsic behavior when number of thermally activated charge carriers equals the number of dopants. What is this temperature for silicon doped with boron at 4E+17 cm^{-3}?

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

$T =$ [ ] K

Submit answer | Clear

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



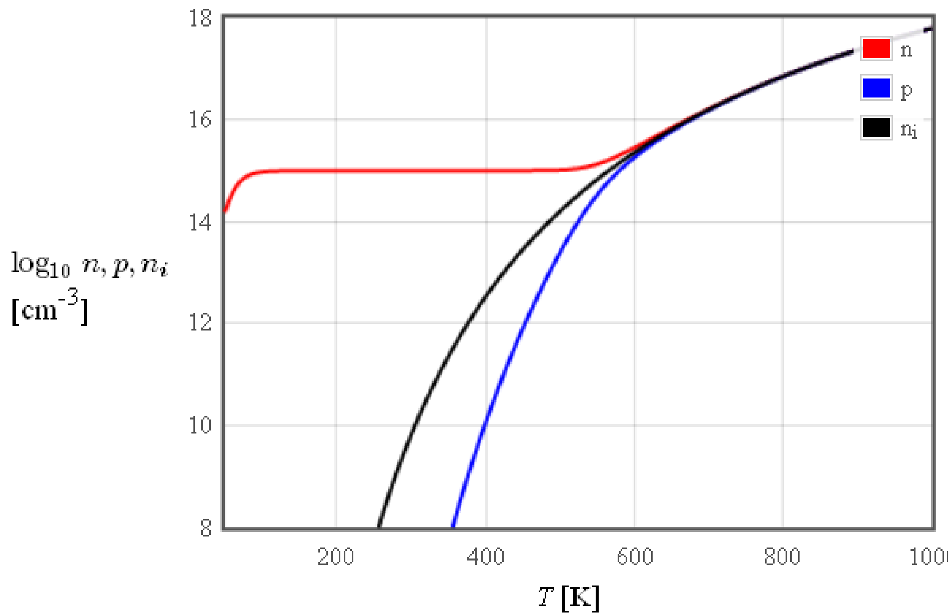
n-type

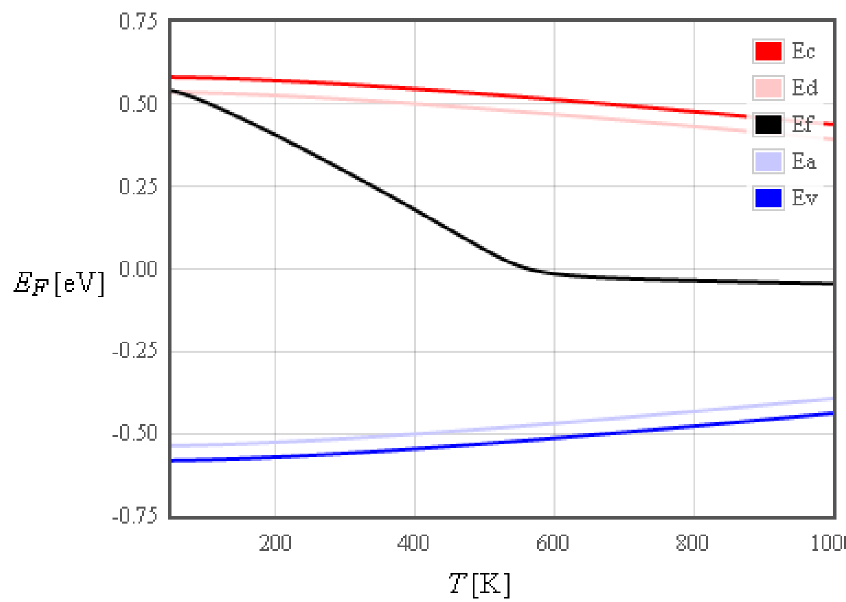
n-type $N_D > N_A$, $p \sim 0$

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

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

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





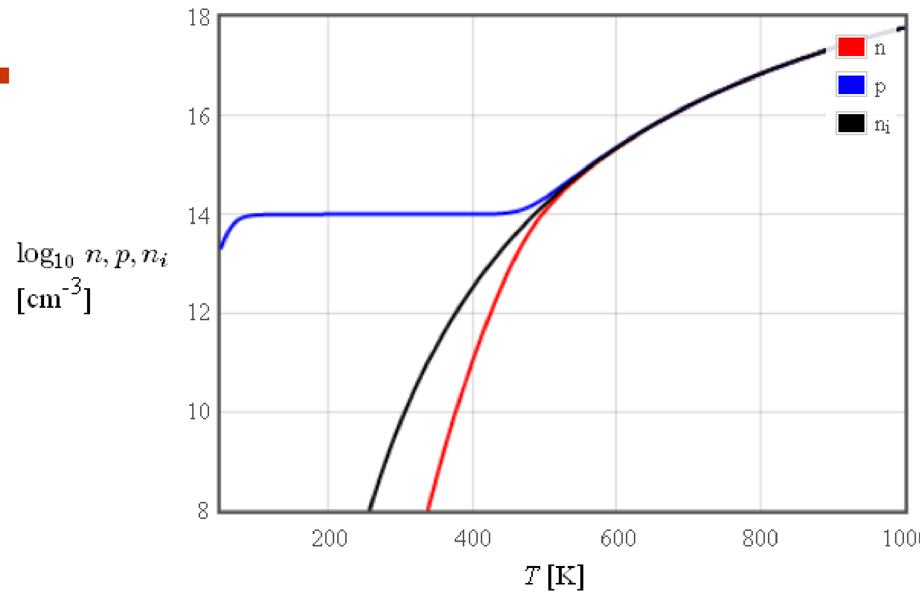
p-type

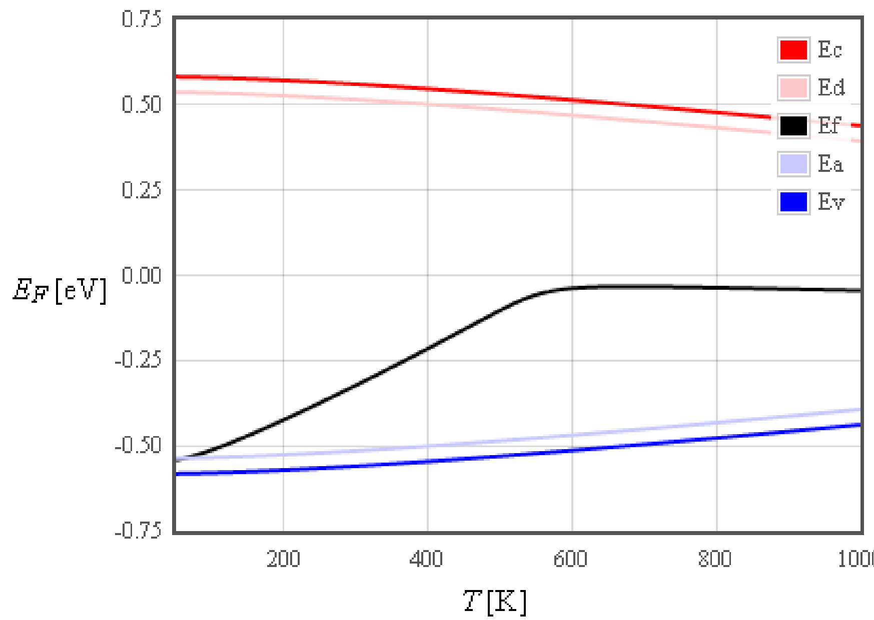
p-type $N_A > N_D$, $n \sim 0$

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

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

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





Intrinsic / Extrinsic

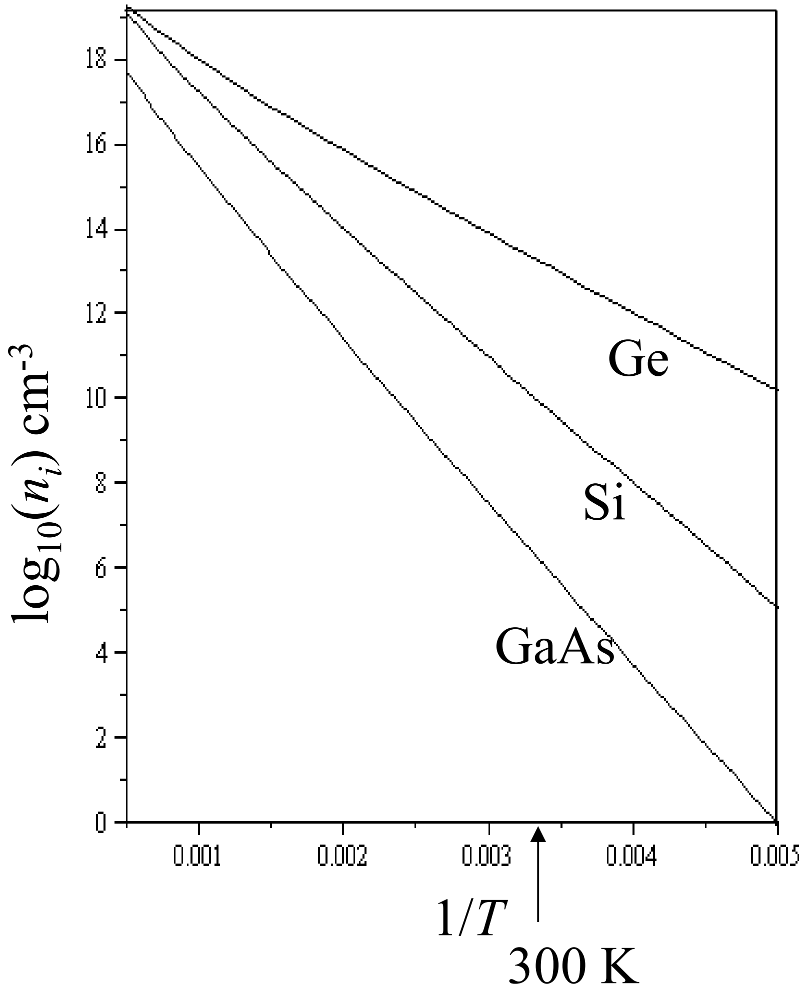
Intrinsic: $n = p$

Conductivity strongly temperature dependent near room temperature

Extrinsic: $n \neq p$

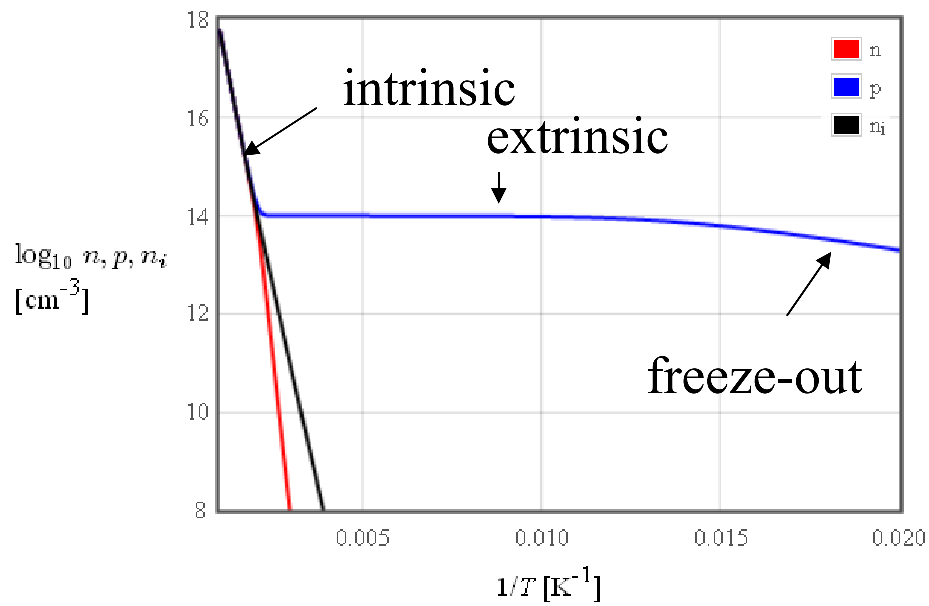
Conductivity almost temperature independent at room temperature

Intrinsic semiconductors



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

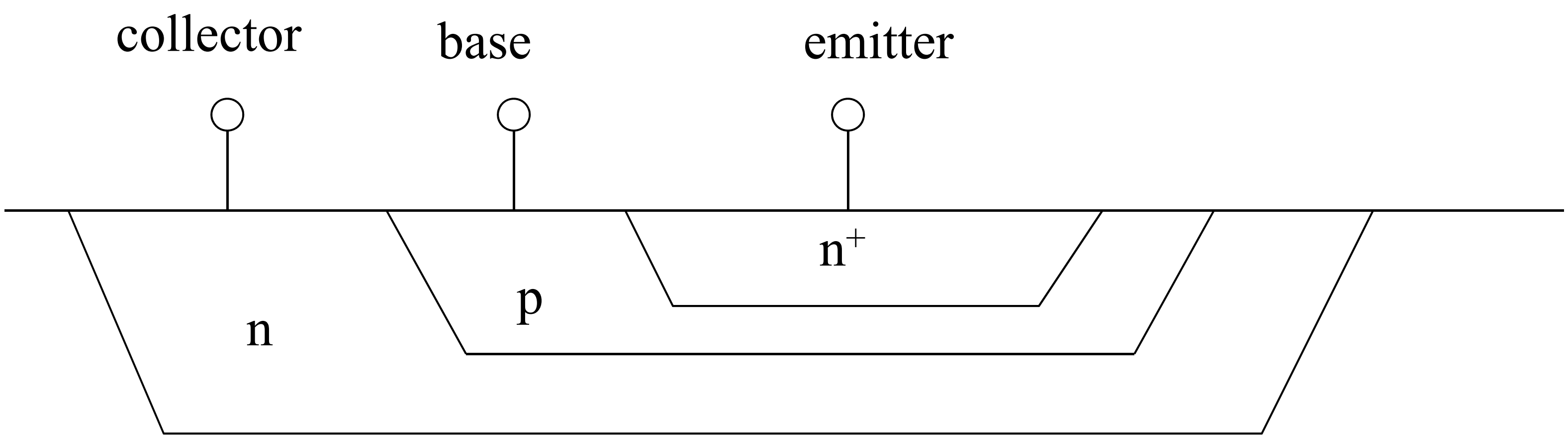
Extrinsic semiconductors



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

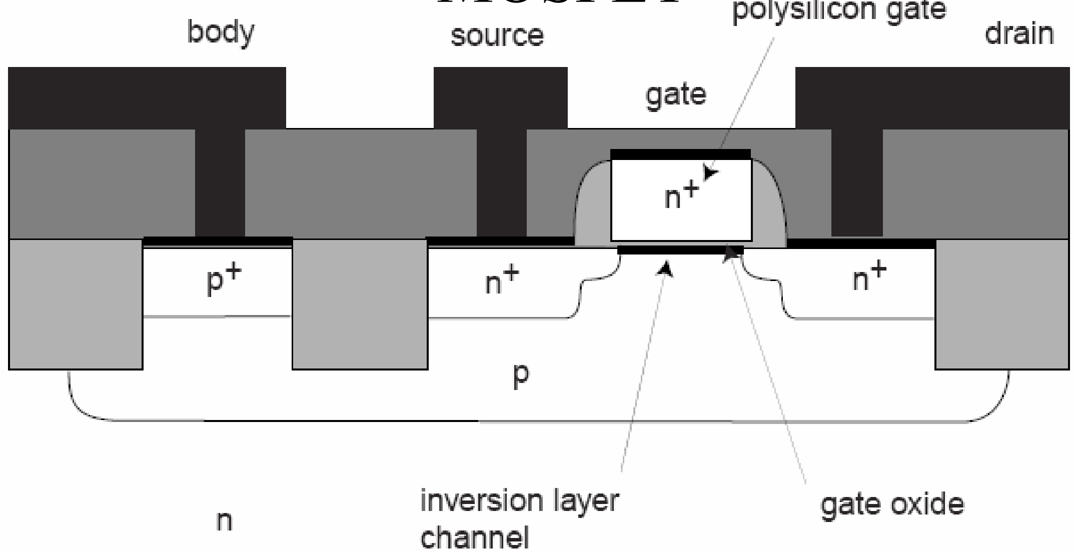
Why dope with donors AND acceptors?

Bipolar transistor

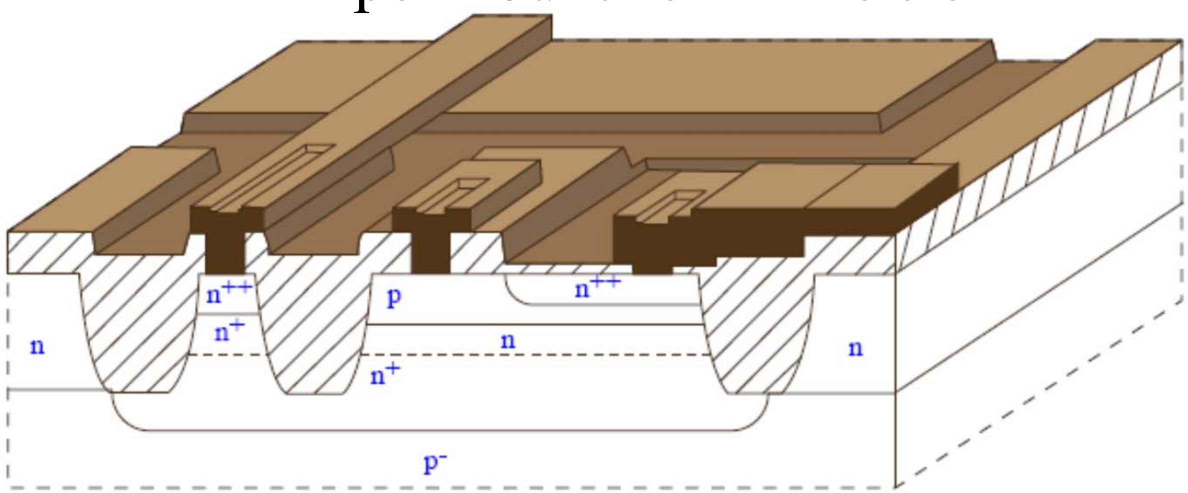


lightly doped p substrate

MOSFET



Bipolar Junction Transistor



Oxide isolated integrated BJT - a modern process

Ionized donors and acceptors

For $E_v + 3k_BT < E_F < E_c - 3k_BT$ Boltzmann approximation

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

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

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

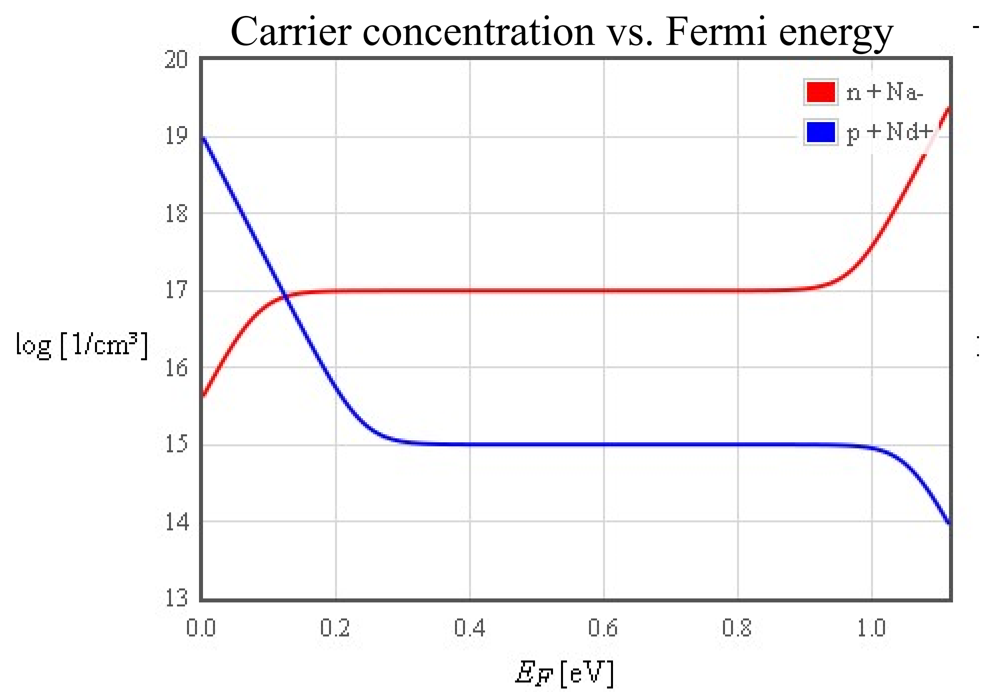
N_D = donor density cm^{-3} N_D^+ = ionized donor density cm^{-3}

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

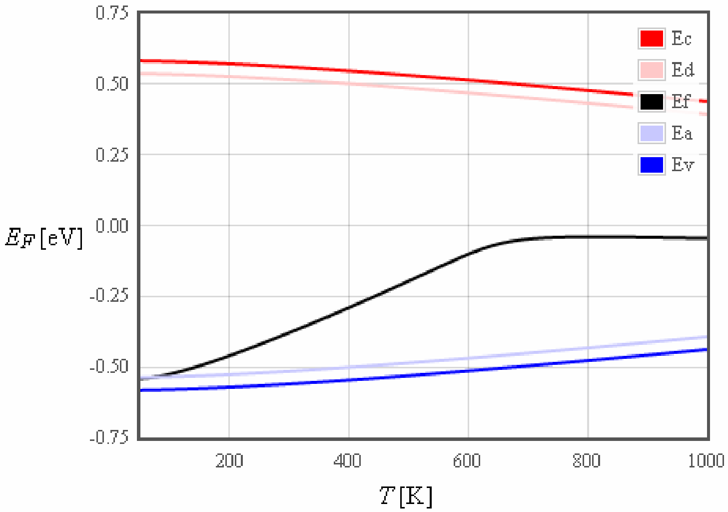
$$n + N_A^- = p + N_D^+$$

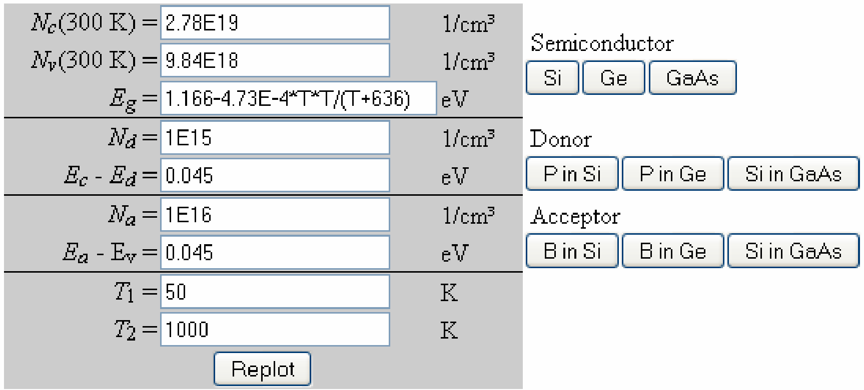



```
for ($i=0; $i<500; $i++) {
  $Ef = $i*$Eg/500;
  $n=$Nc*pow($T/300,1.5)*exp(1.6022E-19*($Ef-$Eg)/(1.38E-23*$T));
  $p=$Nv*pow($T/300,1.5)*exp(1.6022E-19*(-$Ef)/(1.38E-23*$T));
  $Namin = $Na/(1+4*exp(1.6022E-19*($Ea-$Ef)/(1.38E-23*$T)));
  $Ndplus = $Nd/(1+2*exp(1.6022E-19*($Ef-$Ed)/(1.38E-23*$T)));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

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	5.89319462781	6.95665936315E+18	1E+15	5.8356299025E+15	15.7660876957	18.8424631625

Calculating $E_F(T)$ numerically



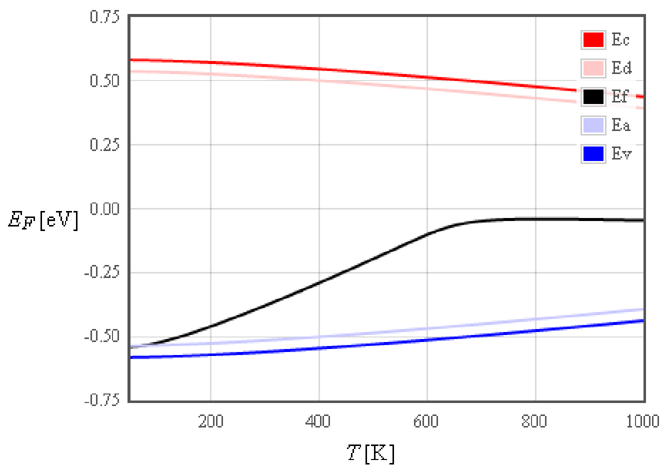


Source code

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

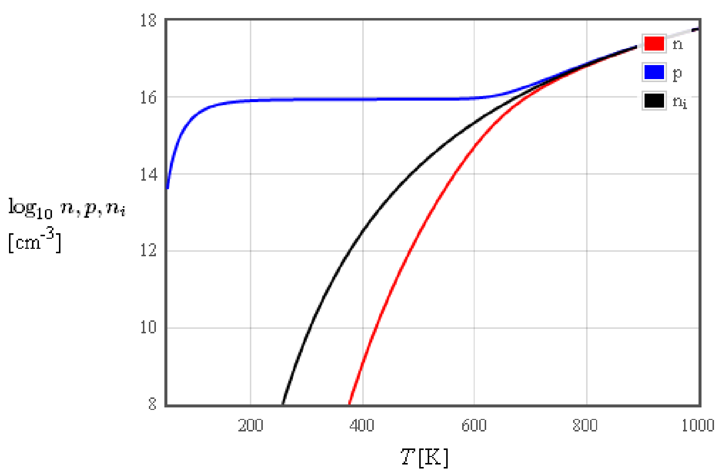
Fermi energy of an extrinsic semiconductor is plotted as a function of temperature. At each temperature the Fermi energy was calculated by requiring that charge neutrality be satisfied.

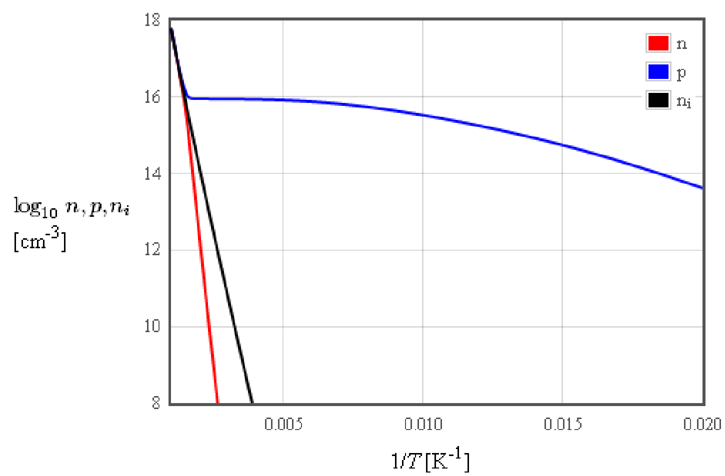


N_c(300 K) =	2.78E19	1/cm³	Semiconductor: Si, Ge, GaAs
N_v(300 K) =	9.84E18	1/cm³	
E_g =	1.166-4.73E-4*T*T/(T+636)	eV	
N_d =	1E15	1/cm³	Donor: P in Si, P in Ge, Si in GaAs
E_c - E_d =	0.045	eV	
N_a =	1E16	1/cm³	Acceptor: B in Si, B in Ge, Si in GaAs
E_a - E_v =	0.045	eV	
T_1 =	50	K	
T_2 =	1000	K	
Replot			

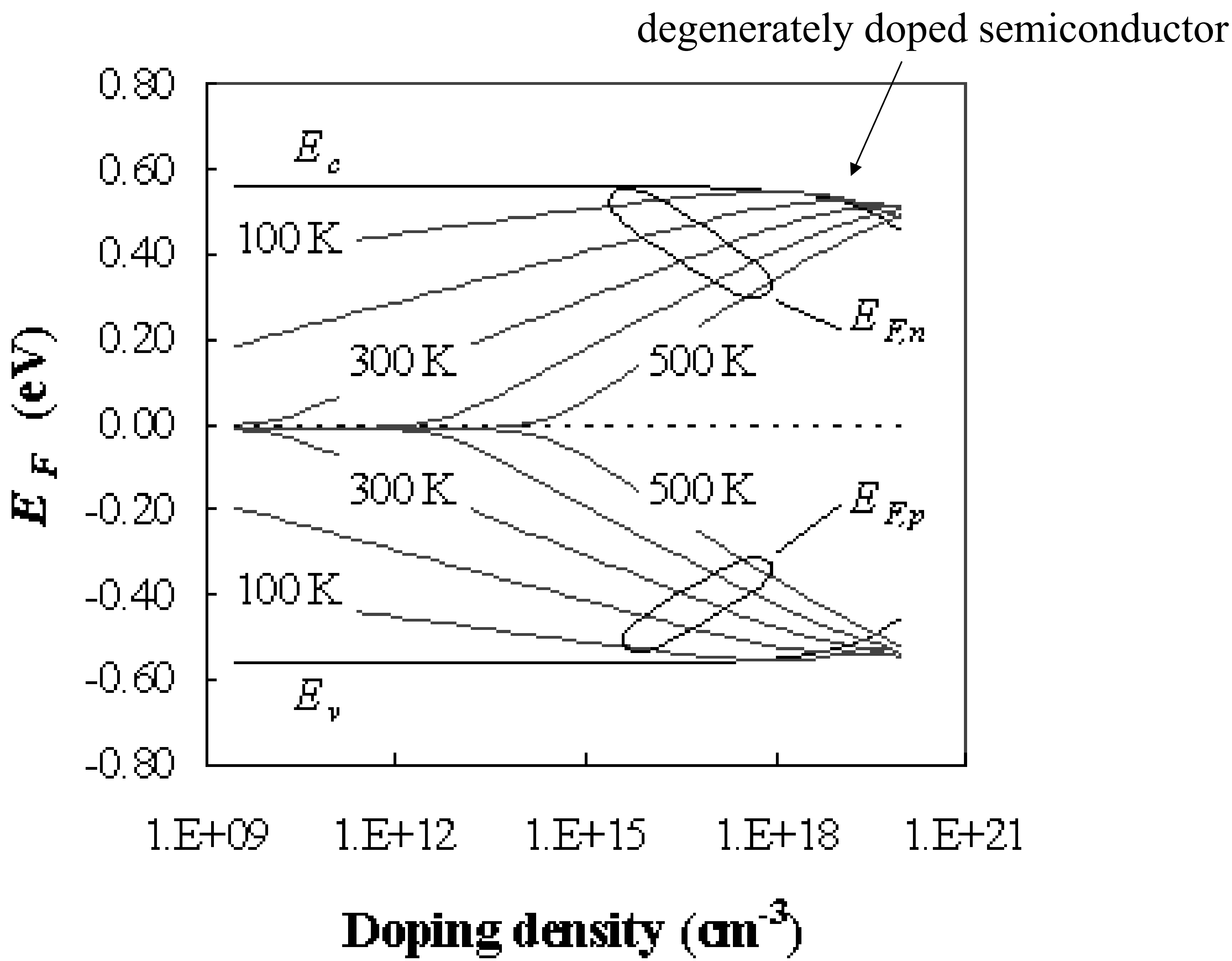
Once the Fermi energy is known, the carrier densities n and p can be calculated from the formulas, $n = N_c\left(\frac{T}{300}\right)^{3/2}\exp\left(\frac{E_F-E_c}{k_BT}\right)$ and $p = N_v\left(\frac{T}{300}\right)^{3/2}\exp\left(\frac{E_v-E_F}{k_BT}\right)$.

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





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



degenerately doped semiconductor
0.80
0.60
0.40
0.20
0.00
-0.20
-0.40
-0.60
-0.80
E_F (eV)
E_c
E_v
100 K
300 K
500 K
E_Fn
E_Fp
1.E+09
1.E+12
1.E+15
1.E+18
1.E+21
Doping density (cm^-3)

Degenerate semiconductor

Heavily doped semiconductors are called degenerately doped

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

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

Heavy doping narrows the band gap

The Boltzmann approximation is not valid

Degenerate semiconductors = metal

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Physics of Semiconductor Devices

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Carriers in a doped semiconductor

Silicon is doped n-type at 2E+18 cm^{-3} and p-type at 3E+16 cm^{-3}. Asumming that all of the dopants are ionized, what is the density of electrons in the conduction band and the density of holes in the valence band?

$n =$ [ ] cm^{-3}

$p =$ [ ] cm^{-3}

Submit answer | Clear

For silicon, $n_i = 1.5 \times 10^{10}$ cm^{-3} at 300 K.

Carrier Transport

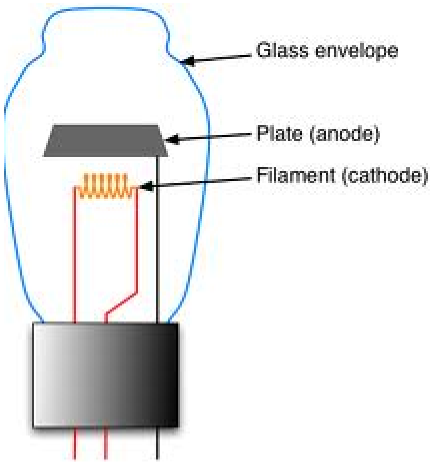
Ballistic transport
Drift
Diffusion
Generation and recombination
The continuity equation
High field effects

Ballistic transport

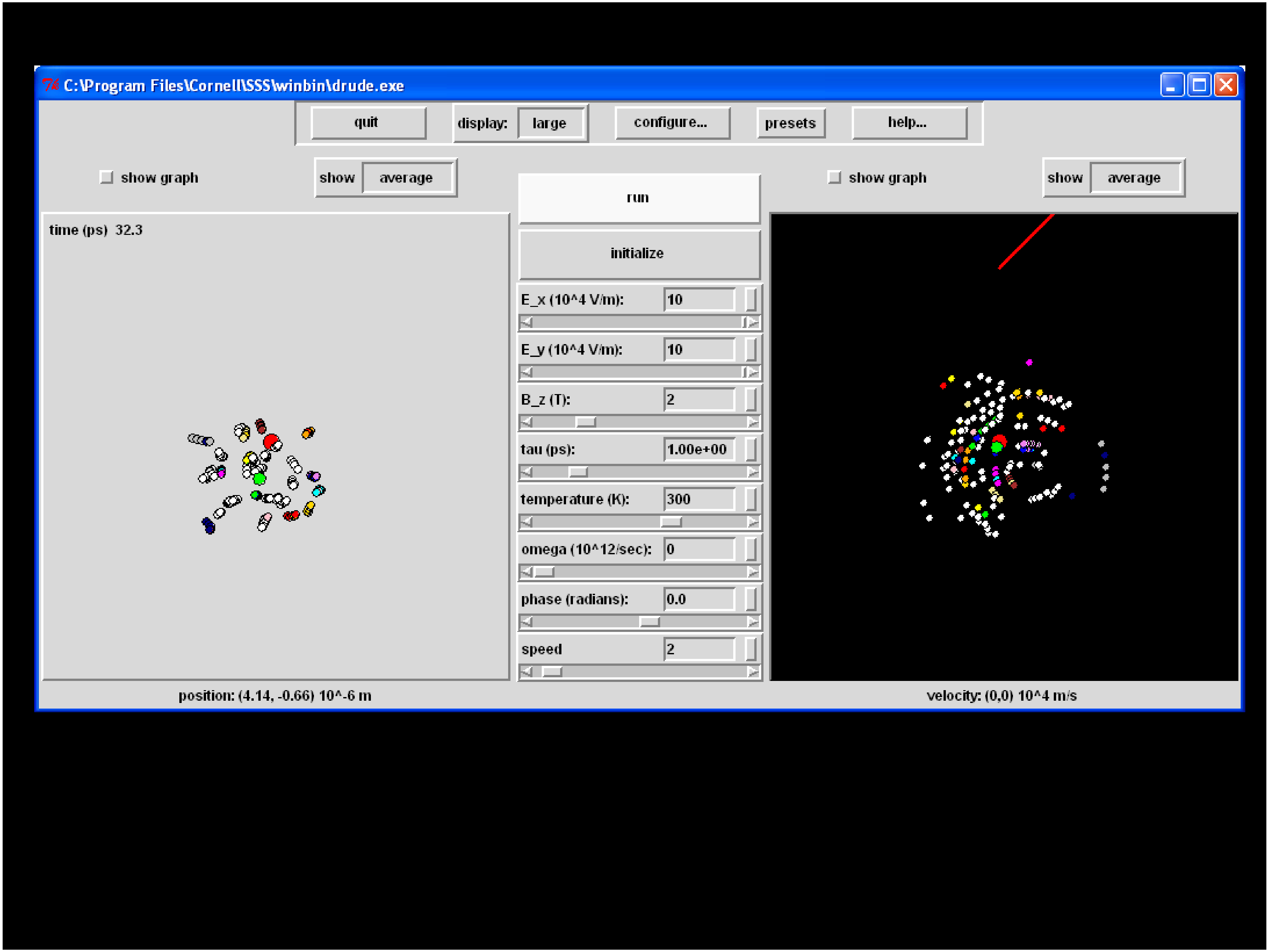
$$\vec{F} = m\vec{a} = -e\vec{E} = m\frac{d\vec{v}}{dt}$$

$$\vec{v} = \frac{-e\vec{E}t}{m} + \vec{v}_0$$

$$\vec{x} = \frac{-e\vec{E}t^2}{2m} + \vec{v}_0 t + \vec{x}_0$$



Electrons moving in an electric field follow parabolic trajectories like a ball in a gravitational field.


C:\Program Files\Cornell\SSS\winbin\drude.exe
quit
display:
large
configure...
presets
help...
show graph
show
average
run
initialize
show graph
show
average
time (ps) 32.3
E_x (10^4 V/m):
10
E_y (10^4 V/m):
10
B_z (T):
2
tau (ps):
1.00e+00
temperature (K):
300
omega (10^12/sec):
0
phase (radians):
0.0
speed
2
position: (4.14, -0.66) 10^-6 m
velocity: (0,0) 10^4 m/s