Extrinsic Semiconductors

Carrier Transport

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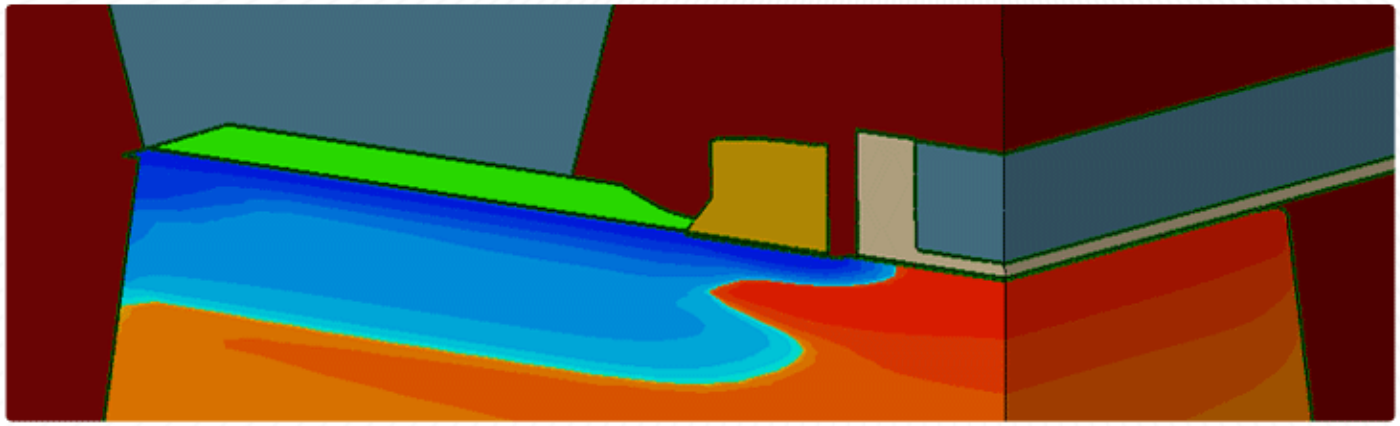
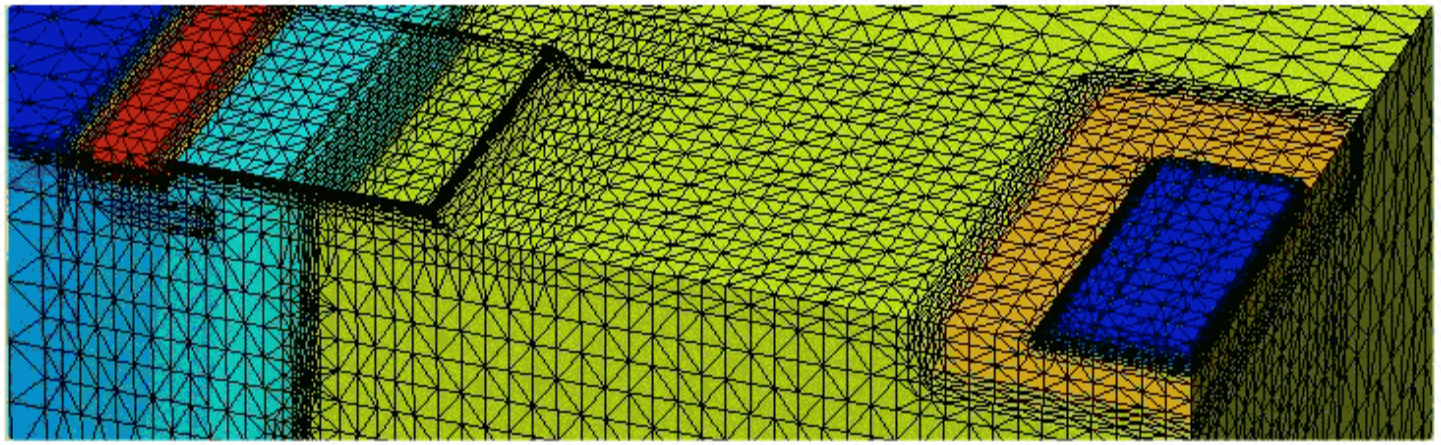
Process Simulation



Device Simulation

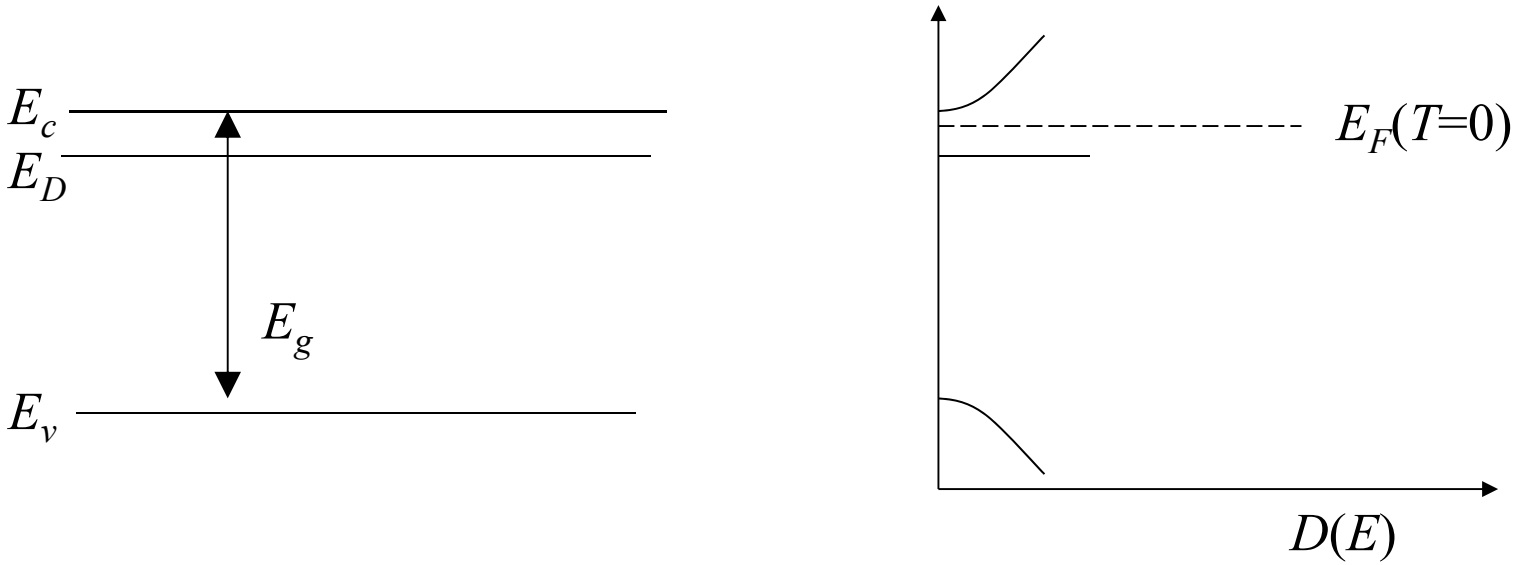


http://www.synopsys.com

Donors

Five valence electrons: P, As

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



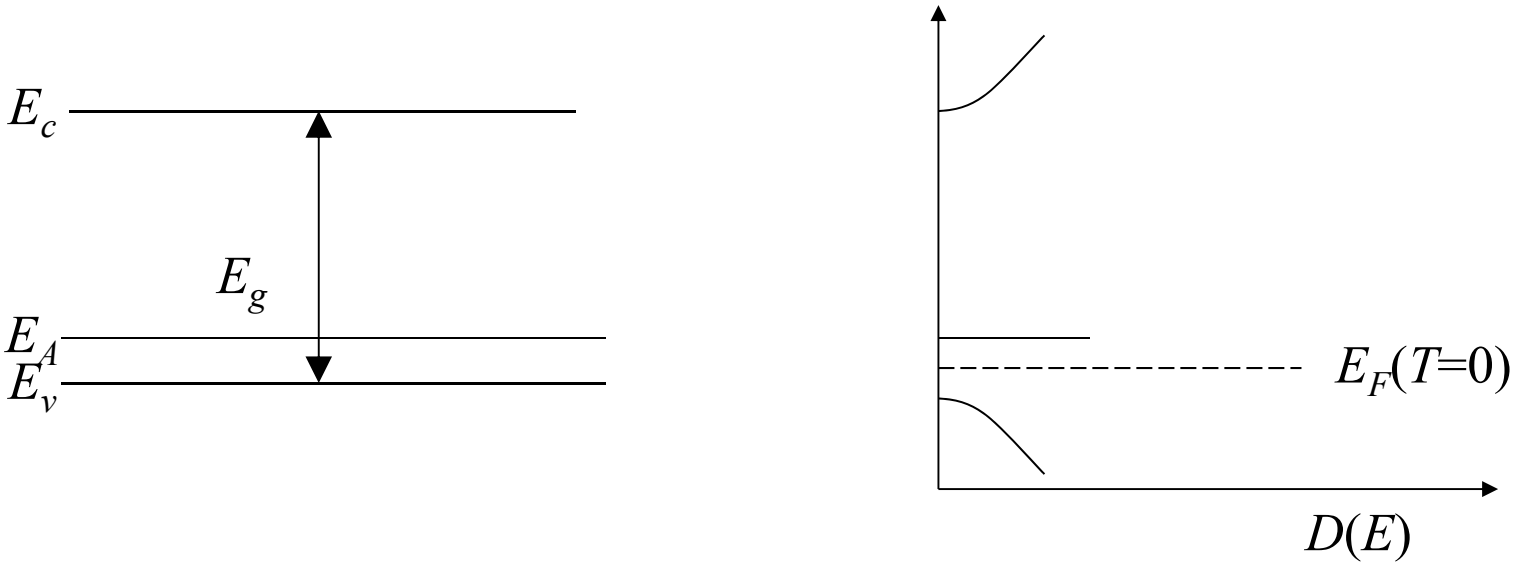
n-type: $n \sim N_D$ Many more electrons in the conduction band than holes in the valence band.

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	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

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

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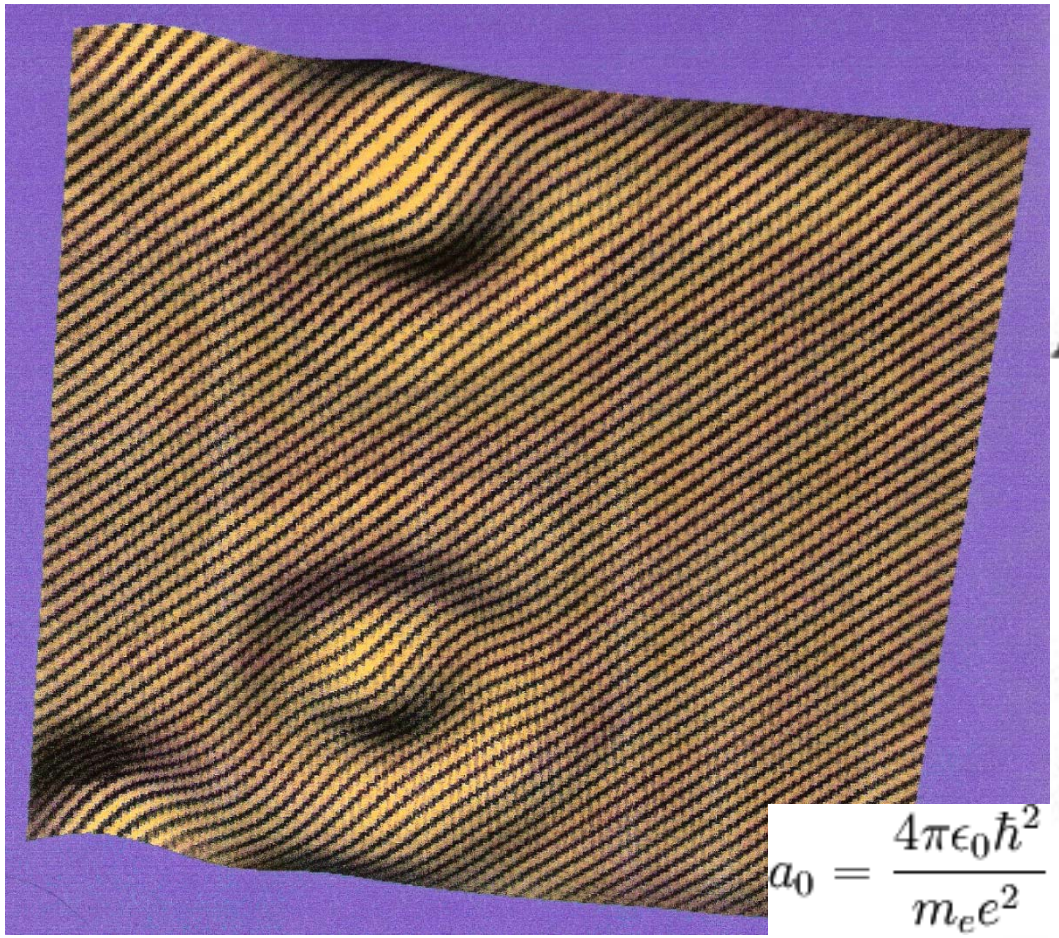
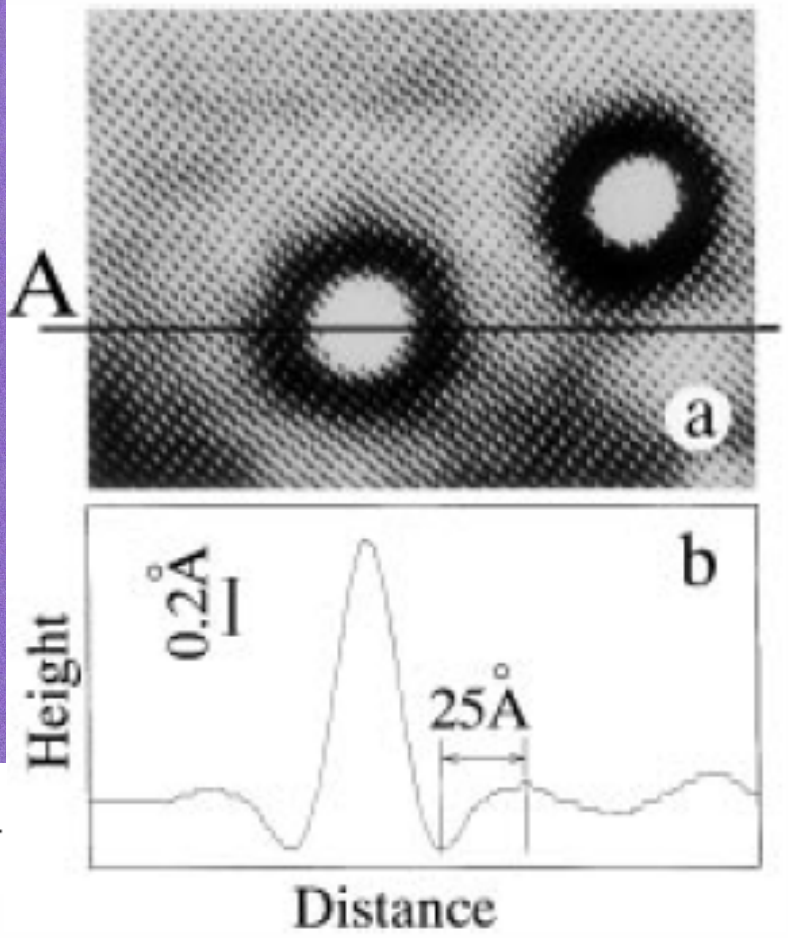
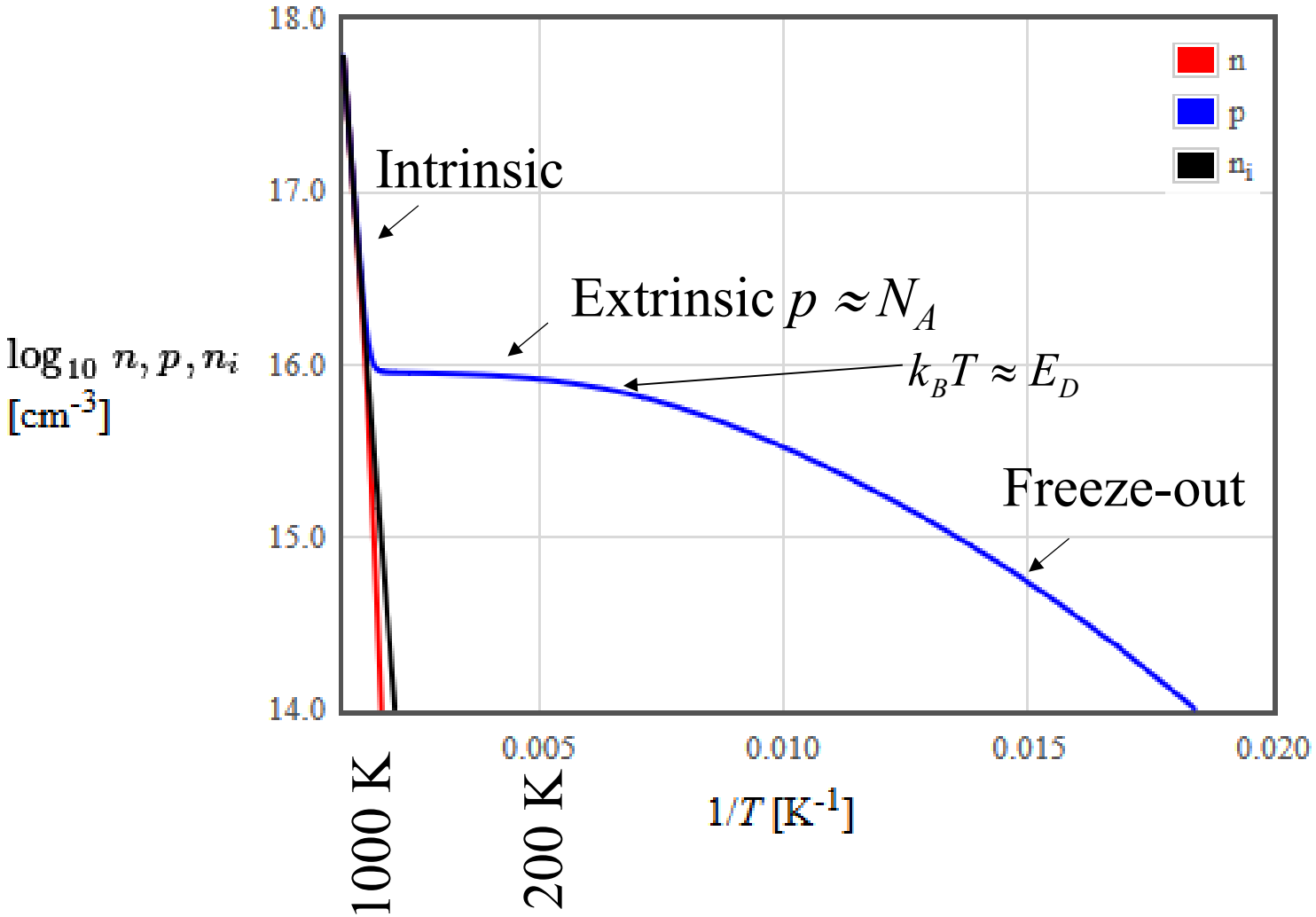
Research Institute for Materials, University of Nijmegen, Toernooiveld 1, 6525 ED Nijmegen, The Netherlands
(Received 25 July 1995)



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



Temperature dependence



Temperature dependent conductivity

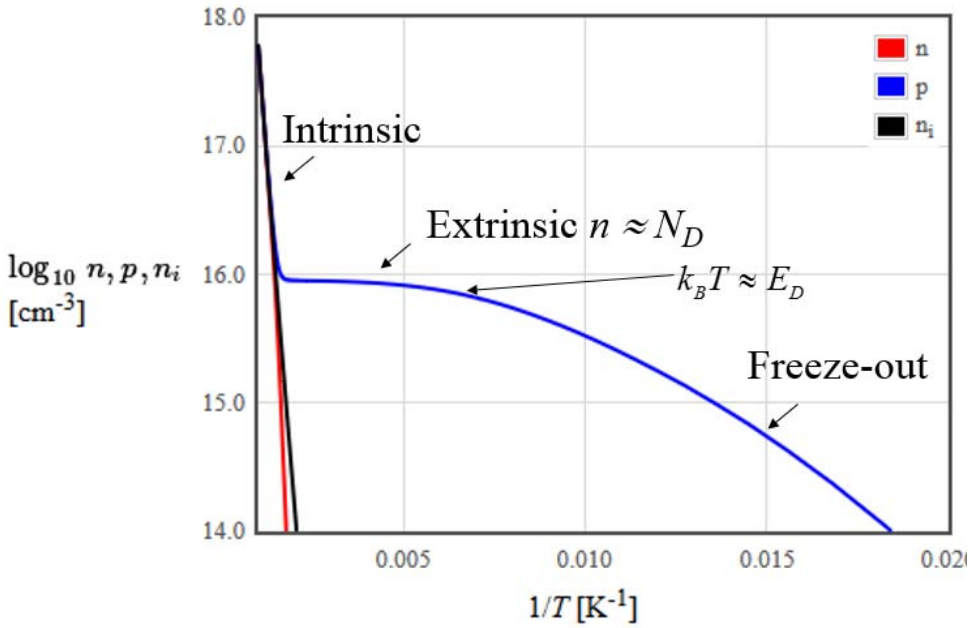
A doped semiconductor makes a transition from extrinsic behavior to intrinsic behavior when number of thermally activated charge carriers equals the number of dopants. What is this temperature for silicon doped with boron at 4E+17 cm^{-3}?

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

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



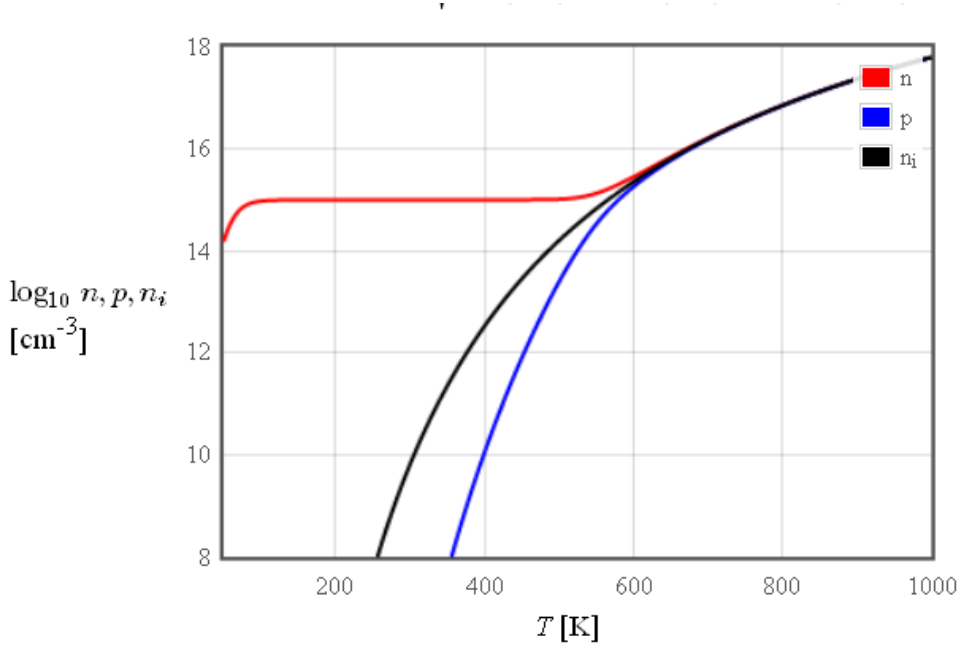
n-type

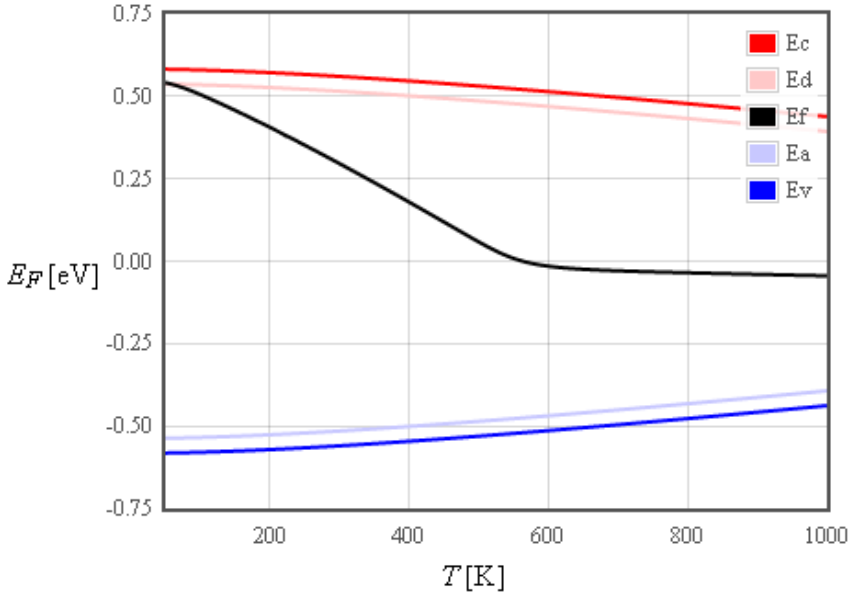
n-type $N_D > N_A$, $p \sim 0$

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

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

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





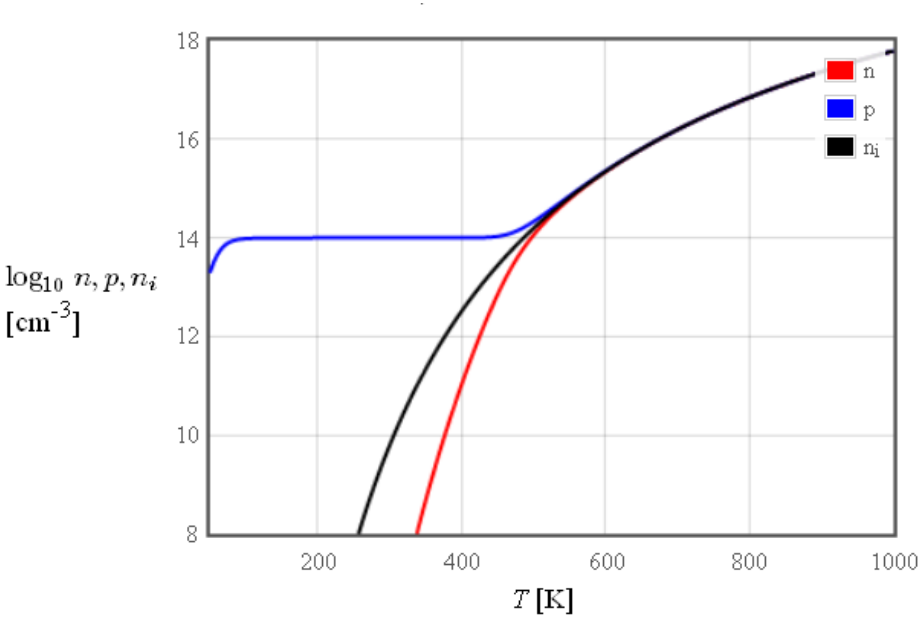
p-type

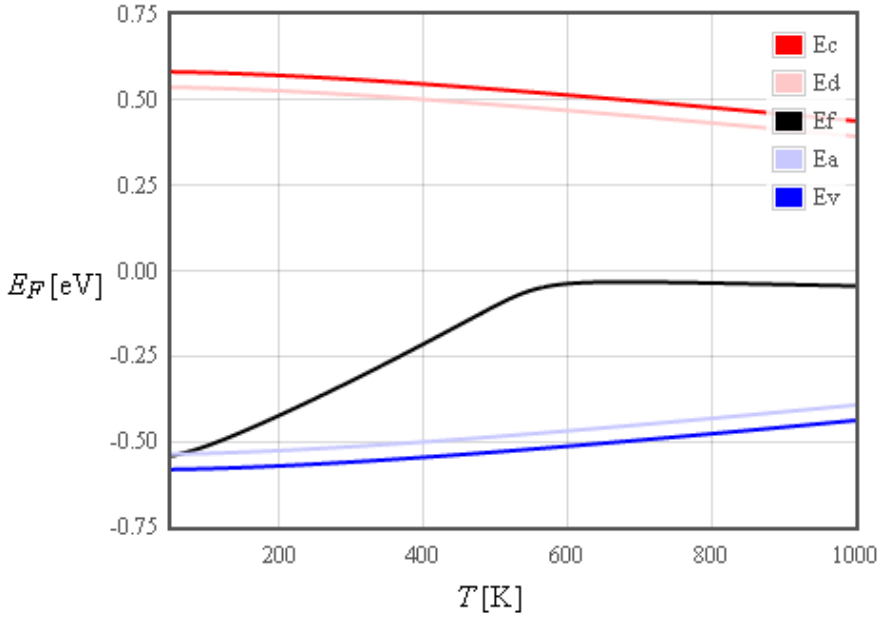
p-type $N_A > N_D$, $n \sim 0$

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

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

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





Intrinsic / Extrinsic

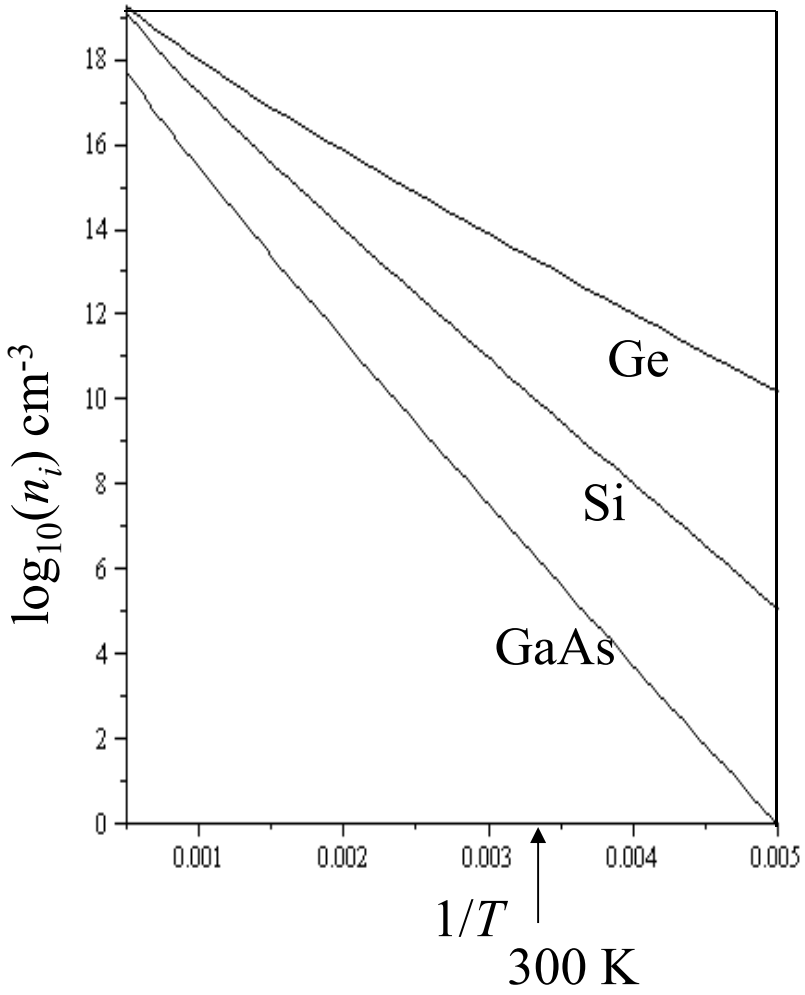
Intrinsic: $n = p$

Conductivity strongly temperature dependent near room temperature

Extrinsic: $n \neq p$

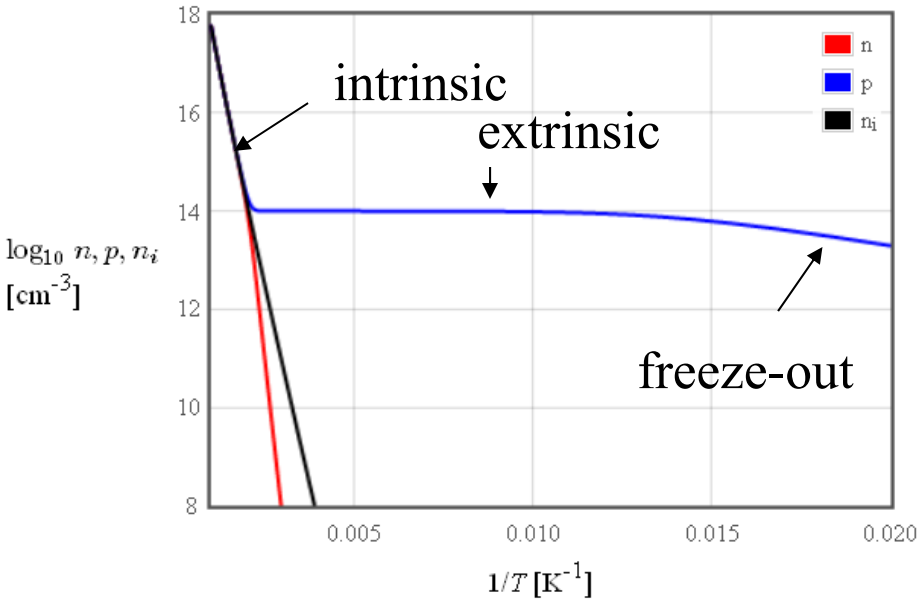
Conductivity almost temperature independent at room temperature

Intrinsic semiconductors



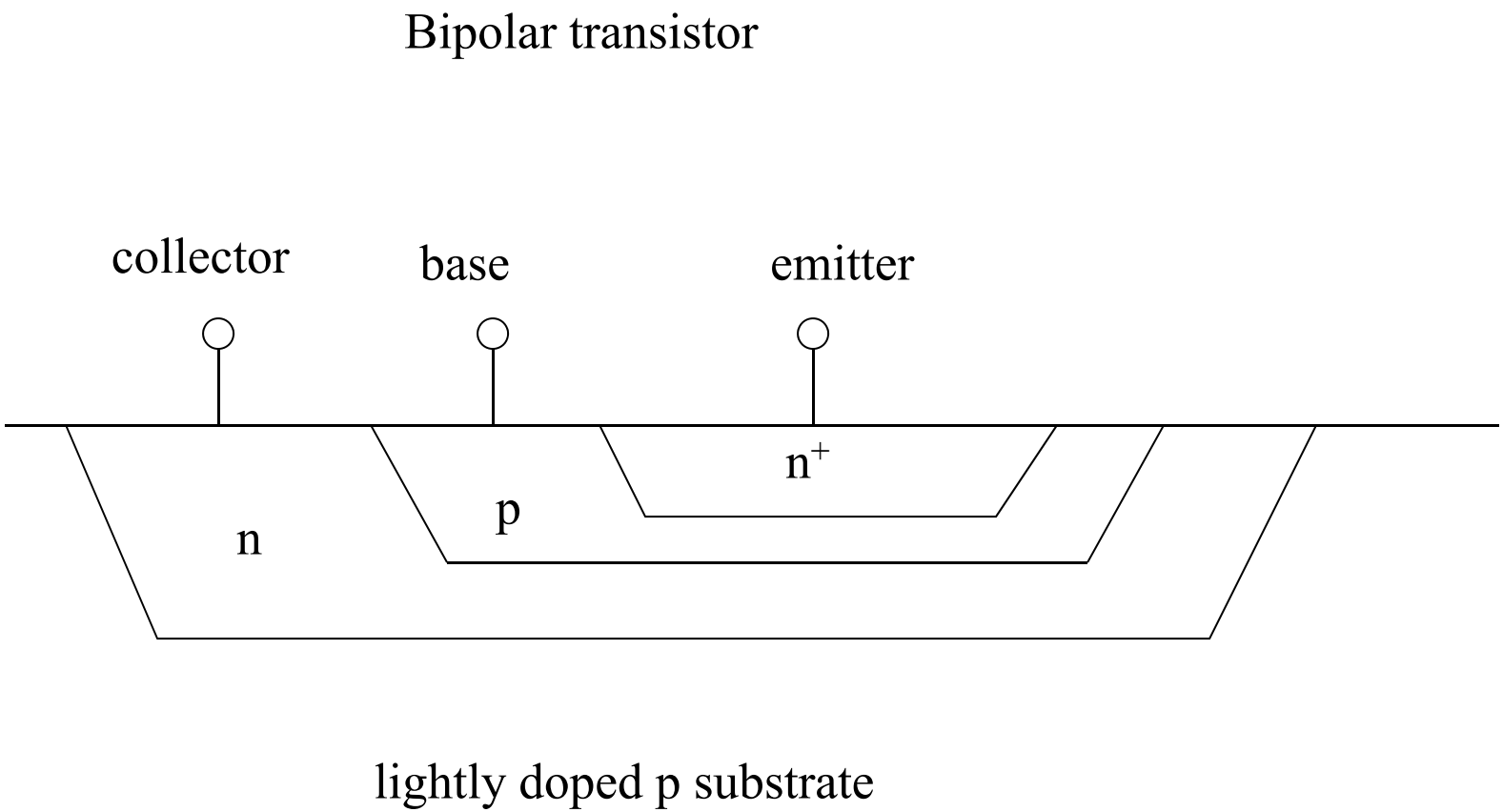
$$n_i = \sqrt{N_v N_c}\exp\left(-\frac{E_g}{2k_B T}\right)$$

Extrinsic semiconductors

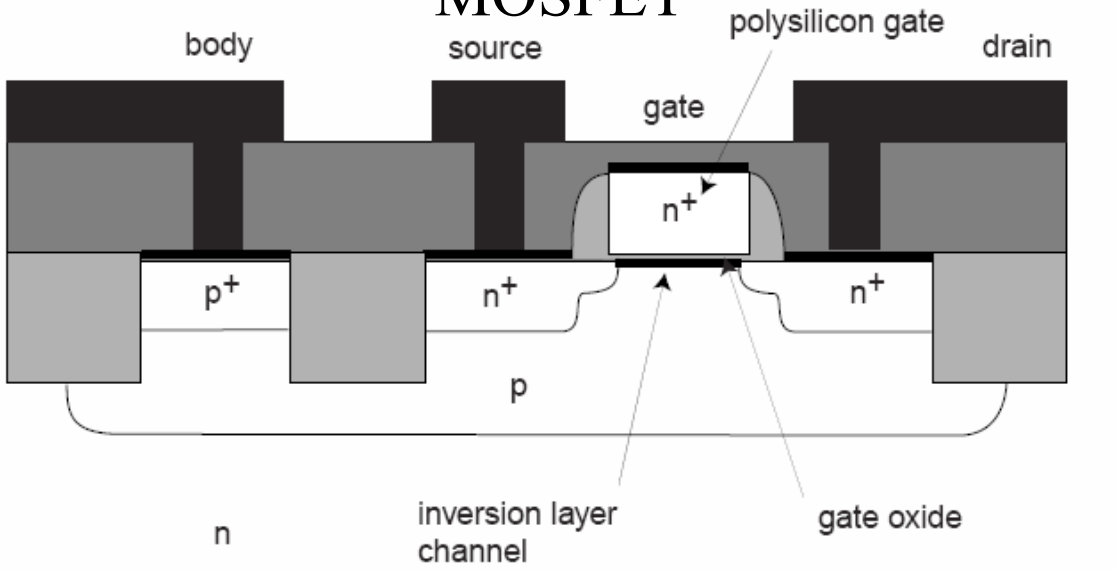


At high temperatures, extrinsic semiconductors have the same temperature dependence as intrinsic semiconductors.

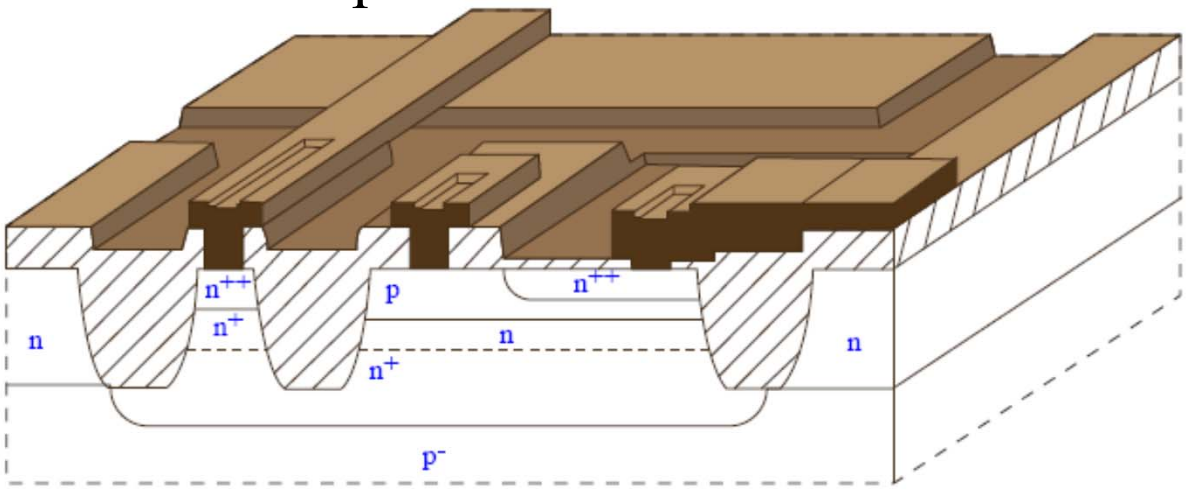
Why dope with donors AND acceptors?



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}

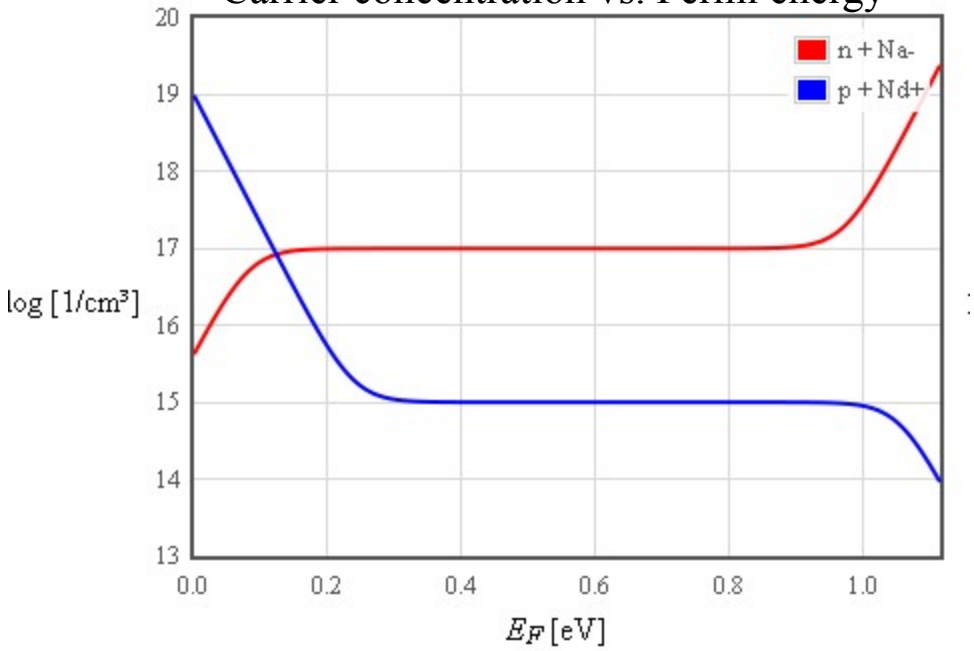
N_A = donor density cm^{-3} N_A^- = ionized donor density cm^{-3}

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

Charge neutrality

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

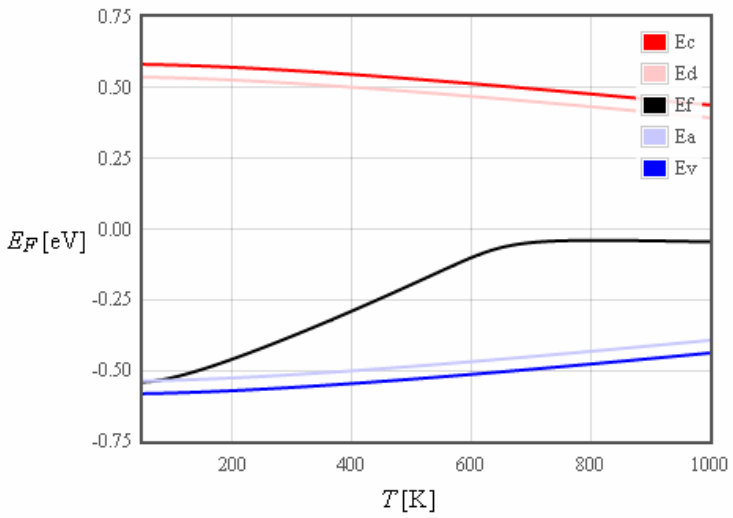
Carrier concentration vs. Fermi energy




```
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

Calculating $E_F(T)$ numerically



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	

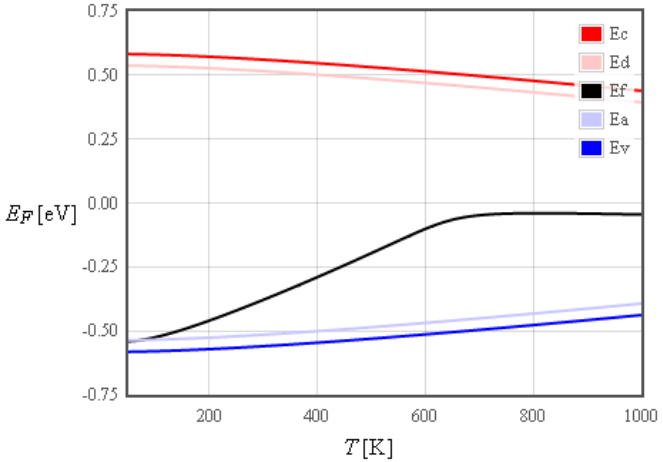
Replot

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.



$N_c(300\ \mathrm{K}) =$	2.78E19	1/cm³
$N_v(300\ \mathrm{K}) =$	9.84E18	1/cm³
$E_g =$	1.166-4.73E-4*T*T/(T+636)	eV
$N_d =$	1E15	1/cm³
$E_c - E_d =$	0.045	eV
$N_a =$	1E16	1/cm³
$E_a - E_v =$	0.045	eV
$T_1 =$	50	K
$T_2 =$	1000	K

Replot

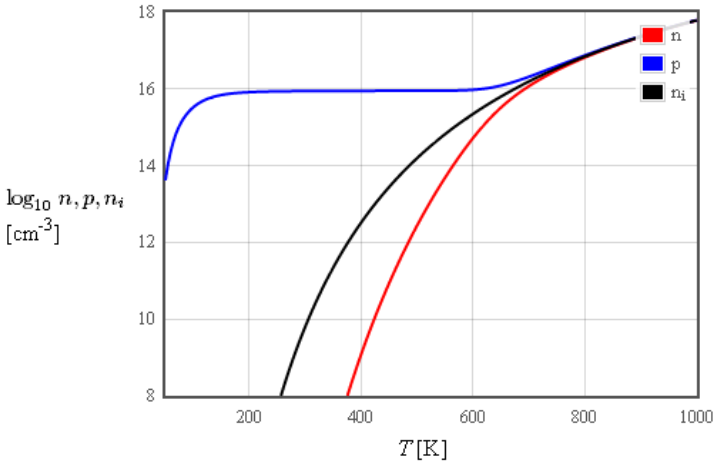
Semiconductor: Si | Ge | GaAs

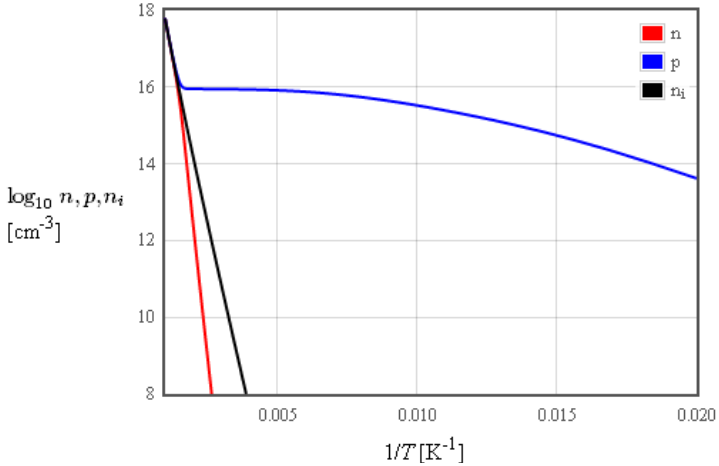
Donor: P in Si | P in Ge | Si in GaAs

Acceptor: B in Si | B in Ge | Si in GaAs

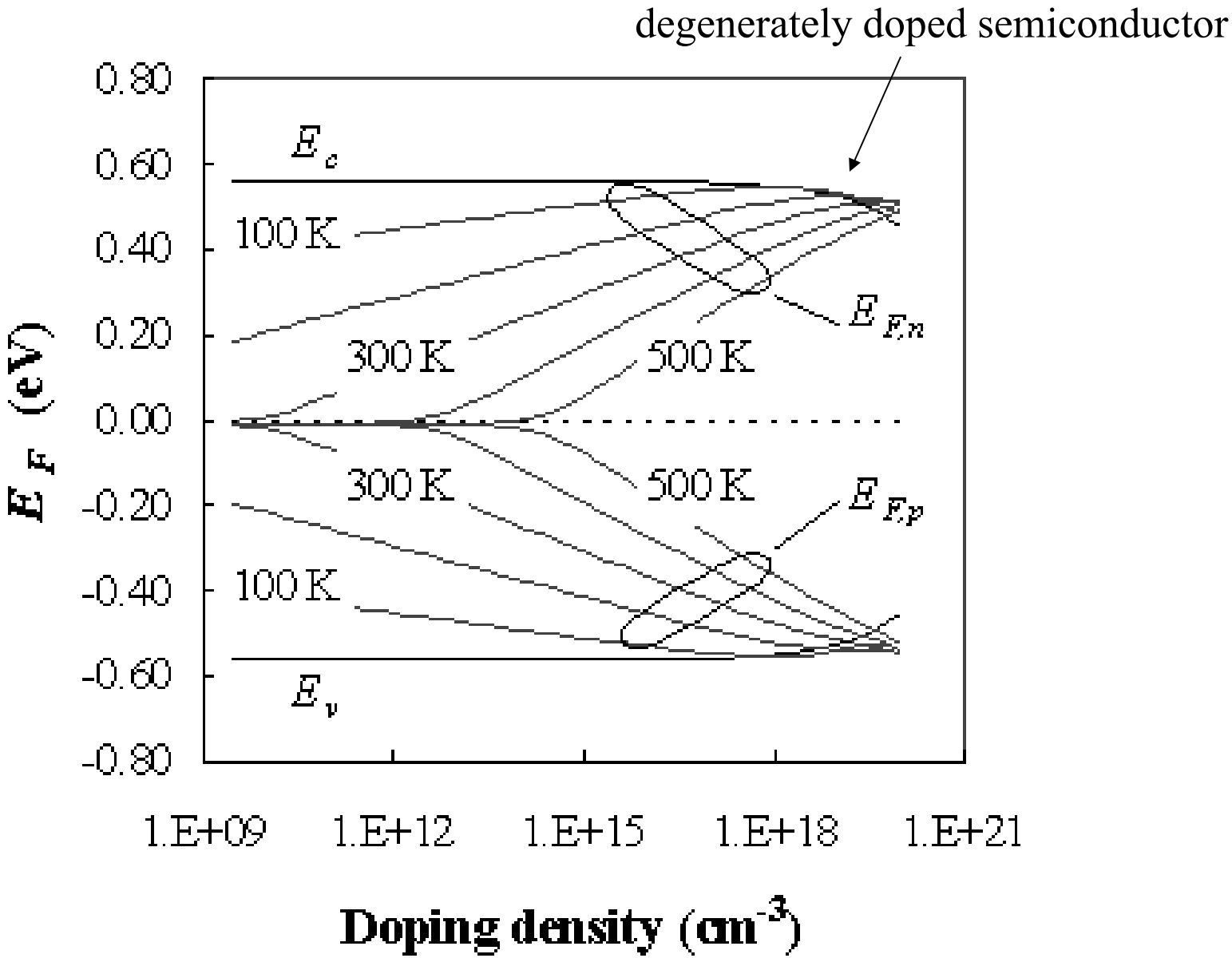
Once the Fermi energy is known, the carrier densities n and p can be calculated from the formulas, $n = N_c \left(\frac{T}{300}\right)^{3/2} \exp\left(\frac{E_F - E_c}{k_B T}\right)$ and $p = N_v \left(\frac{T}{300}\right)^{3/2} \exp\left(\frac{E_v - E_F}{k_B T}\right)$.

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





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_c
100 K
300 K
500 K
E_{Fn}
300 K
500 K
E_{Fp}
100 K
E_v
E_F (eV)
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

Carrier Transport

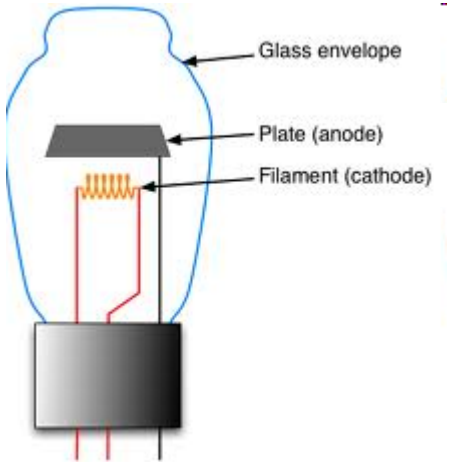
Ballistic transport
Drift
Diffusion
Generation and recombination
The continuity equation
High field effects

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.

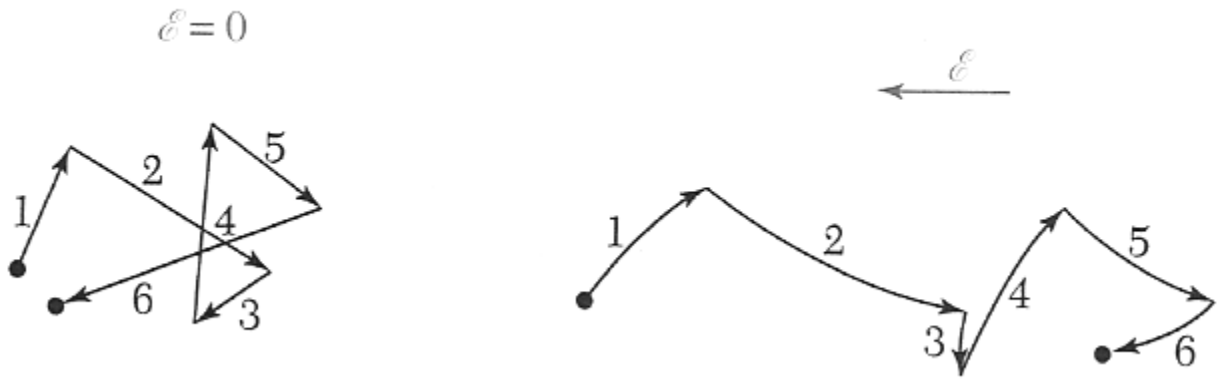
Drift

The electrons scatter and change direction after a time τ_{sc}.

Classical equipartition: $\frac{1}{2} m v_{th}^2 = \frac{3}{2} k_B T$

At 300 K, $v_{th} \sim 10^7$ cm/s.

mean free path: $\ell = v_{th} \tau_{sc} \sim 10$ nm ~ 200 atoms

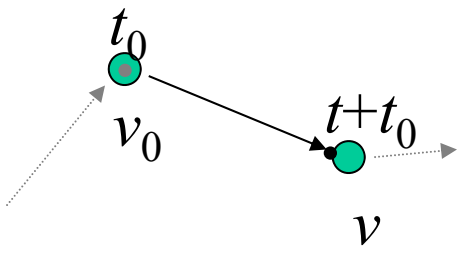


Drift (diffusive transport)

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

$$\vec{v} = \vec{v}_0 - \frac{e\vec{E}}{m^*}(t - t_0)$$

time between two collisions



$$\langle v_0 \rangle = 0 \qquad \langle t - t_0 \rangle = \tau_{sc}$$

$$\vec{v}_d = \frac{-e\vec{E}\tau_{sc}}{m^*} = \frac{-e\vec{E}\ell}{m^* v}$$

drift velocity: $\vec{v}_{d,n} = -\mu_n \vec{E}$ $\vec{v}_{d,p} = \mu_p \vec{E}$

Drift

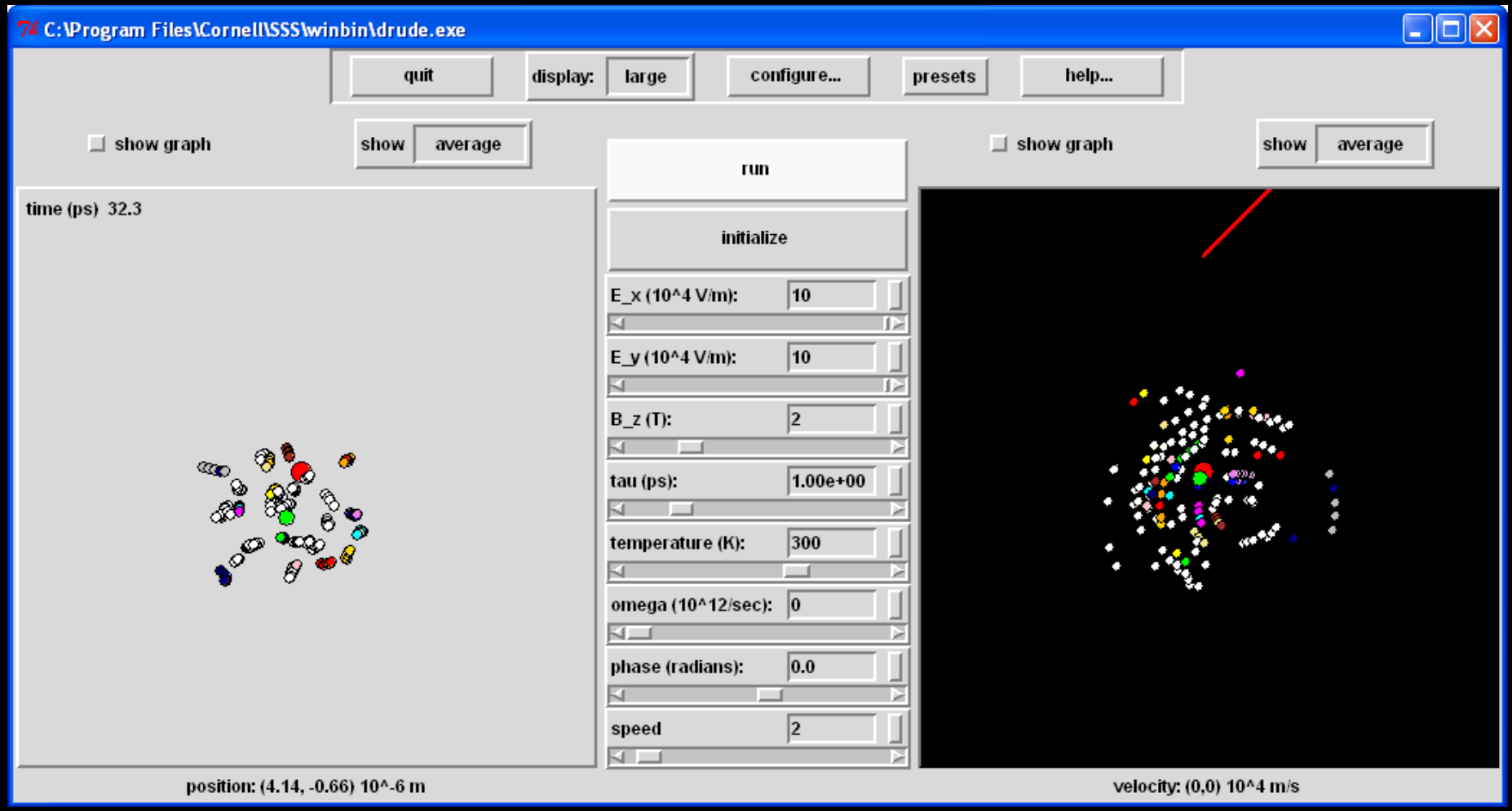
drift velocity: $\vec{v}_{d,n} = -\mu_n \vec{E}$ $\vec{v}_{d,p} = \mu_p \vec{E}$

$$\vec{j} = -ne\vec{v}_{d,n} + pe\vec{v}_{d,p} = \left(ne\mu_n + pe\mu_p\right)\vec{E} = \sigma\vec{E}$$

$$\mu = \frac{-e\tau_{sc}}{m^*} = \frac{-e\ell}{m^* v}$$

for Si: $\mu_n = 1500\ \text{cm}^2/\text{Vs}$
$\mu_p = 450\ \text{cm}^2/\text{Vs}$

For $E = 1000$ V/cm $v_d = 10^6$ cm/s


C:\Program Files\Cornell\SSS\winbin\drude.exe
quit
display: large
configure...
presets
help...
show graph
show average
run
initialize
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
show graph
show average
position: (4.14, -0.66) 10^-6 m
velocity: (0,0) 10^4 m/s

Drift

		E_g (eV)	μ_n (cm^2/V-s)	μ_p (cm^2/V-s)	m^*_n/m_o (m_l, m_t)	m^*_p/m_o (m_{lh}, m_{hh})	a (Å)	ϵ_r	Density (g/cm^3)	Melting point (°C)
Si	(i/D)	1.11	1350	480	0.98, 0.19	0.16, 0.49	5.43	11.8	2.33	1415
Ge	(i/D)	0.67	3900	1900	1.64, 0.082	0.04, 0.28	5.65	16	5.32	936
SiC (α)	(i/W)	2.86	500	—	0.6	1.0	3.08	10.2	3.21	2830
AlP	(i/Z)	2.45	80	—	—	0.2, 0.63	5.46	9.8	2.40	2000
AlAs	(i/Z)	2.16	1200	420	2.0	0.15, 0.76	5.66	10.9	3.60	1740
AlSb	(i/Z)	1.6	200	300	0.12	0.98	6.14	11	4.26	1080
GaP	(i/Z)	2.26	300	150	1.12, 0.22	0.14, 0.79	5.45	11.1	4.13	1467
GaAs	(d/Z)	1.43	8500	400	0.067	0.074, 0.50	5.65	13.2	5.31	1238
GaN	(d/Z, W)	3.4	380	—	0.19	0.60	4.5	12.2	6.1	2530
GaSb	(d/Z)	0.7	5000	1000	0.042	0.06, 0.23	6.09	15.7	5.61	712
InP	(d/Z)	1.35	4000	100	0.077	0.089, 0.85	5.87	12.4	4.79	1070
InAs	(d/Z)	0.36	22600	200	0.023	0.025, 0.41	6.06	14.6	5.67	943
InSb	(d/Z)	0.18	10^5	1700	0.014	0.015, 0.40	6.48	17.7	5.78	525
ZnS	(d/Z, W)	3.6	180	10	0.28	—	5.409	8.9	4.09	1650*
ZnSe	(d/Z)	2.7	600	28	0.14	0.60	5.671	9.2	5.65	1100*
ZnTe	(d/Z)	2.25	530	100	0.18	0.65	6.101	10.4	5.51	1238*
CdS	(d/W, Z)	2.42	250	15	0.21	0.80	4.137	8.9	4.82	1475
CdSe	(d/W)	1.73	800	—	0.13	0.45	4.30	10.2	5.81	1258
CdTe	(d/Z)	1.58	1050	100	0.10	0.37	6.482	10.2	6.20	1098
PbS	(i/H)	0.37	575	200	0.22	0.29	5.936	17.0	7.6	1119
PbSe	(i/H)	0.27	1500	1500	—	—	6.147	23.6	8.73	1081
PbTe	(i/H)	0.29	6000	4000	0.17	0.20	6.452	30	8.16	925

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$$\vec{v}_{d,n} = -\mu_n \vec{E} \quad \vec{v}_{d,p} = \mu_p \vec{E}$$

$$\vec{j} = -ne\vec{v}_{d,n} + pe\vec{v}_{d,p} = \left(ne\mu_n + pe\mu_p\right)\vec{E} = \sigma\vec{E}$$