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Extrinsic Semiconductors

October 22nd, 2025

doping: small admixture of impurities

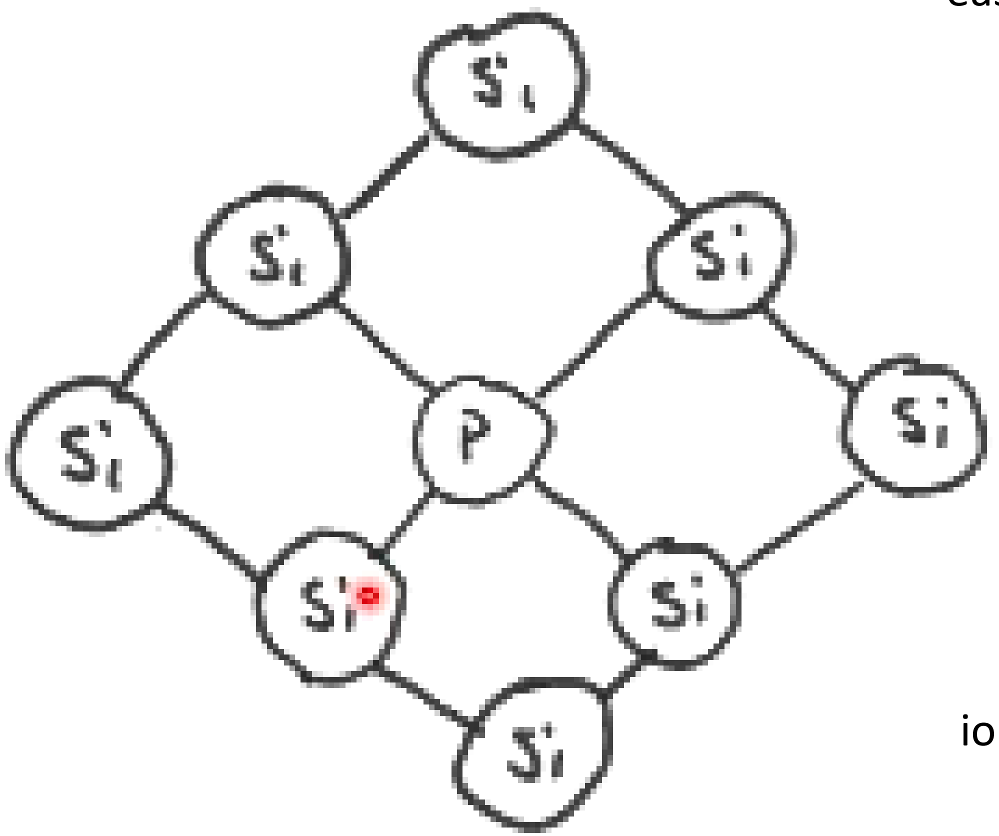
doping: impurity atoms that can add electrons or holes

n-doping: donor atoms add electrons in the conduction band   **P, As in Si**

p-doping: acceptor atoms add electrons in the conduction band   **Al, B, Ga in Si**

- change in macroscopic properties (electric conductivity)

Ionization of dopants



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

remove electron from ground state of a hydrogen-like impurity

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

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

ionization energy ~25 meV

n and p?

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

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

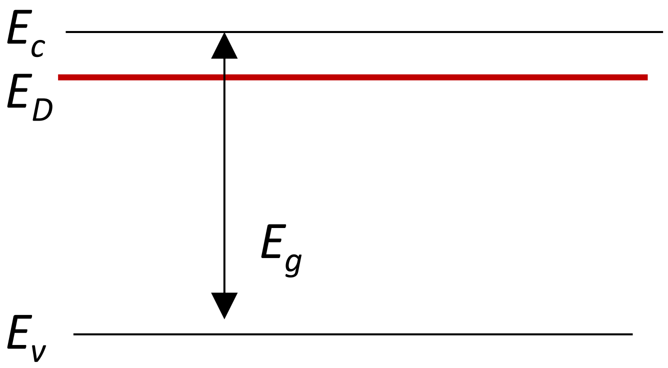
law of mass action

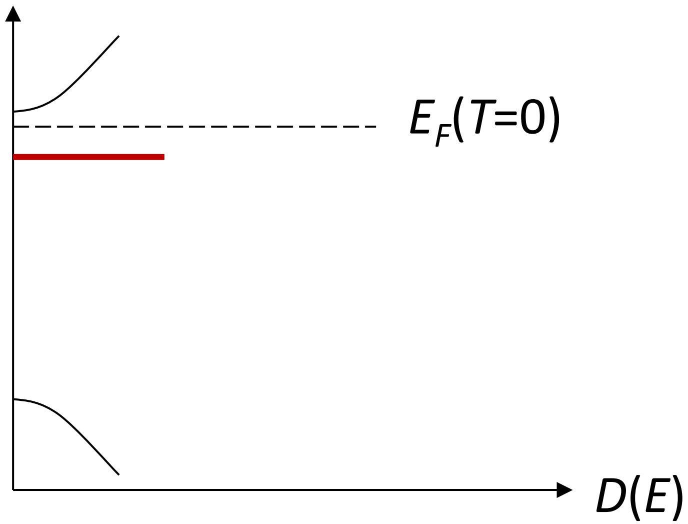
$$np = n_i^2 = N_C N_v \exp\left(-\frac{E_g}{k_B T}\right)$$

n-doping: increase number of electrons

Five valence electrons: P, As

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





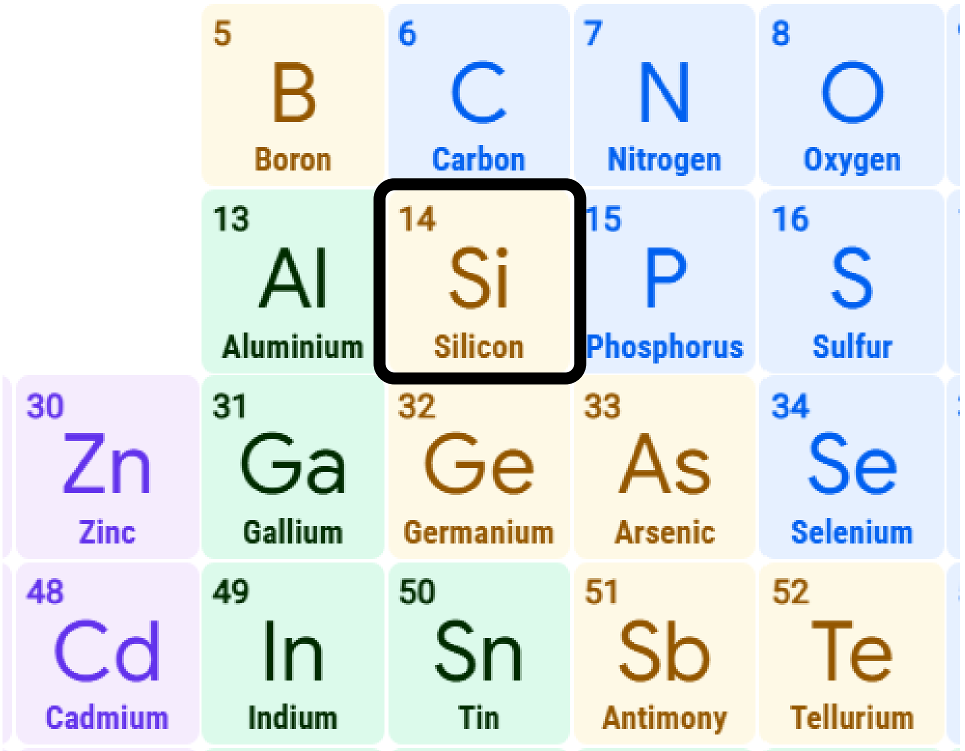
n-type: $n \sim N_D$

many more electrons in the conduction band than holes in the valence band.

majority carriers: electrons; minority carriers: holes

Donors for Si

donors in Si



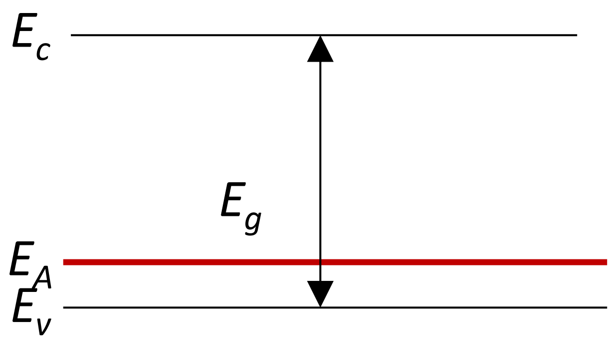
IIb IIIa IVa Va VIa

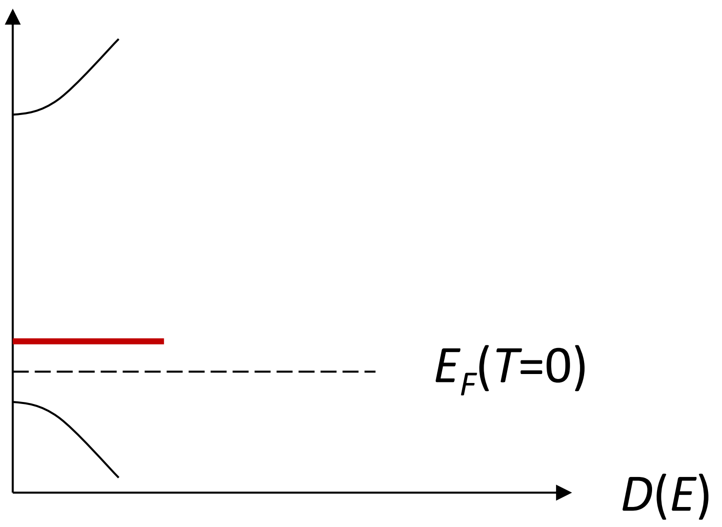
https://artsexperiments.withgoogle.com/periodic-table/?exp=true&lang=en

p-doping: increase number of holes

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

Donors and Acceptors for Si

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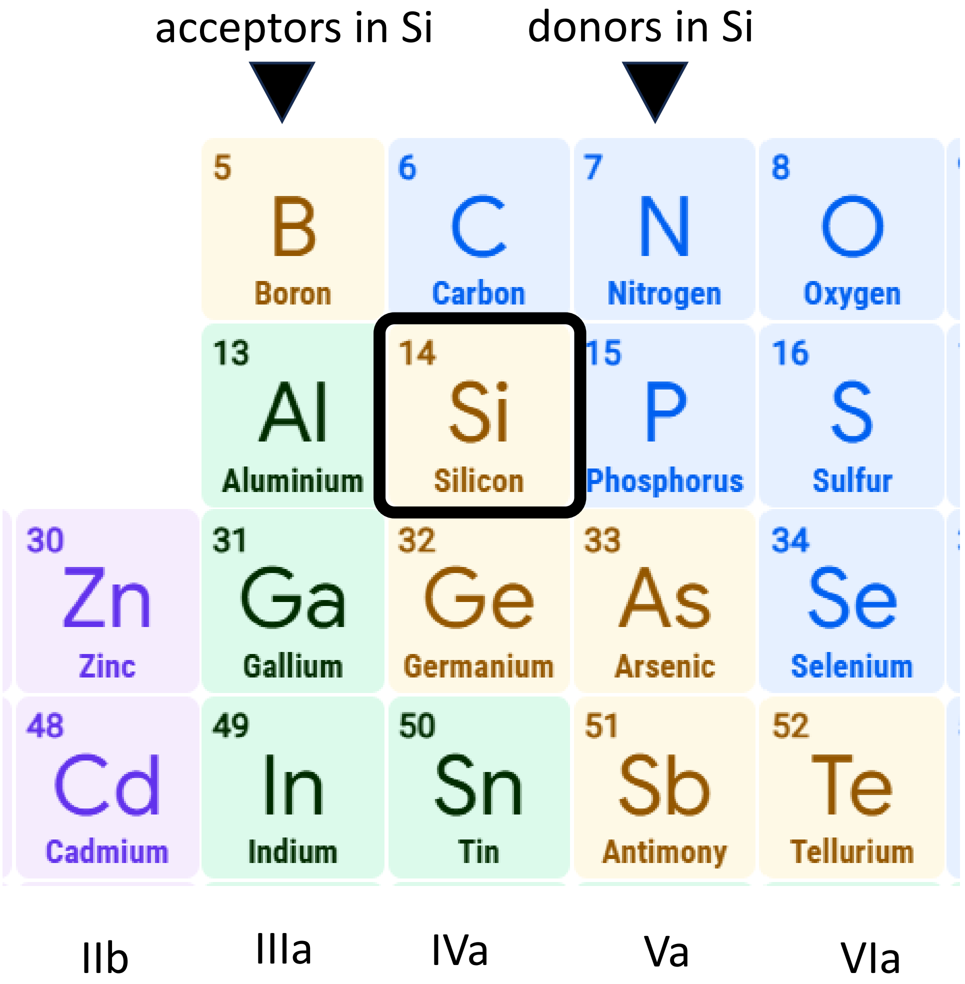


https://artsexperiments.withgoogle.com/periodic-table/?exp=true&lang=en

Donor and Acceptor Energies

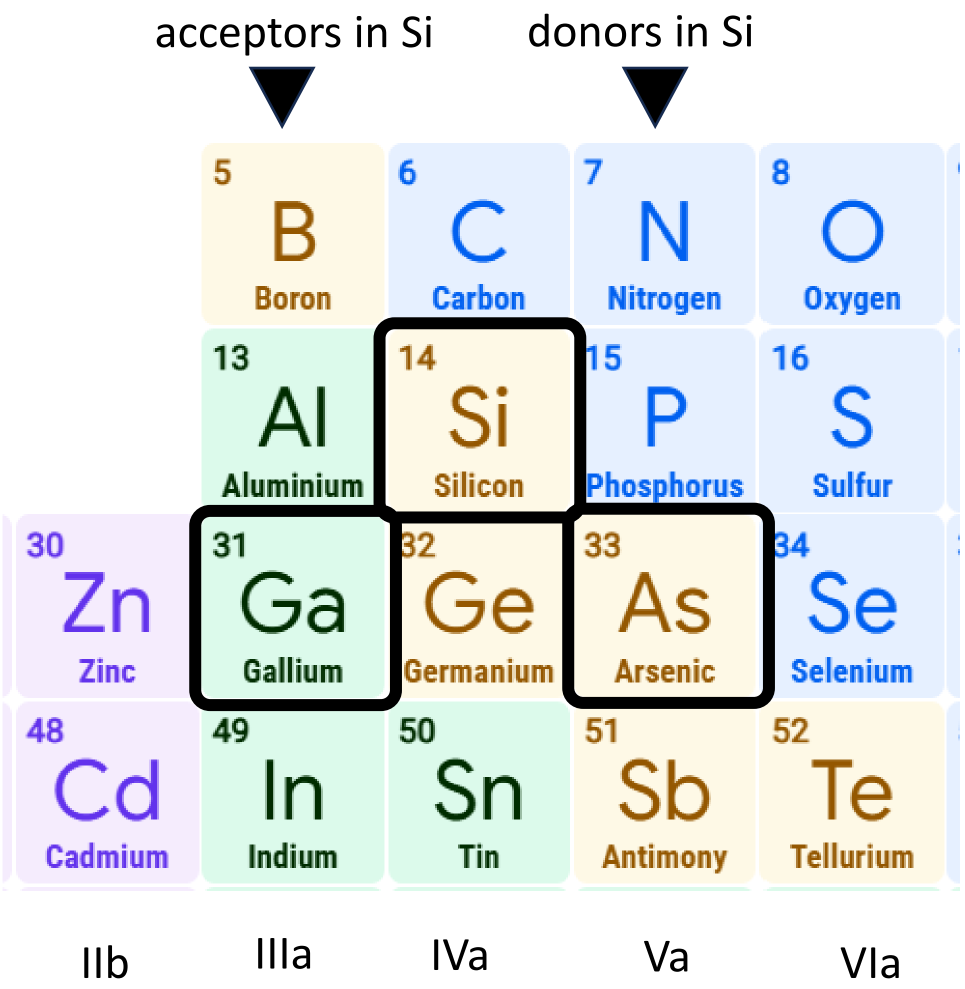
Semiconductor	Donor	Energy (meV)
Si	Li Sb P As	33 39 45 54
Ge	Li Sb P As	9.3 9.6 12 13
GaAs	Si Ge S Sn	5.8 6.0 6.0 6.0

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

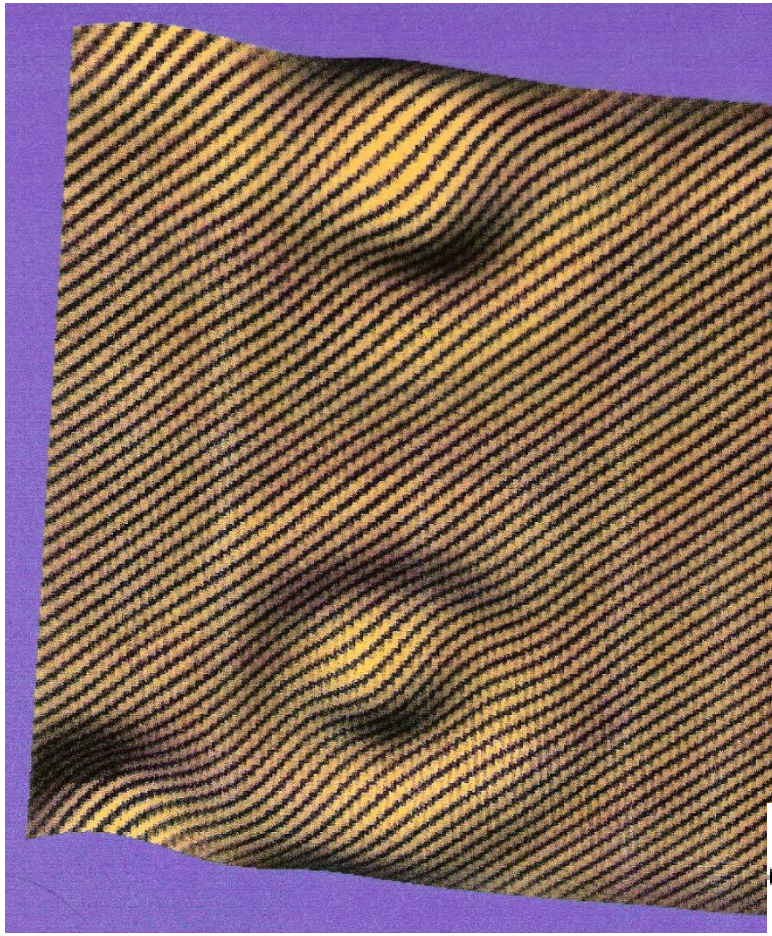
Energy above the valence band

Si as Donor and Acceptor for GaAs

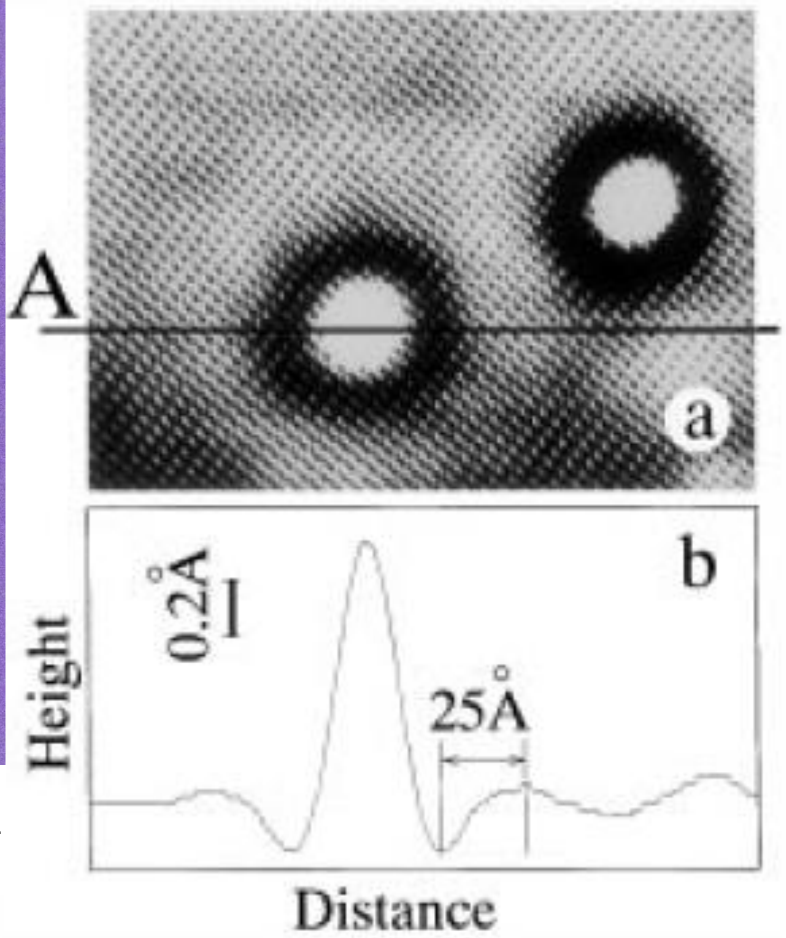


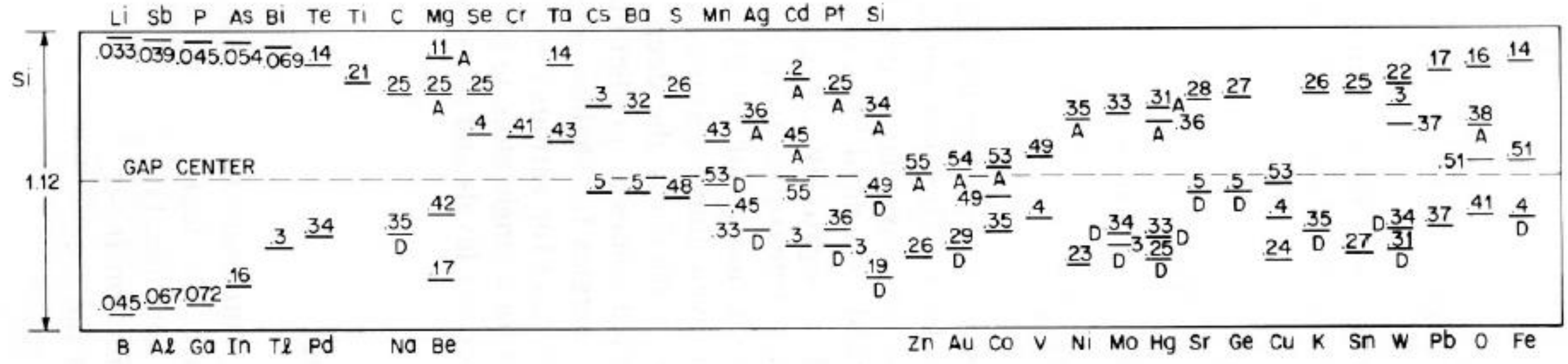
Direct Observation of Friedel Oscillations around Incorporated Si_{Ga} Dopants in GaAs by Low-Temperature Scanning Tunneling Microscopy

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)



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





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

Extrinsic semiconductors

Dopants

Donors

Examples: P, As in Si.

Mobile negative electrons

Fixed positive donors

Acceptors

Examples: B, Ga in Si.

Mobile positive holes

Fixed negative acceptors

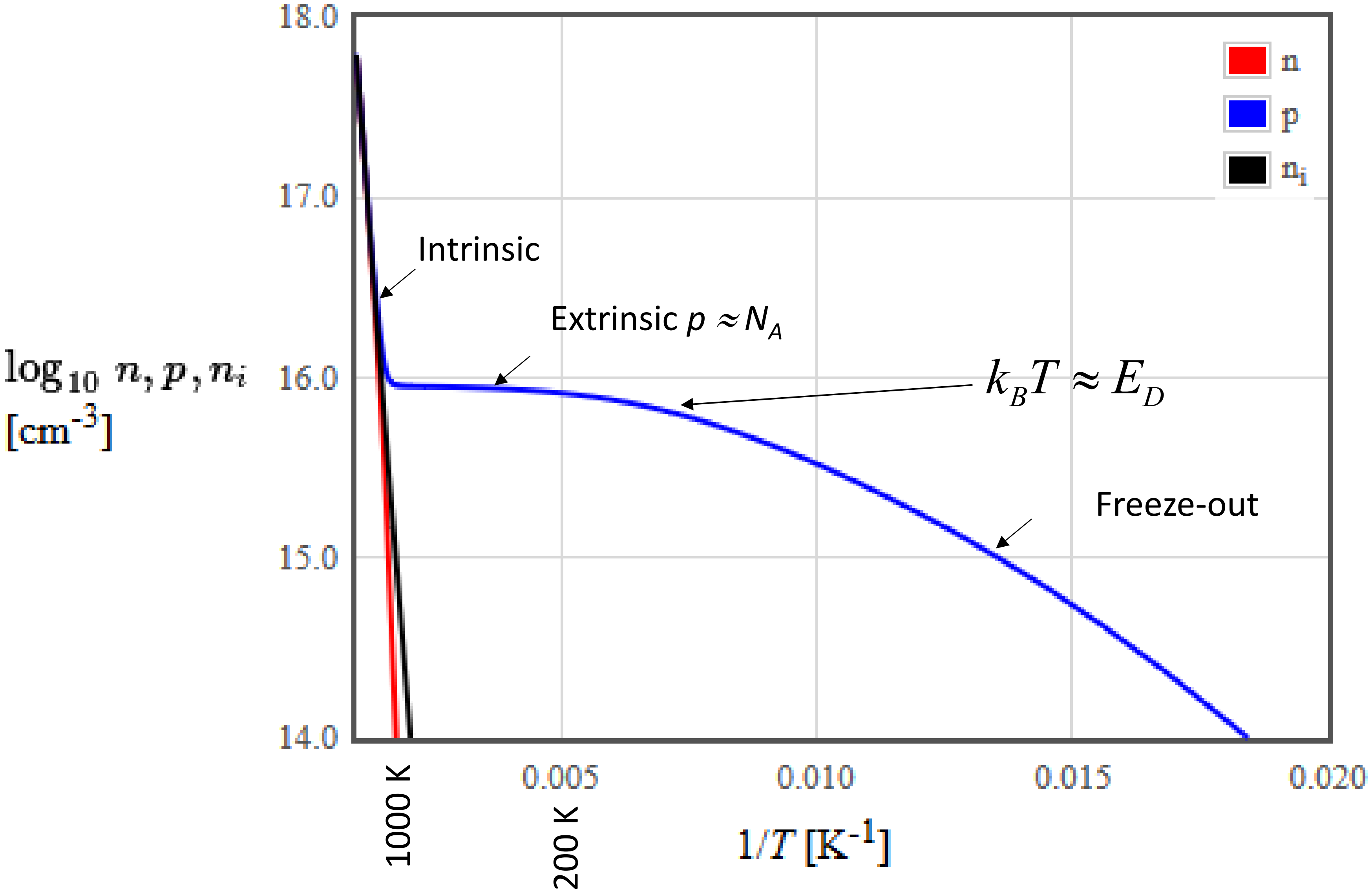
Charge Neutrality

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

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

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

Temperature dependence



Ionized donors and acceptors

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

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

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

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

N_D = donor density cm^{-3}

N_A = acceptor density cm^{-3}

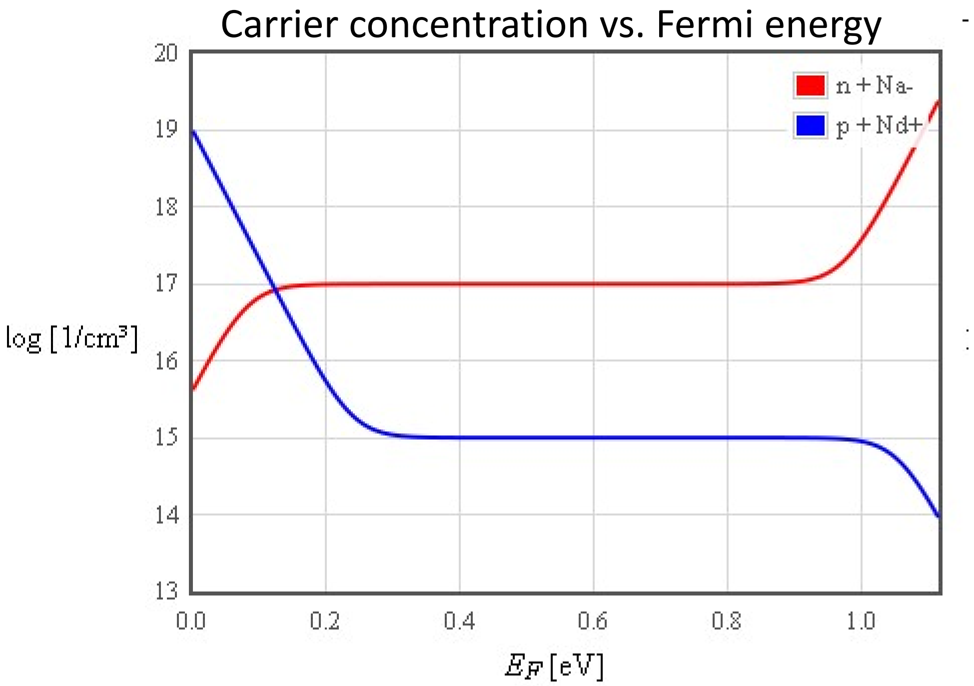
N_D^+ = ionized donor density cm^{-3}

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

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

Ionized donors and acceptors

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

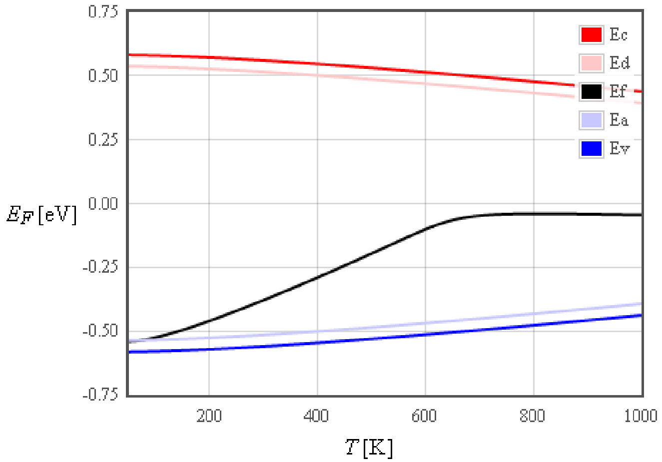



```
for ($i=0; $i<500; $i++) {
  $Ef = $i*$Eg/500;
  $n=$Nc*pow($T/300,1.5)*exp(1.6022E-19*($Ef-$Eg)/(1.38E-23*$T));
  $p=$Nv*pow($T/300,1.5)*exp(1.6022E-19*(-$Ef)/(1.38E-23*$T));
  $Namin = $Na/(1+4*exp(1.6022E-19*($Ea-$Ef)/(1.38E-23*$T)));
  $Ndplus = $Nd/(1+2*exp(1.6022E-19*($Ef-$Ed)/(1.38E-23*$T)));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

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	5.80310462781	6.95665036315E+18	1E+15	5.8356209035E+15	15.7660876057	18.8424631625

Fermi energy vs. temperature

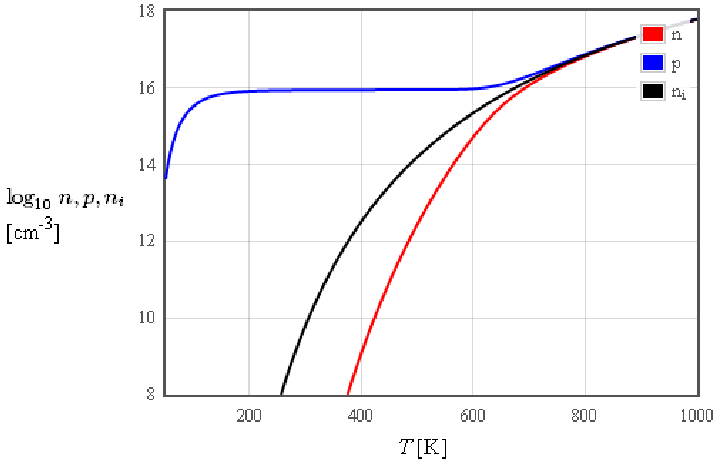
Fermi energy of an extrinsic semiconductor is plotted as a function of temperature. At each temperature the Fermi energy was calculated by requiring that charge neutrality be satisfied.

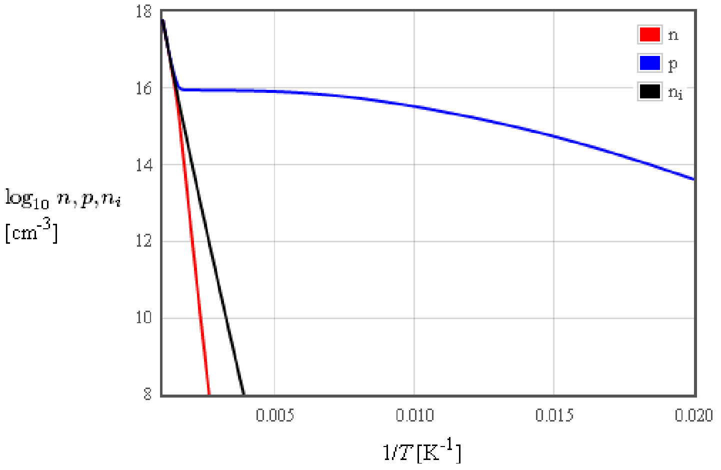


N_c(300 K) =	2.78E19	1/cm³	Semiconductor: Si, Ge, GaAs
N_v(300 K) =	9.84E18	1/cm³	
E_g =	1.166-4.73E-4*T*T/(T+636)	eV	
N_d =	1E15	1/cm³	Donor: P in Si, P in Ge, Si in GaAs
E_c - E_d =	0.045	eV	
N_a =	1E16	1/cm³	Acceptor: B in Si, B in Ge, Si in GaAs
E_a - E_v =	0.045	eV	
T_1 =	50	K	
T_2 =	1000	K	
Replot			

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 $p = N_v\left(\frac{T}{300}\right)^{3/2}\exp\left(\frac{E_v-E_F}{k_BT}\right)$.

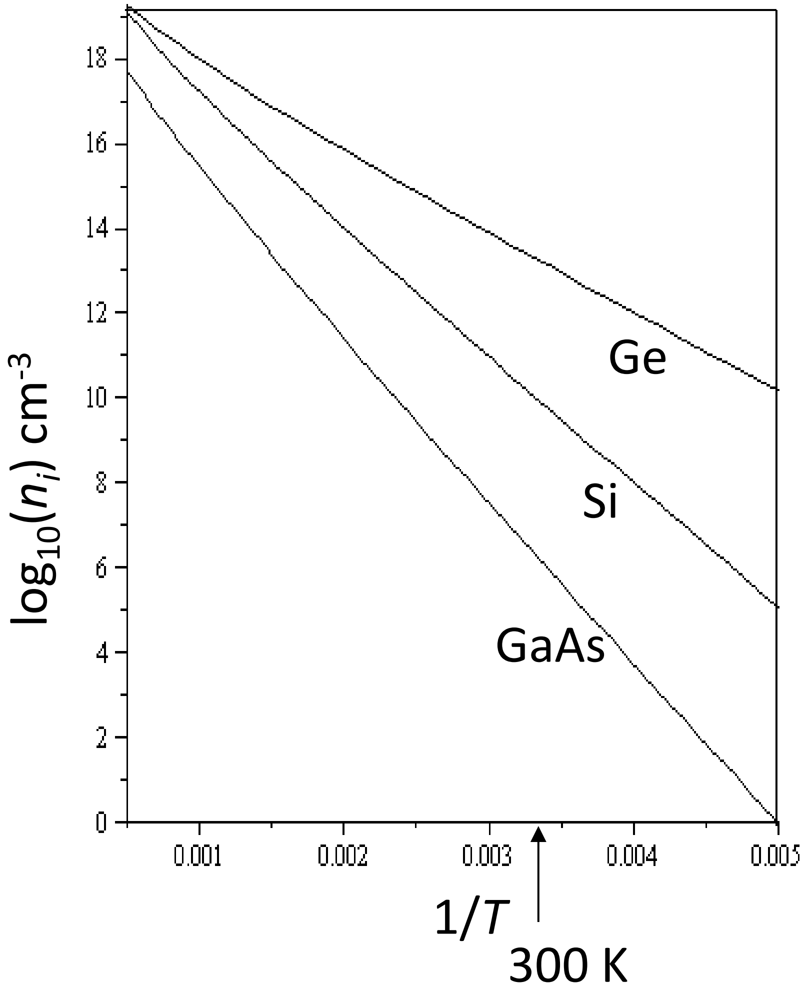
The intrinsic carrier density is $n_i = \sqrt{N_c\left(\frac{T}{300}\right)^{3/2}N_v\left(\frac{T}{300}\right)^{3/2}}\exp\left(\frac{-E_g}{2k_BT}\right)$.





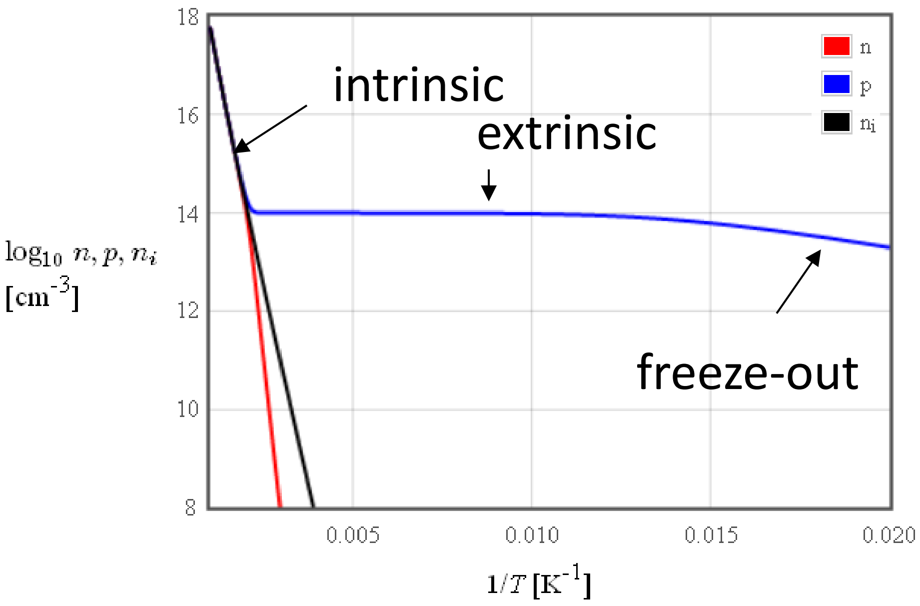
https://lampz.tugraz.at/~hadley/psd/L4/eftplot.html

Intrinsic semiconductors



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

Extrinsic semiconductors



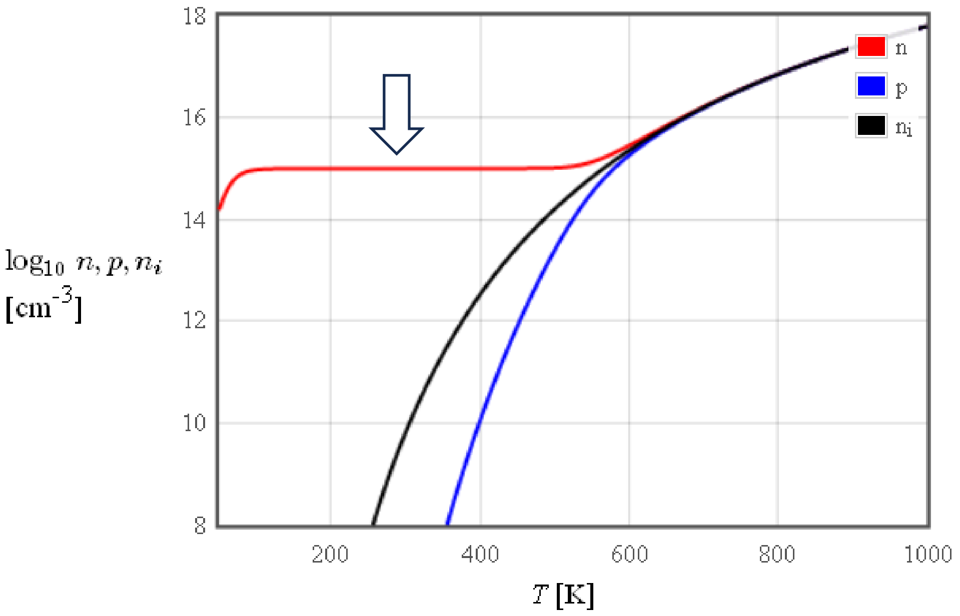
At high temperatures, extrinsic semiconductors have the same temperature dependence as intrinsic semiconductors.

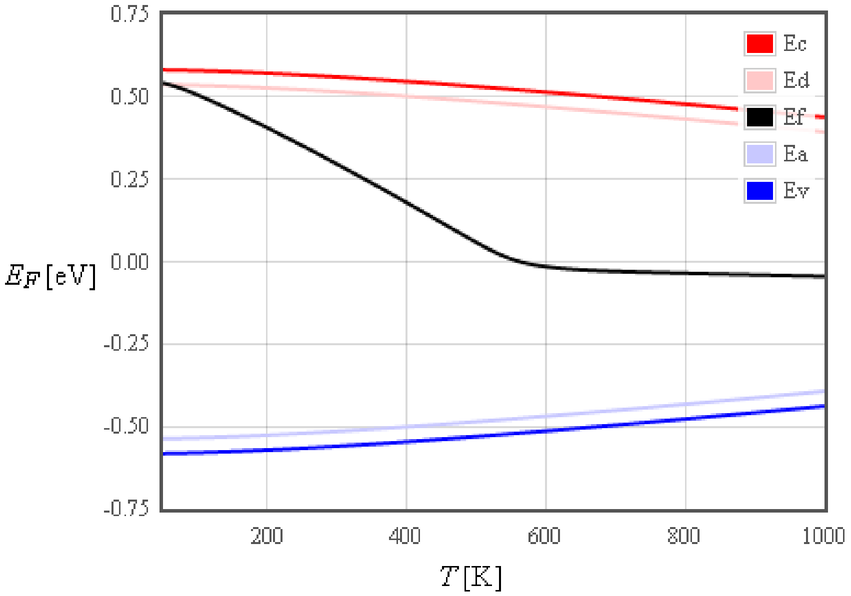
n-type (extrinsic)

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

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

For n-type:
n ~ density of donors,
$p = n_i^2 / N_D$



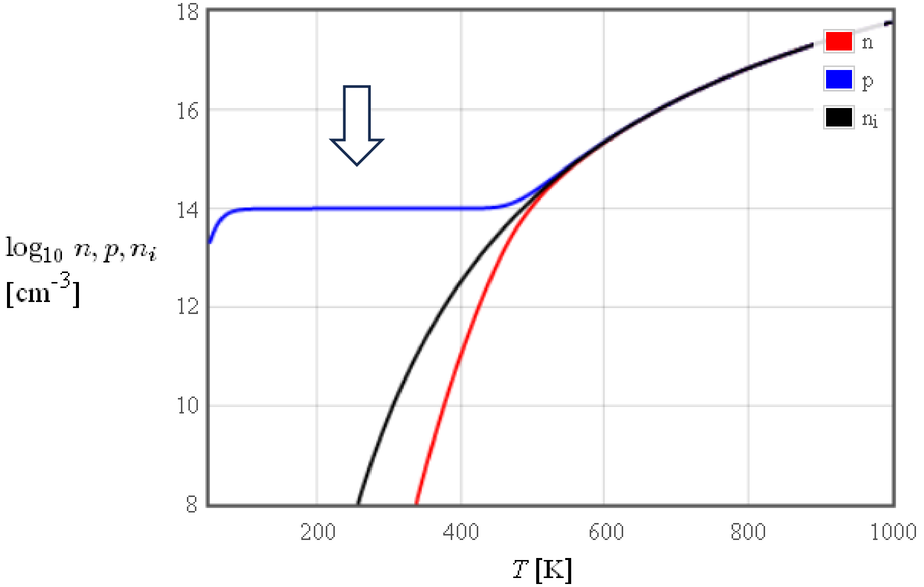


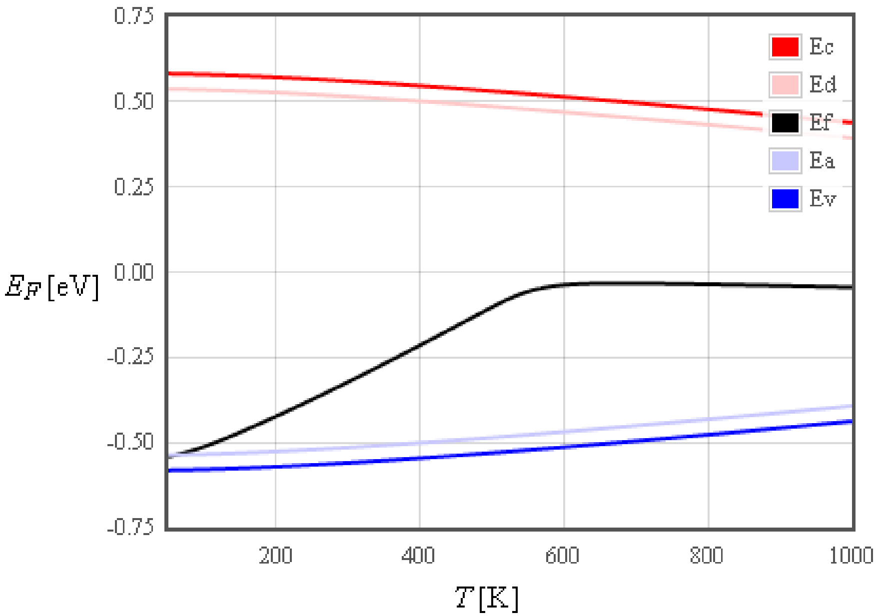
p-type (extrinsic)

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

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

For p-type,
p ~ density of acceptors,
$n = n_i^2/N_A$





Intrinsic / Extrinsic

Intrinsic: $n = p$

Conductivity **strongly temperature dependent**

Conductivity is poor

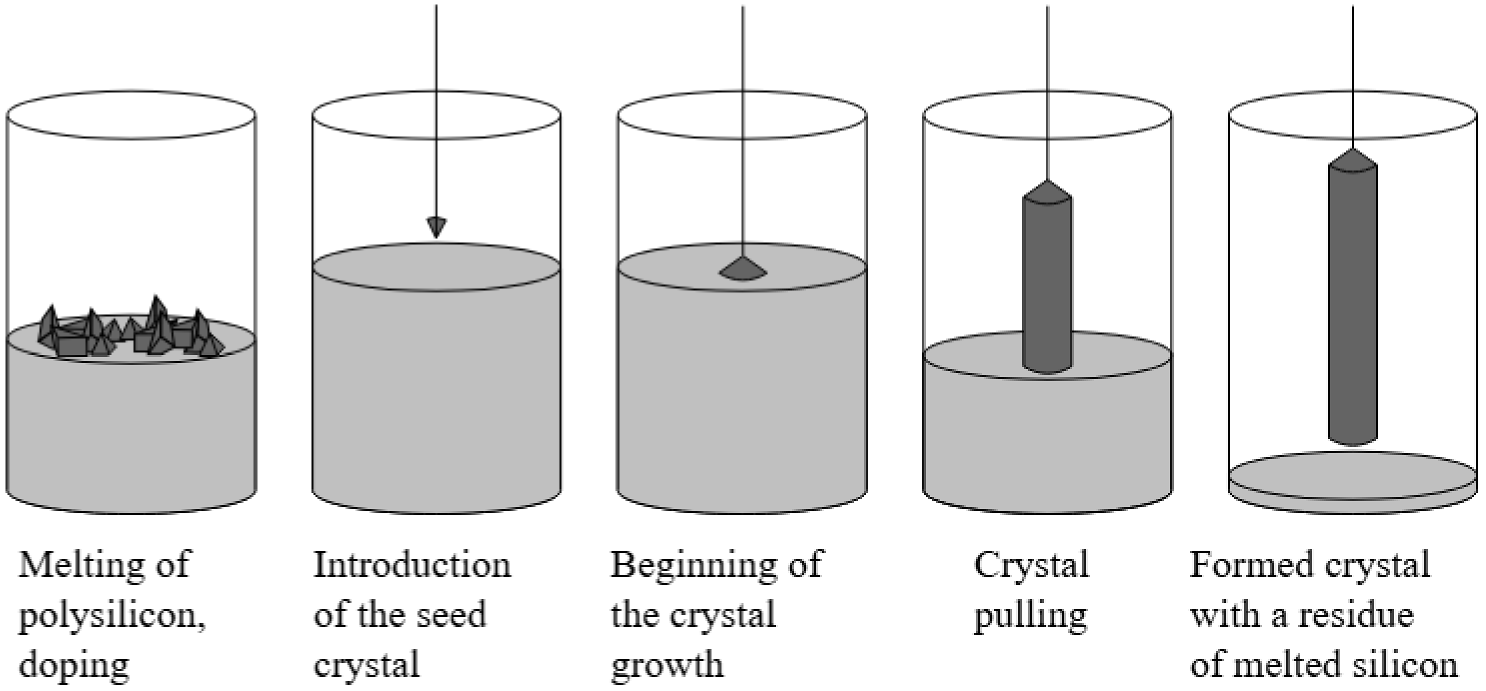
Extrinsic: $n \neq p$

Conductivity **almost temperature independent** at room temperature

Conductivity can be strongly increased (up to a factor of 10^6)

include dopants

Czochralski process



add dopants to the melt

image from wikipedia

include dopants

float zone process

neutron transmutation

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

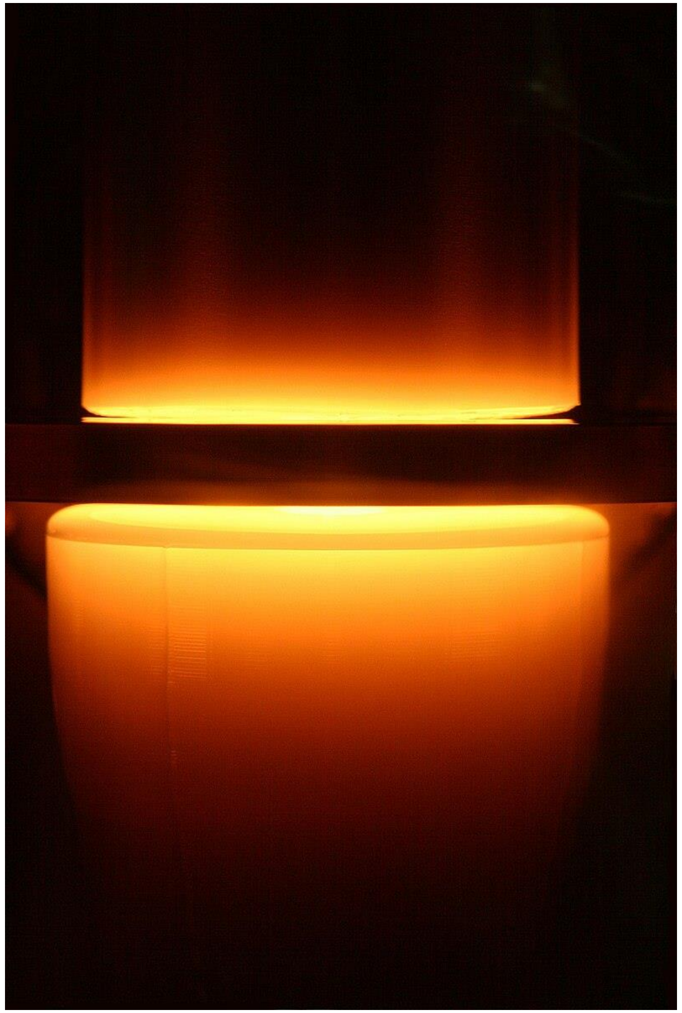


image from wikipedia

include dopants

gas phase diffusion

AsH_3 (arsine) or PH_3 (phosphine) for n-doping

B_2H_6 (diborane) for p-doping

chemical vapor deposition

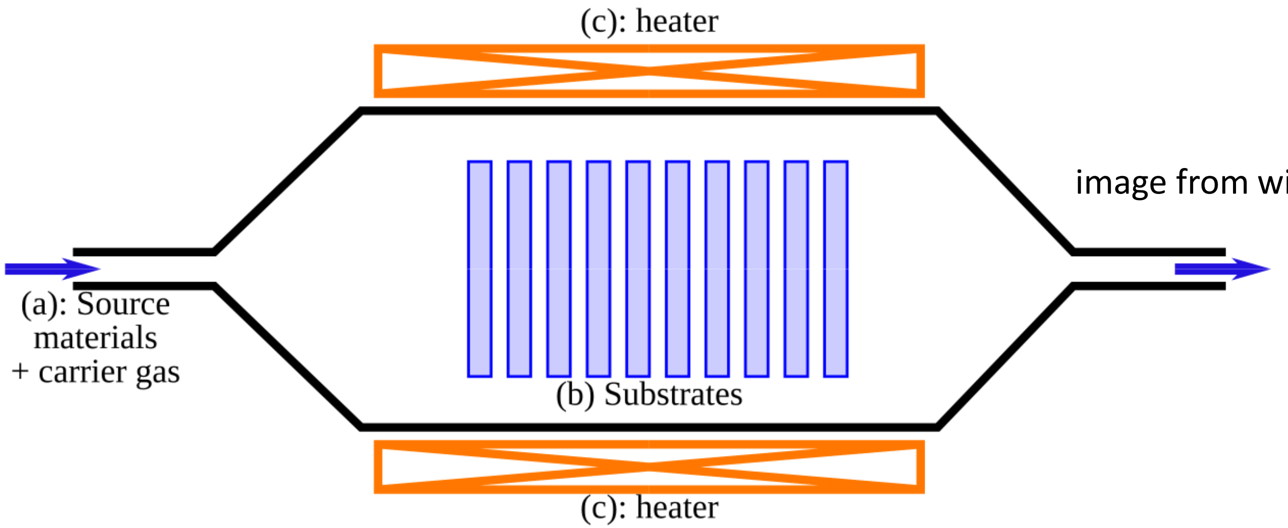


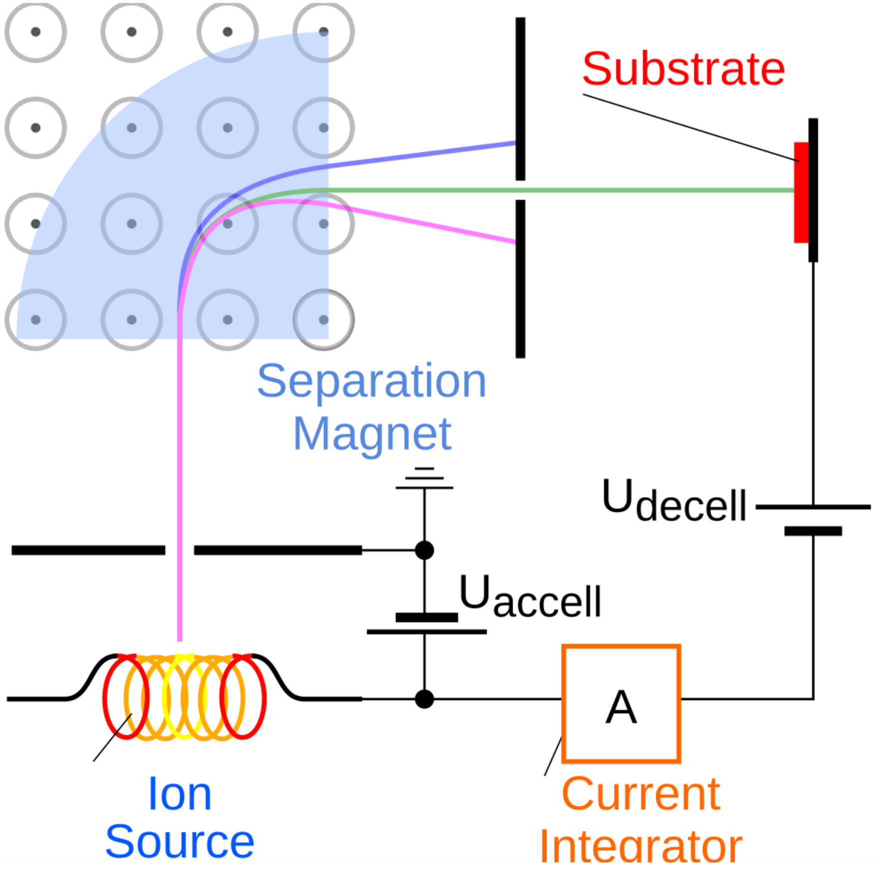
image from wikipedia

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

include dopants

ion implantation

images from wikipedia

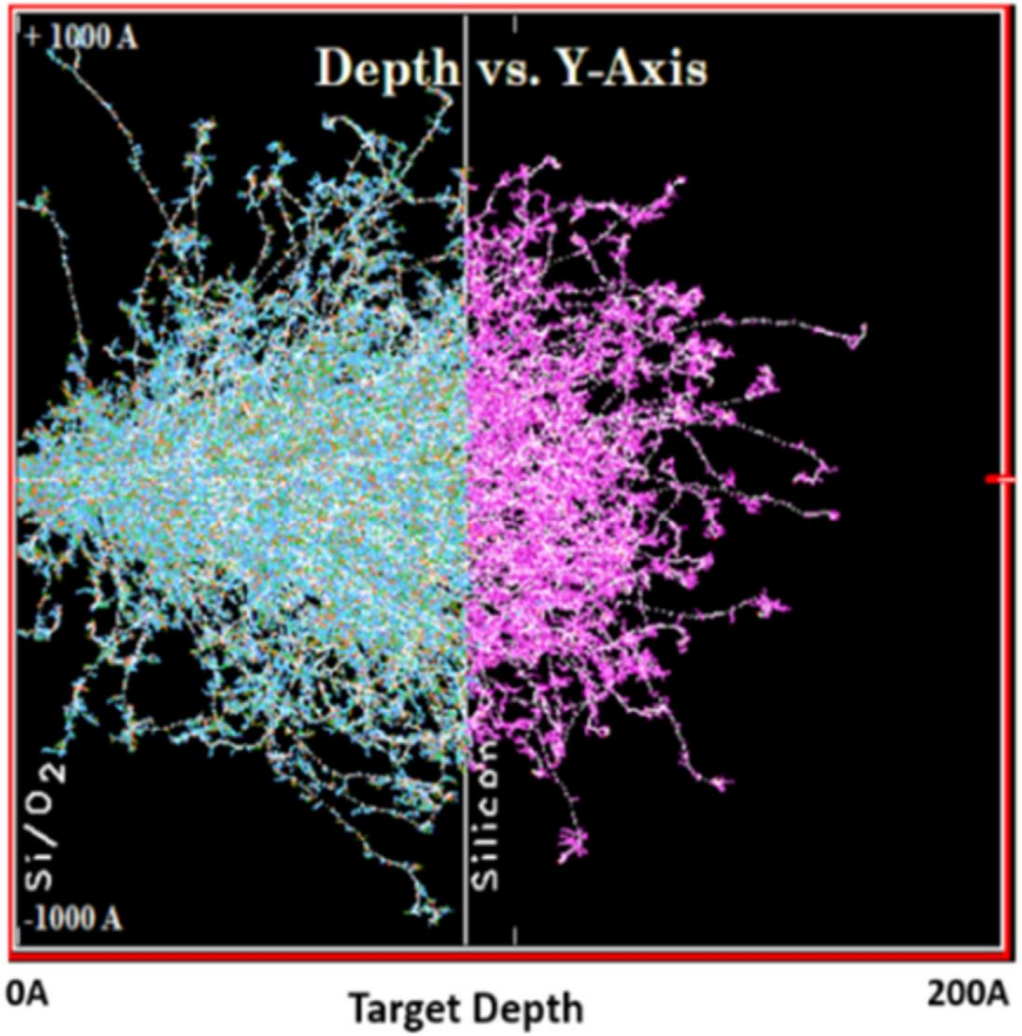


implant at 7 degrees to avoid channeling

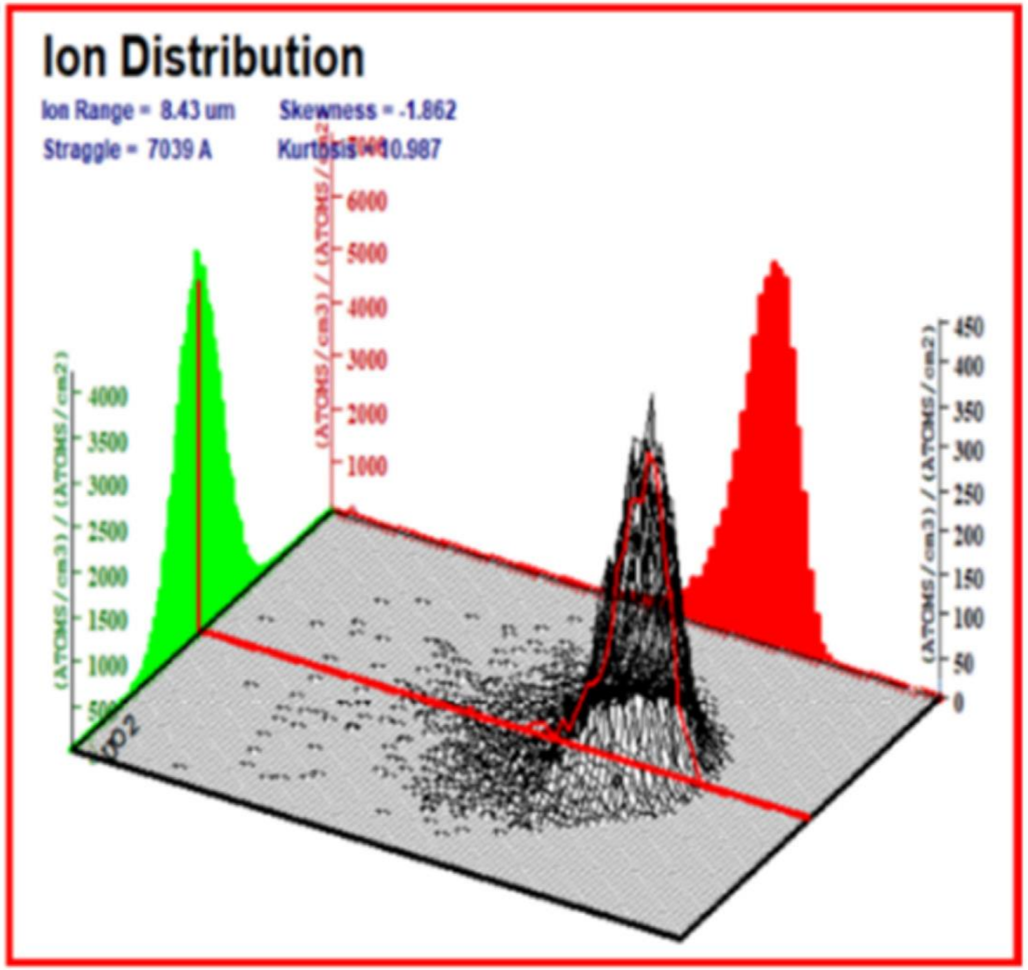
Simulate dopant distribution

the stopping and range of ions in matter

(a)



(b)



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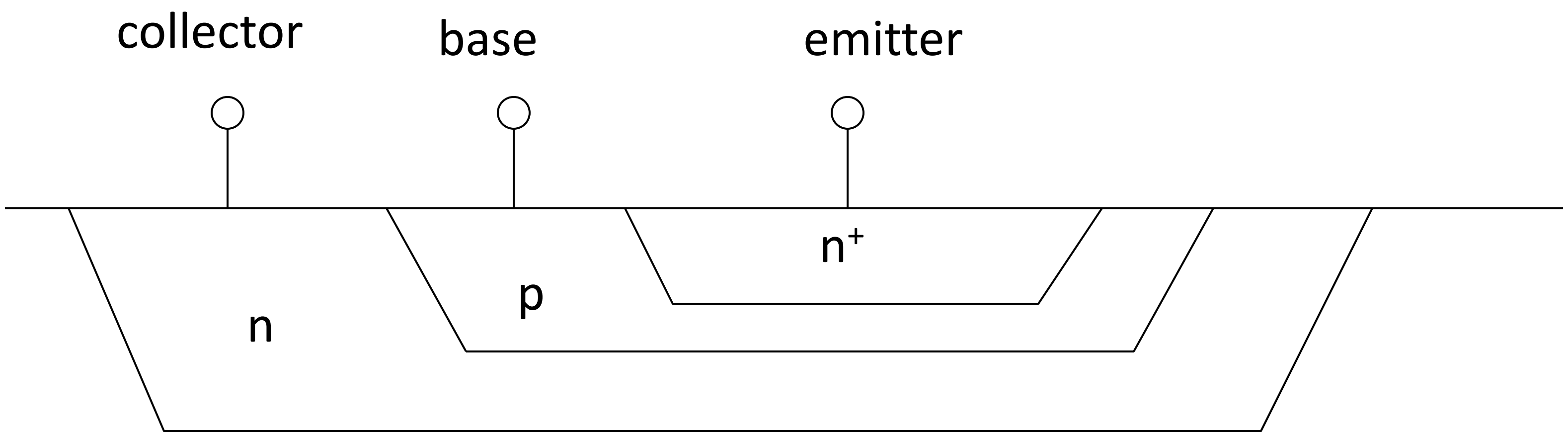
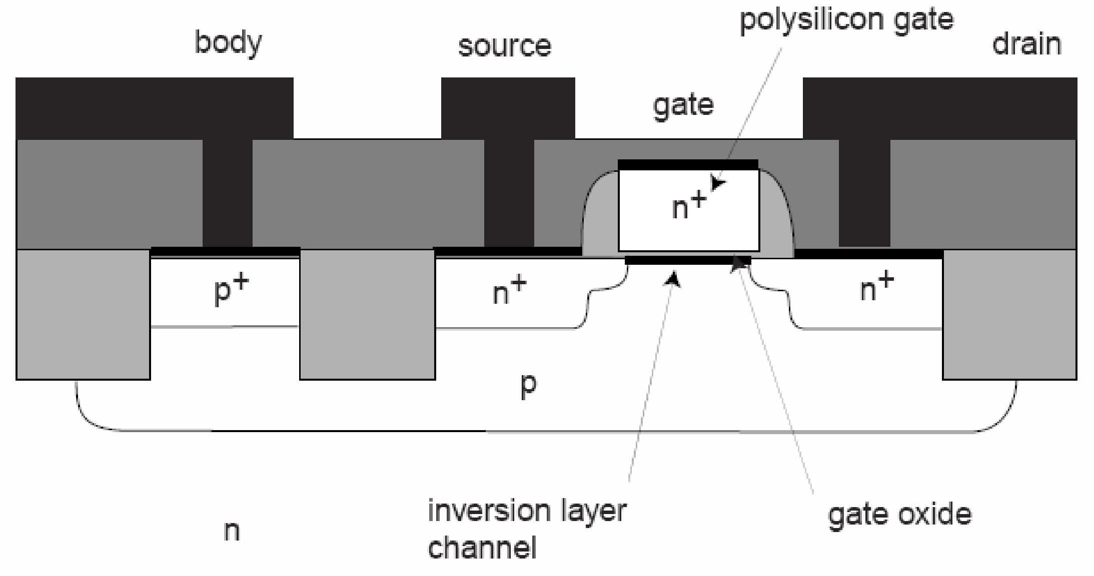
Why dope with donor and acceptors ?

Bipolar transistor

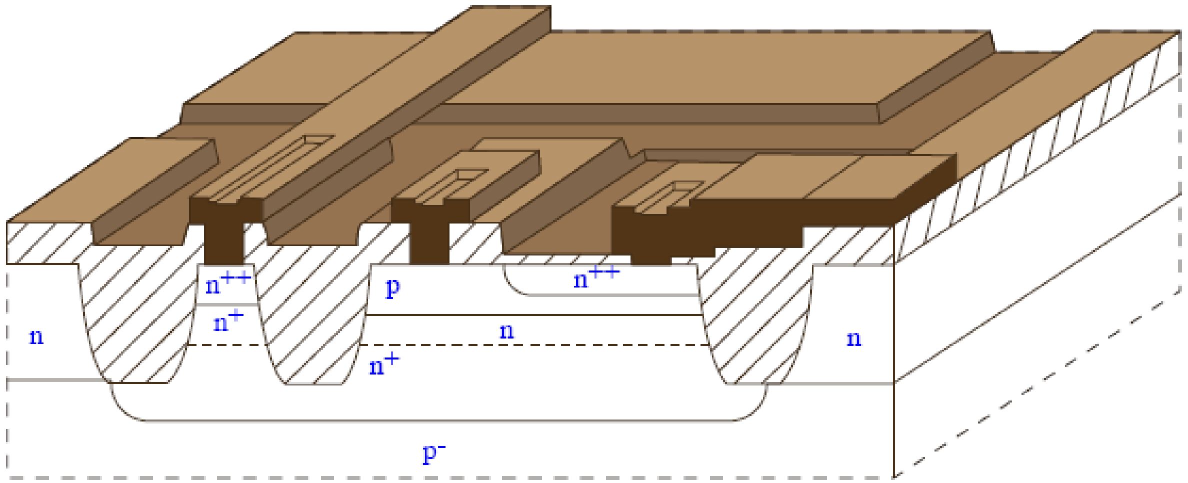


lightly doped p substrate

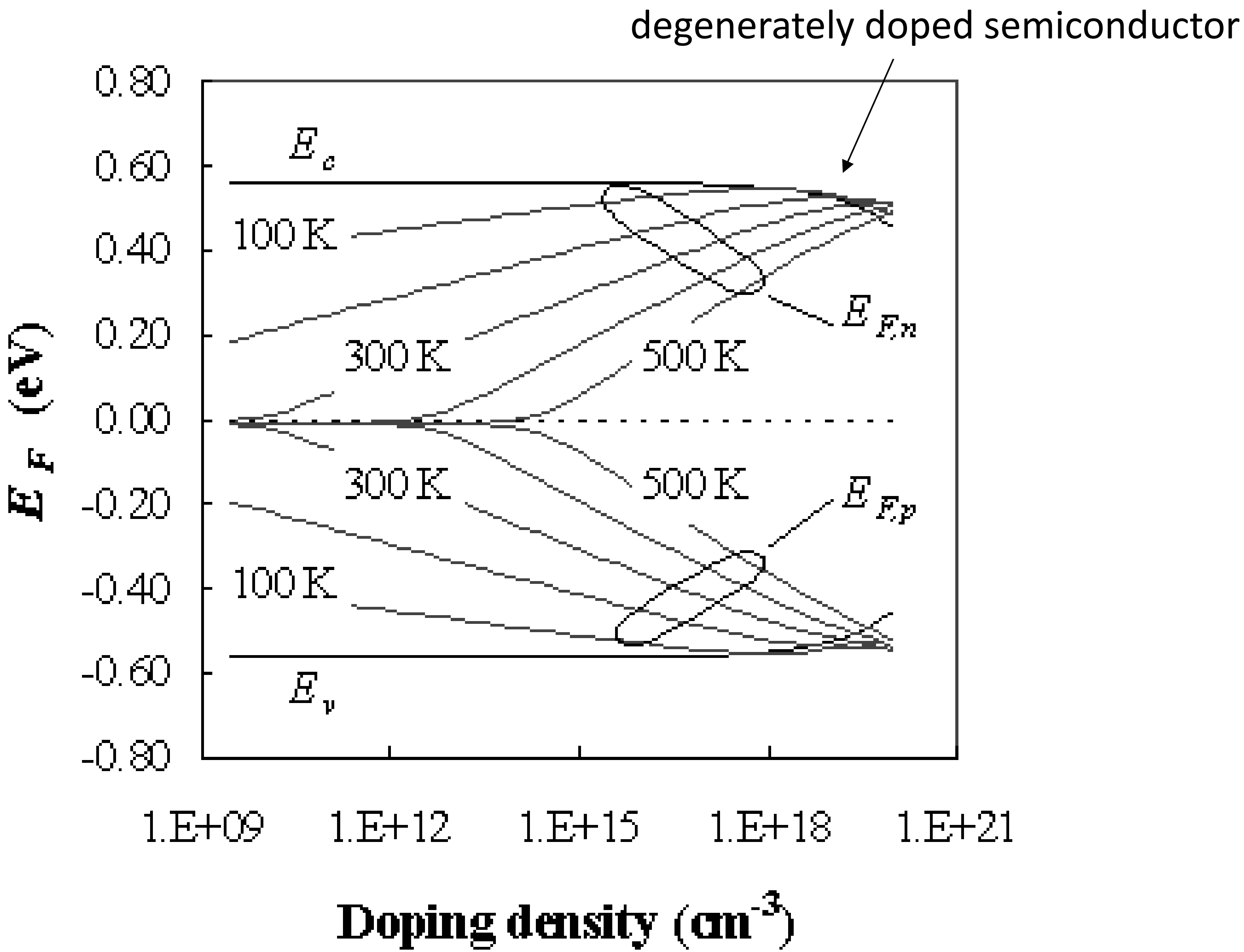
MOSFET



Bipolar Junction Transistor



Oxide isolated integrated BJT - a modern process



degenerately doped semiconductor
0.80
0.60
0.40
0.20
0.00
-0.20
-0.40
-0.60
-0.80
E_c
E_v
100 K
300 K
500 K
300 K
500 K
100 K
$E_{F,n}$
$E_{F,p}$
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
- Boltzmann approximation is not valid
- degenerate semiconductors = metal

6

Carrier transport

Ballistic transport
Drift
Diffusion
Tunneling

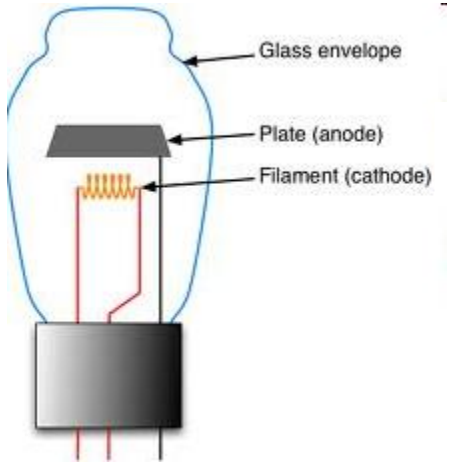
October 22nd, 2025

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.

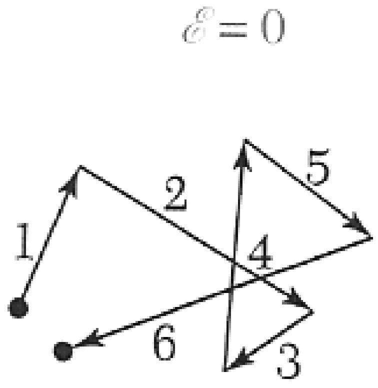
Drift

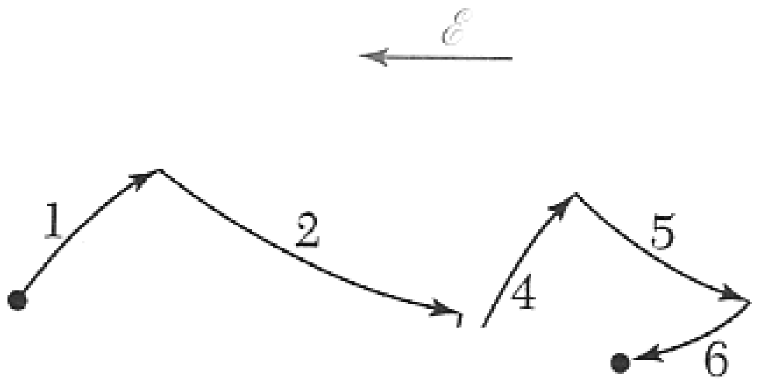
The electrons scatter and change direction after a time τ_{sc}.

thermal velocity $\frac{1}{2}mv_{th}^2 = \frac{3}{2}k_B T$ (classical equipartition)

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

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



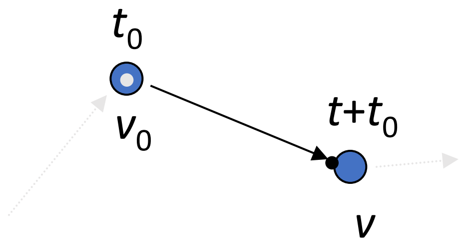


In a metal, the fermi velocity dominates over the thermal velocity. In a semiconductor, the thermal velocity dominates

Drift (diffusive transport)

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

time between two collisions



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

$$<v_0> = 0 \qquad <t - t_0> = \tau_{sc}$$

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

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

Drift

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

for Si: μ_n = 1350 cm^2/Vs
μ_p = 450 cm^2/Vs

current density:

$$\vec{j} = -ne\vec{v}_{d,n} + pe\vec{v}_{d,p}$$

$$= (ne\mu_n + pe\mu_p)\vec{E}$$

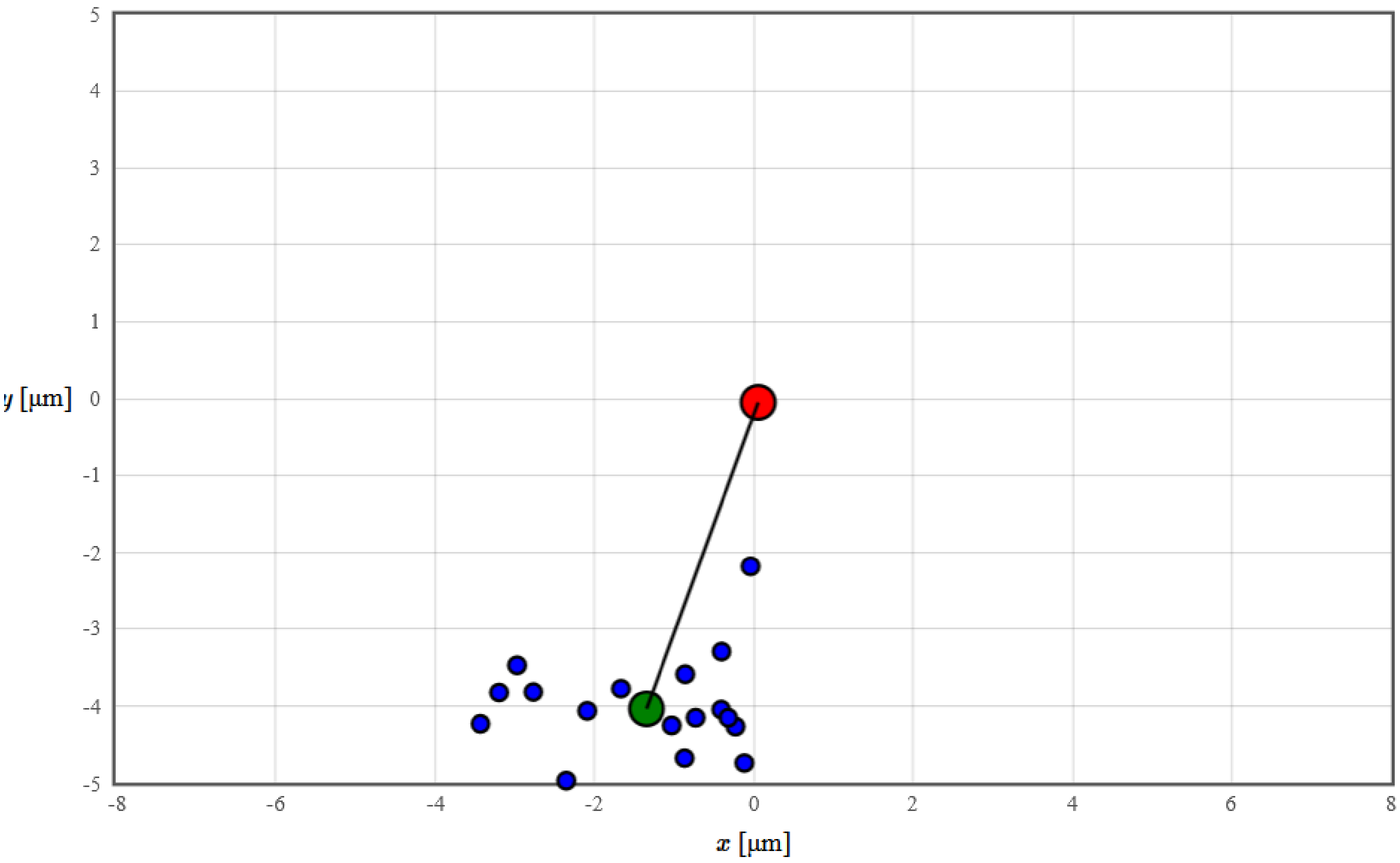
$$= \sigma\vec{E}$$

(Ohm's law)

For E = 1000 V/cm:

$v_d = 10^6$ cm/s

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



https://lampx.tugraz.at/~hadley/psd/L5/drude.php

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

Solid state electronic devices, Streetman and Banerjee

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

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

Matthiessen's rule

rate

$$\frac{1}{\tau_{sc}} = \frac{1}{\tau_{sc,lattice}} + \frac{1}{\tau_{sc,impurity}}$$

mostly temperature independent

phonons, temperature dependent

$$\frac{1}{\mu} = \frac{1}{\mu_{lattice}} + \frac{1}{\mu_{impurity}}$$

$$\sigma = \frac{1}{\rho} = ne\mu_n + pe\mu_p$$

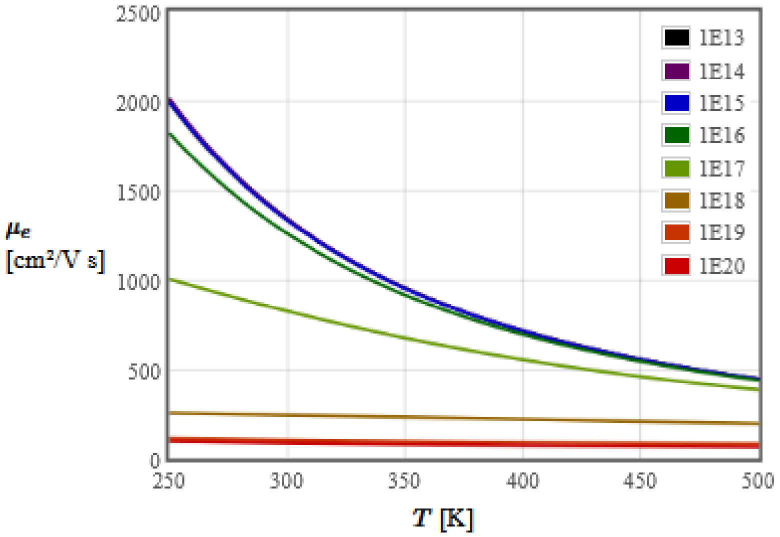
doping increases the conductivity
by increasing the carrier density
but decreases the mobility

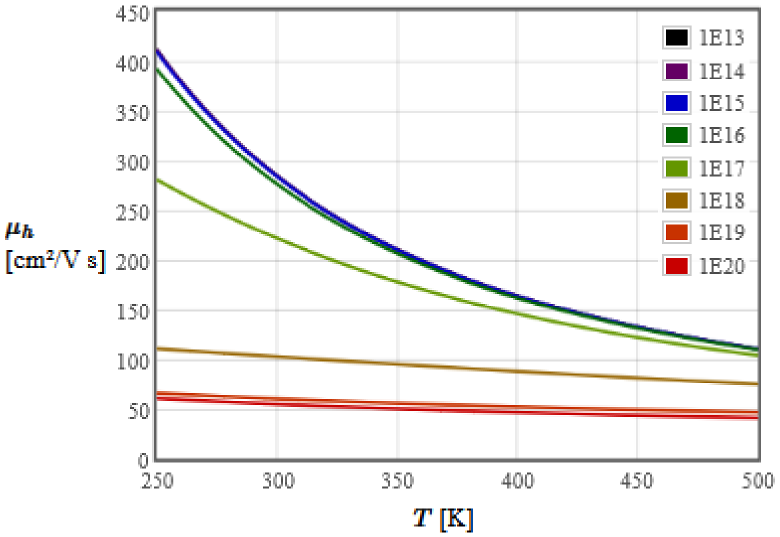
mobility model for Si

$$\mu_e = 88\left(\frac{T}{300}\right)^{-0.57} + \frac{7.4\times 10^8 T^{-2.33}}{1+0.88\left[\frac{N_d}{1.26\times10^{17}\left(\frac{T}{300}\right)^{2.4}}\right]\left(\frac{T}{300}\right)^{-0.146}} \quad \mathrm{cm^2/V\,s},$$

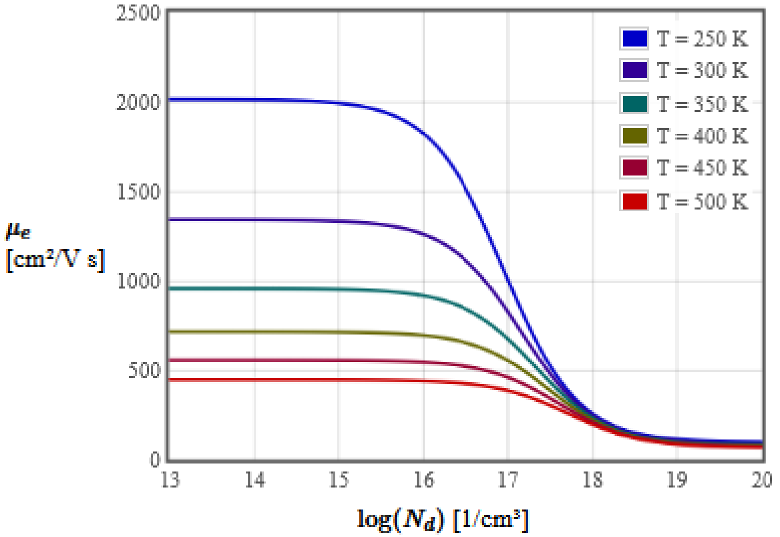
$$\mu_h = 54.3\left(\frac{T}{300}\right)^{-0.57} + \frac{1.36\times 10^8 T^{-2.33}}{1+0.88\left[\frac{N_a}{2.35\times10^{17}\left(\frac{T}{300}\right)^{2.4}}\right]\left(\frac{T}{300}\right)^{-0.146}} \quad \mathrm{cm^2/V\,s}.$$

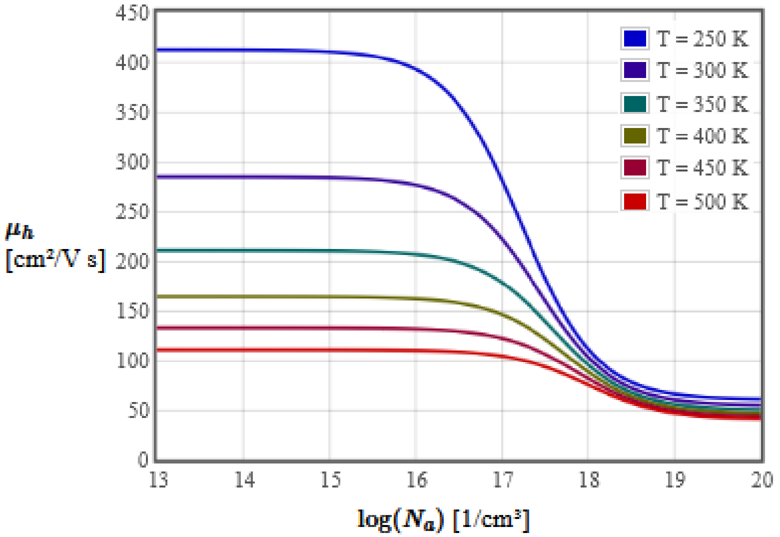
temperature





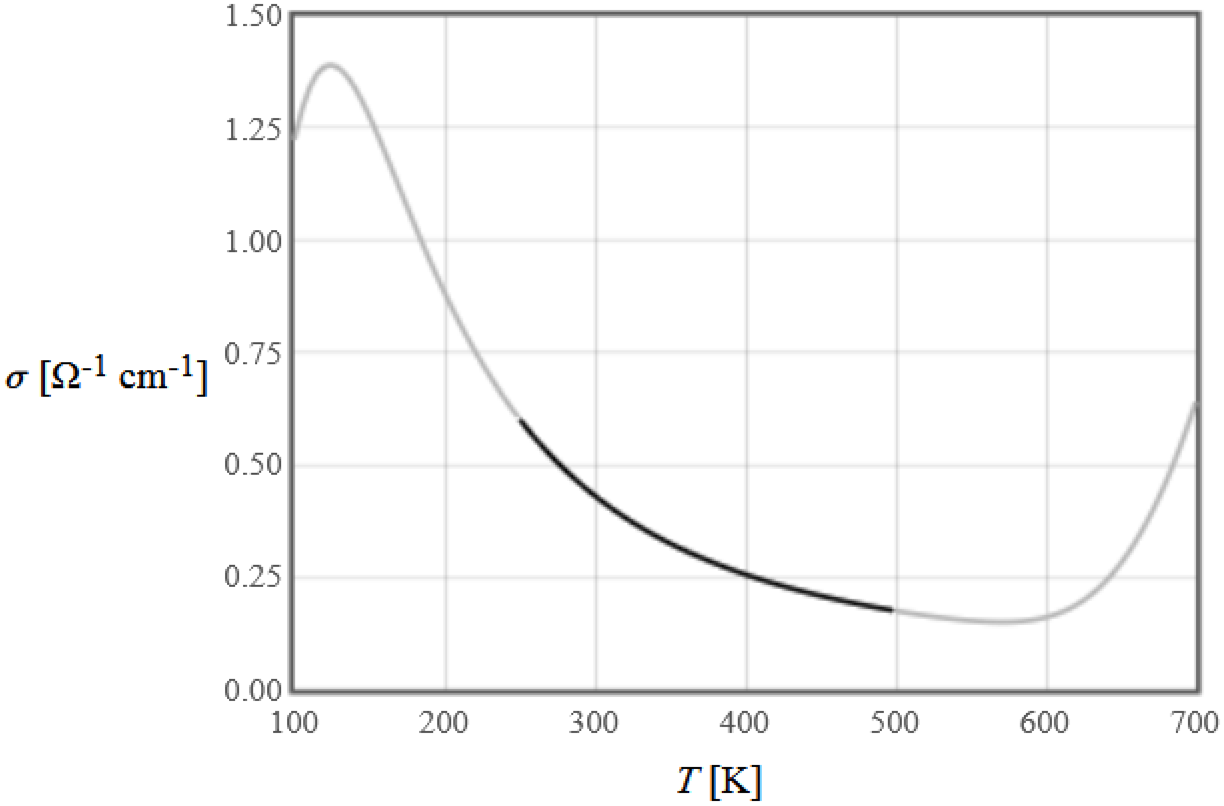
doping density





conductivity in Si

$$\sigma = ne\mu_n + pe\mu_p$$



$N_A = 10^{16}$ 1/cm^3

https://lampz.tugraz.at/~hadley/psd/L4/conductivity.php

Ballistic transport in transistors

The mean free path ~100 nm > gate length ~ 20 nm

enables motion without significant collisions and scattering

v not proportional to *E* $\cancel{\vec{v} = \mu \vec{E}}$

j not proportional to *E* $\cancel{\vec{j} = \sigma \vec{E}}$

nonlocal response

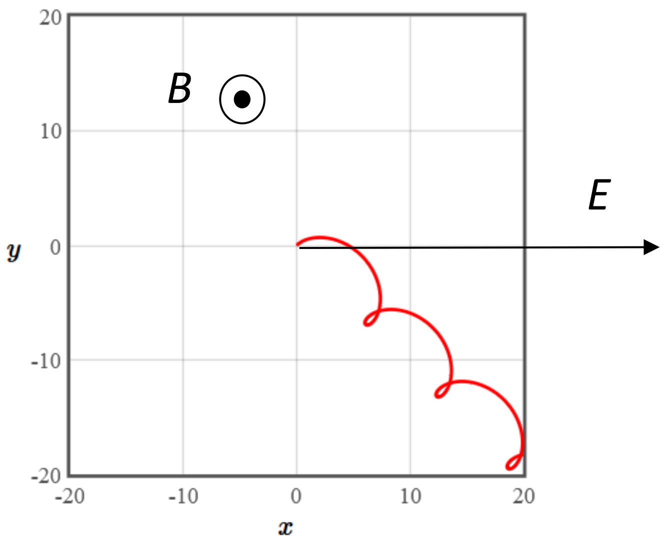
Electrons bend in a magnetic field like they do in vacuum.

The magnetic field slides could be skipped. They are not used later in the semester.

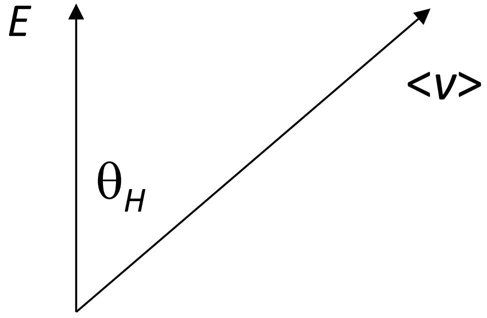
Crossed *E* and *B* fields

Ballistic transport

$$\vec{F} = m\vec{a} = -e\left(\vec{E} + \vec{v} \times \vec{B}\right)$$



Diffusive transport



Hall angle: $$\theta_H = \tan^{-1}\left(-\frac{eB_z\tau_{sc}}{m^*}\right)$$

http://lampx.tugraz.at/~hadley/physikm/script/magnetism/constant_EB.en.php

Magnetic field (diffusive transport)

$$\vec{F} = m\vec{a} = -e\vec{E} = e\frac{\vec{v}_d}{\mu}$$

$$\vec{F} = m\vec{a} = -e\left(\vec{E} + \vec{v}_d \times \vec{B}\right) = e\frac{\vec{v}_d}{\mu}$$

If *B* is in the *z*-direction, the three components of the force are

$$-\mu\left(E_x + v_{dy}B_z\right) = v_{dx}$$

$$-\mu\left(E_y - v_{dx}B_z\right) = v_{dy}$$

$$-\mu E_z = v_{dz}$$

Magnetic field

$$v_{d,x} = -\mu E_x - \mu B_z v_{d,y}$$

$$v_{d,y} = -\mu E_y + \mu B_z v_{d,x}$$

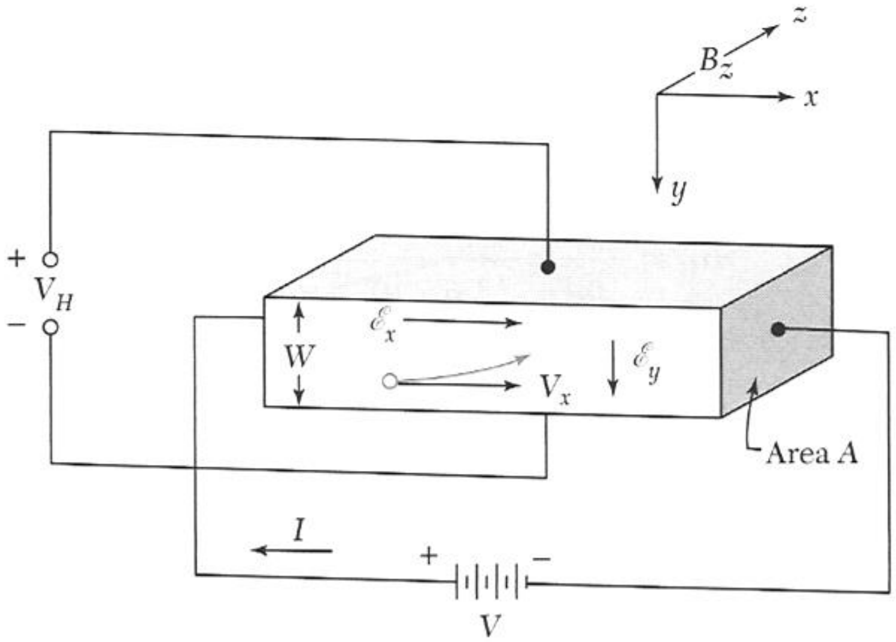
$$v_{d,z} = -\mu E_z$$

If $E_y = 0$,

$$v_{d,y} = -\mu B_z v_{d,x}$$

$$\tan\theta_H = -\mu B_z$$

The Hall Effect (diffusive regime)



$$v_{d,x} = -\mu E_x - \mu B_z v_{d,y}$$

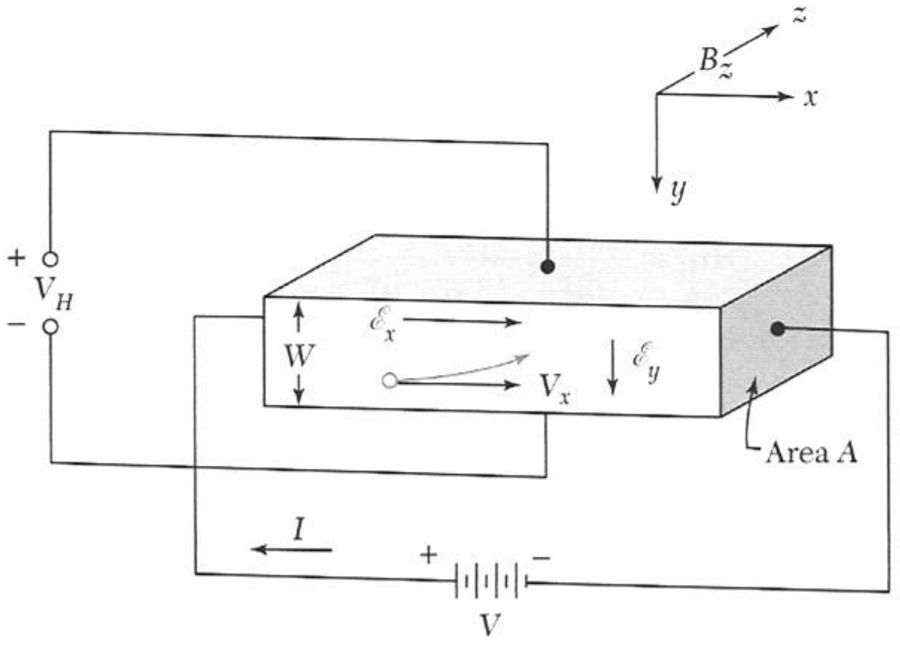
$$v_{d,y} = -\mu E_y + \mu B_z v_{d,x}$$

$$v_{d,z} = -\mu E_z$$

If $v_{d,y} = 0$,

$E_y = v_x B_z = V_H/W = R_H j_x B_z$ $\quad$ V_H = Hall voltage, R_H = Hall Constant

The Hall Effect (diffusive regime)



$$\vec{F} = q\left(\vec{v} \times \vec{B}\right)$$

$E_y = v_x B_z = V_H/W = R_H j_x B_z$ V_H = Hall voltage, R_H = Hall Constant

$R_H = v_x/j_x$

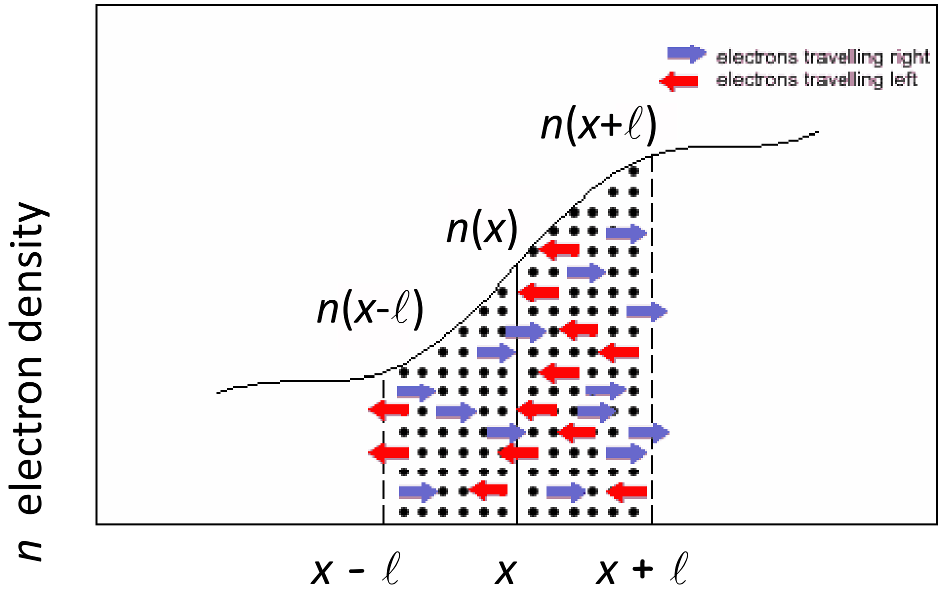
$v_x = -j_x/ne$ for n-type $v_x = j_x/pe$ for p-type

$R_H = -1/ne$ for n-type $R_H = 1/pe$ for p-type

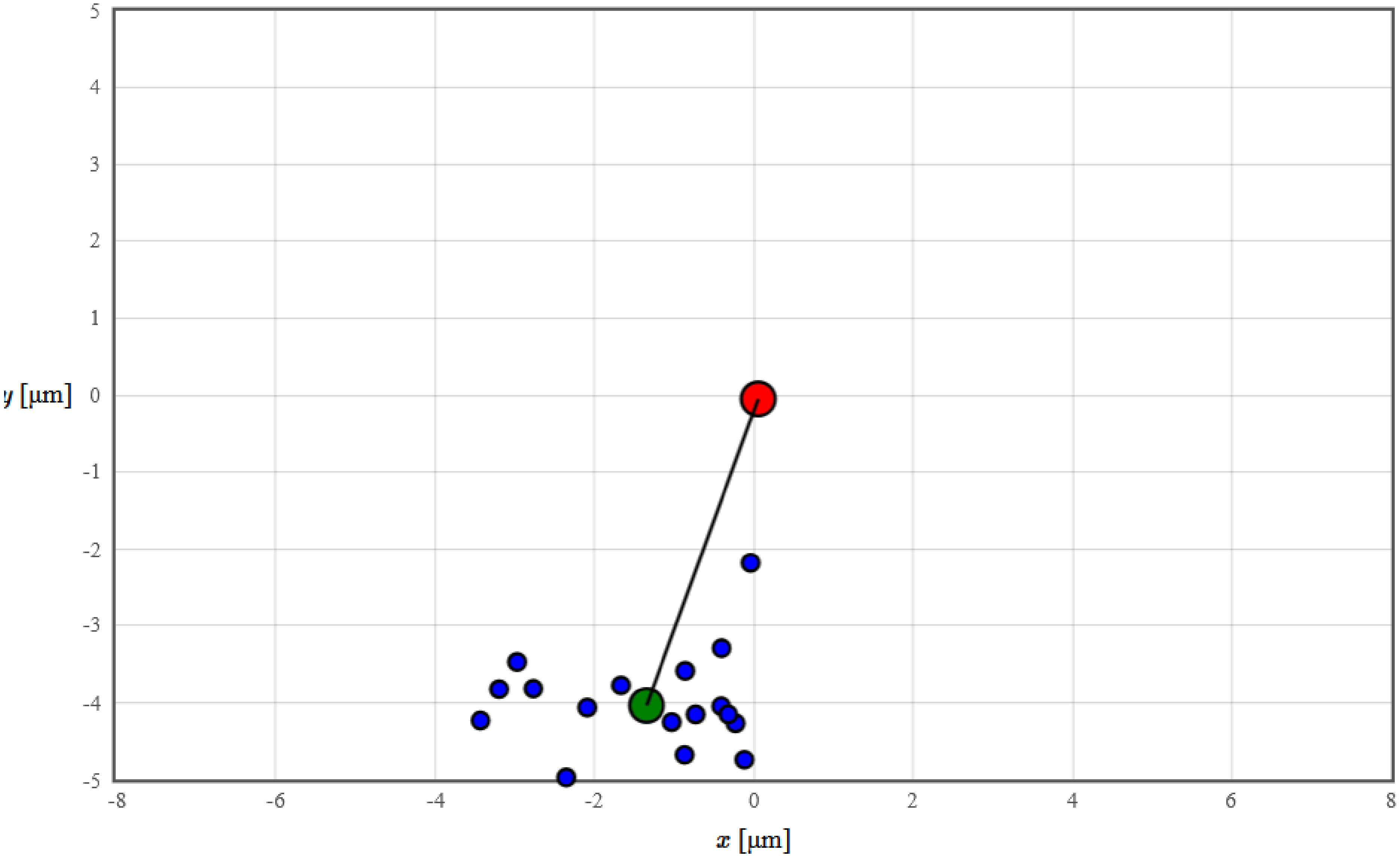
Diffusion

$$j_{n,diff} = |e| D_n \frac{dn}{dx}$$

$$j_{p,diff} = -|e| D_p \frac{dp}{dx}$$



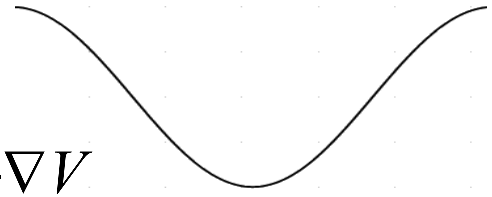
Diffusion is from high concentration to low concentration.



http://lampx.tugraz.at/~hadley/psd/L5/drude.php

Einstein relation

$$\vec{E} = -\nabla V$$



$$n = A\exp\left(\frac{-eV}{k_B T}\right)$$

Boltzmann factor

In equilibrium, drift = diffusion

$$-en\mu\vec{E} + eD\nabla n = 0$$

$$\nabla n = -\frac{e}{k_B T} A\exp\left(\frac{-eV_{pot}}{k_B T}\right)\nabla V = -\frac{ne}{k_B T}\nabla V = \frac{ne\vec{E}}{k_B T}$$

$$-en\mu\vec{E} + eD\frac{ne\vec{E}}{k_B T} = 0$$

$$\boxed{D = \frac{\mu k_B T}{e}}$$

Über die von der molekularkinetischen Theorie der Wärme geforderte Bewegung von in ruhenden Flüssigkeiten suspendierten Teilchen

Current Density Equations

Drift

Diffusion

$$\vec{j}_n = -ne\mu_n \vec{E} + eD_n \nabla n$$

$$\vec{j}_p = pe\mu_p \vec{E} - eD_p \nabla p$$

$$\vec{j}_{total} = \vec{j}_n + \vec{j}_p$$

In Equilibrium

$$\vec{j}_n = en\mu_n\vec{E} + eD_n\nabla n$$

The electric field is proportional to the gradient of the conduction band edge

$$e\vec{E} = \nabla E_c$$

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

If the Fermi energy is constant,

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

$$\vec{j}_n = n\nabla E_c \left(\mu_n - \frac{eD_n}{k_B T}\right)$$

This means that the current density in a semiconductor where the Fermi energy is constant is zero.

Current Density Equations

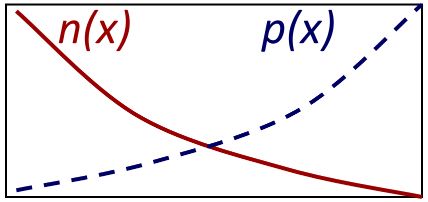
note: electron and hole currents have same direction

electric current = charge × particle flow

drift

$E \longrightarrow$

diffusion



flow ← $-n\mu_e E$ (electron) *flow* → $-D_n(dn/dx)$

current → **current** ←

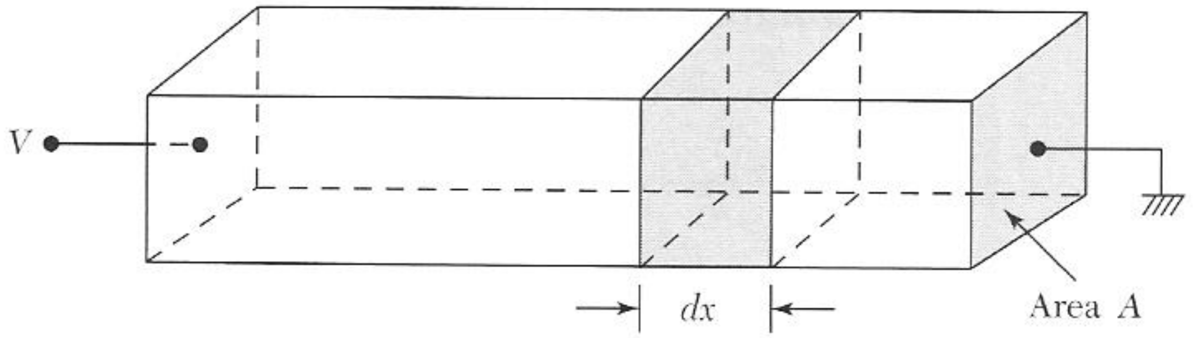
$j_e = -e \times flow$

flow → $p\mu_p E$ (hole) *flow* ← $D_p(dp/dx)$

current → **current** ←

$j_p = e \times flow$

Continuity equations

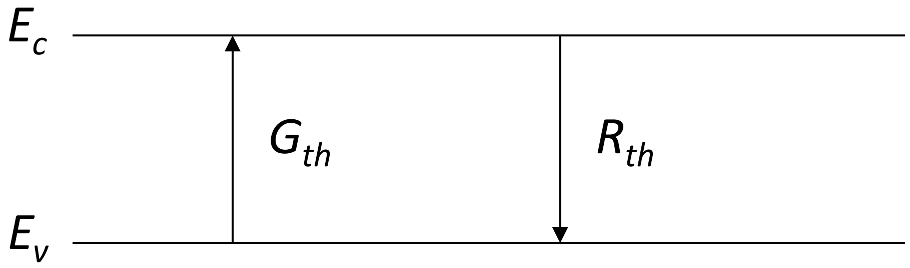


$$\frac{\partial n}{\partial t} = \frac{1}{e} \nabla \cdot \vec{j}_n + G_n - R_n$$

$$\frac{\partial p}{\partial t} = -\frac{1}{e} \nabla \cdot \vec{j}_p + G_p - R_p$$

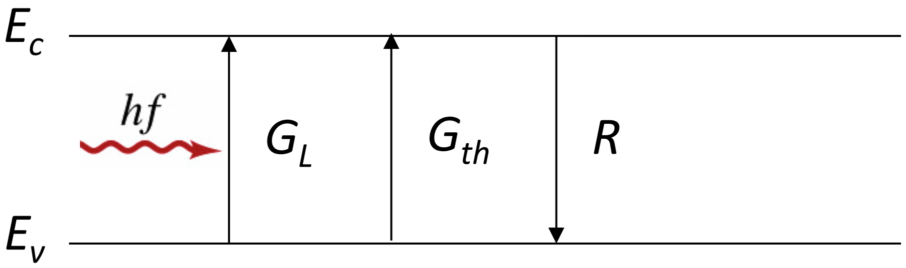
j_n and j_p consist of drift and diffusion terms

Generation and Recombination



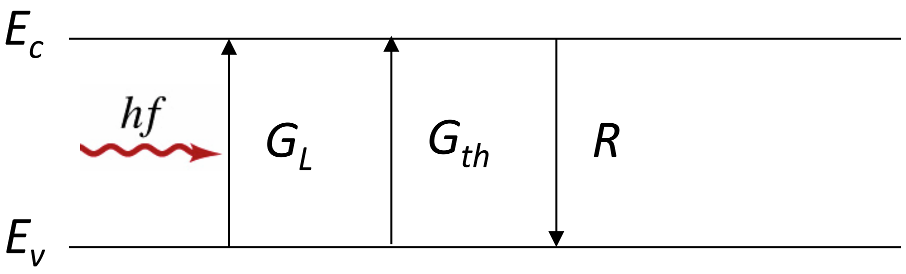
thermal equilibrium

Shining light on a semiconductor or injecting electrons or holes from a contact can result in a **non-equilibrium** distribution $np \neq n_i^2$



non equilibrium

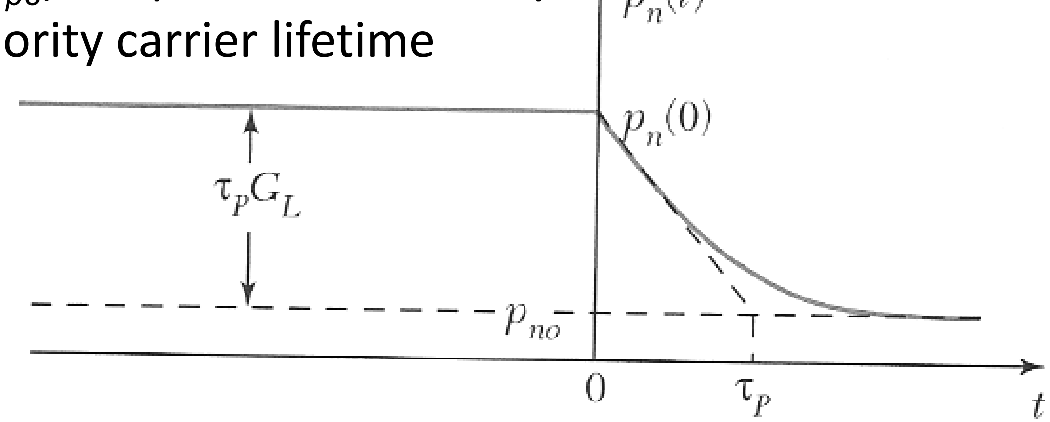
Recombination



$$R - R_{th} = \frac{p_n - p_{n0}}{\tau_p}$$

Recombination rate is limit by the density of minority carriers. The majority carriers have to find a minority carrier to recombine.

p_n (or n_p) = minority carrier concentration
p_{n0} (or n_{p0}) = equilibrium minority carrier concentration
τ_p = minority carrier lifetime



minority carrier lifetimes

p-type

$$n_p(t) = n_{excess}\exp(-t/\tau_n) + n_{p0}$$

minority carrier lifetimes

n-type

$$p_n(t) = p_{excess}\exp(-t/\tau_p) + p_{n0}$$

$$np = n_i^2$$

Continuity equations

$$\frac{\partial n}{\partial t} = \frac{1}{e}\nabla \cdot \vec{j}_n + G_n - R_n$$

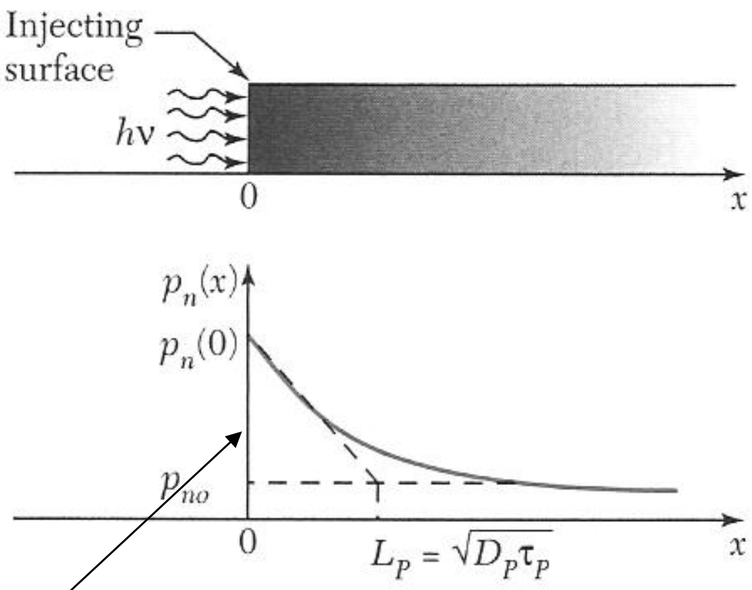
drift: $$\vec{j}_n = -ne\mu_n\vec{E} \qquad \nabla \cdot \vec{j}_n = -en\mu_n\nabla \cdot \vec{E} - e\nabla n\mu_n\vec{E}$$

diffusion: $$\vec{j}_{n,diff} = |e|D_n\nabla n \qquad \nabla \cdot \vec{j}_{n,diff} = |e|D_n\nabla^2 n$$

$$\boxed{\begin{aligned} \frac{\partial n}{\partial t} &= n\mu_n\nabla \cdot \vec{E} + \nabla n\mu_n\vec{E} + D_n\nabla^2 n + G_n - \frac{n-n_0}{\tau_n} \\ \frac{\partial p}{\partial t} &= -p\mu_p\nabla \cdot \vec{E} - \nabla p\mu_p\vec{E} + D_p\nabla^2 p + G_p - \frac{p-p_0}{\tau_p} \end{aligned}}$$

Diffusion Length

n-type



Generation only occurs at the surface. There the minority carrier density is $p_n(0)$.

Steady state

$$\frac{\partial p_n}{\partial t} = 0 = D_p \frac{\partial^2 p_n}{\partial x^2} - \frac{p_n - p_{n0}}{\tau_p}$$

$$p_n(x) = p_{n0} + \left(p_n(0) - p_{n0}\right)\exp\left(\frac{-x}{L_p}\right)$$

Diffusion Length

$$0 = D_p \frac{\partial^2 p_n}{\partial x^2} - \frac{p_n - p_{n0}}{\tau_p} \qquad \Leftarrow \qquad p_n(x) = p_{n0} + \left(p_n(0) - p_{n0}\right)\exp\left(\frac{-x}{L_p}\right)$$

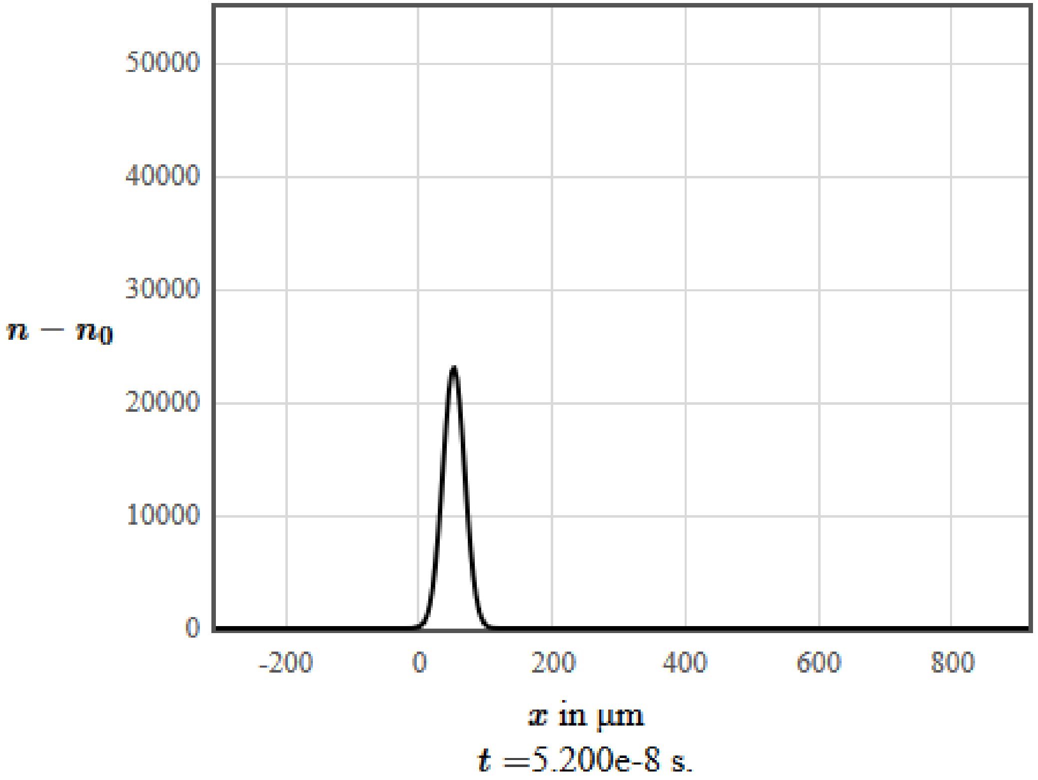
$$0 = \frac{D_p\left(p_n(0) - p_{n0}\right)}{L_p^2}\exp\left(\frac{-x}{L_p}\right) - \frac{\left(p_n(0) - p_{n0}\right)}{\tau_p}\exp\left(\frac{-x}{L_p}\right)$$

$$L_p = \sqrt{D_p \tau_p}$$

diffusion length,
typically microns

Haynes Shockley experiment

$$n_p(x,t)=\frac{n_{generated}}{\sqrt{4\pi D_n t}}\exp\left(-\frac{(x-\mu_n E t)^2}{4D_n t}\right)\exp\left(-\frac{t}{\tau_n}\right)+n_{p0}$$



τ = 1E-6 [s]

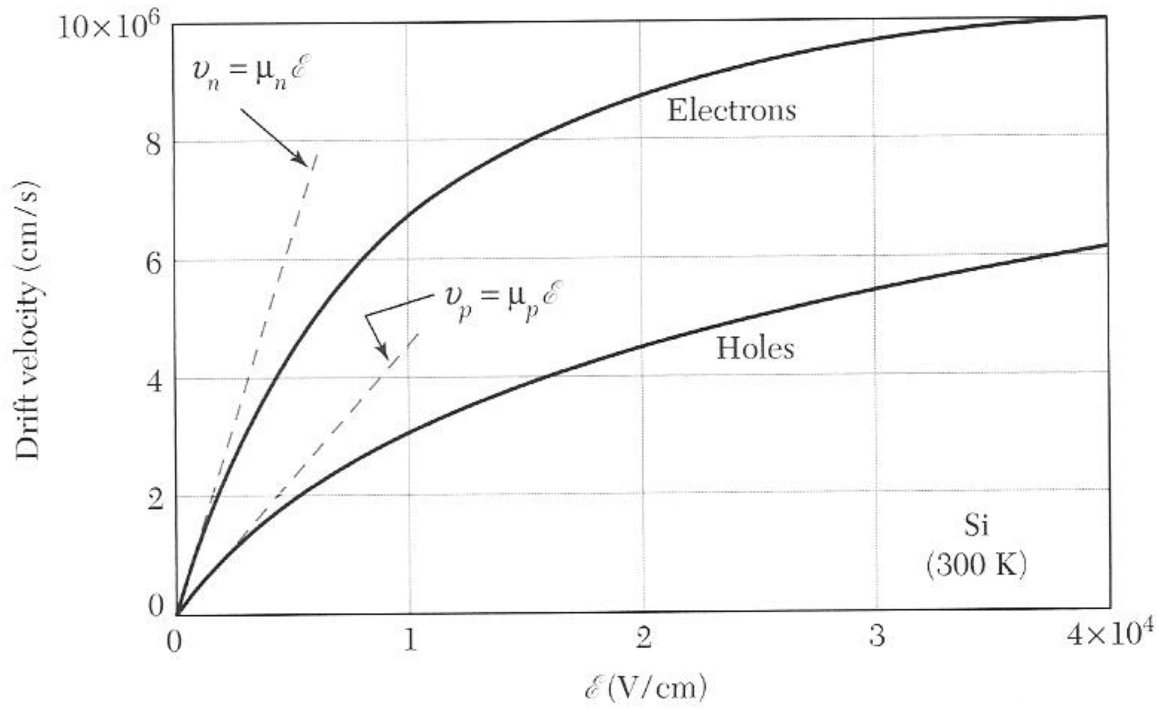
E = 100 [V/cm]

μ = 1000 [cm²/V s]

$D=\mu k_B T/e$ =0.00258 [m²/s]

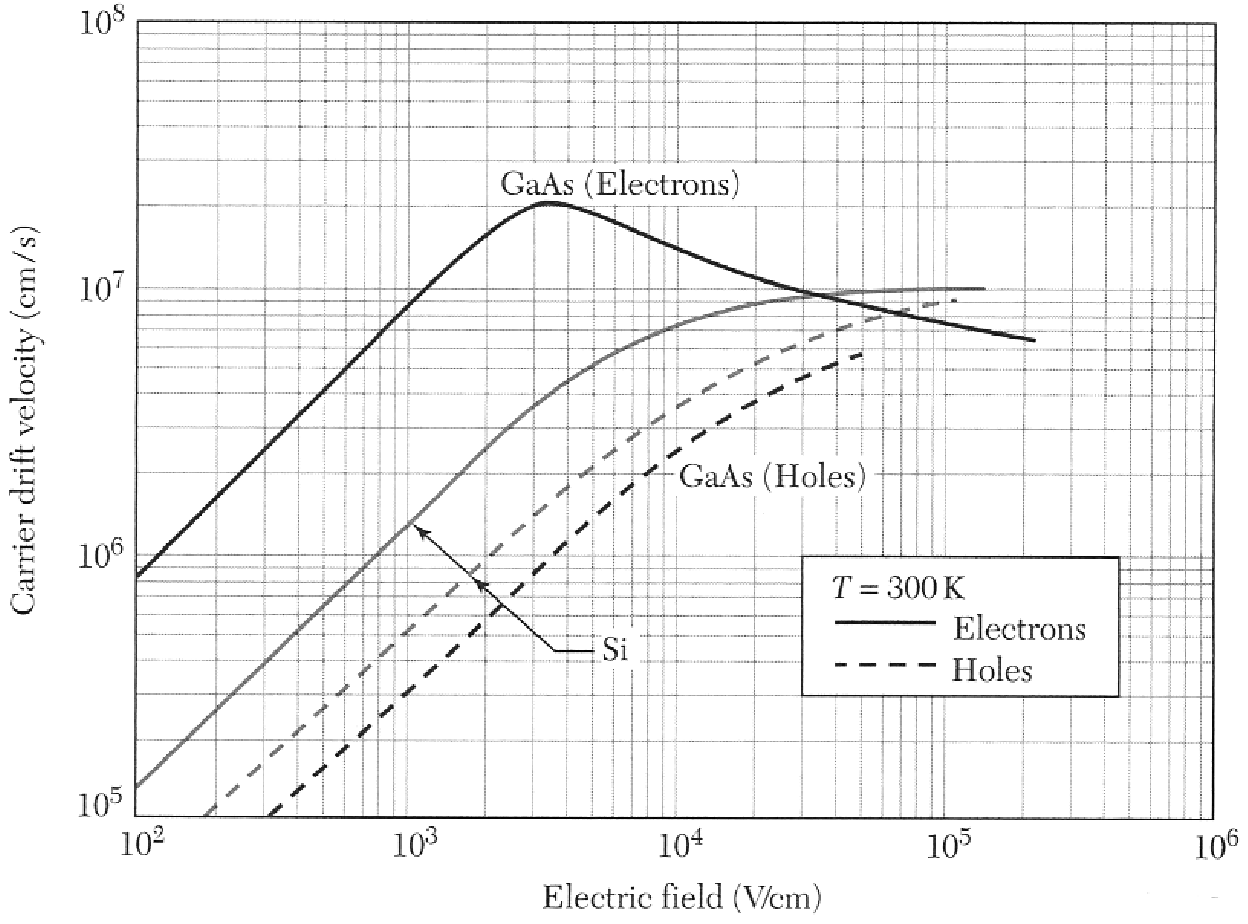
$L=\sqrt{D\tau}$ =50.8 [µm]

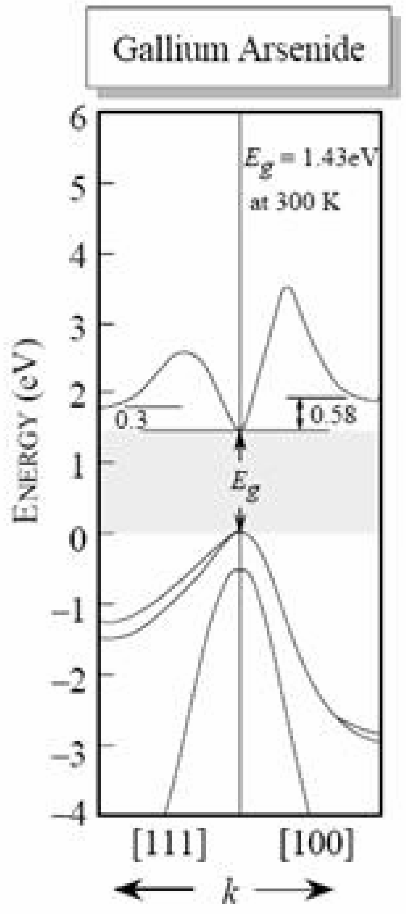
High Fields



Silicon

High Fields



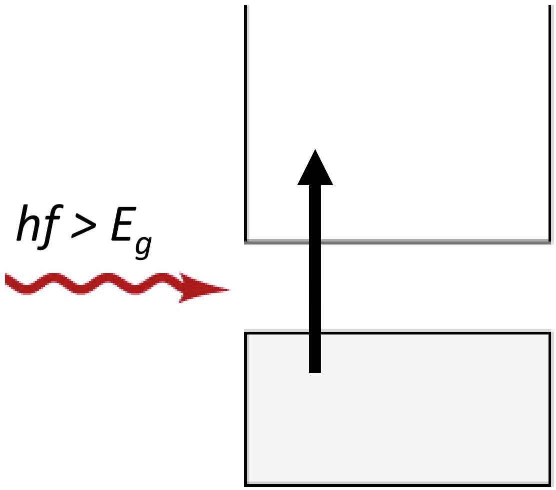


GaAs

Impact ionization

Carriers are accelerated to an energy above the gap before they scatter. They generate more electron-hole pairs. This results in an avalanche breakdown of the device.

Photoconductivity



$$\sigma = ne\mu_n + pe\mu_p$$

Light increases the conductivity of a semiconductor.

Laser printer

semiconductin
g
photoconducto
r