Carrier Transport

Carrier Transport

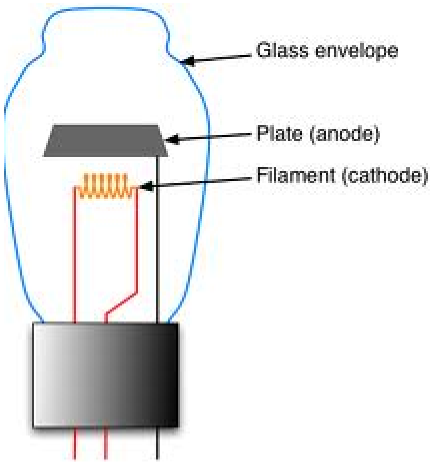
Ballistic transport
Drift
Diffusion
Generation and recombination
The continuity equation
High field effects

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.

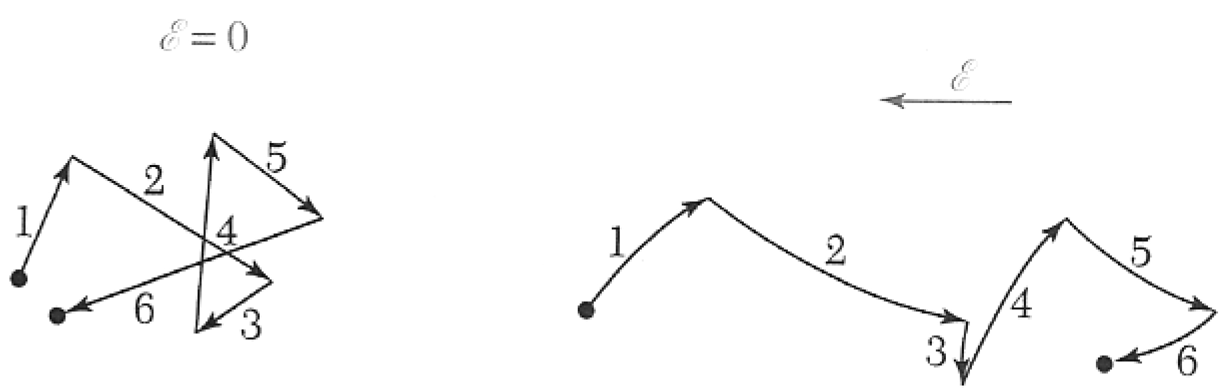
Drift

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.

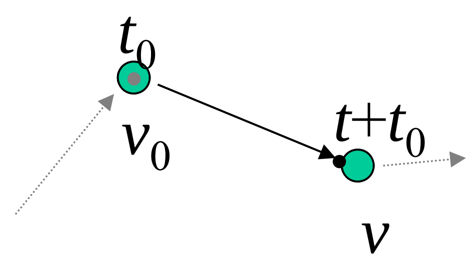
mean free path: $\ell = v_{th} \tau_{sc} \sim 10$ nm ~ 200 atoms



Drift (diffusive transport)

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

time between two collisions



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

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

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

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

Drift

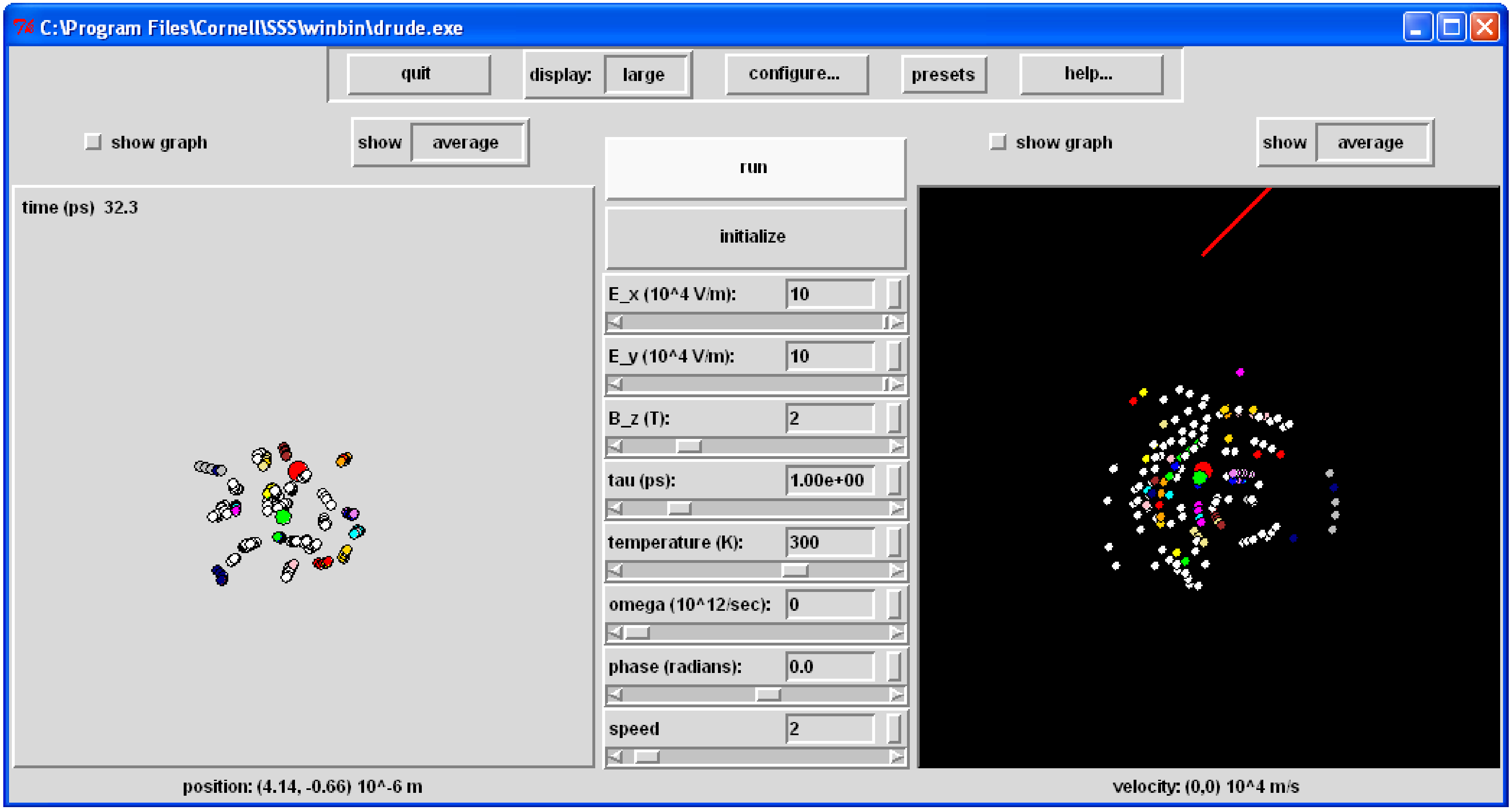
drift velocity: $\vec{v}_{d,n} = -\mu_n \vec{E}$ $\qquad$ $\vec{v}_{d,p} = \mu_p \vec{E}$

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

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

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

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


C:\Program Files\Cornell\SSS\winbin\drude.exe
quit
display:
large
configure...
presets
help...
show graph
show
average
run
initialize
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

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

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

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 calculator

$$\mu = \mu_{min} + \frac{\mu_{max} - \mu_{min}}{1 + (N/N_{ref})^{\gamma}}$$

For Electrons:

$$\mu_{min} = 47\left(\frac{T}{300}\right)^{-1,23} \frac{\text{cm}^2}{\text{Vs}}$$

$$\Delta\mu = \mu_{max} - \mu_{min} = 1373\left(\frac{T}{300}\right)^{-2,38} \frac{cm^2}{Vs}$$

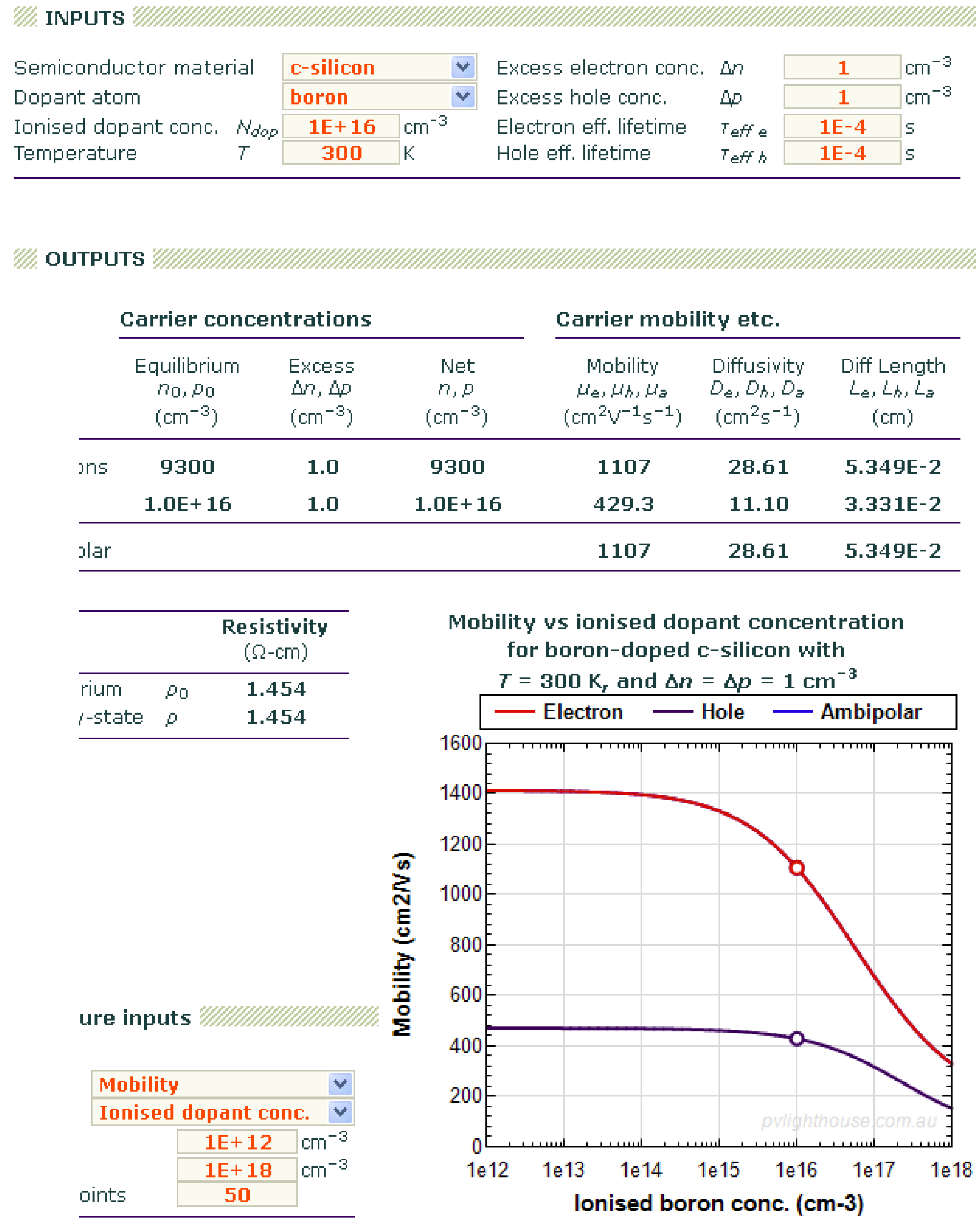
$$N_{ref} = 1,05 \cdot 10^{17}\left(\frac{T}{300}\right)^{3,65} cm^{-3} \; ; \gamma = 0,68\left(\frac{T}{300}\right)^{-0,32}$$

For Holes:

$$\mu_{min} = 36\left(\frac{T}{300}\right)^{-0,87} \frac{\text{cm}^2}{\text{Vs}}$$

$$\Delta\mu = \mu_{max} - \mu_{min} = 438\left(\frac{T}{300}\right)^{-2,01} \frac{cm^2}{Vs}$$

$$N_{ref} = 2,85 \cdot 10^{17}\left(\frac{T}{300}\right)^{2,93} cm^{-3} \; ; \gamma = 0,65\left(\frac{T}{300}\right)^{0,26}$$



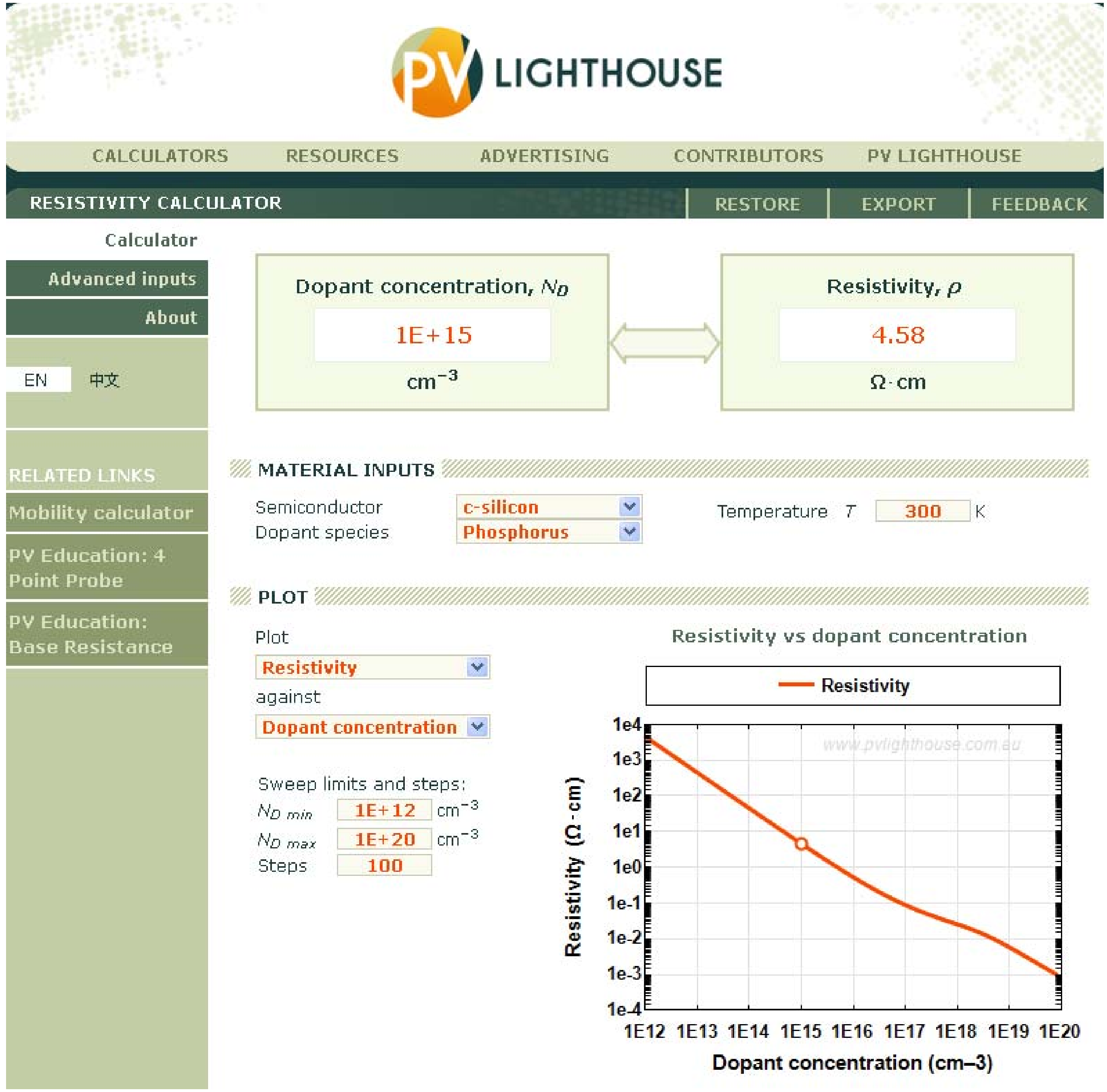
http://www.pvlighthouse.com.au/calculators/mobility%20calculator/mobility%20calculator.aspx

Resistivity calculator

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

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

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

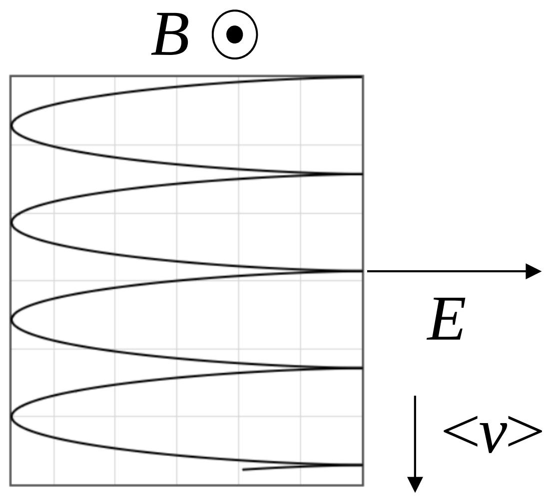


http://www.pvlighthouse.com.au/calculators/Resistivity%20calculator/Resistivity%20calculator.aspx

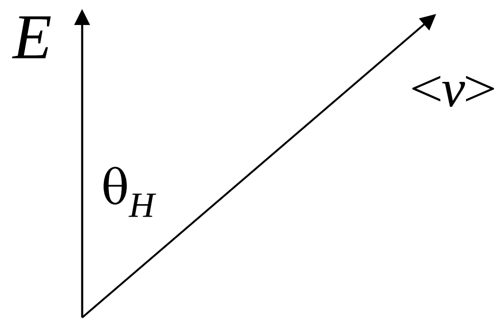
Crossed *E* and *B* fields

Ballistic transport

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



Diffusive transport



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

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

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

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

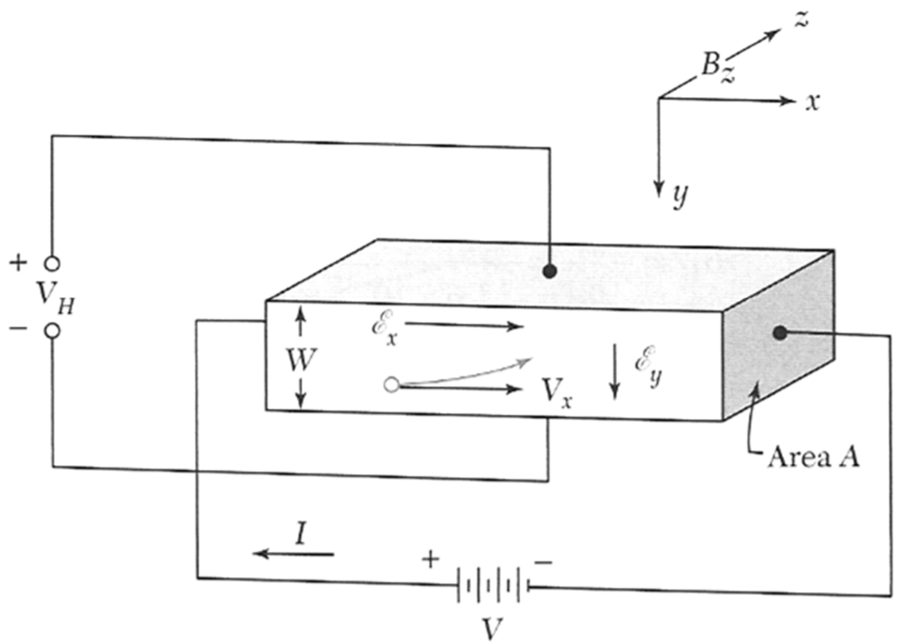
$$v_{d,z} = -\mu E_z$$

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 $v_{d,y} = 0$,

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

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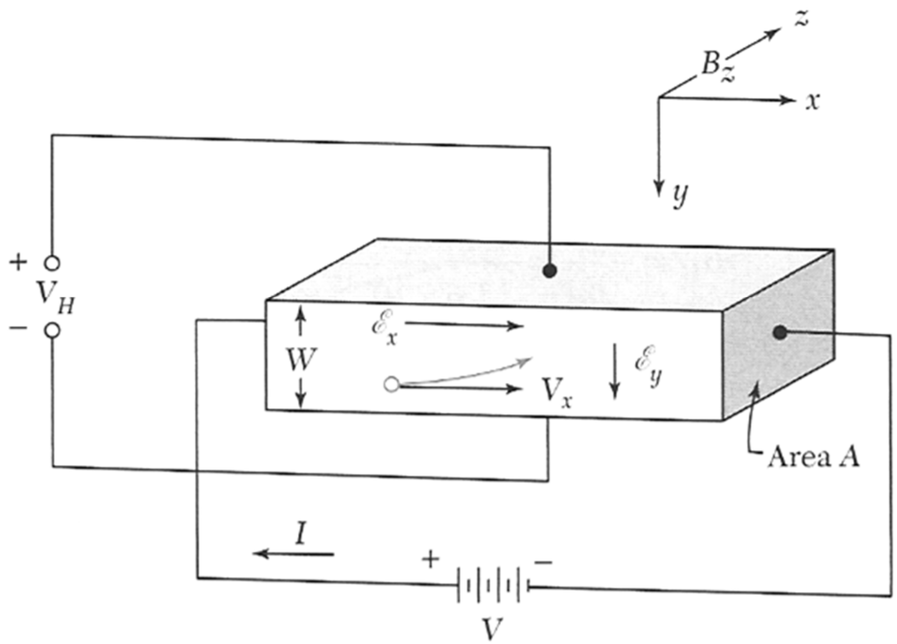

$$\vec{F} = q\left(\vec{v} \times \vec{B}\right)$$

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$j_x = I/A$

$v_x = -j_x/ne$ 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

Ballistic transport in transistors

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

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

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

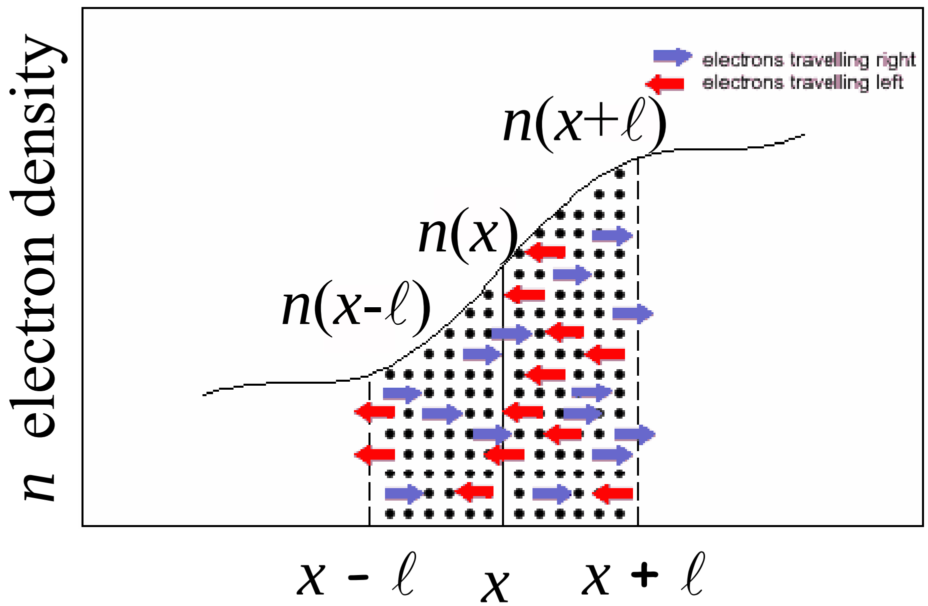
nonlocal response

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

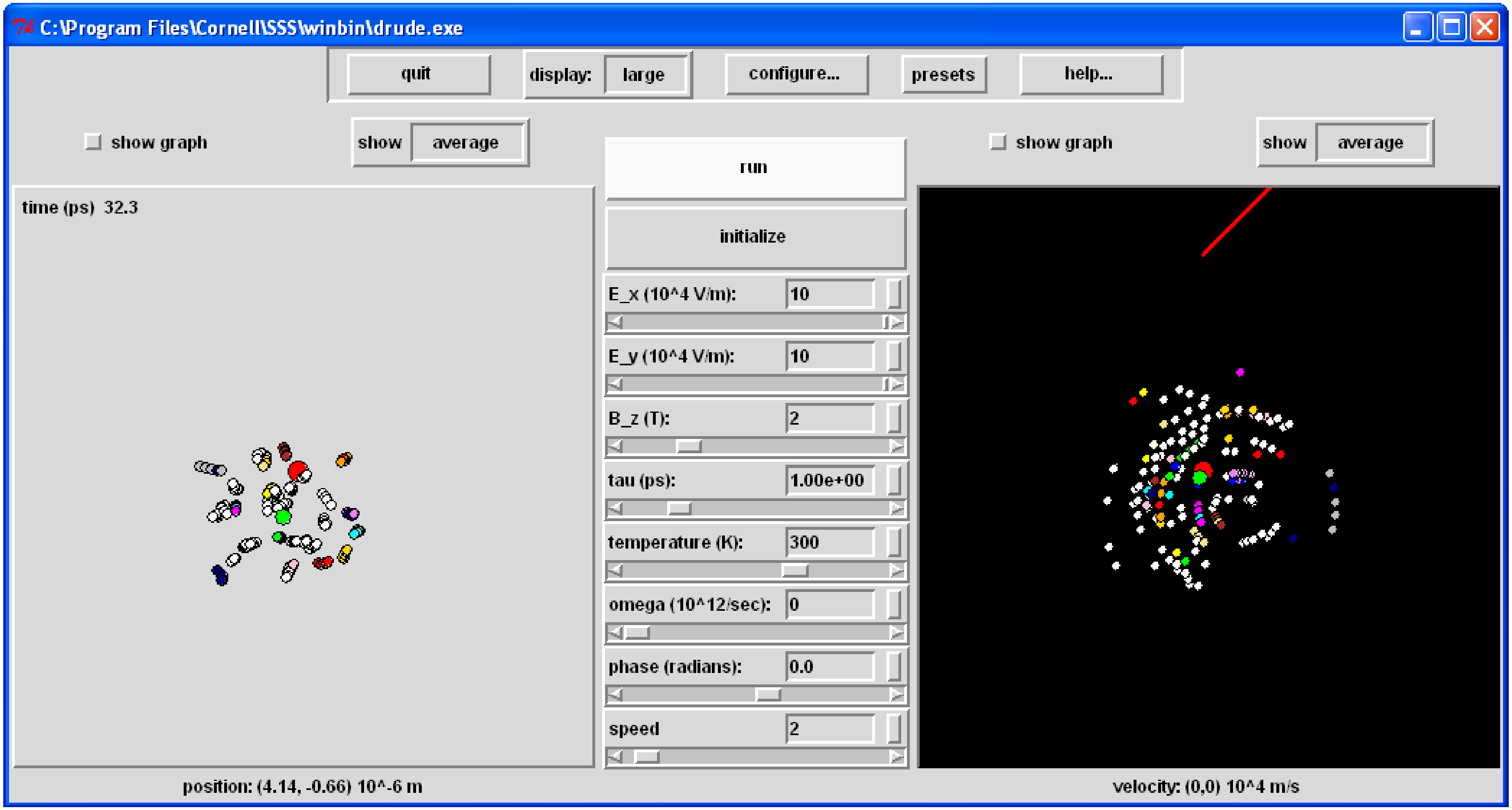
Diffusion

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

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



Diffusion is from high concentration to low concentration.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Drift

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Matthiessen's rule

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mostly temperature independent

phonons, temperature dependent

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

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

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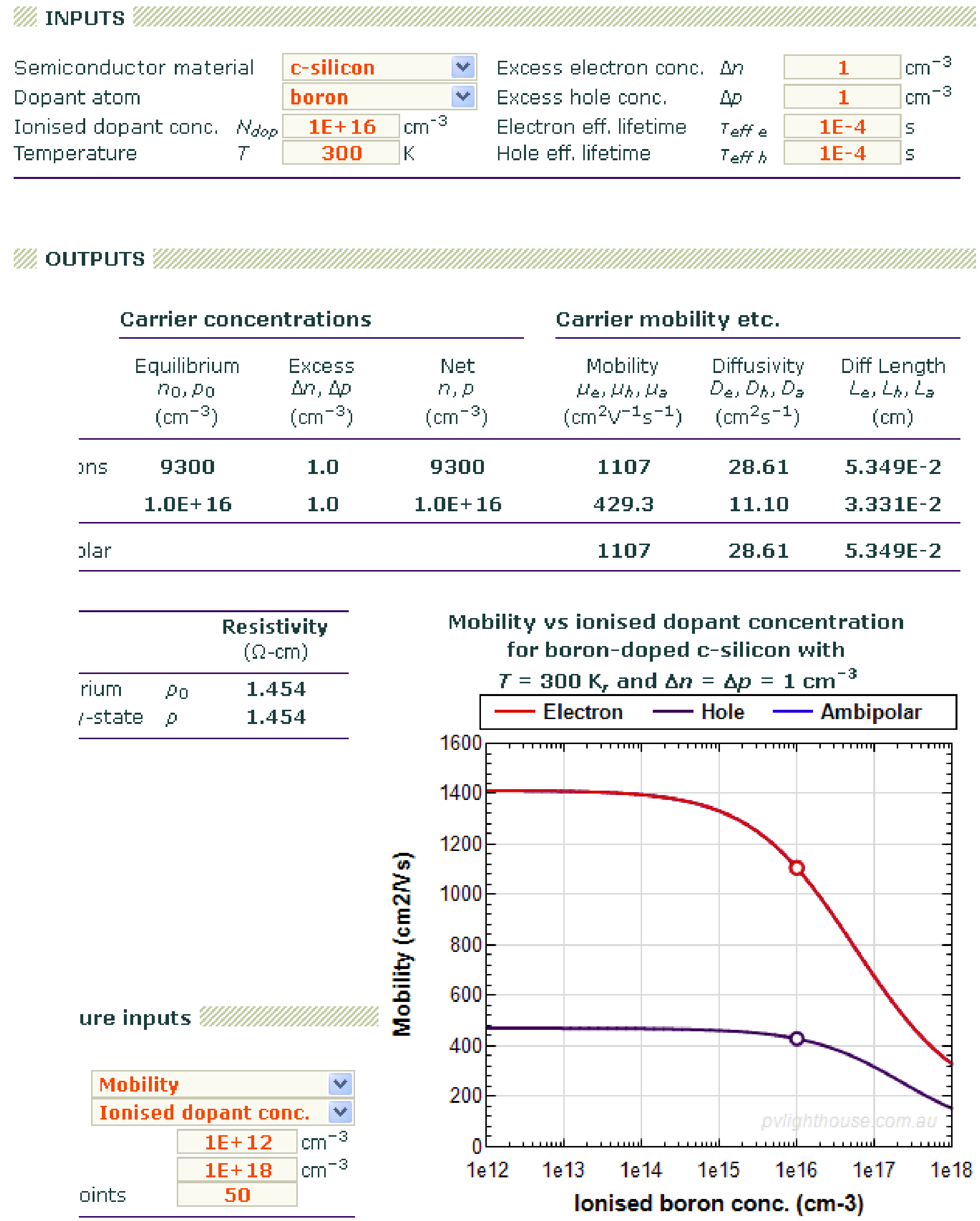

http://www.pvlighthouse.com.au/calculators/mobility%20calculator/mobility%20calculator.aspx

Resistivity calculator

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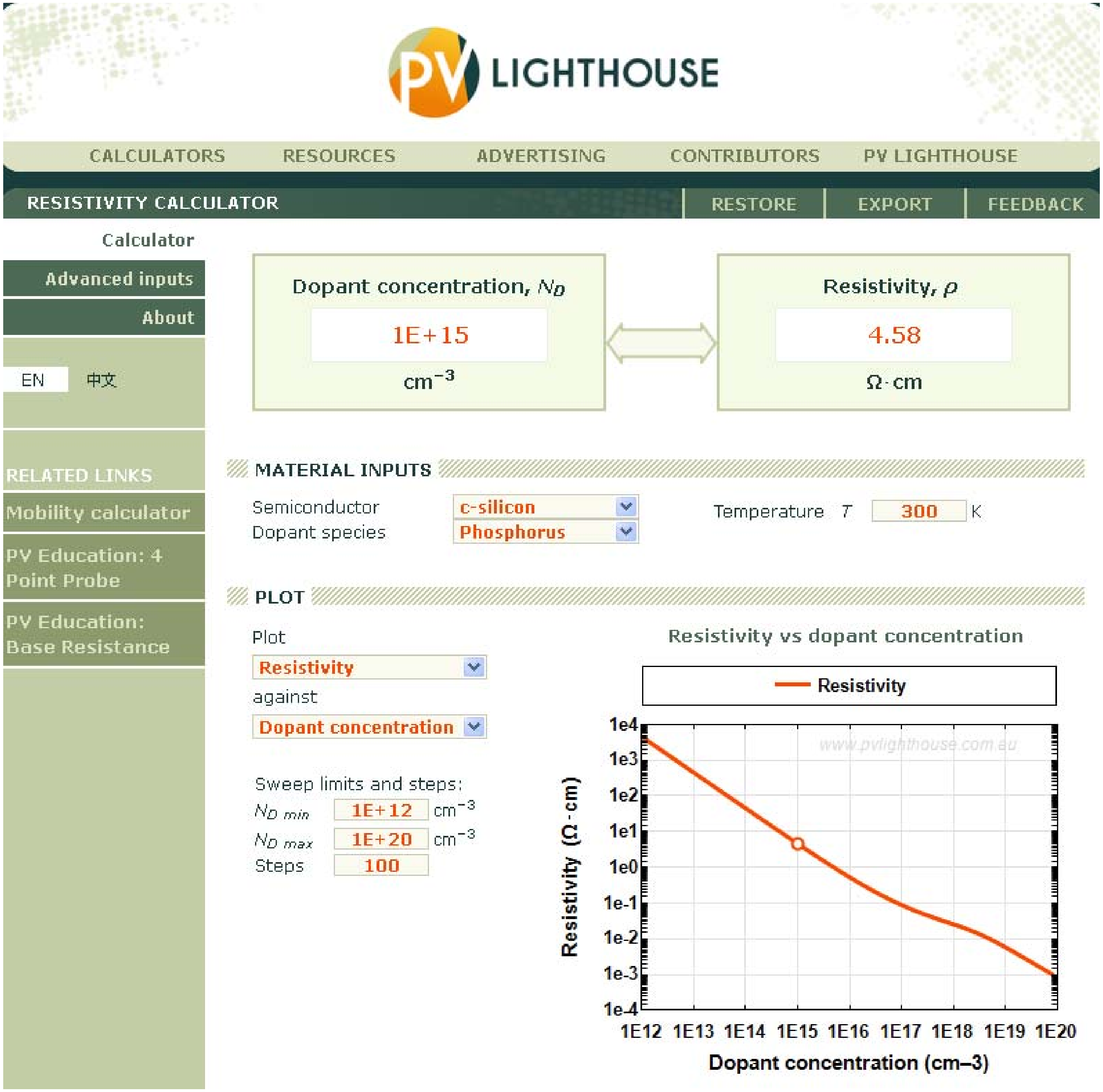
$$p = N_v \exp\left(\frac{E_v - E_F}{k_B T}\right)$$

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



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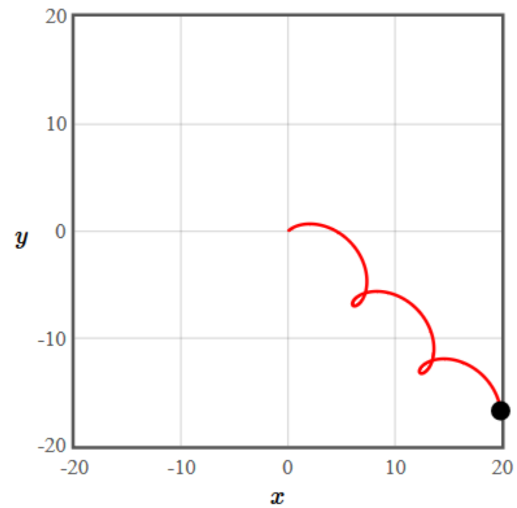
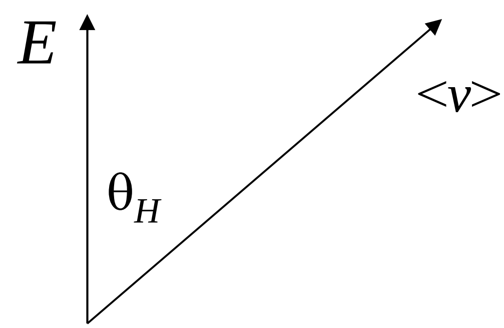


$\odot$ B

Diffusive transport



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

Magnetic field (diffusive transport)

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Magnetic field

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

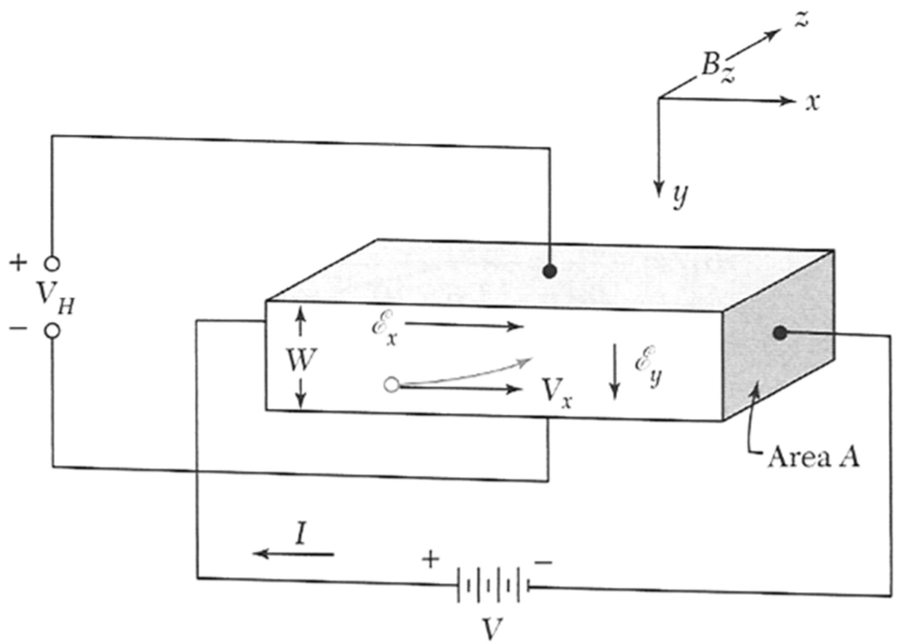
$$v_{d,z} = -\mu E_z$$

If $E_y = 0$,

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

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

The Hall Effect (diffusive regime)



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

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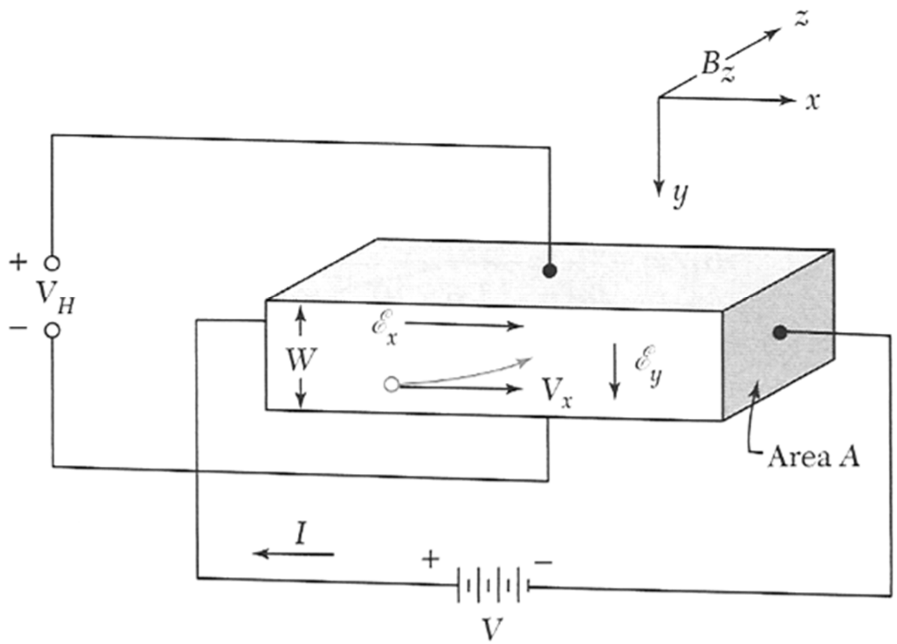

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$R_H = -1/ne$ for n-type $\quad$ $R_H = 1/pe$ for p-type

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

v not proportional to *E* $\quad \vec{v} = \mu \vec{E}$ (crossed out)

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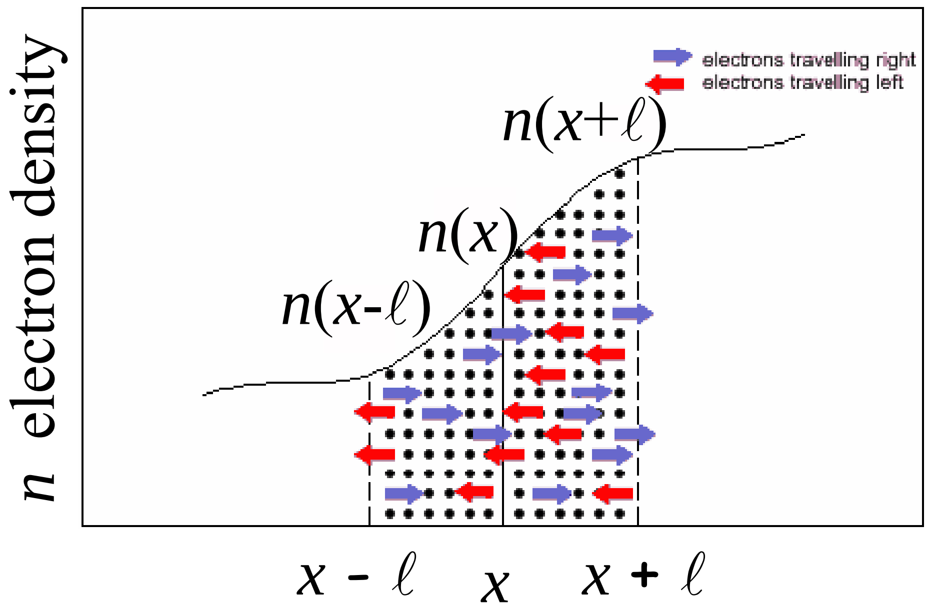
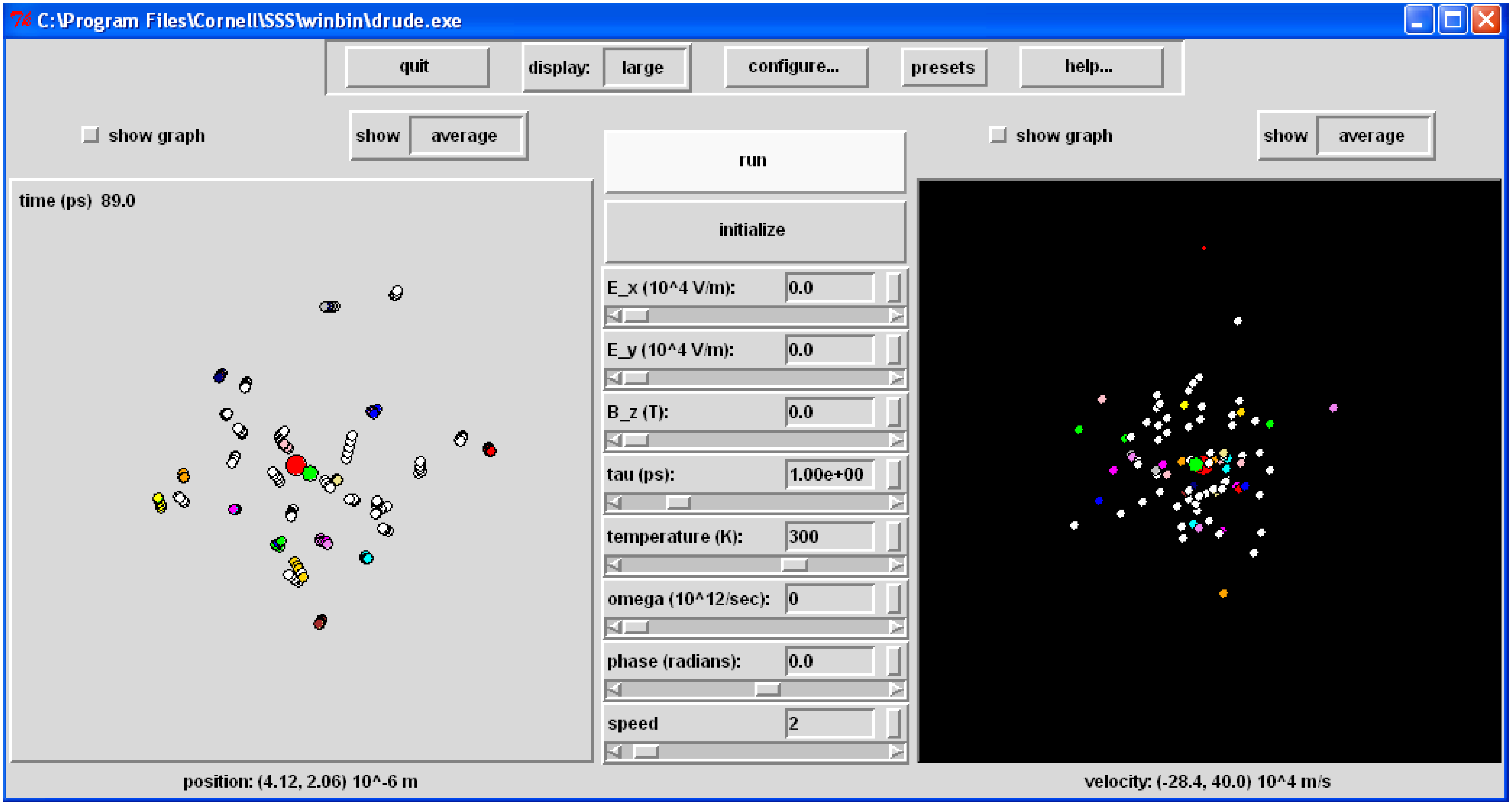
$$j_{n,diff} = |e| D_n \frac{dn}{dx}$$

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



Diffusion is from high concentration to low concentration.



If no forces are applied, the electrons diffuse.
The average velocity moves against an electric field.
In just a magnetic field, the average velocity is zero.
In an electric and magnetic field, the electrons move in a straight line at the Hall angle.

Einstein relation

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

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

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

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

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

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

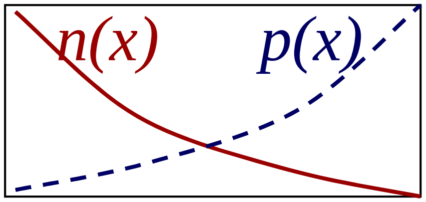
Current Density Equations

note: electron and hole currents have same direction

electric current = charge × particle flow

drift

diffusion



flow ← $-n\mu_e E$ (−) *current* →

$\boldsymbol{j_e = -e \times flow}$

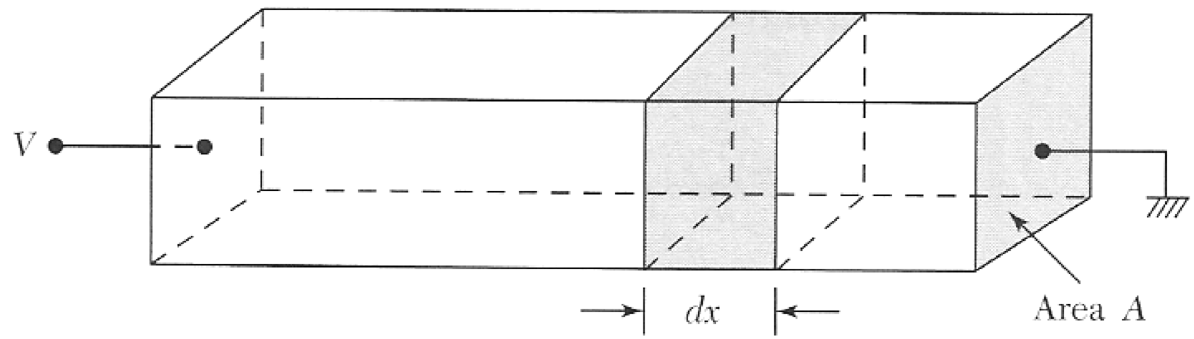
(−) *flow* → $-D_n(dn/dx)$; *current* ←

flow → $p\mu_p E$ (+) *current* →

$\boldsymbol{j_p = e \times flow}$

flow ← $D_p(dp/dx)$ (+) *current* ←

Continuity equations

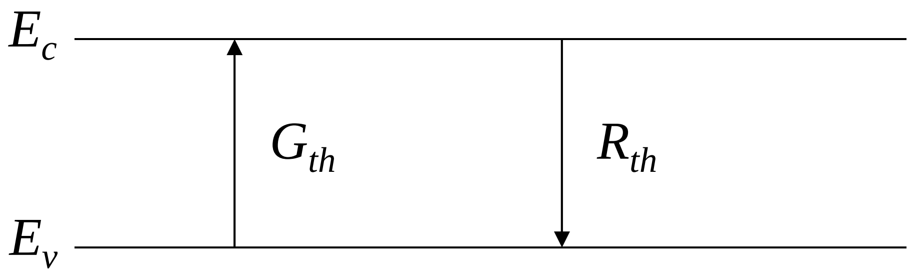


$$\frac{\partial n}{\partial t} = \frac{1}{e}\nabla \cdot \vec{j}_n + G_n - R_n$$

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

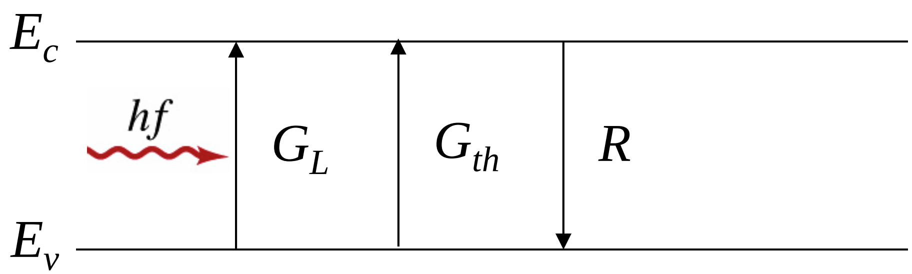
j_n and j_p consist of drift and diffusion terms

Generation and Recombination



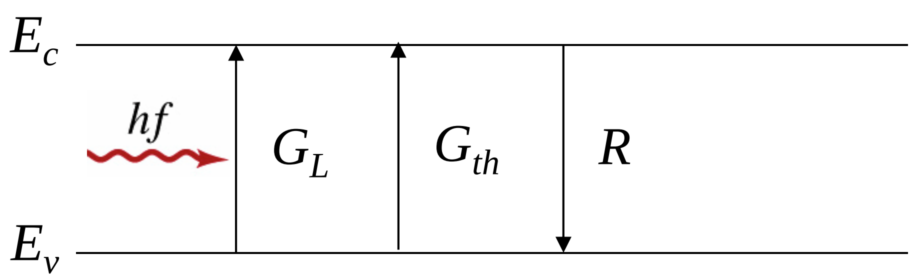
thermal equilibrium

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

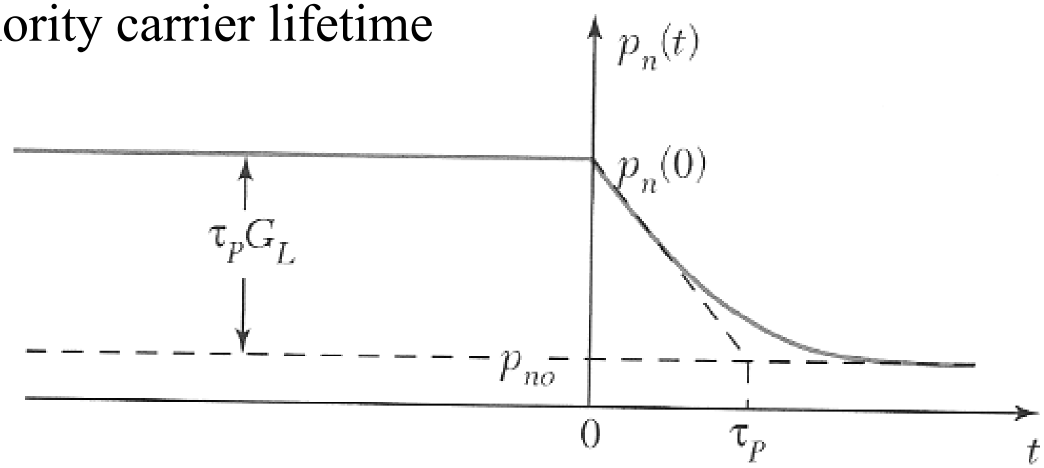
Recombination



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

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

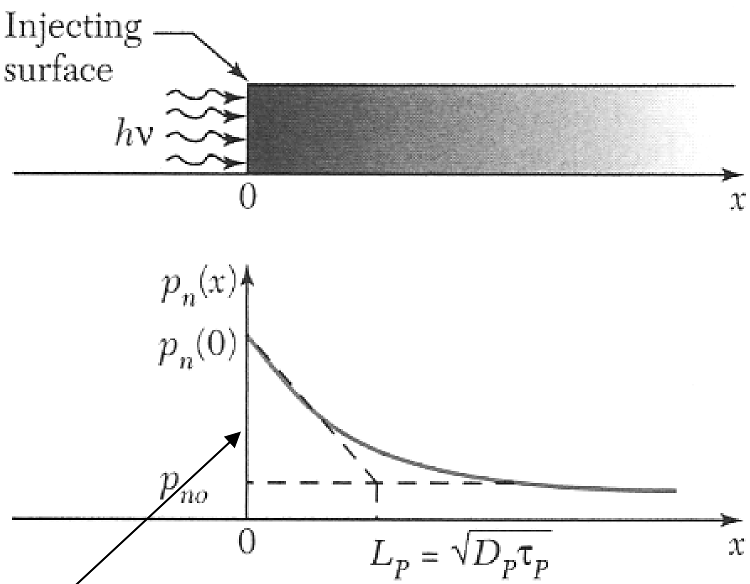
diffusion: $\vec{j}_{n,diff} = |e| D_n \nabla n$ $\quad\nabla \cdot \vec{j}_{n,diff} = |e| D_n \nabla^2 n$

$$\frac{\partial n}{\partial t} = n\mu_n \nabla \cdot \vec{E} + \nabla n\mu_n \vec{E} + D_n \nabla^2 n + G_n - \frac{n - n_0}{\tau_n}$$

$$\frac{\partial p}{\partial t} = -p\mu_p \nabla \cdot \vec{E} - \nabla p\mu_p \vec{E} + D_p \nabla^2 p + G_p - \frac{p - p_0}{\tau_p}$$

Diffusion Length

n-type



Steady state

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

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

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

Diffusion Length

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

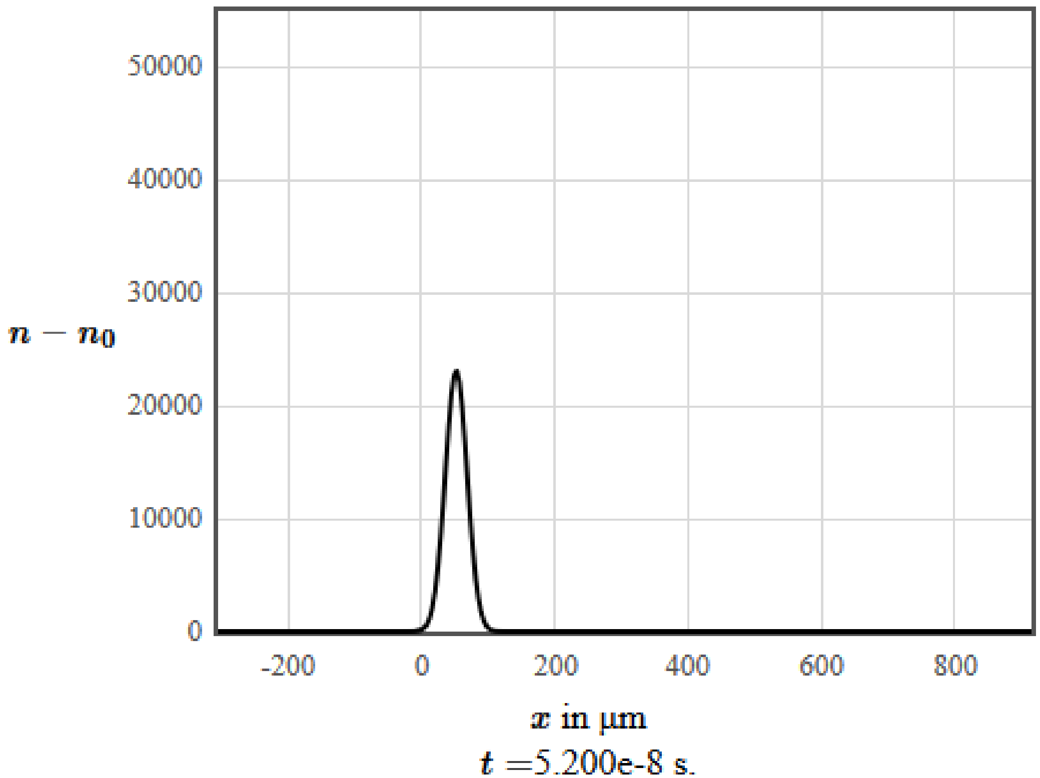
$$0 = \frac{D_p\left(p_n(0) - p_{n0}\right)}{L_p^2}\exp\left(\frac{-x}{L_p}\right) - \frac{\left(p_n(0) - p_{n0}\right)}{\tau_p}\exp\left(\frac{-x}{L_p}\right)$$

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

diffusion length,
typically microrns

Haynes Shockley experiment

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



$\tau =$ 1E-6 [s]

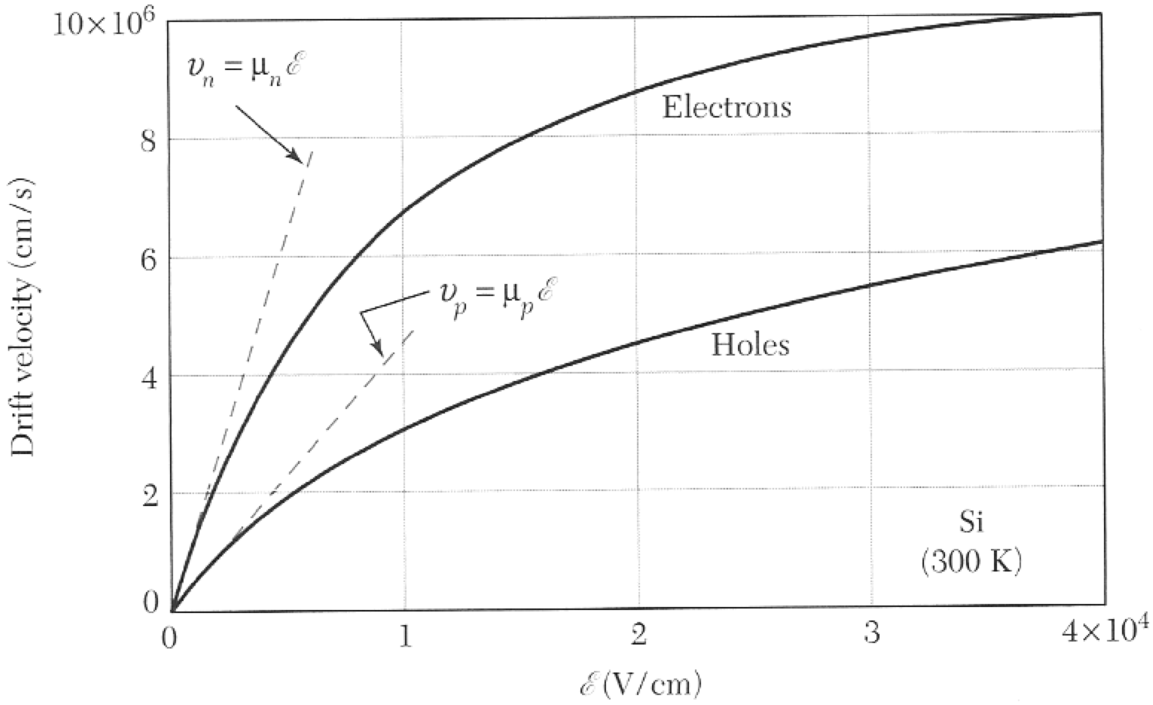
$E =$ 100 [V/cm]

$\mu =$ 1000 [cm²/V s]

$D = \mu k_B T/e =$ 0.00258 [m²/s]

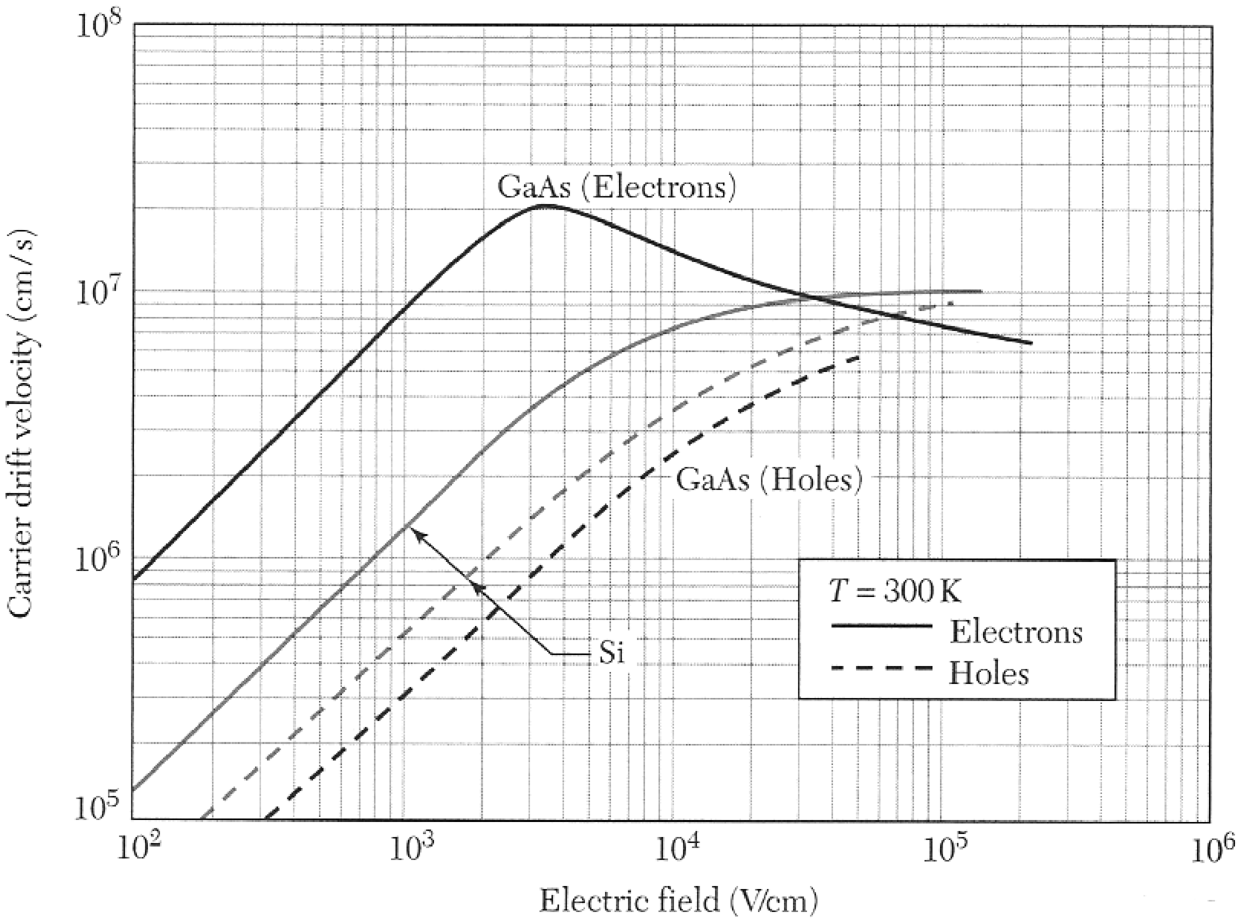
$L = \sqrt{D\tau} =$ 50.8 [μm]

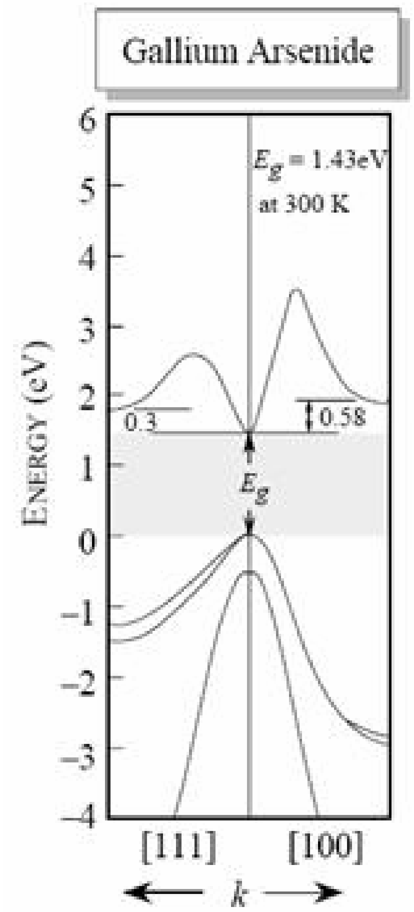
High Fields



Silicon

High Fields



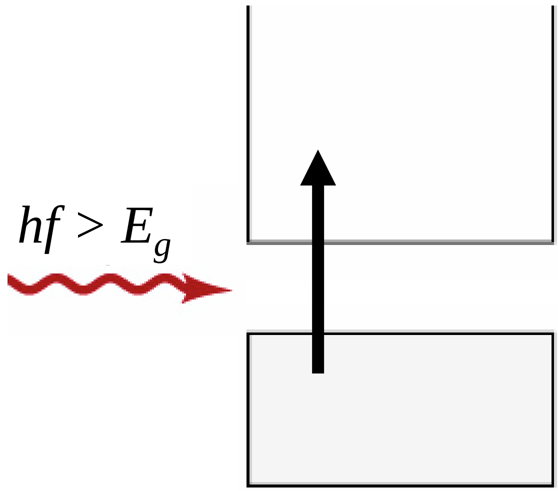


GaAs

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