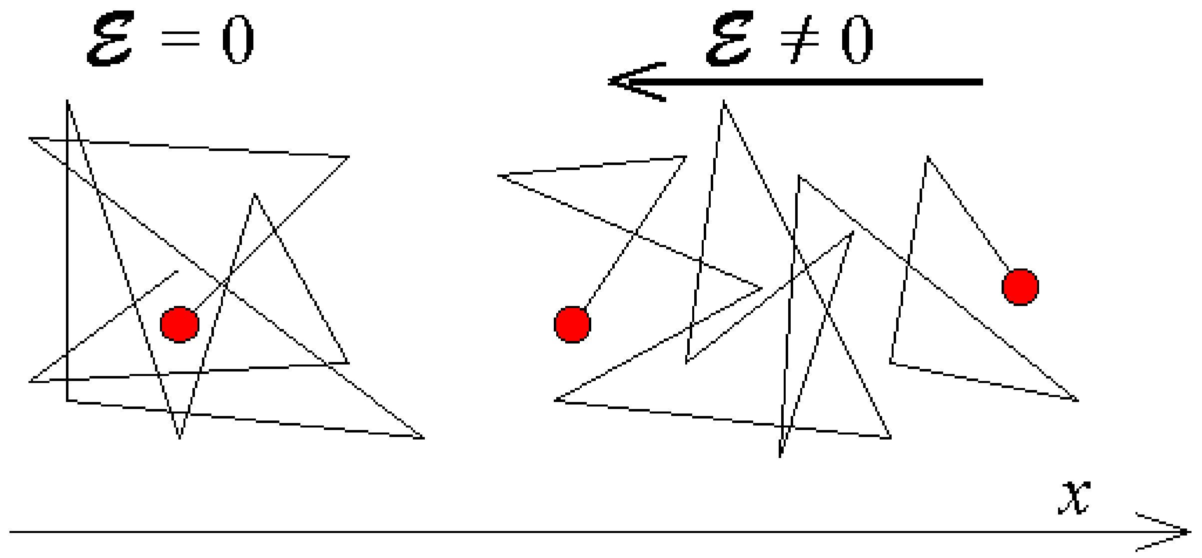
Carrier Transport

Any motion of free carriers in a semiconductor leads to a current. This motion can be caused by an electric field due to an externally applied voltage, since the carriers are charged particles and is known as carrier *drift*. In addition, carriers also move from regions where the carrier density is high to regions where the carrier density is low. This carrier transport mechanism is due to the thermal energy and the associated random motion of the carriers and is known as carrier *diffusion*.

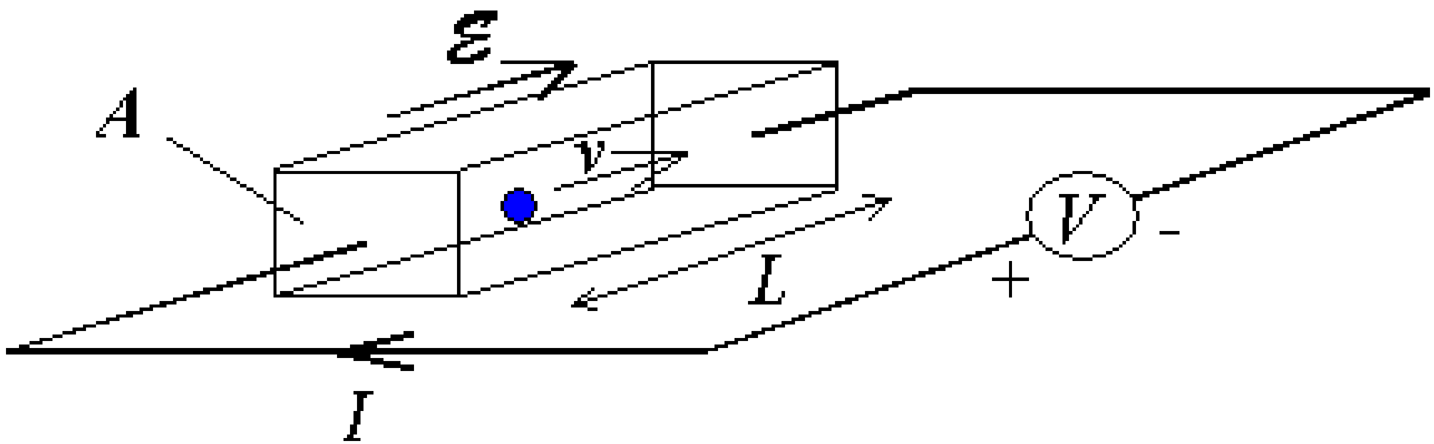
The *total current equals the sum of the drift and the diffusion current*.



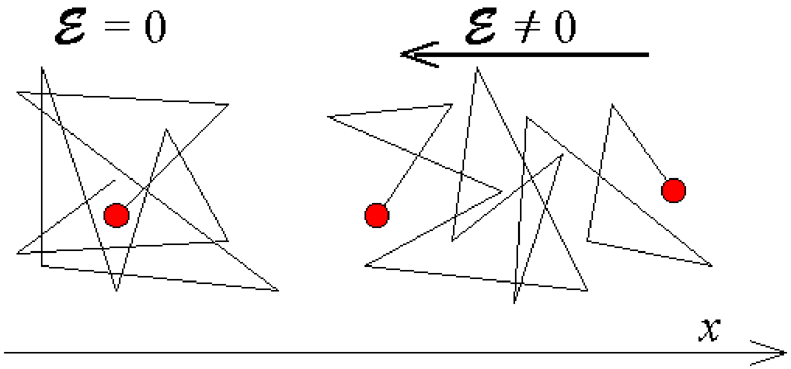
Carrier Drift

$$I = \frac{Q}{t_r} = \frac{Q}{L / v}$$

$$\vec{J} = \frac{Q}{AL}\vec{v} = \rho\vec{v} = qn\vec{v}$$



Carrier Drift Mobility



$$\vec{F} = m\vec{a} = m\frac{d \langle \vec{v} \rangle}{dt}$$

$$\vec{F} = q\vec{\mathcal{E}} - \frac{m < \vec{v} >}{\tau_c}$$

$$q\vec{\mathcal{E}} = m\frac{d < \vec{v} >}{dt} + \frac{m < \vec{v} >}{\tau_c}$$

Define mobility μ as $\mu \overset{\Delta}{=} \frac{|\vec{v}|}{|\vec{\mathcal{E}}|} = \frac{q\,\tau_c}{m}$

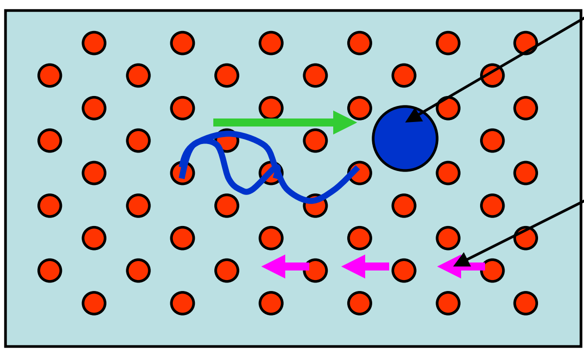
Drift Current for electrons and holes:

$$\vec{J}_n = q\,n\,\mu_n \vec{\mathcal{E}}$$

$$\vec{J}_p = q\,p\,\mu_p \vec{\mathcal{E}}$$

Scattering Mechanisms

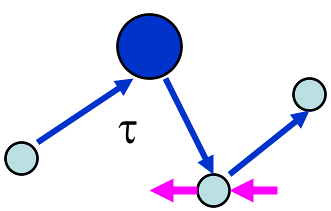
- Drift
  - Electron flux = j = -$n_e$ev
  - After time t_0: Electron velocity = $\dfrac{-eEt_0}{m}$
  - In practice, velocity cannot increase indefinitely



Impurity scattering

Phonon scattering (traveling lattice wave)

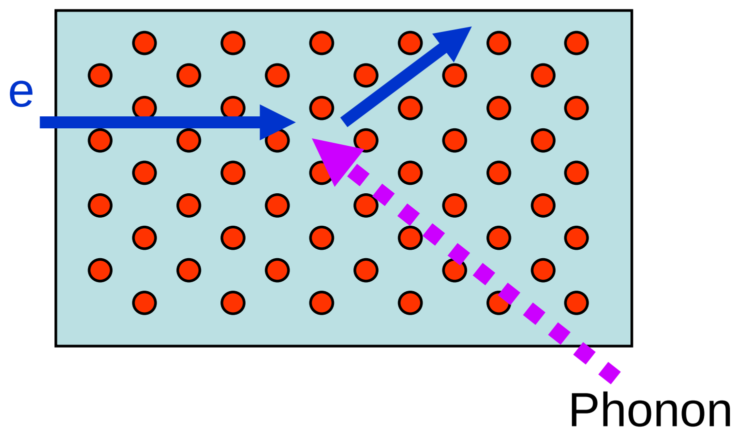
$$V(x) = V1\exp[-i(K\cdot\{x+\Delta x(t)\})]$$



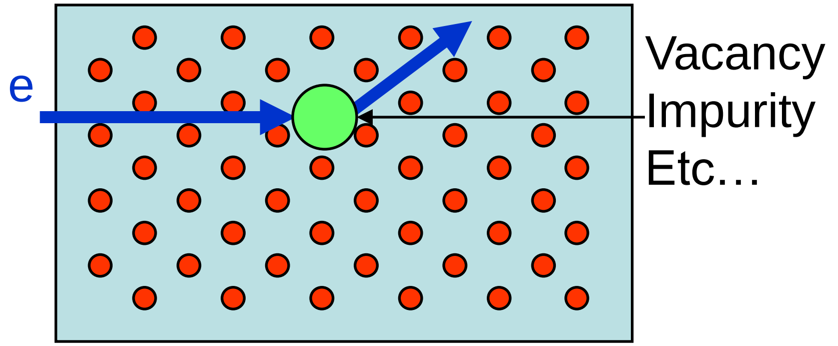
Electron velocity is constant $\dfrac{ne^2\tau}{m}$

Scattering of Bloch Waves

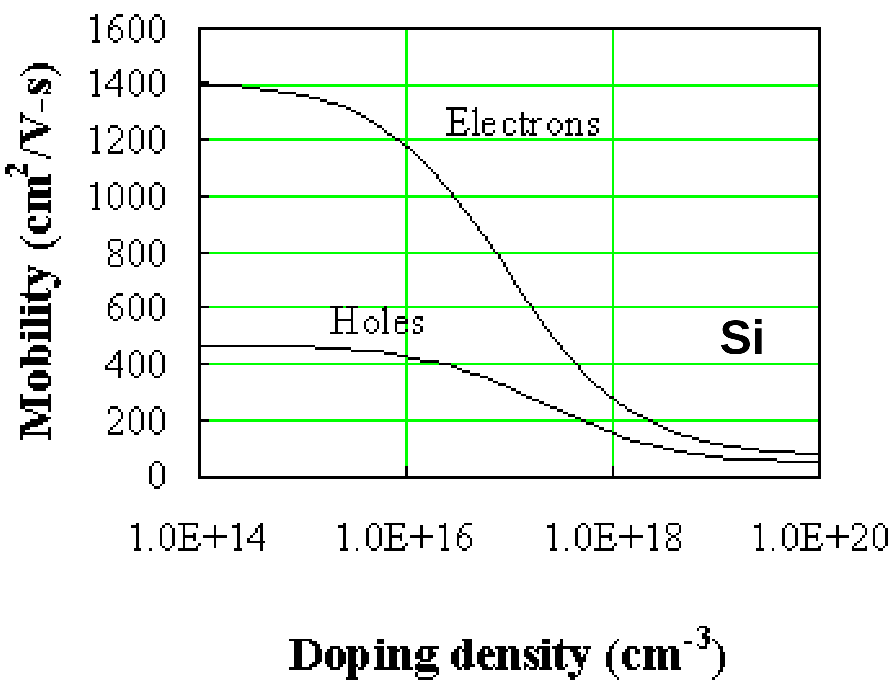
- Perfect crystal = perfect conduction
- Phonon scattering
  - Phonon:
    - Mechanical equivalent to Bloch wave
  - Conductivity ~ 1/T



- Defect scattering
  - Periodicity destroyed
- Surface scattering
  - Reflection from sides
  - Finite size of line



Mobility Doping Dependence



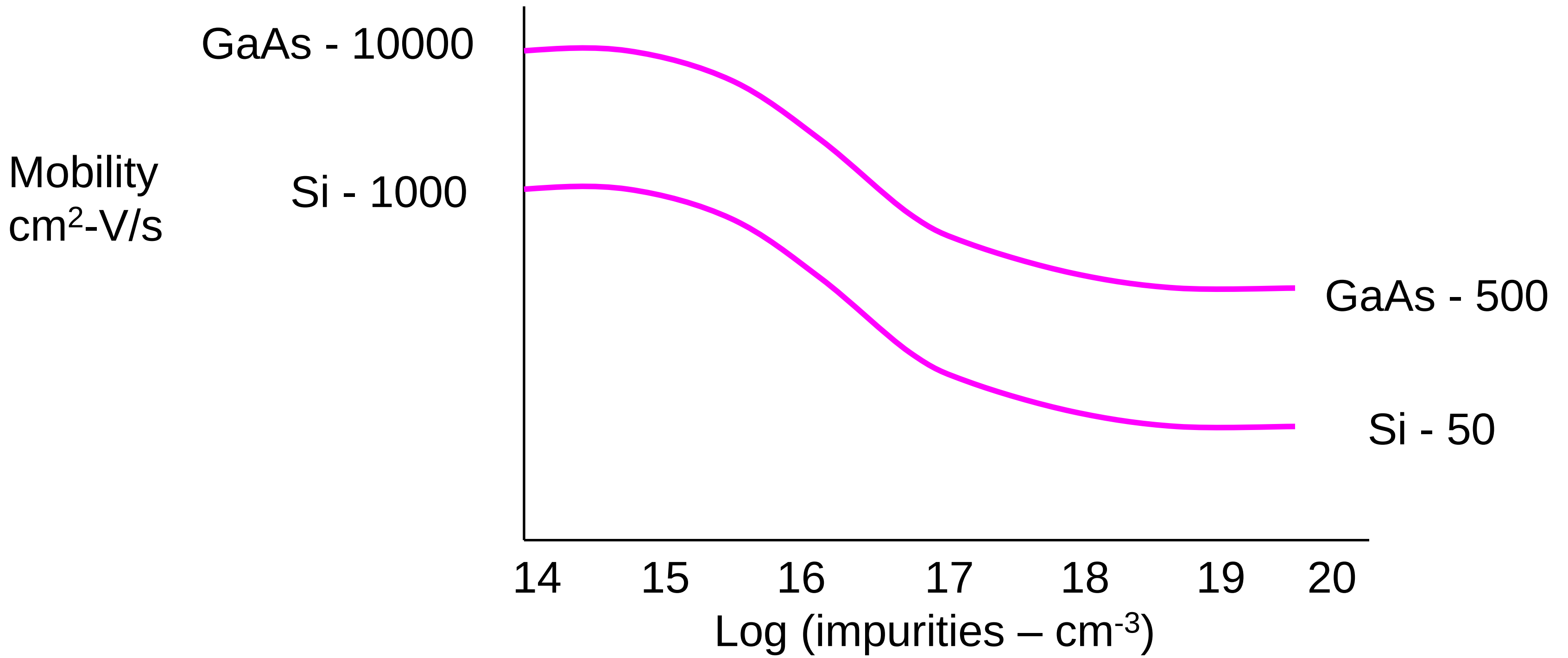
	Arsenic	Phosphorous	Boron
μ_{min} (cm^2/V-s)	52.2	68.5	44.9
μ_{max} (cm^2/V-s)	1417	1414	470.5
N_r (cm^{-3})	9.68×10^{16}	9.20×10^{16}	2.23×10^{17}
α	0.68	0.711	0.719

Typical Mobilities

1) Mobility depends on effective mass $\mu \sim 1/m^*$

2) Scattering times add inversely → mobilities add inversely
   - Scattering: phonons, impurities, dopants, ….
   - Smallest time / mobility will dominate

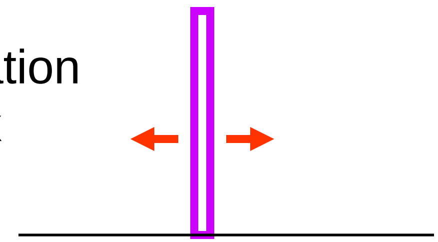
$$\frac{1}{\tau} = \frac{1}{\tau_1} + \frac{1}{\tau_2} + \frac{1}{\tau_2} + \ldots. \qquad \frac{1}{\mu} = \frac{1}{\mu_1} + \frac{1}{\mu_2} + \frac{1}{\mu_2} + \ldots.$$



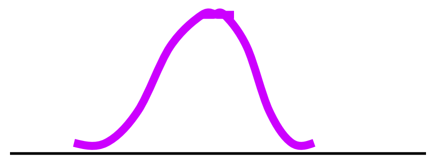
Drift Velocity

Current J = (-q) - D dN/dx   D = diffusion constant

Concentration
N(x)dx



Distance x
T=0

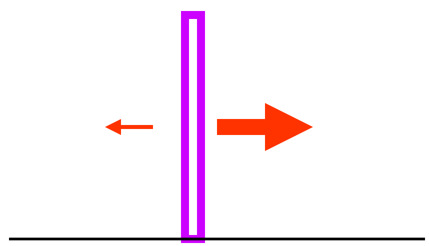


Distance x
t + dt

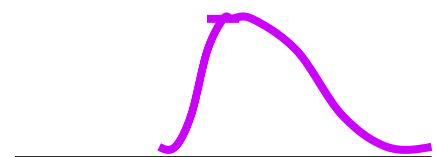
Force in + x direction → velocity + diffusion → scattering probability

$$F_+ = \frac{1}{2}\int_0^{\infty} n(x) v \frac{dx}{\lambda} \exp(-x/\lambda)$$

$$F_- = \frac{1}{2}\int_{-\infty}^{0} n(x) v \frac{dx}{\lambda} \exp(+x/\lambda)$$



Distance x
T=0



Distance x
t + dt

At low fields, electron moves by DIFFUSION in direction of field

Einstein Relationship

Change variables, complete integral:

$F_+ = ½ [N(0) v – (dN/dx) v \lambda]$

At any point along the line, flux is conserved:

$F_- - F_+ = -D\, dN/dx$

$D = < v \lambda > = < v^2 \tau >$

Diffusion constant equal to <u>average</u> velocity * mean free path

Diffusion constant can be related to mobility with **<u>"Einstein Relationship"</u>**

$D = \mu (kT/q)$

Diffusion Current

$$J_n = qD_n \frac{dn}{dx}$$

$$J_p = -qD_p \frac{dp}{dx}$$

Total Current

$$J_n = qn\mu_n \mathcal{E} + qD_n \frac{dn}{dx}$$

$$J_p = qp\mu_p \mathcal{E} - qD_p \frac{dp}{dx}$$