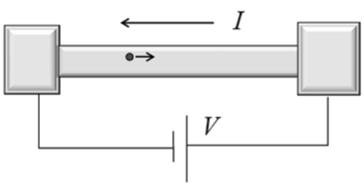
University of Michigan – Shanghai Jiao Tong University Joint Institute
Center of Optics and Optoelectronics

VE 320 – Summer 2012
Introduction to Semiconductor Device

Drift and Diffusion

Instructor: Professor Hua Bao

Current Flow in Semiconductor



$$I = G \times V$$
$$= q \times n \times v \times A$$

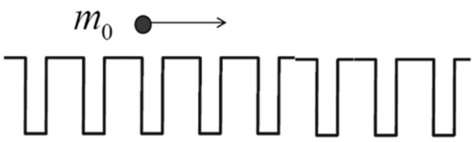
Carrier Density (n) — Velocity (v)

Depends on chemical composition, crystal structure, temperature, doping, etc

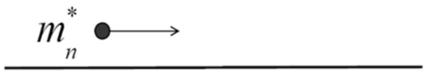
Quantum Mechanics + Equilibrium Statistical Mechanics
-→ Encapsulated into concepts of effective mass and occupation factors

Transport with scattering, non-equilibrium Statistical Mechanics
-→ Encapsulated into drift-diffusion equation with recombination-generation

Meaning of Effective Mass



$$\left(-\frac{\hbar^2}{2m_0}\frac{d^2}{dx^2}+U_{crys}(x)+U_{ext}(x)\right)\psi = E\psi$$



$$\left(-\frac{\hbar^2}{2m_0^*}\frac{d^2}{dx^2}+U_{ext}(x)\right)\phi = E\phi$$

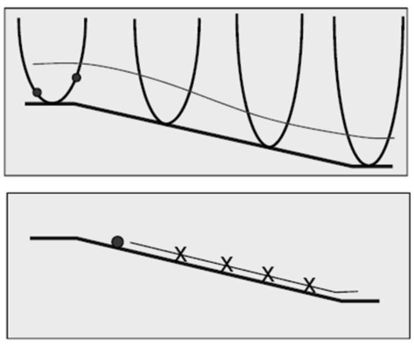
Periodic lattice potential does not “collide” with electrons.

Drift by Electric Field

$$J_n = qn\mu_n\mathcal{E}$$

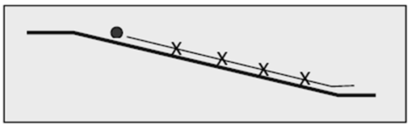
$$\frac{d(m_n^*\upsilon)}{dt} = -q\mathcal{E} - \frac{m_n^*\upsilon}{\tau_n}$$

$$\upsilon(t) = -\frac{q\tau_n}{m_n^*}\mathcal{E}\left[1-e^{-\frac{t}{\tau_n}}\right]$$



Drift by Electric Field cont'd

$$\upsilon(t) = -\frac{q\tau_n}{m_n^*}\mathcal{E}\left[1 - e^{-\frac{t}{\tau_n}}\right]$$

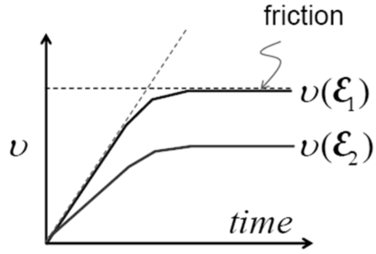


$$= -\frac{q\tau_n}{m_n^*}\mathcal{E} \quad (t \to \infty,\ 1\text{-}2\ \text{ps})$$

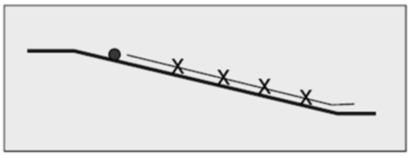
$$\equiv \mu_n \mathcal{E}$$

$$J_n = qn\mu_n\mathcal{E}$$

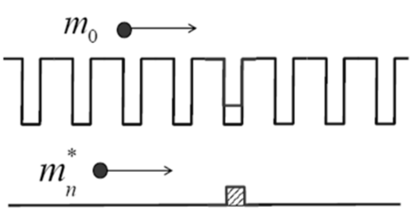
(Theory valid once t > 1-2 ps)



Mobility and Physics of Scattering Time



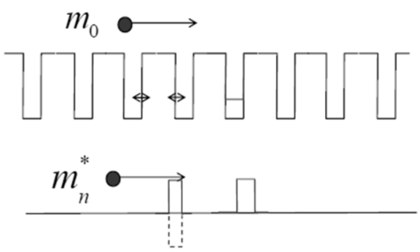
$$\mu_n = \frac{q\tau_n}{m_n^*}$$



Ionized Impurity and Phonon Scattering

Ionized impurity

$$\tau_n \sim \frac{T^{3/2}}{N_D}$$



Higher temperature,
more phonon scattering

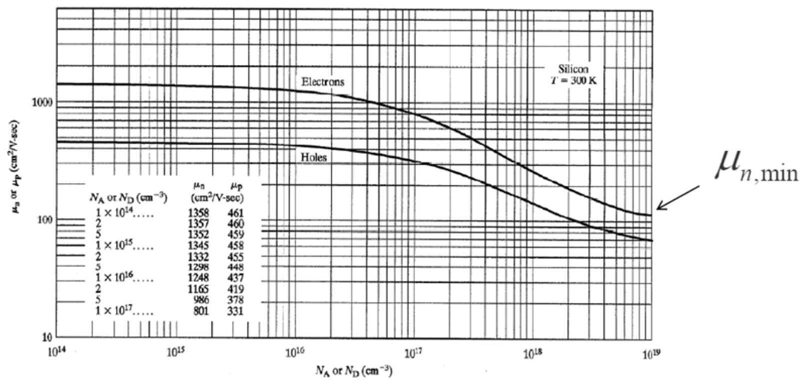
$$\tau_n \sim T^{-3/2}$$

$$\frac{1}{\tau_n} = \frac{1}{\tau_{II}} + \frac{1}{\tau_{ph}} + \frac{1}{\tau_s} + \cdots$$

- ❑ Ionized impurity
- ❑ Phonon scattering
- ❑ others ….

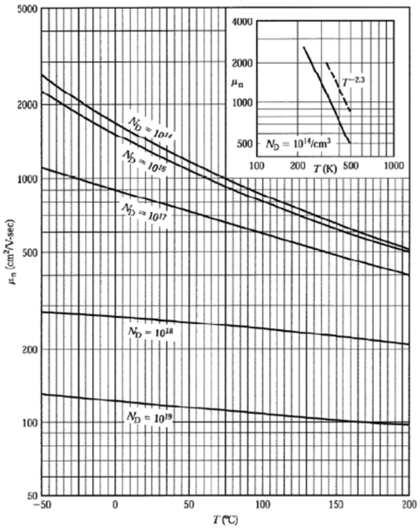
$$\frac{1}{\mu_n} = \frac{m_n^*}{q\tau_n}$$

Doping Concentration

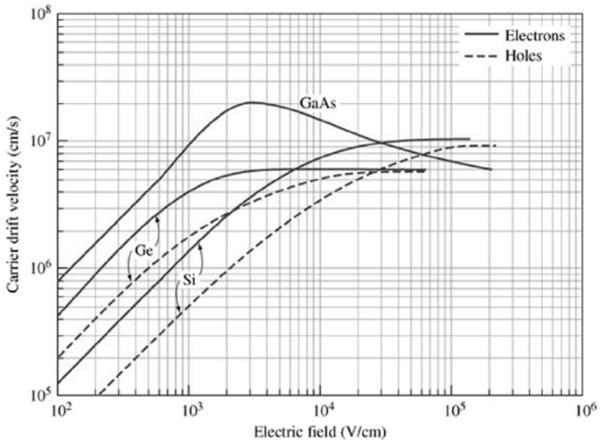


N_A or N_D (cm^{-3})	μ_n (cm^2/V-sec)	μ_p (cm^2/V-sec)
1×10^{14}.....	1358	461
2	1357	460
5	1352	459
1×10^{15}.....	1345	458
2	1332	455
5	1298	448
1×10^{16}.....	1248	437
2	1165	419
5	986	378
1×10^{17}.....	801	331

Temperature Dependence

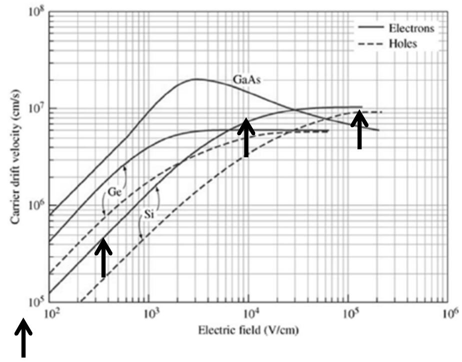


High Field Mobility



At high electric field, mobility is no longer a constant, velocity saturates.

Reason?



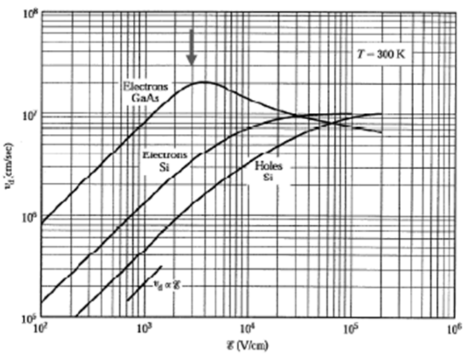
$\mathcal{E}=0 \quad J_1 = J^+ - J^- = 0$

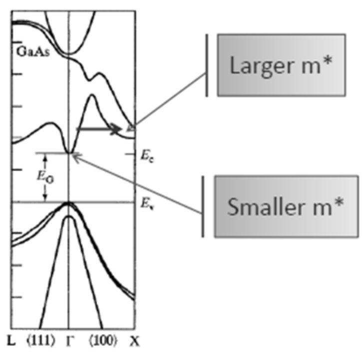
$\mathcal{E} \ll \mathcal{E}_c \quad J_2 = J^+ - J^- > J_1$

$\mathcal{E} \approx \mathcal{E}_c \quad J_3 = J^+ - J^- > J_2$

$\mathcal{E} \gg \mathcal{E}_c \quad J_4 = J^+ - J^- \approx J_3$

More Reason





Drift Current – Equations

$$J_n = qn\mu_n\mathcal{E}$$

$$J_p = qn\mu_p\mathcal{E}$$

Drift Current: $\boxed{J = J_n + J_p = (nq\mu_n + pq\mu_p)\mathcal{E}}$

$$J = \sigma\mathcal{E}$$

Conductivity: $\boxed{\sigma = nq\mu_n + pq\mu_p}$