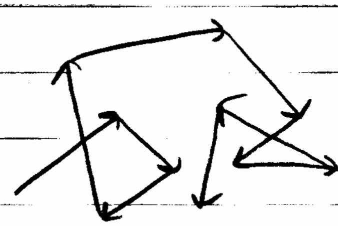
LECTURE #26

CURRENT FLOW IN SEMICONDUCTORS:

CHARGE CARRIERS IN A SOLID ARE IN CONSTANT MOTION EVEN AT THERMAL EQUILIBRIUM.

AT ROOM TEMPERATURE, THERMAL MOTION OF ELECTRONS CAN BE VISUALIZED AS RANDOM SCATTERING FROM PHONONS, IMPURITIES, OTHER ELECTRONS, AND OTHER DEFECTS.

"RANDOM WALK"



ON AVERAGE, THERE IS NO NET MOTION OF CHARGE IN THERMAL EQUILIBRIUM

IF WE APPLY AN ELECTRIC FIELD, HOWEVER, THERE WILL BE A NET MOTION OF CHARGE

$$-ne\vec{\mathcal{E}} = \left.\frac{d\vec{p}}{dt}\right|_{FIELD}$$

WITHOUT COLLISIONS, ELECTRONS WOULD BE CONTINUOUSLY ACCELERATED BY THE ELECTRIC FIELD. HOWEVER, COLLISIONS DECELERATE THE ELECTRONS SUCH THAT THE NET ACCELERATION IS ZERO IN STEADY STATE.

HOW DO WE DESCRIBE THIS BEHAVIOR?

CONSIDER N_0 ELECTRONS AT $t=0$:

LET $N(t)$ = # OF ELECTRONS THAT HAVE NOT UNDERGONE A COLLISION AT TIME t

ASSUME FIRST ORDER KINETICS

i.e., THE RATE OF DECREASE IN $N(t)$ IS PROPORTIONAL TO THE NUMBER LEFT UNSCATTERED:

$$-\frac{dN}{dt} = \frac{1}{\tau} N(t)$$

← CONSTANT OF PROPORTIONALITY (MEAN FREE TIME; MEAN TIME BETWEEN COLLISIONS)

$\Rightarrow N(t) = N_0 e^{-t/\tau}$

SIMILARLY, $\left.\frac{d\vec{p}}{dt}\right|_{COLLISIONS} = \frac{-\vec{p}}{\tau}$

$\therefore$ IN STEADY STATE, $\left.\frac{d\vec{p}}{dt}\right|_{FIELD} + \left.\frac{d\vec{p}}{dt}\right|_{COLLISIONS} = 0$

$\Rightarrow -ne\vec{\mathcal{E}} - \frac{\vec{P}}{\tau} = 0 \Rightarrow \frac{\vec{P}}{n} = \langle\vec{p}\rangle = -e\tau\vec{\mathcal{E}}$

$\Rightarrow$ ELECTRONS HAVE A NET AVERAGE VELOCITY IN THE OPPOSITE DIRECTION OF THE ELECTRIC FIELD:

$$\langle\vec{v}\rangle = \frac{\langle\vec{p}\rangle}{m_n^*} = \frac{-e\tau}{m_n^*}\vec{\mathcal{E}}$$

$\langle \vec{v} \rangle$ IS CALLED THE DRIFT VELOCITY

$$\vec{J} = -en\langle \vec{v} \rangle = \frac{ne^2\tau}{m_n^*}\vec{\mathcal{E}}$$

<u>OHM'S LAW</u>: $\vec{J} = \sigma\vec{\mathcal{E}}$, $\sigma = \frac{ne^2\tau}{m_n^*}$ (CONDUCTIVITY)

ALTERNATIVELY, $\sigma = en\mu_n$, $\mu_n = \frac{e\tau}{m_n^*}$ (MOBILITY)

<u>NOTE</u>: $\langle \vec{v} \rangle = -\mu_n \vec{\mathcal{E}}$, $\vec{J} = en\mu_n\vec{\mathcal{E}}$

FOR HOLES, EVERYTHING IS THE SAME EXCEPT:

$$n \to p,\ -e \to e,\ \mu_n \to \mu_p,\ \langle \vec{v} \rangle = \mu_p \vec{\mathcal{E}}$$

$$\therefore \boxed{\vec{J} = e(n\mu_n + p\mu_p)\vec{\mathcal{E}}}$$

DRIFT CURRENT EQUATION (VALID WHEN $\langle \vec{v} \rangle \propto \vec{\mathcal{E}}$)

<u>NOTE</u>: $R = \frac{\rho l}{A} = \frac{1}{\sigma}\frac{l}{A}$ ← LENGTH (l); ← CROSS-SECTIONAL AREA (A)

RESISTANCE (R)

WHAT AFFECTS THE VALUE OF μ?

$$\mu = \frac{e\tau}{m^*}$$

τ ← TIME BETWEEN COLLISIONS

m^* ← EFFECTIVE MASS

<u>SCATTERING MECHANISMS</u>:

(1) PHONON SCATTERING → INCREASES WITH TEMPERATURE

$$\tau_{PHONON} \propto T^{-3/2}$$

(2) IMPURITY SCATTERING → DECREASES WITH TEMPERATURE (SINCE THERMALLY ENERGETIC CARRIERS ARE LESS LIKELY TO BE SCATTERED BY A CHARGED ION)

$\tau_{impurity} \propto T^{3/2}$

TOTAL SCATTERING PROBABILITY = $\sum_i$ (SCATTERING PROBABILITY)$_i$

SINCE SCATTERING PROBABILITY $\propto \frac{1}{\tau}$ AND $\mu \propto \tau$,

$$\frac{1}{\mu} = \frac{1}{\mu_1} + \frac{1}{\mu_2} + \cdots$$

⇒ SMALLEST MOBILITY DOMINATES → $\boxed{\text{SEE FIG. 3-22}}$

NOTE: IMPURITY SCATTERING WILL INCREASE AS THE DOPING INCREASES

⇓

TOTAL MOBILITY DECREASES WITH DOPING → $\boxed{\text{SEE FIG. 3-23}}$

NOTE: AT HIGH FIELDS, THE DRIFT VELOCITY AND, THEREFORE, THE DRIFT CURRENT WILL EXHIBIT A NON-LINEAR DEPENDENCE ON ELECTRIC FIELD

Si, Ge ⇒ DRIFT VELOCITY SATURATES → $\boxed{\text{SEE FIG. 3-24}}$

GaAs ⇒ DRIFT VELOCITY DECREASES BEFORE SCATTERING

→ "HOT CARRIER EFFECTS" → OCCURS WHEN $\langle \vec{v} \rangle \simeq V_{THERMAL}$

IN THIS CASE, THERE WILL BE DEVIATIONS FROM OHM'S LAW:

$$\vec{J} = -en\langle\vec{v}\rangle$$

WHERE $\langle\vec{v}\rangle$ IS DETERMINED FROM THE NON-LINEAR $\langle\vec{v}\rangle$ VS. $\vec{\mathcal{E}}$ CURVE.

HALL EFFECT: $\boxed{\text{SEE FIG. 3-25}}$

Assume p-type:

IF A MAGNETIC FIELD IS APPLIED PERPENDICULAR TO THE DRIFT VELOCITY, HOLES WILL FEEL A FORCE:

$$\vec{F} = e(\vec{\mathcal{E}} + \vec{v}\times\vec{B})$$

Assume $\vec{v} = v_x\hat{x}$, $\vec{B} = B_z\hat{z}$

$$\Rightarrow F_y = e(\mathcal{E}_y - v_x B_z)$$

$\therefore$ HOLES ARE DEFLECTED UNTIL AN ELECTRIC FIELD IS BUILT UP IN THE +y-DIRECTION

$$\Rightarrow \mathcal{E}_y = v_x B_z \quad \text{(HALL EFFECT)}$$

HALL EFFECT $\Rightarrow$ HALL VOLTAGE: $V_{AB} = \mathcal{E}_y w$

$$\mathcal{E}_y = \frac{J_x}{ep}B_z = R_H J_x B_z \; ; \; R_H = \frac{1}{ep} \quad \text{(HALL COEFFICIENT)}$$

$$\therefore \rho = \frac{1}{eR_H} = \frac{J_x B_z}{e\mathcal{E}_y} = \frac{(I_x/wt)B_z}{e V_{AB}/w} = \frac{I_x B_z}{e t V_{AB}}$$

$$\therefore \boxed{\rho = \frac{I_x B_z}{e t V_{AB}}}$$

$$R = \frac{1}{\sigma}\frac{L}{wt} \Rightarrow \sigma = \frac{L}{Rwt} = \frac{I_x L}{V_{CD} w t}$$

SINCE $\sigma = e p \mu_p \Rightarrow \mu_p = \frac{\sigma}{ep} = R_H \sigma$

$$\therefore \mu_p = \frac{t V_{AB}}{I_x B_z}\frac{I_x L}{V_{CD} w t} = \frac{V_{AB} L}{B_z V_{CD} w} \Rightarrow \boxed{\mu_p = \frac{V_{AB} L}{B_z V_{CD} w}}$$

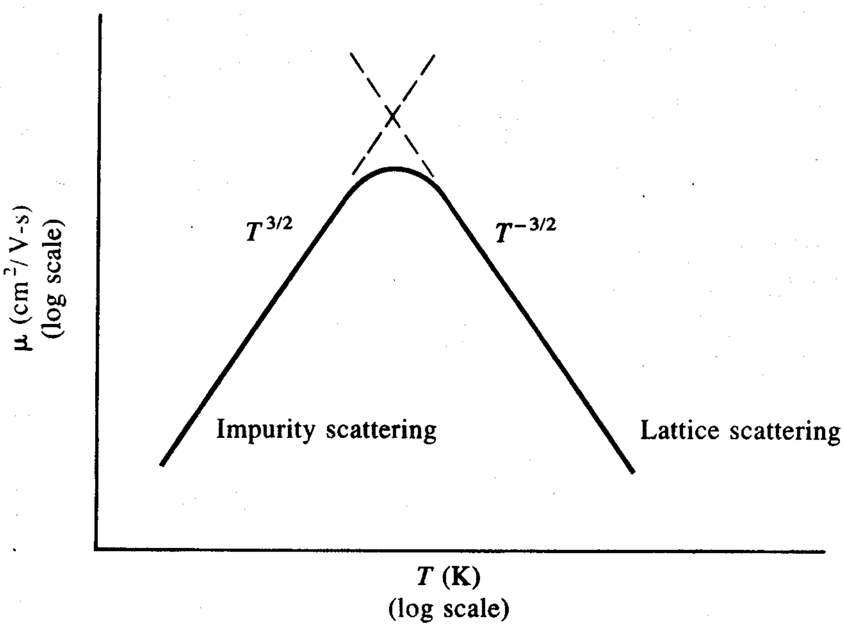
$\Rightarrow$ HALL MEASUREMENTS YIELD THE MAJORITY CARRIER CONCENTRATION AND THE MOBILITY

NOTE: FOR n-type, A SIMILAR ANALYSIS CAN BE PERFORMED. SINCE $e \rightarrow -e$ FOR ELECTRONS, THE HALL VOLTAGE AND HALL COEFFICIENTS WILL BE NEGATIVE

$\Downarrow$

THE SIGN OF THE HALL VOLTAGE CAN BE USED TO DETERMINE IF AN UNKNOWN SAMPLE IS p-type OR n-type

Figure 3-22 Approximate temperature dependence of mobility with both lattice and impurity scattering.



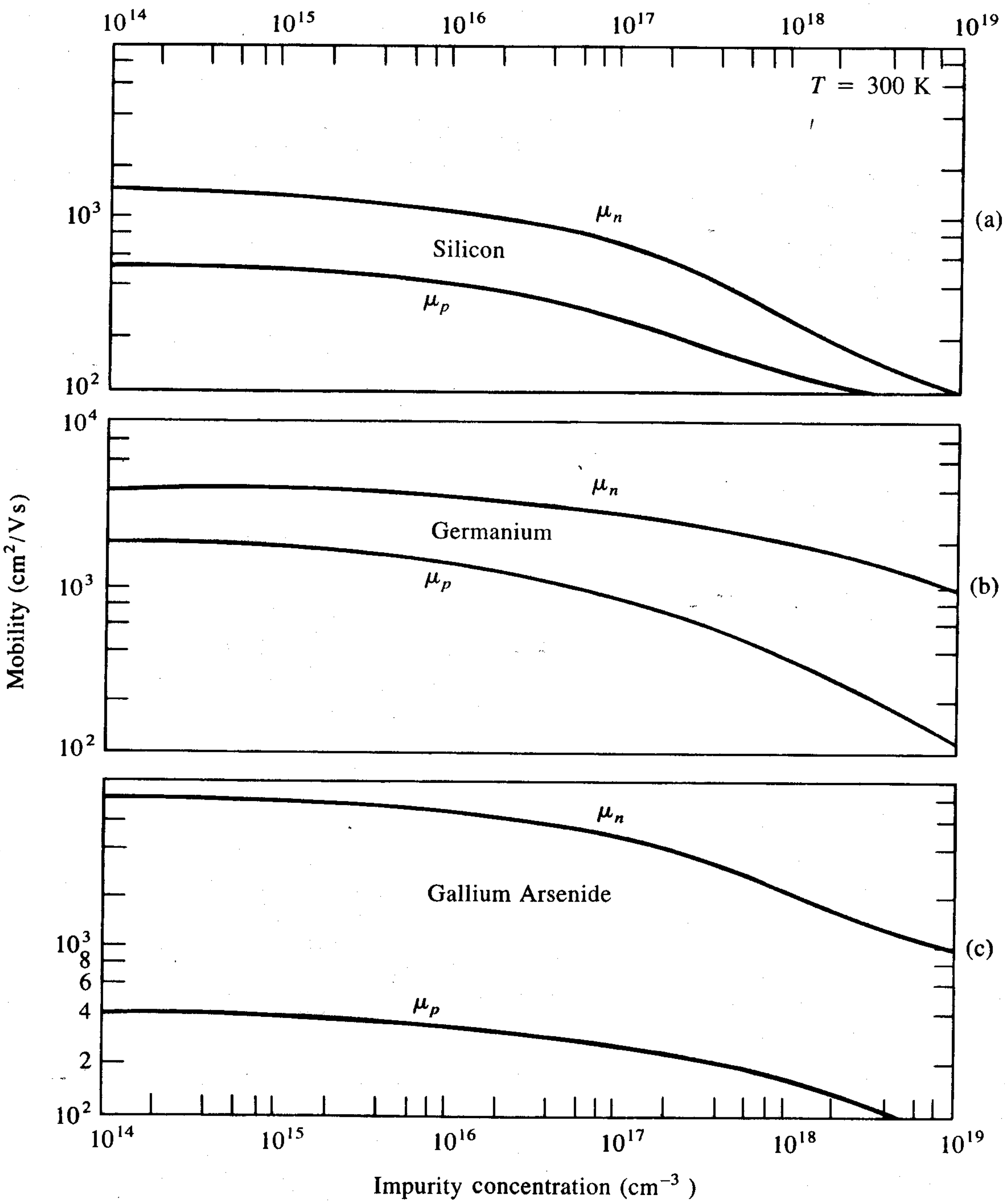
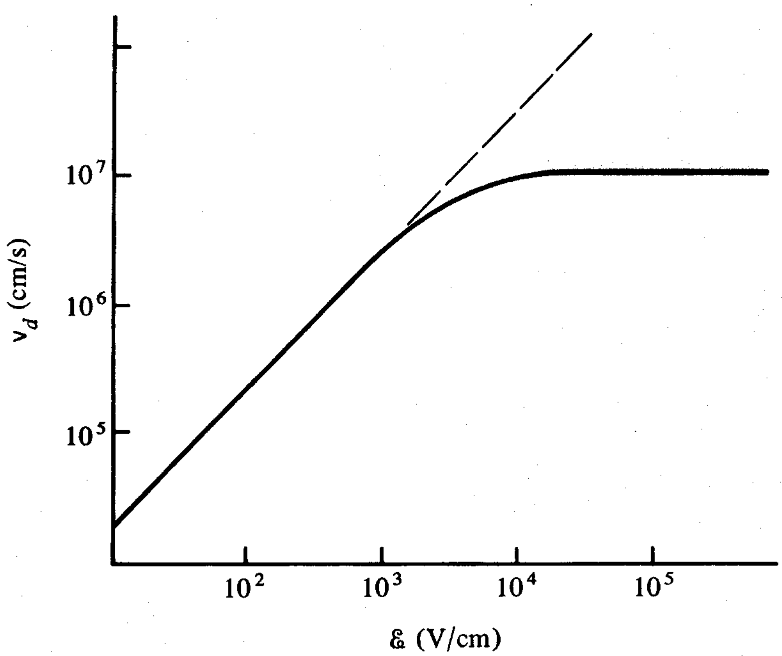


Figure 3-23 Variation of mobility with doping impurity concentration for Ge, Si, and GaAs at 300 K.

Figure 3-24 Saturation of electron drift velocity at high electric fields for Si.



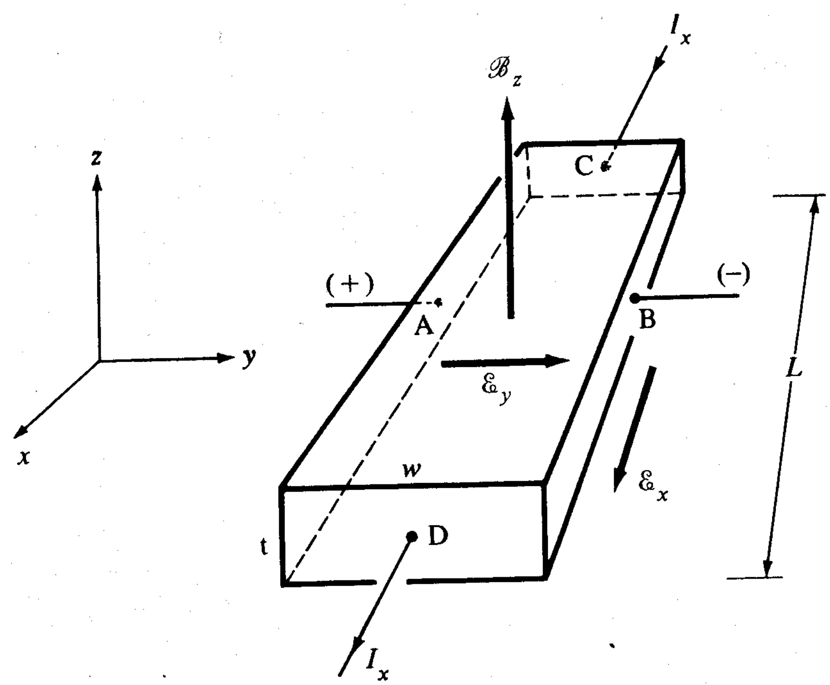


Figure 3-25
The Hall effect.