Lecture 8

COMPENSATION.

- Last time:
  - Wrap-up phasor analysis: 2nd order circuits ✗
  - Start semiconductor properties of Si

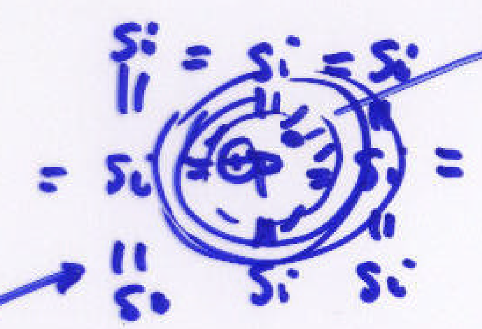
    ↑
    <C> ← diamond

- Today : TRANSPORT.
  - Drift velocity
  - Drift current density
  - Resistivity and resistance

• Si: IV.

$$\overbrace{P, As}^{\text{DONORS.}}$$

↳ add V P, As. (5 bonds)



→ e^- TAKES OFF AT T << ROOM TEMPERATURE. (FREE TO MOVE)

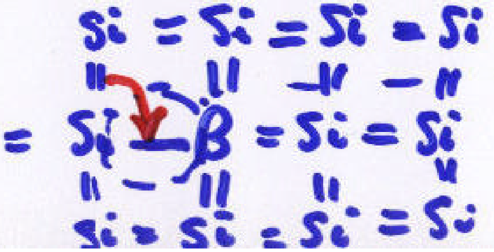
(||) ← <u>SINGLE</u> COVALENT BOND.

START NEUTRAL ... END NEUTRAL

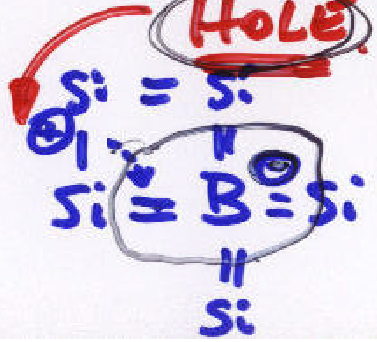
$\left\{ \begin{array}{l} P^+ : \text{IMMOBILE} \\ e^- : \text{MOBILE} \end{array} \right.$

III B

P 137.



T > 300°C



HOLE CAN "FLY"

"ONE ELECTRON PER DONOR"

$$\underline{n \cong N_d}.$$

n-type material ....

only donors

$$\boxed{n = p = n_i} \leftarrow 10^{10}\ \mathrm{cm}^{-3}$$

Intrinsic.

" ONE HOLE PER ACCEPTOR" ← p-type.

$$p \cong N_a \quad (\mathrm{cm}^{-3})$$

BOTH : NET DOPING CONTROLS THE TYPE.

NO $n = N_d$ and $p = N_a$ SAME TIME ??

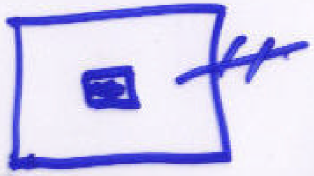
→ $\boxed{p \cdot n = n_i^2 = \mathrm{const.}}$ MASS ACTION LAW.

Ex. $N_d = N_a$. ← CANCEL.

$$n = p = \underline{\underline{n_i}} = \underline{\underline{10^{10}\,\text{cm}^{-3}}}$$

→ $\underline{\underline{\text{COMPENSATION}}}$

T = hot ⇒ LOTS GOING ON!



NO NET TRANSPORT

LOW MASS.

Thermal Equilibrium

Rapid, random motion of holes and electrons at "thermal velocity" $v_{th} = 10^7$ cm/s with collisions every $\tau_c = 10^{-13}$ s.

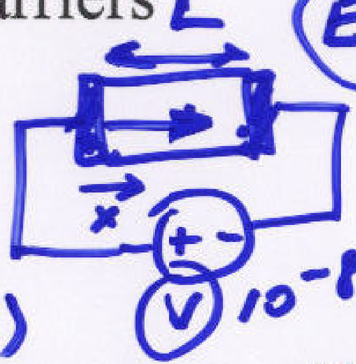
3×10^{10} cm/s

$$\frac{1}{2} m v_{th}^2 = \frac{1}{2} k_B T.$$

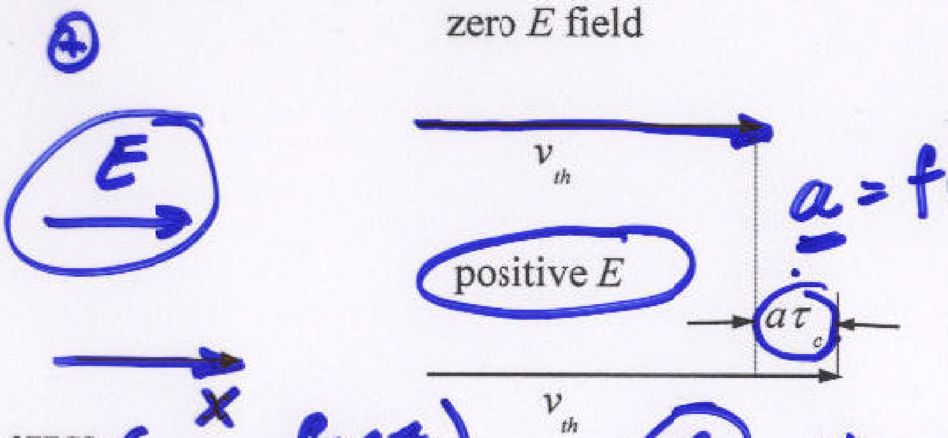
EE 130.

Apply an electric field E and charge carriers accelerate … for τ_c seconds

$$E = \frac{V}{L}.$$



10^{-8} m = 10 nm.



$a = f(E)$

(hole case)

(mean free path.) → $l = v_{th} \cdot \tau_c = 10^7 \times 10^{-13}$ cm $= 10^{-6}$ cm.

THERMAL VEL = $10^7 \, cm \, s^{-1}$

Drift Velocity and Mobility

$$v_{dr} = a \cdot \tau_c = \left(\frac{F_e}{m_p} \right) \tau_c = \left(\frac{qE}{m_p} \right) \tau_c = \left(\frac{q \tau_c}{m_p} \right) E$$

Δv

EE 130/231 HAS AN E_{max}.

m_p = mass of hole

$$\boxed{v_{dr} = \mu_p E}$$

HOLE MOBILITY.

For electrons:

m_e = effective mass of e^{-}

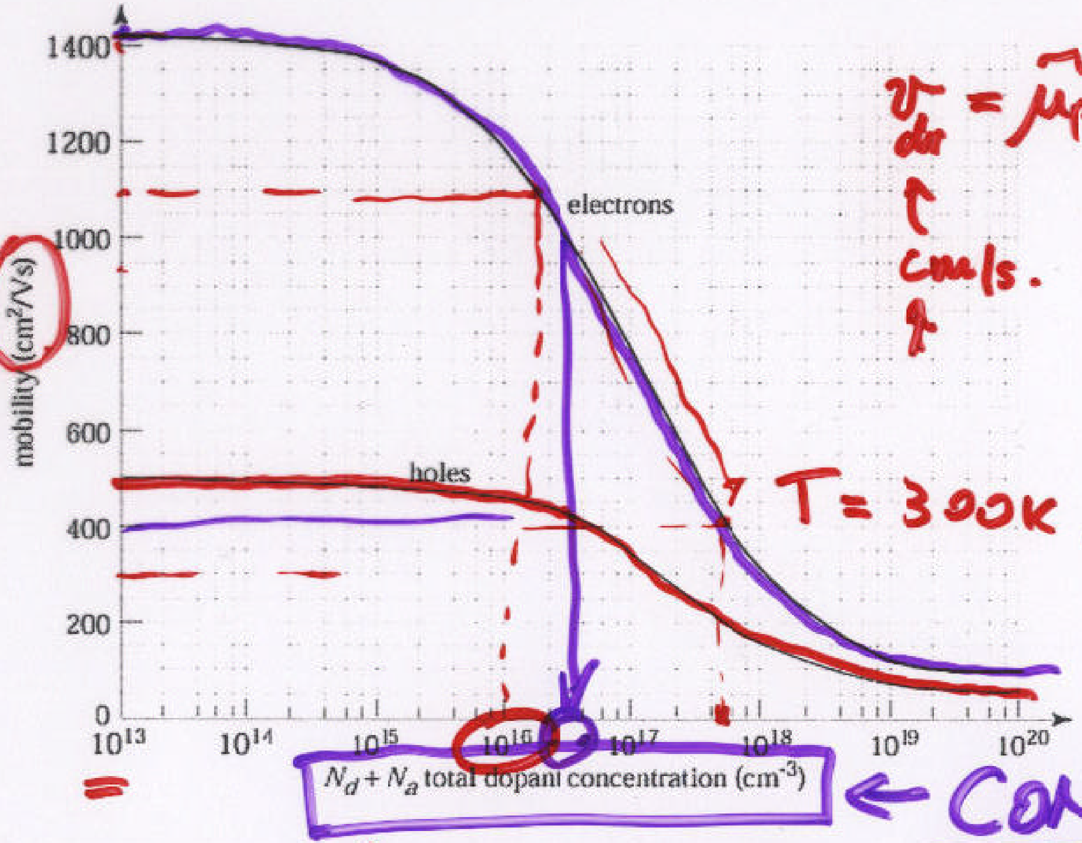
$$v_{dr} = a \tau_c = \left(\frac{F_e}{m_e} \right) \tau_c = \left(\frac{-qE}{m_e} \right) \tau_c$$

thus ⇒ $\boxed{v_{dr} = -\mu_n E}$

Mobility vs. Doping in Silicon at 300 K

μ_n, μ_p ↑ as T↓.

IN THE BOOK



$v_{dr} = \mu_p E$

cm/s

V/cm

WATCH OUT.... ← CONFUSING!

↑ SUM $N_a + N_d$ = TOTAL SCATTERING SITES.

"default" values:

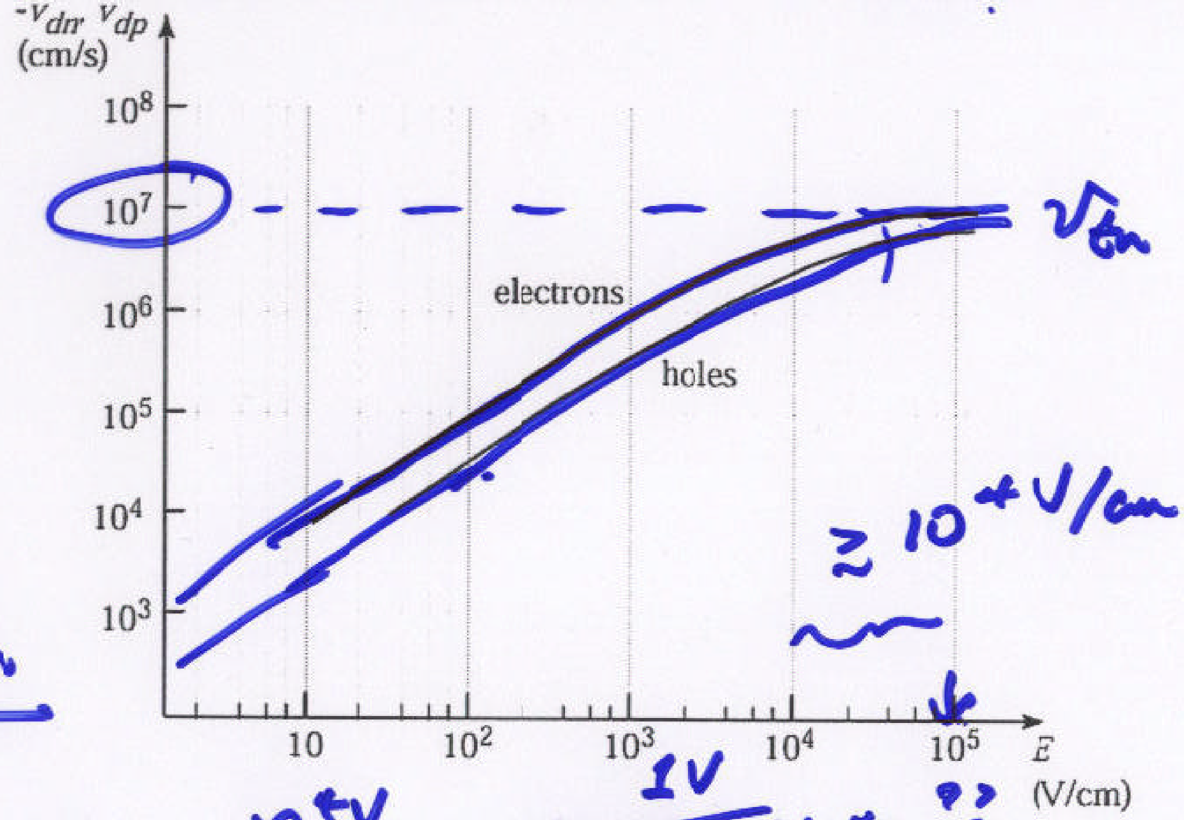
$\mu_n = 1000$, $\mu_p = 400$

— SPEED LIMITS. —

Velocity Saturation

— $c = 3 \times 10^{10} \text{ cm s}^{-1}$

v_{th}



$\gtrsim 10^4$ V/cm.

$L = 0.12 \mu m$

$$E = \frac{10^4 V}{cm} = \frac{\cancel{10,000 V}\ 1V}{cm} \leftarrow ?!$$

$cm \leftarrow 0.1 \mu m = 10^{-5} cm$

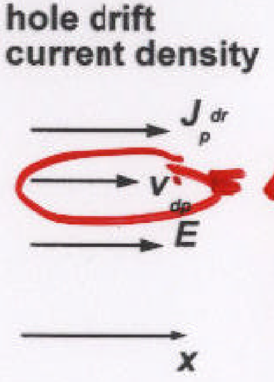
$$= \frac{1 \cdot V}{10^{-5}} = 10^5 V/cm$$

I ↓

$J = I/A$ [A/cm²]

Drift Current Density (Holes)

Hole case: drift velocity is in same direction as E



= Δv DOESN'T AVERAGE TO ZERO.

P-TYPE.

A = C/s

The hole drift current density is:

$$\boxed{J_p^{dr} = \overset{q p v_{dr}}{q\, p\, \mu_p\, E}}$$

$C \rightarrow q \cdot p \cdot v_{dr}$ cm/s

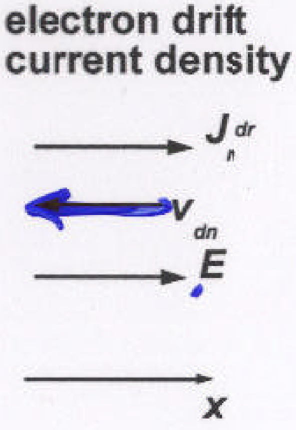
p: cm⁻³

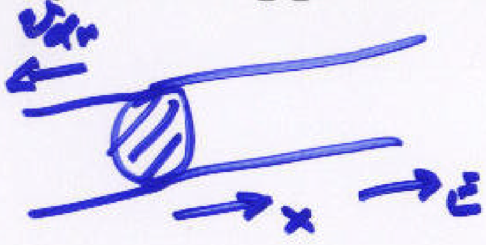
q: +1.6×10⁻¹⁹ C.

$C \cdot \frac{1}{cm^3} \cdot cm \cdot \frac{1}{s} = \frac{C/s}{cm^2} = \frac{A}{cm^2}$

Drift Current Density (Electrons)

Electron case: drift velocity is in *opposite* direction as E





$$J_n^{dr} = (-q)\cdot n\cdot v_{dr}$$
$$= +q\cdot n\cdot(+\overset{\mu_n}{\cancel{q}}E)$$

The electron drift current density is:

$J_n^{dr} = (-q)\ n\ v_{dn}$

$$\boxed{J_n^{dr} = q n \mu_n \vec{E}}$$

units: $\mathrm{Ccm^{-2}\ s^{-1} = Acm^{-2}}$

$$\boxed{J_{TOT} = J_n^{dr} + J_p^{dr}}$$