6.012 - Electronic Devices and Circuits

# Lecture 2 - Uniform Excitation - Outline

- **Announcements**
  - **Handouts** - Lecture Outline, Review, and Summary
- **Review** **(of Lecture 1 and Recitation 2)**
  - **Carrier concentrations in TE given the doping level**
  - **What happens above and below room temperature?**
- **Uniform excitation of uniform samples: drift** **(introduced in Rec. 2)**
  - **Drift motion: carrier velocity verses field**
  - **Mobility, Drift currents, Conductivity**
  - **Impact of temperature on mobility, conductivity**
  - **Integrated circuit resistors**
- **Uniform excitation: optical generation**
  - **Generation/recombination in TE**
  - **Uniform optical generation - external excitation**
  - **Population excesses, $p'$ and $n'$, and their transients**
  - **Low level injection; minority carrier lifetime**
- **Uniform excitation - applied field and optical generation**
  - **Photoconductivity, photoconductors**

# Variation of carrier concentration with temperature

**(Note: for convenience we assume an n-type sample)**

- **Around R.T.**
  **Full ionization**
  **Extrinsic doping**

$N_d^+ \approx N_d,\ N_a^- \approx N_a$

$\left(N_d^+ - N_a^-\right) >> n_i$

$n_o \approx \left(N_d - N_a\right),\ p_o = n_i^2 / n_o$

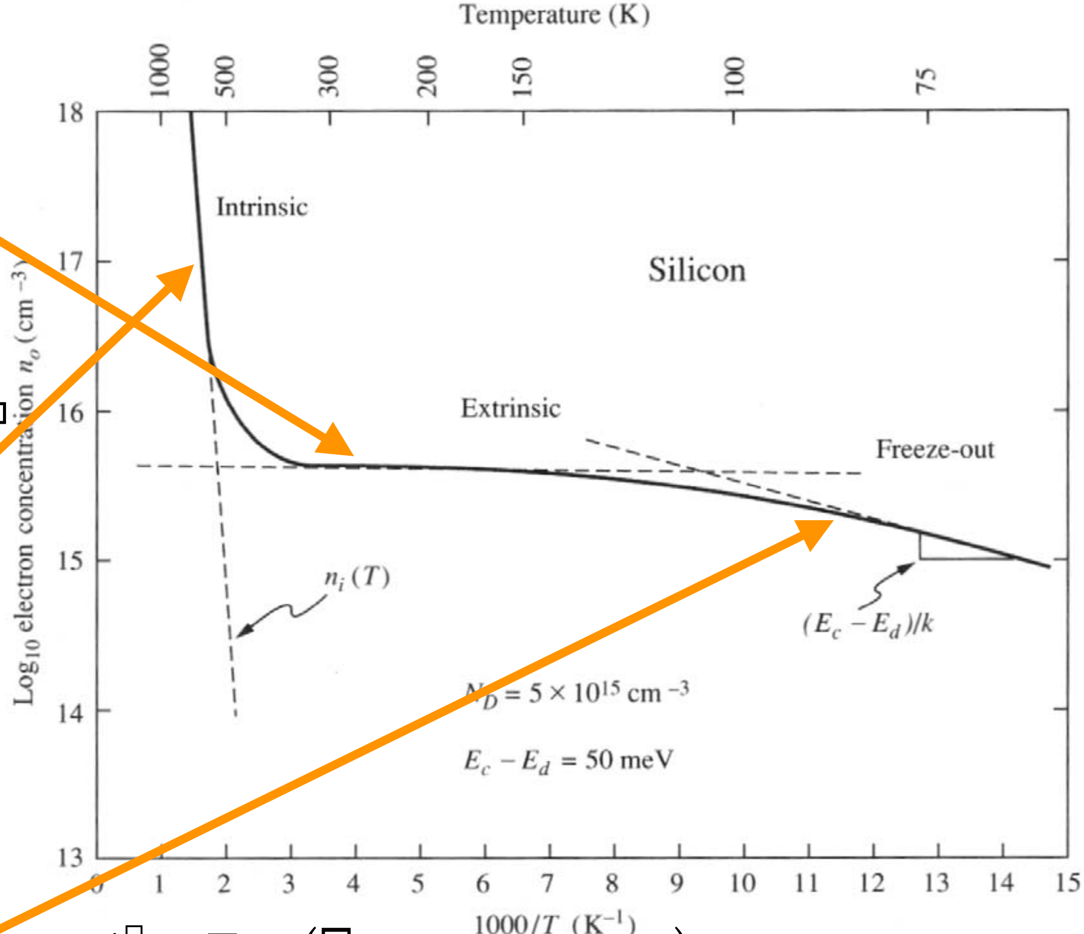
- **At very high T**
  **Full ionization**
  **Intrinsic behavior**

$N_d^+ \approx N_d,\ N_a^- \approx N_a$

$n_i >> \left|N_d^+ - N_a^-\right|$

$n_o \approx p_o \approx n_i$

- **At very low T**
  **Incomplete ionization**
  **Extrinsic doping, but with carrier freeze-out**




$N_d^+ << N_d$ (assuming n – type)

$\left|N_d^+ - N_a^-\right| >> n_i$

$n_o \approx \left(N_d^+ - N_a^-\right) << \left(N_d - N_a\right),\ p_o = n_i^2 / n_o$

# Uniform material with uniform excitations

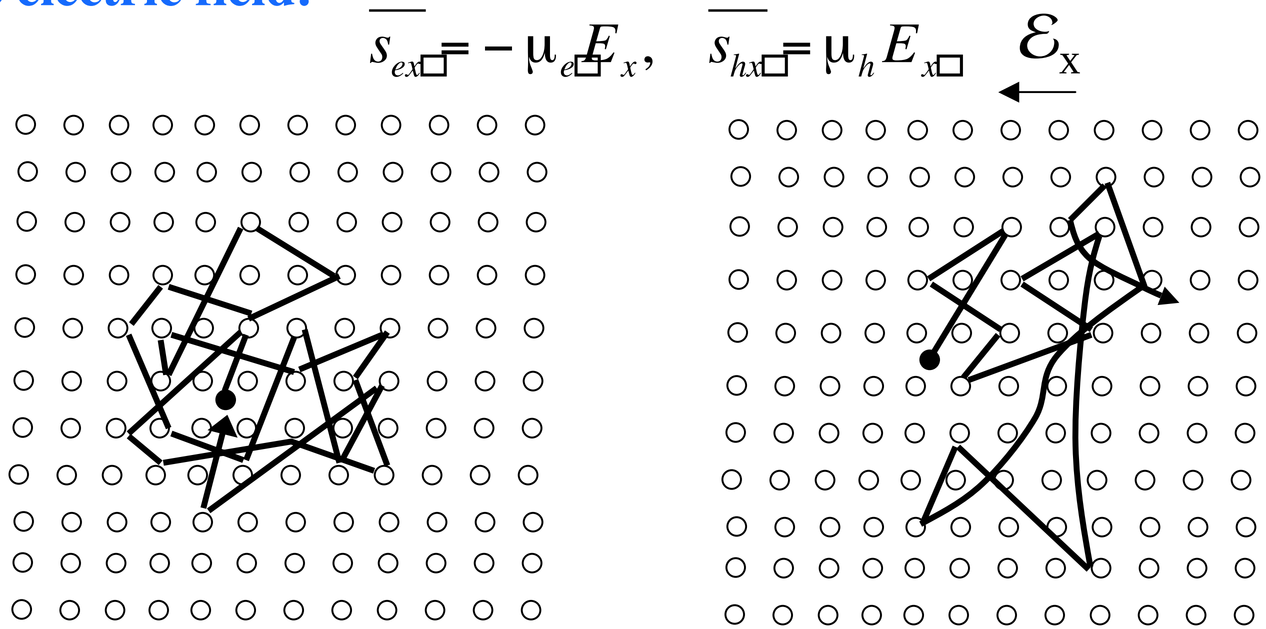
**(pushing semiconductors out of thermal equilibrium)**

## A. Uniform Electric Field, $E_x$

**Drift motion:**

**Holes and electrons acquire a constant net velocity, $s_x$, proportional to the electric field:**

$$\overline{s_{ex}} = -\mu_e E_x, \quad \overline{s_{hx}} = \mu_h E_x$$

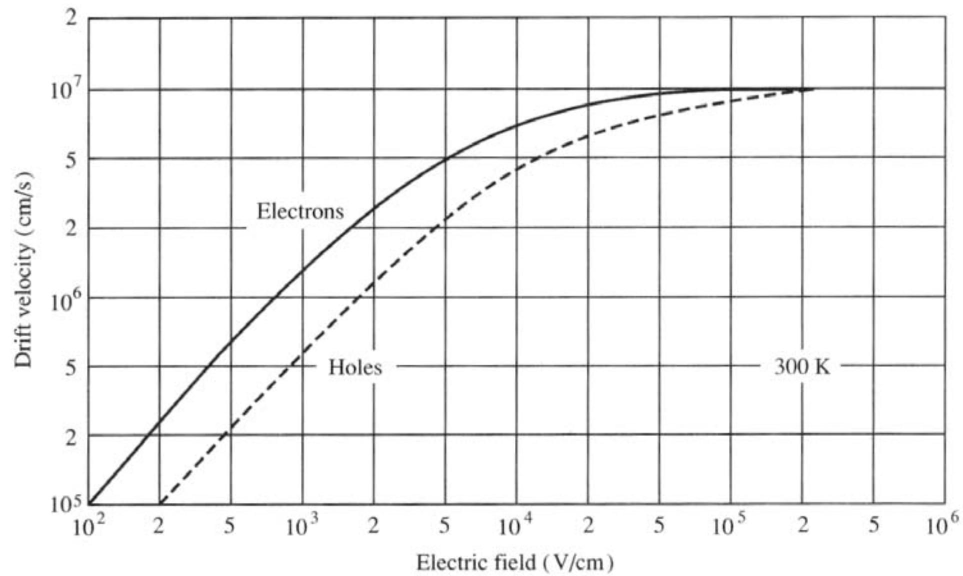



**No field** | **E-field applied**

**At low and moderate |E|, the mobility, $\mu$, is constant.**
**At high |E| the velocity saturates and $\mu$ deceases with increasing |E|.**

# Velocity saturation

**The breakdown of Ohm's law at large electric fields.**




See Fig 5.7, from Neamen, D. *Electronic Circuit Analysis and Design.* McGraw-Hill Higher Education, 1996.

**Above: Velocity vs. field plot at R.T. for holes and electrons in Si (log-log plot).** **(Fonstad, Fig. 3.2)**

**Left: Velocity-field curves for Si, Ge, and GaAs at R.T. (log-log plot).** **(Neaman, Fig. 5.7)**

# Variation of mobility with temperature and doping levels

See Neamen, D. *Electronic Circuit Analysis and Design.* McGraw-Hill Higher Education, 1996.

See Fig 5.3, from Neamen, D. *Electronic Circuit Analysis and Design*. McGraw-Hill Higher Education, 1996.

**Above: $\mu_e$ vs T in Si at several doping levels**

**Left: $\mu$ vs doping for Si, Ge, and GaAs at R.T. (Neaman, Fig. 5.3)**

# Variation of mobility with temperature and doping levels

## in Si near room temperature

See Fig 5.2, from Neamen, D. *Electronic Circuit Analysis and Design.* McGraw-Hill Higher Education, 1996.



Neaman, Fig. 5.2

# Uniform material with uniform excitations

(pushing semiconductors out of thermal equilibrium)

## A. Uniform Electric Field, $E_x$

**Drift motion:**

Holes and electrons acquire a constant net velocity, $s_x$, proportional to the electric field:

$$\overline{s_{ex}} = -\mu_e E_x, \quad \overline{s_{hx}} = \mu_h E_x$$

At low and moderate |E|, the mobility, $\mu$, is constant.

At high |E| the velocity saturates and $\mu$ deceases with increasing |E|.

**Drift currents:**

Net velocities imply net charge flows, which imply currents:

$$J_{ex}^{dr} = -q\, n_o\, \overline{s_{ex}} = q\mu_e n_o E_x \qquad J_{hx}^{dr} = q\, p_o\, \overline{s_{hx}} = q\mu_h p_o E_x$$

Note: Even though the semiconductor is no longer in thermal equilibrium the hole and electron populations still have their thermal equilibrium values.

## Conductivity, $\sigma_o$:

**Ohm's law on a microscale states that the drift current density is linearly proportional to the electric field:**

$$J_x^{dr} = \sigma_o E_x$$

**The total drift current is the sum of the hole and electron drift currents. Using our early expressions we find:**

$$J_x^{dr} = J_{ex}^{dr} + J_{hx}^{dr} = q\mu_e n_o E_x + q\mu_h p_o E_x = q(\mu_e n_o + \mu_h p_o) E_x$$

**From this we see obtain our expression for the conductivity:**

$$\sigma_o = q(\mu_e n_o + \mu_h p_o) \quad [\text{S/cm}]$$

## Majority vs. minority carriers:

**Drift and conductivity are dominated by the most numerous, or "majority," carriers:**

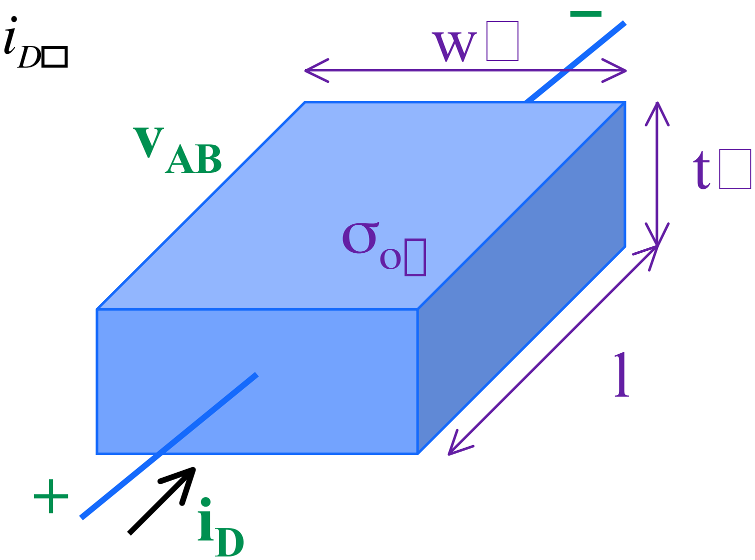
**n-type** $\quad n_o >> p_o \Rightarrow \sigma_o \approx q\mu_e n_o$

**p-type** $\quad p_o >> n_o \Rightarrow \sigma_o \approx q\mu_h p_o$

## Resistance, R, and resistivity, $\rho_o$:

**Ohm's law on a macroscopic scale says that the current and voltage are linearly related:**

$$v_{ab} = R\, i_D$$




**The question is, "What is R?"**

**We have:** $J_x^{dr} = \sigma_o E_x$

with $E_x = \dfrac{v_{AB}}{l}$ and $J_x^{dr} = \dfrac{i_D}{w \cdot t}$

**Combining these we find:**

$$\frac{i_D}{w \cdot t} = \sigma_o \frac{v_{AB}}{l}$$

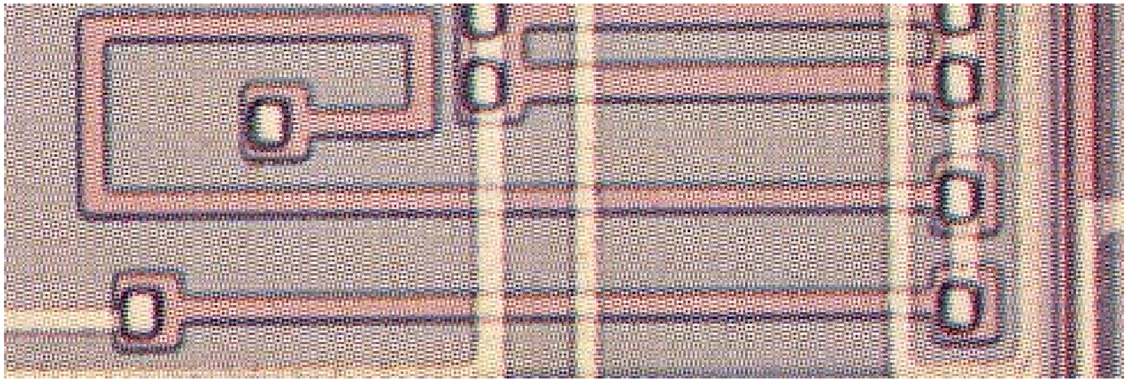
**which yields:** $v_{AB} = \dfrac{l}{w \cdot t} \dfrac{1}{\sigma_o} i_D = R\, i_D$

**where** $R \equiv \dfrac{l}{w \cdot t} \dfrac{1}{\sigma_o} = \dfrac{l}{w \cdot t} \rho_o$

**Note: Resistivity, $\rho_o$, is defined as the inverse of the conductivity:**

$$\rho_o \equiv 1/\sigma_o \qquad [\text{Ohm-cm}]$$

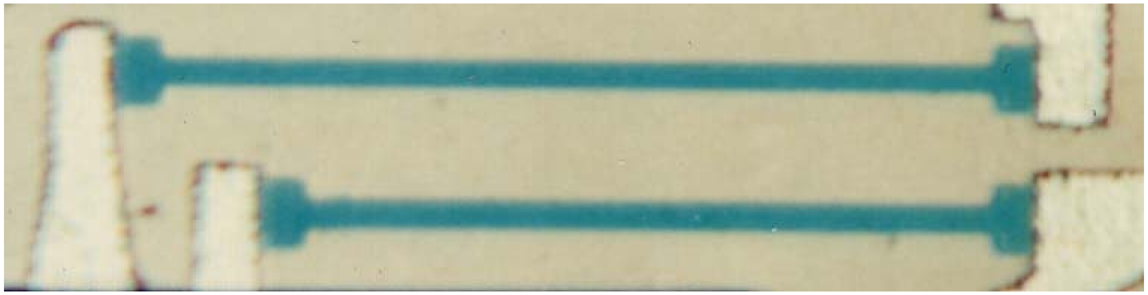
# Integrated resistors **Our first device!!**



Courtesy of Fairchild Semiconductor. Used with permission.

(Courtesy of Fairchild Semiconductor Corporation. Fairchild Semiconductor, A Solid State of Progress, 1964.)

**Diffused resistors: High sheet resistance semiconductor patterns (pink) with low resistance Al (white) "wires" contacting each end.**



**Thin-film resistors: High sheet resistance tantalum films (green) with low resistance Al (white) "wires" contacting each end.**

# Uniform material with uniform excitations

**(pushing semiconductors out of thermal equilibrium)**

## B. Uniform Optical Generation, $g_L$ (t)

**Generation, G, and recombination, R:**

**If G > R, the populations are increasing**

$$G > R \Rightarrow \frac{dn}{dt} = \frac{dp}{dt} > 0$$

**If G < R, the populations are decreasing**

$$G < R \Rightarrow \frac{dn}{dt} = \frac{dp}{dt} < 0$$

**In general**

$$\frac{dn}{dt} = \frac{dp}{dt} = G - R$$

**Optical generation, $g_L$(t):**

**In thermal equilibrium,**

$$G_o = R_o = n_o p_o r(T)$$

**With $g_L$(t):**

$$G = G_o + g_L(t)$$
$$R = n\, p\, r(T) = (n_o + n')(p_o + p')\, r(T)$$

# Lecture 2 - Uniform Excitation - Summary

- **Review**
  Frozen out if too cold; intrinsic-like if too hot
- **Uniform excitation of uniform samples: drift**
  n, p unchanged; carriers attain constant velocity, s (viscous flow)
  $s = \mu E$ at low to moderate fields; s saturates at high fields
  $J_{e,drift} = q\, \mu_e\, n_o\, E$ [A/cm²], $J_{h,drift} = q\, \mu_h\, p_o\, E$ [A/cm²]
  $J_{drift} = J_{e,drift} + J_{h,drift} = q\, (\mu_e\, n_o + \mu_h\, p_o)\, E = \sigma_o\, E$ the majority rules
  Mobility, $\mu$, decreases as temperature goes up from RT
- **Uniform excitation: optical generation**
  In TE, $G_o(T) = R_o(T) = n_o p\, r(T)$
  Uniform illumination adds uniform generation term, $g_L(t)$
  Populations increase: $n_o \rightarrow n_o + n'$, $p_o \rightarrow p_o + p'$, and $n' = p'$
  $dn'/dt = dp'/dt = G_o(T) + g_L(t) - R(T) = g_L(t) - [np - n_o p_o] r(T)$
  focus is on minority $\approx g_L(t) - n'/\tau_{min}$ if LLI holds, with $\tau_{min} \equiv [p_o\, r(T)]^{-1}$
- **Uniform excitation: both optical and electrical**
  Photoconductivity: $\sigma_o \rightarrow \sigma_o + \sigma' = q\, [\mu_e\, (n_o + n') + \mu_h\, (p_o + p')]$
  $= \sigma_o + q\, (\mu_e + \mu_h)\, 2\, p'$
  Photoconductors: an important class of light detectors