6.012 - Electronic Devices and Circuits

Lecture 1 - Introduction to Semiconductors - Outline

• Introductions/Announcements
  
  **Handouts:**
  1. General information, reading assignments (4 pages)
  2. Syllabus
  3. Student info sheet (for tutorials, do/due in recitation tomorrow!)
  4. Diagnostic exam (try it on-line)
  5. Lecture 1

  **Website:** http://stellar.mit.edu/S/course/6/fa12/6.012/

  **Rules and regulations** (next foil)

• Why semiconductors, devices, circuits?

• Mobile charge carriers in semiconductors
  
  Crystal structures, bonding
  Mobile holes and electrons
  Dopants and doping

• Silicon in thermal equilibrium
  
  Generation/recombination; \( n_0 p_0 \) product
  \( n_0, p_0 \) given \( N_d, N_a \); n- and p-types

• Drift
  
  Mobility
  Conductivity and resistivity
  Resistors (our first device)
Comments/Rules and expectations

**Recitations:** They re-enforce lecture.
They present new material.
They are very important.

**Tutorials:** They begin Monday, September 10.
Assignments will be posted on website.

**Homework:** Very important for learning; do it!!

**Cheating:** What you turn in must be your own work.
While it is OK to discuss problems with others, you should work alone when preparing your solution.

**Reading assignment (Lec. 1)**

Chapter 1 in text*
Chapter 2 in text

* "Microelectronic Devices and Circuits" by Clifton Fonstad
http://dspace.mit.edu/handle/1721.1/34219
SEMICONDUCTORS: Here, there, and everywhere!

- Computers, PDAs, laptops, anything “intelligent”
  - Silicon (Si) MOSFETs, Integrated Circuits (ICs), CMOS, RAM, DRAM, flash memory cells
- Cell phones, pagers, WiFi
  - Si ICs, GaAs FETs, BJTs
- CD players, iPods
  - AlGaAs and InGaP laser diodes, Si photodiodes
- TV remotes, mobile terminals
  - Light emitting diodes
- Satellite dishes
  - InGaAs MMICs
- Optical fiber networks
  - InGaAsP laser diodes, pin photodiodes
- Traffic signals, car taillights, dashboards
  - GaN LEDs (green, blue)
  - InGaAsP LEDs (red, amber)
- Air bags
  - Si MEMs, Si ICs
- Solar cells, Themophotovoltaics
  - Si, Ge, InGaAlAs, InGaP

They are very important, especially to EECS types!!

They also provide:
- a good intellectual **framework** and foundation,
- a good vehicle and **context**
- with which
  - to learn about **modeling physical processes**, and
  - to begin to understand **electronic circuit analysis and design**.
**Silicon:** our default example and our main focus

Atomic no. 14

14 electrons in three shells: $2 \ 8 \ 4$

i.e., 4 electrons in the outer "bonding" shell

Silicon forms strong covalent bonds with 4 neighbors

Si bonding configuration

Silicon crystal ("diamond" lattice)
Intrinsic silicon - pure, perfect, R.T.:

- All bonds filled at 0 K, $p_o = n_o = 0$
- At R. T., $p_o = n_o = n_i = 10^{10}$ cm$^{-3}$
- Mobile holes (+) and mobile electrons (-)
- Compare to $\approx 5 \times 10^{22}$ Si atoms/cm$^3$
**Intrinsic Silicon:** pure Si, perfect crystal

All bonds are filled at 0 K.

At finite T, \( n_i(T) \) bonds are broken:

Filled bond \( \Leftrightarrow \) Conduction electron + Hole

A very dynamic process, with bonds breaking and holes and electrons recombining continuously. On average:

- Concentration of conduction electrons \( \equiv n \)
- Concentration of conduction electrons \( \equiv p \)

In thermal equilibrium:

\[
\begin{align*}
\bullet & \quad n = n_o \\
\bullet & \quad p = p_o \\
\text{and} & \quad n_o = p_o = n_i(T)
\end{align*}
\]

The intrinsic carrier concentration, \( n_i \), is very sensitive to temperature, varying exponentially with \( 1/T \):

\[
n_i(T) \propto T^{3/2} \exp(-E_g / 2kT)
\]

In silicon at room temperature, 300 K: \( n_i(T) \cong 10^{10} \text{cm}^{-3} \)

\[\text{A very important number; learn it!!}\]

**In 6.012 we only "do" R.T.**
Extrinsic Silicon: carefully chosen impurities (dopants) added

Column IV elements (C, Si, Ge, α-Sn)

Column V elements (N, P, As, Sb):
- too many bonding electrons → electrons easily freed to conduct (-q charge)
- fixed ionized donors created (+q charge)

$10^{10}$ cm$^{-3}$ is a very small concentration and intrinsic Si is an insulator; we need to do something
A column V atom replacing a silicon atom in the lattice:

- One more electron than needed for bonding.
- Easily freed to conduct at RT.
- Impurity is an electron "donor."
- Mobile electron (-) and fixed donor (+); \( N^+_d \approx N_d \).
Extrinsic Silicon, cont.: carefully chosen impurities (dopants) added

Column IV elements (C, Si, Ge, α-Sn):

Column III elements (B, Al, Ga, In):
- too few bonding electrons $\rightarrow$ leaves holes that can conduct (+q charge)
- $\rightarrow$ fixed ionized acceptors created (-q charge)
A column III atom replacing a silicon atom in the lattice:

- One less electron than needed for bonding.
- Bond easily filled leaving mobile hole; at RT.
- Impurity is an electron "acceptor."
- Mobile hole (+) and fixed acceptor (−); $N_a^- \approx N_a$. 

$E_a \approx 45$ mev
Extrinsic Silicon: carefully chosen impurities (dopants) added

Column IV elements (C, Si, Ge, α-Sn)

Column V elements (N, P, As, Sb):
- too many bonding electrons → electrons easily freed to conduct (-q charge)
  → fixed ionized donors created (+q charge)

Column III elements (B, Al, Ga, In):
- too few bonding electrons → leaves holes that can conduct (+q charge)
  → fixed ionized acceptors created (-q charge)
**Extrinsic Silicon:** What are $n_0$ and $p_0$ in "doped" Si?

- Column V elements (P, As, Sb): "Donors"
  - Concentration of donor atoms $\equiv N_d$ [cm$^{-3}$]

- Column III elements (B, Ga): "Acceptors"
  - Concentration of acceptor atoms $\equiv N_a$ [cm$^{-3}$]

At room temperature, all donors and acceptors are ionized:

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

We want to know, "Given $N_d$ and $N_a$, what are $n_0$ and $p_0$?"

Two unknowns, $n_0$ and $p_0$, so we need two equations.
**Extrinsic Silicon:** Given \( N_a \) and \( N_d \), what are \( n_o \) and \( p_o \)?

**Equation 1 - Charge conservation** (the net charge is zero):

\[
q(p_o - n_o + N_d^+ - N_a^-) = 0 \approx q(p_o - n_o + N_d - N_a)
\]

First equation

**Equation 2 - Law of Mass Action** (the np product is constant in TE):

\[
n_o p_o = n_i^2(T)
\]

Second equation

---

**Where does this last equation come from?**

The semiconductor is in *internal turmoil*, with bonds being broken and reformed continuously:

Completed bond \( \longleftrightarrow \) Electron + Hole

We have *generation*:

Completed bond \( \longrightarrow \) Electron + Hole

occurring at a rate \( G \) [pairs/cm\(^3\)-s]:

Generation rate, \( G = G_{ext} + g_o(T) = G_{ext} + \sum_m g_m(T) \)
And we have recombination:

\[
\text{Electron} + \text{Hole} \rightarrow \text{Completed bond}
\]

occurring at a rate \( R \) [pairs/cm\(^3\)-s]:

\[
R = n_o p_o r_o(T) = n_o p_o \sum m r_m(T)
\]

In general we have:

\[
\frac{dn}{dt} = \frac{dp}{dt} = G - R = G_{\text{ext}} + \sum m g_m(T) - n p \sum m r_m(T)
\]

In thermal equilibrium, \( \frac{dn}{dt} = 0, \frac{dp}{dt} = 0, n = n_o, p = p_o, \) and \( G_{\text{ext}} = 0, \)
so:

\[
0 = G - R = \sum m g_m(T) - n_o p_o \sum m r_m(T) \Rightarrow \sum m g_m(T) = n_o p_o \sum m r_m(T)
\]

But, the balance happens on an even finer scale. The Principle of Detailed Balance tells us that each G-R path is in balance:

\[
g_m(T) = n_o p_o r_m(T) \quad \text{for all m}
\]

This can only be true if \( n_o p_o \) is constant at fixed temperature, so we must have:

\[
n_o p_o = n_i^2(T)
\]
Another way to get this result is to apply the Law of Mass Action from chemistry relating the concentrations of the reactants and products in a reaction in thermal equilibrium:

\[
\text{Electron} + \text{Hole} \leftrightarrow \text{Completed bond}
\]

\[
\frac{[\text{Electron}][\text{Hole}]}{[\text{Completed bond}]} = k(T)
\]

We know \([\text{Electron}] = n_o\) and \([\text{Hole}] = p_o\), and recognizing that most of the bonds are still completed so \([\text{Completed bond}]\) is essentially a constant*, we have

\[
n_o p_o = [\text{Completed bond}] k(T) \approx A k(T) = n_i^2(T)
\]

Back to our question: Given \(N_a\) and \(N_d\), what are \(n_o\) and \(p_o\)?

**Equation 1 - Charge conservation** (the net charge is zero):

\[
q(p_o - n_o + N_d^+ - N_a^-) = 0 \approx q(p_o - n_o + N_d - N_a)
\]

First equation

**Equation 2 - Law of Mass Action** (the np product is constant in TE):

\[
n_o p_o = n_i^2(T)
\]

Second equation

* This requires that \(n_o\) and \(p_o\) be less than about \(10^{19}\) cm\(^{-3}\).
Extrinsic Silicon, cont: Given $N_a$ and $N_d$, what are $n_o$ and $p_o$?

Combine the two equations:

$$\left( \frac{n_i^2}{n_o} - n_o + N_d - N_a \right) = 0$$

$$n_o^2 - (N_d - N_a)n_o - n_i^2 = 0$$

Solving for $n_o$ we find:

$$n_o = \frac{(N_d - N_a) \pm \sqrt{(N_d - N_a)^2 + 4n_i^2}}{2} = \frac{(N_d - N_a)}{2} \left[ 1 \pm \sqrt{1 + \frac{4n_i^2}{(N_d - N_a)^2}} \right]$$

$$\approx \frac{(N_d - N_a)}{2} \left[ 1 \pm \left( 1 + \frac{2n_i^2}{(N_d - N_a)^2} \right) \right]$$

Note: Here we have used $\sqrt{1 + x} \approx 1 + x/2$ for $x \ll 1$

This expression simplifies nicely in the two cases we commonly encounter:

Case I - n-type: $N_d > N_a$ and $(N_d - N_a) > n_i$

Case II - p-type: $N_a > N_d$ and $(N_a - N_d) > n_i$

Fact of life: It is almost impossible to find a situation which is not covered by one of these two cases.
**Extrinsic Silicon, cont.:** solutions in Cases I and II

**Case I - n-type:** \( N_d > N_a; \ (N_d - N_a) \gg n_i \) "n-type Si"

Define the net donor concentration, \( N_D \):
\[
N_D \equiv (N_d - N_a)
\]

We find:
\[
n_o \approx N_D, \quad p_o = n_i^2(T)/n_o \approx n_i^2(T)/N_D
\]

In Case I the concentration of electrons is much greater than that of holes. Silicon with net donors is called "n-type".

**Case II - p-type:** \( N_a > N_d; \ (N_a - N_d) \gg n_i \) "p-type Si"

Define the net acceptor concentration, \( N_A \):
\[
N_A \equiv (N_a - N_d)
\]

We find:
\[
p_o \approx N_A, \quad n_o = n_i^2(T)/p_o \approx n_i^2(T)/N_A
\]

In Case II the concentration of holes is much greater than that of electrons. Silicon with net acceptors is called "p-type".
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:

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

At low and moderate $|E|$, the mobility, $\mu$, is constant.
At high $|E|$ the velocity saturates and $\mu$ deceases with increasing $|E|$.
Uniform material with uniform excitations  
(pushing semiconductors out of thermal equilibrium)

A. Uniform Electric Field, $E_x$, cont.

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

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

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

**Drift currents:**
Net velocities imply net charge flows, which imply currents:

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

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

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

**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)
**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:

\[
J_{x}^{dr} = J_{ex}^{dr} + J_{hx}^{dr} = q\mu_e n_o E_x + q\mu_h p_o E_x = q\left(\mu_e n_o + \mu_h p_o\right)E_x
\]

From this we see obtain our expression for the conductivity:

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

**Majority vs. minority carriers:**

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

- **n-type** \[n_o >> p_o \Rightarrow \sigma_o \approx q\mu_e n_o\]
- **p-type** \[p_o >> n_o \Rightarrow \sigma_o \approx q\mu_h p_o\]
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 $E_x = \frac{v_{AB}}{l}$ and $J_x^{dr} = \frac{i_D}{w \cdot t}$

Combining these we find:

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

which yields:

\[
v_{AB} = \frac{l}{w \cdot t} \frac{1}{\sigma_o} \, i_D = R \, i_D
\]

where

\[
R \equiv \frac{l}{w \cdot t} \frac{1}{\sigma_o} = \frac{l}{w \cdot t} \rho_o = \frac{l}{A} \rho_o
\]

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

$\rho_o = \frac{1}{\sigma_o}$ [Ohm - cm]
Integrated resistors  Our first device!!

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.
Lecture 1 - Introduction to Semiconductors - Summary

- Mobile charge carriers in semiconductors
  - Covalent bonding, 4 nearest neighbors, diamond lattice
  - Conduction electrons: charge = – q, concentration = n [cm\(^{-3}\)]
  - Mobile holes: charge = + q, concentration = p [cm\(^{-3}\)]
  - Donors: Column V (P,As,Sb); fully ionized at RT: \(N_{d}^+ \approx N_d\)
  - Acceptors: Column III (B); fully ionized at RT: \(N_a^- \approx N_a\)

- Silicon in thermal equilibrium
  - Intrinsic (pure) Si: \(n_o = p_o = n_i(T) = 10^{10}\) cm\(^{-3}\) at RT
  - Doped Si: \(n_o p_o = n_i^2\) always; no net charge (mobile + fixed = 0)
    - If \(N_d > N_a\), then: \(n_o \approx N_d - N_a\); \(p_o = n_i^2/n_o\); called "n-type"; electrons are the majority carriers, holes the minority
    - If \(N_a > N_d\), then: \(p_o \approx N_a - N_d\); \(n_o = n_i^2/p_o\); called "p-type"; holes are the majority carriers, electrons the minority
  - Generation and recombination: always going on

- Drift
  - Uniform electric field results in net average velocity
  - Net average velocity results in net drift current fluxes:
    \[ J_{x,dr} = J_{ex,dr} + J_{hx,dr} = q(n_o \mu_e + p_o \mu_h)E_x = \rho_o E_x \]