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

  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; $n_o p_o$ product
  n_o , p_o 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 14.
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

They are very important, especially to EECS types!!

They also provide:

a good intellectual framework and foundation,

and

a good vehicle and context

with which

to learn about modeling physical processes,

and

to begin to understand electronic circuit analysis and design.

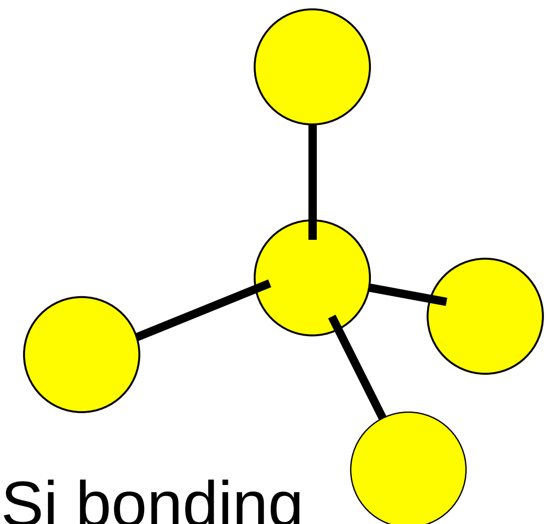
Silicon: our default example and our main focus

Atomic no. 14

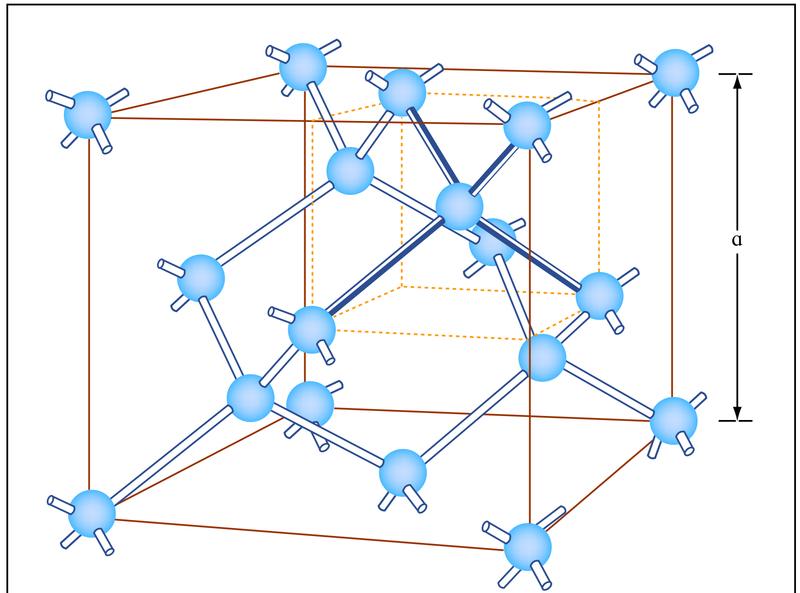
14 electrons in three shells: 2) 8) 4

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

Silicon forms strong covalent bonds with 4 neighbors



Si bonding configuration



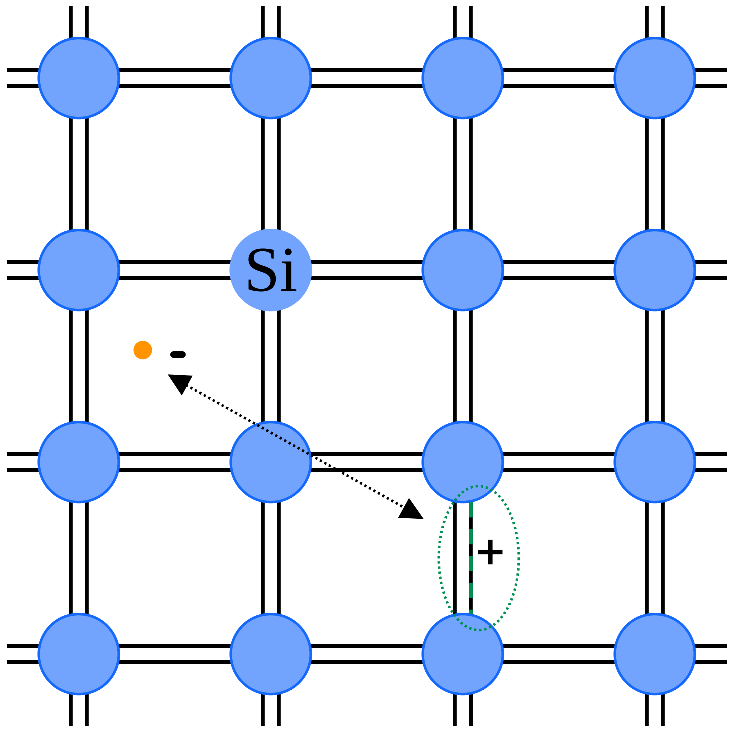
Silicon crystal ("diamond" lattice)

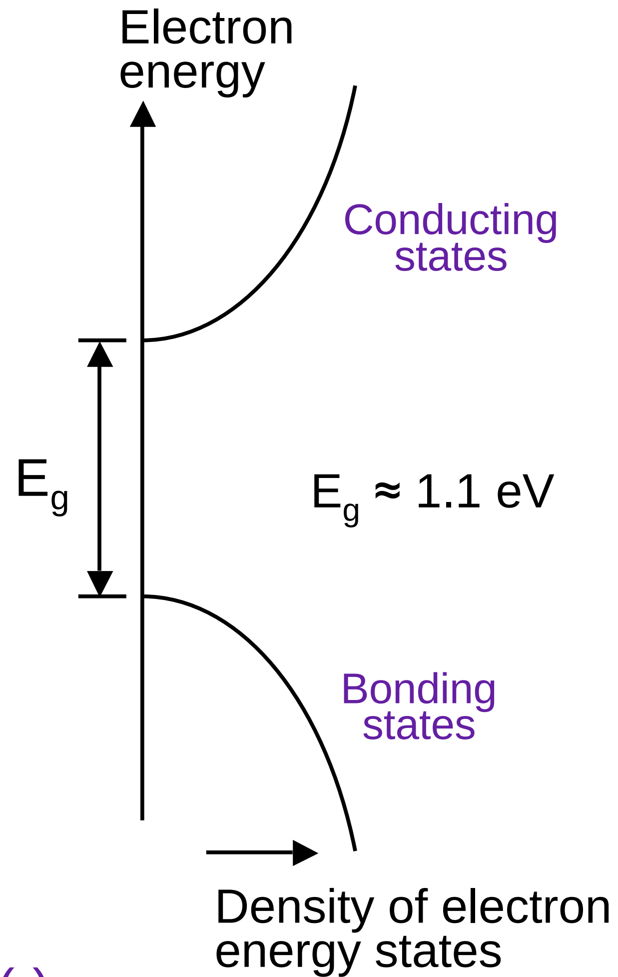
Figure by MIT OpenCourseWare.

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 ≈ 5 x 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:

$$\text{Filled bond} \Leftrightarrow \text{Conduction electron} + \text{Hole}$$

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:

- $n = n_o$
- $p = p_o$

and $n_o = p_o = n_i(T)$

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: $n_i(T) \cong 10^{10}\, cm^{-3}$

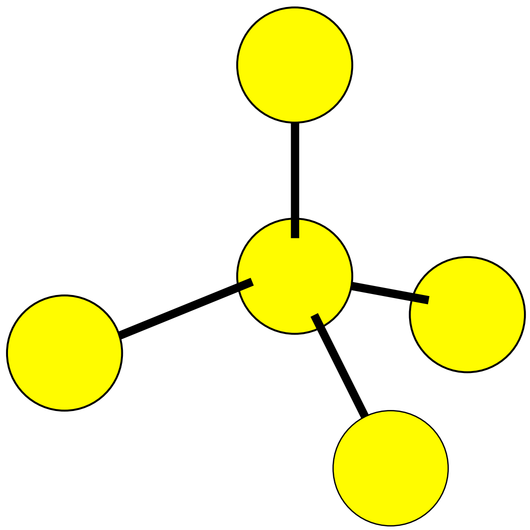
A very important number; learn it!!

In 6.012 we only "do" R.T.

10^{10} cm^{-3} is a very small concentration and intrinsic Si is an insulator; we need to do something

Extrinsic Silicon: carefully chosen impurities (dopants) added

Column IV elements (C, Si, Ge, α-Sn)



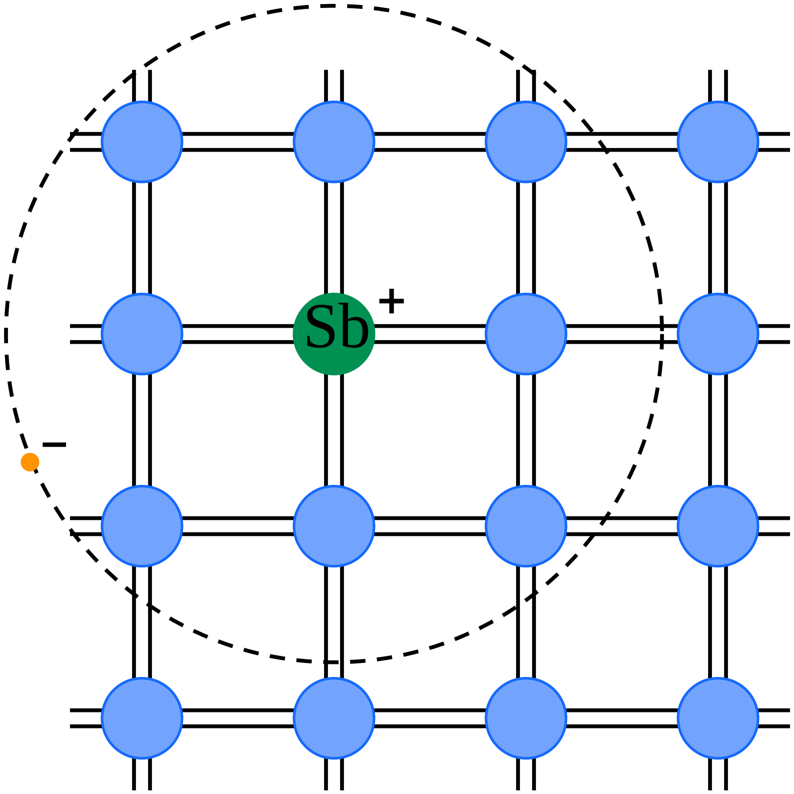
II	III	IV	V	VI
	B 5	**C** 6	**N** 7	**O** 8
	Al 13	**Si** 14	**P** 15	**S** 16
Zn 30	**Ga** 31	**Ge** 32	**As** 33	**Se** 34
Cd 48	**In** 49	**Sn** 50	**Sb** 51	**Te** 52
Hg 80	**Tl** 81	**Pb** 82	**Bi** 83	**Po** 84

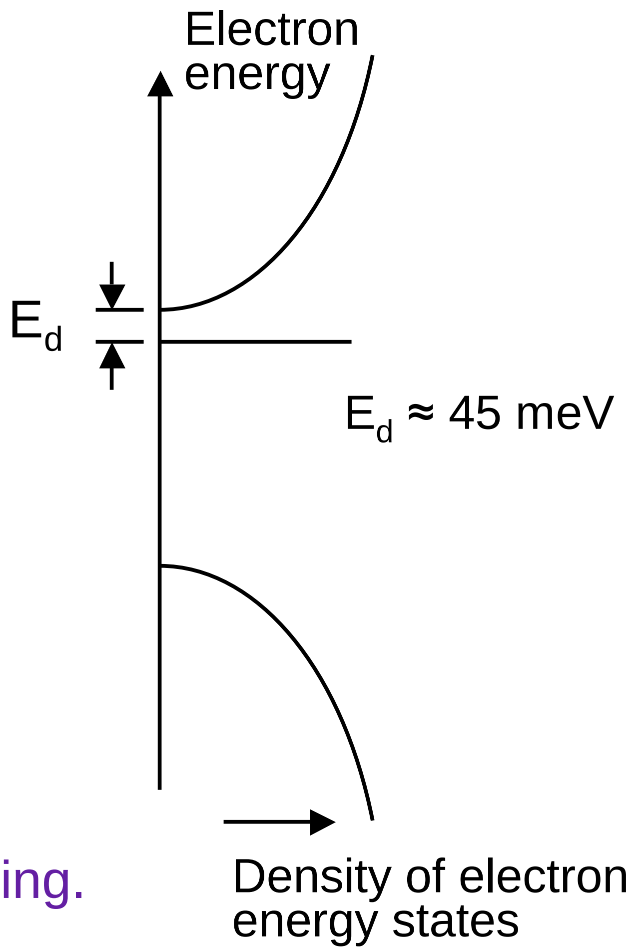
Column V elements (*N*, P, As, Sb):

too many bonding electrons → electrons easily freed to conduct (-q charge)

→ fixed ionized donors created (+q charge)

A column V atom replacing a silicon atom in the lattice:

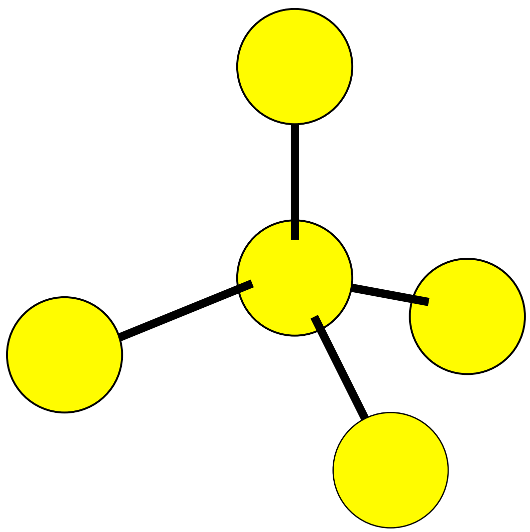




- One more electron than needed for bonding.
- Easily freed to conduct at RT.
- Impurity is an electron "donor."
- Mobile electron (-) and fixed donor (+); $N_d^+ \approx N_d$.

Extrinsic Silicon, cont.: carefully chosen impurities (dopants) added

Column IV elements (C, Si, Ge, α-Sn)



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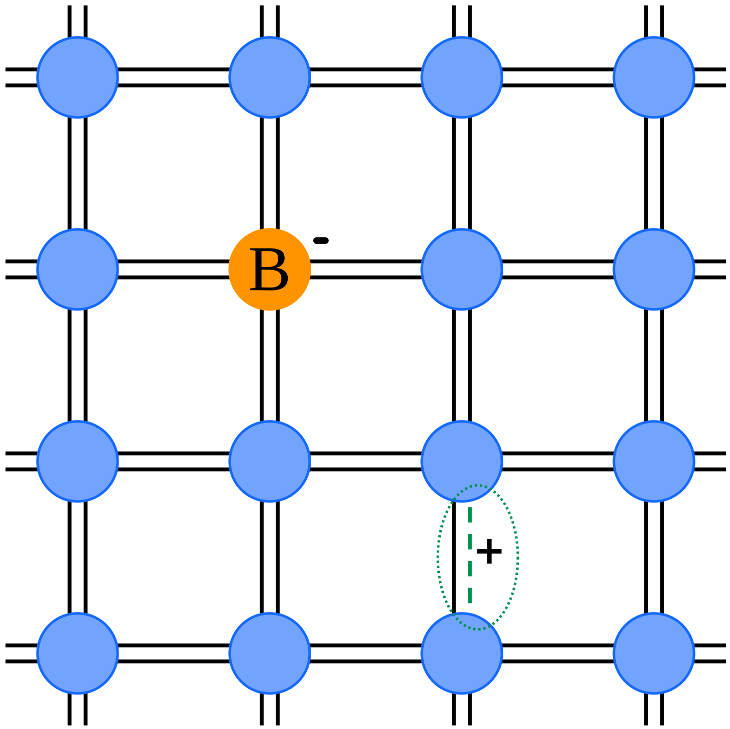
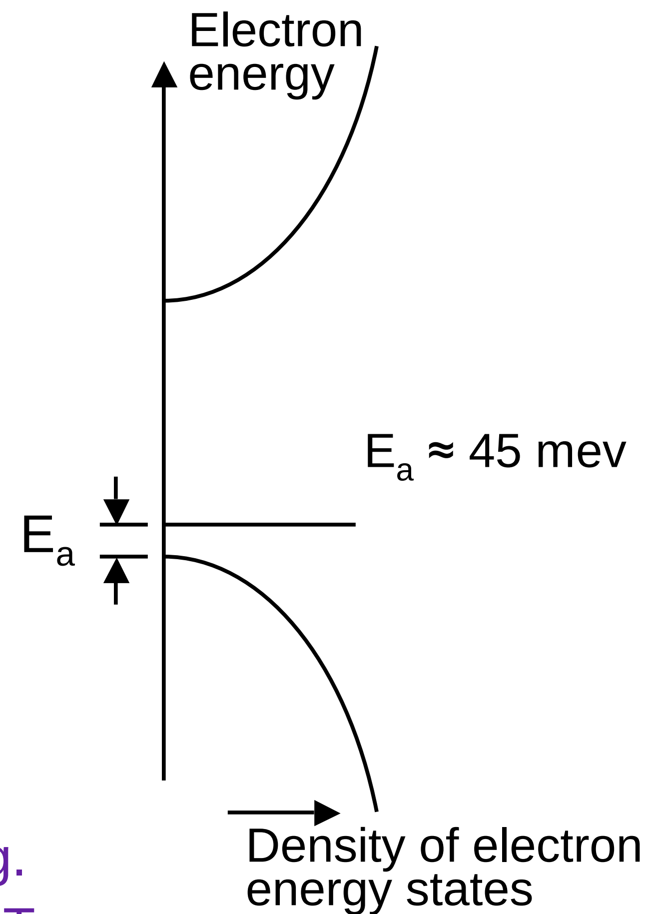
Column III elements (B, *Al, Ga, In*):

too few bonding electrons → leaves holes that can conduct (+q charge)

→ fixed ionized acceptors created (-q charge)

A column III atom replacing a silicon atom in the lattice:

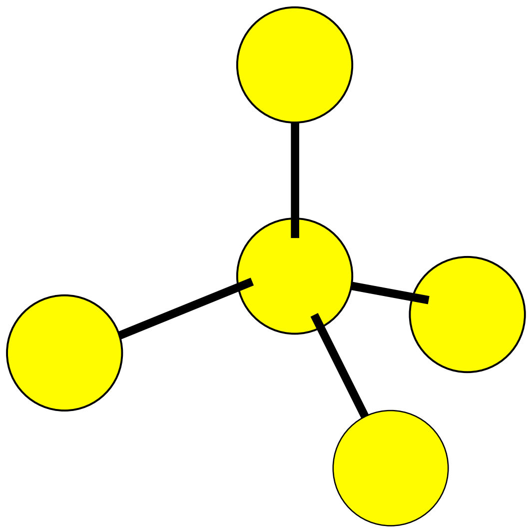




- One less electron than needed for bonding.
- Bond easily filled leaving mobile hole; at RT.
- Impurity is an electron "acceptor."
- Mobile hole (+) and fixed acceptor (–); $N_a^- \approx N_a$.

Extrinsic Silicon: carefully chosen impurities (dopants) added

Column IV elements (C, Si, Ge, α-Sn)



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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_o and p_o 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_o and p_o?"

Two unknowns, n_o and p_o, 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):

$$q(p_o - n_o + N_d^+ - N_a^-) = 0 \approx \underbrace{q(p_o - n_o + N_d - N_a)}_{\text{First equation}}$$

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

$$n_o p_o = n_i^2(T) \qquad \text{Second equation}$$

Where does this last equation come from?

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

$$\text{Completed bond} \longleftrightarrow \text{Electron} + \text{Hole}$$

We have **generation**:

$$\text{Completed bond} \longrightarrow \text{Electron} + \text{Hole}$$

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

$$\text{Generation rate, } G = G_{ext} + g_o(T) = G_{ext} + \sum_m g_m(T)$$

And we have **recombination**:

$$\text{Electron} + \text{Hole} \longrightarrow \text{Completed bond}$$

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

$$\text{Recombination rate,}\quad R = n_o p_o r_o(T) = n_o p_o \sum_m r_m(T)$$

In <u>general</u> we have:

$$\frac{dn}{dt} = \frac{dp}{dt} = G - R = G_{ext} + \sum_m g_m(T) - n\,p \sum_m r_m(T)$$

In <u>thermal equilibrium</u>, dn/dt = 0, dp/dt = 0, $n = n_o$, $p = p_o$, and $G_{ext} = 0$, so:

$$0 = G - R = \sum_m g_m(T) - n_o p_o \sum_m r_m(T) \quad \Rightarrow \quad \sum_m g_m(T) = n_o p_o \sum_m r_m(T)$$

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

$$\text{Electron} + \text{Hole} \longleftrightarrow \text{Completed bond}$$

$$[Electron][Hole]/[Completed\ bond] = k(T)$$

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

$$n_o p_o = [Completed\ bond]\, k(T) \approx A\, k(T) = n_i^2(T)$$

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 $\sqrt{1+x} \approx 1 + x/2 \quad \text{for} \quad x \ll 1$

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

$$\text{Case I - n-type:} \quad N_d > N_a \ \ and \ \ (N_d - N_a) \gg n_i$$

$$\text{Case II - p-type:} \quad N_a > N_d \ \ and \ \ (N_a - N_d) \gg n_i$$

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: $N_d > N_a$:, $(N_d - N_a) >> n_i$ "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: $N_a > N_d$:, $(N_a - N_d) >> n_i$ "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:

$$\bar{s}_{ex} = -\mu_e E_x, \quad \bar{s}_{hx} = \mu_h E_x$$

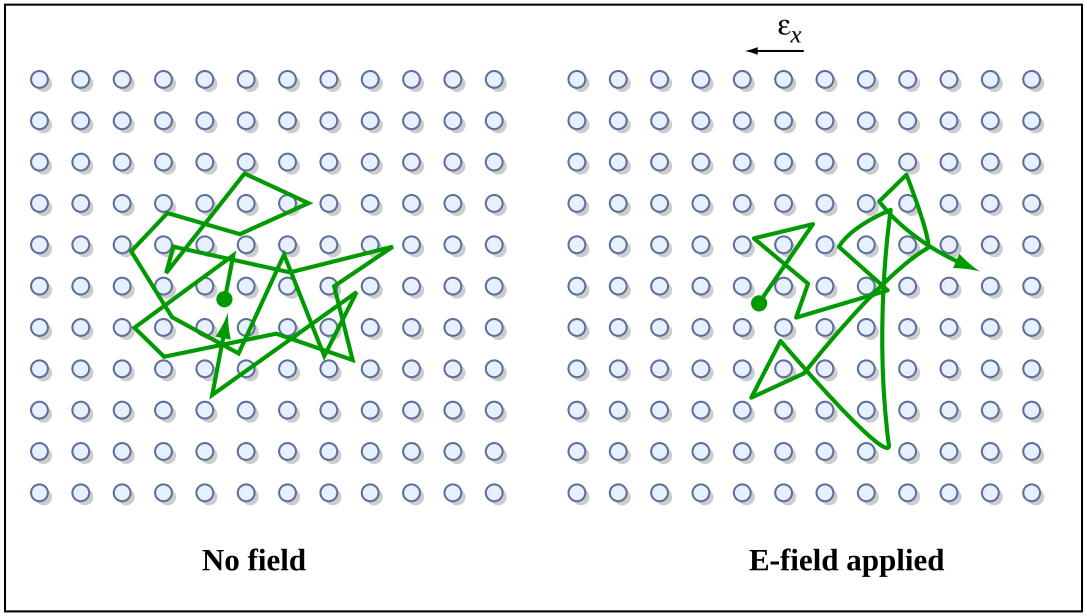


Figure by MIT OpenCourseWare.

At low and moderate |E|, the mobility, μ, is constant.

At high |E| the velocity saturates and μ 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:

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

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

Drift currents:

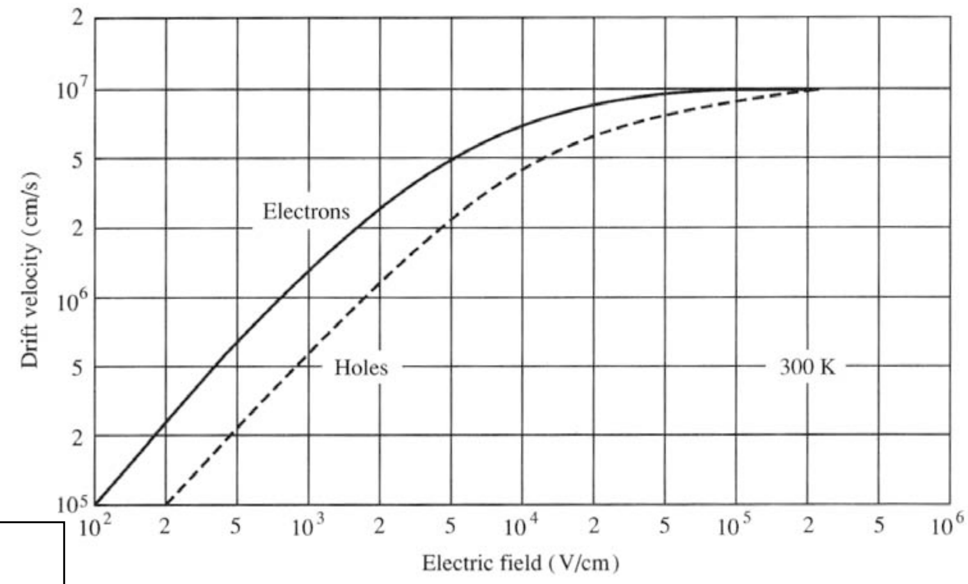
Net velocities imply net charge flows, which imply currents:

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

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

Velocity saturation

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



Silicon

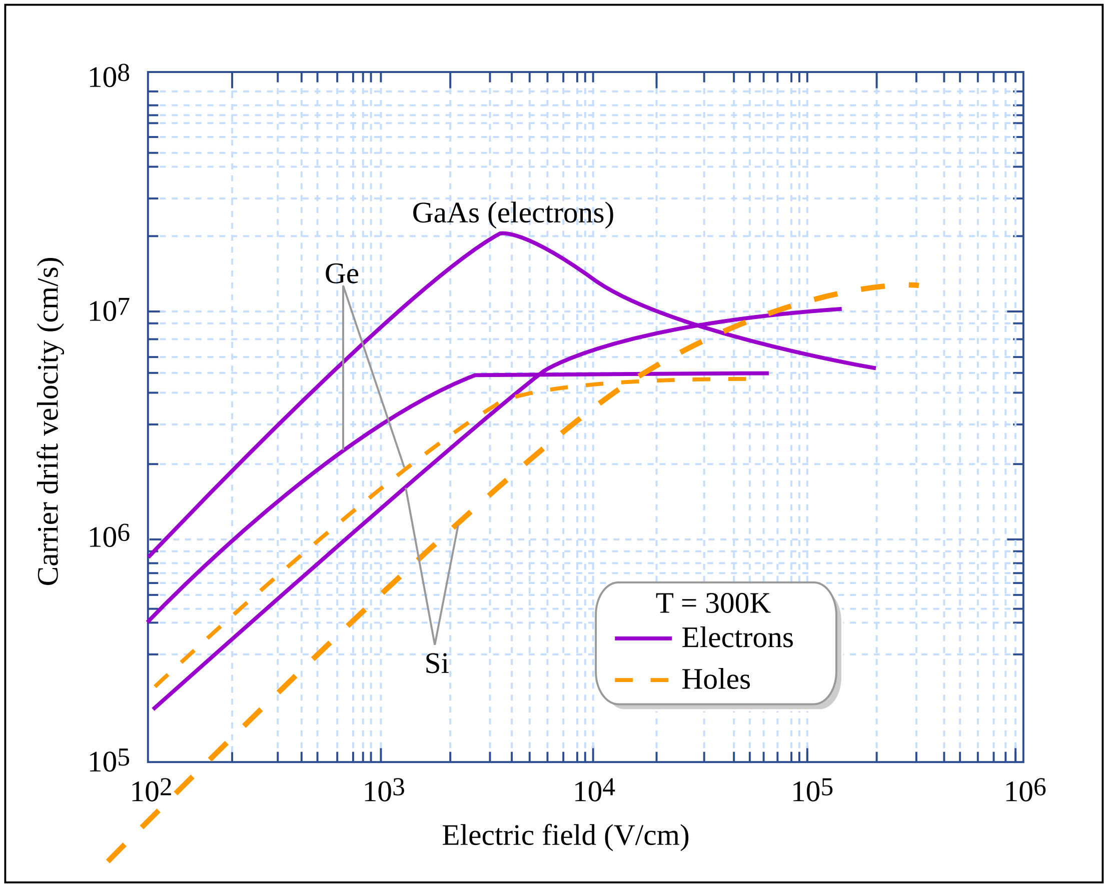


Figure by MIT OpenCourseWare.

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, σ_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:

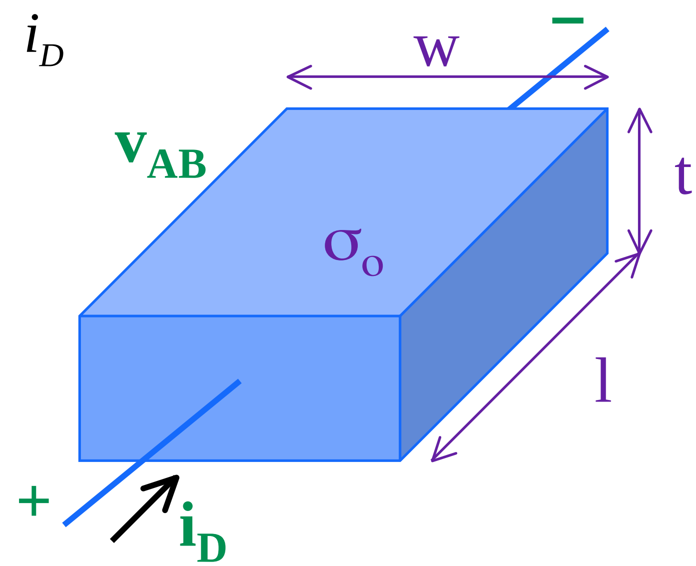
Drift and conductivity are dominated by the most numerous, or "majority," carriers:

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, ρ_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:

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

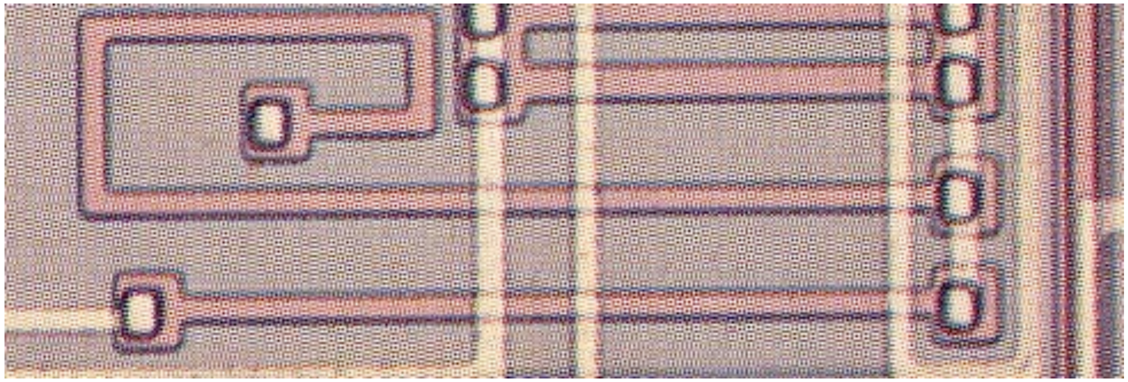
which yields: $v_{AB} = \dfrac{l}{w \cdot t} \dfrac{1}{\sigma_o} i_D = R\, i_D$

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

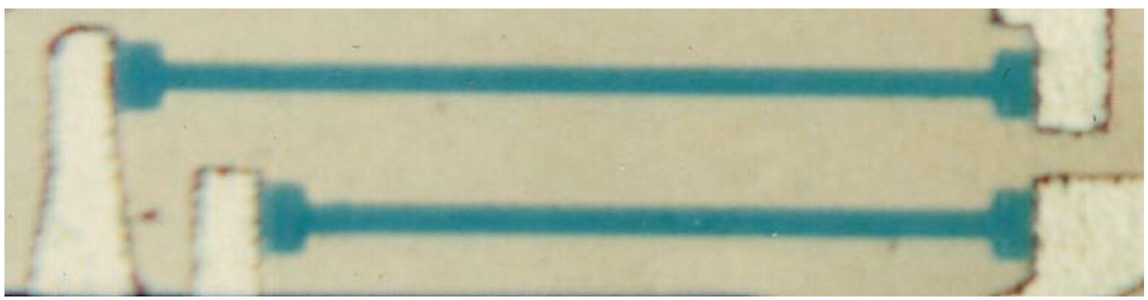
Note: Resistivity, ρ_o, is defined as the inverse of the conductivity:

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

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:**

$$J_{x,dr} = J_{ex,dr} + J_{hx,dr} = q(n_o\mu_e + p_o\mu_h)E_x = \rho_o E_x$$