SEMICONDUCTOR REVIEW

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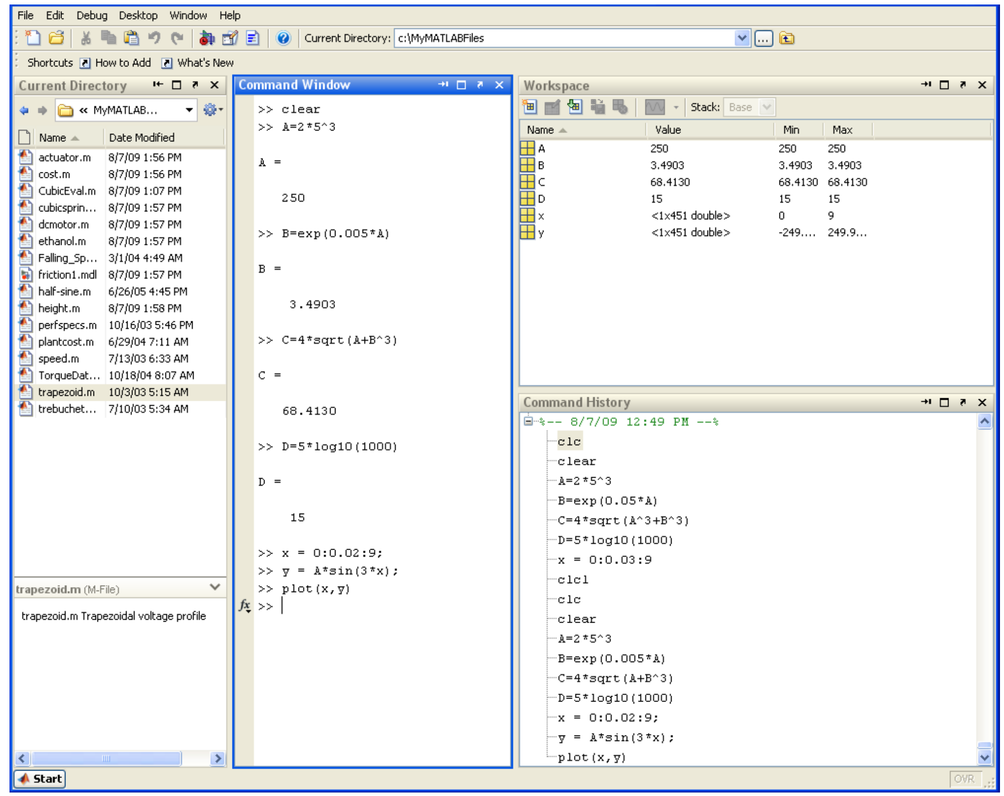
Assignments

- Many of the assignments will use tools to help computation of items to understand what's going on with creating voltage and current.
- It is important you have some mechanism to understand how to compute these computations either in a book or in a computer.
  - It is recommended to get some sort of way of doing repeated computations or programming simple items.
- See the video from Landon on a cool use of MATLAB.



MATLAB

https://matlabacademy.mathworks.com

So, why MATLAB?

- You will need some sort of high-level programming tool for this class.
- Why MATLAB?
  - MATLAB helps differentiate the benefits of higher-level programming.
  - Pretty much, if you can understand basic programming, you can understand MATLAB.
  - MATLAB is no longer just for communication engineering – its for all engineering and its vital for many solutions in engineering!!!!
- What about Python?
  - Yes, interested students can use python – there's an import call *numpy* that can do many of the thinks that MATLAB can
    - https://numpy.org
  - Check out https://matplotlib.org for cool plotting.
- Why I don't recommend C or C++
  - I don't recommend C or C++ because you would need some linear algebra routines and although they are around (e.g., BLAS, LINPACK), why invent them again as well as having to understand the interface!

Software

- I will commonly use MATLAB for many of the problems in your assignments.
  - You are welcome to use any program you want, but I highly recommend MATLAB as I am also using it.
  - Solutions will only be provided by MATLAB as that what I am using and if you decide to use something else, you should vigorously validate your results.
- MATLAB is available for install on your laptops/desktops at this site:
  - https://ceat.okstate.edu/itservices/software/mathworks-matlab-simulink.html
- MathWorks who makes MATLAB has a great tutorial called *onramp* (see Canvas) and they indicate you can learn it quickly with different learning methods.
  - https://matlabacademy.mathworks.com
- I put a folder button on Canvas for MATLAB related questions.
  - Again, feel free to use your own tool.
  - My Ph.D. student Landon has a great video on Canvas that may be useful too.
  - Ask questions on how to do things effectively in MATLAB – it really is easy to use!

Silicon

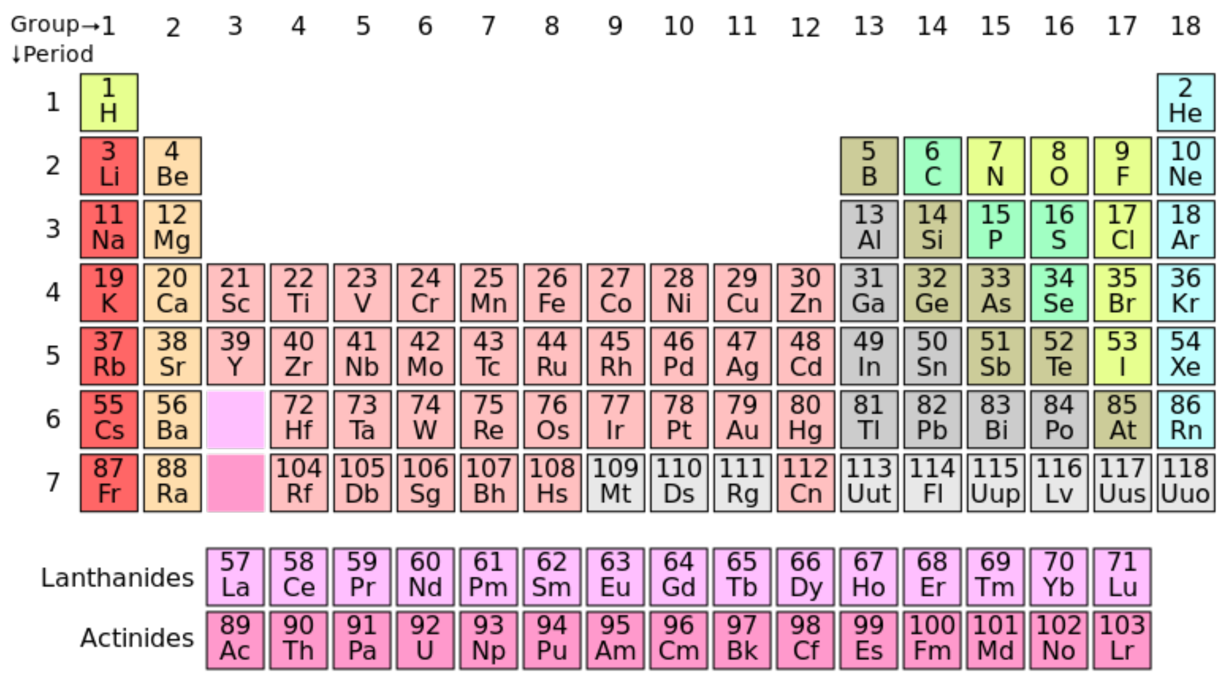
- Silicon is one of the most underappreciated elements, because it is abundance and highly useful for the fabrication of electronics.
- However, far too many people get into the habit of characterizing equations.
  – Remember, the science is what is important!!!!
- Let's start with the basics….
  – Electricity is a fundamental property/phenomena defined by James Clerk Maxwell's equations.

[Wiki]

$$i = \frac{dQ}{dt}$$

Change of charge ∝ current

Periodic Table of Elements



- Periodic table was invented by Mendeleev [1869] to keep properties of elements in groups that have the same properties.
- The key is to pick a chemical that can be used to create charge but be abundant and easy to use.

Silica

- Silicon is a fundamental element from sand and because it is abundant it has the potential of being a good element for utilization of charge (remember, we want charge to move to create current).
- Most importantly, I can easily grow an insulator from it (SiO_2) that can segment circuits from others (thermal oxidation).
- Silica glass has a tetrahedral structure (SiO_4) – is this strong or not?

Oxidation tubes [Wiki]

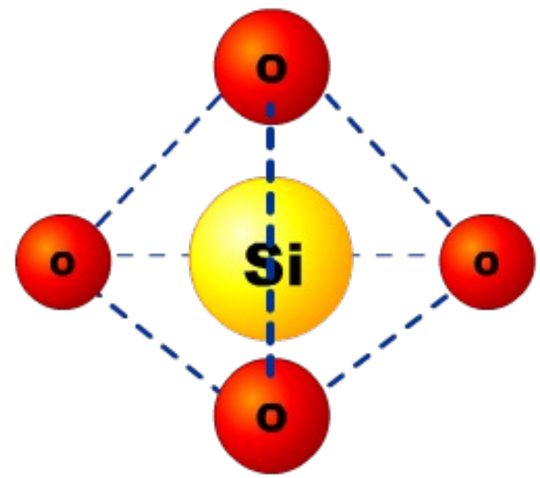
Dry

$$Si + O_2 \xrightarrow{\Delta} SiO_2$$

Wet

$$Si + 2 \cdot H_2O \rightarrow SiO_2 + 2 \cdot H_{2\,(g)}$$

Deal-Grove Oxidation



Initial Assumptions

- No illumination
- No radiation
- No external electric or magnetic fields.
- Single temperature throughout (default: 300 K)
  - 300 K is sometimes called room temperature although it isn't. What temperature is this?
- If there is no exchange of energy with the external world and if the effect of any disturbance has disappeared and we are in a settled state, we way state that the semiconductor is in *equilibrium*.
  - In equilibrium, there is no electric current.

$$T = T + 273.15°\mathrm{C}$$

Engineering Units

- I take great pride in being an engineer (you should too).
- Engineers use units back and forth rather often, so you should get used to using them as well.
  - You don't want to say 0.00253 V as you will sound silly.
  - You should indicate 2.53 mV.
- Sometimes this is called Engineering Notation.
  - Based on an idea by Peter D. Dickinson the first calculator to support engineering notation displaying the power-of-ten exponent values was the HP-25 in 1975.
  - It was implemented as a dedicated display mode in addition to scientific notation.
  - It is a version of scientific notation in which the exponent is a power of 3.
  - Most calculators today that engineers utilize have an `ENG` button or mode.
- You can use MATLAB or your calculator to help you if you are not sure of what the power of 3 is (try it).
  - `format long eng` in MATLAB

SI prefixes

Prefix		Representations		
Name	Symbol	Base 1000	Base 10	Value
yotta	Y	1000^8	10^{24}	1 000 000 000 000 000 000 000 000
zetta	Z	1000^7	10^{21}	1 000 000 000 000 000 000 000
exa	E	1000^6	10^{18}	1 000 000 000 000 000 000
peta	P	1000^5	10^{15}	1 000 000 000 000 000
tera	T	1000^4	10^{12}	1 000 000 000 000
giga	G	1000^3	10^9	1 000 000 000
mega	M	1000^2	10^6	1 000 000
kilo	k	1000^1	10^3	1 000
		1000^0	10^0	1
milli	m	1000^{-1}	10^{-3}	0.001
micro	μ	1000^{-2}	10^{-6}	0.000 001
nano	n	1000^{-3}	10^{-9}	0.000 000 001
pico	p	1000^{-4}	10^{-12}	0.000 000 000 001
femto	f	1000^{-5}	10^{-15}	0.000 000 000 000 001
atto	a	1000^{-6}	10^{-18}	0.000 000 000 000 000 001
zepto	z	1000^{-7}	10^{-21}	0.000 000 000 000 000 000 001
yocto	y	1000^{-8}	10^{-24}	0.000 000 000 000 000 000 000 001

[Wikipedia]

Conversion

- Some people understand conversion of units, some do not.
- I was a dual-major during my first undergraduate degree in Physics and Chemistry and we used unit conversion quite often in Chemistry.
- Sometimes, and most unfortunately, it is given a negative connotation with the word Stoichiometry.
  - Let's do a refresher on a method I use that I call the "slam method" like a slam dunk.

Convert units you are familiar with!

$$3\ \cancel{\text{meters}} \times \frac{39.3701\ \text{inches}}{1\ \cancel{\text{meter}}} = 118.1103\ \text{inches}$$

Cancel out terms you want to get rid of!!

Combine conversions together

$$3\ \cancel{\text{miles}} \times \left(\frac{5{,}280\ \cancel{\text{ft}}}{1\ \cancel{\text{mile}}}\right) \times \left(\frac{12\ \text{inches}}{1\ \cancel{\text{ft}}}\right) = 190{,}080\ \text{inches}$$

- String as many conversion you have together to form the conversion you need.
- Add engineering notation afterwards.
- What is this in engineering notation?
- Yes, this seems simple; but many engineers I meet cannot do this for some reason.

More complicated

- We deal with area and volume many times in digital integrated circuits.
- So, how do you convert these more complicated items.
  - Simple, adapt the "slam method" to this conversion.
  - Add the superscript to the brackets you want to go to.
- Let's try an example conversion cubic feet to cubic cm.

$$3\ \mathrm{ft}^3 \times \left(\frac{12\ \mathrm{inches}}{1\ \mathrm{ft}}\right)^3 \times \left(\frac{2.54\ cm}{1\ \mathrm{inch}}\right)^3 = 8.4951\times 10^4\ cm^3$$

Yes, that's 84.95 kcm^3

Introduction

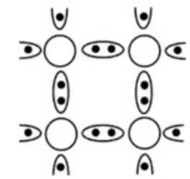
- Hopefully, you have had some of this material.
- I hope to give you a brief introduction so we can get into the juicier of topics related to MOS devices.
- You are welcome to see me anytime to discuss some more background.
- All of this relies on the physics of semiconductors but also heavily relies on its Chemistry.

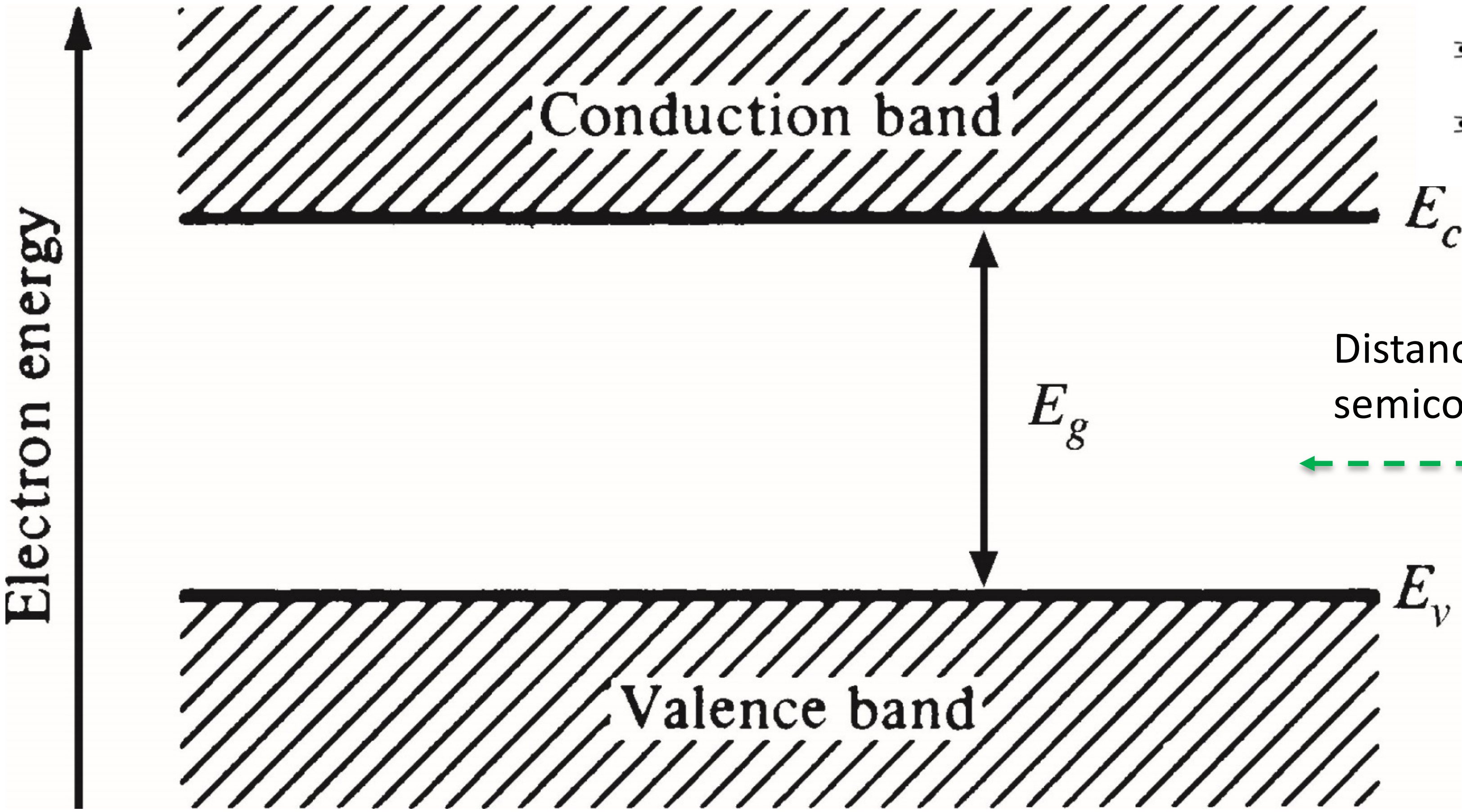
Energy Band Structure

- In solid-state physics, the electronic band structure of a solid describes the ranges of energy than an electron within the solid may occupy.
  - Highly related to its atomic orbit.
  - The band structure is highly simplified and also assumes everything is the same temperature, that there is no illumination, no radiation, and no magnetic fields.
- The true energy band structure is actually 3D, however, it gives us an idea what happens to an electron as the energy in the device increases.
  - How do we get energy into a circuit?
- Why are we interested in equations of energy?
- Band diagram helps us (EE/CpE) explain operation of semiconductor devices.

Energy Band of Semiconductor

2D Si Model

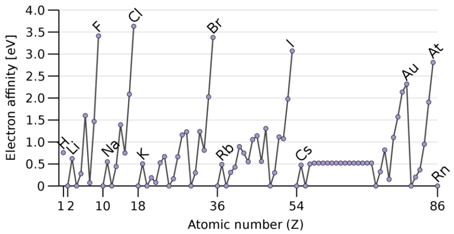




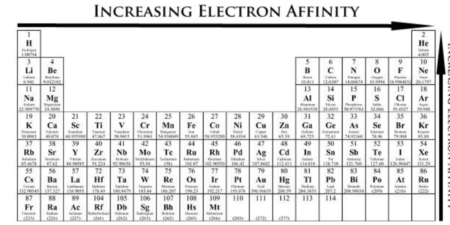
Distance along semiconductor

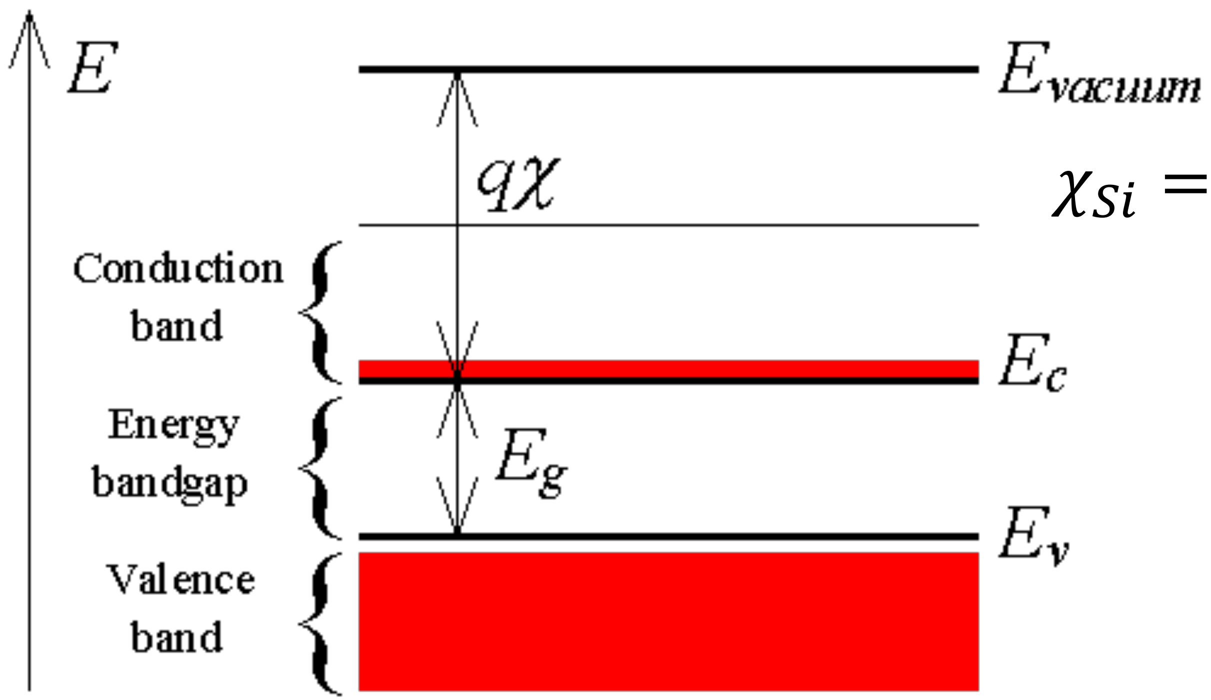
FIGURE 1.1 Energy band model for a semiconductor.

At 0 absolute temperature (no movement), all electrons are frozen in Valence band



Electron Affinity





$\chi_{Si} = 4.05\ eV$

[CU Boulder]

The **electron affinity** of an atom or molecule is defined as the amount of energy *released* or *spent* when an electron is added to a neutral atom or molecule in the gaseous state to form a *negative* ion.

$$X(g) + e^{-} \rightarrow X^{-}(g)$$

Regions in Energy Band

- Valence Band
  - Electrons are bound to individual atoms.
- Conduction Band
  - Electrons are allowed to move freely within the atomic lattice.
- Band gap
  - Energy difference between the top of the valence band and the bottom of the conduction band
  - Electrons can jump from valence band to the conduction band, however, they require a certain amount of energy to do this.
    - Small energy gap or band gap (can overlap) = conductors (metals)
    - Large energy gap or band gap = insulators
    - Somewhat between the two = semiconductor

      Usually, a band gap greater than 3 eV is not considered a semiconductor.

Some Band gaps

Material	Symbol	Band gap [eV]
Silicon	Si	1.12
Germanium	Ge	0.67
Gallium Nitride	GaN	3.40
Silicon Dioxide	SiO_2	9.00

- For metals (conductors), there is no band gap between their valence and conduction bands, since they overlap.
- Silicon is <u>abundant</u> and easy to fabricate (heat).
- It also has excellent electrical and mechanical properties.
- Most important factor: forms high quality thermal oxide for insulation properties.

An eV or ElectronVolt is the product of the magnitude of the electron charge and 1 V; [1 eV = 1.602 x 10^{-19} J]

A case of mixing….

- Our goal is really to get charge moving (or changing), so we can do this by depleting or overextending the concentration of electrons within a given atomic structure.
- This is the process of doping by adding very, very small number of impurities into a structure.
  - We have been doing this for the last thousand years
  - Bronze is an alloy consisting primary of copper usually with tin as an additive (In this case makes copper stronger).
- Doping of Silicon
  - Group III dopants: Boron, Aluminum, Gallium, Indium
    - Called acceptors, because makes broken bonds (holes) since its missing fourth valence electron [p-type semiconductor].
  - Group V dopants: Phosphorous, Arsenic, Antimony, Bismuth
    - Called donors, because extra valence electrons are added that become unbounded from individual atoms [n-type semiconductor].

$$p_i = n_i$$

Its all too many…

- Sometimes large numbers are easier to think about in terms of two values:

$$n_0 \cdot p_0 = n_i^2$$

- The symbol n_i is often used to denote either concentration and is typically referred as the **intrinsic** (no impurities) carrier concentration.
- The value n_0 and p_0 denote equilibrium.
- $n_i = 1.45 \times 10^{10}$ silicon atoms/cm^3
  - **see bottom of page 4 for an equation based on Temperature (useful for HW).**
- The number of atoms in the lattice (density) is about 4.995×10^{22} atoms/cm^3 which is much more than the number of electrons.

intrinsic

$n_i = p_i$

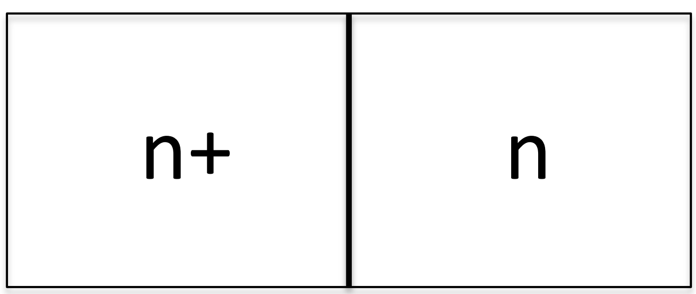
Dopants

- The key is to use the previous simplification and substitute the appropriate dopant (thermal equilibrium, room temperature, and non-degenerate).

$$n_0 \approx N_D \qquad\qquad p_0 \approx N_A$$

0 = At equilibrium

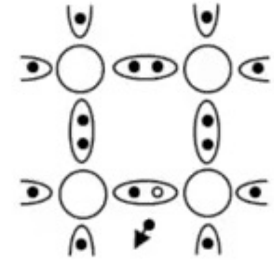
- Extrinsic semiconductors – has dopants or impurities that are introduced!
- One concentration is more than the other and one is called the majority carriers and conversely the minority carriers.
- If a doping concentration is very high (usually higher than 10^{19} cm^{-3}), then its typically called degenerate.



$$n_0 \cdot p_0 = n_i^2$$

Still holds at equilibrium!

Free Electrons and Holes



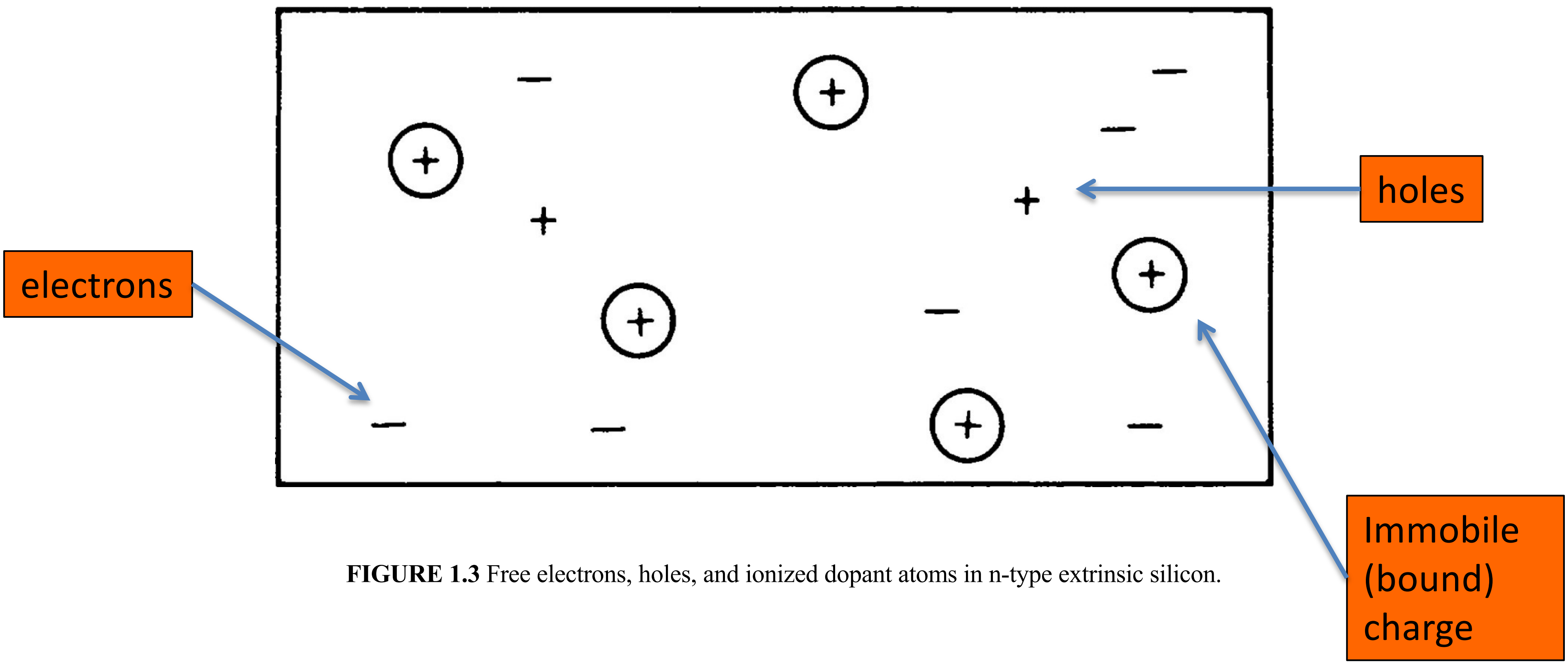
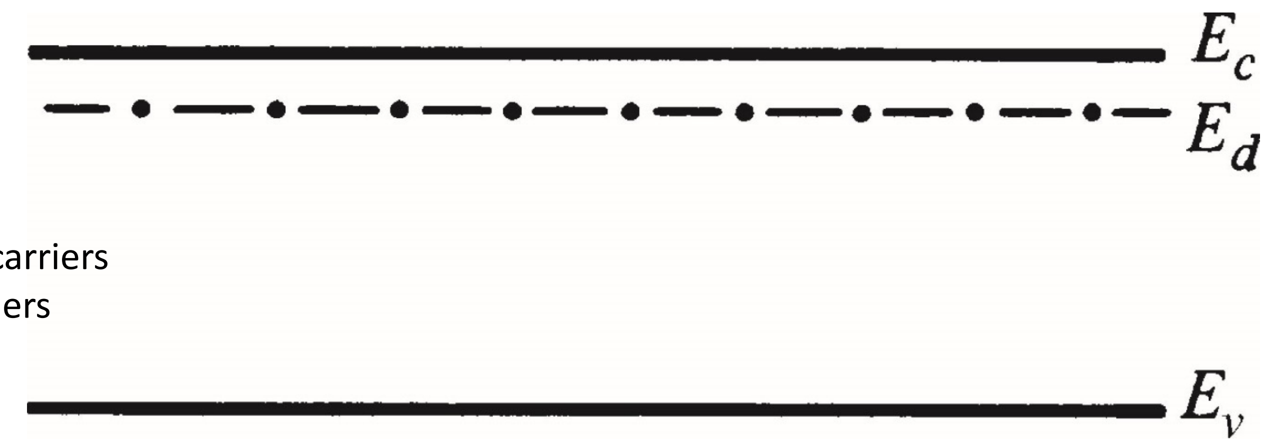


FIGURE 1.3 Free electrons, holes, and ionized dopant atoms in n-type extrinsic silicon.

Sometimes holes and electrons can intercept, and they are typically cancel each other and this phenomena is typically called recombination and plays an important role in LEDs and optical devices.

Semiconductor Energy Band (donors)



Electrons = majority carriers
Holes = minority carriers

$$n_0 \approx N_D$$

$$p_0 \approx \frac{n_i^2}{N_D}$$

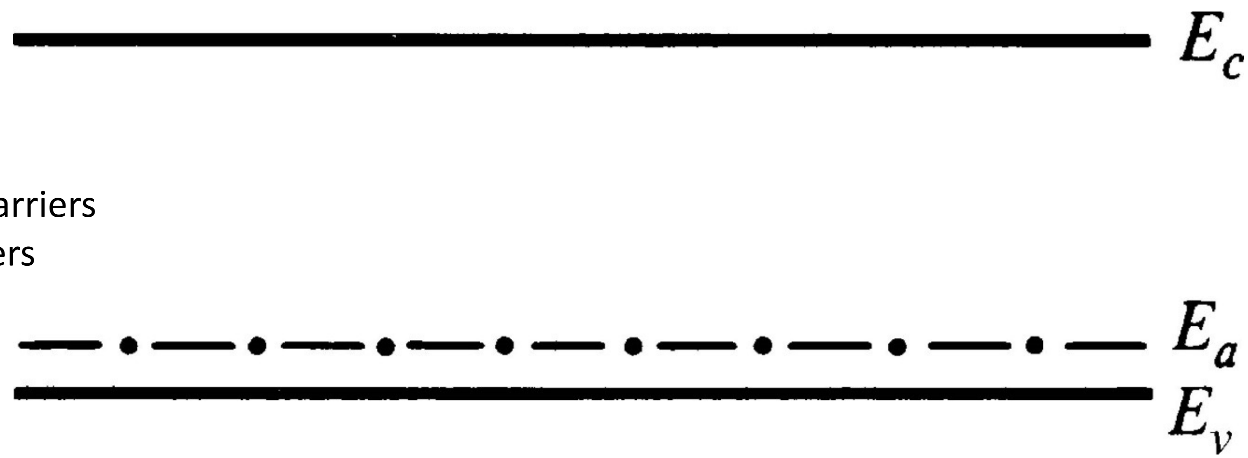
N_D : donor concentration

FIGURE 1.2 Energy band diagram for an n-type extrinsic semiconductor. Ed is the energy level corresponding to donor atoms.

n-type semiconductor – notice closeness of electrons to conduction band

Semiconductor Energy Band (acceptors)

Electrons = minority carriers
Holes = majority carriers



$$p_0 \approx N_A$$

$$n_0 \approx \frac{n_i^2}{N_A}$$

N_A : acceptor concentration

FIGURE 1.4 Energy band diagram for a p-type extrinsic semiconductor. Ea is the energy level corresponding to impurity atoms.

p-type semiconductor – notice closeness of electrons to valence band

The Enrico Brain

- There once was a famous physicist and his name was Enrico – supposedly he had a rapid-fire photographic memory.
- He and his colleague Paul Dirac contributed to the idea of the distribution of particles in certain systems.
  - Albert Einstein opposed many of these ideas, because they used statistics to derive how many elements were in a given distribution.
  - However, they *worked well* showing how certain electrons behave.
  - The key is that electrons and holes behave using Fermi-Dirac statistics, but semiconductors behave more like Maxwell-Boltzmann statistics for <u>non-degenerate</u> semiconductors.

Not Heavily Doped!

$$p_0 = n_i \cdot e^{(E_i - E_F)/_{k \cdot T}}$$

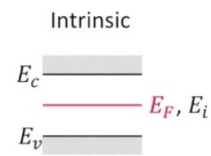
$$n_0 = n_i \cdot e^{(E_F - E_i)/_{k \cdot T}}$$

E_F : Fermi Level that characterizes the semiconductor which is different depending on dopant!

Differences between each other

- Intrinsic Semiconductors

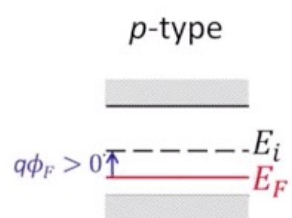
$$n_0 = p_0 = n_i$$



Change the way we look at simplified energy band diagram.

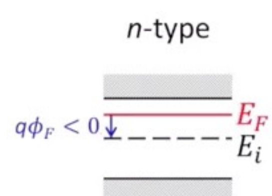
- P-type Semiconductors

$$E_F < E_i$$



- N-type Semiconductors

$$E_F > E_i$$



$$\phi_F \equiv \frac{E_i - E_F}{q}$$

Fermi Potential

Electron charge magnitude: $q = 1.602 \times 10^{-19}\ C$

Relative Energy Band Diagrams

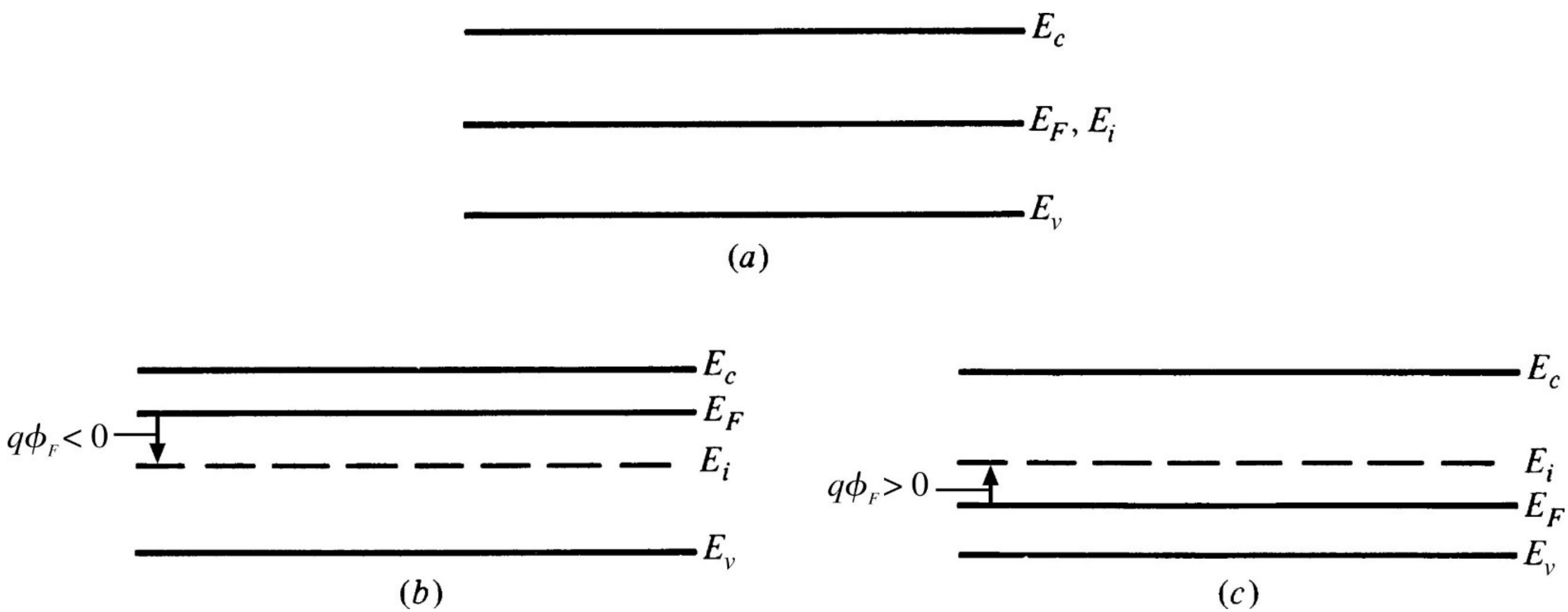


FIGURE 1.6 Relative position of intrinsic energy level (E_i) and Fermi energy (E_F) for (a) intrinsic, (b) n-type, and (c) p-type semiconductors.

For intrinsic semiconductors, $E_F = E_i$

Fermi Potential Dependences on Voltage

- In semiconductors, the relationship between the flow of electrical current and the electrostatic potential depends on a characteristic voltage called the thermal voltage.

$$p_0 = n_i \cdot e^{\phi_F / \phi_t}$$

$$n_0 = n_i \cdot e^{-\phi_F / \phi_t}$$

$$\phi_t = \frac{k \cdot T}{q}$$

Thermal Voltage

Key is that it characterizes the semiconductor material at a given temperature

$$\phi_F \approx +\phi_t \cdot \ln \frac{N_A}{n_i}$$

p-type semiconductor

$$\phi_F \approx -\phi_t \cdot \ln \frac{N_D}{n_i}$$

n-type semiconductor

page 9 – mark it!

- Boltzmann's constant: $k = 1.3807 \times 10^{-23} C \cdot \mathrm{V}/K$ (also $J \cdot K^{-1}$)
- See Wikipedia for other values: https://en.wikipedia.org/wiki/Boltzmann_constant

Fermi Potential vs. Doping

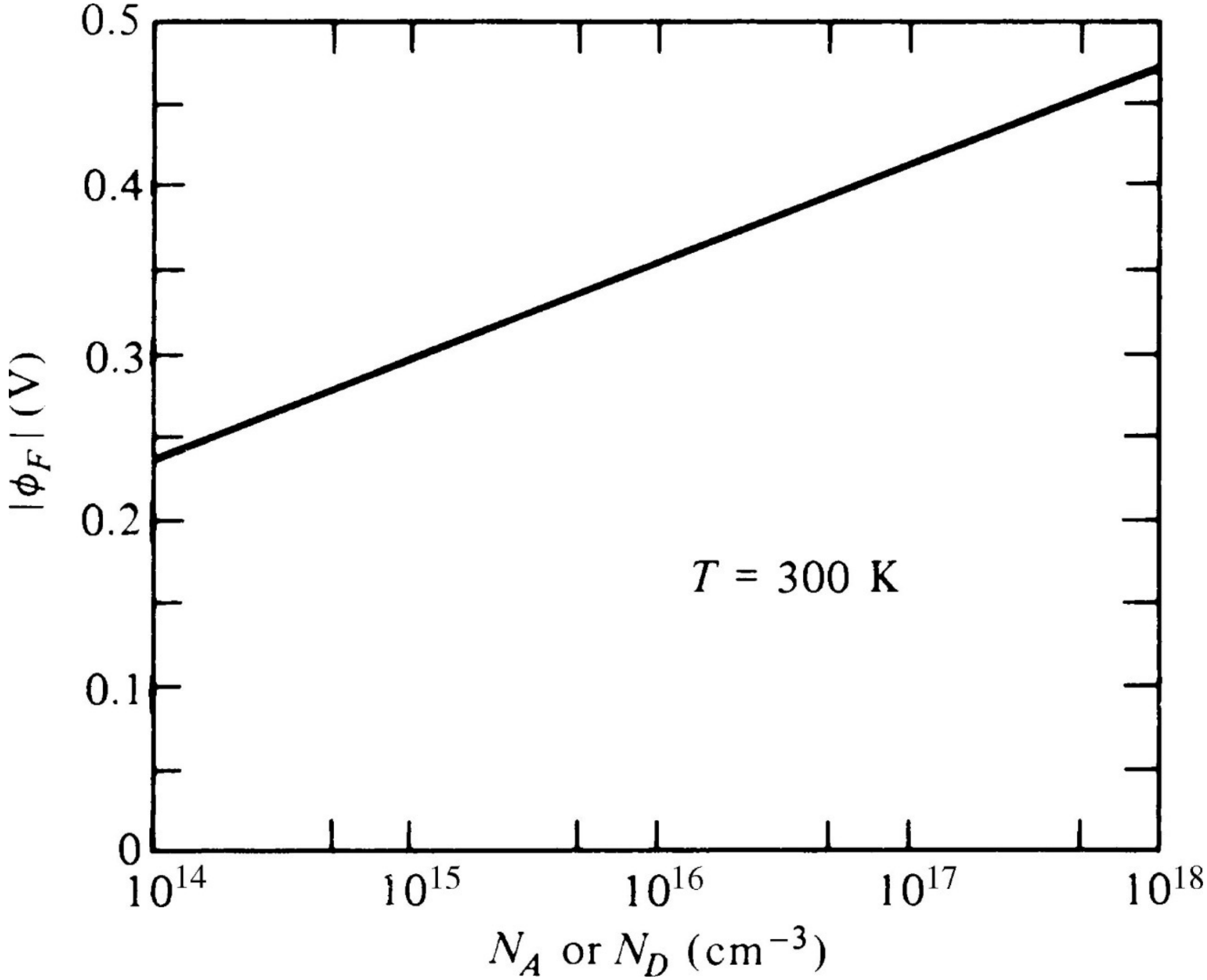
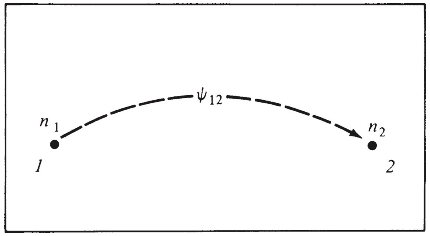


FIGURE 1.7 Magnitude of Fermi potential vs. substrate doping concentration for silicon at room temperature.

Equilibrium in the presences of Electric Field

- Although semiconductors have nice energies, they cannot go anywhere without a little energy pushed from one side to the other.
- The electrostatic potential between two points with different electron concentrations.

$$\Delta\psi = \frac{\Delta \mathrm{E_C}}{-q}$$



$$\frac{n_1}{n_2} = e^{\psi_{12}/\phi_t}$$

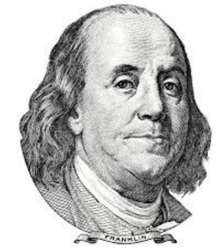
- The book looks at things through a 1-dimensional wall or on a line.
- $n \cdot p = n_i^2$ at each point! (NOTE: n_i varies with temperature – see pg. 4 of text and previous slide)
- Engineers borrowed this notation for positive values to be V_{DD} (drain) and negative values to be V_{SS} (source).
  - Positive = voltage (V_{DD})
  - Negative = ground reference (V_{SS} = GND)

$$\frac{p_1}{p_2} = e^{\psi_{21}/\phi_t}$$

ψ_{12}: electric potential from point 1 to point 2

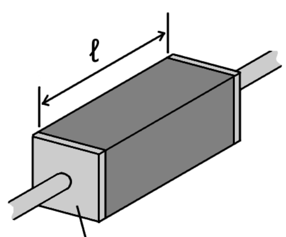
What is resistivity of Silicon?

Conduction

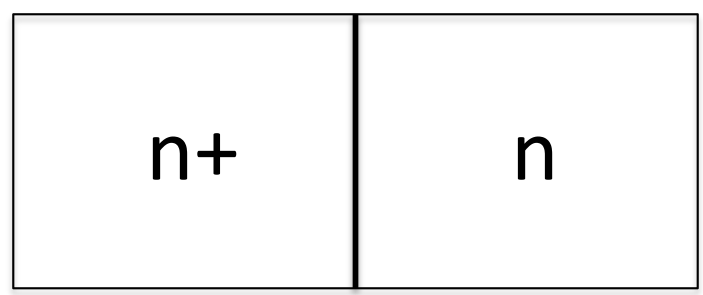


- The best type of electricity is through a conductor (small ρ or large σ)!
- So, if you want to conduct electricity you should use a metal that is highly conductive (e.g., copper $\rho = 16.78 \times 10^{-9} \quad \Omega \cdot m$ @20℃).
  - However, semiconductors are not great conductors (they are in between -- thus, the name semi-)
  - Unfortunately, it is harder to create metal-semiconductor junctions (not difficult).
- Engineers cheat (get used to it -- but not, on assignments/tests) to make simpler devices
- So, they use highly-doped contacts to get the current flowing linearly (this is called an ohmic contact!)

$$\rho = \frac{1}{\sigma} = R \cdot \frac{A}{l}$$

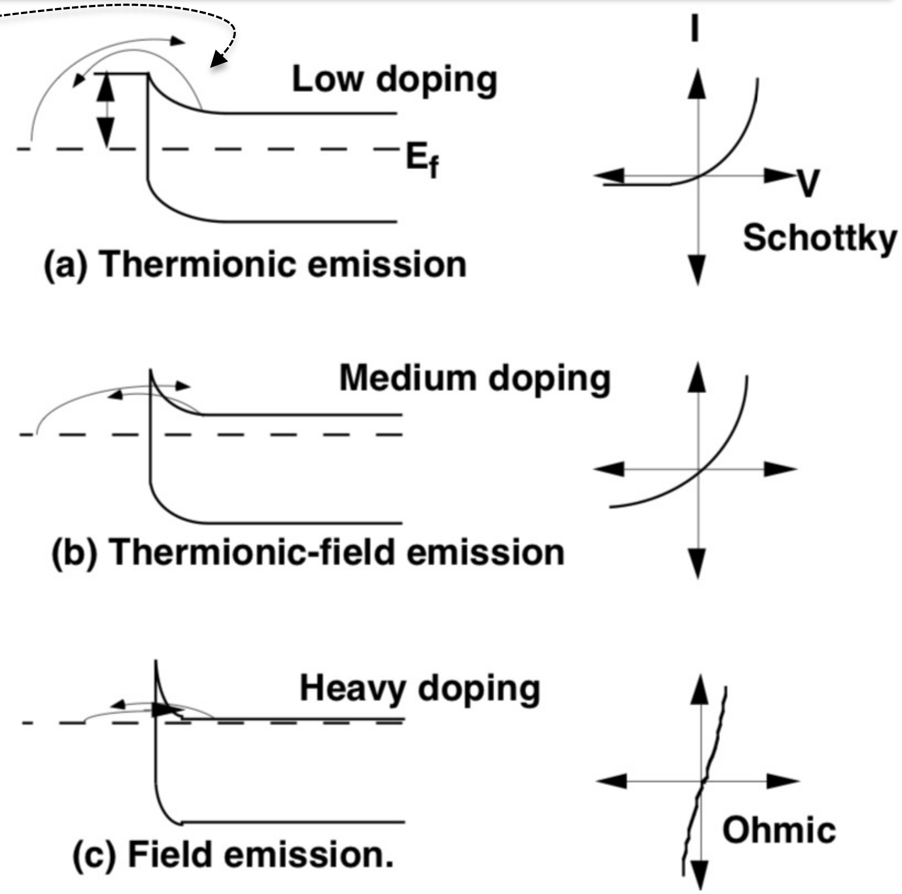


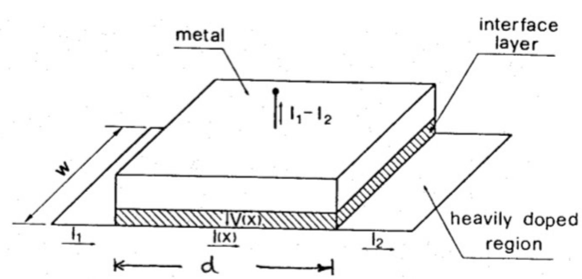
[Wikipedia]



Ohmic Contacts

- Contact resistance (ρ_c) is a measure of the ease with which current can flow across a metal- semiconductor interface.
- In an ohmic interface, the total current density J entering the interface is a function of the difference in the equilibrium Fermi levels on the two sides.
- Contact resistance is important for connecting to a pin.

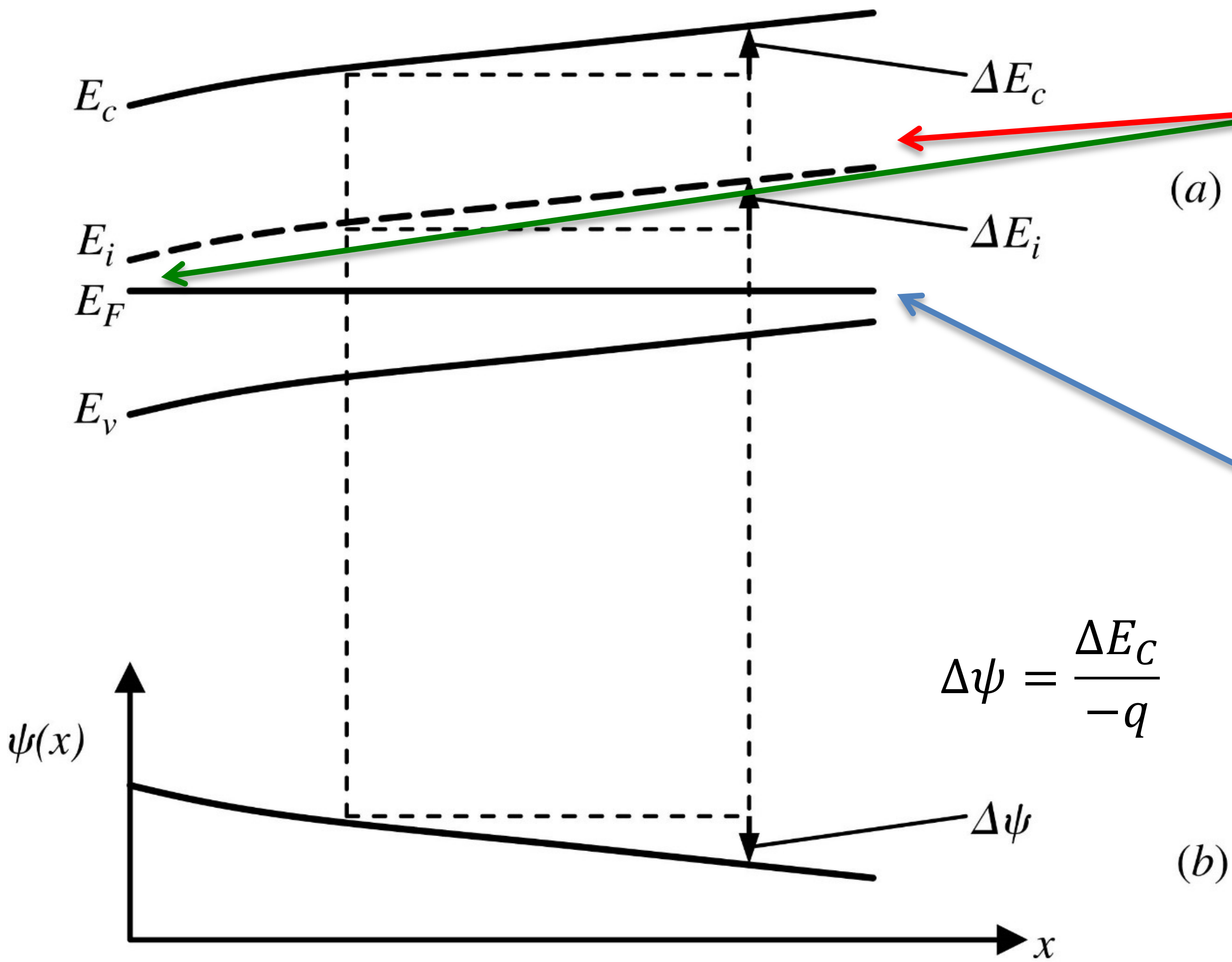




Reminder: EE/CpEs use band diagrams to help aid in describing behavior!

[Saraswat/Stanford]

Equilibrium in the presence of Electric Field (no energy exchange with external world; no current flow)



Energy changes based on the intrinsic Energy, E_i

In <u>equilibrium</u>, Fermi Energy always stays constant!

$$\Delta\psi = \frac{\Delta E_C}{-q}$$

Energy Band Bending

Bend in order to accommodate presence of electric potentials.

FIGURE 1.8 Semiconductor in equilibrium in the presence of electric field; (a) energy band diagram; (b) potential.

Voltage <u>always</u> starts and ends with Poisson Equation

- We know two things from what we have shown today:
  - Doping can change concentration of Energy within a semiconductor to either give off electrons or keep them per holes.
  - Voltages can change Energy across the device.
- Our goal is to see how to get this into action for current!
- Four values can contribute to charge concentration per volume
  - Holes $(+q \cdot p)$
  - Free electronics $(-q \cdot n)$
  - Ionized donor atoms $(+q \cdot N_D)$
  - Ionized acceptor atoms $(-q \cdot N_A)$

$$\rho = q \cdot (p - n + N_D - N_A)$$

$$\frac{d^2\psi}{dy^2} = -\frac{\rho(y)}{\varepsilon_s}$$

Current

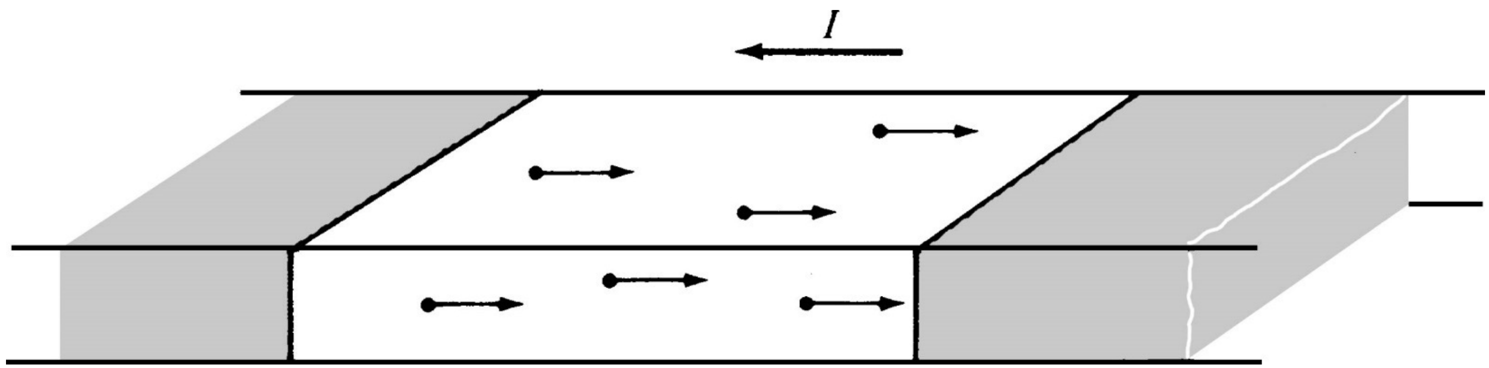


FIGURE 1.10 A piece of material with electrons flowing toward the right.

- Again, our goal is getting current moving in this device (conduction).
  - In our case, they are Field Effect Transistors
- Semiconductors are key to getting the current moving along with a little input Voltage.
- Current will always be composed of two parts to approximate the total current:
  - drift + diffusion

The Big Picture

- Integrated Circuits are printed like picture on huge masks.
- According to Forbes Magazine (February 26, 1996) fabrications facilities cost about $500 million to $1.5 billion US dollars.
  - Many “fabs” share facilities to help improve their innovation and then have separate rooms to keep items secret.
  - Some companies have special R&D fabs to help innovate new ideas (e.g., Intel).
- Key activities in semiconductor technology simulation (often referred to as TCAD) are process and device simulation helping reducing this cost.
- Many field get together to fabricate IC's: chemistry, biology, physics, engineering, economics, mathematics, etc.

Global Foundries 7nm/5nm plant in Saratoga Country, NY

CHIPS Act

- The CHIPS and Science Act is a U.S. federal statute enacted by the 117th United States Congress and signed into law by President Joe Biden on August 9, 2022.
- The act provides roughly $280 billion in new funding to boost domestic research and manufacturing of semiconductors in the United States.
- There is still a lot of unknowns in the CHIPS act, however, semiconductors are an important element of our society and your future!
- Who remembers when they first heard the iPhone and what it did?
- How does the Internet impact you?
  - Many would be lost without the Internet – semiconductors drive the Internet!

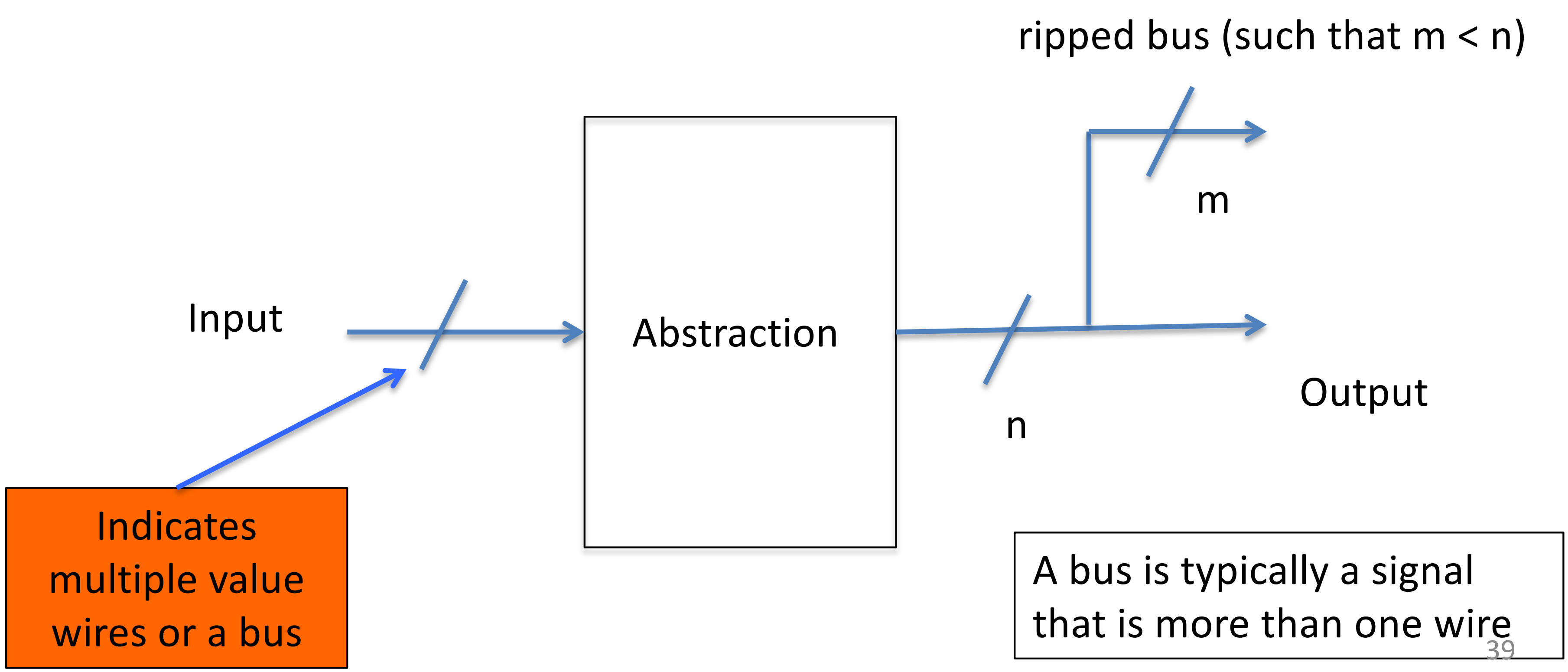
https://www.whitehouse.gov/briefing-room/statements-releases/2022/08/09/fact-sheet-chips-and-science-act-will-lower-costs-create-jobs-strengthen-supply-chains-and-counter-china/

To Abstract or not to Abstract

- VLSI Design is about the process of getting the idea from one level of thought to another
- This level of thought is called abstraction
- abstraction ≡ indicates that something is left out of a description or definition
  - For example, if I say an animal that meows and a cat. Both are abstractions for the same thing.
  - If I am reasonably going to be sane by the time next year, I have to utilize this abstraction to simplify the design problem in VLSI.
  - Need to ensure abstractions represent both the same element i.e., I need constraints!
- To implement the constraints, you need to understand the basics of the underlying technology

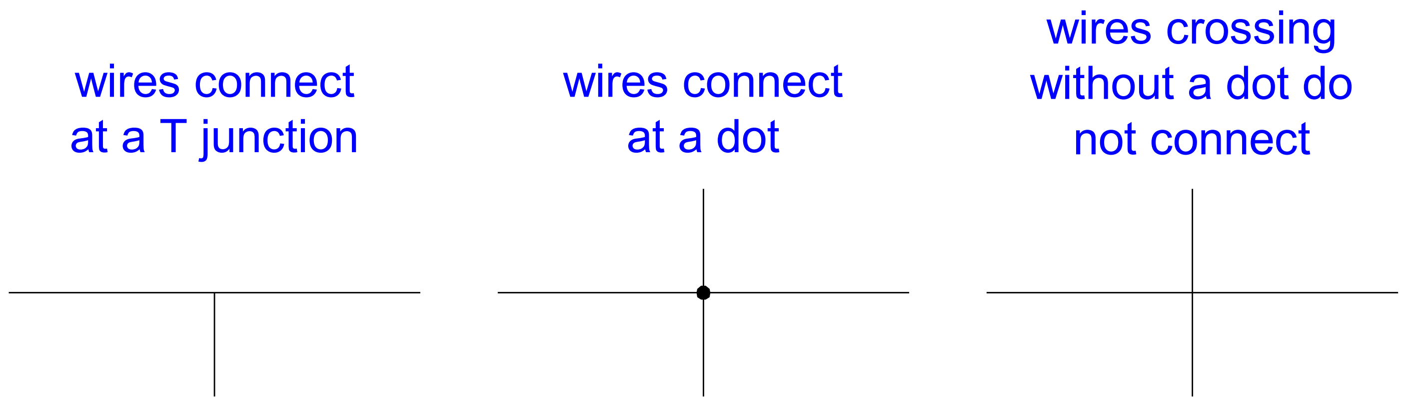
How to Deal with 10^7 transistors and still make a day of it!

- Constraint the design space to simplify the design process
- Strike a balance between design complexity and absolute performance
- Utilize **hierarchy** to break items apart (box with pins)



Circuit Schematic Rules

- Wires always connect at a T junction
- A dot where wires cross indicates a connection between the wires
- Wires crossing *without* a dot make no connection
- Some tools will use a dot for their connection to avoid ambiguity.



Some Abstraction Levels

- Digital Abstraction
  - Signals are 0 or 1.
- Switch Abstraction
  - FETs are simple switches
- Gate Abstraction
  - Unidirectional elements: not, and, or, ….
  - Separable timing structure

The Power of Abstraction

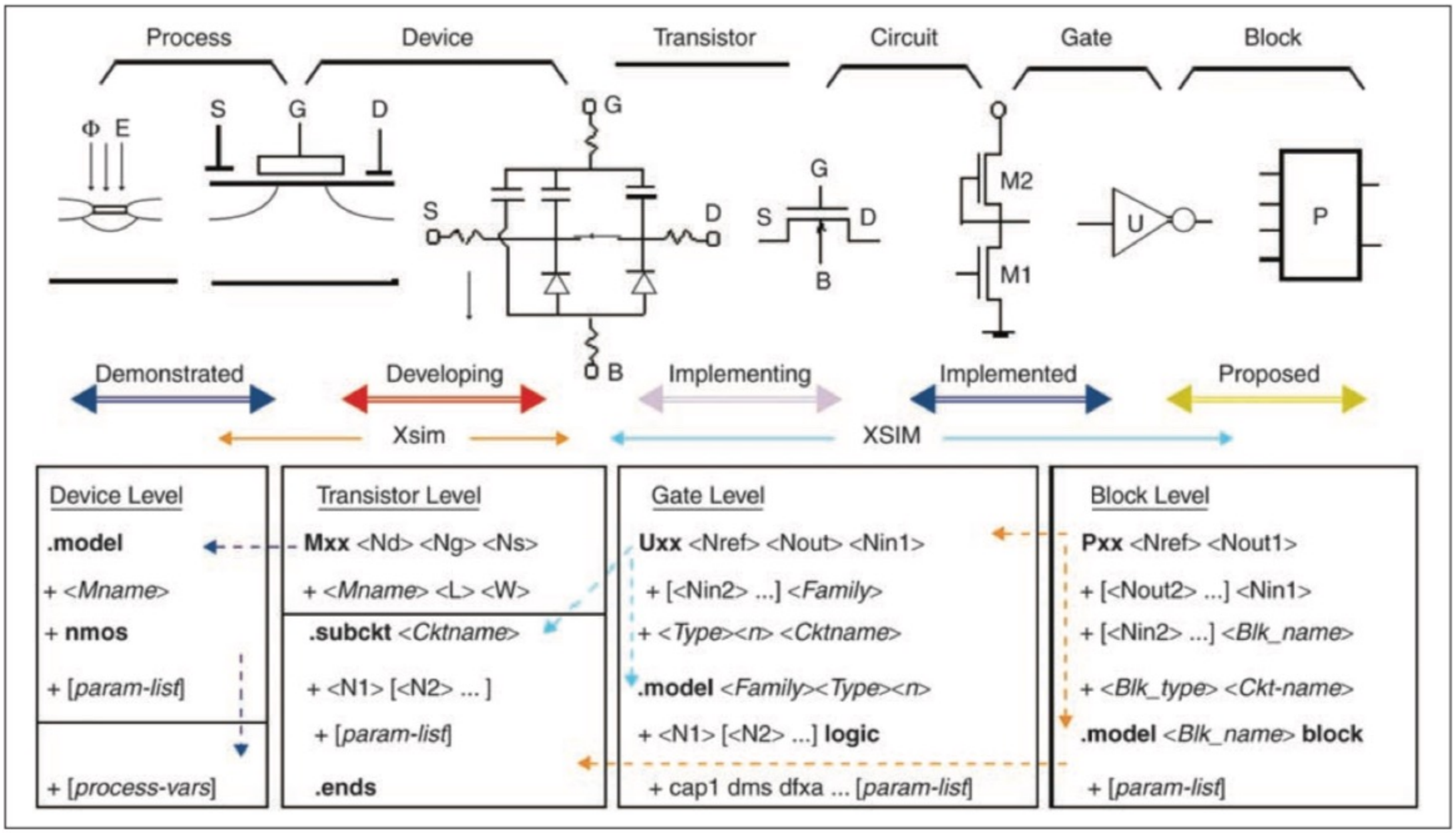
- Levels of transformation create abstractions
  - Abstraction: A higher level only needs to know about the interface to the lower level, not how the lower level is implemented
  - e.g., high-level language programmer does not really need to know what the Instruction Set Architecture (ISA) is and how a computer executes instructions
- Abstraction improves productivity
  - No need to worry about decisions made in underlying levels
  - e.g., programming in Java vs. C vs. assembly vs. binary vs. by specifying control signals of each transistor every cycle
- Then, why would you want to know what goes on underneath or above?

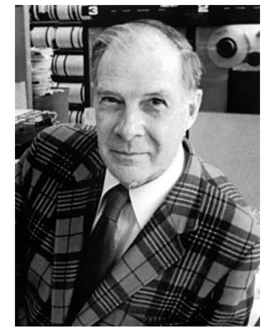
Crossing the Abstraction Layers

- As long as everything goes well, not knowing what happens in the underlying level (or above) is not a problem.
- What if
  - The program you wrote is running slow?
  - The program you wrote does not run correctly?
  - The program you wrote consumes too much energy?
- What if
  - The hardware you designed is too hard to program?
  - The hardware you designed is too slow because it does not provide the right primitives to the software?

Levels of Transformation

"The purpose of computing is insight, not numbers" : We gain and generate insight by solving problems





Richard Hamming [1915-1998]

[Zhou, 2003]

Design Levels in Decreasing Order

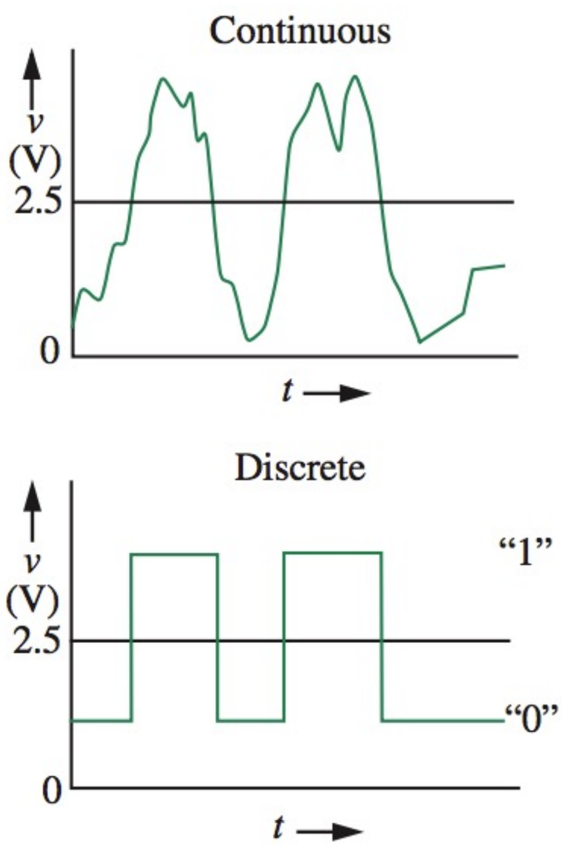
- Specification
  - What the system (or component) is supposed to do.
- Architecture
  - High-level design component where logic is partitioned into major blocks (e.g. ALU).
- Logic
  - Gates, flip-flops, and the connection between them
- Circuit
  - Transistor circuits to realize logic elements
- Device
  - Behavior of individual circuit elements
- Layout
  - Geometry used to define and connect circuit elements.
- Process
  - Steps used to define circuit elements.

We still do not know how to go from one level to another well!

Digital Levels

- Instead of worrying about specific Voltage levels, it would be easier to have certain levels. If a Voltage level falls somewhere in this level, it is either a Logic 0 or Logic 1.
  - Allows us to compute the output only for inputs in the allowable range.
  - Very simple and notice we only talk about voltage.
  - Model transistor as being conducting or non-conducting:
    - Aha!!! a switch!
  - However, always make sure voltage is somewhere in one of the two allowable ranges.
    - Otherwise, the voltage level is not valid.
  - Would also be nice to be able to make levels restore if they fall somewhere in the middle of the allowable range.
  - This makes the abstraction on the digital value of 0 or 1.

Discretization of Signals



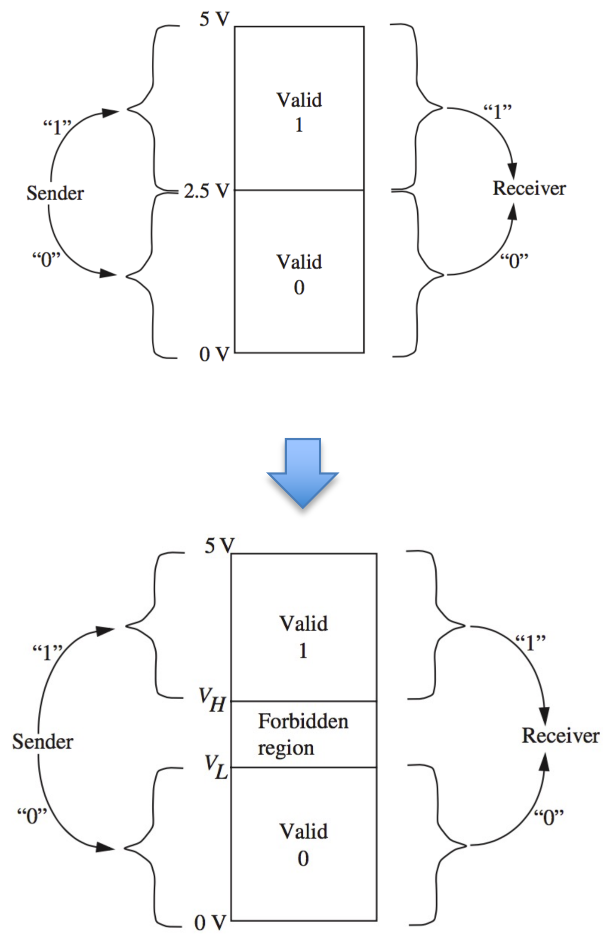
[Agarwal/Lang]

FIGURE 1.45 Voltage value discretization into two levels.

- **<u>All</u>** signals are analog!!!
  - Digital is overdriven analog!
- Discrete signals offer better noise immunity than analog signals, but they do so at the expense of precision.
  - If the noise that corrupts a discrete signal does not move its physical value past a discretization threshold, then the noise will be ignored.
  - Value discretization forms the basis of the *digital abstraction*.

Voltage Levels and Static Discipline

- The *static discipline* is a specification for digital devices.
- The static discipline requires devices to adhere to a common representation, and to guarantee that they interpret correctly inputs that are valid logical signals according to the common representation, and to produce outputs that are valid logical signals provided they receive valid logical inputs.
- Forbidden regions are added to help avoid problems due to confusion of signals or possibly noise mixing with a signal.



[Agarwal/Lang]