Diodes: Physical Operation and Models

Lecture 23, 10/24/05

OUTLINE

- Basic Semiconductor Materials
- Diode Current and Equation
- Some Interesting Circuit Applications

Reading

Hambley 10.1-Skim 10.2-10.7

Motivation for Last 7 Weeks

Digital Circuits, Logic, D/A, etc

① We need a "smart switch," i.e., an electronically controlled switch

② We need a "gain element" – for example, to make comparators.

The device of our dreams exists ! ⇒ **MOS transistor**

- a terrific switch
- low power
- smart

BONUS: MOS is very simple in concept

This week: Basic Semiconductors, Diodes and Diode Uses

Next week: MOS Transistors

Game Plan for Last 6 Weeks

Topical Flow:

1. **Learn a little more about semiconductors and pn junction diodes**
2. **Consider the I vs. V model of diodes and their uses in circuits**
3. **Learn about MOSFET Operation as a voltage controlled resistor whose current saturates**
4. **Quiz #2 Wed Nov 2nd: Phasors Analysis, Frequency Response**
5. **Computer Logic Circuits: Inverter, Gates,**
6. **Midterm #2 Wed Nov 9th: Phasors Analysis, Frequency Response, Diode Circuits**
7. **Computer Logic Circuits: Delays, latches and Clocks**
8. **Circuit Analysis: Transient plus Sinusoidal, 2nd Order Transients**
9. **Microfabrication and Nano Technology**

Thus we begin with a very brief review of semiconductors and doping

Conductors, Insulators and Semiconductors

Solids with "free electrons" – that is electrons not directly involved in the inter-atomic bonding- are the familiar metals (Cu, Al, Fe, Au, etc).

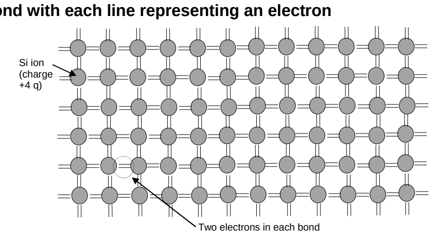
Solids with no free electrons are the familiar insulators (glass, quartz crystals, ceramics, etc.)

Silicon is an insulator, but at higher temperatures some of the bonding electrons can get free and make it a little conducting – hence the term "semiconductor"

***Pure* silicon is a poor conductor (and a poor insulator). It has 4 valence electrons, all of which are needed to bond with nearest neighbors. No free electrons.**

Electronic Bonds in Silicon

2-D picture of perfect crystal of pure silicon; double line is a Si-Si bond with each line representing an electron



Actual structure is 3-dimensional tetrahedral- just like carbon bonding in organic and inorganic materials.

Essentially no free electrons, and no conduction → insulator

How to get conduction in Si?

We must either:

1) Chemically modify the Si to produce free carriers (permanent) or

2) Electrically "induce" them by the field effect (switchable)

For the first approach controlled impurities, "dopants", are added to Si:

Add group V elements (5 bonding electrons vs four for Si), such as phosphorus or arsenic
(Extra electrons produce "free electrons" for conduction.)

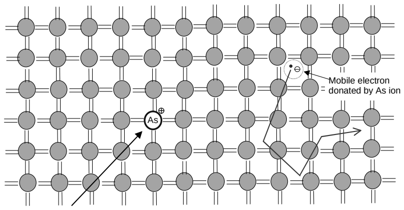
or

Add group III elements (3 bonding electrons), such as boron
Deficiency of electrons results in "free holes"

Doping Silicon with Donors (n-type)

Donors donate mobile electrons (and thus "n-type" silicon)

Example: add arsenic (As) to the silicon crystal:



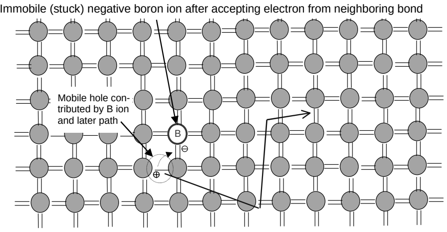
Immobile (stuck) positively charged arsenic ion after 5th electron left

The extra electron with As, "breaks free" and becomes a free electron for conduction

Doping with Acceptors (p-type)

Group III element (boron, typically) is added to the crystal

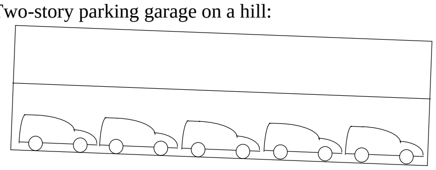
Immobile (stuck) negative boron ion after accepting electron from neighboring bond



The "hole" which is a missing bonding electron, breaks free from the B acceptor and becomes a roaming positive charge, free to carry current in the semiconductor. It is positively charged.

Shockley's Parking Garage Analogy for Conduction in Si

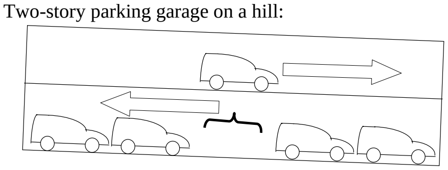
Two-story parking garage on a hill:



If the lower floor is full and top one is empty, no traffic is possible. Analog of an insulator. All electrons are locked up.

Shockley's Parking Garage Analogy for Conduction in Si

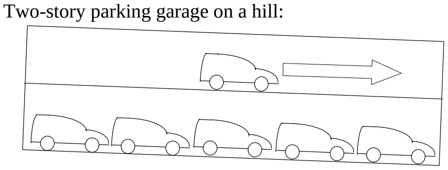
Two-story parking garage on a hill:



If one car is moved upstairs, it can move AND THE HOLE ON THE LOWER FLOOR CAN MOVE. Conduction is possible. Analog to warmed-up semiconductor. Some electrons get free (and leave "holes" behind).

Shockley's Parking Garage Analogy for Conduction in Si

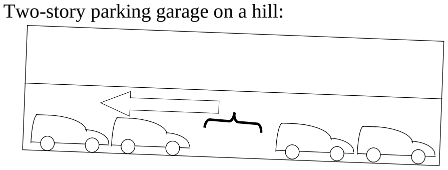
Two-story parking garage on a hill:



If an extra car is "donated" to the upper floor, it can move. Conduction is possible. *Analog to N-type semiconductor.* (An electron donor is added to the crystal, creating free electrons).

Shockley's Parking Garage Analogy for Conduction in Si

Two-story parking garage on a hill:



If a car is removed from the lower floor, it leaves a HOLE which can move. Conduction is possible. *Analog to P-type semiconductor.* (Acceptors are added to the crystal, "consuming" bonding electrons,creating free holes).

Summary of n- and p-type silicon

Pure silicon is an insulator. At high temperatures it conducts weakly.

If we add an impurity with extra electrons (e.g. arsenic, phosphorus) these extra electrons are set free and we have a pretty good conductor (n-type silicon).

If we add an impurity with a deficit of electrons (e.g. boron) then bonding electrons are missing (holes), and the resulting holes can move around … again a pretty good conductor (p-type silicon)

Now what is really interesting is when we join n-type and p-type silicon, that is make a pn junction. It has interesting electrical properties.

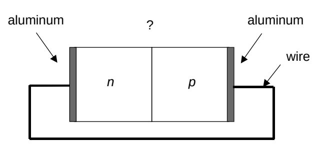
Junctions of n- and p-type Regions

p-n junctions form the essential basis of all semiconductor devices.

A silicon chip may have 10^8 to 10^9 p-n junctions today.

How do they behave*? What happens to the electrons and holes? What is the electrical circuit model for such junctions?

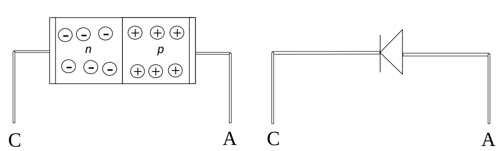
***n* and *p* regions are brought into contact :**



*Note that the textbook has a very good explanation.

A pn junction is formed - what happens?

The structure and the circuit symbol are shown below:

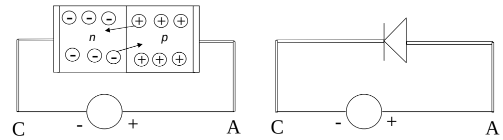


The electrons are depicted as ⊖. Note that the n-type silicon is actually electrically neutral, but we emphasize the “free” electrons..

The holes in the p-type silicon are depicted as ⊕. Again, the material is electrically neutral.

A pn junction is formed - what happens?

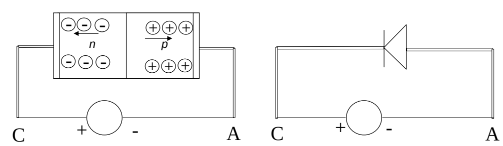
Forward bias (positive on the p-side):



This is the direction of easy current flow. + charges flow to meet up with – charges. Essentially unlimited conduction.

A pn junction is formed - what happens?

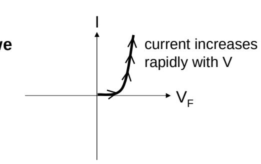
Reverse bias (positive on the n-side):



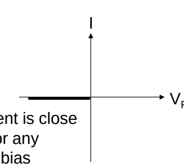
This is the direction of almost zero current flow. The + charges are just pulled away from the junction, and so are the - charges. Essentially zero conduction.

I-V Characteristics

In forward bias (+ on p-side) we have almost unlimited flow (very low resistance). Qualitatively, the I-V characteristics must look like:



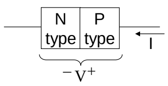
In reverse bias (+ on n-side) almost no current can flow. Qualitatively, the I-V characteristics must look like:



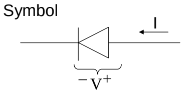
The current is close to zero for any negative bias

Diode Physical Behavior and Equation

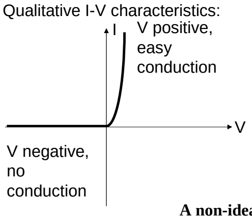
Schematic Device



Symbol



Qualitative I-V characteristics:



Quantitative I-V characteristics:

$$I = I_0(e^{qV/kT} - 1)$$

In which kT/q is 0.026V and I_O is a constant depending on diode area. Typical values: 10^{-12} to 10^{-16} A. Interestingly, the graph of this equation looks just like the figure to the left.

A non-ideality factor n times kT/q is often included.

The pn Junction I vs. V Equation

I-V characteristic of PN junctions

In EECS 105, 130, and other courses you will learn why the I vs. V relationship for PN junctions is of the form

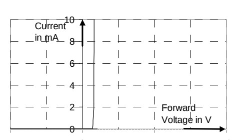
$$\boxed{I = I_0(e^{qV/kT} - 1)}$$

where I_0 is a constant proportional to junction area and depending on doping in P and N regions, $q = \text{electronic charge} = 1.6 \times 10^{-19}$, k is Boltzman constant, and T is absolute temperature.
$KT/q = 0.026\text{V at} 300°\text{K}$, a typical value for I_0 is $10^{-12} - 10^{-15}$ A

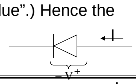
We note that in forward bias, I increases **exponentially** and is in the μA-mA range for voltages typically in the range of 0.6-0.8V. In reverse bias, the current is essentially zero.

Diode Ideal (Perfect Rectifier) Model

The equation $I = I_0 \exp(qV/kT - 1)$ is graphed below for $I_0 = 10^{-15}$ A

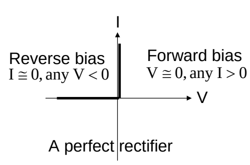


The characteristic is described as a "rectifier" – that is, a device that permits current to pass in only one direction. (The hydraulic analog is a "check value".) Hence the symbol:

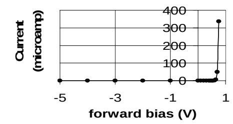


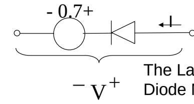
Simple "Perfect Rectifier" Model

If we can ignore the small forward-bias voltage drop of a diode, a simple effective model is the "perfect rectifier," whose I-V characteristic is given below:



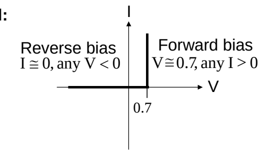
Diode Large-Signal Model (0.7 V Drop)





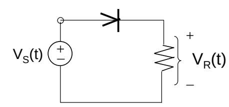
The Large-Signal Diode Model

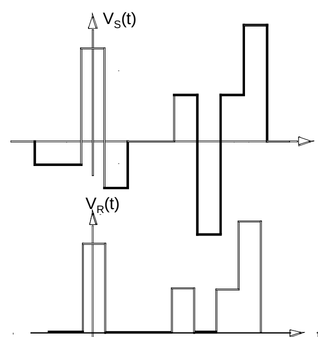
Improved "Large-Signal Diode" Model:
If we choose not to ignore the small forward-bias voltage drop of a diode, it is a very good approximation to regard the voltage drop in forward bias as a constant, about 0.7V. the "Large signal model" results.



Cool Things That a Diode Can Do: Rectifier

Assume the ideal (perfect rectifier) model.

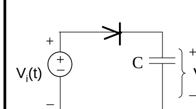


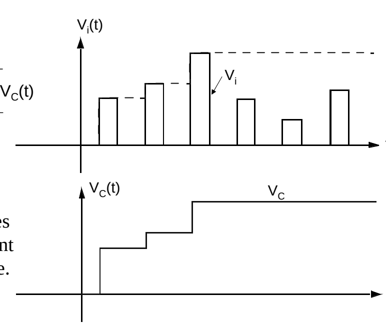


"rectified" version of input waveform

Cool Things That a Diode Can Do: Peak Detector

Assume the ideal (perfect rectifier) model.





Key Point:
The capacitor charges due to one way current behavior of the diode.