Lecture 6

Semiconductors and diodes

Early History of IC Devices

1940's: Vacuum-tube era

Vacuum tubes were used for radios, television, telephone equipment, and computers

… but they were expensive, bulky, fragile, and energy-hungry

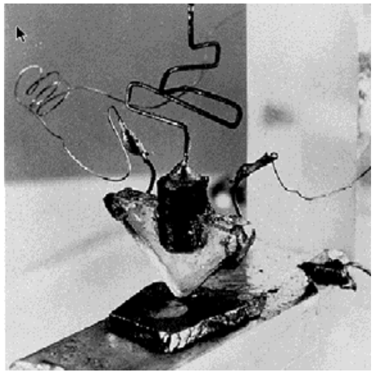
ENIAC-The first digital computer

→ Invention of the point-contact transistor

- **Walter Brattain, John Bardeen, and William Shockley, *Bell Labs*, 1947**

Nobel Prize in Physics 1956

– reproducibility was an issue, however



→ Invention of the bipolar junction transistor (BJT)

- **William Shockley, *Bell Labs*, 1950**

– more stable and reliable; easier and cheaper to make

Discrete Electronic Circuits

- In 1954, *Texas Instruments* produced the first commercial silicon transistor.

~$2.50 each

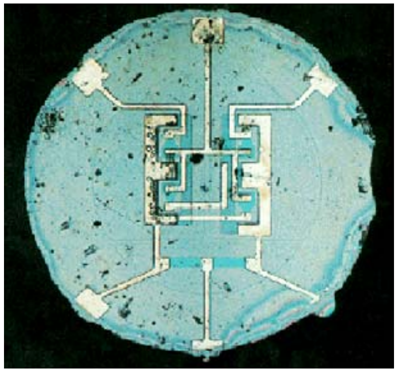
- Before the invention of the integrated circuit, electronic equipment was composed of discrete components such as transistors, resistors, and capacitors. These components, often simply called “discretes”, were manufactured separately and were wired or soldered together onto circuit boards. Discretes took up a lot of room and were expensive and cumbersome to assemble, so engineers began, in the mid-1950s, to search for a simpler approach…

The Integrated Circuit (IC)

- An IC consists of interconnected electronic components in a single piece (“chip”) of semiconductor material.

  – **In 1958, Jack S. Kilby (Texas Instruments) showed that it was possible to fabricate a simple IC in germanium.**

  – **In 1959, Robert Noyce (Fairchild Semiconductor) demonstrated an IC made in silicon using SiO_2 as the insulator and Al for the metallic interconnects.**



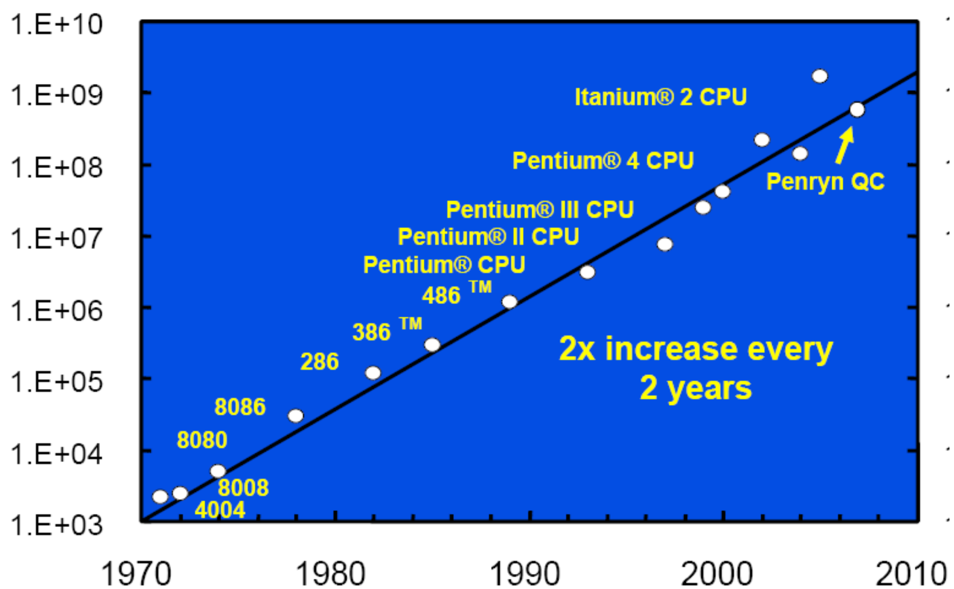
The first planar IC (actual size: ~1.5mm diameter)

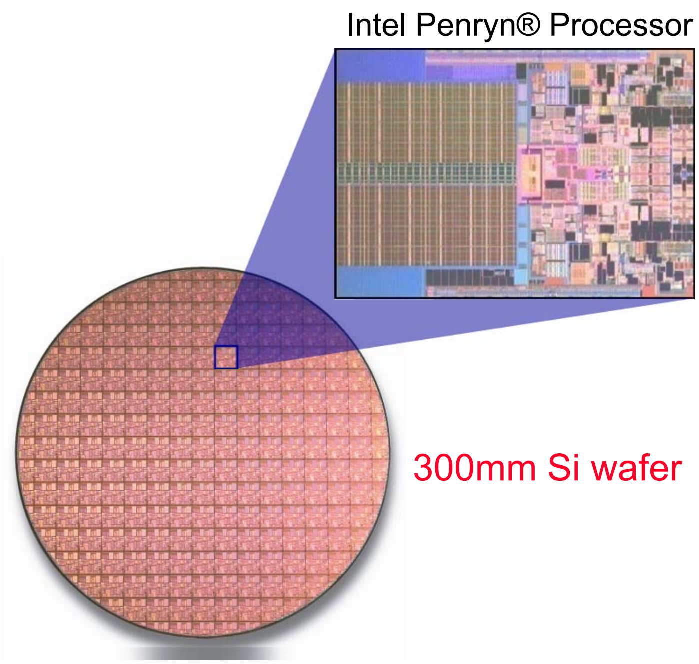
From a Few, to Billions of Components

- By connecting a large number of components, each performing simple operations, an IC that performs complex tasks can be built.

- The degree of integration has increased at an exponential pace over the past ~40 years.
  - The number of devices on a chip doubles every ~2 years, for the same price.

"Moore's Law" still holds today.





The Silicon Revolution

- Steady progress in integrated-circuit technology over 40+ years has had dramatic impact on the way people live, work, and play.
- The semiconductor industry is approaching $300B/yr in sales:


Military
2%


Computers
42%

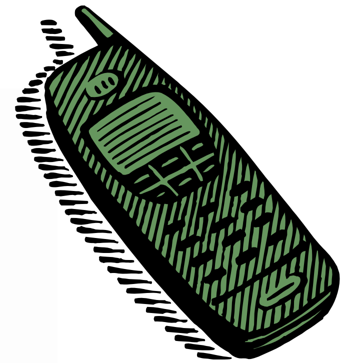
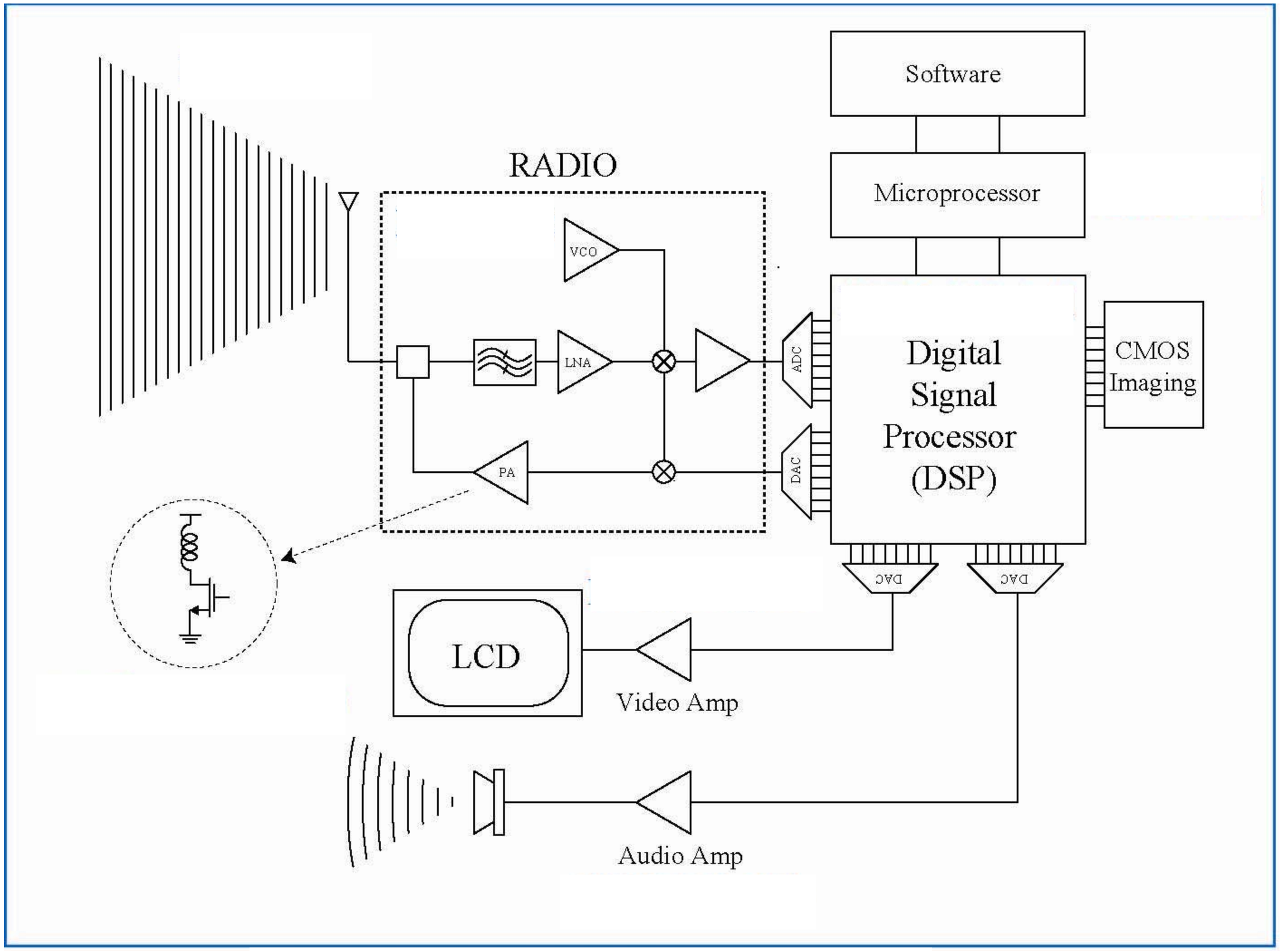

Communications
24%


Industrial
8%


Transportation
8%

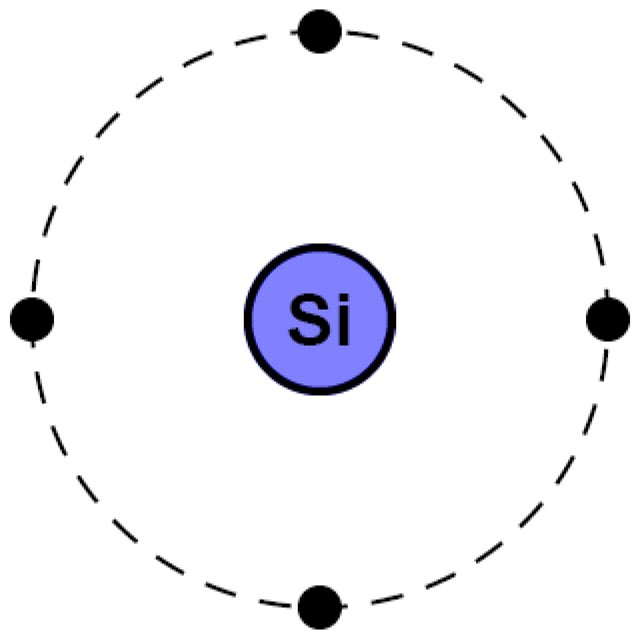

Consumer Electronics
16%

- Example electronic system: cell phone

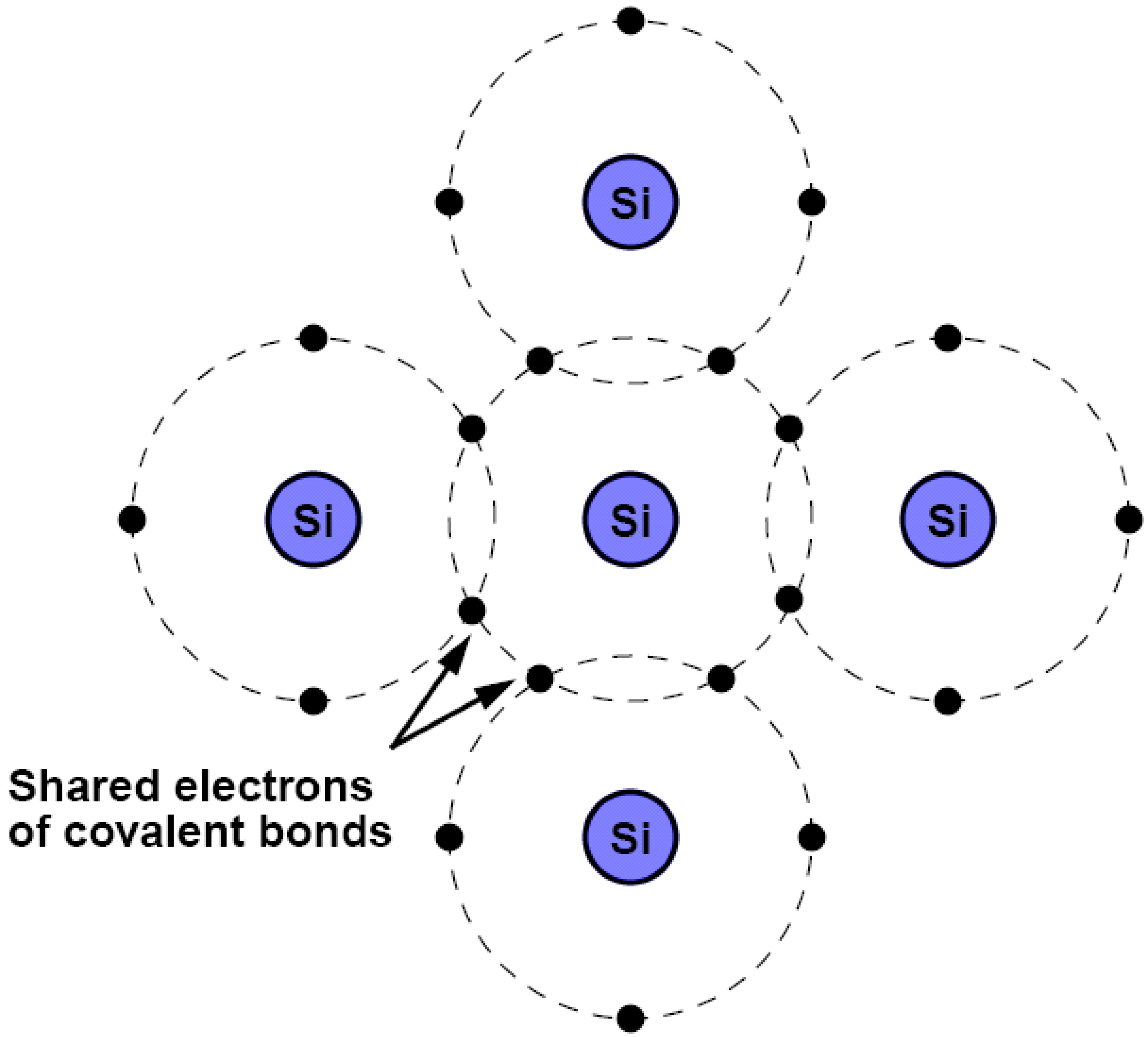
Semiconductor devices are the building blocks for various functional electronic components and systems.

Looking at Silicon

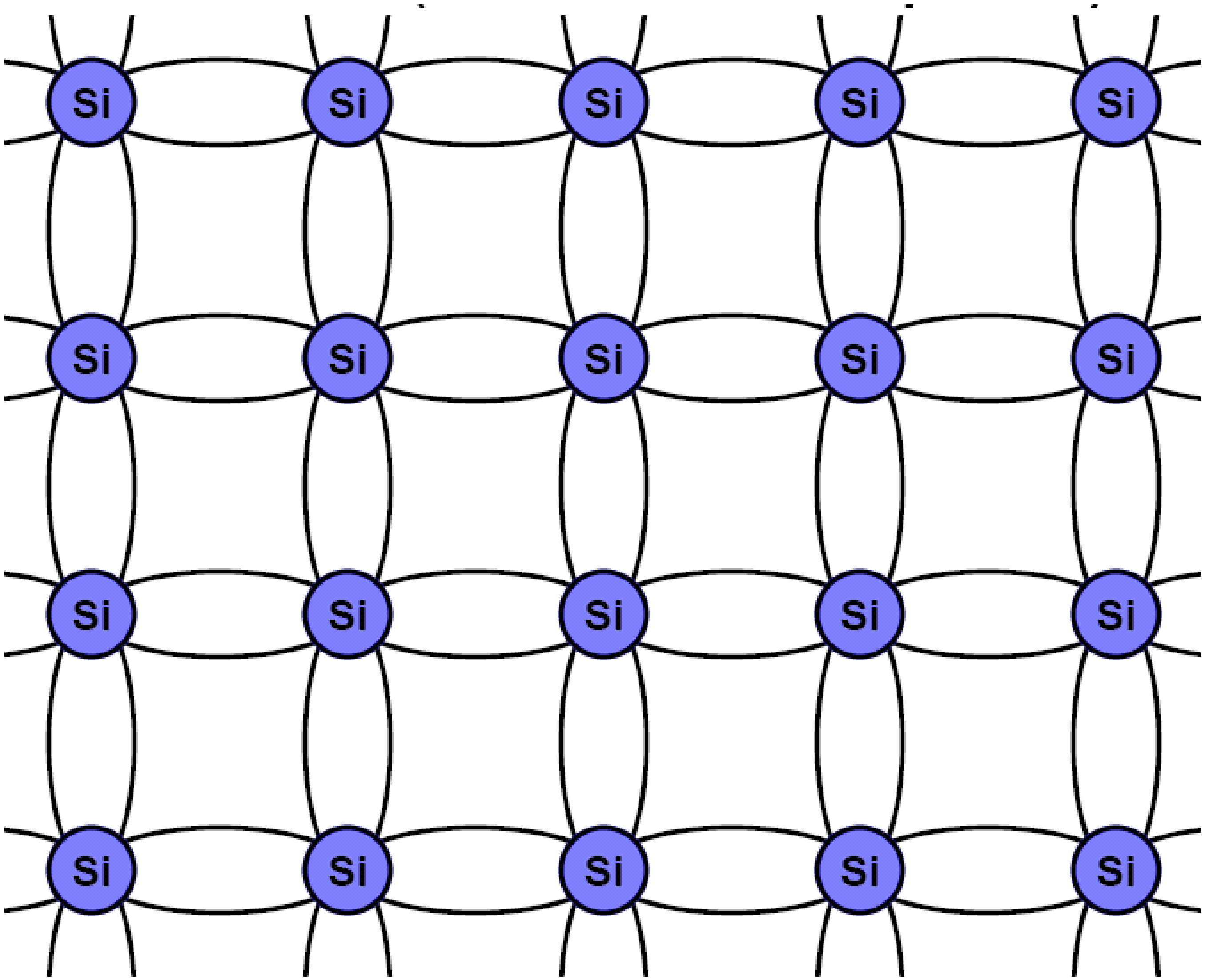


14 protons in nucleus
4 valence electrons

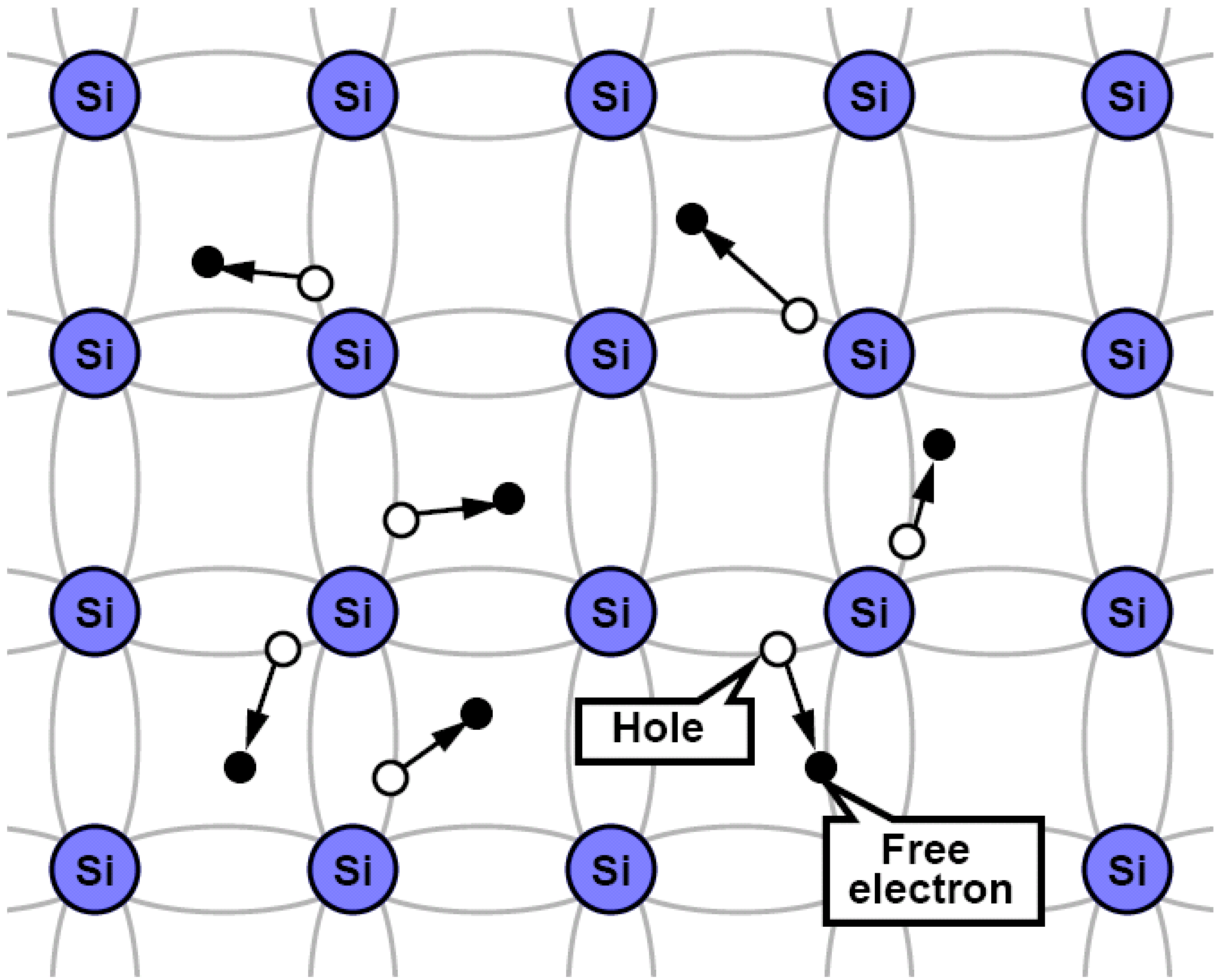
Looking at Silicon



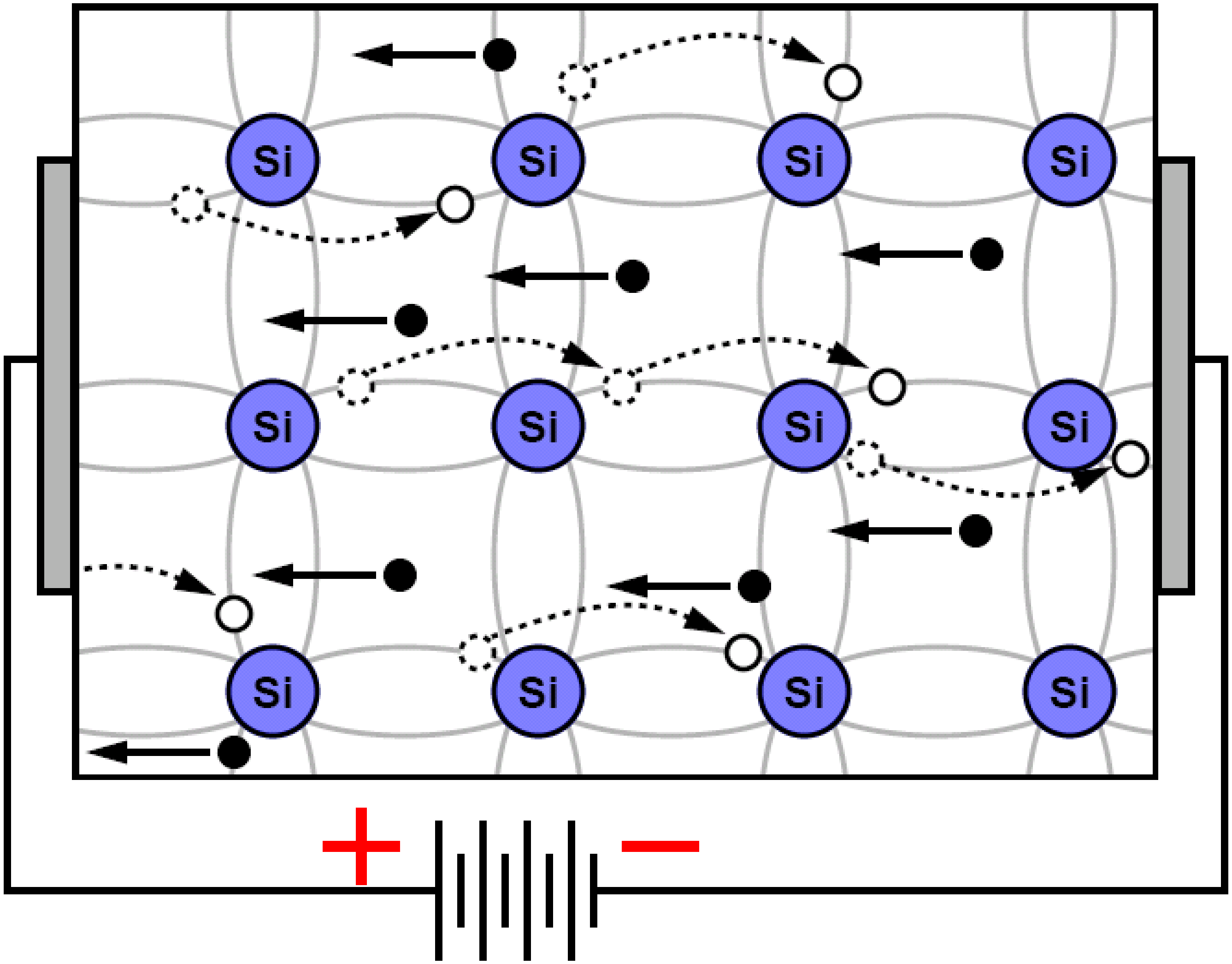
Silicon Lattice



Silicon Lattice

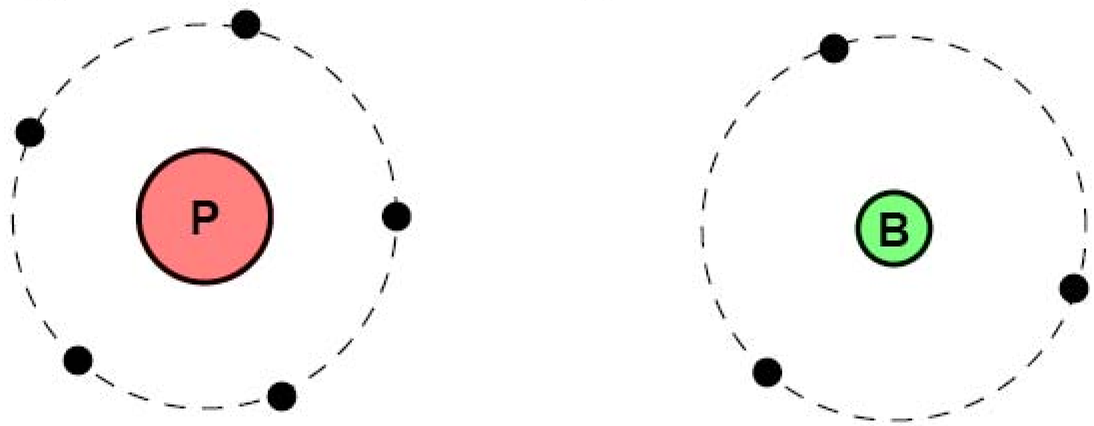


Semiconductor current: electron/hole flow



Doping

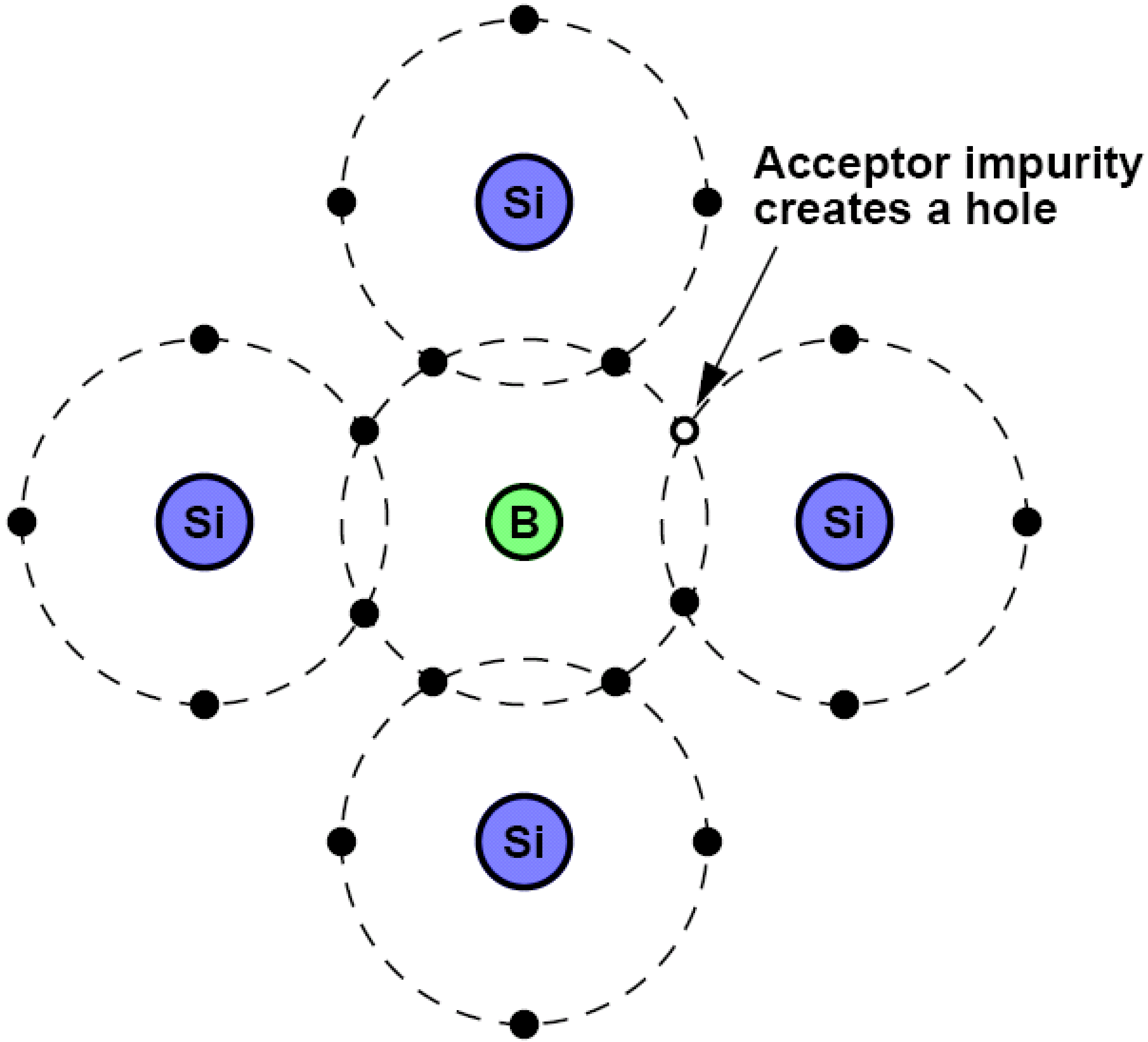
Doping: small % of foreign atoms in lattice



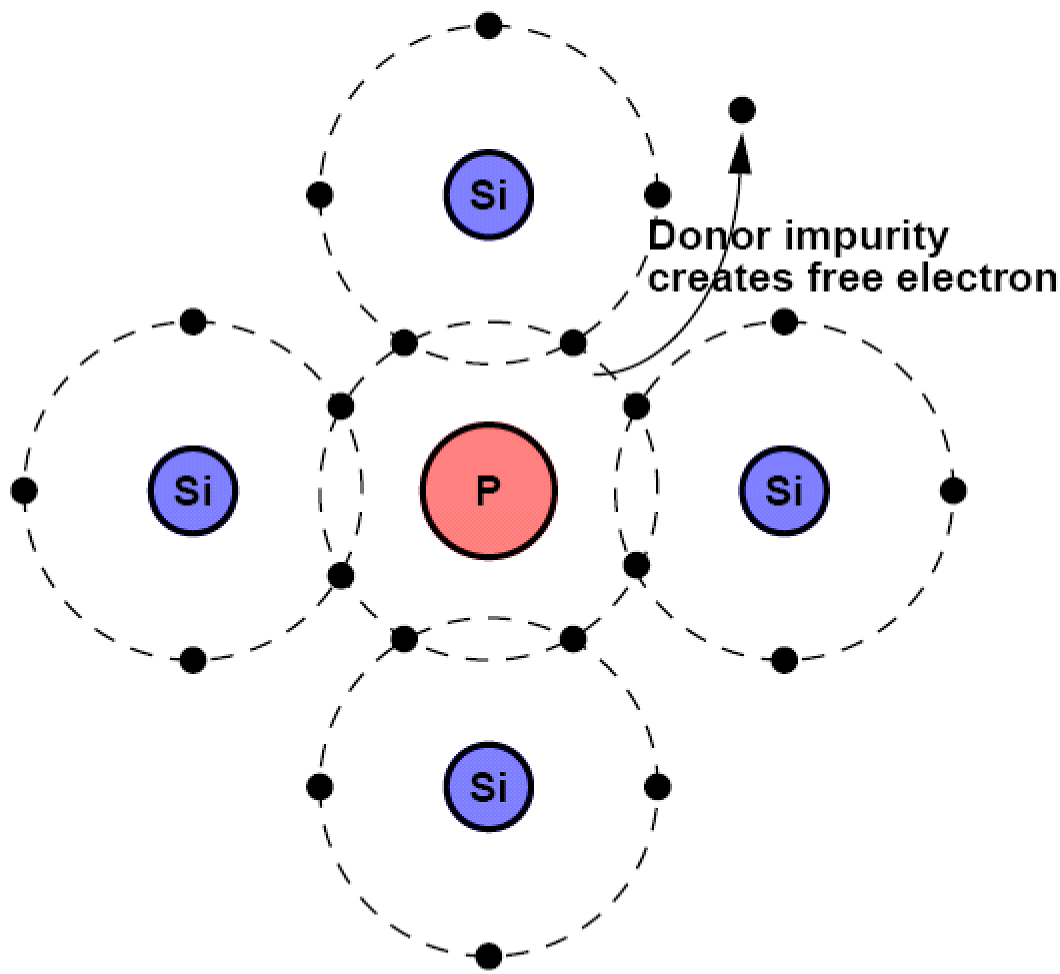
Breaks up regular lattice, produces dramatic changes in electrical properties

- Donors: pentavalent impurities (5 valence electrons) produce n-type semiconductors by adding electrons. E.g. antimony, arsenic, phosphorus
- Acceptors: trivalent impurities (3 valence electrons) produce p-type semiconductors by adding electron deficiencies (“holes”). E.g. boron, aluminum, gallium

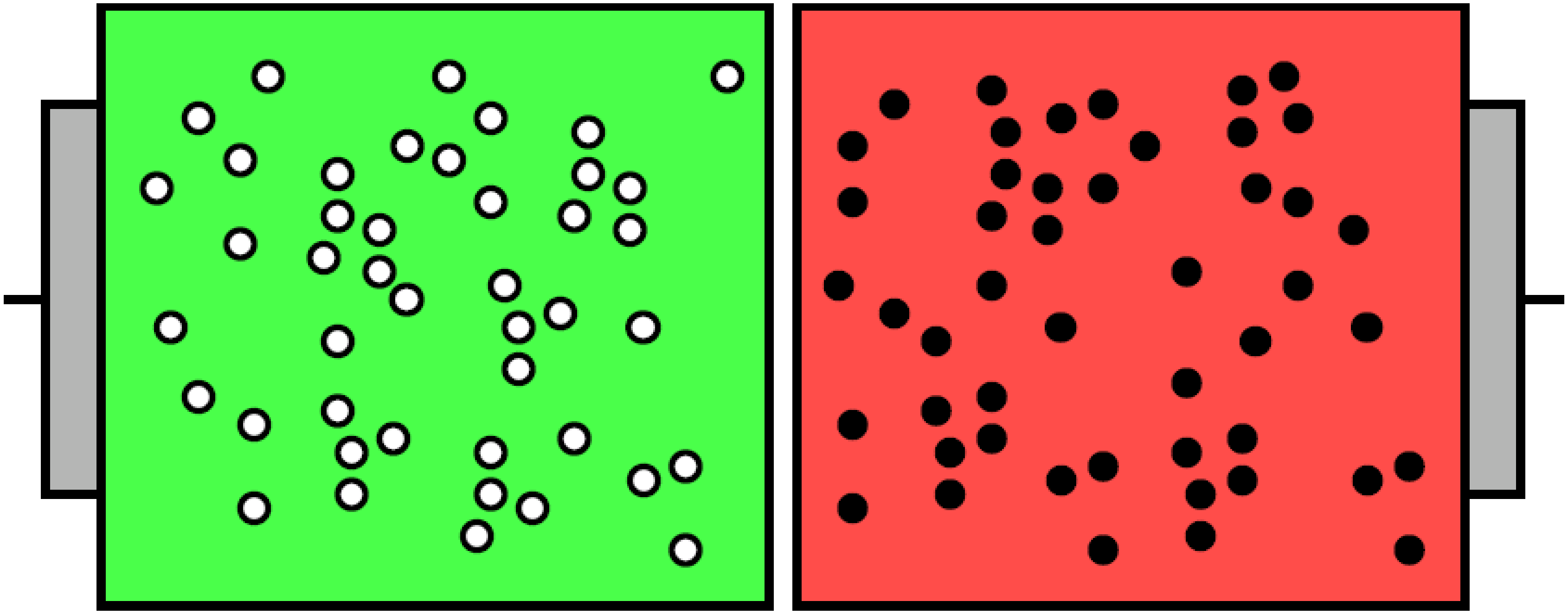
P-Type semiconductor



N-Type semiconductor



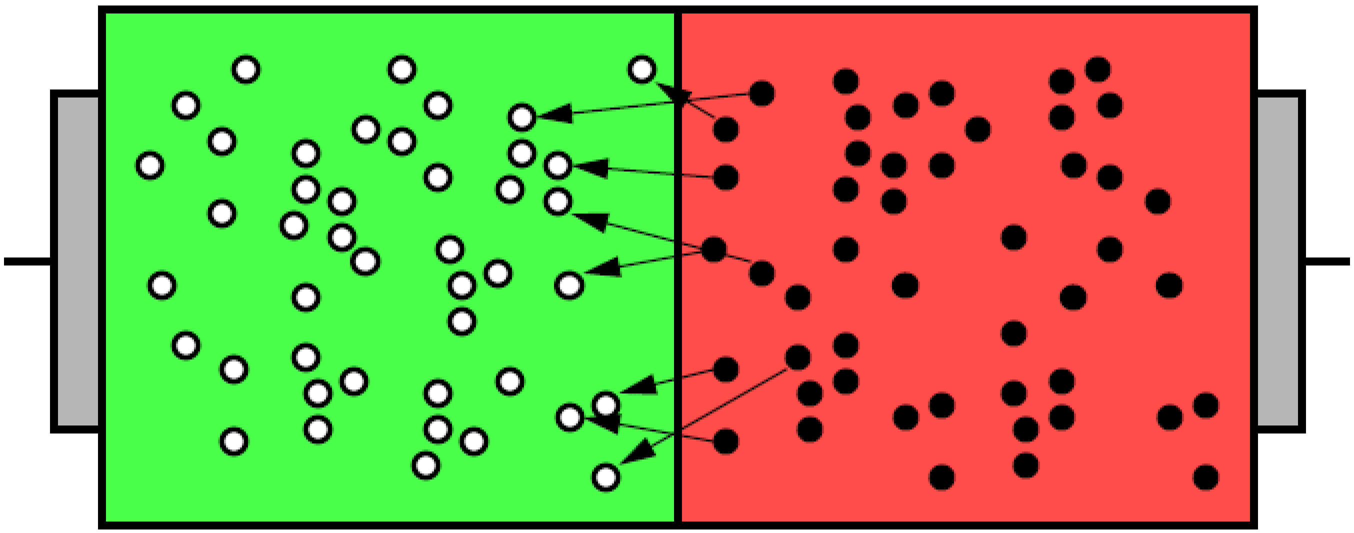
The P/N Junction



If not touching, nothing happens

The P/N Junction

DEPLETION REGION

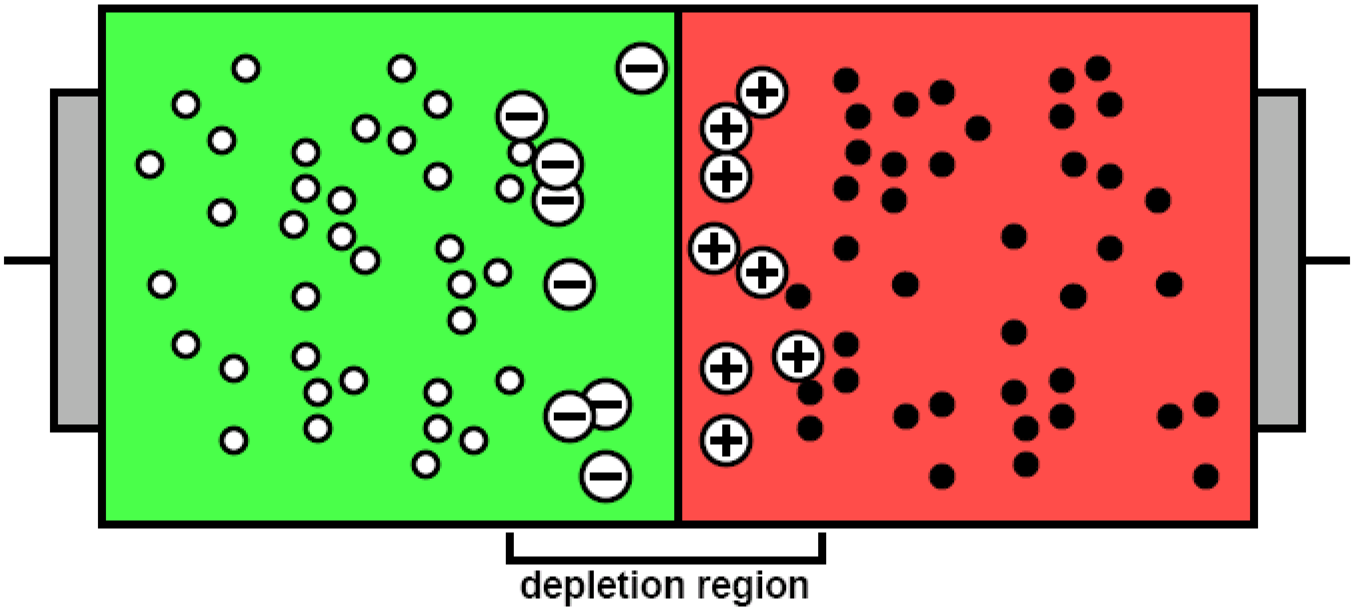


With a connection, electrons from n-region in conduction band diffuse across junction and combine with holes in p-region

(why doesn't this continue indefinitely?)

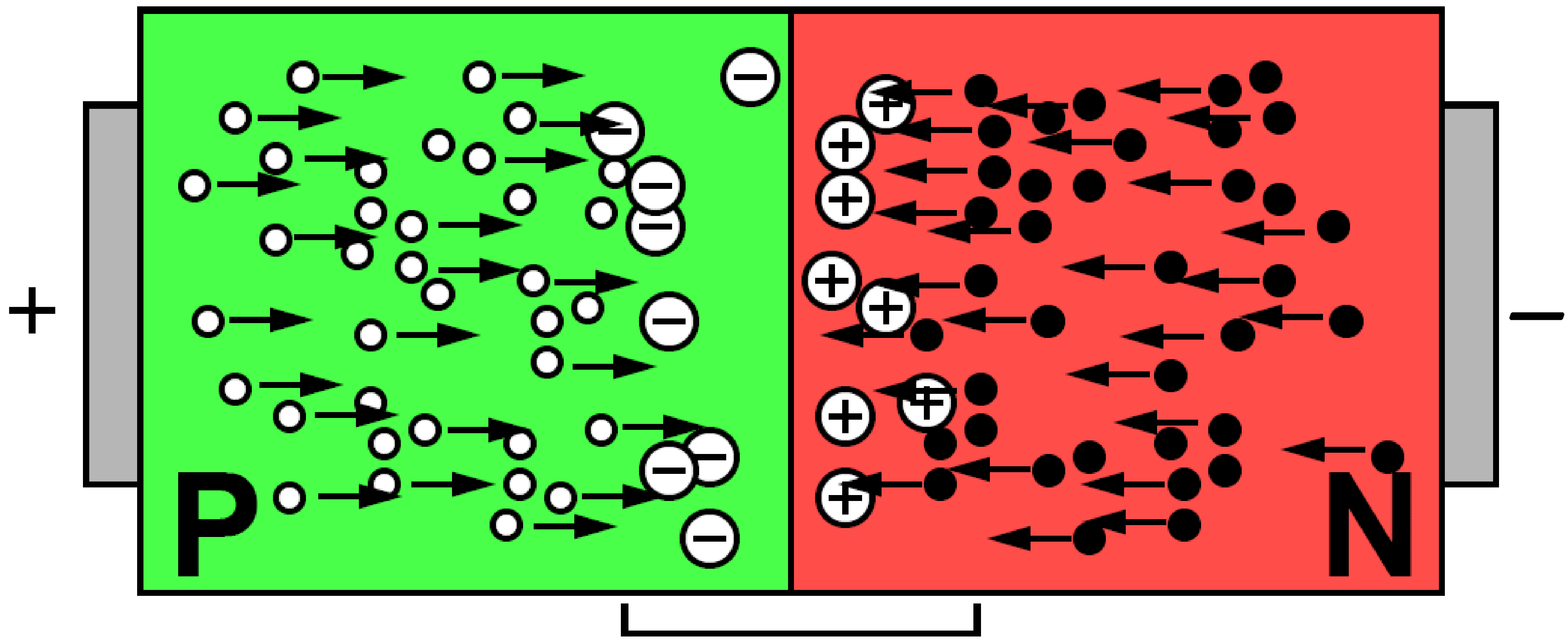
The P/N Junction

DEPLETION REGION



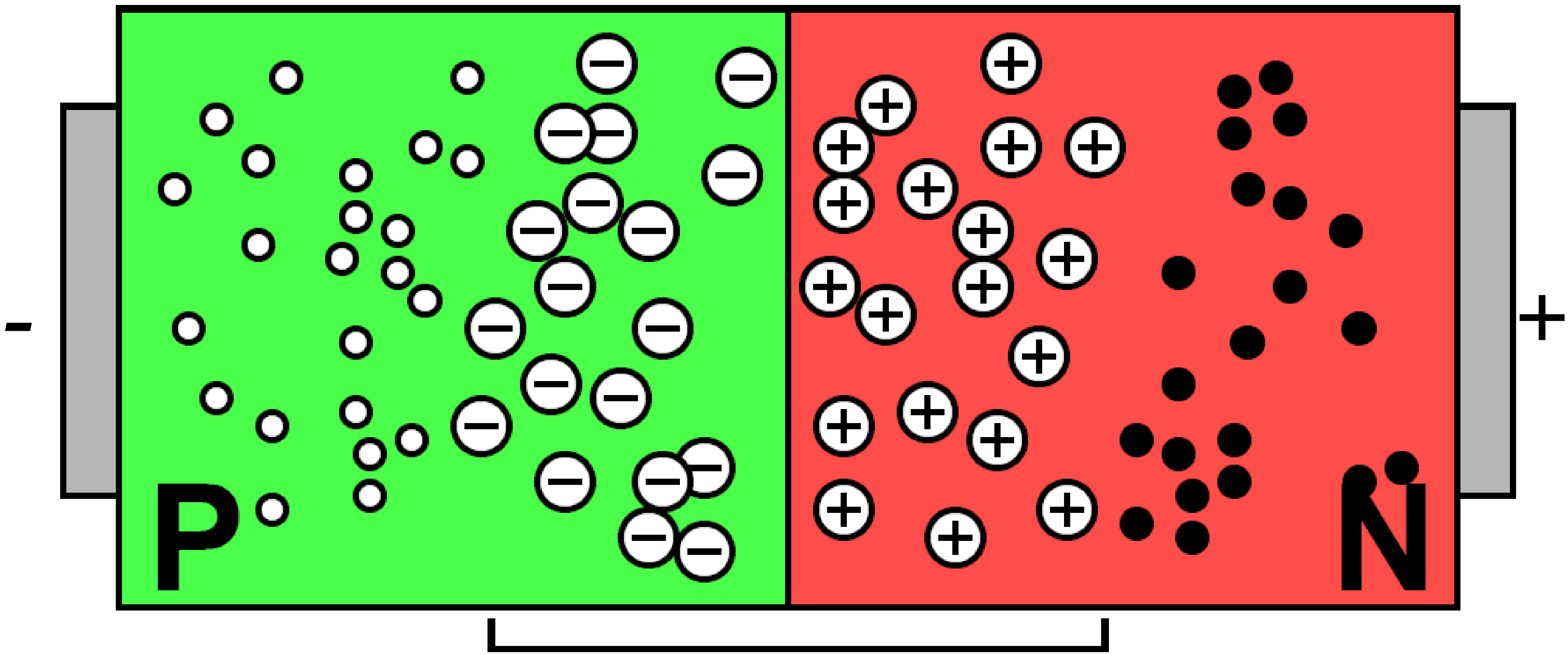
Ions are formed on both sides of junction (negative ion from filled hole; positive ion from removed electron). This forms a space charge that impedes further electron flow.

Forward Bias



Depletion region still exists
But current can flow

Reverse Bias

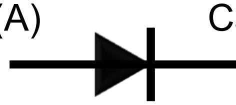


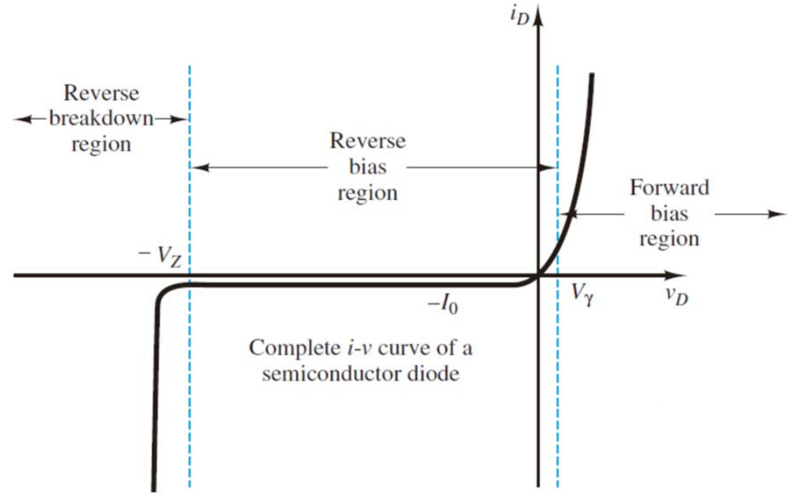
Depletion region increases in size

No current Flow

The diode

SYMBOL





Complete *i*-*v* curve of a semiconductor diode

Basic description:

A semiconductor junction diode consists of a junction between a two different semiconductor types (n-type and p-type), or a junction between a semiconductor and a metal.

- The current (i_D) vs voltage (v_D) behavior depends on the direction the diode is inserted into a circuit;
- A doubling of an applied voltage signal not lead to a doubling in the current – non-linear circuit element

Types of diode:

Signal diodes:

Power diodes:

Special purpose diodes:

Specialist applications.
e.g. voltage reference

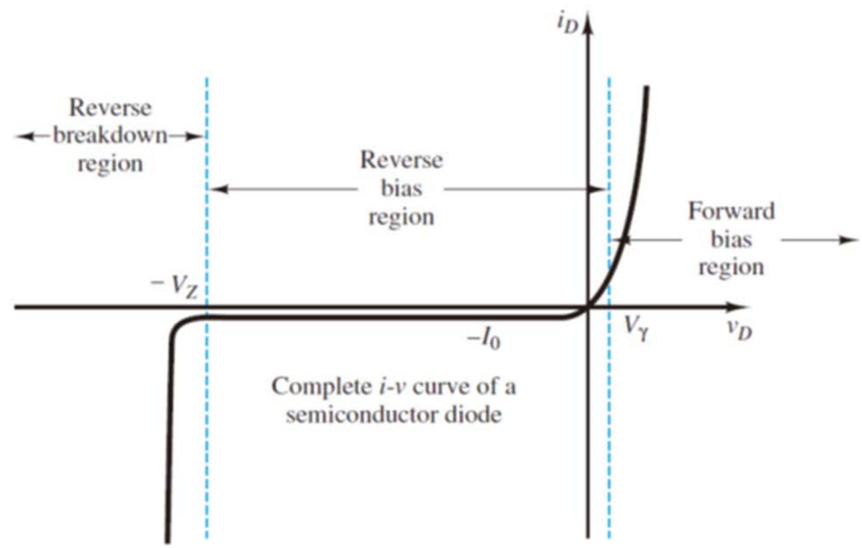
https://www.nationwideautoparts.com.au/alternator-denso-type-24v-50amp-suits-toyota-coast

THE DIODE MODEL EQUATION

- A diode operating in its designed operation region (i.e. outside "breakdown"),
- Ideal diodes characterized by the diode model equation.
- At room temperature, for silicon-based diodes (as they very commonly are), diode model equation becomes:

$$i_D = I_S\left(e^{\frac{V_D}{0.025}} - 1\right).$$

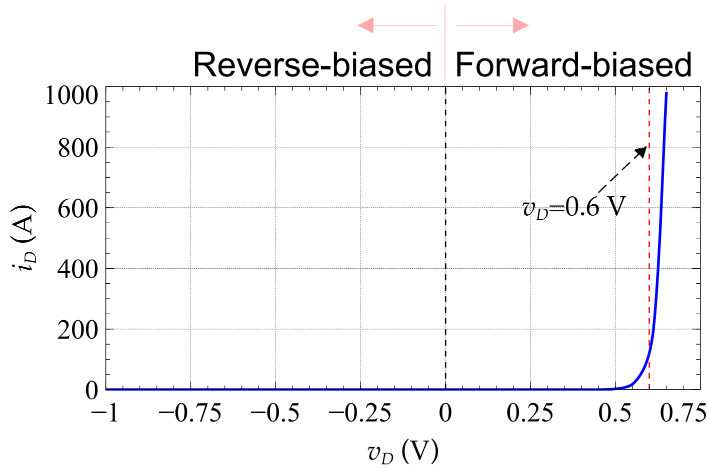
- The factor 0.025 has units of volts (i.e. 25 mV) in the diode model equation, and is a function of temperature, device material properties, and physical constants.
- I_S is termed the "saturation current", and is also a function of temperature, device material properties, and physical constants.

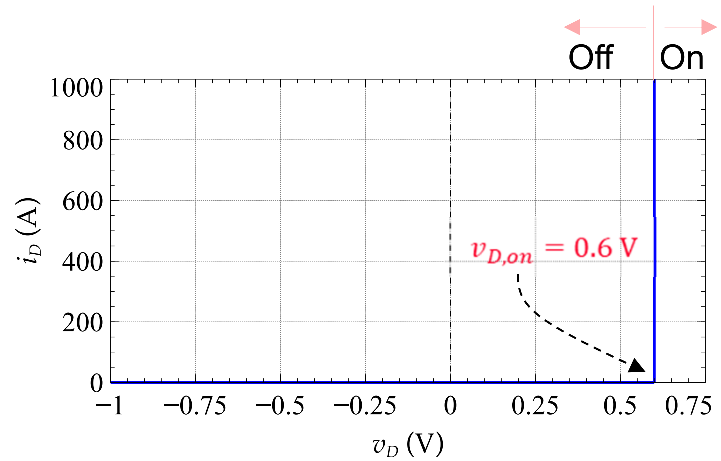


Complete *i-v* curve of a semiconductor diode

Large signal model for the diodes – simple "on/off switch"

- Describe the gross behavior of the device in the presence of relatively large voltages and currents
- Examining this performance, Si diode essentially "switches on" around $v_{D,on} = 0.6$ V.



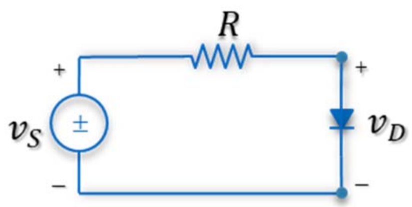


- $v_D > 0 \Rightarrow$ diode "forward-biased"
- $v_D < 0 \Rightarrow$ diode is "reverse-biased"

- **Diode is in "off"-state for $v_D < v_{D,on}$, and conducts no current**
- **Diode is in "on"-state for $v_D \geq v_{D,on}$, and conducts any required current**

A simple diode circuit example

Find the state of the Si diode in the following circuit, if



a) $\boldsymbol{v_S = -5\,V,\ R = 10\,\Omega}$

As $V_S < 0$, there is no way for V_D to be positive. Therefore diode is ***reverse biased***, and *OFF*. In this case, no current flows, and there is no current through the resistor. With no current, there is no voltage drop across the resistor. Hence,

$$v_D = v_S = -5\text{ V}.$$

b) $\boldsymbol{v_S = 0.5\,V,\ R = 10\,\Omega}$

KVL around loop: $v_S - iR - v_D = 0$

$$\Rightarrow v_D = v_S - iR$$

With $v_S < 0.6\,V$, cannot have $v_D > 0.6\,V$

So Diode is *forward biased*, but *OFF*, and $v_D = v_S = 0.5\,V$

c) $\boldsymbol{v_S = 1\,V,\ R = 10\,\Omega}$

Test for "ON" state: $v_D = 0.6$ V

KVL around loop: $\Rightarrow v_D = v_S - iR$

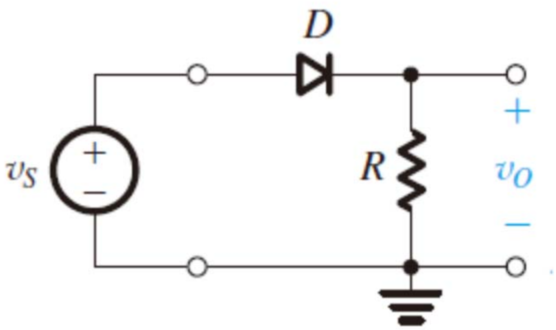
$$0.6 = 1 - i \times 10$$

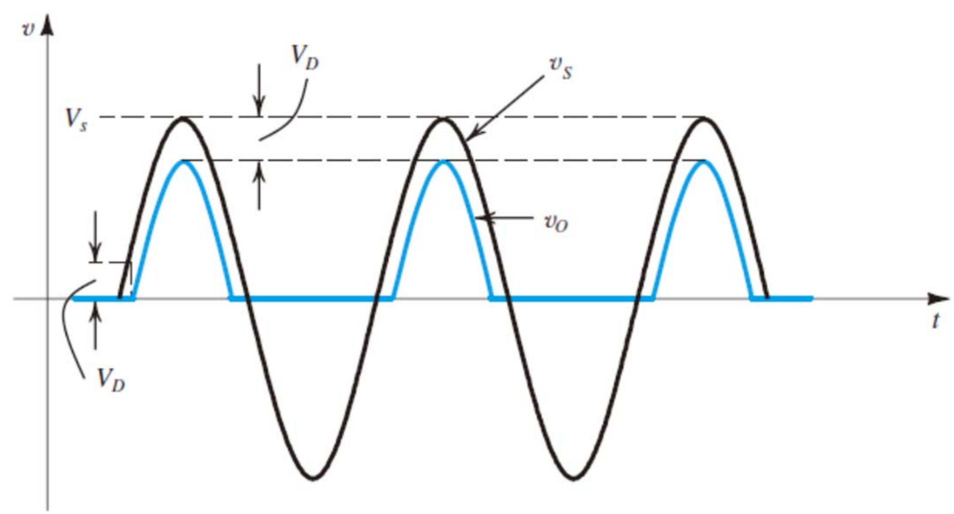
$$i = \frac{1 - 0.6}{10} = 0.04\text{ A}$$

It works! So diode is *forward biased*, *ON*, and $v_D = 0.6$ V.

Dssolfdwlrq#4#, Kdoi0zdyh#uhfwlilhu

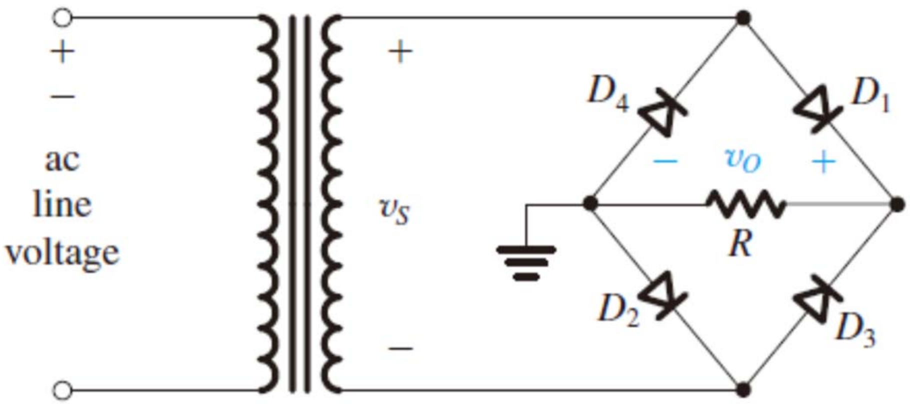
H{dplqh#wkh#ehkdylru#ri#wkh#iroorzlqj#flufxlw

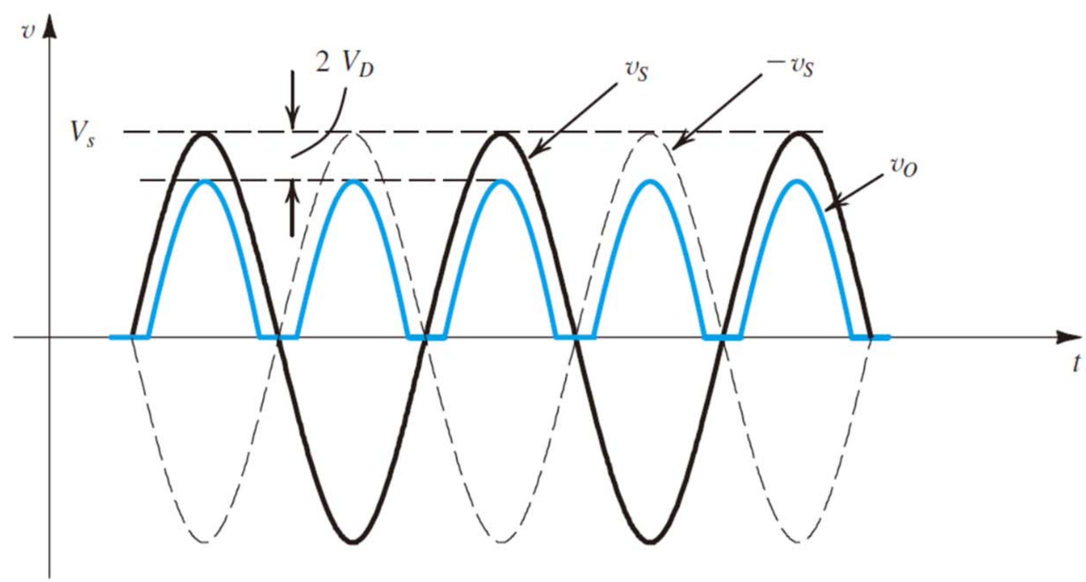




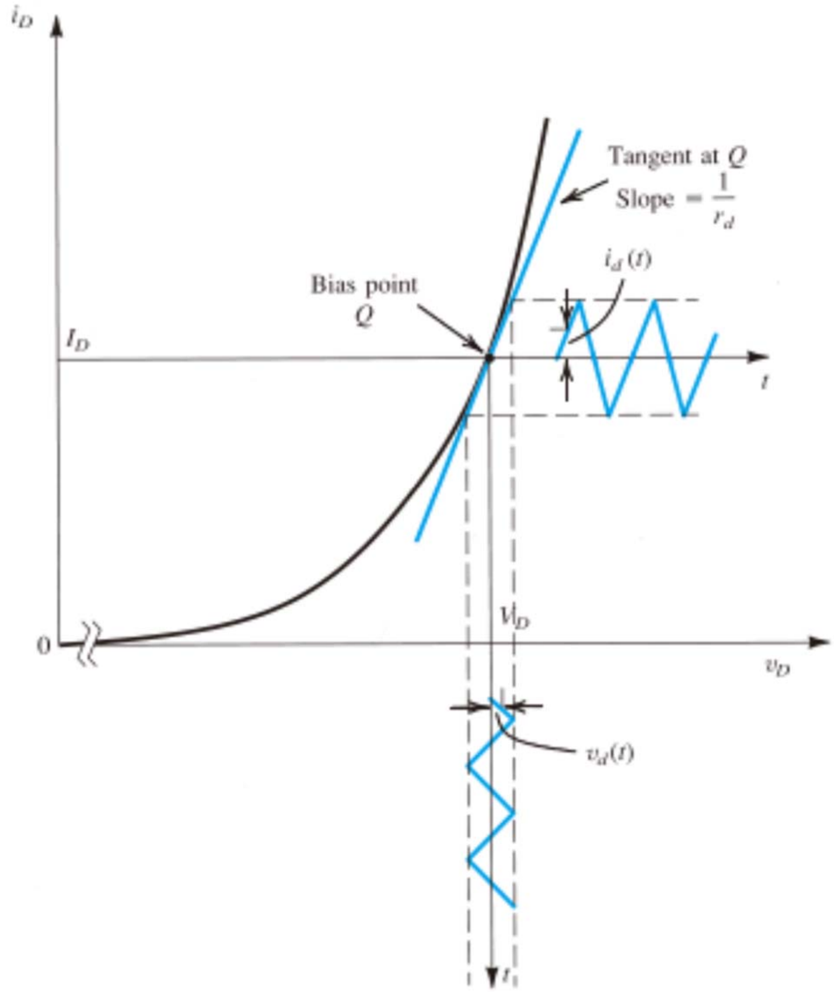
Dssdfdwlrq#5#, Ixoo0z dyh#hfwlhu

H{dp lqh#wkh#ehkdylru#ri#wkh#iroorz lqj#flufxlw





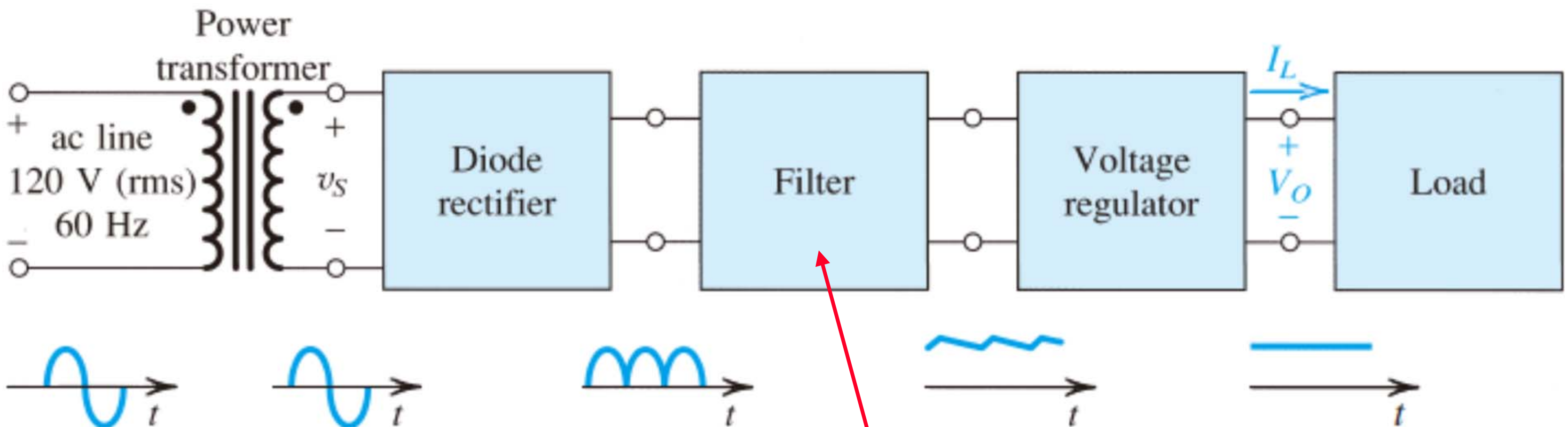
SMALL SIGNAL MODEL FOR THE DIODES

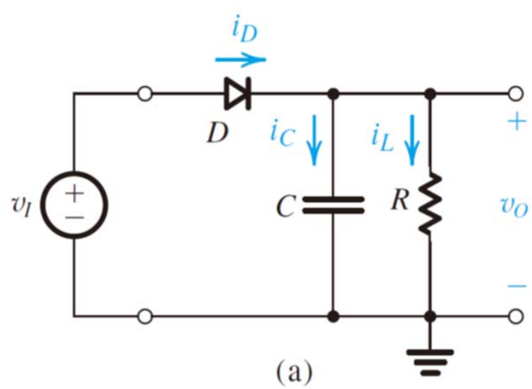


At a certain biasing point, you can turn non-linear relationship into linear relationship for current ~ voltage.

Application: voltage regulator which provide a constant dc voltage between its output terminals.

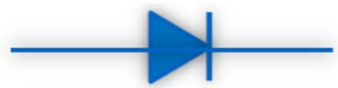
To make a DC power supply:





Rectifier with a
Filter Capacitor

The light emitting diode (LED)



Standard diode

Light emitting diode

- A standard current dissipates power as heat
- A LED dissipates part of its power as an optical (light) emission
- Turn-on voltage of a LED depends on the emission colour (i.e. material used in manufacture)
  The colours at red-end of the spectrum have lower turn-on voltage ($v_{D,on}$) than the blue end
- The light intensity can be tuned via changing the current, see $i_D = I_S\left(e^{\frac{v_D}{0.025}} - 1\right)$.
- A LED behaves electrically as a diode and, accounting for the changed $v_{D,on}$, can be used as a diode in a circuit.

Acknowledgments

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- Credit is acknowledged where credit is due. Please refer to the full list of references.