# ECE 3030
# Physical Foundations of Computer Engineering

## Physics of Semiconductors (Bond Model)

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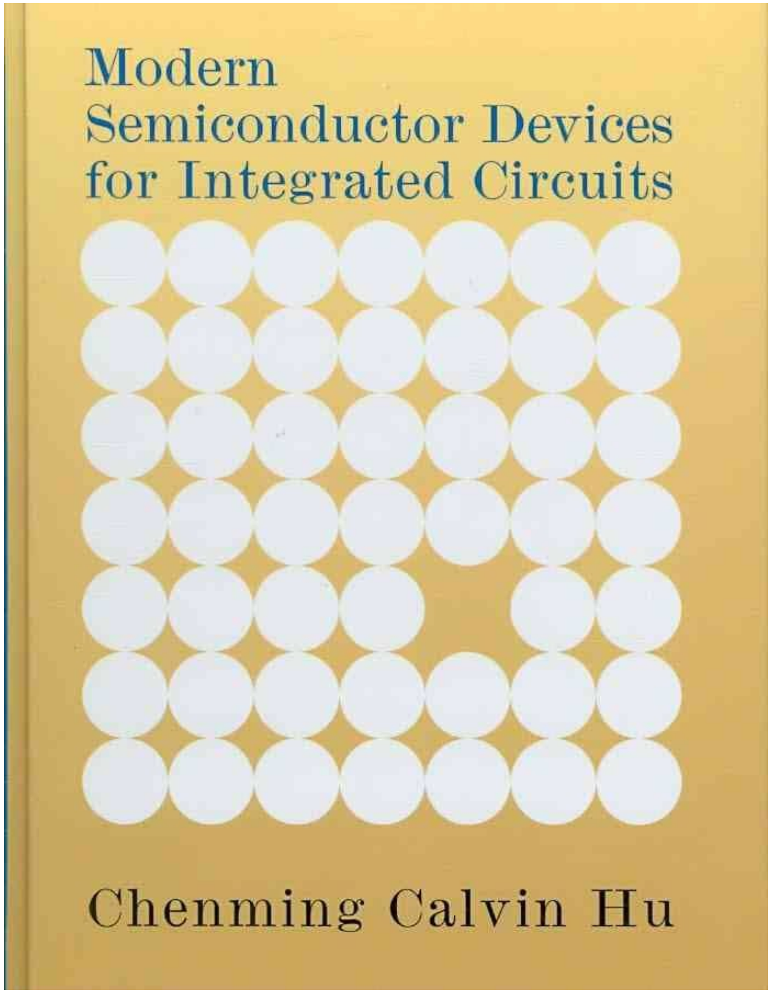
# Reference



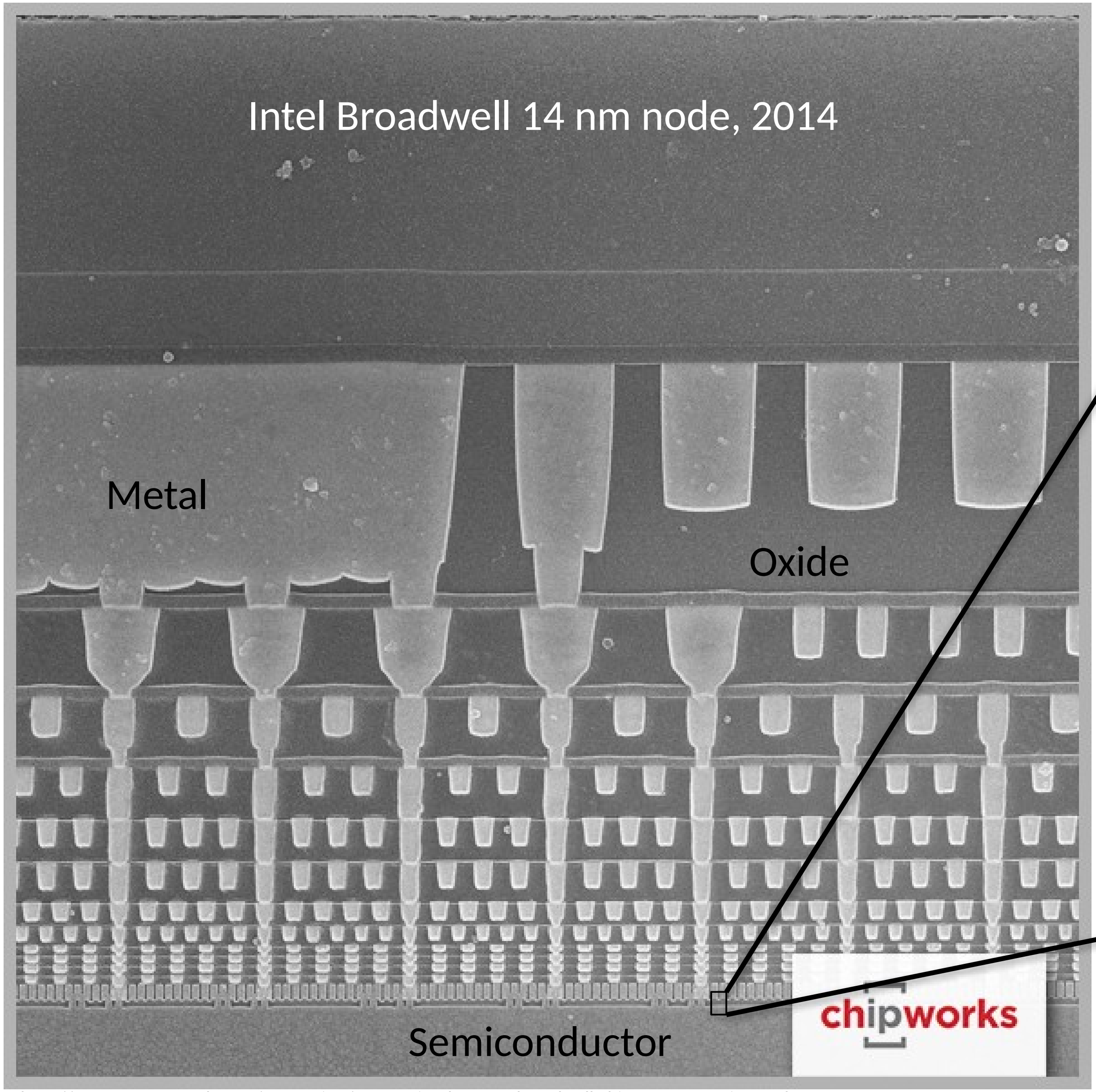

Modern Semiconductor Devices for Integrated Circuits

**Chapter 1: Section 1.2**

# Resources

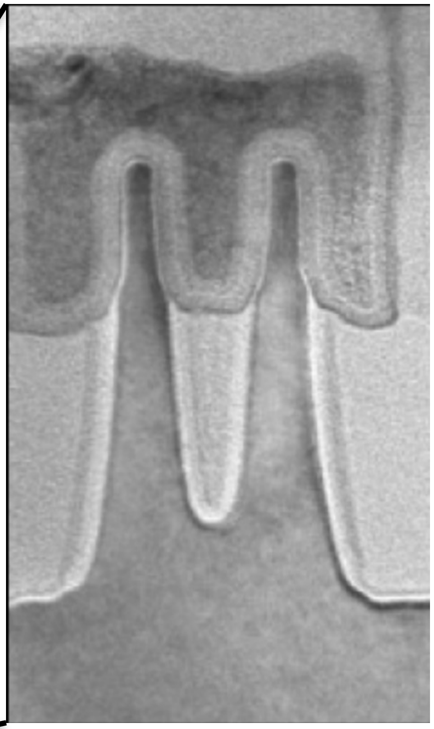
Recorded lecture available at: https://youtu.be/NKPeZBMX6Dw

# Physics of Semiconductors




http://www.extremetech.com/computing/193200-intels-14nm-broadwell-chip-reverse-engineered-reveals-impressive-finfets-13-layer-design

MOSFET



http://electroiq.com/chipworks_real_chips_blog/2014/

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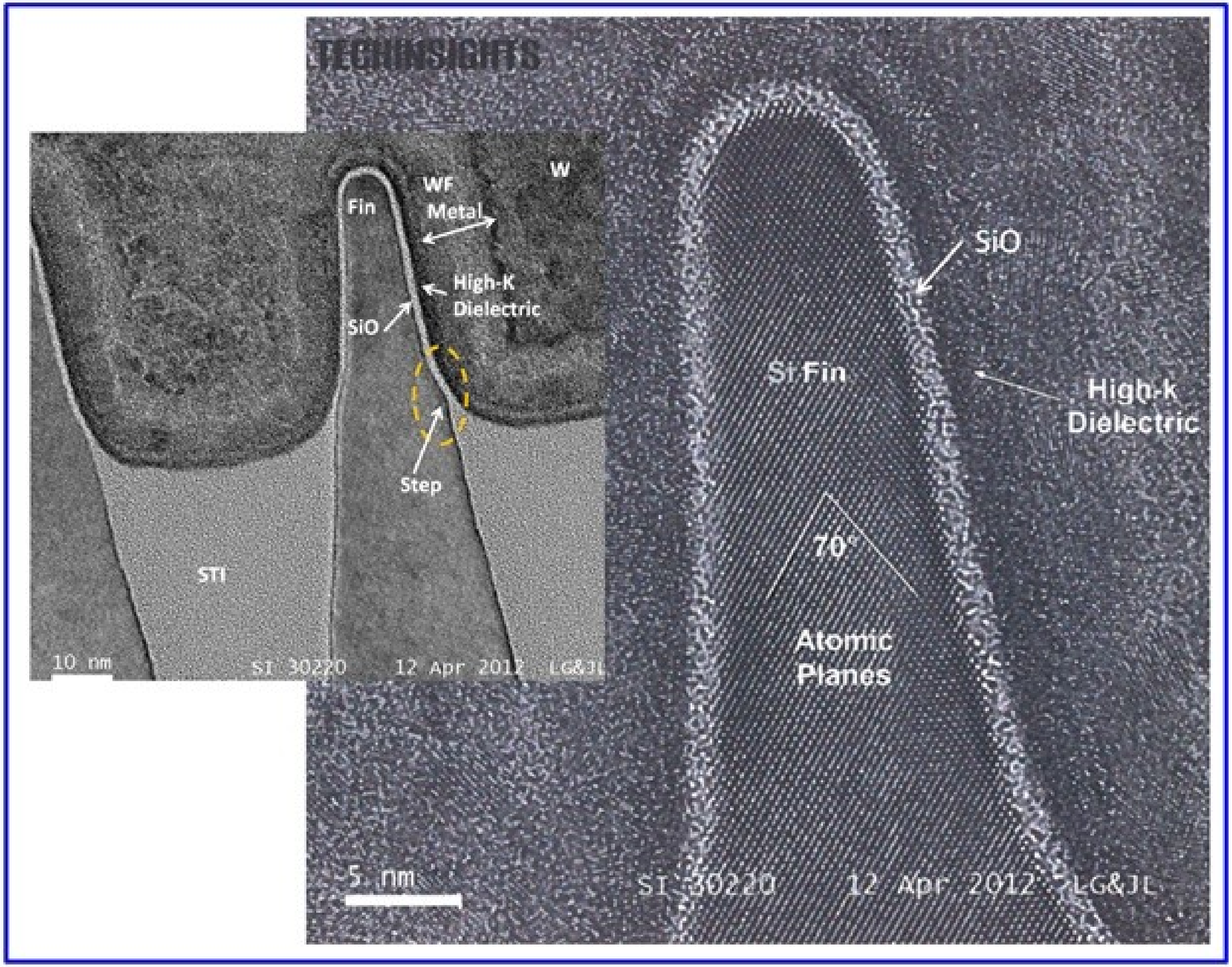
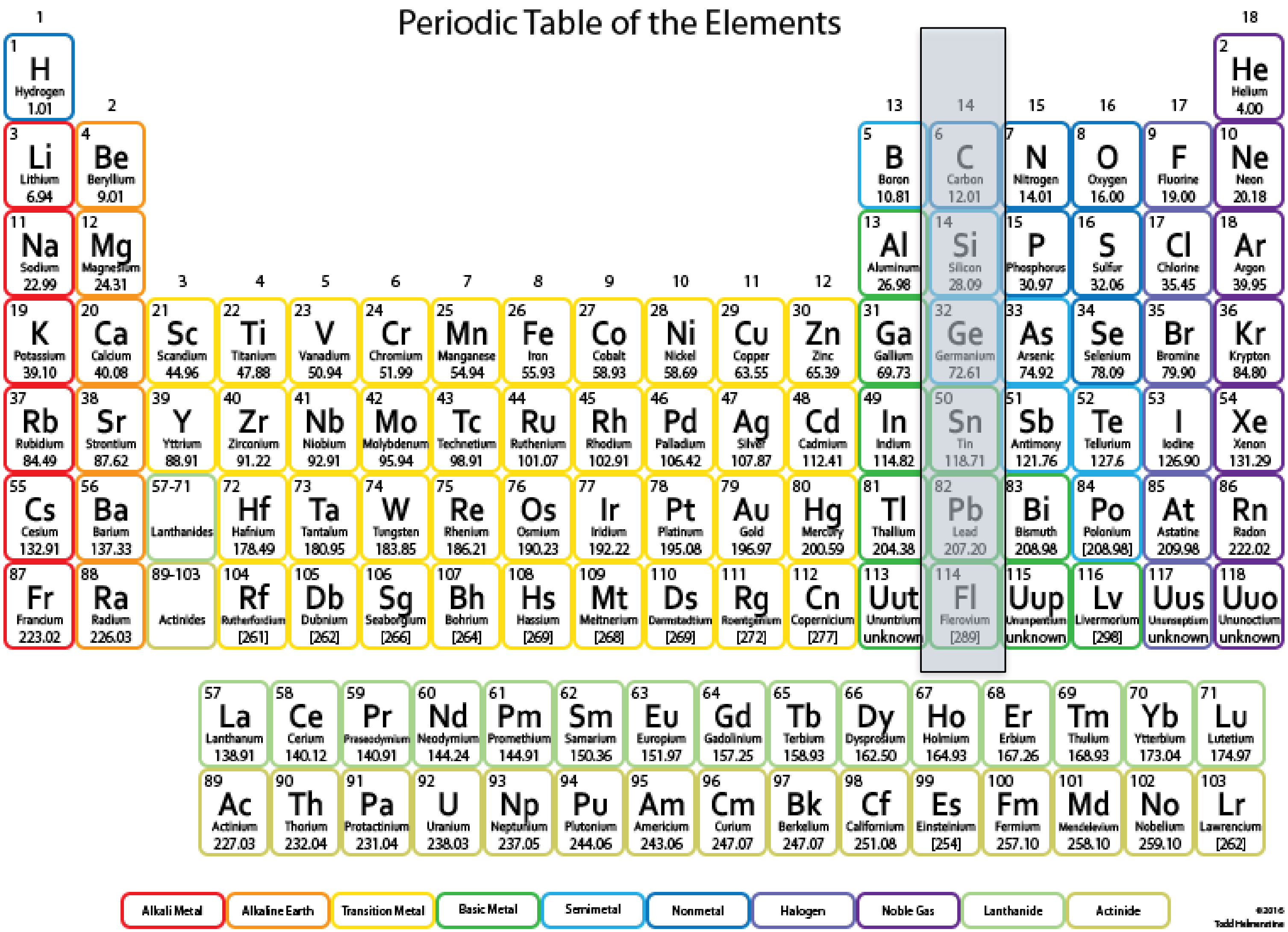
# Physics of Semiconductors



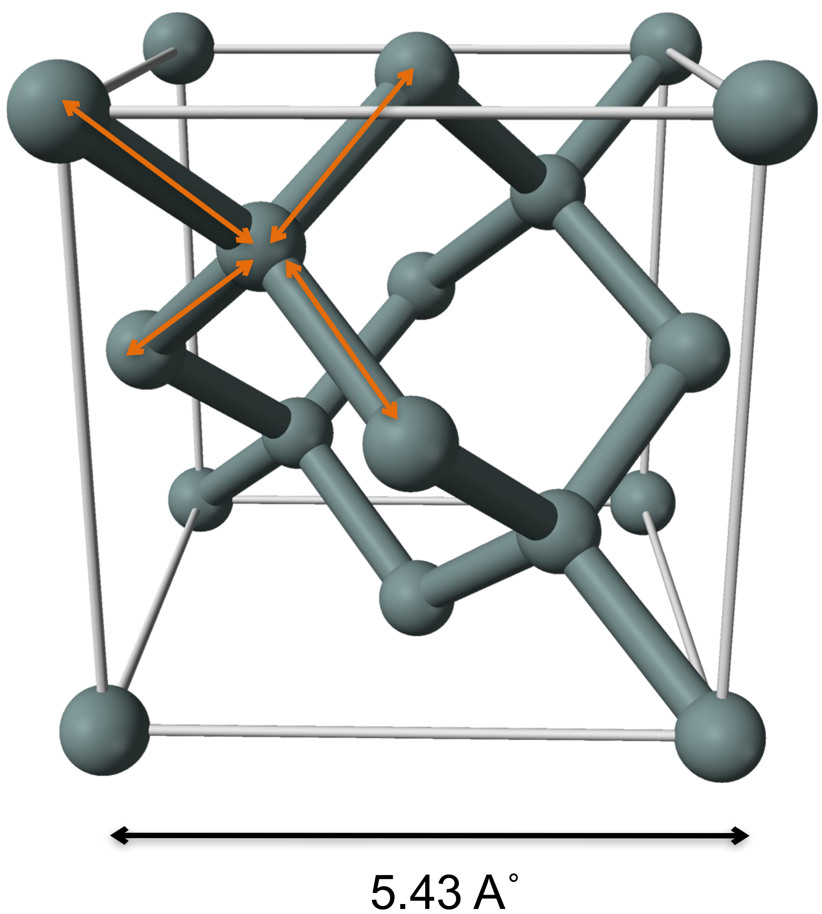

http://www.embedded.com/print/4395587

# Physics of Semiconductors



# Physics of Semiconductors

Si crystal structure




Each atom has 4 nearest neighbors

$$Si(14)=1S^2 2S^2 2P^6 \underbrace{3S^2 3P^2}_{\text{4 valence electrons}}$$

Each atom shares 2 electrons with 4 nearest neighbors to form a covalent bond

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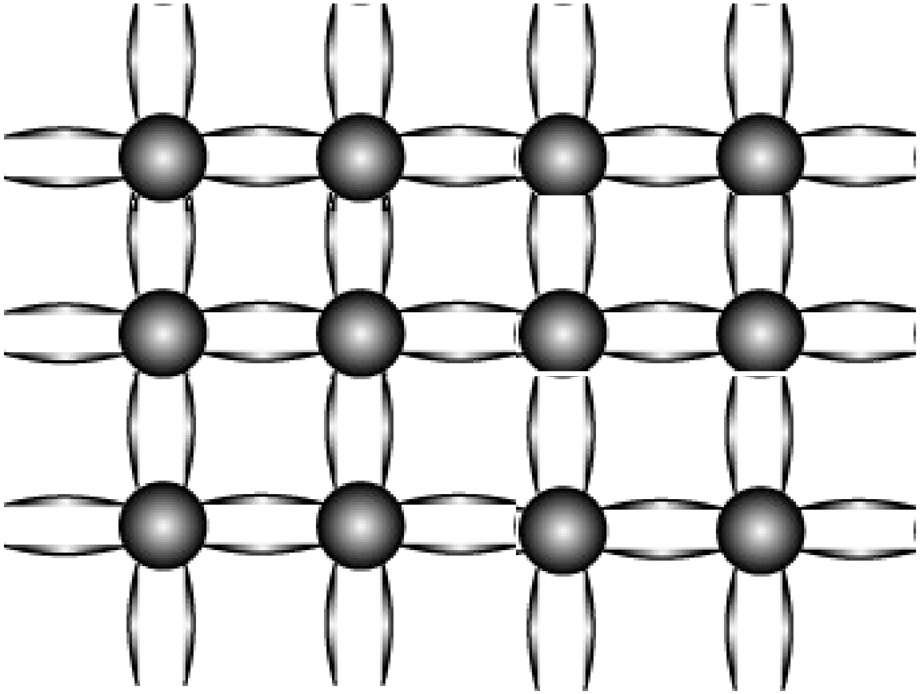
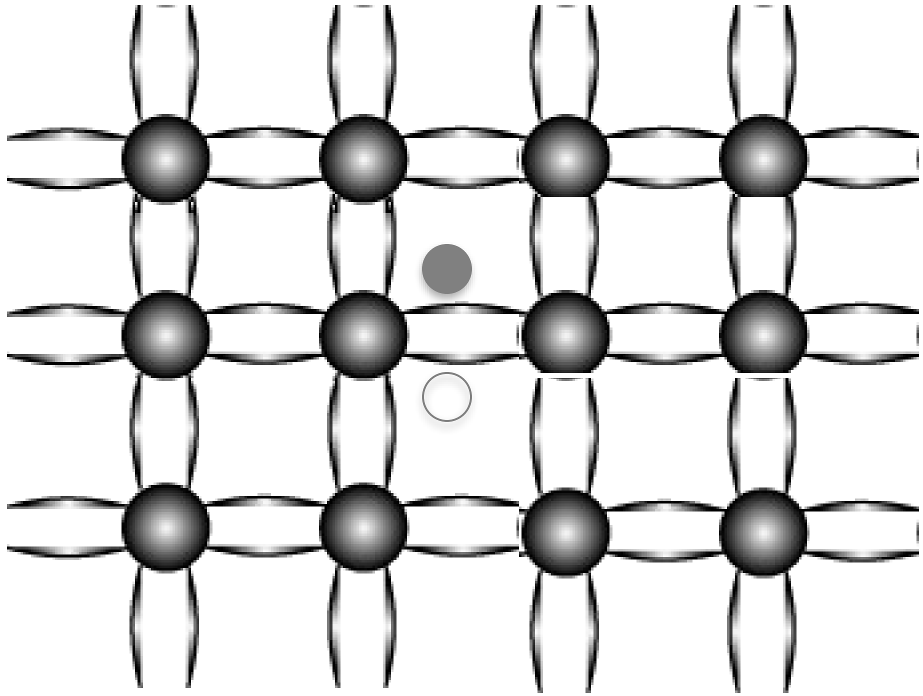
# Intrinsic Si: The Bond Model

Each atom shares 2 electrons with 4 nearest neighbors to form a covalent bond



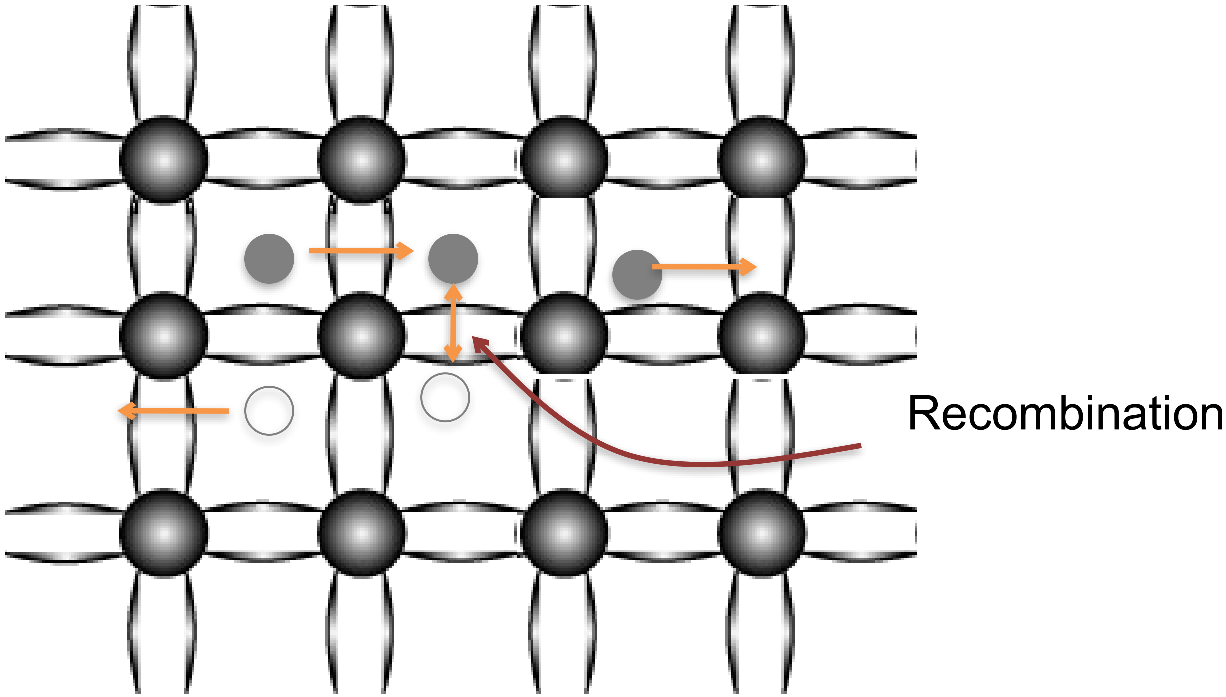
At T=0K, all bonds are satisfied, there are no free carriers, no current flows, looks like an insulator

# Intrinsic Si: The Bond Model: Electrons



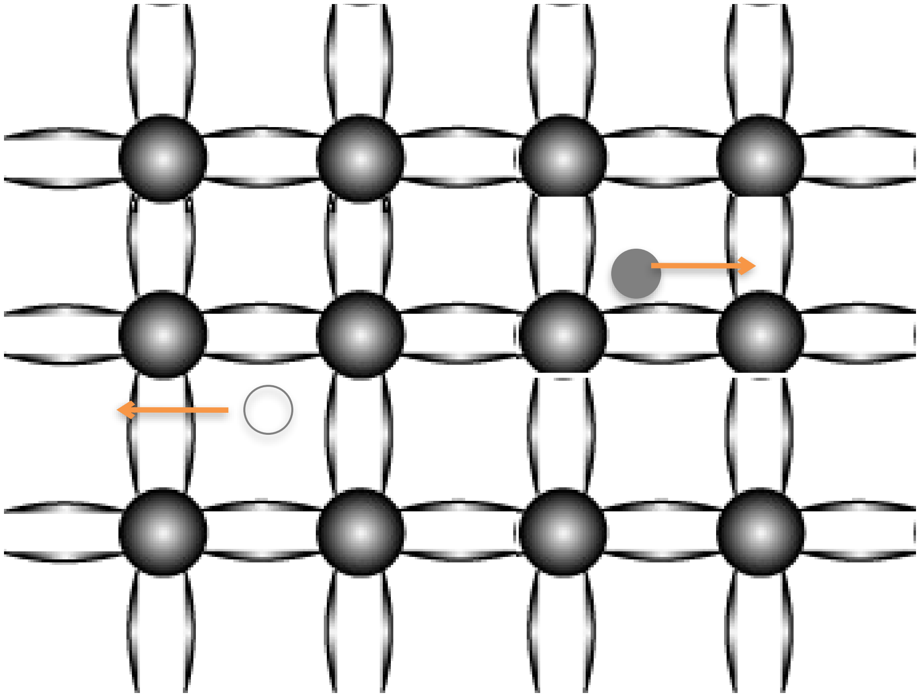
At finite temperature, an electron may gain enough energy to break the covalent bond, become free and move around. As a result, current will flow if a voltage is applied to Si. As the electrons move, they leave behind a hole, which itself can move.

# Intrinsic Si: The Bond Model: Holes




Movement of electrons is equivalent to opposite movement of holes. How? If the electron moves towards right and there is enough thermal energy in the system to dislodge electrons, after some time another electron from left will come and recombine with the hole. The net result is that the hole moves from right to left. <u>For all practical purposes, it is easy to consider holes as equivalent to electrons with positive charge .</u>

# Si: The Bond Model: Holes

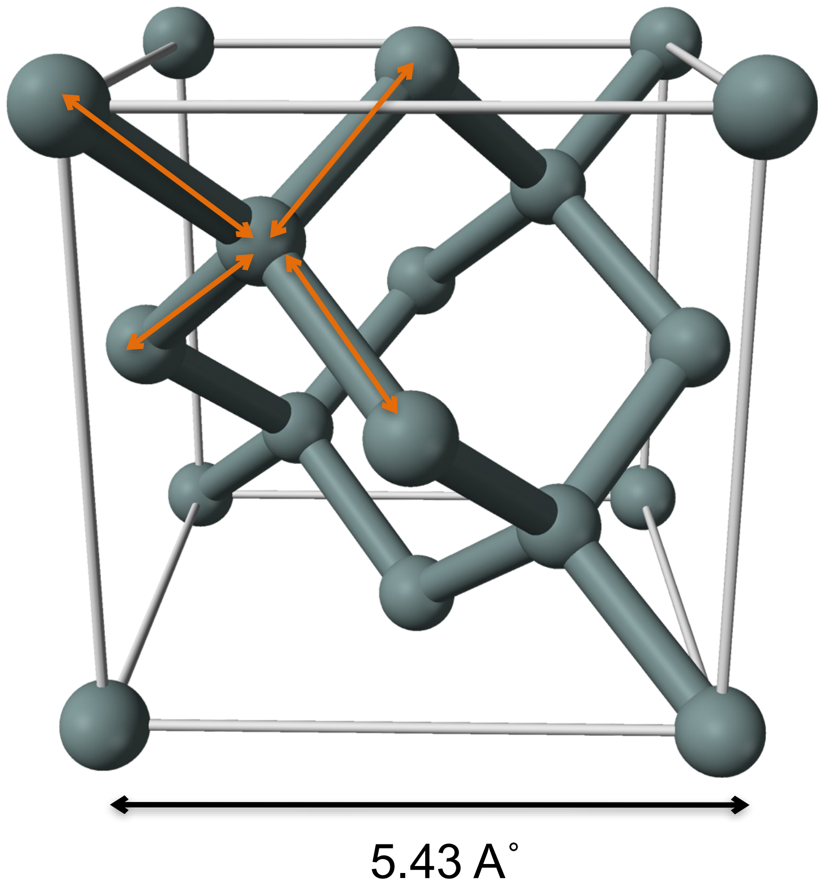


Note that each electron is associated with a complementary hole. So the material is charge neutral.

However, electrons are holes are not exactly the same quantity with opposite charges. We shall see why when we discuss band model.

# Physics of Semiconductors

## What is the atomic density of pure Si?

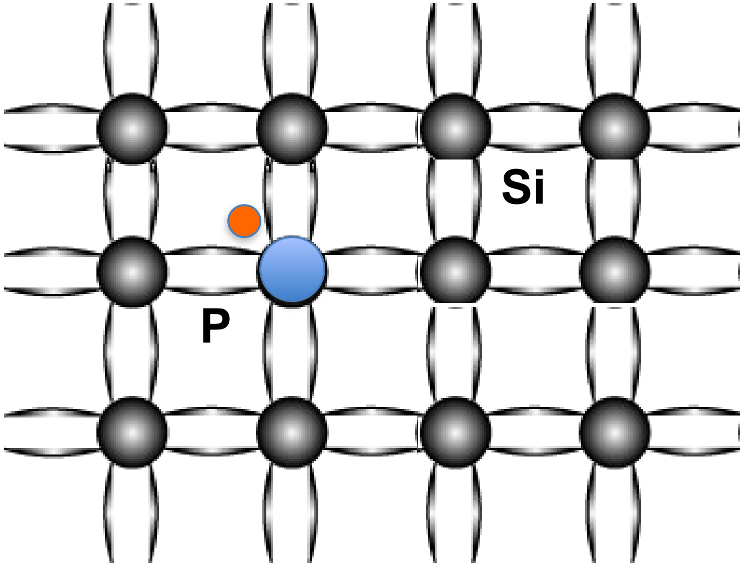



- Atomic Density: $8/(0.543\times10^{-9})^3 = 5\times10^{28}$ /m$^3$
- Bond Density: $2\times10^{29}$ /m$^3$
- Free Carrier: $1.5\times10^{16}$ /m$^3$

Only 1 in ~$10^{13}$ bonds is broken at room temperature in Si!

# Adding Dopants: Donors (non-intrinsic Si)

| III | IV | V |
|---|---|---|
| Boron (B) | Carbon (C) | |
| Aluminum (Al) | Silicon (Si) | Phosphorous (P) |
| Galium (Al) | Germanium (Ge) | Arsenic (As) |




Si(14)= [Ne(10)] $3s^2 3s^2$
P(15): [Ne(10)] $3s^2 3p^3$

Electron density $n=N_D$ (donor doping density)

Group V elements have 5 valence electrons. Therefore, if one Si atom is replaced by one group V atom (e.g. P or As), then 4 electrons are shared among the 4 nearest neighbors which complete the shell, leaving one electron to freely wonder around. Thus each dopant 'donates' an extra electron to the material. Thus the name 'Donors'.

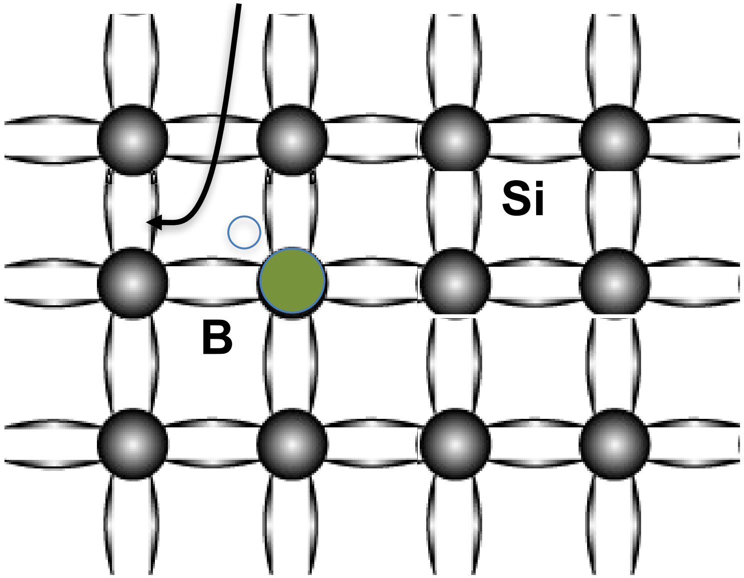
# Dopants: Acceptors

| III | IV | V |
|---|---|---|
| Boron (B) | Carbon (C) | |
| Aluminum (Al) | Silicon (Si) | Phosphorous (P) |
| Galium (Al) | Germanium (Ge) | Arsenic (As) |

Si(14)= [Ne(10)] $3s^2 3p^2$

B(5): [He(2)] $2s^2 2p^1$

A bond breaks to produce the necessary electron




Hole density $p=N_A$ (acceptor doping density)

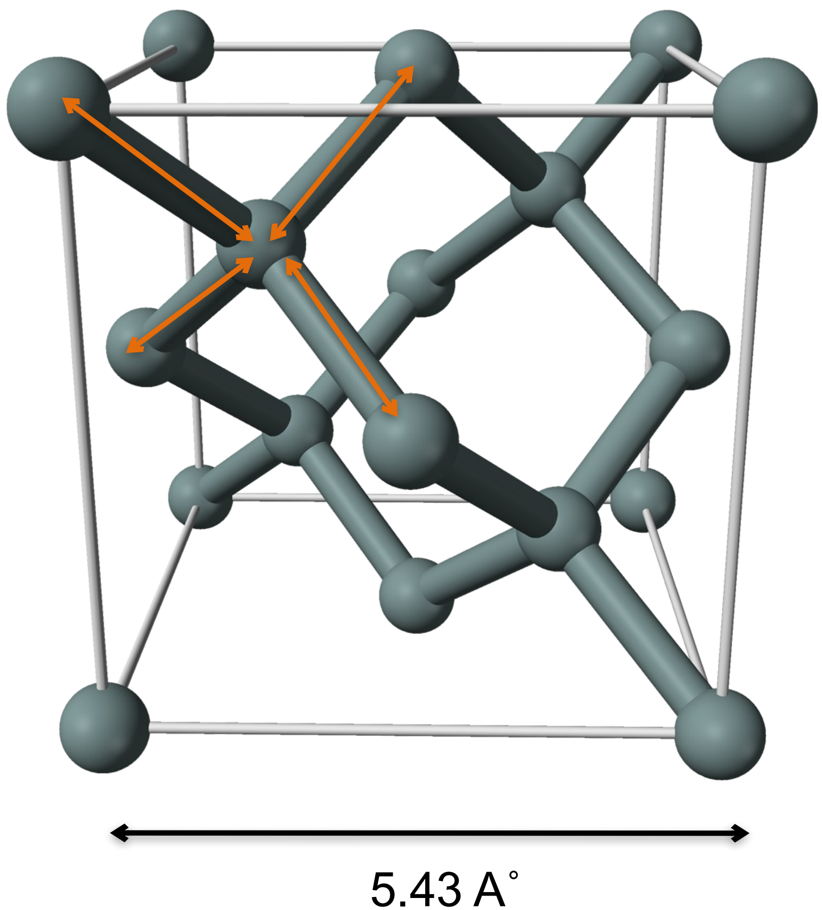
Group III elements have 3 valence electrons. Therefore, if one Si atom is replaced by one group III atom (e.g. B), then 4 electrons are shared among the 4 nearest neighbors which complete the shell, leaving one hole to freely wonder around. Thus each dopant accepts an extra electron leaving one free hole to the material. Thus the name ‘Acceptors’.

# Summary: Dopants

- When a material is doped with Donors, it has many more mobile electrons than holes. It is called a ‘n-type’ semiconductor.
- When a material is doped with Acceptors, it has many more mobile holes than electrons. It is called a ‘p-type’ semiconductor.
- The material is charge neutral. The dopants are charge neutral too. Therefore, even after doping, the material system as a whole remains charge neutral.

# Physics of Semiconductors

What is a reasonable number (to the higher side) of dopants in #/m$^3$ ?




- Atomic Density: $8/(0.543\times10^{-9})^3 = 5\times10^{28}$ /m$^3$
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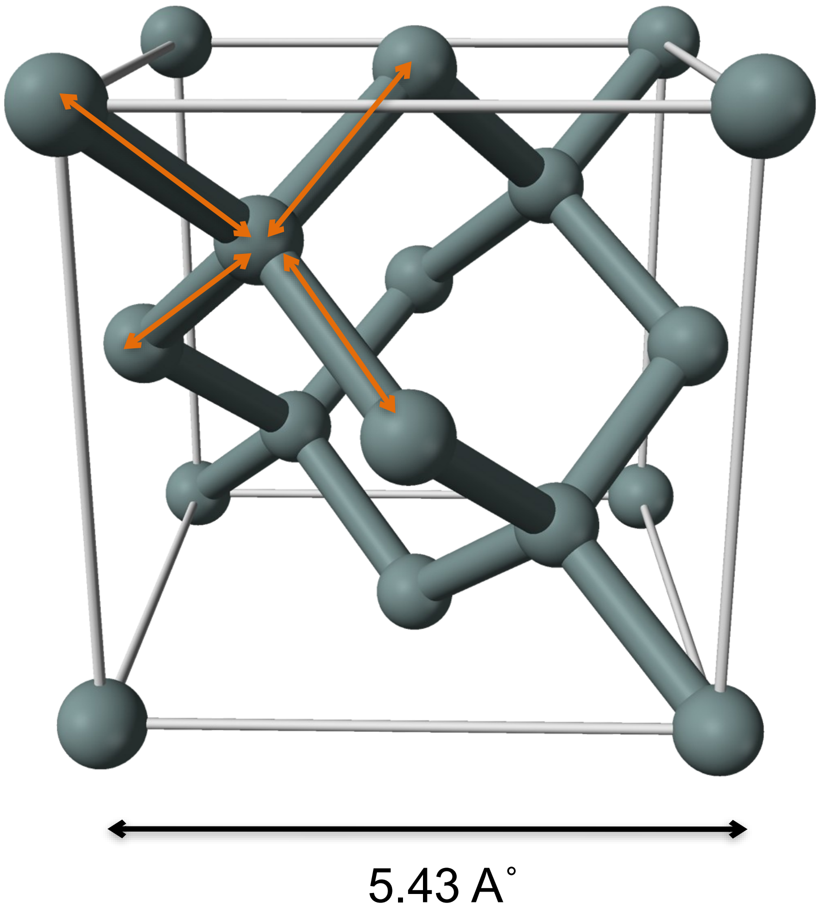
# Physics of Semiconductors

**What is a reasonable number (to the higher side) of dopants in #/m$^3$ ?**




- Atomic Density: $8/(0.543\text{x}10^{-9})^3 = 5\text{x}10^{28}$ /m$^3$
- Intrinsic Free Carrier: $1.5\text{x}10^{16}$ /m$^3$

Highest=0.1 % of the atomic density ($5\text{x}10^{25}$ /m$^3$)

Typical: $10^{21}$-$5\text{x}10^{24}$/m$^3$