Notes for ECE 30500 - Semiconductor Devices

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These are lecture notes for Fall 2025 ECE 30500 by professor Haitong Li at Purdue. Modify, use, and distribute as you please.

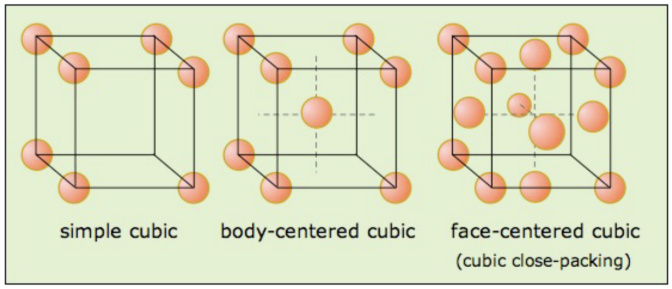
Contents

Properties of Silicon

The core of semiconductors lies in the silicon transistor. But, why silicon (**Si**)?

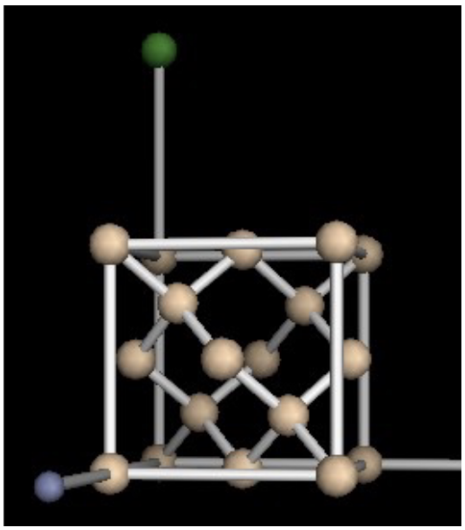
- Si is the second most common element on Earth.
- It is easily purified, and grown defect free, with less than 1 impurity in 10^9 atoms.
- Reasonably good electronic properties
- Resilient to harsh environments
- Excellent mechanical properties
- There are three forms of Si:
  - In a Si crystal, atoms are arranged in an orderly array, allowing arrangements to be easily reproduced.
  - In poly-crystalline Si, many crystalline subsections exist.
  - In amorphous Si, there are no long range patterns or arrangements.

The unit cell is a portion of any crystal that could be used to reproduce the crystal.
The primitive cell is the smallest possible unit cell.
In essence, a unit cell is a subset of a lattice that can be moved in the x, y, z axis, and cover the entire lattice. (*Note the absence of rotation movements.*)
Some examples of cells are the following:



Note: the image is missing a corner atom.

Another important cubic unit cell is the diamond cubic unit cell with 8 silicon atoms in the cell:



Density (diamond cube cell)

Lattice constant: $a = 5.3407 Ang$
Atomic mass: 28.055amu
Density: $\rho = \frac{8*28.0855*1.6605*10^{-23}}{(5.4307*10^{-10})^3} kg/m^3 = 2.3296 g/cm^3$

Miller Indices

Let us consider a plane that intercepts the axes at $x_{int}, y_{int}, z_{int}$. The equation of the plane is:

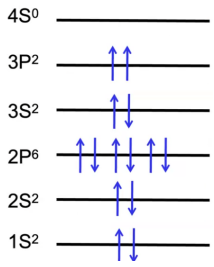
$$\frac{x}{x_{int}} + \frac{y}{y_{int}} + \frac{z}{z_{int}} = 1$$

The vector that is perpendicular to this plane will have the same components as the Miller indices.
The Miller indices are defined as $LCM * (\frac{1}{x_{int}}, \frac{1}{y_{int}}, \frac{1}{z_{int}})$.

Energy Bands

Quantization of Energy Levels

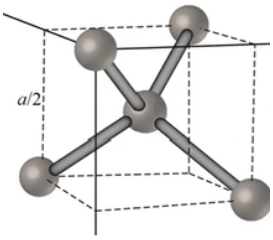
Bohr hypothesized, in his atomic model, that there was a quantization of electron angular momentum and energy levels.
In the context of this class, these levels will be described by $n \in \mathbb{N}$.
Additionally, the energy of these levels is $E_H = -\frac{13.6}{n^2} eV$.
The energy levels of silicon are as shown below:



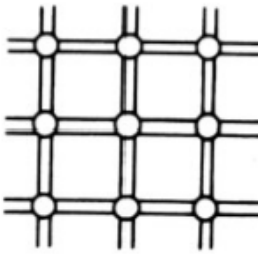
The further from the core, the more energy is within, so, in the image above, $4S^0$ is the layer with the most energy.
The four electrons in the valence region ($3P^2, 3S^2$) are the easiest to break away from the atom.

Bonding Model

Only the four valence electrons are of interest. Each of these, is shared with one of the four nearest neighbors, forming a structure like this:



This is the base of the silicon lattice, from which more complex lattices can be formed. The full model can be abstracted as follows:



where a line is a shared valence electron and a circle is the core of the semiconductor.

Energy Levels

When going from a single Si atom to a Si crystal with many atoms, the atoms are closely packed enough that we cannot treat them as individual atoms. The structure that is formed is very stable as all the atoms and their energy levels are completely filled.

Note: Current cannot flow from full energy levels.

The energy levels of these atoms are in the following order:

conduction band

. . . . . .

↑

band gap

↑

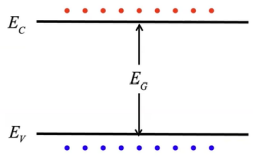
. . . . . .

valence band

The conduction band and the valence band are energy levels where electrons can reside.
Electrons can be freed from their bonds by heating the lattice to temperatures close to $300K$. The thermal energy provided by this is defined by:

$$E = \frac{3}{2}kT$$

The freed electrons are analyzed in terms of their energy states. When freed, they are moving from the valence band (leaving behind a "hole" in the valence band), jumping over the band gap and arriving at the conduction band.
The band representation can be further abstracted to look like this:



Where the red dots are conduction band electrons (n) and the blue dots are valence band holes (p).

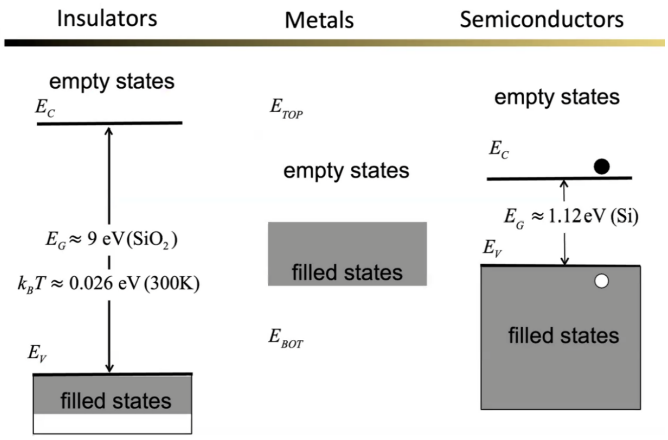
Note: an intrinsic semiconductor is that in which $n = p = n_i$.

$$n_i = BT^{\frac{3}{2}} e^{-\frac{E_g}{2k_B T}}$$

Constants to Remember

$$
\begin{aligned}
E_G(Si) &= 1.12eV \\
E_G(GaAs) &= 1.4eV \\
k_BT &= 0.026eV \text{ at } (T = 300K) \\
P &\approx e^{-E_G/k_BT} \\
n_i(Si) &= 1 \times 10^{10} cm^{-3} \text{ at } (T = 300K) \\
n_i(GaAs) &= 2 \times 10^{6} cm^{-3} \text{ at } (T = 300K)
\end{aligned}
$$

Material Representations



Note that the main difference between an insulator and a semiconductor is the size of the band gap. On the other hand, metals have no band gap at all, and all the electrons are free by default.

Carrier Properties

Electrons are in the conduction band, and they can move between states.
Holes are in the valence band, and they can move between states.
Electrons and holes can recombine and regenerate.
When there are no perturbing forces, equilibrium occurs.
When a highly energetic photon hits an electron in the valence band, it pushes it into the conduction band and leaves a hole behind in the valence band.

$$E_{ph} = hf \gg E_G$$

Usually, the force on an object is defined by $F = m_0 a$, but, this cannot be so simply applied to the case of forces on electrons. Instead, the

formula is:

$$F = m_n^* a$$

where m_n^* is the effective mass of the electrons, and it includes

- Cyclotron
- Conductivity
- **Density of States**

Similarly, for a hole, $F = m_p^* a$.

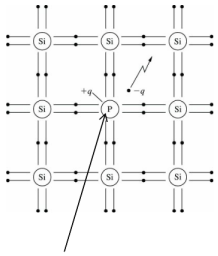
Materials	m_n^*/m_0	m_p^*/m_0
Si	1.18	0.81
Ge	0.55	0.36
GaAs	0.066	0.52

The energy of electrons in vacuum resemble a parabola when compared with momentum:

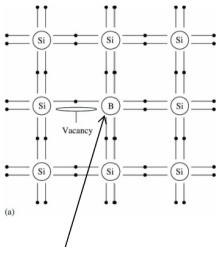
$$E = \frac{p^2}{2m_0} \rightarrow E_n = E_C + \frac{p^2}{2m_n^*}$$
$$p = m_0 v \rightarrow p = \hbar k = \hbar \frac{2\pi}{\lambda}$$

Doping

The following is the process to n-dope a semiconductor sample:



and the process for p-doping:



- N-doping: When n-doping, with group V elements, very little energy is necessary to break the fifth electron from the element. The ionized donor is then left with 4 electrons and is bound to the lattice