

ECE 255, Introduction

9 January 2018

The semiconductor industry is one of the most rapidly growing industries. Many other industries have sprung from this industry, for example, electronics, communications, computer, internet, biomedical etc. Also, the rapid growth is also due to the rapid growth in the **integrated circuit** (IC) capability. It has given rise to the ability to pack a humongous number of transistors on a single chip. As of 2016, over 7 billion transistors can be put on a single chip, called a **monolithic integrated circuit**. The integrated circuit design (ICD) industry is a highly important industry; it is responsible for the design and production of computer chips needed for the modern world. The knowledge of this course is your first step in gathering the knowledge required to become an IC design engineer.

1 Periodic Table and Bandgaps

1.1 Periodic Table, Mole, and Atomic Weight

The periodic table was discovered and put together by Mendeleev (1834-1907). Before him, scientist knew that different elements have different atomic weights. But Mendeleev saw the rhyme and reason behind them, and organized them in columns and rows: that was the beginning of the periodic table.

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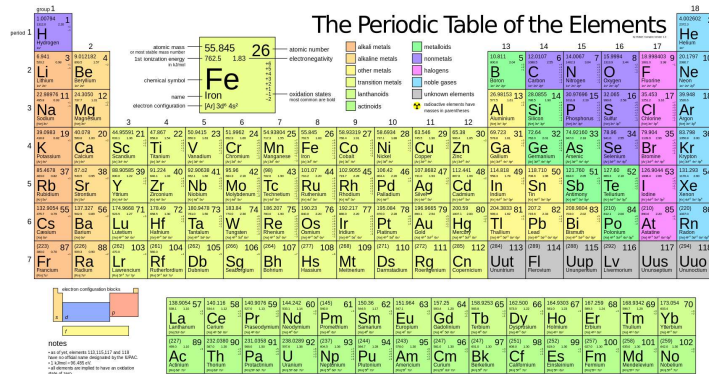


Figure 1: The complete periodic table showing all the elements.

The above shows a complete periodic table, but for this course, only the column with four valence electrons is the most important, plus the elements from the adjacent columns.

	IIIA	IVA	VA	VIA
5	10.811	12.01115	14.0067	15.9994
	B	C	N	O
	Boron	Carbon	Nitrogen	Oxygen
13	26.9815	28.086	30.9738	32.064
	Al	Si	P	S
	Aluminum	Silicon	Phosphorus	Sulfur
30	65.37	69.72	72.59	78.96
	Zn	Ga	Ge	As
	Zinc	Gallium	Germanium	Arsenic
48	112.40	114.82	118.69	121.75
	Cd	In	Sn	Sb
	Cadmium	Indium	Tin	Antimony
80	200.59	204.37	207.19	208.980
	Hg	Tl	Pb	Bi
	Mercury	Thallium	Lead	Bismuth
				Po
				Polonium

Figure 2: The sub-periodic table showing elements around carbon (C) column which has four valence electrons. The important elements are in the shaded area of the table (courtesy of Jaeger and Blalock).

Figure 2 shows a sub periodic table around the carbon column which has four valence electrons. But elements from columns with less than four valence electrons can combine with elements from column with larger than four valence electrons to make a semiconductor. The silicon-germanium (SiGe) compound semiconductor has recently found useful applications in many fronts such as mixed signal circuits (analog plus digital circuits). It was introduced by IBM in 1989.

Semiconductor	Bandgap Energy E_G (eV)
Carbon (diamond)	5.47
Silicon	1.12
Germanium	0.66
Tin	0.082
Gallium arsenide	1.42
Gallium nitride	3.49
Indium phosphide	1.35
Boron nitride	7.50
Silicon carbide	3.26
Cadmium selenide	1.70

Figure 3: Bandgaps of various semiconductors. Some are called III-V or II-VI compounds because they are formed with elements from columns III and V, or columns II and VI (courtesy of Jaeger and Blalock).

Figure 3 shows the bandgaps of various semiconductors. Most are from column IV.

One other concept you should know is Avagadro's number (1776-1856) which is $\approx 6 \times 10^{23}$. It is a humongous number and is the number of atoms in one mole of elements. For instance, one gram of hydrogen has about 6×10^{23} atoms. This concept can be used to define *mole* and *atomic weight* (also called atomic mass).

1.2 Bandgaps, Insulators, Semiconductors, and Conductors

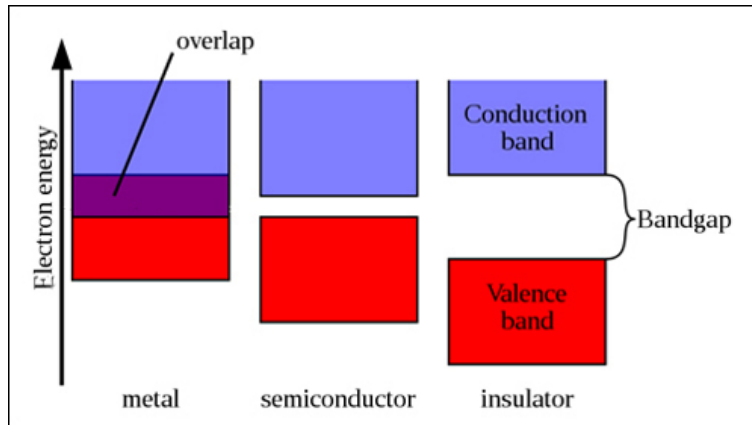


Figure 4: Bandgaps of various materials. Metals have no bandgap, insulators have large bandgaps, and semiconductors have small bandgaps.

Most materials have a bandgap. It is the energy gap between the conduction and valence band of a material. When the gap is large, it is hard for electron to jump from the valence band to the conduction band. Hence, there is no conduction electrons around: electric current cannot flow. This is the mark of an *insulator*. But when the gap is small, the electron may jump from the valence band to the conduction band even at room temperature. This material can conduct electricity but not well. This is the mark of a *semiconductor*. However, when the bandgap is small, or nonexistent, then the conduction band is replete with electrons, which form the conduction electrons. These electrons can conduct electricity well. This is the mark of a *conductor*.

- Electronic materials fall into three categories:
 - Insulators, resistivity $\rho > 10^5 \text{ } \Omega\text{-cm}$
 - Semiconductors, $10^{-3} < \rho < 10^5 \text{ } \Omega\text{-cm}$
 - Conductors, $\rho < 10^{-3} \text{ } \Omega\text{-cm}$
- Elemental semiconductors are formed from a single type of atom, typically silicon.
- Compound semiconductors are typically formed from combinations of column III and V elements or columns II and VI.
- Germaniums was used in many early devices. The first transistor was build with germanium.

- Silicon quickly replaced germanium due to its higher bandgap energy, lower cost, and is easily oxidized to form silicon-dioxide insulating layers.

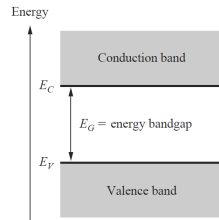


Figure 2.10 Energy band model for a semiconductor with bandgap E_G .

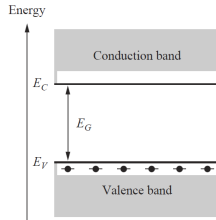


Figure 2.11 Semiconductor at 0 K with filled valence band and empty conduction band. This figure corresponds to the bond model in Fig. 2.2.

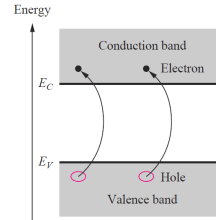


Figure 2.12 Creation of electron-hole pair by thermal excitation across the energy bandgap. This figure corresponds to the bond model of Fig. 2.3.

Figure 5: Figures showing bandgap in a semiconductor at 0 °K and room temperature (courtesy of Jaeger and Blalock).

Figure 5 shows the bandgap of a semiconductor at 0 °K and at room temperature. At 0 °K, the electrons are “frozen” into the valence band, and the semiconductor cannot conduct since there is no conduction electron in the conduction band. At room temperature, some electrons are excited into the conduction band making a semiconductor being able to conduct electricity.

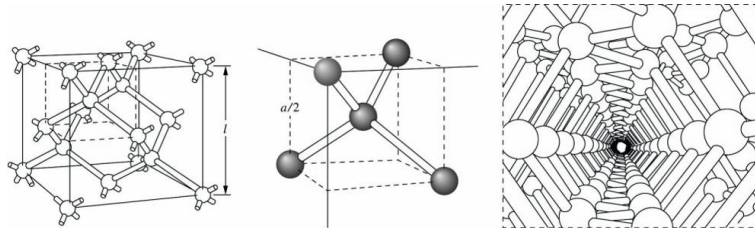


Figure 6: The lattice structure of diamond. (Left) A unit cell. (Center) A carbon atom connected to the next nearest four diamond atoms. (Right) The diamond lattice structure viewed from another angle, along the crystallographic axis (courtesy of Jaeger and Blalock).

2 Intrinsic Semiconductors

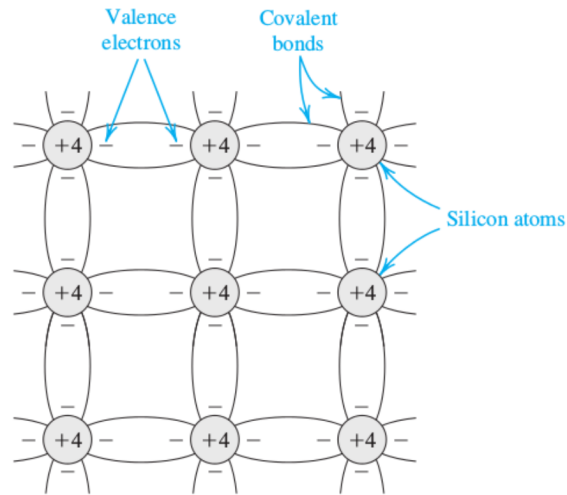


Figure 7: A cartoon picture of the silicon crystal lattice at 0°K (courtesy of Sedra and Smith).

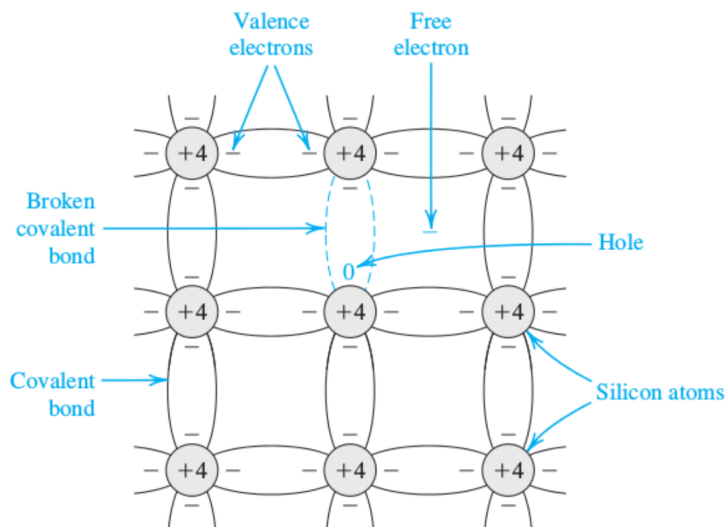


Figure 8: At room temperatures, some of the covalent bonds are broken, freeing some electrons, leaving behind holes (courtesy of Sedra and Smith).

2.1 Electron-hole Concentrations

When a semiconductor is undoped, there will be holes and electrons charge *carriers* generated in the material due to thermal agitation of the environment. The movement of these charge carriers gives rise to electric current flow.

- A vacancy is left when a covalent bond is broken due to thermal agitation of the environment.
- The electron is free to roam, and the vacancy is called a hole. This is called electron-hole pair generation.
- A hole moves when the vacancy is filled by an electron from a nearby broken bond (hole current).
- The hole density or concentration is represented by p . The electron carrier concentration is represented by n .
- For intrinsic silicon with no doping, $n = p = n_i$.
- The product of electron and hole concentrations is $pn = n_i^2$.
- The pn product above holds when a semiconductor is in thermal equilibrium (not with an external voltage applied).

The electron-hole pairs are generated by thermal agitation or breaking of the covalent bonds. They are removed when the electron-hole pairs recombine. The electron-hole pairs recombine with a rate proportional to pn while they are generated with a rate proportional to n_i^2 . At thermal equilibrium, these two rates are the same; hence $np = n_i^2$. It can be shown that this formula remains valid for doped semiconductors.

According to Boltzmann's law (1844-1906), the following formula can be derived: The number of valence bond per cm^3 that is broken forms electron-hole pair. The electron concentration (with similar number for hole concentration) is

$$n_i = BT^{3/2}e^{-E_g/(2k_B T)} \quad (2.1)$$

where

$$B = 7.3 \times 10^{15} \text{K}^{-3/2} \text{cm}^{-3} \quad (2.2)$$

T is the temperature in degree Kelvin K, E_g is the bandgap energy, and k_B is $8.62 \times 10^{-5} \text{K}^{-1} \text{eV}$ is the Boltzmann constant. The hallmark of the above formula is that the higher the temperature T , the larger the number of broken bonds, and hence, more the electron-hole pair generated. The larger the bandgap energy E_g , the harder the bond is to be broken, and hence, the less electron-hole pair generated. A sketch for the derivation of the above formula is given in the Appendix.

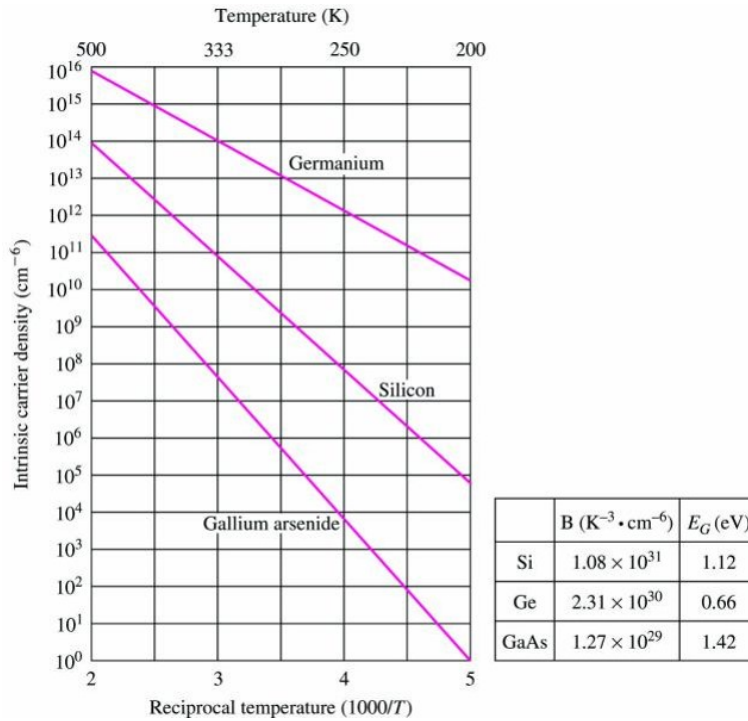


Figure 9: Intrinsic carrier density as a function of temperature. The higher the temperature, the higher the intrinsic carrier density as more covalent bonds are broken (courtesy of Jaeger and Blalock).

The room temperature $T_{\text{room temp}}$ is usually taken at 300°K . The bandgap of silicon $E_{g\text{-si}}$ is 1.12 eV where eV stands for electron volt which is a unit of energy.

For intrinsic silicon, $n_i = 1.5 \times 10^{10}$ carriers/cm³, whereas the number of silicon bonds is about $\approx 5 \times 10^{22}$ /cm³. Therefore, n_i is very small, or one electron per 10^{13} Si bond.

3 Doped Semiconductors

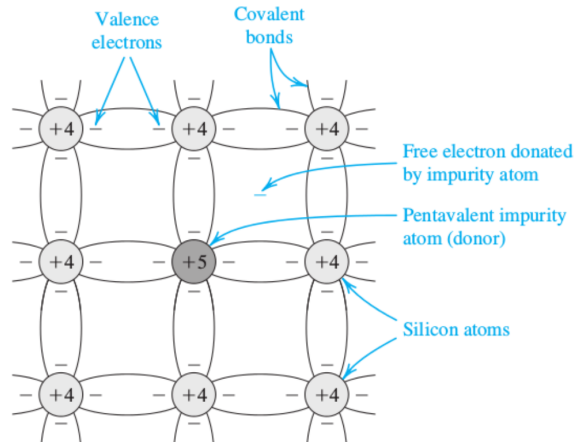


Figure 10: The doping of a column IV semiconductor by a donor impurity from column V with five valence electrons. As a result, an extra electron is free to move around (courtesy of Sedra and Smith).

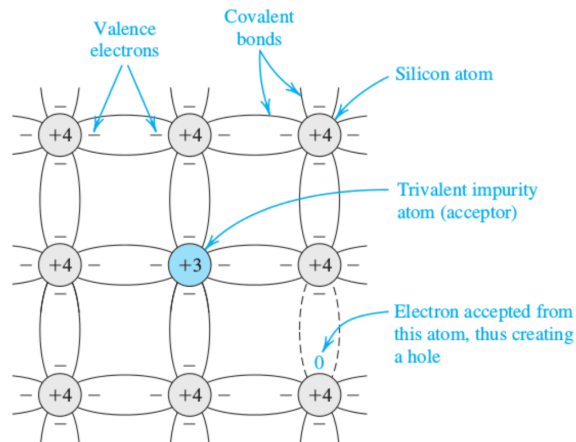


Figure 11: The doping of a column IV semiconductor by an acceptor impurity from column III with three valence electrons. As a result, an extra unfulfilled bond is generated, resulting in a ‘hole’ in the lattice (courtesy of Sedra and Smith).

Because np is approximately a constant, the ratio of electron-hole concentration can be changed by doping. A donor atom contributes to an electron while an

acceptor atom contributes to a hole (or a vacancy in a valence bond). The donor concentration is usually denoted by N_D while the acceptor concentration is denoted by N_A .

3.1 Donor Impurities in Silicon

When silicon is doped with donor impurities from column V elements, the following happens:

- Phosphorous (or other column V elements) atom replaces the silicon atom in the crystallin lattice.
- Since phosphorous has five outer shell electrons, an ‘extra’ electron is released in the lattice structure.
- The material is still charge neutral, but little energy is needed to move electron for conduction since it is not bonded to the atoms.

Such a silicon is called an n -type doped silicon. The electron carrier concentration (density) n is increased. Here, $n_n \approx N_D$, or that the electron concentration is approximately equal to the donor concentration (where the subscript n in n_n implies that it is the electron carrier concentration for n -type silicon).

With this in mind, doping can be used to change carrier density, to increase the conductivity of the semiconductor. Given that $p_n n_n = n_i^2$, and that $n_n \approx N_D$, then

$$p_n \approx \frac{n_i^2}{N_D} \quad (3.1)$$

Since $N_D \gg n_i$ by doping or material processing, it implies that $p_n \ll n_n$. Hence, the holes become minority carriers, while the electrons become majority carriers.

3.2 Acceptor Impurities in Silicon

For doping with column III elements, called acceptor impurities, similar things happen.

- Boron (or other column III elements) has been added to the silicon lattice.
- With only three valence electrons, there is now an incomplete bond pair, creating a vacancy for an electron similar to the hole in a broken covalence bond.
- Little energy is needed to move a nearby electron into this vacancy, creating a hole in its original bond.
- As the hole propagates, charge is moved across the silicon.

Needless to say, such a silicon is a p -type doped silicon. The hole carrier concentration (density) p is increased. Here, $p_p \approx N_A$, or that the hole concentration is approximately equal to the acceptor concentration, where the subscript p in p_p implies that it is the hole concentration for p -type silicon.

If we assume an acceptor concentration of $N_A \approx 10^{16}/\text{cm}^3$, then a silicon wafer is p -doped (or hole-doped or doped with boron), and the hole concentration is

$$p \approx N_A \approx 10^{16}/\text{cm}^3 \quad (3.2)$$

The electron concentration is

$$n = \frac{n_i^2}{p} \approx \frac{10^{20}}{10^{16}} \approx 10^4/\text{cm}^3 \quad (3.3)$$

Hence, the electron concentration is much much less than the hole concentration.

Appendix A Boltzmann's Law and Electron-Hole Pair Generation

Boltzmann's law is the underpinning law for many observations in semiconductor physics. It will not be derived but just stated here. If a system has many possible energy states E_i , $i = 1, \dots, N$, when the system is in thermodynamic equilibrium with another system such as a heat bath, then the probability of the system in a state with energy E_i is proportional to

$$P_i \sim C e^{-E_i/(k_B T)} \quad (A.1)$$

where k_B is Boltzmann constant with value $8.62 \times 10^{-5} \text{ K}^{-1}\text{eV}$, and T is the temperature in degree Kelvin. The above formula makes physical sense that the higher the energy of the state is, the less likely is the system going to be in that state.

The energy it takes to generate electron-hole pair (EHP) is E_g . After EHP, the system is in a higher energy state. Hence, the probability of electron-hole pair generation is proportional to

$$P_{EHP} \sim C e^{-E_g/(k_B T)} \quad (A.2)$$

Also the probability of electron-hole pair generation is proportional to the EHP recombination at equilibrium. The EHP recombination rate is proportional to the product of the densities of the electrons and holes. Hence,

$$P_{EHP} \sim n_i p_i \quad (A.3)$$

where n_i and p_i are the intrinsic electron and hole concentration in the semiconductor. Since $n_i = p_i$ in an undoped semiconductor, we deduce that

$$n_i \sim C' e^{-E_g/(2k_B T)} \quad (A.4)$$

Deriving the constant C' is a lot more advanced and is given in some advanced books. The above is the partial rationale for (2.1). To show that $pn = n_i^2$ will need the understanding of Fermi level which is outside the scope of this course.