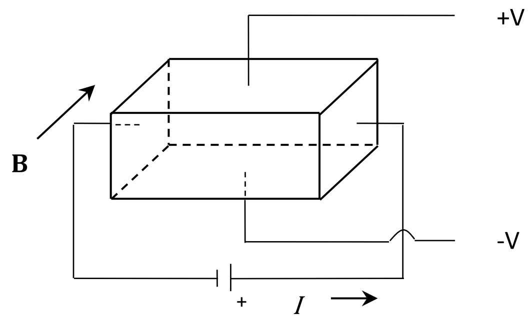
CHAPTER 4

Electricity, Transistors and the Hall Effect

So you are reviewing old fundamentals of engineering exam questions (perhaps you are getting ready to sit the exam or better still, you just like to solve problems) when you run across the following type of question.

Below is a rectangular piece of semiconductor connected to a power source (I; current) *and exposed to a magnetic field* ($\mathbf{B}$). *This Hall effect setup can be used to determine the polarity of the charge carrier and thus determine that the semiconductor is made from the following material**



(A) Metal

(B) P-type

(C) P-type or N-type

(D) Insulator

(E) N-type

*The Best Test Preparation for the Fundamentals of Engineering (FE) Examination, 1991, page 186

Diagram 4.1 - The Hall Effect Question

To answer this question, you need to know a number of things including: what are **P-type** and **N-type** materials; and what is the **Hall effect**? In this chapter we will develop the necessary electrical engineering knowledge to answer these questions and then discuss some of the practical ways that this knowledge is used today.

Basic Chemistry

As with so many things in our modern society, somehow chemistry is involved. Please find below a simple representation of a single **helium** (He) atom.

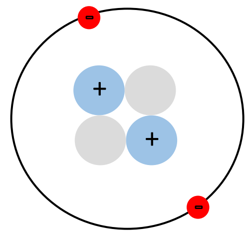


Diagram 4.2 – Helium Atom

Recalling high school chemistry, the helium atom consists of a center core or nucleus that contains two (2) protons and two (2) neutrons and, orbiting around the nucleus, are two (2) electrons. The protons carry a positive charge, the neutrons are neutral (carrying no charge) and the electrons carry a negative charge. The electrons are kept in their orbit around the nucleus because opposite charges attract each other (particles with the same charge, repel each other). The amount of charge on the electron and on the proton is measured in a quantity called a **coulomb** (C); the electron has a negative charge of 1.60×10^{-19} coulombs and the proton has a positive charge of 1.60×10^{-19} coulombs. These charges are very small, but remember the diameter of atoms range from approximately 1×10^{-10} m to 5×10^{-10} m (helium has a diameter of approximately 1.4×10^{-10} m).

As already stated, electrons orbit around the nucleus of the atom and the electron's orbit (including the spin of the electron about its axis) is completely defined by four (4) quantum numbers (**n, l, m_l, m_s**). We are only going to talk about the first or **principal** quantum number, or **shells**. The principal quantum number almost completely defines the energy possessed by an electron. As the quantum number increases, the energy level of the electron increases and the distance of the electron from the nucleus also increases.

Without getting too detailed, let's take a closer look at how electrons are organized around the nucleus. In the case of the helium atom the two (2) electrons share **shell 1**. The shells and the number of electrons that they can hold are shown below in **Table 4.1**.

The shells generally get filled one at a time. So, for example, the two electrons of the helium atom completely fill shell 1. The next chemical in the periodic table after helium is **lithium** (Li). Lithium has two (2) electrons in shell 1 and one (1) electron in shell 2. Understanding elements and their basic electronic structure is important as will be demonstrated as the chapter progresses. Next let's look at four elements that are very important to a discussion about electrons and electricity.

Shell No.	Obs. Max. No. Electrons
1	2
2	8
3	18
4	32
5	32
6	18
7	8
Total	**118**

Increasing Energy Level

Table 4.1 – Atomic Shells

As we all know, **copper** (Cu) is an excellent conductor of electricity, let's see why. Please see **Diagram 4.3**.

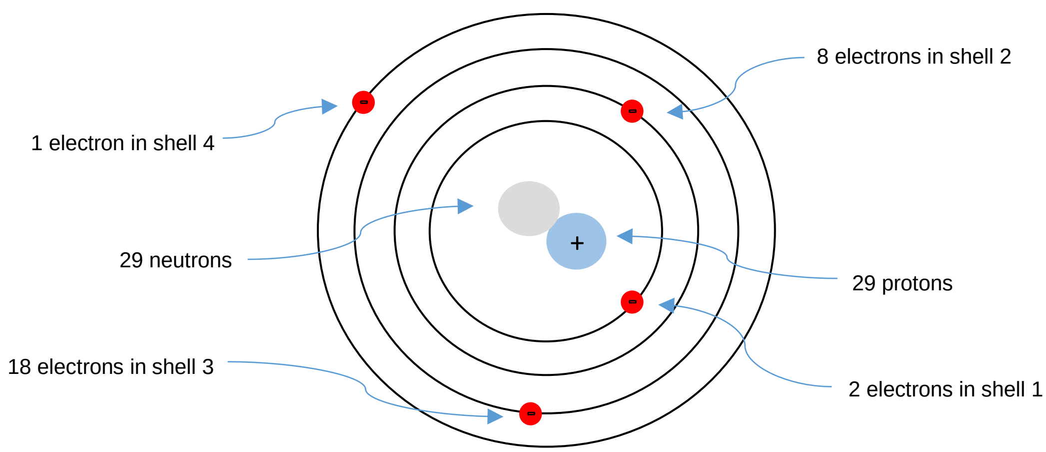


Diagram 4.3 – Copper Atom

The copper atom has a total of 29 electrons orbiting around its nucleus. While copper's outer shell or valence shell can contain up to 32 electrons, the copper atom has just one electron in its outer most shell. This single electron is only loosely attached to the copper atom and it can very easily become a free electron. These free electrons are said to be in the conduction band and are responsible for the fact that copper is an excellent conductor of electricity (see **Diagram 4.4**). More specifically, in the presence of an **electric field** (E) the electrons start to "**drift**". The motion of the electrons makes-up what is called, electric current (I). Current is measured in amperes (A) and 1 A equals 1 C/s or, put another way, the charge (q) associated with 6.25 x 10^{18} electrons where each electron (e) has a charge of -1.60 x 10^{-19} C

$$\text{Number of electrons} = q/e = 1\mathrm{C}/1.60 \text{ x } 10^{-19}\ \mathrm{C}/\text{electron} = 6.25 \text{ x } 10^{18} \text{ electrons}$$

It is important to recognize that the hole created by the absence of an electron is equivalent to a "real" particle that has a $+1.60 \times 10^{-19}$ C charge. Just like electrons, these holes are capable of movement, but generally in the opposite direction to that of electrons. As we shall see, we refer to the presence of electrons and holes as N and P respectively when discussing semiconductors.

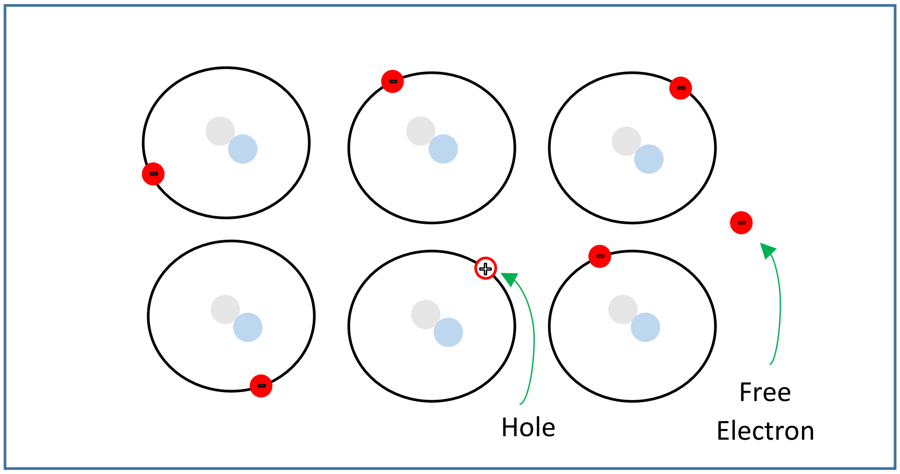


Diagram 4.4 – Conduction Band and Copper Atoms

One of the questions that is often asked is" How fast are these free electrons moving through the conductor that holds them? The speed (velocity) at which these free electrons "drift" is calculated by the following equation:

$$v_d = \frac{I}{qn_eA} = \frac{I}{qn_e\pi(d^2/_4)}$$

Where:

v_d = Drift velocity; cm/s

I = Current; C/s

q = Particle charge; C

n_e = Density of conducting particles; quantity/cm^3

d = Diameter of conducting material (wire); cm^2

Let's calculate the drift velocity of electrons in a no. 14 copper wire (0.1628 cm diameter) carrying 15 A.

$$n_e = (8.95\ \mathrm{g/cm^3})(1/63.5\ \mathrm{mol/g})(6.02\ \mathrm{x}\ 10^{23}\ \mathrm{mol^{-1}}) = 8.48\ \mathrm{x}\ 10^{22}\ \mathrm{cm^{-3}}$$

$$v_d = \frac{15\ \mathrm{A}}{(1.60\ x\ 10^{-19}\ \mathrm{C})(8.48\ x\ 10^{22}\ \mathrm{cm^{-3}})\left(\pi/_4\right)(.1628^2\mathrm{cm^2})} = .053\ \mathrm{cm/s}$$

Before completing the above calculation it may have been easy to expect that electrons travel at close to the speed of light (3 x 10^{10} cm/s). What has to be taken into account is that electrons in copper exist in a very crowded space and they are constantly colliding with other subatomic particles (in the order of once every 10^{-14} seconds). These collisions result in a "drift" not an actual straight line unimpeded travel.

The reason for a light bulb turning on immediately after flipping a switch is that the electric field in the wire changes at close to the speed of light.

Silicon (Si), the main element used in the manufacturing of semiconductors, is a poor conductor of electricity. Silicon has a total of 14 electrons, with its outer shell having four electrons. Silicon in its crystalline form satisfies the "desire" to have a total of eight electrons in its outer shell (please see **Diagram 4.5**).

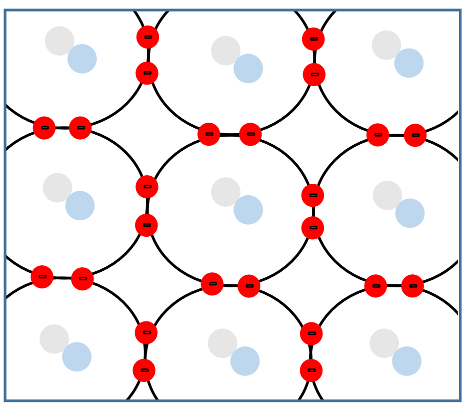


Diagram 4.5 – Crystal Silicon Structure

Silicon only becomes interesting once impurities are added to its crystalline structure; this is known as "**doping**".

Phosphorus (P) has a total of 15 electrons, with five electrons in its outer shell. When united with silicon, which (as was shown above) only needs four electrons to complete its outer shell, the result is a single electron which can freely move through the crystal lattice of the semiconductor. The phosphorus doping of silicon results in an **N-type** semiconductor that readily conducts electrons (-1.60 x 10^{-19} C of charge per electron).

The last element that we will look at is **boron** (B). Boron has a total of three (3) electrons, with electrons in its outer shell. Doping silicon with boron leads to a missing electron in silicon's outer shell (remember silicon needs eight (8) electrons to fill its outer shell). The result is a **P-type** semiconductor that readily conducts holes (+1.60 x 10^{-19} C of charge per hole).

Now that we have a general understanding about semiconductors let's take a look at how we might use semiconductors to put together a simple transistor.

Transistors

Diagram 4.6 shows a cross-section of a simple NPN transistor.

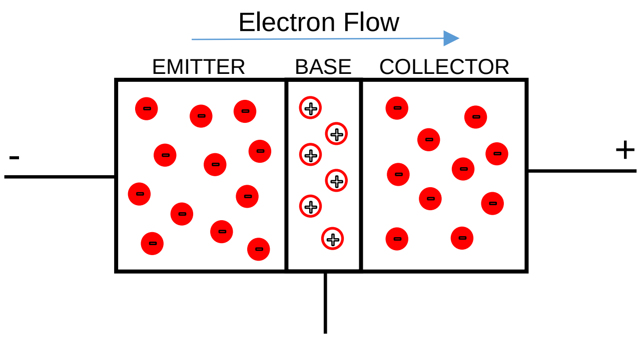


Diagram 4.6 – NPN Transistor

In the above diagram the electrons are attempting to travel from the **emitter** to the **collector**. As the free electrons pass through the very thin **base** it is important to note that the base is not only very thin but it is also very lightly doped (few holes available) and not connected to anything. Given the physical state of the base a large number of electrons do make it across to the collector, right up to the point where all of the holes in the base are filled. Once the holes in the base are filled all electron flow stops. The accumulated negative charge in the base repels the electrons trying to escape the emitter and within approximately 50 nanoseconds all current (electron flow) ceases. To get the electrons moving again a small positive voltage needs to be applied to the base drawing out the electrons that are bound in the holes. For every electron withdrawn from the base approximately 50 electrons move from the emitter to the collector.

The above description of how transistors work should make it is easy to see how transistors can be used as switches (on-off) and as amplifiers (a small current controlling a much larger current).

Now that we have a solid background in what electricity is and how it works in an electronic component like a transistor, let's discuss one more Hall effect related concept.

Direction of Current Flow

Since the time of Benjamin Franklin (1706 – 1790) we have had the following situation (see **Diagram 4.7**). While Franklin was able to discover through experimentation the presence of positive and negative charges, his belief was that the charge carrier that moved through a metal was positive and therefore concluded that electrical current flowed from positive to negative; this is now known as **conventional current flow**. Unfortunately for Franklin, he was wrong. The actual moving charge carrier in metals is negatively charged and therefore the actual current flows from negative to positive (**electron current flow**). However this wasn't proven until the discovery of the Hall effect by Edwin Hall in 1879.

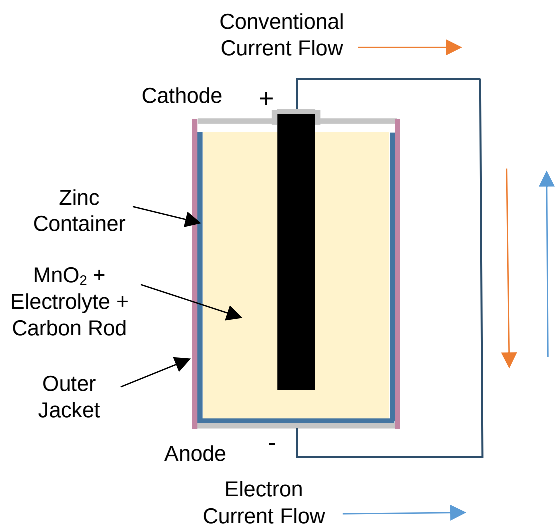


Diagram 4.7 – The Leclanché Cell and the Direction of Current Flow

The Leclanché cell, better known today as the zinc-carbon battery, was first assembled by Georges Leclanché in 1866. The chemical reactions that occur to produce the approximately 1.5 volts of electricity are as follows.

Reaction at the Anode (oxidation – loss of electrons).

$$Zn + 2OH^{-} \rightarrow ZnO + H_2O_{(l)} + 2e^{-}$$

Reaction at the Cathode (reduction – addition of electrons).

$$2MnO_2 + H_2O_{(l)} + 2e^{-} \rightarrow Mn_2O_3 + 2OH^{-}$$

Net Reaction.

$$Zn + 2MnO_2 \rightarrow Mn_2O_3 + ZnO$$

The Hall Effect

Now, to answer the question that started the chapter.

Applying a magnetic field perpendicularly to the thin conductor carrying an electric current will create a force (perpendicular to both the magnet field and the electric current) on the charge carriers, pushing them to one side of the conductor. This is known as the **Hall effect**. By using an apparatus similar to what is shown in **Diagram 4.8** Hall was able to prove that electrons are the charge carrier in metals. And, with the advent of the semiconductor, it was easy enough to repeat the Hall experiment and prove that electrons are the charge carrier in N-type semiconductors.

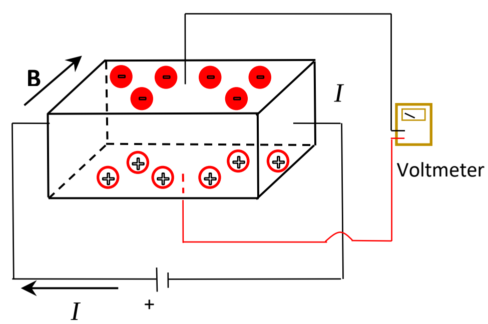


Diagram 4.8 – Hall Effect using Metals or N-type Semiconductors

The setup of the apparatus is straight forward. A strip of metal or N-type semiconductor has a current I passing through it; a magnetic field B placed perpendicularly to the current; and the resulting in the Hall electric potential (voltage) V_{Hall}, which can be measured using a voltmeter. Based on the conventional current flow the voltmeter displays a negative voltage.

Conducting the experiment again (see **Diagram 4.9**, but this time using a strip of P-type semiconductor will result in a reverse of polarity of the Hall electric potential (the voltmeter shows a positive voltage).

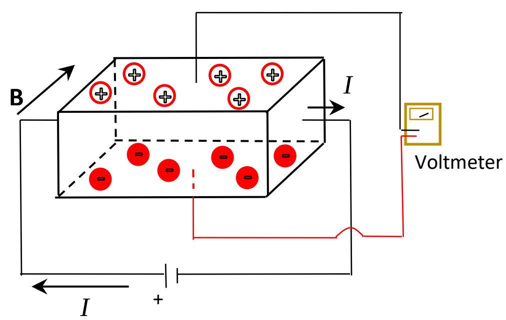


Diagram 4.9 – Hall Effect using P-type Semiconductors

So we have finally arrived at the answer to the question that was at the start of this chapter – the answer is: *(C) P-type or N-type* materials can be identified using the Hall effect.

In order to get some sense as to the magnitude of V_{Hall} let's calculate the Hall potential difference for a simple example.

Given a copper strip 2.5 cm wide and 100 µm thick (*d*) placed in a magnetic field of 1 T. If a current of 5 A is set up in the strip, calculate V_{Hall}.

$$V_{\text{Hall}} = \frac{IB}{qn_e d} = \frac{(5\text{ A})(1\text{ T})}{(1.6 \text{ x } 10^{-19}\text{ C})(8.4 \text{ x } 10^{28}/\text{m}^3)(100 \text{ x } 10^{-6}\text{ m})}$$

$$V_{\text{Hall}} = 3.7 \text{ x } 10^{-6}\text{ V}$$

While measurable, this is a relatively small voltage.

The Hall effect should not be confused with the (**integer**) **quantum Hall effect** (**IQHE**). The quantum Hall effect is an observed phenomenon requiring very cold temperatures (typically -268.95 **°**C), a two dimensional electron gas and a strong magnetic field (several tesla). Under these conditions one can acquire very accurate values for such quantities as **Planck's constant** (h) and the charge of an electron. The quantum effect was discovered by Klaus von Klitzing in 1980 and for which he received a Nobel prize in 1985. The IQHE finds very important use in the field of metrology.

Hall Sensors and their Applications

As was previously demonstrated (please see the calculation of V_{Hall} above), elements such as copper are relatively poor materials for the design of a Hall effect sensor. With the advent of semiconductors and more specifically the development of what are known as III-V compounds, (semiconductors based on periodic table groups III and V) larger Hall effect voltages can be produced. Such semiconductors as InAs (indium arsenide) GaAs (gallium arsenide) and InSb (Indium antimonide) are typically used in the production of Hall sensors. Engineers also use what is called the **open-circuit product sensitivity constant** (K_{HOC}) to calculate V_{Hall}. For example, a 125 mA current, a magnetic field of 3 kilogauss (3kG = 0.3 T) and using a thin film of InAs (K_{HOC} = 1.0 mV/mAkG); calculate the Hall voltage.

$$V_{\text{Hall}} = K_{HOC}\, IB = (1.0\text{ mV/mAkG})(125\text{ mA})(3\text{kG}) = 3.75 \text{ x } 10^{-1}\text{ V}$$

This Hall voltage is 5 orders of magnitude greater than the results of our previous Hall voltage calculation that used a copper strip as the carrier material.

To make this low voltage useful a low noise amplifier can be incorporated into the sensor's package. Temperature compensation can also be included if necessary. The whole sensor can be easily designed as a single **integrated circuit** (IC).

In the 21st century we find tens-of-thousands of different sensors available; many of them based on the Hall effect. Based on sheer quantity alone, Honeywell has produced over one billion Hall effect sensor devices.

Sensors measure the physical world and in the case of Hall effect sensors, they are used in such applications as:

- Valve positioning
- Flow meters
- Limit switches
- Joy sticks
- Security (card or key entry)
- Disk drives
- Ignition systems
- Proximity detection
- Pressure sensors
- Relays
- Lens positioning
- Fan/damper detection
- Vibration sensors
- Compasses

Conclusion

The chapter started by asking a question about the Hall effect and whether it could be used to determine the type of charge carrier in two different types of semiconductor. In order to answer this question we reviewed the basis of electrical conduction, defined two types of semiconductor material (N-type and P-type), how those semiconductors could be used in transistors and what the difference is between the conventional flow of current and electron current flow. Next, we clearly defined what the Hall effect is and showed how it can be used to determine the charge carrier in both conductors and semiconductors. Finally, we took a look at how the Hall effect is used in modern day electronics – it is used everywhere.