Extracted from:

# Things You Should Know

## A Peek at Computer Electronics

## The *Things You Should Know* Series

This series is a little different from our usual books. The *Things You Should Know* series highlights interesting topics in technology and science that you should know about. Maybe you took these courses in school, and promptly forgot about them. Or maybe you've always been curious but never had the opportunity to learn more.

Now you can. With these titles, you can quickly become familiar with (or remind yourself of) an interesting topic area. We hope it gives you something to talk about at the next cocktail party, or brown-bag lunch at work, or user's group meeting. It might even further inspire you to delve into the topic more deeply.

In either case, we sincerely hope you enjoy the show. Thanks,

► **Andy Hunt**

*An expert is a man who has made all the mistakes which can be made in a very narrow field.*

► Niels Bohr

# Chapter 6

# Semiconductors

## 6.1 Electrons through a Vacuum

In the first section of the book, we've introduced to electronics, electrical power, and how it relates to the computer system. In order to continue our study, we need to start focusing on some of the specifics of what makes a computer operate. This section of the book is centered around the processor—the brain that makes the computer tick.

Today's processors are made of millions of tiny semiconductor transistors. So before we can get too far into our study of processors we need to take a look at the building blocks of those transistors.

### The Edison Effect

When Thomas Edison was working on his incandescent bulb design in the 1880s, he ended up choosing a filament made of burnt bamboo. However, after a few hours of time, carbon from the filament built up on the inside walls of the bulb causing it to turn black.

Edison wanted to understand why this was happening. The carbon appeared to be coming from filament toward the power supply and was moving through the vacuum to the walls of the bulb. He surmised that the carbon must be able to carry electrical current even through the vacuum. Edison knew that the particles leaving the filament were negatively charged. To help, he added a second electrode to the bulb, between the filament and the bulb, like in Figure 6.1, on the next page. He reasoned that if he was able to place some positive charge onto this electrode it would attract the carbon and keep it from sticking to the wall.

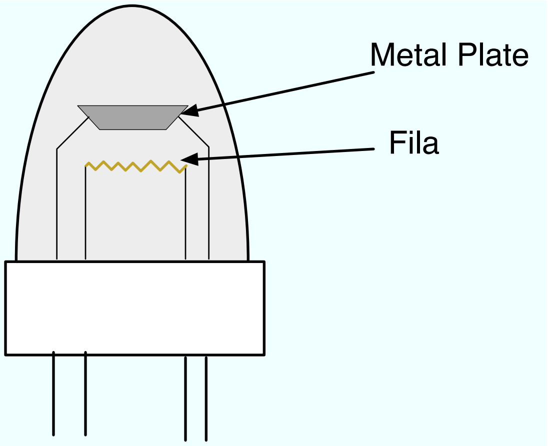


Figure 6.1: Edison's Bulb with Added Electrode and Plate

He found something strange: when the polarity of the electrode was positive with respect to the filament, current would flow into the electrode. However, when the polarities were reversed no current would flow.

Edison was not able to explain the reason why (and the electron would not be identified until some years later). His added electrode did not change the blackening problem caused by the carbon either. So he simply filed it away as an interesting concept and moved on to other projects. He did, however, file a patent on his device in case it turned out to have some special commercial application.

### The Electron (Vacuum) Tube

Edison had showed his invention to many people, including a British professor named Ambrose Fleming. Fleming had experimented greatly with the device. He found that it rectified AC current into DC. But there was still a lack of understanding as to why the device worked. Then, in 1889 Joseph Thompson discovered subatomic particles. Fleming quickly realized that the electron was being emitted from the filament and it gave reason as to why a positively charge electrode would attract them.

Based on his knowledge, Fleming created what he called an "Oscillation Valve", the first formal diode. He had been working a lot with wireless

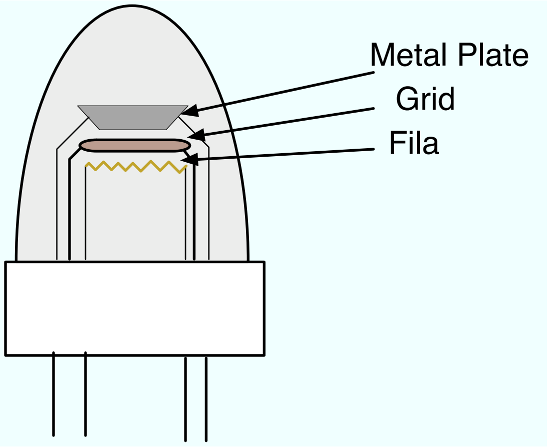


Figure 6.2: DeForest's Audion

### The Buzz. . .

**What's a Crystal Detector?**

Some natural minerals are able to detect radio signals. Using one of these materials along with a very thin wire known as a cat whisker, a capacitor, and an inductor, a circuit can be created that is able to receive radio signals.

communications and this invention was very helpful in the detection of the wireless signals.

Despite its apparent usefulness, the oscillation valve was not widely used. It was expensive to make and used a large amount of power. Competing devices resulted including a crystal detector (see The Buzz).

But investigations into vacuum tube technology continued. In 1907, Lee DeForest added a third electrode made of a grid mesh as shown in Figure 6.2. He found that by varying the amount of negative charge on the grid, he could control the amount of current that flowed through the two other electrodes. He called his invention the Audion.

DeForest had no idea how profound his invention was. Vacuum tubes were ideal for amplification. One interested customer, A.T.&.T. became interested in being able to broadcast voice signals further—even all the way across the country. They bought the patent from DeForest.

Over time, new applications for vacuum electron tubes were found. New devices with more electrodes were invented that allowed other types of control. But nothing was able to overcome how large and bulky vacuum tubes were. The heat generated by the electrodes made large scale use impractical.

Luckily, some scientists were searching for a replacement to the vacuum tube. We discuss this replacement, the solid state *transistor*, in more detail in Chapter 7, *Transistors*, on page 111. However, to understand how this replacement works we have to look into the physics of semiconductors.

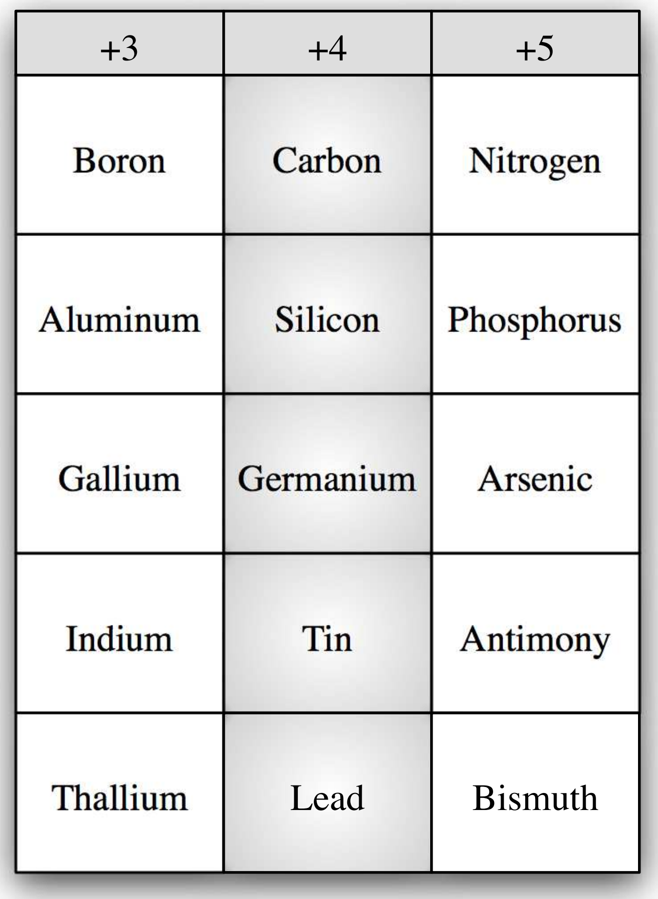
## 6.2 Semiconductors

From the name, you can probably infer that semiconductors are just average conductors. The main features of a natural semiconductor are:

- A higher resistance than metal conductors, but a lower resistance than insulators.
- A valence number of +4. (refer to Appendix A, on page 219 for a refresher on what this means)

The two most commonly used semiconductor elements are Silicon and Germanium. Their +4 valence numbers mean that they have a very stable covalent bond structure, as seen in Figure 6.4, on page 106. In its natural form like this, semiconductor silicon is known as an *intrinsic* semiconductor.

One way that semiconductors differ from conductors, such as metals, is in their how their resistances change with temperature. In metals, a rise in temperature causes the atoms to exhibit more vibration which creates collisions in the structure, impeding the flow of electrons. In a semiconductor, however, added heat actually causes the resistance to decrease. This is because the added energy goes into the valence electrons and makes it easier for them to jump into the conduction band and become charge carriers.



| +3 | +4 | +5 |
|---|---|---|
| Boron | Carbon | Nitrogen |
| Aluminum | Silicon | Phosphorus |
| Gallium | Germanium | Arsenic |
| Indium | Tin | Antimony |
| Thallium | Lead | Bismuth |

Figure 6.3: The periodic table of +3,+4, and +5 valence elements

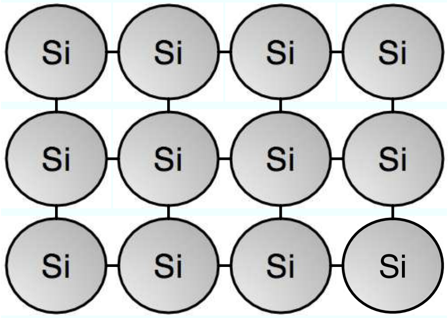


Figure 6.4: silicon's covalent bond structure

## 6.3 Doping

The usefulness of pure silicon as a semiconductor is limited. However, if we add small amounts of non-silicon material into the structure things become much more interesting.

This process of adding *impurities* to a semiconductor is known as *doping*. Doping results in *extrinsic* semiconductors, meaning they are not in their natural form.

Since a normal semiconductor has a valence of +4, a small amount of impurity will cause a charge imbalance. Take for instance the adding of a phosphorus atom to the structure as in Figure 6.5, on the next page. This phosphorus atom in the structure bonds with the silicon atoms around it. However, with its valence of +5, it has an extra electron available for bonding that is unused in the structure.

Doping a pure semiconductor with a small amount of material with a valence number of +5 (which inclues Phosphorus, Arsenic, and Anitmony) creates an *n-type* semiconductor. It is referred to this because of the excess of free electrons in the material.

Similiarly, you create a a *p-type* semiconductor by doping a pure semiconductor with a small amount of material with valence number of +3 (Boron, Aluminum, Gallium, and Indium). This results because of a hole that is left by the absence of an electron in the covalent bond structure.

Note that doping a semiconductor does not add or remove any charge. The resulting product is still electrically neutral. Doping simply redis-

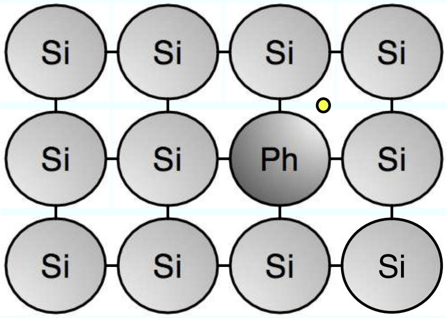


Figure 6.5: A silicon structure with added phosphorus impurity and free electron

tributes valence electrons so more or less free charges are available for conduction.

## Understanding Holes

The idea of holes is a bit intriguing. A hole really is a place where an electron could be, or moreso *wants* to be. If there is an electron nearby, it will jump into a hole and fill it up.

Electron holes aren't really holes at all. It's just a convenient description for visualizing energy interactions between electrons and nuclei. In order for there to be an electron hole at all, some energy has to be used to free an electron from the grasp of the nucleus. The removal of the electron tips the nucleus slightly out of balance. It then begins using this energy to attract another nearby electrons to join back up.

In Section 2.4, *Current Conventions*, on page 25, we talked about the difference between hole and electron current. The same idea exists in semiconductors. Within the n-type semiconductor we think of electrons being the major current carrier. In the p-type semiconductor, holes are the major current carrier.

One interesting thing to remember about holes is that the movement of the hole through the p-type material is due to the movement of the *bound* electrons in the structure. That is, the crystal re-bonds from atom to another atom and the hole "moves" in the opposite direction.

Just remember that a hole is nothing more than an empty place where an electron could be.

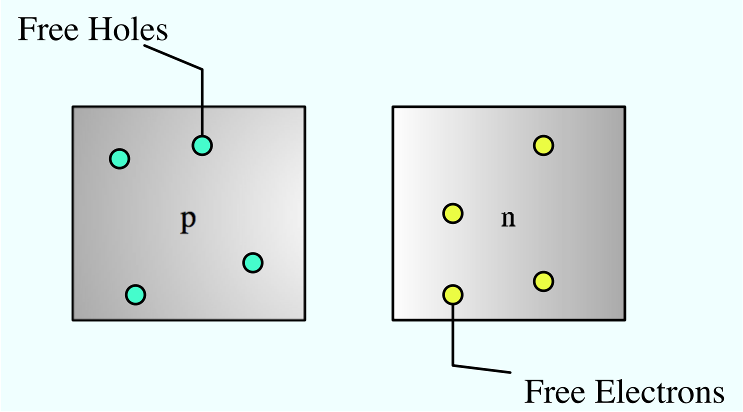


Figure 6.6: P-type and N-type materials

## 6.4 The PN Junction

The first interesting thing we can do with our doped semiconductors is to put a small piece of n-type semiconductor next to a small piece of p-type semiconductor. The extra electrons in the n-type conductor attempt to move over into available holes in the p-type conductor. At the same time, some of the holes in the p-type conductor end up moving over to the n-type to meet up with electrons. When this happens, we end up with an excess of electrons on the p-type side and extra electrons on the n-type side, creating an electrical imbalance.

This electrical imbalance is known as the *barrier potential* and is shown in Figure 6.7, on the next page. In silicon, this barrier potential is about 0.7 Volts.

The p-n junction becomes interesting when we apply an external voltage to it. But in which direction shall we apply the voltage? There are two possibilities which we call the forward and reverse bias.

## 6.5 P-N Bias

### Forward Bias

If we apply a positive voltage to the p-type material and a negative voltage to the n-type material, we are applying a *forward bias* to the semiconductor. First, the negative voltage at the n-type material is going

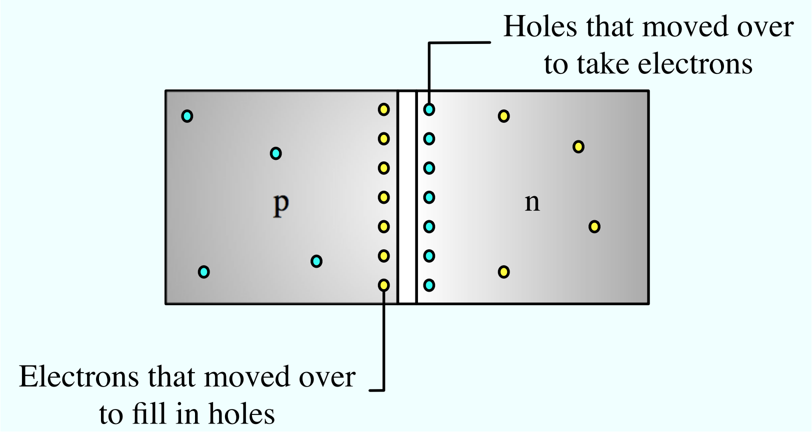


Figure 6.7: The barrier between p-type and n-type materials

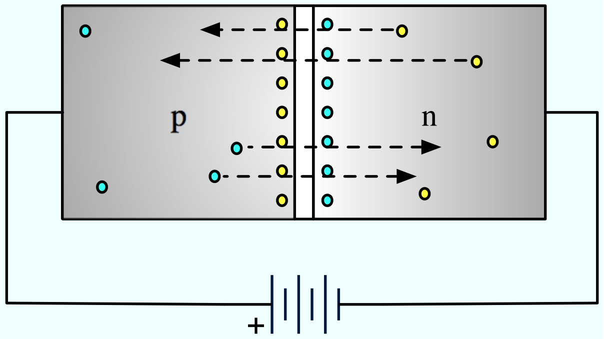


Figure 6.8: A forward biased p-n junction

to attempt to push electrons towards the junction in the middle. The positive voltage at the p-type material will push the holes towards the barrier as well. This reduces the barrier potential.

If the barrier potential is reduced enough, the charge carriers can move through the barrier and out the other side. This means that current flows.

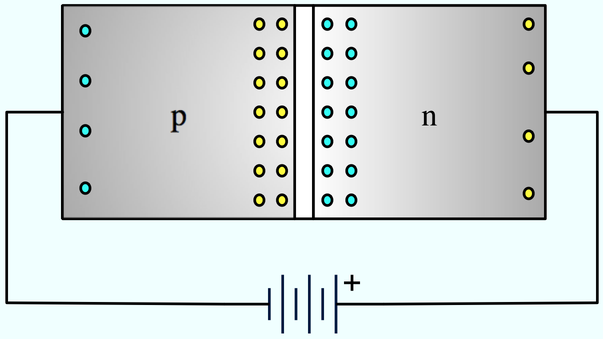


Figure 6.9: A reverse biased p-n junction

## Reverse Bias

Applying a reverse voltage to our semiconductor material is known as *reverse bias*. In this condition, the electrons are pulled away from the barrier on the n-type side and the holes are pulled away from the barrier on the p-type side. This results in a larger barrier, which creates a much greater resistance for charges to flow through. The net result is that no current flows through the barrier.

*If you want to succeed, double your failure rate.*
► Thomas Watson, Inventor of the Transistor

## Chapter 7

# Transistors

## 7.1 The History

After World War II, A.T.&T.'s Bell Laboratories started putting more research into semiconductor technologies. A team of William Shockley, Walter Brattain, and John Bardeen was assembled to work on a semiconductor replacement to the vacuum tube.

In the spring of 1945, Shockley had designed the first semiconductor amplifier. His group refined the concepts, even competing with one another to show up each other with a better design.

By 1948, a refined enough product was available and Bell Labs introduced it to the public. Sales were slow, so Shockley quit Bell Labs to start Shockley Semiconductor Laboratories to focus on a more desirable product.

But Shockley's abrasive personality eventually drove away some of his top people; they started their own company: Fairchild Semiconductor. Soon, other companies such as Intel and Texas Instruments started working on their own transistor designs.

It wasn't long before the viability of the semiconductor transistor as a replacement to the vacuum tube caught on.

## 7.2 The use of transistors

Transistors are three terminal semiconductor devices that are primarily used for two purposes: amplification and switching. One terminal of the transistor is typically used as a control terminal, which a voltage or current applied to the terminal causes the transistor's characteristics

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