LET'S LEARN ABOUT DIODES

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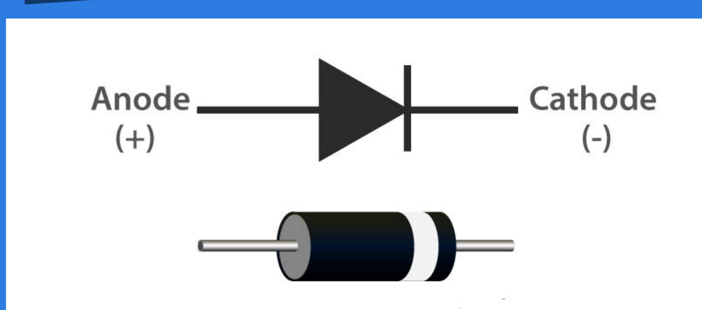
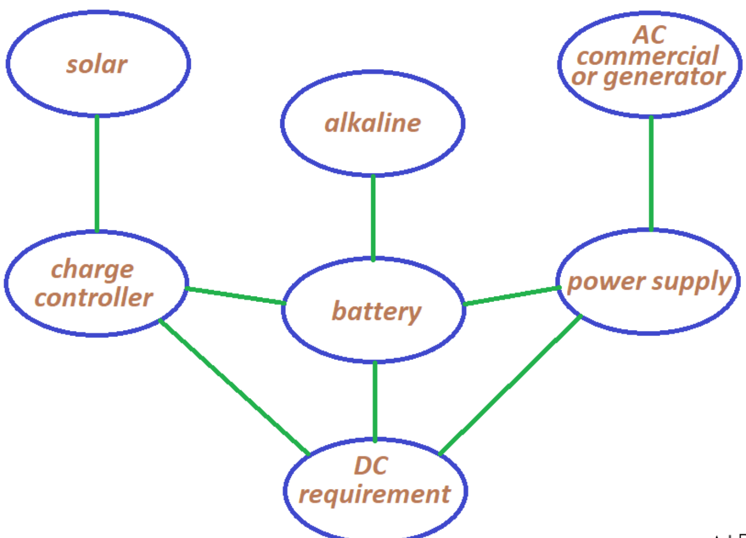


Brass Tacks

An in-depth look at Diodes with MW0JWP

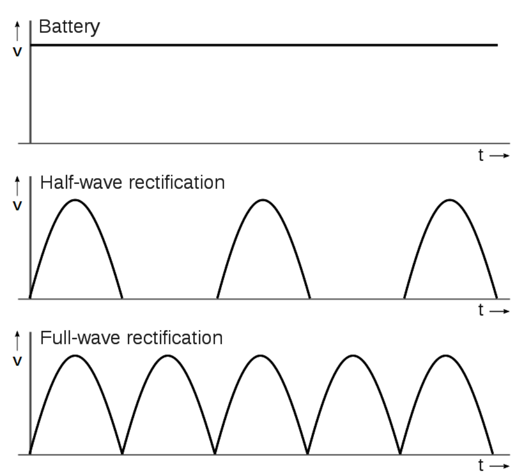
Diodes

DC (*direct current*) makes the electronic world go 'round. At least, most electronic circuitry, especially digital circuits, require the relatively uniform voltage and current supplied as DC. The three most conventional methods of obtaining DC energy are by solar power, with a battery, and through a power supply. Solar power converts sunlight directly into DC, but it's only available during daylight hours. A battery is a great source, night and day, but must be recharged often, either from solar power, or through a power supply. A PSU (power supply unit) is a device that converts AC (alternating current) into DC, and can supply the required DC as long as commercial or generator power is available.



Most of us tend to think of DC as a constant-voltage source, such as that from a battery. However, the non-technical definition of DC is *current flow that does not change directions*. By this description, DC can possess a time-varying value, and not be confined to a steady-state. If a device can therefore convert AC into a signal that does not change direction, we can say that the device has "rectified" (corrected, or made positive) the AC supply into DC. Such a *rectifier* would at least partly satisfy the need to provide a constant DC power source.

A hundred or so years ago, we hadn't yet learned how to harness solar power for electrical use, and batteries were quite primitive, requiring frequent recharging. AC was easily generated, but methods of converting it into DC were crude and sometimes even mechanical. In 1880, Thomas Edison advanced the work of others to observe that heated metal can conduct electrical current in one direction, later called the Edison Effect. It wasn't until 1904, when John Fleming patented the first production electronic ***diode***, the *Fleming valve* (British for *vacuum tube*), that AC rectification became globally available, revolutionizing the generation of DC for electronic equipment generally.



Examples of direct current

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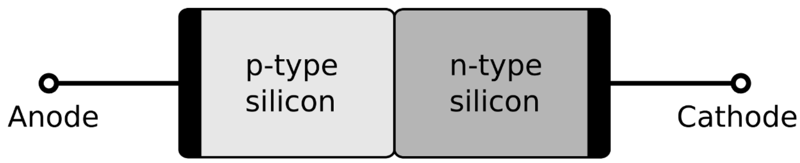
There were a number of solid-state researches in parallel with the development of the tube diode, but it wasn't until 1946 that a generally available *crystal diode* was developed by Sylvania. The 1950s saw the advent of the ***junction semiconductor diode***, the primary type we use today, and the focus of this discussion. Let's take a close look at how this electronic one-way street performs its magic.

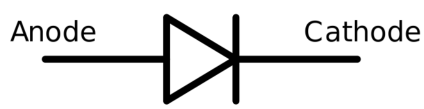
How it works



A semiconductor diode is made from a slice of silicon, which is an insulator. One side of the wafer is infused ("doped") with phosphorus, to form what's known as an *n-type* material for negative charge carriers (electrons), and the other side with boron, to form what's known as a *p-type* material for positive charge carriers (holes). The junction between the two sides, or regions, is a small section of silicon called the depletion region, in which there are no charge carriers (neither electrons nor holes).

When a sufficiently higher electric potential is applied to the "p" side (known as the anode), compared with that of the "n" side (the cathode), electrons are free to flow through the depletion region from the n-type side to the p-type side. (In this usage we say that the diode is *forward-biased*.) When a lower electric potential is applied to the anode, compared with that of the cathode, the junction will prevent the free-flow of electrons in the opposite direction, creating a one-way switch for electrons, if you will. (We say that the diode is *reverse-biased*.)

One thing to keep in mind is the electron-current convention; that is, by agreement, current flow is opposite that of electron flow. Therefore, according to the previous paragraph, electrons flow from the cathode to the anode, while current flows from the anode to the cathode. The cathode side of a semiconductor diode is typically marked on the component package and schematic by a line or similar, while the conventional current flow is marked by the schematic symbol arrow direction.



Diode symbol

The ideal diode

One important caveat needs to be mentioned here. Our discussion examples assume that each diode acts like a perfect device. An *ideal diode* behaves like an electronic switch; that is, a perfect conductor during forward-bias and a perfect insulator during reverse-bias. Actual diodes exhibit all sorts of exceptions to the ideal case, and must be taken into account when designing circuitry that uses them.

For example, conventional diodes a) exhibit a voltage drop (called *threshold voltage*) in the forward-bias configuration (typically 0.7 volts for silicon and 0.3 volts for germanium), b) have a maximum reverse-bias voltage (called the *breakdown voltage*), c) exhibit some resistance, and d) possess a reverse *leakage current*. These non-ideal properties are important, but are largely omitted here, so that we can focus on the fundamental principles of the diode operation and their applications, and still maintain a reasonably meaningful discussion.

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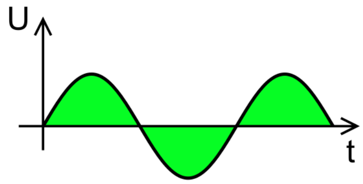
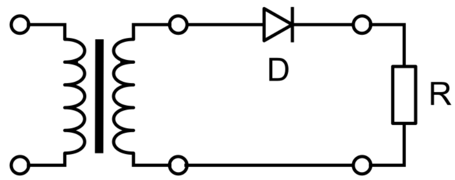
The rectifier

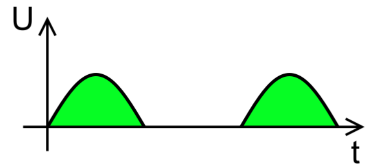
AC power at the light socket, for example, is a 50 Hz sine wave whose voltage is positive half the time and negative the other half. If we were to connect a diode and load right at the wall socket, then the diode will allow current to flow through it for half the time, and will allow no current to flow through it during the other half. The load will therefore experience current through it in only one direction, making this diode circuit a *half-wave rectifier*. In fact, a diode by itself is often referred to as a rectifier.



Original AC input

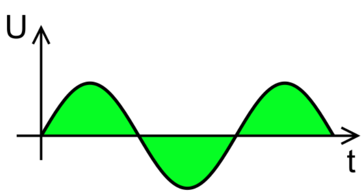


Step-down, rectifier, and load

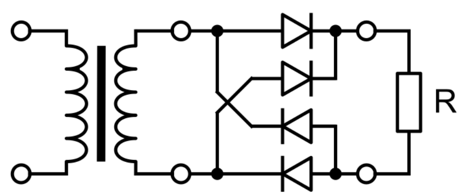


Resulting DC output

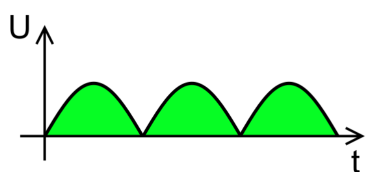
The disadvantage of the half-wave rectifier is that the circuit is basically idle half the time, and the other half of the AC cycle is unused. One popular way to rectify the AC input and preserve the entire AC cycle is by using a *full-wave rectifier*. There are a number of valid methods of performing full-wave rectification using diodes, and this one is known as a *bridge rectifier*:



Original AC input



Step-down, rectifier, and load



Resulting DC output

As you can see from the above diagrams, the output is DC because the current is still flowing in only one direction, but it's a *pulsating DC*, at twice the frequency of the AC input. As I'll explain later, yet another kind of diode can be used to help regulate the output so that its voltage is much closer to a steady-state (doesn't pulsate much) DC.

While full-wave rectification can be achieved using discrete diodes, it's often done by a single convenient package containing the diodes, reducing the soldered connections from eight to four. This also reduces the manufacturing costs of components, their insertion, and testing. The one pictured on the right is rated at 50 volts and 2 amps, and costs £2, for example.

To function effectively as a rectifier, the power-handling capability of a diode must also be considered, ideal or actual. While the input voltage RMS might be safe to use in most cases, I recommend using the input voltage peak value, and comparing it with the specified diode peak reverse voltage.

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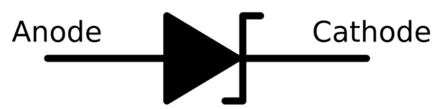
Specific-use diodes

There are many different types of diodes available today, many with very specific applications. The following is far from an exhaustive list, but gives you an idea of the usefulness of diodes. Indeed, many important, industry-wide diode types (varactor, PIN, Schottky, tunnel, and more) are omitted to limit the scope of this discussion.

- **Zener diode**

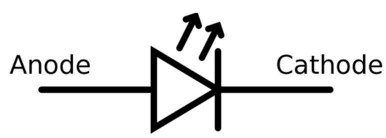


Zener diode symbol

During forward-bias, a Zener diode functions just like any silicon diode, but during reverse-bias, a Zener allows a small amount of reverse current to flow when the negative voltage reaches a level known as the *Zener voltage*.

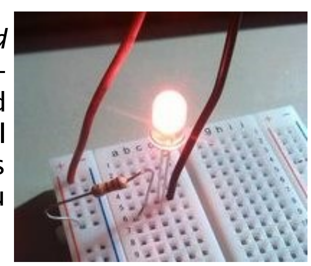
This makes a Zener diode into a kind of voltage regulator, so that the voltage across it'll remain between reference (zero volts) and the Zener voltage, with the diode permitting as much current to flow as needed, to keep the voltage at or below the Zener voltage. Zener diodes are important components in circuits that require a stable reference voltage, such as a power supply, an amplifier, or a surge suppressor.

- **Light-emitting diode**



LED symbol

A light-emitting diode (LED) is one that will produce visible light during forward-bias, and turn off during reverse-bias. When it's installed in the forward-bias direction, it behaves almost like a short circuit. To limit the current through an LED, you should always connect a resistor between the diode and the supply voltage, and calculating the current-limiting (sometimes called *ballast*) resistor is fairly straightforward.



Like most diodes, an LED exhibits a voltage drop, known as the *forward voltage*, and that must be taken into account when calculating the current-limiting resistor value. The difference between the supply ($\mathbf{V}_S$) and LED forward voltage ($\mathbf{V}_{LED}$), divided by the LED rated current ($\mathbf{I}_{LED}$) will give you an appropriate resistor value. For example, if the diode is listed at 3.0 V forward voltage with a 20 mA operating current, and you need to use it in a 12-volt circuit, then the correct resistor value will be

$$R = \frac{V_S - V_{LED}}{I_{LED}} = \frac{12\ V - 3.0\ V}{20\ mA} = 450\ \Omega$$

The LED is quickly becoming the standard in utility and household appliance lighting, replacing the incandescent light bulb, due to its high reliability, longevity, low operating temperature, light weight, small size, and low-cost. So, this particular diode can be seen just about everywhere, and its popularity will not only continue to grow, but will likely spell the extinction of Edison's invention within our lifetimes. Indeed, some light bulb manufacturers have announced their end-of-life production, to be replaced by LEDs encased in bulbs and enclosures of similar footprint.

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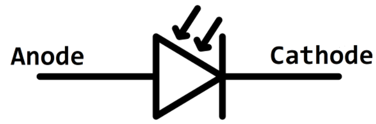
- **Photodiode**



Photodiode symbol

While some diodes emit light, a class of diodes called *photo-voltaic semiconductors* will convert received light energy into electrical energy using the *photovoltaic effect*. The photodiode is one such device, in which photons that strike the p-n junction will produce the effect. Some photovoltaic semiconductors such as solar cells are optimized more for energy conversion efficiency, where a photodiode is optimized for light detection.

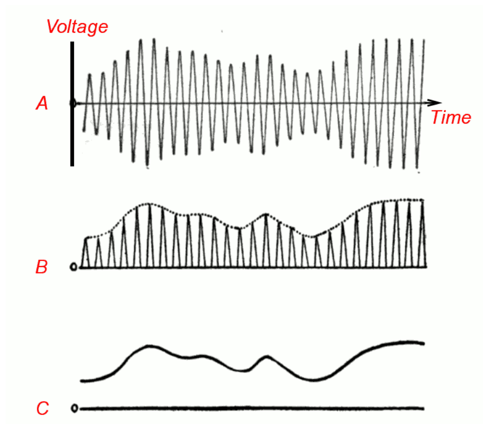
By the way, with the photoelectric effect, like the photovoltaic effect, photons that strike the p-n junction transfer their energy to electrons. However, the photoelectric effect results in the energized electrons being ejected from the material, whereas the photovoltaic effect results in the electrons moving from the valence band to the conduction band, and the electrons become part of the current flow.

Diode-specific uses

There are many roles, for which diodes are well-suited, of which rectification is one, as was shown. A few other popular applications include the following:

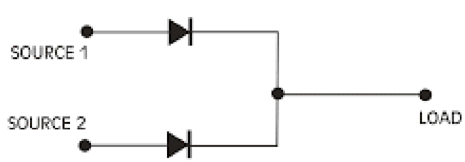
- **Detector**

A diode can be (and was once popularly) used as part of an AM detector, which *demodulates* the incoming signal (step A). The function of the diode detector was to rectify the radio signal (step B), leaving only the positive peaks of the carrier wave. The audio was then extracted from the rectified carrier by a simple filter (step C), then fed into a set of headphones. This is the arrangement for a crystal radio set.



Demodulation steps

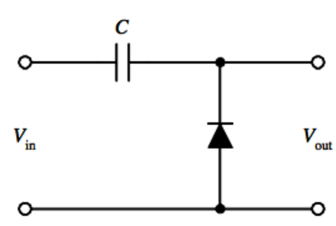
- **Backflow prevention**



While using two or more batteries to serve a load, you can forward-bias a diode from each battery to the load, to prevent the battery currents from flowing back ("backflow") into each other. Keep in mind that this is intended for the battery-load circuit, and not the battery-charger circuit. For the charging circuit, install a diode forward-biased from the charger into each battery, to prevent the battery from draining and to protect the charger from damage.

- **Voltage-clamping**

There are circumstances in which an RF (radio frequency) or AC signal must be preserved, yet it must be presented with only positive values (another form of rectification), instead of the usual positive-negative transitions. A diode clamping circuit can do that, plus a) help guard components against transient voltages or b) set a refer-



Simple clamping circuit

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ence for an op-amp (operational amplifier) input, for example.

Other diode-specific applications include reverse-voltage (reverse-polarity) protection, over-voltage protection, temperature sensing, and as ionizing radiation detectors. Diodes can also be used in current-steering, to draw current away from an unintended path. For example, to prevent a UPS (uninterruptible power supply) from drawing current from its battery until it's necessary.

Early solid-state diodes

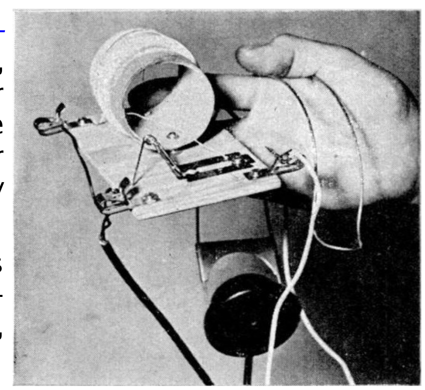
One of the first diode uses was for AM radio demodulation, so quite a lot of time was spent searching for suitable materials that made a natural detector. Even though a few other materials proved slightly better as an RF detector, by far the most popular was lead sulfide, more commonly known as galena, a kind of naturally occurring semiconductor.

Galena and cat's whisker

To make the mineral into a detector, the user would listen on a crystal radio while probing the galena with a thin wire called a *cat's whisker*, which turned the wire-mineral pair into a *point-contact diode*, also known as a *crystal diode*. The wire would then be held in place by gravity or a small pressure spring, completing the diode required for the battery-less receiver.

Another popular AM radio receiver was known as a *foxhole radio*, which was the same as the crystal radio described above, except instead of a galena detector, the radio used a razor blade or similar thin-metal sheet coated with selenium. The foxhole radio often used a pencil or carbon rod from the center of an expired battery in place of the cat's whisker, with a safety pin in contact with the pencil lead or rod.

Later, more common crystal radios used actual crystal diodes made of germanium. Some were even outfitted with small amplifiers to boost the audio, which was often difficult to hear, even with good headphones.



Razor blade foxhole radio

Summary

An ideal diode is an electronic component that allows current to flow through it in one direction, but not the other. The historical search for a way to convert, or rectify, AC into DC led to the development of the tube diode, which was the forerunner of today's junction semiconductor diode. There are many different kinds of diodes available, and most perform some variation of the basic diode function. Diodes in the form of light emitters are quickly becoming the standard for utility and household appliance lighting. Diodes in the form of light acceptors are quickly dominating rooftops for converting light energy into electrical energy.

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