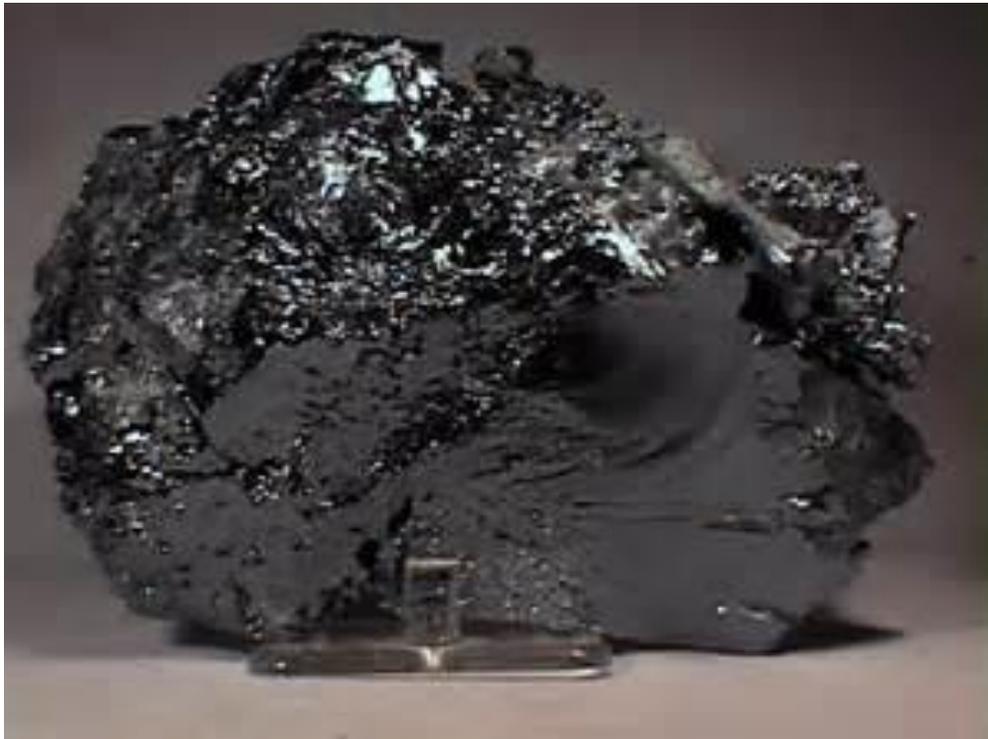


Semiconductor Diode Theory



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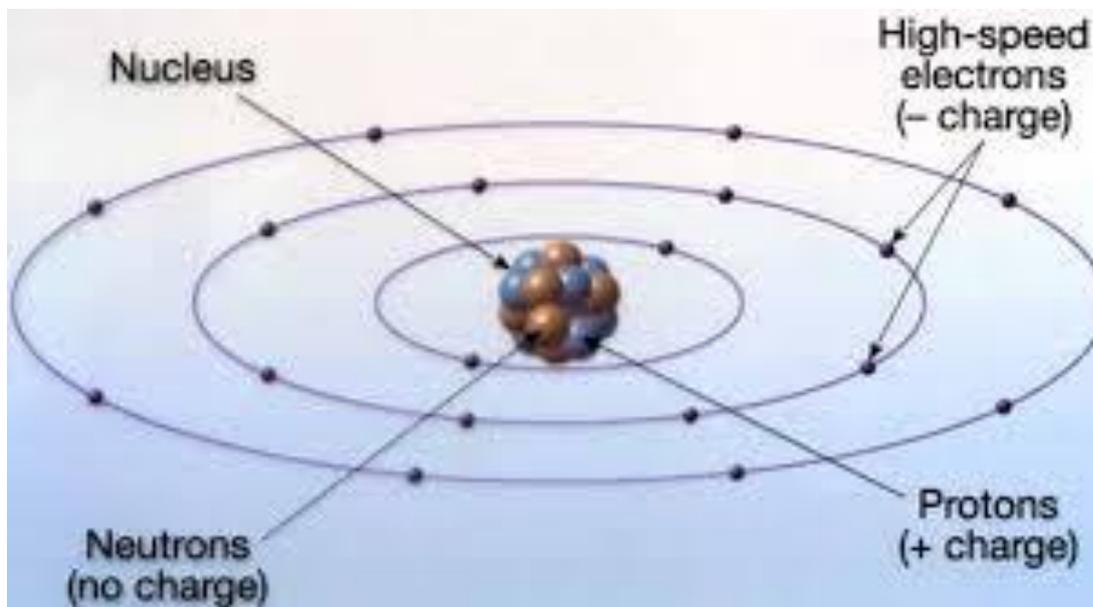
Diodes are normally constructed using Silicon, so their construction and operation needs to be understood.

Structure of the atom consisting of a nucleus of protons and neutrons surrounded by orbiting electrons

An electronic circuit consists of the flow of electrons around a circuit. So understanding how this happens is important. Knowing the structure of the atom is important to understand this concept...

Atomic Structure

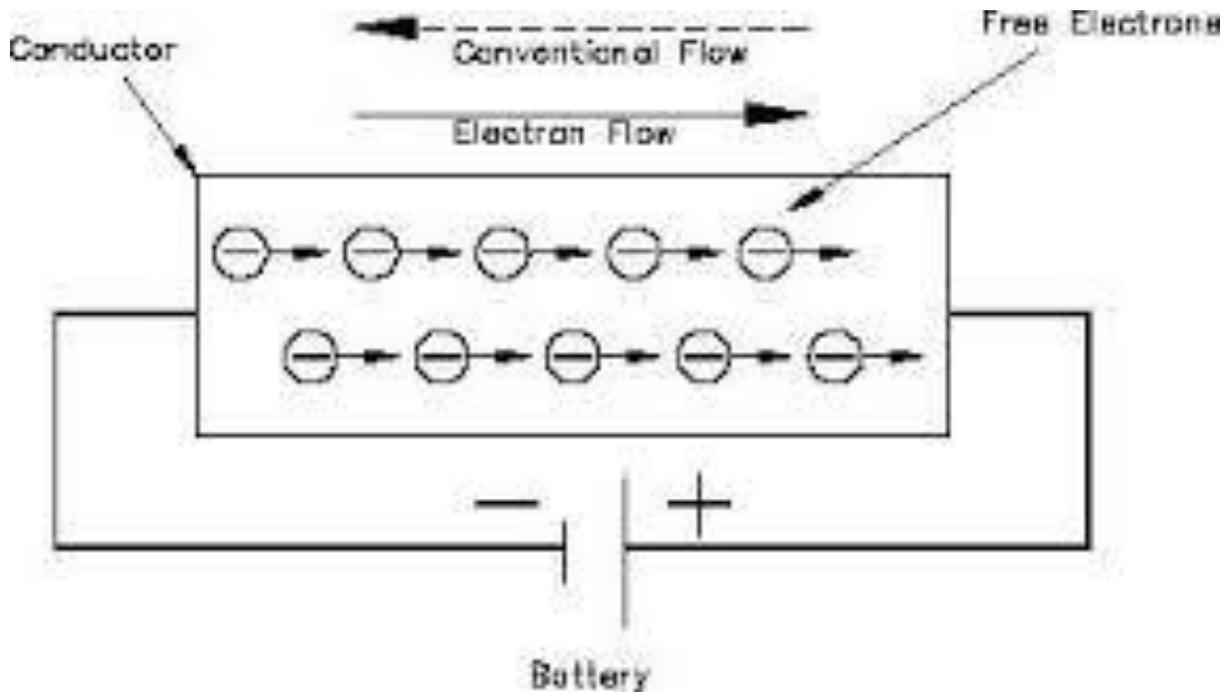
The centre of the atom is known as the nucleus and is positively charged. The nucleus consists of Neutrons, that have no charge and Protons which are positively charged. It has orbital electrons flowing around the nucleus. The atom is in balance by the force of attraction between the positively charged nucleus and the negatively charged electrons.



Research activity: Who is Neil Bohr's and what model is he responsible for?

What is Planck's constant?

Concept of electron movement and conventional current flow



As mentioned previously, the electron possesses a negative charge. It is known that similar charges repel each other and opposite charges attract.

+VE + +VE = repel

-VE + -VE = repel

+VE + -VE = attract

Therefore, in an electrical circuit, as shown above the electrons are repelled by the negative charge at the negative terminal of the battery and attracted by the positive charge at the positive terminal. Therefore, the electrons drift away from the negative terminal and towards the positive terminal.

Conventional current flow

As stated above the movement of electrons and therefore the direction of current flow is from the negative terminal of the battery to the positive terminal. However, before the true nature of electricity was known scientists assumed that current was the result of the movement of positively charged particles and therefore that current flowed from the positive to the negative terminal. This (incorrect) convention is still used today and is called **conventional current flow**. When discussing the true nature of current we call it **electron flow**. In general, conventional current flow is indicated on circuit diagrams and true electron flow is used when we describe how an individual component works.

Characteristics of conductors, insulators and semiconductors

Materials can be classified as one of three types with respect to electrical characteristics:

Insulator

Conductor

Semiconductor

An Insulator is materials which do not conduct electricity an insulator do not have any free electrons available for the carriage of current. This is because the valence band electrons of these materials are bound very tightly to their parent nuclei and require vast amounts of energy to break that bond. Non-metallic solids are said to be good insulators

A Conductor is materials which easily allow the flow of electrons. Outer electrons of the atoms are loosely bound and are free to move through the material. Metals such as copper are typify conductors.

A Semiconductor is situated between insulators and conductors... They consist of lattices and at any temperature above absolute zero; there is a finite probability that an electron in the lattice will be knocked loose from its position, leaving behind an electron deficiency called a "hole". They conduct or allow the flow of current under certain conditions. If a voltage is applied, then both the electron and the hole can contribute to a small current flow. Examples: germanium, silicon.

Conductors		Resistivity (ohm m)
Copper		1.7×10^{-8}
Gold		
Silver		
Insulators		
Mica		9×10^{13}
Wood		
Glass		10^{12}
Quartz (fused)		5×10^{16}

Note: Resistivity is how strongly a given material opposes the flow of electric current

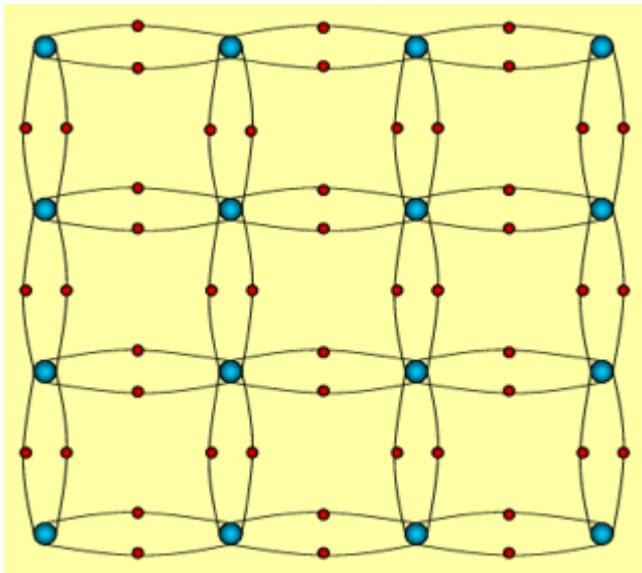
Properties of extrinsic materials and doping agents for n-type and p-type semiconductors

The roots of semiconductor behaviour is due to their unique crystal lattice and the way the atoms are arranged inside the lattice structure. The lattice structure consists of a repeated arrangement of atoms in a geometric pattern.

The naturally occurring semiconductor materials that are used to manufacture electronic devices are Silicon and Germanium (Germanium is an older choice of material which is less used today).

Pure Silicon

First a very pure crystal of silicon must be produced. The atomic structure of the silicon can be represented by the diagram below.



Silicon has only four electrons in the outer shell, 4 valences electrons and it takes eight electrons to fill the outer shell and make it stable. The atoms share their valence electrons with neighbouring atoms so that each atom effectively contains eight electrons in the outer shell. This sharing of valence electrons with neighbouring atoms forms covalent bonds. It is these covalent bonds that bind the atoms together.

- The silicon atoms form a square lattice
- Each silicon nucleus has four electrons in its outer shell
- These electrons are paired with the corresponding electrons in adjacent atoms.
- These are called covalent bonds. Covalent bonds are what bind the material together

The net result is that each nuclei (along with the electrons in the inner shells) are surrounded by eight outer electrons tightly bound in the atomic structure and hence no free electrons to produce an electrical current if a voltage is applied to the material.

Extrinsic semiconductor

Intrinsic is pure

Extrinsic is not pure

To produce extrinsic semiconductor material an impurity is added. This process is called doping where the impurity atoms are called donor atoms.

There are two types of extrinsic semiconductor which are manufactured:

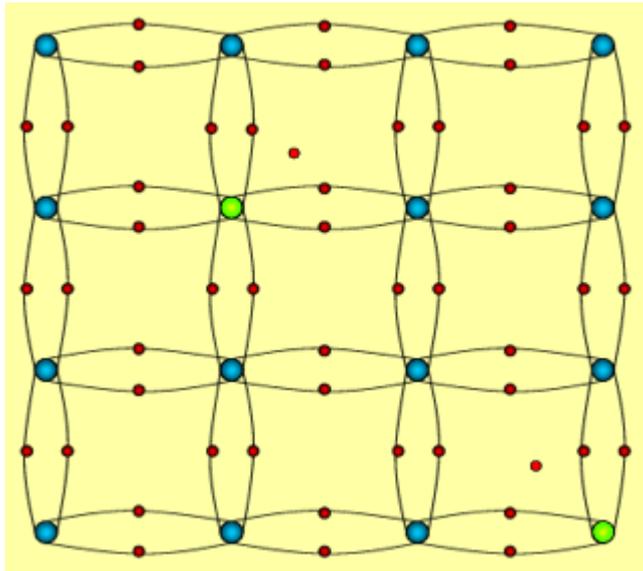
- P type semiconductor
- N type semiconductor

Dependant on the majority carriers or dopant types.

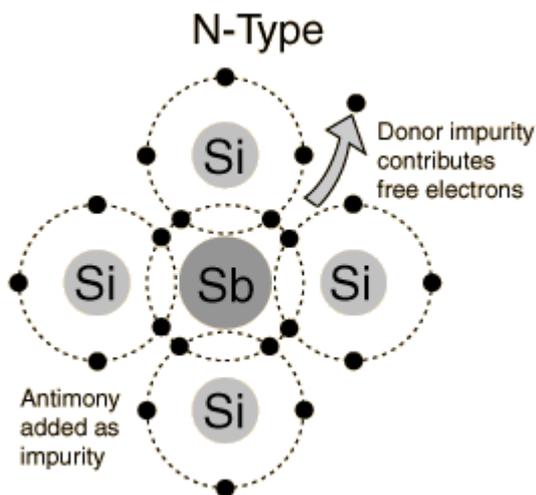
N type semiconductor

The pure silicon is doped with an element having five valence electrons where four of these electrons will form covalent bonds with neighbouring silicon atoms. As there are only four covalent bonds binding the donor atom to the neighbouring silicon atoms the fifth electron is not part of a covalent bond, and is therefore a free electron

Every impurity atom will produce a free electron. Under certain conditions these electrons will drift to produce an electrical current if a voltage is applied to the material and the N type semiconductor is a much better conductor than the intrinsic pure silicon material.

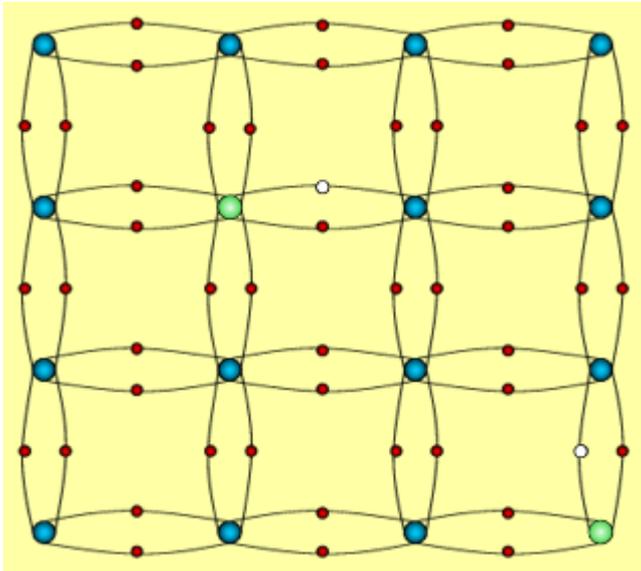


- The silicon atoms form a square lattice
- Four of the five valence electrons form covalent bonds with neighbouring silicon atoms
- The fifth electron has no neighbouring electron to pair with and is a free electron
- Each donor atom produces a free electron



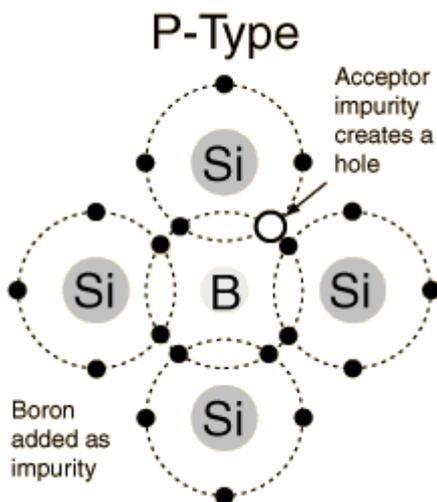
P type semiconductor

The pure silicon is doped with an element having three valence electrons. The three electrons will form covalent bonds with neighbouring silicon atoms. However, there are not enough electrons to form the fourth covalent bond. This leaves a hole in the covalent bond structure. Every impurity atom will produce a hole in the valence band. These holes will drift to produce an electrical current if a voltage is applied to the material and the P type semiconductor is a much better conductor than the intrinsic pure silicon material.



- The silicon atoms form a square lattice
- three of the four covalent bonds are formed with neighbouring silicon atoms
- The fourth bond cannot be formed as there are not enough electrons, this leaves a hole in the valence band
- Each donor atom produces a hole in the valence band

It is called P type semiconductor because the majority of charge carriers which contribute to an electrical current are positively charged holes produced by the doping process



Doping Agents

Donor atoms	Acceptor atoms
Arsenic	Beryllium
Germanium	Cadmium
Phosphorus	Germanium
Selenium	Silicon
Tellurium	
Silicon	
Arsenic	
Typically 1 part in 10^8	

*In chemistry, a valence electron is an electron that is associated with an atom, and that can participate in the formation of a chemical bond; in a single covalent bond, both atoms in the bond contribute one valence electron in order to form a shared pair.

http://en.wikipedia.org/wiki/Valence_electron

Operation of the p-n junction diode, for forward and reverse bias

Understanding the operation of the semiconductor diode is the basis for an understanding of all semiconductor devices, diodes, transistors, etc. The diode is manufactured as a single piece of material but it is much easier to explain the operation if we imagine producing two separate pieces of N type and P type material and then "sticking" them together.

If you have a piece of N type material, it contains mobile charge carriers in the form of free electrons. In the P type material, it is the positively charged holes that are mobile. Both types of material have these carriers distributed across the whole of the material.

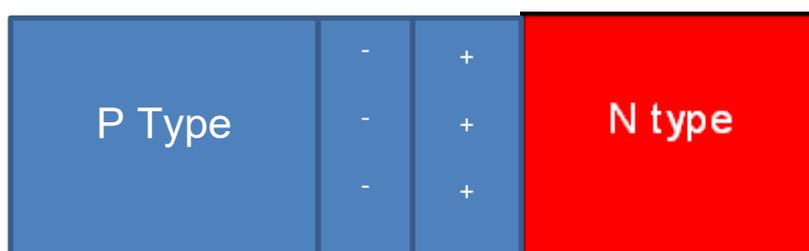
Consider what happens when you place two pieces of silicon together. One P type and one N type.



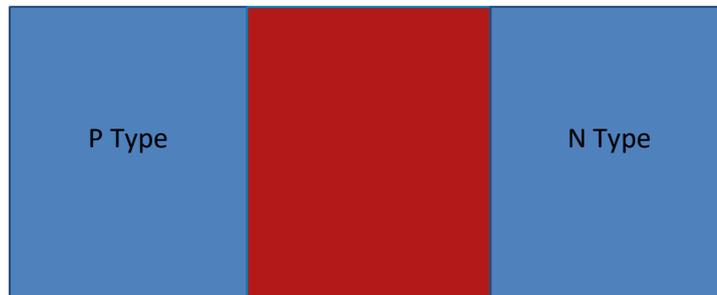
The random motion of the mobile electrons in the N type material and the holes in the P type material would tend to cause an even distribution of electrons and holes throughout the semiconductor. And in fact this is what begins to happen.

Consider the electrons in the N type material. The electrons start to migrate across the junction of the two materials. When they cross into the P type material they recombine with the holes (i.e. they fill in the holes in the valence band by filling in the vacant electron positions around the trivalent donor atoms). This means that the number of holes near to the junction becomes depleted. Also as the electrons leave the previously neutral N type material a positive charge builds up at the junction. (This is because the positive charge from the nucleus of atoms near to the junction is now greater than the negative charge of the electrons in that region. This is due to the reduction in the number of electrons due to those which have moved across the junction.)

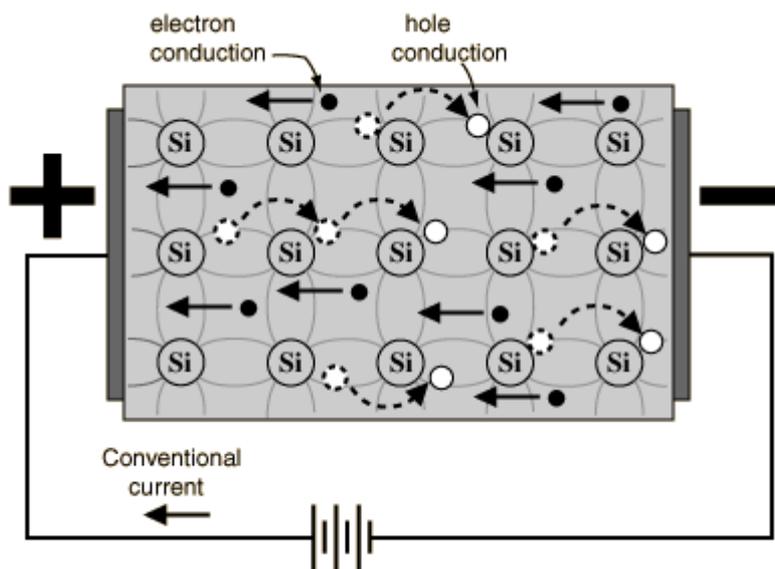
Similarly, as holes migrate from the P to N type material they recombine with electrons (the free electron from the pentavalent atoms completes the fourth covalent bond around the trivalent atom). This leaves a depletion of free electrons near the junction in the N type material. Also a negative charge builds up near the junction in the P type material due to the loss of positively charged holes.



The net result is that the migration of electrons from N to P type material and the migration of holes from P to N have two effects. It results in a depletion of mobile charge carriers near the junction (a depletion of electrons in the N type material and a depletion of holes in the P type material). This depletion layer is typically about 1 micrometre wide (1 millionth of a meter!). Also a voltage is produced across the junction which is called a barrier voltage. The N type material develops a positive charge close to the junction and the P type develops a negative charge. This prevents any further migration of mobile charge carriers.



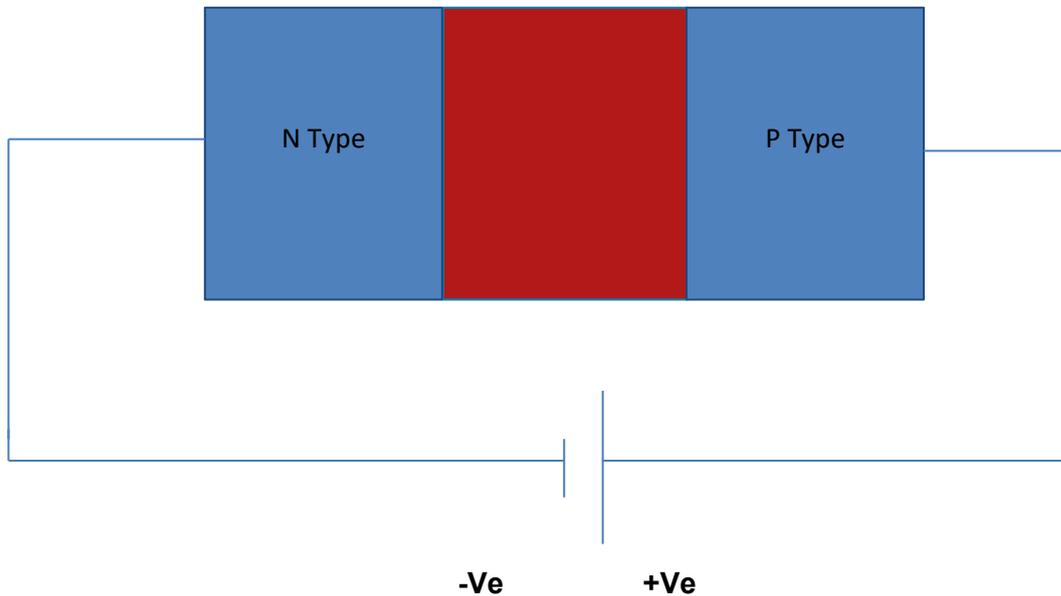
This net effect is to create a Depletion Region. In summary, it can be considered that the holes have been filled with electrons.



This is the PN Diode!

Adding a DC Potential difference

Consider the following circuit



Forward bias

If you apply a potential difference with the positive supply connected to the P Type semiconductor and the negative supply connected to the N type material. The external voltage would tend to cause the movement of electrons from the negative terminal of the supply through the diode and back to the positive terminal (electron flow).

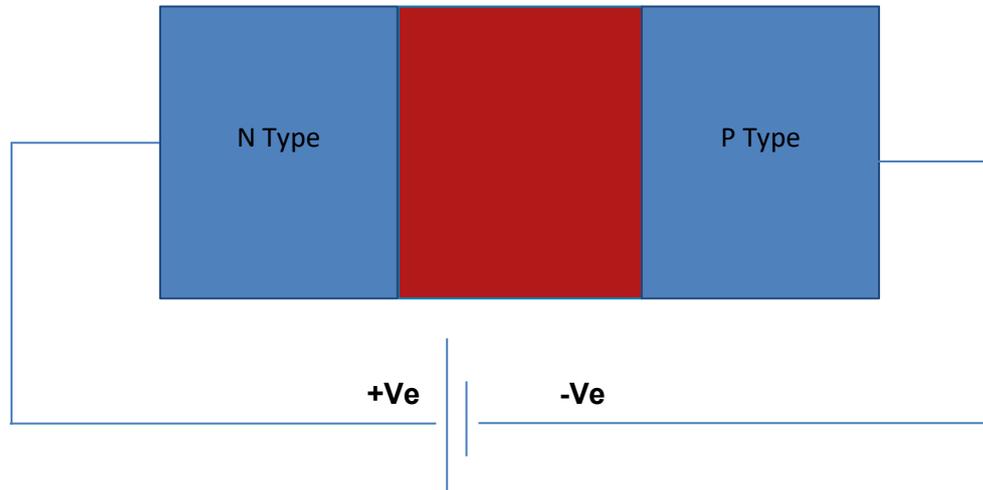
The negative terminal would tend to inject electrons into the N type material. This would increase the number of electrons and therefore reduce depletion layer. This would reduce the positive charge at the junction. Similarly, the positive terminal would tend to pull electrons from the P type material. This would increase the number of holes, reducing the depletion layer and reducing the negative charge at the junction. The net effect is that when the external voltage is connected this way it reduces the barrier voltage and if the applied voltage is greater than the barrier voltage it will overcome it and produce a current flow through the diode. When an external voltage is connected to a diode with this polarity we say that it is forward biased.

This happens at about 0.6v (0,3v for germanium). This is where there is enough energy to overcome the depletion layer and allow the current to flow.

As holes are the majority current carriers in P type material it is more common to consider the movement of holes rather than electrons in the P type material. Therefore, we can say that the positive terminal injects holes rather than removes electrons in the same way that we considered the negative terminal injecting electrons into the N type material. The effect is the same the injection of holes would reduce the depletion layer and reduce the barrier voltage.

Reverse Bias

Consider the following circuit



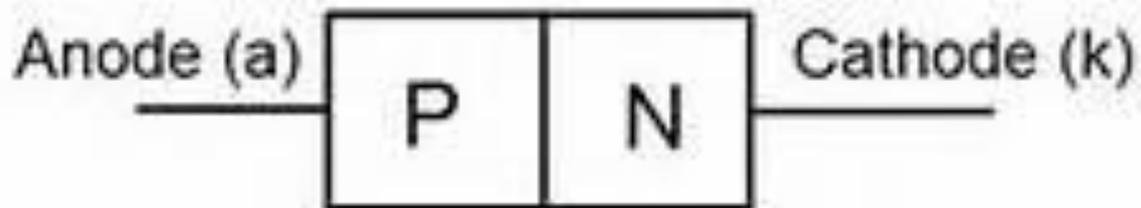
If you apply a positive voltage to the N type material and a negative voltage to P type material, the voltage would tend to cause the movement of electrons from the N type material to the supply and attract the flows of holes to the positive terminal. In fact the negative terminal would tend to inject electrons into the P type material causing a further depletion of holes. This would produce a widening of the depletion layer and an increase in the negative charge at the junction until it was equal in magnitude to the applied voltage. The negative charge at the junction would oppose the negative terminal of the external voltage and this would prevent any further injection of electrons into the P type material.

As mentioned the positive terminal would tend to pull electrons from the N type material. This would further deplete the N type material of electrons, widening the depletion layer and increasing the positive charge at the junction until it was equal to the magnitude of the applied voltage. This would then prevent any further loss of electrons.

The net effect is that when an external voltage is connected this way the effect of the barrier voltage opposes the external voltage. Any initial movement of charge due to the external voltage will just increase the barrier voltage until it is equal to the applied voltage and therefore no current will flow through the diode. When an external voltage is connected to a diode with this polarity we say that it is reverse biased.

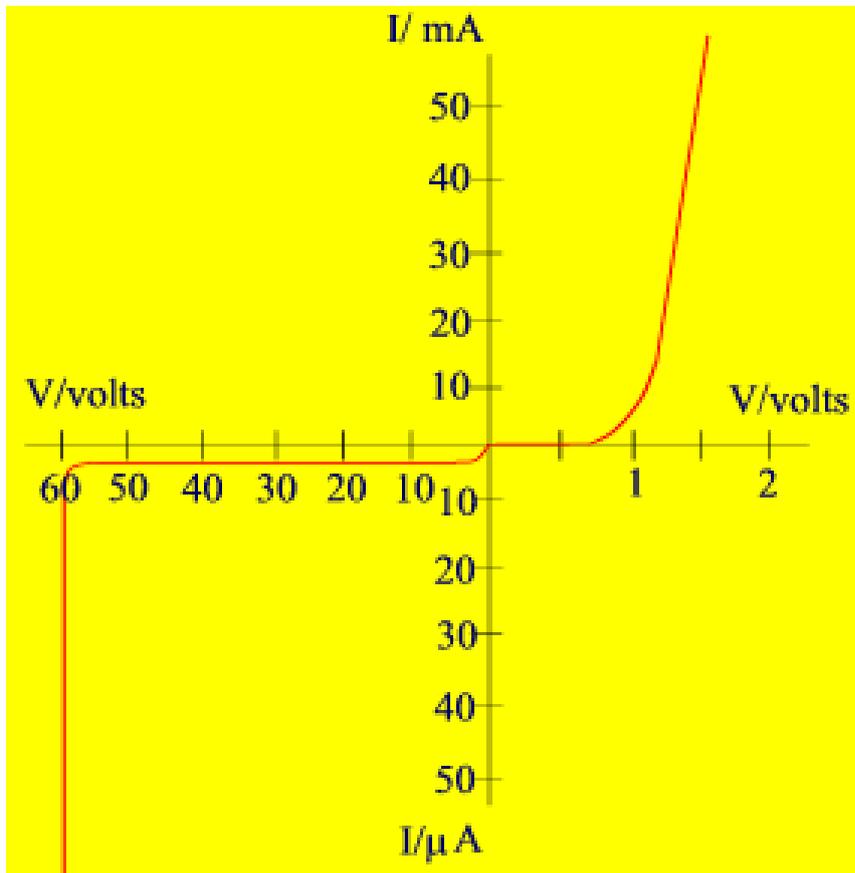
A diode consists of a PN junction. The diode consists of two terminals, the Anode and cathode.

The P type material is the Anode (+Ve) and the N type material is the Cathode (-Ve).



Diode Characteristic

A diode characteristic is simply a graph of the voltage applied to a diode and the current it produces. The negative part of the voltage axis corresponds to when the diode is reverse biased and the positive part is when the diode is forward biased. The negative part of the current axis shows current flowing in the reverse direction through the diode.



The main features of the characteristic are:

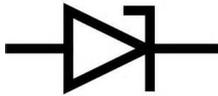
- No current flows when the diode is forward biased until the barrier voltage is overcome (0.6V - 0.7V for silicon 0.2V - 0.3V for germanium)
- The forward characteristic is nonlinear (not a straight line). This shows that the resistance is not constant.
- The gradient of the forward characteristic quickly becomes very steep. This shows that the forward resistance is very low
- The negative current axis is on a different scale (showing millionths of an amp rather than thousandths) this is so we can indicate the very small leakage current which flows due to electron hole pair generation (i.e. due to the natural conduction properties of the pure silicon). The leakage current flows in both directions but is too small to indicate on the current scale used on the forward part of the characteristic

If a large enough reversed bias voltage is applied the diode will eventually conduct due to zener then avalanche breakdown (i.e. due to the natural conduction properties of the pure silicon). The actually voltage that breakdown occurs varies for individual diodes and can be determined by the manufacturing process

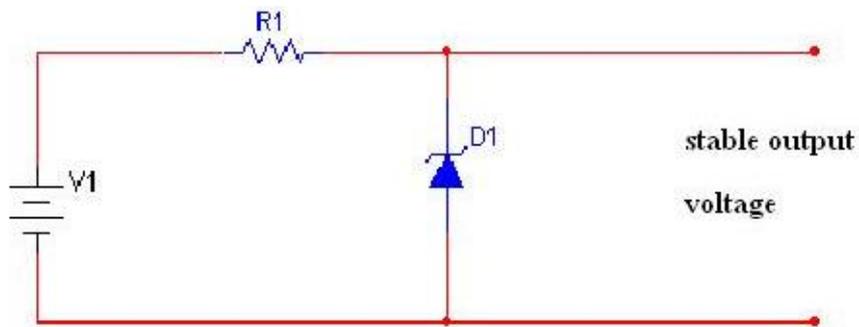
Zener Diode

A Zener diode operates in the reverse-bias region, unlike the signal diode. Its purpose is to regulate the voltage.

Symbol

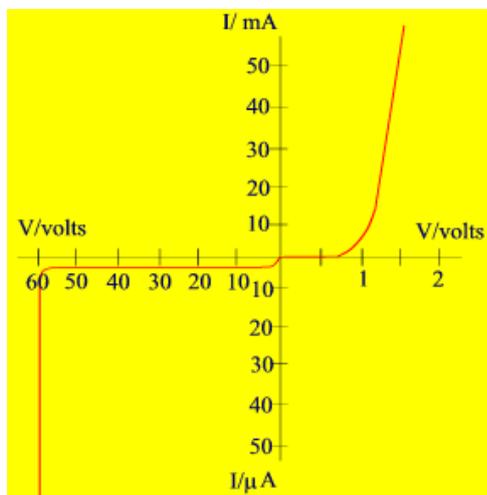


If we consider the following circuit:

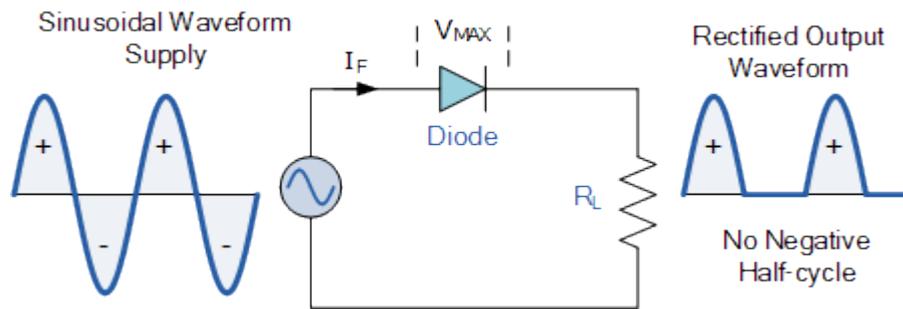


A Zener diode does not break down or damage when in the reverse biased mode but they start conducting when their Zener voltage value is met where they can conduct substantial current, and in doing so will try to limit the voltage dropped across it to that Zener voltage point. So long as the power dissipated by this reverse current does not exceed the diode's thermal limits, the diode will not be harmed.

The function of this circuit is to stabilise the output voltage.

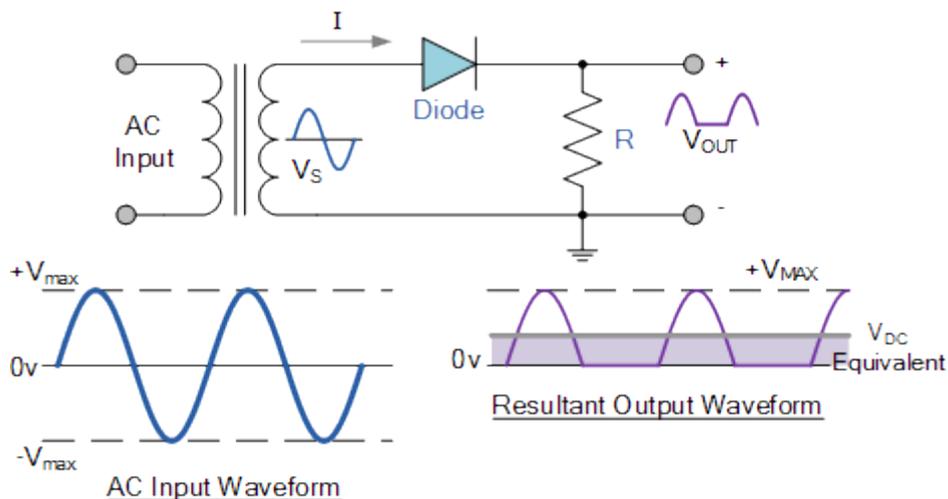


Half Wave Rectification



A diode circuit can be used to create a rectifier. A rectifier is a circuit which converts the *Alternating Current* (AC) input into a *Direct Current* (DC) output. The half-wave rectifier is the most basic circuit for rectification. The diode passes just one half of each complete sine wave of the AC supply in order to convert it into a DC supply. Then this type of circuit is called a “half-wave” rectifier because it passes only half of the incoming AC power supply as shown below.

Half Wave Rectifier Circuit



During each “positive” half cycle of the AC sine wave, the diode is *forward biased* as the anode is positive with respect to the cathode resulting in current flowing through the diode.

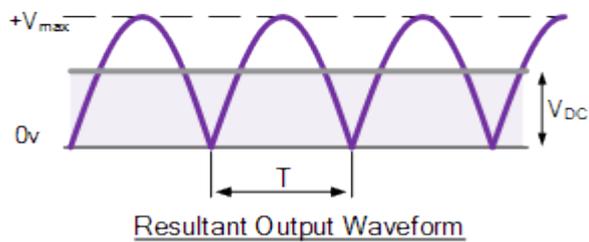
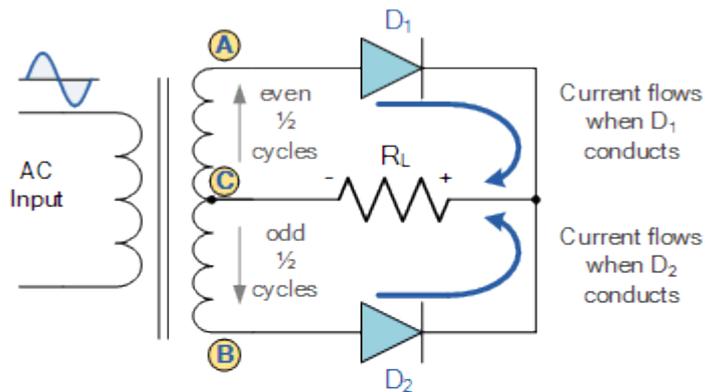
During each “negative” half cycle of the AC sinusoidal input waveform, the diode is *reverse biased* as the anode is negative with respect to the cathode. Therefore, NO current flows through the diode or circuit.

The Full Wave Rectifier

A circuit can be used that uses both halves of the input voltage instead of every other half-cycle. The circuit is called a Full Wave Rectifier.

It produces an output DC. In a **Full Wave Rectifier** circuit two diodes are now used, one for each half of the cycle. A single tap transformer is used whose secondary winding is split equally into two halves with a common centre tapped connection, (C). This configuration results in each diode conducting in turn when its anode terminal is positive with respect to the transformer centre point C producing an output during both half-cycles, twice that for the half wave rectifier so it is 100% efficient as shown below.

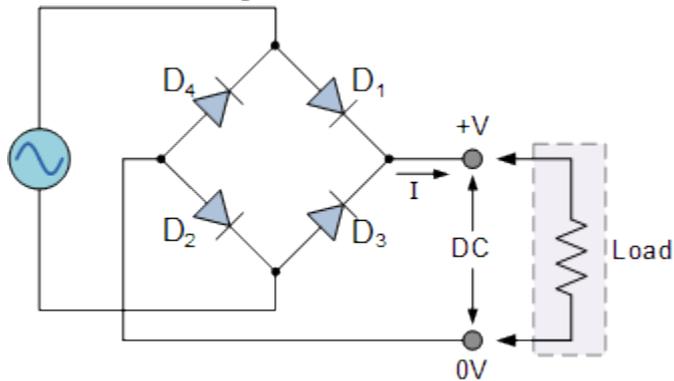
Full Wave Rectifier Circuit



The Full Wave Bridge Rectifier

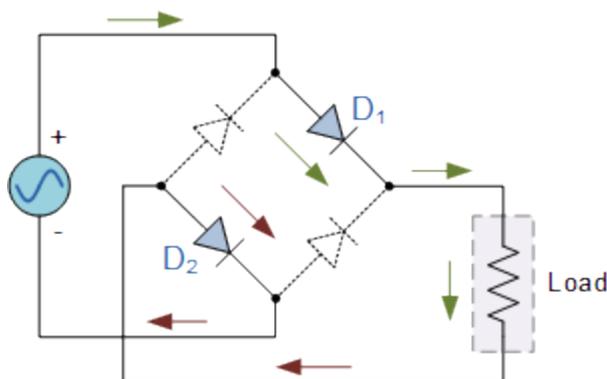
Another circuit that produces the same output waveform as the full wave rectifier circuit above, is that of the **Full Wave Bridge Rectifier**. This type of single phase rectifier uses four individual rectifying diodes connected in a closed loop “bridge” configuration to produce the desired output. The main advantage of this bridge circuit is that it does not require a special centre tapped transformer, thereby reducing its size and cost. The single secondary winding is connected to one side of the diode bridge network and the load to the other side as shown below.

The Diode Bridge Rectifier



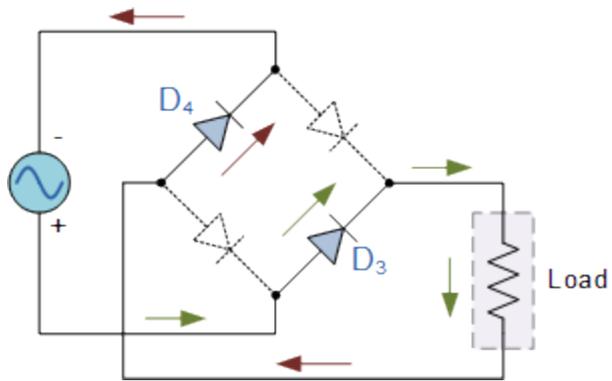
The four diodes labelled D₁ to D₄ are arranged in “series pairs” with only two diodes conducting current during each half cycle. During the positive half cycle of the supply, diodes D₁ and D₂ conduct in series while diodes D₃ and D₄ are reverse biased and the current flows through the load as shown below.

The Positive Half-cycle



During the negative half cycle of the supply, diodes D₃ and D₄ conduct in series, but diodes D₁ and D₂ switch “OFF” as they are now reverse biased. The current flowing through the load is the same direction as before.

The Negative Half-cycle



As the current flowing through the load is unidirectional, so the voltage developed across the load is also unidirectional the same as for the previous two diodes.

Practical: Comparing the forward and reverse characteristics of two different types of semiconductor diode

Introduction

The function of this lab is to study the characteristics of a variety of diodes.

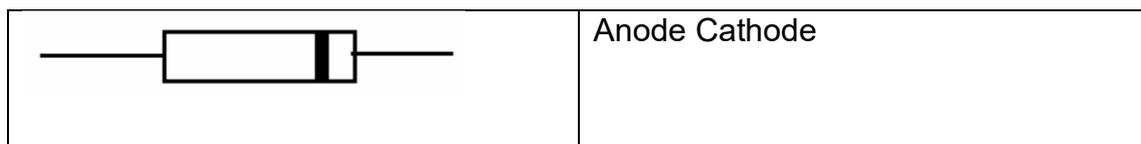
The characteristics that will be investigated are:

- the I-V curve of two silicon diodes
- The characteristics of a range of Zener diodes

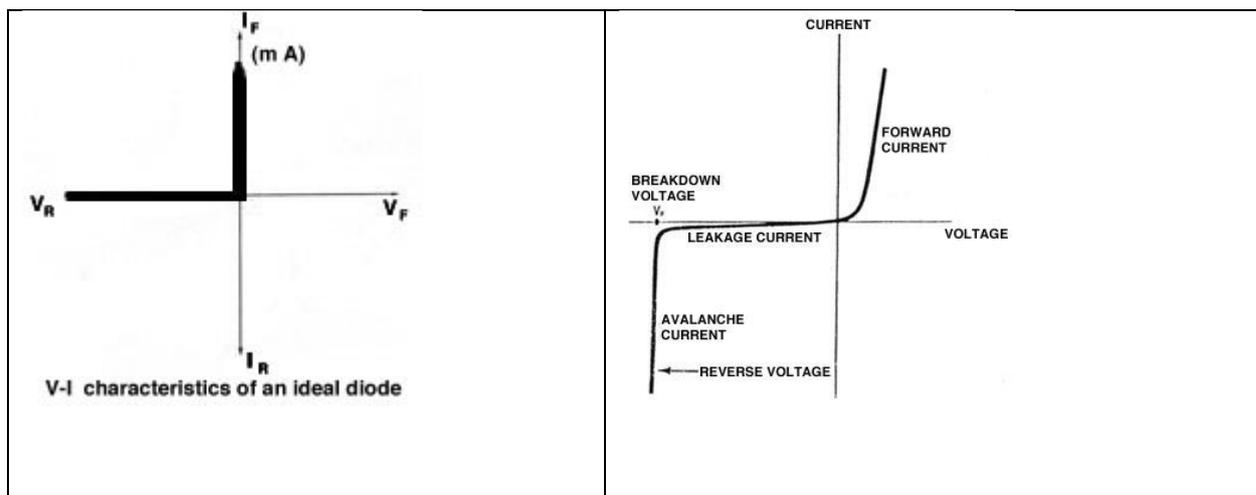
This will be done using both laboratory experiments and the use of the circuit simulator PSPICE.

Theory

The diode is a device formed from a junction of n and p type semiconductor material. The lead connected to the p-type material is called the **anode** and the lead connected to the n-type material is the **cathode**. In general, the cathode of a diode is marked by a solid line on the diode.



The primary function of the diode is the rectification. When it is forward biased (the higher potential is connected to the anode lead), it will pass current. When it is reverse biased (the higher potential is connected to the cathode lead), the current is blocked. The characteristic curves of an ideal diode and a real diode are seen below:



Equipment

Power supply

Two Digital Multimeters

Two Silicon diodes

Breadboard

Part 1 Procedure

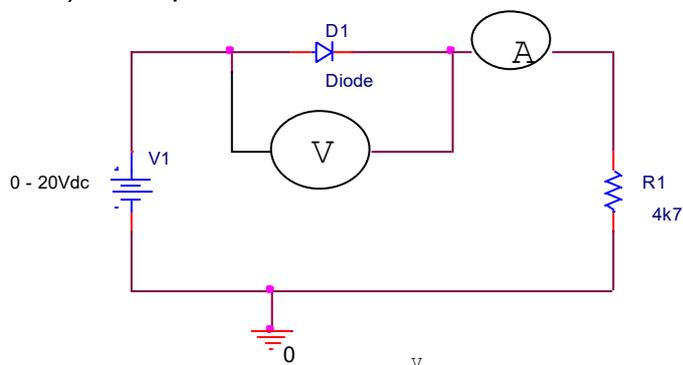
1) Finding Diode specifications

Look up the characteristics of the diodes by making a web search for the diodes shown in Appendix A.

The specifications for different kinds of diodes vary. Copy all of the specifications for each diode as well as of the specification definitions for your final lab report.

2) Diode V-I Characteristics – Forward Bias

a) Set up the circuit as shown.



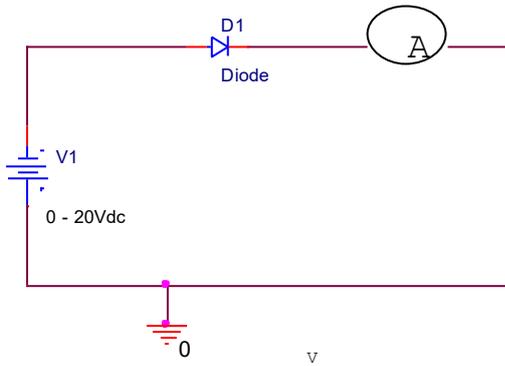
- Monitor the voltage across the diode using a DMM and adjust the power supply so that the meter indicates 0.45v.
- Measure the diode current.
- Repeat for the range 0.4 to 0.7v and record your result in the table below.

	V	0.4	0.45	0.5	0.55	0.6	0.65	0.7
Signal diode	I							
Power diode	I							

- e) Plot the forward characteristics of both diodes (on the same axis).
- f) Calculate the diode resistance at 0.6v for both diodes.

3) Diode V-I Characteristics – Reversed Bias

- a) Set up the circuit as shown.



- b) Set the voltage at 1v and record the current. Repeat for the other voltages,

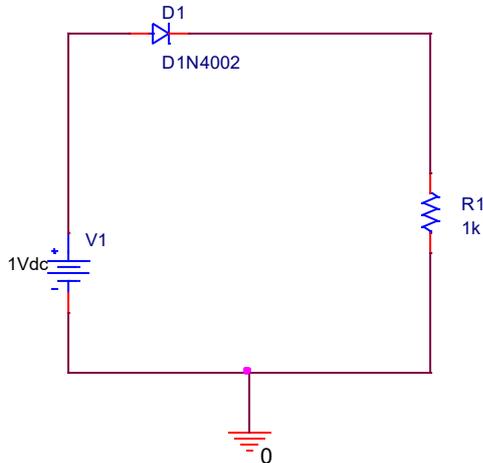
	V	1	4	8	12	16	20
Signal diode	I						
Power diode	I						

- c) Plot the reverse characteristics of both diodes (on the same axis).

Compare the characteristics of the two diodes.

Part 2 PSPICE

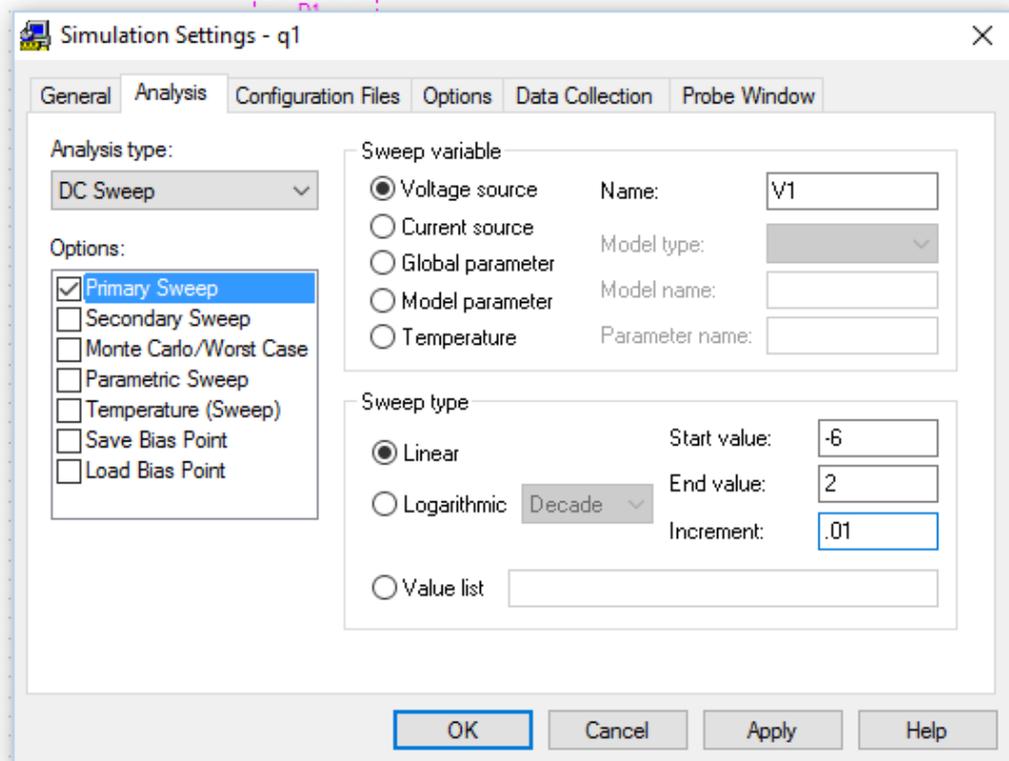
1. Using the booklet pspice or online tutorials create the following circuit:



The practical is to be repeated with a range of diodes from the PSPICE libraries.

2. Set up the following simulation profile.

DC Sweep



3. Simulate the circuit and collect the results.
4. Repeat for another diode.
5. Make a note of the voltage when the diode begins to conduct.

Diode 1

Model _____

Voltage _____

Diode 2

Model _____

Voltage _____

6. How much current flows when the source voltage is negative

Diode 1

Model _____

Current _____

Diode 2

Model _____

Current _____

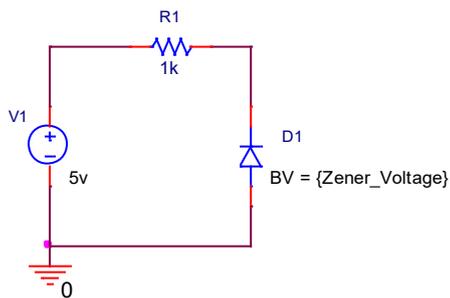
Compare the characteristics of the two diodes.

Part 3 PSPICE

1. Using the booklet pspice or online tutorials create the following circuit:

(Note:

Parametrized part will let you change the model parameter values by directly defining them as instance properties. There is no need to edit library.



PARAMETERS:
Zener_Voltage = 5.1

(Note: The source file and simulation profile is available from the VLE:Unit 6)

1. Simulate the circuit and collect the results.
2. Repeat for a 8.1 v and 10v Zener diode.

The results of this lab will be discussed as a group

Appendix A