

SEMICONDUCTORS

A semiconductor has electrical conductivity intermediate to that of a conductor and an insulator.

Semiconductor materials are useful because their behaviour can be manipulated by the addition of impurities, known as doping.

The comprehensive theory of semiconductors relies on the principles of quantum physics to explain the motions of electrons through a lattice of atoms.

Variable conductivity

A pure semiconductor is a poor electrical conductor as a consequence of having just the right number of electrons to completely fill its valence bonds.

Through various techniques (e.g., doping or gating), the semiconductor can be modified to have excess of electrons (becoming an n-type semiconductor) or a deficiency of electrons (becoming a p-type semiconductor).

In both cases, the semiconductor becomes much more conductive (the conductivity can be increased by one million fold or more). Semiconductor devices exploit this effect to shape electrical current.

A semiconductor has electrical conductivity intermediate to that of a conductor and an insulator

Electrical resistivity is a property of a material; it quantifies how strongly the material opposes the flow of electric current

In copper, every single copper atom donates one movable electron to the "sea of charge."

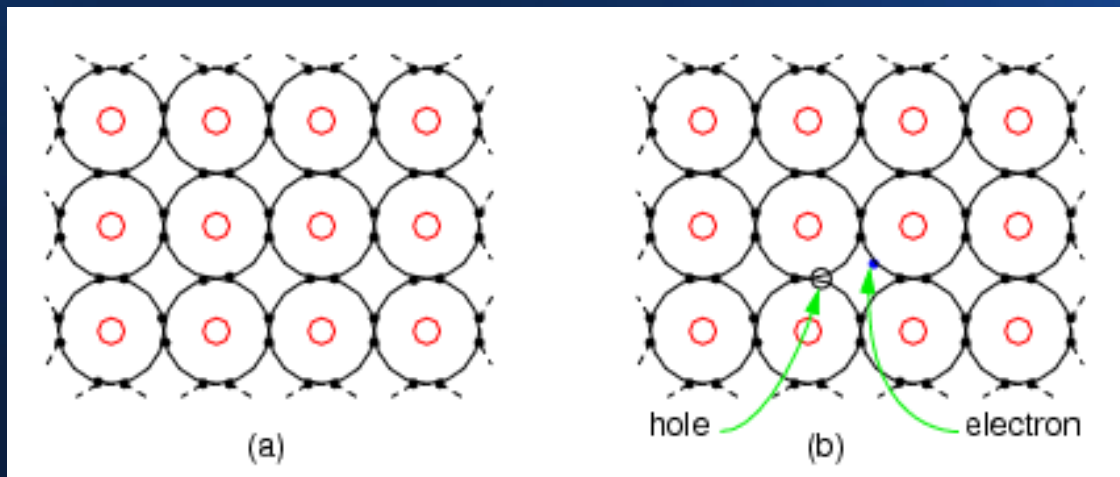
Copper's "electric fluid" is very dense; just as dense as the copper metal

In doped silicon, only one in every billion atoms donates a movable charge. Silicon is like a big empty space with an occasional wandering charge

Pure semiconductors are relatively good insulators as compared with metals, though not nearly as good as a true insulator like glass.

To be useful in semiconductor applications, the intrinsic semiconductor (pure undoped semiconductor) must have no more than one impurity atom in 10 billion semiconductor atoms.

This is analogous to a grain of salt impurity in a railroad boxcar of sugar. Impure, or dirty semiconductors are considerably more conductive, though not as good as metals.



(a) Intrinsic semiconductor is an insulator having a complete electron shell. (b) However, thermal energy can create few electron hole pairs resulting in weak conduction.

Doping

Pure semiconductors, by themselves, are not particularly useful. Though, semiconductors must be refined to a high level of purity as a starting point prior the addition of specific impurities.

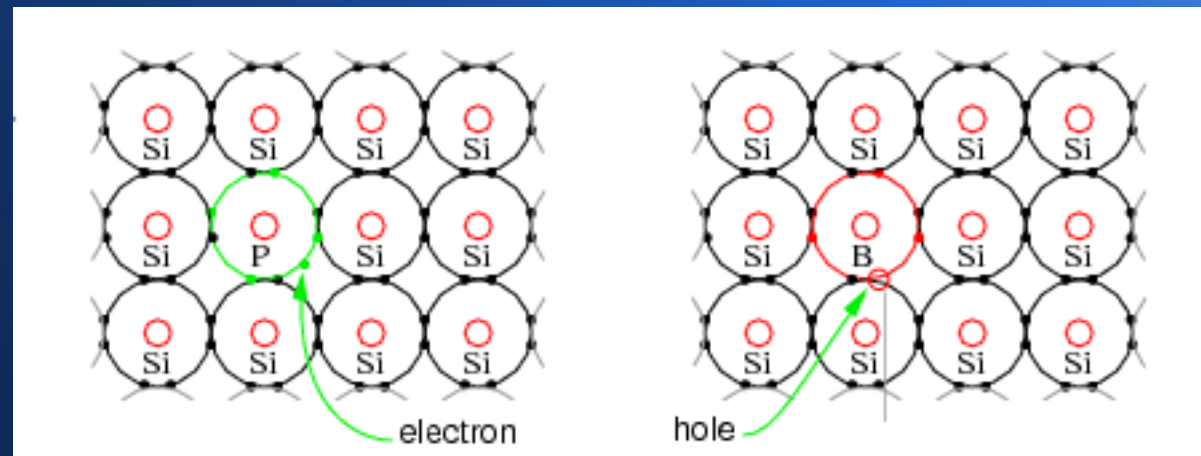
Semiconductor material pure to 1 part in 10 billion, may have specific impurities added at approximately 1 part per 10 million to increase the number of carriers. The addition of a desired impurity to a semiconductor is known as doping. Doping increases the conductivity of a semiconductor so that it is more comparable to a metal than an insulator.

It is possible to increase the number of negative charge carriers within the semiconductor crystal lattice by doping with an electron donor like Phosphorus. Electron donors, also known as N-type dopants include elements from group VA of the periodic table: nitrogen, phosphorus, arsenic, and antimony. Nitrogen and phosphorus are N-type dopants for diamond. Phosphorus, arsenic, and antimony are used with silicon.

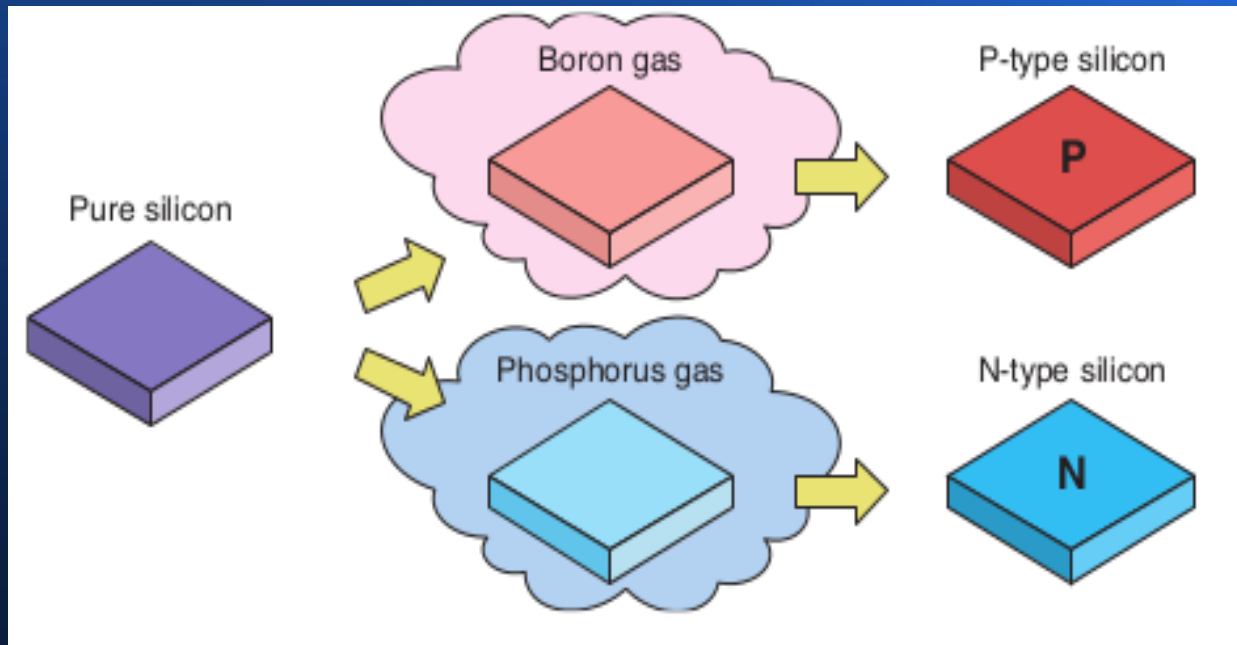
Elemental semiconductors
C(diamond), Si, Ge

13 IIIA		14 IVA	15 VA	
B Boron 10.81 2p ¹	C Carbon 12.011 2p ²	N Nitrogen 14.0067 2p ³		N, P N-type dopant for C
Al Aluminum 26.9815 3p ¹	Si Silicon 28.0855 3p ²	P Phosphorus 30.9738 3p ³		
Ga Gallium 69.723 4p ¹	Ge Germanium 72.61 4p ²	As Arsenic 74.92159 4p ³		P, As, Sb N-type dopant for Si, Ge
In Indium 114.82 5p ¹		Sb Antimony 121.75 5p ³		

B
P-type dopant for C
 B, Al, Ga, In
P-type dopant for Si
 Al, Ga, In
P-type dopant for Ge

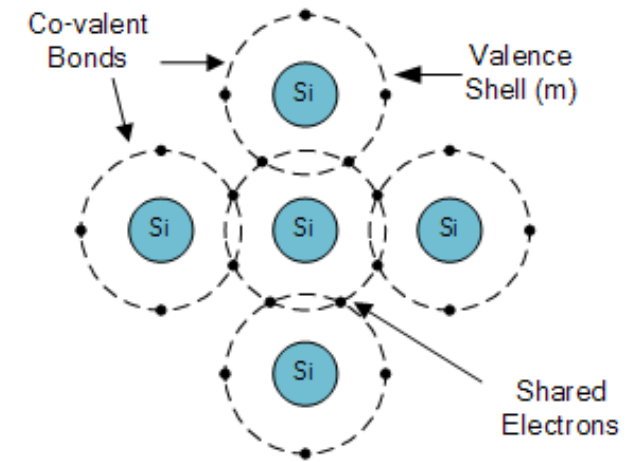


If a piece of pure silicon is surrounded by a gas containing boron or phosphorus and heated in a high-temperature oven, the boron or phosphorus atoms will permeate the crystal lattice and displace some silicon atoms without disturbing other atoms in the vicinity



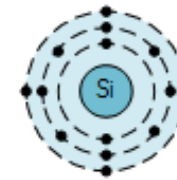
Boron atoms have only three electrons in their outermost electron shells, phosphorous atoms have five electrons in their outermost electron shells

A Silicon Atom Structure

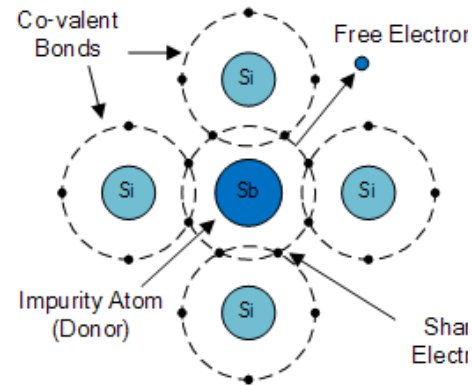


Silicon Crystal Lattice

A Silicon Atom,
Atomic number = "14"

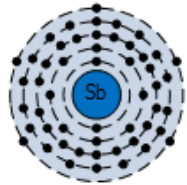


Silicon atom showing
4 electrons in its outer
valence shell (m)



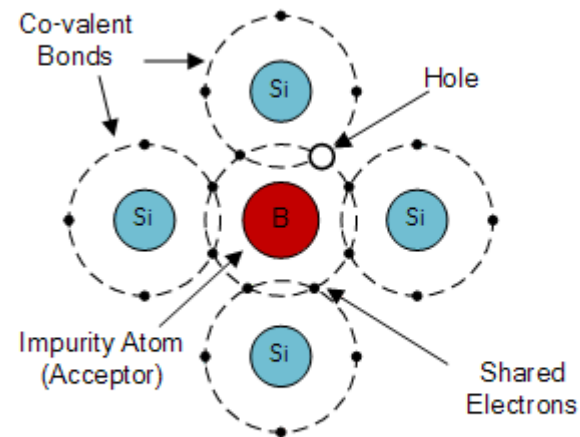
N-Type
Semiconductor

An Antimony Atom,
Atomic number = "51"



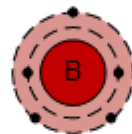
Antimony atom showing
5 electrons in its outer
valence shell (o)

Boron Atom and Doping

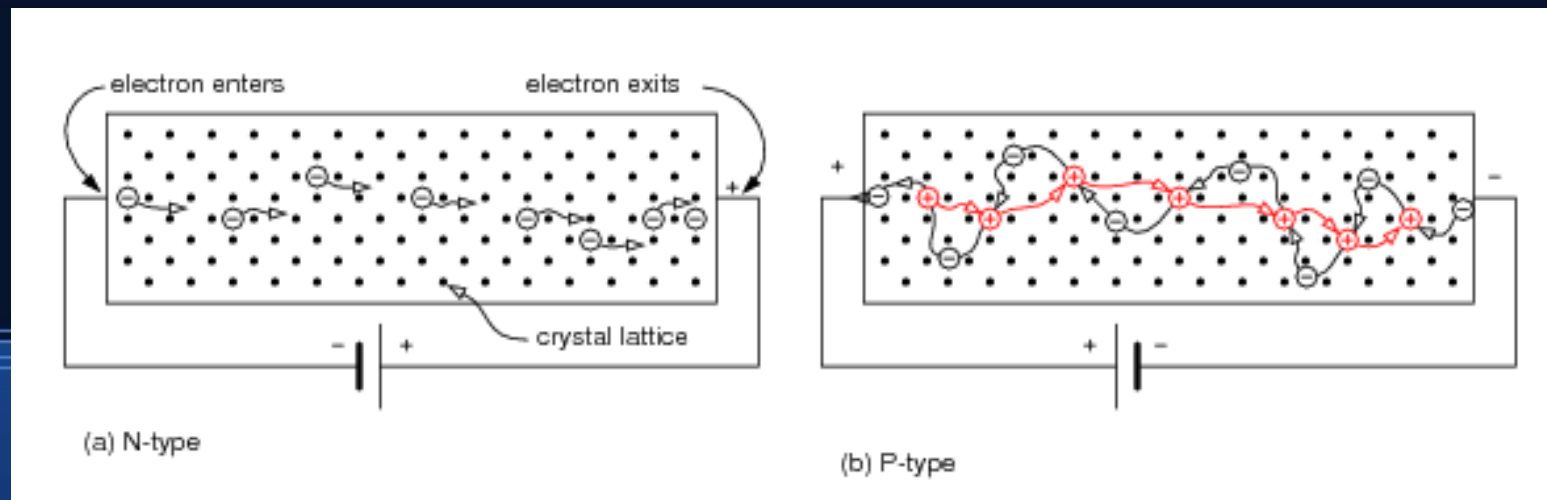


P-Type
Semiconductor

A Boron Atom,
Atomic number = "5"

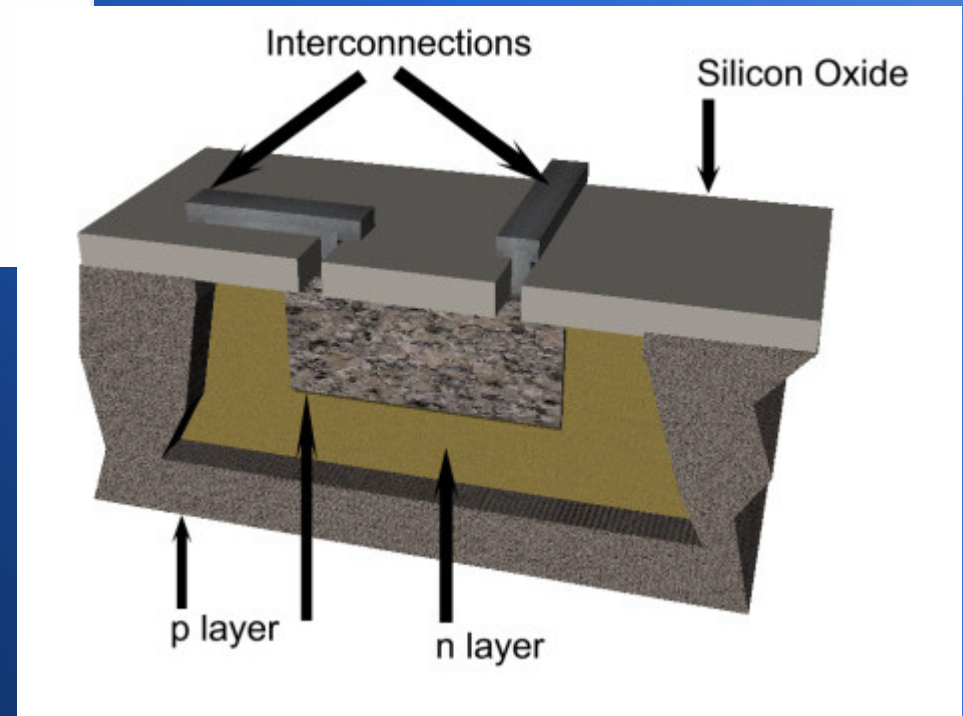
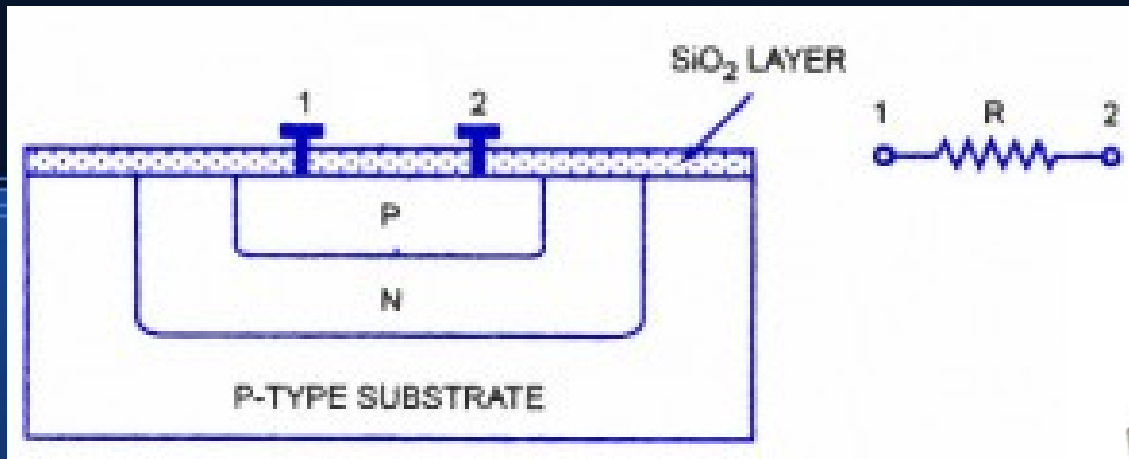


Boron atom showing
3 electrons in its outer
valence shell (L)



Electron flow in an N-type semiconductor is similar to electrons moving in a metallic wire. The P-type dopant, an electron acceptor, yields localized regions of positive charge known as holes. Electron flow is out of the negative battery terminal, through the P-type bar, returning to the positive battery terminal. An electron leaving the positive (left) end of the semiconductor bar for the positive battery terminal leaves a hole in the semiconductor, that may move to the right. Holes traverse the crystal lattice from left to right. At the negative end of the bar an electron from the battery combines with a hole, neutralizing it. This makes room for another hole to move in at the positive end of the bar toward the right. Keep in mind that as holes move left to right, that it is actually electrons moving in the opposite direction that is responsible for the apparant hole movement.

Integrated Circuit Resistor



In IC resistors, the resistance value can be controlled by varying the concentration of doping impurity and depth of diffusion. The range of resistor values that may be produced by the diffusion process varies from ohms to hundreds of kilohms. The typical tolerance, however, may be no better than $\pm 5\%$, and may even be as high as $\pm 20\%$

Depletion

When doped semiconductors are joined to metals, to different semiconductors, and to the same semiconductor with different doping, the resulting junction often strips the electron excess or deficiency out from the semiconductor near the junction.

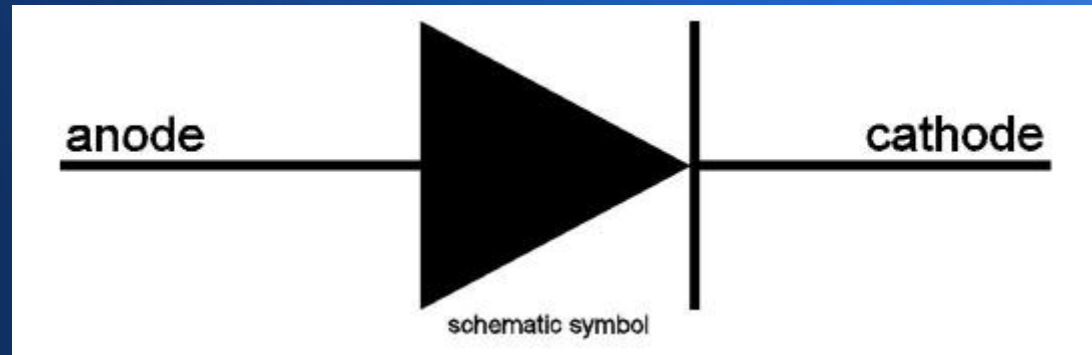
This depletion region is rectifying (only allowing current to flow in one direction), and used to further shape electrical currents in semiconductor devices.

Semiconductor Diode

In electronics, a diode is a two-terminal electronic component with asymmetric transfer characteristic, with low (ideally zero) resistance to current flow in one direction, and high (ideally infinite) resistance in the other.

A semiconductor diode, the most common type today, is a crystalline piece of semiconductor material with a p-n junction connected to two electrical terminals

In a diode, the cathode is the negative terminal at the pointed end of the arrow symbol, where current flows out of the device

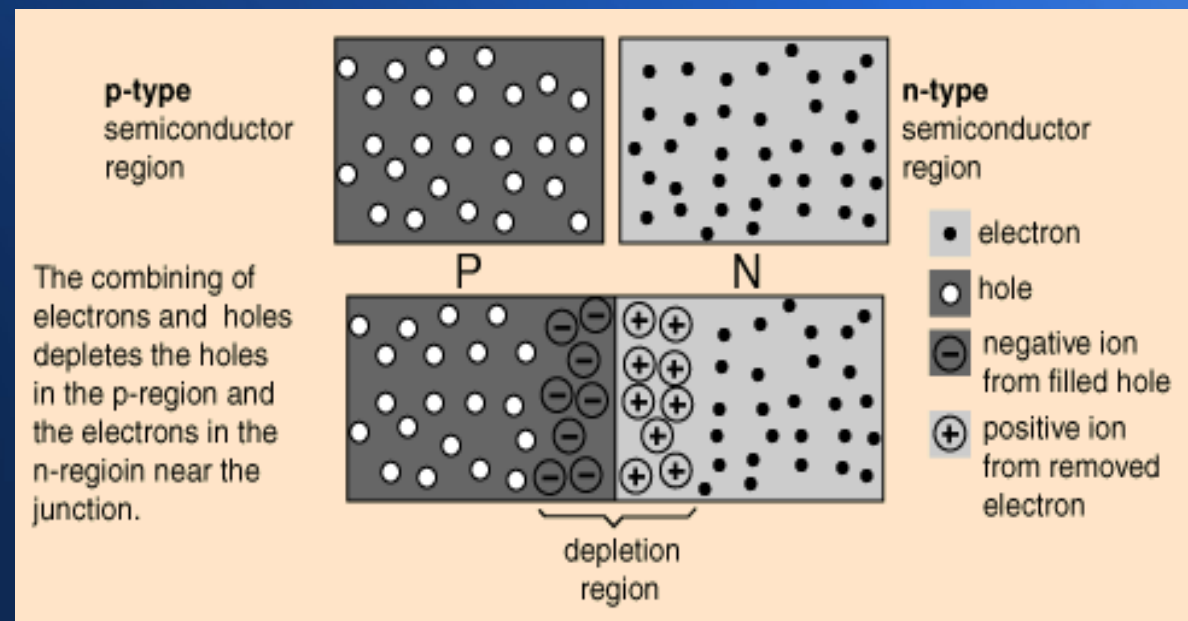


Depletion Region

The P-Type semiconductor has excess holes. The N-Type semiconductor has excess electrons. Due to this difference, some of the electrons get attracted to the corresponding nearest holes and are eliminated by recombination. This process takes place until an equilibrium is reached in the surrounding region of the contact surface.

The net result is the diffused electrons and holes are gone, leaving behind the charged ions adjacent to the interface in a region with no mobile carriers (called the depletion region)

If a block of P-type semiconductor is placed in contact with a block of N-type semiconductor the result is of no value. A single semiconductor crystal manufactured with P-type material at one end and N-type material at the other has some unique properties.



Depletion Region

In semiconductor physics, the depletion region is an insulating region within a conductive, doped semiconductor material where the mobile charge carriers have been diffused away, or have been forced away by an electric field. The only elements left in the depletion region are ionized donor or acceptor impurities.

The Depletion layer appears when electrons fall into holes, so the silicon has turned into an insulator

Following transfer, the diffused electrons come into contact with holes on the P-side and are eliminated by recombination.

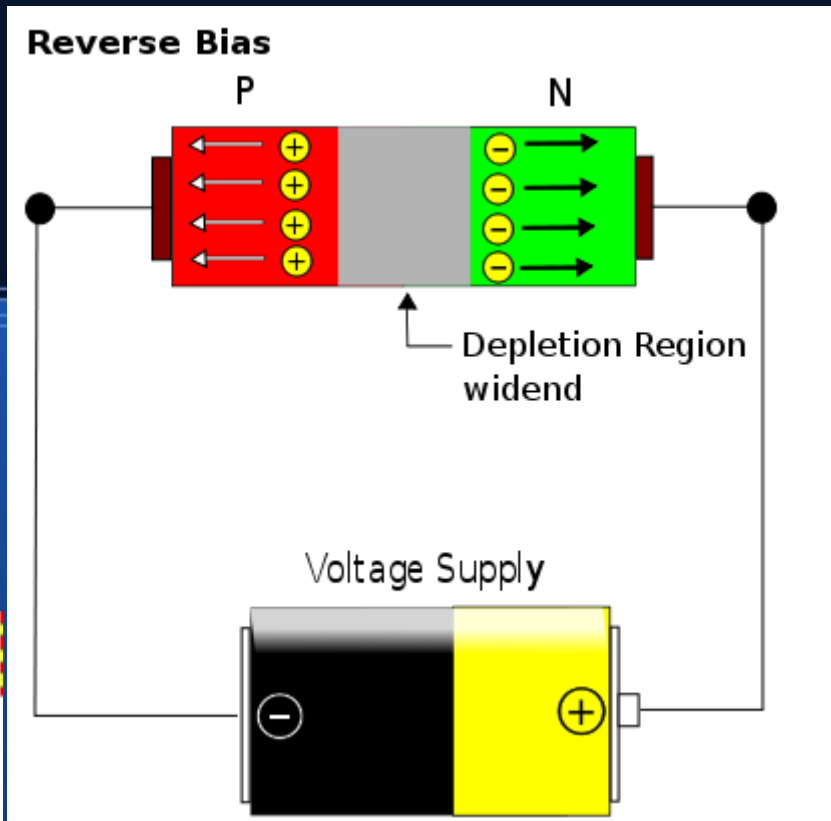
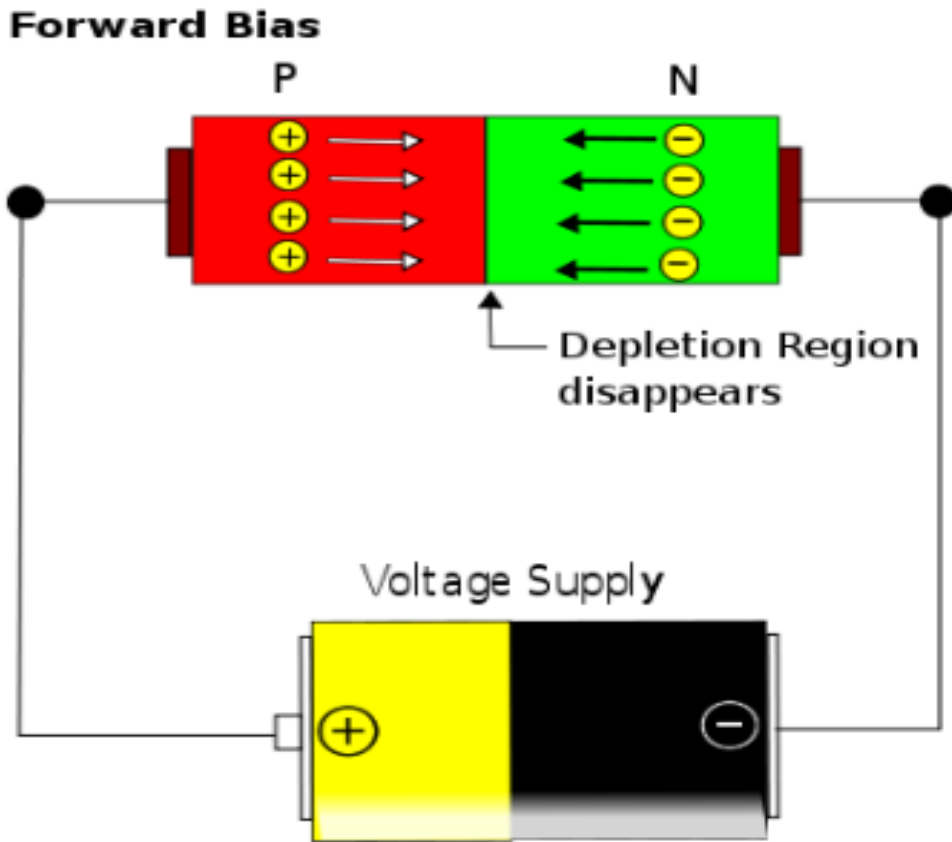
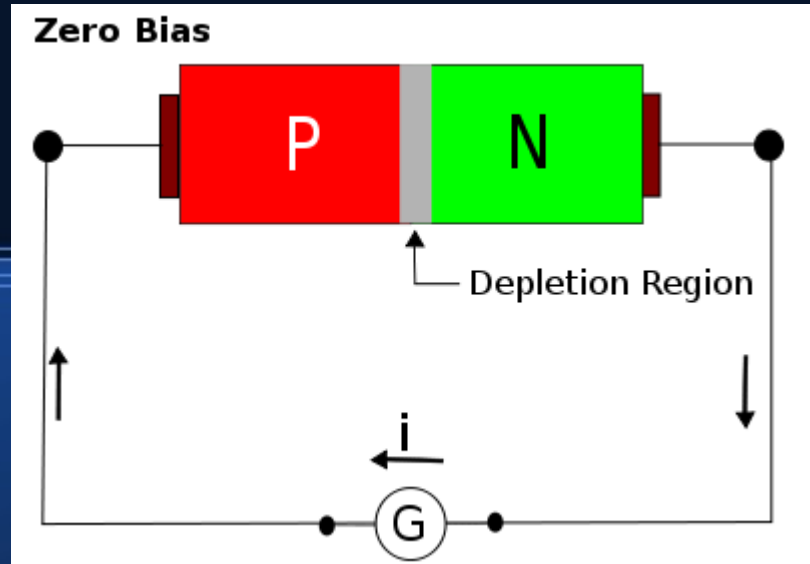
Likewise for the diffused holes on the N-side.

The net result is the diffused electrons and holes are gone, leaving behind the charged ions adjacent to the interface in a region with no mobile carriers (called the depletion region).

The uncompensated ions are positive on the N side and negative on the P side.

This creates an electric field that provides a force opposing the continued exchange of charge carriers.

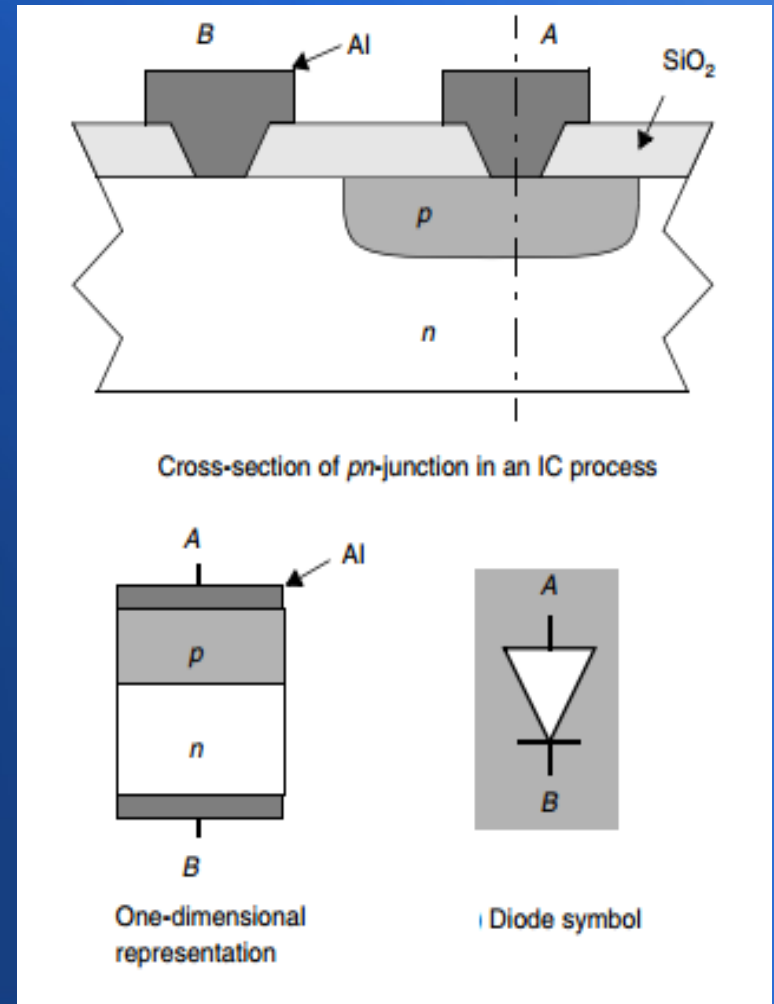
When the electric field is sufficient to arrest further transfer of holes and electrons, the depletion region has reached its equilibrium dimensions



A galvanometer is a type of sensitive ammeter: an instrument for detecting electric current. It is an analog electromechanical actuator that produces a rotary deflection of some type of pointer in response to electric current through its coil in a magnetic field.

If you connect the anode and cathode of the diode you might be able to observe a small voltage or current that is insignificant.

This is because the electromagnetic spectrum that is present in our environment by default knocks off electrons in the semiconductor lattice that constitutes current.



In the N-type region electrons are the majority carriers and in the P-type electron "holes" are the majority carriers.

If **forward-biased** (applying a positive voltage to the P region and a negative voltage to the N region), the depletion region of the diode decreases. The electrons on the N side are repelled and they move towards the P side thus reducing the size of the depletion layer.

If **reverse-biased**, the depletion region increases because the electrons are attracted towards the positive voltage and the holes are attracted towards the negative voltage, and hence the current gets reduced and the current flowing will be very small, on the order of micro amps

At one particular voltage level V_f called the threshold / firing / cut-off voltage the depletion layer disappears (overwhelmed by the charge) and hence from this point on the diode starts to conduct very easily.

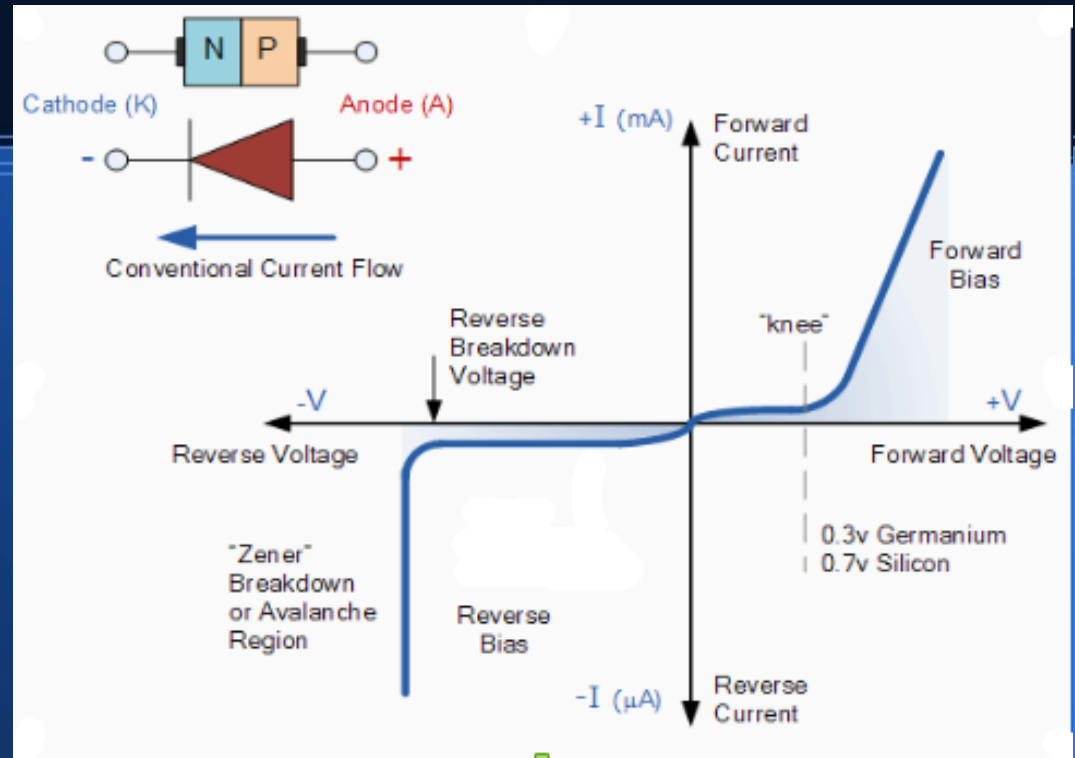
From this point on the diode current increases exponentially to the voltage applied.

I-V Characteristics of a p-n junction diode

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 (ie 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 (ie due to the natural conduction properties of the pure silicon).



For silicon diodes, the typical forward voltage is 0.7 volts, nominal.

For germanium diodes, the forward voltage is only 0.3 volts.

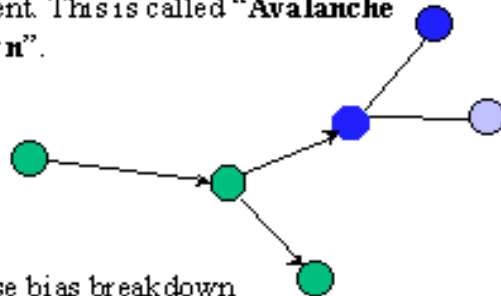
The chemical constituency of the P-N junction comprising the diode accounts for its nominal forward voltage figure, which is why silicon and germanium diodes have such different forward voltages.

Forward voltage drop remains approximately constant for a wide range of diode currents, meaning that diode voltage drop is not like that of a resistor or even a normal (closed) switch.

For most simplified circuit analysis, the voltage drop across a conducting diode may be considered constant at the nominal figure and not related to the amount of current.

Reverse bias breakdown

As the magnitude of the reverse bias voltage is increased, the current remains at I_0 but eventually, the reverse bias field is so strong that thermally generated electrons (or holes) acquire enough kinetic energy to ionise atoms within the crystal structure. These in turn ionise other atoms leading to a very swift multiplication effect and a large current. This is called “**Avalanche breakdown**”.

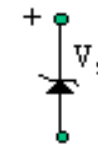
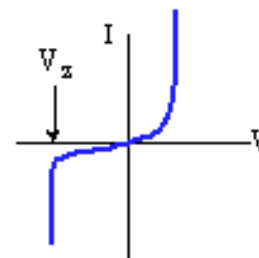


The reverse bias breakdown voltage is about 500V for Germanium and about 1kV for Silicon.

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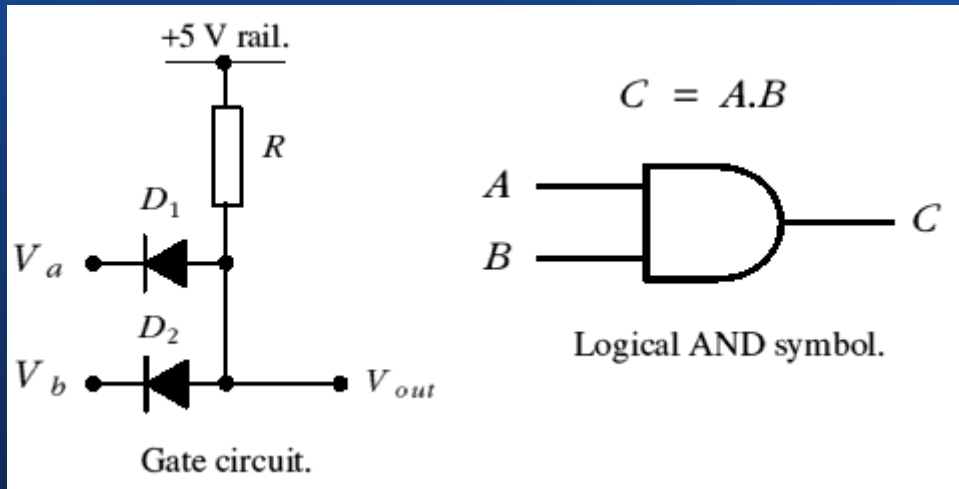
If the impurity doping density is high enough, then the depletion region is narrow enough (even in reverse bias) to allow the electric field across the region to be very high. The high accelerating field and narrow depletion region allows electrons to tunnel through. This is called “**Zener breakdown**”. Zener diodes are designed to breakdown in reverse bias. They can withstand a relatively large reverse current without damage. The reverse bias voltage leading to zener breakdown is adjustable during manufacture of the device.

Typical zener diodes have breakdown voltages anywhere between 2 to 200V depending on the application.



Diode logic (DL), or diode-resistor logic (DRL), is the construction of Boolean logic gates from diodes.

Diode logic was used extensively in the construction of early computers



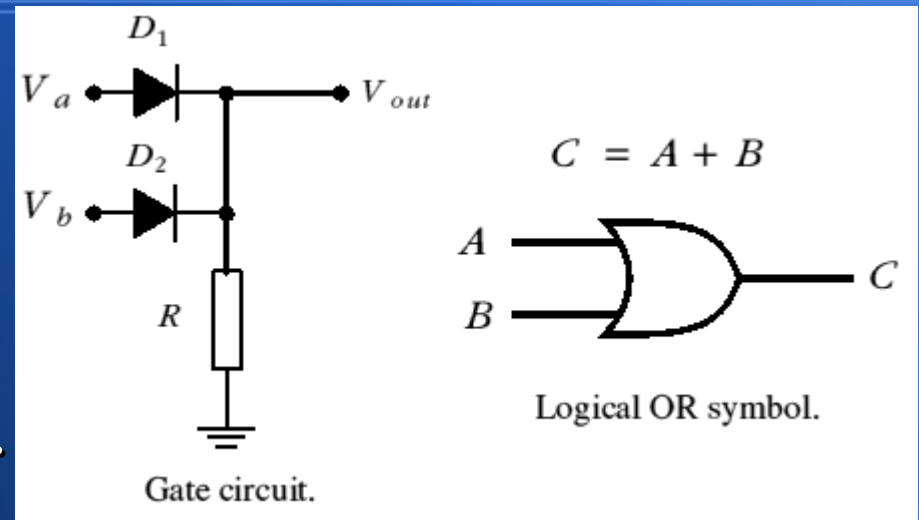
If either input (A or B) is at ground potential (logic 0), then due to the higher potential on the anode side due to the positive voltage from resistor R, current will flow through the diode(s) and the voltage on the output will be equal to the forward voltage of the diode, 0.5v.

If both inputs to the AND gate are high (logic 1), then no current will pass through either diode, and the positive voltage through R will appear on the output

V_a (V)	V_b (V)	V_{out} (V)	A	B	C
0	0	0.5	0	0	0
5	0	0.5	1	0	0
0	5	0.5	0	1	0
5	5	5	1	1	1

Current flows through a diode in the direction of the arrow.

In the case of the OR gate, if there is no potential (i.e. logic 0, or ground) on both inputs, no current will pass through either diode, and the pull-down resistor R will keep the output at ground (logic 0).



If either of the inputs has a positive (logic 1) voltage on its input (a or b), then current will pass through the diode(s) and appear on the output less the forward voltage of the diode (aka diode drop).

V_a (V)	V_b (V)	V_{out} (V)	A	B	C
0	0	0	0	0	0
5	0	4.5	1	0	1
0	5	4.5	0	1	1
5	5	4.5	1	1	1

While diode logic has the advantage of simplicity, the lack of an amplifying stage in each gate limits its application.

Also note that it is not possible to construct an inverter with only diodes and resistors. AND and OR functions by themselves are not a complete logic without NOT.

Thus, there are some logic functions that cannot be implemented in diode-resistor logic. Fortunately, transistors solve all of these problems.