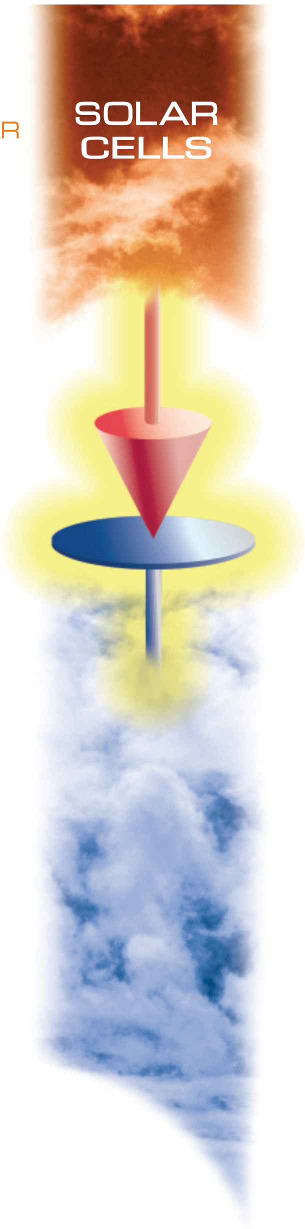


These opposing flows eventually reach a stable equilibrium with the number of electrons flowing due to diffusion exactly balancing the number of electrons flowing back due to the electric field. The net flow of electrons across the junction is zero and the net flow of holes across the junction is also zero.

This begs the question, "If there is no net current flowing, of what use is it?" Although there is no net flow of current across the junction there has been established an electric field at the junction and it is this electric field that is the basis of the operation of diodes, transistors and solar cells.

Depletion Region

Within the depletion region, there are very few mobile electrons and holes. It is "depleted" of mobile charges, leaving only the fixed charges associated with the dopant atoms. As a result, the depletion region is highly resistive and now behaves as if it were pure crystalline silicon: as a nearly perfect insulator.

The resistance of the depletion region can be modified by "adding" an external electric field to the "built-in" electric field. If the "added" electric field is in the same direction as the "built-in" electric field, the depletion region's resistance will become greater. If the "added" electric field is opposite in direction to the "built-in" electric field, the depletion region's resistance will become smaller. The depletion region can therefore be considered to operate as a voltage-controlled resistor.

Forward Bias

If a positive voltage is applied to the p-type side and a negative voltage to the n-type side, current can flow (depending upon the magnitude of the applied voltage). This configuration is called "Forward Biased" (see Figure 5).

At the *p-n* junction, the "built-in" electric field and the applied electric field are in opposite directions. When these two fields add, the resultant field at the junction is smaller in magnitude than the magnitude of the original "built-in" electric field. This results in a thinner, less resistive depletion region. If the applied voltage is large enough, the depletion region's resistance becomes negligible. In silicon, this occurs at about 0.6 volts forward bias. From 0 to 0.6 volts, there is still considerable resistance due to the depletion region. Above 0.6 volts, the depletion region's resistance is very small and current flows virtually unimpeded.

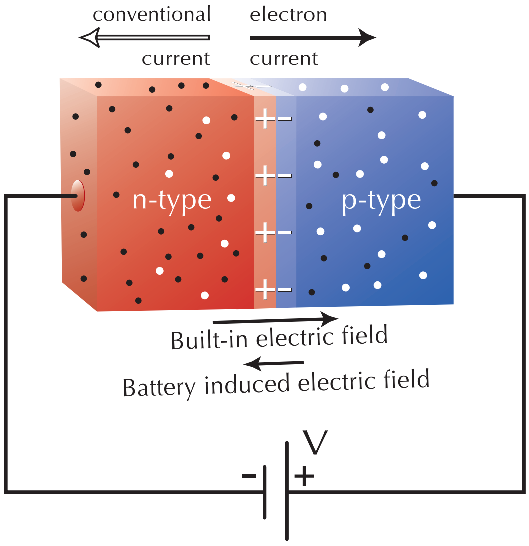


Figure 5 Forward bias of the *p-n* junction.

Reverse Bias

If a negative voltage is applied to the p-type side and a positive voltage to the n-type side, no (or exceptionally small) current flows. This configuration is called "Reverse Biased" (see Figure 6).

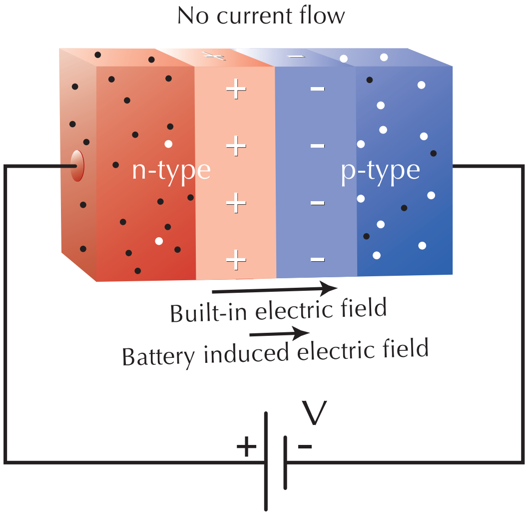


Figure 6 Reverse bias of the *p-n* Junction.

At the *p-n* junction, the "built-in" electric field and the applied electric field are in the same direction. When these two fields add, the resultant larger electric field is in the same direction as the "built in" electric field and this creates a thicker, more resistive depletion region. If the applied voltage becomes larger, the depletion region becomes thicker and more resistive.

In reality, some current will still flow through this resistance, but the resistance is so high that the current may be considered to be zero. As the applied reverse bias voltage becomes larger, the current flow will saturate at a constant but very small value. This is approximately 10^{-12} amperes per cm^2 of *p-n* junction area.

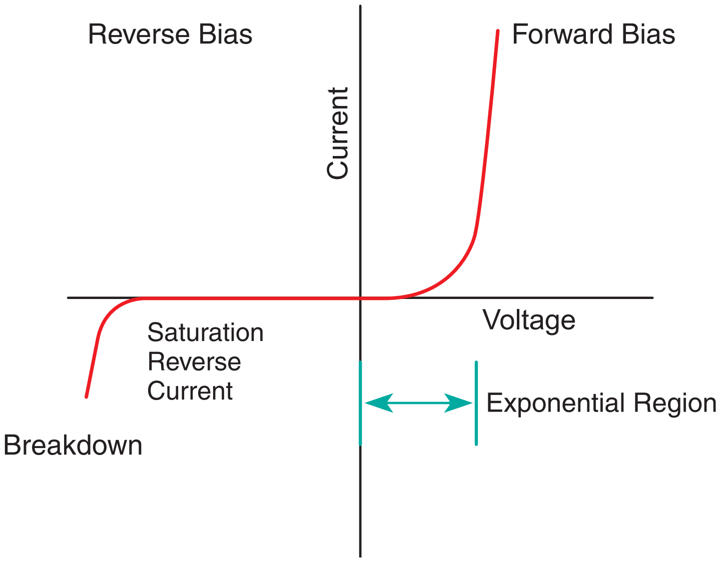


Figure 7 IV curve of the silicon *p-n* junction diode.

The current-voltage relation or IV curve of a silicon *p-n* junction is shown in Figure 7. In reverse bias, the *p-n* junction exhibits extreme electrical resistance and only a very small current flows. If the reverse bias voltage becomes too large then the junction will breakdown and current will flow. It is possible to design silicon *p-n* junctions in such a way that the breakdown voltage is at a specific desired value. Such *p-n* junctions are called zener diodes and are used as voltage references or overvoltage protectors in electrical cir-

In forward bias, the *p-n* junction exhibits an exponential lowering of resistance with applied voltage. From 0 to 0.5 volts, the silicon *p-n* junction is quite resistive. When the applied voltage approaches 0.6 volts, the exponential nature of the junction causes the resistance to drop dramatically. The silicon *p-n* junction diode appears to be an electrical switch that "turns on" when 0.6 volts is applied. Because electrical current flows only when it is forward biased, the diode appears to be an electrical one-way valve.

How a Solar Cell Works

Now it can be seen what happens inside a solar cell. Most solar cells are essentially large area *p-n* junctions. When light shines on them they can generate current and voltage. The reason this can happen is because of the "built-in" electric field at the junction of the p-type and n-type material.

First consider what happens if a silicon solar cell (which is a *p-n* junction) has a low resistance wire connected externally between the p and n contact. In the dark a solar cell will produce no current. If, however, light shines on the solar cell then current will flow through the wire, from the p-type side to the n-type side (conventional current).

How It Happens

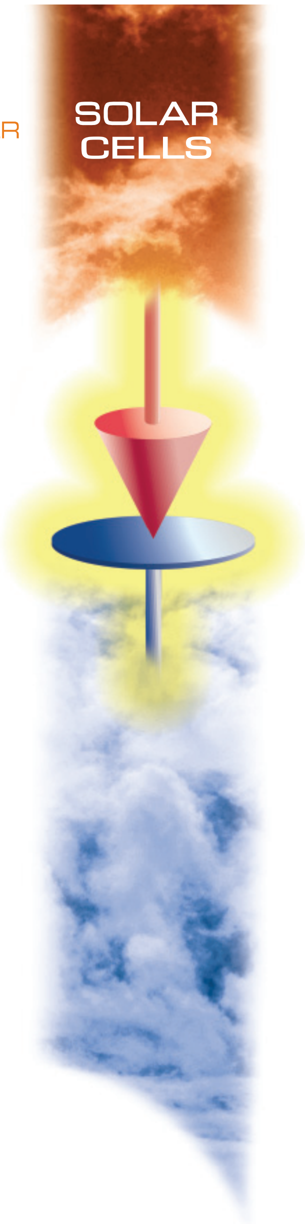
The light has enough energy to break some of the chemical bonds of the silicon crystal. What that means is that electrons, which are normally involved in a silicon bond, are excited by the light into a higher energy state and the bond is broken. Not all of the bonds are broken otherwise the silicon would melt! The sun's light intensity on earth is strong enough to break about 1 bond for every 100 million silicon atoms in the solar cell. So the solar cell doesn't melt under normal conditions.

The excited electrons are now like the electrons from phosphorus dopant atoms - they are free to move through the material. Similarly, the broken bonds created by the light act as holes - just like the missing electrons in bonds between silicon and boron atoms - and these holes are also free to move throughout the material. What goes up, however, must eventually come down! Electrons and holes created in this way are physically near each other: for every electron excited by the light there is a corresponding hole generated. These electrons and holes can remain excited only for a short period of time. In a process called recombination, excited electrons stray too close to holes and the two fall back into bonded positions. When this happens the pair's electrical energy is lost as heat. If there is too much recombination, the solar cell won't work very well.

Current flow from a Solar Cell

The electrons and holes excited by light shining on the solar cell occur throughout the volume of the material, in the p-region, the n-region and at the junction region where there is a “built-in” electric field. It is easiest to understand the flow of current by first considering electrons and holes that are excited by the light in the junction region.

Because of the “built-in” electric field, the electrons are attracted towards the positive charge on the n-type material side. Similarly, the holes are attracted to the negative charge on the p-type material side. This separation of charges causes a current to flow across the junction. The direction of the current flow (conventional current) is the same as the motion of the holes (as they are positively charged). That is, the current flows across the junction from the n-type side to the p-type side.



Similarly, electrons and holes, which are far away from the junction, can be separated by the “built-in” electric field if they can find their way towards the junction before they recombine. This occurs simply because the electrons and holes will randomly diffuse throughout the material. If they manage to randomly wander into the “built-in” electric field region, before recombining, then they will contribute to the current flowing across the junction.

These charges will also cause flow of electrons through the external wire. Electric current can be measured by simply attaching a current meter in series with a solar cell. Because the resistance across the wire and the current meter is very low, there will be essentially no voltage across the solar cell, but current can flow. This is called the short-circuit current.

The Voltage of a Solar Cell

In the situation described above there is current flowing through the wire and meter but there isn't any voltage (yet!). Power can be extracted from the solar cell only if it can produce both voltage and current. What happens if the wire is cut?

In this case, there is no pathway for any light generated current to flow outside of the solar cell. Separation of electrons and holes, however, keeps happening inside the solar cell. Electrons are being pushed over toward the n-type side and holes are being pushed over towards the p-type side (if they manage to wander near the junction without first recombining). When the wire is cut, there is no external circuit for these charges to flow through. Instead, the flow of electrons into the n-type side and the flow of holes into the p-type side, causes a voltage to build up across the solar cell - positive voltage on the p-type side and negative voltage on the n-type side. There is now a voltage across the solar cell, however, there is no current flowing from the solar cell. The "open-circuit voltage" is measured by placing a voltmeter across the illuminated solar cell. For a silicon solar cell, it will measure about 0.6 volts in strong sunlight.

A Closer Look at the Open-Circuit voltage

If a *p-n* junction has an external forward bias voltage applied across it, a current will flow through the junction of the solar cell from the p-type side to the n-type side (conventional current).

When an open circuit solar cell is illuminated, the light generated electrons and holes that wander near the junction will be separated by the “built-in” electric field. The electrons will be pushed into the n-type region and the holes will be pushed into the p-type region. A light generated flow of current through the junction is opposite in direction to a forward bias flow of current.

In an illuminated open circuit solar cell there is a constant value of light generated electrons and holes flowing across the junction and into the corresponding p-type and n-type regions. The light generated current depends only on how intense the sunlight is and how much recombination occurs within the solar cell. This collection of charge creates a voltage across the solar cell. It could be imagined that this separation of charge would continue indefinitely with the result being that the voltage across the solar cell becomes infinite.

Something happens, however, to limit the voltage. The solar cell is now forward biased and just as for the *p-n* junction in the dark, current flows across the junction from the p-type side to the n-type side. This forward bias current is in the opposite direction to the light generated current described above. Both currents are flowing simultaneously. As the voltage across the solar cell builds up, it eventually reaches a point where the forward bias current exactly balances the light generated current. These two internal currents flow inside the solar cell cancelling each other out. The voltage at which this occurs is called the "open-circuit voltage". For a silicon solar cell it is typically 0.6 volts in bright sunshine.

Getting Power from a Solar Cell

For short-circuit conditions there is a low resistance wire connected between the solar cell contacts resulting in a current flowing but no generated voltage. If the wire is cut, the solar cell is now open-circuited resulting in a voltage being generated but no current flowing.

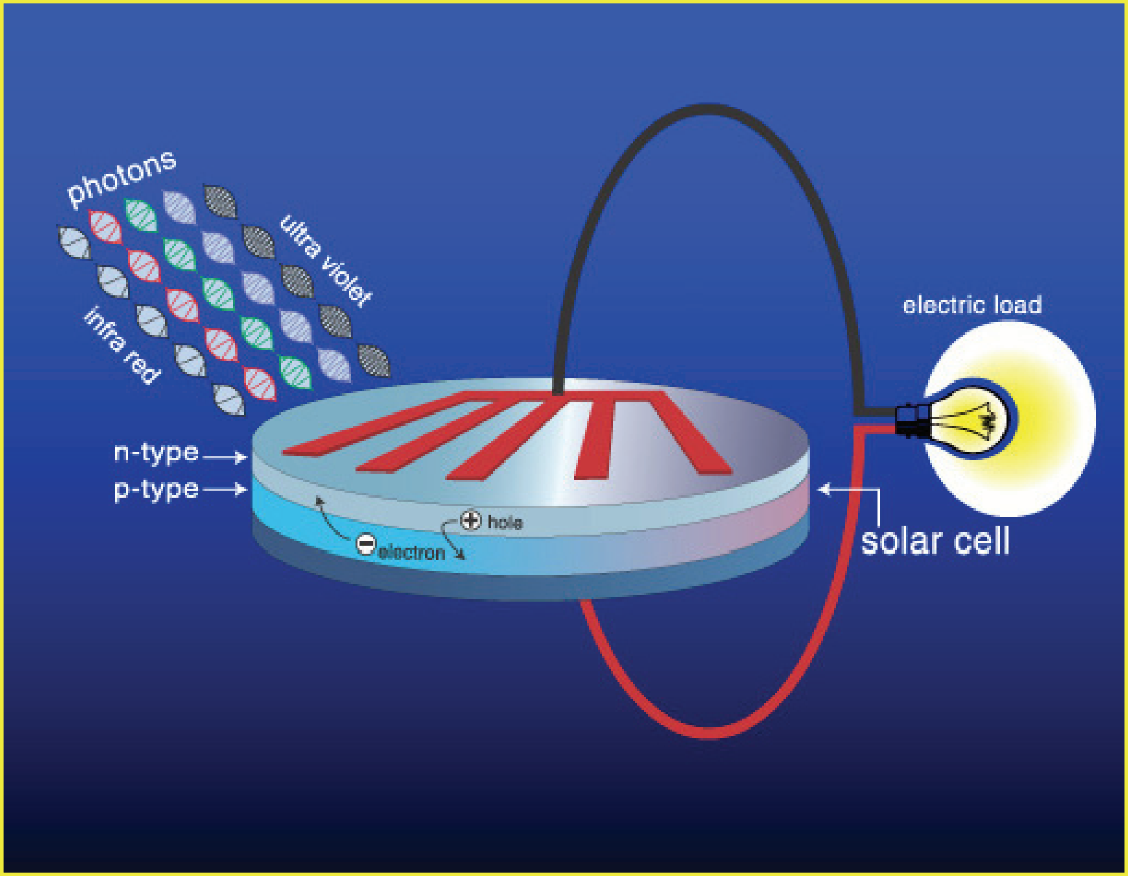
In order to get useful power out of a solar cell there needs to be a resistance between the two contacts that has just the right value. If the resistance is too low, then there will be mostly current coming from the solar cell and very little voltage generated. If too high a resistance is connected across the contacts there will be mostly voltage generated and very little current coming out of the solar cell.

Only when the right resistance is connected across the solar cell will there be an optimal voltage generated with an optimal current flowing. With this value of resistance across the solar cell, the maximum electrical energy available from the solar cell is being delivered to the resistor. Under these conditions, the solar cell is said to be operating at its "Maximum Power Point".

For Large Amounts of Power

In order to generate large amounts of power from solar cells all that is needed is to wire many solar cells together. Collectively, the cells can generate enough power to do useful work. In fact, it is possible to wire together enough solar cells to form a great big solar cell power station. The electricity generated could then be used to power anything from a single light bulb to a large electric train, and with even more solar cells in the circuit, it would be possible to power an entire city!

The Silicon Solar Cell



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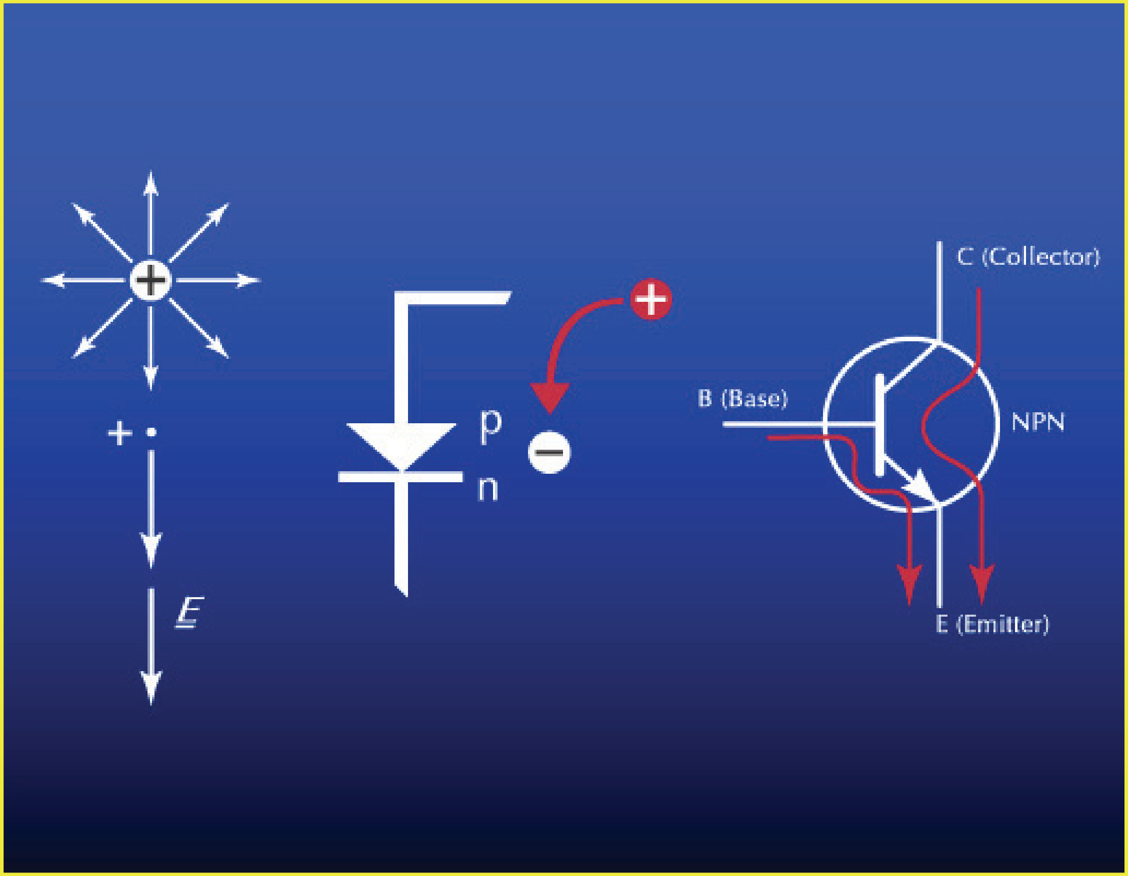
Photovoltaics - Electricity from Sunlight

Direction of Current Flow



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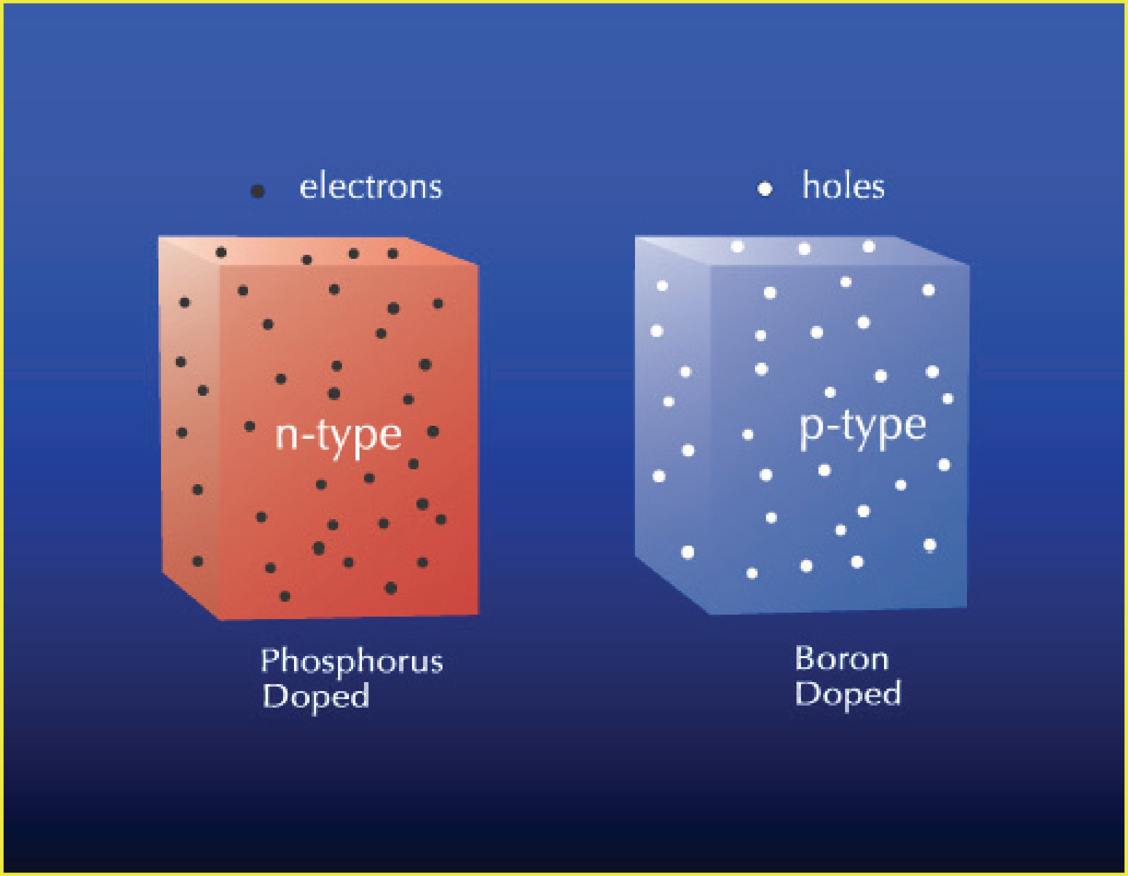
Two Pieces of Doped Silicon



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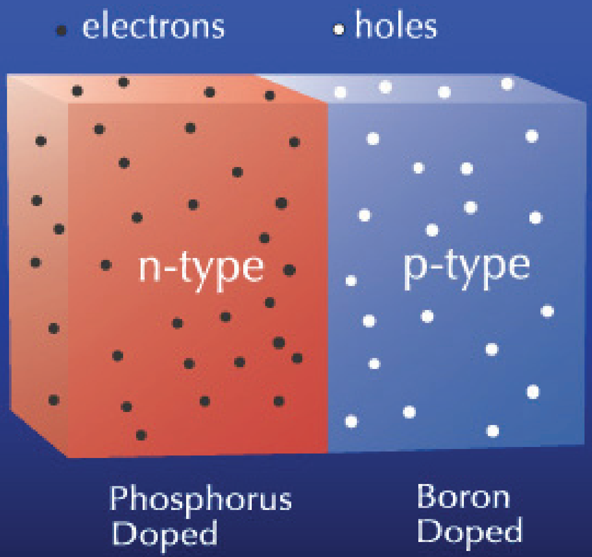
n-Type and *p*-Type Joined



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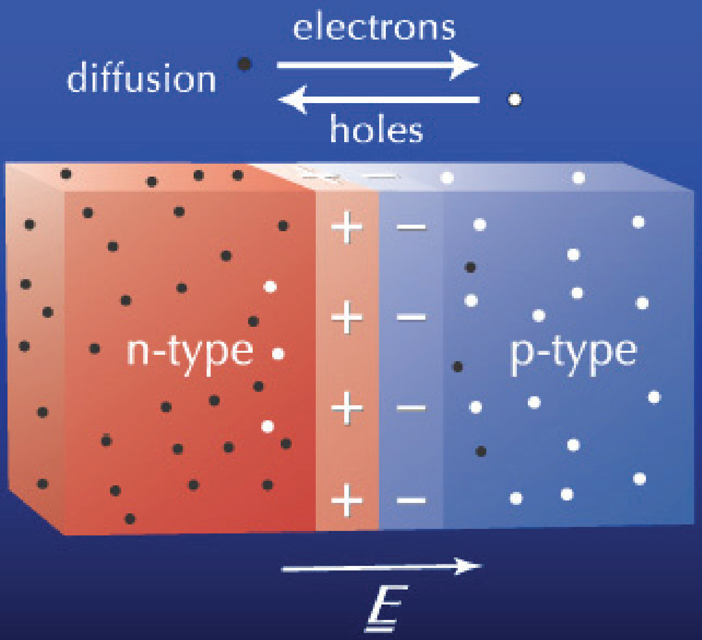
Diffusion via Random Motion



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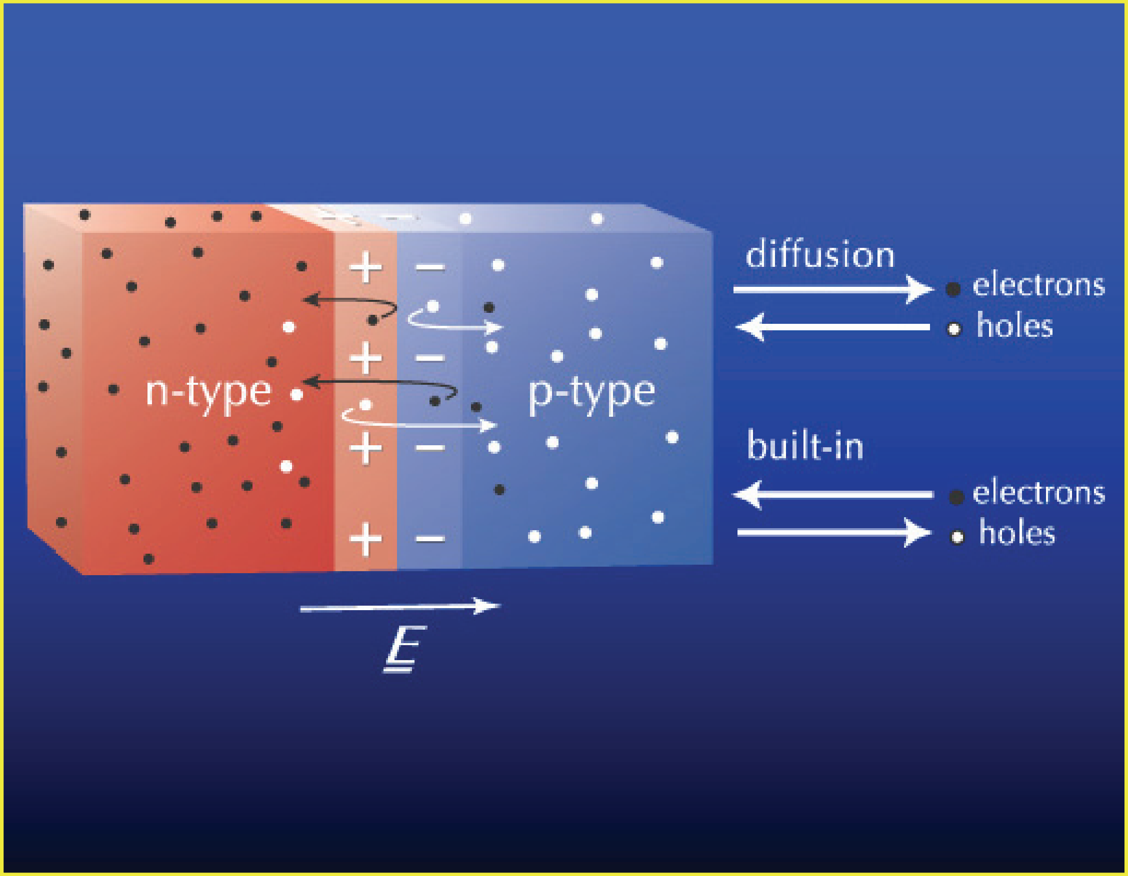
Diffusion & Built-In Currents



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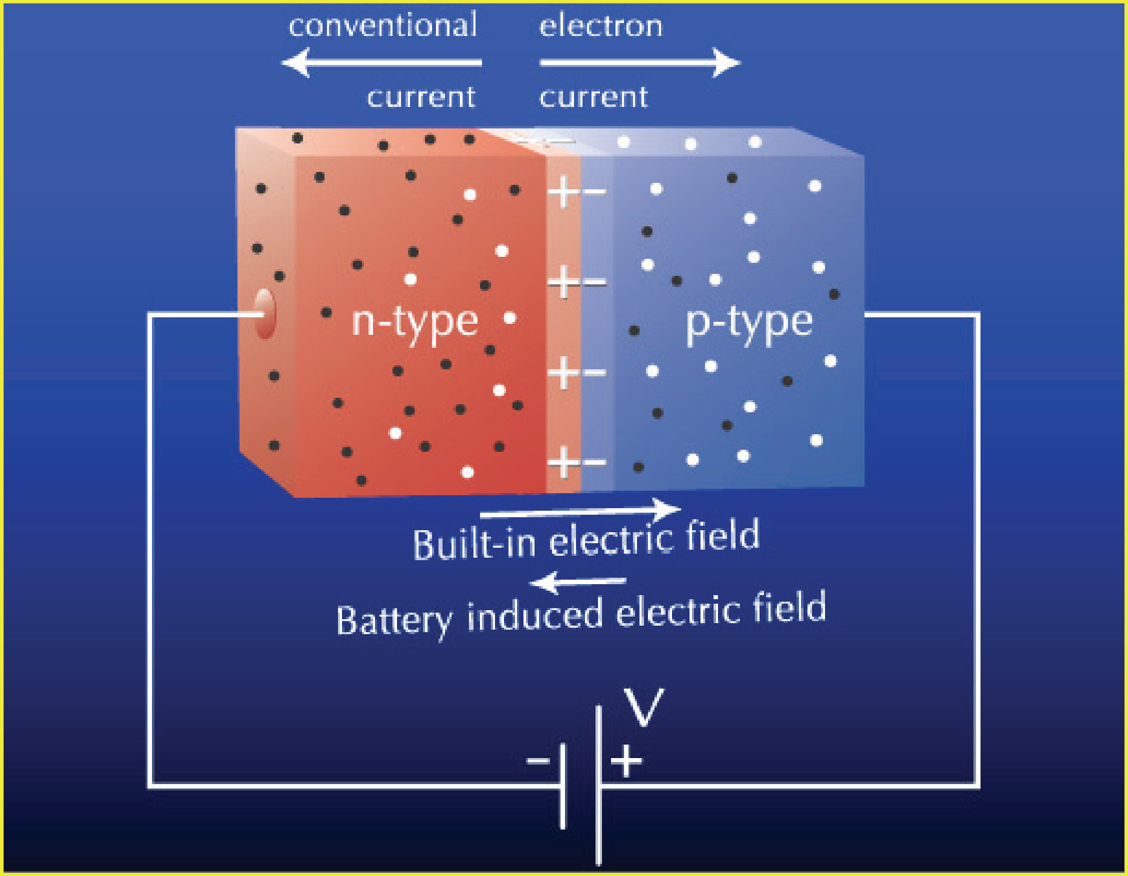
Forward Biased *pn*-Junction



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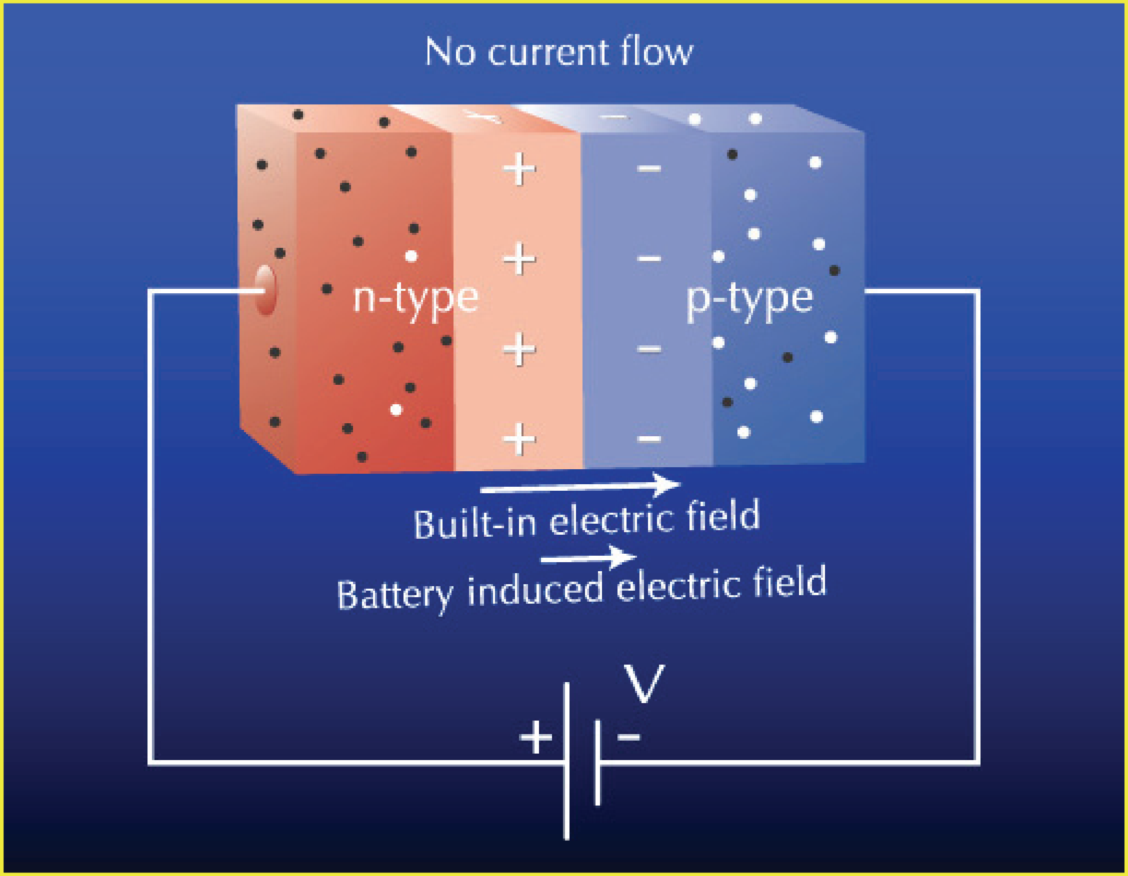
Reverse Biased *pn*-Junction



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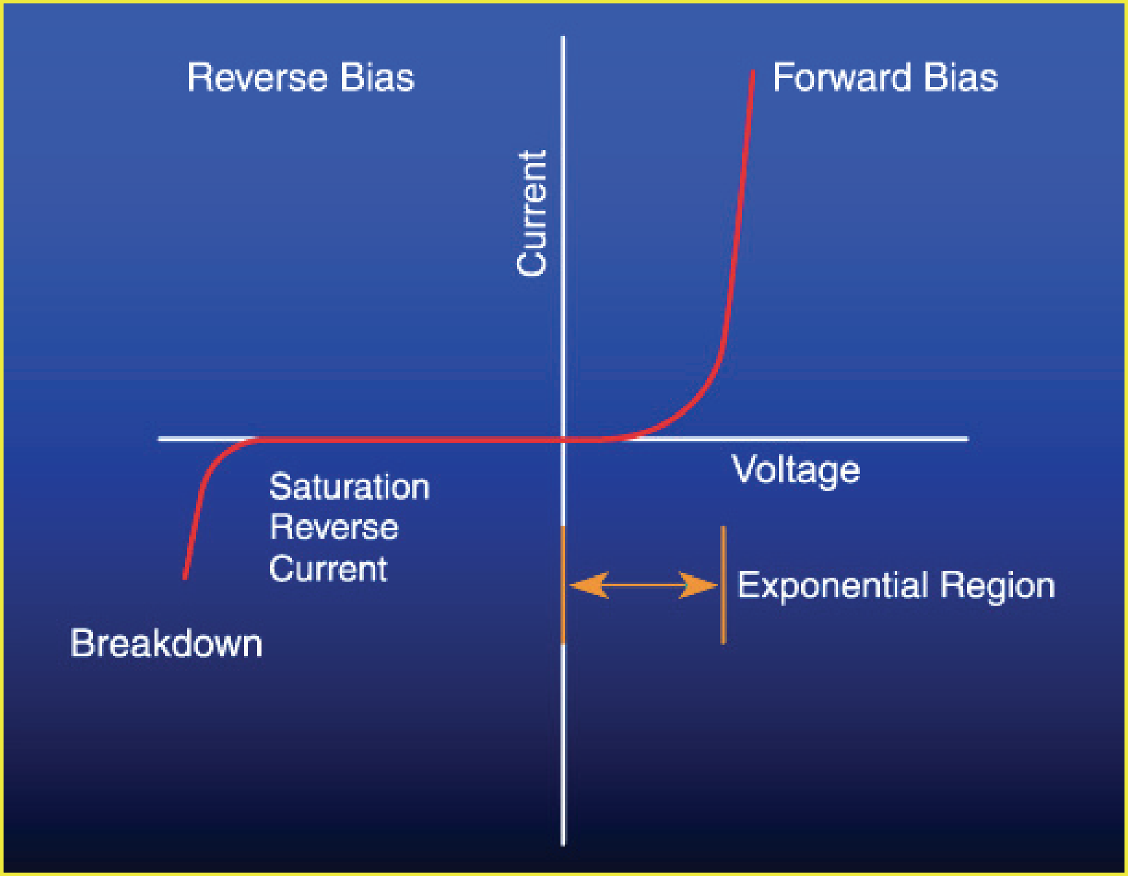
Characteristics of the *pn*-Junction



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