**Photovoltaics**

Photovoltaic (PV) materials and devices convert sunlight into electrical energy, and PV cells are commonly known as solar cells. Photovoltaics can literally be translated as light-electricity. First used in about 1890, "photovoltaic" has two parts: **photo**, derived from the Greek word for light, and: **volt**, relating to electricity pioneer Alessandro Volta. And this is what photovoltaic materials and devices do—they convert light energy into electrical energy, as French physicist Edmond Becquerel discovered as early as 1839. Becquerel discovered the process of using sunlight to produce an electric current in a solid material. But it took more than another century to truly understand this process. Scientists eventually learned that the photoelectric or photovoltaic effect caused certain materials to convert light energy into electrical energy at the atomic level.

PV systems are already an important part of our daily lives. Simple PV systems provide power for small consumer items such as calculators and wristwatches. More complicated systems provide power for communications satellites, water pumps, and the lights, appliances, and machines in some homes and workplaces. Many road and traffic signs also are now powered by PV. In many cases, PV power is the least expensive form of electricity for these tasks.

**Photovoltaic Cells**

Photovoltaic (PV) cells, or solar cells, take advantage of the photoelectric effect to produce electricity. PV cells are the building blocks of all PV systems because they are the devices that convert sunlight to electricity. Commonly known as solar cells, individual PV cells are electricity-producing devices made of semiconductor materials. PV cells come in many sizes and shapes, from smaller than a postage stamp to several inches across. They are often connected together to form PV modules that may be up to several feet long and a few feet wide. Modules, in turn, can be combined and connected to form PV arrays of different sizes and power output. The modules of the array make up the major part of a PV system, which can also include electrical connections, mounting hardware, power-conditioning equipment, and batteries that store solar energy for use when the sun is not shining.

When light shines on a PV cell, it may be reflected, absorbed, or pass right through. But only the absorbed light generates electricity.
The energy of the absorbed light is transferred to electrons in the atoms of the PV cell semiconductor material.
With their newfound energy, these electrons escape from their normal positions in the atoms and become part of the electrical flow, or current, in an electrical circuit. A special electrical property of the PV cell—what is called a: "built-in electric field"—provides the force, or voltage, needed to drive the current through an external load, such as a light bulb.

**Crystalline Silicon Cells**

Crystalline silicon PV cells are the most common photovoltaic cells in use today. They are also the earliest successful PV devices. Therefore, crystalline silicon solar cells provide a good example of typical PV cell functionality.

**Photovoltaic Systems**

A photovoltaic (PV), or solar electric system, is made up of several photovoltaic solar cells. An individual PV cell is usually small, typically producing about 1 or 2 watts of power. To boost the power output of PV cells, they are connected together to form larger units called modules. Modules, in turn, can be connected to form even larger units called arrays, which can be interconnected to produce more power, and so on. In this way, PV systems can be built to meet almost any electric power need, small or large.

The basic PV or solar cell produces only a small amount of power. To produce more power, cells can be interconnected to form modules, which can in turn be connected into arrays to produce yet more power. Because of this modularity, PV systems can be designed to meet any electrical requirement, no matter how large or how small. By themselves, modules or arrays do not represent an entire PV system. Systems also include structures that point them toward the sun and components that take the direct-current electricity produced by modules and "condition" that electricity, usually by converting it to alternate-current electricity. PV systems may also include batteries. These items are referred to as the balance of system (BOS) components.
Combining modules with BOS components creates an entire PV system. This system is usually everything needed to meet a particular energy demand, such as powering a water pump, the appliances and lights in a home, or—if the PV system is large enough—all the electrical requirements of a community.

**Semiconductors and the Built-In Electric Field for Crystalline Silicon Photovoltaic Cells**
To separate electrical charges, crystalline silicon cells must have a built-in electric field. Light shining on crystalline silicon may free electrons within the crystal lattice, but for these electrons to do useful work—such as provide electricity to a light bulb—they must be separated and directed into an electrical circuit.

**PV Semiconductors**
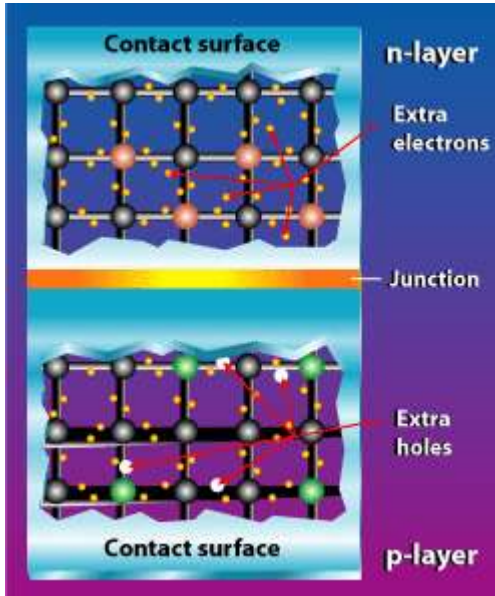


Although both materials are electrically neutral, n-type silicon has excess electrons and p-type silicon has excess holes. Sandwiching these together creates a: p/n junction at their interface, thereby creating an electric field.
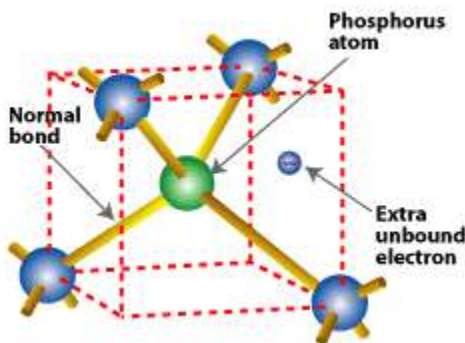


Substituting a phosphorus atom *(with five valence electrons)* for a silicon atom in a silicon crystal leaves an extra, unbonded electron that is relatively free to move around the crystal. To create an electric field within a crystalline silicon photovoltaic (PV) cell, two silicon semiconductor layers are sandwiched together.

**p-type** *(or positive)* semiconductors have an abundance of positively charged holes, and:
**n-type** *(or negative)* semiconductors have an abundance of negatively charged electrons.

When n- and p-type silicon layers contact, excess electrons move from the n-type side to the p-type side. The result is a buildup of: positive charge along the n-type side of the interface and a buildup of negative charge along the p-type side.

Because of the flow of electrons and holes, the two semiconductors behave like a battery, creating an electric field at the surface where they meet what is called the *p/n junction*. The electrical field causes the electrons to move from the semiconductor toward the: negative surface, making them available for the electrical circuit. At the same time, the holes move in the opposite direction, toward the: positive surface, where they await incoming electrons.

## Creating P-Type and N-Type Semiconductors

In a crystalline silicon PV cell, p-type silicon must contact n-type silicon to create the built-in electrical field. The process of: *doping*, which is used to create these materials, introduces an atom of another element into silicon crystal to alter its electrical properties. The *dopant*, which is the introduced element, has either: three or five valence electrons—which is: one less or one more than silicon's four.

Phosphorus atoms, which have: five valence electrons, are used to dope n-type silicon because phosphorus provides its fifth free electron. A phosphorus atom occupies the same place in the crystal lattice formerly occupied by the silicon atom it replaced. Four of its valence electrons take over the bonding responsibilities of the four silicon valence electrons that they replaced. But the fifth valence electron remains free, having no bonding responsibilities. When phosphorus atoms are substituted for silicon in a crystal, many free electrons become available.

The most common method of doping is to coat a layer of silicon material with phosphorus and then heat the surface. This allows the phosphorus atoms to diffuse into the silicon. The temperature is then reduced so the rate of diffusion drops to zero. Other methods of introducing phosphorus into silicon include: gaseous diffusion, a liquid dopant spray-on process, and a technique in which phosphorus ions are precisely driven into the surface of the silicon.

But the: n-type silicon cannot form an electric field by itself. It also needs: p-type silicon. Boron, which has only three valence electrons, is used for doping: p-type silicon. Boron is introduced during silicon processing when the silicon is purified for use in photovoltaic devices. When a boron atom takes a position in the crystal lattice formerly occupied by a silicon atom, a bond will be missing an electron. In other words, there is an extra positively charged hole.

## P-Layer Design

In a PV cell, photons are absorbed in the: p-layer. It is therefore important that this layer be "tuned" to the properties of incoming photons so it can absorb as many as possible and, thus, free up as many electrons as possible. The design of the: p-layer must also keep the electrons from meeting up with holes and recombining with them before they can escape from the PV cell. To accomplish these goals, p-layers are designed to free electrons as close to the junction as possible, so that the electric field can help send the free electrons through the conduction layer (the n-layer) and out into the electrical circuit. By optimizing these characteristics, the PV cell's conversion efficiency *(how much light energy is converted into electrical energy)* is improved.

## Crystalline Silicon Photovoltaic Cells

Crystalline silicon cells are made of silicon atoms connected to one another to form a: crystal lattice. This lattice comprises the solid material that forms the photovoltaic (PV) cell's semiconductors.

## Atomic Structure

All matter is composed of atoms, which are made up of positively charged protons, negatively charged electrons, and neutral neutrons. Protons and neutrons, which are about the same size, are in the close-packed, central nucleus of the atom. The much lighter electrons orbit the nucleus. Although atoms are built of oppositely charged particles, their overall charge is neutral because they contain an equal number of positive protons and negative electrons, whose charges offset each other.
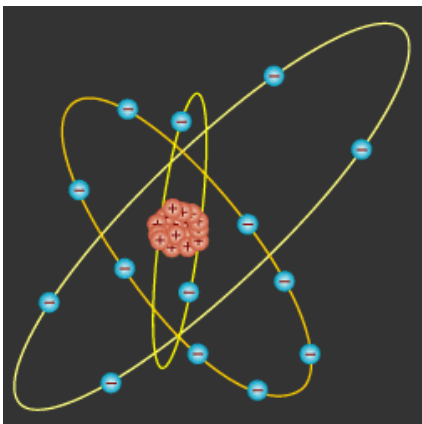
As depicted in this simplified diagram, silicon has: 14 electrons. The four electrons that orbit the nucleus in the outermost "valence" energy level are given to, accepted from, or shared with other atoms.
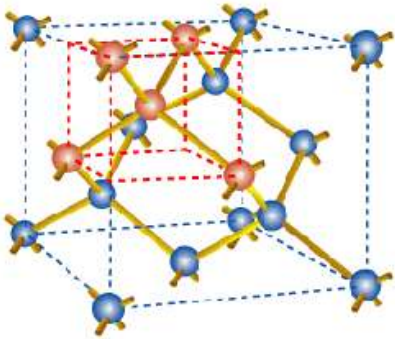


In the basic unit of a crystalline silicon solid, a silicon atom shares each of its four valence electrons with each of four neighboring atoms.

Electrons orbit at different distances from the nucleus, depending on their energy level. Electrons with less energy orbit close to the nucleus, and electrons with more energy orbit farther away. The higher-energy electrons farthest from the nucleus are the ones that interact with neighboring atoms to form solid structures.

A silicon atom has: 14 electrons, but their natural orbital arrangement allows only the outermost four electrons to be given to, accepted from, or shared with other atoms. These four electrons, called: *valence* electrons, play an important role in the photoelectric effect.

Large numbers of silicon atoms bond with one another by means of their valence electrons to form a crystal. In a crystalline solid, each silicon atom normally shares one of its four valence electrons in a covalent bond with each of four neighboring silicon atoms. The solid thus consists of basic units of five silicon atoms: the original atom plus the four atoms with which it shares valence electrons. The solid silicon crystal is thus made up of a regular series of units of five silicon atoms. This regular, fixed arrangement of silicon atoms is known as the: *crystal lattice*.

**Bandgap Energy**

*Bandgap energy* is the amount of energy required to dislodge an electron from its covalent bond and allow it to become part of an electrical circuit. When light shines on crystalline silicon, electrons within its crystal lattice may be freed. But not all photons—as packets of light energy are called—are created equal.

To free an electron, the energy of a photon must be at least as great as the bandgap energy. However, photons with more energy than the bandgap energy will expend the extra as heat when freeing electrons. So it is important for a photovoltaic (PV) cell to be "tuned"—through slight modifications to the silicon's molecular structure—to optimize the photon energy.

Crystalline silicon has a bandgap energy of: 1.1 electron-volts (eV). *(An electron-volt is equal to the energy gained by an electron when it passes through a potential of 1 volt in a vacuum.)* The bandgap energies of other effective PV semiconductors range from: 1.0 to 1.6 eV. In this range, electrons can be freed without creating extra heat.

The photon energy of light varies according to the wavelengths of the light. The entire spectrum of sunlight, from infrared to ultraviolet, covers a range of about: 0.5 eV to about: 2.9 eV.
For example, red light has an energy of about: 1.7 eV, and blue light has an energy of about: 2.7 eV.
Most PV cells cannot use about 55% of the energy of sunlight because this energy is either below the bandgap of the material used or carries excess energy.
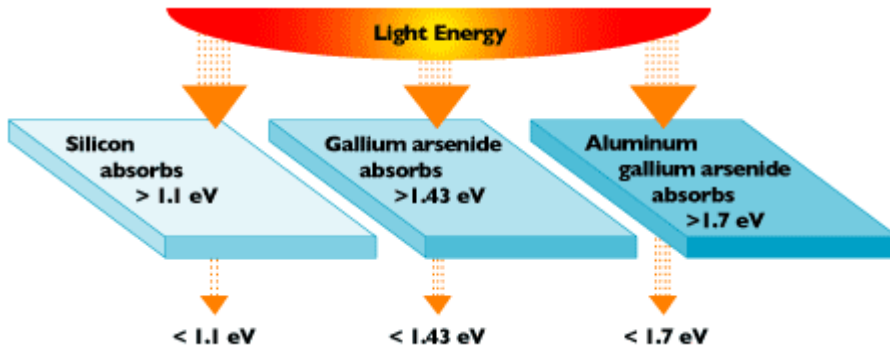
Different PV materials have different energy band gaps. Photons with energy equal to the band gap energy are absorbed to create free electrons. Photons with less energy than the band gap energy pass through the material.

## Photovoltaic Electrical Contacts and Cell Coatings
The outermost layers of photovoltaic (PV) cell, or solar cell, are the electrical contacts and anti-reflective coating. These layers provide essential functions to the cell's operation.

## Electrical Contacts
Electrical contacts are essential to PV cells because they bridge the connection between the semiconductor material and the external electrical load, such as a light bulb.
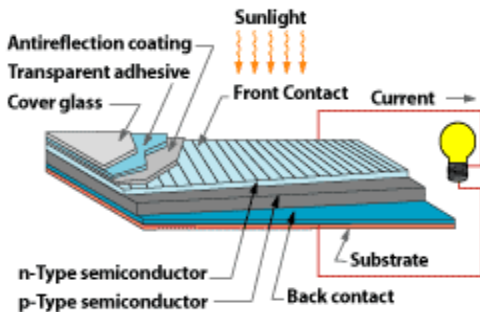


A typical solar cell consists of a glass or plastic cover, an antireflective coating, a front contact to allow electrons to enter a circuit, a back contact to allow them to complete the circuit, and the semiconductor layers where the electrons begin and complete their journey. The back contact of a cell—the side away from the incoming sunlight—is relatively simple. It usually consists of a layer of:  aluminum or  molybdenum metal.

But the front contact—the side facing the sun—is more complicated. When sunlight shines on a PV cell, a current of electrons flows over the surface. To collect the most current, contacts must be placed across the surface of the cell. This is normally done with a grid of metal strips or "fingers." However, placing a large grid, which is opaque, on top of the cell shades active parts of the cell from the sun and reduces the cell's conversion efficiency. To improve conversion efficiency, shading effects must be minimized.

Another challenge in cell design is to minimize the electrical resistance losses when applying grid contacts to the solar cell material. These losses are related to the solar cell material's property of opposing the flow of an electric current, which results in heating the material. Therefore, shading effects must be balanced against electrical resistance losses. The usual approach is to design grids with many thin, conductive fingers that spread to every part of the cell's surface. The fingers of the grid must be thick enough to conduct well (with low resistance) but thin enough not to block too much incoming light.

Grid contacts on the top surface of a typical cell are designed to have many thin, conductive fingers spreading to every part of the cell's surface.

Grids can be expensive to make and can affect the cell's reliability. To make top-surface grids, metallic vapors are deposited on a cell through a mask or painted on via a screen-printing method. An alternative to metallic grid contacts is a transparent conducting oxide (TCO) layer made of, for example, tin oxide (SnO2). The advantages o TCOs are that they are nearly invisible to incoming light and they form a good bridge from the semiconductor material to the external electrical circuit. TCOs are very useful in manufacturing processes involving a glass superstrate, which is the covering on the sun-facing side of a PV module.

In this process, the TCO is generally deposited as a thin film on the glass superstrate before the semiconducting layers are deposited. The semiconducting layers are then followed by a metallic contact that is actually the bottom of the cell. The cell is therefore constructed "upside down," from the top to the bottom.

The sheet resistance of the semiconductor is also an important consideration in grid design. In crystalline silicon, for example, the semiconductor carries electrons well enough to reach a finger of a metallic grid. Because the metal conducts electricity better than a TCO, shading losses are less than losses associated with a TCO. Other semiconductors, such as amorphous silicon, conduct very poorly in the horizontal direction. Therefore, they benefit from having a TCO over the entire surface.

**Cell Coatings**

Silicon is a shiny gray material that can act as a mirror by reflecting more than 30% of the light that shines on it. To improve the conversion efficiency of a solar cell, the amount of light reflected must be minimized. Two techniques are commonly used to reduce reflection.

The first technique is to coat the top surface with a thin layer of: silicon monoxide (SiO). A single layer reduces surface reflection to about 10%, and a second layer can lower the reflection to less than 4%.

The second technique is to texture the top surface. Chemical etching creates a pattern of cones and pyramids, which captures light rays that might otherwise be deflected away from the cell. Reflected light is redirected into the cell, where it has another chance to be absorbed.

**Photovoltaic Cell Materials**

Although crystalline silicon cells are the most common type, photovoltaic (PV), or solar cells, can be made of many semiconductor materials. Each material has unique strengths and characteristics that influence its suitability for specific applications. For example, PV cell materials may differ based on their: crystallinity, bandgap, absorbtion, and manufacturing complexity.

**Solar cell materials:**

Silicon (Si)—including single-crystalline Si, multicrystalline Si, and amorphous Si

Polycrystalline Thin Films—including copper indium diselenide (CIS), cadmium telluride (CdTe), and thin-film silicon

Single-Crystalline Thin Films— including high-efficiency material such as gallium arsenide (GaAs).

**Crystallinity**

The crystallinity of a material indicates how perfectly ordered the atoms are in the crystal structure. Silicon, as well as other solar cell semiconductor materials, comes in various forms, including:

- Single-crystalline,
- Multicrystalline,
- Polycrystalline, and
- Amorphous

In a single-crystal material, the atoms that make up the framework of the crystal are repeated in a very regular, orderly manner from layer to layer. In contrast, in a material composed of numerous smaller crystals, the orderly arrangement is disrupted moving from one crystal to another.

**Bandgap**

The bandgap of a semiconductor material is the:  minimum energy  needed to move an electron from its bound state within an atom to a free state.
This free state is where the electron can be involved in conduction.

The lower energy level of a semiconductor is called the:                              *valence band*, and
the higher energy level where an electron is free to roam is called the:      *conduction band*.

The bandgap *(often symbolized by Eg)* is the  energy difference  between the conduction and valence bands.

**Absorption**

The absorption coefficient of a material indicates how far light with a specific wavelength *(or energy)* can penetrate the material before being absorbed. A small absorption coefficient means that light is not readily absorbed by the material.

The absorption coefficient of a solar cell depends on two factors:

1.       The material of the cell and the
2.       Wavelength or energy of the light being absorbed

Solar cell material has an abrupt edge in its absorption coefficient because light with energy below the material's bandgap cannot free an electron.

**Manufacturing Complexity**

The most important parts of a solar cell are the:  semiconductor layers because this is where electrons are  freed  and electric current  is created.
Several semiconductor materials can be used to make the layers in solar cells, and each material has its benefits and drawbacks. The cost and complexity of manufacturing varies across materials and device structures based on many factors, including deposition in a vacuum environment, amount and type of material used, number of steps involved, and the need to move cells into different deposition chambers.

## Photovoltaic Cell Structures

The actual structural design of a photovoltaic (PV), or solar cell, depends on the limitations of the material used in the PV cell. The four basic device designs are:

### 1.      Homojunction Devices

Crystalline silicon is the primary example of this kind of cell. A single material—crystalline silicon—is altered so that one side is:  p-type, dominated by positive holes, and the other side is:  n-type, dominated by negative electrons. The  p/n junction is located so that the maximum light is absorbed near it. The free electrons and holes generated by light deep in the silicon diffuse to the  p/n junction  and then separate to produce a current if the silicon is of sufficiently high quality.

In this homojunction design, these aspects of the cell may be varied to increase conversion efficiency:

- Depth of the  p/n junction  below the cell's surface
- Amount and distribution of  dopant  atoms on either side of the:  p/n junction
- Crystallinity and purity of the silicon.

Some homojunction cells have also been designed with the  positive and  negative electrical contacts on the back of the cell. This geometry eliminates the shadowing caused by the electrical grid on top of the cell. A disadvantage is that the charge carriers, which are mostly generated near the top surface of the cell, must travel farther—all the way to the back of the cell—to reach an electrical contact. To be able to do this, the silicon must be of very high quality, without crystal defects that cause electrons and holes to recombine.

### 2.      Heterojunction Devices

An example of this type of device structure is a:  copper indium diselenide cell, in which the junction is formed by contacting different semiconductors—cadmium sulfide and copper indium diselenide. This structure is often chosen to produce cells made of thin-film materials that absorb light better than silicon.

The top and bottom layers in a heterojunction device have different roles. The top layer, or *window layer*, is a material with a high bandgap selected for its transparency to light. The window allows almost all incident light to reach the bottom layer, which is a material with low bandgap that readily absorbs light. This light then generates electrons and holes very near the junction, which helps to effectively separate the electrons and holes before they can recombine.

Heterojunction devices have an inherent advantage over homojunction devices, which require materials that can be doped both  p- and  n-type. Many PV materials can be doped either:  p-type or:  n-type but not both. Again, because heterojunctions do not have this constraint, many promising PV materials can be investigated to produce optimal cells. Also, a high-bandgap window layer reduces the cell's series resistance. The window material can be made highly conductive, and the thickness can be increased without reducing the transmittance of light. As a result, light-generated electrons can easily flow laterally in the window layer to reach an electrical contact.

### 3.     p-i-n  and  n-i-p  devices

Typically, amorphous silicon thin-film cells use a:  p-i-n  structure, whereas cadmium telluride (CdTe) cells use an:  n-i-p structure. The basic scenario is as follows:  A three-layer sandwich is created, with a middle intrinsic *(i-type or undoped)* layer between an:  n-type layer and a:  p-type layer. This geometry sets up an electric field between the:  p- and:  n-type regions that stretches across the middle intrinsic resistive region. Light generates  free electrons and  holes in the intrinsic region, which are then separated by the electric field.

In the  p-i-n amorphous silicon (a-Si) cell,
- the top layer is:          p-type  (a-Si),
- the middle layer is:      intrinsic silicon, and
- the bottom layer is:      n-type  (a-Si).

Amorphous silicon has many atomic-level electrical defects when it is highly conductive, so very little current would flow if an: a-Si cell had to depend on diffusion. However, in a: p-i-n cell, current flows because the free electrons and holes are generated *within* the influence of an electric field rather than having to move toward the field.

## 4.      Multijunction Devices

This structure, also called a cascade or tandem cell, can achieve a higher total conversion efficiency by capturing a larger portion of the solar spectrum. In the typical multijunction cell, individual cells with different bandgaps are stacked on top of one another. The individual cells are stacked in such a way that sunlight falls first on the material having the largest bandgap. Photons not absorbed in the first cell are transmitted to the second cell, which then absorbs the higher-energy portion of the remaining solar radiation while remaining transparent to the lower-energy photons. These selective absorption processes continue through to the final cell, which has the smallest bandgap.
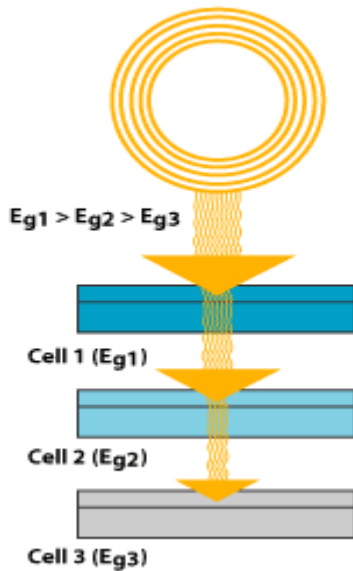


A multijunction device is a stack of individual single-junction cells in descending order of bandgap (Eg). The top cell captures the: high-energy photons and passes the rest of the photons on to be absorbed by: lower-bandgap cells.
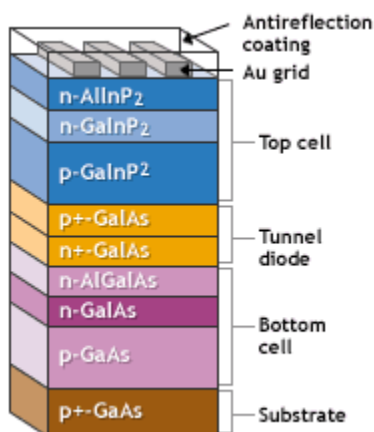


This multijunction device has a top cell of: gallium indium phosphide, a tunnel junction to allow the flow of electrons between the cells, and a bottom cell of gallium arsenide.

In a  CdTe cell, the device structure is similar to the: a-Si cell, except the order of layers is flipped upside down.

Specifically, in a typical  CdTe cell, the:

- top layer is:                 p-type cadmium sulfide (CdS),
- the middle layer is:      intrinsic CdTe, and
- the bottom layer is:      n-type zinc telluride (ZnTe).

**A multijunction cell can be made two ways:**

1. In the mechanical stack approach, two individual solar cells are made independently, one with a high bandgap and one with a lower bandgap. Then the two cells are mechanically stacked, one on top of the other.

2. In the monolithic approach, one complete solar cell is made first, and then the layers for the second cell are grown or deposited directly on the first.

Much of today's research in multijunction cells focuses on gallium arsenide as one *(or all)* of the component cells. These cells have efficiencies of more than 35% under concentrated sunlight, which is high for PV devices. Other materials studied for multijunction devices are:  amorphous silicon and:  copper indium diselenide.

**Photovoltaic Cell Performance**
Photovoltaic (PV), or solar cells use the energy in sunlight to produce electricity. However, the amount of electricity produced depends on the quality of the light available and the performance of the PV cell.

Researchers make measurements of conversion efficiency and quantum efficiency to characterize the performance of PV cells. Based on these results, researchers may redesign aspects of the cell—e.g., material compositions or thicknesses of layers—to improve performance.