

## The physics of solar cells

### The photoelectric effect

The physical basis for solar cells is the *photoelectric effect* (it was the explanation for this for which Einstein won the Nobel Prize). The photoelectric effect allows construction of the automatic door openers that work when you walk through a light beam. Experiments had been done in which both light frequency and light intensity were varied. If the frequency was below a certain characteristic value (a different frequency for each material), nothing was observed to happen no matter how intense the light was made. For frequencies above that critical value, electrons were observed near the surface of the material. If the intensity of the light was increased, many more electrons came away from the material. If the frequency was increased, the electrons moved away from the material with greater kinetic energy. This is shown in Fig. E21.4.1.

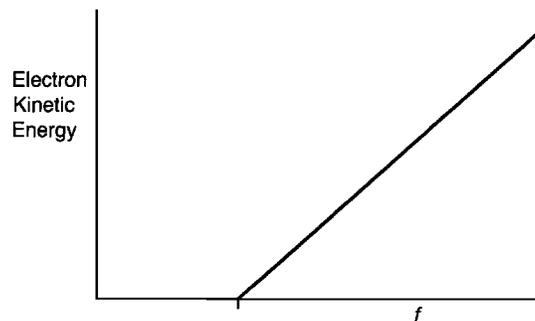


Fig. E21.4.1 In the photoelectric effect, the electron kinetic energy increases as the incident photon frequency increases for the frequency above some critical value. If the photon frequency is below this value, the vertical line on the graph (that is, the photon energy is too low), no electrons are released from the material.

Einstein argued that this was evidence that light has particle nature (an argument for the existence of bundles of light called *photons*). These bundles of light carry energy proportional to their frequency in these photon “packages.” It takes a certain minimum

energy (the ionization energy) to kick an electron completely out of an atom. When atoms are bound together, electrons become associated with the whole material. An energy lower than the atomic ionization energy, known as the work function, is necessary to free an electron. If the energy of the photon is too low (that is, the frequency is too low), then no matter how many photons hit the atom, it cannot remove the electron. If the energy of the photon is above the minimum value, an increase in the intensity increases the number of photons, which in turn increases the number of electrons that can leave atoms.

A useful analogy is that of a person at the bottom of a well. To get water out of the well, the person must raise the water at least as high as the top of the well. Water that does not reach the top falls back in. If water *does* make it over the top, then the harder it was thrown, the farther out it will go.

A simple experiment demonstrates this effect for ultraviolet light. You need a black light and an electroscope (as described in Chapter 4). Charge the electroscope by induction, then place a piece of zinc having a freshly sanded surface atop the electroscope. Exposure to ultraviolet light will cause the leaves of the electroscope to fall gradually. The electrons that leave carry the extra negative charge away.

### Semiconductors, bands, and band gaps

In the solar cell, the photoelectric effect can act in a similar way to generate electrons, with the proviso that the electrons do not leave the surface of the material. Of course, in most materials, recombination of the electron with the ion is almost immediate. Only materials or devices in which it is possible to prevent recombination are candidates for solar cell building materials. Materials called semiconductors are used to make solar cells.

When atoms are stuck together in a solid, they often end up being separated from one another with regular spacings in all three directions, forming a *lattice*. Such a regular array of atoms is called a *crystal structure*. Because the atoms in the lattice influence one another, the electron energy levels of the atoms combine together in such a way that the possible energies of the electrons get spread out into “bands.” Some bands are partially or totally full, and some are empty. In metallic materials, such as silver, the band is not totally full, and the existence of the band allows electrons to wander about wherever they are pushed within the material. Such materials are *conductors*. In other materials, known as insulators, when the bands are formed, all available levels in the band are filled. Since other, unfilled, bands are at a somewhat higher energy, no electrons are free to move unless they receive energy equal to the gap in energy between bands, which is known as the *band gap* (refer to Fig. E21.4.2).

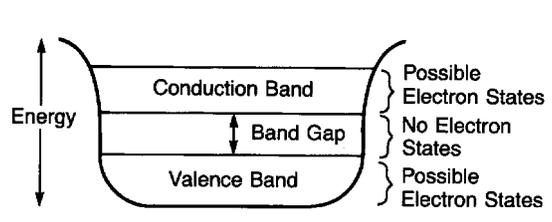


Fig. E21.4.2 Electron bands in a solid. The valence band lies below the band gap and the conduction band lies above the band gap. Acceptor states would lie just above the valence band. Donor states would lie just below the conduction band.

In semiconductors, the filled band (*valence band*) and the band in which electrons are free to move (*conduction band*) are separated by a potential difference of about 1 volt. Hence, light coming in can push an electron from the valence band into the conduction band if it has an energy of about 1 electronvolt (1 eV). The electron in the conduction band is free to move. If it is kept from recombining, it can give up its energy in an external circuit before coming back to the material.

## Doping of semiconductors

To prevent recombination, two different types of *doped semiconductor* are grown together to make the solar cell. Pure silicon is grown in a furnace in the presence of silicon vapor. The silicon vapor is doped with acceptors or donors (*p*-type and *n*-type semiconductors) to deposit layers of *p*-type or *n*-type material. On occasional lattice sites in *p*-type semiconductors are atoms or compounds with *fewer* electrons in the outermost shell than in the rest of the atom. Thus, there are occasionally “vacancies,” or holes for electrons, within the lattice of a *p*-type semiconductor. An *n*-type semiconductor has occasional lattice sites occupied by an atom or compound with *more* electrons in the outermost shells than in the rest of the atoms. There are occasionally excess electrons in the lattice in *n*-type semiconductors. The extra electrons can move around in the *n*-type material in response to an external potential; in the *p*-type material, the holes move around in response to an external potential (that is, an external electric field that is applied). Such materials therefore conduct electricity better than would be guessed from the band gap.

When two different types of semiconductor are bonded together to form a p-n junction, there are combinations of the electrons in the *n*-type region with the holes in the *p*-type in the region near the boundary. This removes free charges from the boundary and sets up a region of internal electric field inside the semiconductor that prevents any more charges from moving. When an external electric field is applied, it could either act against the internal field or in the same direction as the internal field at the boundary. A current can flow in response to an external electric field in only the one direction in which the internal electric field is reduced. Devices that allow current to flow in only one direction are called *diodes*.

### Why solar cells are known as photovoltaic, or PV, cells

The word photovoltaic is made up of pieces, with photo- indicating light, and voltaic implying that a potential difference (measured in volts) is set up by the action of the light. The light directly liberates electrons, and the diode action insures that the current of electrons flows only one way. (Alternatively, the incoming light could liberate vacancies, or lacks of electrons at a site, which are known as holes.)

That is, if one of the materials making up the junction exhibits the photoelectric effect and produces charges, they can flow in only one direction. The current is forced to flow through an external circuit in order to get to the other side of the junction and combine with the opposite sign charge.

So, as long as light is incident on the solar cell, charges will be produced by the photoelectric effect and the current will flow. When there is no light, there is not a current. This is the problem; if the Sun goes down, or if a dark cloud appears, the cell stops producing current. While wind electricity is also intermittent, it is not diurnally intermittent, and as pointed out in **Extension 21.3, *Power from the wind***, that interconnections of wind machines in different areas evens out the energy supply.

This evening-out cannot occur with photovoltaic cells. Depending on the time of year and the latitude, there could be twice as much dark as light or vice versa. If photovoltaic energy is to be a realistic source of electricity, this “down period” must be addressed somehow. This is usually done using some sort of storage (see Chapter 23 for some of these storage possibilities). Of course, hooking up the photovoltaic cells to the grid allows the solar cells to contribute to needs during the day, that is, meet base load, when it is most needed. In Germany, there is currently 56 MW of photovoltaic energy being fed

into the grid from homes all over the country (under the 1,000 and later the 100,000 solar roofs project). Additionally, as we all know, the maximal demand for electricity now comes during hot days during the summer, so photovoltaic cells deliver energy at a time when demand is greatest, another advantage.<sup>(57)</sup>

### Solar cells

Solar cells work to make light into electricity directly. When light shines, electrons are liberated in the *p*-type region and holes produced in the *n*-type region; this lowers the potential energy barrier at the junction. A current flows and establishes an external potential difference. Solar cells act in a way similar to the diode, so that current can flow in only one direction when the cell is exposed to light. Even though Becquerel discovered the effect in 1839, the first solar cell was made only in 1954.

A typical cell solar cell cross section is shown in Fig. E21.4.3 b or c. The way a solar cell looks physically is shown in Fig. E21.4.3 d. The thin lines in Fig. E21.4.3 d are collectors of charge that has been separated within the solar cell. The thicker-looking ridges contain wires that carry the charge from many thin strips.

Energy in excess of the band gap is delivered as thermal energy to the solar cell, raising its temperature.<sup>(109)</sup> It is necessary to match the band gap to the available visible light in order to minimize this heating. It is possible to use materials with band gaps of 1 to 2 eV (corresponding to the size of the visible spectrum), but a band gap of about 1.5 eV is optimum for a solar cell.<sup>(103,110)</sup>

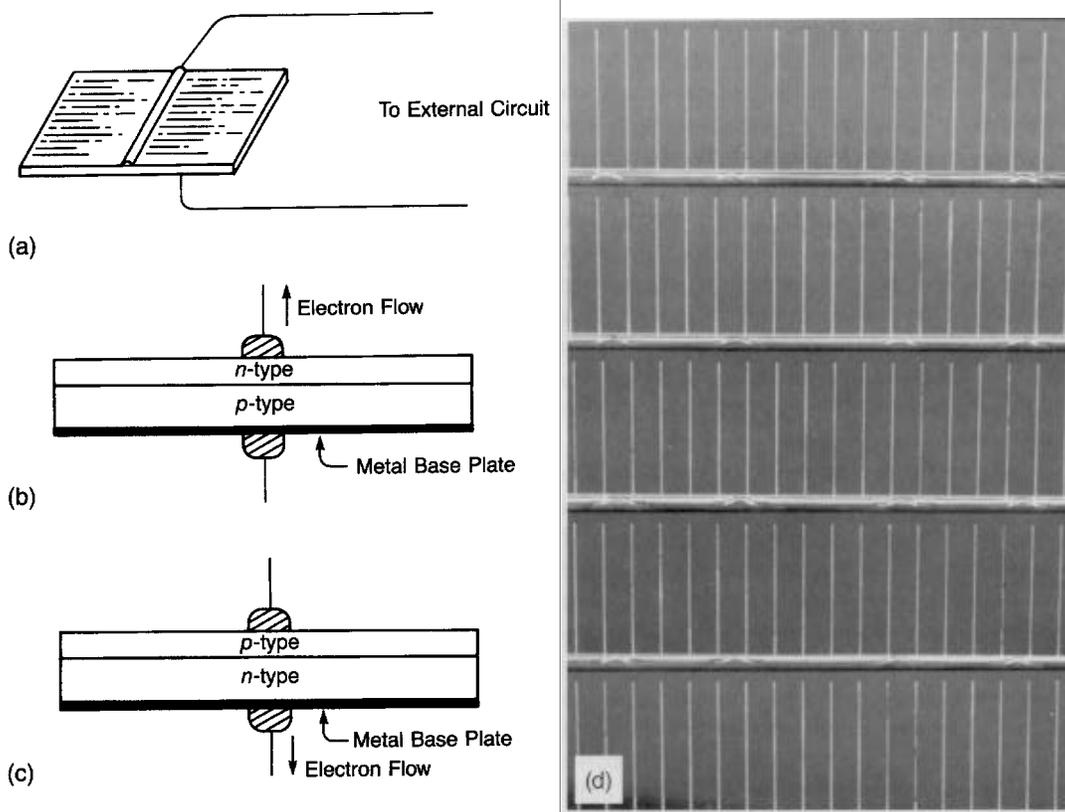


Fig. E21.4.3 a. Drawing of a solar cell. b. Connections for a *p*-type solar cell. c. Connections for a *n*-type solar cell. d. Actual solar cell. (d., National Aeronautics and Space Administration)

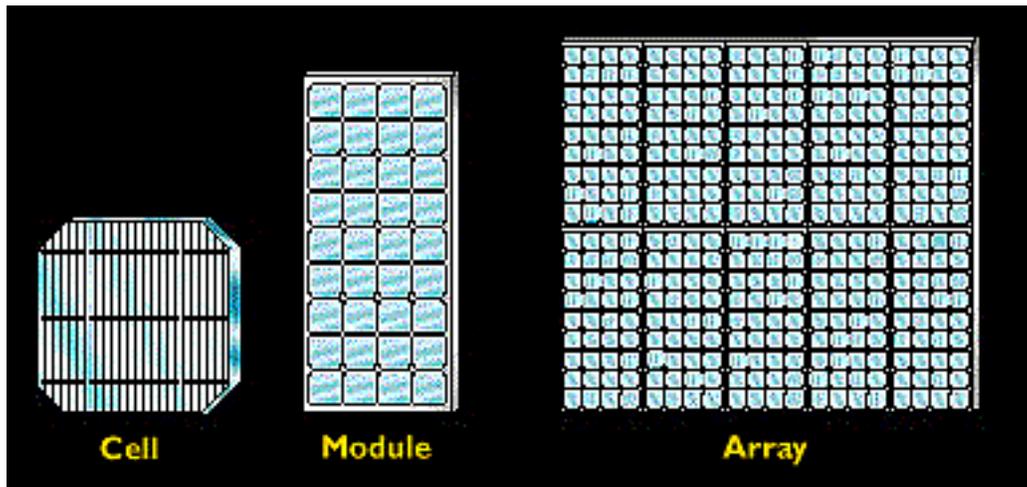


Fig. E21.4.4 Cells are assembled into modules, which are further assembled into arrays. (U.S. Department of Energy Photovoltaics Program)

The cells are single wafers of semiconductor. Each wafer can put out a small amount of power at the potential difference (voltage) determined by its band gap physics. To use the cells, they must be assembled into larger structures (such as already seen in Fig. E21.4 3 d), and then into even larger structures. Figure E21.4.4 (preceding page) shows this progression.

## Types of solar cell

### A. Material used in solar cells

The most popular choice for solar cells is silicon (Si), with a band gap of 1.1 eV, production cell efficiencies of about 12%,<sup>(110-113)</sup> and a maximum efficiency of about 15%, and gallium arsenide, with a band gap of 1.4 eV and a maximum efficiency of about 22%. The maximum theoretical efficiency for a single cell is 33%. For multiple cells, the theoretical maximum is 68%.<sup>(104)</sup> Both of these materials must be grown as single crystals under very precisely controlled conditions to minimize imperfections, which can cause recombination.<sup>(114)</sup> The large crystals are then sawn to make thin slabs of solar cell and mounted and equipped with electrodes.

The material gallium arsenide (GaAs) is also very popular for solar cells. Gallium and arsenic are exactly one atomic higher and lower than silicon, so the system has many similarities to a silicon-based semiconductor. It is less friable than silicon, more resistant to radiation damage, and so is the material of choice in space-based solar cells. Doping this material with atoms from nearby columns in the periodic table changes the properties a bit. Additionally, only very thin films of gallium arsenide need be used since it is so effective at absorbing light.

Figure E21.4.5 shows the different properties of silicon, gallium arsenide, and aluminum gallium arsenide. About half the energy in sunlight is unusable by most PV cells because this energy is below the band gap, and so can't free an electron from the valence to the conduction band, or because it carries excess energy, which must be transferred to the cell as thermal energy, heating up the cell.

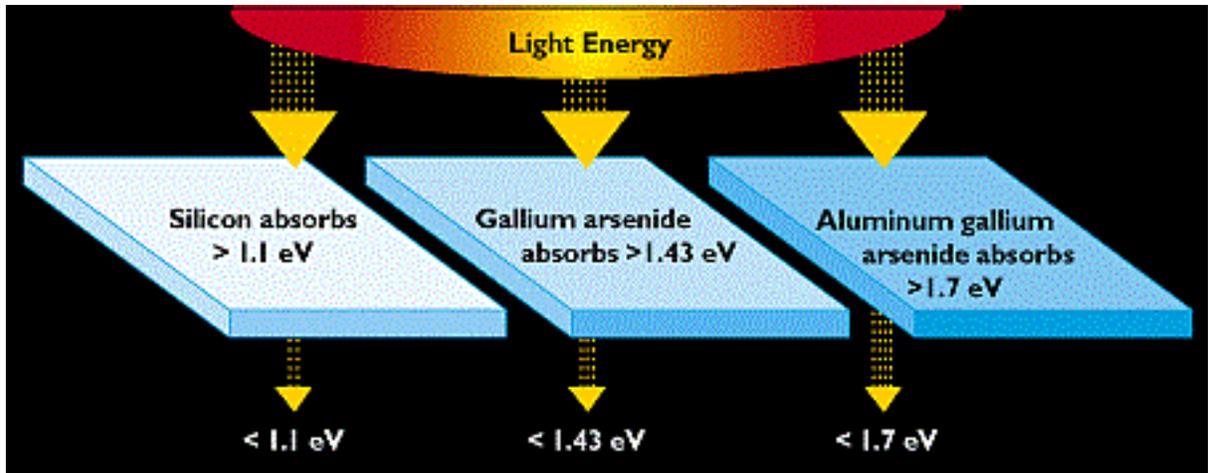


Fig. E21.4.5 Silicon, gallium arsenide, and aluminum gallium arsenide have different band gaps. They therefore absorb light of different energies.  
(U.S. Department of Energy Photovoltaics Program)

### B. Crystalline silicon cells

Crystalline silicon cells are manufactured very carefully. In the original setup, a starter was dipped into a vat of molten silicon ( $\sim 1400\text{ }^{\circ}\text{C}$ ), and a single crystal slowly formed as the crystal was drawn out over a long period of time. It was essential to the process that uniformity be maintained. Nowadays, the process is more automated and requires less care. The cells need to be at least  $100\text{ }\mu\text{m}$  thick because of problems with absorption; the thickness helps allow the light to be absorbed.<sup>(104)</sup> Typical thickness is about  $300\text{ }\mu\text{m}$  for sawn silicon, but it can be made as thin as about  $170\text{ }\mu\text{m}$  using wire-cutting techniques.<sup>(115)</sup> Both silicon and gallium arsenide are easily eaten away by chemical reactions with the holes.<sup>(116)</sup>

### C. Polycrystalline thin films

Polycrystalline wafers are made by a casting process in which molten silicon is poured into a mold and allowed to set directly into ingots in layers (a layer at a time) rather than grown as a single crystal; it is of poorer quality but cheaper and has less environmental impact.<sup>(117)</sup> Sheets of silicon have also been grown by two methods: the edge-defined, film fed, growth ribbon process, in which the silicon rises by capillary action between two graphite plates;<sup>(115)</sup> and the dendritic web process, pulling a thin film of silicon between two spacers from a molten surface that grows.<sup>(110)</sup>

One advantage of polycrystalline thin films is that there is no light-induced degradation of performance. Thin films (1  $\mu\text{m}$  to 10  $\mu\text{m}$  thick, absorbing 90% of light) are made of gallium arsenide (GaAs) or cadmium telluride (CdTe); these are more efficient than silicon in multi-stack orientation because of their larger band gaps.<sup>(110,113)</sup> Both crystalline and polycrystalline semiconductors of silicon can be bonded to a plastic or glass material, which allows light through and provides structural integrity. It also provides protection from the elements and leads to various applications where maintenance is difficult to do, since none is needed except an occasional cleaning. Efficiencies as high as 32.6% have been demonstrated in the lab for such multijunction cells.<sup>(117)</sup>

An additional advantage of polycrystalline silicon is the ease with which large structures can be made. Single crystal cells must be carefully interconnected electrically, whereas the polycrystalline silicon can be made essentially as large as desired. This has implications for the cost of the two competing materials.

### D. Single and multijunction cells

Most current photovoltaic materials are made of a single layer of light absorber. However, given the differences among solar cells in terms of the energy they absorb, it can be advantageous to “stage” or layer them. Cells of different bandgaps stacked atop one another are known as multijunction cells. Figure E21.4.6 shows how a multijunction solar cell would be configured.

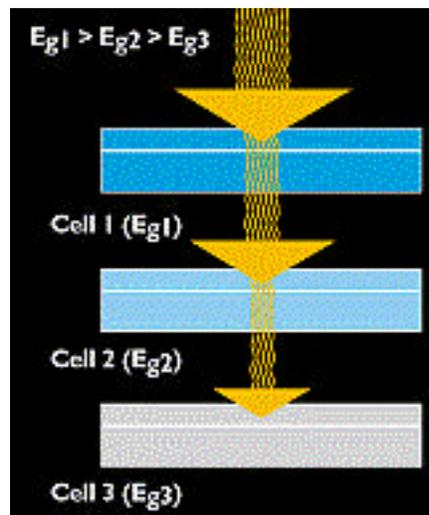


Fig. E21.4.6 A multijunction cell functions by absorbing sequentially lower energy light from the incident light. Because there are several band gaps, more energy from the light is absorbed. Here, the band gap for material 1 is greater than that for material 2, which in turn is greater than that for material 3. (U.S. Department of Energy Photovoltaics Program)

Since blue light has a greater energy than red light, the first layer removes mostly blue light energy, and correspondingly less bluish (or more reddish) light is removed as light descends through the sequence of layers making up the multijunction solar cell shown in Fig. E21.4.6. A two-junction tandem GaInP on GaAs cell exhibited an efficiency of over 30%.<sup>(118)</sup>

### E. Amorphous cells

Materials that have no crystal structure are classed as *amorphous*, from the Greek, meaning “lack of structure.” Amorphous silicon has no crystal structure, and its atoms are ordered over only a very short distance; small pieces of silicon crystal abut one another at random orientations in such a way that no long-distance structure exists. Amorphous silicon solar cells in thin films exhibit better absorption than pure silicon (40 times as efficiently as crystalline silicon),<sup>(104)</sup> but because of the many structural defects, they are only about 11% efficient at maximum, and most cells are about 4% to 8% efficient.<sup>(111)</sup> Amorphous silicon cells can degrade on exposure to sunlight.

Amorphous silicon is much easier to make than grown silicon crystals, and by using several layers, each set for a different band gap “tuned” to a different part of the spectrum, a greater part of the visible spectrum can be used.<sup>(111,112)</sup> Tuning is possible because addition of carbon raises the band gap, while germanium lowers it.<sup>(112)</sup> However, solar cell efficiency falls if too much material is added (see Table 21.3). The traditional crystalline photovoltaic cell has 45% of the 1990s market. Thin film cells have 35% of the market.<sup>(119)</sup>

Semiconductors copper indium diselenide ( $\text{CuInSe}_2$ ) and cadmium telluride ( $\text{CdTe}$ ) are also used to manufacture solar cells. NREL researchers were able to attain an efficiency of copper indium diselenide with added gallium (sometimes known as “CIGS”) devices of between 18.1% and 18.8%.<sup>(120)</sup> Cadmium telluride cells operate at about 10% efficiency.<sup>(120)</sup>

### F. Dye-sensitized cells

M. Grätzel of the Swiss Polytechnic of Lausanne discovered a thin-film titanium dioxide system that is sensitive to ultraviolet radiation can be made to respond to ordinary light. A layer of light-responsive dye overlays the semiconductor, and the charge is transferred back to the dye from an electrolyte. The cells have reasonable efficiencies (~ 10%) in hazy light conditions, and the cost is projected to be very low, since the materials can be worked on at low temperatures in contrast to most other semiconductor solar cell arrays.<sup>(118)</sup>

A new idea to harvest solar energy uses dyes on a metal substrate, quite different from what occurs in normal silicon solar cells. The device developed by McFarland and Tang has multiple layers on ultrathin metal films that constitute a Schottky diode (a diode that works by quantum tunneling).<sup>(121)</sup>

Electrons excited to a higher state by incident light can jump the Schottky barrier and so provide a current. The efficiency is higher than expected. As McFarland and Tang say, “This alternative approach to photovoltaic energy conversion might provide the basis for durable low-cost solar cells using a variety of materials.”<sup>(121)</sup>

### G. Using dye-sensitive solar cells to withstand high temperatures

One drawback of typical solar cells is the inability to withstand high temperatures. Electrolytes break down. Dyes in dye-sensitive solar cells dissociate from the titanium dioxide substrate and dissolve. Using dye-sensitive nanocrystalline solar cells and a new sort of electrolyte, a group was able to build a solar cell that operated for a month at 80 °C with little degradation.<sup>(122)</sup> They made the electrolyte a gel, which made it considerably easier to work with. Unfortunately, the cell performed at 6%, somewhat

below the industry's benchmark 10%, but as with all novelties, the hope is that future versions of the cell will reach a greater efficiency.

### H. Point-contact cells

The point-contact solar cell has a textured surface that reduces the reflection of incident light and a rear-surface mirror. It absorbs 90% of the incident light. Such cells need be only 100  $\mu\text{m}$  thick. The contacts are on the back surface, where they do not prevent light from coming in, arranged in a polka-dot pattern of alternating *n*-type and *p*-type semiconductor. A silicon oxide layer at the surface prevents recombination. These cells can give 22.8% efficiency, which is quite a bit higher than conventional crystalline silicon solar cells.<sup>(104,112)</sup>

All forms of solar cell suffer from the Staebler-Wronski effect, in which new defects in the solar cell material arise as the cell is exposed to light during its first 1000 hours of operation, which has the effect of lowering the output from its initial level to a stable, lower level.<sup>(117,118)</sup> Measures to reduce this effect to under 10% have been put in place, but since the mechanism is not yet totally understood, more work remains.<sup>(118)</sup>

### I. Plastic solar cells

The work using dye-sensitive coatings was a step in the direction of cheaper solar cells. If the cells could be made entirely from plastic, there is hope that they will become a lot cheaper. One step in that direction was made by a group at Berkeley, which developed solar receptive materials of plastic nanotubes.

It could even be possible to paint the surface of a roof with the plastic rods or have them attached to plastic sheets that could be attached to the roof surface and have the roof become a gigantic cell.<sup>(123)</sup>

In its first incarnation, the efficiency is low, in the neighborhood of 1%, but the promise of cheap solar cells is enticing. The cells of the plastic rods attached to a plastic sheet might even be placed on clothes as well as roofs. Sunlight falling on your clothes could end up running your radio or MP3 players, your cellphones, or possibly your laptop if it were redesigned to run at low power levels.

### J. Gallium indium nitride

The semiconductor gallium indium nitride may be the optimal material for utilizing sunlight. A group of researchers from the Lawrence Berkeley Laboratory and the University of Ritsumeikan in Japan found that it exhibits a bandgap of 0.7 eV to 3.4 eV, just about the maximum that can be obtained from sunlight (it ranges from near-infrared to near-ultraviolet). A multilayer solar cell built from gallium indium nitride might be as much as 70% efficient, far more efficient than any current solar cell.<sup>(124,125)</sup>

An additional attraction is that the material exhibits enhanced resistance to external radiation. According to the authors this gives the cells “great potential for radiation-hard high-efficiency solar cells for space applications.”<sup>(125)</sup>

### K. Organic solar cells

The investigation of thin film organic photovoltaic materials has shown some promise. These materials are attractive to manufacturers, because they (presumably) could be

sprayed onto their substrates similar to other films. This could allow increased manufacturing throughput. In addition, organic materials can take on a variety of colors easily. Some theoretical progress has been made, but many open questions remain.<sup>(126)</sup>

The efficiency of current thin organic films is mostly around 1%, but several examples of 2% efficiency were found. Nelson believes that the efficiency should be 5% or more relatively soon.<sup>(126)</sup>

## Transistors

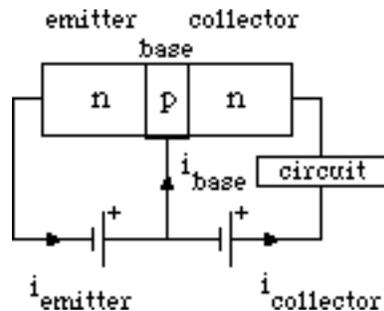


Fig. E21.4.7 An n-p-n transistor. Small changes in the base current strongly affect the current that can flow through the transistor to the circuit. The two sides of the transistor are called emitter and collector.

The ubiquitous transistor is made in a way similar to the solar cell. However, it has three materials (and therefore two junctions). There can be p-n-p transistors or n-p-n transistors. The central region, called the base, is thin (Fig. E21.4.7). As with the diode, the central region will be swept clean of mobile charges by random thermal motion. Changing the electrical conditions slightly in the base region of the transistor can have large effects on the amount of current that can flow through the transistor. This allows a small signal carried to the base to cause a large change in the current that goes to the circuit; the transistor can act as an amplifier. Nowadays, field effect transistors are the most common ones, and while they differ in details of construction from the picture given here, their construction involves doped regions and their effect on a circuit is similar.