

The Basic Physics and Design of III-V Multijunction Solar Cells

This two-part document describes the basic physics and design of multijunction photovoltaic cells. The advanced science reader may wish to proceed directly to Part 2.

- **Part 1, Basic Photovoltaic Physics**, addresses the basic concepts necessary to understand the discussions in the second part.
- **Part 2, Multijunction Photovoltaic Cell Design**, discusses the interaction of semiconductors, light, and the generation of electricity. Part 2 also focuses on the technology of the National Renewable Energy Laboratory (NREL) design of a GaInP/GaAs/Ge triple-junction solar cell that achieved a record-setting conversion efficiency of 34% under concentrated light.

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Part 1: Basic Photovoltaic Physics

A. Energy

Energy is the capacity of a system to do work. Various types of energy can change forms, and the rate at which they change is **power**.

a. Energy

Energy can be found in two forms: **potential energy**, or stored energy, and **kinetic energy**, or moving energy. Each of these forms has a variety of types—heat, light, electrical, and others. Energy is never actually created (nor destroyed or lost),* but it can change. When a power plant produces energy, it does so by transforming the energy stored in coal, or the energy from rushing water, into a more usable form of energy, such as electricity.

Energy is measured in **electron volts (eV)** or **joules (J)**, where $1 \text{ eV} = 1.6 \cdot 10^{-19} \text{ J}$. For example, a photon of yellow light has about 2 eV of energy.

b. Power

Power is the rate at which energy is transformed. For example, if 2 J of energy were used in one second, the power rating would be 2 J/s. Power is often measured in **watts (W)**, where $1 \text{ W} = 1 \text{ J/s}$. We usually discuss the power of electricity rather than the energy because electrical energy usually flows over time. Electrical power is calculated by

$$\text{Power [watts]} = \text{Current [amps]} \times \text{Voltage [volts]}.$$

A typical light bulb requires 60 W of power to operate. For comparison, consider that about 100 mW/cm^2 of power would be incident on a solar cell in sunlight. If the solar cell is 1 cm^2 and 30% efficient, then 30 mW of electrical power would

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be produced. If this cell were used with a 1000-sun concentrator, collecting light from 1000 cm^2 of area, then 30 W of electrical power would be produced.

c. Efficiency

Whenever an energy transformation takes place, energy is always “conserved”—the total amount of energy before the transformation is exactly equivalent to the energy after the transformation. In nearly every practical case, however, one type of energy is never completely transformed into only one different energy form. Any reference to energy being “lost” is most often a reference to this phenomenon, where the lost energy usually has been turned into less useful heat energy.

A system’s **efficiency** is the amount of useful energy derived from a system relative to the amount of total energy going into that system. This is usually expressed as a ratio or percentage:

$$\text{Efficiency of system} = \frac{\text{Useful energy out of system}}{\text{Total energy into system}}$$

Because conceptually, power is identical to energy, except for the addition of the time factor, the efficiency of a photovoltaic cell can also be calculated by dividing the electrical power the cell generates by the total power of the light energy incident on the cell:

$$\text{Efficiency of system} = \frac{\text{Useful power out of system}}{\text{Total power into system}}$$

B. Electricity

Electricity is a flow of charged particles. **Current** is the rate of flow of these charged particles—or moving electrons. **Voltage** is the “pressure” causing the flow, and the **resistance** of a material describes the degree to which this flow is inhibited. As discussed above, power—or the rate at which energy can be delivered—is the product of current and voltage.

a. Electric Fields

An **electric field** is a region of influence of an electrostatic force on charges that could be placed within the field. For example, in its simplest form, a positive charge would attract a negative charge placed nearby.

b. Current

As you recall, electricity is the flow of charged particles. Just like flowing water, electrical **current** is a measure of the flow of * positive charge. Because charge is typically measured in coulombs and time in seconds, the rate at which charges flow is measured in coulombs/second. The term **amps** is used to indicate the number of coulombs per second, where $1 \text{ A} = 1 \text{ C/s}$. People can experience discomfort with only a few hundredths of an amp flowing through them. Multijunction solar cells can generate about 10 A/cm^2 of current when used with solar concentrators at 1000x concentration.

c. Voltage

Voltage describes the amount of energy contained by each charge (or group of charges). Because a joule is the standard unit of energy and coulomb the standard unit of charge, the units for voltage are joules per coulomb, which is more typically referred to as a volt ($1 \text{ J/C} = 1 \text{ V}$). Voltage acts like the pump that causes the current flow through the pipe. GaInP/GaAs/Ge multijunction solar cells, which are our focus here, typically generate about 2.5 volts.

d. Resistance

Resistance can be envisioned as the length and diameter of a “pipe” through which current flows. Resistance restricts the flow of current. The higher the resistance—either because the pipe

diameter is small or the pipe length is long—the less current will be able to flow. The lower the resistance, the more current will flow—or the less voltage is required to cause the same current flow.

The pipe analogy for a resistor is quite literal. The narrower or longer the conducting material, the more resistance it will have. In most cases, a lower resistance is desired, so designers try to keep “diameters” wide and distances short.

Resistance is typically measured in **ohms** and has the following mathematical relationship with current and voltage:

$$\text{Resistance [ohms]} = \frac{\text{Voltage [volts]}}{\text{Current [amps]}}$$

This relationship implies that if a material has a high resistance, even a high voltage will create only small currents. Such materials are referred to as **insulators**. However, if resistance is small, current can be large even with small voltages. Such materials with low resistance are referred to as **conductors**.

e. Circuits

For electrical current to flow and for power to be delivered, there must be a continuous loop, or **circuit**, through which charges move. When using electricity to power an appliance or light fixture, that loop moves through the device in such a way that the power—which is the combination of voltage and current—is converted into some useful task, such as the lighting of a light bulb.

i. Series Circuits

Elements in a circuit are said to be in **series** with each other if the same collection of charges moving in a current must flow through them one after another (see Fig. 1). This is in contrast to elements that are in **parallel**.

ii. Parallel Circuits

Elements in a circuit are said to be in parallel with each other if a split in the current path dictates that

* Note: By convention, current is a flow of positive charges. In reality, the positive charges or protons of atoms are immobile, and negatively charged electrons flow. A flow of negative electrons in one direction, however, generates the conventional positive flow in the opposite direction.

charges must flow through one or the other, but not both elements (see Fig. 1).

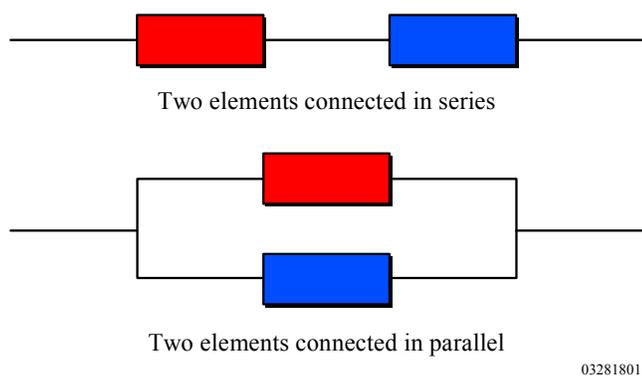


Figure 1. Series and parallel circuits.

iii. Short Circuits

On occasion, sometimes unintentionally, an alternate path is created through which charges can move. This path, called a **short circuit** (see Fig. 2), prevents the appliance from receiving energized charges. If the path has no resistance, there is no voltage change, and thus, no work is done even though current is flowing. Most unintentional alternate paths usually have a non-zero resistance that can result in dangerous levels of power. In the design of photovoltaic cells, the current generated by the cell when it is short-circuited, I_{sc} , is an important characteristic quantity describing the behavior and effectiveness of the cell.

iv. Open Circuits

Open circuits, like short circuits, typically disrupt the normal flow of charges through a device. In an open circuit, however, the flow of charges is prevented entirely. For example, inspecting a burned-out light bulb may reveal a broken filament (the wire that normally glows brightly as current passes through it). This broken filament breaks the flow path of charges. The voltage across an open circuit can be very high, but with no current flow, no power is used.

In the design of photovoltaic cells, an open-circuit situation may be intentionally created to measure

the behavior of the photocell. This open-circuit voltage is denoted as V_{oc} .

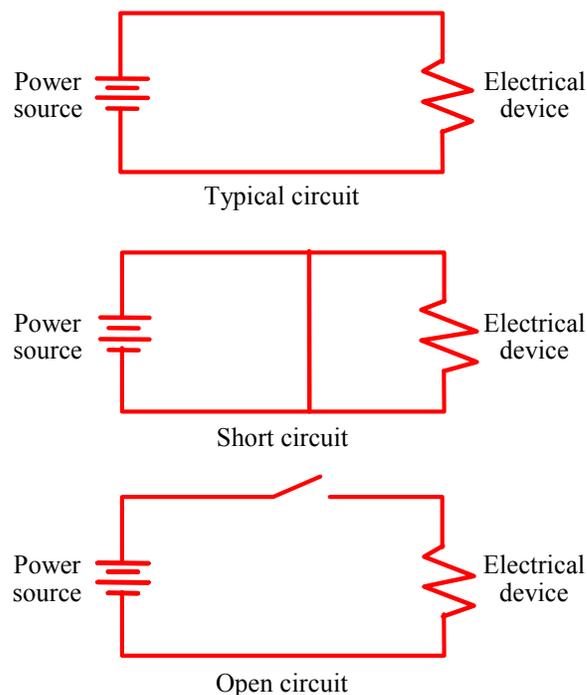


Figure 2. Short circuits and open circuits.

C. Diffusion

Diffusion is the movement of particles from a region of higher concentration to a region of lower concentration. A **concentration gradient** is a difference in the concentrations of a type of particle. When concentration gradients occur in isolation, there is chemical potential energy—the potential for movement exists. In fact, concentration gradients do not normally exist for long because their chemical potential energy changes into kinetic energy with the movement, or diffusion, of the particles.

D. Atomic Theory

Quantum theory dictates that electrons can occupy only discrete energy levels. This situation has interesting implications in crystal structures of semiconductors: photons of light can be absorbed in materials in a way that generates electrical current.

a. Bohr Model of the Atom

Although not literally correct, the traditional **Bohr model** of the atom is helpful in providing an approximate description of an atom. This model places the **electrons** in planetary-like orbits around the center of the atom, which is composed of **protons** and **neutrons**. The outermost orbiting electrons are referred to as **valence electrons**. These electrons are perhaps the most important component of the atom in terms of how it interacts chemically and physically with other matter in its environment.

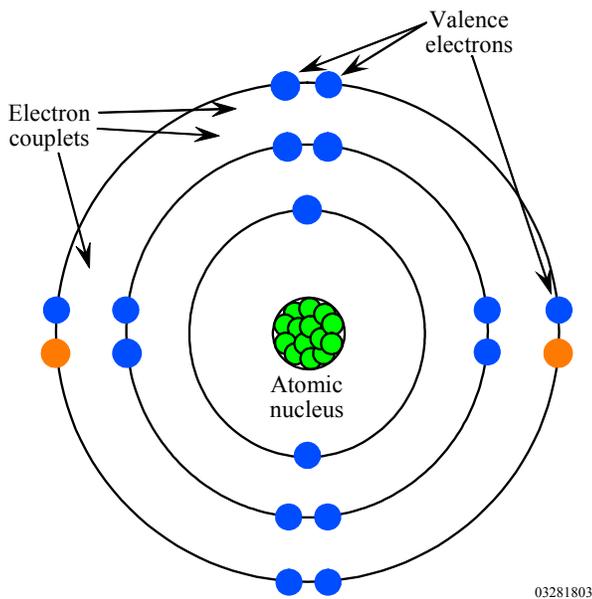


Figure 3. Bohr model of atom.

As mentioned above, modern atomic theory states that electrons in an atom may only occupy certain discrete energy levels about the atom. In addition, the **Pauli exclusion principle** dictates that no more than two electrons may occupy a particular energy level at a given time. This structure is indicated in the Bohr model by a series of concentric circular **orbitals** with couplet pairs of allowable electron positions within each of these orbitals (see Fig. 3).

b. Band Theory of Solids

Atoms in a solid are closely spaced, and their outer orbitals influence one another. The result is that instead of required discrete energy levels, the

outer energy levels become “smeared,” forming **bands** of allowable energy levels. At this point, the limitations of the Bohr model of the atom as a useful model are exceeded. At this point, electrons in these bands are not associated with any particular atom. To understand the electrical properties of a material, it is helpful to consider the two bands commonly referred to as the **valence band** and **conduction band**. The valence band encompasses the energy levels at which *most* of the electrons (and at absolute zero, *all* of the electrons) will be found. Electrons found in the higher-energy conduction band are considered **free electrons**. Free electrons are shared among all the atoms of the solid and are not associated with any one atom. Therefore, they are very mobile. Any applied electric field can create an electrical current with these electrons.

For insulator and semiconductor materials, the valence and conduction bands are separated by a region called the **bandgap**. The bandgap is a region of forbidden energy levels, as defined by the quantum aspects of modern atomic theory. The difference between the lowest energy level of the conduction band and the highest energy level of the valence band is called the **bandgap energy** (E_g).

At temperatures above absolute zero, electrons may possess enough thermal energy (at least E_g) to be excited across the forbidden energy gap into the conduction band. This occurrence is less likely if the bandgap energy is large, as in insulators. In conductors, the conduction band and the valence bands overlap, and conduction of electrons occurs, even at absolute zero.

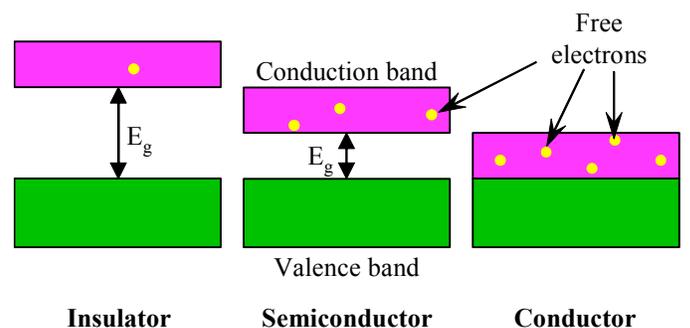


Figure 4. Energy bandgaps.

This situation explains why insulators are poor conductors of electrical current, whereas conductors are not. **Semiconductors** have bandgap energies somewhere in between (see Fig. 4 and Fig. 5).

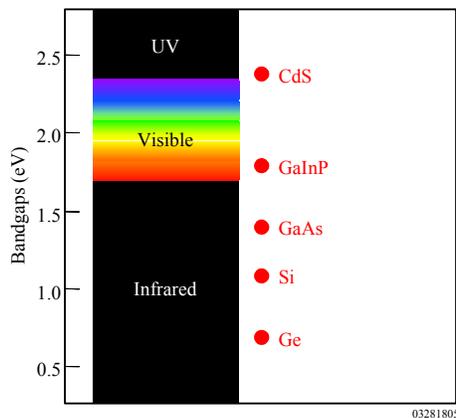


Figure 5. Bandgaps of some common semiconductors.

c. Semiconductors: pn Junctions

Pure semiconductor structures, such as silicon, generally involve the formation of four **covalent** bonds with like atoms. However, common practice is to design electronic devices to intentionally and precisely include impurities in semiconductor materials so that there are fewer or more valence electrons. This practice of “**doping**” a material creates a new set of behaviors in designed materials that are useful in a wide range of applications, including the electronic transistor.

Semiconductors such as silicon and germanium, which are elements in Group IV of the Periodic Table, generally form four covalent bonds. Pure crystal structures of such substances use every electron in forming their covalent bonds. However, when doped with Group V elements such as phosphorus, an extra electron is available that is automatically promoted to the conduction band as the rest of the phosphorus atom takes on the four-bond behavior of a Group IV element. This material is described as **n-doped** (additional free electrons are generated by adding impurities to the basic crystal structure).

An inverse situation occurs when doping with a Group III element such as boron. Instead of creating extra free electrons, “holes” are created where electrons normally occur to complete the four-covalent-bond structure. These **p-doped** regions (**n** is for negative electrons and **p** is for positive holes) take electrons from the valence band, leaving a hole where an electron could have been (in an opposite fashion compared to n-doped regions). Free holes and electrons are **mobile charge carriers**. Both types of mobile carriers are present in n-doped material, but in this case, electrons are referred to as the **majority carriers** and holes are referred to as **minority carriers**. Inversely, in p-doped material, holes are the majority carriers and electrons are the minority carriers. When two different types of semiconductor material are brought together—one being p-doped and the other n-doped—interesting electrical behavior develops near this **pn junction**.

When an n-doped region and a p-doped region are side by side, a concentration gradient exists because there are many more free electrons on the n-doped side of the junction than on the p-doped side. An inverse situation exists for holes. This concentration gradient establishes a condition of **chemical potential energy**.

Unless some other force works to prevent it, this chemical potential energy will initiate diffusion, specifically the movement of electrons from the higher-concentration region on the n-doped side to the lower-concentration region of the p-doped side.

As electrons diffuse to the p-doped region nearest the pn boundary, the availability of holes there becomes a factor. A significant number of the first free electrons that diffuse to the hole side will likely recombine with a hole, creating negative ions. Likewise, holes from the p-doped side diffuse to the n-doped side and recombine with electrons there to produce positive ions. This region near the junction boundary, where ions are present and mobile charges are not, is referred to as the **depletion region** (see Fig. 6).

The presence of oppositely charged ions within the depletion region forms an **electric field**. As this electric field becomes stronger with continued diffusion, it increasingly repels and resists the further movement of electrons from the n-doped side to the p-doped side. Likewise, the diffusion of holes from the p side to the n side is decreased. Eventually, the flow of electrons and holes ceases when the chemical forces of diffusion are exactly offset by the electrostatic forces of the created electric field.

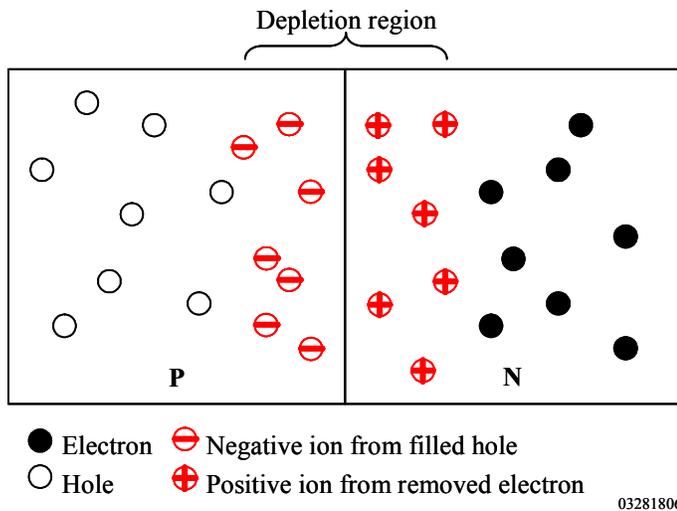


Figure 6. Depletion region of pn junction.

When an energetic photon (see next section) strikes either side of the pn junction, an electron and a hole pair are created. For all practical purposes, **majority-carrier concentrations** (the number of conduction-band electrons in an *n*-type semiconductor, or the number of holes in a *p*-type semiconductor) are unaffected by contributions of additional photons because concentrations of created electron-hole pairs are insignificant relative to the majority-carrier concentrations. However, **minority-carrier concentrations** (the number of conduction-band electrons in a *p*-type semiconductor, or the number of holes in an *n*-type semiconductor) *are* affected: they are significantly increased. This change upsets the balance between the diffusion force and electrostatic force. Electrons that were created in the p region eventually diffuse into the depletion region, where the electric field there propels them

into the n region. Holes created in the n-doped region travel in the opposite direction to the p-doped side. Solar cells are designed to produce this movement of charges.

E. Light

The Earth receives energy from the sun by way of **radiated energy**. This radiated energy is carried by tiny particles having no mass called **photons**. Photons behave like waves and, as such, have a characteristic wavelength, frequency, and energy. It is the energy of these photons that is used in photovoltaic cells to excite electrons so that an electrical current can be produced.

a. Waves

Figure 7 illustrates that the **wavelength** of a wave is the distance between two successive peaks, or maxima, of a wave.

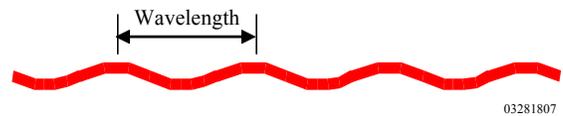


Figure 7. Wavelength of wave.

The **frequency** of a wave is a measure of how many peaks are observed in one second from a stationary point along a wave's path. The product of the wavelength and frequency gives the wave's **velocity**:

$$v = \lambda f,$$

where v = velocity in meters per second, λ = wavelength in meters, and f = frequency in hertz.

All **radiative**, or light, energy travels at the same velocity, commonly known as the **speed of light**, which is about 300,000,000 m/s (3×10^8 m/s, or about 186,000 mi/s). Because the velocity of light is a constant and also a product of frequency and wavelength, specific frequencies of light are associated with specific wavelengths, and vice versa. For example, blue light has a frequency of about 667×10^{12} Hz. To calculate blue light's

associated wavelength, the above equation is rearranged for wavelength, λ , to get

$$\lambda = v / f .$$

Then, substituting the values, we find:

$$\begin{aligned} \lambda_{\text{blue}} &= (300,000,000 \text{ m/s}) / (667 \times 10^{12} \text{ Hz}) \\ &= 450 \times 10^{-9} \text{ m} = 450 \text{ nm}. \end{aligned}$$

The same is true for all colors of the spectrum—each color has a corresponding wavelength and, therefore, a corresponding frequency. The red end of the visible light spectrum has lower frequencies and longer wavelengths, and the blue end of the spectrum has higher frequencies and shorter wavelengths.

Even shorter and longer wavelengths (higher and lower frequencies, respectively) are possible for photons. In fact, the region with frequencies just *less* than that of red is called **infrared** (*infra* means under). **Ultraviolet** light is the region with frequencies just higher than the highest frequency of the visible color violet (*ultra* means higher). The entire range of possible photon wavelengths and frequencies is referred to as the **electromagnetic spectrum**.

b. Electromagnetic Spectrum

All energy carried by photons is referred to as **electromagnetic (EM)** energy and spans all possible values for wavelength and frequencies. Ranges of this spectrum—from shortest wavelength to longest—are referred to as **gamma rays, X-rays, ultraviolet, visible light, infrared, microwaves, and radio waves**.

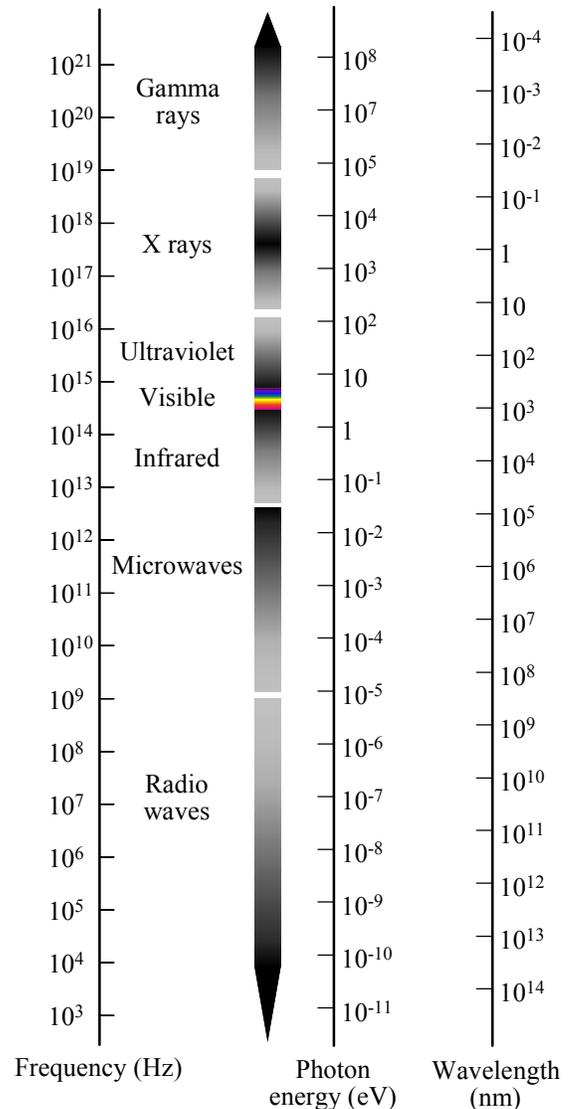
The energy carried by a photon is calculated by multiplying the frequency of the photon by a universal constant, h , called **Planck's constant**:

$$E = hv ,$$

where E is the energy in joules or electron volts, h is Planck's constant (6.6262×10^{-34} J-s, or 4.1357×10^{-15} eV-s), and v is the frequency of the photon in Hz.

When considering photovoltaics and semiconductors, this energy is often measured in **electron volts (eV)**. An electron volt is the energy required to increase the electric potential, or energy, of the charge on one electron by one volt.

Energy, like wavelength and frequency, is unique for a specific part of the electromagnetic spectrum (see Fig. 8).



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Figure 8. Electromagnetic spectrum.

Part 2: Multijunction Photovoltaic Cell Design

Silicon has been the material of choice for photovoltaic designers because it is inexpensive and relatively well understood—and, of course, because it has properties that make it appropriate for photovoltaic applications. Recent advances in photovoltaic technology, however, have made other materials in combination attractive for the design of solar cells. These new cells exceed the inherent limitations of silicon as a solar cell material. New designs layer semiconductor materials with differing bandgap energies to result in higher conversion efficiencies. Although silicon can be used as one of these layers, alloys combining Group III elements with Group V elements are enticing choices because of the wide range of bandgap energies they offer designers. These multijunction cells may someday achieve efficiencies in excess of 50%. NREL has developed a multijunction cell design that has achieved 34% efficiency under concentrated light.

A. The Solar Spectrum

Stars, including our own sun, emit energies covering a range of wavelengths of the EM spectrum. However, different types of stars produce differing amounts of energy in each region of the spectrum. Our sun emits more photons in the visible light and surrounding regions than in any other part of the EM spectrum. This phenomenon may be why our eyes have evolved to see that part of the EM spectrum and not microwaves, gamma rays, or any of the other wavelengths that are emitted at lower intensities by our sun.

Figure 9 includes a spectrum of the sun's light that reaches Earth's upper atmosphere. Notice the peak region is from 400 to 700 nanometers (nm), which is the visible range of the spectrum. Also note that there is a large number of photons through most of the infrared region of the spectrum (700 to 10,000 nm). At the higher-energy, shorter-wavelength end of the spectrum, the number of photons drops off dramatically.

The sun's spectrum contains very little light with wavelengths shorter than about 300 nm (i.e., photon energy greater than about 4 eV).

The Earth's atmosphere protects us from the higher-energy forms of light, such as ultraviolet rays. In fact, the existence of life on Earth would be far less likely if these more damaging forms of energy were more abundant. The terrestrial spectrum in Fig. 9 describes the light that actually reaches the Earth's surface after passing through the atmosphere. Notice that there are various wavelengths in which the number of photons is greatly reduced as compared to the space solar spectrum. This difference is due to photons being absorbed by atmospheric gases, the best known being ozone (O₃), which absorbs higher-energy (lower-wavelength) ultraviolet light below 400 nm. Photons with wavelengths near 900, 1100, and 1400 nm are absorbed by water vapor in the atmosphere.

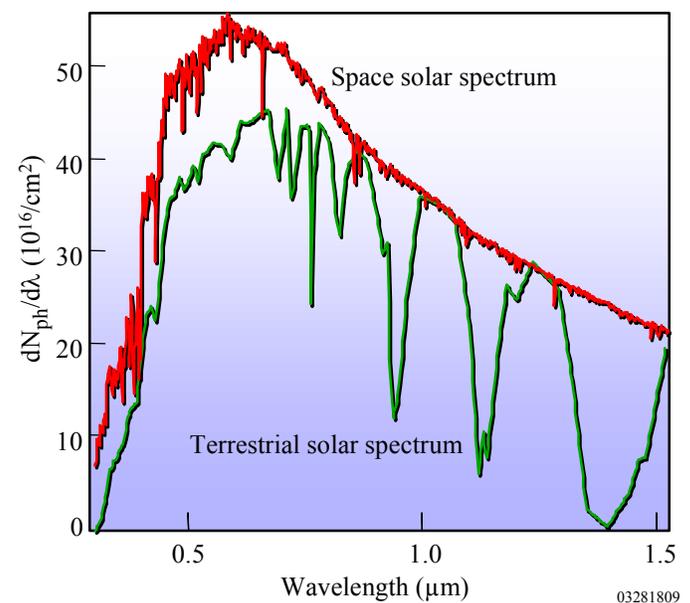


Figure 9. Earth's solar spectra

B. Photon Absorption

Photovoltaic cells are designed to capture the photons of the solar spectrum. Energies in the visible range are especially important to consider, but energy is available in the near-infrared, as well. Solar cell designs that more efficiently

absorb these photons must consider the specific energies of these wavelengths.

Photons with energies equal to or greater than the bandgap are absorbed as their energy promotes electrons into the conduction band. If photons have energy exceeding the semiconductor's bandgap, the excess is usually dissipated as heat and is thus wasted. Alternatively, photons whose energies are less than the bandgap are not absorbed at all, but are transmitted through the material and their energy is not used.

If the photon's energy is equal to the bandgap, the energy transfer, in terms of its photovoltaic usefulness, is as close to 100% efficient as is thermodynamically possible.

C. PV Voltage, Current, and Power

Ultimately, the objective of the photovoltaic cell is to generate power, and creating voltage and current produces power.

a. Photocurrent

The amount of current produced by a photovoltaic cell is directly related to the number of photons absorbed. The lower the bandgap, the more photons are absorbed and the greater the number of electrons promoted into the conduction band, and thus, available for current production.

The absorption of photons, of course, will only occur if their energies exceed the bandgap. But such absorption does not occur precisely at the surface of materials, but rather, may penetrate deeply before being absorbed. Silicon and germanium, for example, have a much lower **absorption coefficient** than does gallium arsenide. For this reason, thicker layers of silicon and germanium are required to absorb equivalent numbers of sufficiently energetic photons. Generated current, then, also depends on the **absorptivity** of a material and its thickness.

Two important performance parameters for a PV cell are its **short-circuit current (I_{sc})**, and **maximum-power current (I_{mp})**. As its name

implies, the I_{sc} is the current produced by the cell when a zero-resistance short is placed across its terminals. The I_{sc} is easily measured in a laboratory setting. The I_{mp} is the current produced under maximum power conditions and is more representative than I_{sc} of operational performance.

b. Photovoltage

The output voltage of a PV cell is directly related to the energy of the electrons promoted or excited into the conduction band. The higher the bandgap, the greater the energy of the electrons in the conduction band must be. The voltage created by a semiconductor can easily be determined by first dividing bandgap (in electron volts) by the charge of an electron (the "e" in eV). For reasons beyond the scope of this text, the voltage generated is typically around 0.4 V lower than the results of such a calculation, so 0.4 V must be subtracted from the previous result. For example, GaAs has a bandgap of 1.4 eV, so it would create an output voltage of 1.0 V ($1.4 \text{ eV}/e = 1.4 \text{ V}$; $1.4 \text{ V} - 0.4 \text{ V} = 1.0 \text{ V}$).

Two important voltage performance parameters are **open-circuit voltage (V_{oc})** and **maximum-power voltage (V_{mp})**. The V_{oc} is a measurement of the output voltage of a solar cell with no current flowing from it, which is a value easily measured in a laboratory setting. But V_{mp} is more indicative than V_{oc} of actual performance.

c. Fill Factor and Maximum Power

Figure 10 is a current-voltage (or I-V) curve showing the behavior of a sample PV cell over its full range of currents and voltages. By definition, V_{oc} and I_{sc} are the x and y intercepts, respectively, of such a plot. And as is characteristic of photovoltaic cells, they represent upper limits for voltage and current, respectively. As already noted, V_{mp} and I_{mp} are more appropriate measures of actual performance. The performance parameter, **fill factor**, is commonly used to collectively describe the degree to which V_{mp} matches V_{oc} and I_{mp} matches I_{sc} . Fill factor is given by the following:

$$\text{Fill factor} = (I_{mp} \times V_{mp}) / (I_{sc} \times V_{oc}),$$

and because the maximum power, $P_{max} = (I_{mp} \times V_{mp})$,

$$\text{Fill factor} = P_{max} / (I_{sc} \times V_{oc}).$$

Fill factors for our high-efficiency cells are typically in the range of 80% to 90%, where 100% would be ideal.

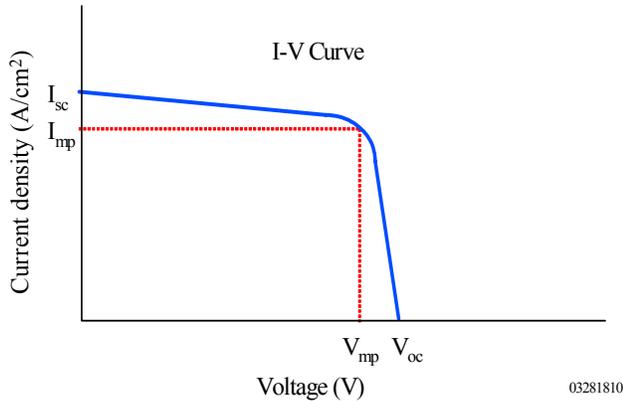


Figure 10. Optimal bandgap for single-junction solar cell.

D. Single-Junction Solar Cell Design

The photovoltaic designer must maximize power by optimizing the tradeoffs between current and voltage. To maximize current, it is desirable to capture as many photons from the spectrum of solar radiation as possible. A small bandgap may then be selected so that even photons with lower radiation energies can excite electrons into the conduction band. However, the small bandgap results in a lower photovoltage. Additionally, the photons with higher energies will have much of their energy wasted as heat, instead of conversion into electrical energy. Alternatively, the designer can choose a higher bandgap, but then will not capture any photon energy less than that bandgap, resulting in a lower photocurrent and, in turn, reducing the output current of the device.

In designing conventional single-junction solar cells, these two competing issues are balanced by

choosing optimal bandgaps near the middle of the energy spectrum for solar radiation.

Conveniently, high-quality wafers of silicon, with a bandgap of 1.1 eV, and GaAs, with a bandgap of about 1.4 eV, are readily available and have nearly the optimal band gap for solar energy conversion in a conventional single-junction solar cell. As Figure 11 shows, such designs are inherently limited to efficiencies of about 25% or less at one-sun* concentrations.

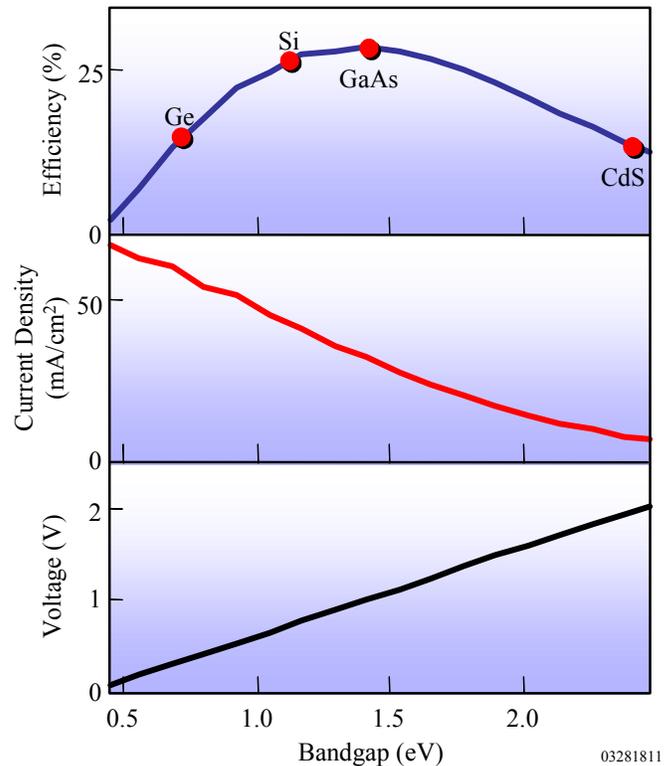


Figure 11. Optimal bandgap for single-junction solar cell.

E. Multijunction Solar Cell Design

Multijunction cells use a combination of semiconductor materials to more efficiently capture a larger range of photon energies. They do so without sacrificing photovoltage or creating

* A “sun” is a unit of concentration. For example, 500 suns would be 500 times the intensity of the sun at all wavelengths. “One-sun” implies no concentration is taking place.

losses of heat to the degree of single-junction cells.

a. Bandgap Selection

Consider the spectrum of sunlight split and distributed over a variety of semiconductor materials by using a prism (see Fig. 12).



Figure 12. Refraction of light through a prism.

In that case, a different semiconductor material could be selected (see Fig. 13a) that would best match each portion of the spectrum. Although such an arrangement is reasonable in theory, mechanically maintaining such a design would be problematic.

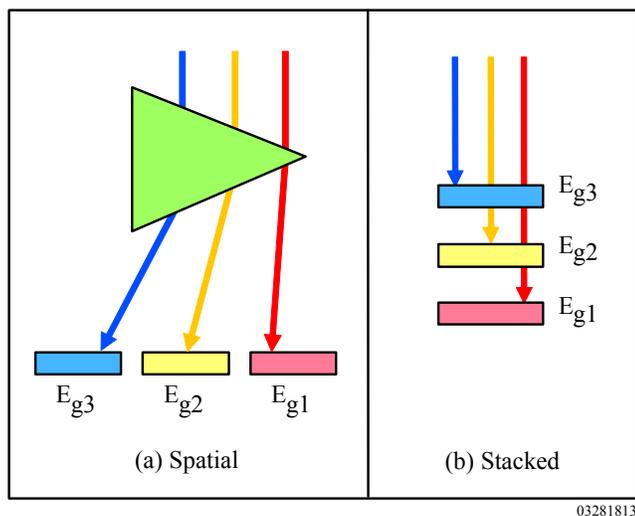


Figure 13. Alternate configurations for multijunction spectral splitting.

A more viable solution is to stack, or grow, multiple layers of semiconductors with decreasing bandgaps (see Fig. 13b). Top layers are designed to absorb higher-energy photons while

transmitting lower-energy photons that are absorbed by lower layers of the cell. In theory, a number of these layers can be so arranged. This strategy is the characteristic feature of multijunction solar cells.

Alloys of Group III and Group V elements, as well as other related compounds, lend themselves well to the design of multijunction cells. Indium phosphide (InP), gallium antimony (GaSb), and the more commonly used GaAs are examples of such III-V materials. By carefully adjusting the compositions, a range of bandgap energies can be achieved. Such selections are usually made in conjunction with lattice-constant constraints (discussed below). For example, $\text{Ga}_{0.5}\text{In}_{0.5}\text{P}$ (also known as GaInP_2) was selected for NREL's record-setting triple-junction cell to produce a material with a bandgap energy of 1.85 eV and a lattice constant of 5.65 angstroms. If a lower-bandgap material were desired, less gallium and more indium would be used in the compound, up to the point at which no gallium is included, and the resulting InP would have a bandgap of about 1.3 eV. Note, however, that such an adjustment in bandgap necessarily changes the lattice constant, as well.

b. Lattice Matching

To produce optical transparency and maximum current conductivity between the top and bottom cells in monolithic multijunction devices, all layers must have similar crystal, or lattice, structures. The **lattice constant** is a measure of the distance between atom locations in a crystal pattern and has a strong descriptive correlation with the overall crystal structure. It is extremely desirable to match the lattice constants of the various layers.

Mismatch in the crystal lattice constants creates **defects** or **dislocations** in the lattice where recombination centers can occur. **Recombination** results in the loss of photogenerated minority carriers (e.g., electrons drop from the conduction band back into the valence band) and significantly degrades the photovoltaic quality of the device. Such effects will decrease the open-circuit voltage, short-circuit current density (J_{sc}), and fill

factor, which represents the relationship, or balance, between current and voltage for effective power output.

Although noted as important in early multijunction designs, lattice matching was initially considered as a secondary concern. However, work at NREL showed that lattice mismatching as low as $\pm 0.01\%$ causes significant degradation of photovoltaic quality. For this reason, great effort is made to not only select materials with ideal bandgap energies, but also, to select a suite of semiconductor materials that have matching lattice constants. The GaInP, GaAs, and Ge of the triple-junction cell developed at NREL were selected because they have a desirable complement of bandgap energies and because they have a matching lattice constant.

c. Cell Optimization

Bandgap and lattice matching are central to multijunction solar cell designs. But to maximize the efficiency of multijunction devices, other characteristics are also desirable. Foremost of these for a **monolithic** (grown all in one piece), series-connected, two-terminal multijunction device is that each of the subcells should have matched currents. That is, they should absorb photons at the same overall rate, thus producing the same current.

i. Current Matching

By the nature of its series connection, the output current of the multijunction solar cell is limited to the smallest of the currents produced by any of the individual junctions. For this reason, it is desirable to design each junction to produce the same amount of photocurrent.

The current produced by a semiconductor junction depends on a number of factors, but most notably, the number of incident photons exceeding the semiconductor's bandgap and the material's absorptivity. If the photons that exceed the bandgap of the material are in abundance, then cell layers need a minimal thickness to collect the

desired current. Likewise, if the absorptivity of a material is relatively high, the photons must pass through less of the material before being absorbed.

In practice, for the GaInP/GaAs/Ge cell, this situation implies a relatively thick Ge layer because of its lower absorptivity. Further, there are design distinctions between terrestrial versions and space versions of the cell to account for the differing number of UV and near-IR photons for these two different environments.

ii. Power Production

One may note that as additional cell layers are added, the level of total current necessarily decreases. This phenomenon occurs because a fixed total number of photons are distributed over increasing numbers of cell layers, which decreases the amount available for electron promotion in any one cell layer. The tradeoff, however, is that the electrons promoted are, overall, more energetic and have a greater electric potential. As additional cell layers are added in series, the voltage each layer produces must be summed with the others. Therefore, the total voltage of a multijunction solar cell is greater than that of a single-junction solar cell.

Maximizing total power—the product of total current and total voltage—is the photovoltaic designer's ultimate goal. Multijunction designs, as compared to single-junction designs, have reduced currents. But this loss is more than compensated for by increases in voltages, so overall power (the product of current and voltage) is greater.

In addition, because resistive losses in circuits are proportional to the square of the current, these losses can be significantly reduced if current can be minimized. Resistive losses are an especially important consideration in concentrator systems, in which currents produced are proportional to the levels of concentration. Again, multijunction designs are advantageous in that they inherently reduce current while increasing voltage.

Present research is identifying and qualifying a 1-eV bandgap semiconductor material. Such a material could either be used as a substitute for the Ge ($E_g = 0.67$ eV) layer presently used in the triple-junction design, or as an additional layer in that design. In either case, the output voltage of the resulting cell would be increased and the current will be further reduced.

d. Concentration Systems

Concentrators are a vital component of terrestrial multijunction solar cell systems. By dramatically increasing the total power produced by a given solar cell 100- to 1200-fold, the increased cost of that cell is more readily justified. In addition, high solar concentrations actually work to improve the performance of multijunction solar cells (as Fig. 14 indicates for the GaInP/GaAs/Ge cell).

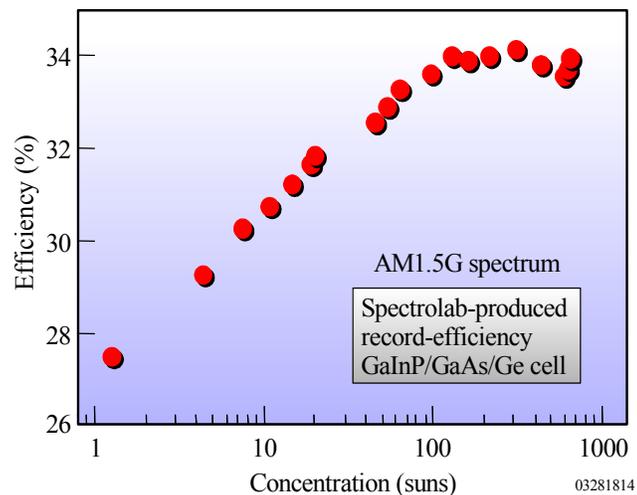


Figure 14. Efficiency under concentration for Spectrolab’s GaInP/GaAs/Ge solar cell.

Concentrator systems are varied and generally scalable. For example, the point-focus system shown in Fig. 15 is a smaller system appropriate for a residential home. Figure 16 depicts a 5200-sun concentrator appropriate for larger-scale energy production. Figure 17 depicts a linear concentrator system in Austin, Texas. All of these systems represent ones that might be used in conjunction with multijunction solar cells.



Figure 15. A 5-kilowatt point-focus Stirling engine concentrator system. (Cummins Power Generation, Inc./PIX01730)



Figure 16. 5200-sun, point-focus concentrator for a solar furnace. (Sandia National Laboratories/PIX01728)



Figure 17. 300-kilowatt linear concentrators.
(Tom Lankes - Austin American Statesman/PIX00014)

NREL is presently funding Amonix, a manufacturer of high-concentration PV systems, and Spectrolab to improve their close-packed array designs specifically for multijunction solar cells.

Concentrator systems have been both costly and complicated. Optics and support structures cost increase further with increasing concentrations. Such systems still hold promise as a viable clean energy alternative as further development and economies of scale reduce costs. Even so, their complexity may make them more appropriate for centralized power production.

e. Triple-Junction GaInP/GaAs/Ge Solar Cell

The GaInP, GaAs, and Ge layers of NREL’s record-setting triple-junction solar cell (see Fig. 18) were selected because of their collective ability to match bandgap energies with the solar spectrum (see Fig. 19). GaInP, with a bandgap energy of 1.85 eV, absorbs the photons in the ultraviolet and visible part of the solar spectra. GaAs ($E_g = 1.42$ eV) absorbs near-infrared light, and Ge absorbs all the lower photon energies in the infrared that are above 0.67 eV.

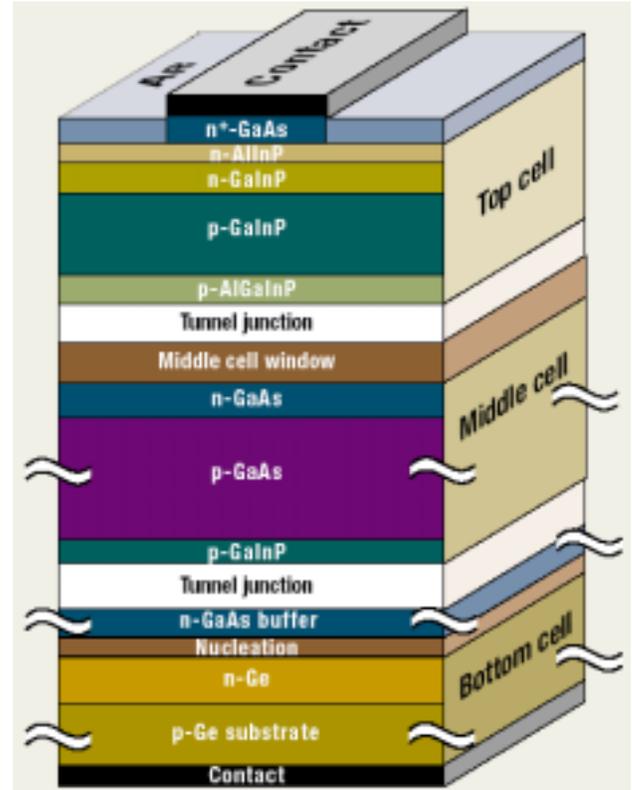


Figure 18. GaInP/GaAs/Ge triple-junction solar cell.

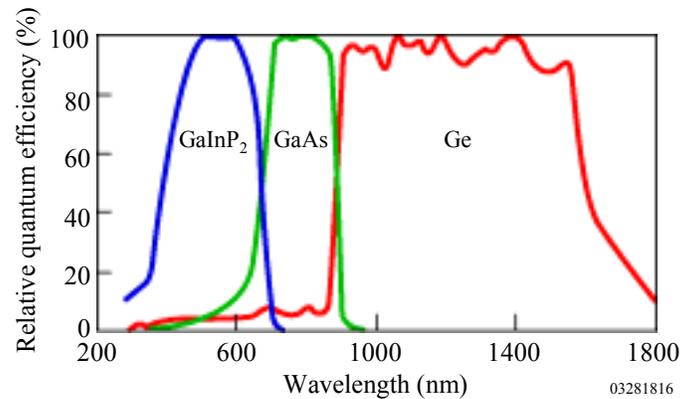


Figure 19. Quantum efficiency of each layer of the GaInP/GaAs/Ge triple-junction solar cell.

In addition, these three semiconductors were selected because they are lattice matched with one another. An alternative to GaInP, with similar lattice constant and bandgap energy, is $Al_{0.37}Ga_{0.63}As$. However, high sensitivity to oxygen and water contamination make $Al_{0.37}Ga_{0.63}As$ an undesirable choice.

Each layer's thickness was selected to best match currents with the other two cells. Two versions of such a current-matched solar cell exist—one to best match the greater amounts of high-energy photons in space, and one with a thicker top cell for terrestrial applications.

The GaInP/GaAs/Ge solar cell is monolithically grown, which means that each of the twenty semiconductor layers were grown *in situ*. The alternative—a physical stacking of independently grown layers—has been accomplished by others with comparable efficiencies. But the bulkiness, additional expense, and heat-sinking challenges make mechanically stacked multijunction cells an less-desirable alternative.

The monolithic growth of the cell, accomplished by **metal-organic chemical vapor deposition (MOCVD)** (see Fig. 20), helps to ensure high crystal quality throughout the device. Impurities are exceptionally detrimental to the performance of multijunction solar cells. Despite its reputation as a “dirtier” process, the MOCVD is preferable to the “cleaner” **molecular-beam epitaxy (MBE)** (see Fig. 21) process because it is easily scaled to large production capacities.

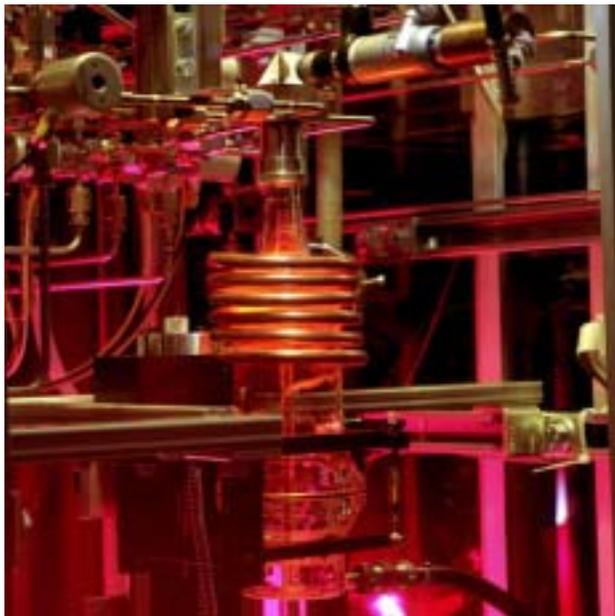


Figure 20. Metal-organic chemical vapor deposition system. (Jim Yost/PIX01460)



Figure 21. Molecular-beam epitaxy system. (Warren Gretz/PIX01144)

The result is a cell that achieves an efficiency of 34% under high concentration. NREL licenses this design to Spectrolab, Inc. and to EMCORE, the two manufacturers of space solar cells in the United States. The design is now in development for terrestrial concentrator systems.

Spectrolab's production version of NREL's record-breaking GaInP/GaAs/Ge triple-junction solar cell is shown in Fig. 22.

f. Current Research and the Future of Multijunction Cells

The development of new semiconductor materials tops the list of research efforts at NREL and elsewhere. In particular, research focuses on developing materials with a bandgap of 1.0 eV or 1.25 eV.

The Ge layer of the GaInP/GaAs/Ge triple-junction cell absorbs a larger proportion of solar spectrum photons than is ideal for current matching of the three layers. By replacing the GaAs layer with a 1.25-eV bandgap material, this second layer could collect a larger current, while reducing the number of photons transmitted to the germanium layer. The top GaInP layer would be thickened to increase its current production. And overall, the multijunction device would generate a higher matched current, and thus, more power.

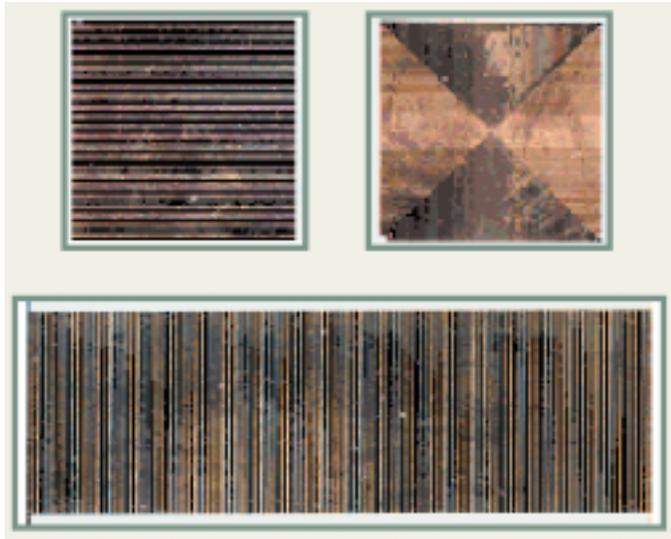


Figure 22: Spectrolab’s production version of the GaInP/GaAs/Ge solar cell.

The economic viability and competitiveness of multijunction solar cell systems will continue to improve over time. Process technologies, particularly techniques with commercial scalability, can be expected to progress, as will designers’ understanding of materials behavior. Material costs are expected to decline as demand grows for solar cell technologies. The final goal is a multijunction solar cell with an efficiency exceeding 40%, and energy costs from such a device below 30 cents per watt at 300 to 500 suns.

Brenton Burnett, a science teacher and coordinator at the Cherry Creek Challenge School in Denver, Colorado, created this document while he was a visiting associate of the NREL’s III-V research group in the summer of 2002.

The next generation of multijunction solar cells may have four layers. The most direct path to such an achievement is to develop a 1.0-eV bandgap material that is lattice matched with the GaInP, GaAs, and Ge of the present triple-junction solar cell. The theoretical results of such efforts are summarized in Fig. 23.

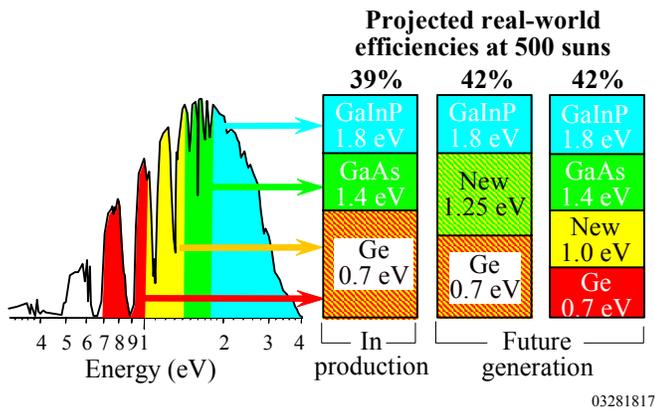


Figure 23. Projected real-world 500-sun concentrator efficiencies of multijunction designs.