Multi-Junction Photovoltaic Devices

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Abstract

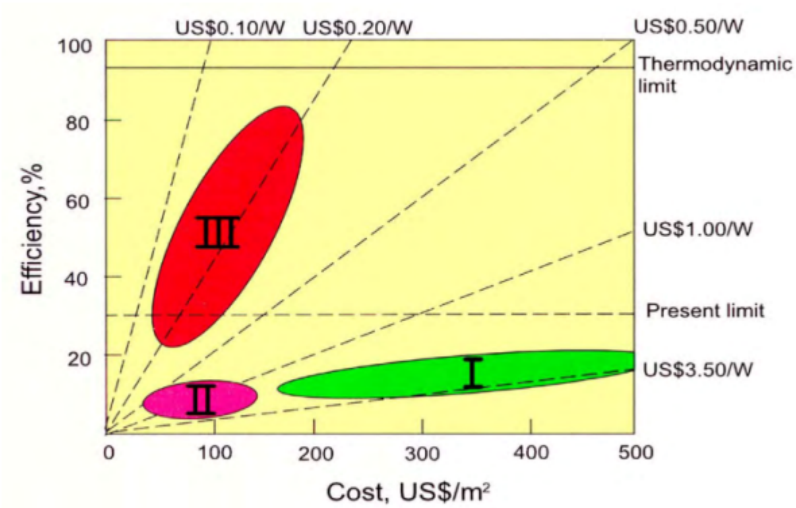
We researched the theory of and applications of multi junction photovoltaic cells. In the past few decades, these devices have come a long way, both in efficiency, and cost. They have been sent to space and have started to be used in terrestrial applications. Multijunction cells are increasing in popularity because of the high efficiency that can be obtained by using multijunction cells as opposed to single cells. We will discuss relevant issues and designs of current multi junction cells, as well as future development.

Introduction

Prior to multijunction solar cells, the efficiency of a single junction solar was only 20 percent. As of recent, the highest recorded efficiency in a multijunction solar cell was 42 percent. This is over two times as efficient as a single junction solar cell. Theoretically, multijunction solar cells can have an efficiency of 87 percent. First we go into the history of multijunction solar cells, including events that led up to the discovery. Next, we discuss the physics of multijunction solar cells and why they work. Then we will discuss important physics topics relating to multijunction solar cells are bandgaps, the photoelectric effect, and pn junctions. Following that we will explain the design and manufacturing processes. After that we will delve into the current applications for this device, including various situations where it is used. And finally we will consider the prospects of future uses for these photovoltaic devices, and examine the ongoing research for the betterment of this technology.

History

Solar cells as we know them today can be attributed to many great people over the past two centuries. The first was a French Physicist by the name of Edmund Becquerel who discovered the photoelectric effect. This is defined as the emergence of an electric voltage between two electrodes attached to a solid or liquid system upon shining light onto this system [1]. For much of the next hundred years, scientists made many discoveries that lead to the initial creation of the first silicon solar cell in 1954. Some of these discoveries include experimental proof of the photoelectric effect, explanation of the pn junction behavior, and a way to grow single-crystal silicon [2]. The first generation solar cells, based on silicon wafer technology, are still the dominant form for solar applications today [3]. Second generation solar cells are classified as thin film deposits of semiconductors, which can be created much cheaper but with less efficiency [3]. With an efficiency of 6 % that later climbed to 10 %, there was an obvious need for a more efficient solar cell.

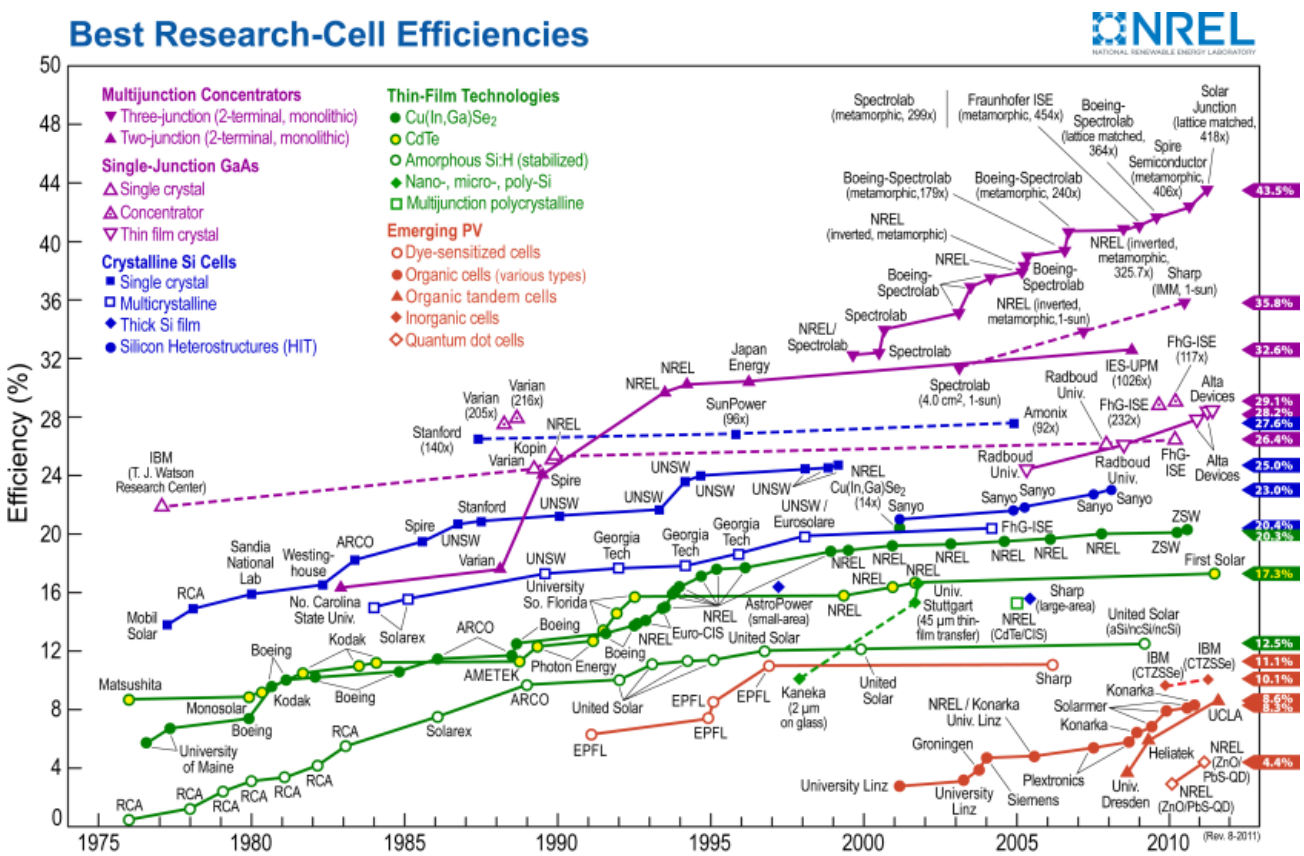


Efficiency vs. cost for the three generations

It was some time in the early 1960's when the multijunction, or tandem solar cells, were first studied [4]. It wasn't until around the mid to late 1980's that an actual device was created that surpassed 20 % efficiency. This was the beginning of the third generation category of photovoltaic devices [3]. Many groups were working on double junction solar cells, but most failed due to the lattice mismatch between the two cells. This is when researchers at the National Renewable Energy Laboratory (NREL) began to work on a double junction solar cell made of

GaInP/GaAs [5]. This device was a small amount less efficient than the AlGaAs/GaAs tandem cell, but was much more manufacturable and easier to produce [5].

As you can see by the diagram below, multijunction solar cells have been steadily increasing in efficiency over the last twenty years. This is compared to traditional silicon only photovoltaic devices, which have not shown the same increase.

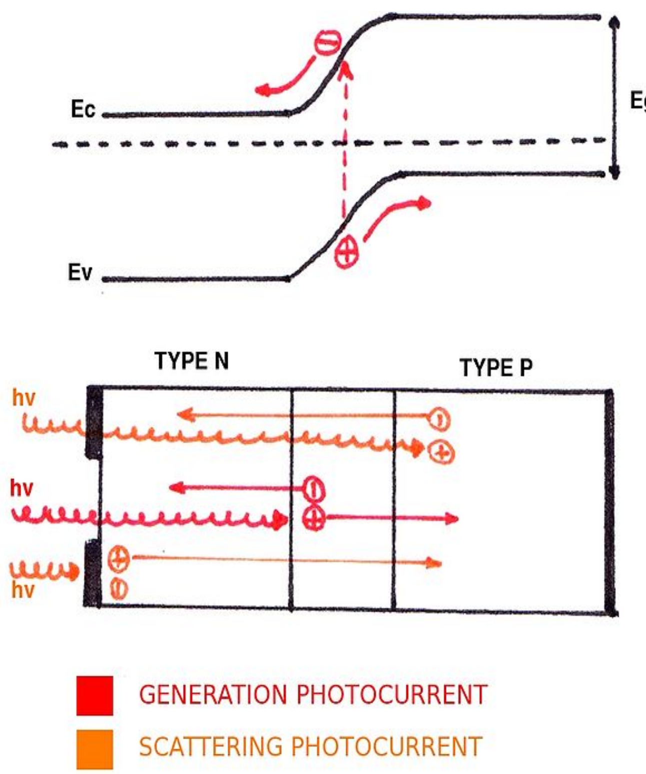


Efficiency of various PV devices over the last three decades

Background Physics

Multijunction photovoltaic cells take advantage of the photoelectric effect. This is when a material is able to absorb some energy from light and eject an electron because of the absorbed energy. Electromagnetic radiation is composed of many tiny particles that each have some energy. When these particles enter a conductive metal, they give off some energy to the electrons in the metal. These electrons then have enough energy to move throughout the metal. This flow of electrons becomes a current because current is the movement of charges. In terms of solar cells, this means that the cells can absorb energy from incoming light and use this energy in the form of electrical energy to power some device. The energy that is absorbed is equal to Planck's constant multiplied by the frequency of the incoming light [6].

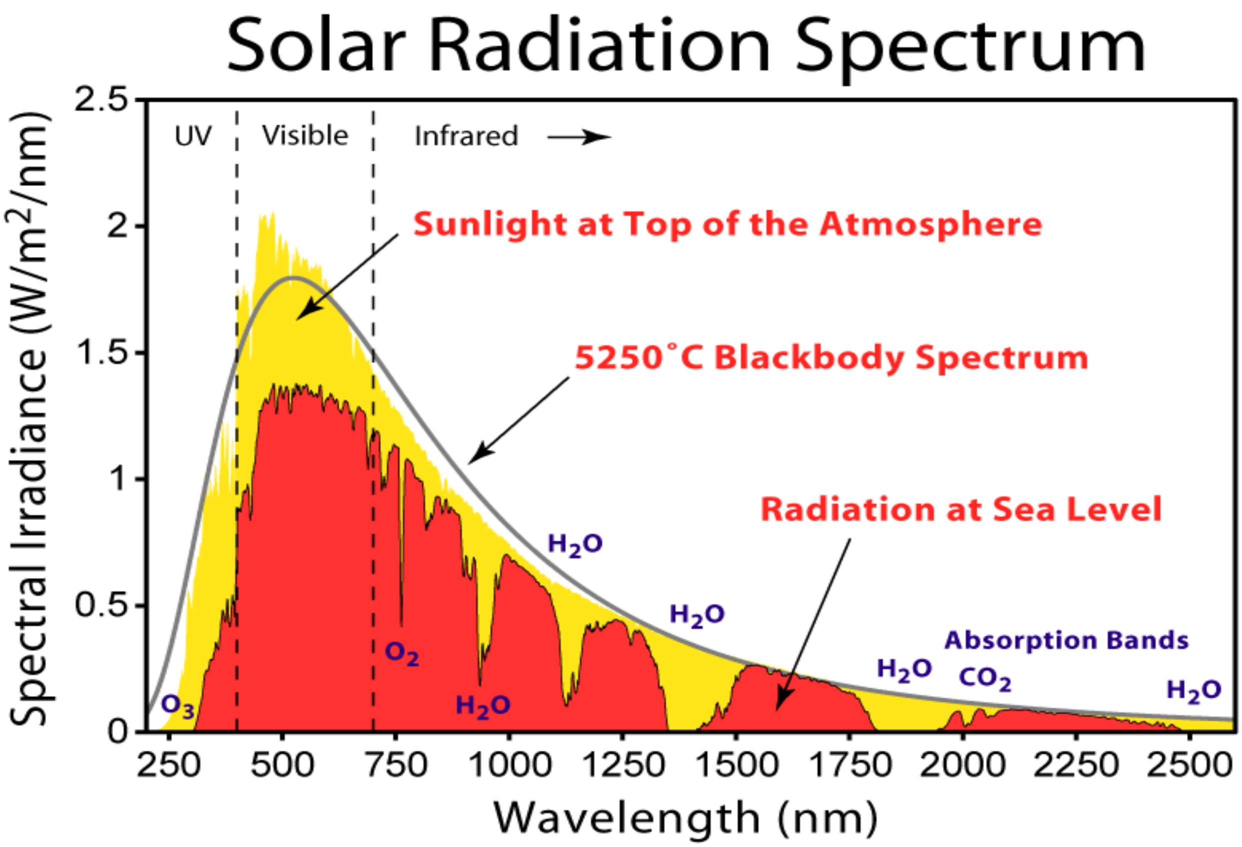
Multijunction photovoltaic cells are made of multiple pn junctions. The pn junction can be thought of as a positively charged material coming into contact with a negatively charged material. When these two materials come in contact, it forms a built in electric field. This is because there is a high buildup of positive charges on the p-type material near the junction, and a large buildup of negative charges on the n-type material near the junction. This forms because positive and negative charges are oppositely charged and therefore attracted to each other. Because of this charge build up, there is a built in potential difference. The built in potential difference is typically very small(less than 1 eV). The built in voltage can be increased by adding more dopants to either side or increasing the thermal energy that is going through the junction. Without adding any outside energy to the junction, the device is not very useful as a solar cell. When an applied voltage is put across the pn junction, it creates a current. Incoming light can be thought of as an applied voltage because it is adding energy to the system just like an applied voltage. When the light is added to the system, it generates a current between the pn junction. This current is generated because the light forces the positive charges to be accelerated toward the n type material and the negative charges to be accelerated toward the p type material. This creates a potential difference between the two regions and consequently generates a current. This process is illustrated in the figure [7]. As the applied voltage is increased, current is able to freely flow across the junction. This current can be used to power a device or be used as a component to a circuit.



Incoming light creates a current in a pn junction [7].

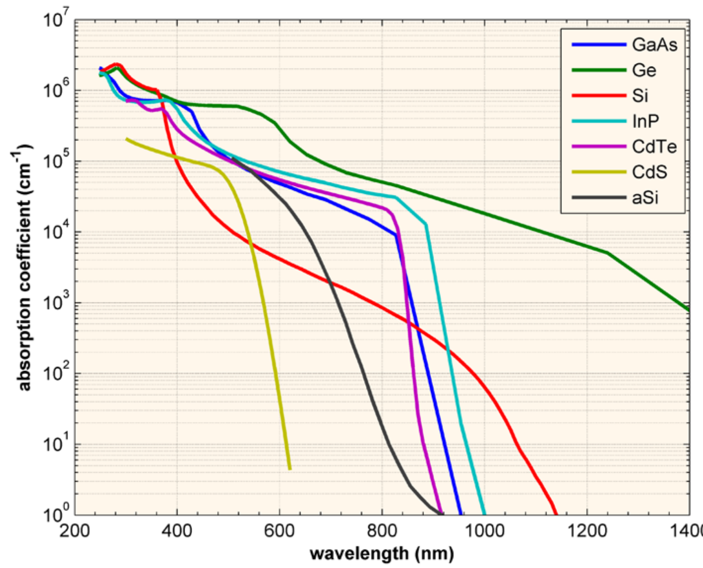
Junction Characteristics

Sunlight is made up of electromagnetic waves of different wavelengths. A solar cell is made with one pn junction that has a specific bandgap. Since the sun gives off electromagnetic waves of many different frequencies, a typical solar cell is only absorbing a small portion of the suns energy. A multijunction photovoltaic cell is comprised of multiple junctions that have different bandgaps. Therefore, a multijunction photovoltaic cell can absorb a greater portion of the sun's energy. The materials chosen for each section of the multijunction are very important because it determines which frequency of light can be absorbed.



Material Properties

The materials chosen for multijunction photovoltaic junctions must have some specific properties. A material must have a relatively large optical absorption coefficient to be considered for use in a junction. The absorption coefficient of a material determines how easily light can penetrate into the material. Large absorption coefficients are desired because light should easily be able to penetrate into the junctions and deliver energy. The absorption coefficient is not a constant value for all types of electromagnetic radiation. It depends on the wavelength of the light that is trying to penetrate the material. The absorption coefficient of a specific material will usually decrease as the wavelength increases. This is because as the wavelength of a wave increases, the frequency decreases. This causes the energy of the wave to be less, so it will have less energy to penetrate through a material. Materials do not have linear absorption coefficients with respect to wavelength. Typically, there will be a certain wavelength when the absorption coefficient drops off significantly. It is important to know which wavelengths will be absorbed in a particular application so that the most energy can be absorbed. For instance if the incoming light will have wavelengths ranging from 400 to 800 nm, cadmium sulfide would be a poor choice of a semiconductor because it does not absorb waves with wavelengths over 500 nm very efficiently. The absorption coefficient of materials is a major consideration in multijunction photovoltaic cells because they are used to absorb light [9].



The absorption coefficient of common semiconductor materials plotted against wavelength of incoming light [8].

Another material consideration is the minority carrier concentration lifetime and the mobility of a specific material.

When choosing a material for a junction, both the minority carrier concentration lifetime and mobility should be relatively high. This is because current flowing through a junction is affected by these two parameters. If a material with a low mobility is chosen to be a part of the junction, then the current flowing through the junction will not be at the most efficient level. Since solar cells are not very efficient as it is, the current flowing through the junction should not be limited by the mobility or minority carrier concentration lifetime.

Design

The main factors to consider when designing a multijunction photovoltaic cell are the bandgaps of each individual cell, lattice matching, and current matching. A perfect combination of these factors will result in a very efficient multijunction PV cell.

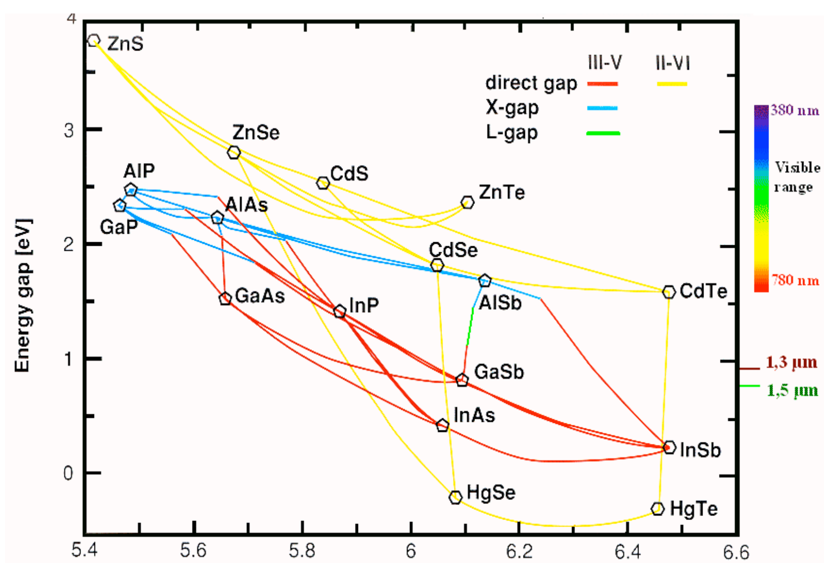
The bandgaps of each cell is an important factor in the design process. The junction will be able to absorb this energy if the energy of the light is greater than the bandgap of the material used in the junction. In other words, the frequency of the light multiplied with Planck's constant must be greater than the bandgap of the material or it will not be absorbed. If the energy is not greater than the bandgap of the material than there will not be enough energy for an electron to be emitted because if will not be able to have enough energy to make it past the barrier of the conduction band. The electron will be stuck somewhere in the bandgap and will eventually lose the energy from the light and go back to its initial state [10]. Therefore this limits the single PV cell. In a multijunction PV cell, multiple cells with multiple bandgaps are used. These bandgaps needs to cover a wide range, in order to capture more photon energy than a single PV cell. The top layer of the multijunction PV cell is designed to absorb higher energy photons. The bandgap of the top cell is the highest in the multijunction PV cell. Since it has the largest bandgap, it will absorb the highest amount of energy. The next junction the light passes through will have the next largest bandgap. Since the next junction has a smaller bandgap than the first, there will be some bandgap light that is transferred from the first junction to the second

Material	Energy gap (eV)	
	0K	300K
Si	1.17	1.11
Ge	0.74	0.66
InSb	0.23	0.17
InAs	0.43	0.36
InP	1.42	1.27
GaP	2.32	2.25
GaAs	1.52	1.43
GaSb	0.81	0.68
CdSe	1.84	1.74
CdTe	1.61	1.44
ZnO	3.44	3.2
ZnS	3.91	3.6

Energy Gap of various materials [11]

junction. In general, the junctions are arranged from highest to lowest bandgap so that there can be some transfer of energy between the different junctions in order to obtain the same amount of current through the entire device. This will create the most efficient photovoltaic cell. A table of many common semiconductor materials and their bandgaps at 0 and 300 Kelvin is shown in the table above. If someone was developing a multijunction cell with two different junctions, they would choose a GaAs homojunction to come before a Si homojunction. This is because the bandgap of GaAs is 1.43 eV and the bandgap of Si is only 1.11eV. Using this configuration will result in the largest efficiency and the smallest amount of thermal losses. The challenge in the design process is to create materials that have the specific bandgaps needed. Alloys of group III and V are used mostly in the industry because of they can provide a range of bandgap energies with adjustments to their composition [12].

Having the individual cells with the bandgaps is only one of the factors that determine the outcome of the multijunction PV cell. Lattice matching is another very important step in the process. Lattice matching is when all the different layers have the same or close to the same lattice constant. Lattice constant is a measure of distance between atom locations in a crystal pattern. The crystals lattice constants are matched in the different layers to ensure that there are no dislocations or defects that will decrease efficiency. The mismatch of the lattice constants can cause recombination to occur. Recombination leads to the loss of photo-generated minority carriers which will decrease open-circuit voltage, short-circuit current density, and fill factor. The decrease in these values will lead to loss of power [13]. This is also important because materials with the same lattice constant will result in the maximum amount of growth when growing one material on the other. It also makes the crystal that is grown to be of higher quality than if the lattice constants were very different.



Energy Gap (eV) vs. Lattice constants [14]

Current matching is also a vital step in maximizing the efficiency of a multijunction photovoltaic cell. The sub-cells in the main multifunction PV cell are connected in series. This means that the current entering and exiting any junction in the main cell must be equal. Therefore, the output current is limited to the smallest current in the sub-cells. So in Multijunction PV design, each sub-cell produces the same amount of current. There are 3 main factors that determine the current in the sub-cells; number of incident photons with energy greater than the band gap, material's absorptivity, and the thickness of each sub-cell. The thickness of the sub-cells would be the easiest factor to manipulate in order to match currents. For example, a sub-cell with low absorption coefficient should ideally have a thicker layer in order to absorb the same amount of photons as another sub-cell with a high absorption coefficient [15].

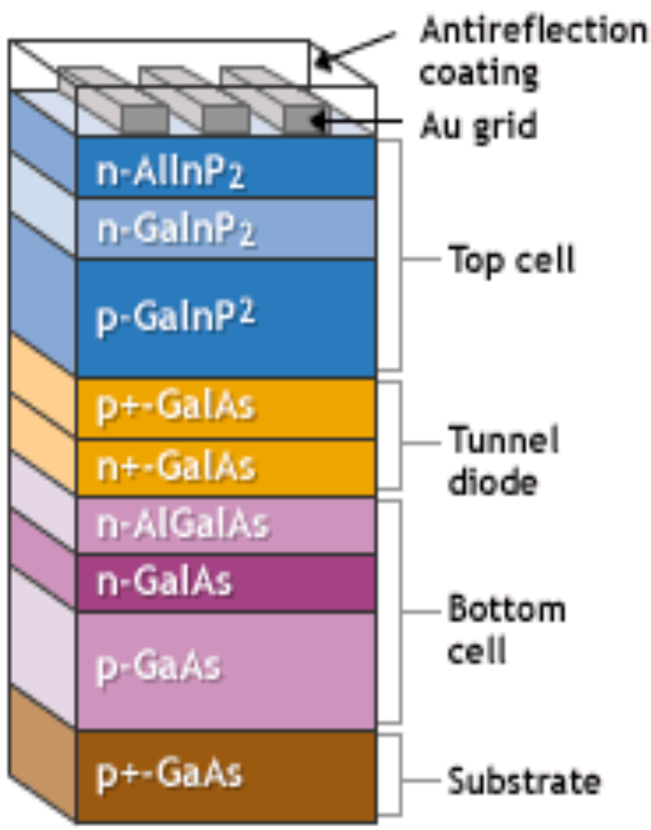
Another design characteristic of a multijunction PV cell is that there is reduced current compared to a single PV cell. This is due to the fact that there are more layers in the multijunction PV cell and the total number of photons in the system is distributed over the multiple layers. This reduction in current helps increase the efficiency by reducing resistive loss. Another advantage of having multiple layers is that the voltage increases with the amount of layers. This occurs because the layers are in series and their individual voltages are added. This increase in voltage overcomes the loss of current and still produces more power than a single PV cell.

Concentrator system – Solar systems Pty [16]

Multijunction PV cells can be combined with concentrator systems to increase the power produced. Concentrator systems can increase the total power produced by a multijunction PV cell 100 to 1200 fold [15]. These systems are used terrestrially to decrease the cost/efficiency ratio of multijunction PV cells. Multijunction PV cells by themselves are not worth the cost but the addition of a concentrator system justifies the use of it terrestrially [17]. Another advantage of using a concentrator system is that it reduces the solar cell size [16]. There are 2 main types of concentrator systems. They are refractive lenses and reflective lenses. In these systems, light hitting a large surface on the concentrator is concentrated into a smaller cell. Concentrator systems usually track the sun to get the maximum amount of sun light.

Tunnel Junctions

One problem with multijunction photovoltaic cells is the connection between two different junctions. Often the p-doped side of one junction is connected to the n-doped side of a different junction. This causes a problem because it creates a new junction between the two junctions. Also, this new junction has the opposite polarity of the other two junctions. If the p-doped side of the first cell and n-doped side of the second cell were to come in contact, then this junction would be in reverse bias whenever the other junctions were in forward bias. This would make a very inefficient solar cell because no current would ever be allowed to flow through all of the junctions at the same time. To fix this problem, a highly doped, wide band gap junction is connected in between the two junctions. This type of junction is typically called a tunnel junction because it takes advantage of tunneling. Tunneling occurs when the conduction band of the p-doped side is at the same level as the n-doped side of the junction. Since electrons from the valence band on the n-doped side of the junction are at the



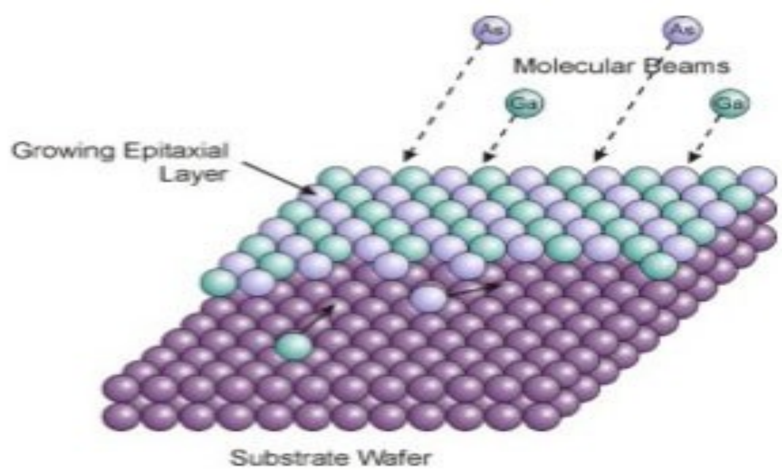
Multijunction cell with tunnel diode separating the two junctions [18].

same level as holes in the conduction band of the p-doped side, the electrons tunnel across the barrier to go to the lower energy state. When a voltage is applied to a tunnel junction, the aligned bands of the n and p sides become unaligned and the current flowing through the junction decreases. This creates an inverse current voltage relationship. This property makes a tunnel junction a good divider between the different junctions in the cell because it has very low resistance and optical losses when there is a small voltage going through the tunnel junction.

Manufacturing

Single PV cells are combined to create Multijunction PV cells and this combination can be done using two main methods. One method is to construct the Multijunction Photovoltaic cell mechanically. In mechanical construction, individual single PV cells with different band gaps are stacked on top of each other. However this method is the less popular method because the Multijunction PVs created can be bulky, as well has have heat-sinking problems. The other method of construction is monolithic growth. This is where individual cells are grown on top of each other to create on main cell with one set of contacts.

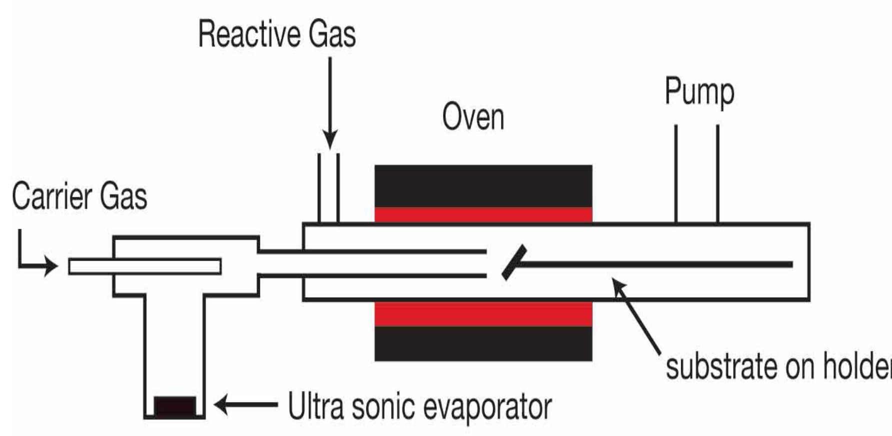
There are two methods to monolithically grow a multijunction PV. One method is molecular-beam epitaxy (MBE). Epitaxial growth is the arrangement of atoms on an ordered substrate [19]. The atoms or molecules that are to be arranged on the substrate are beamed to the heated substrate, creating a thin layer. This process is done in a high vacuum or ultra-high vacuum environment. The other monolithic growing method is metal-organic chemical vapor disposition (MOCVD). This method involves the transport of molecules or atoms with a carrier gas on to the



Molecular-beam epitaxy (MBE) [20]

heated substrate. The main difference between the two methods is that metal-organic chemical vapor disposition (MOCVD) uses chemical reaction to create the layer and molecular-beam epitaxy (MBE) uses physical deposition.

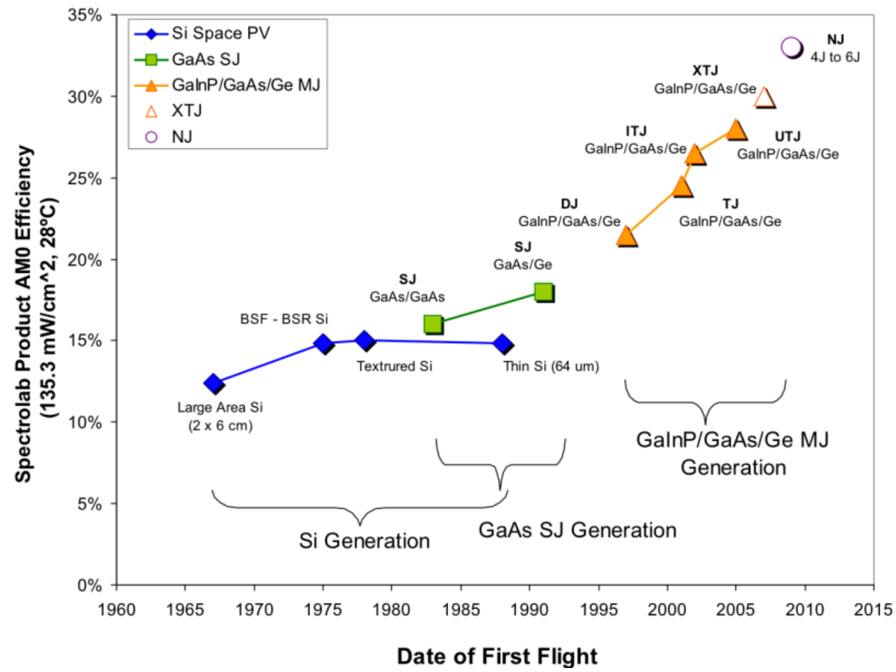
Molecular-beam epitaxy (MBE) is a clean process with precise control. However, metal-organic chemical vapor disposition (MOCVD) is the more preferred process to create multijunction PVs because this process can be done in a large production scale. MOCVD also creates high crystal quality.



Metal-organic chemical vapor disposition (MOCVD) [21]

Past and Current Applications

As with all types of photovoltaic devices, where it is used depends on many factors. These include cost, efficiency, manufacturability, availability of materials, and ability to mass-produce. The characteristics of multijunction solar cells have made them a great fit for use in space. The first investigation of these devices began in the early 1980's, which later lead to an exploratory research phase, that eventually lead to the development for use in the satellite power market in the 1990's [22]. "The higher efficiencies and radiation resistance of III-V cells have made them an attractive replacement for silicon cells on many satellites and space vehicles. Over the years GaAs cells have replaced silicon cells on new satellite launches. The GaInP/GaAs/Ge cells are integrated into modules very much like single junction GaAs solar cells and have the added advantage of operating at high voltage and low current, as well as having excellent radiation resistance. They also have a smaller temperature coefficient than silicon, which implies better performance under the operating conditions encountered in space applications [5]." The first launch of a commercial satellite powered by a multijunction technology was in 1997, using solar arrays based on Spectrolab's dual junction cells [23]. When first launched, the cells had an efficiency of 21.5 %, and over the years have been upgraded to even higher efficiencies. By incorporating Ge as a sub cell, the device was now a triple junction, becoming 25.1 % efficient. Currently the efficiency of multijunction solar cells used in space is around 30 %. Right now, multijunction photovoltaic devices are just too expensive for most "one-sun" applications. Cost is a major limiting factor in the development of solar farms. Large scale operations have cost in the hundreds of millions of dollars, but prices are expected to drop as technology improves [24]. The extra cost is acceptable for satellites, but for uses here on earth, it is not feasible [5].



Product efficiency of different Multijunction devices versus first launch date

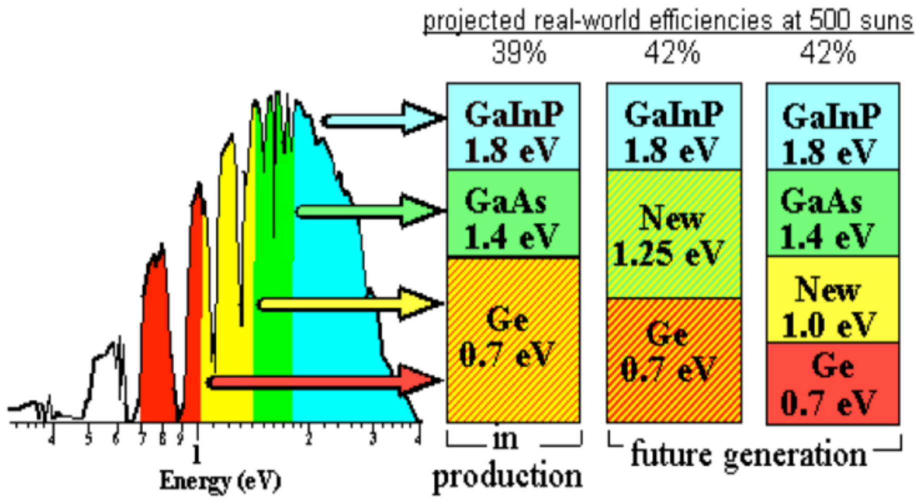
Future Use and Current Research

With current global population and economic growth, the energy consumption rate is projected to be doubled by 2050, and photovoltaics are expected to provide much of that energy [3]. Not only do we need more solar cell farms, but we need actual solar cells that are more efficient and more cost effective. Multi junction cells are efficient and are getting even better, but there is still a lot of work to do in creating a better photovoltaic device. Many experts agree that a considerable industry investment will be required to develop this product. "Investors are now exploring the feasibility and viability of very large multi-megawatt concentrator PV projects requiring funding 10 to 100 times larger than the early funding of research for III-V multijunction cells [22]." With the world record highest efficiency recorded at around 41 %, many companies are setting that as their current target on the pathway to significant market deployment and commercialization. Most research being done on multijunction solar cells are in the area of efficiency, some examples follow [22].

-California Institute of Technology is developing a 4-junction solar cell with 40% target efficiency fabricated by wafer bonding and layer transfer

-The University of Delaware is focusing on high performance tandem solar cells based on the InGaN material system

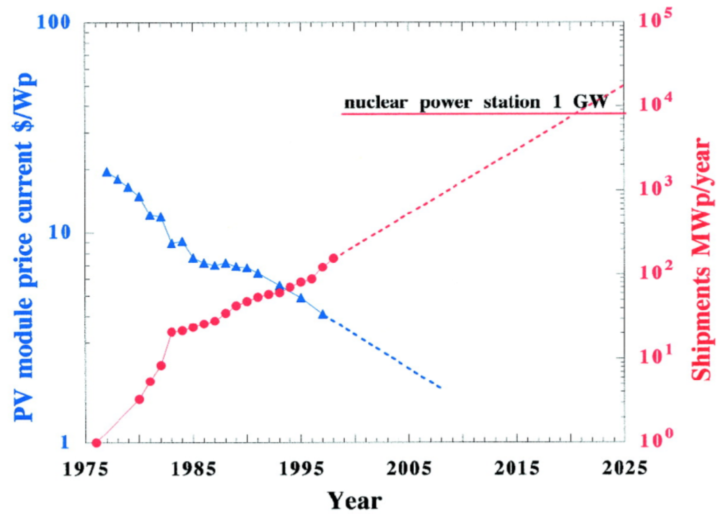
-Ohio State is developing the use of 3-D substrate engineering to grow III-V multijunction devices on Si or Ge



Current and future multijunction technology

Not just universities are working on these devices, but companies such as Spectrolab and Amonix are currently researching in order to improve efficiency. Right now NREL, the National Renewable Energy Laboratory, is developing new semiconductor materials. Their focus is to develop a material with a band gap of either 1.0 or 1.25 eV. The next generation of devices could even have four or more layers [25].

Along with efficiency we need more cost effective solutions. Right now the present cost of electricity from PV installations is generally about an order of magnitude higher than current commercial prices of electricity generated by hydraulic, nuclear, and fossil fuel power [26]. "In order to apply multi junction photovoltaics widely, it is necessary to develop a large-area, cost-effective, and highly reproducible fabrication process [3]." Right now, generating electricity is expensive, but "it is expected that the use of high-efficient multijunction solar cells with innovative concepts in concentrators has the potential to establish a new milestone in photovoltaics, generating electricity at 7-10 cents per kilowatt/hour in a visible future [3]." As you can see in the figure below, prices of photovoltaic devices are steadily decreasing, and because of that, shipments are increasing.



Photovoltaic price decline and shipment incline over time

Conclusion

Multijunction solar cells have had a profound effect on space exploration. We have shown how these devices are the more desirable solution than single junction cells for many reasons. For one they have a much higher efficiency, they also have the potential to go much higher. Multijunction solar cells in conjunction with concentration systems can be cost effective. Compared to the conventional methods of generating power (i.e. coal, nuclear) solar technology is much better because it does not require fuel and has no moving parts therefore there is virtually no wear and tear on the system. Multijunction solar cells are the future of solar cell technology and will have a plethora of uses in future applications.

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