High-efficiency multi-junction solar cells:
Current status and future potential

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Introduction

Solar electricity, or photovoltaics has shown since 1970s that the human race can get a substantial portion of its electrical power without burning fossil fuels (coal, oil or natural gas) or creating nuclear fission reactions [1]. The Sun provides us with a staggering amount of free, environmentally friendly, quiet and reliable energy supply. Earth's ultimate recoverable resource of oil, estimated at 3 trillion barrels, contains $1.7\text{x}10^{22}$ joules of energy, which the Sun delivers to our planet in 1.5 days [2]. Since 120,000 TW of solar radiation strikes on the surface of the Earth, 10% efficient solar conversion systems covering 0.16% of the land would produce 20 TW of power, nearly twice the annual global energy consumption [3].

Photovoltaics can generate electricity for a wide range of applications, scales, and climates; it is a cost-effective way to provide power to remote areas and for space applications. Table 1 lists some of the technical, economical and infrastructural features of photovoltaics, showing that photovoltaics helps us avoid most of the threats associated with our present techniques of electricity production and also has many other benefits [1].

Table 1 [1]

Advantages	Disadvantages
Fuel source is vast and essentially infinite	Fuel source is diffuse (sunlight is a relatively low-density energy)
No emissions, no combustion or radioactive fuel for disposal (does not contribute perceptibly to global climate change or pollution)	
Low operating cots (no fuel)	High installation costs
No moving parts (no wear)	
Ambient temperature operation (no high temperature corrosion or safety issues)	
High reliability in modules (>20 years)	Poorer reliability of auxiliary (balance of system) elements including storage
Modular (small or large increments)	
Quick installation	
Can be integrated into new or existing building structures	
Can be installed at nearly any point-of-use	
Daily output peak may match local demand	Lack of widespread commercially available system integration and installation so far
High public acceptance	Lack of economical efficient energy storage
Excellent safety record	

The enormous gap between the potential of solar energy and our currently slight use of it is due to the modest energy density of the radiation, low conversion efficiencies of photovoltaics, and cost of materials currently required. The cost effective raising of conversion efficiency is primarily a scientific challenge: breakthroughs in fundamental understanding enable the development of materials and methods leading to the photovoltaic market progress.

A history of photovoltaics goes back to 1839, when Edmund Becquerel observed a photovoltaic effect in liquid electrolytes [4]. However it was not until 1954 that the first solar cell was developed at Bell Laboratories [5].

Modern research in the area of photovoltaic technologies has lead to creation of a huge spectrum of solar cells, which are commonly classified as three generations, which differ from one another based on the material and the processing technology used to fabricate the solar cells. The material used to make the solar cell determines the basic properties of the solar cell, including the typical range of efficiencies [6-10], (Appendix 1).

The first generation of solar cells, also known as silicon wafer-based photovoltaic, is the dominant technology for terrestrial applications today, accounting for more than 85% of the solar cell market. Single-crystalline and multi-crystalline wafers, used in commercial production, allow power conversion efficiencies up to 25%, although the fabrication technologies at present limit them to about 15 to 20%.

The second generation of photovoltaic materials is based on the use of thin-film deposits of semiconductors, such as amorphous silicon, cadmium telluride, copper indium gallium diselenide or copper indium sulfide. The efficiencies of thin film solar cells tend to be lower compared to conventional solar cells, around 6% to 10%, but manufacturing costs are also lower, so that a price in terms of $/watt of electrical output can be reduced. Besides, decreased mass allows fitting panels on light materials or flexible materials, even textiles.

The third generation of photovoltaic cells is a research goal: a dramatic increase in efficiency that maintains the cost advantage of second-generation materials. The approaches include dye-sensitized nanocrystalline or Gratzel solar cells, organic polymer-based photovoltaics, tandem (or multi-junction) solar cells, hot carrier solar cells, multi-band and thermophotovoltaic solar cells.

This project is focused on multi-junction solar cells that use a combination of semiconductor materials to more efficiently capture a larger range of photon energies [11-15]. Depending on the particular technology, present-day multi-junction solar cells are capable of generating approximately twice as much power under the same conditions as traditional solar cells made of silicon.

Multi-junction solar cells have a highest theoretical limit of efficiency conversion as compared to other photovoltaic technologies [16-18]. A present-day record efficiency of 40.7% was achieved exactly with a multi-junction solar cell by Boeing Spectrolab Inc. in December 2006 [19].

At first, fundamentals of photovoltaics and the basic features of multi-junction solar cells will be described. Then, current solar cell design and performance will be presented, and future design improvements will be suggested, such as optimization of existing triple-junction design, increasing the number of junctions in a solar cell, or quantum dot incorporation into the layers.

Finally, the paper will conclude that multi-junction solar cells have a great potential not only for high performance space applications, - concentrators will be the platform for making these high-efficiency photovoltaic technologies cost competitive in terrestrial applications and enabling continuous cost reductions in the near future.

Fundamentals of photovoltaics

The solar spectrum in outer space resembles the theoretical radiation provided by a black body of 5900 K [20]. As the light passes through the atmosphere, some of the light is absorbed or reflected by gasses such as water vapour and the ozone. The spectrum of the sun’s light that reaches Earth's upper atmosphere ranges from the ultraviolet to the near infrared radiation, with peak region (48%) from 400 to 700 nm, which is the visible diapason (Figure 1).

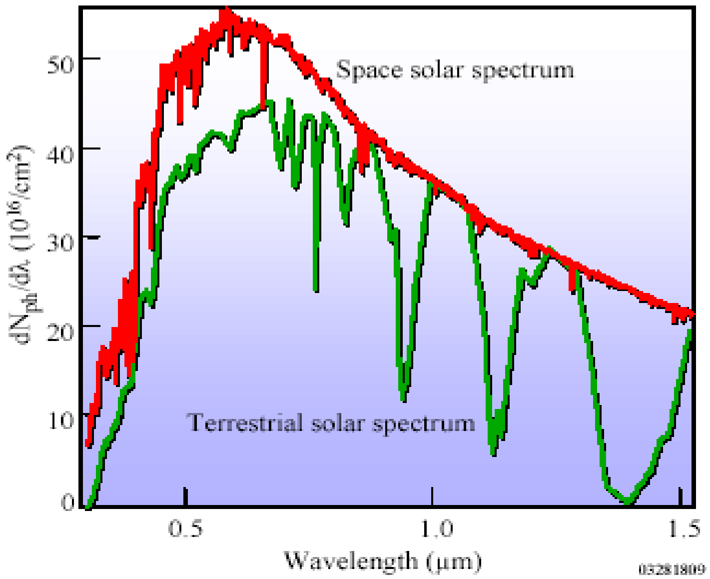


Figure 1. Terrestrial and space solar spectrum [14].

Photovoltaic cells can be defined as p-i-n photodiodes, which are operated under forward bias. They are designed to capture photons from the solar spectrum by exciting electrons across the bandgap of a semiconductor, which creates electron-hole pairs that are then charge separated, typically by p-n junctions introduced by doping. The space charge at the p-n junction interface drives electrons and holes in opposite directions, creating at the external electrodes a potential difference equal to the bandgap (Figure 2) [20-22]. A semiconductor can only convert photons with the energy of the bandgap with good efficiency. Photons with lower energy are not absorbed and those with higher energy are reduced to gap energy by thermalization of the photogenerated carriers.

Behaviour of a solar cell is represented by current versus voltage curves on Figure 3 [23]. The point at which a curve intersects the vertical axis is known as the short circuit condition, and it defines how the cell operates if a wire is connected between its terminals, shorting it out. The current flow here is known as **short-circuit current**, I_{sc}. For an ideal solar cell at most moderate resistive loss mechanisms, the short-circuit current and the light-generated current are identical. Therefore, the short-circuit current is the largest current which may be drawn from the solar cell [22].

The point at which a curve intersects the horizontal axis is known as the open circuit condition. The **open-circuit voltage**, V_{oc}, is the maximum voltage available from a solar cell, and this occurs at zero current. The open-circuit voltage corresponds to the amount of forward bias on the solar cell due to the bias of the solar cell junction with the light-generated current. V_{oc} depends on the saturation current of the solar cell and the light-generated current. Open-circuit voltage is then a measure of the amount of recombination in the device [22].

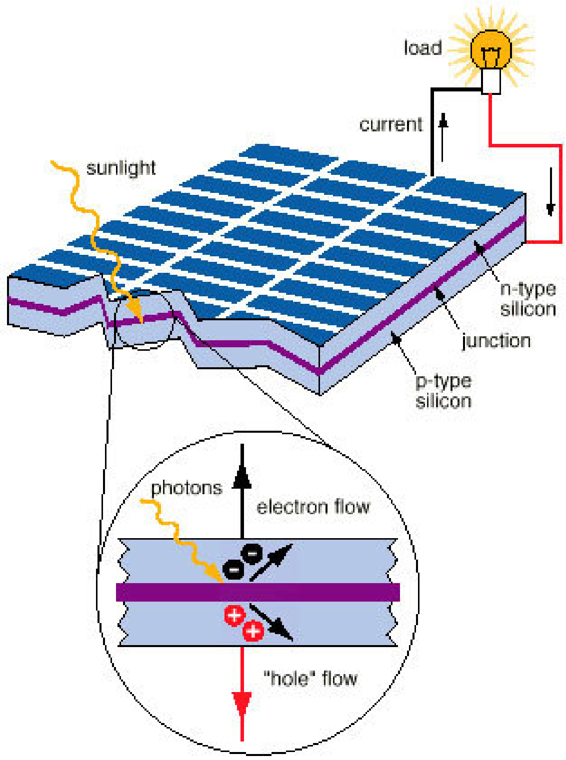


Figure 2. A diagram of a solar cell [23].

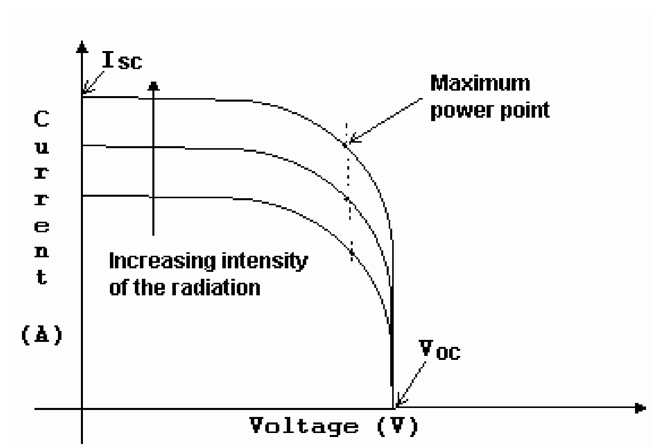


Figure 3. Characteristic I-V curves for a solar cell [23].

For each point on the graph, the voltage and current can be multiplied to calculate power. **Maximum power point** is the point on the I-V curve of a solar cell corresponding to the maximum output electrical power, $P_m[Watts] = V_{\max} \cdot I_{\max}$.

Maximizing total power is the goal of solar cell's design. Multi-junction photovoltaics, as compared to single-junction cells, have reduced currents, because fixed total number of photons is distributed over increasing number of cell layers, so that the amount available for electron promotion in any one layer is decreased. At the same time, the electrons excited are more energetic and have a greater electric potential, so the reduction of currents is compensated for by increase in voltages, and the overall power of the cell is greater. Moreover, multi-junction design is advantageous, because resistive losses, which are proportional to the square of the current, can be significantly reduced [6].

Another defining term in the overall behaviour of a solar cell is the **fill factor,** FF **.** This is the ratio that describes how close the I-V curve of a solar cell resembles a perfect rectangle, which represents the ideal solar cell: $FF = \frac{P_m}{V_{oc} \cdot I_{sc}}$.

Quantum efficiency is a term intrinsic to the light absorbing material and not the cell as a whole; it refers to the percentage of absorbed photons that produce electron-hole pairs. Whereas **energy conversion efficiency**, is the percentage of incident electromagnetic radiation that is converted to electrical power, when a solar cell is connected to an electrical circuit. This overall efficiency depends on many factors including the temperature, amount of incident radiation and the surface area of the solar cell [21].

Basic Principles of Multi-Junction Solar Cells

The highest-efficiency solar cells use multiple materials with bandgaps that span the solar spectrum. Multi-junction solar cells consist of some single-junction solar cells stacked upon each other, so that each layer going from the top to the bottom has a smaller bandgap than the previous, and so it absorbs and converts the photons that have energies greater than the bandgap of that layer and less than the bandgap of the higher layer [14].

Multi-junction solar cells experience a fundamental limitation relating to the availability of materials with optimal band gaps that simultaneously allow high efficiency through low defect densities. Alloys of groups III and V of the periodic table are good candidates for fabricating such multijunction cells: their bandgaps span a wide spectral range, and most of the bandgaps have direct electronic structure, implying a high absorption coefficient, and their complex structures can be grown with extremely high crystalline and optoelectronic quality by high-volume growth techniques [24-28]. Figure 4 shows the solar energy that can be theoretically used by single- and III-V triple - junction cells.

Multi-junction solar cells have been studied since 1960 [29]. The first multi-junction device was demonstrated in early 1980s, and it converted 16% of the solar energy into electricity [1]. In 1994, US National Renewable Energy Laboratory (NREL) broke the 30% barrier. A present-day record 40.7% efficiency was achieved with a triple-junction version of the cell [19]. The maximum theoretical limit efficiency of multi-junction solar cells is 86.8% [30].

Bandgaps

In order to optimize conversion efficiency of a photovoltaic cell, the solar cell should absorb as much of the spectrum as possible, and so bandgaps should cover a wide range. Besides, bandgaps of adjacent layers should differ by as small amount as possible, because the amount of excess energy from light converted to heat is equal to the difference between the photon energy and the bandgap of the absorbing material [21].

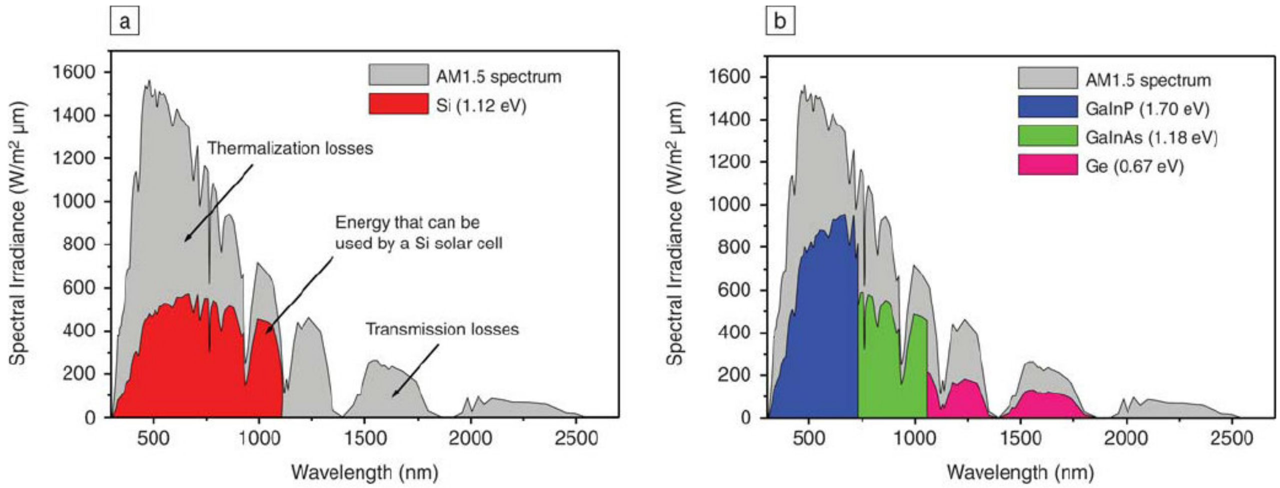


Figure 4: The AM1.5 solar spectrum[1] and the parts of the spectrum that can, in theory, be used by: (a) Si solar cells; (b) $Ga_{0.35}In_{0.65}P/Ga_{0.83}In_{0.17}As/Ge$ solar cells [25].

Dependency of the conversion efficiency on the semiconductor bandgap is shown on Figure 5. GaAs has nearly the optimal band gap (1.4 eV) for solar energy conversion in a conventional solar cell design, which is inherently limited to efficiencies of about 25% or less at one-sun concentration.

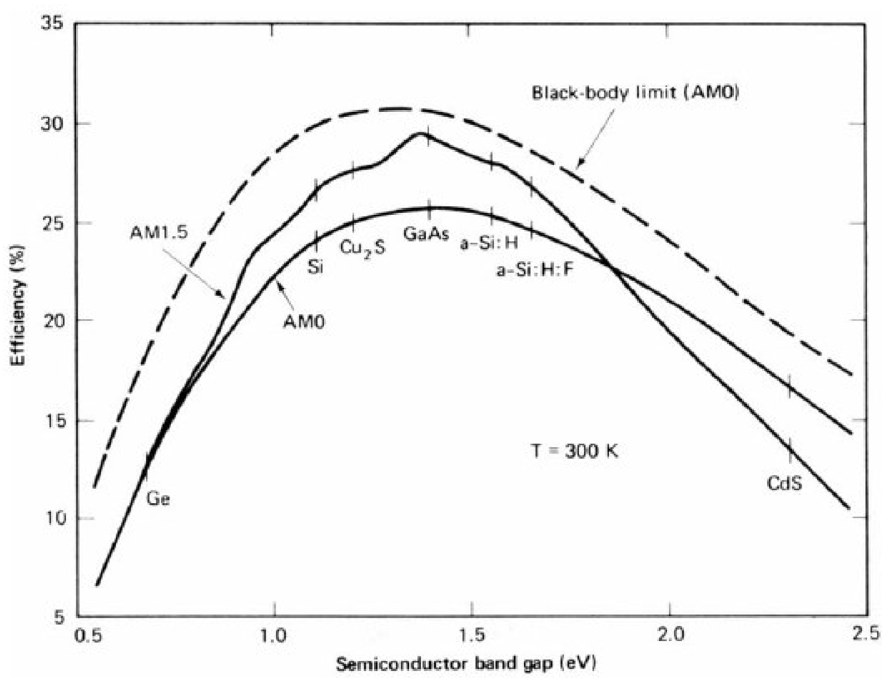


Figure 5. Dependency of the conversion efficiency on the semiconductor bandgap [26].

[1] An absolute air mass of 1.5 - this spectral distribution standard is typically used at the latitudes of northern Europe

Triple-junction solar cells currently in production are made of GaInP (1.9 eV), GaAs (1.4 eV), and Ge (0.7 eV); advanced multi-junction solar cell concepts foresee use of AlGaInP (2.2 eV), AlGaAs (1.6 eV), GaInP (1.7 eV), GaInAs (1.2 eV), GaInNAs (1.0-1.1 eV) [26].

For example, Spectrolab's record-breaking cell used $Ga_{0.5}In_{0.5}P$ (or $GaInP_2$) with bandgap energy of 1.85 eV and the lattice constant of 5.65 angstroms. Less gallium and more indium would be used in the compound, if a lower bandgap material were desired, up to the resulting InP with bandgap energy of 1.3 eV and the lattice constant of 5.88 angstroms. However, such an adjustment in bandgaps should be made in conjunction with lattice-constant constraints [14].

Lattice Constants

To produce optical transparency and maximum current conductivity in monolithic multijunction solar cells, where different semiconductor layers are grown directly on top of the other layers using the same substrate, all layers must have similar crystal structure. The lattice constant describes the spacing of the atom locations in a crystal structure. Mismatch in the crystal lattice constants of different layers creates dislocations in the lattice of the cell layers and significantly deteriorates the efficiency of the solar cell. NREL showed that a lattice mismatch as small as 0.01% significantly decreases the current produced by the solar cell [14]. The lattice constants and bandgap energies of common semiconductor materials are shown on Figure 6. Lines between different materials represent semiconductors that can be created by combining different amounts of the two materials. Ge, GaAs and AlAs have roughly the same lattice constant with different bandgaps, and compositions of these materials are currently used to create high-efficiency triple-junction cells [25].

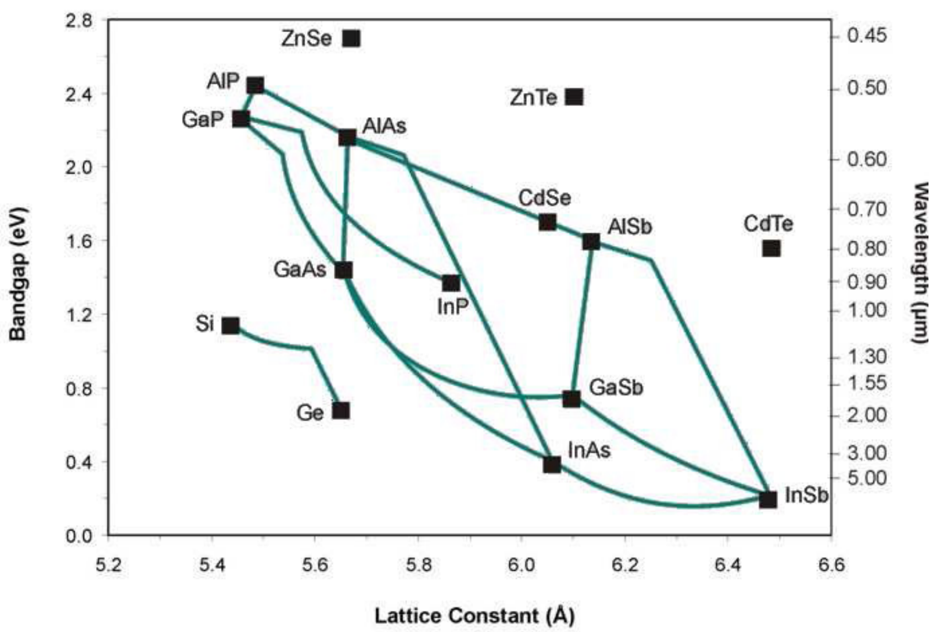


Figure 6: Ternary and quaternary III-V compounds relation between lattice constant and bandgap [25].

Current matching

The serial architecture of monolithically-grown multi-junction solar cells makes matching of currents a desirable characteristic [22]. The output current of the multijunction solar cell is limited to the smallest of the currents produced by any of the individual junctions. If this is the case, the currents through each of the subcells are constrained to have the same value. The current is proportional to the number of incident photons exceeding the semiconductor's bandgap, and the absorption constant of the material. A layer must be made thinner if the photons that exceed the bandgap are in abundance. At the same time, a layer with a low absorption constant must be made thicker, since on average a photon must pass through more of the material before being absorbed.

After materials are selected with desired bandgaps and lattice constants, the thickness of each layer must be determined based on the material's absorption constant and the number of incident photons with a given energy, so that each layer will generate the same photocurrent. The absorption constant for various semiconductors as a function of photon wavelength is shown on Figure 7.

The design of GaInP/GaAs/Ge solar cell implies a relatively thick Ge layer because of its lower absorptivity, while thickness of other layers differ: terrestrial and space versions of the cell vary to account for the different number of UV and near-IR photons for these two different environments [14].

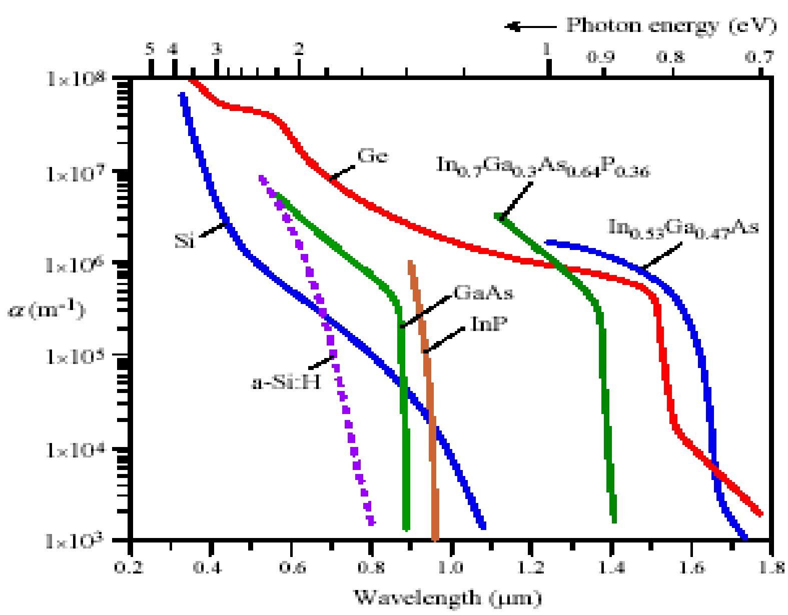


Figure 7: Absorption coefficient versus wavelength for various semiconductor materials [32].

Fabrication of Present-Day Multi-Junction Solar Cells

Multi-junction solar cells can be fabricated either by mechanical stacking of independently-grown layers, or each semiconductor layer can be monolithically grown on top of the other as one single piece by molecular organic chemical vapour deposition (MOCVD) or molecular beam epitaxy (MBE) [1, 33]. The mechanically stacking is a less-desirable method due to the bulkiness, additional expense, and heat-sinking [14]. MOCVD is preferable alternative to the MBE, because it is not only ensures high crystal quality throughout the device, but it is also easily scaled to large production capacities.

The transportation of electrons between layers in monolithic multi-junction solar cells is addressed using a tunnel junction, which is a stack of highly-doped layers, producing an effective potential barrier for both minority-carriers. The strong doping is necessary in order to have a thin depletion region, promoting tunneling across the junction and minimizing optical losses. Elements used as n-type dopants are S, Se, Te, Sn, Si, C, Ge, and p-type dopants are Zn, Be, Mg, Cd, Si, C, Ge, where the last three ones act as n-type or p-type if they replace a Ga or a As atom in the crystalline structure [25]. The antireflection coating is a broadband dual-layer dielectric stack, such as TiO_2/Al_2O_3, Ta_2O_5/SiO_2 or ZnS/MgF_2, whose spectral reflectivity characteristics are designed to reduce typically large reflectance (~30%) of the device in the spectral region of importance to <1%.

The most efficient present-day multi-junction photovoltaic cells are made of GaInP, GaAs, and Ge layers on Ge substrate. The principal scheme of such a triple-junction solar cell, usually containing about 20 layers, is shown on Figure 8. Quantum efficiencies of each layer of this cell are demonstrated on Figure 9 [14].

The first layer of this record-breaking cell is composed of GaInP (1.85 eV), converting short-wavelength portions of spectrum, such as blue and UV, the second GaAs-layer (1.42 eV) captures near-infrared light, and the third layer is made of Ge, effectively absorbs the lower photon energies of the IR radiation that are above 0.67 eV [26-28].

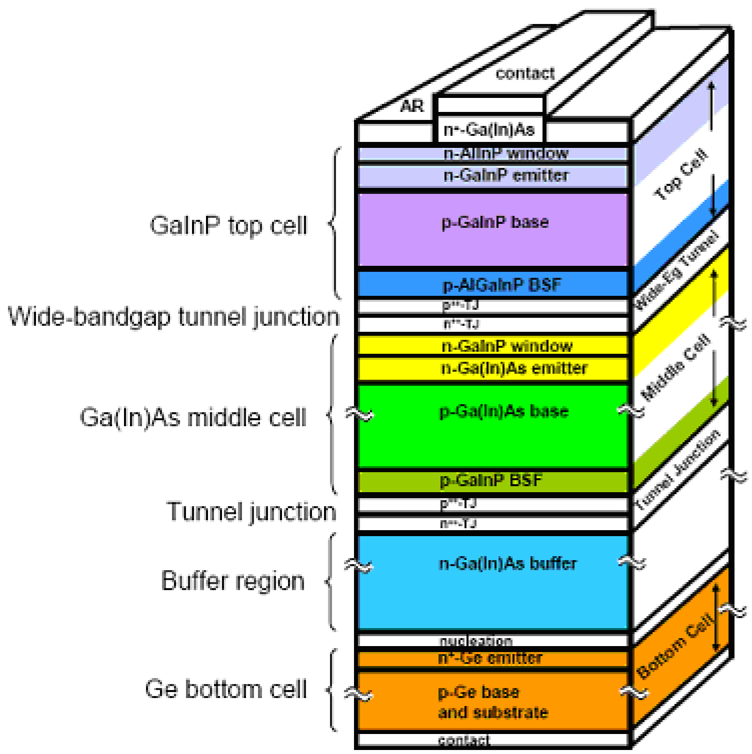


Figure 8: Structure of a triple-junction photovoltaic cell [34].

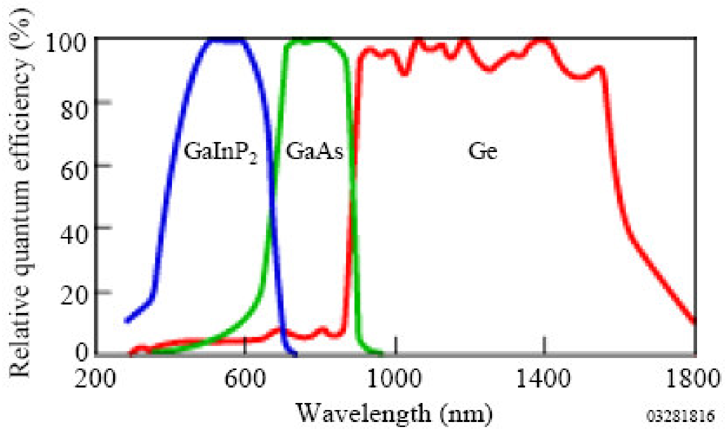


Figure 9: Quantum efficiency of each layer of a GaInP/GaAs/Ge triple-junction solar cell [14].

The energy of photons that have wavelengths below approximately 650 nm and pass through the GaInP into the GaAs layer is not being efficiently captured. A larger portion of the spectrum is absorbed by the Ge layer, since the difference between the bandgap of the top two layers is 0.4 eV while the difference between the bottom two layers is 0.7 eV. Layers in this configuration are lattice matched with one another [34].

In order to match currents among the layers, two variations of the layers' thicknesses exist: one with a thicker top cell for terrestrial applications and another is for the absorption of the greater amounts of high-energy photons in space.

The configuration of the record-efficient triple-junction Spectrolab's device is $Ga_{0.44}In_{0.56}P/Ga_{0.92}In_{0.08}As/Ge$. Its behaviour is represented by current versus voltage curve on Figure 10.

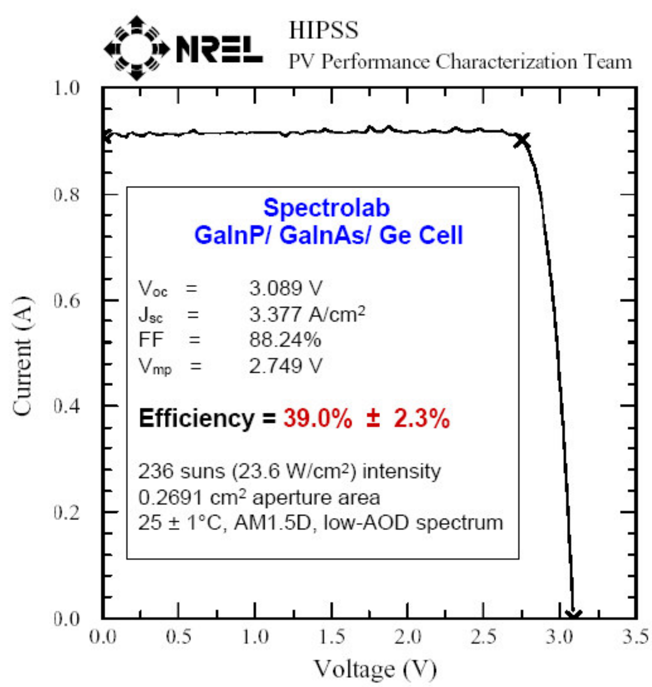


Figure 10. Performance characteristics of Spectrolab's GaInP/GaInAs/Ge solar cell [34].

Future Design Improvements

Design optimization of the existing layers

The efficiency of the present-day triple-junction solar cell can be improved by design optimization of each subcell.

In the past, triple-junction cell efficiency has been improved by using disordered GaInP instead of ordered as top cell material: disordered GaInP has the higher bandgap than ordered (1.88 eV vs. 1.78 eV) [27, 35].

Besides, the top GaInP layer could be thickened to increase its current production, so as the overall multi-junction cell would generate a higher matched current, and thus, more power [1].

An alternative to GaInP - top layer, $Al_{0.37}Ga_{0.63}As$ or AlGaInP with the bandgap of 1.98 eV can be used, which has the similar lattice constant and bandgap energy. In the past, the drawback for this approach was a high sensitivity of these materials to oxygen and water contamination, but recent results are promising [35-37].

The efficiency can be increased by replacing the GaAs layer with a 1.25eV-bandgap material: this second layer could collect a larger current, while reducing the number of photons transmitted to the Ge layer [27, 31].

Increasing the number of junctions

Another possible design improvement is to progress to devices with more junctions. Four-junction solar cells have been suggested using a material with a bandgap of 1.0 eV [1]. For this purpose GaInNAs is considered as the most studied and it can be grown lattice matched to Ge. Progress has been achieved with regard to reduction of background doping and of defect concentration by special growth and annealing conditions, but there is a problem of low current generation [12, 38]. Thus, present-day four-junction solar cells do not lead to higher efficiencies than triple-junction devices.

Five- and six-junction cell designs partition the solar spectrum into narrower wavelength ranges than triple-junction cells that allows all the subcells to be better current matched to the low-current-producing subcell [1, 27, 30]. Besides, the finer division of the incident spectrum reduces thermalization losses from electron-hole pairs photogenerated by photons with energy far above the bandgap energy, and the smaller current density in 5- and 6- junction cells lowers resistive losses [36]. Figure 11 shows design of 5- junction cells developed at Fraunhofer Institute for Solar Energy Systems.

Theoretical efficiency limits for multijunction devices based on thermodynamic fundamentals are 37, 50 and 56% for 1, 2 and 3 band gaps correspondingly [1, 31]. The improvement in efficiency on going from one to two or three band gaps is considerable, but, as Table 2 shows, the returns diminish as more junctions are added, so the practicality of the solar cell with more than four or five junctions is doubtful. However, theoretical studies show that efficiencies of up to 86.8% can be achieved using an infinite number of band gaps.

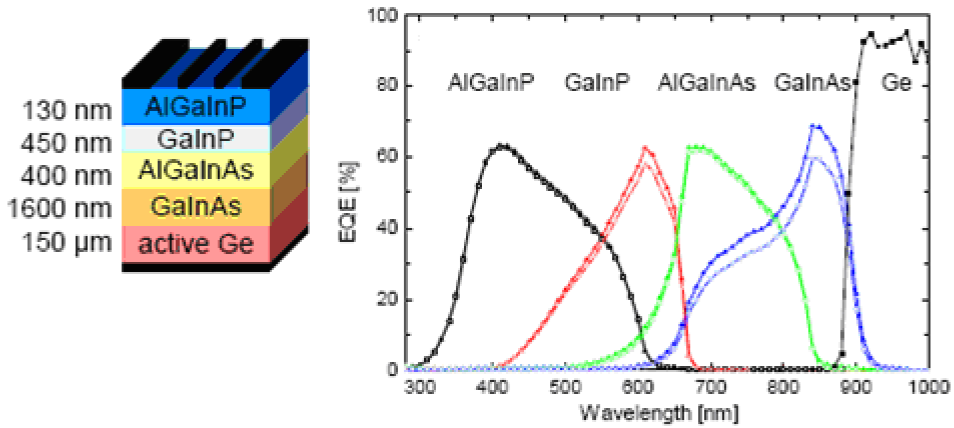


Figure 11: 5- junction cell design [39].

Table2 [31]

n	*Values of Band Gap (eV)*	*η %*
4	0.60, 1.11, 1.69, 2.48	62.0
5	0.53, 0.95, 1.40, 1.93, 2.68	65.0
6	0.47, 0.84, 1.24, 1.66, 2.18, 2.93	67.3
7	0.47, 0.82, 1.19, 1.56, 2.0, 2.5, 3.21	68.9
8	0.44, 0.78, 1.09, 1.4, 1.74, 2.14, 2.65, 3.35	70.2

Inclusion of semiconductor quantum dots

In recent years it has been proposed and experimentally verified that the use of nanostructures, such as quantum wells, quantum wires, superlattices, nanorods, or nanotubes, offer the potential for high photovoltaic efficiency by tailoring the properties of existing materials, and for reducing of cost using self-assemblance of nanostructures [40-49].

Semiconductor quantum dots (QD) are currently a subject of the most interest mainly due to their size-dependent electronic structures, and therefore tunable optoelectronic properties [50-52]. For example, corresponding effective bandgaps of InAs quantum dot with sizes 5 nm, 10 nm and 12 nm are 1.071 eV, 0.553 eV and 0.045 eV correspondingly [56].The quantized energy states of QDs can function as intermediate bands for efficient absorption of photons in the solar cell structure, and a mixture of quantum dots of different sizes can be used for harvesting the maximum proportion of the incident light. Theoretically, a single intermediate electronic band created by QDs would offer a 63.2% efficiency of an ordinary solar cell, which greatly exceeds the maximum conversion efficiency of 31% for even a single-junction device [43]. A system with an infinite number of sizes of QD has the same theoretical efficiency as an infinite number of band gaps or 86.8% [1].

As material systems for these QD, III-V-compound semiconductors and other material combinations such as Si/Ge or Si/Be Te/Se can be used [53-56]. Self-assembled QD can be grown by MBE providing high dot quality. By controlling growth temperature and rate, dot size and density can be controlled, leading to practical and desirable features for photovoltaic applications.

When quantum dots are formed into an ordered three-dimensional array, there will be strong electronic coupling between them so that excitons will have a longer life, facilitating the collection and transport of "hot carriers" to generate electricity at high voltage. In addition, such an array makes it possible to create more than one electron-hole pair from a single absorbed photon, and thus enhance photocurrent, through the process of impact ionization. This process happens when the energy of the photon is far greater than the semiconductor bandgap; while in bulk semiconductors the excess energy is simply dissipates away as heat, in QDs the charge carriers are confined within an infinitesimal volume, thereby increasing their interactions and enhancing the probability for multiple exciton generation. For example, in [57] it was demonstrated that ultraviolet-spectrum photons can release seven electrons with the use of 8nm lead selenide quantum dots.

In [52] it was shown by the example of InAs self-assembled QDs, incorporated into GaAlAs/GaAs heterostructure for solar cell applications, that an integration of QD into photovoltaic cell can provide an additional spectral response and stronger light absorption at long wavelength.

Moreover, quantum dots may offer improved radiation resistance and favourable temperature coefficients, which is very important for space applications [53-56].

The key challenges in inclusion of nanostructures in photovoltaic devices is that the design rules for achieving a high efficiency nanostructured solar cells are substantially different than for conventional devices, and many design parameters do not have sufficient theoretical or experimental guidance. Though I believe, the recent progress in investigation of nanomaterials and nanostructures will make a significant impact on developments in photovoltaics.

Concentrator Photovoltaics

Multi-junction solar cells are very expensive and firstly they were used only in space applications. Concentration of sunlight made these cells economically viable for the use on Earth [59-64].

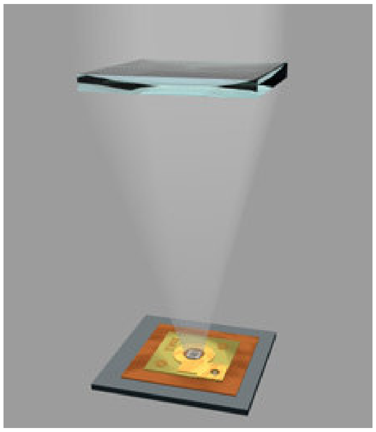
The key elements of a photovoltaic concentrator are low-cost concentrating optics (a system of lenses or reflectors) to focus sunlight on a small area of solar cells, mounting, single or dual-axis tracking to improve performance of the system, and high-efficiency solar cells. If the concentration factor is very high, then the cost of the solar cell is only a small part of system cost and therefore the cost of the cell is justified.

Concentrator operation well suited for multi-junction photovoltaic cells also because increasing the concentration ratio improves the performance of the photovoltaic cells even more. Theoretical maximum efficiencies of multi-junction solar cells without concentration and for concentration ratio of 500x are cited in Table 3 [31]. Additionally, high efficiencies can be maintained in multi-junction cells up to concentration levels exceeding 1000 sun [1].

Table 3 [31]

# junctions in solar cell	1 sun η	Max con. η
1 junction	30.8%	40.8%
2 junction	42.9%	55.7%
3 junction	49.3%	63.8%
∞ junction	68.2%	86.8%

The first concentrator photovoltaic system was proposed in the mid 1970's of by Sandia Labs. Despite the advantages of concentrating technologies, their application has been limited by the costs of focusing, tracking and cooling equipment. Optimization of a concentrator system is complex problem: as all its components like solar cells, optics and tracking systems have to be specifically optimized, and all the interactions have to be regarded.

a) 

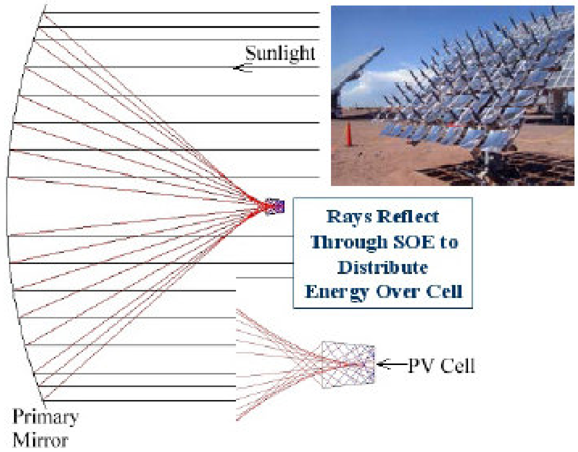
b) 

Figure 12: a) Concentrix concentrator using Fresnel lenses [65];
b) Spectrolab's reflective-optics concentrator module [64]**.**

Many large companies, such as Motorola, NREL, Boeing, Martin Marietta, Entech, Acurex and so on, tried their hand at developing cost-effective concentrator systems. At present, several effective concentrator designs are available: Amonix is installing 250x concentrators using Fresnel lenses; Solar Systems, Spectrolab and Concentrating Technologies are installing reflective dishes; SunPower is designing a high-concentration, thin (flat-plate-like) concentrator; the Ioffe and Frauhofer Institutes are developing a 130x glass-Fresnel concentrator [1]. Figure 12 shows two schemes of PV concentrators: Spectrolab's reflective-optics concentrator module, and the system of Concentrix Solar that use Fresnel lenses; both companies use III-V multi-junction solar cells.

Present-day commercially available silicon concentrator systems have reached efficiencies of 25%, while III-V based systems have reached about 32%. Figure 13 shows that concentrator photovoltaics can beat flat plate systems on cost by using high-efficient multi-junction solar cells.

On October 25, 2006, Australia announced that it would construct a largest - 154 MW - solar plant, using concentrator photovoltaic technology, to come online in 2008 and be completed by 2013. In March 2007, Delta Electronics of Taiwan has developed a manufacturing process for concentrating photovoltaic modules using the 40.7%-efficiency solar cells recently developed by Spectrolab, and their system is expected to boast greater than 35% efficiency [66].

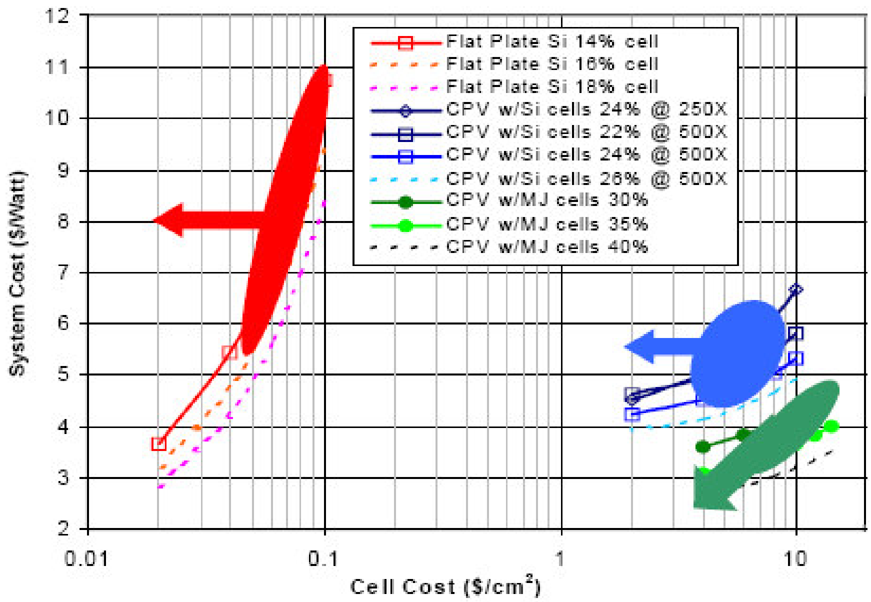


Figure 13: Flat-plate versus concentrator photovoltaics [34].

Conclusion

Projected global population and economic growth will more than double the energy consumption rate by the middle of 21th, and photovoltaics is expected to make a sizeable contribution, to world electricity production, reaching 65% portion in 2100 (Figure 14) [67].

At present, the most efficient photovoltaic cells use multiple III-V-semiconductor materials with bandgaps spanning the solar spectrum. Today, commercially available multi-junction photovoltaic devices are triple-junction solar cells made of GaInP, GaAs, and Ge layers that achieve typical conversion efficiencies above 30%. At present, only Emcore and Spectrolab in US and Aixtron in Germany are producing this type of cells in relatively large volumes.

One exciting aspect of multi-junction photovoltaics is that there are still many possibilities to explore. A current record efficiency of 40.7%, achieved with a triple-junction version of the cell, corresponds to less than a half of the maximum theoretical limit efficiency of 86.8% [17]. By the contrast, efficiencies of single-junction solar cells are almost reached their potential limits.

It was shown in this project, that the current design of multi-junction photovoltaics can be improved by design optimization of each layer, by increasing the number of junctions in a photovoltaic structure, or by inclusion of semiconductor quantum dots, which offer the potential for high conversion efficiency by tailoring the material properties of existing materials. Prospectively, the gap between the ideal and real values of the conversion efficiency is expected to decrease due to fundamental advances in understanding of materials behavior. New approaches and concepts, relying on phenomena allowed by nanotechnologies, may also revolutionize multiple junction devices by allowing control over band structure, growth, and defects. Besides, in order to apply multi-junction photovoltaics widely, it is necessary to develop a large-area, cost-effective, and highly reproducible fabrication processes.

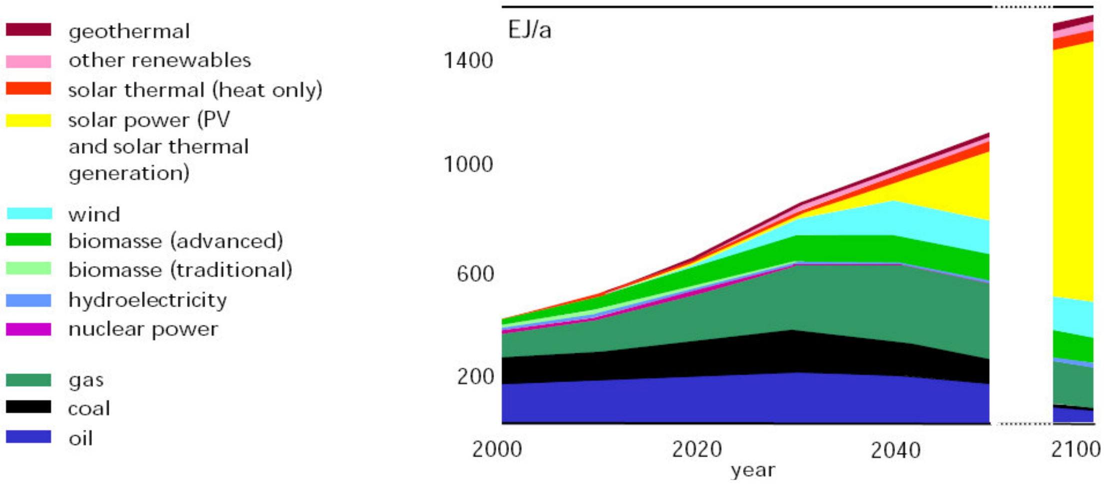


Figure 14: Global primary energy scenario by German Advisory Council on Global Change [67].

Solar electricity market installations reached a record high of 1,744 megawatts in 2006 [68]. Photovoltaic industry is growing >40% per year, and high-efficiency multijunction solar cells will help the solar industry grow even faster. On April 26, 2007, the Canadian Press has announced that California "OptiSolar" plans to will build Canada's largest solar farm near Sarnia, Ontario, installing more than 1 million photovoltaic panels to generate 40 megawatts of power. This company will be paid 42 cents per kilowatt-hour for the solar power. Though solar electricity is currently expensive, 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 [1, 19].

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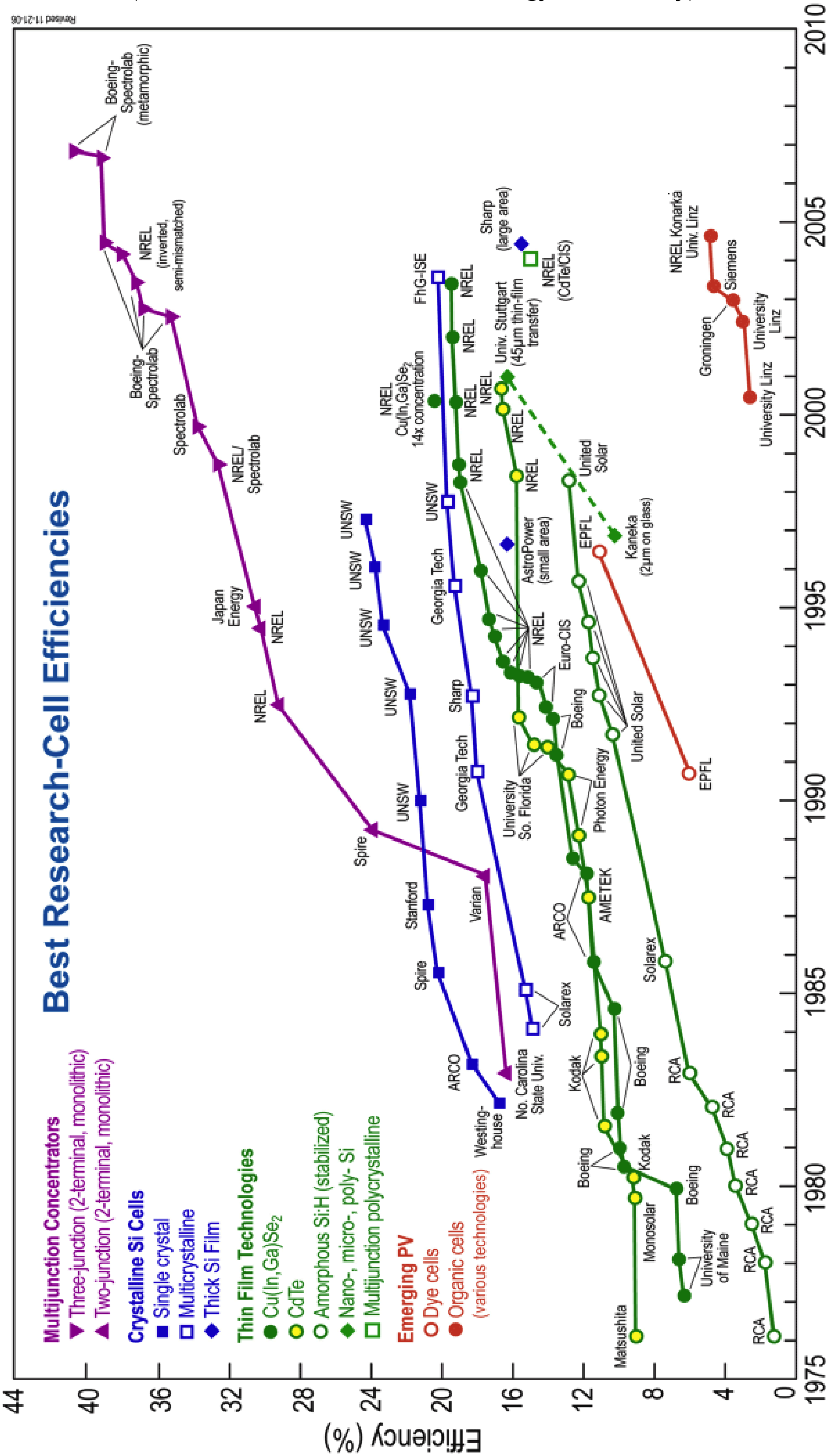
***Appendix 1:* Best research solar cell efficiencies**

(Source: National Renewable Energy Laboratory)



Appendix 2: Related patents

Date	Invention	Inventor	USA Patent #
July 6, 1982	Stacked multijunction photovoltaic converters	Antypas	4,338,480
Mar. 22, 1983	High efficiency thin-film multiple-gap photovoltaic device	Dalal	4,377,723
June 7, 1983	Tandem junction amorphous semiconductor photovoltaic cell	Dalal	4,387,265
Sep. 13, 1983	Ternary III-V multicolor solar cells and process of fabrication	Fraas	4,404,421
May 29, 1984	Three-terminal ternary III-V multicolor solar cells and process of fabrication	Fraas	4,451,691
Mar.11, 1986	Ternary III-V multicolor solar cells containing a quaternary window layer and a quaternary transition layer	Fraas	4,575,577
Dec. 3, 1986	High band gap II-VI and III-V tunneling junctions for silicon multijunction solar cells	Daud	4,631,352
Feb. 16, 1988	Process for the fabrication of a gallium arsenide grating solar cell	Fraas	4,725,559
May 15, 1990	Multiple junction solar power generation cells	Yamagishi	4,926,230
Apr., 1991	Tandem solar cell	Yoshida	5,009,719
May 28, 2001	Monolithic tandem solar cell	Wanlass	5,019,177
Sep. 21, 1993	Multijunction photovoltaic device and fabrication method	Arya	5,246,506
July 19, 1994	Gallium arsenide/aluminum gallium arsenide photocell including environmentally sealed ohmic contact grid interface and method of fabricating the cell	Chang	5,330,585
Apr. 4, 1995	Multijunction photovoltaic device and method of manufacture	Arya	5,403,404
Apr. 11, 1995	High efficiency multi-junction solar cell	Ho	5,405,453
Dec. 5, 1995	Method of producing solar cell	Matsuno	5,472,885
Nov. 13, 2001	Multijunction photovoltaic cell with thin 1st (top) subcell and thick 2nd subcell of same or similar semiconductor material	King	6,316,715
Jan. 22, 2002	Multijunction photovoltaic cells and panels using a silicon or silicon-germanium active substrate cell for space and terrestrial applications	King	6,340,788
Aug. 20, 2002	Solar cell having multi-quantum well layers transitioning from small to large band gaps and method of manufacture therefor	Tran	6,437,233
Feb.4, 2003	Solar cell having a three-dimensional array of photovoltaic cells enclosed within an enclosure having reflective surfaces	Aylaian	6,515,217
Sep. 12, 2003	Multi-junction photovoltaic cell	Patton	6,660,928
July 4, 2006	Method and apparatus of multiplejunction solar cell structure with high band gap heterojunction middle cell	Faterni	7,071,407