

# Space and Terrestrial Photovoltaics – Synergy and Diversity

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## ABSTRACT

A historical view of the research and development in photovoltaics from the perspective of both the terrestrial and the space communities is presented from the early days through the '70s and '80s and the '90s and beyond. The synergy of both communities in the beginning and once again in the present and hopefully future are highlighted, with examples of the important features in each program. The space community which was impressed by the light-weight and reliability of photovoltaics drove much of the early development. Even up to today, nearly every satellites and other scientific space probe that has been launched has included some solar power. However, since the cost of these power systems were only a small fraction of the satellite and launch cost, the use of much of this technology for the terrestrial marketplace was not feasible. It was clear that the focus of the terrestrial community would be best served by reducing costs. This would include addressing a variety of manufacturing issues and raising the rate of production. Success in these programs and a resulting globalization of effort resulted in major strides in the reduction of PV module costs and increased production. Although, the space community derived benefit from some of these advancements, its focus was on pushing the envelope with regard to cell efficiency. The gap between theoretical efficiencies and experimental efficiencies for silicon, gallium arsenide and indium phosphide became almost non-existent. Recent work by both communities have focused on the development thin film cells of amorphous silicon, CuInSe<sub>2</sub> and CdTe. These cells hold the promise of lower costs for the terrestrial community as well as possible flexible substrates, better radiation resistance, and higher specific power for the space community. It is predicted that future trends in both communities will be directed toward advances through the application of nanotechnology. A picture is emerging in which the space and terrestrial solar cell communities shall once again share many common goals and, in fact, companies may manufacture both space and terrestrial solar cells in III-V materials and thin film materials. Basic photovoltaics research including these current trends in nanotechnology provides a valuable service for both worlds in that fundamental understanding of cell processes is still vitally important, particularly with new materials or new cell structures. It is entirely possible that one day we might have one solar array design that will meet the criteria for success in both space and on the Earth or perhaps the Moon or Mars.

## INTRODUCTION

In 1839 Becquerel observed that a photovoltage resulted from the action of light on an electrode in an electrolytic solution. In the 1870s it was discovered that the solid material selenium demonstrated the same effect and by the early 1900s selenium photovoltaic cells were widely used in photographic exposure meters. By 1914 these cells were still less than 1% efficient. In 1954, Chapin reported a solar

conversion efficiency of 6% for a silicon single-crystal cell marking the beginning of modern day photovoltaics. At approximately the same time the first thin film solar cells of CdS/CuS<sub>2</sub> were being developed by the US Air Force Laboratory in Dayton, Ohio. These cells had an efficiency of ~1.5%. In 1955 the first III-V cells (GaAs, InP) were made and by 1956 GaAs had a reported efficiency of 6%. By 1958, small area Silicon solar cells had reached an efficiency of 14% under terrestrial sunlight. The big push to develop solar power, however, came from its obvious space application. On March 17, 1958 the world's first solar powered satellite was launched, Vanguard 1. It carried two separate radio transmitters to transmit scientific and engineering data concerning, among other things, performance and lifetime of the 48 p/n silicon solar cells on its exterior. The battery powered transmitter operated for 20 days; the solar cell powered transmitter operated until 1964, at which time it is believed that the transmitter circuitry failed. Setting a record at the time for satellite longevity, Vanguard 1 proved the merit of space solar cell power. The solar cells were fabricated by Hoffman Electronics for the U.S. Army Signal Research and Development Laboratory at Fort Monmouth. In 1961 many of the staff from the silicon cell program at Fort Monmouth transferred to NASA Lewis Research Center (now Glenn Research Center) in Cleveland, Ohio. From that time to the present, the Photovoltaic Branch at Glenn has served as the research and development base for NASA's solar power needs. Impressed by the light-weight and reliability of photovoltaics, almost all communication and military satellites and scientific space probes have been solar powered.

## **The Early Years**

As the first photovoltaic devices were being created there were corresponding theoretical predictions emerging citing ~20% as the potential efficiency of Si and 26% of an optimum bandgap material (1.5eV) under terrestrial illumination. In addition the concept of a tandem cell was proposed to enhance the overall efficiency. An optimized three-cell stack was soon to follow with a theoretical optimum efficiency of 37%. Research was focused on understanding and mitigating the factors that limited cell efficiency (e.g., minority carrier lifetime, surface recombination velocity, series resistance, reflection of incident light, and non-ideal diode behavior). However, it was pointed out that solar cells were too expensive to compete with fossil fuels for electricity, citing that a 10% efficient Si cell would cost \$357 per peak watt.

The launch of the USSR Sputnik in 1957 provided the missing application for solar cells and therefore, funding, for continued photovoltaic research. Early satellites needed only a few watts to several hundred watts. The power source must be available, reliable and ideally have a high specific power (W/kg) since early launch costs were ~ \$10K/kg or more. The cost of the power system for these satellites was not of paramount importance since it was a small fraction of the satellite and launch cost. The size of the array was important for many early satellites due to the body-mounted array design, therefore limiting total power. Thus there were multiple reasons to focus on higher efficiency solar cells. Explorer I launched in 1958 discovered the van Allen radiation belts, adding a new concern for space solar cells that was not present in the terrestrial environment (i.e., electron and proton irradiation damage). Radiation damage studies at the Naval Research Laboratories in the '60s provided guidance to the spacecraft designers with regard to cell degradation. The launch of Telstar in 1962 created new markets for space photovoltaics (i.e., terrestrial communications). Telstar's beginning of life (BOL) power was 14 W but high radiation caused by a nuclear weapon test reduced the power output.

There was a great deal of both theoretical and experimental research in the '60s. The early CdS/CuS<sub>2</sub> solar cells were found to degrade over time. CdTe cells were developed reaching efficiencies of ~ 7.5%. However, the higher efficiency and stability of the silicon solar cells assured their preeminence in satellite power for the next 3 decades. Research on thin film cells, because of their higher specific power and projected lower costs, was also funded at lower levels by the space

community. Aside from the cell response to a radiation environment, the goals of both the terrestrial and space community were the same.

### The '70s and '80s

As the '70s began, solar cells were still too expensive at around \$300/W for widespread terrestrial use. Nuclear power plants were being built for large power utilities. It was clear that the focus of the terrestrial community would be best served by reducing costs. This would include addressing a variety of manufacturing issues and raising the rate of production. Figure 1 shows PV module production and cost as a function of time from 1980 to 1999 (data courtesy of National Center for Photovoltaics Research).

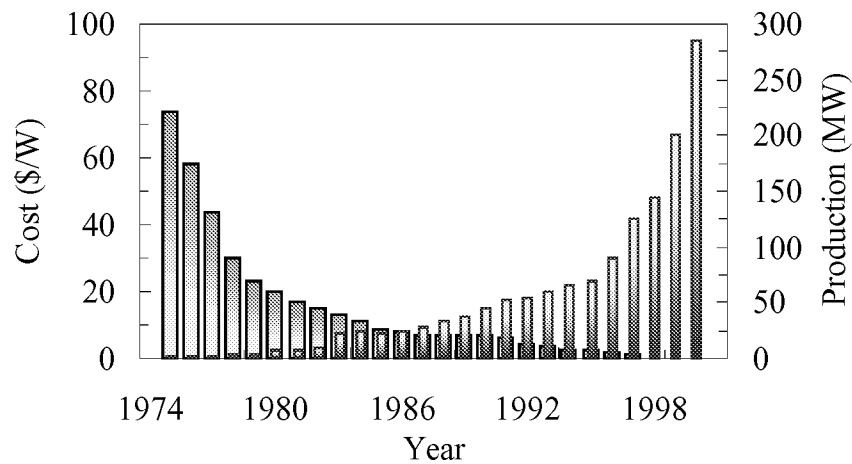


Figure 1. Photovoltaic cell cost and photovoltaics shipments per year from 1975 to 2000. (The wider bar shaded at the top are for cost and the narrow bars shaded at the bottom represent production).

The OPEC oil embargo of 1973 also provided impetus to the photovoltaic community. The US Solar Energy Research Institute in Golden Colorado was established. The DOE Photovoltaic Budget by fiscal year is shown below in Figure 2.

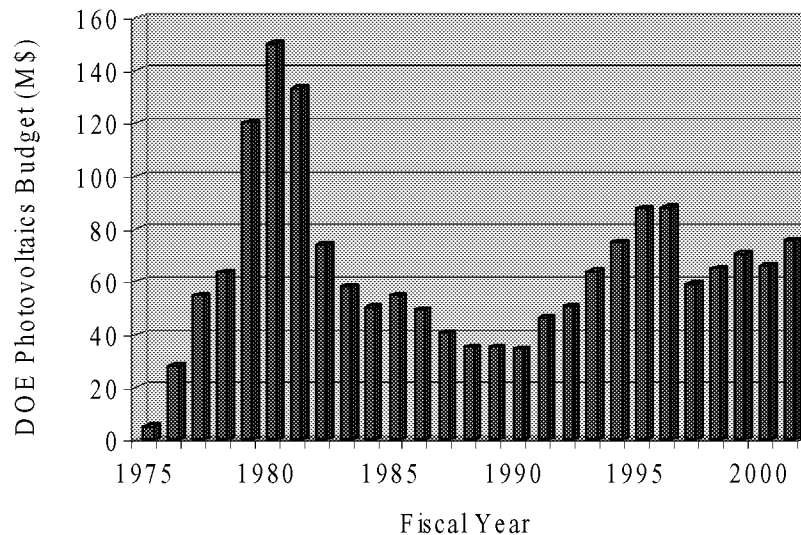


Figure 2. US Department of Energy Budget by Fiscal Year.

In the '80s other countries developed national programs in Photovoltaics. The increased funding in both photovoltaic research and in private industry yielded a substantial reduction in PV module costs from \$300/W in 1980 US dollars to \$5/W in 1990 US dollars and production increased by a factor of 4. The gap between theoretical efficiencies and experimental efficiencies for silicon, gallium arsenide and indium phosphide became almost non-existent (see Figure 3). New thin film cells of amorphous silicon,  $\text{CuInSe}_2$  and  $\text{CdTe}$  renewed the enthusiasm for the promise of lower costs for the terrestrial community and the potential for increasing the thin film efficiency and making them on flexible substrates excited the space community.

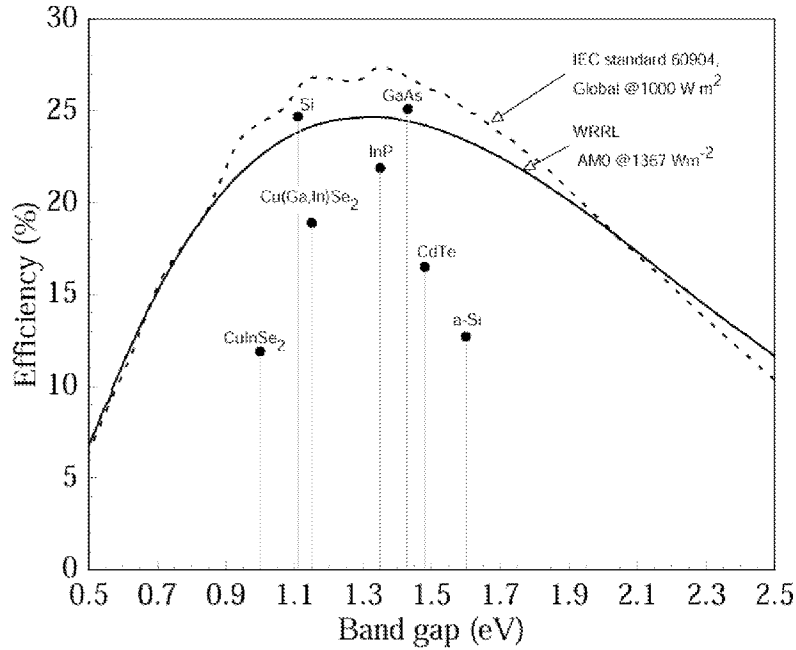


Figure 3. Theoretical efficiency for a single-junction cell with 100% external quantum efficiency as a function of energy gap at one-sun and 25 °C using the model described in reference 11. The standard global<sup>12</sup> and AM0<sup>13</sup> reference spectra are used. Independently confirmed efficiencies at one-sun, 25 °C global for several state-of-the-art single-junction solar cells are also shown for comparison purposes.<sup>14, 15</sup>

During these two decades silicon provided the power for space, culminating in the design of the solar arrays for Space Station, which became an International Space Station (ISS) in 1988, see Figure 4.

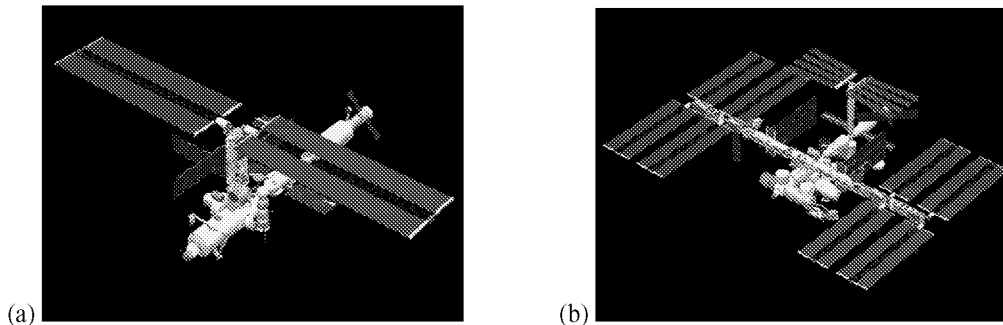


Figure 4. (a) Current status of ISS and (b) Planned Configuration of ISS by 2004.

The International Space Station will have the largest photovoltaic power system ever present in space. It will be powered by 262,400 (8cm x 8cm) silicon solar cells with an average efficiency of 14.2% on 8 US solar arrays (each ~ 34 m x 12 m). This will generate about 110 kW of average power, which after battery charging, life support, and distribution, will supply 46 kW of continuous power for research experiments. The Russians also supply an additional 20kW of power to ISS.

Research in the 80's however focused more on the III-V solar cells and multi-junction cells which had higher efficiencies and were more tolerant of the radiation environment. Satellites grew in both size and power requirements and structures were designed to deploy large solar arrays during this decade. However, the mass and fuel penalty for attitude control still dictated a move to more efficient cells. Costs for satellite power system remained at about a US\$1000/W.

### The '90s and beyond

In the terrestrial world, cost is still the driver in photovoltaic development, but more options seem imminent in the thin film systems. The smaller material costs and higher production potential for thin film arrays may drive PV modules below current costs with US\$1/W as a goal. This necessitates the development of a 20% thin film cell. The problem is more complicated for space applications since these cells must be developed on a low cost, light-weight flexible substrate with at least 15% air mass zero (AM0) efficiencies to be cost-effective for satellite power systems. The space world has transitioned to commercially available III-V cells with 24-26% AM0 of GaInP/GaAs/Ge. Tables I and II below list the current status of cell efficiencies for AM1.5 and AM0.

Cells	Efficiency(%) AM 1.5 global	Efficiency(%) AM 0	Area (cm <sup>2</sup> )	Description
c-Si	24.7		4.0	UNSW PERL <sup>16</sup>
c-Si	22.3	21.1	21.45	Sunpower <sup>16</sup>
Poly-Si	19.8		1.09	UNSW/Eurosolare <sup>16</sup>
Poly-Si	18.6	17.1*	1.0	Georgia Tech/HEM <sup>16</sup>
c-Si(thin film transfer)	15.3		1.015	U. Stuttgart (24µm thick) <sup>16</sup>
c-Si film	16.6	14.8*	.98	Astropower <sup>16</sup>
GaAs	25.1	22.1*	3.91	Kopin <sup>16</sup>
GaAs	23.8	20.7	4.0	ASE Heilbronn <sup>17</sup>
InP	21.9	19.3*	4.02	Spire <sup>16</sup>
GaInP (1.88ev)	14.7	13.5	1.0	ISE <sup>17</sup>
GaInP/GaAs/Ge	31.0	29.3	.25	Spectrolab <sup>18</sup>
GaInP/GaAs/Ge	25.0	21.7*	4.0	ASEC <sup>17</sup>
Cu(Ga,In)Se	18.8	16.4*	1.04	NREL, on glass <sup>16</sup>
CdTe	16.4	14.7*	1.131	NREL, on glass <sup>16</sup>
a-Si/a-Si/a-SiGe**	13.5	12.0	.27	USSC <sup>16</sup>
Photo-electrochemical	10.6	9.8*	.25	EPFL,nanocrystalline dye <sup>16</sup>

The efficiency and Jsc for global reference conditions (25°C, 1000 W/m<sup>2</sup>, IEC 60904-3, ASTM E892 global) were taken from the references and translated to AM0 using the new ASTM E490-2000 reference spectrum. The calculated efficiency assumes that the fill factor does not change for the increased photocurrent. Quantum efficiencies corresponding to the table entries were used in the calculations.

\*\* unstabilized

Table I. AM1.5 and AM1.0 Efficiencies for Small Area Cells

Module	Efficiency (%) Global AM1.5	Area (cm <sup>2</sup> )	Description
c-Si	22.7	778	UNSW?Gochermann <sup>16</sup>
multi-c-Si	15.3	1017	Sandia/HEM <sup>16</sup>
CIGSS	12.1	3651	Siemens Solar <sup>16</sup>
CdTe	10.7	4874	BP Solarex <sup>16</sup>
a-Si/a-Si/a-SiGe	10.4	905	USSC <sup>16</sup>
photochemical	4.7	141.4	nanocrystalline dye sub module <sup>16</sup>

Note: that an approximate conversion from global AM1.5 to AM0 depends on cell type and ranges from 0.87 for GaAs and CIGS to 0.945 for crystalline Si and GaInP/GaAs/Ge. The assumed intensities are 1000 W/m<sup>2</sup> AM1.5 and 1367 W/m<sup>2</sup> AM0 at 25 °C for both.

Table II. AM1.5 Efficiencies for Modules.

Research in the III-V multi-junction solar cells has been focused on fabricating either lattice-mismatched materials with optimum stacking bandgaps or new lattice matched materials with optimum bandgaps. In the near term this will yield a 30% commercially available space cell and in the far term possibly a 40% cell. Cost reduction would be achieved if these cells could be grown on a silicon rather than a germanium substrate since the substrate is ~65% of the cell cost. The advent of this new competitor in 1998 and other factors combined to reduce space cells costs by ~40% of their 1997 cost. A few possible cell structures for future III-V devices are illustrated in Figure 5.

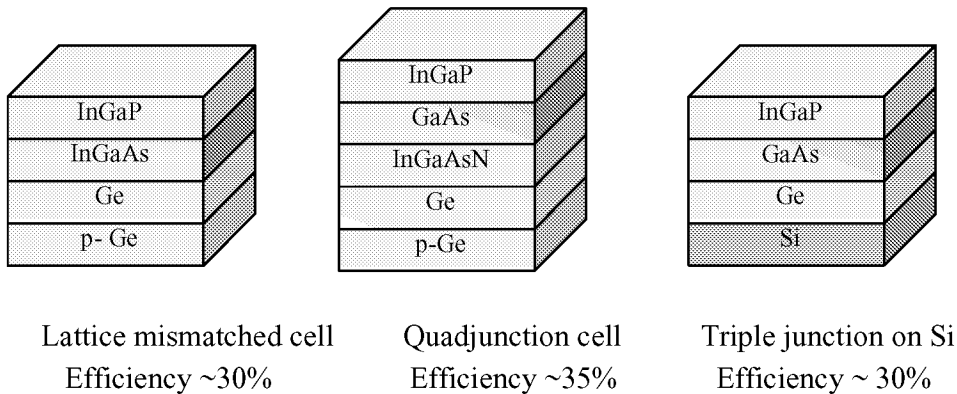


Figure 5. Proposed structures for III-V tandem cell development

The problem areas with projected III-V cell development include the material growth difficulty of the InGaAsN 1.05 eV bandgap material, minimizing defect growth in lattice mismatched material, and current limiting in the Ge subcell.<sup>19</sup> Other approaches using GaAs substates (higher cost and efficiency), mechanical stacking, or 3 and 4-terminal monolithic designs are also being pursued. Longer-term projects in the area of multi-junction III-V cells would include the potential of growing these cells on a low cost ceramic substrate and the possibility of efficiency enhancement by nano-structures. With a recurring interest in terrestrial concentrators, once again the space community and terrestrial community may also have common goals for high efficiency III-V cells.

A recent USAF driven initiative has renewed interest in thin film array development for space. The program addresses the concern of higher efficient cells on flexible substrates and also the development of light-weight array structures. An example of a large structure for solar electric propulsion is shown below in Figure 6.

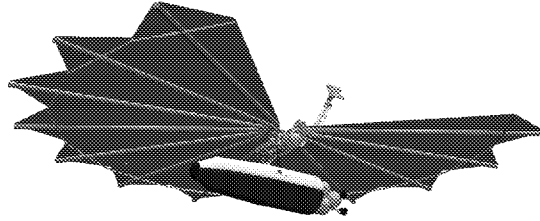


Figure 6. Proposed Mars solar electric propulsion vehicle

Spacecraft systems studies which consider the system level implications of increased array area indicate that thin film cells of less than 15 to 20 % efficient would not be cost effective except for certain applications which might involve a high radiation environment, or a stowage volume problem in the launch configuration, or perhaps a unique spacecraft configuration. This is due to a variety of possible cost considerations including array development, spacecraft attitude control,

Current terrestrial thin film programs will benefit the space community as manufacturing techniques are improved bringing the small area cell efficiencies in Table I closer to the large area modules in Table II. The Space community requires that thin film cells must be produced on a lightweight substrate due to the mass penalties imposed in launching. The best thin film cells to date have required processing temperatures in excess of 600°C, which prohibit the use of current polyimide substrates. Research has focused on both finding high temperature tolerant substrates and on reducing the processing temperature of the thin film cells. A low cost flexible substrate would also benefit the terrestrial community by replacing the expensive and fragile heavy glass structures.

Clearly, the ability to increase thin film cell efficiencies would impact both the terrestrial and space cell communities. Semiconductor quantum dots are currently a subject of great interest by both communities. This is mainly due to their size-dependent electronic structures, in particular the increased band gap and therefore tunable optoelectronic properties. A quantum dot is a granule of a semiconductor material whose size is on the nanometer scale. These nanocrystallites behave essentially as a 3-dimensional potential well for electrons (i.e., the quantum mechanical “particle in a box”). To date these nanoparticles have been primarily limited to sensors, lasers, LEDs, and other optoelectronic devices. However the unique properties of the size dependent increase in oscillator strength due to the strong confinement exhibited in quantum dots and the blue shift in the band gap energy of quantum dots are properties that can be exploited for developing photovoltaic devices that offer advantages over conventional photovoltaics. The increased oscillator strength of the quantum dots will produce an increase in the number of photons absorbed and consequently, the number of photogenerated carriers. On the other hand, the blue shift in the band gap energy allows for engineering an ensemble of quantum dots in a size range that will capture most of the radiation from the terrestrial and space solar energy spectrum (see Figure 7a).

There have been several proposed methods to improve solar cell efficiency through the introduction of quantum dots. One of the main methods is to produce an ordered array of quantum dots within the intrinsic region of a p-i-n solar cell (see Figure 7b). The overlap of the discrete wavefunctions associated with the electronic states of the individual dots will produce narrow electronic energy bands or “mini-bands.” By adjusting the dot size and spacing, a device can be manufactured such that these mini-bands will lie energetically between the valence and conduction bands of the host semiconductor, or in other words within their bandgap. The quantum dots in an intermediate bandgap solar cell can be thought of as an array of semiconductors that are individually size-tuned for optimal absorption at a desired region

of the solar energy emission spectrum. This is in contrast with a bulk material where photons are absorbed at the band gap and energies above the band gap where the photogeneration of carriers is less efficient. In addition, bulk materials used in solar energy cells suffer from reflective losses at energies about the band gap, whereas for individual quantum dots reflective losses are minimized. It is also predicted that quantum dot solar cells may have other attractive features for space utilization (i.e., high radiation tolerance and small temperature coefficients). To a first approximation the energy levels of quantum dot structures are temperature independent. In fact thermal energy assists in populating those levels. This implies a lower temperature coefficient than a normal pn-junction solar cell. Unfortunately, it is difficult to estimate the potential temperature range due to the temperature dependence of other cell components.

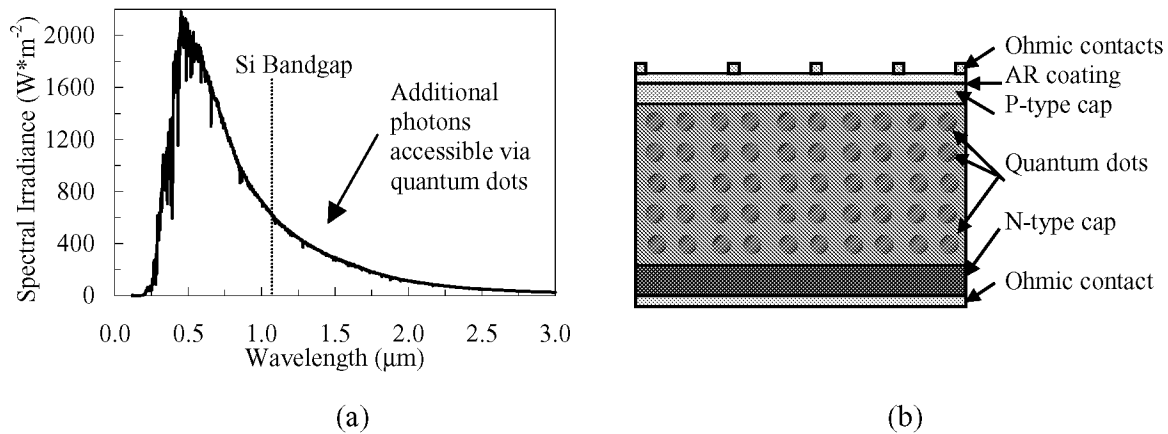


Figure 7. a) Air mass zero spectrum (ASTM E-490) and (b) proposed quantum dot solar cell structure.

Including graded quantum dots in a solar cell offers the opportunity to engineer the band gap energy of a solar cell over a wide range, thereby maximizing the capability of the emitted photons of the sun's spectrum to photogenerate carriers. Theoretical studies predict a potential efficiency of 63.2 %, for a single size quantum dot, which is approximately a factor of 2 better than any state-of-the-art (SOA) device available today.<sup>20</sup> For the most general case, a system with an infinite number of sizes of quantum dots has the same theoretical efficiency as an infinite number of bandgaps or 86.5%.<sup>20</sup> Furthermore, the use of quantum dot technology is also applicable to thin-film devices offering a potential 4-fold increase in power-to-weight ratio over SOA thin film cells.

## Conclusions

A picture of the future is emerging in which the space and terrestrial solar cell communities shall once again share many common goals and, in fact, companies may manufacture both space and terrestrial solar cells in III-V materials and even thin film materials. The research community provides a valuable service for both worlds in that fundamental understanding of cell processes is still vitally important, particularly with new materials or new cell structures. It is entirely possible that one day we might have one solar array design that will meet the criteria for success in both space and on the ground on Earth or perhaps the Moon or even Mars.



## References

- [1] Becquerel E. (1839), *On electron effects under the influence of solar radiation*, Comptes Rendues 9, 561.
- [2] Chapin D.M., Fuller C.S., Pearson, G.L. (1954), *A new silicon photocell for converting solar radiation into electrical power*. J. Appl Phys. 25, 676.
- [3] Reynolds D.C., Leies G., Antes L., Marburger R.E. (1954), *Photovoltaic effect in cadmium sulfide*, Phys. Rev. 96, 533.
- [4] Jenny D.A., Loverski J.J., Rappaport P. (1956), *Photovoltaic effect in GaAs p-m-junctions and solar energy conversion*, Phys. Rev. 101, 1208.
- [5] Easton R.L., Votaw M.J. (1959), *Vanguard I IGY Satellite (1958 Beta)*, Rev. of Scientific Instruments, 30, 2, pp. 70-75.
- [6] Loeferski J.J. (1956), *Theoretical considerations governing the choice of the optimum semiconductor for the photovoltaic solar energy conversion*, J. Appl. Phys. 27, 777.
- [7] Jackson E.D. (1955), *Areas for improvement of the semiconductor solar energy converter*. Trans. Of the Conf. On the Use of Solar energy, Tucson, Arizona, 5, 122.
- [8] Cherry W. (1955), *Military considerations for a photovoltaic solar energy converter*, Trans. of the Conf. On the Use of Solar energy, Tucson, Arizona, 5, 127.
- [9] Statler R.L., Curtin D.J. (1973), *Silicon solar cell degradation in the space environment*, Proc. International Conf. On the Sun in the Service of Mankind, p. 361.
- [10] *The Telstar Experiment* (1963), Bell Syst. Tech. J. 42.
- [11] M.W. Wanlass, K.A. Emery, T.A. Gessert, G.S. Horner, C.R. Osterwald, and T.J. Coutts, "Practical Considerations in Tandem Cell Modeling," Proc. SERI 9th Photovoltaics Advanced Research and Development meeting, May 24-26, 1989, Solar Cells, vol. 27, pp. 191-204, 1989.
- [12] M.A. Green and K. Emery, D.L. King, S. Igari, and W. Warta "Solar Cell Efficiency Tables (version 19)," Progress in Photovoltaics Research and Applications, vol. 10, pp. 55-61, 2002.
- [13] W. E. Devaney, R. A. Mickelsen, and W. S. Chen, "Recent improvements in CuInSe<sub>2</sub>/ZnCdS thin film solar cell efficiency," presented at Eighteenth IEEE Photovoltaic Specialists Conference, Las Vegas, NV, p. 1733, 1985
- [14] Standard IEC 60904-3, Measurement Principles for Terrestrial PV Solar Devices with Reference Spectral Irradiance Data, International Electrotechnical Commission, Geneva, Switzerland.
- [15] Wehrli C, Extraterrestrial Solar Spectrum, Physikalisches-Meteorologisches Observatorium and World Radiation Center, Tech. Report 615, Davos-Dorf, Switzerland, July 1985
- [16] M.A. Green and K. Emery, D.L. King, S. Igari, and W. Warta "Solar Cell Efficiency Tables (version 18)," Progress in Photovoltaics Research and Applications, vol. 9, pp. 287-293, 2001.
- [17] K. Bücher, S. Kunzelmann, "The Fraunhofer ISE PV Charts: Assessment of PV Device Performance," Proc. 2nd World Conference and Exhibition on Photovoltaic Solar Energy Conversion, Vienna Austria July 6-10, 1998, Joint Research Center report EUR 18656, pp. 2329-2333.
- [18] M.A. Green, K. Emery, K. Bücher, D.L. King, and S. Igari "Solar Cell Efficiency Tables (version 11)," Progress in Photovoltaics: Research and Applications, vol. 6, pp. 35-42, 1998.
- [19] R.R. King, M. Haddad, T. Isshiki, P. Colter, J. Ermer, H. Yoon, D.E. Joslin, and N.H. Karam, "Metamorphic GaInP/GaInAs/Ge Solar Cells," 28<sup>th</sup> IEEE Photovolt. Specialist Conference, Achorage, AK, 2000.
- [20] A. Luque and A. Marti, *Phys. Rev. Lett.* **78**, 5014 (1997).