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Space Applicable DOE Photovoltaic Technology — An Update

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ABSTRACT

An examination of the main terrestrial photovoltaic development projects (LSA and Concentrator), as well as the research sponsored by the Solar Energy Research Institute has been performed. Technologies that have applicability to space power are identified. When appropriate, the type of NASA support that would be necessary to implement these technologies for space use is indicated. It is concluded that the relatively small market and divergent operational requirements for space power are mainly responsible for the limited transfer of terrestrial technology to space applications.

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INTRODUCTION

This report is an update of a study performed to identify photovoltaic technology being developed by the Department of Energy, which has the potential to be applicable to the needs of the space power program. Future space missions using solar electric propulsion or involving orbiting power modules, space processing, communications satellite platforms and space based radar, will require sources capable of delivering 25 to 100 kW. Presently, photovoltaic energy conversion remains the best choice for providing these levels. Thus, there is a strong stimulus to gain the cost and technological advantages offered by the DOE terrestrial photovoltaics program.

The original report concluded that little technology then being developed by the DOE could be considered for space applications. The reasons for this conclusion, some rather subtle, were not fully developed. In addition, some potentially beneficial activities had not reached a state of maturity sufficient to allow a meaningful assessment of their utility for space power needs to be made. The purpose of this report is to update the investigation of maturing and newly developed terrestrial photovoltaic technology deemed potentially useful for space power needs, and to provide more information on the factors which control the cost and type of photovoltaic technology considered to be applicable for space utilization.

Besides examining the LSA and Concentrator Projects managed respectively by the Jet Propulsion Laboratory and Sandia Laboratories, the activities sponsored by the Solar Energy Research Institute (SERI) will be surveyed for the first time. At SERI the emphasis is oriented towards the next generation of terrestrial modules using new semiconductor materials and innovative processing. Thus it would not be expected that near term applicable technology for space would be identified. However, it is worth reporting the strategy SERI has adopted and the trends that seem to be taking shape in this effort.

OPERATIONAL REQUIREMENTS

The technology and materials used in any system will be critically influenced by operational requirements. Cells and modules used in space must possess a unique set of characteristics. Radiation tolerance, low outgassing, ultraviolet stability and the ability to withstand thermal cycling over a wide temperature range (-180 to +150°C) are some of the more basic requirements. Reliability is a critical concern because module maintenance cannot be performed during the mission. Weight is very important because of the vehicle launch capability. Efficiency and radiation tolerance are maximized to keep the size and mass of the solar panel from placing undue constraints on mission duration or limiting the satisfactory operation of the other satellite subsystems. For most current space missions, the cost of the solar array is not a limiting factor.

The terrestrial environmental requirements are different from those of space. In a few cases such as humidity, thermal cycling and ultraviolet exposure, there is some limited degree of commonality. The humidity environment is of critical importance for terrestrial operation since exposure is continuous. For space it is of concern only prior to launch. The temperature extremes and the rate at which they are achieved is much less severe for terrestrial applications, although the 20 year lifetime requirement for the modules does result in thousands of such cycles. In the case of ultraviolet exposure the magnitude and distribution of energy is different because of the influence of the atmosphere.

Uniquely terrestrial requirements include impact resistance, wind loading, resistance to atmospheric pollutants and protection against vandalism and wildlife. Presently, such needs are met by the design of relatively massive and fully enclosed modules. This runs counter to the weight concerns of space application. Balance of system costs place a fairly high premium on module efficiency which is in concert with space power needs. Cost is a critical requirement for terrestrial photovoltaics because the module is the main element of the system. Based on these observations, it can be seen why much of the terrestrial technology being developed cannot be considered for space power needs.

COST FACTORS

The cost of space qualified solar arrays is approaching $1000/watt, while the solar cell has exceeded $100/watt. The relatively small market for arrays coupled with the unique requirements of space missions is largely responsible for this situation. The strong demand for reliability acts as an additional constraint to the implementation of lower cost technology. In a typical space satellite, the array subsystem makes up a small fraction, (<5% typically) of the entire system cost. Generally, new technology is only implemented when absolutely necessary for the success of the mission objective.

It is estimated that a three orders of magnitude increase in the market for space solar arrays would create a situation resulting in a cost reduction of a factor of 30 without any major changes in the materials or processes currently employed. This is illustrated in Table 1. It is assumed that the increased demand would lead to array standardization and a realignment of the organizational structure presently responsive to the space market. Automation would result, of necessity, provided that the increased demand were anticipated to extend for a number of years.

On a dollar per watt basis, the cost of space qualified arrays would be approximately a factor of three greater than today's terrestrial modules, the difference being largely due to the cost of materials used. It should be noted that the present terrestrial market is at least an order of magnitude lower than that used in this model, and therefore even lower costs for terrestrial photovoltaics would be anticipated. However, the differential would still be primarily due to materials cost.

As high production volumes and automation reduce overhead and labor costs, the module cost more nearly reflects the cost of materials utilized, so that ultimately the minimization of those costs must be considered. As addressed by the DOE effort, these reductions can be achieved either through a reduction in the quantity of materials used (e.g., sheet silicon) or through the use of less expensive materials (copper as a replacement for silver contacts, low cost polysilicon). The extent of these reductions and replacements will depend mainly on the constraints impressed upon the system by environmental concerns.

In some areas such as low cost polysilicon development, two divergent directions can be considered. If the cost of silicon is not reduced significantly, terrestrial efforts would likely move in directions parallel to space type cell needs; i.e., thin, high efficiency devices. If, however, success is achieved in reducing the cost of silicon, then less emphasis on near term

Table 1

SPACE POWER COSTS ($/WATT) FOR TWO ANNUAL DEMAND LEVELS

Cost Element	50 kW	50 MW	Notes
Cell			
Materials	10	5	Yield increase (50 to 95%)
Labor	20	1	Yield, automation
Overhead	50	-0-	Integration of suppliers
G & A	12	-0-	Integration of suppliers
Profit	18	-0-	Integration of suppliers
Array			
Materials	100	5	Yield, automation, integration (excludes cells)
Handling	20	0.5	Volume, standardization
Labor	50	5	Automation
Engineering	30	0.3	Standardization
Tooling	30	0.3	Standardization, volume
Inspection & Test	40	0.2	Standardization, automation
Overhead	180	7	Volume, but increased depreciation (150 to 100%)
G & A	110	1.2	Volume, market stability (20 to 5%)
Profit	130	1.2	Volume, decreased risk
TOTAL	800	25.7	

silicon utilization reduction would be expected. This in turn will have an impact on processing technology developments. Thus, the development of a very low cost, relatively impure polysilicon, would probably completely separate a terrestrial and space cell industry.

It is concluded that until there is a significant increase in the demand for space solar arrays, very little incentive will exist to reduce cost by replacing the present "space qualified" materials and processes with lower cost substitutes. Based on this observation, this report will concentrate on innovations in technology which might improve the performance characteristics of the space array without increasing risk.

LSA PROJECT

The substantial cost difference between today's space and terrestrial cells means that progress in developing low cost polysilicon and sheet material will have a much greater overall impact on the cost of terrestrial cells which already benefit from the reductions brought about by volume, low cost processes and improved yield. To illustrate this, it will be assumed that DOE developed low cost polysilicon and silicon sheet suitable for space needs are available. The cost of terrestrial cells would be cut in half from the present \$6-8/watt and the reduction at the module level would be 25 percent. In contrast, the cost of space cells might be reduced by 25 percent, but the overall cost savings at the module or panel level would be less than 5 percent! For this reason, the materials portion of the LSA cost reduction effort is not emphasized in this report.

Dendritic web grown silicon still appears to be the one materials oriented DOE technology that has potential for space. This technique allows very thin (50-150 μm) silicon to be grown, of interest to space because of the trend towards thinner (50-200 μm) solar cells. Data is available to show that dendritic web cells can be made with high efficiencies (13-14% AMO)[1]. Other silicon sheet technologies do not offer the combined thickness and efficiency advantages, but the significant progress made in some areas [2,3] warrants continued NASA monitoring. The success of certain ingot technologies has increased DOE attention to developing improved as well as lower cost silicon slicing technology. If this effort proves successful, the technology will be commercially available and the space cell suppliers will have the option to purchase the more efficient slicing machines.

Since the initial report on this subject, many innovative processes for fabricating solar cells have been reduced to practice. Some have the potential to enhance the space solar cell suppliers' capability to produce thin cells at acceptable (cost effective) yields. Another benefit is that these processes eliminate many "wet chemical" operations involving organic solvents and acids. This is very important due to the growing national concern about atmospheric pollution, worker safety and industrial waste disposal. Consideration of these new processing approaches is warranted in order to avoid the possibility that environmental concerns may, in the future, severely compromise the ability of the suppliers to produce solar cells for space use. Ion implantation,[4] chemical vapour deposited (CVD) coatings and plasma etching[5] are DOE developed technologies which can improve the yield for very thin (<100 μm) silicon cells and eliminate the need for such potential hazards as acids and solvents.

Ion implantation is capable of "tailoring" the dopants used to form silicon junctions. This flexibility can produce cells with sophisticated dopant gradients and junction structures not possible by means of conventional gaseous diffusion techniques. This could yield space cells with higher efficiency and increased radiation resistance. Within the last two years, ion implanted back surface fields in silicon solar cells have been demonstrated.[6] This could eliminate a major obstacle to the production of thin, high efficiency space cells at a high yield.

CVD coatings have been shown to be suitable as antireflection coatings and contact definition masks.[7] The process by which the coating mask is applied and removed would eliminate the use of large quantities of organic solvents. This technology is automated, well controlled and could offer many advantages over the present techniques used to fabricate space cells. CVD coatings offer a potential solution to the wraparound contact isolation problem. This process could foster an economic approach to the employment of photolithography for cell contacts. Plating in conjunction with CVD coatings could increase the utilization of the precious metals now used for space cells.

Plasma etching appears to be very compatible with thin cell fabrication. Breakage caused by interactions with liquid interfaces, common in standard processing, would be eliminated along with the chemicals responsible for this situation. Any etching operation employing acids could be replaced by this automated process, eliminating labor and materials cost. Since metal masks are quite suitable for plasma etching, new methods of forming sophisticated contact configurations can be considered. Implementation of cost effective methods for producing more efficient contact patterns on space cells would result in higher power output. Even without the potential advantages described previously, plasma etching is an attractive alternative to standard space cell processing because of the elimination of wet chemicals and the problems associated with their use.

Terrestrial contact systems and the application methods are varied. Based on cost, it appears that plated systems are best. A number of plated contact systems have been developed which have sufficient adherence and reliability to warrant investigation for space application. The current DOE activities are concentrated on eliminating the need for precious metals such as silver. The rapid fluctuations in the cost of this metal, which is used for all space cells, has already created some problems for space cell manufacturers. The DOE work indicates that nickel or copper may be an adequate substitute for silver, and plated contact systems based on these metals have been developed. [8,9] This is an area of technology which would benefit space power needs if NASA were to demonstrate that copper or nickel based contact systems could meet the qualification requirements now mandated for space applications.

Since the initial study, certain aspects of DOE developed photovoltaic technology have been incorporated by space cell manufacturers. Not unexpectedly, because of risk, only process innovations have been utilized. Laser scribing, developed by DOE, is presently being used in the processing of cells for space. Of even greater significance, space cell processing is now keyed to large area rectangular or circular wafers which are subsequently cut to final size, demonstrating the appreciation of a basic concept (economy of size) fostered by the DOE terrestrial photovoltaics program.

The basic strategy employed to assemble terrestrial modules is based on encapsulation technology which reduces material and labor costs. Unfortunately, the processes and materials now used are not compatible with the environmental and weight requirements of space power. The reasons for this situation were discussed in great detail in the original report. Perhaps the major obstacle to implementation of the approach used for terrestrial module fabrication is the lack of a space worthy encapsulant. The encapsulants now used for terrestrial applications are sensitive to ultraviolet radiation, although some progress has been made in incorporating ultraviolet screening agents into the encapsulants[10]. This is an area that could have a substantial impact on space module fabrication costs and the efforts now being undertaken by DOE merit close attention.

There are other areas of module assembly technology that should be monitored for future application. Automated equipment to accurately locate and interconnect terrestrial cells is being developed for DOE by various organizations.[11,12] As this effort matures, it may be possible that such equipment could be modified to perform certain space panel (module) assembly operations. As predicted in the initial report, there is growing interest in considering welded rather than soldered interconnects for terrestrial modules. Preliminary work has begun to investigate the suitability of ultrasonic welding for use with dendritic web cells.[13] These activities should be closely monitored.

CONCENTRATOR PROJECT

A significant portion of this effort has been devoted to systems design and in particular, structural designs, needed to provide high solar concentration and accurate sun tracking. Accomplishments in concentrator cell performance have been impressive; 20 percent for silicon cells at 30 suns incidence[14] and nearly 25 percent for AlGaAs at 180 suns.[15] Since these measurements are made at a fixed temperature (27°C) and under terrestrial sunlight, it is not possible to accurately equate these reported efficiencies to space (AMO) sunlight conditions.

Present trends are towards operation at very high concentrations, up to 1000 suns for AlGaAs, thus requiring very efficient active cooling techniques and highly specialized solar cell designs. For space, much lower concentration levels (2-100 suns) are being considered, with emphasis on low mass structures and controlled array/vehicle dynamic interactions.

Due to the very high terrestrial concentration range desired, significant differences in cell design are evolving. The two critical aspects of cell design for concentrator use are operating temperature, and device series resistance. The former is controlled by cooling designs, active or passive. The latter involves a number of parameters in the cell design. In particular, lower resistivity silicon material becomes advantageous. In other cases at high concentrations, injection effects will alter the basic conductivity mechanism in the cell to effectively lower cell resistance. The result is to yield cells which are very sensitive to particulate radiation, or may not operate efficiently at lower concentrations. So, independent from concern regarding the mass and structural dynamics of large concentration ratio systems, which tend to be disadvantageous for space use, cell designs are not optimized for use in practical space concentrator designs. As a result, direct transfer of structures or cells will be highly unlikely.

However, a review of the program indicates a number of technology areas that may be useful for space. The high concentration cell requires a strong emphasis on a very low resistance contact system, one which does not mask significant amounts of active cell area. This can be satisfied by the use of very small area cells or the development of advanced gridline and conductor concepts. Both are being examined with examples including high aspect metal line formation,[16] and vertical multiple junction cells.[17]

The vertical multiple junction (VMJ) concept has been examined for space use because its particular geometry seemed capable of improved radiation resistance compared to planar devices. Unfortunately, the cell that evolved was a modified, although easier to fabricate, version and additional problems associated with space requirements prevented its implementation.[18] The terrestrial VMJ cell employs a configuration favorable for radiation resistance. This structure, made in p-type bulk silicon, could prove useful for space because of its potential for radiation tolerance and better efficiency at higher levels of solar concentration.

The study of advanced concepts and devices such as spectrum splitting [19] and monolithic cascade junction cells,[20,21] since they encompass newly developed technology, may provide benefits for space, inasmuch as these areas are new and will offer greater chances for providing "breakthroughs" than the highly mature silicon technology. Beam splitting involves using a dichroic filter to separate the incoming sunlight into energy bands that can be much more effectively utilized by the two different cell types used. This concept, employed with GaAs and silicon cells, has achieved a system efficiency well in excess of what could be expected by using either cell alone.[22] The ability of current dichroic filter materials to survive the space environment is questionable, as is the prospect for achieving in space the very high concentration ratios required to make this approach effective.

The cascade, or series connected multiple junction cell, is another method of separating and more efficiently employing the incoming solar spectrum. By vertically coupling cells made from materials with varying bandgaps, it is possible to achieve extremely high conversion efficiency per unit of active area. Theory predicts that 2 junction devices are capable of 25 percent AMO and 3 junction devices can exceed 30 percent. Further discussion of the progress in this technology is provided in the next section of this paper.

On a cost per unit area basis, concentrator cells can be relatively expensive, since the advantage in their use involves very high concentration. In fact, terrestrial concentrator cells are in some cases nearly equal in cost to space solar cells. Cost reduction at the cell level is not as critical an issue as with unconcentrated (flat plate) photovoltaic modules. For example, if 1000 sun concentration levels were implemented, the number of cells required for a 50 MW annual market would be approximately equal to the present yearly demand for space solar cells ($\sim 10^6$ 2 x 2 cm cells). Therefore, it is more likely that high performance and innovative technology benefits for space will occur from this effort.

SERI

A significant amount of DOE resources has been committed to the development of semiconductor materials which have the potential to reduce the cost of terrestrial photovoltaics to well below the 1986 target goal of 70 cents (1980$) per peak Watt. The strategy adopted implies that thin film or very high efficiency (>20 per AMO) cells are the goal. Since these objectives are in concert with space power needs (low weight, low cost, high efficiency), it is important that this "long range" research and development be carefully monitored by NASA.

The technology being developed in these "long range" programs may appear, at first glance, to be incompatible with space power needs. Trade off studies involving cost, panel fabrication techniques, weight and end of life performance will be required in order to accurately assess the utility of many technologies now being pursued by SERI. Since this program is a long range effort, it will probably be 3 to 5 years before SERI developed technology warrants any in-depth NASA trade-off studies.

Four areas are being emphasized in this program; emerging materials, high efficiency concentrator cells, amorphous silicon and thin film polycrystalline materials. Emerging materials are defined as semiconductor compounds such as cadmium telluride (CdTe), indium phosphide (InP) and zinc phosphide (Zn_3P_2) which have the potential to achieve terrestrial sunlight efficiency greater than 10 percent. This work is at a very preliminary stage, and it will probably be a few years before any serious consideration of its potential for space can be made.

The concentrator part of the program does seem to be, in some respects, directly applicable to space. In fact, two of the main concepts, cascade [23] and vertical multijunction solar cells,[18] have been supported for space use. All of the approaches taken depend on achieving very high efficiency ($\sim$20 percent AMO) at concentration levels of at least 100 suns. It is not known if such a scheme would be suitable for space due to systems constraints such as pointing accuracy and attitude control. There is, however, a new space power concept employing cassegrain optics operating at fairly high concentration (100 suns)[24] which could directly benefit from this DOE activity.

Cascade cells are being investigated for use in high concentration systems, but this device is capable of achieving very high efficiency under one sun illumination. The principle of the cascade junction cell has been recently demonstrated. A cell based on the AlGaAs/GaAs structure has been produced which has an AMO efficiency greater than 15 percent (without an antireflection coating) and of more importance, an open circuit voltage exceeding 2.0 volts, thus proving cascade action.[23] Much work remains to be done in optimizing this device, but based on present progress; it shows promise for space power applications. A secondary benefit for space resulting from this research is the additional knowledge gained concerning methods to better understand and control such sophisticated materials growth techniques as liquid phase epitaxy, organo-metallic chemical vapour deposition and molecular beam epitaxy. This information will support the present space oriented research in gallium arsenide and other compound semiconductors.

Two other technologies receiving attention are beam splitting and vertical multiple junction solar cells. Both approaches were originally developed to support the Sandia managed concentrator program. Efforts are now being undertaken by SERI to improve the materials and device fabrication techniques in order to achieve higher efficiency. Details and a discussion of the potential of these technologies for space were provided in a previous section of this report.

Major emphasis is being given to research and development of amorphous (α) silicon. This material is believed to be capable of achieving better than 10 percent (AM1) efficiency, and since only a micron layer of silicon is needed, the cost potential is most attractive. Currently, the technology is in a tremendous state of flux. Cells with approximately 6 percent efficiency in terrestrial sunlight have been achieved.[25] There are questions concerning device stability and no general consensus concerning the principle of operation. A great deal of the progress made to date is based on empirical approaches. At this time α-silicon cannot be considered applicable for space. The long term potential as far as cost and weight certainly exist, but it would be premature to adopt any position concerning future applicability until the technology stabilizes.

The polycrystalline thin film materials portion of the program is divided into research addressing silicon and cadmium sulfide based compounds.

The silicon work is focused on approaches to developing epitaxially grown layers onto low cost substrates and to producing sheet material by novel processes. Epitaxial silicon cells were previously investigated by NASA [26] and the JPL managed LSA Project. [27] The present work has achieved some success in that cells with terrestrial sunlight efficiencies in the range of 10 percent have been produced. More time is necessary before a realistic assessment of space applicability can be made. At present, the innovative sheet silicon technologies under development have not been shown to be competitive on an efficiency or cost basis to dendritic web silicon.

During the 1960s, NASA committed significant resources to the development of thin film CdS solar cells because of their cost, weight and efficiency potential. Failure to achieve high efficiency coupled with a lack of stability led to the termination of this effort. The present DOE sponsored program has encountered similar difficulties although a new cell using a heterojunction composed of $CuInSe_2$ on CdS has yielded a terrestrial sunlight efficiency approaching 10 percent.[28] Until a major improvement in CdS based cell stability is demonstrated, this technology can not be considered applicable for space use.

SUMMARY AND CONCLUSIONS

Table 2 summarizes those elements of DOE photovoltaic technology development identified as most likely to be applicable to future space power needs. Many other areas have high potential for space use provided that DOE continues its present level of support. An estimate of when the selected elements will become available for NASA implementation is provided, as well as the type of benefit anticipated for space power. If additional support from NASA is estimated to be necessary, this is noted, with a recommendation of the area in which this support should be applied.

The conclusions of the original report remain unchanged. Terrestrial photovoltaic technology will not have a major impact on space power cost because of the divergent operational requirements of space and terrestrial photovoltaic power systems. As long as the space power market remains low volume and risk dominated, it will not fully benefit from the lower cost and innovative technology offered by the terrestrial photovoltaics program.

Table 2

SPACE APPLICABLE DOE TECHNOLOGY

Technology	Availability (yrs)	Benefit	NASA Input
Dendritic Web Silicon	3-5	Cell Weight	Development & Environmental Testing
Ion Implantation	3-5	Cell Weight & Performance	Research & Development
CVD Coatings	0	Cell Weight, Environmental	
Plasma Etching	1-2	Cell Weight, Environmental	
Plated Contact Systems	1-2	Cell Cost	Environmental Testing
Encapsulants	2-4	Panel Cost	Environmental Testing
Welded Interconnects	2-4	Panel Weight & Performance	Environmental Testing
VMJ Cell	1-2	Cell Performance	Development & Testing
Cascade Cell	5-10	Cell Performance	Development & Testing

REFERENCES

1. Applied Solar Energy Corp., "Silicon Solar Cell Process Development, Fabrication and Analysis," JPL Contract 955089, (1980).

2. Mobil Tyco Solar Energy Corp., "Large Area Silicon Sheet by EFG," JPL Contract 954355, (1980).

3. Crystal Systems, Inc., "Silicon Ingot Casting - Heat Exchanger Method (HEM)," JPL Contract 954373, (1980).

4. Spire Corp., "Development and Fabrication of a Solar Cell Junction Processing System," JPL Contract 955640, (1980).

5. Coleman, M. G., Grenon, L. A. and Hild, N. R., "Environmental Control: An Evaluation of the Economic and Ecological Requirements for the Silicon Photovoltaic Industry," 14th IEEE PVS Conf., p. 1042, Jan. (1980).

6. Lockheed Missiles and Space Co., Inc., "Evaluation of Laser Annealing for Solar Cell Junction Formation," JPL Contract 955696, (1981).

7. Motorola Inc., "Phase 2 of the Automated Array Assembly Task of the Low-Cost Silicon Solar-Array Project," JPL Contract 954847, (1980).

8. Coleman, M. G., Pyror, R. A. and Sparks, T. G., "The Pd_2Si-(Pd)-Ni-Solder Plated Metallization System for Silicon Solar Cells," 13th IEEE PVS Conf., p. 597, June (1978).

9. Coleman, M. G., Pryor, R. A. and Sparks, T. G., "A Base-Metal Conductor System for Silicon Solar Cells," 14th IEEE PVS Conf., p. 793, Jan. (1980).

10. U. of Massachusetts, "Polymeric UV Absorbers," JPL Contract 955531, (1980).

11. Kulicke and Soffa Industries, Inc., "Automated Solar Module Assembly Line," JPL Contract 955287, (1980).

12. MB Associates, "Automated Solar Module Production," JPL Contract 955699, (1980).

13. Westinghouse Electric Corp., "Silicon Dendritic Web Material Process Development," JPL Contract 955624, (1980).

14. Rodriguez, J. L. and Sexton, F. W., "Design, Fabrication and Performance of a 20 Percent Efficient Silicon Solar Cell," Sandia Report 80-2225, Oct. (1980).

15. Cape, J. A., et al., "Gallium Arsenide Photovoltaic Dense Array for Concentrator Applications," Sandia Report 78-7056, Dec. (1980).

16. Grenon, L., "Silicon Concentrator Solar Cell Manufacturing Development," Sandia Report 80-7018, May (1980).

17. Allendorf, G., et al., "High Concentration Silicon Photovoltaic Cell Development," Sandia Report 80-7068, June (1980).

18. Lindmayer, J. and Wrigley, C., "New Developments in Vertical-Junction Solar Cells," 12th IEEE PVS Conf., p. 30, Nov. (1976).

19. Vander Plas, H. A. and Gregory, P. E., "Further Development of a Novel Solar Cell Concentrator Photovoltaic Converter System," Final Report SAND 80-7072, May (1980).

20. Bedair, S. M., et al., "Recent Progress in the Development of the Cascade Solar Cell," 14th IEEE PVS Conf., p. 337, Jan. (1980).

21. Zehr, S. W., Cape, J. A. and Harris, Jr., J. S., "Performance Losses in High-Efficiency Monolithic Multijunction Solar Cells," 14th IEEE PVS Conf., p. 346, Jan. (1980).

22. Moon, R. L., et al., "Multigap Solar Cell Requirements and the Performance of AlGaAs and Si Cells in Concentrated Sunlight," 13th IEEE PVS Conf., p. 859, June (1978).

23. Bedair, S. M., "Fabrication of AlGaAs/GaAs Cascade Solar Cell by LPE," Space Photovoltaic Research and Technology 1980 Conference, NASA Conf. Pub. 2169, p. 157, Oct. (1980).

24. Patterson, R. E., et al., "High Efficiency, High Concentration Ratio, Solar Cell Array," 16th Intersociety Energy Conversion Engineering Conference, Aug. (1981).

25. Carlson, D. E., et al., "Amorphous Thin Films for Solar-Cell Applications," 4th Annual Photovoltaic Advanced Research and Development Conference Abstracts, SERI/CP-611-956, p. 101, Nov. (1980).

26. RCA Laboratories, "Epitaxial Solar Cell Fabrication," NASA Contract NAS3-19401, June (1977).

27. RCA Laboratories, "Epitaxial Film Growth on Low-Cost Silicon Substrates," JPL Contract 954817, (1978).

28. Buldhaupt, L. F., Mickelsen, R. A. and Chen, W. S., "Cadmium Sulfide/Copper Ternary Heterojunction Cell Research," 4th Annual Photovoltaic Advanced Research and Development Conference Abstracts, SERI/CP-611-956, p. 119, Nov. (1980).

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