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# Review of Photovoltaic Research in the U.S.

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## ABSTRACT

This paper describes U.S. research efforts to develop new generations of photovoltaic technologies having the potential for lower cost and better performance than the older generations of crystalline silicon technologies. The newer generations consist primarily of single and multi-junction thin film devices destined for either flat plate or concentrator photovoltaic systems. The principal sponsors for the research are the U.S. Department of Energy, U.S. photovoltaic companies, the Electric Power Research Institute, and those U.S. government agencies interested in the use of photovoltaics in space. The paper concludes with a description of future research activities in the areas of amorphous silicon, polycrystalline thin films, high efficiency concepts, and fundamental research.

## INTRODUCTION

Characteristic of progress in technology is the displacement of an older technology generation by a new one when it becomes mature and viable. The classic example is the displacement of vacuum tubes by transistors and the subsequent displacement of transistors by integrated micro-circuits (1). As many as five generations of photovoltaic (PV) technologies have been suggested, although the dominant technology in today's market is still the first generation single crystal silicon solar cell (2). The five generations are single crystal silicon, polycrystalline silicon, silicon sheet (or ribbon silicon), single junction thin films, and multijunction thin films (see Table 1). Materials for the fourth and fifth generations consist of thin film semiconductors having direct band gaps. Direct band gap semiconductors have intrinsically higher solar absorption characteristics which considerably reduce the amount of semiconductor material needed for solar cells and provide the potential for greatly reduced cost.

There exist several opportunities for improvements in performance and reductions in cost of photovoltaics. For example, single junction photovoltaic technologies, which have an optimum conversion efficiency at a single wavelength of the solar spectrum, have an intrinsic limitation to their performance. They simply cannot convert other parts of the solar spectrum to electricity as well as a multiple junction device, having optimum conversion efficiency at multiple wavelengths, which has been fully developed. Another important factor concerns material costs. The cost of the purified semiconductor quality silicon used in the first, second, and third generation technologies is already a significant fraction of today's photovoltaic module costs. Thin-film devices, however, are more than one hundred times thinner than those of the first three generation technologies which are based on crystalline silicon, an indirect band gap semiconductor. Thin-film technologies have an additional cost advantage related to their energy content. Energy content is the sum of the equivalent electrical energy needed for all steps from mining and refining ore to constructing and encapsulating a module of solar cells. On an energy content per unit area basis, the thin-film technologies better the thick silicon technologies by a factor of ten (3).

The fifth generation multijunction thin-film technology has the potential for both higher performance and greatly reduced cost. It has the ingredients to be the long-term winner if aggressive research and development efforts are successful. Table 1 summarizes the potential benefits of the different generations.

Table 1

The Five Generations of Photovoltaic Technology
and Their Accruing Potential Benefits

**First Generation: Single Crystal Silicon**
Baseline Technology

**Second Generation: Polycrystalline Silicon**
Reduced Processing Costs

**Third Generation: Silicon Sheet**
Reduced Processing Costs
Reduced Semiconductor Material Costs

**Fourth Generation: Single-Junction Thin Films**
Greatly Reduced Processing Costs
Greatly Reduced Semiconductor Material Costs

**Fifth Generation: Multijunction Thin Films**
Greatly Reduced Processing Costs
Greatly Reduced Semiconductor Material Costs
Higher Conversion Efficiency

U.S. RESEARCH ACTIVITIES

The Department of Energy (DOE) has a highly visible program of research and development (R&D) in photovoltaics with the aim of improving the conversion efficiency, reliability, and life expectancy while reducing the cost of photovoltaic systems. The program sponsors high risk, potentially high payoff R&D which industry can use for developing final products for competitive application in U.S. electrical energy markets. The development of production lines, final products, and near-term markets is left to industry (4).

Because of the proprietary nature of much of the applied R&D conducted by photovoltaic companies, their activities are less visible. Many of the companies do present the results of their own R&D efforts, on a selective basis, in professional journals and technical conferences. Of course, the results of industrial R&D funded by DOE appear in government-distributed publications as well as professional publications.

Many electric utilities have sponsored photovoltaic projects not because photovoltaics is viable today, but because it has the potential to be viable for some of them within ten years. Their projects tend to emphasize the system aspects of the technology although the Electric Power Research Institute (EPRI), supported by almost 500 utilities, has an important photovoltaic R&D program focused on improving the performance of photovoltaics.

Finally, a few government agencies, principally the U.S. Air Force and the National Aeronautics and Space Administration (NASA), have R&D programs to develop high reliability, high power to weight photovoltaic systems capable of withstanding the radiation extremes of space.

The DOE National Photovoltaics Program

The National Photovoltaics Program has three research activities: materials research, collector research, and systems research. Funding in the fiscal year 1984 was distributed among these activities as follows: materials research, 53 percent; collector research, 27 percent; and systems research, 20 percent (5). Materials research is divided into five research tasks entitled single-junction thin films, high efficiency, multijunction concepts, innovative concepts, advanced silicon sheet, and silicon materials; over 80 percent of the materials research funding went to the first three tasks. The second research activity, collector research, has two research tasks, one on flat plate collectors and another on concentrator collectors. Finally, the systems research activity has three tasks: module reliability, array and balance-of-system development and systems experiments.

About half of the 1984 budget ($45.6 million) supported photovoltaic R&D in U.S. companies and universities. This support provided the basis for a government-industry-university partnership; the support is not one-sided as many of the companies contribute their own funds to achieve the objectives in the R&D contracts. The remaining half of the budget supported in-house research and management activities at the Solar Energy Research Institute (SERI), Sandia National Laboratories, Jet Propulsion Laboratory (JPL), and DOE.

From this discussion of funding, we discern an emphasis on the first three tasks of the materials research activity. To quote from the National Photovoltaics Program Five Year Research Plan: "The primary research emphasis is the development of promising new approaches to photovoltaic cells such as thin film and multijunction concepts" (4). In terms of the discussion in the previous section, the emphasis is on the fourth and fifth generation of photovoltaic technologies; those technologies holding the most promise but requiring long-term R&D support to realize their promise.

U.S. Photovoltaic Companies

There are as many different PV R&D strategies as there are PV companies in the U.S. Each company chooses to pursue a particular PV technology or set of technologies based on its internal strengths and visions of the future. There is at least one company, and sometimes many, involved in the development of each of the five generations of PV technology. Their activities range from basic research to commercialization. Without attempting to list all of the U.S. companies involved in PV research, SERI has large multimillion dollar subcontract efforts with Solarex, 3M Company, Chronar, and Spire for R&D on single junction amorphous silicon cells and, in the case of Spire, multijunction amorphous silicon cells. ARCO Solar Inc. and Energy Conversion Devices have large significant R&D programs, not funded by the government, for the development of multijunction thin film devices. U.S. PV companies tend to publish at the extremes of the technology development cycle, that is to say, their publications often describe either their basic research activities or their PV field projects. The Photovoltaics Specialists Conferences sponsored by the Institute of Electrical and Electronics Engineers (IEEE) has long been a common forum for describing the R&D activities of U.S. PV companies.

The Electric Power Research Institute

The Electric Power Research Institute (EPRI) recently increased its R&D activities in photovoltaics. EPRI R&D on concentrator systems has expanded and a new program in tandem amorphous thin film systems was launched (6). The emphasis in the EPRI program, a subcontracted program with no in-house laboratory research activities, is to push solar conversion efficiencies toward their practical physical limits. An EPRI advisory committee evaluation of photovoltaics judged the practical physical limits to be higher than those needed to make the systems viable (7). The EPRI effort in concentrators is trying to develop PV cells that are 25 percent to 27 percent efficient in high-volume production. Efficiencies of over 20 percent have been achieved for two candidate materials, crystalline silicon and gallium arsenide, in concentrator systems but continued R&D is needed to not only fabricate higher efficiency cells, but to produce them consistently. The EPRI effort also supports additional R&D on concentrator collector components, in particular, the cell mount and optical and tracking components.

The EPRI activities in thin films centers first on basic research in amorphous silicon materials to improve the understanding of electronic and optical properties and degradation processes. Second, EPRI emphasizes basic and applied research aimed at improving device efficiency, initially for single junction cells and later for more complex multijunction structures. Practical limit efficiencies are believed to be about 16 percent to 17 percent.

EPRI is also cofunding the development of dendritic web silicon sheet in an effort to achieve efficiencies of 15 percent to 17 percent at a production rate, measured in $cm^2$/min, high enough to reduce production costs. However, the margin for meeting both the cost and efficiency targets was judged small enough that the R&D is striving to simultaneously improve efficiencies to their practical limits and to increase the sheet growth rate to higher values.

U.S. Space PV Research

The U.S. Air Force is the principal funding source for space PV research. The Aero Propulsion Laboratory, AFWAL/ASD, located at Wright Patterson Air Force Base, manages these activities. Another source is NASA whose subcontracted R&D efforts are managed by the NASA Lewis Research Center. Space applications have markedly different constraints than do terrestrial applications. For low and medium altitude orbits a primary limitation is the effect of space radiation. For high orbits, such as geosynchronous, the primary considerations are system weight and lifetimes up to ten years. Space PV R&D has therefore focused on higher efficiencies, radiation resistance, and lower array weight. The efforts have also supported some production R&D activities to produce, for example, large numbers of high efficiency gallium arsenide (GaAs) solar cells.

The Seventh Space Photovoltaic Research and Technology Conference, held at NASA Lewis Research Center in May 1985, had many presentations on gallium arsenide and its alloys. Single crystal silicon systems have, of course, served as reliable power sources for satellites for many years. But there are other non-PV technologies vying as power sources for future space systems and GaAs, especially GaAs-based multijunction cells, offers the potential for higher efficiency, radiation resistant systems to meet this competition.

FUTURE R&D IN PHOTOVOLTAICS

An important factor in determining future R&D in photovoltaics is the tangible progress realized for the newer generations of photovoltaics. Extraordinary progress has been achieved in developing new materials and thin films. The efficiency of amorphous silicon cells (a-Si:H), which was only 1 percent in 1975, has increased more than tenfold. Similarly, the sizes of cells have gone from a few square millimeters to pilot modules more than 3,000 $cm^2$ in area. Other thin-film cells, such as copper indium diselenide/cadmium sulfide ($CuInSe_2$/CdS) and cadmium telluride/cadmium sulfide (CdTe/CdS) also have achieved efficiencies above 11 percent and are now being developed by industry. Over 19 percent efficiencies have been realized in thin-film gallium arsenide solar cells. As previously mentioned, multijunction or multiple-stacked cells with various band gaps to cover a greater portion of the solar spectrum have the potential for higher conversion efficiency than single-junction cells. It appears that a conversion efficiency of near 35 percent is achievable for concentrator collector systems having a concentration of more than 500 suns. Several approaches to providing multiple bandgap cells have shown promise, and laboratory cells with efficiencies of 25 percent have been achieved. In summary, improvements in materials and cell fabrication techniques have resulted in extraordinary gains in cell efficiency for thin-film devices during the past five years. The dramatic advances in the field are expected to continue during this decade. As the physics and technology of preparing thin films are better understood and controlled, the ability to fabricate efficient multijunction thin-film cells will emerge.

Amorphous Silicon R&D

The newly created Amorphous Silicon Research Project (ASRP), an R&D management structure established by DOE at SERI, completed a Five Year Research Plan for the successful development of hydrogenated amorphous silicon photovoltaic technology (8). The ASRP research activities are organized into two primary and five secondary activities. The two primary activities are single-junction solar cells and multijunction stacked solar cells. The five secondary research activities focus on material deposition rate, alternative material deposition methods such as photochemical vapor deposition, light-induced effects, device testing and reliability, and supporting research in, for example, theory, plasma kinetics, and transparent conductors.

As mentioned earlier, several of the large multimillion dollar subcontracts are part of the single-junction solar cell primary research activity. The deposition method used by these teams is currently restricted to the glow-discharge method which government-sponsored research had earlier identified as the best technique yet discovered for growing amorphous material for a-Si:H thin film solar cells. Multichamber deposition systems will be developed for growing individual amorphous silicon layers (p-type, i-type, and n-type) since such systems permit control over the material properties of the individual layers and considerably reduce cross contamination of the layers.

The multijunction solar cell activity concerns stacked cell devices, consisting of two or three single-junction solar cells in a stack, which are fabricated from amorphous silicon alloys. Stacked cell efficiencies are currently limited by the quality of the alloy material which limits the current from the devices. Research in this area involves amorphous silicon alloy materials, deposition techniques, stacked cell structures, as well as advanced research concepts such as amorphous semiconductor superlattices. The amorphous semiconductor superlattice consists of very thin alternating layers of hydrogenated amorphous semiconductors based on silicon, germanium, silicon nitride, or silicon carbide. The study of such structures could provide valuable information about amorphous semiconductor interfaces and could even lead to new types of solar cell structures having improved properties.

Polycrystalline Thin Films

The materials being studied most intensively in this area are $CuInSe_2$ and CdTe. The DOE/SERI program emphasizes single junction, multijunction, and advanced deposition research (9). Single junction research in $CuInSe_2$ has an important element producing and evaluating alloys of $CuInSe_2$ to raise its band gap. Major problems with CdTe are poor contacting and high bulk resistivity. One approach is introducing Hg in CdTe to produce higher p-type conductivity and better contacting. Another approach to producing a stable ohmic contact has been the insertion of an antimony-doped layer between the p-type CdTe and its back contact. Both materials are expected to benefit from the study of alternate window materials, the heterojunction partners. $CuInSe_2$ devices have already benefitted from the addition of Zn to CdS and researchers are considering such materials as n-ZnO, n-CdO, n-$SnO_2$ and new p-type materials. Both materials are expected to benefit from fabrication research which studies deposition techniques as well as post-deposition heat and chemical treatments.

Exploratory multijunction research in this field is investigating two- and four-terminal stacked devices exploiting the high and low band gaps of $CuInSe_2$ and CdTe. Another possible partner for $CuInSe_2$ is a-Si:H. This research is triggering studies into transparent back contacts for the top cell, new lower band gap window materials for the bottom cell, sub-band gap light loss pathways in the top cell, different alloy compounds to optimize band gaps, and optical and electrical optimization of interfaces and intermediate layers making up the cell stack.

High Efficiency Concepts

The inherent electro-optical properties of GaAs and related III-V compounds in addition to the ability to alloy GaAs with other column III and column V elements while maintaining a single crystal structure has led to the fabrication of many of the highest efficiency photovoltaic devices. The DOE/SERI program in this area is researching three fronts: thin films, III-Vs on silicon, and multiple junction cells (10).

High efficiency GaAs solar cells are typically grown on GaAs substrates, substrates which are hundreds of microns thick and very expensive. The active region of the cells, however, is only a few microns thick. The thin film work is directed at retaining only the active region of the cells by either physically separating the thin cells by mechanical means, growing the GaAs on soluble substrates such as NaCl, or growing the GaAs on substrates much less expensive than GaAs. Cells as efficient as 17 percent have been prepared as a result of the separation technique (10).

Growing GaAs on silicon can yield either a high efficiency cell using Si only as a substrate or a two-junction cell when the Si has been fabricated as an active device. The reason for this effort is to build upon the mature silicon photovoltaic technology although the GaAs band gap is too low for an optimized two-junction structure. A higher band gap alloy, such as AlGaAs, could yield much better performance in such a structure.

Multiple junction cells involve GaAs alloys, such as $Al_{1-x}Ga_xAs$ and $GaAs_{1-x}P_x$ for high band gap top cells and $In_{1-x}Ga_xAs$ and $GaAs_{1-x}Sb_x$ for low band gap bottom cells. Several of these single junction cells have achieved over 20 percent efficiency and the intent of future research is to combine two of these devices to achieve efficiencies approaching 30 percent. Such cells are destined for concentrator photovoltaic systems where high efficiency exerts a strong influence on the cost of energy produced by the system.

All of the above efforts are benefitting from advances in surface passivation techniques, contacting studies leading to reduced recombination velocities, improved anti-reflection materials, more effective optical trapping, and better control of the purity of the starting materials used to grow and dope the devices.

Fundamental Research

An important facet of the National Photovoltaics Program and its Five Year Research Plan is embodied in the objective of the innovative concepts task of the materials research activity. Its objective is "to identify new materials, device configurations, and concepts and to conduct preliminary research and development in the most promising areas" (4). This is a vital and necessary task to ensure all opportunities are explored to achieve the program's aim of improving PV conversion efficiency, reliability, and life expectancy while reducing the cost of photovoltaic systems.

Another critical activity involves the development and maintenance of measurement, characterization, and analysis facilities to monitor and aid the progress of all photovoltaic research. As the technology progresses the importance of detailed solar resource data will also grow for the developers of complex multijunction devices as well as engineers designing new field projects. The devices and measurements facilities at SERI have proven extremely important in providing comprehensive information from the several techniques available for evaluating and characterizing photovoltaic devices and materials (11). Many new techniques can be expected to be important in the future of this activity as the demand increases for more detailed and quantitative data on photovoltaic devices and materials.

## CONCLUSION

Future R&D activities in photovoltaics will continue to close the gap between today's conversion efficiencies and practical limit efficiencies. Future R&D activities in photovoltaics will provide many opportunities; opportunities for scientists and engineers to conduct exciting basic and applied research, opportunities for PV companies to build their strength with a PV technology to fill a niche they have identified in the market, and opportunities for the nation to develop a secure, inexhaustible energy supply.

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