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THE STATUS AND FUTURE OF GOVERNMENT-SUPPORTED AMORPHOUS SILICON RESEARCH IN THE UNITED STATES

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ABSTRACT

The Amorphous Silicon Research Project (ASRP) was established at the Solar Energy Research Institute in 1983 and is responsible for all U.S. Department of Energy government supported research activities in the field of amorphous silicon photovoltaics. The objectives and research directions of the project have been established by a Five-Year Research Plan, which was developed at SERI in cooperation with the Department of Energy in 1984 and is divided into research on single-junction and multi-junction solar cells. DOE/SERI has recently initiated a new three year program to be performed in collaboration with U.S. industry to perform work on high efficiency amorphous silicon solar cells and submodules. The objectives of this initiative are: i) to achieve 18% efficiencies for small area multi-junction amorphous silicon cells, and ii) to achieve amorphous silicon submodule efficiencies in the 10 to 13% range for single-junction and multi-junction submodule configurations over areas of at least 1000 cm^2.

INTRODUCTION

By a number of measures, the rate of progress in the amorphous silicon technology during the twelve month period in 1985 has increased significantly and the trend continues into 1986. One measure of progress is the extent to which the amorphous silicon technology has penetrated the world market for photovoltaics. Figure 1 shows the rapid increase in amorphous silicon sales, represented primarily by the use of solar batteries in Japanese consumer products, over the six year period beginning in 1980 (1). During the past year, sales of amorphous silicon solar batteries increased from approximately 6 MW_p in 1984 to 8 MW_p in 1985. As shown in Figure 2, the resultant market share of amorphous silicon photovoltaic products grew to more than 30% of the world photovoltaic market in 1985 (1).

As reflected in the market figures, a strong industrial base for amorphous silicon research and development has been established worldwide. In the United States, there were at least eight companies in 1986 with internal R&D programs consisting of greater than 30 scientists devoted to amorphous silicon research. Four of these companies, including ARCO Solar, Chronar, Energy Conversion Devices, and Solarex, are actively commercializing the amorphous silicon technology and have constructed or initiated construction on factories with annual production capacities of approximately 1 MW_p. One square foot power modules rated at 5 W were introduced in the United States in 1984. Beginning in 1986, several companies have begun marketing power modules greater than seven square feet in area and rated between 4 and 5 W per square foot. In addition, a 100 kW_p amorphous silicon test bed constructed by Chronar and the Alabama Power Company became operational in May, 1986. This is currently the largest amorphous silicon array field in the world. Several thousand additional watts of amorphous silicon modules are undergoing testing in smaller array fields at several locations in Japan and in the United States.

Progress in improving the operating performance of state-of-the-art amorphous silicon research devices also continues to increase at an impressive rate. During the past decade of research, as shown in Figure 3, the efficiencies of laboratory scale single-junction cells (1 cm^2 in size) increased from 1-2% in 1976 to 11-12% in 1985. An important technical milestone was achieved in 1982 when RCA reported the fabrication of the first 10% amorphous silicon p-i-n solar cell (2). Since 1982, approximately seventeen organizations worldwide have reported achieving greater than 10% cell efficiencies, and more than 30% of these organizations report cell efficiencies over 11%. Another important milestone was achieved in 1985, when Energy Conversion Devices reported a 13% efficiency for an all amorphous silicon multi-junction cell containing a-Si,Ge:H:F (3). The ECD result marks the first time that an all amorphous silicon multi-junction cell efficiency has exceeded the concurrent state-of-the-art single-junction cell efficiency.

In order to ensure the long term success of the amorphous silicon photovoltaic technology, there are still several research issues which must be addressed. Achieving practical cell efficiencies of 18% and greater, promised by the multi-junction cell technology, requires further research to optimize amorphous silicon alloy materials. A more thorough understanding of the Staebler-Wronski effect and light induced degradation is required to ultimately achieve module lifetimes of 20 years and beyond. Other research issues relate to the need to increase deposition rate, explore alternative deposition techniques, and standardize cell and submodule efficiency measurements.

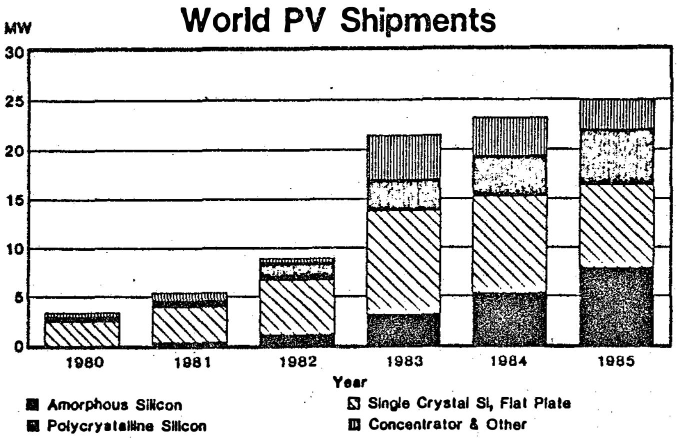

Figure 1. Estimates of World PV Shipments as a Function of Time Broken Down by Module Type

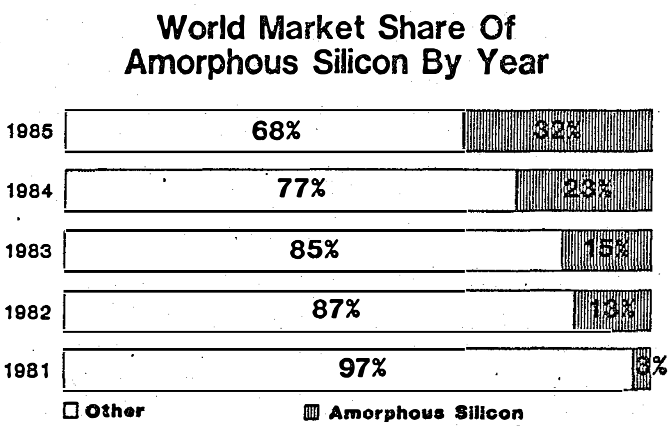

Figure 2. Estimate of World Market Share of a-Si as a Function of Time from Figure 1

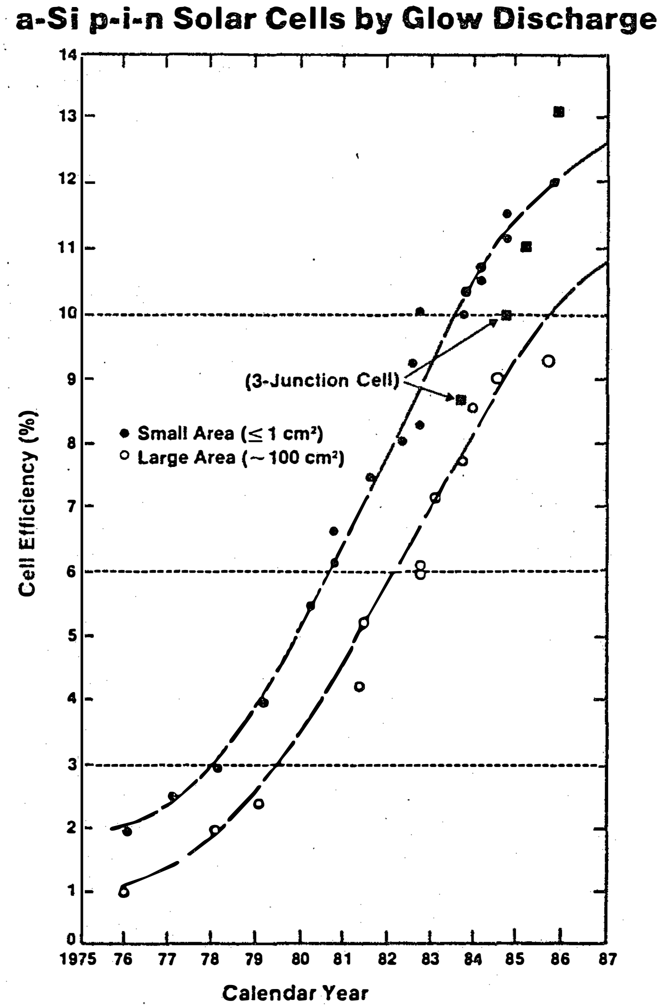

Figure 3. Efficiency as a Function of Time for a-Si:H p-i-n Solar Cells Prepared by Glow Discharge

AMORPHOUS SILICON RESEARCH PROJECT

The U.S. Department of Energy established the Amorphous Silicon Research Project (ASRP) at SERI in mid-1983 to coordinate all government-supported research activities in the amorphous silicon photovoltaic field. In 1984 a Five-Year Research Plan (1984-1988) outlining an aggressive research program was prepared and implemented by SERI in cooperation with DOE as a quideline for technology development (4). The goals of the plan have since been extended to the 1989-1990 time frame. In order to achieve the goals of the Five-Year Research Plan, the funding philosophy of the ASRP was structured around the concept of partnerships between DOE and U.S. industry and universities to form a core applied Government/Industry program supported by a strong fundamental research program.

Cost-shared, multi-year subcontracts with large multi-disciplinary R&D teams form the Government/ Industry partnership program. This program is devoted to achieving aggressive and significant goals representing an extension of the state-of-the-art in the amorphous silicon single-junction and multi-junction technologies. The first three-year program was initiated in FY 1984 with the primary goals of demonstrating a single-junction p-i-n solar cell efficiency of 12% (1 cm^2) and a submodule efficiency of 8% (1000 cm^2). The long-term goal of the multi-junction research activities is a cell efficiency of 18% (1 cm^2) based on amorphous silicon alloy materials to be achieved in the 1989-1990 time frame. Four subcontracts valued at a total of 18.6 million dollars, of which 30% was cost shared by industry, were awarded to Chronar, Solarex, and 3M for single-junction research and to Spire for multi-junction research in FY 1984. An overview of the technical options persued by each industrial team is given in Figure 4. Each organization is persuing a technical approach which draws upon pre-existing technical expertise within the company in order to improve the probability of success in achieving overall objectives.

Government-Industry Partnerships
Multiyear, Multidisciplinary Subcontracts

Chronar

- Single junction p-i-n cells
- RF glow discharge, two electrodes
- Three chambers
- Glass substrate

3M

- Single junction p-i-n cells
- RF glow discharge, two electrodes
- Three chambers
- Flexible polymer substrate

Solarex

- Single junction p-i-n cells
- DC glow discharge, three electrodes
- Three chambers
- Glass substrate

Spire

- Multi-junction cells, a-Si alloy cells
- RF glow discharge, three electrodes
- Six chambers
- Glass substrate

Figure 4. Description of the Technical Approaches of the Four Multi-Year Subcontracts

Government funding of small flexible research groups, primarily in universities, forms the core of the basic research program in the ASRP. Basic research is directed toward key fundamental issues and toward the expansion of the present boundaries of the amorphous silicon technology. In FY 1986, the program consisted of ten subcontracts with universities, four subcontracts with industrial groups, and research at five government laboratories, including SERI's in-house amorphous silicon program. The basic research program is divided into six fundamental research activities, including light-induced effects, alloy materials, alternative deposition methods, material deposition rate, plasma and material characterization, and device modeling, testing, and reliability (5).

SIGNIFICANT ADVANCES IN 1985-1986

A number of significant advances were achieved during 1985 in the amorphous silicon research activities supported by the U.S. Department of Energy and progress has continued into 1986. In the ASRP Five-Year Research Plan, two major milestones were met and exceeded by industrial research teams in 1985: i) the demonstration of a 7% efficiency for a 100 cm^2 submodule, and ii) the establishment of several operating multi-chamber deposition systems for single-junction and multi-junction cell research. In the Government/Industry program, single-junction amorphous silicon p-i-n solar cells 1 cm^2 in area have achieved efficiencies in the 10-11% range. In addition, single-junction amorphous silicon submodules fabricated on tin oxide coated glass substrates have achieved efficiencies of 7-8.0% over areas up to 1000 cm^2 and efficiencies of 7-8.5% over areas up to 420 cm^2. These efficiency levels were measured for submodules in which the three scribing steps necessary to interconnect cells in series on a single substrate were performed both by laser scribing and by a combination of laser scribing and chemical etching techniques.

A number of multi-chamber deposition systems of various designs are operational and are being tested in the program. 3M has constructed a three chamber RF glow discharge system for the roll-to-roll deposition of amorphous silicon on 4" wide metallized polyimide substrates. Chronar has constructed a vacuum-interlocked and load-locked four chamber RF glow discharge deposition system using vertical electrodes capable of handling one square foot glass substrates. Chronar also has several large batch RF glow discharge systems using multiple interdigital electrodes and capable of handling multiple square foot substrates. Spire has constructed a six sector RF glow discharge deposition system for the deposition of multi-junction devices using amorphous silicon alloy materials. Finally, Solarex has constructed a fully operational, in-line, DC glow discharge system capable of highly uniform and reproducible deposition of amorphous silicon on 12" x 13" glass substrates. In addition, Solarex has had considerable experience with the use of single-chamber load-locked deposition systems and to date has obtained their best cell and submodule efficiencies in such systems.

With respect to efficiency measurements, the ASRP created an Amorphous Silicon Measurements Task Force consisting of a group of government/industry/university experts which began deliberations in October, 1984. The objective of the Task Force was to make recommendations to the amorphous silicon community for the standardization and accurate reporting of indoor and outdoor performance measurements for amorphous silicon cells and submodules. A report summarizing the initial activities of the Task Force was published in 1985 (6). Specific recommendations were developed for the standardization of amorphous silicon single-junction cell measurements and the use of reference cells, which have been adopted by SERI. Improved measurement procedures have resulted in highly reproducible cell efficiency measurements in the U.S. amorphous silicon community. Standard measurement procedures are now being applied at SERI for indoor and outdoor submodule measurements as well.

Significant progress has also been made in the understanding of light-induced effects in amorphous silicon materials based upon theoretical modeling and extensive measurements on high quality materials and cells. Two specific models have been developed at Xerox (7) and MIT (8) which are both based on the existence of metastable defect states in amorphous silicon materials, and both models predict self-limiting degradation behavior on long time scales. A review of the status of light-induced effects in amorphous silicon was published by the ASRP in 1985 (9). An international workshop to be conducted jointly with Japan has also been organized and will be held in San Francisco during January, 1987.

Other significant program highlights include the development of two new materials, dimethyldichlorotin and tin tetrachloride, for the preparation of high quality fluorinated tin oxide using atmospheric CVD. These materials are a substitute for toxic tetramethyltin. Researchers have also demonstrated that adding fluorine to an a-SiGe:H alloy improves the photoconductivity of material with a bandgap in the range of 1.4-1.5 eV, enchancing the probability that a high quality low bandgap material can be developed for multi-junction cells. Further information is provided in a recent review (5).

THE FUTURE

In 1986, The Amorphous Silicon Research Project issued a major new initiative outlining an aggressive research program to 1990. The initiative is based on the highly successful format of government/industry partnerships involving multidisciplinary research teams, with a strong fundamental research program at universities addressing specific problem areas. An RFP outlining a three-year, cost-shared research effort with industry valued at 50 million dollars represents the core of the new program. The goals of the RFP, which was issued in January, 1986, are: i) to achieve efficiencies of 10% and 13% for a single-junction and a multi-junction amorphous silicon submodule, respectively, with areas of 1000 cm^2 each and ii) to achieve an efficiency of 18% for an amorphous silicon multijunction cell with an area of 1 cm^2.

CONCLUSION

The momentum for amorphous silicon technology development continues to increase. Small area single-junction and multi-junction cell efficiencies of 12-13% have been reported, and one square foot submodule efficiencies of approximately 8% have been achieved by several organizations. Worldwide, a growing industrial support base for the amorphous silicon technology has already established a production capacity of several megawatts per year for solar batteries and power modules. Sales of amorphous silicon solar cells for consumer products captured over 30% of the photovoltaic market in 1985, and in 1986 amorphous silicon power modules will make a significant contribution to sales of photovoltaic modules. As the amorphous silicon technology advances, other important applications such as electrophotography, electronic switches, image sensors, computer memory, and displays will gain significance. A wide range of applications will help ensure the continued development of a broad industrial support base for the technology.

Through the Amorphous Silicon Research Project, DOE and SERI have established a partnership with U.S. industry and universities to assist in the development of the amorphous silicon technology. In 1984, a major three-year multi-million dollar committment to technology development was initiated by DOE and SERI. This first Government/Industry program has been very successful in meeting ASRP milestones and will be completed at the end of 1986. In 1986, the U.S. Government continued its committment to the future of amorphous silicon technology development by issuing a new three-year, multi-million dollar initiative to achieve significant amorphous silicon submodule and multi-junction cell milestones in the 1989-1990 time frame.

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