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Promising Thin-Film Solar Cells — An Overview

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Promising thin film solar cells - an overview

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Abstract

Several thin film solar cell materials have demonstrated greater than 10% conversion efficiency, including amorphous silicon, polycrystalline silicon, cadmium sulfide/copper sulfide, cadmium sulfide/copper indium diselenide, gallium arsenide (CLEFT), cadmium sulfide/cadmium telluride, and gallium arsenide/silicon. The generic category of thin film solar cells is examined to determine prerequisites for use of these materials for large quantities of competitive electrical energy production. The future extrapolated performance, low cost potential, and areas for further research are discussed.

Introduction

Single crystal silicon has long enjoyed the position as the leader in high performance solar cells both for space and terrestrial applications. The price of photovoltaics has continued to decrease, with recent large megawatt buys priced less than $5 per peak watt. However, if renewable solar energy produced by photovoltaics is to be competitive with conventionally generated electricity, the price must continue to come down as the performance increases. Recent studies from the Electric Power Research Institute (EPRI) indicate certain windows that exist for PV power to be competitive with electrical energy produced by a variety of fossil or nuclear sources. As one example, in order to produce electricity at 15¢ per kilowatt hour, flat plate solar modules priced between $\$50/\text{meter}^2$ and $\$70/\text{meter}^2$ must have a conversion efficiency of 13% to 17% assuming the balance of system costs vary from $\$50/\text{meter}^2$ to $\$75/\text{meter}^2$. If these performance-cost goals are to be realized, many feel that thin film solar cells must be developed to replace conventional flat plate single crystal silicon.

Why thin films? Most of the reasons for pursuing low cost thin film solar cells lie in the material conservative nature of the processes, a wide range of material types and properties to choose from, and unique structures that are afforded by the thin film technology. Most of the materials that are under serious consideration have high absorption in the spectrum of interest (hence they can be "thin", typically less than 10 micrometers), more optimum bandgaps can be chosen for efficient solar to electric conversion (on the order of 1.4 eV), the processes are potentially scaleable to large areas using high throughput deposition approaches, encapsulation requirements are relaxed by integrating the substrate or superstrate as part of the encapsulation, and monolithic approaches similar to integrated circuits can be used to avoid costly interconnects and afford unique structures. With many of the material systems, the important physical parameters can be synthesized for the given application.

The fast expanding area of thin film research is relatively new, with the most significant activity occurring over the last five years. Although progress has been very rapid, much remains to be done. In the following sections, each of the important areas will be statused.

Status of important thin film technologies

In each of the following sections, the thin film materials are grouped as closely as possible to their common positions in the periodic table. Readers interested in further information are referred to other papers in the four sessions of this conference 407, SPIE Proceedings Volume 407.

Amorphous silicon

Amorphous silicon-hydrogen alloys are among the most promising thin film materials to achieve low cost photovoltaics. There has been significant research progress over the past five years resulting in a reported 10.1%, 1 cm^2 single junction amorphous silicon solar cell. This research field has attracted worldwide interest among researchers in universities and industry with an estimated over 100 organizations and 1000 researchers participating worldwide.

Most of the device research is directed towards the p-i-n structure consisting of a glass substrate, a transparent conducting oxide front contact, a thin p-type layer, an intrinsic or i-layer, an n-type layer, and a metal back contact. The total cell thickness is on the order of one micrometer. Larger area cells for practical applications have been built, but at somewhat lower efficiency. A 100 cm^2 cell has achieved 7.5%. Because of the unique structures afforded thin films, p-i-n cells which are series connected laterally across the device have been fabricated for use in consumer electronics. This integrated cell module can be designed to a specific voltage by varying the number of series connected elements.

One of the primary improvements for pushing the efficiency of amorphous silicon beyond 10% has been the development of a high quality, p-type window layer. Such a layer allows more light into the device without deleterious absorption in the p-layer. Amorphous silicon-carbon alloys which have optical gaps dependent on the carbon-silicon ratio have been used. The use of alloy materials promises further improvements in conversion efficiency by going to a multi-junction, stacked cell configuration. Such multi-color cells have potential for greater than 20% using appropriate combinations of alloys such as silicon-germanium, silicon nitride, and silicon-tin to name a few. The first demonstration of this concept achieved 8.5%.

Although much progress has been made, there still exist key research areas that must be addressed. A key consideration is to show long term stability of these materials under operating environments. Many of the high performance devices exhibit an initial decrease in efficiency of about 10% under light soaking conditions. Intensive research is going into understanding this instability and to preventing it. Currently deposition rates are limited to approximately 3 angstroms/second. In order to be cost effective, rates exceeding 10 angstroms/second will be required. Several approaches have been tried including alternate deposition techniques (glow discharge, reactive sputtering, and CVD) as well as alternate silicon source materials such as disilane which decompose more readily than conventional silane. Also key to successful deployment of thin films is the ability to scale to large areas. It still remains to be demonstrated that the high quality material, pinhole free, can be maintained for the larger areas of deposition. Another problem is that there is currently little or no theoretical base from which to predict future research directions.

With intensive research programs in the United States, Japan, and Europe, this important area will undoubtedly continue to progress at a very healthy rate.

Cadmium sulfide

Heterojunction solar cells with cadmium sulfide as the window material have been extensively studied over the past twenty years. In particular, the combination cadmium sulfide/copper sulfide has had very good performance characteristics. By the addition of a small amount of zinc to the CdS, the open circuit voltage could be improved to such an extent that this cell was the first thin film solar cell to achieve 10%. Unfortunately the stability of this cell could not be established without extensive encapsulation. Intrinsically stable CdS/Cu_2S can be demonstrated by laser burn out of shunt defects; however, the cells still must be protected from atmospheric contamination. In order to circumvent the stability problem associated with Cu_2S, research was initiated on $CuInSe_2$ as a replacement for the CdS hetero-partner. $CuInSe_2$ is a direct bandgap material with a bandgap near 1.04 eV with a strong absorption coefficent over most of the solar spectrum. The early results of this research have been very encouraging. The small area, 1 cm^2, conversion efficiency of 11% has been demonstrated with short circuit currents the highest of any solar cell, approaching 40 mA/cm^2. The open circuit voltage and fill factors still have room for improvement, and suggest that a 15 - 17% performance may well be achieved. Even more important, extended stability tests in excess of 9000 hours under constant light soak and elevated temperatures have shown no decrease in the performance characteristics. The cell structure is a 5 micrometer thick vacuum evaporated sandwich structure. $CuInSe_2$ is evaporated from individual elemental sources. Initially, a 2.5 micrometer high conductivity layer is deposited on the substrate followed by a 0.8 micrometer high resistivity layer which forms the absorber layer. Two layers of CdZnS layers are then deposited in order to form the heterojunction. An 0.8 micrometer thick high resistivity layer is followed by a low resistivity layer. The heterojunction is then activated by a 200°C anneal in air. Further research is necessary to understand how to improve the open circuit voltage of the device and to look at alternate deposition approaches to increase the throughput over the low rates associated with vacuum evaporation.

Cadmium telluride is another PV material of interest, having a direct bandgap at 1.47 eV with a strong absorption coefficient similar to $CuInSe_2$. CdTe can be deposited by a number of methods. One that seems to be potentially cost effective is electrodeposition. Cells of 1 cm^2 area, 6.2% efficient and 2 mm^2, 8.6% have been demonstrated. Recent results on CdTe deposited by close-spaced vapor transport have yielded cells in excess of 10%. Other attractive fabrication approaches such as screen printing have also yielded good performance. An interesting concept may be to combine CdTe with $CuInSe_2$ in a tandem structure since these material components have near optimum bandgaps for this two cell structure.

The II-VI thin film solar cells have attracted new business ventures to exploit these cells for applications allowing lower performance, but also low cost. Continued research must be devoted to addressing such questions as stability, enhanced open circuit voltage, alternate deposition approaches for greater throughput, and understanding of the various interfaces controlling the heterostructure.

Gallium arsenide

The III-V materials have been long recognized as the near optimum materials for solar conversion. However, due to the high cost, and potentially low availability of gallium for large volume PV production, GaAs has not been considered to be a serious competitor to single crystal silicon. However, recent results on thin film GaAs and other III-V material systems for use in advanced concentrator systems, have revived the interest in these materials.

To date, only one approach, CLEFT (Cleavage of Lateral Epitaxial Films for Transfer) has achieved greater than 10%. In this process, thin films of single crystal GaAs on the order of 5 micrometers thick are cleaved from a reuseable GaAs substrate. The film is grown by lateral epitaxy through stripe openings in a carbonized photoresist mask. Using this approach, a 0.5 cm^2 homojunction solar cell of 17% has been achieved. Other polycrystalline GaAs approaches such as growth on reuseable substrates or sacrificial substrates such as tungsten-coated graphite, germanium-coated silicon, and sodium chloride have been pursued. The best results to date have been 8.5% for a MIS structure (9 cm^2) and an 8.8%, 1 cm^2 homojunction on tungsten-coated graphite. Another approach, not truly thin film but yet interesting, was the achievement of 11.7% for GaAs films grown on Ge-coated single crystal silicon substrates. As with other polycrystalline approaches, the performance efficiency increases with the size of the grains which are also proportional to the thickness of the film. Thus it would appear to be difficult, if not impossible, to achieve high efficiency for truly thin film III-V polycrystalline devices. Perhaps suitable techniques for passivation of the effects at grain boundaries can be found similar to those used to enhance the performance of polycrystalline silicon. In the meantime, however, most of the research activity in the III-V area will center on the advanced concentrator approaches which have potential for achieving greater than 30% conversion efficiency.

Conclusions

The preceding discussions have been focused on those thin film materials which appear to be close to achieving the performance characteristics necessary for competition with single crystal silicon for application for energy production. Many other candidates are being pursued for deployment in the long term. Significant industrial interest has been attracted to commercialize some of the more advanced thin films. However, much research is needed to guarantee that thin films will eventually be manufacturable with the necessary performance-cost prerequisites.

Acknowledgements

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References

Interested readers are referred to the following important sources for additional material related to the materials discussed in this paper:

1. Proceedings of the Sixteenth IEEE Photovoltaic Specialists Conference, 1982, San Diego, California.

2. Proceedings of the Fourth European Communities Photovoltaic Solar Energy Conference, 1982, Stresa, Italy.

3. Proceedings of the Third Photovoltaic Science and Engineering Conference in Japan, 1982, Tokyo, Japan.