OVERVIEW OF SERI'S HIGH EFFICIENCY SOLAR CELL RESEARCH

John P. Benner, Lee A. Cole and Cecile M. Leboeuf
Solar Energy Research Institute
Golden, Colorado

The general level-of-interest in high efficiency terrestrial solar cells is increasing. Projected efficiencies of more than 20% are now considered attainable, not only in GaAs based cells, but also in multijunction amorphous and polycrystalline devices. As III-V solar cells approach this high performance level, increasing concern is directed toward questions regarding large area production potential. SERI's program will increase research emphasis on the study of mechanisms involved in growth of III-V semiconductors in order to develop answers to these questions.

INTRODUCTION

In 1983, the U.S. Department of Energy established the Five Year Research Plan for the National Photovoltaics Program.(1) The objective of this plan is to perform the high risk research needed to establish a technology base from which industry can develop photovoltaic systems for central station applications. The targeted performance of such installations is to provide power to the grid at a cost of less than fifteen cents per kilowatt hour. (thirty-year levelized cost). One approach to achieve this goal is to greatly increase the efficiency of flat plate and concentrator solar cells. The plan contains milestones to achieve efficiencies of 20% in thin-film gallium arsenide (GaAs) solar cells in 1986 and to reach 35% efficiencies in multijunction concentrator cells in 1988. In order to achieve these goals, research is needed to improve the quality of the III-V semiconductor crystal layers and to improve the solar cell structures to compensate for less-than-ideal semiconductor properties. The High Efficiency Concepts Task at the Solar Energy Research Institute (SERI) supports research to achieve these milestones.

Currently, the task supported research can be grouped into three different techniques for preparation of semiconductor layers. These are growth on low cost substrates which typically results in polycrystalline layers; growth of single crystal thin films and separation from the substrate; and heteroepitaxial growth of GaAs or ternary alloys on GaAs or silicon. Each of these approaches presents some difficult problems for the crystal grower and device designer.

Polycrystalline Gallium Arsenide

The first approach has so far proved to be most difficult. The films are generally polycrystalline with an average grain size less than a few millimeters. Achievement of this grain size requires various recrystallization processes. This can result in segregation of impurities and possibly precipitates at the grain boundaries.(2) The grain boundaries may then provide shunt paths reducing the performance of the cells. Several studies of films prepared with impurity-free grain boundaries have shown the validity of the double depletion layer model for polycrystalline GaAs.(3,4) This model suggests that even clean boundaries will be detrimental to solar cell performance. One study has shown that the intragrain properties of a few defective grains may be the dominant cause of poor performance in some solar cells.(4) Thus, the approach using low-cost substrates presents several challenging problems. Some topics of interest include grain size enhancement or formation of single crystal films on low-cost substrates; passivation or neutralizaton of grain boundaries; doping of polycrystalline films; and development of device structures which minimize the detrimental effects of the non-ideal films.

Single Crystal Thin Films

The second approach, relying on reuse of a more expensive substrate which promotes single crystal growth, has shown more success. Using lateral overgrowth of a masked GaAs substrate, with film separation by controlled cleavage, thin film cells have achieved reported efficiencies of nearly 19%.(5) Continued research on this approach (termed Cleavage of Lateral Epitaxial Films for Transfer or CLEFT) is expected to achieve the 1986 DOE Five Year Plan milestone for thin-film gallium arsenide. Other techniques for separation of single crystal films heteroepitaxially grown on low melting point or selectively etchable layers provide promise of useful alternative technologies.(6,7) Another opportunity for this general approach is the separation of high efficiency cells having a bandgap of approximately 1.75 eV which can be mechanically stacked or silicon solar cells to form a very high efficiency optically cascaded stacked concentrator cell or flat plate module. Given that the films are single crystal, the device design and development are somewhat more straight forward. However, control of the solar cell's thickness may yield higher performance than is obtainable in a bulk device.(8) This area will benefit from research on alternatives to the CLEFT process for growth, separation and handling of thin single crystal films.

Heteroepitaxy

The final area, heteroepitaxial growth of single crystal layers, covers both growth of ternary and quaternary alloys on GaAs substrates for concentrator cells as well as growth of III-V semiconductors on silicon or germanium-silicon substrates. The preparation of monolithic multijunction cells of very high efficiency is attractive for both concentrator and flat plate modules due to the simplicity of interconnection in the overall system. They also offer potential for lower optical losses and fewer problems with removal of heat. With the exception of the AlGaAs/GaAs system, heteroepitaxial III-V systems introduce problems of control of lattice misfit dislocations and, in some systems, mismatch of thermal expansion coefficients. Various techniques for composition grading and superlattices are under study to provide control of propagation of dislocations.(9,10) The use of controlled strain between layers is seen to minimize propagation of dislocations. However, in the case of growth of GaAs solar cells on silicon substrates, it is suggested that the strain induced by dopants forming the p-n junction actually causes dislocations to bend over at the junction.(11) This would place the highest density of recombination centers in the space charge region. This reasoning would explain the lower measured open circuit voltage and fill factor than would be expected from the observed defect density at the surface of the sample. In systems with mismatched thermal expansion coefficients, some samples will develop micro-cracks upon cooling from growth temperatures. These problems can be best addressed by joint efforts in crystal growth and device design.

Basic Studies

In addition to the specific problem areas listed above, the High Efficiency Concepts Task at SERI is interested in several other general research problems. Most of the current efforts use metalorganic chemical vapor deposition (MO-CVD). Several studies have identified impurities in current source materials which create electrically active defects (12,13) in the resulting semiconductors. MO-CVD is still a relatively new crystal growth technology with new generations of potential source materials still being introduced. There is considerable room for improvement in the understanding of the chemistry of the reactions which result in growth of the crystals and production of effluents. Analysis of gas flows and of source depletion is important for the development of an analytic approach to design of CVD reactors.

Reducing the temperature required to grow high quality III - V semiconductors may also provide an important tool for achieving high efficiency solar cells. A wider range of allowable growth temperatures may provide greater control over the strain in heteroepitaxial crystals. This may be important for minimizing dislocation density and microcracks in III-V layers. The predicted existence of superalloys has also generated increased interest in low temperature crystal growth. Alloys of III - V binary compounds are generally thought to exist only as random metastable systems. Research at SERI has shown that minimization of the total quantum mechanical energy of ordered phases of alloys predicts that, if grown at low enough temperatures (but with sufficient surface mobility), stable ordered intermediate phases "superalloys" would form, e.g. ordered phases of $GaInP_2$, Ga_3AsP_4, etc. Relative to random alloys of the same composition these superalloys would have the same lattice constant, somewhat larger bandgaps, and significantly higher carrier mobilities, and would be thermodynamically stable. These new materials may be very valuable for reaching new levels of photovoltaic efficiency.

As the high efficiency cell technology begins to approach the limits imposed by the best materials, increased attention will be placed on further developing "tools" for device designers to optimize cell performance. Measurements of critical electronic parameters of III-V semiconductors present new areas for research. Studies of potential techniques for passivating surfaces (and grain boundaries) could improve efficiencies. Studies of techniques for interconnecting top and bottom cells of a monolithic tandem device will also be needed. Research to improve light collection and improve open circuit voltage and fill factor to bulk recombination limits will be essential for achieving and exceeding the efficiency goals of the Five Year Plan.

Conclusions

The bulk of the research efforts supported by SERI's High Efficiency Concepts area have been directed towards establishing the feasibility of achieving very high efficiencies, 30% for concentrator and more than 20% for thin film flat plate, in solar cell designs which could possibly be produced competitively. The research has accomplished a great deal during the part two years. Even though the desired performance levels have not yet been demonstrated, based on the recent progress, a greater portion of the terrestrial photovoltaics community believes that these efficiencies are attainable.

The program can now allocate a larger portion of resources to low cost, large area deposition technology. The program is currently shifting greater emphasis on to the study of crystal growth in order to provide the understanding and tools needed to design a large area process.

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