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PHOTOVOLTAIC RESEARCH OPPORTUNITIES

FINAL REPORT

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MASTER

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ABSTRACT

The purpose of this "Photovoltaic Research Opportunities" study is to identify opportunities for photovoltaic (PV) research projects to capitalize on related but non-PV research. The study is sponsored by the U.S. Department of Energy (DOE) under the assumption that a considerable body of ongoing semiconductor research in non-PV areas could be of value to its PV Program and the PV community in general. Research related to III-V compounds, thin films, and crystalline silicon materials is included. Research that is known to be PV-related or sponsored by DOE was excluded from consideration. The study resulted in 11 recommendations (research areas) and a subset of 58 specific research projects. In addition, over 75 non-PV research managers in the semiconductor field are identified as potential sources of ideas which could benefit photovoltaics.

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EXECUTIVE SUMMARY

INTRODUCTION

The purpose of this "Photovoltaic Research Opportunities" study is to identify opportunities for photovoltaic (PV) research projects to capitalize on related but non-PV research. The study is sponsored by the U.S. Department of Energy (DOE) under the assumption that a considerable body of ongoing semiconductor research in non-PV areas could be of value to its PV Program and the PV community in general. Research related to III-V compounds, thin films, and crystalline silicon materials is included. Research that is known to be PV-related or sponsored by DOE was excluded from consideration. The study resulted in 11 recommendations (research areas) and a subset of 58 specific research projects. In addition, over 75 non-PV research managers in the semiconductor field are identified as potential sources of ideas which could benefit photovoltaics.

APPROACH

The technical work on this project was performed by the Study Team:

- R&D Specialists - Three university researchers who provided technical expertise in each of the three materials areas:
  - Dr. Sorab Gandhi, Rensselaer Polytechnic Institute, III-V Compounds
  - Dr. Allen Barnett, University of Delaware, Thin Films
  - Dr. Fredrik Lindholm, University of Florida, Crystalline Silicon
- Expert Panel - Eight experts who provided a peer group review of the work and developed the final recommendations:

- John Benner, SERI	- Don Morel, ARCO
- John Fan, MIT	- Richard Reynolds, DARPA
- Harold Hovel, IBM	- Donald Roberts, Westinghouse
- Roger Little, Spire	- Brown Williams, RCA

The R&D Specialists reviewed over 10,000 abstracts describing non-PV research. Based on this review, the Study Team developed an initial list of 110 potential PV research projects. Because there was considerable commonality and overlap among these projects, and because the Expert Panel found it difficult to prioritize and select among many worthwhile ideas, the final 11 recommendations represent areas of interest rather than specific projects. However, 58 of the 110 specific projects were retained as subsets of the 11 research opportunities.

RECOMMENDATIONS

This study was conducted using several of the most outstanding experts in the PV research field. These researchers identified 11 research areas in which non-PV, non-DOE work is most likely to have positive implications for PV devices. These are identified in Exhibit E-0. In addition, Exhibit E-1 identifies first-step implementation activities for each research opportunity (RO). Each of these 11 areas was carefully selected. They represent areas in which:

- (1) there is considerable non-PV research;
- (2) the research could benefit photovoltaics;
- (3) the research is currently not being transferred to photovoltaics;
and
- (4) technology transfer to photovoltaics is not likely to occur
without government assistance.

In addition, 58 specific research projects were identified within the 11 areas of interest. These projects represent the best ideas resulting from an exhaustive literature search and productive technical discussion. However, it was beyond the scope of this study to conduct an intensive investigation into any one area or project. This study serves to identify potential projects and prioritize areas of interest. It is believed that many more projects could be identified if a more focused, intensive investigation were conducted into any of the 11 research areas. Interaction with the semiconductor research managers listed in this report should be a major component of such an investigation.

Research Opportunity #9 (RO#9) "Improved Interaction Between DOE, DoD, and Other Research Groups," represents the only non-technical recommendation. Several members of the Study Team suggested that this item be highlighted because of its importance in implementing the technical recommendations. Four programmatic recommendations are included in RO#9:

- (1) Convene a liaison group to meet once or twice a year to facilitate information exchange between PV and non-PV researchers.
- (2) Encourage PV researchers to attend the semiconductor conferences.
- (3) Encourage unsolicited proposals for innovative research in the 11 research areas.
- (4) Investigate each recommendation in this report in greater depth in search of specific activities that could be incorporated into the existing DOE PV Program.

The recommendations in this study represent a consensus of the Study Team. There is, however, one dissenting opinion. Dr. Don Morel believes that the recommendations place too much emphasis on III-V compounds and not enough emphasis on II-VI thin films. They believe that non-PV research in this area has been growing at a rapid pace, and that the photovoltaic community is missing numerous opportunities to take advantage of recent advances in II-VI thin-film materials.

CONCLUSIONS

When this study was initiated, it was believed that a thorough review of semiconductor research would uncover one or two "great" new ideas. The result, however, is a list of many good ideas. The volume of related research being conducted in fields other than photovoltaics is overwhelming. As a result, it was not possible to review any one area or project in detail. However, this study has served to screen the many research areas, identify those of interest to photovoltaics, and prioritize 11 areas according to their likelihood of success should further research be pursued. Therefore, the final recommendations of this study should be viewed as a first attempt to sort through a wealth of information to uncover several good ideas. Considerable additional work is necessary for these ideas to be fully defined, developed, and brought to fruition.

EXHIBIT E-0. Prioritized PV Research Opportunities

Very High Priority

1. Fundamentals of heterogeneous nucleation and growth on dissimilar substrates.
2. Better understanding of heterojunctions (theoretical and experimental) in all material areas.

High Priority

3. Alternative device designs which exploit processes used for non-PV devices.
4. Exploitation of single crystal II-VI and related films.
5. Exploration of transient thermal processing.
6. Investigation of non-equilibrium energy beam assisted processes.
7. Advanced characterization methods for examining materials -- basic research and process control.
8. Passivation of surfaces and grain boundaries.
9. Improved interaction between research groups -- one-on-one liaison between DOE, DoD, and other research groups.

Medium-High Priority

10. Long-term reliability due to degradation phenomena.
11. Development of procedures to deal with safety.

EXHIBIT E-1. Recommended First-Step Implementation Actions

Very High Priority

1. RO#1. Identify and characterize relevant materials and processes under development by the semiconductor industry for heterogeneous nucleation and growth on dissimilar substrates.
2. RO#2. Conduct a seminar or workshop on heterojunctions in all material areas that may relate to PV.

High Priority

3. RO#3. Sponsor research to develop alternative device designs which exploit processes used for non-PV devices, especially in the microcrystalline area.
4. RO#4. Conduct a review of the state-of-the-art knowledge of material properties of II-VI compounds and epitaxial growth techniques (especially MOVPE and MBE).
5. RO#5. Investigate advanced thermal processes used to solve semiconductor fabrication problems to determine which may be applicable to photovoltaics.
6. RO#6. Conduct a survey of non-equilibrium energy beam assisted processes in the semiconductor field to determine those that may be applicable to PV device fabrication.
7. RO#7. Establish one or more centers with advanced characterization methods for examining materials.
8. RO#8. Conduct a survey of advanced passivation techniques now being used for semiconductors.
9. RO#9. See discussion of institutional recommendations on page v.

Medium-High Priority

10. RO#10. Conduct a review of reliability problems in semiconductor devices and how these problems are being addressed.
11. RO#11. Organize a workshop on safety with an appropriate industry organization (such as SEMI, the Semiconductor Equipment and Materials Institute) with photovoltaics as a component of the workshop.

1.0 INTRODUCTION

1.1 Purpose of the Study

The purpose of this "Photovoltaic Research Opportunities" study is to identify opportunities for photovoltaic (PV) research projects to capitalize on related but non-PV research. Research relating to III-V compounds, thin films, and crystalline silicon materials is included in this study. Research that is known to be PV-related or sponsored by the Department of Energy (DOE) was excluded from consideration. The study resulted in eleven recommendations. These recommendations identify areas in which non-PV, non-DOE work is most likely to have positive implications for photovoltaics.

A considerable amount of semiconductor research is being pursued under the auspices of organizations other than the DOE. Although not specifically related to PV cells, this research may result in insights that could prove valuable in reducing the cost and/or enhancing the performance of PV systems. In particular, the Department of Defense (DoD) sponsors a considerable amount of basic and applied research in the semiconductor area. Many of these activities involve materials of interest to photovoltaics, such as gallium arsenide, crystalline silicon, and cadmium telluride.

1.2 Background

This study is sponsored jointly by the Department of Energy's Office of Energy Research (OER) and the Photovoltaic Energy Technology Division (PETD) of the Office of Conservation and Renewable Energy. The Director of OER functions as a science and technology advisor to the Office of the Secretary of Energy on matters relating to physical research programs, utilization of multi-purpose laboratories, and cross-discipline research and development projects, as well as managing outlay programs in the Offices of Basic Energy Sciences, High Energy and Nuclear Physics, Fusion Energy, and Health and Environmental Research. This responsibility includes the identification of gaps and duplications in DOE research programs and of research needed to fulfill the Department's research mission.

The majority of photovoltaic research sponsored by the DOE is managed by PETD. The technical goals of the DOE PV Program are based on an electric utility planning target of 6.5¢ per kilowatt hour (kWh) for photovoltaic generated electricity. The planning target is stated in constant 1982 dollars and represents the 30-year levelized life cycle cost of a central station photovoltaic power plant. The federal role is to undertake activities that contribute to the planning target in areas that industry is unlikely to pursue because of the costs and risks involved. For more information on the DOE PV goals, refer to the National Photovoltaics Program Five-Year Research Plan 1984-1988 (U.S. Department of Energy, DOE/CE-0072, May 1983).

1.3 Report Organization

A summary of the approach used in the study is presented in Section 2.0, "Approach." Section 3.0, "Research Opportunities," presents detailed discussions of the 11 recommendations, including the names of non-PV researchers who could be contacted for more information. Section 4.0, "Conclusions," provides a summary of the conclusions of this study. Appendix A, "Research Project Ideas," provides descriptions of 58 research projects that are subsets of the 11 recommendations. Appendix B, "Research Index," provides a page-number index of all researchers identified in this report.

2.0 APPROACH

2.1 Overview

The technical work on this project was performed by two groups that form the Study Team (see Exhibit 2-0):

- R&D Specialists - Three senior university researchers who provided technical expertise in each of the three materials areas; and
- Expert Panel - Eight nationally recognized experts who provided a peer group review of the work and developed the final recommendations of research opportunities.

The overall approach to the study included:

1. Data Collection. A structured data collection activity was conducted by Meridian Corporation to obtain literature describing non-DOE, non-PV semiconductor research being performed both in the U.S. and abroad. Over 10,000 research abstracts were obtained through a systematic computerized review of relevant literature, supplemented by personal contact with the research community. Emphasis was placed on research sponsored by the Department of Defense, but included that of other federal agencies and some private organizations.
2. Data Screening. Three R&D Specialists screened and evaluated the 10,000 abstracts within their respective areas of expertise to identify approximately 100 non-PV research projects with potential contributions and applications to PV.
3. Development of Research Ideas. Based on the results of this research review, the R&D Specialists proposed 79 PV research projects. The Expert Panel added an additional 31 projects for a total of 110.
4. Development of Final Recommendations. The Expert Panel met for two days with the R&D Specialists to develop a prioritized list of 11 major recommendations and 58 specific research projects.

EXHIBIT 2-0. Study Team

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Each of the steps involved in the study approach is described in the following sections.

2.2 Data Collection

A search was performed to collect a comprehensive representation of literature describing non-DOE, non-PV semiconductor research of advanced materials and concepts related to III-V compounds, thin films, and crystalline silicon, being conducted in areas of science and engineering other than photovoltaics. This was accomplished primarily through the computer data bases of DIALOG and DTIC, supplemented by direct contact with federal agencies and private industry.

The effort focused on the collection of abstracts describing unclassified research conducted within the last 5 years. Exhibit 2-1 presents the results of the non-PV research literature collection effort. Exhibit 2-2 summarizes the data sources accessed.

EXHIBIT 2-1. Abstracts/Materials Retrieved

<u>Materials Area</u>	<u>Total*</u>
III-V Compounds	3,716
Thin Films	3,811
Crystalline Silicon	<u>2,773</u>
TOTAL	10,300

* Some abstracts were applicable to more than one materials area; totals reflect some duplication.

EXHIBIT 2-2. Literature/Data Sources Accessed

- DIALOG (Computer Information Retrieval System)
    - National Technical Information Service (NTIS)
    - Information Services in Physics, Electrotechnology, Computers and Control (INSPEC)
    - Commerce Business Daily (CBD)
  - FEDERAL DATA BASES/AGENCIES
    - Department of Defense (DoD)
      - Defense Technical Information Center (DTIC)
      - DoD Advisory Group on Electron Devices
      - Research Oriented DoD and Military Command Offices
    - National Aeronautics and Space Administration (NASA)
    - National Science Foundation (NSF)
    - National Bureau of Standards (NBS)
  - SEMICONDUCTOR RESEARCH CORPORATION (SRC)
-

2.3 Data Screening

The semiconductor research information was disaggregated into the three materials areas of interest to the project and was screened by the R&D Specialist of the corresponding expertise area:

- Dr. Sorab Gandhi - III-V Compounds
- Dr. Allen Barnett - Thin Films
- Dr. Fredrik Lindholm - Crystalline Silicon

During their examination of the literature, the R&D Specialists requested several additional abstracts and full reports to supplement their understanding of current non-PV research activities. The Specialists also contributed additional literature to the collection.

The R&D Specialists screened the collected materials to:

- Evaluate the completeness and accuracy of the retrieved materials and the research described;
- Identify what areas of study could have some significance for achieving the performance and cost goals of the DOE PV Program; and
- Propose preliminary research ideas that potentially would aid in integrating the benefits of non-PV research into PV research.

2.4 Development of Research Ideas

Based on this review, the R&D Specialists proposed 79 research projects that appeared to promise significant contributions and applications of non-PV research to enhancing PV systems and achieving PV research goals. These are categorized as follows:

- III-V Compounds - 34 ideas
- Thin Films - 27 ideas
- Crystalline Silicon - 18 ideas

Each Specialist evaluated the individual research ideas assigned to him and provided information describing his estimates of R&D needs, and funding and time requirements. They also provided citations of abstracts describing related ongoing non-PV research. After reviewing the R&D Specialists' work, the Expert Panel members contributed an additional 31 research ideas, thus expanding the list of research ideas to a total of 110. This information provided the initial input to the Expert Panel for their evaluation and final selection of research recommendations at the two-day Expert Panel meeting.

2.5 Development of Final Recommendations

The primary role of the Expert Panel was to review the results of the data collection and screening and the proposed research projects, contribute their personal expertise and, from this, develop a list of prioritized research opportunities. To accomplish this, a two-day meeting of the Study Team was held on May 23-24, 1985. To develop their recommendations, the Panel was asked to evaluate the proposed research ideas and develop a list of research recommendations that respond to the following criteria:

What are the most critical research projects that could be undertaken by the DOE to integrate non-PV research into PV research programs to enhance the achievement of the cost goal of 6.5¢/kWh (late 1990s), based on the following research need, time, and funding considerations:

- Probability of success of the project;
- Potential contribution of the project to system cost and efficiency improvement;
- Probability that private industry will make use of the results of the federally-funded R&D project;
- Probability that private industry would not initiate and conduct this R&D project without government assistance; and
- Government R&D time and funding requirements?

During Day 1 of the Panel meeting, the Nominal Group Technique (NGT) was employed to select the highest priority research projects based solely on research needs. At the conclusion of the NGT session, 11 research opportunities were selected from the initial list of 110 as having the most significant potential contribution to PV research needs.

During Day 2 of the meeting, further assessment of the 11 research opportunities was conducted by the Expert Panel and the R&D Specialists to provide in-depth technical characterization and to determine relative priorities of the final recommendations. This assessment included:

- Defining each research opportunity;
- Establishing overall priorities of the research opportunities to reflect their relative importance;
- Categorizing specific research projects (from the initial list of 110) under each research opportunity; and
- Identifying known organizations currently conducting and/or funding research related to each research opportunity.

There was considerable commonality and overlap among the initial 110 research projects. In addition, the Study Team found it difficult to prioritize and select among many worthwhile ideas. Therefore, the 11 research opportunities selected by the Study Team represent areas of interest rather than specific projects. However, 58 of the 110 specific projects were retained. Each of these is correlated to one of the 11 research opportunities, as described in the following section.

3.0 RESEARCH OPPORTUNITIES

The development of semiconductor devices, including photovoltaic devices, dates back to the late 1940s. To date, however, progress in the basic understanding of PV materials, structures, and devices has lagged behind advances in the development of other functional and commercial semiconductors. There are two reasons for this. First, a lower level of investment in the PV research area has resulted from a substantially smaller and later-developing commercial PV market. Second, photovoltaic devices are more area- and materials-intensive. Larger semiconductor areas must perform nearly as well as smaller areas when photovoltaic devices are made. Also, the raw materials represent a major cost driver for photovoltaic devices, whereas in other semiconductor devices, even the most expensive materials represent only a minor cost component. Nevertheless, the basic materials, processing techniques, and device structures are similar in both technology areas, and many of the advances in other semiconductors are directly or indirectly applicable to PV devices.

The optimization of production processes, increased basic understanding of the starting materials, exploration of alternative device structures and manufacturing processes, and the development and improvement of characterization and testing techniques have all occurred as a natural part of the optimization of non-PV semiconductor devices. These same development activities are just now being applied in the PV area.

The objective of most private sector research in the PV area is to improve the "performance" of the commercial products. The ultimate goal of this work, however, is to lower the cost of the technology, leading to lower device and systems costs and, ultimately, wider use of this technology. To achieve this 'lower cost' goal, three alternative research directions are being investigated. These include:

- Materials Cost - Lowering the effective cost of the base material either by improving the quality and performance of available commercial materials, or by developing new materials with enhanced performance characteristics;

- Design Improvements - Lowering the effective cost of the existing devices either by using alternative component materials (contacts, passivation layers, etc.), or by improving processing and manufacturing techniques; and
- Novel Devices - Lowering the effective cost of potential devices by developing new device structures which enhance the performance of existing materials, or allow the use of new, less expensive starting or component materials.

The 11 research opportunities developed by the Study Team directly target these three principal alternatives for PV device improvement by identifying areas in which non-PV, non-DOE work is most likely to have positive implications for PV devices. These ROs attempt to achieve:

- Better understanding of basic starting materials and growth mechanisms through more detailed studies of available commercial materials, and the development of new testing and characterization techniques to facilitate further expansion of this level of understanding;
- Improvements in available devices through enhanced starting materials, improved growth processes, and/or better device structures; and
- Identification of new materials for the basic components of a PV device and advanced device structures to utilize these materials.

The three principal areas for cost improvements should be kept in mind when evaluating the ROs.

Exhibit 3-0 presents the ROs, categorized within three priority ratings: Very High, High, and Medium-High. These prioritized recommendations represent a consensus opinion of the Study Team, based on the assessment criteria described in Section 2.5. Note that the lowest of the priority ratings is Medium-High, indicating that all of these recommendations are considered to be important, as they represent a selection of the best of over 100 ideas.

EXHIBIT 3-0. Prioritized PV Research Opportunities

Very High Priority

1. Fundamentals of heterogeneous nucleation and growth on dissimilar substrates.
2. Better understanding of heterojunctions (theoretical and experimental) in all material areas.

High Priority

3. Alternative device designs which exploit processes used for non-PV devices.
4. Exploitation of single crystal II-VI and related films.
5. Exploration of transient thermal processing.
6. Investigation of non-equilibrium energy beam assisted processes.
7. Advanced characterization methods for examining materials -- basic research and process control.
8. Passivation of surfaces and grain boundaries.
9. Improved interaction between research groups -- one-on-one liaison between DOE, DoD, and other research groups.

Medium-High Priority

10. Long-term reliability due to degradation phenomena.
11. Development of procedures to deal with safety.

Most of the initial 110 research projects represent unique ideas. The 11 final research opportunities, however, represent areas that could envelop several projects. The Study Team felt that it was difficult to prioritize and select among the many proposed projects, given the level of uncertainty associated with each one. Consequently, the 11 research opportunities selected by the Panel are areas in which specific research projects would most likely meet the assessment criteria outlined in Section 2.5. The 58 selected projects have each been correlated to a specific research opportunity. These are listed at the end of each of the following research opportunity descriptions and are presented in detail in Appendix A.

The following 11 sections present a discussion of each of the 11 research opportunities. For each, the following is presented:

- Rationale - why the idea is of benefit to PV;
- Description of the idea;
- On-going Non-PV Research - a listing of representative research efforts in this area; and
- Specific Research Projects proposed by the Study Team within the area of interest. Each project is further explained in Appendix A.

3.1 Research Opportunity #1: Fundamentals of Heterogeneous Nucleation and Growth on Dissimilar Substrates

Rationale

A potential method of reducing photovoltaic materials costs and increasing performance is to deposit films of high performance material on low-cost substrates. This may include, for example, deposition of thin gallium arsenide layers on silicon substrates, or deposition of gallium arsenide or silicon films on non-semiconductor substrates. A better understanding of the process of heterogeneous nucleation and growth will help to produce more uniform, higher quality, and, therefore, higher performance films. Furthermore, by understanding the general and specific mechanisms of nucleation and the growth and processing parameters that impact them, photovoltaic growth processes can be designed to produce desirable photovoltaic properties.

In the semiconductor area, work is being done to characterize growth and nucleation phenomena in order to design processes with high throughput that are compatible with subsequent processing of the same semiconductor device. For example, with sputtering, a layer can be deposited that is compatible with subsequent high temperature processing of the device. Characterization of the nucleation process for depositing dissimilar layers is important because different types of processes (e.g., sputtering and chemical vapor deposition) have different nucleation characteristics, and these will affect the subsequent processing conditions that can be tolerated. As almost identical process problems exist in the manufacturing of PV cells, much of this knowledge should be transferable to PV with positive results.

Description

The Study Team recommends that materials and processes that enable the combination of dissimilar materials for use in the semiconductor industry be identified and characterized. These same processes can be applied, where applicable, to the PV manufacturing process to result in savings in materials costs as well as to enhance process throughputs. Initial efforts should be focused on the identification of materials of known photovoltaic performance (e.g., band gap) characteristics. Further research can support the investigation

of these materials and processes in order to enhance specific desirable performance characteristics of PV devices.

Ongoing Non-PV Research

Relevant non-PV research efforts are being conducted in the U.S. for nucleation and growth of HgCdTe and CdTe on GaAs, and Al₂O₃. GaAs on Si and Si on SiO₂ activities are underway in both the U.S. and Japan. This research is being conducted for such applications as focal plane arrays, electronic displays, integrated circuits, and optoelectronics. Research institutions involved with this work in the U.S. are listed in Exhibit 3-1.

Specific Research Projects

The Expert Panel correlated one specific research project to this area of interest (a discussion is presented in Appendix A):

- TF-1: Fundamental thin-film crystal growth revealed through nucleation in chemical vapor deposition (CVD).

In addition, it is believed that further investigation into the work conducted by those researchers listed in Exhibit 3-1 will reveal additional ideas.

Exhibit 3-1. Ongoing Work Related to Research Opportunity #1

RO#1. Fundamentals of Heterogeneous Nucleation and Growth on Dissimilar Substrates..

<u>Researcher</u>	<u>Organization</u>	<u>Research Area</u>
Prof. J.P. Faurie	University of Illinois at Chicago	II-VI's on GaAs, sapphire, by molecular beam epitaxy (MBE)
Prof. Jan Schetzna	North Carolina State University	II-VI's on GaAs, sapphire, by MBE
Prof. Robert Gunshor	Purdue University	II-VI's on GaAs, sapphire, by MBE
Prof. Jim Harris	Stanford University	GaAs on Si by MBE
Prof. Herb Kroemer	University of California at Santa Barbara	GaAs on Si by MBE
Dr. Bor-Yeu Tsaur	Massachusetts Institute of Technology (MIT)/ Lincoln Laboratories	GaAs on Si by MBE
Dr. Grady Roberts	Texas Instruments	II-VI's on GaAs by metal-organic chemical vapor deposition (MOCVD)
Dr. Derek Cheung	Rockwell Int'l Science Center	II-VI's on GaAs by MOCVD
Dr. Dave Kisker	Bell Telephone Laboratories	II-VI's on GaAs by MOCVD
Dr. B.J. Morris	McDonnell Douglas Aerospace Corporation	II-VI's on GaAs by MOCVD
Dr. Joseph Schmidt	Honeywell R&D Center Minneapolis, MN	II-VI's on GaAs by MOCVD
Dr. George Celler	Bell Telephone Laboratories	Si on SiO ₂ by a range of transient and/or beam processing methods
Dr. Mike Geis	MIT/Lincoln Laboratories	Si on SiO ₂ by a range of transient and/or beam processing methods
Dr. A. Chaing	Palo Alto Research Center Xerox Corporation	Si on SiO ₂ by a range of transient and/or beam processing methods
Prof. S. Ghandhi	Rensselaer Polytechnic Institute Troy, NY	II-VI's on GaAs by MOCVD

Exhibit 3-1 (cont'd)

<u>Researcher</u>	<u>Organization</u>	<u>Research Area</u>
Dr. J. Fan	MIT/Lincoln Laboratories	GaAs on Ge by MOCVD
Dr. D. Shuskus	United Technologies	GaAs on Si by MOCVD
Prof. Henry Smith	MIT	Si on SiO ₂ by a range of transient and/or beam processing methods
Dr. H.Y. Lam	Texas Instruments	Si on SiO ₂ by a range of transient and/or beam processing methods
Dr. Jim Gibbons	Stanford University	Si on SiO ₂ by a range of transient and/or beam processing methods

3.2 Research Opportunity #2: Better Understanding of Heterojunctions (Theoretical and Experimental) in All Material Areas

Rationale

Many photovoltaic devices are composed of two or more layers of dissimilar semiconductors, and thus incorporate one or more heterojunctions. Therefore, better understanding of the properties of heterojunctions, in general, will result in a better understanding of the performance of a very broad class of photovoltaic devices. Furthermore, this understanding will result in the ability to access a wider variety of material properties in order to optimize photovoltaic performance, and potentially to reduce costs if lower-cost semiconductor materials can be utilized or the performance of existing materials can be improved. Development of alternative photovoltaic materials also opens up the possibility of developing more efficient, lower cost, and stable thin-film photovoltaic devices.

Because many new semiconductor devices also incorporate heterojunctions, considerable research is underway to characterize their properties and to optimize device performance. Work is also being carried out to tailor the specific material properties of heterojunctions to optimize performance for a given application, e.g., high electron mobility transistors and high speed optoelectronic devices. This research has resulted in an increased body of knowledge regarding heterojunctions that is directly applicable to PV, as many of the materials are the same for both the semiconductor and the PV technologies.

Description

Much of the work being carried out on the characterization and understanding of heterojunction properties for semiconductor applications is undoubtedly directly applicable to PV. The Study Team recommends that this work be thoroughly reviewed, abstracted, and disseminated to the PV research community. Emphasis should be placed on those heterojunction materials that have known photovoltaic properties. Some provision for a communication vehicle, for example, an "information clearinghouse," or seminar, or workshop, would also enhance the information transfer.

Ongoing Non-PV Research

Relevant non-PV research efforts involving heterojunctions of various materials are being conducted for light emitting diodes (LEDs), lasers, detectors, integrated circuits, and microwave field effect transistors (FETs). Additional applications include high speed analog and digital integrated circuits, optoelectronics, and focal plane arrays. Some research institutions involved with this work are identified in Exhibit 3-2. The U.S. Office of Naval Research, Defense Advanced Research Projects Agency (DARPA), and the Wright-Patterson Materials and Avionics Laboratories are currently funding domestic efforts in this area of research.

Specific Research Projects

The following research ideas are related to this area of interest (discussions of each are presented in Appendix A):

- 3V-1: Deep level transient spectroscopy (DLTS) studies of strained layer structures - use as feedback to improve growth methods;
- 3V-2: Use of scanning electron microscopy (SEM) techniques for characterizing interfaces in heterostructures;
- 3V-3: Atomic-plane doping studies in p and n dopants in MOCVD;
- 3V-4: Electronic transport through heterojunction barriers - theoretical and experimental studies for different systems;
- 3V-5: Strained layer superlattices - use of photo-luminescence as a tool for diagnostics;
- 3V-7: Electrical measurement of graded layers and correlations with physical parameters;
- TF-2: Zn(SSe) is used as a heterojunction or window in PV devices;
- TF-3: ZnO as a window or heterojunction in PV devices; and
- TF-4: Metal silicide-silicon photodiodes versus P-N junctions.

EXHIBIT 3-2. Ongoing Work Related to Research Opportunity #2

RO#2. Better understanding of heterojunctions (theoretical and experimental) in all material areas.

<u>Researcher</u>	<u>Organization</u>	<u>Research Area</u>
Prof. Tom McGill	California Institute of Technology	Theory, MBE growth, experimental measurements on III-V and II-VI heterojunctions
Prof. Dave Ferry	Arizona State University	Theory, particularly III-Vs
Dr. Bob Bauer	Palo Alto Research Center Xerox Corporation	MBE & MOCVD growth and experimental measurements on III-Vs
Dr. R. Ludeke	International Business Machines (IBM) Research Center Yorktown, NY	Growth and theory of III-Vs
Prof. J.P. Faurie	University of Illinois at Chicago	Theory and growth, and measurement of II-VI's
Prof. Jan Schetzina	North Carolina State University	Growth and measurement of II-VI's
Dr. A. Gossard	Bell Telephone Laboratories	Growth of III-V's
Prof. A. Milnes	Carnegie Mellon Institute	Fundamental Studies
Prof. A. Nussbaum	Univ. of Minnesota	Fundamental Studies
Prof. R. Anderson	Univ. of Vermont	Fundamental Studies

3.3 Research Opportunity #3: Alternative Device Designs which Exploit Processes Used for Non-PV Devices

Rationale

In the photovoltaics area, device designs are needed that are tolerant of properties that are inherent in the materials being employed in the device, such as defects in single crystal silicon and defects and grain boundaries in polycrystalline silicon. The goal of these new designs is to improve device performance and reliability without having to undertake expensive processing steps that improve the material to near perfection.

Researchers in the semiconductor industry are also working with material properties that are limiting device performance. These efforts are directed at surmounting the given limitations rather than developing materials with perfect properties. For example, polycrystalline silicon is being used as a conductive element in semiconductor devices. The characteristics of this material (e.g., higher than desirable resistivity in advanced applications requiring thinner and thinner films) are negatively impacting device performance. Work is being directed toward minimizing grain boundary effects of the polysilicon material through recrystallization processes or by combining thin layers of polysilicon with layers of more conductive materials.

Semiconductor research is also underway to provide a better understanding of the general nature of all silicon material in the range of forms from amorphous silicon to polycrystalline silicon. Investigators are paying specific attention to intermediate crystalline structures, generally referred to as microcrystalline silicon, which may offer the benefits of polycrystalline material at the cost of amorphous silicon material.

Description

The Study Team recommends an examination of specific processes used in the semiconductor industry to tailor device performance, such as passivation and recrystallization, to determine their applicability to photovoltaic devices. New device structures involving the combination of polycrystalline silicon with other materials should be investigated for applicability to PV devices, with special

attention given to microcrystalline material. Additional research or, at the very least, some technology transfer activity in each of these areas would be of direct benefit to PV technology.

Ongoing Non-PV Research

Relevant non-PV research efforts are being conducted for alternative device designs by both the private and government sectors. The private sector is focusing primarily on bipolar device designs while the Department of Defense's R&D in electron devices has focused on transient thermal processing for abrupt junctions and contact formation. Exhibit 3-3 identifies specific researchers.

Specific Research Projects

The Study Team identified the following specific projects related to this area of interest (discussions on each are presented in Appendix A):

- 3V-7: Optimization of epitaxial growth methods, including selective epitaxy;
- 3V-8: Use of oxygen/hydrogen implantations for fabrication of series-connected structures;
- 3V-9: Investigation of multiple impurity species for improved ohmic contacts;
- TF-5: Modulation of grain boundary conductivity in polycrystalline CdSe;
- TF-6: Transport properties of amorphous silicon;
- TF-7: Device designs for CdTe and CdSe solar cells;
- TF-8: Ultra-fine tin oxide particles for grids of PV devices;
- TF-9: Preparation of ZnO films by magnetron sputtering;
- TF-10: Remelting deposited thin films;
- TF-11: Cost:performance optimization of silicon PV devices;
- TF-12: Toleration of faults in design of PV devices;
- CS-1: Research studies to define the optimal processing parameters;
- CS-2: Research studies involving alternate designs and processing;
- CS-3: Research studies aimed toward combining crystalline silicon research ideas CS-1 and CS-2;

- CS-4: Applications of molecular beam epitaxy to silicon photovoltaics; and
- CS-5: Integrated circuits (IC) industry computer programs for PV device design.

In addition, attention to certain non-PV conferences would reveal additional ideas from related work. These conferences include the International Electron Devices Meeting and the Materials Research Society Annual Meeting (see Section 3.9 for more information).

EXHIBIT 3-3. Ongoing Work Related to Research Opportunity #3

RO#3. Alternative device designs which exploit processes used for non - PV devices

<u>Researcher</u>	<u>Organization</u>	<u>Research Area</u>
Dr. John Bean	Bell Telephone Laboratories	Si structures by MBE, Ge/Si Strained layer structures by MBE
Prof. Jim Gibbons	Stanford University	Si and insulators by limited reaction processing
Dr. Jeff Cheung	Rockwell Int'l Science Center	II-VI's by laser-assisted deposition
Dr. R.T. Tung	Bell Telephone Laboratories	Si/Silicide Schottky barrier growth and characterization
Dr. F. Capasso	Bell Telephone Laboratories	Superlattice structures
Dr. G.C. Osbourn	Sandia National Laboratories	Strained layer superlattice devices
Dr. Jim Mayer	Cornell University	Schottky barriers, layers, and doping by ion beam mixing
Dr. P.D. Persans	Exxon Research	Amorphous superlattice structures

3.4 Research Opportunity #4: Exploitation of Single Crystal II-VI and Related Films

Rationale

The II-VI and mixed II-VI compounds, such as CdTe and its alloys, represent materials that could have high solar cell efficiencies as well as reduced production costs. These materials use relatively thin films manufactured with relatively low cost processes. In many cases, single crystal II-VI materials have a better band gap match to the solar spectrum than single crystal silicon. In addition, these materials are potentially more stable than other thin-film materials such as amorphous silicon. In some cases relatively inexpensive processes, such as screen printing, have also been developed for depositing these materials on substrates.

Progress in this area has been limited because of an inability to investigate the limits of these materials in single-crystal form. Most work in photovoltaic II-VI compounds has been in polycrystalline materials, which offer lower efficiencies than single crystal materials. This is because the preparative techniques for single crystal II-VI semiconductors are not as advanced as those of the III-V semiconductors. Thus, a study of single crystal II-VI materials could open up a promising new area for photovoltaics.

In the semiconductor area, current research in II-VI compounds has been especially associated with metal-organic vapor phase epitaxy (MOVPE) and MBE. Use of these techniques permits tailoring of material structures down to the molecular layer and perhaps eventually the creation of defect-free structures. In this manner, the materials can be designed to exhibit unique performance parameters and thus match specific device requirements. For PV, therefore, this semiconductor research represents not only the potential of new, higher performance materials, but also the potential of creating specific, defect-free forms of these materials. The MOVPE and MBE processes under development may also be applicable to improving the performance of existing commercial materials.

Description

The Study Team recommends the identification and definition of specific material characteristics of the various II-VI compounds which most significantly affect photovoltaic performance. The fundamental understanding of vapor phase epitaxial process parameters of these compounds, which has received a comparatively small share of support and effort, also needs to be expanded. A review should be carried out of the status of II-VI MOVPE and MBE deposition techniques and the results made available to the PV research community. Research into the fundamental aspects of epitaxial CVD growth processes should be undertaken. This data should be made available to the PV community to offer the potential of improved processing alternatives.

Ongoing Non-PV Research

Relevant non-PV research efforts are being conducted within the U.S. by the researchers listed in Exhibit 3-4. Many of these research efforts are being conducted for such funding organizations as DARPA, Night Vision Electrooptics Laboratory, Air Force Materials Laboratory, the Army Research Office, and the Naval Research Laboratory.

Specific Research Projects

No specific research projects were identified for single crystal II-VI materials.

EXHIBIT 3-4. Ongoing Work Related to Research Opportunity #4

RO#4. Exploitation of single crystal II-VI and related films

<u>Researcher</u>	<u>Organization</u>	<u>Research Area</u>
Prof. J.P. Faurie	University of Illinois at Chicago	MBE of alloys and superlattices for Infrared (IR) devices
Prof. Jan Schetzina	North Carolina State University	MBE of alloys and superlattices for Infrared (IR) devices
Dr. Grady Roberts	Texas Instruments	Monolithic circuits on II-VI's
Dr. Kevin Reilly	Santa Barbara Research Center	IR photodiodes
Dr. Derek Cheung	Rockwell Int'l Science Center	IR photodiodes
Prof. Tom Sigmon	Stanford University	Ion implantation in II-VI's
Dr. Peter Becla	MIT/National Magnet Laboratory	Photodiodes in (HgMn)Te
Prof. Robert Gunshor	Purdue University	Electrooptical structures in wide band gap II-VI's
Dr. Peter Chow	Phi (The Perkin-Elmer MBE equipment subsidiary)	MBE equipment and process research and development
Dr. Joseph Schmidt	Honeywell R&D Minneapolis, MN	MOCVD of II-VI's
Prof. Sorab Ghandhi	Rensselaer Polytechnic Institute	MOCVD of II-VI's
Prof. Peter Wolff	MIT/National Magnet Laboratory	Growth and properties of widegap II-VI compounds
Dr. Dave Kisker	Bell Telephone Laboratories	MOVPE
Dr. Stan Whitely	McDonnell Douglas	MOVPE
Dr. W. Algnen	Santa Barbara Research Center	MOVPE
Dr. R. Hoke	Raytheon	MOVPE
Dr. Brian Mullin	Royal Signals and Radar Equipment (RSRE) (England)	MOVPE
Dr. B. Hylands	General Electric Company (GEC) (England)	MOVPE

Rationale

A number of new processing techniques for photovoltaic cells have been developed, such as ion implantation, which can create better and more precisely defined junctions and contacts as well as stable passivation layers. However, many of these new processing techniques also result in damage to the crystal lattice, negatively impacting device performance. Therefore, new thermal processing techniques, including rapid recrystallization processes such as laser recrystallization, need to be developed if advantage is to be taken of these junction formation and other improved processing techniques.

Related research is being carried out in the semiconductor area, primarily motivated by the need to reduce the thermal budget (temperature multiplied by time) in order to quickly add and remove heat to a device that is being processed. In particular, with the thin junctions that are becoming more common in semiconductor devices, excessive heat causes diffusion between layers, resulting in unwanted side effects. These problems have become critical as the junctions have become thinner. In addition, other issues being addressed in the semiconductor area that result from consecutive heating during processing include the creation of reliable contacts, removing lattice damage, recrystallization of polycrystalline silicon to remove grain boundaries, and so forth.

Description

Although this area can be considered a subset of Research Opportunity #3 (Alternative device designs...), the panel identified it as a separate item to highlight its importance.

The concept of a thermal budget and its effect on the potential interaction between the various layers of thin-film devices has not yet been widely investigated in the PV area. Research should be initiated in this area.

In addition, investigations should be carried out on advanced thermal processes being used to solve semiconductor fabrication problems to determine which of these may be applicable to photovoltaics. The transfer of general

information concerning advanced thermal processes and their capabilities should be a starting point. Additional work should also be undertaken to characterize the effect that these techniques would have on the processing of PV cells. This is because of the different requirements placed on these processes. The goal of rapid thermal processing in high speed devices is usually the formation of low resistance contacts. For photovoltaics, the enhancement of lifetime is of much greater importance.

Ongoing Non-PV Research

Sponsorship of relevant non-PV research efforts is dispersed throughout the Department of Defense, in agencies such as the Air Force-Rome Air Development Center (AF-RADC), DARPA, U.S. Office of Naval Research (GaAs work), and Hanscom Air Force Base. Researchers are listed in Exhibit 3-5. Most of these researchers are doing work in crystalline silicon. There has been little application of transient thermal processing to III-V materials, largely because very early attempts failed. There may be a need for an investigation into transient thermal processing for III-V materials.

Specific Research Ideas

The Study Team identified the following research projects in transient thermal processing (discussions on each are presented in Appendix A):

- 3V-10: Rapid thermal anneal for contact formation;
- 3V-11: Ion beam techniques for contact formation;
- TF-13: Flash evaporation of amorphous silicon and CuInSe₂ films;
- TF-14: Beam recrystallization of polycrystalline thin films;
- CS-6: Fabricate and test solar cells using laser annealing of heavily-doped emitters;
- CS-7: Investigate the feasibility of using the excimer laser to produce extremely thin and heavily doped layers;
- CS-8: Research to remove impurities and lessen recombination by gettering.

EXHIBIT 3-5. Ongoing Work Related to Research Opportunity #5

RO#5. Exploration of transient thermal processing

<u>Researcher</u>	<u>Organization</u>	<u>Research Area</u>
Dr. Arnon Gat	AG Associates, Inc.	Transient processing equipment development and sales
Prof. Jim Gibbons	Stanford University	Limited reaction processing of silicon and GaAs structures
Dr. Bor-Yea Tsaur	MIT/Lincoln Laboratories	Thin film silicon processing
Dr. T.O. Sedgwick	IBM Research Center Yorktown, NY	Transient processing of implanted silicon
Dr. J.C. Gelpey	Eaton Ion Beam Systems	Transient processing equipment
Dr. R.E. Sheets	Tamarack Scientific Co.	Transient processing equipment
Dr. J.P. Krusuis	Cornell University (Submicron Facility)	Oxidation and Nitridation of Silicon

3.6 Research Opportunity #6: Investigation of Non-Equilibrium Energy Beam Assisted Processes

Rationale

It is of considerable interest to the photovoltaic industry to produce high-quality, stable thin-film devices with low manufacturing costs. This involves the production of stable, high-quality films at high deposition rates. Various non-equilibrium energy beam assisted processes can both increase the speed of film deposition and enhance film quality by reducing plasma damage to the films. In many cases, this reduces the operational temperature of a specific deposition process so that the initial layer of the structure is not disturbed by subsequent deposition or processing steps.

In the semiconductor industry, goals are similar to those for photovoltaics -- to achieve lower temperature deposition processes in order to realize very shallow junctions and contacts, deposit a wider variety of materials more uniformly, resulting in better quality films. Reduction of plasma damage is again a primary consideration. An example of work in this area is the deposition of dielectric and metallic materials on top of semiconductor wafers. In devices where there are multiple layers, this must be done without damaging underlying, previously deposited layers. Additional advanced processing, such as trenching into the silicon wafer in order to provide device isolation and to construct vertical capacitors, will also require carefully controlled, preferably low temperature deposition processes. These advanced growth processes allow more exact control over device dimensions and, subsequently, improve the ultimate reliability of the finished device.

Description

As with Research Opportunity #5, this area can be considered a subset of Research Opportunity #3 (Alternative device designs...), but is identified separately to highlight its importance. The Study Team recommends that a survey be conducted of the various non-equilibrium energy beam assisted processes that have been developed for the semiconductor industry to identify those that may be applicable to thin-film PV device fabrication. Special

emphasis should be placed on those processes that have the potential for increasing film deposition rates at low cost, while preserving or enhancing film quality. While the initial efforts should again be directed at technology transfer, additional research using these techniques for the manufacture of PV devices, at least at the laboratory level, should be undertaken in order to evaluate these techniques and their importance to the PV community.

Ongoing Non-PV Research

A wide base of industrial and university research is being conducted in this area. The major research efforts listed in Exhibit 3-6 are being conducted for such funding organizations as Air Force Office of Scientific Research (AFOSR), DARPA, Electric Power Research Institute, and the Night Vision Laboratory. In addition, private sector efforts are being conducted by Bell Laboratories and IBM.

Specific Research Projects

The Study Team identified the following specific research ideas (discussions on each are presented in Appendix A):

- 3V-12: Laser stimulated MOCVD growth and photolytic and/or plasma growth techniques for large areas cells; and
- CS-9: Applicability of photo-induced chemical vapor deposition of silicon dioxide to solar cells.

EXHIBIT 3-6. Ongoing Work Related to Research Opportunity #6

RO#6. Investigation of non-equilibrium energy beam assisted processes

<u>Researcher</u>	<u>Organization</u>	<u>Research Area</u>
Prof. N. Bloembergen	Harvard University	Pulsed laser interaction with materials
Prof. Richard Osgood	Columbia University	Ultraviolet photoelectric deposition of semiconductor materials
Dr. Robert Seliger	Hughes Research Laboratory	Focused ion beam processing
Dr. Dan Ehrlich	MIT/Lincoln Laboratory	Laser-induced photochemical deposition and etching
Dr. R.M. Lum	Bell Telephone Laboratories	Laser-induced photochemical deposition and etching
Prof. D. Adler	MIT	Laser-induced chemical vapor deposition
Prof. G.J. Collins	Colorado State University	Electron and photochemical cleaning processes
Dr. A.R. Calloway	Aerospace Corporation	Photoabsorption cleaning processes
Dr. Dave Kisker	Bell Telephone Laboratories	Photo-induced MOVPE
Dr. Stan Whitely	McDonnell Douglas	Photo-induced MOVPE
Dr. Brian Mullin	RSRE (England)	Photo-induced MOVPE

3.7 Research Opportunity #7: Advanced Characterization Methods for Examining Materials -- Basic Research and Process Control

Rationale

The development of new material structures for photovoltaic devices, especially in the thin-film area, requires the use of various advanced instrumentation and analytical techniques to determine the effect of changes in process variables on the characteristics of the devices. Also, the performance of advanced devices needs to be correlated with device structures so that alternative structures can be evaluated and optimized to achieve maximum performance. Finally, especially in the thin-film area where device degradation has become a key problem, advanced characterization procedures are required to correlate the observed degradation with observable changes in material properties. This will enable the mechanism of degradation to be better understood. With this understanding will come the potential of control. Examples of some of the types of instrumentation that are being used to characterize materials, particularly thin films, are:

- X-ray photoelectron spectroscopy (XPS);
- Energy dispersive x-ray analysis (EDXA);
- Ion scattering spectroscopy (ISS);
- Photo and Cathode Luminescence (PL,CDL);
- Auger electron spectroscopy (AES);
- Rutherford back scattering (RBS);
- Deep level transient spectroscopy (DLTS); and
- Secondary ion mass spectrometry (SIMS).

In the semiconductor area, work is being carried out essentially along the same lines as that in photovoltaics, although the type of material properties and parameters that must be optimized are often different. Many of the characterization techniques and much of the instrumentation developed for the semiconductor industry have been found to be applicable to the characterization of photovoltaic devices as well. While some of this body of knowledge and the instruments themselves have already been applied to PV research, the cost of the equipment used for such characterizations and measurements is very high.

Description

Much of the advanced characterization instrumentation required for photovoltaic material analysis is very expensive. Therefore, a valuable service to the photovoltaic research community, in particular to universities although to some extent to industry as well, would be to make such equipment available at a central location for use by the industry. Alternatively, such capabilities could be dispersed in several regions around the country, for example, at several of the national laboratories where photovoltaic research is being conducted. Access to such advanced equipment would certainly enhance the research efforts of the many universities and industrial companies involved.

Ongoing Non-PV Research

Relevant non-PV research efforts are scattered throughout private laboratories, particularly instrument manufacturers, and DoD contractors. DoD sponsorship is provided by such funding organizations as the Air Force Avionics Laboratory, DARPA, Air Force Tactical Air Command (AFTAC), NSF, and the U.S. Office of Naval Research. Exhibit 3-7 identifies specific research teams.

Specific Research Projects

The Study Team identified the following research projects in this area of interest (discussions on each are presented in Appendix A):

- 3V-1: DLTS studies of strained layer structures - use as feedback to improve growth methods;
- 3V-2: Use of SEM techniques for characterizing interfaces in heterostructures;
- 3V-13: New techniques for measuring minority carrier diffusion length, especially for interior layers in devices;
- 3V-14: DLTS to study interface states between layers - improvement of growth methods based on this data;
- 3V-15: The use of DLTS as a process tool;
- 3V-16: Correlation of impurities in a reactor environment with quality of grown layer;
- 3V-17: Surface acoustic wave diagnostics for III-V alloys;

- 3V-18: Electrolyte electro-reflectance (EER) techniques for large-area devices;
- 3V-19: Use of high-resolution Fourier transform infrared (FTIR) techniques to complement photoluminescence and DLTS as diagnostic tools;
- 3V-20: Non-invasive techniques for measurement of layer composition, as well as layer doping across a wafer;
- 3V-21: Mass spectrometry studies of the gas ambient - both at reactor entry and exit;
- TF-15: Analysis of polysilicon devices;
- TF-16: Electronic structures of new crystalline materials and amorphous silicon; and
- CS-10: Application of the optical modulation technique for the determination of photogenerated carrier lifetime in silicon.

EXHIBIT 3-7. Ongoing Work Related to Research Opportunity #7

RO#7. Advanced characterization methods for examining materials -- basic research and process control

<u>Researcher</u>	<u>Organization</u>	<u>Research Area</u>
Prof. Cal Quate	Stanford University	Acoustic and scanning tunneling microscopy
Dr. C.A. Evans	C.A. Evans and Associates	Development and application of SIMS, RBS, and related high resolution surface analysis methods
Prof. Peter Williams	University of Arizona	Research in SIMS techniques
Prof. Tom Signmon	Stanford University	RBS research and applications
Prof. Robert Helms	Stanford University	Auger electron spectroscopy and related methods (research and applications)
Dr. Pierre Petroff	Bell Telephone Laboratories	Transmission Electron Microscopy (TEM) for analyses of semiconductor layered structures
Prof. Bill Spicer and Ingolf Landau	Stanford University	Semiconductor analysis applications of synchrotron radiation
Prof. Gareth Thomas	University of California at Berkeley	TEM
Dr. R.F. Pinizzotto	Ultrastructure, Inc.	TEM and surface analysis methods (applications)
Dr. F.A. Ponce	Palo Alto Research Center Xerox Corporation	High resolution TEM and lattice imaging
Dr. N. Otsuka	Purdue University	High resolution TEM and lattice imaging
Prof. A. Milnes	Carnegie Mellon Institute	DLTS techniques for compound semiconductors
Prof. Greg Stillman	University of Illinois	FTIR studies of compound semiconductors
Prof. Paul Raccah	University of Illinois at Chicago	EER studies of compound semiconductors

Rationale

Surface recombination effects and grain boundary effects (impurities acting as recombination centers) have consistently been a major source of reduced performance in photovoltaic devices. Efficiency of single crystal and polycrystalline photovoltaic devices could be improved significantly through the use of various passivation techniques that neutralize these effects. Since recombination centers exist at surfaces, in the bulk and at grain boundaries, a variety of passivation techniques need to be explored, including the use of minority carrier mirrors, as well as layers which can act to getter impurities from the bulk. Other surface and grain boundary passivation techniques, such as the use of hydrogen in polycrystalline silicon cell passivation, have also been proven to be quite effective in improving device performance.

Use of surface passivation techniques as a treatment of semiconductor devices has a somewhat different orientation. In particular, passivation is used to protect sensitive device surfaces from damage and also acts to keep the surface free from contaminants. On the other hand, techniques such as the use of back surface passivation have been applied to getter impurities from the bulk material, whereas back surface fields (BSF) have been used as minority carrier mirrors. These approaches are also applicable to PV, and in some limited cases, these techniques have already been transferred.

Description

Some techniques for passivation of surfaces and grain boundaries have been independently developed for PV devices while others have already been transferred from the semiconductor industry. However, the Study Team recommends that a new survey be conducted to identify and define advanced passivation techniques now being used for semiconductors. This survey should analyze whether these techniques are applicable to PV and, specifically, how they would be applied. A research program to apply these to PV on an experimental basis should be initiated, with the resulting experimental information and data widely communicated to the PV community.

Ongoing Non-PV Research

Virtually every industrial and university microelectronics integrated circuits (IC) laboratory is doing something in the area of passivation, particularly the GaAs IC community. Organizations such as IBM, Motorola (in bipolar IC's), Dow Corning, and Rome Air Development Center (RADC) have major research programs. Two specific research teams are identified in Exhibit 3-8. In addition, the DoD agencies listed in RO#9 all have programs of interest.

Specific Research Projects

The Study Team identified the following specific research projects of interest to this area (discussions on each are presented in Appendix A):

- 3V-22: Passivation of InP surface using oxides, polysulfides, etc., and evaluation of the results;
- TF-5: Modulation of grain boundary conductivity in polycrystalline CdSe;
- TF-17: BP on silicon as a surface passivant;
- TF-18: Improved understanding of semi-insulating polysilicon (SIPOS);
- TF-19: SiC as surface passivant or new transparent contact;
- TF-20: Surface passivation of GaAs solar cells;
- TF-21: Inherent surface passivation of GaAs;
- TF-22: True thin-film polycrystalline silicon;
- CS-1: Research studies to define the optimal processing parameters;
- CS-2: Research studies involving alternate designs and processing;
- CS-3: Research studies aimed toward combining crystalline silicon research ideas CS-1 and CS-2;
- CS-11: Exploration of a method for improving recombination properties of silicon;
- CS-12: Determination of the dominant defect responsible for unavoidable recombination;
- CS-13: Adaptation of SIPOS to solar cells; and
- CS-14: Explore the use of phosphorous diffusion in gettering.

EXHIBIT 3-8. Ongoing Work Related to Research Opportunity #8

RO#8. Passivation of surfaces and grain boundaries

<u>Researcher</u>	<u>Organization</u>	<u>Research Area</u>
Dr. Keith Michael	Dow-Corning Research	Si, SiO ₂ and Si ₃ N ₄ polymers for passivation and hermetic sealing
Dr. Robert Thomas	Rome Air Development Command (RADC)	IC reliability

3.9 Research Opportunity #9: Improved Interaction -- One-on-One Liaison Between DOE, DoD, and Other Research Groups

Rationale

There is a great deal of ongoing research in the semiconductor device and materials areas sponsored by DoD and other government organizations. Because of the smaller amount of funding available and the smaller size of the research community in photovoltaics, much less research is sponsored. Therefore it is likely, as this particular study has shown, that a great deal of semiconductor-related research is potentially of interest for application to photovoltaic devices. Thus, by transferring this research to the photovoltaic community, opportunities for research into new devices and materials can be stimulated and the pace of existing PV research can be accelerated.

Description

The Study Team recommended several ways of improving interaction between the PV community and other research groups. First, formalize a liaison group to meet at least once each year to exchange information and provide guidance to the PV Program and its liaison efforts. This group should be similar to the Study Team for this report, but with more DoD researchers such as those listed in Exhibit 3-9. Second, distribute this report (to both PV and non-PV researchers) in conjunction with one of the PV Program's innovative research programs, to encourage the transfer of DoD technology to PV and to attract the interest of non-PV researchers. Third, the PV Program should carefully review this report in search of specific ideas which can be incorporated into the Program as it is now structured. Finally, encourage PV researchers to attend non-PV conferences such as those identified in Exhibit 3-10.

EXHIBIT 3-9. Ongoing Work Related to Research Opportunity #9

RO#9. Improved Interaction: -- One-to-One Liaison Between DOE, DoD, and Other Research Groups

Potential DoD Liaison Contacts

<u>Researcher</u>	<u>Organization</u>	<u>Research Area</u>
Dr. John Dimmock	Air Force Office of Scientific Research (AFOSR)	Basic research in defense sciences
Dr. Ken Davis	Office of Naval Research (ONR)	Basic research in electron materials and devices
Dr. Merrill Mengus	Air Force Materials Laboratory (AFML)	Basic research in electron materials and devices
Dr. Howard Lessoff	Naval Research Laboratory (NRL)	Basic research in electron materials
Dr. Ken Slager	Naval Research Laboratory (NRL)	Basic research in integrated circuits
Dr. James Ionson	Strategic Defense Initiative (SDI)	Basic research in electron materials and devices
Dr. Gordon Rabanus	Avionic Laboratory	Basic research in electron materials and devices
Dr. John Hurt	Army Research Office (ARO)	Basic research in electron materials and devices
Mr. Sven Roosild	Defense Advanced Research Projects Agency (DARPA)	Basic research in electron materials and devices
Dr. Leo Young	Office of the Under Secretary of Defense for Research and Engineering (OUSDRE)	Basic research in electron materials and devices
Advisory Group on Electron Devices - Dr. Jack Kilby, Chairman (reports to Dr. E.G. Maynard Director VHSIC and Electron Devices)	Office of the Under Secretary of Defense for Research and Engineering (OUSDRE)	Reviews DoD applied research and development of electronic devices and materials

EXHIBIT 3-10. Specialty Research Conferences Pertinent To PV Materials and Devices

Physics and Chemistry of Semiconductor Interfaces (PCSI)	Held annually end of January (Pasadena, CA 1986). Largely III-V oriented.
Semiconductor Interface Specialists Conference (SISC)	Held annually first week of December (Ft. Lauderdale, FL 1985). Largely silicon and SiO ₂ oriented.
Materials Research Society (MRS)	Annual meeting first week of December in Boston; spring meeting in Western U.S. covers all materials & processes.
U.S. Workshop on HgCdTe	Held every 12-18 months (next meeting in Dallas, TX Oct. 1986). Covers all research on Hg containing II-VIs.
International Conference on Crystal Growth (ICCG)	Held every other year (next meeting July 1987 in San Francisco, CA).
American Conference on Crystal Growth (ACCG)	Held annually in May or June, usually at Falls Leaf Lake, CA. Covers all research aspects of semiconductor crystal growth.
International Conference on Vapor Phase Epitaxy and Crystal Growth	Held every other year in July (next meeting is 1986). Covers all aspects of semiconductor crystal growth and characterization.
GaAs IC Symposium	Held every year in the fall (next meeting is Nov 12-14, 1985 in Monterey, CA). Covers all aspects of GaAs materials and processes for ICs as well as ICs themselves
International Electron Devices Meeting (IEDM)	Held first week of December each year (next meeting is Dec 1-3, 1985 in Washington, DC). Covers all aspects of silicon, GaAs, etc., materials processes and devices.
Electronic Materials Conference (EMC) and Device Research Conference (DRC)	Held back-to-back in last week of June each year. More fundamental than IEDM. Strong III-V materials/devices/optoelectronics emphasis, but also deals with silicon technologies. (Next meeting is at University of Massachusetts in June 1986).

3.10 Research Opportunity #10: Long-Term Reliability Due to Degradation Phenomena

Rationale

One of the key problem areas in developing thin-film photovoltaic technology for outdoor power module applications is the long-term stability and reliability of the devices. Device stability can be reduced by a number of different phenomena, including contact problems between electrodes and the underlying films (e.g., SnO_2 /amorphous Si), intrinsic characteristics of the bulk material, impurities, and mechanical stress on the film during deposition. Mechanical stress induced over a longer term, due to thermal cycling of the glass substrate in the application environment, is also a key problem area. Understanding of degradation mechanisms affecting each of these areas is fundamental to the long-term success of the photovoltaic thin-film industry. At this time, some of the intrinsic properties of thin films, particularly amorphous silicon, that result in degradation upon long-term exposure to light are now beginning to be understood. However, many of the problems involving contact problems and stress in films are poorly understood and require significant amounts of additional research if solutions are to be found and implemented.

As integrated circuit devices and their components become smaller and smaller, long-term reliability is also becoming more of a problem for the semiconductor industry. This is especially significant in relation to metallic interconnections and the migration of materials within a layer, as well as from one layer to the next. This migration can be induced by elevated operational temperatures, high current densities, and electrostatic fields that are present in devices due to the inherent designs. Measurement and assessment of device reliability to address these problem areas is an ongoing process in the semiconductor industry, and is considered a very high priority activity, now and for the foreseeable future.

Description

The Study Team recommends that a program be initiated to review the reliability problems that occur in semiconductor devices, how reliability and the parameters that affect it are being measured, and the techniques that are

being used to increase reliability. If any of these can be shown to be applicable to PV reliability problems, then a technology transfer program should be initiated to ensure that the PV community benefits from such knowledge and techniques.

Ongoing Non-PV Research

Most organizations involved in major IC research are also participating in the area of reliability. Dr. Robert Thomas of Rome Air Development Command is the center of activity for DoD's IC reliability R&D. Also involved in this area is Professor Jay Sathrop of Clemson University.

Specific Research Projects

No specific research projects were identified within this area of interest.

3.11 Research Opportunity #11: Development of Procedures to Deal With Safety

Rationale

As the use of alternative materials and devices in the photovoltaic industry becomes more prevalent, the potential for a greater exposure of both research and manufacturing personnel to toxic gases and liquids will exist. This includes materials such as arsenic, mercury, selenium and their compounds as well as other potentially hazardous materials such as disilane, which is explosive. As the use of these materials becomes more widely adopted, there will have to be a greater emphasis on personal safety in the industry than has been demonstrated to date. Environmental protection will also need to be emphasized as new by-products and waste gases resulting from advanced device processing have the potential of being released to the atmosphere or to water supplies, either directly or indirectly.

Many of the problems that are being encountered in the photovoltaic industry have already been encountered in the semiconductor industry. This industry was once thought to be a "clean" industry, presenting a relatively low level of hazard to workers. However, this attitude has changed in the past few years as the extent of the exposure to various types of toxic materials has been appreciated, and as some of the waste disposal problems, in particular contamination of groundwater, have come to light. Advanced processing of devices has also introduced new hazards. In particular, the by-products of plasma etching and ion implantation are known to be very toxic and their disposal is a problem, although the amounts in question are very small. As new materials and processes are developed and utilized, new control techniques will have to be developed to ensure the safety of the workers and the environment.

Description

To date, the photovoltaic community has practiced careful control of its use of toxic materials. However, the number and quantities of these materials in use, many of which are already used in the semiconductor industry, is increasing in the PV industry. Because the photovoltaic industry could benefit greatly from experience already obtained in the semiconductor industry, workshops and seminars should be organized in which information about safety and

environmental problems could be transferred to cognizant individuals within the photovoltaic community. Alternatively, a workshop on safety could be organized with an appropriate industry organization such as SEMI (Semiconductor Equipment and Materials Institute) with photovoltaics as a component of the workshop.

In addition, the photovoltaic community could encourage use of those processes which use materials which are less toxic, or use smaller quantities of toxic materials. For example, vacuum MOCVD uses less reactant than ordinary (atmospheric pressure) MOCVD.

Ongoing Non-PV Research

Today, the primary supplier of MOCVD materials is Alfu Ventron Corporation. However, most major chemical companies are considering entry into the high technology electronic materials field, principally as suppliers of MOCVD sources. These companies include American Cyanamid, Stauffer Chemical Corporation, Ethyl Corporation, and Celanese Research Corporation. It should also be noted that the Solar Energy Research Institute (SERI) is conducting a photovoltaics safety workshop in early 1986.

Specific Research Projects

No specific research projects were identified within this area of interest.

4.0 CONCLUSIONS

This study was conducted with the cooperation of several leading experts in the PV research field. These researchers developed 11 recommendations. Ten of these recommendations represent technical areas in which non-PV research would most likely contribute to the advancement of photovoltaics. One recommendation, Research Opportunity #9 (Improved Interaction...) is an institutional recommendation.

The technical areas were carefully selected. For example, Research Opportunity #1 is "Fundamentals of Heterogeneous Nucleation and Growth on Dissimilar Substrates". This item was selected because it represents an area in which:

- (1) there is considerable non-PV research;
- (2) the research could benefit photovoltaics;
- (3) the research is currently not being transferred to photovoltaics;
and
- (4) technology transfer to photovoltaics is not likely to occur
without government assistance.

In addition, 58 specific research projects were identified within the 11 areas of interest. These projects represent the best ideas resulting from an exhaustive literature search and productive technical discussion. However, it was beyond the scope of this study to conduct an intensive investigation into any one area or project. This study serves to identify potential projects and prioritize areas of interest. It is believed that many more projects could be identified if a more focused, intensive investigation were conducted into any of the 11 research areas. Interaction with the semiconductor research managers listed in this report would be a major component of such an investigation.

The recommendations in this study represent a consensus of the Study team. There is, however, one dissenting opinion. Dr. Don Morel believes that the recommendations place too much emphasis on III-V compounds and not enough emphasis on II-VI thin films. They believe that non-PV research in this area has been growing at a rapid pace, and that the photovoltaic community is missing numerous opportunities to take advantage of recent advances in II-VI thin film materials.

Research Opportunity #9, "Improved Interaction Between DOE, DoD, and Other Research Groups," represents the only non-technical recommendation. Several members of the Study Team suggested that this item be highlighted in this report because of its importance in implementing the technical recommendations. To support this request, the authors have developed a list of recommendations for implementing the results of this study. These recommendations were put forth by members of the Study Team but not necessarily voted upon by the entire team. Programmatic, or institutional recommendations are as follows:

- (1) Convene a liaison group to meet once or twice a year to facilitate information exchange between PV and non-PV researchers. This group should be similar to the Study Team but with the addition of additional semiconductor (non-PV) experts.
- (2) Encourage PV researchers to attend the semiconductor conferences listed in Exhibit 3-10. DOE could help sponsor this activity through existing R&D contracts.
- (3) Encourage unsolicited proposals for innovative research in the 11 research areas. This could be done by SERI as part of their innovative ideas program. To facilitate this activity, this report could be distributed to PV researchers and to selected researchers in the IC community by SERI, along with an innovative ideas program announcement.
- (4) Investigate each recommendation in this report in greater depth to define specific activities that could be incorporated into the existing DOE PV Program (other than in innovative ideas).

Each of the technical recommendations also includes suggestions on how to begin implementing activities in each research area. These suggestions, summarized below, represent a "shopping list" of potential activities suitable for DOE sponsorship.

- (1) R0#1. Identify and characterize relevant materials and processes under development by the semiconductor industry for heterogeneous nucleation and growth on dissimilar substrates.
- (2) R0#2. Conduct a seminar or workshop on heterojunctions in all material areas that may relate to PV. The workshop must include non-PV researchers.
- (3) R0#3. Sponsor research to develop alternative device designs which exploit processes used for non-PV devices, especially in the microcrystalline area.
- (4) R0#4. Conduct a review of the state-of-the-art knowledge of material properties of II-VI compounds and epitaxial growth techniques (especially MOVPE and MBE). Make results available to the PV research community.
- (5) R0#5. Investigate advanced thermal processes used to solve semiconductor fabrication problems to determine which may be applicable to photovoltaics. Disseminate results.
- (6) R0#6. Conduct a survey of non-equilibrium energy beam assisted processes in the semiconductor field to determine those that may be applicable to PV device fabrication. Disseminate results and sponsor laboratory-level research in selected processes.
- (7) R0#7. Establish one or more centers with advanced characterization methods for examining materials. These should be accessible to industry and program contractors. An investigation of advanced equipment should precede establishment of the centers.
- (8) R0#8. Conduct a survey of advanced passivation techniques now being used for semiconductors. Disseminate results to the PV research community and encourage proposals for research to incorporate these techniques in PV processes.
- (9) R0#9. See institutional recommendations (on page 49).

- (10) RO#10. Conduct a review of reliability problems in semiconductor devices and how these problems are being addressed. Identify areas that are applicable to PV. Encourage research proposals to incorporate these ideas into PV devices, particularly in the thin films area.
- (11) RO#11. Organize a workshop on safety with an appropriate industry organization (such as SEMI, the Semiconductor Equipment and Materials Institute) with photovoltaics as a component of the workshop.

When this study was initiated, it was believed that a thorough review of semiconductor research literature would uncover one or two "great" new ideas. The result, however, is a list of many good ideas. The volume of related research being conducted in fields other than photovoltaics is overwhelming. As a result, it was not possible to review any one area or project in detail. However, this study has served to screen the many research areas, identify those of interest to photovoltaics, and prioritize 11 areas according to their likelihood of success should further research be pursued. Therefore, the final recommendations of this study should be viewed as a first attempt to sort through a wealth of information to uncover several good ideas. Considerable additional work is necessary for these ideas to be fully defined, developed, and brought to fruition.

APPENDIX A: RESEARCH PROJECTS

- A.1 III-V Compounds
- A.2 Thin Films
- A.3 Crystalline Silicon

RESEARCH PROJECTS

A.1 III-V COMPOUNDS

3V-1: DLTS Studies of Strained Layer Structures -
Use as Feedback to Improve Growth Methods

IDEA DESCRIPTION/RATIONALE:

Problems to be solved include development of practical measurement schemes and proper interpretation of the data.

The strained layer structure is considered by many to be the answer to the heteroepitaxy of materials with a large amount of mismatch. Their growth is relatively simple by MOCVD. However, the resulting active layers must be acceptable if the technique is to be useful. Deep level transient spectroscopy is a possible tool for determining active layer acceptability since it is capable of providing defect data in bulk materials and also at interfaces. The extension of this technique to strained layer structures may result in a very valuable diagnostic tool.

LITERATURE CITATION:

"Minority-Carrier Diffusion Lengths in GaP/GaAs_x/P_{1-x}/ Strained-Layer Superlattices," Gourley, P.L., Biefeld, R.M., Zipperian, T.E., Wiczer, J.J.; Sandia Nat. Lab., Albuquerque, NM; Appl. Phys. Lett. (USA), Vol. 44, No. 10, pp. 983-5; May 15, 1984.

3V-2: Use of SEM Techniques for Characterizing Interfaces in Heterostructures

IDEA DESCRIPTION/RATIONALE:

Specifically, by altering the beam energy of the scanning electron microscope, depth probing of a device can be performed. Problems are in the area of proper interpretation of the results.

The scanning electron microscope allows the probing of a semiconductor by a high resolution energetic beam. Its use, in combination with charge collection techniques, has been exploited to determine minority carrier lifetime in active layers, as a function of both depth and area. (This work was done in conjunction with the diagnostics of poly-GaAs solar cells). The technique has also been extended to probing the interface between a layer and the substrate. Results of this type can provide feedback to the growth process, with the eventual goal of minimizing these effects.

LITERATURE CITATION:

"Study of Compound Semiconductor Surfaces and Interfaces," Spicer, W.E.; Stanford Univ., Stanford, CA.

3V-3: Atomic-Plane Doping Studies for P and N Dopants in OMCVD

IDEA DESCRIPTION/RATIONALE:

Atomic layer epitaxy is closely related to this approach and has possibilities for strain accomodation in multi-layer structures.

This is a relatively new approach -- most work has been conducted in Finland with some recent work done in Japan. It appears useful as a means for precise doping in a thin layer and also for precise growth of thin layers at low temperature. This approach could result in improvement in tunnel junctions for wide band gap materials.

LITERATURE CITATION:

"Free Carrier Profile Synthesis in MOCVD Growth GaAs by 'Atomic Plane' Doping," Ohno, H., Ikeda, E., Hasegawa, H.; Department of Electrical Engineering, Hokkaido University, Sapporo, Japan; Japan Journal of Applied Physics Part 2 (Japan), Vol. 23, No. 6, pp. L369-70; June 1984.

"Molecular Layer Epitaxy," Nishizawa, J., Abe, H., Kurabayashi, T.; Journal Electrochem. Soc., Vol. 132, p. 1197; 1985.

3V-4: Electronic Transport Through Heterojunction Barriers -
Theoretical and Experimental Studies for Different Systems

IDEA DESCRIPTION/RATIONALE:

Most modern solar cell devices incorporate herterojunctions. Better theoretical understanding of these structures is required at the present time.

LITERATURE CITATION:

"Electron Transport Through the MOCVD Grown GaAs/AlGaAs/GaAs Heterojunction Barrier," Hase, I., Kawai, H., Kaneko, K., Watanabe, N.; Res. Center, Sony Corp., Yokohama, Japan; Electron. Letter (Great Britain), Vol. 20, No. 12, pp. 491-2; June 7, 1984.

"Interface Properties of Lattice-Matched InGaAsP/InP Heterojunctions," Stillman, G.E., Tashima, M.M.; Department of Electrical Engineering, Illinois University at UrbanaChampaign; Final Report, August 21, 1977 - August 22, 1980.

3V-5: Strained Layer Superlattices -
Use of Photoluminescence as a Tool for Diagnostics

IDEA DESCRIPTION/RATIONALE:

Very little is known about these structures except that they are promising and they sometimes work. This idea is part of the general problem of investigating strained layer superlattices (SLS) structures. (See III-V compounds research ideas #1 and #15).

LITERATURE CITATION:

"Photocurrent Spectroscopy of a Strained-Layer Superlattice," Fritz, I.J., Biefield, R.M., Osborn, G.C.; Sandia Nat. Labs., Albuquerque, NM; Solid State Commun. (USA), Vol. 45, No. 4, pp. 323-5; January 1983.

3V-6: Electrical Measurement of Graded Layers and Correlations with Physical Parameters

IDEA DESCRIPTION/RATIONALE:

Layers with graded composition and/or doping can occur during materials growth because of the nature of the growth process and its parameters. Often, such changes are intentionally used as part of the solar cell design. The characterization of these layers is extremely difficult, especially if they are internal to a device. Here, knowledge of the mobility and lifetime are especially important. Composition is another parameter of interest, but this can usually be measured by a sequential "etch and determine" process.

LITERATURE CITATION:

N/A

3V-7: Optimization of Epitaxial Growth Methods,
Including Selective Epitaxy.

IDEA DESCRIPTION/RATIONALE

Epitaxial layers are usually grown over a complete wafer. This allows unconstrained, stress-free growth. Patterned epitaxy is a useful fabrication tool, because it allows for a cell structure to be built as an integrated circuit. Thus, interconnect patterns are possible, as well as lateral connected cells.

Novel approaches for tandem cell structures can be developed using this technique; however, growth of epitaxial layers through a mask usually results in constrained growth and in stress, especially at the edge of the layer. This in turn can reduce layer quality by introducing deep stress-related defects. These problems must be resolved.

LITERATURE CITATION:

"Lateral GaAs Growth Over Tungsten Gratings on (001) GaAs Substrates by Metalorganic Chemical Vapor Deposition and Applications to Vertical Field-Effect Transistors," Asai, H., Adachi, S., Ando, S., Oe, K.; Musashino Electrical Communication Lab., Tokyo, Japan; Journal of Applied Physics (USA), Vol. 55, No. 10, pp. 3868-70; May 15, 1984.

"A New Method for the Growth of GaAs Epilayers at Low H₂ Pressure," Duchemin, J.P., Bonet, M., Koelsche, F., Huyghe, D.; J. Crystal Growth, Vol. 45, p. 181; 1978.

3V-8: Use of Oxygen or Hydrogen Implantations for
Fabrication of Series-Connected Structures

IDEA DESCRIPTION/RATIONALE:

Both hydrogen and oxygen implants can be used for isolating devices in GaAs and in most other compound semiconductors. Use of this technique may open up possibilities for series-connected solar cell configurations. This would avoid etching and more complex schemes, which usually waste more active area.

LITERATURE CITATION:

"Multiple Energy Proton Bombardment on N^+ -GaAs," Donnelly, J.P., Leonberger, F.; Solid State Electron, Vol. 20, p. 183; 1973.

3V-9: Investigation of Multiple Impurity Species
for Improved Ohmic Contacts

IDEA DESCRIPTION/RATIONALE:

Ion implantation (or diffusion), using two different types of species, has been shown to result in higher doping than individual dopants. Often, this is because the stress produced by them is of different type (i.e., compressive or dilatory). Thus, their use in combination can relieve the stress created by each one singly.

LITERATURE CITATION:

"Superior Ohmic Contacts to III-V Semiconductor by Virtue of Double Donor Impurity," Yoder, M.; Department of the Navy, Washington, D.C.; March 1981.

3V-10: Rapid Thermal Anneal for Contact Formation and for Fabrication
of Shallow Junctions with High Sheet Conductance Regions

IDEA DESCRIPTION/RATIONALE:

Early results on the use of this process have shown higher dopant incorporation (ion implant or diffusion) than by the conventional approach. Thus, it may be especially useful in contact formation and in the making of heavily doped layers. Work along this line has been done, but it is in bits and pieces at the present time. Such work is particularly applicable to concentrator devices.

LITERATURE CITATION:

"Infrared Rapid Thermal Annealing of Si-Implanted GaAs," Kuzuhara, M., Kohzu, H., Takayama, Y.; Basic Technology Research Labs., Nippon Electric Co. LTD., Kawasaki, Japan; Applied Physics Letter (USA), Vol. 41, No. 8, pp. 755-8; October 15, 1982.

"Laser Annealed and Thermal Annealed Refractory Ohmic Contacts to GaAs," Anderson, W.T., Christou, A., Guiliani, J.F., Dietrich, H.B.; Naval Research Lab., Washington, D.C.; IEFF Trans. Ind. Electron (USA), Vol. IE-29, No. 2, pp. 149-53; May 1982.

3V-11: Ion Beam Techniques for Contact Formation

IDEA DESCRIPTION/RATIONALE:

Specific approaches would involve multiple implantations and the formation of damaged regions prior to contact metal deposition.

These techniques are particularly applicable to concentrator solar cells, where there is a great need for low resistance ohmic contacts. Ion techniques are very useful for deposition and surface preparation of these contact regions; however these techniques are not fully understood at the present time.

LITERATURE CITATION:

"Ion Beam Mixing of Pt/GaAs and Formation of Ohmic Contacts," Tsutsui, K., Furukawa, S.; Graduate School of Science and Engineering, Tokyo Institute of Technology, Yokohama, Japan; Journal of Applied Physics (USA), Vol. 56, No. 2, pp. 560-2; July 15, 1984.

3V-12: Laser Stimulated MOCVD Growth and Photolytic
and/or Plasma Growth Techniques for Large Area Cells

IDEA DESCRIPTION/RATIONALE:

The emphasis should be placed on layer uniformity (in particular, thickness, doping and lifetime).

There are many advantages to growing materials at reduced temperatures (e.g. minimization of stress, abruptness of junctions, etc.). Laser stimulation, if done properly, can result in energetic species which react at lower temperatures. At present, low temperature growth has been demonstrated; however, the resulting material has been loaded with carbon and is of small area. Thus, contamination and scale-up issues must still be resolved.

LITERATURE CITATION:

"Excimer Laser Induced Deposition of InP and Indium-Oxide Films," Donnelly, V.M., Geva, M., Long, J., Karlicek, R.F.; Atandt Bell Labs., Murray Hill, NJ; Applied Physics Letter (USA), Vol. 44, No. 10, pp. 951-3; May 15, 1984.

"Properties of Several Types of Films Deposited by Laser CVD," Allen, S.D., Trigubo, A.B., Teisinger, M.L.; Univ. of Southern California, University Park, Los Angeles, CA; Journal of Vacuum Science and Technology (USA), Vol. 20, No. 3, pp. 469-70; March 1982.

"Low Temperature Plasma - Enhanced Epitaxy of GaAs," Pande, K.P., Seabaugh, A.C.; Bendix Advanced Technology Center, Columbia, MD; Journal Electrochemical Society (USA), Vol. 131, No. 6, pp. 1357-9; June 1984.

"Plasma-Assisted Epitaxial Growth of GaSh in Hydrogen Plasma," Sato, Y., Matsushita, K., Hariu, T., Shibata, Y.; Dept. of Electronic Engng., Tohoka Univ., Sendai, Japan; Applied Physics Letter (USA), Vol. 44, No. 6, pp. 592-4; March 15, 1984.

"A Study of UV Absorption Spectra and Photolysis of Some Group II and Group VI Alkyls," Irvine, S.J.C., Mullin, J.B., Robbins, D.J., Glasper, J.L.; Journal of Electrochemical Society (USA), Vol. 132, p. 968; 1985.

3V-13: New Techniques for Measuring Minority Carrier Diffusion Length, Especially for Interior Layers in Devices

IDEA DESCRIPTION/RATIONALE:

There is certainly a need for characterizing these layers when they are part of a working device. Specifically, there is a need to determine the minority carrier diffusion length of the material. Mobility is also a good parameter to characterize since it is an indicator of scattering centers and overall crystal quality. At the present time, measurements are made using "test" structures and as a result are not really meaningful.

LITERATURE CITATION:

"Method of Monitoring Epitaxial Semiconductor Films of Variable Composition," Kovalenko, V.F.; Avtometriya (USSR), No. 6, pp. 54-64; November-December 1980.

"Properties of Several Types of Films Deposited by Laser CVD," Allen, S.D., Trigubo, A.B., Teisinger, M.L.; Univ. of Southern California, University Park, Los Angeles, CA; Journal of Vacuum Science and Technology (USA), Vol. 20, No. 3, pp. 469-70; March 1982.

3V-14: DLTS to Study Interface States Between Layers -
Improvement of Growth Methods Based on this Data

IDEA DESCRIPTION/RATIONALE:

This idea involves the same technique as identified in III-V compounds research idea #1 except it is used for a different application area (See III-V compounds research idea #1 for details on DLTS). Instead of using DLTS as a diagnostic tool for strained layer structures, this idea proposes examination of interfaces. Such a tool is important for multi-layer devices.

LITERATURE CITATION:

"MOS Surface State Density Measurements Using Transient Capacitance Spectroscopy," Wang, K. L., IEEE Trans. On Electron Dev., ED-27, pp. 2174; 1980.

3V-15: The Use of DLTS as a Process Tool, Preferably in
Combination with Photoluminescence and Fourier Transform
Infrared Measurements to Determine the Effect of Changing
Growth Parameters on the Resulting Material

IDEA DESCRIPTION/RATIONALE:

Minority carrier lifetime is perhaps the most important parameter in solar cell layers. Its measurement is usually by DLTS, photoluminescence, and by IR measurements. Each technique has been studied individually. However, there is a need for a systematic study of how these methods can be correlated to growth parameters in a reactor.

LITERATURE CITATION:

"DLTS Studies of Deep Levels in Semiconducting n-CdTe Single Crystals," Takebe, T., Hirata, T., Scraie, J., Matschami, H.; Journal of Crys. Growth, Vol. 43, p. 5; 1980.

"The Trend of Deep States in OMVPE With Varying As/Ga Ratios," Bhattacharya, P.K., Ku, J.W., Owen, S.J.T.; Appl. Phys. Lett., Vol. 36, p. 45; 1980.

3V-16: Correlation of Impurities in a Reactor Environment with
Quality of Grown Layer - Understanding and Improvement

IDEA DESCRIPTION/RATIONALE:

These techniques can be used to improve the quality of the grown layers and for measurement of reactor temperature. Approaches involve Raman and other laser probes, IR, and mass spectroscopy.

There is a great need for in-situ monitoring of the reactor environment. This is especially difficult in an MOCVD reactor, where there are many species in addition to the desired ones. The setting up of a meaningful experiment is thus difficult.

LITERATURE CITATION:

"Development of Laser Diagnostic Probes for Chemical Vapor Deposition of InP/InGaAsP Epitaxial Layers," Donnelly, V.M., Karlicek, R.F.; Bell Labs, Murray Hill, NJ; J. Appl. Phys. (USA), Vol. 53, No. 9, pp. 6399-407; September 1982.

3V-17: Surface Acoustic Wave Diagnostics for III-V Alloys
This is a Non-Invasive Technique Suitable for Large-Area Devices

IDEA DESCRIPTION/RATIONALE:

Surface acoustic wave diagnostics allows for rapid nondestructive evaluation of the electrical properties of a large-area layer.

LITERATURE CITATION:

"Effect of Photo-Carrier Densities and Lifetimes in Silicon," Stearns, R.G., Khurl-Yakub, B.T., Kino, G.S.; Appl. Phys. Lett. Vol. 45, P. 1181; 1984.

3V-18: EER Techniques for Large-Area Devices -
Determine Composition Across a Slice and in Multiple Layers

IDEA DESCRIPTION/RATIONALE:

EER techniques allow determination of composition and stress through an epitaxial layer and also give areal dependence. This technique should be applied to solar cell materials. It is one of the few methods which identifies stress in the layers and should be especially useful when tied in with the actual growth process. The approach should be extended so that it can be used outside of the research laboratory.

LITERATURE CITATION:

"Topographic Examination of Semiconductor Systems," Sundaram, S., Raccah, P.M.; Dept. of Physics, Illinois Univ. at Chicago, Chicago, IL; Final Technical Report, June 1, 1978 - July 30, 1980.

"Topographic Examination of Semiconductor Systems," Brown, R.L., Sundaram, S., Raccah, P.M.; Dept. of Physics, Illinois Univ. at Chicago, Chicago, IL; Annual Technical Report, June 1, 1978 - June 30, 1979.

3V-19: Use of High-Resolution FTIR Techniques to
Complement Photoluminescence and DLTS as Diagnostic Tools

IDEA DESCRIPTION/RATIONALE:

Fourier Transform Infrared (FTIR) methods can be used to probe epitaxial layers for shallow defects. Thus, they complement photoluminescence (PL) and DLTS. Very little work has been done with FTIR as compared to the other two.

LITERATURE CITATION:

"Photothermal Ionization Identification of Sulfur Donors in GaAs," Low, T.S., Stillman, G.E., Nakanishi, T., Udagana, T., Wolfe, C.M.; Electrical Engng. Res. Lab., Univ. of IL, Urbana, IL; Appl. Phys. Lett. (USA), Vol. 41, No. 2, pp. 183-5, July 15, 1982.

"Impurities in GaAs," Stillman, G.E.; Department of EE, Univ. of IL, Urbana, IL.

3V-20: Non-Invasive Techniques for Measurement of Layer Composition,
as well as Layer Doping, Across a Wafer

IDEA DESCRIPTION/RATIONALE:

There is a great need for techniques of this type as PV moves from research into production. High sensitivity and high resolution are both important. III-V compounds research idea #17 represents such an approach.

LITERATURE CITATION:

"Evaluation of III-V Semiconductor Wafers Using Non-Destructive Organic-on-Inorganic Contact Barriers," Forrest, S.R., Kaplan, M.L., Schmidt, P.H., Gates, J.V.; J. Appl. Phys., Vol. 57, p. 2892; 1985.

3V-21: Mass Spectrometry Studies of the Gas Ambient -
Both at Reactor Entry and Exit

IDEA DESCRIPTION/RATIONALE:

Mass spectrometry and residual gas analysis are useful means for determining the quality of starting chemicals, as well as the actual growth process. They offer the possibility of in-situ monitoring of dopant incorporation during layer growth as well. Thus, improved growth and dopant control can result. See III-V compounds research idea #16.

LITERATURE CITATION:

"Development of Laser Diagnostic Probes for Chemical Vapor Deposition of InP/InGaAsP Epitaxial Layers," Donnelly, V.M., Karlicek, R.F.; Bell Labs., Murry Hill, NJ; J. Appl. Phys. (USA), Vol. 53, No. 9, pp. 6399-407; September 1982.

"Growth Monitoring and Characterization of (Al,Ga) As Heterostructures by Ellipsometry," Lawrence, G., Hottier, F., Hallais, J.; Labs. d'Electronique et de Phys. Appliquee, Limeil-Brevannes, France; J. Cryst. Growth (Netherlands), Vol. 55, No. 1, pp. 198-206; October 1981.

3V-22: Passivation of InP Surfaces Using Oxides, Polysulfides, etc.,
and Evaluation of the Results

IDEA DESCRIPTION/RATIONALE:

P-N solar cells require surface passivation for high efficiency structures. InP, and In-based alloys can be passivated, so that their use is expanding. Hand in hand, there is a need for passivation technology. Oxidation appears to work, but recent results with KP₁₅, as well as those with amorphous sulfur, are extremely interesting.

LITERATURE CITATION:

"Surface Passivation Techniques for InP and InGaAs P P-N Junction Structures," Diadiuk, V., Armiento, C.A., Groves, S.H., Hurwitz, C.E.; MIT, Lexington, MA; IEEE Electron Device Lett. (USA), Vol. EDL-1, No. 9, pp. 177-8; September 1980.

"InGaAsP/InP Photodiodes Antireflectively Coated With InP Native Oxide," Sakai, S., Aoki, T., Tobe, M., Amemiya, Y., Umeno, M.; Dept. of Electronics, Nagoya Univ., Nagoya, Japan; IEEE J. Quantum Electron (USA), Vol. QE-15, No. 10, pp. 1077-8; October 1979.

"Polyimide Passivation of In_{0.53}Ga_{0.47}As, InP and InGaAs/ InP P-N Junction Structures," Yeats, R., Von Dessonneck, K.; Varian Assc. Inc., Corporate Solid State Lab., Palo Alto, CA; Appl. Phys. Lett. (USA), Vol. 44, No. 1, pp. 145-7; January 1, 1984.

"Amorphous Polyphosphide Thin Films Prepared by Sputtering," Schacter, R., Viscogliosi, M.; Materials Research Society Meeting, Boston, MA; 1984.

"Passivation of the GaAs Surface by an Amorphous Phosphorus Over-layer," Olego, D., Schacter, R., Bauman, J.A., Appl. Phys. Lett., Vol. 45, p. 1127; 1984.

RESEARCH PROJECTS

A.2 THIN FILMS

TF-1: Fundamental Thin-Film Crystal Growth
is Revealed Through Heterogeneous Nucleation in CVD

IDEA DESCRIPTION/RATIONALE:

This abstract discusses heterogeneous nucleation in chemical vapor deposition. Research in this area can give insights into the fundamentals of thin-film crystal growth for PV devices.

Virtually all thin-film solar cells are fabricated with some form of heterogeneous nucleation. However, this aspect of the growth cycle is rarely addressed in PV thin-film literature. Insight into the fundamentals of crystal growth may help improve the performance of PV devices.

LITERATURE CITATION:

"The Formation of Epitaxial Semiconductor Films by Chemical Vapor Deposition (CVD)," Jackson, C.M., Nonferrous Metallurgy Div., Battelle, Columbus Laboratories, Columbus, OH; and Hirth, J.P., Dept. of Metallurgical Engineering, Ohio State Univ., Columbus, OH.

TF-2: Zn(SSe) is Used as a Heterojunction or Window in PV Devices

IDEA DESCRIPTION/RATIONALE:

The abstract describes the deposition of Zn(SSe) - a high conductivity, wide energy band gap material. These semiconductor films might substitute for (ZnCd)S as a heterojunction or window in PV devices.

Wide band gap, high conductivity films are sought to replace CdS in CuInSe₂ heterojunctions and CdTe. The advantages of such a replacement are greater transparency, lower resistance and possibly a better electron affinity match.

LITERATURE CITATION:

"High Conductivity Zinc Sulphoselenide Thin Films," Leigh, W. and Wessels, B.W.; Dept. of Materials Sci. & Engng., Northwestern Univ., Evanston, IL; Applied Physics Letter (USA), Vol.41, No.2, pp. 165-7; July 15, 1982.

TF-3: ZnO as a Window or Heterojunction in PV Devices

IDEA DESCRIPTION/RATIONALE:

The abstract reports on thin semiconducting ZnO. This material could be applicable as a window or heterojunction in PV devices.

Much effort has been expended on finding a suitable heterojunction partner for Zn₃P₂. ZnO has been seen to have too high a resistivity. The abstract reports relatively low resistivity for thin ZnO. If the resistivity is low enough, thin ZnO could be used as a window or heterojunction, particularly for Zn₃P₂.

LITERATURE CITATION:

"Semiconducting Zinc Oxide Films Prepared by Metal Organic Chemical Vapor Deposition from Diethyl Zinc," Roth, A.P., Williams, D.F.; Div. of Chemistry, Natural Resources Council of Canada, Ottawa, Ontario, Canada; Journal of Electrochemical Soc. (USA), Vol. 128, No. 12, pp. 2684-6; December 1981.

TF-4: Metal Silicide-Silicon Photodiodes Versus P-N Junctions

IDEA DESCRIPTION/RATIONALE:

Metal silicide-silicon photodiodes are described as being superior to P-N junctions. If this is true, then it is most important in terms of PV.

If there is a silicide with the correct optical and electronic properties, it could be an improved window material and minority carrier collector.

LITERATURE CITATION:

"Metal Silicide-Silicon Photodiode," Ohdomari, I., Seki, H.; IBM Corp., Armonk, NY; IBM Tech. Disclosure Bulletin (USA), Vol. 24, No. 5, p.2392; October 1981.

TF-5: Modulation of Grain Boundary Conductivity in Polycrystalline CdSe

IDEA DESCRIPTION/RATIONALE:

Modulation of grain boundary conductivity in polycrystalline CdSe thin-film transistors was reported. This modulation of grain boundaries should have a greater impact on solar cells than on transistors and therefore should be pursued.

Research in this area could give new insights into electronic device design leading to improved PV devices without perfect materials. This could be a way to process devices with material faults.

LITERATURE CITATION:

"Gate Modulation of Grain Boundary Dominated Conductivity in Polycrystalline Semiconductor Thin Film Transistors," Levinson, J., Shepherd, R., Scanlon, P.J., Westwood, W.D.; Soreq Nuclear Research Centre, Yavne, Israel; IEEE 13th Convention of Electrical and Electronics Engineers in Israel Proceedings, 2.4.5/1-4; January 1984.

TF-6: Transport Properties of Amorphous Silicon

IDEA DESCRIPTION/RATIONALE:

This abstract describes transport properties of many amorphous semiconductors based on temperature dependence of Fermi Energy. The work is applicable to PV in terms of amorphous silicon.

Understanding and modifying the transport properties of amorphous silicon is critical to raising efficiency. The new transport model that is described, if applied to amorphous silicon, may be helpful in this regard.

LITERATURE CITATION:

"The Influence of a Long-Ranged Potential on the Electronic Transport Properties of Amorphous Semiconductors," Overhof, M.; Fachberidhi Phys., Univ. Paderborn, Paderborn, Germany; Journal of Non-Crystalline Solids (Netherlands), Vol.66, No.1-2, pp. 261-72; July 1984.

TF-7: Device Designs for CdTe and CdSe Solar Cells

IDEA DESCRIPTION/RATIONALE:

CdSe transistors are described. Polycrystalline thin-film, CdSe transistors could give insight into new device designs for CdTe and CdSe solar cells (in general, transistors are more complicated than PV devices).

There could be applicable ideas or processes in this work to PV device design.

LITERATURE CITATION:

"Conductivity Behavior in Polycrystalline Semiconductor Thin Film Transistors," Levinson, J., Shepherd, F.R., Scanlon, P., Westwood, W.D., Este, G., Rider, M.; Bell-Northern Res., Ottawa, Canada; Journal of Applied Physics (USA), Vol. 53, No. 2, pp. 1193-202; February 1982.

TF-8: Ultra-Fine Tin Oxide Particles for Grids of PV Devices

IDEA DESCRIPTION/RATIONALE:

The technology and properties of ultrafine particles of tin oxide were described in the abstract. These particles could be applicable to the grids of PV devices.

This technology could provide a transparent grid option for PV devices, thus improving efficiency. The technology was also described as being highly reproducible.

LITERATURE CITATION:

"Preparation of Tin Oxide Films from Ultrafine Particles," Ogawa, H., Abe, A., Nishikawa, M., Hayakawa, S.; Matsushita Electrical Industrial Co. Ltd., Kadoma, Osaka, Japan; Journal of Electrochemical Soc. (USA), Vol. 128, No. 3, pp. 685-9; March 1981.

TF-9: Preparation of ZnO Films by Magnetron Sputtering

IDEA DESCRIPTION/RATIONALE:

This abstract describes the preparation of highly conductive ZnO films by magnetron sputtering. ZnO could have applications in PV for windows, heterojunctions and ZnO/Zn₃P₂.

As discussed in thin films research idea #3 the problems encountered with ZnO in PV has been its high resistivity (i.e. low conductivity). Thin-film ZnO seems to offer a possible solution.

LITERATURE CITATION:

"Highly Conductive and Transparent Aluminum Doped Zinc Oxide Thin Films Prepared by RF Magnetron Sputtering," Minami, T., Nanto, H., Takata, S.; Dept. of Electrical Enging., Kanazawa Inst. of Technol., Ishikawa, Japan; Japan Journal of Applied Physics Part 2 (Japan), Vol. 23, No.5, L280-2; May 1984.

TF-10: Remelting Deposited Thin Films

IDEA DESCRIPTION/RATIONALE:

Work on remelting deposited thin films is described. Such work may lead to a new way to grow the thin-film semiconductor into a final desirable form.

This different thin-film growth technique could lead to improved performance and insight.

LITERATURE CITATION:

"Crystal Growth in Substrate-Confined Liquids," (Technical Report, sponsored by Defense Advanced Research Projects Agency, DoD); McCaldin, J.O.; California Institute of Technology; December 15, 1982.

TF-11: Cost:Performance Optimization of Silicon PV Devices.

IDEA DESCRIPTION:

If one considers a continuum from amorphous silicon to large-grain polysilicon, there is probably a cost:performance optimum between these two extremes.

This was the top-ranked idea of the 1983 PV Cell Research Opportunities report (OER., Dec. 1983). To date, there has been no follow-up on this idea.

LITERATURE CITATION:

Photovoltaic Cell Research Priorities; U.S. Dept. of Energy, DOE/ER/30029-T2, pp. 2-28; December 1983.

TF-12: Toleration of Faults in Design of PV Devices

IDEA DESCRIPTION:

New semiconductor device designs based on tolerating the faults in the materials are discussed. The semiconductor device industry does not rely on perfect materials. It designs new devices and structures to accomodate material faults. This approach may be appropriate in the PV industry as well.

Currently, the dominant approach at DOE is based on improved materials science, emphasizing more perfect materials, their deposition and understanding. An alternative is semiconductor device engineering, the addition of which could add an important new dimension to PV technology development.

LITERATURE CITATION:

"Design Principles for High Efficiency Small-Grain Polysilicon Solar Cells, with Supporting Experimental Studies," Lindholm, F.A., Neugroschel, A.; Univ. of Florida, Gainesville, and Sah, C.T.; Univ. of Illinois, Urbana, IEEE; 1982.

TF-13: Flash Evaporation of Amorphous Silicon and CuInSe₂ Films

IDEA DESCRIPTION/RATIONALE:

The abstract describes the flash evaporation of thin amorphous semiconductor films. It is claimed that the compositions of the film and source materials were identical. If this is true, the technique may be applicable to PV in the deposition of CuInSe₂ and amorphous silicon.

In the development of PV technology, new deposition techniques are being sought for the scale-up of CuInSe₂ devices.

LITERATURE CITATION:

"Modified Flash Evaporation Technique for the Preparation of Thin Amorphous Semiconductor Films," Kahnt, M., Feltz, A.; Dept. of Chemistry, Friedrich Univ., Jena, Germany; Thin Solid Films (Switzerland), Vol. 98, No.3, pp.211-14; December 17, 1982.

TF-14: Beam Recrystallization of Polycrystalline Thin Films

IDEA DESCRIPTION/RATIONALE:

Beam recrystallization of thin films using a single crystal seed in juxtaposition is described. This technique can be used to increase grain size of polycrystalline thin films for PV devices.

This process may be a new way of modifying thin films, leading to increased performance.

LITERATURE CITATION:

"Single Crystal Thin Films," Patent Application - 80846, Inventor: Aklufi, M.E.; US Dept. of Navy, ONR, (Filed October 1, 1979).

TF-15: Analysis of Polysilicon Devices

IDEA DESCRIPTION/RATIONALE:

This abstract describes the influence of impurities in the liquid phase chemical vapor deposition (LPCVD) reactor on lateral polysilicon PN diodes. This use of the device to measure impurities could lead to new ways to analyze polysilicon devices.

Further research may give insight into fault-tolerant solar cell designs and may assist in the development of polysilicon surface passivation.

LITERATURE CITATION:

"Influence of Impurities on Lateral Polysilicon PV Diodes," Dutoit, M.; Centre Electronique Horloger SA, Neuchatel, Switzerland; Journal of Electrochemical Soc. (USA), Vol. 130, No. 4, pp.967-8; April 1983.

TF-16: Electronic Structures of New Crystalline Materials
and Amorphous Silicon

IDEA DESCRIPTION/RATIONALE:

Electronic structures of complex crystalline and amorphous semiconductors are described. There may be some insights from this work that are applicable to new crystalline materials and amorphous semiconductor for PV devices.

This work may lead to increased understanding of new materials and, accordingly, improved performance and designs.

LITERATURE CITATION:

"Electronic Structure of Complex Crystalline and Amorphous Semiconductors," Joannopoulos, J.; Dept. Physics, Inorganic Materials Research Division, Lawrence Berkeley Laboratory and Univ. Of California, Berkeley, CA.

TF-17: BP on Silicon as a Surface Passivant

IDEA DESCRIPTION/RATIONALE:

The abstract describes the deposition of thin BP on silicon. The method and material may have potential application as a surface passivant for PV devices.

Surface passivation is the latest focus of high performance (efficiency) silicon research.

LITERATURE CITATION:

"Thin Boron Phosphide Coating as a Corrosion-Resistant Layer,"
(Patents-US -- A6411396, S.N. 411,396(79), S-55,563, filed
8-25-82). August 25, 1982.

TF-18: Improved Understanding of SIPOS

IDEA DESCRIPTION/RATIONALE:

This abstract claims an improved understanding of SIPOS. SIPOS relates to PV in terms of surface passivation.

SIPOS is being studied as a new silicon surface passivant. If successful, it will lead to higher performance.

LITERATURE CITATION:

"Density of States at the Interface between Semi-Insulating Polycrystalline and Single Crystalline Silicon," Taylor, D.M., Tong, D.W.; Corporate Res. and Dev. Center, General Electric Co., Schenectady, NY; Journal of Applied Physics (USA), Vol. 56, No. 6, pp.1181-3; September 15, 1984.

TF-19: SiC as Surface Passivant and New Transparent Contact

IDEA DESCRIPTION/RATIONALE:

These abstracts describe the epitaxial growth of SiC on silicon. In PV devices, SiC could serve as a surface passivant or a new transparent contact.

SiC is a very stable material that could have applicability as a heteroface junction to reduce surface (or contact) recombination and thus increase efficiency.

LITERATURE CITATION:

"Single Crystal Epitaxy and Characterization of Beta-Silicon Carbide," (Annual Technical Report to ONR); Davis, R.F.; Engineering Research Services Division, North Carolina State Univ., Raleigh, NC; March 1981.

"Single Crystal Epitaxy and Characterization of B-SiC," (Final Technical Report to ONR); Davis, R.F.; Materials Engineering Department, North Carolina State University, Raleigh, NC; July 1982.

TF-20: Surface Passivation of GaAs Solar Cells

IDEA DESCRIPTION/RATIONALE:

This abstract describes insulating films of GaAs to be used as a surface passivant. Surface passivation has been a key problem in GaAs solar cells.

Top surface passivation is very important for GaAs. Of equal importance, these techniques may be applicable to grain boundary passivation for polycrystalline GaAs. Resolution of passivation issues will result in increased performance.

LITERATURE CITATION:

"Insulating Films on GaAs," (Final Report to ONR); Robinson, G.Y.; Univ. of Minnesota, Minneapolis, MN, September 30, 1979.

TF-21: Inherent Surface Passivation of GaAs

IDEA DESCRIPTION:

This work states that the "preliminary studies of pyrolytic silicon nitride/GaAs structures yielded electrical results consistent with the conclusion that inversion of the n-type GaAs surface can be achieved with this system." If correct, this has applicability to GaAs solar cells.

If the results of this work are correct, an MIS inversion device could be developed that would lead to record efficiencies due to inherent surface passivation. This device would be similar to that reported by Green for the 19 percent efficient silicon solar cells. This work could have great potential for all III-V materials, not just GaAs.

LITERATURE CITATION:

GaAs Surface Passivation for Device Applications, (Final Report to Air Force Systems Command); Anderson, C.L., Clark, M.D.; Hughes Research Laboratories, Malibu, CA; March 1982.

TF-22: True Thin-Film Polycrystalline Silicon

IDEA DESCRIPTION/RATIONALE:

There has been some promising work with atomic hydrogen passivation. Research in this area could lead to a true thin-film polycrystalline silicon solar cell.

Such a device could combine the low cost of thin films with the high performance of crystalline silicon.

LITERATURE CITATION:

"Passivation of Grain Boundaries in Polycrystalline Silicon," Photovoltaic Cell Research Priorities; U.S. Dept. of Energy, DOE/ER/30029-T2, pp. 2-30; December 1983.

RESEARCH PROJECTS
A.3 CRYSTALLINE SILICON

CS-1: Research Studies to Define the Optimal Processing Parameters and Donor or Acceptor Impurities Species to Yield a Minimum Surface Recombination Velocity at the Back Surface via Deposited Heavily-Doped Polysilicon.

IDEA DESCRIPTION/RATIONALE:

The polysilicon would cover the entire back surface of the crystalline silicon and would be contacted using an appropriate metal.

The use of such a passivant is anticipated to yield an increased open-circuit voltage as well as other solar-cell parameters even for substrate or base doping concentrations of the order of $10^{17}/\text{cc}$. For such concentrations, conventional back-surface-field regions are ineffective in reducing the surface recombination velocity. No masking or other definition procedures are needed.

This is a good project for transferring research experience in non-PV areas because CVD polysilicon is extensively used in the integrated-circuit industry. Some more attention needs to be given, however, to the selection of processing parameters and of chemical species for optimal passivation of the back surface. In the IC industry, CVD polysilicon is used for the heavily-doped emitter regions. The base or substrate of a solar cell is not so nearly heavily doped. Thus, some research is needed to adapt to this new application.

LITERATURE CITATION:

"Effective Recombination Velocity of Polysilicon Contacts for Bipolar Transistors," Bakker, G.W., Roulston, D.J., Ettonkhy, A.A.; Univ. of Waterloo, Waterloo, Canada; Electronic Lett., Vol. 20, No. 15, pp. 622-4; July 19, 1984.

"Current Gain of Silicon Bipolar Transistor with Polysilicon Emitter Contact," Menta, S.K.; Solid State Phys. Lab, Delhi, India; Electronic Lett., Vol. 20, No. 7, pp. 294-5; March 29, 1984.

CS-2: Research Studies Involving Alternate Designs and Processing
that Utilize Heavily-Doped Polysilicon Deposited on the Front
Surface a Silicon Solar Cell--The Surface Where the Sunlight is Incident

IDEA DESCRIPTION/RATIONALE:

These studies require considerations distinct from those pertaining to polysilicon deposited on the back surface (crystalline silicon research idea #1). The front surface consists of two singly connected regions, defined by (a) the metallic contact area and (b) the rest of the front surface. High conversion efficiency requires for region (a) an ohmic contact for majority carriers and a blocking contact (low surface recombination velocity) for minority carriers. For region (b), one needs a low surface recombination velocity and optical properties consistent with a passage of the incident photon energy into the crystalline silicon. Thus, for region (a), one needs deposited polysilicon, the utility of which has been proved effective by the referenced work in bipolar integrated circuits. For region (b), several choices exist: use thin enough polysilicon that the absorption of photon energy by the polysilicon layer is negligible; or use some other passivant, such as silicon dioxide or possibly some deposited or plasma-derived oxide or nitride, over the non-metallized surface. Research is needed to investigate all choices, to investigate the passivation properties of very thin polysilicon layers, and to investigate different methods for that do interleave regions covered by polysilicon with those covered by silicon dioxide for example.

LITERATURE CITATION:

"Effective Recombination Velocity of Polysilicon Contacts for Bipolar Transistors," Bakker, G.W., Roulston, D.J., Ettonkhy, A.A.; University of Waterloo, Waterloo, Canada; Electronic Lett, Vol. 20, No. 15, pp. 622-4, July 19, 1984.

"Current Gain of Silicon Bipolar Transistor with Polysilicon Emitter Contact," Mehtan, S.K.; Solid State Physics Lab., Dehli, India; Electronic Lett; Vol. 20, No. 7, pp. 294-5; March 29, 1984

"Isolated Resistor Having Doped Polysilicon Contacts and Method of Manufacture," Barson, F., Horng, C.T., Kemlage, B.M., Ku, S.M.; IBM Corp. Armonk, NY, USA; IBM Technical Disclosure Bulletin, Vol. 25, No. 7a pp. 3585-6; December 1982.

"Arsenic Profiles in Bipolar Transistors with Polysilicon Emitters," Ashburn, P., Soerwirdjo, B.; Dept. of Electronics, Southampton Univ. Southampton, England; Solid State Electronics, Vol. 24, No. 5, pp. 475-6; May 1981.

CS-3: Research Studies Aimed Toward Combining Crystalline
Silicon Research Ideas #1 and #2 in Order to Yield a
Solar Cell Having Full Polysilicon
Passivation on the Back Surface and Either Full
or Partial Passivation on the Front Surface

IDEA DESCRIPTION/RATIONALE:

Passivation on the lateral edges should also be explored to determine whether that improves efficiency by reducing leakage current. Establishing the proper sequence of processing steps is part of this research.

See rationale for crystalline silicon research ideas #1 and #2.

LITERATURE CITATION:

"Effective Recombination Velocity of Polysilicon Contacts for Bipolar Transistors," Bakker, G.W., Roulston, D.J., Ettonkhy, A.A.; University of Waterloo, Waterloo, Canada; Electronic Lett., Vol. 20, No. 15, pp. 622-4; July 19, 1984.

"Current Gain of Silicon Bipolar Transistor with Polysilicon Emitter Contact," Mehtan, S.K.; Solid State Physics Lab., Dehli, India; Electronic Lett., Vol. 20, No. 7, pp. 294-5; March 29, 1984.

"Isolated Resistor Having Doped Polysilicon Contacts and Method of Manufacture," Barson, F., Horng, C.T., Kemlage, B.M., Ku, S.M.; IBM Corp., Armonk, NY, USA; IBM Technical Disclosure Bulletin, Vol. 25, No. 7a pp. 3585-6; December 1982.

"Arsenic Profiles in Bipolar Transistors with Polysilicon Emitters," Ashburn, P.; Soerwirdjo, B.; Dept. of Electronics, Southampton Univ. Southampton, England; Solid State Electronics, Vol. 24, No. 5, pp. 475-6; May 1981.

CS-4: Application of Molecular Beam Epitaxy to Silicon Photovoltaics

IDEA DESCRIPTION/RATIONALE:

The burgeoning technology of molecular beam epitaxy, in this case, silicon beam epitaxy, needs exploration for its application to silicon photovoltaics.

This technology constitutes a new means for the formation of p/n junctions and for heterojunctions (blocking contacts to minority carriers, transparent to the solar spectrum) at the surfaces.

LITERATURE CITATION:

"Silicon Beam Epitaxy for Fabrication of Devices," Bose, G., Vaya, P.R., Kakati, D.; Dept. of Electrical Engng., Indian Inst. of Technol., Madras, India; Phys. Status Solidi A (Germany), Vol. 55, No. 2, pp. 135-8; October 16, 1979.

CS-5: IC Industry Computer Programs for PV Device Design

IDEA DESCRIPTION/RATIONALE:

The proposed research would seek exploitation of computer programs developed by workers in the IC industry that have enough generality and power to assist any conceivable photovoltaic device design.

The program in the abstract is apparently the most powerful. It simulates semiconductor devices of arbitrary shape in one, two and three dimensions. It works for steady state or transient operating conditions. It enables users to rapidly generate designs and analyze the results. For photovoltaics, it is particularly useful for high concentration structures (e.g., v-groove). Apparently such powerful computer programs have received no attention by the photovoltaic community.

LITERATURE CITATION:

E. Buturala, et. al.; IBM Journal of Research and Development, Vol. 25, pp. 218-231; 1981.

CS-6: Fabricate and Test Solar Cells Using Laser Annealing
of Heavily-Doped Emitters

IDEA DESCRIPTION/RATIONALE:

Surface concentrations higher than surface solubility are achievable. The effects of such doping concentrations on efficiency for very thin emitters is a subject for research.

This process reduces recombination losses in the emitter and thus yields higher efficiency. Moreover, steeper doping profiles may result, which would reduce recombination losses in the junction transition region and thus yield higher efficiency.

LITERATURE CITATION:

Method for Making Defect-Free Zone by Laser-Annealing of Doped Silicon, Narayan, J., White, C.W., Young, R.T.; Dept. of Energy, Washington, D.C.; Patent January 1, 1980.

Laser Annealing of Ion-Implanted Cz Silicon for Solar-Cell-Junction Formation (Final Report); Katzeff, J.S.; Lockheed Missiles and Space Co., Inc., Sunnyvale, CA; DOE/JPL 955696-81/4; June 1981.

Laser Annealing of Ion Implanted Cz Silicon for Solar Cell Junction Formation (Qtrly Rpt. No. 1); Katzeff, J.S.; Lockheed Missiles and Space Co., Inc., Sunnyvale, CA; July 1980.

"Beam Processing for High-Efficiency Si Solar Cells," Van Der Leeden, G.S., Young, R.T., Sandstrom, R.L., Wood, R.F., Westbrook, R.D.; Oak Ridge National Lab., Oak Ridge, TN; Photovoltaic Solar Energy Conference, Athens, Greece; October 17, 1983.

"Pulsed Laser Annealing of Single-Crystal and Ion-Implanted Semiconductors" Kim, D.M., Kwong, D.L.; Dept. of Electrical Engng., Rice Univ., Houston, TX; IEEE J. Quantum Electronics (USA), Vol. QE-18, No. 2, pp. 224-32; February 1982.

CS-7: Investigate the Feasibility of Using the Excimer Laser to
Produce Extremely Thin and Heavily-Doped Layers at Front
and Back Surface of a Simple P/N Junction
Silicon Solar Cell

IDEA DESCRIPTION/RATIONALE:

The solidification following melting can yield impurity concentrations an order of magnitude or more above the equilibrium solid solubility. These layers may have extremely low mobility and diffusivity, similar to the values seen in amorphous silicon. If so, and if the recombination rate from impact Auger mechanisms does not dominate, these layers will act in effect as insulators for the minority carriers while passing the majority carriers easily as in an ideal ohmic contact system. The result would be an absence of recombination losses at the front and back surface. Since the layers would be very thin, the optical properties of the front such layer would be of no consequence.

LITERATURE CITATION:

"Pulsed Excimer-Laser (308 MN) Annealing of Ion-Implanted Silicon and Solar-Cell Fabrication; Lowndes," Cleland, D.H., Christie, J.W., Eby, W.H., Jellison, R.E.; Oak Ridge National Lab., Oak Ridge, TN; Int'l Symp. on the Scientific Basis for Radioactive Waste Management, Boston, MA; November 1982.

Excimer Laser Annealing to Fabricate Low Cost Solar Cells (Quarterly Tech. Report); Spire Corp., Bedford, MA; NASA-CR-173938; July 1984.

"Laser Annealing with a 308 NM XE-CL Pulsed Excimer Laser," Hodgson, R.T.; IBM Watson Res. Center, Yorktown Hts., NY; Conference on Lasers and Electro-Optics, 1981.

"Characterization of Excimer Laser Annealing of Ion-Implanted Si," Young R.T., Van Der Leeden G.A., Narayan, J., Christie, W.H., Wood, R.F., Rothe, D.E., Levatter, J.I.; Solid State Div., Oak Ridge National Lab., Oak Ridge, TN; IEEE Electronic Device Lett. (USA), Vol. EDL-3, No. 10, pp. 280-3; Oct. 1982.

"Excimer Laser Annealing of Ion-Implanted Silicon," Narayan, J., Holland, O.W., White, C.W., Young R.T.; Solid State Div., Oak Ridge National Lab., Oak Ridge, TN; J. Applied Physics (USA), Vol. 55, No. 4, pp. 1125-30; February 15, 1984.

"Excimer Laser Annealing to Fabricate Low Cost Solar Cells," (Quarterly Tech Report No. 1); Spire Corp., Bedford, MA; July 1984.

CS-8: Research to Remove Impurities and Lessen Recombination
(See Crystalline Silicon Research Idea # 14)
by Gettering Following Intentional Damage to
the Back Side of the Wafer

IDEA DESCRIPTION/RATIONALE:

Back-side damage can be generated by ion implantation of argon, neon, or oxygen, sand blasting, or lasers.

The damage region acts as a sink for impurities as long as it does not anneal out. Implantation of argon and laser damage appear to be the most effective of the gettering methods because the damage does not anneal out as easily as it does for the other techniques.

This technique has also received little attention in photovoltaics.

LITERATURE CITATION:

"The Annealing and Gettering Behavior of Inert Gas Ion Implantation Damage in Silicon," Cullins, A.G., Seide, T.E.; Electrochem. Soc. Meeting, Extended Abstracts, Abstract No. 486; Los Angeles, CA; October 1979.

CS-9: Applicability of Photo-Induced Chemical Vapor
Deposition of Silicon Dioxide to Solar Cells

IDEA DESCRIPTION/RATIONALE:

Extension of Air Force research on photo-induced chemical vapor deposition of silicon dioxide to assess its applicability to solar cells is proposed.

If it provides a good passivant, then costs would drop and efficiency might improve because of the resultant absence of need to tailor the high temperature processing of solar cells to achieve good thermal oxides.

LITERATURE CITATION:

"Supporting Data for Fiscal Year 1985 Budget Estimates, Submitted to Congress February 1984, - Descriptive Summaries - Research, Development, Test and Evaluation," Department of the Air Force, (Program Element #62102F, Engineering Technology, paragraph 7.G. - "Electromagnetic Windows and Electronic Materials"); p. 42.

CS-10: Application of the Optical Modulation Technique
for the Determination of Photogenerated Carrier Lifetime in Silicon

IDEA DESCRIPTION/RATIONALE:

This technique could have broad application in the photovoltaics industry. The technique is simple, contactless, and non-destructive. It may have significant potential as a high-resolution, high-sensitivity tool for silicon wafer screening, crystal growth studies, and process evaluation.

LITERATURE CITATION:

"Determination of Carrier Lifetime in Si by Optical Modulation," Polla, D.L.; IEEE Electron Device. Lett., EDL-4, 185; 1983.

CS-11: Exploration of a Method for Improving
Recombination Properties of Silicon

IDEA DESCRIPTION/RATIONALE:

This abstract describes a method for improving recombination and other electrical properties of silicon by removing defects prior to and after junction formation. Research is needed to explore the results of this method to well designed silicon solar cells. These explorations should examine the effects both before and after the formation of the p/n junction. At the outset the study should concentrate on attaining high efficiency in laboratory solar cells comparing the results obtained by this method against various control samples, both efficiency and in the profile of defects or lifetime measured against position.

Two of the most important material parameters for a solar cell are the recombination lifetime within the volume of the device and the surface recombination velocity at its surface. Both parameters relate to the loss of electrically charged carriers, electrons and holes, and hence to the consequent degradation of power conversion efficiency.

LITERATURE CITATION:

"Method for Making Defect-Free Zone by Laser-Annealing of Doped Silicon," Narayan, J., White, C.W., Young, R.T.; Dept. of Energy, Washington, D.C.; Pat-Appl-945-925; January 1980.

CS-12: Determination of the Dominant Defect Responsible
for Unavoidable Recombination

IDEA DESCRIPTION/RATIONALE:

The prominence of the recombination lifetime as a limiter to conversion efficiency suggests the high desirability of a research program aiming theoretically and experimentally at determining the dominant defect responsible for unavoidable recombination. Once identified, a subsequent effort would seek means for its removal. The benefit accruing to back-surface-field solar cells in which the base region has high resistivity could be marked.

LITERATURE CITATION:

"The Connection Between Carrier Lifetime and Doping Density in Nondegenerate Semiconductors," Landsberg, P.J., Kovich, G.S.; J. Appl. Phys., vol. 56, p. 1696; 1984.

CS-13: Adaptation of SIPOS to Solar Cells

IDEA DESCRIPTION/RATIONALE:

Research is proposed to exploit the advances in the uses and understanding of SIPOS (semi-insulating polycrystalline silicon) made recently in the integrated-circuits industry. SIPOS is used as a surface passivant for highly reliable silicon devices. The proposed research includes both adaptation of the technology to the needs of solar cells and also to a detailed study of the electrical and optical properties of SIPOS having various ranges of shallow dopant impurities such as phosphorous and boron.

SIPOS can be used as a surface passivant for silicon solar cells; however research to fully determine the optical characteristics is desirable to exploit the adaption of SIPOS to solar cells. Further, phosphorous or boron doped SIPOS has been used as the emitter material of a heterojunction transistor with the base and the collector being made of silicon. Very high injection efficiencies, 50 times above the standard values from conventional technology, have resulted for npn transistors. For solar cells, this translates to large increases in the open-circuit voltage and the fill factor, and thus to large increases in conversion efficiency.

LITERATURE CITATION:

"A Silicon Heterojunction Transistor," Matsushita, T, Oh-Uchi, N., Hayashi, H., Yamoto, H.; Semiconductor Div., Sony Corp., Atsugi, Kanagawa, Japan; Applied Physics Letter (USA), Vol. 35, No. 7, pp. 549-50; October 1, 1979.

"Characterization and Modelling of SIPOS on Silicon High Voltage Devices," Slatter, J.A.G, Sandoe, J.N., Hughes, J.R.; IEEE Colloquium on Power Semiconductors, London, Eng; (Digest No. 71), 3/1/84; May 31, 1984.

"Characteristics of CO/Sub 2/Deposited SIPOS Films," Zommer, N.; Power MOS Operations, Intersil, Inc. Cupertino, CA; IEEE Trans. Electron Devices (USA), Vol, 3d-27, No. 11, pp. 2056-63; November 1980.

"Oxygen Determination in SIPOS Using a Differential Thickness Measurement," Widmer, A.E., Hitchman, M.L.; Lab. RCA Ltd., Zurich, Switzerland; Journal of Electrochem. Soc. (USA), Vol. 25, No. 10, pp. 1723-5; October 1978.

CS-14: Explore the Use of Phosphorous Diffusion in Gettering

IDEA DESCRIPTION/RATIONALE:

By gettering we mean the removal of metal impurities and their interactions with such micro defects as stacking faults, dislocations, and point defects. Both diffused and implanted emitters in solar cells could serve as effective gettering layers.

Gettering reduces the concentration of trapping and recombination centers in the silicon. It thus improves the carrier lifetime, lowers the recombination current in both the space-charge region and quasineutral regions. Apparently this has received only a little attention in photovoltaics.

LITERATURE CITATION:

"Influence of Phosphorus-Induced Point Defects on a Gold-Gettering Mechanism in Silicon," Lecroenier, D., Paugam, J., Richou, F., Pelous, G.; J. Appl. Phys., 51, 1980.

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APPENDIX C: ABBREVIATIONS

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AES	Auger Electron Spectroscopy
ACCG	American Conference on Crystal Growth
AFML	Air Force Materials Laboratory
AFOSR	Air Force Office of Scientific Research
AF-RADC	Air Force-Rome Air Development Center
AFTAC	Air Force Tactical Air Command
ARCO	Atlantic Richfield Company
ARO	Army Research Office
BSF	Back Surface Fields
CBD	Commerce Business Daily
CS	Crystalline Silicon
CVD	Chemical Vapor Deposition
DARPA	Defense Advanced Research Projects Agency
DIALOG	Computer Information Retrieval System
DLTS	Deep Level Transient Spectroscopy
DOD	Department of Defense
DOE	Department of Energy
DRC	Device Research Conference
DTIC	Defense Technical Information Center
EDAX	Energy Dispersive X-Ray Analysis
EMC	Electronic Materials Conference
FETS	Field Effect Transistors
FTIR	Fourier Transform Infrared

GEC	General Electric Company
IBM	International Business Machines
IC	Integrated Circuits
ICCG	International Conference on Crystal Growth
IEDM	International Electron Device Meeting
INSPEC	Information Services in Physics, Electrotechnology, Computers and Control
IR	Infrared
ISS	Ion Scattering Spectroscopy
KWh	Kilowatt hour
LEDs	Light Emitting Diodes
LPCVD	Liquid Phase Chemical Vapor Deposition
MBE	Molecular Beam Epitaxy
MIT	Massachusetts Institute of Technology
MOCVD	Metal-Organic Chemical Vapor Deposition
MOVPE	Metal-Organic Vapor Phase Epitaxy
MRS	Materials Research Society
NASA	National Aeronautics and Space Administration
NBS	National Bureau of Standards
NGT	Nominal Group Technique
NRL	Naval Research Laboratory
NSF	National Science Foundation
NTIS	National Technical Information Service

OER	Office of Energy Research
ONR	Office of Naval Research
OUSDRE	Office of the Under Secretary of Defense for Research and Engineering
PCSI	Physics and Chemistry of Semiconductor Interfaces
PETD	Photovoltaic Energy Technology Division
PL	Photoluminescence
PL, CDL	Photo and Cathode Luminescence
PV	Photovoltaics
RADC	Rome Air Development Center
RBS	Rutherford Back Scattering
RO	Research Opportunity
RSRE	Royal Signals and Radar Equipment
SDI	Strategic Defense Initiative
SEM	Scanning Electron Microscopy
SEMI	Semiconductor Equipment and Materials Institute
SERI	Solar Energy Research Institute
SIMS	Secondary Ion Mass Spectroscopy
SIPOS	Semi-Insulating Polysilicon
SISC	Semiconductor Interface Specialists Conference
SLS	Strained Layer Superlattices
SRC	Semiconductor Research Corporation
TEM	Transmissive Electron Microscopy
TF	Thin Films
XPS	X-Ray Photoelectron Spectroscopy
3V	III-V Compounds