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# SERI Photovoltaic Subcontract Reports: 1988 Abstracts and Document Control Information

Photovoltaic Program Branch

June 1990

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**Solar Energy Research Institute**
A Division of Midwest Research Institute

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## PREFACE

This report contains the document control information and abstracts for SERI Photovoltaic (PV) Program Branch publications resulting from SERI's subcontracted PV research. The information is presented for reports published or distributed during fiscal year (FY) 1988. In the past, copies of the subcontractor reports were distributed to a broad spectrum of researchers in the field of photovoltaics at a considerable cost to the program. In an attempt to reduce costs and ensure that all researchers receive those current publications that are of specific interest to them, this report will outline these publications, organized by technology, on a regular basis. A list of additional publications and sources is included herein to provide the photovoltaic community with other sources of information. All of the documents represented here are available from the National Technical Information Service (NTIS) and can be purchased using the NTIS order form at the end of this document. Further information on a given subcontracted program may be obtained from the SERI technical monitor identified on each Document Control Page.

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4. Title and Subtitle

Low-Band-Gap, Amorphous-Silicon-Based Alloys by Photochemical Vapor Deposition, Final Subcontract Report, 1 October 1985 -- 30 November 1986

5. Publication Date: February 1988

6.

7. Author(s)

B.N. Baron, S.S. Hegedus, and S. C. Jackson

8. Performing Organization Rept. No.

9. Performing Organization Name and Address

Institute of Energy Conversion
University of Delaware
Newark, Delaware 19716

10. Project/Task/Work Unit No. PV740601

11. Contract (C) or Grant (G) No.

(C) XL-5-04074-3

(G)

12. Sponsoring Organization Name and Address

Solar Energy Research Institute
1617 Cole Boulevard
Golden, Colorado 80401-3393

13. Type of Report & Period Covered: Technical Subcontract

14.

15. Supplementary Notes

SERI Technical Monitor: R. Mitchell (303) 231-1379

16. Abstract (Limit: 200 words)

Thin films of hydrogenated amorphous silicon-germanium alloys were deposited by mercury-sensitized photochemical vapor deposition using a novel photo-CVD reactor. Thin films of a-$Si_{1-x}Ge_x$:H with 0 less than or equal to x less than or equal to 1 and 1.0 less than $E_g$ less than 1.8 eV were deposited from mixtures of silane and disilane with germane and inert gas diluents at substrate temperatures from 160° to 200°C. Alloy films were characterized by measurements of photo- and dark conductivity, electron mobility-lifetime product, sub-band-gap absorption, and density of states. Dilution with hydrogen increased the photovonductivity to $10^{-5}$ S/cm and mobility-lifetime product to 6 x $10^{-8}$ $cm^2/V$ for alloys having a band gap of 1.4 eV.

17. Document Analysis

a. Descriptors: Silicon solar cells ; amorphous state ; thin films ; chemical vapor deposition

b. Identifiers/Open-Ended Terms

c. UC Categories: 271

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| Document Control Page | 1. SERI Report No. SERI/STR-211-3256 | 2. NTIS Accession No. DE88001117 | 3. Recipient's Accession No. |
|---|---|---|---|

**4. Title and Subtitle**
Investigation of the Origins of Metastable, Light-Induced Changes in Hydrogenated Amorphous Silicon, Annual Subcontract Report, 1 February 1986 - 28 February 1987

**5. Publication Date**
October 1987

**6.**

**7. Author(s)**
J. D. Cohen

**8. Performing Organization Rept. No.**

**9. Performing Organization Name and Address**
Department of Physics
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**10. Project/Task/Work Unit No.**
PV740201

**11. Contract (C) or Grant (G) No.**
(C) XB-6-06024-1
(G)

**12. Sponsoring Organization Name and Address**
Solar Energy Research Institute
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**13. Type of Report & Period Covered**
Technical Report

**14.**

**15. Supplementary Notes**
Technical Monitor: Byron Stafford (303) 231-7126

**16. Abstract (Limit: 200 words)** This report presents results of an investigation into the metastable changes in the density of deep mobility gap states in hydrogenated amorphous silicon, using a variety of junction capacitance techniques. This work extends previous studies (using drive-level capacitance profiling) to some new samples. With these measurements, researchers examined how the distribution of occupied gap states changes with light soaking and partial annealing through a series of intermediate states between states A and B. The results on two phosphorus-free samples indicate no qualitative change from previous results, which revealed a large metastable increase in the concentration of $D^-$ centers with light soaking, so phosphorus contamination is not crucial to this increase. Because such an increase is inconsistent with the Si-Si bond-breaking model, this result favors a model in which local configurational changes shift the gap-state energies of existing defects. Transient photocapacitance was applied to undoped films to investigate metastable changes in more detail. Results seemed to confirm the magnitude of the metastable defect creation found by drive-level analysis on the same samples.

**17. Document Analysis**
a. Descriptors Amorphous state ; silicon solar cells ; energy losses ; doped materials ; metastable states

b. Identifiers/Open-Ended Terms

c. UC Categories
63

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|---|---|---|---|

4. Title and Subtitle

Diagnostics of Glow Discharges Used To Produce Hydrogenated Amorphous Silicon Films, Annual Subcontract Report, 15 April 1986-14 June 1987

5. Publication Date: February 1988

6.

7. Author(s)

A. Gallagher, J. Doyle, M. He, G. Lin, J. Scott

8. Performing Organization Rept. No.

9. Performing Organization Name and Address

National Bureau of Standards
Boulder, Colorado

University of Colorado
Boulder, Colorado

10. Project/Task/Work Unit No. PV740201

11. Contract (C) or Grant (G) No.

(C) DB-4-04078-1

(G)

12. Sponsoring Organization Name and Address

Solar Energy Research Institute
1617 Cole Boulevard
Golden, Colorado 80401-3393

13. Type of Report & Period Covered: Technical Report

14.

15. Supplementary Notes

SERI Technical Monitor: W. Luft (303) 231-1823

16. Abstract (Limit: 200 words)

This report presents results of research done to measure the neutral species produced in silane, silane-hydrogen, disilane, disilane-hydrogen, germane, germane-hydrogen, and silane-germane discharges. Interpretation and modeling of the data in terms of discharge chemistry are also desirable. Mass-spectrometric measurements were made of the stable gases flowing through and produced in silane, disilane, and silane-germane discharges. From these observations, the discharge stoichiometry was determined and the reaction pathways that lead to film deposition clarified. The importance of one processing parameter (power/flow) is explained, and a high ratio of germane/silane depletion in mixed-gas discharges is identified. A calculation of radical deposition in pure silane discharges shows the dominance of $SiH_3$ deposition at low powers and suggests the reason (surface mobility) why this produces good-quality films. Measurements of postdeposition sputtering of a-Si:H films were diagnosed to yield the thickness of the H-rich, growing film surface layer, which is important in understanding and modeling the deposition reactions as well as the effect of ion bombardment on film properties and sputtering. A new, potentially high-rate deposition method was also developed and studied.

17. Document Analysis

a. Descriptors

Amorphous state ; silicon solar cells ; deposition ; glow discharges

b. Identifiers/Open-Ended Terms

c. UC Categories

271

18. Availability Statement

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|---|---|---|---|

**4. Title and Subtitle**
Research on High-Efficiency, Stacked, Multijunction, Amorphous Silicon Alloy Thin-Film Solar Cells, Final Subcontract Report, 11 October 1983 - 30 October 1986

**5. Publication Date**
October 1987

**6.**

**7. Author(s)**
J. Bragagnolo

**8. Performing Organization Rept. No.**

**9. Performing Organization Name and Address**
Spire Corporation
Bedford, Massachusetts 01730

**10. Project/Task/Work Unit No.**
3493.10

**11. Contract (C) or Grant (G) No.**
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**12. Sponsoring Organization Name and Address**
Solar Energy Research Institute
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1617 Cole Boulevard
Golden, Colorado 80401-3393

**13. Type of Report & Period Covered**
Technical Report

**14.**

**15. Supplementary Notes**
Technical Monitor: Werner Luft (303) 231-1823

**16. Abstract (Limit: 200 words)**
This report covers the third year of a three-year project to develop high-efficiency, stable, multijunction amorphous silicon alloy solar cells. It describes new deposition techniques to obtain pinhole-free, a-Si:H alloy films by avoiding dust formation in the plasma; the deposition of low-absorptance, textured $SnO_2$ layers by thermal CVD of $Sn(CH_3)_4$; a more stable, high-reflectance Ti/Ag back contact; the application of the new deposition techniques to achieve efficiencies of 10.5%, 10.1%, and 9.4% for a-Si:H p-i-n devices; the development of a-(Si,Ge):H cells with efficiencies from 5.4% for a-(Si,Ge):H cells to 7.5% for graded-bandgap cells; and the development of a-Si/a-(Si,Ge) tandem cells with 6.5% and 7.2% efficiencies.

**17. Document Analysis**
a. Descriptors Amorphous state ; silicon solar cells ; chemical vapor deposition ; graded band gaps

b. Identifiers/Open-Ended Terms

c. UC Categories
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|---|---|---|---|

**4. Title and Subtitle**

Optimization of Transparent and Reflecting Electrodes for Amorphous Silicon Solar Cells, Final Subcontract Report, 1 October 1986 -- 31 November 1987

**5. Publication Date**
June 1988

**6.**

**7. Author(s)**
R. G. Gordon et al.

**8. Performing Organization Rept. No.**

**9. Performing Organization Name and Address**

Department of Chemistry
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Cambridge, Massachusetts 02138

**10. Project/Task/Work Unit No.**

**11. Contract (C) or Grant (G) No.**
(C) XB-7-06110-1
(G)

**12. Sponsoring Organization Name and Address**

Solar Energy Research Institute
1617 Cole Boulevard
Golden, Colorado 80401-3393

**13. Type of Report & Period Covered**
Technical Report

**14.**

**15. Supplementary Notes**
SERI Technical Monitor: J. Ohi (303) 231-7681

**16. Abstract (Limit: 200 words)**

In this research, hydrogenated amorphous silicon (a-Si:H) films were deposited by an inexpensive, thermally induced, atmospheric-pressure chemical vapor deposition (CVD) process. High-quality films were grown at 300 Å/s, more than two orders of magnitude faster than those produced by conventional glow discharge. Sources of uncontrolled oxygen, boron, phosphorus, and carbon contamination were identified and eliminated. The efficiency of a-Si solar cells can be increased by using rough, rather than smooth, tin oxide as the front-surface transparent electrode, because the rough tin oxide-silicon interface increases the absorption of red light (light trapping) and reduces the reflection loss of light across the whole spectrum. We produced, by CVD, rough tin oxide films from tetramethyltin. Cells grown on the rough films had higher efficiencies than those grown on smooth tin oxide. We also used a precursor tin compound (dimethyltin dichloride) that is less costly and less hazardous than some others. Rough films can be grown from dimethyltin dichloride more than three times faster than from tetramethyltin. To combine the CVD processes, we need a layer that prevents the tin oxide layer from being attacked by the silicon, such as a barrier layer of titanium oxide, which seems to be effective.

**17. Document Analysis**

**a. Descriptors**
Photovoltaic cells ; amorphous state ; silicon solar cells ; chemical vapor deposition ; efficiency

**b. Identifiers/Open-Ended Terms**

**c. UC Categories**
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|---|---|---|---|

**4. Title and Subtitle**

Research on High-Efficiency, Single-Junction, Monolithic, Thin-Film Amorphous Silicon Solar Cells, Semiannual Subcontract Report No. 3, 1 Dec. 1985-31 May 1986

**5. Publication Date**
June 1988

**6.**

**7. Author(s)**
F.E. Aspen et al.

**8. Performing Organization Rept. No.**

**9. Performing Organization Name and Address**
Electronic and Information Sector Latoratories
3M Company
St. Paul, Minnesota 55144

**10. Project/Task/Work Unit No.**

**11. Contract (C) or Grant (G) No.**
(C) ZB-4-03056-2
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**12. Sponsoring Organization Name and Address**
Solar Energy Research Institute
1617 Cole Boulevard
Golden, Colorado 80401

**13. Type of Report & Period Covered**
Technical Report

**14.**

**15. Supplementary Notes**
SERI Technical Monitor: W. Wallace (303)231-1380

**16. Abstract (Limit: 200 words)**

This report describes progress in research on high-efficiency, single-junction, monolithic, thin-film amorphous silicon solar cells. The work was divided into five tasks, wich include research on a-Si materials; nonsemiconductor materials; web growth; and monolithic, intraconnected cells and submodules. Also described is work done with a multichamber deposition system. Results included achieving an optical band gap of 1.73-1.75 eV in the intrinsic i-layer. A new roll coater was acquired for use as a multilayer transparent top-contact deposition system. Textured substrates were also investigated to increase the short-circuit current. In doping profile work, a model indicated that a carbon profile could be used in place of the boron profile to raise the open-circuit voltage. Silver-filled epoxy-ITO contacts were found to be unstable over time. Two web-growth methods were demonstrated to obtain submodule performance that is about 80% of small-area ( 1 $cm^2$) efficiency. With the multichamber deposition system, a-Si p-i-n layers were deposited onto metallized polyimide web in a continuous, roll-to-roll process.

**17. Document Analysis**

a. Descriptors Photovoltaic cells ; amorphous state ; silicon solar cells ; thin films ; deposition ; doped materials

b. Identifiers/Open-Ended Terms

c. UC Categories
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|---|---|---|---|

**4. Title and Subtitle**
Research on Amorphous-Silicon-Based Thin-Film Photovoltaic Devices, Semiannual Subcontract Report, 1 July 1987--31 December 1987

**5. Publication Date**
May 1988

**6.**

**7. Author(s)**
W. Bottenberg, K. Mitchell, and R. Wieting

**8. Performing Organization Rept. No.**

**9. Performing Organization Name and Address**
ARCO Solar, Inc.
Camarillo, California 93010

**10. Project/Task/Work Unit No.**
PV840201

**11. Contract (C) or Grant (G) No.**
(C) ZB-7-06003-3
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**12. Sponsoring Organization Name and Address**
Solar Energy Research Institute
1617 Cole Boulevard
Goden, Colorado 80401-3393

**13. Type of Report & Period Covered**
Technical Report

**14.**

**15. Supplementary Notes**
SERI Technical Monitor: W. Luft (303)231-1823

**16. Abstract (Limit: 200 words)**

The objective of this work is to develop 13% (aperture area) efficient, 850-$cm^2$ four-terminal hybrid tandem submodules. The module design consists of a copper-indium-diselenide (CIS)-based bottom circuit and a semitransparent, thin-film silicon-hydrogen (TFS)-based top circuit. High-performance, semitransparent TFS devices and submodules were fabricated in which ZnO was used in the front and rear transparent conductors. High-performance CIS devices and submodules were also fabricated; however, the location and nature of the junction are not yet understood. Representative four-terminal hybrid tandem devices and submodules were fabricated from TFS and CIS component circuits. Optical coupling between the circuits was lower than expected, because of reflection losses at key interfaces. Efficiencies obtained for these devices and modules include 14.17% for a four-terminal, 4-$cm^2$ tandem cell and 12.3% for a four-terminal, tandem module.

**17. Document Analysis**

a. Descriptors Photovoltaic cells ; silicon solar cells ; copper selenide solar cells ; thin films

b. Identifiers/Open-Ended Terms

c. UC Categories
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**18. Availability Statement**
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|---|---|---|---|

**4. Title and Subtitle**

Research of Amorphous Silicon-Germanium Alloys for Tandem Solar Cells, Annual Subcontract Report, 1 July 1986--31 August 1987

**5. Publication Date**
May 1988

**6.**

**7. Author(s)**
W. Paul and K.D. Mackenzie

**8. Performing Organization Rept. No.**

**9. Performing Organization Name and Address**
Division of Applied Sciences
Harvard University
Cambridge, Massachusetts 02138

**10. Project/Task/Work Unit No.**
PV840201

**11. Contract (C) or Grant (G) No.**
(C) XB-7-06071-1
(G)

**12. Sponsoring Organization Name and Address**
Solar Energy Research Institute
1617 Cole Boulevard
Golden, Colorado 80401-3393

**13. Type of Report & Period Covered**
Technical Report

**14.**

**15. Supplementary Notes**
SERI Technical Monitor: W. Luft (303) 231-1823

**16. Abstract (Limit: 200 words)**

The objective of this work is to explore the deposition conditions necessary to produce amorphous Si-Ge alloys with a band gap near 1.3 to 1.4 eV whose photoelectronic properties will be comparable to those of a-Si:H. It is essential to understand why the photoconductivity of a-$Si_{1-x}Ge_x$:H:F is superior to that of a-$Si_{1-x}Ge_x$:H, while most of the commonly measured optical and electronic properties remain unchanged. The focus of this investigation was on deposition conditions and on the microstructure of the films as revealed by transmission electron microscopy, gas evolution, and differential scanning calorimetry, concentrating on alloys with a high Ge content. Films were made both by glow discharge and by photochemical vapor deposition in a new type of apparatus. Structure, very important in determining photoelectronic properties, depends on the totality of the deposition parameters, and it is therefore important to understand the conditions in the plasma and at the interface of the growing film, when $SiH_4$, $GeH_4$, and $H_2$ are present in different concentrations, whatever the method of deposition.

**17. Document Analysis**

**a. Descriptors** Photovoltaic cells ; amorphous state ; silicon solar cells ; energy gap ; deposition

**b. Identifiers/Open-Ended Terms**

**c. UC Categories**
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|---|---|---|---|

4. Title and Subtitle

Structure of Amorphous Silicon Alloy Films, Annual Subcontract Report, 15 January 1987--14 January 1988

5. Publication Date: May 1988

6.

7. Author(s)

R. E. Norberg and P. A. Fedders

8. Performing Organization Rept. No.

9. Performing Organization Name and Address

Department of Physics
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St. Louis, Missouri

10. Project/Task/Work Unit No.: PV840201

11. Contract (C) or Grant (G) No.

(C) XB-7-06055-1

(G)

12. Sponsoring Organization Name and Address

Solar Energy Research Institute
1617 Cole Boulevard
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13. Type of Report & Period Covered: Technical Report

14.

15. Supplementary Notes

SERI Technical Monitor: W. Luft (303) 231-1823

16. Abstract (Limit: 200 words)

The principal objective of the first year of this research program was to improve our understanding at the microscopic level of amorphous silicon-germanium alloy films deposited under various conditions to assist researchers in producing higher quality films. The method was a joint theoretical and experimental approach to the correlation of muclear magnetic resonance (NMR), electron spin resonance (ESR), and other characterizations, especially relating to rearrangements of hydrogen. Deuteron magnetic resonance reveals the presence of (and changes in) tightly bonded hydrogen (deuterium), weakly bonded hydrogen, molecular hydrogen, and rotating silyl groups. Ge-D configurations appear to be more varied than Si-D. It has been shown that ESR hyperfine structure results can be interpreted very well via dangling bonds, but not with floating bonds. The presence of fluorine correlates with the occurrence of larger microvoid dimensions.

17. Document Analysis

a. Descriptors: Photovoltaic cells ; amorphous state ; silicon solar cells ; semiconductor materials ; fluoride ; germanium ; laboratory equipment ; nuclear magnetic resonance

b. Identifiers/Open-Ended Terms

c. UC Categories

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18. Availability Statement

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4. Title and Subtitle

Amorphous Silicon Photovoltaic Devices Prepared by Chemical and Photochemical Vapor Deposition of Higher Order Silanes, Annual Subcontract Report, 1 September 1986 -- 31 August 1987

5. Publication Date: June 1988

6.

7. Author(s)

A.E. Delahoy and H.E. Schade

8. Performing Organization Rept. No.

9. Performing Organization Name and Address

Chronar Corporation
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10. Project/Task/Work Unit No.

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(C) XB-5-04092-1

(G)

12. Sponsoring Organization Name and Address

Solar Energy Research Institute
1617 Cole Boulevard
Golden, Colorado 80401

13. Type of Report & Period Covered: Technical Report

14.

15. Supplementary Notes

SERI Technical Monitor: B. Stafford (303) 231-7126

16. Abstract (Limit: 200 words)

This report describes results of research on preparing high-efficiency photovoltaic devices by photochemical vapor deposition of higher order silanes. The photostability of these devices was compared to that of devices produced by the glow-discharge technique. Hydrogenated amorphous silicon cell efficiencies of at least 7.5% were obtained using p-i-n structures and aluminum back contacts. Using silver contacts increased the efficiency to about 8%. After 6 minutes of light soaking, there was no significant difference between the photostabilities of these cells and those produced by glow discharge. The efficiencies might be increased further if some remaining problems can be addressed, such as by using a different substrate preparation method or a higher pumping speed at the deposition chamber.

17. Document Analysis

a. Descriptors

Photovoltaic cells ; silicon solar cells ; amorphous state ; efficiency

b. Identifiers/Open-Ended Terms

c. UC Categories

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18. Availability Statement

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4. Title and Subtitle

Preparation and Properties of High-Deposition-Rate a-Si:H Films and Solar Cells Using Disilanes, Annual Subcontract Report, 1 May 1987--30 April 1988

5. Publication Date: June 1988

6.

7. Author(s)

P.K. Bhat, H. Chatham, and A. Madan

8. Performing Organization Rept. No.

9. Performing Organization Name and Address

Glasstech Solar, Inc.
Wheatridge, Colorado 80033

10. Project/Task/Work Unit No.

11. Contract (C) or Grant (G) No.

(C) ZB-7-06002-1

(G)

12. Sponsoring Organization Name and Address

Solar Energy Research Institute
1617 Cole Boulevard
Golden, Colorado 80401-3393

13. Type of Report & Period Covered

14.

15. Supplementary Notes

SERI Technical Monitor: W. Luft (303) 231-1823

16. Abstract (Limit: 200 words)

This report contains results of the first year of research on producing p-i-n amorphous silicon solar cells with the intrinsic layer deposited from higher order silanes at deposition rates of 1 nm/s or more. The research was divided into three major areas: (1) diagnostic studies of monosilane and disilane RF discharges using optical emission spectroscopy and mass spectrometry to assist in optimizing discharge conditions and gas-phase processes; (2) parametric studies of material properties of i-layers prepared from disilane as a function of deposition rate and other process parameters; and (3) parametric studies of p-i-n devices with the i-layer prepared from disilane at various deposition rates. The focus during the first year was to fabricate a p-i-n solar cell with 9% AM1.5 efficiency over an area greater than 0.08 $cm^2$ with the i-layer deposited at 1 nm/s or more. Material properties such as the dark and AM1.5 light conductivities, optical band gap, and conductivity activation energy showed a weak dependence on deposition rate. The performance characteristics of unoptimized p-i-n solar cells with i-layers prepared from disilane were independent of the deposition rate of the i-layer. A p-i-n device was prepared at a rate close to 1 nm/s with an AM1.5 efficiency of 9%.

17. Document Analysis

a. Descriptors

Photovoltaic cells ; silicon solar cells ; amorphous state ; deposition

b. Identifiers/Open-Ended Terms

c. UC Categories

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18. Availability Statement

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4. Title and Subtitle
$CuInSe_2$ Solar Cell Research by Sputter Deposition, Annual Subcontract Report, 1 January 1986 - 31 December 1986

5. Publication Date
June 1987

6.

7. Author(s)
J. A. Thornton, T. C. Lommasson, and H. Talieh

8. Performing Organization Rept. No.

9. Performing Organization Name and Address
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University of Illinois
Urbana, Illinois 61801

10. Project/Task/Work Unit No.
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12. Sponsoring Organization Name and Address
Solar Energy Research Institute
A Division of Midwest Research Institute
1617 Cole Boulevard
Golden, Colorado 80401-3393

13. Type of Report & Period Covered
Technical Report

14.

15. Supplementary Notes
Technical Monitor: H. S. Ullal (303) 231-1841

16. Abstract (Limit: 200 words)
This report contains results of research on $CuInSe_2$ solar cells by sputter deposition. Most of the $CuInSe_2$/CdS devices fabricated from $CuInSe_2$ deposited by reactive sputtering have been characterized by relatively low open-circuit voltages. Typical values range from 0.22 to 0.32 V. A contributing factor may be the lower In composition in the top layer of composite two-layer $CuInSe_2$ films (Cu-rich base layer, In-rich top layer) that we used in cell fabrication. The reason for the lower In content is an In rejection process occurring during deposition at elevated temperatures. Therefore, the major emphasis of this work was to increase the In content in the top layer of $CuInSe_2$ films deposited in composite two-layer configurations on Mo-coated, glass substrates. Variations in the relative currents to the Cu and In sputtering sources, the $H_2Se$ injection rate, and the substrate temperature were explored. A temperature decrease from 450° to 400°C increased the In composition from 25 at. % to about 27 at. %. A second approach, in which the In sputtering source was operated for a short time with no Cu sputtering, also yielded promising results.

17. Document Analysis
a. Descriptors
Photovoltaic cells ; copper selenide solar cells ; deposition ; thin films

b. Identifiers/Open-Ended Terms

c. UC Categories
63

18. Availability Statement
National Technical Information Service
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Form No. 0069 (3-25-82)

| Document Control Page | 1. SERI Report No. SERI/STR-211-3190 | 2. NTIS Accession No. | 3. Recipient's Accession No. |
|---|---|---|---|

4. Title and Subtitle

Preparation and Properties of Evaporated CdTe Films, Final Subcontract Report, 16 February 1985 - 31 March 1987

5. Publication Date: July 1987

6.

7. Author(s): R.H. Bube, A.L. Fahrenbruch, K.F. Chien

8. Performing Organization Rept. No.

9. Performing Organization Name and Address

Department of Materials Science and Engineering
Stanford University
Stanford, California 94305

10. Project/Task/Work Unit No.: 3494.10

11. Contract (C) or Grant (G) No.

(C) XL-4-04022-1
(G)

12. Sponsoring Organization Name and Address

Solar Energy Research Institute
1617 Cole Boulevard
Golden, Colorado 80401

13. Type of Report & Period Covered: Technical Report

14.

15. Supplementary Notes

SERI Technical Monitor: Richard Mitchell

16. Abstract (Limit: 200 words)

Previous work on evaporated CdTe films for photovoltaics showed no clear path to successful p-type doping of CdTe during deposition. Post-deposition annealing of the films in various ambients thus was examined as a means of doping. Anneals were done in Te, Cd, P, and As vapors and in vacuum, air, and Ar, all of which showed large effects on series resistance and diode parameters. With As, series resistance values of In/p-CdTe/graphite structures decreased markedly. This decrease was due to a decrease in grain boundary and/or back contact barrier height, and thus was due to large increases in mobility; the carrier density was not altered substantially. Although the series-resistance decreases were substantial, the diode characteristics became worse. The decreases were not observed when CdS/CdTe cells were fabricated on Te vapor-annealed films. Preparation of ZnO films by reactive evaporation yielded promising results. Deposition of p-ZnTe films by hot-wall vapor evaporation, using conventional techniques, yielded acceptable films without intentional doping.

17. Document Analysis

a. Descriptors

Photovoltaic cells ; thin films ; cadmium telluride solar cells ; deposition

b. Identifiers/Open-Ended Terms

c. UC Categories

63

18. Availability Statement

National Technical Information Service
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| Document Control Page | 1. SERI Report No. SERI/STR-211-3215 | 2. NTIS Accession No. DE88001159 | 3. Recipient's Accession No. |
|---|---|---|---|

**4. Title and Subtitle**
Device Physics Related to the Granular Nature of $CuInSe_2$ Solar Cells, Annual Subcontract Report, 1 April 1986 - 31 March 1987

**5. Publication Date**
February 1988

**6.**

**7. Author(s)**
J. R. Sites

**8. Performing Organization Rept. No.**

**9. Performing Organization Name and Address**
Department of Physics
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**10. Project/Task/Work Unit No.**
PV740301

**11. Contract (C) or Grant (G) No.**
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**12. Sponsoring Organization Name and Address**
Solar Energy Research Institute
A Division of Midwest Research Institute
1617 Cole Boulevard
Golden, Colorado 80401-3393

**13. Type of Report & Period Covered**
Technical Report

**14.**

**15. Supplementary Notes**
Technical Monitor: H. S. Ullal (303) 231-1841

**16. Abstract (Limit: 200 words)**
Several aspects of the impact of $CuInSe_2$ polycrystallinity on solar cell performance were investigated. Reflection measurements on a variety of $CuInSe_2$ layers and completed cells show large variations in both the magnitude and angular distribution of scattered light. Localized illumination reveals spatial variations in photovoltaic response which imply collection losses as high as 10%. Capacitance studies allow extraction of the density of extraneous electronic states at the diode junction. These decrease in reverse bias but increase under illumination and, hence, forward bias. A physical model of polycrystalline $CuInSe_2$ is presented, and finally the status of $CuInSe_2$ cells is analyzed in terms of the extent to which various factors are limiting performance.

**17. Document Analysis**
a. Descriptors Photovoltaic cells ; copper indium diselenide solar cells ; efficiency ; thin films

b. Identifiers/Open-Ended Terms

c. UC Categories
273

**18. Availability Statement**
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| Document Control Page | 1. SERI Report No. SERI/STR-211-3216 | 2. NTIS Accession No. | 3. Recipient's Accession No. |
|---|---|---|---|

**4. Title and Subtitle**

Growth and Characterization of Thin Films of $ZnSnP_2$, Final Subcontract Report, 15 October 1983 -- 31 May 1987

**5. Publication Date**
February 1988

**6.**

**7. Author(s)**
P.K. Ajmera and H.Y. Shin

**8. Performing Organization Rept. No.**

**9. Performing Organization Name and Address**
Department of Electrical and Computer Engineering
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Baton Rouge, Louisiana 70803

**10. Project/Task/Work Unit No.**
PV840601

**11. Contract (C) or Grant (G) No.**
(C) XL-4-03032-2
(G)

**12. Sponsoring Organization Name and Address**
Solar Energy Research Institute
1617 Cole Boulevard
Golden, Colorado 80401-3393

**13. Type of Report & Period Covered**
Technical Subcontract Report

**14.**

**15. Supplementary Notes**
SERI Technical Monitor: R. Mitchell

**16. Abstract (Limit: 200 words)**

This research involved the vacuum deposition of thin films of $ZnSnP_2$. This ternary chalcopyrite semiconductor has a direct energy gap of 1.66 eV. Its constituent elements, zinc and phosphorus, are plentiful in the U.S. and tin is readily available from abroad. This makes $ZnSnP_2$ an attractive material for low-cost terrestrial photovoltaic applications. Growth conditions were experimentally determined to obtain near-stoichiometric vacuum growth of thin films of $ZnSnP_2$ on GaAs, quartz, and molybdenum substrates utilizing elemental sources. The grown films were characterized by chemical, electrical, and optical measurements and by morphological studies. Attempts were made to fabricate simple heterostructure devices on the grown layers. This research provides information on the relevant properties of vacuum-grown thin films of $ZnSnP_2$ for its potential application in polycrystalline thin-film PV devices.

**17. Document Analysis**

**a. Descriptors**
Photovoltaic cells ; thin films ; semiconductor materials ; deposition

**b. Identifiers/Open-Ended Terms**

**c. UC Categories**
273

**18. Availability Statement**
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|---|---|---|---|

**4. Title and Subtitle**
CdZnTe as a Wide-Band-Gap Absorber for a Tandem, Thin-Film Solar Cell, Final Subcontract Report, 1 April 1986-31 August 1987

**5. Publication Date**
October 1987

**6.**

**7. Author(s)**
K. R. Zanio

**8. Performing Organization Rept. No.**

**9. Performing Organization Name and Address**
Ford Aerospace and Communications Corporation
Newport Beach, CA 92658

**10. Project/Task/Work Unit No.**
PV740601

**11. Contract (C) or Grant (G) No.**
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(G)

**12. Sponsoring Organization Name and Address**
Solar Energy Research Institute
A Division of Midwest Research Institute
1617 Cole Boulevard
Golden, Colorado 80401-3393

**13. Type of Report & Period Covered**
Technical Report

**14.**

**15. Supplementary Notes**
Technical Monitor: Richard Mitchell (303) 231-1379

**16. Abstract (Limit: 200 words)**
The objective of this program was to prepare by low-cost ultra-high-vacuum (UHV) methods an all-thin-film (approximately 1.6 eV) wide-bandgap solar cell using CdZnTe as the absorber layer. ZnTe/CdZnTe/n-CdS/ITO/glass structures were prepared by congruent evaporation in UHV. Ohmic contact to the ZnTe with HgZnTe and conversion of the high-resistivity ZnTe and CdZnTe was simultaneously undertaken by the closed-space vapor deposition of HgZnTe. Mesa structures did not show blocking action. Single-crystal cells were prepared by the deposition of CdS on bulk p-CdTe and thin-film, single-crystal p-CdTe-on-sapphire and p-CdZnTe-on-sapphire. A comparison of results suggests that the all-thin-film polycrystalline structure is limited by the CdZnTe.

**17. Document Analysis**

**a. Descriptors**
Photovoltaic cells ; cadmium telluride solar cells ; thin films ; crystal growth ; energy gaps

**b. Identifiers/Open-Ended Terms**

**c. UC Categories**
63

**18. Availability Statement**
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| Document Control Page | 1. SERI Report No. SERI/STR-211-3218 | 2. NTIS Accession No. | 3. Recipient's Accession No. |
|---|---|---|---|

4. Title and Subtitle

MOCVD Techniques for CdTe Solar Cells, Final Subcontract Report, 15 February 1985-1 April 1987

5. Publication Date: February 1988

6.

7. Author(s): D. E. Schafer

8. Performing Organization Rept. No.

9. Performing Organization Name and Address

Honeywell Physical Sciences Center
Bloomington, Minnesota 55420

10. Project/Task/Work Unit No.: PV740601

11. Contract (C) or Grant (G) No.

(C) XL-5-04074-4

(G)

12. Sponsoring Organization Name and Address

Solar Energy Research Institute
1617 Cole Boulevard
Golden, Colorado 80401-3393

13. Type of Report & Period Covered: Technical Report

14.

15. Supplementary Notes

SERI Technical Monitor: R. Mitchell

16. Abstract (Limit: 200 words)

This report summarizes the application of metal-organic chemical vapor deposition (MOCVD) film growth to two aspects of CdTe/ITO solar cell fabrication: (1) the growth of large-area CdTe films on ITO, and (2) the formation of low-resistance ohmic contacts to p-type CdTe. A reduced-temperature MOCVD process was developed for the deposition of CdTe films in order to minimize the potential for chemical and physical changes in the ITO layer during cell fabrication. MOCVD growth of HgTe and ZnTe were developed for fabrication of ohmic contacts (opaque and long-wavelength transparent, respectively) to the CdTe layer of the photovoltaic structure. This report details the MOCVD reactor geometries and process parameters used in the development of the CdTe, HgTe, and ZnTe layer growth, as well as the results of C-V analysis of the carrier concentration in the MOCVD CdTe layers and resistance characteristics of various interfaces formed by CdTe, HgTe, and ZnTe.

17. Document Analysis

a. Descriptors: Photovoltaic cells ; cadmium telluride solar cells ; thin films ; chemical vapor deposition

b. Identifiers/Open-Ended Terms

c. UC Categories: 273

18. Availability Statement

National Technical Information Service
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| Document Control Page | 1. SERI Report No. SERI/STR-211-3229 | 2. NTIS Accession No. DE8800183 | 3. Recipient's Accession No. |
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**4. Title and Subtitle**
Thin-Film Cadmium Telluride Solar Cells, Annual Subcontract Report, 1 May 1986-31 May 1987

**5. Publication Date**
October 1987

**6.**

**7. Author(s)**
T. L. Chu

**8. Performing Organization Rept. No.**

**9. Performing Organization Name and Address**
Southern Methodist University
Dallas, Texas 75275

**10. Project/Task/Work Unit No.**
3494.10

**11. Contract (C) or Grant (G) No.**
(C) XL-5-05039-1
(G)

**12. Sponsoring Organization Name and Address**
Solar Energy Research Institute
1617 Cole Boulevard
Golden, Colorado 80401

**13. Type of Report & Period Covered**
Technical Report

**14.**

**15. Supplementary Notes**
SERI Technical Monitor: H.S. Ullal (303) 231-1841

**16. Abstract (Limit: 200 words)**

Cadmium telluride, with a room-temperature band-gap energy of 1.5 eV, is a promising thin-film photovoltaic material. The major objective of this research has been to demonstrate thin-film CdTe heterojunction solar cells with a total area greater than 1 $cm^2$ and photovoltaic efficiencies of 13% or more. Thin-film p-CdTe/CdS/$SnO_2$:F/glass solar cells with an AM1.5 efficiency of 10.5% have been reported previously. This report contains results of work done on (1) the deposition, resistivity control, and characterization of p-CdTe films by the close-spaced sublimation process; (2) the deposition of large-band-gap window materials; (3) the electrical properties of CdS/CdTe heterojunctions; (4) the formation of stable, reproducible, ohmic contacts (such as p-HgTe) to p-CdTe; and (5) the preparation and evaluation of heterojunction solar cells.

**17. Document Analysis**

**a. Descriptors**
Photovoltaic cells ; cadmium telluride solar cells ; thin films ; deposition

**b. Identifiers/Open-Ended Terms**

**c. UC Categories**
63

**18. Availability Statement**
National Technical Information Service
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|---|---|
| 4. Title and Subtitle<br>Cadmium Sulfide/Copper Ternary Heterojunction Cell Research, Final Subcontract Report, 1 October 1984-31 May 1987 | 5. Publication Date<br>November 1987<br>6. |
| 7. Author(s)<br>W. E. Devaney, et al. | 8. Performing Organization Rept. No. |
| 9. Performing Organization Name and Address<br>Boeing High Technology Center<br>Seattle, Washington 98124-6269 | 10. Project/Task/Work Unit No.<br>PV740301<br>11. Contract (C) or Grant (G) No.<br>(C) ZL-4-04068-1<br>(G) |
| 12. Sponsoring Organization Name and Address<br>Solar Energy Research Institute<br>1617 Cole Boulevard<br>Golden, Colorado 80401 | 13. Type of Report & Period Covered<br>Technical Report<br>14. |

15. Supplementary Notes
SERI Technical Monitor: H. S. Ullal (303) 231-1841

16. Abstract (Limit: 200 words)
This is the Final Technical Report on a 32-month study of $CuInSe_2$- and $CuInGaSe_2$-based thin-film polycrystalline heterojunction solar cells. $CuInGaSe_2$ films incorporating Ga fractions (x in $CuIn_{1-x}Ga_xSe_2$) from 0.04 to 1.0 were prepared and characterized. $CuInGaSe_2$/CdZnS heterojunction devices were fabricated for a range of Ga contents and show the expected variations in $V_{oc}$ and spectral response with Ga content. A 10.2% efficiency (Solar Energy Research Institute (SERI) test, American Society for Testing and Materials (ASTM) 87) was measured for a cell with Ga fraction of 0.23, the highest efficiency reported. A $CuInSe_2$/CdZnS monolithically interconnected four-cell series string 91 $cm^2$ in area was fabricated with 9.5% total area efficiency (SERI test, ASTM87). Results are presented on ion-assisted deposition of the selenide and sulfide, a new design for the Se evaporation source, indium-tin oxide reactive sputter deposition, and CdZnS films prepared from an E-gun evaporation source. Spectral response and current-voltage characteristic variations with selenide composition before and after heat treatment are discussed for the $CuInSe_2$/CdZnS devices. The highest AM1 total area efficiency for the $CuInSe_2$/CdZnS cell is now 11.9% (Boeing test, AM1 spectrum), with five cells measured over the previously reported high of 10.9%.

17. Document Analysis
a. Descriptors
Photovoltaic cells ; thin films ; copper selenide solar cells ; deposition
b. Identifiers/Open-Ended Terms
c. UC Categories
63

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| 18. Availability Statement<br>National Technical Information Service<br>U.S. Department of Commerce<br>5285 Port Royal Road<br>Springfield, Virginia 22161 | 19. No. of Pages<br>130<br>20. Price<br>A07 |

| Document Control Page | 1. SERI Report No. SERI/STR-211-3249 | 2. NTIS Accession No. DE8800111G | 3. Recipient's Accession No. |
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**4. Title and Subtitle**
Stable, High-Efficiency, $CuInSe_2$-Based, Polycrystalline Thin-Film Tandem Solar Cells, Final Subcontract Report, 16 March 1984 - 15 March 1987

**5. Publication Date**
October 1987

**6.**

**7. Author(s)**
R. W. Birkmire and J. E. Phillips

**8. Performing Organization Rept. No.**

**9. Performing Organization Name and Address**
Institute of Energy Conversion
University of Delaware
Newark, Delaware

**10. Project/Task/Work Unit No.**
PV740301

**11. Contract (C) or Grant (G) No.**
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**12. Sponsoring Organization Name and Address**
Solar Energy Research Institute
A Division of Midwest Research Institute
1617 Cole Boulevard
Golden, Colorado 80401-3393

**13. Type of Report & Period Covered**
Technical Report

**14.**

**15. Supplementary Notes**
Technical Monitor: Richard Mitchell (303) 231-1379

**16. Abstract (Limit: 200 words)** The long-term objective of this research was to obtain a stable, thin-film solar cell based on polycrystalline materials with an efficiency of 15%. The approach was to make a tandem cell based on $CuInSe_2$/CdS as the bottom cell and CdTe/CdS as the top cell. An essential feature was to develop a CdTe cell with transparent contacts. A suitable contacting system was developed using transparent conducting oxides (ITO and $SnO_2$) in conjunction with a thin layer of copper. Cells were made with efficiencies over 8.5%. A reproducible fabrication process for $CuInSe_2$/(CdZn)S cells was developed based on $CuInSe_2$ films grown by vacuum evaporation using Knudsen-type effusion sources. These cells were made with efficiencies over 10%. The composition of the $CuInSe_2$ films can be varied over a considerable range and still yield high-efficiency cells. Adding Zn to the CdS did not increase the $V_{oc}$ of the devices; analysis showed that the $V_{oc}$ is not controlled by interface recombination. The effect of oxidizing and reducing heat treatments on $CuInSe_2$ cells is to change carrier concentration and thus $V_{oc}$. Analysis suggests that $J_o$ is controlled by band-to-band recombination. Monolithic tandem $CuInSe_2$ CdTe cells have been made with efficiencies of ~3%, demonstrating the feasibility of this approach.

**17. Document Analysis**

**a. Descriptors**
Photovoltaic cells ; copper selenide solar cells ; thin films ; efficiency

**b. Identifiers/Open-Ended Terms**

**c. UC Categories**
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**18. Availability Statement**
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**4. Title and Subtitle**

Ternary Adamantine Materials for Low-Cost Solar Cells, Final Subcontract Report, 1 November 1984-31 December 1986

**5. Publication Date**
February 1988

**6.**

**7. Author(s)**
D. Cahen and G. Hodes

**8. Performing Organization Rept. No.**

**9. Performing Organization Name and Address**
Weizmann Institute of Science
Rehovot, Israel

**10. Project/Task/Work Unit No.**
PV740301

**11. Contract (C) or Grant (G) No.**
(C) IL-5-04132-1
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**12. Sponsoring Organization Name and Address**
Solar Energy Research Institute
1617 Cole Boulevard
Golden, Colorado 80401-3393

**13. Type of Report & Period Covered**
Technical Report

**14.**

**15. Supplementary Notes**
SERI Technical Monitor: H. S. Ullal (303) 231-1841

**16. Abstract (Limit: 200 words)**

Several methods were investigated to prepare $CuInS(e)_2$, using electroplating techniques near room temperature, to explore them for obtaining photovoltaically active films. No significant photoactivity resulted, unless an annealing step (at greater than or equal to 400°C) was added to the process. Promising PV activity was found only if this anneal was carried out in a S(e)-containing atmosphere. Therefore, in part of this project, the two steps, metal deposition and chalcogen incorporation, were separated. These experiments showed that chalcogenization is the most critical step in obtaining films that are PV active. The composition of the films obtained after the chalcogenization step can be varied considerably by a chemical, postannealing treatment. PV activity of films was checked in a simple, rapid way by sputtering Cd onto them. Both these junctions, as well as those obtained by ITO deposition, show improved rectification and PV activity, after air anneal of the chalcogenized film, before junction formation. Possible causes for this are discussed. Separate C-V experiments on $Al/CuInSe_2/Mo$ structures, using $CuInSe_2/Mo$ films, provided direct evidence of the persistence of two types of $CuInSe_2$ layers, distinquishable by their doping concentration.

**17. Document Analysis**

**a. Descriptors** Photovoltaic cells ; thin films ; copper indium diselenide solar cells ; chalcogenides ; annealing

**b. Identifiers/Open-Ended Terms**

**c. UC Categories**
273

**18. Availability Statement**
National Technical Information Service
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4. Title and Subtitle

Thin-Film Cadmium Telluride Solar Cells, Final Subcontract Report, 1 May 1985--31 May 1988

5. Publication Date: June 1988

6.

7. Author(s): T. L. Chu

8. Performing Organization Rept. No.

9. Performing Organization Name and Address

Southern Methodist University
Dallas, Texas 75275

10. Project/Task/Work Unit No.

11. Contract (C) or Grant (G) No.

(C) XL-5-050390-1

(G)

12. Sponsoring Organization Name and Address

Solar Energy Research Institute
1617 Cole Boulevard
Goden, Colorado 80401-3393

13. Type of Report & Period Covered: Technical Report

14.

15. Supplementary Notes

SERI Technical Monitor: H. S. Ullal - (303) 231-1841

16. Abstract (Limit: 200 words)

This report describes results of research performed to demonstrate thin-film cadmium telluride heterojunction solar cells with a total area greater than 1 $cm^2$ and efficiencies of 13% or higher. Efforts were directed to (1) the deposition, resistivity control, and characterization of p-CdTe films by combining the vapor of the elements (CVE) and close-spaced sublimation (CSS) techniques; (2) the deposition and characterization of transparent conducting semiconductors: (3) the deposition of p-HgTe as a low-resistance ohmic contact to p-CdTe; (4) the electrical properties of CdS/CdTe heterojunctions; and (5) the preparation and evaluation of heterojunction solar cells. CdS/CdTe solar cells showed the best photovoltaic characteristics, and the best cell had a conversion efficiency of about 10.6%.

17. Document Analysis

a. Descriptors

Photovoltaic cells ; cadmium telluride solar cells ; thin films ; heterojunctions

b. Identifiers/Open-Ended Terms

c. UC Categories

273

18. Availability Statement

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| Document Control Page | 1. SERI Report No. SERI/STR-211-3188 | 2. NTIS Accession No. DE87012260 | 3. Recipient's Accession No. |
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4. Title and Subtitle
Gallium Arsenide and Multibandgap Solar Cell Research, Final Subcontract Report, April 1984 - April 1986

5. Publication Date
July 1987

6.

7. Author(s)
S. M. Vernon, S. P. Tobin, and R. G. Wolfson

8. Performing Organization Rept. No.

9. Performing Organization Name and Address
Spire Corporation
Bedford, MA 01730

10. Project/Task/Work Unit No.
3496.20

11. Contract (C) or Grant (G) No.
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12. Sponsoring Organization Name and Address
Solar Energy Research Institute
A Division of Midwest Research Institute
1617 Cole Boulevard
Golden, Colorado 80401-3393

13. Type of Report & Period Covered
Technical Report

14.

15. Supplementary Notes
Technical Monitor: Cécile Leboeuf (303) 231-1066

16. Abstract (Limit: 200 words)

This report presents results of research in high-efficiency, low-cost solar cells, emphasizing heteroepitaxial growth of a III-V compound material onto a single-crystal silicon wafer. The report describes the start-up and characterization of a new metal-organic vapor deposition (MOCVD) reactor for the growth of GaAs, GaAlAs, and GaAsP on 2-in.-diameter substrates with excellent uniformity; optimization of the growth of Ge films on Si by a simple CVD technique; and production of a 9% efficient GaAs-on-Ge-on-Si solar cell. The advancements in the understanding of the GaAs-on-Si growth process and in the quality of the films are described. The work also included production of a 7% efficient GaAs-on-Si cell; development of a GaAsP-on-GaAs growth technology; production of a 16.5% efficient GaAsP cell and a 17.7% efficient GaAlAs cell on GaAs; and production of a 20.8% efficient GaAs-on-GaAs cell. Also described are improvements in cell processing technologies, including the use of a double-layer antireflection coating.

17. Document Analysis

a. Descriptors
Photovoltaic cells ; silicon solar cells ; gallium arsenide solar cells ; chemical vapor deposition ; efficiency

b. Identifiers/Open-Ended Terms

c. UC Categories
63

18. Availability Statement
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4. Title and Subtitle

Research on Multibandgap Solar Cells, Final Subcontract Report, 1 March 1984 - 31 January 1987

5. Publication Date: July 1987

6.

7. Author(s)
J.A. Cape, L.M. Fraas, P.S. McLeod, L.D. Partain

8. Performing Organization Rept. No.

9. Performing Organization Name and Address
Chevron Research Company
Richmond, California 94802

10. Project/Task/Work Unit No.
3496.20

11. Contract (C) or Grant (G) No.
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12. Sponsoring Organization Name and Address
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1617 Cole Boulevard
Golden, Colorado 80401

13. Type of Report & Period Covered
Technical Report

14.

15. Supplementary Notes
SERI Technical Monitor: Cecile Leboeuf (303) 231-1066

16. Abstract (Limit: 200 words)

This report describes research in multibandgap solar cells. In early work, two-color solar cells with efficiencies exceeding 20% were grown monolithically, comprising a GaAsP top junction over a GaAs or GaAsSb bottom junction. Researchers attempted to understand the effects of lattice mismatch and optimize growth conditions for these structures. Severe unreproducibility was encountered and traced to source material impurities. $CP_2Mg$, the p-dopant, was found to be undependable, and efforts were made to purify it. Impurity effects were also traced to the arsine (predominantly water vapor) and the gallium alkyls. Efforts were also made to purify these. Work focused on optimizing component cells of GaAsP and GaAsSb and on developing the growth process. This, though, did not lead to higher efficiencies. In developing component cells, work was also done on optimizing vacuum chemical epitaxy growth conditions (temperatures, flow rates, III-V ratios, chamber designs, etc.); on developing cell transition layers and reducing lattice-mismatch effects; on improving cell processing; on reducing impurities; and on improving material and cell characterization.

17. Document Analysis

a. Descriptors
Photovoltaic cells ; gallium arsenide solar cells ; efficiency ; doped materials ; epitaxy

b. Identifiers/Open-Ended Terms

c. UC Categories
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18. Availability Statement
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**4. Title and Subtitle**
Research on Single-Crystal CdTe Solar Cells, Final Subcontract Report, 1 February 1985-1 February 1987

**5. Publication Date**
October 1987

**6.**

**7. Author(s)**
J. M. Borrego, S. K. Ghandhi

**8. Performing Organization Rept. No.**

**9. Performing Organization Name and Address**
Electrical, Computer, and Systems Engineering Department
Rensselaer Polytechnic Institute
Troy, New York 12180

**10. Project/Task/Work Unit No.**
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**12. Sponsoring Organization Name and Address**
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A Division of Midwest Research Institute
1617 Cole Boulevard
Golden, Colorado 80401-3393

**13. Type of Report & Period Covered**
Technical Report

**14.**

**15. Supplementary Notes**
Technical Monitor: Richard Mitchell (303) 231-1379

**16. Abstract (Limit: 200 words)**
This report outlines two years of work on the growth and characterization of single-crystal CdTe layers, to explore their potential for high-efficiency solar cells. It was demonstrated that high-quality layers can be grown by organometallic vapor phase epitaxy (OMVPE), whose photoluminescence peak has a FWHM of 5.8 meV, the lowest value for them yet achieved. CdTe layers were extrinsically doped both n- and p-type with indium and arsenic, respectively. The doping level achieved for p-type is the highest yet reported in the literature, achieved for the first time in an OMVPE system. A hole lifetime of 2.0 μm was measured. In the n-type material, five deep levels were isolated; their capture cross section, energy level, and concentration were determined. A thermodynamic analysis was made to identify their defect character. Both Schottky and p-n junction devices were produced on these layers. The diode characteristics were superior to those of GaAs so this is a potentially superior material for solar cells.

**17. Document Analysis**
a. Descriptors: Photovoltaic cells ; cadmium telluride solar cells ; semiconductor materials ; Schottky barrier solar cells

b. Identifiers/Open-Ended Terms

c. UC Categories
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**18. Availability Statement**
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Annual Report, Photovoltaic Measurements and Performance Branch, FY 1988. (January 1989). SERI/PR-213-3590. 160 pp. Available NTIS: Order No. DE89009500.

Annual Report, Photovoltaic Program Branch, FY 1988. (March 1989). SERI/PR-211-3483. 302 pp. Available NTIS: Order No. DE89000898.

Annual Report, Solid State Photovoltaic Research Branch, FY 1988. (July 1989). SERI/PR-212-3494. 265 pp. Available NTIS: Order No. DE89009463.

Conference Record of the Nineteenth IEEE Photovoltaic Specialists Conference - 1987; New Orleans, Louisiana; May 4-8, 1987. (1987). New York: The Institute of Electrical and Electronics Engineers, Inc.; 1530 pp. Available from IEEE, 345 E. 47th St., New York, NY 10017.

Conference Record of the Twentieth IEEE Photovoltaic Specialists Conference - 1988; Las Vegas, Nevada; September 26-30, 1988. (1988). New York: The Institute of Electrical and Electronics Engineers, Inc.; 2 Volumes, 1664 pp. Available from IEEE, 345 E. 47th St., New York, NY 10017.

Current Abstracts: Photovoltaic Energy, Electricity from Sunlight. Prepared by the Office of Scientific and Technical Information for the Office of Conservation and Renewable Energy, U. S. Department of Energy. Nov.-Dec. 1989, PB89-933006. Available from the Office of Scientific and Technical Information, P.O. Box 62, Oak Ridge, TN 37831.

Current Abstracts: Photovoltaic Energy, Electricity from Sunlight. Prepared by the Office of Scientific and Technical Information for the Office of Conservation and Renewable Energy, U. S. Department of Energy. Jan.-Feb. 1990, PB90-933001. Available from the Office of Scientific and Technical Information, P.O. Box 62, Oak Ridge, TN 37831.

Photovoltaic Energy Program Summary, Volume I: Overview, Fiscal Year 1988. (January 1989). DOE/CH10093-40. Golden, CO: Solar Energy Research Institute; 15 pp. Prepared for the U.S. Department of Energy, Assistant Secretary, Conservation and Renewable Energy, Washington, DC, by the Solar Energy Research Institute, Golden, Colorado. Available NTIS: Order No. DE89000855.

Photovoltaic Energy Program Summary, Volume II; Research Summaries Fiscal Year 1988. (January 1989). DOE/CH10093-39. Golden, CO: Solar Energy Research Institute; 188 pp. Prepared for the U.S. Department of Energy, Assistant Secretary, Conservation and

Renewable Energy, Washington, DC, by the Solar Energy Research Institute, Golden, Colorado. Available NTIS: Order No. DE89000832.

Photovoltaics: Entering the 1990s. (November 1989). SERI/SP-220-3461. 42 pp. Produced by the Development and Communications Office. Available NTIS: Order No. DE89009509.

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Riordan, C. J.; Hulstrom, R. L.; Cannon, T. W.; Stoffel, T. L.; Myers, D. R.; (February 1989). Photovoltaic Advanced Research and Development Project, Solar Radiation Research, Annual Report, 1 October 1987 - 30 September 1988. SERI/PR-215-3445. 24 pp. Available NTIS: Order No. DE89000884.

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Ullal, H. S.; Zweibel, K.; Mitchell, R. L. (November 1989). U.S. Polycrystalline Thin Film Solar Cell Program. SERI/TP-211-3595. 6 pp. Prepared for the Materials Research Society 1989 Fall Meeting, 27 November - 2 December 1989, Boston, Massachusetts. Available NTIS: Order No. DE89009506.

Ullal, H. S.; Zweibel, K.; Sabisky, E. S.; Surek, T. (August 1988). Solar Photovoltaic Technology: The Thin Film Option. SERI/TP-211-3390. 10 pp. Presented at the AIChE Summer National Meeting, Denver, Colorado, 21-24 August 1988. Available NTIS: Order No. DE88001195.

U.S. Photovoltaic Patents: 1951-1987. (September 1988). SERI/SP-210-3357. 616 pp. Available NTIS: Order No. DE88001178.

Zweibel, K. (May 1989). Thin Film Photovoltaics. SERI/TP-211-3501. 7 pp. Prepared for the 24th Intersociety Energy Conversion Engineering Conference, Washington, D.C., 6-11 August 1989. Available NTIS: Order No. DE89009425.

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