340
11/3/80 T.S

Lh. 1953

MASTER

DSE-4042-T30

ADVANCED PHOTOVOLTAIC CONCENTRATOR CELLS

Quarterly Technical Progress Report No. 1 for period August 28—November 30, 1979

By
S. W. Zehr
H. T. Yang
J. S. Harris, Jr.

December 1979

Work Performed Under Contract No. EG-77-C-01-4042

Solar Energy Research Institute
Photovoltaics Program Office
Golden, Colorado

U.S. Department of Energy

Solar Energy

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency Thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

DISCLAIMER

"This book was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof."

This report has been reproduced directly from the best available copy.

Available from the National Technical Information Service, U. S. Department of Commerce, Springfield, Virginia 22161.

Price: Paper Copy \$6.00
Microfiche \$3.50

ADVANCED PHOTOVOLTAIC CONCENTRATOR CELLS

Quarterly Technical Progress Report No. 1
for period 08/28/79 through 11/30/79

By

S. W. Zehr, H. T. Yang and J. S. Harris, Jr.
Rockwell International Electronics Research Center
Thousand Oaks, California 91360

For

Solar Energy Research Institute
Photovoltaics Program Office
PVPO - Documentation
1536 Cole Boulevard
Golden, Colorado 80401

December, 1979

Prepared under Contract No. XJ-9-8058-1

Approved by:

J. S. Harris, Jr.
Program Manager

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

TABLE OF CONTENTS

	<u>Page</u>
1.0 INTRODUCTION.....	1
2.0 MODELING.....	3
2.1 Accomplishments.....	3
2.2 Estimation of Optical Losses from Intercell Ohmic Contacts.....	4
2.3 Improvement of Stacked Cell Computer Models.....	7
2.4 Modeling of Existing AlGaAs Cells.....	8
2.5 Modeling of AlGaSb Cells and Stack Optimization.....	10
2.6 Optical Losses Caused by the Presence of GaAs Substrate in the Stack.....	14
2.7 Window Layer Composition Effects on Performance of Low Bandgap Subcells.....	14
3.0 MATERIALS DEVELOPMENT.....	18
3.1 Accomplishments.....	18
3.2 Substrates.....	18
3.2.1 GaSb Substrates.....	18
3.2.2 GaAs Substrates.....	19
3.3 AlGaAs Subcells.....	19
3.4 AlGaSb Subcells.....	19
3.4.1 AlGaSb Low Bandgap Cell Structures.....	19
3.5 Thermal Bonding for IOC Fabrication.....	22
3.5.1 Ohmic Junction Formation.....	22
3.5.2 In Situ Window Formation During Thermal Bonding.....	26
3.5.3 Pressure Bonding.....	27
3.6 Indium Tin Oxide IOC Studies.....	27
3.7 Laser Bonded IOC Structures.....	28
4.0 DEVICE FABRICATION AND CHARACTERIZATION.....	29
4.1 Accomplishments.....	29
4.2 AlGaSbAs Subcells.....	29
4.3 AlGaAs Subcells.....	31
4.4 Measurements.....	35
5.0 REFERENCES.....	37

LIST OF FIGURES

	<u>Page</u>
Fig. 2.1 Typical reflectance vs. wavelength curves for various thicknesses, d_1 , of a transparent conductive oxide of refractive index $n_1 = 2.2$ sandwiched between a transparent large bandgap semiconductor of refractive index $n_0 = 3.5$ and an absorbing small bandgap semiconductor of refractive index $n_2 = 3.6$ and absorptive index $k_2 = 1$	5
Fig. 2.2 Reflectance vs. wavelength curves for various airgap thicknesses, d_1 , between the transmitting and absorbing semiconductors of Fig. 2.1.....	6
Fig. 2.3 Schematic of current baseline large-bandgap structure for bonded, high efficiency stacked multijunction solar cell.....	9
Fig. 2.4 Calculated spectral response curves for optimized AlGaAs and AlGaSb structures having the properties and dimensions listed in Table 2.1.....	12
Fig. 2.5 Free carrier absorption in n-type GaAs.....	15
Fig. 2.6 Modeled photoresponse of GaAl _{0.25} Sb solar cell having GaAlSb windows of indicated thickness and composition.....	17
Fig. 3.1 Morphology of a typical wafer after growth.....	23
Fig. 3.2 Schematic of interface bonding arrangement.....	24
Fig. 3.3 Ohmic contact between bonded non-lattice matched semiconductors. (a) Photomicrograph of bonded interface, (b) I-V curve for above contact. Contact area 0.15 cm^2 . Contact resistance $< 0.09 \Omega\text{-cm}^2$	25
Fig. 4.1 Schematic low bandgap subcell structures, (a) homo-junction: $x_1 = 0.3\text{-}0.65$, $x_2 = 0$, $0.1\text{-}0.2$, $y \cong 0.007$, (b) heterojunction: $x_1 = 0.3\text{-}0.65$, $x_3 = 0.1\text{-}0.2$	30
Fig. 4.2 Illuminated I-V curve for 0.8 eV AlGa _{0.1} Sb solar cell.....	32
Fig. 4.3 Dark I-V characteristics of $p^+\text{-Ga}_{0.7}\text{Al}_{0.3}\text{AsSb/p-Ga}_{0.9}\text{Al}_{0.1}\text{Sb/n-Ga}_{0.9}\text{Al}_{0.1}\text{Sb/n-GaSb}$ subcell.....	33
Fig. 4.4 Spectral response of a heteroface homojunction GaAlAsSb/GaSb subcell.....	34

ERC41033.8TPR

ABSTRACT

This report describes first quarter activities for a project aimed at demonstrating the technical feasibility of advanced high efficiency concentrator solar converters. The goal of the program is to achieve 30% conversion efficiency with a converter operating at 30°C under 500-1000 SUN AM2 illumination and 25% conversion efficiency with a converter operating at 150°C under 500-1000 SUN AM2 illumination. The approach is to fabricate two cell, non-lattice matched, monolithic stacked converters using optimum pairs of cells having bandgaps in the range of 1.6 - 1.7 eV and 0.95 - 1.1 eV. The high bandgap cells are to be fabricated using MOCVD or LPE to produce the needed AlGaAs layers of optimized composition, thickness and doping to produce high performance, heteroface homojunction devices. The low bandgap cells are to be similarly fabricated from AlGaSb(As) compositions by LPE. These subcells are then to be joined into a monolithic structure by an appropriate thermal bonding technique which will also form the needed transparent intercell ohmic contact (IOC) between the two subcells.

The activities this quarter have been largely focused on the development and study of low bandgap cell structures and attempts to develop suitable techniques for the thermal bonding operation.

ERC41033.8TPR

1.0 INTRODUCTION

Within the last several years, there has been growing interest in exploiting the significantly improved levels of power conversion efficiency which is theoretically available from multibandgap solar photovoltaic converters⁽¹⁻⁵⁾. This interest has been sparked by the recognition that even a partial realization of these potential performance gains can provide significant leverage for reduction of the cost of output electric power from concentrator photovoltaic systems⁽⁶⁾.

Upper bound conversion efficiencies near 40% and 47% have been calculated, respectively, for optimum bandgap two and three junction converters operating at 300°K under terrestrial sunlight concentrated to several hundred to one thousand SUNs⁽¹⁻⁵⁾. Even when practical losses are taken into account, such converters offer a reasonable prospect for achieving at least 30% efficiency from stacked, monolithic, two-bandgap structures of well-optimized design, operating at 30°C under 500-1000 SUN AM2 illumination.

Such devices also offer the option of operating at these levels of sunlight concentration at moderately elevated temperatures (~150°C) with at least 25% electrical conversion efficiency and the added bonus of providing usable quality heat for total energy applications.

It is the objective of this project to demonstrate the technical feasibility of producing monolithic stacked multibandgap solar cells having 30% conversion efficiency at 30°C and 25% conversion efficiency at 150°C under 500-1000 SUN AM2 illumination.

To meet this objective, the following tasks will be performed:

1. Grow and optimize single junction AlGaAs cells having bandgaps of 1.6 eV and 1.7 eV and AlGaSb cells having bandgaps of 0.95 eV and 1.1 eV.
2. Develop techniques for joining these optimized single junction cells by means of non-lattice matched intercell ohmic contacts

having sufficient optical transparency combined with low electrical and thermal resistance to meet the overall performance objective.

3. Characterize performance of the individual cells and stacked combinations using appropriate light and dark I-V and spectral response measurements over the operating temperature range of 30-200°C and for illumination levels of 1-1000 SUNs AM2.

ERC41033.8TPR

2.0 MODELING

2.1 Accomplishments

We have completed the initial stage of cell design optimization. The goal of this stage has been to determine the structure for each subcell which will provide optimum performance based on the known properties of currently available materials. Later in the program, as we succeed in improving material properties, particularly diffusion lengths, the structures will be reoptimized accordingly.

A quantitative study of expected losses from various stacked cell design alternatives has been initiated. We have completed the detailed estimation of the optical losses to be expected from various intercell ohmic contact (IOC) design approaches. The results suggest that tunnel junction structures will provide the least reflection loss by a considerable margin. In addition, a detailed consideration of the magnitude of absorption losses of transmitted low bandgap photons indicates the necessity for total elimination of the high bandgap substrate from the region between the subcells.

We have also begun work on extending our stacked-cell computer models to allow direct, detailed comparison of predicted and measured device performance. We have applied our existing heteroface window cell model to fitting spectral response data from some existing high bandgap AlGaAs cells with various window layer thicknesses and junction depths. The results are providing valuable guidance in optimizing the design of cell structures to be grown for this program.

We are proceeding with the development of a macroscopic stacked cell device model which will take account of the effects of variation in test temperature as well as variations in electrical and light bias during electrical characterization.

2.2 Estimation of Optical Losses from Intercell Ohmic Contacts

The optical losses from the following types of intercell ohmic contacts were analyzed: (a) an intercell layer of conductive oxide such as indium tin oxide (ITO), (b) an intercell metal contact grid, and (c) a bonded or grown semiconductor tunnel junction contact between cells.

Based on typical refractive indices of $n \sim 3.5$ to 3.6 for the semiconductors of interest for the component cell structures, and $n \sim 2.2$ for typical transparent conductive oxides such as ITO, we have calculated the reflectance vs. wavelength curves shown in Fig. 2.1 for the indicated thicknesses of the transparent conductive oxide interlayer. While the reflectance for a $100\text{\AA}$ layer is low enough to be tolerable, such a thin layer may be impractical. Constraints of surface roughness on the bonding semiconductors seem likely to place a practical lower limit of at least 0.5 to $1\text{ }\mu\text{m}$ on the intercell contact thickness. In this thickness range, the calculated reflective losses with an oxide contact layer are intolerably high for the present application.

For a metal grid pattern, the calculated low bandgap light reflection at the unmetallized semiconductor/air interfaces is shown in Fig. 2.2 for several air gap thicknesses. Again, the losses appear to be intolerably high at practical air gap thicknesses. To mitigate these losses, an additional AR coating at the low bandgap semiconductor-air interface would be required.

For a tunnel junction IOC structure, earlier calculations⁽⁷⁾ have indicated that reflective losses of $<2\%$ can be expected due to refractive index mismatch between GaAlAs and GaAlSb, and that $<1\%$ absorption loss is to be expected from tunnel junction layers $<500\text{\AA}$ thick. Thus, based strictly on these preliminary loss estimates for the various IOC alternatives, it appears that either bonded or grown tunnel junction IOC's currently show the most promise for the IOC application.

Fig. 2.1 Typical reflectance vs. wavelength curves for various thicknesses, d_1 , of a transparent conductive oxide of refractive index $n_1 = 2.2$ sandwiched between a transparent large bandgap semiconductor of refractive index $n_0 = 3.5$ and an absorbing small bandgap semiconductor of refractive index $n_2 = 3.6$ and absorptive index $k_2 = 1$.

ERC41033.8TPR

Fig. 2.2 Reflectance vs. wavelength curves for various airgap thicknesses, d_1 , between the transmitting and absorbing semiconductors of Fig. 2.1.

ERC41033.8TPR

2.3 Improvement of Stacked Cell Computer Models

Our existing stacked cell computer model is essentially a direct extension of a detailed single cell model. It does not presently include an adequate consideration of a number of sources of loss (such as the IOC optical losses discussed above) which are unique to stacked cell structures and could potentially have a major influence on optimum design of the total device. Furthermore, in the past we have had no analytical capability for modeling the effects of externally applied electrical and/or white light bias during spectral response measurements. It has recently been found from work on our companion Air Force stacked cell contract, that variation of these test parameters can add important new information about the electrical characteristics of the individual junctions included in the stacked cell structure.

The contemplated future inclusion of cell temperature and light and voltage bias as variables during spectral response measurements promises to significantly aid in separating and interpreting the diode behavior of the temperature sensitive light converting subcell structures from the nearly temperature-independent tunneling behavior of the intercell ohmic contact structures. The inclusion of appropriate mathematical models and parameters to allow direct comparison of theoretical and measured behavior over significant ranges of these variables would greatly expand our characterization capability and should more efficiently lead to improvements in device design and processing.

The specific activities in this area are the addition of subroutines to our existing stacked cell model which quantitatively account for (1) the additional performance losses unique to stacked cell designs and (2) provide the capability of modeling variation in spectral response caused by applied light and/or electrical bias and variations in sample temperature. It is anticipated that continued activity in this area will be strongly guided by the details of the experimental results obtained throughout the course of the contract.

2.4 Modeling of Existing AlGaAs Cells

Improved AlGaAs cell design has resulted from using our existing models to match experimental photoresponse results with known structural parameters as inputs. To do this, minority carrier diffusion length and interface recombination velocity (IRV) are varied parametrically to provide a best fit of the experimental curves. Then, using the best fit values of diffusion length and IRV thus obtained, layer thicknesses and junction depth are parametrically adjusted to obtain optimum performance. Based on these results and the measured performance of a variety of AlGaAs cells previously produced under our companion Air Force contract, our current baseline AlGaAs cell design is that shown in Fig. 2.3. This will be modified appropriately as new information and/or improved materials are developed.

A second outcome of this modeling effort has been the identification of an inadequacy in the correction procedure used for converting our raw measured spectral response data to absolute internal quantum efficiency and short circuit current density. In the past, our procedure has been simply to multiply the directly measured spectral response intensity data by correction factors intended to account for variations of the photon flux with wavelength (inherent in the light source, optics and feedback controller) as well as for variations of the sample reflectance with wavelength. These latter reflectance corrections were obtained from direct measurements on particular GaAs heteroface cells, and were assumed to be valid in general for such cell structures.

Recent lack of success in adequately modeling some measured spectral response curves for wide bandgap AlGaAs cell structures of non-conventional thicknesses and compositions indicated that these particular reflectance corrections can not be generally applied. It now appears that where absolute internal quantum efficiency information is required, concurrent reflectance and spectral response measurements must be made for each sample. We are currently developing this capability in the course of assembling our new automated spectral response facility.

ERC41033.8TPR

Fig. 2.3 Schematic of current baseline large-bandgap structure for bonded, high efficiency stacked multijunction solar cell.

2.5 Modeling of AlGaSb Cells and Stack Optimization

We have collected and incorporated in our heteroface window cell model the available absorption and electrical parameter data for the AlGaSb alloy system. A large number of computer runs have been made using these data to determine the optimum design of the low bandgap cell which gives the best match to the high bandgap AlGaAs cell. Table 2.1 summarizes the expected electrical parameters, preferred layer thicknesses, and expected AM2 short circuit current densities for the initial AlGaAs and AlGaSb cells. The calculated internal spectral response curves for both cells over their design spectral range is shown in Fig. 2.4. Based on our experience to date with these types of cells, we estimate the performance parameters shown in Table 2.2 for the initial devices of this design.

The computer model has also been used to examine the sensitivity of performance (as represented by short circuit current density) to possible variations in the electrical properties of the cell materials. As might be expected, the greatest leverage for improved subcell performance was found to come from increased electron diffusion length in the p-junction layer. While no attempt has yet been made to rigorously optimize cell design based on longer diffusion lengths, the trend suggested by available results is that increasing the electron diffusion length to $\sim 2.0 \mu\text{m}$ in both the AlGaAs and AlGaSb combined with appropriate junction depth adjustments would lead to internal collection efficiencies averaging $\sim 80\%$ over the usable spectral ranges. This would potentially increase the 1 SUN AM2 J_{sc} from roughly 13 mA/cm^2 to $\sim 17 \text{ mA/cm}^2$. Ignoring reflection losses, the corresponding stacked cell efficiencies would rise to $\sim 24\%$ and 35% for 1 SUN and 500 SUNs respectively.

We intend to pursue this large performance payoff from improved diffusion length as a major goal of the materials development effort.

Table 2.1 Baseline Design and Calculated Short Circuit Current Densities for the AlGaAs and AlGaSb Components of the Proposed Monolithic Stacked Cell

	<u>AlGaAs</u>	<u>AlGaSb</u>
Junction Bandgaps (eV) (Direct)	1.65	0.95
Junction Layer Al Fraction	0.20	0.25
Junction Depth (μm)	0.5	0.75
Electron Diffusion Length in p Junction Layer (μm)	0.7	1.0
Hole Diffusion Length in n Junction Layer (μm)	0.5	0.5
Interface Recombination Velocity (cm/sec)	10^4	10^4
Window Bandgap (eV) (Indirect)	2.1	1.58
Window Al Fraction	0.85	0.8
Window Thickness (μm)	0.1	0.1
Window Electron Diffusion Length (μm)	0.05	0.05
Surface Recombination Velocity (cm/sec)	10^6	10^6
Useful Spectral Range (Wavelengths in μm)	0.36 to 0.75	0.75 to 1.31
Calculated J_{sc} (mA/cm^2)* at 1 SUN AM2	13.16	13.2

* Assumes no shadowing or reflection losses.

Fig. 2.4 Calculated spectral response curves for optimized AlGaAs and AlGaSb structures having the properties and dimensions listed in Table I.

Table 2.2 Expected Performance for Baseline Stacked Cell Operating at 25°C Under AM2 Illumination (74.9 mW/cm²)

	HIGH BANDGAP AlGaAs CELL ALONE		LOW BANDGAP AlGaSb CELL ALONE		COMPLETE STACK	
	1 SUN	500 SUNs	1 SUN	500 SUNs	1 SUN	500 SUNs
Illumination Level						
Cell Series Resistance (Ohms)	.02	.02	.02	.02	.02	.02
Dark Saturation Current Density (Amp/cm ²)	10 ⁻¹³	10 ⁻¹³	10 ⁻⁶	10 ⁻⁶	---	---
Diode Factor	2	2	2	2	4	4
Short Circuit Current Density (Amp/cm ²)	13.16 x 10 ⁻³	6.58	13.2 x 10 ⁻³	6.6	13.2 x 10 ⁻³	6.6
Open Circuit Voltage (Volt)	1.1	1.4	0.40	0.75	1.5	2.15
Fill Factor	0.8	0.81	0.64	0.68	0.69	0.72
Peak Output Power Density (W/cm ²)	11.6 x 10 ⁻³	7.46	3.38 x 10 ⁻³	3.37	13.68 x 10 ⁻³	10.22
Efficiency (%)	15.5	19.9	4.5	8.9	18.3	27.3

ERC41033.8T PR

2.6 Optical Losses Caused by the Presence of GaAs Substrate in the Stack

We have examined the magnitude of absorption losses in GaAs substrate material to assess the tolerance of the device performance to the possible presence of substrate material between cells. The strong absorption of 1.42 eV to 1.65 eV photons by GaAs reduces the J_{sc} of the low bandgap cell by $\sim 28\%$ for an AM2 spectrum (5.6 mA/cm^2 lost out of a possible 19.6 mA/cm^2 available) for thicknesses of GaAs in the 10-20 mil range typical of substrate wafers. Even if the GaAs thickness were reduced to $\sim 10 \text{ }\mu\text{m}$, the absorption loss in this spectral range would still amount to $\sim 3.6 \text{ mA/cm}^2$. In addition to this above-bandgap absorption, there is significant loss of below-bandgap photons due to free carrier absorption. The magnitudes of the losses to the low bandgap cell from this source are indicated in Fig. 2.5. This figure shows the fraction of below bandgap photons absorbed in n-type GaAs at several doping levels. The plot was generated using the published absorption data of Spitzer and Whelan⁽⁸⁾. For our usual substrate doping levels of $\sim 5 \times 10^{18}$, the percentage of lost photons lie in the range of 45-80% for the substrate thicknesses in the range of 10-20 mils. By reducing the doping level to 10^{17} , these below bandgap losses become tolerable at 2 to 4%. Unfortunately, the 28% loss in the 1.42 - 1.65 eV range can hardly be improved by changes in doping level. Thus it appears that the elimination of the GaAs substrate from the final structure is necessary for acceptable performance. To facilitate handling during this additional processing step, we plan to grow the high bandgap structures inverted (i.e., window layer first) to allow stacking and bonding to the AlGaSb cell prior to substrate removal.

2.7 Window Layer Composition Effects on Performance of Low Bandgap Subcells

The possibility of obtaining acceptable photon transmission to the low bandgap cell through AlGaSbAs windows containing only 65% Al was

ERC41033 .8TPR

Fig. 2.5 Free carrier absorption in n-type GaAs

ERC41033.8TPR

examined. Layers of this composition have been successfully grown with good morphology (see Sect. 3.4.1) and if their optical transmission were adequate, the anticipated challenges and development effort of growing the needed low bandgap subcell structures would be significantly relaxed.

Based on the absorption data for the GaAlSb alloy system used in our modeling, it appears that thin 65% Al window layers will provide acceptable photon transmission for the spectral range of 0.75 eV - 1.2 eV. Comparison of the spectral response curves calculated for windows of Al_{0.65}GaSb and Al_{0.85}GaSb of both 1000Å and 5000Å thickness is made in Fig. 2.6. It can be seen that there is only a slightly greater loss of photons having energies below the 0.75 eV cut-off of the high bandgap top cell associated with the lower Al composition window at a thickness of 1000Å. Even at 5000Å, the loss is not significantly greater.

Based on this result, we will produce our initial AlGaSb cells with 1000Å thick 65% Al windows.

ERC41033.8TPR

Fig. 2.6 Modeled photoresponse of GaAl₂₅Sb solar cell having GaAlSb windows of indicated thickness and composition.

3.0 MATERIALS DEVELOPMENT

3.1 Accomplishments

Several preliminary LPE GaSb structures have been successfully grown in the initial stages of the effort to produce baseline 0.95 eV AlGaSb low bandgap cell structures.

A number of LPE AlGaAs structures have been produced for use in the study of the feasibility of ITO intercell ohmic contacts. In spite of the high reflective losses calculated for such structures (see section 2.2), a few feasibility experiments will be done to directly check the validity of the calculations.

Arrangements have been made to obtain initial MOCVD AlGaAs high bandgap cell structures sometime in December.

A pressure bonding apparatus has been designed and fabricated for use in developing thermally bonded intercell ohmic contacts between Al containing alloy semiconductors.

3.2 Substrates

3.2.1 GaSb Substrates

Arrangements have been made to have a boule of GaSb produced for this program within the Rockwell International Science Center facility. This will provide the doping type, orientation and quality of substrates needed for the low bandgap structures of this program. The initial boule is intended to be <100> orientation n-type ($\sim 2 \times 10^{17}$ Sn doped)

A small quantity of similar type GaSb substrate wafers is available currently, and is serving in the interim for initial bonding experiments aimed at the development of tunneling IOC's between dissimilar semiconductors and for the preliminary LPE growth experiments.

ERC41033.8TPR

3.2.2 GaAs Substrates

There is sufficient GaAs substrate materials currently on hand to satisfy the requirements of this program. However, it will be necessary to replace whatever is consumed as the work progresses.

3.3 AlGaAs Subcells

The major thrust of the AlGaAs subcell growth effort will employ MOCVD as the growth technique. Some LPE growth of analogous structures will be done to allow direct comparison of the suitability of the two methods on the basis of relative cell performance. Some LPE growths involving minor phosphorous additions will also be done in an effort to further improve performance by reducing the interface recombination losses resulting from the modest lattice mismatch between the GaAs substrate and the various AlGaAs layers.

The initial AlGaAs cell structures grown by MOCVD for this program are scheduled to become available sometime in December. Those grown by LPE are expected in January.

As mentioned earlier, some of these structures will be grown inverted to allow thermal bonding prior to GaAs substrate removal.

In anticipation of processing these AlGaAs structures, we are working to establish the required handling and processing technique associated with the substrate removal and bonding operations. So far there is no evidence that serious difficulties will be encountered.

3.4 AlGaSb Subcells

3.4.1 AlGaSb Low Bandgap Cell Structures

Some of the available GaSb substrate wafers have been used these past months to begin the LPE growth program for the low bandgap cell struc-

tures. The initial runs were undoped GaSb layers grown on both n- and p-type <100> GaSb substrates having doping densities of $\sim 4 \times 10^{17} \text{ cm}^{-3}$ for both types. The main purpose of these growths was to check out the thermal behavior and background doping level of the growth furnace and LPE boat. The morphology of the layers grown so far have been reproducibly smooth with good melt wipe off. The typical starting growth temperature is 510°C . The growth rates for GaSb are found to be $\sim 4.5 \mu\text{m}/^\circ\text{C}$ or $\sim 3 \mu/\text{min}$. using a cooling rate of $\sim 0.67^\circ\text{C}/\text{min}$.

Based on the morphological success of these initial GaSb layers, we began the growth of AlGaSb structures of various layer compositions and thicknesses. The initial window layer compositions were either 0.3 or 0.65 Al fraction. These relative low Al contents were used to improve the chances of early success in growing usable cell structures. A summary of the structures grown to date is shown in Table 3.1.

The $\text{Ga}_{1-x}\text{Al}_x\text{As}_{1-y}\text{Sb}_y$ layers were grown by conventional liquid phase epitaxy (LPE)⁽⁹⁻¹¹⁾ using a horizontal multi-compartment sliding boat⁽¹²⁾. <100> oriented Te doped (from 4×10^{17} to $1 \times 10^{18} \text{ cm}^{-3}$) n-type GaSb is used as substrates. Te doped GaSb polycrystal is used as a dopant source for n-type layers, and Ge is used for p-type layers. A 0.1% Br-CH₃OH solution is used to polish the substrate surface to mirror smoothness. Prior to growth, the substrates are solvent degreased and etched in 3% Br-CH₃OH solution for 1 to 2 minutes, before loading into the furnace.

The structures are grown from Ga-rich melts. The Ga, GaAs polycrystal, Sb, and the dopant are pre-baked at 700°C in purified hydrogen for 15 hours. The Al and the substrate are subsequently loaded into the furnace such that the Al and the melt do not initially contact each other. The furnace is heated to 600°C and kept at this temperature for one hour to reduce the oxide formed on the melt and substrate⁽¹³⁾. The Al is then dropped into the oxide-free melt to complete the saturation.

Before starting growth, the saturation temperature of each melt is determined by direct observation through the semitransparent furnace.

TABLE 3.1

NO.	LAYER STRUCTURE	PURPOSES
1	p+GaAl _{0.2} Sb/pGaSb	a. To assure a good growth of GaAl _{0.2} Sb layer. b. For the ITO contact experiment in the last section.
2.	p+GaAl _{0.65} Sb/pGaSb	a. For the ITO contact experiment in the last section.
3.	p+GaAl _{0.65} Sb/pGaSb/nGaSb	a. To assure good two layer growth techniques. b. Compare with the junction without window. c. For stack cell bonding.
4.	p+GaAl _{0.2} Sb/nGaAl _{0.2} Sb/nGaSb	a. GaAl _{0.2} Sb homojunction characteristics examination. b. Prepare for window cell.
5.	p+GaAl _{0.65} Sb/p+GaAl _{0.2} Sb/nGaAl _{0.2} Sb/nGaSb	a. Complete low bandgap cell for stacked cell bonding. b. Compare with the junction without window.

Growth temperatures are typically between 500 and 515°C. The binary ($x = 0$, $y = 0$) and ternary ($y = 0$) compounds are usually grown using 2 to 3°C supersaturation. For quaternary layers, a 5°C supersaturation is necessary to prevent etchback of the substrates. The cooling rate is typically 0.75°C/min. Growth rates are found to decrease with increasing Al composition, x . The morphology of a typical wafer after growth is shown in Fig. 3.1.

3.5 Thermal Bonding for IOC Fabrication

3.5.1 Ohmic Junction Formation

The preliminary fabrication of IOC tunneling structures has been successfully demonstrated using the flash heating thermal bonding technique described by Rediker et al. ⁽¹⁴⁾ and depicted schematically in Fig. 3.2. A photomicrograph of a typical thermally bonded interface between misoriented wafers of $\langle 100 \rangle$ GaAs and $\langle 100 \rangle$ GaSb is shown in Fig. 3.3(a). A corresponding I-V curve trace showing the nearly ohmic I-V characteristic is displayed in Fig. 3.3(b). There is no indication here of the characteristic negative resistance region associated with classical "Esaki" tunnel diodes. However, low temperature measurements of (dv/dI) as a function of applied voltage show resistance maximum centered at zero bias which is characteristic of a dominant tunneling process. These measurements were done by Debbie Duchin at UCLA. She also found evidence of the characteristic GaAs phonon assisted tunneling peak near 30 meV. An additional resistance peak centered near 120 meV may be due to phonon assisted tunneling processes in GaSb. To our knowledge, there is no report of this peak in the literature, but it would be a reasonable explanation of the current data in the absence of information to the contrary.

The dominant tunneling processes at this lattice mismatched hetero-face probably involve a quasi-continuum of interface states formed by the

ERC41033.8TPR

Fig. 31 Morphology of a typical wafer after growth.

ERC41033.8TPR

SC79-4328

Fig. 3.2 Schematic of interface bonding arrangement.

THERMALLY BONDED INTERFACE
 GaSb GaAs

(a)

(b)

Fig. 3.3 Ohmic contact between bonded non-lattice matched semiconductors. (a) Photomicrograph of bonded interface, (b) I-V curve for above contact. Contact area 0.15 cm^2 . Contact resistance $< 0.09 \Omega\text{-cm}^2$.

lattice imperfections (dislocations, stacking faults, etc.) generated by the large lattice misorientation and mismatch as well as from included chemical impurities.

Estimates of specific contact resistance have been made for these structures using the multiple area dot technique of Cox and Strack⁽¹⁵⁾. The resulting estimated values constitute upper bounds since they include contributions from the contact resistance of the metallization as well as the tunnel junction. For the particular structure here, the contact resistance was found to be $\sim 0.09 \Omega\text{-cm}^2$ at 50 mV bias.

To put this value in the perspective of usefulness for the IOC of a two junction stacked cell operating at 500 SUNs AM1, consider the following: for an ideal stacked device involving collecting junctions in 1.6 eV and 0.95 eV materials and operating at 25°C, a current density of $\sim 10 \text{ amp/cm}^2$ would be flowing through the IOC. The corresponding expected output power ideally would be $\sim 15 \text{ watt/cm}^2$. For an IOC specific contact resistance of $0.09 \Omega\text{-cm}^2$, the resulting voltage drop across the IOC would be $\sim 0.9 \text{ V}$. This implies a resistive power loss of $\sim 57\%$ due to the IOC. Thus, it is clear that at least an order of magnitude reduction in specific contact resistance is required to reduce ohmic losses to an acceptable level.

3.5.2 In Situ Window Formation During Thermal Bonding

In an effort to conveniently provide a window layer for the low bandgap cell, initial attempts have been made to produce an AlSb layer during the bonding cycle in situ between the GaAs and GaSb. The approach is to evaporate Al and Sb layers on the GaAs wafer having proper thickness to ultimately yield a stoichiometric layer of AlSb at the GaAs/GaSb interface after local melting, mixing, reaction and bonding. The attempts have so far been unsuccessful in producing a bond of good mechanical or electrical integrity.

ERC41033.8TPR

3.5.3 Pressure Bonding

Because of the difficulty experienced in obtaining good thermal bonds whenever Al is present at the interface, an apparatus for applying pressure to the semiconductor sandwiches during the thermal bonding operation has been designed and built. It will be used particularly to aid bonding between the Al containing semiconductor alloys by ensuring good physical contact between the surfaces to be bonded.

3.6 Indium Tin Oxide IOC Studies

The calculated optical losses from reflection at a conductive oxide IOC appear to be unacceptably large. However, in compliance with Task II, part 5 of the work statement, we will proceed with some feasibility experiments on such structures. In particular, we will (1) attempt to confirm the validity of the reflectance calculations, (2) determine if ohmic contacts can be formed between ITO and AlGaAs and ITO and AlGaSb, and (3) examine the feasibility of using <100> thick layers of ITO in IOC applications to reduce reflection losses to acceptable levels. Because of other more promising (we feel) approaches to IOC formation, the ITO effort is not expected to be very extensive unless the early results show unexpected potential.

The planned experiments consist of growing n- and p-doped AlGaAs and AlGaSb layers of appropriate Al content by LPE; depositing transparent conductive ITO layers on them; applying ohmic contacts, and measuring electrical and optical characteristics. If suitable ohmic and optical behavior can be achieved, we will attempt to form a stacked cell having an ITO IOC.

The AlGaAs layers for the experiments have been grown and it is planned to have the ITO layers deposited by DC sputtering in the Stanford Materials Science Lab as soon as the needed AlGaSb layers have been produced.

3.7 Laser Bonded IOC Structures

The Nd-glass laser for use in this bonding approach has been ordered and facilities modification to install required safety interlocks has been initiated.

ERC41033.8TPR

4.0 DEVICE FABRICATION AND CHARACTERIZATION

4.1 Accomplishments

Low bandgap subcells are being fabricated and electrical measurements begun on the series of structures produced by LPE from the AlGaAsSb alloy system. Preliminary performance results on these non-optimized structures are quite encouraging with regard to the ultimate attainment of the performance goals of this project.

Work will begin next quarter on the fabrication and characterization of companion high bandgap AlGaAs subcells.

Preliminary experiments with thermally bonded GaAs/GaSb wafers qualitatively indicate the desired ohmic behavior (see Section 3.5.1). Characterization of similar AlGaAs/AlGaSb thermally bonded junctions must await their successful fabrication.

4.2 AlGaSbAs Subcells

The initial types of low bandgap subcell structures are shown in Fig. 4.1. Comparable structures without the window layers were also grown. The performance results from this set of devices should provide valuable information on the relative merits of homo- vs. heterojunctions and windowed vs. windowless cell structures in the GaAlSb(as) alloy system.

A small amount of As is incorporated in the high Al window layer to more closely match the quaternary alloy lattice constant to that of low Al ternary or GaSb layers. In both homo- and heterojunction cell structures, the thickness of the window, p- and n-layers have been around 2, 2, and 5 microns, respectively. Cells with $x_1 = 0.3$, $x_2 = 0.3$ in the homojunction structures and $x_3 = 0.1$ in the heterojunction structure have been grown and fabricated. The back ohmic contact of the cells are formed by vacuum evapor-

Fig. 4.1 Schematic low bandgap subcell structures, (a) homojunction: $x_1 = 0.3-0.65$, $x_2 = 0, 0.1-0.2$, $y \cong 0.007$, (b) heterojunction: $x_1 = 0.3-0.65$, $x_3 = 0.1-0.2$.

ating 3000Å gold film onto the wafers heated to 200°C. Openings for front grid ohmic contacts are produced by photolithographic techniques. Multi-layers of Ag + Mn (2000Å), Pt (150Å), Au (1000Å) are successively vacuum evaporated on the front surface with the wafer at room temperature. After the photoresists are lifted off, alloying is carried out at 275°C for 2 minutes. The active area of the cell is then defined by etching a multiple square mesa pattern having mesa dimensions of 0.5 x 0.5 cm. A representative set of light and dark I-V and spectral response data for an early device from this series is included in Figs. 4.2, 4.3 and 4.4, respectively. Characterization of this set of devices has not yet been completed, so detailed discussion and comparison of the overall results will be deferred until the next report period.

It is worth noting that for the device shown here, there is significant photoresponse even at wavelengths longer than the expected cut-off of 1.46μm for the 0.1 Al junction material. This photoresponse apparently has its origin in the GaSb substrate even though the overlying thickness of ternary alloy materials is of the order of 5 μm.

The excess photoresponse phenomenon is welcome but unexpected based on the conventional wisdom of short diffusion lengths for this alloy system. If carriers generated by low energy photons in the GaSb substrate are truly being collected at the Al_{0.1}GaSb p-n junction, a minority hole diffusion length of at least several microns is implied. Experiments are planned to directly measure diffusion lengths during the coming quarter.

4.3 AlGaAs Subcells

No fabrication or characterization of AlGaAs subcells has been carried out for this project during this quarter. This activity will begin as soon as the initial MOCVD structures are received in December.

Fig. 4.2 Illuminated I-V curve for 0.8 eV AlGa_{0.1}Sb solar cell.

ERC41033.8TPR

ERC79-7054

Fig. 4.3 Dark I-V characteristics of $p^+-\text{Ga}_{0.7}\text{Al}_{0.3}\text{AsSb}/p-\text{Ga}_{0.9}\text{Al}_{0.1}\text{Sb}/n-\text{Ga}_{0.9}\text{Al}_{0.1}\text{Sb}/n-\text{GaSb}$ subcell.

Fig. 4.4 Spectral response of a heteroface homojunction GaAlAsSb/GaSb subcell.

ERC41033.8TPR

4.4 Measurements

An effort aimed at generally upgrading our measurement capability is underway which will increase the convenience, reliability and throughput of electrical measurements. While this effort is not being funded under this contract, it is expected to have a significant and favorable impact on the progress of this project.

**THIS PAGE
WAS INTENTIONALLY
LEFT BLANK**

ERC41033.8TPR

5.0 REFERENCES

1. E. D. Jackson, Trans. Conf. on the Use of Solar Energy, Tucson, 1955, U. of Arizona Press, Tucson, Vol. 5, p. 122-126, 1958.
2. J. J. Loferski, 12th IEEE PV Spec. Conf. Proc., p. 957 (1976).
3. N. S. Alvi, C. E. Backus, G. W. Masden, 12th IEEE PV Spec. Conf. Proc., p. 948 (1976).
4. Kim Mitchell, 12th IEEE PV Spec. Conf. Proc., p. 529 (1976).
5. (a) Papers in 13th IEEE PV Spec. Conf. Proc. Session IX-B, Basic Studies: Tandem Cells, p. 853 ff., (1978).
(b) Papers in 30 Percent Device Section, NASA Conf. Publ. 2097, Proc. of Conf. on Solar Cell High Efficiency and Radiation Damage, NASA Lewis Research Center, Cleveland, Ohio, June 13-14 (1979), p. 255 ff.
6. L. W. James and R. L. Moon, Appl. Phys. Lett. 26, 467 (1975).
7. S. W. Zehr, D. L. Miller and J. S. Harris, Jr., NASA Conf. Publication 2097, Proc. of Conf. on Solar Cell High Efficiency and Radiation Damage, NASA Lewis Research Center, Cleveland, Ohio, June 13-14, 1979, p. 283.
8. W. G. Spitzer and J. M. Whelan, Phys. Rev. 114, 59 (1959).
9. K. Y. Cheng and G. L. Pearson, J. Electrochem. Soc. 124, 753, (1977).
10. S. J. Anderson, F. W. Scholl and J. S. Harris, Jr., Inst. Phys. Conf. Ser. No. 33b, 346, (1977).
11. H. D. Law, J. S. Harris, Jr., K. C. Wond and L. R. Tomasetta, Inst. Phys. Conf. Ser. No. 45, 420 (1979).

12. M. B. Panish and S. Sumski, J. Phys. Chem. Solids 30, 129 (1969).
13. T. Sukegawa, T. Hiraguchi, A. Tanaka and M. Hagino, Appl. Phys. Lett. 32, 376 (1978).
14. R. H. Rediker et al., Sol. St. Elect. 7, 621 (1964).
15. R. H. Cox and H. Strack, Sol. St. Elect. 10, 1213 (1967).