FINAL REPORT

A high Intensity Solar Cell Invention:

THE EDGE-ILLUMINATED VERTICAL MULTI-JUNCTION (VMJ) SOLAR CELL

Work Performed under:

The Energy - Related Invention Program
Grant DE-FG01-87CE 15337

Received by OSTI

AUG 17 1992

Submitted to:

Inventions and Innovation Program Office
Conservation and Renewable Energy
Department of Energy
Washington, DC 20585

Submitted by:

Bernard L. Sater, Inventor
High Intensity Photovoltaics, Inc.
9007 Westlawn Boulevard
Olmsted Falls, OH 44138

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.

Bernard L. Sater, Inventor
August 7, 1992

"The concern for man and his fate must always be the chief interest of all technical effort." - Albert Einstein, 1931.

MASTER

DISCLAIMER

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

Abstract

This report contains a summary of a High Intensity Solar Cell (HI Cell) development carried out under the NIST/DOE Energy-Related Invention Program. The HI Cell, or Edge-Illuminated Vertical Multi-junction Solar Cell, eliminates most major problems encountered with other concentrator solar cell designs. Its high voltage and low series resistance features make it ideally suited for efficient operation at high intensities. Computer modeling shows efficiencies near 30 % at 500 suns intensity are possible with state-of-art processing. Development of a working model was largely successful before encountering an unexpected problem during the last fabrication step with the anti-reflection coating. Unfortunately, funding was exhausted before its resolution. Recommendations are made to resolve the AR coating problem and to integrate all the knowledge gained during this development into a viable prototype model. The invention will provide the technical and economic performance needed to make photovoltaic systems cost-effective for wide use.

INDEX

	<u>Page</u>
Abstract	i
1.0 Introduction	1
2.0 HI Cell Features and Advantages	2
3.0 HI Cell Development	4
3.1 Theoretical Analysis	4
3.2 Unit Cell Optimization - Diffusions	6
3.3 Metallization and Alloying	7
3.4 Surface Passivation and Anti-Reflection Coatings	8
4.0 Summary	11
5.0 Recommendations	12
6.0 Acknowledgements	12
7.0 References	13
8.0 Figures	14

1.0 INTRODUCTION

This report contains a summary of development work on a High Intensity Solar Cell invention carried out under the Energy-Related Invention Program jointly administered by the Federal National Institute of Standards and Technology (NIST) and the U.S. Department of Energy (DOE).

The fundamental objective of the High Intensity Solar Cell (HI Cell) invention is to make photovoltaic (PV) systems cost-effective for wide-spread electrical power generation.

The need for the invention is real. Profound social and political forces are reshaping the way man deals with energy. Electricity consumption is growing rapidly as countries rise in their level of economic development. The traditional methods of generating electricity are impairing our health, depleting the world's limited fossil-fuel resources and damaging the environment with pollution and carbon dioxide induced global warming. Although PV is universally recognized as an ideal technology for safe, clean and an inexhaustible source of electrical power, its high-cost remains a major barrier to broad acceptance in the marketplace.

Conventional PV hardware cost has been declining with increasing production; however it is apparent that new technologies are necessary to breakthrough the impeding market cost-barriers. Presently and in the foreseeable future, PV systems using sunlight concentrators will provide the lowest-cost power: primarily because major economic advantages are gained using low-cost optical components (large area plastic lenses or glass reflectors that are much cheaper than solar cells) to collect and concentrate sunlight on much smaller area solar cells. With PV concentrator systems, the key element increasing cost-effectiveness is having efficient solar cells capable of operating at high intensities. Obviously for a given PV system design, higher efficiency means more electrical power will be generated while higher intensity means fewer expensive solar cells will be required; consequently, more electricity at less cost and greater marketplace acceptance.

The High Intensity Solar Cell (HI Cell) invention, shown schematically in figure 1, is an integrally bonded, series connected array of miniature vertical junction unit cells [Reference 1]. The HI Cell structure eliminates most of the major problems encountered with other concentrator solar cell designs and it can be manufactured at a low-cost in high volume within the present industrial sector. Most importantly, the invention provides the essential technical and economic performance needed to make cost-effective concentrator PV systems.

This report discusses the following:

- (1) The unique features and advantages of the HI Cell compared to other concentrator solar cell designs. Its inherent characteristics make the device ideally suited for efficient operation at high intensities.
- (2) The development work that has been completed on the HI Cell; considerable progress has been made and there is full understanding of what is required to achieve high conversion efficiencies. Computer modeling shows that efficiencies approaching 30% at concentrator intensities of 500 suns are possible with state-of-the-art processing. (No new technology has to be invented.)

The development was primarily a "cut and try" approach to identify processes that were suitable for fabricating a viable "working model" HI Cell. This was successful up to the final passivation and anti-reflection coating step where a problem was encountered.

Excellent surface passivation was demonstrated by the high short-circuit current densities observed. However the anti-reflection (AR) coating evaluated had an unexpected shunt resistive loss at operating voltage level that limited conversion efficiency. Apparently the AR coating was not insulating as expected, but resistive.

Unfortunately, applying the AR coating is the last step in fabrication and funding was exhausted before work could be completed to resolve the problem.

- (3) Recommendations are made for resolving the problem encountered and for developing and testing a prototype HI Cell model with high efficiency. There are no technological barriers to prevent a successful demonstration of the HI Cell invention and its wide application in PV concentrator systems.

The inventor acknowledges many people who contributed to making this development effort largely a success considering the technical complexity and the limited budget available.

2.0 HI CELL FEATURES AND ADVANTAGES

The HI Cell invention is a series connected array of miniature vertical junction p+nn+ unit cells which are integrally bonded together electrically and mechanically as shown schematically in Figure 1. The upper illuminated surface is passivated, with an anti-reflection coating applied, and the lower surface is infrared (IR) reflecting (or transparent). It is bonded to a

heat-sink for thermal control and electrical output leads are attached at each end. Because of the orientation of its junctions to sunlight, the HI Cell is also referred to in technical literature as the Edge-Illuminated Vertical Multi-Junction Solar Cell or VMJ solar cell.

The basic fabrication steps are illustrated in Figure 2. Basically, silicon wafers are diffused, metallized, stacked, and alloyed together; the stack is cut into thin slices and trimmed to size; the silicon surfaces are etched to remove saw damage and passivated; an anti-reflection coating is applied to the illuminated surface; and, finally electrical leads are attached. As an example, a 40 wafer alloyed stack of 10 mil thick, 3 inch diameter diffused wafers should yield more than 1300 HI cells of 1 cm x 1 cm size.

The HI cell has simplicity of design and low manufacturing cost compared to other concentrator solar cell designs. A single high temperature diffusion forms both p+n and nn+ junctions and there is no photolithography or anisotropic etching processes involved. One optimized design is suitable for a wide range of intensities and lends itself to a high volume production capability within the present industrial sector.

The major advantages of the HI cell structure compared to other solar cell configurations are as follows:

1. edge illumination - this eliminates the need for front and back ohmic contacts; there is no sheet resistivity component of the series resistance, equal collection probability for excess carriers generated at any depth, and improved spectral response in the violet and infrared regions; it is more responsive to light incident at relatively large angles as would be associated with most concentrator systems because of the absence of a dead layer at the surface of incidence; and internal reflection from the metallization;
2. series connection - this provides a high voltage, low current operation, a better compatibility to power processing units and loads, and a tolerance to relatively high series resistance values;
3. use of high resistivity base material - this gives a high minority carrier lifetime, eliminates the need for a high packing density of junctions as with other VMJ cells, and considerably reduces the manufacturing costs;
4. use of an nn+ high-low junction to provide a drift field for considerably improved carrier collection and to also give a higher open circuit voltage;
5. at high intensities, a very low series resistance with an almost linear reduction of the series resistance and increasing intensity due to conductivity modulation; an increase in efficiency with an increase in intensity; a temperature coefficient of efficiency degradation decreases by a factor of 2 as the intensity increases from 1 to 1000 solar intensities;
6. non-absorbing back surface (transparent or reflecting surface) providing improved heat rejection and good thermal characteristics; since approximately 25% of the solar spectrum is not responsive to silicon, this represents 25 W/cm² less dissipation at 1000 solar intensities;
7. with good heat sinking, the possibility of obtaining large amounts of thermal energy for heating and cooling while efficiently generating electrical energy;
8. simplicity of design which requires no photolithography or anisotropic etching and low manufacturing costs compared to other concentrator photovoltaic devices; one optimized design suitable for all intensities;
9. comparatively very high energy payback ratio when operated at high solar intensities;
10. existence of high-volume production capability within the present industrial sector capable of providing more than 1 MW_e per day photovoltaic power generation capacity;
11. structural configuration permits high packing densities with easy interconnecting of electrical output leads;
12. tolerance of extreme nonuniform illumination in one spatial dimension;
13. an integrally bonded, series connected stack which is extremely rugged electrically, mechanically, and thermally for high power usage.

3.0 HI CELL DEVELOPMENT

The proposed development was to fabricate a viable "working model" of the HI Cell invention. Although the HI Cell has a theoretical efficiency near 30% at 500 suns intensity, a performance level of 20% at 500 suns was chosen as a realistic development goal at this stage considering funding.

Developing a working model HI Cell involves several different areas of technology as reflected in the work breakdown tasks reported. Development was planned using technical milestones, rather than schedule milestones, for better cost control. Within each technology area, an initial baseline design was established based upon prior research and experimentation. If a problem was encountered with the baseline design, parallel efforts were initiated to quickly identify a solution for the working model. The prime objective at this stage was not to optimize but to identify suitable approaches in each technology area. Optimizing fabrication processes will be the goal during prototype development at a later stage.

This development approach was methodical and focussed. For work support it was expedient to go directly to those sources identified as having a specific expertise, with proven facilities and personnel available to support the task. The inventor's role was managing all development tasks and directing activities while coordinating the efforts and people involved. By working closely, staying on top of things, shifting emphasis when needed and monitoring and evaluating results, it was possible to identify and demonstrate viable processes to incorporate in the fabrication of working model HI Cell devices. Most development results will be appropriately applied as processes suitable for making prototype devices as well.

Development was more of a "cut and try" approach. Although analysis played a role, it was not the primary role. There are many subtle complexities and synergistic interactions involved, each could become a research project in itself in a well funded program. Basically the effort focused on finding workable solutions for fabricating a working model, not making it a research project.

A discussion of the development task efforts and results follows:

3.1 Theoretical Analysis

Theoretical analyses of the HI Cell were performed using a two-dimensional (2-D) solar cell modeling computer program developed at Purdue University [Reference 2]. The ability to analyze in 2-D is important for the HI Cell since the direction of current flow is perpendicular to light absorption and photo-generation of carriers (unlike that in the conventional cell where they are in

the same direction and can be adequately modeled in one-dimension).

The 2-D computer model predicts expected performance (voltage, current, fill-factor and efficiency) as a function of intensity and temperature while showing where performance degrading losses occur. The model includes physical and intrinsic parameters in the HI Cell; such as unit cell width and depth, bulk resistivity, junction depth and doping profiles, minority-carrier lifetime, and surface recombination velocities. The primary purpose for the analyses was to provide insight in operational characteristics and to determine the critical sensitivities and tradeoffs that may be process dependent.

2-D solar cell modeling has been used extensively in the analysis of various high efficiency solar cell structures with considerable success. The simulations show the need to have a long minority-carrier diffusion length (preferably greater than three times the unit cell width) for good carrier collection, low surface recombination velocities at both the front and back surfaces, and low effective recombination velocities at both the p+ and n+ regions near the metal contacts by using built-in minority-carrier reflecting electric fields. These are important parameters to control in all high performance silicon solar cells.

Example of a HI Cell simulation:

The cell simulated was 200 microns wide by 600 microns deep in cross section. Junctions 0.3 microns deep with surface concentrations of $4 \times 10^{19} \text{ cm}^{-3}$ were placed along the long dimension, the p+ on one side and the n+ on the other. The base was 100 ohm-cm n-type with a lifetime of 1 millisecond. Surface recombination velocities of 20 cm/sec were assumed. These parameters are characteristic of high efficiency solar cells. The metal contacts were treated as minority carrier reflectors with effective surface recombination velocities of 100 cm/sec. (This is the most uncertain of the assumptions.) The design of the metal-semiconductor contact is an important factor controlling the performance of high efficiency solar cell structures.

The HI Cell described above was simulated at 1 and 500 AM1.5 suns (100 mW/cm^2 at 1 sun) assuming no reflection losses. The results are as follows:

<u>Parameters</u>	<u>1 Sun</u>	<u>500 Suns</u>
V_{oc}	0.655 V	0.833 V
J_{sc}	42.1 mA/cm ²	21.0 A/cm ²
Efficiency	21.2%	29.3

These results are very encouraging and they establish the HI Cell as a viable solar cell for high intensity applications.

3.2 Unit Cell Diffusions

A high minority-carrier lifetime in the bulk region is important for all efficient solar cells but is more essential for the HI cell. Its correspondingly related minority-carrier diffusion length (L_p) determines how effectively photo-generated carriers are collected in the bulk n-type region of each unit cell, especially in regions further away from the p+n junction as illustrated in Figure 1. (This diffusion length is defined as the average distance the minority carriers travel before recombining: thus a higher minority-carrier lifetime gives a correspondingly longer diffusion length, increasing the unit cell active area that results in higher photo-generated carrier collection and cell efficiency.)

A minority-carrier lifetime greater than 500 microseconds was established as a goal for the development effort since it represents a diffusion length about three times the unit cell width. This will result in very good current collection over the entire bulk region of unit cells. Unfortunately this goal was not met during the present development. Since lifetime values in the low-millisecond range are routinely reported in literature by others developing competing solar cell technologies, it will certainly be obtainable during the prototype development stage as it is a processing technology that can be acquired.

Single-crystal silicon refining has matured enough to give wafer lifetimes in the millisecond range but maintaining this high lifetime through solar cell fabrication is a challenge and requires extremely clean processing, careful handling procedures and contamination-free furnace tubes. The inventor encountered a problem in locating an independent service supplier for obtaining high lifetime quality diffusions. (Most service suppliers supporting the semiconductor industry are not required to control carrier lifetime parameters and, apparently, they have not developed the expertise that now exists among the competitors within the solar cell industry.)

N-type float-zone refined silicon wafers, 10 mils thick, with $\langle 100 \rangle$ crystal orientation and 600 to 1000 ohm-cm resistivity were selected for diffusion. (High resistivity silicon gives inherently higher carrier lifetimes and that was the main reason for the choice.) The HI Cell does not have series resistance problem when using high resistivity silicon. With its edge-illuminated orientation, there is essentially uniform photoconductivity modulation from contact-to-contact in the unit cells; so the series resistance in the bulk regions is actually controlled by the intensity of sunlight and not by the starting material resistivity. Consequently, the higher the intensity,

the lower the series resistance. (This is a unique feature of the HI cell design: with conventional solar cell designs photo-conductivity modulation is extremely non-uniform from contact-to-contact; so often it is necessary to design conventional solar cells using low-resistivity material while making a performance tradeoff compromise between carrier lifetime and series resistance.)

There are several processes that could be employed for making the p+n and nn+ diffusions. Initially the baseline design plan was to rely on hydrogen chloride (HCl) "gettering" during high temperature diffusion. With this process, lifetime-limiting contamination reacts with the chlorine gas to form volatile metal chlorides that are transported out of the furnace tube in the gas flow. Unfortunately, the service supplier chosen had an electrical fire that destroyed their diffusion furnace equipment equipped for gettering and because of low demand it was not replaced.

The first batch of wafers diffused used a low-temperature chemical vapor deposition (CVD) reactor to deposit a boron-doped glass layer on one side of a wafer and a phosphorous-doped glass on the opposite side. These depositions were also capped with a pure silicon dioxide layer. The doped glass layers became dopant sources for forming the p+ and n+ junctions that were diffused into the silicon with a single high temperature drive-in step. Unfortunately, the minority-carrier lifetimes measured in the diffused wafers were only about 60 microseconds, far less than needed for good performance.

The second source selected for processing the next batch of wafers used ion implantation of the dopant species. A thin high quality thermal oxide was grown and Boron and Phosphorous ions were implanted on opposite sides into the silicon wafers just below thin oxide layer. The implanted species become the diffusion sources that were driven further into the silicon at a high temperature to form the p+ and n+ junctions. The results were better with lifetimes in the 120 to 150 microsecond range that gives a diffusion length roughly the unit cell width. Although this was less than desired, these diffused wafers were used to support the rest of the development effort.

3.3 Metallization and Alloying

The baseline metallization scheme used to alloy diffused silicon wafers together was based on the formation of aluminum-silicon diffusion bonds at the interfaces. Diffusion welding occurs while the stack is held under pressure at the alloying temperature.

For the working model development it was more practical and less costly to use smaller pieces, not full wafers, cut from full size

diffused and metallized wafers. This was adequate for evaluating processing procedures while conserving materials. The processes and fixtures will be easily scaled up for full size wafers during prototype development.

There were several precautions necessary when preparing wafers for aluminum alloying:

- (1) At the n+ contact, a heavy phosphorous diffusion is necessary because Aluminum is a p-type impurity in silicon. A large surface concentration of phosphorous in the n+ region is required in order to prevent formation of an inadvertent pn junction when aluminum is alloyed into the silicon while forming the interfacial bonds.
- (2) At the p+ contact, the underlying p+n junction is a major concern as excessive aluminum-silicon interactions could cause degrading junction leakage currents or even shorting. A full interfacial alloying is needed to assure mechanical strength of the bonds, but it is necessary to limit alloying depth to prevent degrading the critical electrical characteristics of the silicon p+n junctions.
- (3) Sufficient metallization must be applied to each wafer to accommodate all silicon surface irregularities and the pressure applied to the stack during alloying has to be sufficient to achieve a complete minimum bond line in the finished HI cells.

The metallization scheme for HI cell fabrication also includes plating the outside end wafer surfaces to accept soldering of electric output leads after the cutting, etching and passivation steps.

3.4 Surface Passivation and Anti-reflection Coating

The HI Cell requires well passivated silicon surfaces and an anti-reflection (AR) coating on the illuminated surface for good performance. Surface passivation minimizes loss of photo-generated carriers at the silicon surfaces due to the presence of surface states that arise from "dangling bonds", chemical residues, metal precipitates, native oxides, etc.. The AR coating reduces reflection to increase sunlight absorption within the silicon and its photo-generation of carriers.

The rate at which carriers are lost at a surface is described as the surface recombination velocity. A low recombination velocity at the illuminated surface is of critical importance in the HI Cell since the number of carriers generated for a given wavelength is highest at this surface and decreases exponentially with distance into the cell. With low recombination at the surface, these carriers will diffuse to the sides where they are

collected by the appropriate diffused regions; electrons to the n+ side and holes to the p+ side. (With a poorly passivated surface there will be a loss of carriers by recombination at the surface before they can be collected at the diffused regions.)

A passivated HI Cell has an enhanced response in ultraviolet (UV) region of the solar spectrum that is not obtainable in a conventional solar cell. The high energy short UV wavelength photons are quickly absorbed in the silicon, generating carriers near the illuminated surface. Because the HI Cell is largely lightly doped and passivated silicon, it will have a very high probability of collecting carriers created near the surface. (In contrast, the illuminated surface of the conventional solar cell is very heavily doped to form the pn junction; therefore surface recombination velocity will be very high and very few carriers generated there will be collected at the junction -it is a "dead layer" with very little UV spectral response.)

There are several precautions in developing the passivation and AR coating processes for the HI Cell:

- (1) The aluminum metallization used to alloy wafers together will limit succeeding process temperatures to about 600 C. (This will exclude the use of conventional thermal oxides since temperatures around 1000 C are required for its growth. With thermal oxides, the oxidation process consumes silicon which forms a pristine interface and usually good passivation.) Consideration processing temperature limitation, chemical surface treatments and low temperature vapor deposited coatings are more suitable for the HI Cell. However deposition is an additive process and does not significantly modify the silicon surface; so the interface properties are extremely sensitive to surface treatments prior to deposition and that will be a key aspect for development. Fortunately there are many critical semiconductor devices having similar processing temperature limitations: there are many suitable processing techniques already developed in the industry and they are available for HI Cell evaluation.
- (2) The HI Cell structure has a long p+n junction perimeter length at exposed silicon surfaces compared to that of a conventional cell. Using a 1 cm x 1 cm size example for comparison: the HI Cell will have 40 unit cells each with 2 cm of junction perimeter (top and bottom) with a total of 80 cm; while the conventional cell will have a total of 4 cm around its edges. Typically, surface losses at the junction perimeter in conventional cells are ignored, but they must be to be minimized by passivation for good performance in the HI Cell.

- (3) There is a relatively high electric field gradient at the p+n junction perimeter region at operating voltages; so any surface treatments and AR coatings must leave the surface at this region insulating and non-conducting to prevent shunt losses from occurring there.

Initial development work involved screening four commonly used solar cell AR coatings and several different surface treatments. The AR coatings were silicon nitride, silicon dioxide, tantalum oxide and aluminum oxide. Optically, they are all suitable AR coatings for silicon; and electrically, they are excellent dielectric materials in their stoichiometry or fully oxidized state. The first two coating were applied by plasma CVD and the last two by vacuum electron-beam heated physical vapor deposition (PVD).

Based on the initial screening results, tantalum oxide was selected as the baseline design. Excellent surface passivation was achieved as indicated by short-circuit currents (I_{sc}) densities measured (more than 40 ma/cm²). This was very good considering that the HI Cell devices coated had less than desirable bulk minority-carrier lifetimes. The excellent surface passivation was attributed to a strong electrical charge in the coating which introduced an accumulation layer at the silicon surface, forming an electrostatic-field that reflected minority carriers away from the surface for improved collection at the junctions.

However a shunt resistance problem was encountered with the tantalum oxide AR coating when exposed to a Xenon lamp solar simulator that was not observed with initial testing under a Tungsten lamp source. The AR coating did not remain fully insulating as expected, but partially conducting. This then introduced a current shunt path at the junction perimeter region at the operating voltage. Consequently, the shunt resistance adversely affected cell performance.

Unfortunately this unexpected problem was encountered at the final stage of development and funding was exhausted before it could be fully investigated and resolved.

There were clues observed and the problem may be multi-faceted: First, the vacuum tank pressure increased when depositing the tantalum oxide which may indicate that free oxygen was being released. This would result in a deposited coating not fully oxidized but somewhat metallic and conducting. An attempt was made to complete the oxidation of the tantalum coating by heating it in an oxygen environment at 500 C. However with further testing the HI Cell performance degraded significantly when exposed to a solar simulator spectrum with UV photons. This may be similar to a problem observed by others and attributed to hot electrons being generated in the silicon by UV photons that are

injected into the interface oxide, increasing surface interface states and surface recombination velocity, and thus degrading cell performance (Reference 3). However, it could also be attributed to UV absorption within the AR coating layer and affecting its conductivity.

Fortunately there are solutions to these problems. The inventor recommends additional testing to fully identify the real nature of the problem and to demonstrate a viable solution.

4.0 SUMMARY

The work performed was largely successful in developing a viable working model HI Cell. Computer modeling showed efficiencies approaching 30% at intensities of 500 suns are possible with state-of-art processing. The important parameters to control are similar to most other high performance silicon solar cells: a long minority-carrier lifetime in the bulk region; low surface recombination velocities at all silicon surfaces; an anti-reflection coating at the illuminated surface and low effective recombination velocities at both the p+ and n+ contacts.

The best wafer diffusions obtained during the development used ion implantation of the dopants species and a single thermal drive-in. Bulk lifetimes in the 120 to 150 microseconds range were measured. This was shorter than the desired 500 microseconds; nevertheless, excellent short-circuit current densities were measured (40 mA/cm^2) at a simulated one sun AMO intensity.

Aluminum metallization proved to be compatible with the diffused junctions. No junction degradation was observed as a result of alloying multi-wafer stacks together under pressure and temperature. The metallization also proved satisfactory with etchants used to remove saw damage at the silicon surface that occurred in the cutting operation.

The surface treatment and passivation were successful as demonstrated by the high short-circuit densities measured. However an unexpected problem was encountered with the tantalum oxide AR coating evaluated; it was not insulation as expected, but partially conducting when tested under a xenon lamp solar simulator source with a high UV spectral content. This created a shunt resistance loss at the p+n junction region at operating voltage that affected cell performance.

Unfortunately, the shunt resistance problem was encountered at the last processing step and funding was exhausted before sufficient testing could be done to fully identify the problem and find a solution. Determining the underlying phenomena will lead to the most viable solution.

5.0 RECOMMENDATIONS

The inventor recommends that the passivation and anti-reflection coating problem encountered be fully investigated and resolved. There are proven processing technologies to eliminate these types of problems. All knowledge gained during the development of a working model should then be integrated into fabricating a pre-production prototype model with good performance. Improvements will be the result of changes applied from the working model experience. There are no technical barriers to developing and demonstrating viable prototype HI Cells with excellent performance at high intensity. Undoubtedly, the invention will provide the technical and economic performance needed to make PV systems cost-effective for wide use.

6.0 ACKNOWLEDGEMENTS

The inventor acknowledges the contributions of many supporters in the HI cell development:

Jack Aellen of DOE in Energy-Related Inventions Program was extremely helpful in steering the inventor through difficulties encountered during the proposal phase while resolving legalities concerning the rights of an individual inventor. Aellen was also very patient during the invention development which involved significant technical challenge and was managed by technical milestones, rather than schedule.

In the following task areas of expertise:

Modeling - Professor Jeff Gray of Purdue University;

Diffusions - Dr. Swang Yoon of MA/COM-PHI;

Wafer characterization - Dr. James Gee of DOE Sandia Laboratories;

Metallization - Professors Marc Nicolet and Mier Bartur of California Institute of Technology;

Fabrication - Professor George Valco and Graduate Student Chris Davis of Ohio State University;

Passivation - Professor Fred Terry Jr. of University of Michigan and Ohio State team of Professor Valco and Chris Davis; and,

Solar simulator - Dr. Dave Brinker of NASA Lewis Research Center.

This work is dedicated to Professor Chandra Goradia, of Cleveland State University, who was the inventor's technical mentor in the early research and experimental stage. Chandra's insight, analysis and support provided the technological impetus to continue through early difficulties encountered by the lone inventor. If the HI cell lives up to its promise and contributes to the benefit of man with safe, clean and sustainable photovoltaic energy, much credit will be due to Professor Goradia's vision.

7.0 REFERENCES

1. U.S. Patents 4,332,973, 4,409,422 and 4,516,314
2. J. L. Gray and R. J. Schwartz, "Two-Dimensional Computer Simulation of Single Crystal Silicon Solar Cells," Seventeenth Photovoltaic Specialists Conference, Kissimee, Florida, May 1-4, 1984.
3. P. E. Grienbaur, J. Y. Gan and R. W. Swanson, "Use of Ultrathin Oxides and Thin Polycrystalline Silicon Film for Stable High-Efficiency Solar Cells", Applied Phys Lett 58(9) March 4, 1991.

The HI Cell:
Edge-Illuminated Multijunction Solar Cell

Figure 1

Figure 2