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Si CONCENTRATOR SOLAR CELL DEVELOPMENT

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ABSTRACT

This is the final report of a program to develop a commercial, high-efficiency, low-cost concentrator solar cell compatible with Spectrolab's existing manufacturing infrastructure for space solar cells. The period covered is between 1991 and 1993. The program was funded through Sandia National Laboratories through the DOE concentrator initiative and was also cost shared by Spectrolab. As a result of this program, Spectrolab implemented solar cells achieving an efficiency of over 19% at 200 to 300X concentration. The cells are compatible with DOE guidelines for a cell price necessary to achieve a cost of electricity of 12 cents a kilowatthour.

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Final Report

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1.0 INTRODUCTION AND MAJOR ACCOMPLISHMENTS

Spectrolab, Inc., as one of the DOE/Sandia Concentrator Initiative contractors, has developed a low-cost high-efficiency concentrator solar cell compatible in size, geometry, price and performance with today's concentrator systems designed for operation at medium concentrations, between 200 and 400X. We selected an approach for this program that will lead to commercialization of Si concentrator cells in the shortest possible period. In addition, we used concurrent engineering and design for manufacturability and assembly (DFMA) to ensure compatibility with modern manufacturing practices in use at Spectrolab.

Spectrolab has completed Phase II of the DOE/Sandia Concentrator Initiative contract to develop Si concentrator solar cells and demonstrate manufacturing capacity of these cells. Significant progress has been achieved in a number of areas of cell design. We identified major roadblocks and major cost drivers of concentrator cell manufacturing. We were also able to produce cells of various complexity. We feel confident that we will be able to supply cells compatible with desired goals of \$2/watt at a system level.

2.0 PROGRAM SUMMARY

Concentrator systems have been identified as an enabling technology for utility-level photovoltaic power generation.¹ Concentrator-based systems can provide a system efficiency exceeding 15%, which is considered crucial for widespread application of PV in the power generation industry.

The goal of this program is to develop a production- ready solar cell capable of working under 200-350 sun AM1.5 direct illumination and to achieve an efficiency over 20% at concentration. In this report we present the results of our design and experimental work.

The cell is a low resistivity (0.2 Ohm-cm) float zone, passivated emitter (PESC) Si solar cell with a top/bottom configuration. The solar cell features a randomly textured surface and passivated emitter. The emitter region of the cell is removed from underneath the front metal bus bars except for a small overlap to prevent shunting. Front metallization is separated from the base using a thick SiO₂ dielectric layer. Planar isolation of the emitter perimeter region assures low recombination currents.

The size of the cells was chosen to fit in the Sandia SBM-3 module for simplicity of testing and integration. Solar cell front and back contact metallization is designed for compatibility with soldered and welded interconnects.

3.0 SOLAR CELL DESIGN

3.1 DEVICE DESIGN

The design of the solar cells has evolved during the program. The originally proposed two mask PESC design (Figure 1A) proved to be unmanufacturable in a production environment. This design was replaced by a three mask design (Figure 1B) and by a simplified single mask design (Figure 1C). Both of these approaches provided promising results and may be useful in servicing particular customer requirements.

Three Cell Structures

Original Two Mask Structure

Figure 1A

Three Mask Structure

Figure 1B

Simplified One Mask Structure

Figure 1C

Figure 1 THREE CELL STRUCTURES EXAMINED BY SPECTROLAB

The original two mask PESC design relied heavily on fine alignment of field/gate oxide patterning mask to prevent shunting between busbar, gridlines and the base of the device. Early experiments and examination of the process capability demonstrated that this approach cannot be manufactured in production environment. The areas of potential shunting are shown in Figure 2. The field oxide thickness was also insufficient to isolate the busbar from the base of the device.

A somewhat more complex approach was implemented. This cell design relies on a three mask process (Figures 1B and 2). The design relies on a deposited thick oxide dielectric to separate buss bar and the base. A sufficient oxide over emitter overlap allows for a high degree of isolation at the emitter perimeter edges as well. The three mask process was fully implemented with several process variations on the basic design.

Another cell design, relying on a simple, lower cost, single mask process, was examined as well. This design also features PESC device. The obvious trade-off in this approach of cell efficiency vs. cost may benefit certain system designs. Possible efficiency improvement ideas for this approach are discussed.

From the point when the three mask process was selected as a basic approach to achieving program goals, several process-related features were considered. The basic masking steps for fabrication of the parts is shown Figure 3. The detailed cell blown-up sketch is shown in Figure 4.

3.2 AREAS OF DESIGN

- 1) Dielectric selection
- 2) Low-cost masking approaches
- 3) Junction removal vs. localized diffusion

Potential Shunt

Shunt eliminated due to small overlap of field oxide and diffused area

- Early two mask, limited area diffusion solar cell suffered from shunting problems
- By switching to three mask process and optimizing dielectric, shunting has been reduced to negligible amounts

Figure 2 SHUNTING PROBLEM

Three Mask Process

Figure 3 THREE MASK PROCESS

Figure 4 THREE MASK CONCENTRATOR CELL STRUCTURE

1) Several dielectric isolation approaches were considered and examined.

- Thermal oxide growth
- Oxide deposition
- Alternative dielectric

a) Several experiments were performed early in the program with native oxide growth to form the dielectric. As a result of these studies it was determined that to achieve the necessary thickness of thermal oxide substantial time is required at elevated temperatures. A substantial increase in junction depth was observed. This resulted in decreased performance of the

cells, particularly in the blue region of the spectrum. Since a single diffusion step was selected as a baseline approach to this program, thermal oxide growth process was abandoned from consideration for dielectric.

b) Both CVD and LPCVD methods are available for deposition of dielectric oxides. An open-plate CVD system did not provide sufficient quality oxides to prevent shunting. Therefore an LPCVD system was used for cell production. This method produces high-reliability good quality oxide of sufficient thickness (1 um) to resolve all shunting issues.

c) Alternative dielectric approaches were examined. Experimental studies were performed using layers of polyimide material. The advantages of alternative dielectrics is the availability of high-quality dielectric materials for this approach as well as a reliance on spin-on processes rather than the more expensive LPCVD based process. Several experiments using photodefineable polyimides were performed, with the results showing no shunting.

2) Low cost masking

Low cost masking methods were considered for junction patterning. Since this step does not require alignment or even the use of photoresist, several ways of obtaining a mask resistant to an acid or basic etch of Si were considered. Screen printing of the mask proved to be possible, but solving the many additional issues of a completely new process went beyond the scope of this program.

It will be possible to revisit the low cost masking issue, should this product ever become commercially viable. In the meantime, a three mask photoresist process was used to fabricate the parts.

3) Junction removal vs. localized diffusion

Two methods of achieving the necessary structure shown in Figure 1B, were considered:

- a) Junction removal (mesa isolation)
- b) Localized diffusion

The merits of both methods were considered. Junction removal (mesa isolation) was selected over localized diffusion for two reasons. First, it avoids the restriction of using oxide patterned wafers during diffusion. Second, it removes one process step (oxide deposition) and thus lowers the cost of the product.

Because of the extreme sensitivity of the low-resistivity float-zone Si used in this product to process conditions, special care was taken to minimize the use of processes that may result in potential contamination of the wafer prior to the high temperature diffusion step. Thus, mesa isolation was used to fabricate the cells.

3.3 MATERIAL CHOICE AND AVAILABILITY

To meet the necessary operating conditions float zone P-type Si wafers of 0.1 to 0.3 ohm-cm., 100 mm diameter were chosen for this program. Only one wafer manufacturer is available world-wide that is capable of providing four-inch float zone silicon material in substantial quantities. It would be desirable to be able to obtain the material from a domestic source with a demonstrated capability to deliver very large quantities of consistently high-diffusion-length Si material.

3.4 GRID DESIGN

Two possible grid geometries were evaluated (Figures 5a and 5b). While there is no over-all electrical advantage for the choice of the grid structure, radial geometry is expected to be better in manufacturing. In addition, radial multi-tier geometry will allow for redundancy should some of the grid line be broken or missing. Radial grid geometry is also better for non-uniform illumination conditions.

Figure 5 GRID DESIGN

3.5 CELL SIZE

Solar cells were designed to be compatible with the Sandia Baseline Module [3] (SBM-3). Therefore these cells have 1X1-cm active region and over-all dimensions of approximately 1.3 x 1.3 cm. A small reduction in the cell size will allow an increase in the number of cells we can produce from a single four-inch wafer to 34 from 25. Solar cells are 8 mils thick. We are considering a reduction to 6 mils, since it will allow us to increase material resistivity and assure more uniform electrical performance with lower bulk conductance losses and longer diffusion length.

4.0 PROCESS DEVELOPMENT

4.1 LOW COST

One of the major goals of this program is to achieve price/performance goals established by DOE.[1] Rather than design a complicated and expensive cell, our approach is to build a cell that will have the maximum possible electrical performance while meeting the goal of compatibility with low-cost manufacturing principles.

4.2 ENVIRONMENTALLY SOUND MANUFACTURING

Spectrolab's manufacturing practices must comply to the most strict environmental policies in the world because of its location in Southern California. With a vision for the future, Spectrolab established an effort to minimize the use of those substances that may be subjected to strict control in the future. While operation and product design are often difficult in these conditions, we strongly feel that in the long run the results will be beneficial. Therefore concentrator solar cells were designed with the goal of minimizing the use of volatile solvents. To this end we eliminated completely the use of negative photoresist and most of ozone-depleting chemicals.

4.3 PROCESS FLOW

Concentrator Cell Processing

- 1) First Wafer Etch, 8.0 Mils +/- 0.5 Mil
- 2) Texture Etch, 40-50 minutes, 70°C, agitation
- 3) CVD Backs
- 4) Diffusion

- 5) Acid Clean (deglaze in HF)
- 6) a) Photoresist, Soft Bake
b) Batch Exposure, Mask 1 (Mesa Isolation, Junction Removal)
c) P/R Develop and Hard Bake
- 7) Etch in 19-1-3 NHO_3 - HF - H_2O to remove junction
- 8) Strip Resist, Second BOE dip
- 9) LPCVD (Both Sides of the wafer), 1um target for dielectric isolation
- 10) a) Photoresist, Soft Bake
b) Fine Align and Expose, Mask 2 (Field Oxide Mask)
c) Develop P/R and Hard Bake
- 11) BOE Wafer, Until Oxide is removed
- 12) Strip PR completely and BOE dip
- 14) Oxidation in Dry O_2 , 950°C, 15 minutes
- 15) a) Spin Photoresist, 9 μm target, Soft Bake
b) Align and Expose Mask 3 (Grid Pattern)
c) Develop PR Hard Bake PR
- 16) Etch
- 17) Evaporate Back Contacts, Al-Ti-Pd-Ag
- 18) Evaporate Front Contacts. Ti-Pd-Ag, (5 to 6.5 um Ag)
- 19) Lift-off
- 20) Sinter (350°C)
- 21) AR Coat, AR BAKE/Sinter (390°C)
- 22) Laser Scribe Cells

4.4 PASSIVATED EMITTER

Thin, gate-quality oxide is grown to passivate the emitter. The oxide thickness is optimized to minimize reflectance losses and to produce only small redistribution of phosphorous in the emitter. We have achieved sheet resistivity of approximately 50 Ohm/square, after diffusion and thin oxide passivation (Figure 6). A good degree of passivation has been experimentally observed on a number of fabricated lots. Figure 7 shows quantum

Oxide thickness matched w/ AR coating to Maintain high current (~ 100 nm)
 Oxide growth time minimized to achieve compromise between junction depth,
 doping and oxide thickness
 Low sheet rho to achieve good fill factor (50 Ohm/sq)

Figure 6 EMITTER FORMATION AND PASSIVATION

Figure 7 COMPARISON OF QUANTUM EFFICIENCY FOR PASSIVATED EMITTER AND UNPASSIVATED SOLAR CELLS

efficiency for one of the cells with a passivated emitter. The high degree of surface passivation observed is typical of all cells fabricated for this program.

4.5 SURFACE TEXTURE

Surface texture is optimized to achieve small uniform pyramids. Recent implementation of some of the features of the texture formation procedure described by Sandia[2] helped to improve the uniformity of the pyramids and reduce their size. As an additional environmental benefit, we reduced the use of isopropanol.

4.6 JUNCTION REMOVAL FROM UNILLUMINATED AREAS

The junction is removed from the areas under bus bars. An effective dielectric is used to separate the base and top metallization. Issues related to junction removal were described in the previous section.

5.0 RESULTS

5.1 EARLY TWO MASK CELLS

The performance characteristics of our early two mask cell were dominated by shunting. The shunting occurred due to misalignment in the metal covering area between the diffused emitter edge and the base. Therefore we switched to a three mask process to produce the cell with its emitter/base border hidden under a dielectric. The shunting problem was completely eliminated.

5.2 THREE MASK CELLS

Three mask cells fabricated in 1992 demonstrated very promising results. We were able to observe a high degree of emitter passivation and very respectable current densities in these cells. Figure 8 demonstrates the performance of the cells from lot 485, one of the first lots fabricated with a revised three mask process.

The efficiency of the cells peaked at 20.5% at a concentration of 70-80X. The performance dropped to about 19% at 200X.

Dark IV curves and spectral response are shown in Figure 9. The devices show low J_{01} currents, which is consistent with modeled results for high-quality material of this type. Very high red response is also consistent with sufficiently high lifetime in the cells.

5.3 ONE MASK CELLS

One mask solar cells fabricated at same time also demonstrated very respectable results. These are lower cost, one mask PESC devices without planar isolation. These cells show good fill factor stability (Figure 10) as a function of concentration with a peak efficiency of 19.5%. Because of the higher dark diode component their efficiency is 1 to 2% lower than the efficiency of the best three mask cells. The distribution of 19 cells of this type is shown on Figure 11. It is possible, however, to improve one mask devices further by reducing bus bar area and the unused Si border around the edges. These changes will also allow more cells to be produced from a single wafer, thus reducing the cell cost further.

Three Mask Process Cells, Lot 485

Lot 485 One Sun Isc Range: 33.5 to 34.2 mA/cm²

Figure 8 ELECTRICAL RESULTS, LOT 485

Figure 9 DARK IV AND QUANTUM EFFICIENCY FOR LOT 496 CELLS

Figure 10 ONE MASK CELL PERFORMANCE

Figure 11 ONE MASK CELL PERFORMANCE DISTRIBUTION

One mask cells are also easily adaptable to plating operation. Plated up cells can be compatible with operation at concentrations higher than 300X.

5.3.1 Lifetime Problems and Sandia Verification Run

Following our early success with three and one mask cells, for a substantial period of time we experienced problems with lifetime in finished cells. We were unable to find an exact cause of this problem.

A verification run at Sandia demonstrated that the starting material quality cannot be the cause of the degraded lifetime in the finished cells. In fact, the solar cells fabricated at Sandia's PDFL using Spectrolab's Float Zone Si achieved 21.1% efficiency, while control cells fabricated on Sandia's Si material (higher resistivity) achieved 21.7%. These are excellent results indicating that the starting material is not the cause of the degraded lifetime in cells fabricated at Spectrolab during this time. These results also show the high level of capability available at the PFDL.

Further examination of our processes revealed that lifetime reduction may be related to contamination in the texture etching bath.

5.4 RECENT FULL-PRODUCTION LOT

The most recently fabricated cells show good performance. Even though, we did not approach the same Isc as achieved in lot 485, performance at concentration of these cells is even better. The Isc of these cells was in the range of 32.6 to 33 mA/sq.cm.

The production lot yielded over 1000 solar cells. These devices were delivered to Sandia as deliverable items of this contract. The performance results of a random sample from this lot measured at Sandia is shown in Figure 12. The cells peak with efficiencies over 20% at 100X. They show good fill factor stability, exceeding 19% efficiency at 200X (Figure 13).

If installed in an operating concentrator system with 15% efficiency, the delivered 1000 cells can produce of 2.4 kW of power.

In addition, it must be noted that the latest production run also demonstrated excellent mechanical and electrical yield of the product.

6.0 CONCLUSIONS

As a result of this contract, commercial concentrator solar cells have been developed at Spectrolab. Spectrolab demonstrated production readiness by delivering to Sandia over 1000 concentrator cells with efficiencies of 19 to 20% at a concentration of 200 suns.

The commercially produced top/bottom contact PESC Si solar cells provide for module efficiencies near 15% under concentration above 200X. As a result of this program Spectrolab was able to demonstrate manufacturing readiness to deliver substantial quantities of concentrator solar cells to customers.

Figure 12 ELECTRICAL PERFORMANCE OF A SAMPLE OF DELIVERED 1000 CELLS

Figure 13 TYPICAL PERFORMANCE OF LOT 563 CELLS

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