BURIED CONTACT CONCENTRATOR SOLAR CELLS

J. H. Wohlgemuth and S. Narayanan

Solarex Corporation
Frederick, Maryland 21701 USA

ABSTRACT

As part of the DOE sponsored Concentrator Initiative, Solarex is developing the buried contact solar cell for use in the ENTECH 22x linear Fresnel Concentrator System. The cell design is optimized for use with the actual nonuniform concentration profile expected from the ENTECH system and for use with prismatic covers to eliminate grid line shadow loss. Under these conditions and maintaining a high sheet resistance for maximum current collection, the series resistance loss from the cell grid pattern is less than 5% of the generated cell power.

Results of the initial fabrication experiments are reported. The results strongly support the value of using prismatic covers to improve efficiency.

INTRODUCTION

The buried contact solar cell was developed at the University of New South Wales as a lower cost route to high efficiency silicon solar cells[1]. Buried contact cells utilize heavily diffused deep grooves in the emitter into which the front metallization is plated. While these cells were originally developed for one sun applications, they are also well suited for use as concentrator cells. Advantages of buried contact cells for use as concentrator cells include:

- Higher efficiency achievable on lower cost polycrystalline and CZ substrates.
- Use of lower cost plated nickel - copper metallization.
- Does not require costly photolithography.
- Process is self-aligning.
- Deeper diffusion in the grooves provides good screening of the metal from the emitter, while allowing for a lightly doped higher efficiency emitter.
- There is reduced contact resistance because of the large plated wall area and the heavily doped contact region.
- The vertical geometry of the metal in the grooves provides for increased grid conductivity without increased shadowing.

The cells are designed for use in the ENTECH 22X linear Fresnel lens concentrator system[2], where they will replace the space type cells that has TiPdAg contacts evaporated in a photolithographically defined grid pattern. The buried contact cell process offers potential higher efficiency and lower cost.

CELL DESIGN

The cell for this project is designed to match the ENTECH system. It is a linear cell with bus bars down each side of the cell and parallel grid lines running between the bus bars, as shown in Figure 1. The cell it is replacing was designed to provide 2 cells from a 5" diameter wafer. This cell is 3.82" (9.7 cm) long and 1.91" (4.85 cm) wide with an active area width of 1.6" (4.06 cm). The grid pattern on the original cells consisted of 0.004" (100 micron) wide silver plated grid lines spaced 0.02" (.0508 cm) apart. The resultant 20% shadowing was eliminated by using prismatic cover slides[3]. The buried contact cell is designed to obtain 2 cells from a Solarex 11.4 cm x 11.4 cm polycrystalline wafer. The new cell is 4.4" (11.18 cm) long by 2.1" (5.33 cm) wide with an active area width of 1.8" (4.57 cm). The greater length means fewer cells per receiver. The larger active width results in the requirement for less accurate tracking, which will lower the overall system cost.

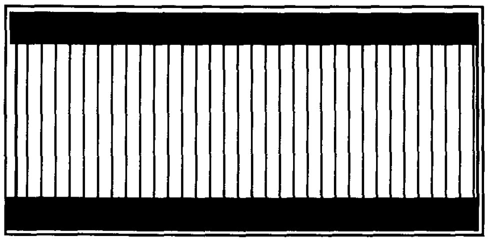

Figure 1: ENTECH 22X Concentrator Cell Geometry

Design of the front metallization pattern is based on minimization of the total power loss due to the front grid system. This power loss has components due to 1) shadowing, 2) series resistance loss in the diffused emitter as the current flows to the grid lines, 3) contact resistance of the metallization as the current flows into the grid lines and 4) series resistance loss in the metal as the current flows to the collecting leads. Since the buried contact cell has such a large area contact to a highly diffused region, the contact resistance term should be negligible. For the rectangular grid pattern used in the ENTECH cell, where all of the grid lines are the same width, length and thickness, the expressions for power loss of the other 3 components for uniform illumination are:

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$$\Delta P_{shadow} = sP_o\ A/x$$

$$\Delta P_{Emitter} = j^2rx^2\ A/12$$

$$\Delta P_{Metal} = j^2xL^2\ \rho A/(12A')$$

Where:

s = Width shadowed by grid line
P_o = Idealized power without series or shadow loss
A = Active area of cell
x = Spacing between grid lines
j = Current density in silicon
r = Sheet resistance of emitter
L = Length of grid lines
ρ = Resistivity of gridline metallization
A' = Cross sectional area of metallization

If all of the values are known except for spacing, the total power loss (that is the sum of the three components) can be minimized mathematically by taking the derivative with respect to x and setting it equal to zero. Solving the above equation using the parameters expected for the ENTECH buried contact cell including an emitter sheet resistance of 150 Ohms/square, yields a value of 0.055 cm (0.02") for the optimum grid spacing, exactly the grid geometry used in the Austin and PVUSA ENTECH jobs. To better understand the relationship between grid spacing and expected performance, Figure 2 is a plot of the calculated power as a function of grid spacing for three different emitter sheet resistances.

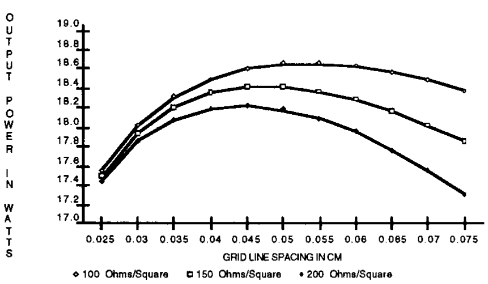

Figure 2: Calculated output power of ENTECH cell under uniform 16.7 suns illumination as a function of grid spacing for 3 emitter sheet resistances with no prismatic cover.

This analysis would lead to the selection of 0.05 cm spacing just as with the previous cell technology. However, there are two additional considerations to be addressed:

1) ENTECH plans to use prismatic covers if they are cost effective. Use of prismatic covers results in the power loss term for shadowing (ΔP_{Shadow}) becoming zero. Therefore, the optimum spacing is determined by the design that minimizes series resistance losses. It can be seen in Figure 6 that for uniform illumination the minimum series resistance occurs for the closest spacing physically possible, which for the covers themselves is projected to be 0.025 cm. At this grid spacing the power increases from 17.49 Watts without the cover to 20.9 Watts with a prismatic cover. The calculation of cost effectiveness of using prismatic covers under uniform illumination must compare the best result without cover, that is the 18.42 Watts at 0.05 cm spacing, versus the best result with prismatic cover, which is the 20.9 Watts at 0.025 cm spacing.

2) The initial calculations assumed uniform illumination across the width of the cell. This will not be the case in an operational system. Indeed the illumination pattern depends upon the tracking accuracy specified for the system. A large tolerance in tracking will result in a lower cost system. Figure 3 shows data from ENTECH for a uniform illumination level, a 0.75° tracking error and a 1.0° tracking error. To accurately reflect operation in a real system, the cell grid pattern should be optimized for the illumination pattern expected from the system, not for a uniform illumination pattern.

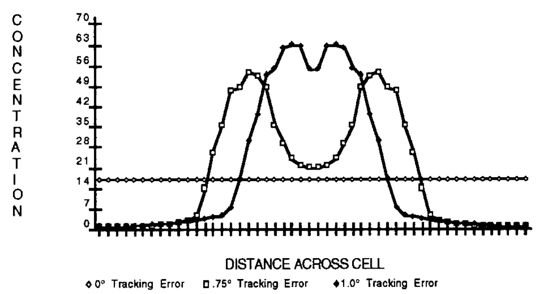

Figure 3: Concentration pattern across the cell for three system different tracking errors.

The problem now is to calculate the optimum cell geometry for these nonuniform concentration patterns. As long as the total amount of energy incident on the cell remains constant and the grid line are all of the same uniform width, the term for shadowing loss remains the same. The current density in the emitter now becomes a function of the concentration profile.

$$j = C(y)j_o$$

Where:

C(y) = Concentration level across cell.
j_o = Current density at 1 sun.

Now the emitter component of power loss is given by:

$$\Delta P_{Emitter} = \frac{j_o^2 r x^2 A}{6 L} \int_0^{\frac{L}{2}} C^2(y)\, dy$$

This term can easily be solved numerically once the concentration profile is defined.

The term for the power loss in the grid lines becomes:

$$\Delta P_{Metal} = \frac{2 \rho A x}{L A'} \int_0^{\frac{L}{2}} \left[\int_0^{y} j(y')\, dy' \right]^2 dy$$

Since the current density is proportional to concentration, the following substitution can be made:

$$j(y') = j_o\, C(y')$$

This equation can also be solved numerically, being careful to include the current flowing down the grid line as well as that produced within each region.

With nonuniform concentration the full set of equations for power loss can no longer be solved explicitly for the optimum grid spacing. The three components of power loss must be calculated for each set of conditions and the optimum spacing selected by observation. Figure 4 shows the calculated output power versus grid line spacing for the 0.75° tracking error concentration pattern. Figure 5 shows the power versus grid spacing for the 1.0° tracking error case. As the tracking error increases the peak concentration ratio increases. Therefore the optimum grid line spacing moves to closer spaced lines. The optimum spacing moves from 0.05 cm in the uniform case to less than 0.03 cm for the 1.0° tracking error at 200 ohms/square emitter sheet resistance.

If the power loss is calculated based on the use of a prismatic cover, the shadow loss term is zero. The result of this calculation is shown in Figure 6. The expected power is plotted for 150 ohms/square emitter sheet resistance the process baseline. For all three concentration patterns the 0.025 cm grid spacing produces the *maximum* output power. Selecting a 0.025 cm spacing has the following advantages:

- Provides maximum output power for all concentration patterns when using a prismatic cover.
- Is the least sensitive to changes in emitter sheet resistance in all cases with or without prismatic cover.
- Is the least sensitive to tracking errors.

Indeed, our selection of the 0.025 cm grid spacing means that the ENTECH tracking system can be designed to allow up to a 0.75° tracking error without loss of any system output power.

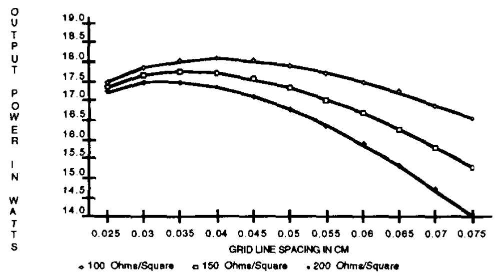

Figure 4: Calculated output power of ENTECH cell with 0.75° tracking error as a function of grid spacing for 3 emitter sheet resistances with no prismatic cover.

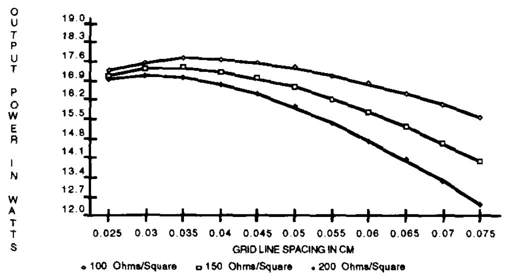

Figure 5: Calculated output power of ENTECH cell with 1.0° tracking error as a function of grid spacing for 3 emitter sheet resistances with no prismatic cover.

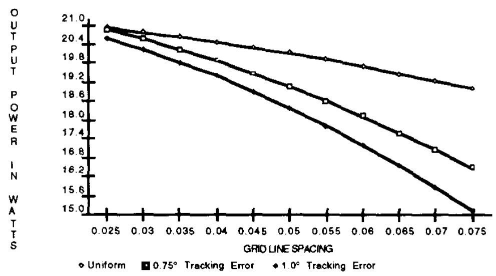

Figure 6: Calculated output power for ENTECH cell using prismatic cover with 150 ohm/square emitter sheet resistance for 3 different concentration patterns.

BULK RESISTIVITY

The PC-1D solar cell modelling program has been utilized to calculate cell performance at 20 suns to determine the optimum bulk resistivity. PC-1D provides diffusion lengths as a function of bulk resistivity assuming ideal single crystal silicon. The program was then used to calculate the expected efficiency for various bulk resistivities. The results are shown in Figure 7 for 3 different front surface recombination velocities. A bulk resistivity of 0.2 Ohm-cm is best for all front surface recombination velocities. This result will not necessary hold for polycrystalline silicon, because the relationship between bulk resistivity and diffusion length is different for polycrystalline silicon.

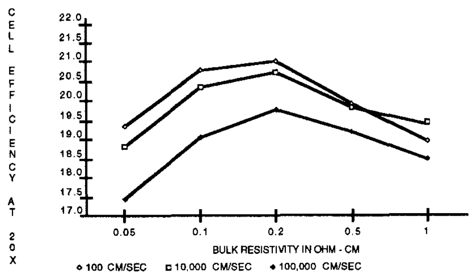

Figure 7: Calculated solar cell efficiency at 20 suns concentration as a function of bulk resistivity for 3 different front surface recombination velocities.

CELL PROCESS

The buried contact cell process sequence as developed at the University of New South Wales (UNSW) is shown in Figure 8 [4]. As developed at UNSW the grooves were cut using a laser, hence the name laser grooved cells. The laser technique may not be cost effective for high throughput production and does not provide the flexibility to change depth and width of the grooves for different applications. At Solarex a sawing technique[5] has been utilized to mechanically cut the grooves. This process will be easier to automate in production, yields more uniform grooves and can more easily be modified to produce different groove geometries.

In this process the silicon oxide produced in the wet oxidation step serves as an etchant and diffusion mask as well as being the final antireflective (AR) coating on the cell. However, the index of refraction of silicon oxide is lower than desired for effective optical coupling. This is not a serious problem for float zone (FZ) or Czochralski (CZ) silicon because they can be texture etched to improve the optical absorption. However, polycrystalline silicon does not texture etch uniformly, so for polycrystalline silicon a better AR coating material is required. Other materials such as silicon nitride or titanium dioxide will be evaluated for use as mask and AR coating.

BURIED CONTACT CELL PROCESS

Damage Etch

Light Emitter Diffusion

Wet Oxidation

Cut Grooves

Groove Etch

Deep Groove Diffusion

Al Deposition

Al Sinter

Ni-Cu Plate

Cut To Size

Figure 8: Buried contact cell process sequence.

PRELIMINARY CELL RESULTS

Buried contact cells were fabricated on untextured CZ and polycrystalline silicon substrates using the old 0.05 cm grid line spacing. The best cells were approximately 12 % efficient under Standard Test Conditions (STC = 1,000 W/m^2, AM1.5 spectrum and 25° C). When measured under concentration the current increased linearly with concentration and the voltage increased with the natural logarithm of the concentration as typical of low resistivity crystalline silicon. The fill factor increased at low concentrations up to about 6 suns and then started to decrease. At the design concentration of 16.7 suns the efficiency had fallen to about the 1 sun level.

Besides the need to utilize silicon with a lower bulk resistivity as calculated above, the major issue related to fill factor at higher concentrations is the development of the groove plating process. Plating too rapidly results in trapping of voids in the grooves and excess plating around the tops of the grooves. Plating too slowly results in the grooves never filling up. Initial experiments indicate that metal adhesion depends on the use of the correct groove etch.

Several of these buried contact cells were covered with prismatic covers at ENTECH. After covering, the grid lines were no longer visible to the naked eye. The short circuit current increased by more than 10%, consistent with there being no grid line shadowing. However, the blue oxide AR coating also disappeared upon covering, showing how inadequate the silicon oxide is as an AR coating.

DISCUSSION

Buried contact cells are well suited for use as linear concentrator cells. Coupling properly designed cells with prismatic covers will result in high systems efficiency without stringent requirements on tracking accuracy. Efforts must now focus on process development, transferring the high efficiency cell process from UNSW into a cost effective manufacturing process at Solarex.

ACKNOWLEDGEMENT

This work is part of the DOE sponsored Concentrator Initiative and is supported by Sandia Contract No. 54-2191C. The authors wish to thank S. Roncin and J. Creager of Solarex for processing the cells, D. Whitehouse of Solarex for assistance in the modelling, M. O'Neill of ENTECH for assistance in cell design and covering of the sample cells and J. Gee of Sandia for helpful discussions and assistance in cell processing.

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