HIGH VOLTAGE SILICON VMJ SOLAR CELLS FOR UP TO 1000 SUNS INTENSITIES

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ABSTRACT

High voltage silicon vertical multi-junction (VMJ) solar cells are ideally suited for providing efficient operation at solar intensities exceeding 1000 suns AM1.5. This paper discusses the unique features and advantages of the VMJ cell. The authors believe the high output power performance capability and manufacturing simplicity of VMJ cells will enable more cost-effective photovoltaic concentrator system designs. Preliminary test data is shown for a 0.78 cm^2 VMJ cell with 40 series connected junctions producing 31.8 watts at 25.5 volts at near 2500 suns AM1.5 intensity (40.4 watts per cm^2 output at 211 watts per cm^2 input with an estimated efficiency near 20%).

INTRODUCTION

Solar concentrators are a promising approach for lowering photovoltaic (PV) power cost in the near term. This is mainly due to the fact that one-sun PV hardware remains hampered by high cost semiconductor silicon used to make conventional solar cells. In this regard, PV concentrators use lower cost materials (e.g. large area glass mirrors) to intensify sunlight as a means to minimize the amount of expensive semiconductor material needed in solar cells for a given power level. Thus PV concentrators will effectively lower the $/watt cost barrier that impedes the conventional PV Industry. In addition, PV concentrators will provide performance advantages since higher cell efficiencies are possible and sun tracking will increase the total power delivered over time.

However, the authors believe the most important element needed to achieve maximum cost effectiveness in the near term is having silicon solar cells that are capable of operating efficiently at very high intensities and can be readily produced at low manufacturing cost. This paper discusses the unique design features and performance characteristics of VMJ cells that make them ideally suited for this task.

VMJ CELL DISCUSSION

The VMJ cell, shown schematically in figure 1, is an integrally bonded series-connected array of miniature silicon vertical junction unit cells. (Because of its unique orientation to illumination it has also been descriptively referred to as an "edge-illumination" multi-junction cell.)

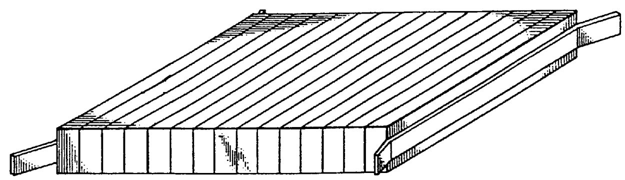

Fig. 1. Schematic drawing of VMJ cell

The VMJ cell fabrication steps, shown in figure 2, are relatively simple: For an example, 40 diffused p+nn+ silicon wafers of 250 microns thickness are metallized, stacked and alloyed together to form a multi-layer stack that is 1 cm high. This stack of diffused wafers, when appropriately cut, will yield around1000 VMJ cells of 1 cm x 1 cm x .05 cm size, each containing 40 series-connected unit cells for high voltage operation. Exposed silicon surfaces are etched to remove saw damage and passivated with an anti-reflection coating applied to the illuminated side. Finally electrical leads are attached to the end contacts. For clarity an edge-illuminated vertical junction p+nn+ unit cell is also shown schematically.

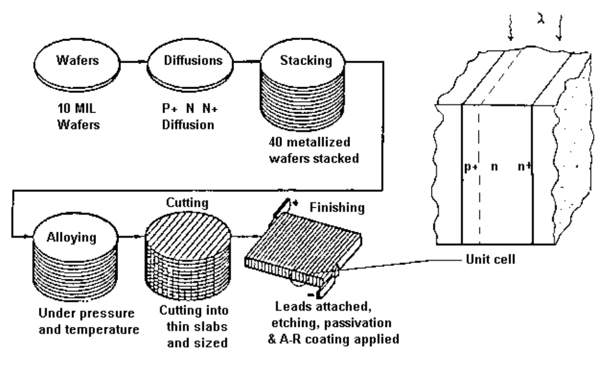

Fig. 2. VMJ Cell fabrication processes

A key feature of the VMJ cell is its design simplicity. During wafer processing a single high temperature diffusion forms both p+n and nn+ junctions and no photolithography is involved. One optimized diffused wafer design is suitable for all intensities and for fabrication of a wide range of finished cell sizes. Thus its manufacture lends itself to a high volume production capability within the present industrial sector at low manufacturing cost.

The major inherent advantages of the VMJ cell design are given in Table I. In brief, it is a rugged high voltage and low series resistance solar cell with vertical junctions and contacts providing near optimum current collection without sheet resistance, current crowding, or blockage of illumination.

Table I. Major Advantages of the VMJ cell:

- Edge-illumination – eliminates the need for front and/or back contacts. There are no sheet resistivity components of the series resistance and generated current carriers crossing unit cell junctions are immediately collected by their adjacent vertical contacts. There is equal collection probability for excess carriers generated at any depth, which gives improved spectral responses for both the short and long wavelengths.

- Series-connection – provides a high voltage, low current operation with a better compatibility to most power processing loads and a high tolerance to series resistance values within the electrical system. It gives very high reversed-voltage breakdown immunity, which reduces the need for adding by-pass diode protection.

- Low series resistance at high intensities – is assured by effective photoconductivity modulation throughout the bulk region of unit cells, giving an almost linear decrease in series resistance with increasing intensity.

- Structural design – provides an extremely rugged configuration electrically, mechanically and thermally. It permits high packing densities with easy interconnecting of electrical output leads in high power density systems.

Development status

The VMJ cell fabrication processes are being finalized under a DOE Inventions and Innovation Program Grant along with support from a Space Act Agreement with NASA Glenn Research Center. VMJ cell samples have been prepared for test and evaluation with preliminary results reported in this paper. When baseline design processes are finalized in the near future, pre-production prototype VMJ cells will be produced for further testing and for supporting several groups planning outdoor solar concentrator system evaluations at high intensities.

Testing challenges

Testing VMJ cells at high intensities has challenges. As with any solar cell with series connected junctions, light uniformity to each cell in series is needed because the lowest current cell will essentially limit the overall output current. Therefore, non-uniform light to junctions in series will affect test results and even more so when using short circuit current (I_{sc}) ratios for measurement of intensity, as is a common practice in testing concentrator cells.

A simple test using an experimental VMJ cell exposed to a light intensity near 1500 suns AM1.5 was used to demonstrate this effect. An initial flash test with uniform light showed an intensity of 1608 suns AM1.5 based on the I_{sc} ratio using the one sun I_{sc} for reference. However in the second flash test conducted at the same intensity, a piece of transparent tape was used to simply cover a few unit cells in the series connected array. The tape reduced light only to those covered unit cells, and hence the overall I_{sc}. Although the actual intensity was the same in both flash tests, the calculated intensity in the second test based on the I_{sc} ratio dropped from 1606 suns to 1188 suns. While I_{sc} dropped in the second test due to partial tape coverage, the overall IV curve sharpened, increasing the fill-factor by 21.3 % and the I_{sc} calculated efficiency by 21.9%, clearly an obvious distortion of actual results. However this test points out that PV concentrator advocates will need to develop high intensity AM1.5 spectrum solar simulators that provide uniform illumination along with calibration standards for accurately measuring of intensities to establish efficiencies.

Furthermore, the one-sun I_{sc} of VMJ cells can be influenced positively or negatively by different surface treatments. Since the VMJ cell illuminated surface is primarily lightly doped bulk silicon, chemicals or coatings that will induce an electrostatic field at the surface can readily affect it. Consequently, testing VMJ cells using I_{sc} ratios as a measurement of intensity based on the one-sun I_{sc} data as a reference could give questionable results so an effort was made to eliminate this potential problem in testing VMJ cells.

VMJ Cell testing procedure

In view of the fact that there are no calibrated standards available for high intensity testing, the procedure developed for testing VMJ cells established the 100 suns AM1.5 intensity based on physical distances and optical relationships between the simulator flash lamps and VMJ cells being tested. The optical relationship for intensity, based on the inverse square of the distance law between the lamp and cell position, was used to determine the 100 suns AM1.5 intensity position where high intensity testing commenced.

The NASA LAPSS flash simulator designed by Spectrolab was used for high intensity flash testing VMJ cells. It was designed to illuminate large 4 m^2 area arrays at 1 sun AM0 intensity (1367 watts per m^2) at a position of 253.5 inches from the lamps. The illumination uniformity over this area has been determined to be within 2%.

(For discussion in this paper, 1 sun AM0 = 1.608 suns AM1.5 intensity-wise to comply with the Concentrator Photovoltaic Alliance recommendation for using 850 watts per m^2 AM1.5 spectrum as the standard for solar concentrator testing. However the NASA flash simulator is closer to the AM0 spectrum, and not the AM1.5 spectrum that would be better matched to silicon VMJ cells.)

There are two parallel arc discharge lamps in the NASA flash simulator. It was determined that moving closer along the centerline up to 32.15 inches from the lamps, the light remained uniform within its solid angle design, which allowed establishing the 100 suns AM1.5 intensity (62.2 suns AM0) position based on the inverse square of the distance relationships. That position would be where a series of flash tests for higher intensities would commence. For higher intensities the VMJ cells would be moved closer to the flash lamps along the centerline, using I_{sc} ratios based on the 100 suns AM1.5 intensity I_{sc} for reference. It was assumed that the I_{sc} ratios above this intensity was a linear relationship, which needs to be confirmed in future testing.

Before flash testing, VMJ cells were also tested under steady state one-sun AM0 simulation and the data was used to determine I_{sc} linearly going from one-sun AM0 to 100 suns AM1.5 intensities. (For clarity one-sun AM0 = 0.1367 watts/cm^2 and 100 suns AM1.5 = 8.50 watt/cm^2.) These tests showed VMJ cells had an I_{sc} current ratio that increased super linearly with intensity by 26.2% at 100 suns. (Super linearity in VMJ cell I_{sc} is expected as minority carrier lifetime increases with carrier concentration and recombination losses that are more dominant at low intensities become less significant at higher intensities.)

TEST RESULTS

High intensity flash test results are presented in figure 3 for VMJ cell D1-7, containing 40 series junctions with an area of 0.78 cm^2. The IV data was taken over the range of 100 to near 2500 suns AM1.5 intensities (from 8.5 to 211 watt/cm^2).

The IV data shows efficiency peaks at about 1200 suns AM1.5 intensity (about 100 watts input per cm^2) with an efficiency of 19.48% and fill-factor of 0.765. However at twice this intensity to around 2500 suns AM1.5 (211 watts per cm^2) the performance drop is slight with an efficiency of 19.19% and a fill-factor of 0.735. Such performance characteristic undoubtedly validates the low series resistance characteristics of VMJ cells.

Analysis of the 2480 suns flash data shows unit cells operating at current densities nearly 70 amperes per cm^2 with a VMJ cell output maximum power density of 40.4 watts per cm^2 at 25.5 volts. This output power density performance (> 400 kilowatts per m^2) is more than 2500 times that of conventional one-sun silicon solar cells and demonstrates the viability of silicon VMJ cells for application in high intensity solar concentrators.

Outdoor solar testing

In addition to indoor flash testing, preliminary outdoor solar testing has been conducted at various times during the past year in the Seattle, WA area. Four experimental VMJ cells were mounted on a water-cooled copper heat sink to evaluate cells and thermal control mounting techniques for high intensity operation. The cells have operated about 100 hours total but remained in the weather continuously during this year. The peak solar flux in the concentrator system was 65 w/cm^2, which is over 700 suns intensity. However with normal conditions the intensity was about 50 w/cm^2 due to sun angle, haze, dirt, etc. Peak flux conditions are rare in Seattle. The VMJ cells were tested in an open circuit or short circuit mode and not under steady state load. Typically a 20% voltage drop due to cell temperature increasing occurred within about 0.7 seconds after sun acquisition at peak flux, which is attributed to the heat sink design. There have been no indication of voltage or current degradation over the first year; so preliminary testing indicates VMJ cells are stable and rugged

Plans include testing pre-production prototype VMJ cells in the near future. A new heat sink design is expected to provide improved thermal control for a larger array of VMJ cells of several hundred watts. The concentrator has also been modified for higher intensity with controls incorporated for unattended longer-term operation.

COST ASPECTS

Manufacturing cost estimates have not been completed for VMJ cells but are projected to be modest in view of their design simplicity. But more importantly, their ability in producing very high output power densities means they will deliver very low $/watt performance.

The following example highlights the semiconductor silicon material cost aspects in VMJ cells. With the cited fabrication example, there is a production yield of 25 VMJ cells of 1 cm^2 size per each four-inch diameter diffused wafer. Assuming prime grade silicon wafers cost $10 per wafer in volume gives $0.40 of silicon material per VMJ cell for the example. At 1200 suns AM1.5 intensity (about 100 watts/ cm^2 solar) with 20% efficiency, the VMJ cell peak power rating would be 20 watts per cm^2, which means a silicon material cost of $0.02/watt. If one considers that intensity is too high, then designing for a more modest 600 suns AM1.5 intensity will increase the silicon material cost to $0.04/watt. That is still a fairly small material cost factor for PV technologies.

The PV Industry currently relies heavily on low or scrap grade silicon for making conventional one-sun solar cells in order to reduce cost. Nevertheless the silicon material cost in one-sun solar cells is still more than a dollar per watt. The fundamental problem stems from the fact that refining and producing semiconductor silicon is both capital and energy intensive, making it expensive. Conventional one-sun solar cells also have very poor energy payback estimated at several years. In contrast

VMJ cells made with prime grade silicon material costing of a few pennies per watt in our example, will have their energy payback period in a matter of a few sunny days. Considering all these important aspects, the VMJ cell will enable the development of a viable cost-competitive PV Concentrator Industry that is capable of taking its rightful role in the Nation's economy.

CONCLUSIONS

High voltage silicon VMJ cells are shown to be ideally suited for providing efficient operation at solar intensities exceeding 1000 suns AM1.5. The unique features and characteristics of the VMJ cell are discussed in this paper. High intensity PV concentrator systems using VMJ cells could effectively alter the competitive dynamics of the PV Industry.

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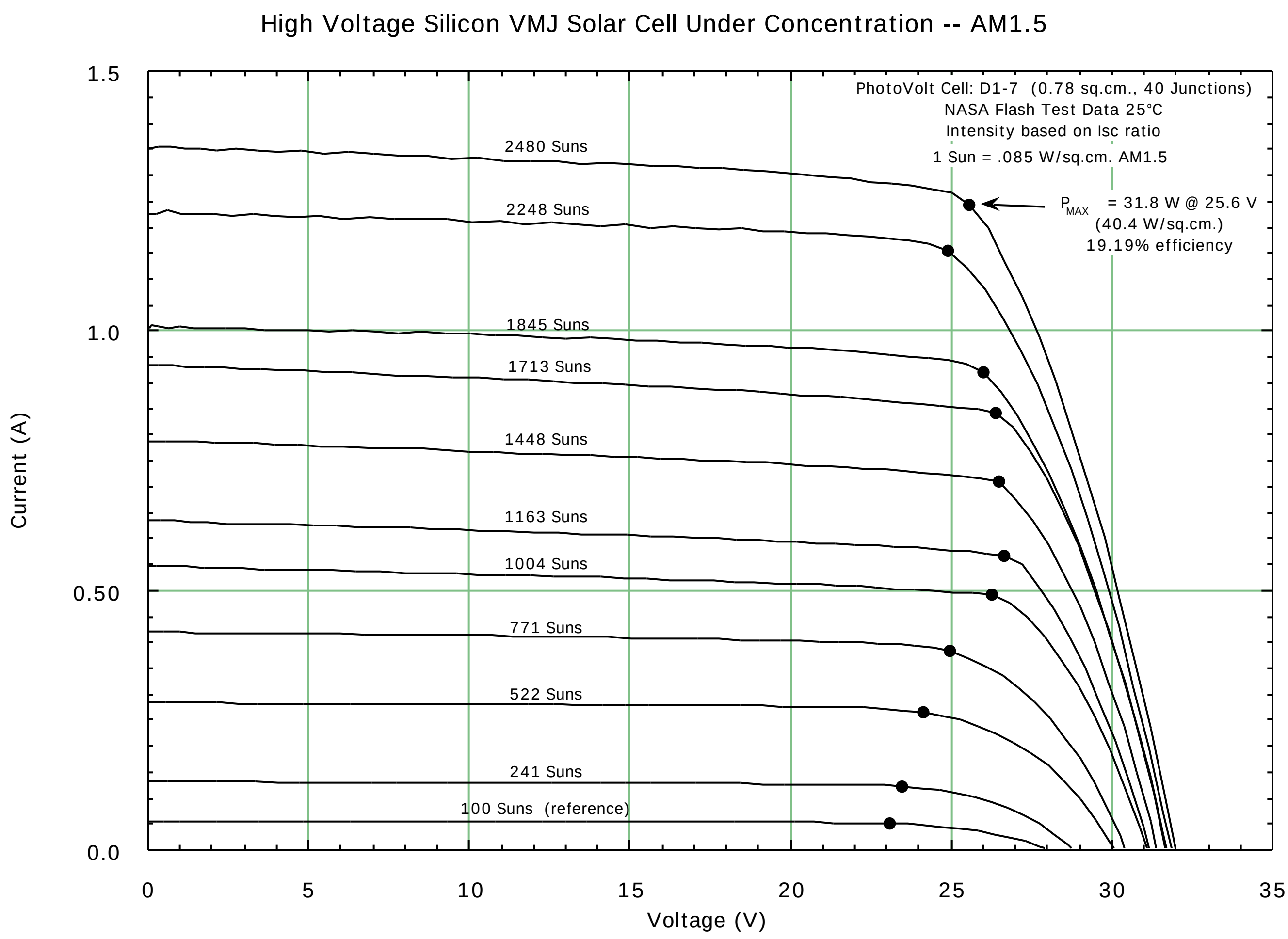

Fig. 3. IV curves for VMJ cell taken over the range of 100 to 2500 suns AM1.5 intensities