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John C. Evans, Jr. and An-Ti Chai
Lewis Research Center
Cleveland, Ohio

and

Chandra Goradia
Cleveland State University
Cleveland, Ohio 44115

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John C. Evans, Jr., An-Ti Chai, and Chandra Goradia*

National Aeronautics and Space Administration
Lewis Research Center
Cleveland, Ohio 44135

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ABSTRACT

This paper presents technical considerations, preliminary results, and fabrication details on a new family of high-voltage Planar Multi-junction (PMJ) solar cells. The new cells combine the attractive features of planar cells with conventional or interdigitated back contacts and the Vertical Multijunction (VMJ) solar cell. The PMJ solar cell is internally divided into many voltage-generating regions, called unit cells, which are internally connected in series. The key to obtaining reasonable performance from this device was the separation of top surface field regions over each active unit cell. Using existing solar cell fabricating methods, output voltages in excess of 20 volts per linear centimeter are possible. Analysis of the new device is complex, and numerous geometries are being studied which should provide substantial benefits in both normal sunlight usage as well as with concentrators.

INTRODUCTION

In a number of existing and future applications of photovoltaic systems, one can see the desirability of having solar cells which can provide two orders of magnitude higher voltages, while still retaining the characteristics of present wafer devices. Other desirable features include simplicity of fabrication, ease of interconnection and panel assembly, ready bonding of cover glasses for space usage, and reduced losses due to grid shadowing, series resistance and high temperature.

Various innovative designs such as the Interdigitated Back Contact (IBC) solar cell (1), the Tandem Junction Cell (TJC) (2), the Vertical Multijunction (VMJ) solar cell (3), the Horizontal Multijunction (HMJ) solar cell (4), and the V-Groove Multijunction (VGMJ) solar cell (5), have been proposed to reduce or eliminate losses due to grid-shadowing and the sheet resistance component of series resistance. Also, all cells except the IBC and the TJC operate as high-voltage, lowcurrent devices and further reduce series resistance as well as temperature effects due to I^2R heating. Significant transparency to infrared photons further reduces high temperature effects in these cells.

However, while these cell structures share many good features, each structure suffers from its own drawbacks. None of these structures is a high voltage cell on a single substrate with the advantage of simple fabrication. The IBC and the TJC are not high-voltage solar cells, the VMJ is not a planar device on a single substrate, the HMJ is felt to involve a fairly complex fabrication process and the VGMJ ends up having physically separate semiconductor unit cells held together on a glass plate.

It is the purpose of this paper to present preliminary experimental results on a new cell, the Planar Multijunction (PMJ). This new device is not only a high voltage solar cell fabricated on a single semiconductor substrate, but it is also expected to share the good features common to the previous structures, such as elimination of losses due to gridshadowing, reduction of the sheet resistance component of series resistance, and reduction of high temperature effects. Also, the relatively simple geometry of the PMJ solar cell should allow for a simple fabrication process using standard integrated circuit techniques.

PRELIMINARY DESIGN CONSIDERATIONS

Figure 1 shows the PMJ cell in schematic cross-section. The illuminated top surface area is divided into several field regions corresponding to the unit cells positioned beneath. These unit voltage-generating cells are electrically connected in series within the wafer. A number of alternate concepts are being considered including the inverted structure of that shown in Figure 1, a cell with unit cells both top and bottom, and a concentric unit cell device with center and perimeter output pads, which may be used with sunlight concentrators, and a six unit cell device containing circuitry for alternating current output.

Because we have not developed the mathematical theory completely for this device, it is not presently possible to optimize geometric and material design parameters. However, some preliminary design values of key parameters may be obtained from physical considerations and from theory developed from a somewhat similar structure, the TJC (2). In

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*NASA-ASEE Faculty Fellow, Cleveland State University, Cleveland, Ohio 44115.

Figure 1, W is the width of the unit voltage-generating cell, while the subscripts refer to the respective widths of the n^+ and p^+ doped regions and the gap separating them. The implanted or diffused metal interconnection bar is intended to be as narrow as possible, but its exact dimensions are not presently known.

From simple physical considerations the longest path which a photo-generated electron needs to travel in order to be collected is approximately:

$$\sqrt{h^2 + \left(\frac{W_{p+} + W_g}{2}\right)^2}$$

This path length should be shorter than a diffusion length of electrons in the base region to obtain high collection efficiency. Then, it follows that both h and $(W_{p+} + W_g)/2$ must be individually shorter, preferably much shorter, than the electron diffusion length in the base region. Within this constraint, it has been found experimentally that for the TJC, fractional stripe widths of $W_{n+} = 0.85W$: $W_{p+} = 0.1W$, and $W_g = 0.05W$ give high collection efficiency without sacrificing the fill factor due to high series resistance. These same fractional stripe widths should also apply to the PMJ cell. For a low voltage PMJ solar cell with only eight unit cells per centimeter, the above considerations give $W = 1{,}250$ µm, $W_{n+} = 1{,}063$ µm, $W_{p+} =$ 125 µm, and $W_g = 62$ µm. A high voltage PMJ with 40 unit cells per centimeter would have the dimensions, $W = 250$ µm, $W_{n+} = 213$ µm, $W_{p+} =$ 25 µm, and $W_g = 12$ µm. In either of these two cases, if the cell thickness is 75 µm, then the path length for collection will be 120 µm, in the low voltage cell and 77 µm in the higher voltage cell. A diffusion length in the base of 250 µm or greater would ensure a high collection efficiency in either cell provided that surface recombination losses at the front and back surfaces are low.

Based upon experimental results for the TJC, the junction depth of the diffused regions on the front surface should be 0.2 to 0.3 µm, while back junctions equal to or greater than one micrometer are preferred to reduce series resistance. Base material resistivity as low as 2 ohm-cm has been found to yield PMJ devices without serious shunt losses when used at higher light levels. Possible internal shunting of the output voltage across the base or substrate material was also considered. However, our preliminary results from fabrication and measurement of the solar cells shows that this problem is not of great consequence.

EXPERIMENTAL FABRICATION

Cell fabrication occurred in three stages. The first experimental cells, shown schematically in Figure 2, were made with Czochralski grown silicon, boron-doped of 2 and 10 ohm-cm resistivities as the base or substrate material. A n^+/p junction was formed over the entire surface of each circular wafer with conventional phosphine diffusion in a tube furnace at 850° C: for 30 minutes. The diffusion oxide was removed from one face of the wafer and a pattern of parallel bars of aluminum paste was screen-printed on the cleaned surface and fired in a belt furnace at 650° C. with a 40 second pass. The firing time was sufficient to assure penetration of the aluminum through the diffused n^+ region on this face. The wafer was then cut into a 1 1/2 cm x 1 1/2 cm device.

A narrow portion of the n^+ region was removed alongside of each aluminum bar on one side of the wafer by making a shallow cut with a dicing saw. This formed the required gap between the p^+ and the n^+ collector regions. The finished devices of this first group consisted of from four to six unit cells per device. Contact to the end p^+ and n^+ regions was made with fired silver paste.

These first high voltage solar cells exhibited open circuit voltages only slightly higher than the voltage from a single junction conventional solar cell. We reasoned that this lower than expected voltage was caused by the top diffused region rising to an intermediate voltage over its entire conductive surface and effectively short-circuiting the unit cell voltages. Individual field regions over each unit cell were then isolated from each other by dicing shallow grooves between them. The solar cell voltages subsequently increased substantially. In all of the devices in this study, it was found necessary to separate these surface field regions to obtain high voltages.

The second and third groups of experimental cells were made by modifying portions of TJC solar cells kindly provided by Mr. Bernard G. Carbajal of Texas Instruments, Inc.. These devices approached the desired geometrical configurations and dimensions of the PMJ. For this second part of our work we studied the series connection of several regions on a single substrate. Each region was, in effect, a unit cell having a surface field and interdigitated back junctions. We made a number of devices having two and three unit cell regions as shown schematically in Figure 3. Some of these devices were series connected on their surfaces with silver paste, while others had leads attached to bring the output of each unit cell out for testing and external connection in various combinations.

The third group of cells more nearly approached the true PMJ structure and were made by removing the side bars of TJC cells and shorting out every other gap to produce unit cell interconnections. Shorting was accomplished by applying small dots of silver paste between the contact bars and firing. Leads were attached to the ending n^+ and p^+ regions in a similar manner.
The front field regions of all of the unit cells were separated by shallow cuts through the diffused layer with a dicing saw. These cuts were precisely located over the unit cell boundaries. One of the cells of the third group is shown in the photograph of Figure 4.

RESULTS AND DISCUSSION

Solar cells from each of the three groups were tested in the X-25 AMO sunlight simulator as well as at 3 and 10 Suns in a large area pulsed solar simulator. Open circuit voltages of cells from each group are shown in Table 1. Unit cell voltages were not measured for the Group I and III cells. Current-Voltage curves of these first experimental cells showed that they suffered from both shunt and series resistance problems which caused low fill factors. It will be noted that the PMJ cells, in general, do not display output voltages equal to the sum of the unit cell voltages at one Sun but do reach this value at higher light levels. One possible explanation of this is that the voltage difference between unit cells does not change very much from one Sun to ten Suns. Shunting currents in the bulk therefore remain essentially constant at varying light levels. However, because the light-generated current has increased significantly with illumination intensity, the effects of shunting between unit cells becomes less important.

The one-Sun current-voltage curve of the Group III cell pictured in Figure 4 is shown in Figure 5. This device measures approximately 0.8 cm^2 in area and contains six unit cells in series. The series resistance problem shown by the slope of the curve near the open circuit voltage point is once again believed to be due to poor interconnection of the unit cells. At one Sun, voltages are below the expected sum of the unit cell voltages, while at a 10 Sun level, voltages over 0.5 volts per unit cell are demonstrated.

Group II cell No. 10-31-1 had two equally-performing junctions prior to paste interconnection. Apparently, one junction was partially short-circuited by the silver paste. In spite of this problem, the voltage of the interconnected cell was equal to the sum of the two unit cell voltages. With cells made up of more than two unit cells this was not the case, as can be seen from the results of cell No. 11-2-1, also of Group II but having 3 unit cells. However, this same solar cell showed more than 0.5 volts per unit cell at 3 Suns and approached 0.6 volts per unit cell at 10 Suns. In addition to the cited interconnection problem it is felt that there are other phenomena at work as yet not fully understood that account for the complex behavior of these cells at the various illumination levels.

In order to determine whether the high shunt resistance seen in this 3 unit series cell of Group II was genuine or caused by a single low current unit cell, a series of measurements were made. In this experiment, six leads were brought out from the wafer so that external connections could be made to the cells individually and in various series combinations. Beginning at one end, the unit cells are numbered 1, 2, and 3, and their IV curves measured individually with the other cells floating at open circuit are shown in Figure 6.

When adjacent unit cells 1 and 2 were connected in series with unit cell 3 left floating, the curve 1+2 resulted. It may be seen that the total current is greater than that of either unit cell while the voltage is less than the sum of the unit cell voltages. However, when unit cells 1 and 3 at the wafer extremes were connected in series with the center unit cell 2 left floating, the very different curve 1+3 resulted. Near short circuit current, the curve follows that of unit cell 3. However, this combination produces an open circuit voltage considerably higher than combination 1+2. Even more interesting, when all three unit cells were connected in series, very little gain in voltage was noted over combination 1+3. Calculations from the curves show unit cells 1 and 2 have shunt resistances of approximately 1,700 ohms each, while their series combination is 1,250 ohms. These experiments suggest that collection is taking place from adjacent unconnected regions. Thus it appears that the geometrical relationships of unit cells in PMJ series devices must be further studied to fully understand this effect. Also, the factors affecting the addition of such series-connected junctions such as the influence of cell reverse characteristics, shunt and series resistance must be studied further.

The effects of increased illumination on the PMJ solar cell are shown in Figure 7. This cell, which is the same device shown in the photograph of Figure 4, had its one Sun IV shown in Figure 5. The overall device measures approximately 0.8 cm^2 in area and contains six unit cells in series. The shape of its 10 Sun IV curve is quite complex. A dramatic increase in both current and voltage with increased light levels is shown. The increase in current is more than linear with intensity. Clearly, the factors affecting both the magnitude and the shape of this curve with intensity are complex and warrant further study.

SUMMARY AND CONCLUSIONS

It has been shown that the Planar Multijunction (PMJ) concept is feasible. The shunting problems generally associated with a multijunction device on a single wafer do not interfere with the successful performance of such devices. However, it was found necessary to isolate front junction or field regions over the unit voltage-generating cells to achieve high voltages. High series resistance in these first experimental cells became less important at higher light levels and voltages approached those expected by summing the unit cell voltages at intensities of 3 Suns.

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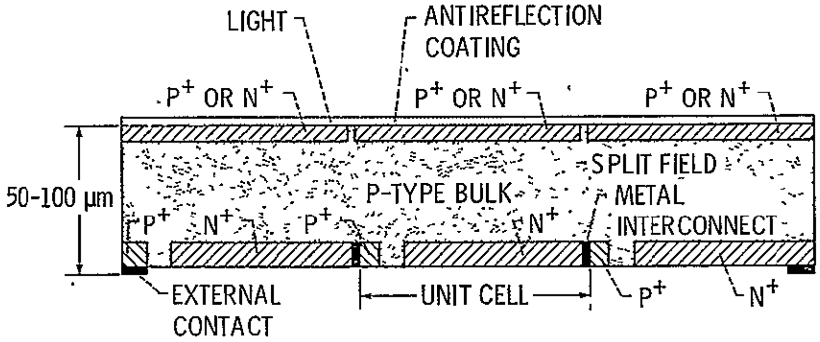

Figure 1. - Schematic cross-section of planar multijunction (PMJ) solar cell.

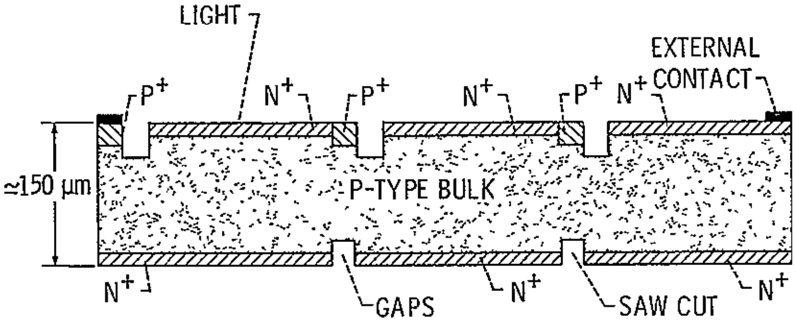

Figure 2. - First experimental high voltage structure.

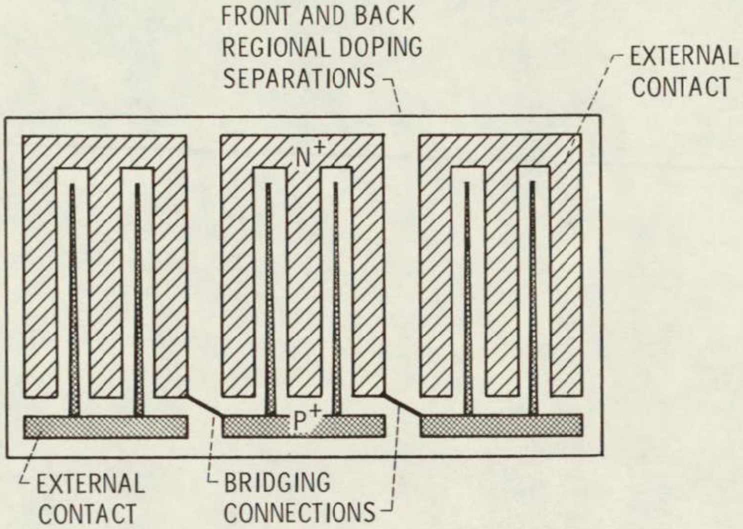

Figure 3. - Back view of high voltage cell made from IBC structure.

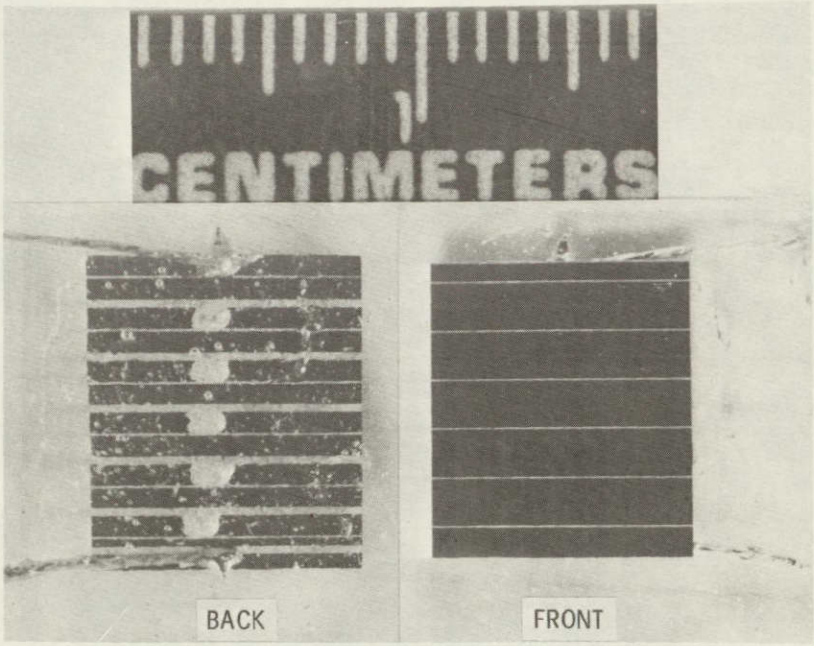

Figure 4. - Experimental PMJ high voltage solar cell.

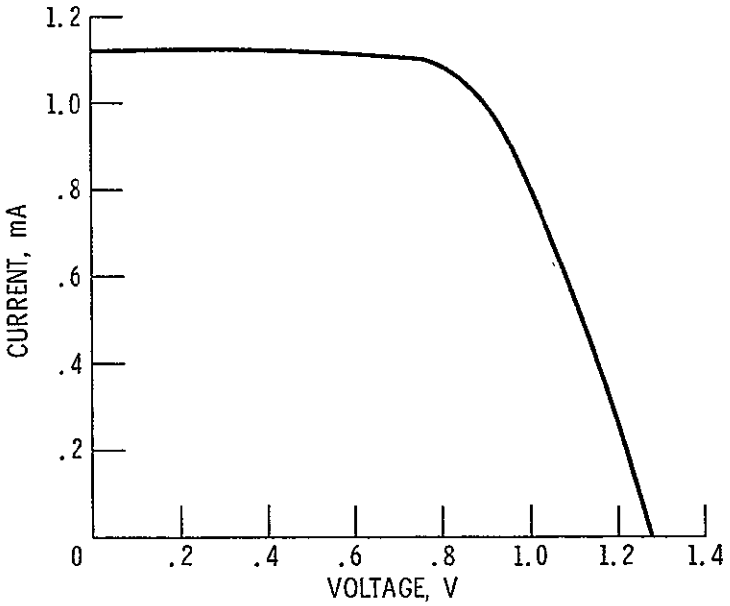

Figure 5. - Current-voltage curve of experimental PMJ solar cell.

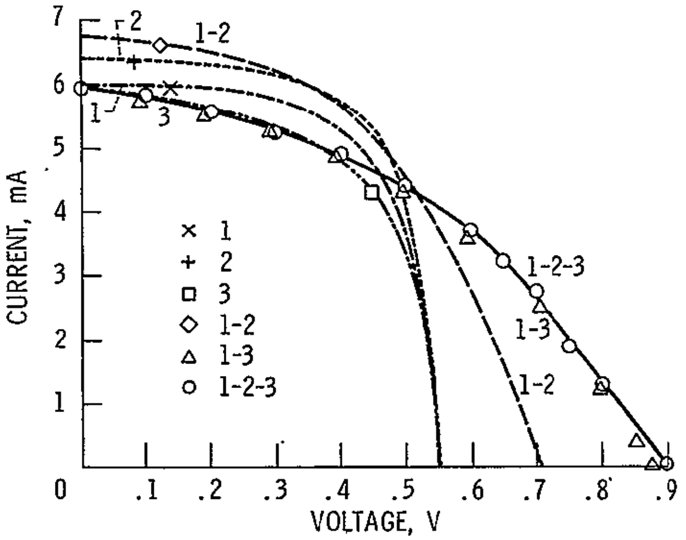

Figure 6. - Device 11-3-1 and its unit cells.

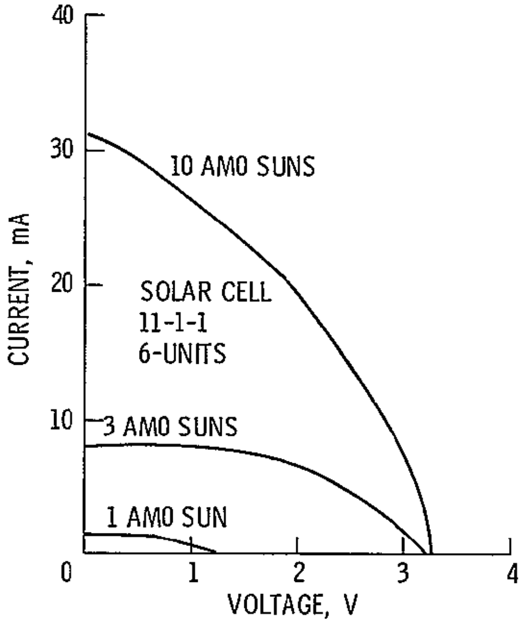

Figure 7. - Current-voltage characteristic at increased illumination.

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15 Supplementary Notes

John C. Evans and An-Ti Chai, Lewis Research Center, and Chandra Goradia, NASA-ASEE Faculty Fellow; Cleveland State University, Cleveland, Ohio 44115.

16 Abstract

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