MASTER

AN INTERDIGITATED BACK CONTACT SOLAR CELL WITH HIGH-CURRENT COLLECTION*

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ABSTRACT

Internal current-collection efficiencies greater than 90 percent and energy-conversion efficiencies of 18 percent at 30 suns have been measured on a laboratory version of the interdigitated back contact (IBC) solar cell. The quantum efficiency at 600 nm was greater than 90 percent which implies a minority carrier lifetime of greater than 350 μ sec and a front surface recombination velocity of less than 30 cm/sec on the better devices. To achieve these high-current collection efficiencies, a phosphorous gettering diffusion was performed on the front surface and then etched off. Also, thermal oxides were grown on the front and back of the cell to passivate the silicon surfaces. Although the internal collection efficiencies of the cell were high, series resistance caused the fill factor (FF) to decrease at concentrations above 30 suns. Dark current measurements on cells with a new grid spacing indicate that the series resistance is much lower than in the previous cell design. This should result in higher efficiencies at high concentration.

INTRODUCTION

The interdigitated back contact (IBC) solar cell structure has several potential advantages over conventional cell designs, especially for high-intensity applications. Among these are no shadowing loss due to the collecting grid, lower electrode resistances, and the absence of sheet resistance effects arising from lateral current flow in diffused regions. On the other hand, previous experience indicates that there are possible problems with this design in obtaining high-current collection, maintaining the fill factor at high values at high concentrations, and in adequately mounting and cooling the cell.

First, concerning current collection, a possible disadvantage of the IBC structure is that electron-hole pairs are generated far from the collecting junction. Thus to achieve high-current collection, long minority carrier lifetime (τ) must be maintained in the bulk, and the surface recombination velocity must be low. Nevertheless, cells have been fabricated at Sandia National

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Laboratories with 90 percent current collection efficiency and an energy conversion efficiency of 18 percent at 30 suns on a laboratory version of this cell.

As was reported earlier (1), although IBC cells have been fabricated with high-current collection efficiency, a low fill factor (FF) at high concentration resulted in a reduction of efficiency at high concentration. This low fill factor was believed to be a result of n^+ and p^+ diffusion widths which were not optimized. The dark current-voltage characteristic of this cell has been found to exhibit much more series resistance than a recently fabricated lot of cells with a new grid spacing. Thus the low fill factor problem may have been solved, and this could result in high efficiency cells at high concentration.

A problem in maintaining the high fill factor is that, in the fabrication of this cell, the metal must be ~ 10 - 20 μ m thick without any of the interpenetrating fingers shorting to the opposite contacts which have an intercontact (n-p) spacing of ~ 25 μ m. To date, silver contacts have been plated to a thickness of ~ 15 μ m with an intercontact separation of less than 25 μ m. This has been achieved by using a dry thick film photoresist to constrain the growth of the contacts during electroplating.

The third problem area for this structure, which is not related to processing, is that of cooling the cell without shorting the close metal contacts. Presently, a system is being constructed to directly cool the back of the cells with a fluid which when completed will then allow obtaining more complete performance data. This problem will not be discussed further in this report.

THE IBC STRUCTURE AND FABRICATION

A cross section of the cell structure is shown in Figure 1. The front surface has a SiN_x antireflection coating on a thermally grown passivating oxide. The unmetallized portion of the back surface has also been passivated by a thermally grown oxide layer followed by a forming gas anneal. The base material of the present cell is 10 Ω -cm FZ, n-type silicon of 300 μ m thickness. The p^+ emitter was formed by a gaseous source (diborane) diffusion and had a sheet resistivity of about 30 $\Omega/\square$ and a junction depth of about

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0.3 μm . The n^+ region was formed by a gaseous-source (phosphine) diffusion which also serves as a gettering process. This region has a sheet resistivity of 10 $\Omega/\square$ and a depth of about 1 μm . The basic cell design and previous work have been presented by R. J. Schwartz (2).

Figure 1. The interdigitated back contact solar cell structure.

For this structure, most of the minority carriers are generated in the top 100 μm of the substrate material and must then diffuse to the back junction. In order to have high-current collection efficiency in this cell, the minority carrier diffusion length in the bulk material must be long compared to the thickness of the wafer, and recombination at the silicon surfaces must be low.

Initially, a 10 $\Omega\text{-cm}$ base has been used to obtain long minority carrier lifetime and diffusion length, especially for the 300 μm -thick wafers. Phosphorous gettering (3,4) and care to avoid processing steps above 1000°C have yielded long lifetimes in conventional cells processed at Sandia (5,6) and similarly in this cell structure. A low front surface recombination velocity was obtained by growing a 300 Å-thick front surface thermal oxide followed by a forming gas anneal at 450°C. The forming gas anneal is essential to good surface passivation. Passivation at the back surface between the interdigitated contacts is also necessary. This was accomplished by using a thermally grown oxide of 300 Å thickness both between the fingers and over the diffused layers.

Although the back of this cell is almost completely covered with metal, the high currents obtained under high concentration require thick metal contacts to reduce the current voltage losses in the metal fingers. To obtain thick silver contacts which do not short to the opposite fingers, dry film photoresist was applied and patterned on the Ti-Pd to provide a mask which would constrain the Ag from spreading and shorting during electroplating. This technique has produced 15 μm thick contact fingers with a separation of ~ 20 μm as seen in Figure 2.

EFFICIENCY VERSUS CONCENTRATION AND THE DARK CURRENT VOLTAGE CHARACTERISTICS

Since the minority carrier diffusion length is long, a high surface recombination velocity at

the edge of the cells (produced when they are separated from the full wafer) produces appreciable minority carrier recombination rates. For these long diffusion lengths, approaching 1 mm, this effect can produce a substantial loss in current at the cell edges for the typical cell sizes (1.3 cm^2 for the devices in this study). In order to separate the edge losses from intrinsic device performance, the cell perimeter was optically masked leaving an illuminated area of 0.54 cm^2 . The current density and energy-conversion efficiency are determined for this area. Thus the results which follow may be considered "laboratory" performance. On the other hand, the illumination pattern on the cell is quite similar to that expected in a point focus concentrator system, wherein a dark band is desired around the cell periphery to prevent light loss. These results thus represent efficiencies obtainable in a likely application for the IBC cell.

Figure 2. An S.E.M. picture of the contacts which have been plated to a thickness of ~ 15 μm with a separation of ~ 20 μm . The positive contacts are wider than the negative contacts. This picture was taken at a magnification of 300X.

As shown in Figure 3, the efficiency of a cell with the old grid design and with edges masked peaks at 18.1 percent at 30 suns. The efficiency equals ~ 14 percent at 1 sun and increases rapidly to the peak at 30 suns. Since the cell is masked to ~ 50 percent of its active area, the average concentration which affects V_{OC} is a factor of two below the value of concentration on Figure 3. Thus the efficiency at low concentrations will be most greatly reduced by this reduced V_{OC} . As the concentration increases, the effect of the reduced concentration on the

V_{oc} is smaller. The efficiency above 30 suns decreases with increasing concentration due to a reduction of FF with increased concentration, as seen in Figure 3. Since low series resistance was expected in this type of cell, this decrease of fill factor is probably the result of a geometrical problem in the cell design or high resistance in the metal contacts. This cell had a spacing of $\sim 75 \mu\text{m}$ between fingers, and the widths of the p^+ and n^+ diffusions were approximately 300 and 200 μm , respectively. With these large dimensions, current crowding at the back contacts or some other high-current density effect may cause this high series resistance and reduction of FF with increasing insolation.

Figure 3. The efficiency and fill factor of an IBC cell (1.28 cm^2 active area with a 0.54 cm^2 illuminated area) plotted versus concentration at 27°C . The edges of the cell were masked for this measurement to reduce edge effects, and thus the illumination pattern is quite similar to that expected in a point focus concentrator system.

To overcome this problem, the width and spacing of the fingers was reduced by a factor of 2.5, and new cells were fabricated. The dark current-voltage characteristics of a new cell with the grid spacing (curve b) and a cell with the previous design (curve a) are shown in Figure 4. In the voltage range of 0.5-0.7 V, the current of both cells increases with an effective diode factor of ~ 1.3 , but above $\sim 1 \text{ amp}$ (or $\sim 30 \text{ suns}$), the current of the cell with the old grid design deviates from this line. On the other hand, the current-voltage characteristics of the cell with the new grid structure does not exhibit this series resistance deviation until a current of $\sim 10 \text{ amps}$ (or $\sim 300 \text{ suns}$). Thus the series resistance of the new grid structure is much lower than that of the old grid structure. Although this would suggest that the FF of the cells with the new grid design should remain high to much higher insolation, the current flows in the illuminated cell may be very different from those in the dark current-voltage characteristics due to the three dimensionality of this cell structure and could still produce a low fill factor.

Figure 4. The dark current-voltage characteristics of (a) a cell with the old grid design and (b) a cell with the new grid design. The total cell area was 1.28 cm^2 .

CURRENT COLLECTION AND QUANTITY EFFICIENCY

The better cells had J_{sc} values of 34 mA/cm^2 (with the cell masked and an illumination level of 100 mW/cm^2 , AM1 spectra) compared to a maximum calculated value of 42.5 mA/cm^2 . After accounting for reflection losses ($\sim 12 \text{ percent}$), the overall current collection efficiency equals 90 percent. This indicates that the cell has a long minority carrier lifetime.

The normalized quantum efficiency, QE, at short wavelengths (Figure 5) also support this conclusion. At a wavelength of 600 nm, the absorption depth is less than $2.0 \mu\text{m}$. The generated carriers must diffuse the wafer thickness of 300 μm , and yet when compared with the total current collection data, the QE is about 90 percent or greater; a result possible only with diffusion lengths on the order of 1 mm.

To estimate the values for the minority carrier lifetime and surface recombination velocities from the QE, the transport equations were analytically solved in one dimension. In this solution of the transport equation, the concentration of minority carriers at the back surface was assumed to be zero. A plot of normalized QE (at 600 nm) as a function of τ is shown for different values of surface recombination velocity in Figure 6. Since the QE of the cell at 600 nm is greater than 0.9, the minority carrier lifetime is greater than 350 μsec and the surface recombination velocity is less than $\sim 30 \text{ cm/sec}$, as shown in Figure 6. This

lifetime corresponds to a diffusion length of about 700 μm , more than twice the cell thickness. These values are in agreement with lifetimes obtained on the better BSF cells processed in a similar manner and from the same base material (6). It must be noted, considerable care in processing is necessary to obtain these long minority carrier lifetimes. Furthermore, the sensitivity of minority carrier lifetime to processing and unknown parameters may present problems in obtaining high processing yields.

Figure 5. The normalized quantum efficiency versus wavelength of an IBC solar cell.

Figure 6. The calculated internal quantum efficiency of an IBC cell with 600 nm light as a function of minority carrier lifetime for surface recombination velocities of (a) 1 cm/sec, (b) 10 cm/sec, (c) 50 cm/sec, and (d) 100 cm/sec.

These results show that the first two conditions for high-current collection (i.e., long τ and low front-surface recombination velocities) in this structure are met. Furthermore, the passivation of the back surface is also critical to the cell current collection. Cells fabricated

without the thermal oxide on the back surface were found to have current collection reduced by ~15 percent from that of cells with a thermal oxide.

SUMMARY

In summary, a laboratory version of an IBC cell has been fabricated which exhibits 90 percent internal-collection efficiency and a maximum energy conversion efficiency above 18 percent at 30 suns on cells with the old grid structure. Furthermore, cells have been fabricated with the new grid structure which have high-current collection and apparently reduced series resistance. Due to the reduced series resistance, this new geometry cell should maintain high FF to high concentration.

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