

The Interdigitated Back Contact Solar Cell: A Silicon Solar Cell for Use in Concentrated Sunlight

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Abstract—The theoretical and experimental performance of an interdigitated back contact solar cell is described. This type of cell is shown to have significant advantages over a conventional solar cell design when used at high concentration levels, namely, reduced internal series resistance, nonsaturating open-circuit voltage, and an absence of shadowing by front surface contacting fingers. The results of a computer study are presented showing the effects of bulk lifetime, surface recombination velocity, device thickness, contact dimensions, and illumination intensity on the conversion efficiency and general device operation. Experimental results are presented for solar illumination intensities up to 28 W/cm^2 .

I. INTRODUCTION

AT PRESENT, the cost per unit area of solar concentrators is less than that of solar cells; consequently, a net reduction in the total cost of a solar energy conversion system may be attained using concentrators. However, the use of conventional silicon solar cells with concentrators has been seriously limited by the low efficiencies obtained at high illumination intensities.

Efforts to improve the conventional silicon solar cell's efficiency at high intensities have been directed toward reducing the device's internal series resistance, which is mainly caused by the high resistivity of the thin front surface diffused layer. The series resistance can be lowered by the addition of a metal grid pattern using narrow, closely spaced metal fingers [1] or by a criss-cross pattern of metal lines [2]. In such cells the grid pattern can block a significant portion of the light.

The open-circuit voltage V_{oc} saturates at high intensities when injection conditions are reached in the side of the junction containing the lower impurity concentration [3], [4]. The V_{oc} saturation can be prevented by using a low resistivity base material, but the accompanying lower carrier diffusion lengths in the base region would result in lowered collection efficiencies.

An alternate cell for use at high intensities is the interdigitated back contact solar cell (IBC), whose structure is shown in Fig. 1. In this device the hole-electron pairs are generated in a high-lifetime bulk region and are collected at interdigitated diffused junctions on the back side of the cell. Since the IBC solar cell can have heavily doped

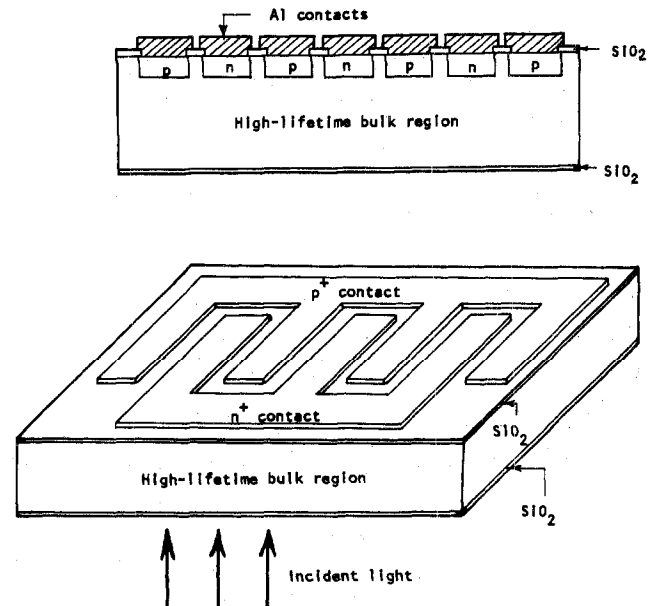


Fig. 1. An interdigitated back contact solar cell and cross section.

junctions, high intensity saturation effects in the open-circuit voltage will be minimized until V_{oc} becomes comparable to the bandgap potential. With both the p^+ and n^+ junctions on the back side of the device, there is no metallization pattern on the front surface to shadow the incident photon flux. Also, since nearly one half of the back surface is covered with the metallization pattern of each type of junction, the series resistance of the metal pattern can be reduced to a few milliohms through an appropriate choice of thickness. Furthermore, there is no lateral current flow through a thin diffused layer which might contribute to the device's internal series resistance as in the conventional solar cell. The current flow in the diffused layers of the IBC cell is perpendicular to the thin dimension. The internal series resistance in the IBC solar cell is directly proportional to the excess carrier concentration; and therefore, the internal series resistance is inversely proportional to the incident intensity. With negligible metallization resistance, no series resistance degradation will be seen in the device's curve factor since the series resistance decreases as fast as the short-circuit current rises.

This paper discusses the results of a computer study of the IBC solar cell considering the effects of bulk lifetime, surface recombination velocity, device thickness, and incident intensity. Experimental results are presented of device performance as a function of illumination intensity.

Manuscript received September 20, 1976; revised November 30, 1976. This work was supported by NSF-MRL Program DMR 72 03018A03.

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Finally, an estimate is made of the device efficiency that can be achieved with the improvements of lowered metallization resistance, lowered reflectance, better heat sinking, more heavily doped junctions, and improved bulk lifetime.

II. THEORY

The IBC cell was analyzed with the aid of a computer program originally developed by Gardner for the analysis of a germanium p-i-n cell [5]. The effects of bulk lifetime, front and back surface recombination velocities, cell thickness, finger width and spacing, background doping in the bulk region, and incident intensity were studied with this program.

Although the details of the two-dimensional boundary value problem solved by the computer program will not be discussed in this paper, the assumptions made in the formulation of the boundary-value problem will be presented for a better understanding of the results. The following assumptions were made in simplifying the boundary-value problem:

- 1) Electrons and holes in the conduction and valence bands obey Maxwell-Boltzmann statistics.
- 2) Diffusion coefficients (mobilities) are constants.
- 3) Space-charge quasi-neutrality holds in the bulk region.
- 4) The n and p junctions are modeled as ideal junctions at all illumination intensities.
- 5) The bulk hole-electron generation data used in the computer program are that of a 5630.7 K blackbody spectrum, which has the best blackbody spectral match to an Air Mass 0 spectrum [6].
- 6) Fringe effects at the outer edges and ends of the device fingers are ignored.
- 7) No incident photons are reflected.
- 8) There is negligible resistance in the metallization pattern.

With the assumptions of ideal junctions, zero reflectance, no metallization resistance, and no fringe effects, the computer calculations should be taken as being close to the optimum device performance. However, by using heavily doped junctions, a good antireflecting coating, and thick metallization on a large area device on which fringe effects are small, the actual device performance should be close to that predicted by the calculations.

In the theoretical cell performance calculations the following device parameters were used except where explicitly noted:

- 1) device thickness—100 μm
- 2) n-type finger width—75 μm
- 3) p-type finger width—125 μm
- 4) spacing between fingers—25 μm
- 5) front and back surface recombination velocity—10 cm/s
- 6) bulk lifetime—10, 20, 100, or 1000 μs
- 7) incident intensity—10 W/cm².

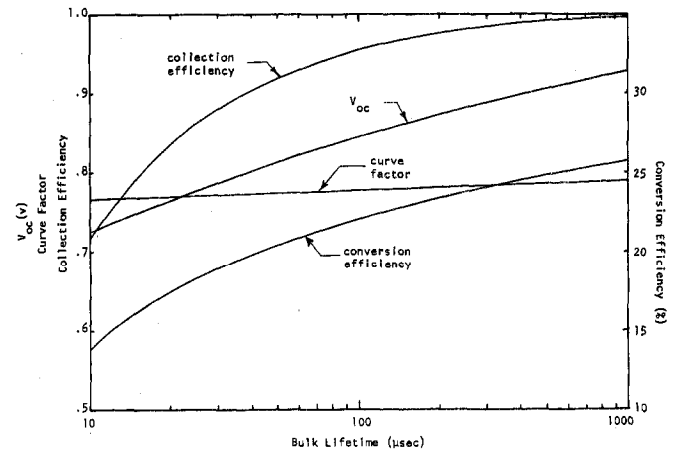


Fig. 2. Calculated open-circuit voltage, curve factor, collection efficiency, and conversion efficiency as a function of bulk lifetime at an intensity of 10 W/cm².

A. Effect of Device Finger Width and p:n Finger Width Ratio

The n and p finger widths were varied keeping the finger width ratio constant. The device efficiency was found to be relatively insensitive to finger width for all bulk lifetimes, between 10 and 1000 μs , for finger widths up to 250 μm . When the finger width ratio was varied, keeping the wider finger widths at 125 μm , the device collection efficiency was found to be the greatest when the p finger width was about 2.5 times as great as the n finger width. Varying the finger width ratio had the greatest effect on devices with bulk lifetimes less than 100 μs .

B. Effect of the Bulk Lifetime

Plots of the open-circuit voltage, curve factor, collection efficiency, and conversion efficiency as a function of bulk lifetime are shown in Fig. 2. The most significant result of the curves shown in Fig. 2 is the very rapid increase in the collection efficiency, from 72 to 95 percent as the bulk lifetime increases from 10 to 100 μs . Also, it should be noted that with high bulk lifetimes the IBC solar cell can achieve higher collection efficiencies than the conventional solar cell.

C. Effect of Surface Recombination

In Fig. 3 the effect of front surface recombination on the device efficiency is shown for various bulk lifetimes. From these curves it can be seen that if the surface recombination velocity is below 10 cm/s, which can be attained using surface annealing techniques developed for MOS technology, then the front surface recombination will have little effect on the device performance. Similar calculations on the back surface recombination velocity showed that for back surface recombination velocities below 100 cm/s, there is almost no degradation of device performance.

D. Effect of Device Thickness

The effect of the device thickness on the conversion efficiency is shown in Fig. 4 for various bulk lifetimes. For

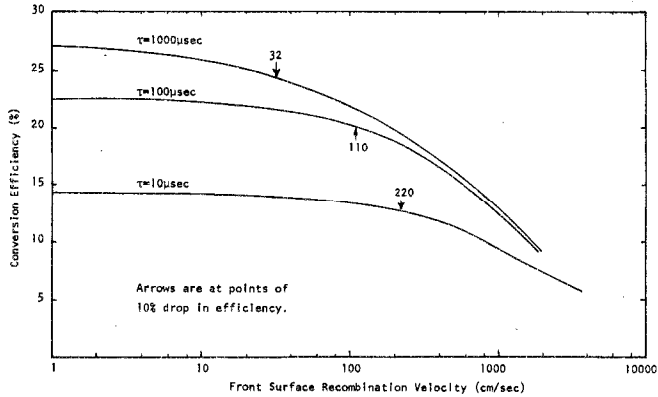


Fig. 3. Calculated conversion efficiency versus front surface recombination velocity for bulk lifetimes of 10, 100, and 1000 μs .

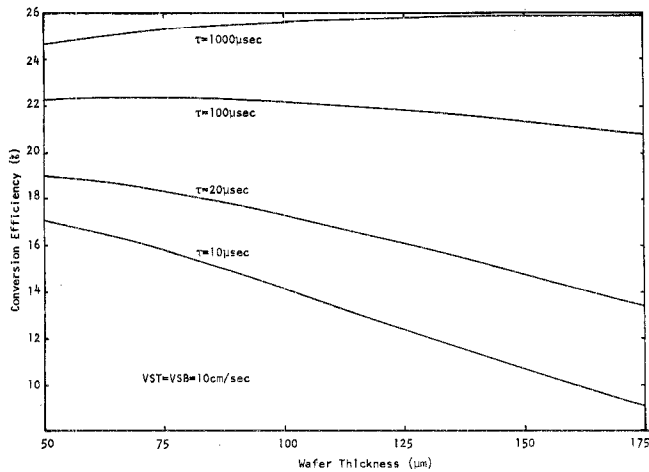


Fig. 4. Calculated conversion efficiency versus wafer thickness for bulk lifetimes of 10, 20, 100, and 1000 μs .

bulk lifetimes greater than 100 μs , the thickness does not have a large effect on the device efficiency over a thickness range of 50 to 175 μm . However, for devices with bulk lifetimes less than 20 μs the efficiency decreases rapidly with increasing thickness as a result of the lower collection efficiency of thicker devices.

E. Effect of Incident Intensity

Plots of the conversion efficiency as a function of intensity, showing the effects of bulk lifetime, surface recombination velocity, and the doping concentration in the bulk region are presented in Fig. 5. Curves #1 and #2 demonstrate the effect of surface recombination velocity as a function of intensity at a bulk lifetime of 1000 μs . For a bulk lifetime of 1000 μs the efficiency at all intensities is about 1.5 percent greater for a recombination velocity of 0 cm/s than for 10 cm/s. For bulk lifetimes of 100 μs and less the efficiency was nearly the same at all intensities for 0 cm/s and 10 cm/s surface recombination velocities.

The effect of the doping level in the bulk region on the device efficiency is shown in curves #3 and #4 of Fig. 5. The higher open-circuit voltages at low intensities for the more highly doped bulk region result in a higher efficiency. However, at high intensities when the excess carrier con-

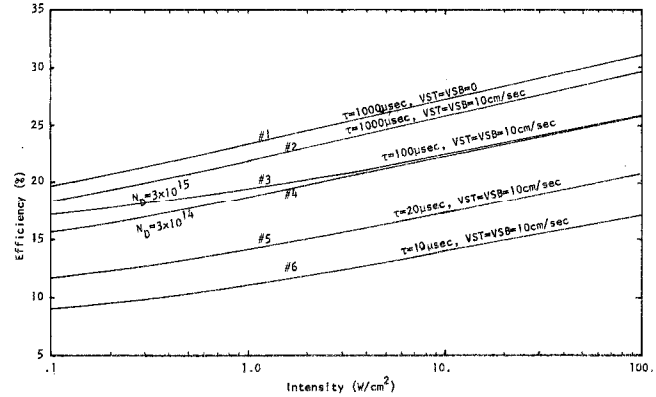


Fig. 5. Calculated efficiency versus intensity curves as a function of bulk lifetime.

centration is larger than the bulk doping concentration, the device efficiency becomes independent of the bulk doping concentration.

III. EXPERIMENTAL WORK

A. Device Fabrication

IBC solar cells were fabricated with phosphorus and boron diffused junctions on 13–25 $\Omega \cdot \text{cm}$ (100) n-type wafers which were Syton polished on both sides. The diffused n^+ finger widths were 72 μm , the p^+ finger widths were 126 μm , and the spacing between the fingers was 18 μm . The overall dimensions of the diffused junctions were 0.40 cm by 0.50 cm, resulting in an active device area of 0.20 cm^2 .

Thermal oxide masks for standard boron and phosphorus diffusions were grown in 1–3-percent HCl in dry O_2 . Prior to the n^+ diffusion the oxide was removed from the front surface for a phosphorus gettering to improve the bulk lifetime. Before the final oxidation, the front surface n^+ layer was removed and the device's thickness was reduced to 100 μm by chemically etching the front surface. The interdigitated back contact metallization pattern was formed by first evaporating 10 μm of aluminum on the back surface from a tungsten filament. A thin (1000-Å) Al film was evaporated onto the front surface, and then the wafer was annealed at 450°C in N_2 to reduce the surface recombination velocity [7]. Finally, the back contact metallization pattern was etched and the front surface aluminum film was removed.

The devices were scribed and broken 100 to 150 μm from the edge of the diffused junctions and then mounted with thermally conducting epoxy on a water cooled Al heat sink. The contact pad areas of the metallization pattern extended over the edge of the heat sink. Copper strips, epoxied to the heat sink, were electrically connected to the metal contact pads of the device with silver epoxy. Gold tipped tungsten wires were also connected to the device contact pads as voltage probes for a 4-point probe I - V curve measurement.

B. Measurement of I - V Curves in Concentrated Sunlight

Sunlight was concentrated with a 16-cm-diameter lens that had a 30-cm focal length. The sunlight was focused into a 0.75-cm-diameter stainless tube, 3.3 cm long, with polished inner walls to slightly defocus the concentrated sunlight and provide a more uniform intensity over the entire device area. The intensity was varied with an iris diaphragm placed between the lens and the stainless steel defocusing tube.

The device's current-voltage characteristics were measured by a 4-point probe arrangement with the device's voltage probes connected to the horizontal input of a differential input oscilloscope. The voltage across a small 1-percent resistor in series with the device was applied to the vertical input of the scope. The device voltage was increased until the short-circuit current was reached; then the I - V curves were photographed from the scope waveform.

C. Determination of the Concentrated Sunlight Intensity

To calculate the device's conversion efficiency, the incident illumination intensity had to be calculated. A standard method of determining the intensity of concentrated sunlight is to assume that the cell's short-circuit current increases directly with intensity, that is, the collection efficiency is independent of intensity. In that case the concentrated sunlight intensity is the ratio of the high intensity short-circuit current to the one-sun short-circuit current, times the one-sun measured intensity. This method was used to determine the concentrated sunlight intensity, with the exception that measurements were taken to determine the dependence of the collection efficiency on the intensity using a calibration high-intensity Eppley lamp as a source. Measurements indicated that the normalized collection efficiency, i.e., the short-circuit current to intensity ratio, improved by about 20 percent as the device output current increased from about 0.5 to 30 mA. Above a device short-circuit current of 20 mA, the collection efficiency remained constant within experimental error. A correction for the improving device collection efficiency was included in the calculation of the concentrated sunlight intensity. However, since the collection efficiency only improved by approximately 8 percent as the sunlight intensity increased from one-sun to about 7 suns (thereafter remaining constant), the correction for the collection efficiency had only minor influence on the concentrated sunlight calculation.

The one-sun intensity was measured with an Eppley Normal Incidence Pyrheliometer, which had a 10:1 length to diameter collimating tube. As a consequence only sunlight within $2^\circ 52'$ of normal incidence is measured by the NIP. A stainless steel tube with inner walls blackened with carbon black that had a similar 10:1 length to diameter ratio was placed in front of the IBC cell during the one-sun calibration to insure that the field of view of the cell was the same as that of the NIP.

Four-point probe I - V curves were then measured to determine the one-sun short-circuit current. Knowing the one-sun short-circuit current, the one-sun intensity, and the collection efficiency correction factor, the intensity of

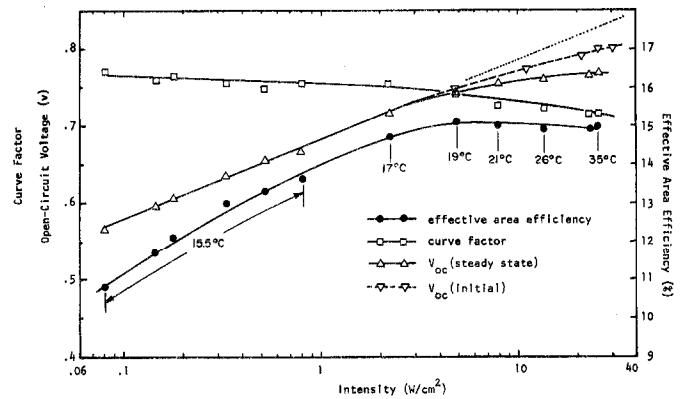


Fig. 6. Curve factor, open-circuit voltage, and effective area efficiency of device #14-4H as a function of intensity with concentrated sunlight as the source. The cell temperature is indicated for each data point. The thermal resistance of the cell mounted on the heat sink is $0.75^\circ\text{C} \cdot \text{cm}^2/\text{W}$. The cooling fluid temperature is 15.5°C .

the concentrated sunlight could be calculated as

Intensity (conc.)

$$= \frac{I_{sc}(\text{conc.})}{I_{sc}(\text{one-sun})} \times \Gamma \times \text{Intensity (one-sun)}$$

where Γ is the ratio of collection efficiency at one-sun to collection efficiency at the concentrated intensity.

The device I - V curves were measured over a range of intensities from $80 \text{ mW}/\text{cm}^2$ to $28 \text{ W}/\text{cm}^2$ at an approximate air mass number of 1.3. From I_{sc} on the photographs of the I - V curves, the intensity of the concentrated sunlight was calculated using the above equation, and the maximum power point was found.

D. Calculation of Device Efficiency

Although the active device area, as defined by the diffused junction area, is 0.2 cm^2 , the effective device area is somewhat greater since some of the hole-electron pairs generated in the perimeter region of the device will be collected at the junctions. A hole-electron pair generated in the perimeter region 1) may be collected at the p^+ and n^+ junctions, 2) may be lost via surface recombination at the scribed and broken edge, or 3) may be lost via bulk recombination in the perimeter region. Assuming that mechanism 3) is small and that the probabilities of mechanisms 1) and 2) are nearly equal, an effective device area can be defined as the active device area plus $\frac{1}{2}$ of the perimeter area.

The effective device area, which was 6 percent greater than the actual diffused junction area, was used in determining the device efficiency. Plots of the effective area of efficiency, the open-circuit voltage, and the curve factor as a function of intensity are shown in Fig. 6.

E. Experimental Results

The device efficiency was found to increase from 11 percent at a one-sun intensity ($80 \text{ mW}/\text{cm}^2$) to 15 percent at an intensity of $5 \text{ W}/\text{cm}^2$, thereafter remaining nearly constant at 15 percent up to $28 \text{ W}/\text{cm}^2$. The failure of the efficiency to continue to increase with intensity, as pre-

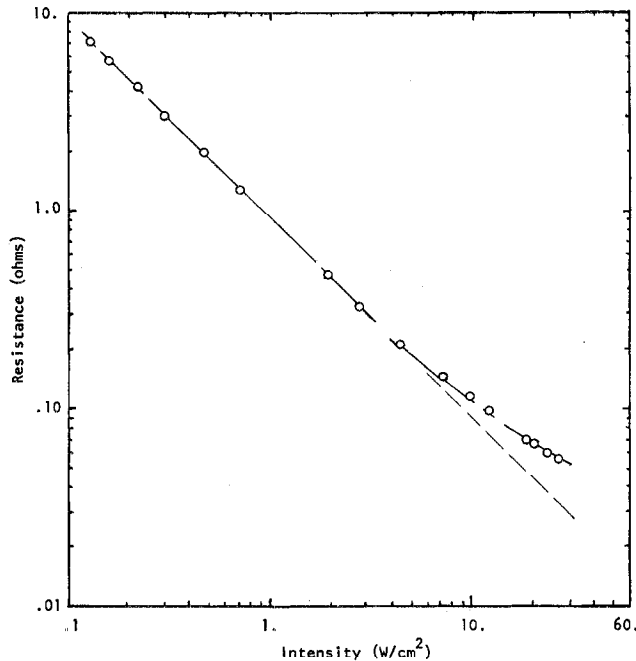


Fig. 7. Measured internal series resistance of an IBC cell as a function of intensity.

dicted by the theoretical calculations shown in Fig. 5, was the result of the curve factor decreasing and the slope of the V_{oc} curve decreasing at intensities above 5 W/cm^2 .

Further experiments were carried out to determine the cause of the decreasing curve factor and the decreasing slope of the open-circuit voltage curve. The initial open-circuit voltage was measured by photographing the I - V curve as the shutter in front of the device was opened to see if the decrease in the slope of the V_{oc} curve was due to thermal degradation. From the results of these measurements, shown in Fig. 6 as V_{oc} (initial), it is apparent that nearly one-half of the degradation in the open-circuit voltage at high intensities is caused by increased device temperature. The remaining high intensity V_{oc} degradation is possibly caused by the excess carrier concentration approaching the doping level in the junctions.

The cell temperature rise at high illumination intensities corresponds to a thermal resistance of $0.75^\circ\text{C} \cdot \text{cm}^2/\text{W}$. Cell temperature for each data point is indicated on Fig. 6.

The decrease in the curve factor with increasing intensity was found to be caused by the series resistance in the metallization pattern. Measurements were taken of the device's series resistance, determined from the initial slope of the I - V curve near the open-circuit voltage, as a function of intensity. The series resistance versus intensity plot is given in Fig. 7. At low intensities the series resistance decreases directly with intensity, but above 5 W/cm^2 it decreases somewhat slower. This series resistance versus intensity curve can be explained by assuming the device's series resistance is the sum of an internal resistance that decreases directly with intensity and a fixed resistance of approximately $25 \text{ m}\Omega$ in the metallization contact pattern. The fixed resistance of only $25 \text{ m}\Omega$ in the metallization pattern is sufficient to account for the decreasing curve factor at high intensities.

IV. DISCUSSION

Although the 15-percent high-intensity efficiency obtained with this device is considerably greater than that reported for other silicon solar cells at very high sunlight concentrations, the IBC cell has the potential of achieving even higher efficiencies by utilizing: 1) better heat-sink design, 2) more heavily doped junctions, 3) reduced reflectance, 4) lower metallization resistance, and 5) improved bulk lifetime.

As can be seen from Fig. 6, there is a significant degradation in the open-circuit voltage at high intensities from device heating. However, measurements have shown that a significant portion of the temperature rise above the cooling water temperature occurs at the water-heat sink interface. Therefore, the device heating problem is one that can be solved by redesigning the heat sink for better heat transfer from the heat sink to the water. By keeping the device temperature within 5°C of the cooling water, the open-circuit voltage and the efficiency at 300 suns can be improved by a factor of 1.04.

Also, if the junctions are more heavily doped, perhaps by using ion implanted junctions, the high intensity open-circuit voltage degradation can possibly be eliminated. This would result in another improvement in the efficiency by a factor of 1.04.

The effect of the metallization resistance reducing the curve factor at high intensities can be nearly eliminated by increasing the metal thickness. The IBC cell, for which the experimental results are shown in Fig. 6, was originally designed for use at 50 to 100 suns and therefore did not have the metal pattern built up before it was epoxied to the heat sink. By plating up the metal contacts, the metal series resistance could be reduced to the order of $1 \text{ m}\Omega$, which would improve the device efficiency at 300 suns by a factor of 1.08.

One of the largest improvements yet to be made in the IBC cell is to reduce the device reflectance. With only a quarter wavelength SiO_2 film on the illuminated surface, the present device had a measured weighted-average reflectance of about 18 percent. However, techniques presently used on other solar cells, which can reduce the reflectance to about 3 percent, are applicable to the IBC solar cell. In particular, the use of a preferential etch to form a texturized nonreflecting surface would be compatible with the present device processing. Reducing the weighted-average reflectance to 3 percent would improve the efficiency by a factor of 1.15.

With the above improvements of better heat sinking, more heavily doped junctions, thicker metallization, and lowered reflectance the device conversion efficiency would be increased to 20 percent at 300 suns. One other area for improvement in the IBC solar cell is in the bulk lifetime, although the magnitude of the improvement is somewhat uncertain. The present excess carrier lifetime is estimated to be $50 \mu\text{s}$, based on comparisons of actual device performance to computer results shown in Figs. 2-5. If the excess carrier lifetime could be increased to $300 \mu\text{s}$, perhaps by using higher quality silicon wafers and cleaner processing,

then the device efficiency would improve by about 20 percent. Therefore, with the additional improvement of bulk lifetime a conversion efficiency of 24 percent could be attained at an intensity of 300 suns.

Independently of how one assesses the possibility of improving the various factors described above, the IBC cell has already demonstrated a means of eliminating the primary limiting factor, series resistance, in the use of conventional solar cells at high concentration ratios.

ACKNOWLEDGMENT

The authors would also like to acknowledge the many helpful discussions with Dr. Emil Kittl of ECOM during the early stages of this work.

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A First Order Theory of the p^+-n-n^+ Edge-Illuminated Silicon Solar Cell at Very High Injection Levels

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Abstract—A first order theory of the edge-illuminated p^+-n-n^+ silicon solar cell under very high injection levels has been derived. The very high injection level illuminated J - V characteristic is derived for any general base width to diffusion length (W/L) ratio and it includes the minority carrier reflection by the $n-n^+$ high-low junction. The beneficial effects of the high-low junction are shown to be significant until extremely high injection levels are reached. The theoretical dependencies of J_{sc} and V_{oc} on temperature, incident intensity, and base resistivity are derived and discussed in detail. Some experimental results are given and these are discussed in relation to the theory.

I. INTRODUCTION

THE BEHAVIOR of solar cells under rather high levels of illumination is of both scientific and economic interest. From the scientific point of view, it is of interest to study the behaviors of both the internal physical processes and the external performance parameters as functions of the illumination level as it takes on very large values. In this regard, several papers have ap-

peared in recent years on the saturation of the open-circuit photovoltage at extremely high light intensities [6], [7], [17]–[19]. From the economic standpoint, the development of a high-efficiency solar cell operating under highly concentrated sunlight is of interest due to its application in low-cost terrestrial photovoltaic systems.

One of the solar cell structures being investigated for the purpose of high intensity operation is the edge-illuminated multijunction silicon solar cell [11], [14], [15]. In this structure, several p^+-n-n^+ (or n^+-p-p^+) unit cells are bonded together in series and illuminated edge-wise. The illuminated surface is perpendicular to the planes of the p^+-n and $n-n^+$ junctions. The light-generated carrier concentrations vary with depth from the illuminated surface due to both the photon absorption varying with depth and because of surface recombination at the illuminated and lower surfaces. Under a uniform surface illumination, although the carrier generation rate does not vary with distance from the p^+-n junction, the boundary conditions at the p^+-n and the $n-n^+$ junctions cause charge carriers to flow in a direction normal to the p^+-n junction, thus resulting in a photocurrent through the solar cell.

It is seen from the above discussion that the magnitude of the photocurrent in an edge-illuminated solar cell will vary with depth from the illuminated surface. Hence, the

Manuscript received September 20, 1976; revised November 23, 1976.

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