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# Voltage Controlling Mechanisms in Low Resistivity Silicon Solor Cells – A Unified Approach

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# VOLTAGE CONTROLLING MECHANISMS IN LOW RESISTIVITY SILICON SOLAR CELLS - A UNIFIED APPROACH

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## SUMMARY

An experimental technique capable of resolving the dark saturation current into its base and emitter components is used as the basis of an analysis in which the voltage limiting mechanisms were determined for a variety of high voltage, low resistivity silicon solar cells. The cells studied include the University of Florida hi-low emitter cell, the NASA and the COMSAT multi-step diffused cells, the Spire Corporation ion-implanted emitter cell, and the University of New South Wales MINMIS and MINP cells. The results proved to be, in general, at variance with prior expectations. Most surprising was the finding that the MINP and the MINMIS voltage improvements are due, to a considerable extent, to a previously unrecognized optimization of the base component of the saturation current. This result is substantiated by an independent analysis of the material used to fabricate these devices.

## INTRODUCTION

Low resistivity silicon solar cells hold out the promise of high open-circuit voltage. Although initial attempts to realize theoretically predicted values were not successful, more recent efforts involving diverse and unconventional approaches have yielded devices that appear to be approaching these goals. The voltage capability of the low resistivity cell has risen incrementally from the 600 mV range of 10 years ago to the mid 680 mV range with the recent development of the MINP cell.

Because each voltage improvement step has been made on an essentially unique device, it has been difficult to pinpoint the actual mechanisms involved. Indeed it requires a significant effort even to determine, with any certainty, whether a given voltage increase is due to improvements in the base or the emitter, or both. This information is critical, however, because if further advances are to be made, we must know to which region of the cell we must direct our attention.

While there are several attempts in the literature to determine the relative influence of the base and the emitter in low resistivity cells, they are, for the most part, based on questionable assumptions of idealized behavior (ref. 1). There is one technique, however, that provides an experimental and essentially assumption-free determination of the relative magnitudes of the base ($I_{ob}$) and emitter ($I_{oe}$) components of the dark saturation current ($I_o$) (ref. 2). It has been determined that one can, from a knowledge of the variation of $V_{oc}$ and diffusion length with 1 MeV electron fluence, separate $I_o$ into its base and emitter components.

The purpose of this paper is to present the results of our efforts to use this technique to determine in a consistent manner the magnitudes of $I_{ob}$ and $I_{oe}$ for the various types of low resistivity ($\rho \leq 0.1$ ohm cm) silicon solar cells that have been developed over the past decade in the quest for increased voltage.

## CELL DESCRIPTION

The following is a brief description of the five types of cells included in these investigations. As will be seen, each one is of unconventional design. As an aid to comparing their relative voltage capabilities, they are listed in table I in order of increasing voltage (decreasing $I_o$). For a more detailed discussion, the reader is referred to the cited references.

### Diffused Emitter Cells

The diffused cells used in this analysis were fabricated using the multistep diffusion (MSD) schedule developed at NASA Lewis (ref. 2) and exploited further by the COMSAT Corporation (ref. 3). The MSD schedule consists of a deep initial diffusion followed by chemical removal of the emitter surface. The emitter etching step is, in turn, followed by a shallow second diffusion. The primary difference between the NASA and the COMSAT MSD cells is in their final junction depths. The COMSAT cells, being more heavily etched between diffusions, have considerably shallower junctions ($X_j < 0.2$ μm).

### Ion-Implanted Emitter Cells (ref. 4)

These cells, fabricated by the Spire Corporation, were made by (1) forming the junction via phosphorus ion-implantation, (2) annealing the implant damage using an appropriate heat treatment, (3) growing a thick thermal oxide on the emitter surface, followed by (4) chemical thinning of the oxide to improve its anti-reflection properties.

### Hi-Lo Emitter (HLE) Cells (ref. 5)

This cell was developed by the University of Florida. Thick (5 to 10 μm) emitters were epitaxially deposited on both 0.1 and 0.025 ohm-cm substrate material. After epitaxy, an attempt was made to induce an accumulation layer or hi-low junction on the surface of the emitter via a charged, thermally grown oxide.

### MINMIS Cells (ref. 6)

Developed by the University of New South Wales (UNSW), these cells were prepared by growing a thin (<16 A) oxide layer on the substrate surface which was followed by the deposition of a fine, low work function metal grid.

## MINP Cells (ref. 7)

These cells, also developed by the UNSW, are a result of incorporating MINMIS technology into the diffused cell. After a shallow phosphorus diffusion ($X_j < 0.2$ μm), the MINP structure is completed by depositing the MINMIS oxide and low work function metallization on the emitter surface.

## $I_o$ SEPARATION TECHNIQUE

The technique used here to resolve $I_o$ into its base and emitter components has two major advantages over other attempts to do so: (1) It is based on direct experimental evidence, and (2) It involves only a few easily verifiable assumptions. The method assumes, for example, that in the voltage region near $V_{oc}$ the saturation current component originating in the depletion region is negligibly small. The fact that the cells studied here all display ideal diode characteristics in the vicinity of $V_{oc}$ indicates that this condition is indeed fulfilled.

The relative degree of control exercised by the remaining two components can be determined by considering the effect of 1 MeV electron irradiation. It is well known that when a silicon solar cell is irradiated, its red response drops rapidly due to a reduction in the base diffusion length. The blue response, on the other hand, which is a measure of the emitter diffusion length, is usually not appreciably affected, at least for low to moderate fluences. Because of this invariance in the blue response, we can consider $I_{oe}$ to be a constant, independent of fluence. This fact can be used to determine the relative magnitudes of $I_{oe}$ and $I_{ob}$ as follows:

The cells of interest are irradiated in steps to fluences of $1 \times 10^{13}$, $3 \times 10^{13}$, $1 \times 10^{14}$, $3 \times 10^{14}$, and $1 \times 10^{15}$ 1 MeV electrons/cm$^2$. At each fluence level, the current-voltage (I-V) characteristic, the spectral response, and the base diffusion length are measured (ref. 8). The value of $I_o$ determined from the equation

$$V_{oc} = \frac{kT}{q} \ln \frac{I_{sc}}{I_o} ,$$

is then plotted against the measured value of diffusion length for all fluence levels up to that at which the blue response begins to degrade. The expression $I_o = I_{oe} + I_{ob}$, which can be written as

$$I_o = I_{oe} + \frac{A}{L} \frac{S + \tanh d/L}{1 + S \tanh d/L} \qquad (1)$$

where $A = qn_i^2 D/N_A$, is then fitted to the data using $I_{oe}$ and $A$ as adjustable parameters. In the above expressions, L is the base diffusion length, d is the base thickness, $N_A$ is the base doping level, D is the base diffusivity, and S is the normalized surface recombination velocity at the rear of the cell. Once $I_{oe}$ has been determined, it and the known value of $I_o$ can be used to calculate $I_{ob}$.

It should be mentioned at this point that there are two potential sources of error in this analysis, i.e., the diffusion length determination and the determination of S at the rear surface of the cell. The former will be discussed further in a following section. In regard to the latter concern, we have found that the value of S assumed is not very critical. The reason for this is rooted in the fact that the same value of S is assumed both in the determination of L and in the $I_0$ resolution calculations. As it turns out, the equations are such that any errors due to a poor choice for the value of S tend to cancel themselves out. The results have thus been found to be quite insensitive to the assumed value of S.

## RESULTS

### Diffused and Ion-Implanted Cells

The results of applying the $I_0$ resolution technique to a thin (175 μm) NASA MSD cell are shown in table II. As can be seen, the base component was found to be dominant with an $I_{ob}$ of $2.2 \times 10^{-13}$ A/cm$^2$. This value is about 3 times larger than one would calculate using commonly accepted values for the parameters in the expression for $I_{ob}$ (ref. 1). Since the results have been shown to be insensitive to the value assumed for S, the only other source of error that could cause such a large discrepancy is the diffusion length measurement. To test the accuracy of our diffusion length measurement technique, therefore, the following experiment was performed.

A number of cells were fabricated that were identical to the 175 μm cell except that they were about 530 μm thick. The measured values of $V_{oc}$ and $I_0$ for this thick cell are shown in table II. As can be seen, the thick cell produced a $V_{oc}$ of 646 mV, 6 mV more than its thin twin. Using the same values of $I_{oe}$ and A that were determined for the thin cell, as well as the same value of diffusion length (measured the same for both cells), and correcting $I_{ob}$ only for the difference in cell thickness, the expected thick cell voltage was calculated (see table) to be 646 mV, identical to the measured value. This close agreement between theory and experiment indicates that the diffusion length measurement technique used here is indeed valid and accurate.

Having thus eliminated both the diffusion length measurement and the surface recombination velocity determination as sources of error, we can conclude that the $I_{ob}$ value determined above for this cell is indeed several times larger than previously thought. Further evidence supporting this conclusion will be presented in the next section.

Similar conclusions can be drawn for the COMSAT MSD cell. The increased value of $I_{oe}$ in this cell is thought to be due to its relatively shallow junction.

The Spire IIE cell was found to show the greatest deviation from theoretical expectations with an $I_{ob}$ 4 to 5 times that calculated from simple theory.

### HLE Cells

A requirement for the use of the present technique on a given cell is that the cell's blue response be independent of electron fluence. Unfortunately, a plot of HLE spectral response as a function of fluence reveals a severe drop in the short as well as the long wavelength response. These cells, therefore, do not meet the above criterion.

However, even though we could not use the $I_o$ separation technique on these cells, we were able to get a rough idea of the $I_o$ split by analyzing I-V and diffusion length data taken on HLE cells with different base resistivities. Using the measured diffusion length and $I_o$ data given in table II for 0.1 and 0.025 ohm-cm HLE cells, one can set up a pair of simultaneous equations, analogous to equation (1), with $I_{oe}$ and a modified A value (both assumed invariant with resistivity) as adjustable parameters. Solution of the equations, using literature values for the ratios of the diffusivity and the doping concentration at the two resistivity levels, (refs. 9 to 11) yielded the values of $I_{oe}$ and $I_{ob}$ given in the table.

As can bee seen, the voltage in the 0.1 ohm-cm device is base controlled, as it is in the diffused emitter cells. The fact that the HLE emitter component is of the same magnitude as that found in the diffused cells indicates that the hi-low emitter has no advantage over the diffused emitter.

It is interesting to note the low value of $I_{ob}$ in the 0.025 ohm-cm cell in spite of the fact that it has an extremely low (30 μm) diffusion length. This is due to the combined effects of the increased doping level and the attendant lowered mobility that more than compensate for the very low L value.

## UNSW MINMIS Cells

Unfortunately, when we subjected the MINMIS cell to 1 MeV electron irradiation, its ideal diode characteristics ($n = 1$) were instantly destroyed, (ref. 12) thus precluding analysis by the present technique. We therefore tried an alternative approach, similar to that used in the HLE cell analysis, which makes use of published I-V and diffusion length data taken on cells with various base resistivities.

The data selected for analysis were taken at the UNSW on 0.5 and 0.1 ohm-cm float-zone MINMIS cells (ref. 6). Before the data could be used it had to be corrected for temperature (from 28° to 25° C) and adjusted to reflect total area output. Grid coverage was assumed to be 25 percent and the temperature coefficient to be 2 mV/°C. Published diffusion lengths of 200 and 300 μm were used for the 0.1 and the 0.5 ohm-cm cells, respectively. After determining $I_o$ from the I-V characteristics, we performed essentially the same calculations used in the preceeding section to determine $I_{oe}$ and $I_{ob}$. The results are given in table III.

Although this cell has been reported as having a highly optimized emitter, the present analysis indicates that its $I_{oe}$ is inferior to that found in diffused cells. The base component, on the other hand, was found to be considerably better (by a factor of 3) than the $I_{ob}$ values found in the other cells. It is apparently, therefore, not the emitter but an unrecognized improvement in the base that is responsible for high voltage in the MINMIS cell.

The numerous assumptions involved in this type of calculation where the behavior of two different cells are compared add a degree of uncertainty to the results. However, the fact that the same low value of $I_{ob}$ was found for the MINP cell (fabricated at the same laboratory) using the more rigorous electron irradiation technique, greatly increases confidence in the results.

## UNSW MINP Cells

Table III shows the results of subjecting a fairly good MINP cell (cell A) to the $I_o$ resolution technique. As can be seen, $I_{oe}$ has been reduced to very small value and $I_{ob}$, while low, is not as low as that determined for the MINMIS cell. Also listed in table III are the voltage increases ($\Delta V+$) produced by depositing positive charge on the emitter surface by means of an electrostatic gun (ref. 13). It is obvious that a voltage increase brought about in this manner can only be attributed to a decrease in $I_{oe}$. A decrease of about $0.26 \times 10^{-13}$ A/cm$^2$ is calculated for the 6 mV charge induced voltage increase in cell A. It can thus be concluded that the effect of surface charge on this cell is to reduce $I_{oe}$ to negligible values.

Cell B in table III can be seen to have a higher voltage than cell A but almost the same $\Delta V+$. Using the above reasoning, the 5 mV $\Delta V+$ increase corresponds to an initial $I_{oe}$ of $0.19 \times 10^{-13}$ A/cm$^2$. The corresponding base component is then calculated to be $0.86 \times 10^{-13}$ A/cm$^2$ which is close to that found for the MINMIS cell and considerably lower than that in cell A. The lower voltage in cell A, therefore, appears to be due to a slightly degraded base.

Cells C and D in the table are very high voltage MINP cells. In contrast to cells A and B, these cells do not respond to the charging action of the electrostatic gun, indicating that the emitter components have been optimized to very low (essentially zero) values. The projected $I_{ob}$ value can be seen to agree quite well with those from cell B and the MINMIS cell. Thus the MINP cell has, as well as a highly optimized emitter, a base component that is several times smaller than those found in equivalent MSD, HLE, or IIE cells.

## DISCUSSION

The preceding analysis has suggested the existence of some hitherto unrecognized base improvements in the MINP/MINMIS cells relative to the other 0.1 ohm-cm cells. If we compare, for instance, the 175 μm MSD cell in table II with MINP cell C in table III we find that, after taking into account differences in cell thickness, diffusion length, and rear surface recombination velocity, the base saturation currents still differ by a factor of two. Having discounted the effects of $d$, $L$, and $S$, we turned our attention to the possibility of differences in the acceptor concentration or the minority carrier mobility, $\mu_e$.

Acceptor level differences were ruled out when the results of a CV analysis indicated a close correspondence between the doping levels in the two materials. Measurements of $\mu_e$, on the other hand, revealed that the electron mobility in the MSD material was considerably larger than one would have expected (ref. 14). The results, obtained via an AC phase shift technique, are shown in table IV. As can be seen the measured 680 $cm^2/V$ sec is almost twice that cited in the literature for 0.1 ohm-cm silicon. We are thus able to explain the high $I_{ob}$ values found in the NASA MSD cell (and presumably all the other cells in table II) as being due to an unexpectedly high minority carrier mobility.

Since no apparent special treatment was given to the base of the (UNSW) MINP/MINMIS cells, we can conclude that either the UNSW group succeeded in obtaining starting material that was substantially better than that used by other investigators in the field, or that the latter group all used cell fabrication procedures that resulted in an increase in $\mu_e$.

The suprising finding that, for a given acceptor concentration, the minority carrier mobility can vary over a considerable range leads to some interesting conclusions. For example, while mobility is generally believed to be a function of acceptor concentration only, these results suggest that it is not. They suggest that an additional scattering site has been introduced that is independent of doping level. It is thus tempting to speculate that, once this site is identified, one could possibly tailor mobility levels to suit one's need. In the case of the base controlled MINP cell, even higher voltages would result from a further reduction in $\mu_e$.

Mobility variations aside, it is interesting to explore the voltages potentially achievable if the MINP surface passivation techniques were applied to cell geometries that were unsuccessful in the past because it was not possible to lower S sufficiently. Consider, for instance, a thin (50 μm) 0.1 ohm-cm cell with MINP-type passivation on both front and rear surfaces. Straightforward calculations show that such a device should be capable of yielding voltages of the order of 730 mV. In a similar manner, a thin, 0.1 ohm-cm MINP passivated grating cell with a 10 percent front face junction coverage can be shown to be capable of delivering voltages approaching the 800 mV built-in voltage. Potential improvements such as these indicate that the future is bright for the silicon solar cell. Thanks to the technology developed by the UNSW group, AMO efficiencies above 20 percent are probably not too far away.

## SUMMARY

The major conclusions to be drawn from the preceding analysis are as follows:

1. Contrary to what one may calculate using commonly accepted values for the parameters in the expression for $I_{ob}$, the present analysis shows that $I_{ob}$ is the dominant component for diffused cells of normal (200 μm) thickness. As the thickness is increased to several diffusion lengths, the emitter component becomes dominant.

2. The values of $I_{oe}$ for both the 0.1 and the 0.025 ohm-cm HLE cells were found to be essentially the same as those found in diffused cells, indicating that the hi-low emitter has no advantage over the diffused emitter.

3. It is not the perfection of the emitter but a hitherto unrecognized improvement in the base that is responsible for high voltage in the MINMIS cell.

4. High voltage in the MINP cell is due to the same previously unrecognized base improvement found in the MINMIS cell coupled with an emitter improvement that has reduced $I_{oe}$ to negligible values.

5. The enhanced base characteristics in the MINP/MINMIS cells are due to a reduced minority carrier mobility in the silicon material used to fabricate these cells.

6. Voltages approaching 800 mV appear to be achievable in 0.1 ohm-cm silicon cells with full utilization of MINP surface passivation techniques.

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TABLE I. - VOLTAGE CHARACTERISTICS OF HIGH VOLTAGE, LOW RESISTIVITY SILICON SOLAR CELLS USED IN THIS STUDY

| Cell type[a] | $V_{oc}$,[b] mV | $I_o$, A/cm$^2$ | Reference |
|---|---|---|---|
| Ion implanted emitter, Spire Corporation | 629 | $5.86\times10^{-13}$ | 4 |
| Hi-Lo emitter, 0.1 ohm-cm, University of Florida | 634 | 4.72 | 5 |
| Multi-step diffused (MSD) emitter, COMSAT | 637 | 4.22 | 3 |
| Multi-step diffused (MSD) emitter, NASA | 640 | 3.78 | 2 |
| MINMIS cell, University of New South Wales | 646 | 2.99 | 6 |
| Hi-Lo emitter, 0.025 ohm-cm, University of Florida | 648 | 2.77 | 5 |
| MINP cell, University of New South Wales | 666 | 1.35 | 7 |

[a] 0.1 ohm-cm resistivity unless otherwise stated.
[b] Measured at 25 mA/cm$^2$, 25° C.

TABLE II. - SATURATION CURRENT RESOLUTION FOR THE MSD, HLE, AND IIE CELLS

[Parentheses Indicate Calculated Values.]

| | d, µm | L, µm | $I_{ob}$,[a] A/cm$^2$ | $I_{oe}$,[a] A/cm$^2$ | $I_o$,[a] A/cm$^2$ | $V_{oc}$,[b] mV |
|---|---|---|---|---|---|---|
| MSD (NASA) | 175 | 250 | 2.20 | 1.58 | 3.78 | 640 |
| MSD (NASA) Measured | 533 | 250 | ------ | ------ | 2.99 | 646 |
| MSD (NASA) Calculated | 533 | 250 | (1.37) | (1.58) | (2.95) | (646) |
| HLE (0.1 ohm-cm) | 300 | 80 | 2.79 | 1.93 | 4.72 | 634 |
| HLE (0.025 ohm-cm) | 508 | 30 | 0.84 | 1.93 | 2.77 | 648 |
| MSD (COMSAT) | 200 | 218 | 2.18 | 2.04 | 4.22 | 637 |
| Spire ion implant | 295 | 220 | 3.42 | 2.44 | 5.86 | 629 |

[a] All values $\times10^{-13}$.
[b] Measured at 25 mA/cm$^2$, 25° C.

TABLE III. - SATURATION CURRENT RESOLUTION FOR THE MINMIS AND THE MINP CELLS

[Parentheses Indicate Calculated Values.]

| Cell | $I_{ob}$,[a] A/cm$^2$ | $I_{oe}$,[a] A/cm$^2$ | $I_o$,[a] A/cm$^2$ | $V_{oc}$,[b] mV | ΔV+, mV |
|---|---|---|---|---|---|
| MINMIS | 0.79 | 2.20 | 2.99 | 646 | - |
| MINP A | 1.13 | 0.22 | 1.35 | 666 | 6 |
| MINP B | (0.86) | (0.19) | 1.05 | 673 | 5 |
| MINP C | (0.85) | (0) | 0.85 | 678 | 0 |
| MINP D | (0.74) | (0) | 0.74 | 682 | 0 |

[a] All values $\times 10^{-13}$.
[b] Measured at 25 mA/cm$^2$, 25° C.

TABLE IV. - SUMMARY OF EXPERIMENTALLY DETERMINED VALUES FOR THE ELECTRON MINORITY CARRIER MOBILITY IN 0.1 ohm-cm SILICON, 300° K

| Reference | $\mu_e$ | Remarks |
|---|---|---|
| 9 | 300 | Extrapolated from 0.3 ohm-cm |
| 10 | 200-400 | Extrapolated from 0.5 ohm-cm |
| 11 | 425 | |
| 14 | 680 | NASA MSD material |

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