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STUDIES OF SILICON PN JUNCTION SOLAR CELLS

By

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Gainesville, Florida 32611

FINAL TECHNICAL REPORT
covering the period September 1977 - December 1979

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This report summarizes the results obtained in the research program at the University of Florida sponsored by NASA Lewis Research Center under Grant No. NSG-3018. The report covers the period of September 1977 - September 1979.

In addition to the senior investigators, graduate students S. C. Pao and M. A. Shibib participated in the research. The technical collaboration with M. P. Godlewski and W. H. Brandhorst, Jr., of NASA Lewis Research Center was very helpful during the research work. Discussions with C. T. Sah and J. G. Fossum also contributed to our research.
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CHAPTER 1

INTRODUCTION

The previous reports covering the period ending September 1977 concentrated on studies of basic mechanisms limiting the power conversion efficiency $\eta$, and particularly the open-circuit voltage $V_{OC}$ of $n^+ p$ junction silicon solar cells. Both theoretical and experimental studies were done to determine which mechanisms are responsible for the discrepancy between the theoretical and experimental efficiencies and open-circuit voltages.

In the classical analysis of silicon p-n junction solar cells, which neglects certain fundamental physical mechanisms [1], the limit value of $V_{OC}$ is calculated to be about 700 mV. The values of $V_{OC}$ observed experimentally fall well below this limit value. The efficiency $\eta$ of silicon solar cells will be limited by $V_{OC}$, as first noted by Brandhorst [2]. The conclusion from our experimental work [3,4] was that the factors which most influence $V_{OC}$ are the dark recombination currents in the emitter and base regions of the solar cell. In particular, for cells with base resistivity of about 0.1 $\Omega cm$, the emitter dark recombination current is dominant [3].

One of the possible mechanisms contributing to this dominance is bandgap narrowing $\Delta E_G$ [1] in heavily-doped regions of p-n junction solar cells. In our previous report we proposed a new method [5], based on the temperature dependence of the emitter current, for measuring $\Delta E_G$ in the emitter quasi neutral region as a function of the emitter doping concentration. Chapter 2 gives a detailed theoretical treatment underlying this method including now the effects of the Fermi-Dirac statistics. Experimental results for the emitter dark current density and $\Delta E_G$ for
emitter doping concentrations from $3 \times 10^{19}$ cm$^{-3}$ to $2 \times 10^{20}$ cm$^{-3}$ are given for n$^+$-type emitters. These data are the first accurate experimental results covering the range of dopings above $10^{19}$ cm$^{-3}$.

To provide theoretical support for investigating different ways to obtain high open-circuit voltages in p-n junction silicon solar cells, in Chapter 3 an analytical treatment of heavily doped transparent-emitter devices is presented that includes the effects of bandgap narrowing, Fermi-Dirac statistics, a doping concentration gradient, and a finite surface recombination velocity $S$ at the emitter surface [6]. Transparency of the emitter to minority carrier is defined by the condition that the transit time $\tau_t$ is much smaller than the minority carrier lifetime in the emitter $\tau_p$, $\tau_t \ll \tau_p$. As part of the analytical treatment, a self-consistency test is formulated that checks the validity of the assumption of emitter transparency for any given device. The transparent-emitter model is applied to calculate the dependence of the open-circuit voltage $V_{OC}$ of n$^+$-p junction silicon solar cells made on low-resistivity substrates. The calculated $V_{OC}$ agrees with experimental values for high $S_p (\geq 5 \times 10^4$ cm/s) provided the effects of bandgap narrowing (modified by Fermi-Dirac statistics) are included in the transparent-emitter model.

As was discussed earlier, the dark emitter recombination current has to be suppressed in order to achieve $V_{OC}$ of about 700 mV. A new structure to achieve that goal, the high-low-emitter (HLE) solar cell was proposed [7,8]. The study of HLE devices was one of the main purposes of the research under this grant. A detailed report of our accomplishments is in Chapter 4. Chapter 4 deals specifically with the cell in which the high-low (H-L) junction is induced by a positive oxide charge in the silicon-dioxide layer covering the emitter surface [9]. The maximum $V_{OC}$ achieved to date is 647 mV (measured by NASA Lewis in May 1979).
About 50 fabrication runs were made using different substrates and fabrication procedures. The most important results are summarized and described in detail. High values of $V_{OC}$ in a range of 640-647 mV were obtained in at least 20 fabrication runs, repeatedly and reproducibly, using base substrate resistivities of 0.1 $\Omega$cm and 0.025 $\Omega$cm. The first devices, fabricated in January 1978, still maintain $V_{OC}$ observed originally two years ago.

Chapter 5 discusses new methods for the determination of lifetimes and recombination currents in p-n junction solar cells and diodes [10]. These methods are particularly applicable to devices in which the minority carrier diffusion length is longer than the width of the region of the interest (HLE, BSF, IBC, FSF, and TJ cells). These methods are then directly applicable to determine the lifetime in the epitaxial emitter of the HLE cells described in Chapter 4. Once the lifetime is determined, this result allows determination of the dark recombination current in the emitter and also leads to the determination of the effective surface recombination velocity $S_{eff}$ at the n$^+$-n H-L junction in the emitter.

Chapter 6 discusses a new approach for the fabrication of BSF cells [11], in which the heavily doped region in the base of a BSF cell is eliminated. Instead, the desired high concentration of majority carriers at the back surface is obtained by a biased metal-oxide-semiconductor structure (MOS-BSF cell).

Chapter 7 deals with design proposals for high efficiency high-low-emitter solar cells [12]. A first-order analysis of HLE cells is presented for both beginning-of-life (BOL) and end-of-life (EOL) conditions. Based on this analysis and on experimentally observed values for material parameters, we present design approaches for both space and terrestrial cells.
The approaches result in specification of doping levels, junction depths and surface conditions. The proposed structures are projected to have both high $V_{OC}$ and high $J_{SC}$, and consequently high $\eta$.

REFERENCES FOR CHAPTER 1


CHAPTER 2

EXPERIMENTAL DETERMINATION OF BANDGAP NARROWING
IN THE EMITTER REGION OF SILICON P-N JUNCTION DEVICES

2.1 Introduction

Bandgap narrowing in heavily-doped regions of silicon p-n junction devices has been the subject of several publications [2,6-12]. The degradation in open-circuit voltage in low resistivity p-n junction solar cells [2] and the low values of emitter efficiency observed in silicon bipolar transistors [8,9] have been attributed, in part, to the excessive minority carriers stored in the heavily-doped emitter region as a result of bandgap narrowing in that region.

Recently several methods have been proposed to determine the magnitude of bandgap narrowing $\Delta E_g$ in the base region of bipolar transistors. These methods employ measurements of the temperature dependence of the transistor emitter-base junction voltage, at a fixed collector current [6], and of the transistor collector current [7,13]. Because the base doping concentration of transistors is limited to about $10^{19}$ cm$^{-3}$, these methods do not allow investigation of an entire range of high doping densities up to about $10^{21}$ cm$^{-3}$. The higher levels of doping concentration are often present in the emitter region of conventional p-n junction solar cells and bipolar transistors and can significantly influence the device performance.

To determine $\Delta E_g$ of the emitter, we propose an alternative method which makes use of the temperature-dependence measurement of the
injected minority-carrier current in the emitter region. This method applies over the entire range of emitter doping concentration present in p-n junction devices and allows, for the first time, determination of $\Delta E_G$ as a function of doping concentration up to about $10^{21}$ cm$^{-3}$.

In the context of this dissertation, we assume that the classical parabolic quantum density of state description is adequate for both carriers (rigid-band approximation) and that the minority carriers obey the traditional macroscopic flow equation in uniformly-doped regions. Discussions related to these subjects can be found in literature [14-20]. In the interpretations of experimental results, we have taken into account the effects of Fermi-Dirac statistics, which decrease the minority-carrier concentration below the values predicted if Boltzmann statistics are used.

2.2 Theoretical Grounds for the Method

2.2.1 Injected Minority-Carrier Current in Heavily-Doped Emitter Region

We consider the structure shown in Fig. 2.1. For simplicity of discussion, we assume the quasi-neutral emitter region ($0 \leq x \leq W_E$) to be uniformly doped with donor concentration $N_{DD}$. Devices with an uniformly-doped emitter region allow direct correlation between the measured value of bandgap narrowing and the doping concentration without complications arising from the built-in electric field and quasi-field [18] associated with a position-dependent doping profile. We further assume the emitter to be transparent to the minority holes; that is, the hole transit time $\tau_h$ across the n$^+$ region is assumed to be much shorter than the hole recombination lifetime $\tau_p$ in the n$^+$ region. A
Figure 2.1 A diode structure under external bias $V_{BE}$.
thin emitter with large surface recombination velocity helps to decrease the hole transit time. Experiments with p⁺-n⁻-n⁺ back-surface-field solar cells indicate that even some n⁺ layers as thick as 1 µm (formed by phosphorous diffusion at 1000°C for 30 min) exhibit transparency properties [21].

Under the above assumptions, the injected hole current density \( J_p \) is spatially constant:

\[
|J_p| = qD_p \frac{d\Delta P(x)}{dx} = qD_p \frac{\Delta P(0)}{W_E} \tag{2.1}
\]

where \( D_p \) is the hole diffusivity, \( W_E \) is the width of the quasi-neutral emitter region, and \( \Delta P(0) \) is the excess hole density at the edge of the quasi-neutral emitter, which we next discuss.

### 2.2.2 Excess Minority-Carrier Concentration in Degenerate Silicon

In thermal equilibrium, for a parabolic quantum density of states, the concentrations of charge carriers in a semiconductor are given by

\[
N_0 = N_C F_b(\eta_C) = 2(2\pi m^*_d kT/h^2)^{3/2} F_b(\eta_C) \tag{2.2}
\]

\[
P_0 = N_V F_b(\eta_V) = 2(2\pi m^*_d kT/h^2)^{3/2} F_b(\eta_V) \tag{2.3}
\]

where \( N_C \) and \( N_V \) are the effective density of states in the conduction and valence bands respectively, \( m^*_d \) and \( m^*_d \) are the density-of-state effective masses for electrons and holes respectively, \( F_b \) is the Fermi-Dirac integral of order \( b \), and

\[
\eta_C = (E_f - E_c)/kT \tag{2.4}
\]

\[
\eta_V = (E_v - E_f)/kT \tag{2.5}
\]
For an n-type region, independent of the doping concentration, equation (2.3), which describes the minority hole concentration, reduces to the familiar form given by Boltzmann's statistics:

\[ P_0 = N_V \exp\left[\frac{(E_V - E_f)}{kT}\right] \]  

(2.6)

If we use the analytic approximation for \( F_L(n) \) [18],

\[ F_L(n) = \frac{e^n}{1 + C(n)e^n} \]  

(2.7)

where \( C(n) \) is a function of \( n \) given in reference [22], then the thermal equilibrium value of PN product is

\[ P_0 N_0 = \frac{N_C N_V e^n}{1 + C(n)e^n} \]  

(2.8)

When an external bias is applied to the structure shown in Fig. 2.1, the hole quasi-Fermi level in the \( n^+ \) region shifts from its equilibrium value. The electron quasi-Fermi level, however, remains fixed relative to the conduction band as given by the relation

\[ N_{DD} = N = \frac{N_C \frac{n}{e}}{1 + C(n)e^n} \]  

(2.9)

where we assume for doping concentrations above \( 2 \times 10^{18} \text{ cm}^{-3} \) all impurity atoms are ionized [23,24]. Thus we have

\[ N_{DD} P(x) = \frac{N_C N_V e^{(E_f - E_{fp}(x))/kT}}{1 + C(n)e^n} \]  

(2.10)
and, at x=0,

\[ P(0) = \frac{\frac{E_G}{kT} \frac{qV}{kT}}{N_D N_V e^{\frac{E_G}{kT}} e^{\frac{qV}{kT}} \left[ 1 + C(n_c)e^n \right]} \]

(2.11)

where \( E_{fn} \) and \( E_{fp} \) are the electron and hole quasi-Fermi levels, respectively, \( V_{BE} \) is the external voltage bias, and \( E_G \) is the energy bandgap, which for lightly doped silicon is [25,26]

\[ E_G = E_{G0} - \alpha T \]

\[ = 1.206 - 2.8 \times 10^{-4} T \text{ eV for } 300 \text{ K} < T < 400 \text{ K} \]

(2.12)

Here \( E_{G0} \) is the extrapolated energy bandgap at 0 K which differs from the actual energy bandgap value of 1.170 eV at 0 K due to the parabolic dependence of the energy bandgap on temperature at lower temperatures [27]. The experimental uncertainty in (2.12) is about \( \pm 0.0015 \) eV [25].

Combining (2.11), (2.12), and using the equilibrium value of \( P_0 \) in (2.8), we obtain the excess hole concentration

\[ \frac{\alpha/k}{N_D N_V e^{\frac{E_{G0}}{kT}} e^{\frac{qV}{kT}} \left[ e^{\frac{E_{G0}}{kT}} - 1 \right]} \]

\[ \Delta P(0) = \frac{\frac{E_{G0}}{kT} \frac{qV}{kT}}{N_D N_V e^{\frac{E_{G0}}{kT}} e^{\frac{qV}{kT}} \left[ e^{\frac{E_{G0}}{kT}} - 1 \right]} \]

(2.13)

\[ \Delta n_1^2 \frac{qV}{kT} \left[ e^{\frac{qV}{kT}} - 1 \right] \]

\[ \Delta \frac{n_1^2}{N_D n_1^2 \left[ e^{\frac{qV}{kT}} - 1 \right]} \]

where \( n_1^2 \) is defined to be the intrinsic carrier concentration squared corresponding to energy bandgap \( E_{G0} \). The usefulness of the analytic approximation for \( F_1 \) is obvious. It allows direct assessment of the effects of
carrier degeneracy on the minority carrier storage and therefore on the recombination current in the heavily-doped region. Specifically, the effect of Fermi-Dirac statistics decreases the minority carrier concentration by a factor of \(1 + C(n_c)\exp(n_c)\) below that resulting if Boltzmann statistics were used. In Table 2.1 and also in Figure 2.2, we display numerical results of the reciprocal of this quantity as a function of temperature for several doping concentrations. It is noted that the hole concentration is depressed by as much as 70% at 300 K in an n-type region with \(N_{DD} = 10^{20} \text{ cm}^{-3}\) as a result of electron degeneracy. The value of effective density of states in the conduction band [28] used in these calculations is \(N_c = 2.88 \times 10^{19} (T/300)^{3/2}\). For \(n \leq 4\), \(F_h(n)\) in (2.7) can be approximated by \(\exp(n)/[1 + (0.3-0.0413n)\exp(n)]\) to within 4% [18].

2.2.3 Temperature Dependence of Injected Minority-Carrier Current in Heavily-Doped Emitter Region

The expression for the injected minority-carrier current in a heavily-doped thin region can be obtained by combining (2.1) and (2.13)

\[
|J_p| = -\frac{qD_p n_i^2}{N_{DD}} \frac{qV_{BE}/kT}{[e^{e_{BE}/kT} - 1]}
\]

\[
\frac{n}{N_{DD}[1 + C(n_c)e^c]W_E}
\]

If we use Einstein's relation between carrier diffusivity and mobility for the minority holes, \(D_p = (kT/q)\nu_p\), and assume the hole mobility to be independent of temperature in the degenerate material [23], the hole saturation current then varies with temperature as

\[
|J_{p0}| = T^4 \exp(-E_{G0}/kT)/[1+C(n_c)\exp(n_c)]
\]

\[\text{[2.15]}\]
<table>
<thead>
<tr>
<th>T(K)</th>
<th>N_DD=3x10^19 cm^-3</th>
<th>N_DD=3x10^20 cm^-3</th>
<th>N_DD=1.5x10^20 cm^-3</th>
<th>N_DD=2.1x10^20 cm^-3</th>
</tr>
</thead>
<tbody>
<tr>
<td>300</td>
<td>0.392</td>
<td>2.428</td>
<td>3.08</td>
<td>4.279</td>
</tr>
<tr>
<td>320</td>
<td>0.263</td>
<td>2.218</td>
<td>2.17</td>
<td>0.171</td>
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<tr>
<td>340</td>
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<td>2.030</td>
<td>1.861</td>
<td>3.153</td>
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<td>0.780</td>
<td>3.576</td>
</tr>
<tr>
<td>380</td>
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<td>1.793</td>
<td>1.799</td>
<td>3.366</td>
</tr>
<tr>
<td>400</td>
<td>-0.158</td>
<td>1.569</td>
<td>1.69</td>
<td>3.169</td>
</tr>
</tbody>
</table>

Table 2.1 Numerical Result of $n_c$ and $f(n_c) = (1 + C(n_c)) e^{-\alpha n_c}$ as a Function of Temperature for Several Donor Doping Concentrations ($n_c$ is obtained by solving eq. 2.9).
Figure 2.2 Ratio of minority carrier concentration with consideration of Fermi-Dirac statistics to the same quantity without consideration of Fermi-Dirac statistics.
The value of $E_{GO}$ in units of eV is then equal to the slope of the plot $\ln(J_{PO} [1+C(\eta_C)\exp(\eta_C)/T^4])$ versus $q/kT$. Values of $E_{GO}$ smaller than 1.206 eV correspond to an increase of minority-carrier concentration not accountable by traditional theory and we attribute this phenomenon as a consequence of an effective reduction in the energy bandgap. Thus we define

$$\Delta E_G = 1.206 - E_{GO\text{(measured)}} \text{ eV} \quad (2.16)$$

To incorporate the effect of bandgap narrowing, we re-write from (2.14) the expression for the emitter saturation current

$$|J_{p0}| = \frac{qD_{p}n_{i0}^2 \exp(\Delta E_G/kT)}{N_{DD}[1 + C(\eta_C)e^{-\eta_C}]W_E} \quad (2.17)$$

where $n_{i0}^2$ is the intrinsic density squared corresponding to $E_{GO} = 1.206$ eV.

### 2.3 Illustration of the Method

In this section we illustrate the above method with two device structures: a transistor structure and a diode structure.

The transistors under study are n-p-n silicon bipolar transistors. There are two transistors studied, which we will designate as SHF 70 and TXA. The n+ emitter region of transistor SHF 70 is ion-implanted with a uniform arsenic concentration of $1.5 \times 10^{20}$ cm$^{-3}$. The depth of the emitter-base junction from the silicon surface is about 0.37 μm. The net impurity profiles obtained by incremental sheet resistance measurement is shown in Fig. 2.3. The n+ emitter region of transistor TXA is arsenic diffused with a near-uniform dopant concentration of $1.5 \times 10^{20}$ cm$^{-3}$. The impurity profile is shown in Fig. 2.4.
Figure 2.3 Impurity profile of transistor SHF 70 (n-p-n).
Figure 2.4 Impurity profile of transistor TXA (n-p-n).
A convenient way to study the injected minority-carrier current in the heavily-doped emitter region would be by measuring the transistor base current $I_B$ as a function of the forward biased emitter-base junction voltage $V_{BE}$ as shown in Fig. 2.5. However, the transistor base current consists not only of the injected minority hole current (in a n-p-n transistor) supporting recombination in the quasi-neutral bulk region and the surface of the emitter; it also has a component of current supporting bulk recombination in the quasi-neutral base region and a component of current supporting recombination in the emitter-base junction space-charge region \cite{29}. We have already discussed the recombination current in the thin heavily-doped emitter in Section 2.2.1 and 2.2.2. The bulk recombination current in the base region is often negligible; indeed if this were the only component of the transistor base current, the static common-emitter current gain $h_{FE}$ of conventional silicon $p$-polar transistors would be several orders of magnitude higher than the values of $h_{FE}$ commonly seen ($\sim 10^2$). The transistors under study have values of $h_{FE}$ less than 100. The component of current due to recombination in the emitter-base junction space-charge region prevails at lower values of $V_{BE}$. This current component has a characteristic exponential dependence on voltage: $I \propto \exp(qV_{BE}/mkT)$ with $m > 1$ \cite{3,4}. At higher biases, this current component is less significant due to the weaker exponential dependence on voltage but nevertheless still constitutes a portion of the total current. Thus, in order to obtain the emitter recombination current, which has an ideal exponential voltage dependence ($m = 1$), the space-charge region recombination current must be subtracted from the total measured terminal current \cite{4,8}.

A computer program written to analyze data resulting from the transistor
Figure 2.5 Circuit diagram for transistor base current measurement.
In Appendix I, base current measurements are listed. A typical $I_B$ versus $V_{BE}$ plot for transistor SHF 70 is shown in Fig. 2.6. In Tables 2.2 and 2.3, we summarize the values of emitter saturation current $I_{EO}$ determined for several temperatures for the two transistors under study. The values of $n_c$ and $I_{EO}[1+C(n_c)\exp(n_c)/T^4]$ are also tabulated in Tables 2.2 and 2.3. In Fig. 2.7, $\ln(I_{EO}[1+C(n_c)\exp(n_c)/T^4])$ versus $1000/T$ is plotted. $E_G$ in units of eV can be obtained by multiplying the magnitude of the slope of the least-square-fitted straight line by 1000k/q. For transistor SHF 70, $E_G$ is found to be 0.981 eV. This corresponds to a bandgap narrowing $\Delta E_G$ of 0.225 eV. For transistor TXA, $\Delta E_G$ is found to be 0.227 eV.

We have also studied bandgap narrowing in heavily-doped n+ regions using diode structures. The starting material is boron-doped p-type silicon wafers with doping concentration of $2.0 \times 10^{17}$ cm$^{-3}$. The wafers are cleaned and oxidized at 800°C for two hours in dry oxygen to grow 200 Å of silicon dioxide. The wafers are then implanted with different arsenic doses and annealed at 1050°C for 20 min. in dry nitrogen. The thin oxide on both surfaces of the wafers is removed and the wafers are metallized with Ti-Ag on both surfaces. Square chips of 110 mil x 110 mil are scribed from the wafers and circular mesa structures of different areas are made on the chips as shown in Fig. 2.8. The devices are mounted on TO-5 headers with silver epoxy at room temperature and ultrasonically wire-bonded at room temperature.

The measurement circuit for the diode I-V characteristic is shown in Fig. 2.9. The current source used is an EDC-CR 103 current standard. The current is incremented such that the terminal voltages across the diode are 10 mV apart for each reading, starting from 0.1 V to 0.7 V.
Figure 2.6 $I_B$ vs. $V_{BE}$ plot for transistor SHF 70 at 342.8 K.
Table 2.2 Experimental Values of Emitter Saturation Current $I_{ES}$ and Calculated Values of $\eta_c$ at Different Temperatures for Transistor SHF 70 ($N_{DD} = 1.5 \times 10^{20} \text{ cm}^{-3}$).

<table>
<thead>
<tr>
<th>T(K)</th>
<th>$I_{ES}$ (amp)</th>
<th>$\eta_c$</th>
<th>$I_{ES}[1+C(\eta_c)e^{\eta_c/T}]$</th>
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<tbody>
<tr>
<td>317.2</td>
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<td>3.139</td>
<td>$5.08 \times 10^{-26}$</td>
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<tr>
<td>327.3</td>
<td>$2.12 \times 10^{-16}$</td>
<td>3.080</td>
<td>$8.79 \times 10^{-26}$</td>
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<tr>
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<td>$3.93 \times 10^{-16}$</td>
<td>3.022</td>
<td>$1.48 \times 10^{-25}$</td>
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<td>2.968</td>
<td>$2.47 \times 10^{-25}$</td>
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<td>$3.61 \times 10^{-14}$</td>
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<td>$6.68 \times 10^{-24}$</td>
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Table 2.3 Experimental Values of Emitter Saturation Current $I_{\text{EO}}$ and Calculated Values of $\eta_c$ at Different Temperatures for Transistor TXA ($N_{\text{DD}} = 1.5 \times 10^{20} \text{ cm}^{-3}$).

<table>
<thead>
<tr>
<th>$T$(K)</th>
<th>$I_{\text{EO}}$ (amp)</th>
<th>$\eta_c$</th>
<th>$I_{\text{EO}}[1+C(\eta_c)e^{\eta_c}/T^4]$</th>
</tr>
</thead>
<tbody>
<tr>
<td>318.6</td>
<td>$5.23 \times 10^{-16}$</td>
<td>3.181</td>
<td>$2.57 \times 10^{-25}$</td>
</tr>
<tr>
<td>327.2</td>
<td>$1.56 \times 10^{-15}$</td>
<td>3.080</td>
<td>$6.48 \times 10^{-25}$</td>
</tr>
<tr>
<td>337.5</td>
<td>$5.55 \times 10^{-15}$</td>
<td>2.965</td>
<td>$1.90 \times 10^{-24}$</td>
</tr>
<tr>
<td>348.0</td>
<td>$1.83 \times 10^{-14}$</td>
<td>2.854</td>
<td>$5.20 \times 10^{-24}$</td>
</tr>
<tr>
<td>358.2</td>
<td>$5.57 \times 10^{-14}$</td>
<td>2.749</td>
<td>$1.32 \times 10^{-23}$</td>
</tr>
</tbody>
</table>
Figure 2.7 Plot of \( \ln \left( \frac{I_{E0}(1+C(n_c) \exp(n_c))}{T^4} \right) \) vs. 1000/T for transistor SHF 70 and TXA.
Figure 2.8 Mesa diode structure. The silicon etchant used is 1HF : 1CH₃COOH : 6HNO₃. Etching time is about 1 min.
Figure 2.9 Circuit diagram for diode I-V characteristic measurement.
There are several groups of diodes under study, which we designate in Table 2.4. All these devices have shallow n⁺ emitters with uniform doping concentrations. The impurity profile in the n⁺ emitter region of these devices as measured by a spreading resistance method are shown in Fig. 2.10. A typical I-V characteristic of these devices is displayed in Fig. 2.11. All devices selected for measurements have an easily recognizable space-charge recombination current component at lower biases, that is, \( I \approx \exp(qV/kT) \) with \( m > 1 \) and \( m \) approximately constant for two orders of magnitude range of current. This allows straightforward extraction of the ideal recombination current component \( (m = 1) \) from the measured terminal current [4]. The computer program used to analyze the transistor current can be also used in this case (Appendix I).

The pertinent geometrical and electrical parameters including minority carrier diffusion length in the substrate material measured by an X-ray irradiation method [30] for these devices are summarized in Table 2.4. The extracted values of saturation current \( I_{\text{QNO}} \) for the ideal recombination current component at different measurement temperatures are tabulated in Table 2.5a-2.5d.

In a diode structure, the ideal recombination current has two components: a component supporting recombination in the bulk region and surface of the emitter and a component supporting recombination in the bulk region and back contact of the base. For diffused p⁺-n diodes fabricated on low-resistivity silicon, it has been demonstrated that the recombination current in the emitter region can be significant [4]. For the n⁺-p diodes under study we expect the emitter recombination current to be even more significant, partly due to the thin emitter with large surface recombination velocity and partly due to a larger value.
Table 2.4 Geometrical and Electrical Parameters of Arsenic-Implanted Diodes Under Study.

<table>
<thead>
<tr>
<th>Device</th>
<th>Device Area (cm²)</th>
<th>( N_{DD} ) (cm(^{-3}))</th>
<th>Emitter-Base Junction Depth (µm)</th>
<th>( N_{DD} ) (cm(^{-3}))</th>
<th>( L_n ) (µm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>UF 2-2</td>
<td>2.29x10(^{-2})</td>
<td>3.0x10(^{19})</td>
<td>0.15</td>
<td>2.0x10(^{17})</td>
<td>65</td>
</tr>
<tr>
<td>UF 3-2</td>
<td>1.06x10(^{-2})</td>
<td>2.1x10(^{20})</td>
<td>0.32</td>
<td>2.0x10(^{17})</td>
<td>67</td>
</tr>
<tr>
<td>UF 8-2</td>
<td>9.90x10(^{-3})</td>
<td>1.5x10(^{20})</td>
<td>0.31</td>
<td>2.0x10(^{17})</td>
<td>76</td>
</tr>
<tr>
<td>UF 12-2</td>
<td>1.37x10(^{-2})</td>
<td>1.0x10(^{20})</td>
<td>0.30</td>
<td>2.0x10(^{17})</td>
<td>62</td>
</tr>
</tbody>
</table>
Figure 2.10 Impurity profile of the $n^+$ emitter region of the ion-implanted diodes under study.
Figure 2.11 Typical I-V characteristic for group UF 2 diode (322.5 K).
Table 2.5a Ideal Saturation Current for Device UF 2-2
(N_{DD} = 3.0 \times 10^{19} \text{ cm}^{-3}).

<table>
<thead>
<tr>
<th>T (K)</th>
<th>I_{QNO} (amp)</th>
<th>J_{QNO} (amp/cm^2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>322.5</td>
<td>2.23 \times 10^{-12}</td>
<td>9.74 \times 10^{-11}</td>
</tr>
<tr>
<td>327.3</td>
<td>4.05 \times 10^{-12}</td>
<td>1.77 \times 10^{-10}</td>
</tr>
<tr>
<td>332.3</td>
<td>7.47 \times 10^{-12}</td>
<td>3.26 \times 10^{-10}</td>
</tr>
<tr>
<td>337.5</td>
<td>1.42 \times 10^{-11}</td>
<td>6.20 \times 10^{-10}</td>
</tr>
<tr>
<td>342.6</td>
<td>2.63 \times 10^{-11}</td>
<td>1.15 \times 10^{-9}</td>
</tr>
<tr>
<td>347.8</td>
<td>4.70 \times 10^{-11}</td>
<td>2.05 \times 10^{-9}</td>
</tr>
<tr>
<td>353.6</td>
<td>8.60 \times 10^{-11}</td>
<td>3.76 \times 10^{-9}</td>
</tr>
</tbody>
</table>

Table 2.5b Ideal Saturation Current for Device UF 3-2
(N_{DD} = 2.1 \times 10^{20} \text{ cm}^{-3}).

<table>
<thead>
<tr>
<th>T (K)</th>
<th>I_{QNO} (amp)</th>
<th>J_{QNO} (amp/cm^2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>322.3</td>
<td>3.90 \times 10^{-13}</td>
<td>3.68 \times 10^{-11}</td>
</tr>
<tr>
<td>327.3</td>
<td>7.56 \times 10^{-13}</td>
<td>7.13 \times 10^{-11}</td>
</tr>
<tr>
<td>337.5</td>
<td>2.57 \times 10^{-12}</td>
<td>2.42 \times 10^{-10}</td>
</tr>
<tr>
<td>342.9</td>
<td>4.85 \times 10^{-12}</td>
<td>4.58 \times 10^{-10}</td>
</tr>
<tr>
<td>347.9</td>
<td>8.45 \times 10^{-12}</td>
<td>7.97 \times 10^{-10}</td>
</tr>
<tr>
<td>358.7</td>
<td>2.58 \times 10^{-11}</td>
<td>2.43 \times 10^{-9}</td>
</tr>
</tbody>
</table>
Table 2.5c  Ideal Saturation Current for Device UF 8-2
\((N_{DD} = 1.5 \times 10^{20} \text{ cm}^{-3})\).

<table>
<thead>
<tr>
<th>T (K)</th>
<th>(I_{QNO} ) (amp)</th>
<th>(J_{QNO} ) (amp/cm(^2))</th>
</tr>
</thead>
<tbody>
<tr>
<td>322.2</td>
<td>(5.66 \times 10^{-13})</td>
<td>(5.72 \times 10^{-11})</td>
</tr>
<tr>
<td>327.2</td>
<td>(1.08 \times 10^{-12})</td>
<td>(1.09 \times 10^{-10})</td>
</tr>
<tr>
<td>332.3</td>
<td>(2.00 \times 10^{-12})</td>
<td>(2.02 \times 10^{-10})</td>
</tr>
<tr>
<td>337.5</td>
<td>(3.67 \times 10^{-12})</td>
<td>(3.71 \times 10^{-10})</td>
</tr>
<tr>
<td>342.6</td>
<td>(6.77 \times 10^{-12})</td>
<td>(6.84 \times 10^{-10})</td>
</tr>
<tr>
<td>348.1</td>
<td>(1.23 \times 10^{-11})</td>
<td>(1.24 \times 10^{-9})</td>
</tr>
</tbody>
</table>

Table 2.5d  Ideal Saturation Current for Device UF 12-2
\((N_{DD} = 1.0 \times 10^{20} \text{ cm}^{-3})\).

<table>
<thead>
<tr>
<th>T (K)</th>
<th>(I_{QNO} ) (amp)</th>
<th>(J_{QNO} ) (amp/cm(^2))</th>
</tr>
</thead>
<tbody>
<tr>
<td>332.5</td>
<td>(1.76 \times 10^{-12})</td>
<td>(1.28 \times 10^{-10})</td>
</tr>
<tr>
<td>337.5</td>
<td>(3.11 \times 10^{-12})</td>
<td>(2.27 \times 10^{-10})</td>
</tr>
<tr>
<td>342.6</td>
<td>(5.76 \times 10^{-12})</td>
<td>(4.23 \times 10^{-10})</td>
</tr>
<tr>
<td>348.1</td>
<td>(1.08 \times 10^{-11})</td>
<td>(7.88 \times 10^{-10})</td>
</tr>
<tr>
<td>353.7</td>
<td>(1.99 \times 10^{-11})</td>
<td>(1.45 \times 10^{-9})</td>
</tr>
<tr>
<td>358.5</td>
<td>(3.30 \times 10^{-11})</td>
<td>(2.41 \times 10^{-9})</td>
</tr>
</tbody>
</table>
of effective density of states in the conduction band for silicon in comparison with the value of effective density of states in the valence band. This expectation of large $I_\mu$ is consistent with experimental findings [3] on diffused $n^+$-p solar cells having a 0.1 $\Omega$-cm base resistivity. We will discuss this effect in the next section.

To illustrate that the emitter recombination current is the dominant current component in these diodes, we measure the minority carrier diffusion lengths in these devices using the X-ray irradiation method [30]. Consider device UF 2-2, for example. The extracted ideal recombination current $I_{\text{QNO}}$ is shown in Fig. 2.11. The base recombination current component (dashed line) as calculated from

$$I_{\text{rec base}} = \frac{qA_n^2}{A}\frac{D}{N_L} N \exp\left(\frac{qV}{kT}\right)$$

is only a few percent of the total ideal recombination current. The emitter of the device is designed to be thin and with a large surface recombination velocity so that the dominant recombination process in the emitter is mainly at the emitter surface and therefore (2.15) and (2.17) apply. This requires the hole lifetime in the emitter region to be longer than the hole transit time across the emitter region, which we will discuss in further detail in the next section.

In Fig. 2.12, we display a plot of $\ln(I_{\text{QD}}(1+C(n_c)\exp(n_c))/T^4)$ versus $1000/T$ for two devices having different values of $\Delta E_G$. The values of $\Delta E_G$ determined for different values of arsenic concentration using the diode structure are summarized in Table 2.6. The values of $\Delta E_G$ obtained using the transistor structure are also included. In Fig. 2.13, we show the results graphically. The experimental values of $\Delta E_G$ as a function of impurity concentration $N_{\text{DD}}$ can be fitted by

$$\Delta E_G = 0.037 \ln(N_{\text{DD}}/10^{20}) + 0.210 \text{ eV} \quad (2.18)$$
Figure 2.12 $\ln\left(\frac{I_{EO} (1+C(n_c) \exp(n_c))}{T^4}\right)$ vs. $1000/T$ for diode UF2-2 and UF 8-2.
Table 2.6 Bandgap Narrowing $\Delta E_G$ as a Function of Emitter Doping Concentration.

<table>
<thead>
<tr>
<th>Device</th>
<th>Emitter Concentration (cm$^{-3}$)</th>
<th>$\Delta E_G$ (eV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>UF 2-2 (diode)</td>
<td>$3.0 \times 10^{19}$</td>
<td>0.175</td>
</tr>
<tr>
<td>UF 12-2 (diode)</td>
<td>$1.0 \times 10^{20}$</td>
<td>0.204</td>
</tr>
<tr>
<td>UF 8-2 (diode)</td>
<td>$1.5 \times 10^{20}$</td>
<td>0.236</td>
</tr>
<tr>
<td>SHF 70 (transistor)</td>
<td>$1.5 \times 10^{20}$</td>
<td>0.225</td>
</tr>
<tr>
<td>TXA (transistor)</td>
<td>$1.5 \times 10^{20}$</td>
<td>0.227</td>
</tr>
<tr>
<td>UF 3-2 (diode)</td>
<td>$2.1 \times 10^{20}$</td>
<td>0.247</td>
</tr>
</tbody>
</table>
Figure 2.13 Experimentally determined $\Delta E_G$ as a function of arsenic doping concentration.
2.4 Discussion

We have demonstrated an experimental method to study energy bandgap narrowing in heavily-doped emitter regions. This method employs the study of temperature dependence of the minority carrier recombination current in a thin transparent emitter. The accuracy in determining $\Delta E_G$ relies on an accurate description of the variation of emitter saturation current $I_{ED}$ with temperature and also on the accuracy in obtaining the emitter saturation current from the I-V characteristics.

In deriving (2.15), which describes the temperature variation of the emitter saturation current, we have assumed that the minority-carrier mobility and majority-carrier concentration are temperature independent and that the energy bandgap in intrinsic silicon varies linearly with temperature. At lower temperatures (below 200 K), these assumptions may be questionable [6,25], particularly for emitters with lower doping concentrations (below $10^{19}$ cm$^{-3}$). To minimize these possible sources of error, we have selected the measurement temperature range to be between 320 K and 380 K. We note that (2.15) and (2.17) hold only for a transparent emitter. This requires the hole lifetime $\tau_p$ in the emitter to be longer than the hole transit time $W_e^2/2D_p$. As an example, for an $n^+$ emitter with a doping concentration of $10^{20}$ cm$^{-3}$ and $W_e = 0.25$ μm, the hole transit time is approximately 0.2 nsec which is smaller than the hole Auger lifetime of 0.6 nsec reported for this doping concentration [31,32]. In this calculation, we assume $D_p = 1.5$ cm$^2$/sec at 320 K. At higher temperatures, $D_p$ increases slightly with temperature and therefore the transit time is shorter. For thicker emitters, recombination processes such as Auger recombination and Shockley-Read-Hall recombination can be important in the emitter bulk region and $W_e$ in (2.14) should be replaced
by the corresponding diffusion length $L_p$. Under this situation, the emitter is defined to be opaque to the minority holes. However, if $L_p$ does not vary significantly with temperature in the range of measurement temperature, (2.15) remains valid. Despite these possible sources of error, it is preferable to use (2.15) to determine $\Delta E_G$ rather than determining $\Delta E_G$ from a single value of $I_{EO}$ using (2.17). The uncertainty in $D_p$ in the heavily-doped $n^+$ region may cause large error in $\Delta E_G$.

The experimental accuracy in the I-V measurement is extremely good. The current standard we use has an accuracy about ± 1 nA. Thus the accuracy in determining $I_{EO}$ from the I-V characteristics depends mostly on the device having a well-defined space-charge recombination current component so that the ideal recombination current component can be separated from the measured I-V characteristics accurately. Devices with surface and other leakage current components are not suitable for this measurement. We estimate the error in determining $I_{EO}$ to be less than 3%. Assuming the values of $I_{EO}$ can be obtained sufficiently accurate, the uncertainty in $\Delta E_G$, which is related to the slope of the activation energy plot, can be reduced by taking more values of $I_{EO}$ at closer temperature intervals. The experimental accuracy in determining $\Delta E_G$, as obtained by a least-square-fit to the measured data as shown in Figs. 2.7 and 2.12, is estimated to be ± 5 meV.

We now discuss the experimental results further. Consider device UF 8-2, for example. $I_{EO}$ is found to be $5.72 \times 10^{-11}$ amp/cm$^2$ at 322.2 K for this device. The large value of dark saturation current density in this device cannot be explained by an opaque emitter with very short minority-carrier lifetime alone. If we ignore the effect of bandgap
narrowing and relate the saturation current in an opaque emitter,
\[ q n^2 D / N L [1 + C(n_c) \exp(n_c)] \], to the measured dark saturation current density, a minority-carrier lifetime as low as \(10^{-16}\) sec. is required to account for the dark recombination current measured. These low values for minority-carrier lifetime are not consistent with lifetimes reported in heavily-doped silicon [31,32] and are lower than the mean free time between collisions. Inclusion of the effect of bandgap narrowing provides a model that is consistent with the large observed value of saturation current density.

In this chapter, we have concentrated our study on \(n^+\) emitters. For devices with \(p^+\) emitters we anticipate the effect of Fermi-Dirac statistics to be more significant because \(N_V < N_C\). For silicon, the value of \(N_V\) is about a factor of three lower than the value of \(N_C\). Thus for an \(n^+\) emitter with doping concentration of \(3 \times 10^{19}\) cm\(^{-3}\) (\(= N_C\)), the effect of majority-carrier degeneracy depresses the minority-carrier concentration by about a factor of 0.7 at 300 K, as shown in Fig. 2.2; but, for a \(p^+\) emitter, a doping concentration of \(1 \times 10^{19}\) cm\(^{-3}\) (\(= N_V\)) suffices to depress the minority-carrier concentration by the same factor of 0.7. We note here that other workers [7,8,13] have not taken into account the effect of Fermi-Dirac statistics in their studies of energy bandgap narrowing in silicon p-n junction devices. Our results indicate that, for an \(n^+\) region with doping concentration of \(3 \times 10^{19}\) cm\(^{-3}\) (device UF 2-2), this neglect underestimates \(\Delta E_G\) by about 0.015 eV. For an \(n^+\) region with doping concentration of \(2.1 \times 10^{20}\) cm\(^{-3}\) (device UF 3-2), the underestimation in \(\Delta E_G\) is about 0.070 eV. These results can be obtained from the plot of \(\ln[I_{EO}/T^4]\) versus 1000/T. For a \(p^+\) emitter with the same doping concentration, the underestimation in \(\Delta E_G\) by neglecting the effect of Fermi-Dirac statistics would be even greater.
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CHAPTER 3
HEAVILY-DOPED TRANSPARENT EMITTER REGIONS
IN JUNCTION SOLAR CELLS, DIODES, AND TRANSISTORS
I. Introduction

Excess minority carrier injected into the emitter of p-n junction devices recombine in the bulk and at the surface of the emitter. If the emitter junction is shallow enough, the minority carriers can cross the quasi-neutral emitter region without appreciable bulk recombination. The minority carriers then recombine at the emitter surface. For this case the emitter is transparent to the injected minority carriers, and an important parameter then is the surface recombination velocity $S$ at the emitter surface.

This parameter is particularly important for p-n junction silicon solar cells in which most of the illuminated surface is not covered by metal. In devices in which thermal SiO$_2$ covers this nonmetallized portion of the surface, experiments show that $S$ can be less than $10^4$ cm/sec for both p-cells (p-type substrate) [1] and n-cells [1]. This value of $S$ is orders of magnitude less than that at an ohmic contact and is consistent with values determined earlier by different experimental methods [2]. Furthermore, recent experiments on p-cells [1] and n-cells [1] demonstrate that the emitter can be completely transparent.

The purpose of this paper is to provide an analytical treatment of transparent emitter devices, particularly solar cells, that is more complete than treatments previously available [3-8]. In this treatment, we include the effects of: (a) bandgap narrowing [9,10], (b) Fermi-Dirac statistics, (c) built-in field due to the impurity profile, and (d) a finite surface recombination velocity $S$. Detailed numerical studies including these various effects have been done [11-13], but they have not treated the case of the transparent emitter.
A major result of the paper is the demonstration that the transparent-emitter model can predict experimental values of $V_{OC}$ observed on $n^+ - p$ thin diffused junction silicon solar cells made on low-resistivity (0.1 Ω-cm) substrates. Thus, the transparent-emitter model is shown to provide an explanation for the discrepancy between the prediction of simple classical theory ($V_{OC} \approx 700$ mV) and the measured maximum value ($V_{OC} \approx 600$ mV). The transparent-emitter model gives $V_{OC} \approx 600$ mV for high values of $S_P$ ($S_p > 10^4$ cm/sec) provided the effects of bandgap narrowing (modified by Fermi-Dirac statistics) are included. This result suggests that $V_{OC}$ can be increased toward the classical value of 700 mV if $S_P$ is decreased and the effects of bandgap narrowing are reduced. This is accomplished in the HLE solar cells, early versions of which have shown increases in $V_{OC}$ to the 640-650 mV range [14].

In addition to the development of the theory for the transparent-emitter device, and its application to solar cells, the paper will include a test for the self-consistent validity of the transparent-emitter model. This test compares the calculated transit time of minority carriers across the emitter with the Auger-impact minority carrier lifetime within the emitter region.

II. Derivation

We consider an $n$-type heavily doped quasi-neutral emitter region; analogous results apply to $p$-type emitters. The minority carrier current density in the $n$-type region is

$$J_p(x) = q\mu_p A_p(x) E(x) - qD_p \frac{dA_p(x)}{dx}$$  \hspace{1cm} (1)

If low-level injection in the emitter is assumed, then $E(x)$ is given by its thermal-equilibrium value,
We now define an effective intrinsic density $n_{ie}$ such that

$$n_{ie}^2(x) = P_0(x) N_0(x)$$

in which $P_0(x)$ and $N_0(x)$ are the hole and electron concentrations in thermal equilibrium. The parameter $n_{ie}^2$ depends on position for two reasons:

1. the influence of Fermi-Dirac statistics, and
2. the influence of bandgap narrowing.

These influences are discussed in section III. For Maxwell-Boltzmann statistics and no bandgap narrowing, $n_{ie}^2$ is the square of the intrinsic carrier concentration in silicon and is a function of temperature only.

If the expressions in (2) and (3) are used in (1), we get, after some manipulations,

$$J_p(x) \frac{N_0(x)}{n_{ie}^2(x)} \frac{dP_0(x)}{dx} = -qD_p \left\{ \Delta P(x) \cdot \frac{N_0(x)}{n_{ie}^2(x)} \right\}.$$  \hfill (4)

If we integrate (4) over the quasi-neutral emitter region, we get

$$\int_0^{WE} J_p(x) \cdot \frac{N_0(x)}{n_{ie}^2(x)} \ dx = -q \bar{D}_p \left\{ \Delta P(x) \cdot \frac{N_0(x)}{n_{ie}^2(x)} \right\}_{0}^{WE} \hfill (5)$$

where $\bar{D}_p$ is some average value of $D_p$. If the emitter is transparent (transit-time limited), that is, if the minority carrier transit time $\tau_t$ is much less than the minority carrier lifetime $\tau_p$ (for an n-type emitter), then $J_p$ is constant independent of position in the emitter.
Use of the minority carrier boundary conditions [15]

\[ \Delta P(0) = P_0(0) \left( e^{QV/kT} - 1 \right) \]  
(6)

at the edge of the emitter space charge region, and

\[ J_P(W_E) = q \cdot S_p \cdot \Delta P(W_E) \]  
(7)

at the emitter surface, enable (5) to be expressed as

\[ J_P(x) = \frac{q \bar{P}(e^{QV/kT} - 1)}{\int_{W_E}^{W_E} n_e(x) \cdot \Delta P(W_E) \ dx + \frac{\bar{P} \cdot N_0(W_E)}{S_p \cdot n_e^2(W_E)}} \]  
(8)

Equation (8) is the general expression for the minority carrier current in a transparent emitter.

To check the condition, \( \tau_t \ll \tau_P \), required for transparency, we must determine the steady-state transit time \( \tau_t \), which is defined by the charge control relation,

\[ \tau_t = \frac{Q_p}{J_P} \]  
(9)

Here \( Q_p \) is the excess minority carrier charge storage in the emitter:

\[ Q_p = q \int_{W_E}^{W_E} \Delta P(x) \ dx \]  
(10)

Using (4), (8), and (10) to express \( Q_p \), and combining with (9), we
find the following expression for the minority carrier transit time:

\[
\tau_t = \int_0^{W_E} \frac{N_0(x)}{n_{ie}(x')} \, dx + \int_0^{W_E} \frac{N_0(W_E)}{S_p \cdot n_{ie}^2(W_E)} \, dx

\]

Some special cases are of interest. For a flat impurity concentration profile, the above expression reduces to

\[
\tau_t = \frac{W_E}{2D_p} \left( \frac{W_E}{S_p} + \frac{W_E}{S_p} \right)

\]

If, furthermore, \(S_p\) is infinite, (12) reduces to the familiar expression,

\[
\tau_t = \frac{W_E^2}{2D_p}

\]

III. Heavy Doping Effects

In thermal equilibrium, heavy doping concentrations of shallow level impurities affect the minority carrier concentration in a quasi-neutral region by two mechanisms: bandgap narrowing and Fermi-Dirac statistics. These two mechanisms affect the minority carrier concentration in opposite ways. For any given position of the Fermi level relative to the band edges, bandgap narrowing tends to increase the
minority carrier concentration, while inclusion of Fermi-Dirac statistics tends to decrease the minority carrier concentration below the value calculated using Maxwell-Boltzmann statistics. The dominance of either of the two effects, at any specific impurity concentration, depends on the model of bandgap narrowing adopted.

In this treatment, we assume that bandgap narrowing occurs without changing the parabolic dependence on energy of the density of states in the conduction and valence bands. This is the rigid-band approximation.

The effects of bandgap narrowing and Fermi-Dirac statistics can be lumped into a position-dependent effective intrinsic carrier concentration at thermal equilibrium given by

$$n_{ie}^2(x) = \frac{n_i^2 e^{\Delta E_C(x)/kT}}{1 + C(\eta) e^{\eta}}$$  \hspace{1cm} (14)

where

$$\eta = \eta_C = (E_F - E_C)/kT$$  \hspace{1cm} (15)

for n-type material, and

$$\eta = \eta_V = (E_V - E_F)/kT$$  \hspace{1cm} (16)

for p-type material. The derivation of (14) appears in the Appendix.

In (15) and (16), $E_C$ and $E_V$ are the edges of the conduction and valence bands, respectively, and $E_F$ is the Fermi level. The factor $C(\eta)$ is a function of $\eta$, which, for $\eta \leq 4$ (e.g., $N_0 \leq 2 \times 10^{20}$ cm$^{-3}$ in n-type silicon), is [16]

$$C(\eta) \equiv -0.04\eta + 0.3$$  \hspace{1cm} (17)

The above approximation of $C(\eta)$ gives values of the Fermi-Dirac integral of order $\frac{1}{\eta}$ (see Appendix) with less than 4% error.
In nonequilibrium conditions, bandgap narrowing increases the minority carrier current by:

1. Increasing the minority carrier concentration.
2. Decreasing the retarding built-in electric field acting on the minority carriers.

The increase in the minority carrier concentration \( n^2_{\text{ie}}(x) \) results from the increase in \( n^2_{\text{ie}}(x) \). The decrease of the built-in electric field is due to the position dependence of \( n^2_{\text{ie}}(x) \) (and hence of the effective bandgap) in the inhomogeneously doped emitter.

To develop a simple expression illustrating the reduction of the electric field, we now include only bandgap narrowing excluding the effect of Fermi-Dirac statistics for the present. Then the effective electric field acting on the minority carriers, given in (2), can be expressed by using (3) and (4) as:

\[
E(x) = A(N_0) \left[ -\frac{D_N}{\mu_N} \cdot \frac{1}{N_0(x)} \cdot \frac{dN_0(x)}{dx} \right]
\]

where

\[
A(N_0) = \left( 1 - \frac{N_0(x)}{\frac{d\Delta E_0(x)}{dN_0(x)}} \right)
\]

The factor \( A(N_0) \) measures the reduction of the built-in electric field due to bandgap narrowing. For any model of bandgap narrowing, \( A(N_0) \) is always less than one. Figure 1 shows \( A(N_0) \) as a function of the electron (majority carrier) concentration for three models of bandgap narrowing: Slotboom and DeGraaff [17], Hauser [18], and Lanyon and Tuft [19].
In the absence of bandgap narrowing, the holes experience a retarding electric field in an n-type diffused emitter. Equations (18) and (19) indicate that the position dependence of the bandgap narrowing, in effect, decreases the retarding electric field. The more it is decreased the smaller is the transit time for a specific surface recombination velocity. In (11) the transit time is shown to be a function of \( n_{ie}^2 \). In Figure 2 the transit time is plotted as a function of \( W_E \), the width of the quasi-neutral emitter region, in two cases: neglecting bandgap narrowing, and including bandgap narrowing (Slotboom and De Graaff model). Note that inclusion of bandgap narrowing makes the transit time close to the value it has if the impurity profile is flat. In general, bandgap narrowing decreases the transit time if the impurity profile is not flat.

Conversely, inclusion of Fermi-Dirac statistics increases the transit time as can be seen in Figure 2. Inclusion of Fermi-Dirac statistics shifts the value of the transit time closer to that calculated when heavy doping effects are neglected.

IV. Discussion

From (9), the minority carrier saturation current for a transparent emitter is

\[
J_{PO} = \frac{qD_p}{\int_0^{WE} \frac{DpN_0(W_E)}{n_{ie}^2(x)} \, dx + \frac{D_p N_0(W_E)}{S_p n_{ie}^2(W_E)}}
\]

(20)

If

\[
S_p \gg \frac{N_0(W_E)}{n_{ie}^2(W_E)} \cdot \frac{\bar{D}_p}{\int_0^{WE} \frac{N_0(x)}{n_{ie}^2(x)} \, dx}
\]

(21)
then (20) reduces to

\[
J_{\text{PO}} = \frac{qD_p}{\int_{0}^{\infty} \frac{W_E N_0(x)}{n_{ie}^2(x)} \, dx}
\]

which is the exact expression for an infinite surface recombination velocity. For

\[
S_p \ll \frac{N_0(W_E)}{n_{ie}^2(W_E)} \int_{0}^{\infty} \frac{W_E N_0(x)}{n_{ie}^2(x)} \, dx
\]

(20) reduces to

\[
J_{\text{PO}} \approx \frac{qS_p n_{ie}^2(W_E)}{N_0(W_E)}
\]

It is desirable to make \(J_{\text{PO}}\) small for the bipolar transistor. This results in a large emitter efficiency. For the p-n junction solar cell, if the emitter recombination current \(J_{\text{PO}}\) is small compared with the base recombination current, the value of \(V_{\text{OC}}\) can approach the classical theoretical limit.

To illustrate the dependence of \(J_{\text{PO}}\) on \(S_p\), consider the desirable case in the transparent-emitter model in which \(S_p\) is small enough to satisfy (23). Figures 3 and 4 show the variation of the emitter saturation current density, \(J_{\text{PO}}\), and the transit time, \(\tau_c\), as a function of \(S_p\) for three models of bandgap narrowing: Slotboom and De Graaff [17], Hauser [18], and the recent model of Lanyon and Tuft [19], which has the form.
\[ \Delta E_G = 22.5 \times 10^{-3} \left( \frac{N}{10^{18}} \right)^{1/2} \text{ eV} \]
for non-degenerately doped silicon, and
\[ \Delta E_G = 162 \times 10^{-3} \left( \frac{N}{10^{20}} \right)^{1/6} \text{ eV} \]
for degenerately doped silicon.

A Gaussian impurity profile is assumed with a surface impurity concentration of \(10^{20} \text{ cm}^{-3}\) and a junction depth of \(0.25 \mu\text{m}\). Full ionization of the impurity atoms is also assumed.

For values of \(S_p\) below \(10^6 \text{ cm/sec}\), \(J_{PO}\) and \(\tau_l\) vary rapidly with variations in \(S_p\), while for values of \(S_p\) above \(10^6 \text{ cm/sec}\), both \(J_{PO}\) and \(\tau_l\) saturate. \(J_{PO}\) saturates to its largest value, and \(\tau_l\) saturates to its lowest value. The largest value of \(J_{PO}\) at any \(S_p\) occurs for the Lanyon-Tuft model of bandgap narrowing.

The validity of the transparent emitter model is based on the condition that the minority carrier transit time is much smaller than the minority carrier lifetime: \(\tau_l \ll \tau_p\). To test this condition, \(\tau_l\) is calculated from (11). Values of \(\tau_l\) are plotted in Figures 4 and 5. In Figure 4, \(\tau_l\) is plotted as a function of \(S_p\) for the three models of bandgap narrowing (assuming \(W_E = 0.25 \mu\text{m}\)). While in Figure 5, values of \(\tau_l\) are plotted as a function of the quasi-neutral emitter region width, \(W_E\), for \(S_p = 5 \times 10^5 \text{ cm/sec}\).

The recombination lifetime \(\tau_p\) has an upper bound determined by the Auger band-to-band recombination at high impurity concentration.

To illustrate the self-consistency test for transparency, we assume the surface concentration of a diffused emitter to be \(10^{20} \text{ cm}^{-3}\). With the impurity profile assumed gaussian, this corresponds to an average
Auger lifetime of \( \tau_A = 2.4 \times 10^{-9} \) sec [20]. In Figures 4 and 5, we compare this lifetime with \( \tau_L \) for each of the three bandgap narrowing models (assuming that \( W_E = 0.25 \mu m \)). Note that the emitter is completely transparent if \( S_p \) exceeds \( 10^5 \) cm/sec and is opaque if \( S_p \) is below \( 10^4 \) cm/sec.

V. Application to p-n Junction Silicon Solar Cells

In this section, we apply the transparent-emitter model to calculate the open-circuit voltage of silicon p-n junction solar cells having low substrate resistivity.

The open-circuit voltage is given by

\[
V_{OC} = \frac{kT}{q} \ln \frac{J_{SC}}{J_0}
\]

(26)

where \( J_{SC} \) is the short-circuit current density and \( J_0 \) is the saturation current of the solar cell in the dark. The saturation current density \( J_0 \) of the diode is

\[
J_0 = J_{PO} + J_{NO}
\]

(27)

where \( J_{PO} \) is the emitter minority carrier saturation current density and \( J_{NO} \) is the base minority carrier saturation current density.

The base saturation current density is

\[
J_{NO} = \frac{q \mu n_s D_n}{N_{AA} L_N^2}
\]

(28)

Consider low-resistivity silicon solar cells with base doping concentration of \( N_{AA} = 5 \times 10^{17} \) cm\(^{-3} \). Measurements made on such cells indicated the minority carrier diffusion length, \( L_N \), to be 80 \( \mu m \) [21], corresponding to \( J_{NO} = 6.2 \times 10^{-14} \) A/cm\(^2 \). The general expression for
the transparent emitter current density, given in (8), has yielded
$J_{PO}$ as a function of $S_p$, as shown in Figure 3.

Combining these characterizations for $J_{NO}$ and $J_{PO}$ with $J_{SC} = 23 \text{ mA/cm}^2$
(AMO conditions) [22], we plot, in Figure 6, $V_{OC}$ versus $S_p$. For low $S_p$
(about $10^3 \text{ cm/sec}$), $V_{OC}$ is limited by the base current, and for higher
values of $S_p$, $V_{OC}$ is limited by the emitter current, as has been
observed experimentally [22]. Note that for $S_p > 10^5 \text{ cm/sec}$, $V_{OC}$
saturates to its lowest value. Note also that the Lanyon and Tuft
model of bandgap narrowing gives lower values of $V_{OC}$ (for any given
value of $S_p$) than those given by the Slotboom and De Graaff and
Hauser models.

So far we have assumed, for simplicity, that all of the emitter
surface is characterized by a single value of $S_p$. We now consider
a more realistic structure of silicon solar cells, Figure 7(a). The
emitter saturation current $J_{PO}$ is the sum of three components from
regions 1, 2, and 3 shown in Figure 7(b), [23]. The components of
the current density from the metal-covered surface, region 1, and
the nonmetal-covered surface, region 2, are given by (8). In region
3, the flow of minority carriers is two-dimensional since the minority
carriers within about a diffusion length from region 1 are much more
influenced by the high value of $S_p$ of region 1 than they are by the
relatively low value of $S_p$ of region 2. To avoid the complexity of
two-dimensional analysis, we make the first-order approximation that
the component of $J_{PO}$ from region 3 is essentially the same as that
from region 1 ($J_{P3} \equiv J_{P1}$) because $S_p$ of the unmetallized surface can be
made orders of magnitude smaller than $S_p$ of the ohmic contact.
The emitter saturation current is then

$$I_{p0} = (A_1 + A_3) \frac{J_{p01}}{A_l} + A_2 \frac{J_{p02}}{A_l}$$  \hspace{1cm} (29)$$

where $A_1$ is the metallized surface area and $(A_2 + A_3)$ is the unmetallized surface area and $J_{p01}$ and $J_{p02}$ are the corresponding currents. The area $A_3$ is approximately equal to

$$A_3 \approx 2 n L_G L_P$$  \hspace{1cm} (30)$$

where $n$ is the number of metal grid lines (or fingers), $L_G$ is the length of the grid lines (see Figure 7), and $A_2 = A_T - (A_3 + A_1)$, $A_T$ being the total area of the cell.

As a numerical example, let $A_T = 4$ cm$^2$, $L_G = 2$ cm, $n = 6$, $L_P \approx 1\mu$m, and assume 10% metal coverage. Then $A_1 \approx 0.4$ cm$^2$, $A_2 \approx 3.59$ cm$^2$, and $A_3 \approx 0.0024$ cm$^2$. In this case, $A_3$ is negligible, and

$$V_{OC} = \frac{kT}{q} \ln \left( A_1 \frac{J_{SC}}{A_T} \right) + \frac{J_{p01}}{A_T} + \frac{J_{p02}}{A_T} + J_{NO}$$  \hspace{1cm} (31)$$

This expression can be used to estimate $S_p$ of the nonmetallized surface from experimental values of $V_{OC}$. For diffused, thin-junction p-n junction solar cells made on low resistivity ($\approx 0.1$ $\Omega$-cm) material, the maximum observed open-circuit voltage is about 600 mV [22]. As one example, if we consider the Lanyon-Tuft model of bandgap narrowing, and let $S_p$ of the ohmic contact be $10^6$ cm/sec, let the doping concentration be gaussian with a surface concentration of $10^{20}$ cm$^{-3}$, then by using (31), with $A_1/A_T = 0.1$ and $V_{OC} = 600$ mV, we get $S_p$ (nonmetal) = $5 \times 10^6$ cm/sec. Thus this value for $S_p$ could result in the low $V_{OC}$ seen in conventional,
diffused, thin-junction solar cell. Note that Figures 4 and 5 indicate the self-consistent validity of the transparency assumption for this device in the Lanyon-Tuft model which permits use of (30).

Although the preceding discussion has focused on the transparent emitter model applied to n\textsuperscript{+}-p silicon solar cells, the model can also be applied to p\textsuperscript{+}-n cells. It is straightforward to show that heavy doping effects (bandgap narrowing and Fermi-Dirac statistics) degrade n\textsuperscript{+}-p cell performance more than that of p\textsuperscript{+}-n cells because the effective mass of electrons in silicon is greater than the effective mass of holes. The resulting different effective densities of states in the conduction and valence bands (N\textsubscript{C} and N\textsubscript{V}) cause the onset of degeneracy to occur at lower impurity concentrations in p-type material than in n-type material [13], if both n-type and p-type regions have the same bandgap narrowing. Thus the net effect of bandgap narrowing and Fermi-Dirac statistics is to degrade the n-type heavily doped region more than the p-type region with the same impurity concentration. This may, in part, be responsible for the high efficiency p\textsuperscript{+}-n-n\textsuperscript{+} cells that have been observed experimentally [24].

VI. Perspective

This paper has dealt with the transparent-emitter model of a solar cell, which is defined by the condition that the minority carriers in the dark quasi-neutral emitter recombine mainly at the surface rather than in the bulk. Surface recombination can predominate over bulk recombination if the emitter junction depth is shallow enough and if the surface recombination velocity is high enough. In fact, this occurs in typical pn-junction silicon solar cells, as demonstrated by recent
experiments showing the sensitivity of $V_{OC}$ to the surface recombination velocity \cite{1}. From a theoretical standpoint, the self-consistency test in Section IV can determine the validity, for a given solar cell, of the transparent-emitter model, provided the emitter recombination center density is low enough for the Auger process to dominate over the Shockley-Read-Hall process.

Although the transparent-emitter model may describe many conventional shallow pn-junction silicon solar cells, the high value of the surface recombination velocity $S$ necessary to validate the transparent-emitter model is not necessarily desirable from a design point of view. Growth of a thermal SiO$_2$ layer on the emitter surface can substantially decrease $S$ and increase $V_{OC}$, particularly if a high-low junction barrier is present near the emitter surface \cite{14}. For such devices, the dark emitter recombination current is determined mainly by bulk recombination.
Appendix

In thermal equilibrium, for a parabolic quantum density of states, the concentrations of charge carriers in a semiconductor are given by

\[ N_0 = N_C F_{\frac{1}{2}}(\eta_C) \] (A-1)

\[ P_0 = N_V F_{\frac{1}{2}}(\eta_V) \] (A-2)

where \( N_C \) and \( N_V \) are the effective density of states in the conduction and valence bands, respectively, \( F_{\frac{1}{2}} \) is the Fermi-Dirac integral of order \( \frac{1}{2} \), and

\[ \eta_C = (E_F - E_C)/KT \] (A-3)

\[ \eta_V = (E_V - E_F)/KT \] (A-4)

As suggested by Landsberg et al. [16], the analytic approximation

\[ F_{\frac{1}{2}}(\eta) = \frac{e^\eta}{1 + C(\eta)e^\eta} \] (A-5)

can be used in the range \(-4 \leq \eta \leq +10\). Here \( C(\eta) \) is a function of \( \eta \) given in figure 4 of [16].

Using (A-5) in (A-1) and (A-2), we can write

\[ N_0 = \frac{N_C e^{\eta_C}}{1 + C(\eta_C) e^{\eta_C}} \eta_C \] (A-6)
Thus, from (A-6) and (A-7),

\[ n_{ie}^2 (x) = N_0 P_0 = \frac{N_C N_V e^{-E_G(x)/KT}}{1 + C(\eta_C) e^\eta_C + C(\eta_V) e^\eta_V + C(\eta_C) C(\eta_V) e^{-E_G(x)/KT}} \]

(A-8)

where

\[ E_G(x) = E_{GO} - \Delta E_G(x) \]

(A-9)

in which \( E_{GO} \) is the bandgap of the intrinsic semiconductor, and \( \Delta E_G(x) \) is the bandgap narrowing due to heavy doping. For an n-type heavily doped region, \( \eta_V \ll 0 \) and \( C(\eta_V) = 0 \) in (A-8). Furthermore, the term \( C(\eta_C) C(\eta_V) e^{-E_G(x)/KT} \ll 1 \). Therefore, for a heavily doped n-type region, (A-8) reduces to

\[ n_{ie}^2 (x) = N_0 P_0 = \frac{\Delta E_G(x)/KT}{1 + C(\eta_C) e^\eta_C} \]

(A-10)

Similarly, for a p-type heavily doped region
\[ a_{ie}^2(x) = N_0 P_0 = \frac{n_i^2 e^{\Delta E_g(x)/kT}}{1 + C(\eta_V) e^{\eta_V}} \]  \hspace{1cm} (A-11)

In (A-10) and (A-11), \( n_i \) is the intrinsic concentration in the pure semiconductor.
REFERENCES FOR CHAPTER 3


[20] The average Auger recombination lifetime was calculated from a model similar to that of W. W. Sheng in "The Effect of Auger Recombination on the Emitter Injection Efficiency of Bipolar Transistors", IEEE Trans. Elec. Dev., Corres., ED-22, 25-27 (1975), in which the emitter is divided into two regions; one region has Shockley-Read-Hall recombination, and the surface region is dominated by Auger recombination.


Figure 1: The bandgap-narrowing reduction factor $A(N)$ versus the electron (majority-carrier) concentration $N$ for: (A) Lanyon-Tuft model, (B) Hauser model, and (C) Slotboom-De Graaff model.

Figure 2: The transit time $\tau_t$ versus the width of the emitter region $W_e$ for $S = 5 \times 10^5$ cm/sec and a gaussian profile with: no heavy doping (NHD), bandgap narrowing (Slotboom-De Graaff model) and Fermi-Dirac statistics (BGN+FD), bandgap narrowing (Slotboom-De Graaff model) only (BGN), and for a flat profile (NHD+FLAT).

Figure 3: The emitter saturation current density $J_{P0}$ as a function of the surface recombination velocity $S_p$, for $W_e = 0.25$ μm, Fermi-Dirac statistics and bandgap narrowing included: (A) Lanyon-Tuft, (B) Hauser, and (C) Slotboom-De Graaff. For low values of $S_p$ (less than about $10^4$ cm/sec) the self-consistency test yields $\tau_t > \tau_p$ so the emitter current is then due to Auger recombination and may be larger than values reported above.

Figure 4: $\tau_t$ as a function of surface recombination velocity $S_p$ for $W_e = 0.25$ μm, Fermi-Dirac statistics and bandgap narrowing are included: (A) Lanyon-Tuft, (B) Hauser, and (C) Slotboom-De Graaff.

Figure 5: $\tau_t$ versus $W_e$ for $S = 5 \times 10^5$ cm/sec. Fermi-Dirac statistics and bandgap narrowing are included: (A) Lanyon-Tuft, (B) Hauser, and (C) Slotboom-De Graaff.
Figure 6: $V_{OC}$ versus $S_p$ for $W_e = .25 \mu m$. Fermi-Dirac statistics and bandgap narrowing are included: (A) Lanyon-Tuft, (B) Hauser, and (C) Slotboom-De Graaff. In (D) heavy doping effects are not included. For low values of $S_p$ (less than $10^6 \text{ cm/sec}$) $V_{OC}$ is limited by the Auger-recombination current in the emitter because $\tau_e > \tau_p$ and $V_{OC}$ may be lower than values reported above.

Figure 7: (a) The structure of p-n junction solar cell

(b) The three components of the emitter current: $J_{P1}$, $J_{P2}$, and $J_{P3}$. 
\[ S = 5 \times 10^5 \text{ cm/sec} \]

FIGURE 2
FIGURE 5

\[ \tau_\parallel (\text{sec}) \]

\[ \begin{align*}
10^{-8} \\
10^{-9} \\
10^{-10} \\
10^{-11}
\end{align*} \]

\[ W_E (\mu\text{m}) \]

\[ S = 5 \times 10^5 \text{ cm/sec} \]
FIGURE 7
CHAPTER 4
HIGH-LOW-EMITTER SOLAR CELL

4.1 Introduction

As Brandhorst first noted [1] the power conversion efficiency \( \eta \) in silicon p-n junction solar cells is considerably less than the maximum theoretical value of \( \eta \) mainly because the open-circuit voltage \( V_{OC} \) is smaller than simple p-n junction theory predicts. Experiments [2] on \( n^+ \)-p silicon cells have shown that this discrepancy in \( V_{OC} \) results from the dominance, in the non-illuminated cell, of the emitter recombination current \( J_E \) over the base recombination current \( J_B \). In cells having base doping concentrations of the order of \( 10^{17} \text{ cm}^{-3} \), for which the largest values of \( V_{OC} \) are seen, \( J_E \) exceeds \( J_B \) by about an order of magnitude [2], rather than being several orders of magnitude less than \( J_B \) as is predicted by simple p-n junction theory. The excess \( J_E \) has been attributed to the mechanisms [3,4] of energy bandgap narrowing and lifetime degradation that accompany heavy doping concentrations in the \( n^+ \) emitter. The excess \( J_E \) may also arise, in part, from a large surface recombination velocity over the non-metallized portion of the surface.

To suppress \( J_E \) and thus raise the achievable values of \( V_{OC} \), a new structure, the High-Low-Emitter (HLE) solar cell has been proposed and its performance has been calculated on theoretical grounds [5-7]. This device contains a high-low junction near an emitter surface of low
surface recombination velocity. In the second section of this chapter we outline the theory underlying HLE solar cell behavior; then we discuss early experimental results on test devices employing the HLE structure. In particular, we focus on one category of HLE solar cell: the Oxide-Charge-Induced (OCI) HLE solar cell in which an electron accumulation layer is used to form a high-low junction [7,8].

4.2 Physical Basis Underlying Emitter Current Suppression in HLE Solar Cells

As is illustrated in Fig. 4.1(a), the HLE cell differs from the conventional p-n junction solar cell in that it contains a high-low junction in the emitter. The mechanisms underlying the suppression of the emitter current resemble, in part, those which suppress base current in Back-Surface-Field (BSF) solar cells: as the injected minority carriers (holes) diffuse across the lightly-doped n region into the n+ region, where the electron density is much higher, the partially reflecting boundary condition [9] at the high-low junction depresses the hole density near the emitter surface. In contrast to the BSF cell, however, in the HLE cell the emitter surface, which is close to the high-low junction, is designed to have a low surface recombination velocity $S_p$. The combination of low hole density and low $S_p$ results in a suppression of the injected hole current.

In Fig. 4.1(b) we contrast the spatial distributions of the excess hole concentrations in the quasi-neutral emitters of two structures: one, an HLE structure, the other, a structure with no H-L junction and with a large value of $S_p$. In this comparison, it is assumed that the holes injected from the base into the emitter recombine mainly at the emitter surface ($x=0$). Figure 4.1(c) shows qualitatively the effect
Figure 4.1 (a) High-Low-Emitter junction solar cell structure under external bias voltage $V_A$.

(b) Excess hole distribution in a HLE structure (dashed line) and in a structure with no H-L barrier and with high value of $S_p$ (solid line).

(c) Energy band diagram showing the Coulomb repulsion of injected holes by the H-L barrier.
of Coulomb-force repulsion associated with the high-low barrier on injected holes in the vicinity of the high-low junction.

To study the emitter current in the HLE structure more quantitatively, we make use of the discussion in Chapter 3 for the Back-Surface-Field solar cells. Analogous to (3.1), the emitter current in HLE structure can be decomposed into two components: \( J_{E}^{+} \), the current component due to recombination in the \( n^+ \) bulk and surface region and \( J_{E}^{-} \), the current component due to recombination in the \( n \) bulk region. Using the same notations as in (3.1), we write the total emitter current \( J_{p}(x_3) \) as

\[
|J_{p}(x_3)| = qS_{E} + q \frac{[\Delta P(x_2) + \Delta P(x_3)]}{2} \frac{W_{E}}{r_{p}} \tag{4.1}
\]

where the first term on the right hand side represents \( J_{E}^{+} \), the second term represents \( J_{E}^{-} \), \( S_{E} \) is the effective recombination velocity for holes at \( x = x_2 \), and the geometrical variables \( x_2 \), \( x_3 \), and \( W_{E} \) are as defined in Fig 4.1(a).

For good cell performance both \( J_{E}^{+} \) and \( J_{E}^{-} \)must be made small. The current \( J_{E}^{+} \)must be small so that the injected carriers can interact with the high-low barrier. This imposes the following conditions on the \( n \) region: (a) its hole lifetime must be long compared to the hole transit time across the \( n \) layer so that nearly all the holes injected from the base diffuse through to the high-low junction rather than recombining within the region, and (b) its doping concentration must be low enough (less than \( 10^{17} \) to \( 10^{18} \) \( \text{cm}^{-3} \)) to avoid the effects of energy band-gap narrowing and severe hole lifetime degradation. These considerations suggest that a 5 to 20 \( \mu \text{m} \) thick \( n \)-type epitaxial layer with resistivity in the range of 0.1 \( \Omega \)-\text{cm} to 1 \( \Omega \)-\text{cm} would be appropriate.
Note that higher conductivity offers the advantage of reducing the lateral component of series resistance.

We next investigate $J^+_E$, the recombination current component in the $n^+$ region. For concreteness in the discussion, we assume for now that the $n^+$ region is formed by a heavy doping concentration of donor atoms, resulting from diffusion or ion implantation or some other method of fabrication. A later discussion, in Section 4.3, generalizes to include the possibility that the large electron concentration in the $n^+$ region is formed without heavy doping as in the OCI-HLE solar cell.

For this diffused (or ion-implanted) HLE device, we assume the $n^+$ region to be thin enough that all the holes recombine mainly at the surface which can be characterized by a surface recombination velocity $S_P$. We further assume the quasi-neutral $n^+$ region to be field-free, as a result of the built-in electric field due to the doping gradient being balanced approximately by the quasi-field due to the gradient of the energy band-gap narrowing $\Delta E_G(x)$. Solution of the continuity equation for holes then yields [7].

$$|J^+_E| = \frac{q n_i^2 (x_1)}{N_{DD}(x_1)} \cdot \left[ \frac{1}{S_P} + \frac{1}{D_F/W^+_E} \right]^{-1} \left[ \exp(qV_A/kT) - 1 \right]$$

(4.2)

where $D_F$ is the hole diffusivity, $W^+_E$ is the thickness of the quasi-neutral $n^+$ region, $x_1$ is the quasi-neutral region edge of the high-low junction nearest the surface, $N_{DD}$ is the doping concentration, and $n_i^2$ is the effective intrinsic density squared which can differ from $n_{i0}^2$, the intrinsic density squared for intrinsic silicon because of the effects of Fermi-Dirac statistics [10] and energy band narrowing [3,11].
In the field-free model for the $n^+$ region [10], note that

$$n_{ie}^2(x_1) / N_{DD}^+ (x_1) = n_{ie}^2 (x) / N_{DD}^+ (x) \quad (4.3)$$

where $x$ is any point in the $n^+$ region. This relation can simplify the quantitative use of (4.2) in analysis.

For a well passivated surface, $S_p$ is low and often $W_E$ is thin enough that $D_p/W_E^+$ is much larger than $S_p$. Under this assumption, the total emitter current is

$$|J_p(x_3)| = \left[ \frac{q \, n_{ie}^2 S_p}{N_{DD}^+} + \frac{q \, n_{io}^2 W_E}{N_{DD}^+} \right] \left[ \exp(qV_A/kT) - 1 \right]. \quad (4.4)$$

Here we assume $\Delta P(x_2) = \Delta P(x_3) = n_{io}^2 / N_{DD}$, where $N_{DD}$ is the doping concentration in the $n$ region.

Provided that the bulk recombination in the $n$-type region is negligible, the emitter current is then

$$J_p(x_3) = \frac{q \, n_{ie}^2 S_p}{N_{DD}^+} \left[ \exp(qV_A/kT) - 1 \right]. \quad (4.5)$$

The same suppression would occur in a conventional $n^+ - p$ solar cell if all the holes were transported across the emitter to the surface and if the surface were passivated to reduce $S_p$. The advantage of the HLE structure is that the $n^+$ layer of the HLE cell can be made very thin ($\leq 1000 \, \text{Å}$) with lower doping concentration to decrease the heavy-doping effects. The lower sheet resistance of the $n^+$ layer will be compensated by the parallel resistance of the $n$-type epitaxial layer. The low-doped emitter epitaxial region will contribute significantly to the short-circuit current, since for low $S_p$, most of the optically
generated carriers will be collected by the p-n junction. The low doping of the n region is consistent with long minority-carrier lifetime which enables the achievement of a high collection efficiency.

In the Oxide-Charge-Induced HLE structure, which we will study in the following section, the emitter current is suppressed so low by the surface and the high-low barrier that the base current $J_B$ alone determines the dark current.

4.3 Oxide-Charge-Induced HLE Solar Cell: Structure, Fabrication, and Performance

4.3.1 Structure

As is shown in Fig. 4.2, the high-low junction in the emitter results from an electron accumulation layer induced in the n-type epitaxial emitter region by a positive oxide charge $Q_{OX}$. The charge $Q_{OX}$ is created near the silicon-silicon dioxide interface during a low-temperature oxygen heat treatment [12]. Experiments on MOS capacitors indicate that the positive oxide charge $Q_{OX}$ resides within about 300 Å from the silicon-silicon dioxide interface and strongly depends on the last high temperature process and the crystal orientation [12,13]. For <111> wafers annealed in 700°C dry oxygen, $Q_{OX}$ is found to be about $5.5 \times 10^{11}$/cm$^2$ [12,13]. The total charge accumulated near the silicon surface is approximately $Q_{OX}$. The electron distribution is described by MOS theory [26], and most of the electrons in the accumulation layer reside within about three extrinsic Debye lengths from the surface.

For the above value of $Q_{OX}$, the electron surface concentration is about $9.3 \times 10^{17}$ cm$^{-3}$ for $\rho_{epi} = 1.5$ Ω-cm and about $1.2 \times 10^{18}$ cm$^{-3}$ for $\rho_{epi} = 0.1$ Ω-cm. To assure a good ohmic contact, a shallow phosphorous diffusion is
Figure 4.2 Cross section of an oxide-charge-induced high-low-emitter (OCI-HLE) solar cell. Electron accumulation layer is induced by a positive oxide charge $Q_{OX}$. 
made under the metallized portion of the top surface area. This n+ diffusion also provides a high-low barrier and a small effective surface recombination velocity [9] for holes. The p-type base has a doping concentration \( N_{AA} = 5 \times 10^{17} \text{ cm}^{-3} \), which approximately minimizes \( J_B \) in a cell without a back-surface field [1].

From a device performance point of view, the oxide-charge-induced H-L structure of Fig. 4.2 is an attractive realization of the HLE solar cell because it avoids a high concentration of donor impurity atoms in the thin H layer near the surface. This diminishes some sources of degrading heavy-doping effects [3], such as some mechanisms that give rise to band-gap narrowing [14] and hole lifetime degradation in the H layer, and it can also help the achievement of low values of surface recombination velocity. The avoidance of a diffusion step to form a highly-doped H layer eliminates, over the nonmetallized portion of the surface, the diffusion of unwanted impurities and vacancies into the silicon along with the donor atoms. These advantages can result without the occurrence of a large lateral component of the series resistance \( R_s \), and consequent degradation of the fill factor \( FF \) [15], because the thickness and doping concentration of the L portion of the H-L junction can be adjusted to supply the needed lateral conductance. For applications in concentrated sunlight, this is particularly important.

The preceding section contains expressions for the dark emitter current for the diffused (or ion-implanted) HLE. These were based on a field-free model of the n+ region in which the built-in electric field and the quasi-field nearly cancelled one another. For the OCI-HLE solar cell, however, this is an inappropriate model because the gradient of the energy band gap that produces the quasi-field is small for the
low values ($\approx 10^{18}$ cm$^{-3}$) of electron concentration induced at the surface while the electron concentration can change by several orders of magnitude in a Debye length thereby producing a large built-in electric field. To derive an expression for the dark emitter current in the OCI-HLE cell, note that the large electron concentration and the desired suppressed hole current suggest that the quasi-Fermi levels for both electrons and holes are nearly flat throughout the emitter region, as Fig. 4.1(b) indicates. Then by multiplying together the expressions for the electron and hole densities (in terms of the quasi-Fermi levels), one finds the excess hole density at the surface. If the injected holes recombine mainly at the surface, which is a preferred design for the reasons indicated in the preceding section, then the surface excess hole density times $q_S$ gives the magnitude of the dark emitter current:

$$|J_p| = q_S \frac{n_{ies}^2}{N_s} [\exp (qV_A/kT)-1]$$

(4.6)

where $N_s$ is the electron concentration at the surface and $n_{ies}^2$ is the effective intrinsic density squared at the surface. It can differ from $n_{10}^2$ even though the electron concentration $N_s$ is low because of the effects of minority-carrier screening by the majority carriers [14,16] and of Fermi-Dirac statistics [10]. Note that (4.6) is essentially the same as (4.5) for the field-free model of the used (or ion-implanted) HLE cell. Indeed, an alternate, but not equivalent, derivation of (4.5) could follow the reasoning directly above employing the near flatness of the quasi-Fermi levels in the emitter region.
4.3.2 Fabrication

The fabrication of the OCI-HLE solar cell is simple. A major portion of the devices fabricated in this study are made using the following basic processing steps:

1. Wafer cleaning.
2. Thermal oxidation of silicon surfaces.
3. Defining ohmic contact windows on front surface using photolithographic process (mask #1).
4. Phosphorous diffusion through contact windows.
5. Low temperature oxygen annealing.
6. Etching oxides over contact windows.
7. Metal deposition on front surface.
8. Defining metal grid pattern on front surface by photolithographic process (mask #2).
9. Lapping the back surface.
10. Metal deposition on back surface.
11. Annealing the wafer in forming gas (10% hydrogen, 90% nitrogen).

Details regarding processing temperature and time for devices fabricated using the above schedule are summarized in Appendix II and Appendix III. We have also fabricated some devices using processing schedules that are slightly different from the above and they are also listed in Appendix III. The layout of masks used are shown in Appendix IV.

4.3.3 Performance of OCI-HLE Cells

We now discuss the experimental results of process runs number 25 and 26. The starting material for run #25 is <111> p-type Czochralski-grown wafer with a 10 μm, 1.4 Ω-cm n-type arsenic-doped epitaxial
layer. The p base is boron-doped with a resistivity of 0.14 Ω-cm and a thickness about 300 μm. The wafer was oxidized in dry oxygen with 0.3% trichloroethylene (TCE) at 1100°C for three hours to grow a 2500 Å thick oxide. The temperature of 1100°C was chosen for this cell to assure a good quality oxide and a low value of surface recombination velocity. Holes were opened in the oxide for a phosphorous diffusion done at 900°C for 15 minutes. The phosphosilicate glass was etched off and the wafer was heat treated in dry oxygen for two hours at 700°C to increase the oxide charge $Q_{OX}$ [12]. The thin oxide over the contact opening was then etched and the field oxide was thinned to 1100 Å to improve the antireflection properties. An aluminum grid pattern was defined photolithographically on the front surface. The back surface was lapped in silicon carbide abrasive powder, and aluminum was evaporated on the back surface. The wafer was then annealed in forming gas at 450°C for 15 minutes. This serves to anneal the surface states at the silicon-silicon dioxide interface [17] as well as to make the aluminum-silicon contact ohmic. The wafer was then scribed into cells of different sizes. It is found that the scribing process introduces crystal damages at the periphery of the cell. The effect manifests itself as an edge recombination current in the current-voltage characteristics of the cell. Although the magnitude of this current is insignificant at higher voltages (> 0.6 V), its presence at lower voltages can often decrease the fill factor and hinder proper data analysis, for example, the determination of the quasi-neutral saturation current [18]. To eliminate this current component, all finished cells are etched in CP4 solution (3 parts hydrofluoric acid, 5 parts nitric acid, 3 parts acetic acid) for 10 minutes. The front
and back surfaces of the cells are protected by wax while the edges are left clear of wax during the etching.

The base diffusion length $L_n$, measured using the X-ray excitation method [19] was $L_n = 20 \mu m$. Measurement of the dark I-V characteristics shows that the ideal saturation current (determined by subtracting the space-charge-region recombination current [18]) is $2.9 \times 10^{-13} \text{Amp/cm}^2$ at $294.8^\circ K$. The corresponding base saturation current at this temperature, $q n_0^2 D_n/(N_A L_n)$, is $2.8 \times 10^{-13} \text{Amp/cm}^2$. This demonstrates that $J_e \ll J_b$. Thus the open-circuit voltage $V_{OC}$ is determined mainly by $J_b$ in this device. The results of the measurements show further that the emitter saturation current $J_{EO}$ is suppressed to less than about $1.5 \times 10^{-14} \text{Amp/cm}^2$, assuming an experimental uncertainty of 5%.

This current component corresponds to a voltage, $kT/q \ln(J_{SC}/J_{EO}) > 720 \text{mV}$, for a short-circuit current density $J_{SC}$ of $35 \text{mA/cm}^2$ (measured in this device). Thus $J_e$ is suppressed to values so low that it presents no barrier to the achievement of $V_{OC} = 700 \text{mV}$, which is the maximum value of $V_{OC}$ predicted by classical theory for a 0.1 $\Omega$-cm base resistivity for Air-Mass-Zero (AMO) illumination.

The experimental setup for the $V_{OC}$ and $J_{SC}$ measurements is shown in Fig. 4.3. The light source is a General Electric 300 watt ELH lamp. The standard cell is a diffused HLE solar cell which has $J_{SC} = 36.7 \text{mA/cm}^2$ and $V_{OC} = 620 \text{mV}$ at $25^\circ C$ under AMO conditions as measured by NASA Lewis Research Center. The value of $J_{SC}$ for the standard cell, as well as for all cells we measured, are calculated on an per-effective-area basis.

For the $V_{OC}$ measurement, both standard and test cell are placed side by side and the intensity of the light source is adjusted by a
Figure 4.3 Experimental setup for $V_{OC}$ and $J_{SC}$ measurement.
variatic such that $V_{OC}$ of the standard cell is 620 mV. A reading on
the test device is then taken. This value of $V_{OC}$ is then the $V_{OC}$
of the test cell at 25°C. This method works even when the ambient
temperature is slightly different from 25°C since the change in $V_{OC}$
with temperature is mainly due to the change of $n_{10}^2$ for both the
standard and the test device. Likewise, for the $J_{SC}$ measurement, the
$J_{SC}$ of the test device, as measured by a high impedance voltmeter across
the 1 Ω resistor, is taken when the short-circuit current in the standard
cell corresponds to a value of 36.7 mA/cm$^2$. The experimental accuracy
is about ±3mV for $V_{OC}$ and ±0.3 mA/cm$^2$ for $J_{SC}$, determined by comparing
with the measurements done at NASA Lewis Research Center on the same
devices.

The open-circuit voltage measured on devices of Run #25 is
$V_{OC} = 627$ mV at 25°C and AM0 illumination, the short-circuit current
density is $J_{SC} = 35.5$ mA/cm$^2$.

For Run #26, the starting material is different from that of Run #25.
It is a <111> p type Czochralski-grown wafer with a 10μm, 0.1 Ω-cm
n-type arsenic-doped epitaxial layer. The p-type substrate is boron-
doped with a resistivity of 0.1 Ω-cm. The processing schedule for
Run #26 is summarized in Appendix III. For this device, the emitter
current again is completely suppressed. The measured $V_{OC}$ is 634 mV
at 25°C and $J_{SC}$ is 32.8 mA/cm$^2$. Although the base diffusion length
for these devices is only about 13 μm, the higher doping concentration
and lower electron diffusivity reduce the base recombination current so
that $V_{OC}$ is higher than that of Run #25. The smaller value of $J_{SC}$ is
probably due to the heavier-doped epitaxial layer and a shorter base
diffusion length.
Although the emitter current is suppressed in these devices, the results suggest that if the base diffusion length of these wafers can be improved, better cell performance can be expected. One approach would be to modify the fabrication procedures, particularly the higher temperature steps, to achieve a longer base diffusion length. Another approach would be to obtain better quality starting material. We will discuss these approaches in the next section.

4.4 Fabrication Considerations for OCI-HLE Junction Solar Cells

In Section 4.3 we have discussed the experimental results of process runs #25 and #26 which were the first runs made. It is noted that the degrading effects of heavy doping concentration and large surface recombination in the emitter region have been avoided in the OCI-HLE junction solar cell so that the open-circuit voltage in these cells is determined primarily by the base recombination current. However, the base minority-carrier lifetime in these devices is more than an order of magnitude lower than that of conventional n⁺-p solar cells fabricated on substrate materials with about the same doping concentration. Diffusion lengths in the substrates of wafers used in Run #25 and #26 before processing were about 50 μm and 25 μm respectively, compared to a diffusion length of about 100 μm measured on some 0.1 Ω-cm substrates without the epitaxial layer. The low values of lifetime observed in these epitaxial wafers is probably due in part to the poor starting substrate, and to the defects or impurities introduced into the substrate during the epitaxial growth. The introduction of stacking faults during the initial high temperature oxidation can also reduce the bulk lifetime.
In this section we discuss the results of a sequence of device runs that employ fabrication schedules designed to improve the bulk minority-carrier lifetime compared to the schedules used for Run #25 and #26. These methods include the use of phosphorous gettering for metallic impurity removal [20] (Run #27), lower oxidation temperature (Run #31, #32), slow cooling of wafers after high temperature processes (Run #35, #36), and prolonged high temperature oxidation in the presence of chlorine compounds for annihilation of oxidation-induced stacking faults [21-23] (Run #48). Not all of these methods are suitable for the OCI-HLE solar cell fabrication since some of these processes may cause degradation in the emitter region, such as an increase in surface recombination velocity. The purpose of this study is to implement the most compatible method to improve the open-circuit voltage of the device. The relevant descriptions of the epitaxial wafers used for these runs are listed in Appendix III.

To find the bulk lifetime of the starting material, measurements were performed utilizing the existing p-n junction between the epitaxial layer and the substrate (Run #28). A low temperature $n^+$ phosphorous layer was diffused into the epitaxial wafer. This provides a better electrical contact to the lightly-doped epitaxial layer. The $n^+$ layer at the back side was removed and ohmic contacts at both surfaces of the wafer were created by evaporating Ti-Ag to both surfaces. Several 1 cm x 1 cm diodes were scribed from the middle of the wafer and the edges were etched in CP4 solution. Diffusion lengths in these devices were measured using the X-ray irradiation technique. The results were $L_n = 50 \mu m$ for the 0.15 $\Omega$-cm bulk material and $L_n = 25 \mu m$ for the 0.1 $\Omega$-cm material.
We now discuss the results of Run #27, 31, 32, 35, 36, and 48. The starting material of Run #27 is the same as Run #26 and except for an additional phosphorous gettering step the two runs are identical. The bulk diffusion length measured is about 15 μm, which is about the same as that for Run #26. While phosphorous gettering is known to result in significant improvement of bulk lifetime in lightly-doped materials [24], the ineffectiveness of this method to improve the bulk properties of these heavier-doped substances suggests that metallic impurities are not the dominant factors limiting the bulk lifetime in these materials. The result is consistent with the observed decrease in bulk diffusion length with higher substrate doping concentrations [25].

Run #31 and #32 investigate the possibility of improving bulk lifetime using lower oxidation temperatures. The main differences between these runs and the previous ones are the 900°C wet oxidation step (Run #31) and the 800°C dry oxidation step (Run #32). Details of the fabrication schedule are summarized in Appendix III. The diffusion lengths measured on these devices are low in comparison with that of Run #28. The open-circuit voltages of these devices are also low. Analysis of dark I-V characteristics [18] shows that the recombination current in the emitter region is significant. The results are displayed in Table 4.1. The low values of open-circuit voltages observed suggest the presence of a high density of surface states at the silicon-silicon dioxide interface as indicated by a control MOS capacitor made on 1 Ω-cm n-type wafers as shown in Fig. 4.4.

In Run #35 the epitaxial wafers are cooled slowly in nitrogen after the 1100°C oxidation and the 850°C phosphorous diffusion. In
Figure 4.4 C-V plot for control MOS capacitor of Runs #31 and #48.
Run #36 the wafers were cooled in an oxygen ambient. For devices of Run #35, the diffusion lengths measured were $L_n = 54 \mu m$ for cells fabricated on 0.15 $\Omega$-cm substrate and $L_n = 21 \mu m$ for cells fabricated on 0.1 $\Omega$-cm substrate. If the emitter recombination current is suppressed and the space-charge region recombination current is small, the open-circuit voltages of these devices would be about 660 mV and 650 mV at 25°C respectively. However, the observed $V_{OC}$ is only 604 mV for cells made on the 0.15 $\Omega$-cm material and 623 mV for cells made on the 0.1 $\Omega$-cm material. Analysis of dark I-V characteristics reveals that the emitter recombination current in these devices constitutes about 90% and 60%, respectively, of the total quasi-neutral region recombination current. The results again suggest the influence of surface states associated with low temperature oxides [12,13]. The diffusion length for devices of Run #36 is $L_n = 35 \mu m$ for the 0.15 $\Omega$-cm material. The degradation in $L_n$ is probably due to prolonged heat treatment in oxygen.

In Run #48 the wafers are oxidized in 1150°C for 5 hours with 1.5 l/min dry oxygen with 0.3% TCE. An oxidation time of five hours was chosen with the intent to suppress the oxidation-induced stacking faults (OISF) [21,22]. Following the standard $n^+$ contact diffusion the phosphosilicate glass is etched off and the wafers are annealed in dry oxygen at 700°C for 2 hours. The diffusion lengths for this run are $L_n = 50 \mu m$ for the 0.15 $\Omega$-cm material and $L_n = 23 \mu m$ for the 0.1 $\Omega$-cm material. Although we have obtained long diffusion lengths for these materials, the open-circuit voltages of these devices are still low. They are 606 mV and 622 mV respectively. Capacitance-Voltage measurement on control MOS capacitors made on 1 $\Omega$-cm n-type wafers indicates the surface state density is low, as would be expected for
higher temperature oxides (Fig. 4.4). The low values of $V_{OC}$ are due to an inadequate density of oxide charge to induce a sufficient high-low barrier ($Q_{OX}/q=4.2\times10^{11}\text{ cm}^{-2}$). In Run #51 we repeat Run #48 except the wafers are annealed in dry oxygen at 700°C for 12½ hours to allow more time to form the oxide charges ($Q_{OX}/q=5.5\times10^{11}\text{ cm}^{-2}$). The results are $L_n=34\text{ m}, V_{OC}=635\text{ mV}$ for the 0.15 Ω-cm material and $L_n=16\text{ m}, V_{OC}=659\text{ mV}$ for the 0.1 Ω-cm material. We have also fabricated devices using epitaxial wafers with heavily-doped (0.025 Ω-cm) substrates. $V_{OC}$ of 640 mV has been obtained. These results emphasize the importance of the properties of the front surface.

Although the values of $L_n$ are smaller for Run #51 than Run #48, values for $V_{OC}$ are higher due to a more effective high-low barrier.

We have discussed several approaches of OCI-HLE solar cell fabrication to improve the open-circuit voltage. It is important that these devices have a well passivated surface with low recombination velocity as well as long diffusion length in the substrate for good cell performance. Oxidation in dry oxygen at elevated temperatures with TCE, followed by low temperature dry oxygen annealing was found to be the best approach for the silicon materials used in this study. In Table 4.1 we summarize all pertinent results obtained for the devices under study. In Table 4.2 we characterize the surface properties of the OCI-HLE solar cells under study. The oxide charge density $Q_{OX}/q$ is obtained from the flatband voltage shift in the C-V plot for control MOS capacitors, the electron concentration at the surface $N_s$ follows from classical MOS theory [26], and the surface recombination velocity $S_p$ is evaluated using (4.6).
<table>
<thead>
<tr>
<th>Run #</th>
<th>Wafer</th>
<th>$\rho_{\text{base}}$ (Ω·cm)</th>
<th>$A$ (cm$^2$)</th>
<th>$A_e$ (cm$^2$)</th>
<th>$T$ (K)</th>
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<td>0.99</td>
<td>0.75</td>
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<td>0</td>
<td></td>
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<td>293.1</td>
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Table 4.1 (extended)

| L_n (μm) | J_QNO (Amp/cm²) | J_BO (Amp/cm²) | J_EO (Amp/cm²) | V_OC|25°C (mV) | I_SC/Ae (mA/cm²) | Fill Factor |
|----------|-----------------|----------------|----------------|----------|---------------|-----------------|
| 20.1     | 2.86x10^-13     | 2.83x10^-13    | <1.5x10^-14    | 627*     | 35.5*         | 0.762*         |
| 13.5     | 1.90x10^-13     | 1.90x10^-13    | <1.0x10^-14    | 634*     | 32.8*         | 0.801*         |
| 14.1     | 1.87x10^-13     | 1.87x10^-13    | <1.0x10^-14    | 635      | 32.8          |                |
| 49.4     |                 |                |                |          |               |                |
| 26.6     |                 |                |                |          |               |                |
| 19.3     | 1.40x10^-12     | 2.94x10^-13    | 1.11x10^-12    | 584      | 32.2          |                |
| 9.6      | 3.39x10^-12     | 5.94x10^-13    | 2.80x10^-12    | 566      | 29.4          |                |
| 26.3     | 7.50x10^-13     | 1.61x10^-13    | 5.89x10^-13    | 603      | 28.7          |                |
| 53.5     | 7.93x10^-13     | 8.36x10^-14    | 7.10x10^-13    | 605      | 35.2          |                |
| 21.0     | 3.16x10^-13     | 1.28x10^-13    | 1.88x10^-13    | 623      | 31.3          |                |
| 34.5     | 7.05x10^-13     | 1.30x10^-13    | 5.75x10^-13    | 602      | 33.6          |                |
| 49.9     | 5.62x10^-13     | 7.83x10^-14    | 4.84x10^-13    | 606      | 34.6          |                |
| 22.7     | 3.85x10^-13     | 1.16x10^-13    | 2.69x10^-13    | 622      | 32.7          |                |
| 33.8     | 1.73x10^-13     | 1.20x10^-13    | 5.30x10^-14    | 635*     | 36.0*         | 0.717*         |
| 17.0     | 2.13x10^-13     | 1.60x10^-13    | 5.30x10^-14    | 639*     | 34.3*         | 0.806*         |
| 2.5      | 1.25x10^-13     | 4.00x10^-14    | 8.50x10^-14    | 640*     | 29.1*         | 0.739*         |
Table 4.2 Characterization of Surface Properties of OCI-HLE Solar Cells Fabricated.

<table>
<thead>
<tr>
<th>Run #</th>
<th>Wafer</th>
<th>$Q_{ox}/q$ (cm$^{-2}$)</th>
<th>$N_s$ (cm$^{-3}$)</th>
<th>$S_p$ (cm/sec)*</th>
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<td>$4.8 \times 10^{11}$</td>
<td>$6.9 \times 10^{17}$</td>
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<tr>
<td></td>
<td>9900AQ</td>
<td>$5.8 \times 10^{11}$</td>
<td>$1.0 \times 10^{18}$</td>
<td>$2.4 \times 10^{5}$</td>
</tr>
<tr>
<td>32</td>
<td>9900AQ</td>
<td>$3.3 \times 10^{11}$</td>
<td>$3.3 \times 10^{17}$</td>
<td>$2.4 \times 10^{4}$</td>
</tr>
<tr>
<td>35</td>
<td>9900AP</td>
<td>$5.9 \times 10^{11}$</td>
<td>$1.1 \times 10^{18}$</td>
<td>$6.2 \times 10^{4}$</td>
</tr>
<tr>
<td></td>
<td>MONSANTO</td>
<td>$5.9 \times 10^{11}$</td>
<td>$1.3 \times 10^{18}$</td>
<td>$2.6 \times 10^{4}$</td>
</tr>
<tr>
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<td>$8.5 \times 10^{11}$</td>
<td>$2.2 \times 10^{18}$</td>
<td>$1.3 \times 10^{5}$</td>
</tr>
<tr>
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<td>$5.2 \times 10^{17}$</td>
<td>$3.1 \times 10^{4}$</td>
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<td>$7.2 \times 10^{3}$</td>
</tr>
<tr>
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<td>$2.4 \times 10^{17}$</td>
<td>$2.3 \times 10^{3}$</td>
</tr>
</tbody>
</table>

* UPPER limit (recombination losses in the n-type epitaxial layer neglected)
4.5 Additional Experiments

About 20 additional runs were made using wet oxidation in a temperature range of 1100-1150°C. The oxidation time was 15-45 min. Best results obtained using wet oxides to date were: (a) $V_{OC} = 647$ mV for a Motorola wafer described in Appendix III with base resistivity of 0.024 Ωcm, and (b) $V_{OC} = 643$ mV for wafer with 0.1 Ωcm base resistivity and an 8 μm, 0.15 Ωcm epitaxial layer. These results are reproducible and were repeated at least five times. The values of $V_{OC}$ using wet oxides were always above 640 mV in all runs.

Wet oxidation at high temperatures has several advantages compared to dry oxidation for the fabrication of the OCI-HLE cells:

(a) Shorter oxidation times are required to grow about 2000 Å $\text{SiO}_2$. This will reduce the damage to both the substrate and epitaxial layers that results from long (\textgreater 5 hrs) dry thermal oxidation.

(b) Oxidation temperatures of about 1100°C were sufficient to obtain $V_{OC} = 640$ mV compared to 1150°C required for dry oxide.

(c) Wet oxides have a smaller density of surface states at the $\text{Si}-\text{SiO}_2$ interface and a higher density of oxide charge, resulting in smaller values for $S_{eff}^+$. One fabrication run using a diffused $n^+n$ HLE junction was done. This run used the 0.1 Ωcm p-type Monsanto substrate (Appendix III). Phosphorous was diffused into the entire area of the epitaxial emitter at 850°C for 15 min, followed by a thermal oxidation at 900°C for 10 min in a dry-wet oxygen ambient. This device had $V_{OC} = 625$ mV and a dark emitter recombination current $J_{E0} = 3 \times 10^{-13}$ A/cm$^2$ at 25°C, AM0.
REFERENCES FOR CHAPTER 4


APPENDIX I

PROGRAM TO ANALYZE TRANSISTOR AND DIODE I-V CHARACTERISTIC

DIMENSION V(100), AMP(100), X(100), Y(100)
REAL MX, Ixo, IX, ID, ISAT
CHARACTER*10 DEVICE, DATE
1 FORMAT(F10.3)
2 FORMAT(2F10.2, I10)
3 FORMAT(8E10.3)
4 FORMAT(9X, 'V', 12X, 'I(DATA)', 9X, 'ISAT '/)
5 FORMAT(F10.3, 1PE20.4)
6 FORMAT(F10.3, 1PE20.4, E16.4)
7 FORMAT(9X, 'T=', F9.3/)
8 FORMAT(F10.3, 1PE11.4)
9 FORMAT('O',' T=', F9.3/)
11 FORMAT(9X, 'DATE:', A10, ' DEVICE NUMBER: ', A10, 
11 'SOLAR CELL PROJECT, UNIVERSITY OF FLORIDA', 'GAINESVILLE, FLORIDA' /1X, 'PROGRAM PA05 I - V DATA', 'FITTING'/)
22 FORMAT(2A10)

C THIS PROGRAM COMPUTES MX AND Ixo FROM A SET OF PRECHOSEN I-V DATA
C POINTS AT LOWER BIASES WITH INITIAL VALUE AT V1 AND SUBSEQUENT VALUES
C AT DV1 APART. THE CONTRIBUTION OF THIS COMPONENT AT HIGHER BIASES
C IS SUBTRACTED FROM THE ACTUAL MEASURED DATAS AT HIGHER BIASES
C (STARTING AT V2 WITH AN INCREMENT OF DV2) TO OBTAIN THE DIFFUSION
C COMPONENT ID. ISAT IS CALCULATED USING ISAT = ID/EXP(V/VT)
C N1 = NUMBER OF DATA POINTS FOR MX, Ixo FIT
C N2 = NUMBER OF DATA POINTS FOR ISAT CALCULATION
C MX = SLOPE FACTOR OF LOWER PORTION OF I-V CURVE
C Ixo = PRE-EXPONENTIAL FACTOR FOR LOWER PORTION OF I-V CURVE
C IX = SPACE-CHARGE COMPONENT AT BIAS V
C ID = DIFFUSION COMPONENT AT BIAS V
C VT = KT/Q
C ISAT = ESTIMATED DIFFUSION SATURATION CURRENT. THERE WILL BE A
C RANGE OF VOLTAGES THAT ISAT IS APPROXIMATELY CONSTANT (VALUES
C OF ISAT AT LOWER BIASES CALCULATED USING THIS ALGORITHM ARE NOT
C THE REAL VALUES OF DIFFUSION SATURATION CURRENT DUE TO THE
C DOMINANCE OF SPACE-CHARGE RECOMBINATION CURRENT AND VALUES OF
C ISAT AT HIGHER VOLTAGES ARE ALSO NOT THE TRUE VALUES OF DIFFUSION
C SATURATION CURRENT DUE TO THE EFFECTS OF SERIES RESISTANCE).
C A SINGLE VALUE OF ISAT CAN BE OBTAINED BY AVERAGING ALL VALUES
C OF ISAT IN THE VOLTAGE RANGE WHERE THEY ARE APPROXIMATELY
C CONSTANT.
C
888 READ(5, 222) DEVICE, DATE
READ(5, 1) T
IF (T.LE.0) GO TO 999
READ (5,2) V1, DV1, N1
READ (5,3) (AMP(I), I=1,N1)
VT = T*8.616E-5
DO 10 I=1,N1
  V(I) = V1 + (I-1)*DV1
  X(I) = V(I)/VT
10 Y(I) = ALOG(AMP(I))
   CALL LSQ3 (X,Y,N1, MX, I XO)
   I XO = EXP (IXO)
   WRITE (6,111) DATE, DEVICE
   WRITE (6,4)
   DO 20 I=1,N1
20 WRITE (6,5) V(I), AMP(I)
READ (5,2) V2, DV2, N2
READ (5,3) (AMP(I), I=1,N2)
DO 30 I=1, N2
  V(I) = V2 + (I-1)*DV2
  IX = IXO*EXP(V(I)/(MX*VT))
  ID = AMP(I) - IX
  ISAT = ID/EXP(V(I)/VT)
30 WRITE (6,6) V(I), AMP(I), ISAT
WRITE (6,7) T
WRITE (6,8) MX, I XO
GO TO 688
999 STOP
END

SUBROUTINE LSQ3 (X,Y,N, A,B)
DIMENSION X(N), Y(N), XN(30)
XBAR = 0
DO 10 I=1,N
10 XBAR = XBAR + X(I)
XBAR = XBAR / N
F = 0
FX1 = 0
X2 = 0
DO 20 I=1,N
  XN(I) = X(I) - XBAR
  FX1 = FX1 + Y(I)*XN(I)
  F = F + Y(I)
20 X2 = X2 + XN(I)*XN(I)
A = FX1 / X2
B = F / N
B = B - A * XBAR
A = 1. / A
RETURN
END
APPENDIX II

STANDARD WAFER CLEANING PROCESS

1. Scrub with cotton swab soaked with TCE.
2. Boil in TCE, 5 min.
3. Boil in ACE, 5 min.
4. Boil in methyl alcohol, 5 min.
5. Rinse in deionized water, 5 min.
6. Dip in 1HCl:1H₂O₂:6H₂O solution at 80°C, 15 min.
7. Rinse in deionized water, 5 min.
8. Deglaze in 1HF:10H₂O solution, 10 sec.
9. Rinse in deionized water, 5 min.
10. Spin dry with N₂ gas flow.
APPENDIX III

FABRICATION SCHEDULE FOR OXIDE-CHARGE-INDUCED HIGH-LOW EMITTER JUNCTION SOLAR CELL

We have fabricated OCI-HLE solar cells on several types of wafers. We will identify them as follows:

1. 9900AP - 1.5 Ω-cm, 10 μm thick n-type arsenic-doped epitaxial layer on 300 μm thick <111> 0.15 Ω-cm boron-doped Czochralski-grown substrate.
2. 9900AQ - 1.5 Ω-cm, 4 μm thick n-type arsenic-doped epitaxial layer on 300 μm thick <111> 0.15 Ω-cm boron-doped Czochralski-grown substrate.
3. MONSANTO - 0.1 Ω-cm, 10 μm arsenic-doped epitaxial layer on 300 μm thick <111> 0.1 Ω-cm boron-doped Czochralski-grown substrate.
4. MOTOROLA - 0.15 Ω-cm, 5 μm n-type epitaxial layer on 500 μm thick <100> 0.025 Ω-cm boron-doped Czochralski-grown substrate.

In the following process runs all push-in and pull-out of wafers for the oxidation, phosphorous diffusion, and oxygen annealing processes are done in a nitrogen ambient in about 5 min unless otherwise specified.
Run #25

Wafer: 9900AP with 5000 Å of chemical-vapor-deposited (CVD) oxide on front surface.

Steps:

1. Phosphorous gettering: 1100°C, 3 hr.
2. Etch oxides from both sides.
4. Oxidation: 1100°C, 3 hr with 1 l/min dry O₂ and 5 cc/min N₂ bubbling through TCE. Oxide thickness = 2500 Å.
5. Define front contact openings using mask #1.
7. Phosphorous diffusion through contact openings: 900°C, 15 min with 20 cc/min N₂ bubbling through POCl₃ at 30°C, 100 cc/min O₂, and 1.5 l/min N₂ as carrier gas. $R_s = 30 \ \Omega$/square.
8. Etch phosphosilicate glass in BOE etch for 10 sec.
9. Oxygen anneal: 700°C, 2 hr with 1.5 l/min dry O₂.
10. Oxide etch until field oxide reaches 1100 Å.
11. Aluminum deposition on front surface.
12. Define metal grid pattern using mask #2.
13. Remove the n⁺ diffusion from the backside by lapping with silicon carbide abrasive powder.
14. Aluminum deposition on back surface.
15. Forming gas anneal (10% H₂, 90% N₂): 450°C, 15 min.
16. Scribing and edge etching.
Run #26

Wafer: MONSANTO

Steps:
1. Standard wafer cleaning.
2. Oxidation: 1100°C, 7 hr with 1 l/min dry O₂ and 5 cc/min N₂ bubbling through TCE. Oxide thickness ≈ 3750 Å.
3. Define front contact openings using mask #1.
5. Phosphorous diffusior through contact openings: 900°C, 20 min with 20 cc/min N₂ bubbling through POCl₃ at 30°C, 100 cc/min O₂, and 1.5 l/min N₂ as carrier gas. Rₛ = 25 Ω/square.
6. Oxygen annealing: 700°C, 10 hr with 1.5 l/min dry O₂.
7. Etch oxide until field oxide is about 1100 Å.
8. Aluminum deposition on front surface.
10. Lapping the back surface.
11. Aluminum deposition on back surface.
13. Scribing and edge etching.
Run #27: Effect of phosphorous gettering on bulk lifetime

Wafer: MONSANTO

Steps:

1. Standard wafer cleaning.

2. Oxidation: 1100°C, 7 hr with 1 l/min dry O₂ and 5 cc/min N₂ bubbling through TCE.

3. Remove oxide at the back surface.

4. Phosphorous gettering: 1000°C, 45 min with 20 cc/min N₂ bubbling through POCl₃ at 30°C, 100 cc/min O₂, and 1.5 l/min N₂ as carrier gas.

5. See steps 3 - 13 of Run #26.
Run #28: Determination of bulk lifetime in starting wafers
Wafer: 9900AQ, MONSANTO

Steps:
1. Standard wafer cleaning.
3. Etch oxides from both sides.
4. Remove n⁺ diffusion from back side.
5. Evaporate aluminum on both front and back surfaces.
6. Scribing and edge etching.
Run #31: Oxidation (wet) at lower temperature (900 C)

Wafer: 9900AP, 9900AQ, both with CVD oxide on front surface.

Steps:
1. Define contact windows through CVD oxide for n⁺ contact diffusion.
2. Standard wafer cleaning.
3. Phosphorous diffusion: 850°C, 15 min with the same flow rates and source temperature as previous runs. Cool wafers down to 700°C in N₂ (90 min).
4. Strip oxides on both surfaces.
5. Oxidation: 900°C, 5 min dry oxidation, 10 min wet oxidation, 5 min dry oxidation. Wafers cooled to 700°C in dry O₂ (900°C).
6. Reopen contact windows using mask #1.
7. Standard metallization and annealing process (steps 11-16 of Run #25).
Run 032: Oxidation (dry) at lower temperature (800°C)

Wafer: 9900AQ with CVD oxide on front surface.

Steps:

1. See steps 1 - 4 of Run #31.

2. Oxidation: 800°C, 16 hr and cool wafers down to 700°C in 
   N₂ in 1 hr then in O₂ for 2 hr at 700°C in same furnace.

3. Reopen contact windows using mask #1.

4. Standard metallization and annealing process (steps 11 - 16 
   of Run #25).
Run #35: Slow cooling of wafers in $N_2$ after high temperature processes

Wafer: 9900AP, MONSANTO

Steps:

1. Standard wafer cleaning.

2. Oxidation: 1100°C, 3 hr with 1 l/min dry $O_2$ and 5 cc/min $N_2$ bubbling through TCE. Cool wafers down to 1000°C at 0.5°C/min and to 900°C at 1.5°C/min and then to 700°C in 90 min. The cooling was done in a nitrogen ambient.

3. Define contact openings using mask #1.


5. Phosphorous diffusion: 850°C, 20 min. Cool wafers down to 700°C in $N_2$ in 90 min.

6. Etch oxide until field oxide is about 1100 Å.

7. Oxygen annealing: 700°C, 2 hr.

8. Etch thin oxide over contact windows.

9. Standard metallization and annealing process (as steps 11 - 16 of Run #25).
Run #36: Slow cooling of wafers in O₂ after high temperature processes.

Wafer: 9900AP

Steps:

1. Standard wafer cleaning.

2. Oxidation: 1100°C, 3 hrs with 1 l/min dry O₂ and 5 cc/min N₂ bubbling through TCE. Cool wafers down to 1000°C at 0.5°C/min and to 900°C at 1.5°C/min and then to 700°C in 90 min. The cooling was done in an oxygen ambient.

3. Define contact openings using mask #1.


5. Phosphorous diffusion: 850°C, 20 min. Cool wafers down to 700°C in O₂ in 90 min.

6. Etch oxide until field oxide is about 1100 Å.

7. Standard metallization and annealing process (as steps 11 - 16 of Run #25).
Run #48: Oxidation with TCE at 1150°C

Wafer: 9900AP, MONSANTO

Steps:

1. Standard wafer cleaning.

2. Oxidation: 1150°C, 5 hr with 1.5 l/min dry O₂ and 3cc/min N₂ bubbling through TCE.

3. Define front contact openings using mask #1.


6. Oxygen annealing: 700°C, 2 hr.

7. Oxide etch until field oxide reaches 1100 Å.

8. Usual metallization and annealing process (steps 11 - 16 of Run #25).
Run #51

Wafer: 9900AP, MONSANTO, MOTOROLA

Steps:

As Run #48 except the wafers are annealed in dry oxygen at 700°C for 12½ hours in Step 8.
APPENDIX IV

LAYOUT OF MASKS USED IN SOLAR CELLS FABRICATION

We use photolithographic techniques to define the contact openings to the front emitter surface and also the metal grid pattern on the front surface. The layout of masks used are shown below. The shaded areas correspond to the darkened area in the emulsion plate. Waycoat negative photoresist is used throughout.

Mask #1: Mask used for contact openings to the front emitter surface. It consists of thirty nine 2 mil x 800 mil strips, with 20 mil center to center spacing.
Mask #2: Mask used for defining metal grid pattern on the front surface. The thin contact fingers occupy 10% of the area excluding the collection strips.
CHAPTER 5

DETERMINATION OF LIFETIMES AND RECOMBINATION
CURRENTS IN p-n JUNCTION SOLAR CELLS AND DIODES
I. INTRODUCTION

The minority carrier base diffusion length is an important material parameter determining the performance of solar cells. Very long diffusion lengths, longer than the base width, are desirable for the successful operation of BSF, TBC, FSF, and TJ cells [1] - [4]. Such long diffusion lengths are necessary to achieve large values of the short circuit current \( J_{SC} \), to minimize the base dark current, and thus lead to large cell efficiency \( \eta \). A long diffusion length is also necessary in the emitter of the HLE cell [5] for similar reasons.

Numerous methods exist to measure the base diffusion length \( L_B \) [6,7]. These methods are based on the measurement of some device parameter, such as current, capacitance, etc., which is dependent on \( L_B \). To measure \( L_B \) accurately, \( L_B \) has to be smaller than the base width \( W_B \), i.e., \( L_B < W_B \). In this case, the minority carriers recombine within the base without interacting with a back contact. If, however, \( L_B \approx W_B \) the minority carriers interact with the back contact and the measured parameter is dependent on a slowly varying (hyperbolic) function of \( W_B/L_B \) [7]. If \( L_B > W_B \), the measured parameters depends on \( W_B \) only, and is independent of \( L_B \). Thus, existing methods of measurement do not work well for cells with \( L_B > W_B \).

An accurate knowledge of \( L_B \) is still very important even if \( L_B > W_B \), since the dark base recombination current \( Q_B/\tau_B \) can still significantly contribute to the total dark current of the device.

In this paper, methods for the accurate measurement of \( L \) in a narrow region \( W \) in cells for which \( L > W \) are described. The methods are applicable to essentially all cells and diodes with a narrow region either in the base or in the emitter.

The first method, described in Section II, is based on basewidth-modulation of n-p-n or p-n-p transistor-like structures. The method involves measurement of the low-frequency small signal conductances which arise from the basewidth-
modulation by a small ac signal. TJ cells are directly applicable for the method, since they are, in essence, transistor structures. For other cells, transistor-like structures can be obtained by modification of the cell structures done at low temperature. The method requires only a knowledge of the base width $W_b$ and the base doping, and the accuracy is better than about $\pm 10\%$. The method applies for both high and low levels of carrier injection.

Section III discusses the small-signal admittance method. This method can be applied to practically any cell with a narrow region either in the base, or in the emitter which is the case for the HLE cell [5]. It also leads to determination of the recombination velocity at the back of the narrow region. Section IV describes a simple method to determine the diffusion length, which is based on measurements of dc currents on two related structures.

Based on an accurate knowledge of $L$, a simple analysis of the cells can be made. This analysis, described in Section V, uses measurement of dark currents and small-signal admittance, and leads to determination of the recombination currents in each region of the cell. Section VI shows illustrative examples of the analysis of three cells: $n^+-p^-n^+$ TJ cell, $n^+-p^-p^+$ BSF cell, and $p^+-n^-n^+$ BSF cell. Section VII discusses the accuracy of the measurements.

II. BASEWIDTH-MODULATION METHOD

A. Minority carrier lifetime

The basewidth-modulation (BWM) method for determination of the minority carrier base lifetime of junction transistors was recently published (8). This method is applied here for the case of very wide base regions in solar cells. The method is also extended to determine the recombination currents in the quasi-neutral emitter and collector regions of the cells.

The basewidth-modulation effects arise from voltages appearing across the base-collector junction of the transistor. Any change in the base-collector voltage will produce a change in the width of the junction space-
charge-region (SCR) which, in turn, produces a change in the width, $W_B$, of the quasi-neutral base (QNB) region, as illustrated in Fig.1 for an $n^+\!-\!p\!-\!n^+$ transistor. The change in the base width, $\Delta W_B$, produces three effects:

a) the amount of excess minority carrier (electron) charge $Q_B$ stored in the QNB changes by $\Delta Q_B$; b) the component of the base current due to recombination within the QNB changes by $\Delta Q_B/\tau_B$; and c) the collector current changes because of the change in the slope of the excess minority electron distribution $N(x)$ in the base.

The BWM effects can be detected by measuring a low-frequency small-signal output conductance $G_o$ and a reverse transconductance $G_r$ [2] of the device:

\[
G_o = \frac{i_c}{v_{ce}} \bigg|_{v_{be} = 0} = \frac{3I_c}{3W_B} \frac{W_B}{V_{CB}} \bigg|_{V_{BE}}
\]

\[
G_r = \frac{i_b}{v_{ce}} \bigg|_{v_{be} = 0} = \frac{3I_B}{3W_B} \frac{W_B}{3V_{CB}} \bigg|_{V_{BE}}
\]

$G_o$ and $G_r$ result from modulation of the base width by a small ac signal applied between the collector and emitter terminals with base-emitter voltage $V_{BE}$ kept constant. For an $n$-$p$-$n$ transistor (for example) with uniform base doping $N_{AA}$, under condition of low-injection and negligible recombination in the QNB ($L_n \gg W_B$), the charge-control minority carrier (electron) lifetime $\tau_n$ is [8]

\[
\tau_n = -\tau_F \frac{G_o}{G_r}
\]

where

\[
\tau_F = \frac{W_B}{2D_n}
\]

is the minority-carrier transit time across the QNB and $D_n$ is the electron diffusion coefficient. The minus sign in (3) results from the fact that $G_r$ is negative. $G_o$ and $G_r$ are both proportional to $\exp(qV_{BE}/kT)$ [8]. The minority carrier lifetime in the base can thus be determined by measuring $G_o$ and $G_r$ and calculating $\tau_F$ from the base width and base doping.
This method can be extended for use under the condition of high-injection occurring in the p-type base. In high injection [9]

\[ N(0) = n_1 \exp \frac{qV_{BE}}{2kT} \quad (5) \]

Using (5), we obtain for the collector and base currents:

\[ I_C = \frac{A_{BE}2qDn_1}{W_B} \exp \frac{qV_{BE}}{2kT} \quad (6) \]
\[ I_B = \frac{A_{BE}qW_B}{2\tau_H} \exp \frac{qV_{BE}}{2kT} \quad (7) \]

where \( \tau_H = \tau_n + \tau_p \) is the high-injection lifetime [9].

Using (1) and (2) we obtain:

\[ \tau_H = -\frac{1}{2} \frac{G_o}{G_r} \quad (8) \]

This expression is similar to (3) for the low-injection case except for a factor of 1/2. Note also that \( G_o \) and \( G_r \) are both proportional to \( \exp(qV_{BE}/2kT) \) in high-injection [9]. Equation (6) is valid if \( W < L \) and if the recombination current in the emitter is negligible [9]. This will apply to many devices with a wide low-doped base region. If the above conditions do not apply, then a more general solution is required to obtain \( \tau_H \) [9].

Our treatment was restricted so far to the case for which \( L_n > W_B \), resulting in a linear dependence of \( N(x) \) on distance within the base. The method, however, is applicable also for \( L < W_B \). It can be easily shown that for this general case:

\[ \frac{G_o}{G_r} = -\frac{\cosh \frac{W_B}{L_n}}{\sinh \frac{W_B}{2L_n}} \quad (9) \]

This expression converges to (3) for \( W_B/L_n < 1 \). For \( W_B/L_n = 1 \), the difference between \( L_n \) determined from (3) and (9) is only about 8%, i.e., for \( W_B = L_n \), (3) can be used with only a small error.
Conductances $G_o$ and $G_r$ are due only to changes in the QNB region provided $V_{CB}$ is low enough to make the generation currents in the collector depletion layer negligible. They are independent of the recombination currents in the emitter and in the base-emitter space-charge region, since $V_{BE}$ is held constant. Therefore, $G_o$ and $G_r$ will follow the ideal $\exp(qV_{BE}/kT)$ dependence in low-injection and $\exp(qV_{BE}/2kT)$ dependence in high-injection. This ideal exponential dependence of both $G_o$ and $G_r$ on voltage serves as a very convenient self-consistency measurement check of the method. This check also assures us that series resistance is low enough, mainly in high-injection, to validate the assumptions underlying the method.

B. Determination of the emitter current

Once the base lifetime, $\tau_n$, is measured using the BWM technique, the emitter contribution to the base current can be easily found. The total measured base current $I_{BT}$ for forward-active operation in low-injection is [10,11]

$$I_{BT} = \frac{Q_B}{\tau_n} + \frac{Q_E}{\tau_E} + \frac{Q_{SCR}}{\tau_{SCR}}$$

where $Q_B$, $Q_E$ and $Q_{SCR}$ are the excess minority carrier charges in the base, emitter, and SCR, respectively; and $\tau_n$, $\tau_E$ and $\tau_{SCR}$ are the respective charge-control time constants. The SCR recombination current $Q_{SCR}/\tau_{SCR}$ can be removed from the measured $I_B-V_{BE}$ characteristic by an appropriate subtraction[10,11]. The remaining base saturation current, $I_{BO}$ is then

$$I_{BO} = \frac{Q_{BO}}{\tau_n} + \frac{Q_{EO}}{\tau_E}$$

where $Q_{BO}$ and $Q_{EO}$ are the minority charges at equilibrium: $Q_B = Q_{BO} \exp(qV_{BE}/kT)$, $Q_E = Q_{EO} \exp(qV_{BE}/kT)$.

The ideal common emitter current gain is given by [11]

$$h_{FE(\text{ideal})} = \frac{I_C}{I_B} = \frac{Q_{BO}/\tau_F}{Q_{BO}/\tau_n + Q_{EO}/\tau_E}$$

(12)
Solving for $Q_{EO}/\tau_E$ and combining with (3), the recombination current occurring within the quasi-neutral emitter is

$$\frac{Q_{EO}}{\tau_E} = \frac{Q_{BO}}{\tau_n} \left( \frac{G_o/G_r}{h_{FE}^{(ideal)}} - 1 \right)$$

(13)

$Q_{EO}/\tau_E$ is thus found by combining the small-signal ac measurements ($G_o/G_r$) with dc characteristics of the transistor ($h_{FE}^{(ideal)}$).

For a transistor with negligible recombination losses in the emitter, $Q_{EO}/\tau_E << Q_{BO}/\tau_B$, note that

$$h_{FE}^{(ideal)} = \frac{Q_{BO}/\tau_F}{Q_{BO}/\tau_n} = \frac{\tau_n}{\tau_F}$$

(14)

in accord with conventional transistor theory. The minority carrier base lifetime is then simply $\tau_n = \tau_F h_{FE}^{(ideal)}$. This provides a method for finding $\tau_n$ that is an alternative to that based on (3). But finding $h_{FE}^{(ideal)}$ requires subtraction of the SCR current component from $I_{BT}$. This subtraction is subject to errors depending on magnitude and voltage dependence of components in (10). Thus, the method based on (3) is the more accurate method.

The current due to recombination in the $n^+$-collector quasi-neutral region can be measured by reversing the roles of collector and emitter and using (13) again.

III. SMALL-SIGNAL ADMITTANCE METHOD

A. Minority carrier lifetime

The BWM technique described in the previous section is directly applicable for TJ cells, since the TJ cell is actually a transistor-like structure. It cannot, however, be applied directly to some other cells with a narrow base or emitter region which are diode structures only, without a collector. In these cases, a different measurement method has to be used. In this section we present a method applicable to all cells with a narrow base or emitter region.
Fig. 2 shows two different cells with either narrow base, BSF cell—Fig. 2(a), or narrow emitter, HLE cell—Fig. 2(b). In both cases a high-low junction exists in the narrow region of the cell, and is characterized by an effective surface recombination velocity $S_{\text{eff}}$ for the minority carriers. Fig. 2(c) shows the basic structure of the IBC, FSF, and TJ cells [2,3,4]. In this structure both the n$^+$ region and the p$^+$ contacts to the base are on the bottom nonilluminated surface. The p$^+$ regions cover only a small portion ($<10\%$) of the total area. The top illuminated surface is left floating and is characterized by the surface recombination velocity $S$ for the IBC cell. If a p$^+$-p junction (FSF cell) or an n$^+$-p junction (TJ cell) is used on the top surface, then the surface region can be characterized by an effective surface recombination velocity $S_{\text{eff}}$. Due to structural similarities which are evident in Fig. 2, the cells shown in Fig. 2 will all have a similar treatment for the narrow region small-signal admittance. The treatment shown below is done for a n$^+$-p-p$^+$ BSF cell as an illustration.

Consider, for example, a n$^+$-p-p$^+$ BSF cell, Fig. 3, with a base width $W_p$ and minority carrier base lifetime $\tau_n$ corresponding to the diffusion length $L_n = \sqrt{D_n \tau_n}$. The electron current at the high-low junction ($x = W_p$) is [12]

$$J_n(W_p) = qS_{\text{eff}}^n(W_p)$$

where $S_{\text{eff}}$ is the effective surface recombination velocity for electrons at $x = W_p$. By solving a continuity equation [13] in low-injection for an ac signal superimposed on a steady forward bias, and using boundary condition (15), we can derive the expressions for the small-signal quasi-neutral base capacitance $C_{\text{QNB}}$ and conductance $G_{\text{QNB}}$ valid for a low frequency signal with $\omega \tau_n << 1$:

$$C_{\text{QNB}} = \frac{q A_0 D_{\text{n}}^2}{kT 2N_A L_n} \left[ \frac{W_p D_n}{L_n} - \frac{L W_p S_{\text{eff}}^2}{D_n} - S_{\text{eff}} L_n \right]^2 + \tau_n \left[ \frac{D_n}{L_n} \frac{S_{\text{eff}} \coth \frac{W_p}{L_n}}{L_n} + \frac{W_p}{L_n} \right] \exp \left( \frac{qV}{kT} \right) - 1$$
The expression for $C_{QNB}$ can be simplified for the following conditions:

$$\frac{W_p}{L_n} \ll 1$$ \hspace{1cm} (18)

$$S_{eff} \sim 100 \text{ cm/sec}$$ \hspace{1cm} (19)

These conditions are not restrictive for an actual device, with good performance and a narrow base. Under these conditions the first term inside of the parentheses in (16) can be neglected and combining (16) and (17) yields

$$\tau_n = \frac{C_{QNB}}{\frac{C_{QNB}}{G_{QNB}}}$$ \hspace{1cm} (20)

This expression for $\tau_n$ is similar to that valid for $W_p \gg L_n$ [14].

To determine $C_{QNB}$, we measure the capacitance at two frequencies: $C_{LF}$ at $\omega \tau_n << 1$ and $C_{HF}$ at $\omega \tau_n >> 1$ to obtain [14]:

$$C_Q = C_{QNB} = C_{LF} - C_{HF}$$ \hspace{1cm} (21)

This results because the $n^+$ base and $p^+$ emitter regions are much narrower than $W_p$ and the amount of minority-carrier charge in these regions will be negligible compared to that in the wide base, giving $C_Q = C_{QNB}$.

To determine $G_{QNB}$, we measure a total conductance $G$ at the terminals which consists of a few components [10]:

$$G = G_{QNE} + G_{QNB} + G_{SCR}$$ \hspace{1cm} (22)

where $G_{SCR}$ is the conductance from the bulk and surface base-emitter space-
charge region, and \( G_{QNE} \) designates the contribution of the emitter quasi-neutral region. \( G_{SCR} \) can be eliminated from the data by a subtraction technique to give

\[
G_{QN} = G_{QNE} + G_{QNB}
\]  

(23)

If \( G_{QNE} < G_{QNB} \), then \( G_{QN} \approx G_{QNB} \) and \( \tau_n \) can be then determined from (20). This condition will apply for many devices made on high resistivity substrates (\( \approx 10 \ \Omega \text{cm} \)) with wide base. If \( G_{QNE} \) is not negligible, an independent method is required to determine it before we can calculate \( \tau_n \) from (20).

One simple method involves thinning the base region to assure \( W_p < L_n \) and providing an ohmic contact to the base instead of a high-low junction. The narrow-base current can then be calculated using a conventional formula and subtracted from the total measured diode current to give the emitter current or \( G_{QNE} \).

For the case of the HLE cell of Fig. 4, we note that the n-type emitter is the narrow region of interest, with a minority carrier (hole) lifetime \( \tau_p \). To determine \( \tau_p \), we proceed as follows: we measure the electron diffusion length in a wide base by an X-ray technique, [15] or some other suitable method, and calculate \( C_{QNB} \) and \( G_{QNB} \). These two values are then subtracted from measured \( C_{QN} \), \( G_{QN} \) to give \( C_{QNE} \), \( G_{QNE} \), and

\[
\tau_p = 2 \frac{C_{QNE}}{G_{QNE}}
\]  

(24)

The small-signal admittance method can be also applied for conditions of high-injection in the narrow region. Following the derivation of (16) and (17) for \( P = N \) we obtain for high-injection lifetime:

\[
\tau_H = 4 \frac{C_{QNB}}{G_{QNB}}
\]  

(25)

Equation (25) is similar to (20) except for a factor of two which results because the electron diffusion constant \( D_n \) is doubled in high-injection [9]. This
equation is valid for the common case of a negligible emitter current and \( W_{p/n} < 1 \) [9].

A more complicated, but accurate way to determine both \( G_{QNE} \) and \( \tau_n \) in the BSF cell and other structures of Fig. 2 is to use the BWM technique described in the previous section. In order to do that, we have to first create a modified transistor-like structure from the actual cells. This can be done quite easily as shown in Fig. 5. For the case of \( p^+\text{-}n\text{-}n^+ \) BSF cell, the \( n^+ \) region on the back can be etched-off from about 90% of the area and Al can be evaporated on n-type base to create a Schottky barrier collector; the remains of \( n^+ \) BSF region serve as a contact to the base, see Fig. 5(a). This procedure can be also used for \( n^+\text{-}n\text{-}p \) HLE cell from Fig. 2(b). In the case of a \( n^+\text{-}p\text{-}p^+ \) BSF cell, Fig. 5(b), an \( n^+ \)-diffusion is performed simultaneously from both sides of the p-type substrate. Emitter can then be a mesa-type and the \( p^+ \) region for the base contact over about 10% of the area can be done by a standard method used to create a BSF region. Schottky barrier collector using Al cannot be used on p-type substrates because a metal-semiconductor junction on p-type substrates is usually very poor. Similar transistor-like structures can be made also from the FSF and IBC cells.

B. Determination of \( S(S_{\text{eff}}) \)

Once the minority carrier lifetime in the narrow region is found, then \( S(S_{\text{eff}}) \) can be determined either from small-signal quasi-neutral conductance or capacitance of this region. The capacitance is, however, a much better choice because of reasons discussed earlier (see also Section VI C). This procedure is strictly valid only if \( S(S_{\text{eff}}) \) is constant, independent of applied voltage. This condition will be satisfied at low-injection for BSF, FSF, and HLE cells [12], but may not be satisfied for TJ and IBC cells. If \( S(S_{\text{eff}}) \) is not constant, then using (16) or (17) will result in an average value.
IV. MINORITY CARRIER BASE LIFETIME FROM DC CURRENT MEASUREMENTS

An alternative method, suitable for TJ cells or the transistor-like structures, Fig. 5, is proposed. This method requires only dc current measurements on two related structures. The first structure is the actual TJ cell (for example), Fig. 6(a). The other structure, Fig. 6(b), is created by removing the n+ layer on one side of the cell and replacing it by an ohmic contact.

We will neglect the contribution of the SCR, which can be removed by an experimental procedure [10]. The base saturation current of the transistor-like structure is given by (11), the collector saturation current is $I_{C0} = Q_{BO}/\tau_F$.

The saturation current $I_0$ of the narrow-base diode from Fig. 6(b) is

$$I_0 = \frac{Q_{BO}}{\tau_F} + \frac{Q_{EO}}{\tau_E}. \quad (26)$$

Combining (11) and (26), we obtain for $\tau_n$:

$$\tau_n = \frac{I_{C0}}{I_{BO} + I_{C0} - I_0} \tau_F. \quad (27)$$

In (27) all currents are measured and $\tau_F = W_B^2/2D_n$ is calculated.

The disadvantage of this procedure is that the separation of SCR current components [10] is subject to errors. This will limit the applicability of this method, mainly if $I_{BO} + I_{C0} \sim I_0$, which is the case when the emitter dominates the current. The recombination current in the emitter is simply found from (26)

$$\frac{Q_{EO}}{\tau_E} = I_0 - I_{C0}. \quad (28)$$

An expression similar to (28) can be derived for $\tau_H$, differing only by a factor of 1/2 on the right side of (28). Note that in this case the currents in (27) are proportional to $\exp(qV/2kT)$. Also note that a highly-doped emitter will remain in low-injection.

V. ANALYSIS OF DARK CURRENTS IN THE CELL

The analysis of dark currents in the cell is demonstrated for a $n^+p-p^+$
BSF and for n⁺-n-p HLE cell shown in Figs. 3 and 4, which also show distribution of minority carriers in these cells. The analysis is based on independent measurement of \( \tau_n \) by one of the three methods described before. The effective surface recombination velocity is determined from a small-signal capacitance using (16). This allows us to calculate \( N(x) \) [9] and the recombination currents in the \( p \) and \( p^+ \) portions of the base. The SCR current, \( I_{SCR} \) is determined graphically [10], the recombination current in the emitter region can be obtained by the BWM technique or using the dc method. The sum of all currents recombining within the cell has to be equal to the total measured dark current \( I \). This serves as a self-consistency check of the analysis. Another check for dark current \( I \) results from measurement of the short circuit current \( I_{SC} \) and open-circuit voltage \( V_{OC} \) through

\[
V_{OC} = \frac{kT}{q} \ln \frac{I_{SC}}{I_0}
\]

where \( I_0 \) is the dark saturation current corresponding to \( I \).

The analysis of the n⁺-n-p HLE solar cell, Fig. 4, starts with the wide p-type base. The electron diffusion length is measured by the X-ray method [15], and the base dark current and small-signal quasi neutral capacitance [14] are calculated. The hole lifetime \( \tau_p \) and \( S_{eff} \) at the n⁺-n junction are then evaluated as was described in Section 3A, 3B. The rest of the analysis follows the BSF case above.

For high-injection conditions in the low-doped part of the base in the BSF cell or low-doped part of the emitter in the HLE cell, we again measure \( \tau_H \) in these regions as described in Sections IIA, IIIA, and IV. The value of \( S_{eff} \) increases with applied voltage in high-injection [12]. The analysis has to be then made for a certain voltage, for example \( V = V_{OC} \) corresponding to a certain illumination level; \( S_{eff} \) can then be calculated based on its low-injection value provided that the voltage drop in the quasi neutral low-doped portion of the base is negligible [12]. The high-doped regions of the cell will remain in low-injection. The analysis then follows the low-injection case.
VI. ILLUSTRATIVE EXAMPLES

To demonstrate the various methods for analysis of the cells, we have done measurements on three different types of cells. The complete analysis for these devices is summarized in this section.

A. n+p-n+ TJ cell

This cell is fabricated on 6 Ω cm(N_A = 2 x 10^{15} cm^{-3}) p-type substrate. The top illuminated n+ layer is about 0.3 μm deep, the surface is texturized and covered by an AR coating. The bottom n+ layer is about 0.7 μm deep. The base width is 160 μm. Measured performance at one-sun AM0 illumination at 25°C with top junction floating was: V_OC = 577 mV, J_SC = 30.5 mA/cm².

An ohmic contact to the top junction was provided after removing the AR coating. The measured dc and ac characteristics for this transistor-like structure are shown in Fig. 7. The data were taken with the bottom n+ region serving as an emitter. The BWM conductances were measured at 2 kHz using a Wayne-Kerr H224 admittance bridge. The dependencies of I_C, G_o and G_r are proportional to \exp q(V_{BE}/kT), which confirms that the BWM effects alone are responsible for G_o and G_r. For V_{BE} < 0.4 V the leakage of the base-collector junction may dominate G_o and G_r, in some devices, giving almost constant values independent on V_{BE}. These values can be then subtracted from the measured G_o and G_r to extend the range of the exponential dependence on V_{BE}.

From Fig. 7 we have for the low-injection case: G_o/G_r = n/T_F = 13; h_{FE(ideal)} = 13. Using (4) and (13) we then obtain: \tau_n = 50 μsec (L_n = 410 μm) and Q_{E0}/\tau_E = 0, i.e. Q_{E0}/\tau_E << Q_{B0}/\tau_n. Examination of the I_B-V_{BE} dependence in Fig. 7 shows that the base will be in high-injection for V_{BE} > 0.6 V. The base current follows an \exp q(V_{BE}/2kT) dependence in accord with (7), provided that the effects of series resistance R_s are negligible. Because Q_{E}/\tau_E << Q_{B}/\tau_B, \tau_H can be found from (7): \tau_H = 200 μsec. Further analysis of the cell, described in Section V, with the top junction left floating leads to determination
of recombination losses in the top n+-layer and in the p-base region. A summary of all results obtained for this cell are shown below. The dark currents are given as a fraction of the total dark current density $J = 3 \times 10^{12} \text{ A/cm}^2$ measured at $V = V_{OC} = 577 \text{ mV}$. The results are:

- $\tau_n = 50 \mu\text{sec}$
- $L_n = 410 \mu\text{m}$
- $\tau_H = 200 \mu\text{sec}$
- $S_{\text{eff}} = 350 \text{ cm/sec}$
- $J_E = 0.52 J$
- $J_B = 0.42 J$
- $J_{\text{SCR}} = 0.06 J$
- $J_C << J_B$

The measurements of $G_o$ and $G_r$ in high-injection were not possible, because the collector current in this region exceeded the maximum allowable current of the bridge for the large area (4 cm$^2$) device used.

B. n+-p-p+ BSF cell

This cell was fabricated on 1.5 $\Omega\text{cm}(N_{AA} = 1 \times 10^{16} \text{ cm}^{-3})$ substrate. The n+-region is about 0.3 $\mu$m deep, sheet resistance is about 55 $\Omega$/square. The BSF high-low junction was created by an Al-paste alloying \cite{16}. The cell was 220 $\mu$m thick and has a Ta$_2$O$_5$ AR coating on the top. The parameters measured at one-sun (AM0, 25°C) illumination are: $V_{OC} = 617 \text{ mV}$, $J_{SC} = 38 \text{ mA/cm}^2$.

The values for $\tau_n$ and $Q_{E}/\tau_E$ were measured by the BWM method on a modified structure shown in Fig. 5(b). The recombination currents in the p and p+-region were then measured on the actual BSF cell, $S_{\text{eff}}$ was determined from the dark base current using (17). The inspection of the dark I-V characteristic showed that this cell is in low-injection at one-sun illumination level.

The results are:

- $\tau_n = 120 \mu\text{sec}$
- $L_n = 600 \mu\text{m}$
\[ \begin{align*}
S_{\text{eff}} &= 380 \text{ cm/sec} \\
J_E &= 0.4 \text{ J} \\
J_B &= 0.15 \text{ J} \\
J_B^+ &= 0.4 \text{ J} \\
J_{\text{SCR}} &= 0.05 \text{ J}
\end{align*} \]

where \( J = 3.8 \times 10^{-2} \text{ A/cm}^2 \) is the measured total dark current density at \( V = V_{\text{OC}} = 617 \text{ mV} \).

C. \( p^+-n^-n^+ \) BSF cell

This cell was fabricated on about 7 \( \Omega \) cm (\( N_{\text{DD}} = 6 \times 10^{14} \text{ cm}^{-3} \)) float zone silicon wafer. The \( p^+ \)-emitter is about 0.25 \( \mu \text{m} \) deep. The \( n^+ \)-layer on the back is about 1 \( \mu \text{m} \) deep. Thickness of the cell was 320 \( \mu \text{m} \). The details of the fabrication process are in Ref. 17.

The one-sun (AM1.5, 25°C) data were: \( V_{\text{OC}} = 605 \text{ mV}, J_{\text{SC}} = 39 \text{ mA/cm}^2 \).

We will demonstrate here the use of the small-signal admittance method, described in Section III. Fig. 8 shows the measured dependencies of \( C \) and \( G \) on voltage \( V \). The low frequency capacitance \( C_{\text{LF}} \) and conductance \( G_{\text{LF}} \) were measured at 500 Hz, \( C_{\text{HF}} \) was measured at 100 kHz using a Wayne-Kerr B224 bridge. Subtraction of these two dependencies yields \( C_{\text{QN}} = C_{\text{LF}} - C_{\text{HF}} \) which follows the \( \exp(qV/kT) \) dependence for about 2 decades. Similar procedure is used to extract \( G_{\text{QN}} \) [10].

Using a simple test described in Section IIIA we found that \( G_{\text{QNE}} \ll G_{\text{BNB}} \).

The hole lifetime is then obtained from (20) and \( S_{\text{eff}} \) from (16):

\[ \begin{align*}
\tau_p &= 200 \mu\text{sec} \quad S_{\text{eff}} = 80 \text{ cm/sec}.
\end{align*} \]

Using these values for \( \tau_p \) and \( S_{\text{eff}} \), we find that the first term in the parentheses in (16) is indeed small compared to the second term, which then validates (20). These results are consistent with measurements on \( p^+-n^-n^+ \) cells reported by others [17, 18].

The advantages of calculating \( S_{\text{eff}} \) from \( C_{\text{QN}} \) (instead of from) \( G_{\text{QN}} \) are clearly evident in Fig. 8. The measured \( C_{\text{LF}} \) characteristic is almost an ideal one; the correction by subtracting \( C_{\text{HF}} \) is very small. On the other hand, the correction due to \( C_{\text{SCR}} \) to obtain \( G_{\text{QN}} \) is very substantial.
For \( V > 0.6 \) Volts the n-region of the base is in high-injection as shown by \( G_{QN} \propto \exp(qV/2kT) \) for \( V > 0.6 \) Volts, which was obtained by subtracting \( G_{SCR} \) from \( G \). The \( C_{LF} \) dependence on voltage for \( V > 0.6 \) Volts is also expected to be proportional to \( \exp(qV/2kT) \). The \( C_{LF} \) in Fig. 8 shows, however, an excessive bending due to the contact resistance between the cell and the measurement probes. The \( C_{LF} \) was measured using only 2 probes, however 4 probe measurements are necessary to eliminate the contact resistance. Such capacitance measurements are possible. The series resistance \( R_s \) will have a negligible effect on \( C_{LF} \) [19].

The G-V curve was taken using 3 probe arrangement, effectively suppressing \( R_s \) for \( V < 0.7 \) Volts. Due to the difficulty with the high-injection value of \( C_{LF} \), \( \tau_H \) could not be found using the admittance method. The estimate of \( \tau_H \) follows from recognizing that \( G_{QNE} < G_{QNB} \) at \( V = 600 \) mV, \( W_n < L_p \) and \( S_{eff} \) is small. This will result in a nearly flat profile of \( P(x) \) in the n-base, and

\[
L_B = A q n_i W_n / \tau_H \left[ \exp(qV/2kT) \right],
\]

which yields \( \tau_H = 320 \) \( \mu \)sec. The fact that \( G_{QN} \propto \exp(qV/2kT) \) indicates that the low-doped portion of the base dominates the dark current at \( V = V_{OC} = 605 \) mV.

The results for this cell are summarized below:

\[
\begin{align*}
\tau_p & = 200 \ \mu \text{sec} \\
L_p & = 500 \ \mu \text{m} \\
\tau_H & = 320 \ \mu \text{sec} \\
S_{eff} & = 80 \ \text{cm/sec} \ (\text{low injection}) \\
J_B & = 0.8 \ \text{J} \\
J_{SCR} & = 0.2 \ \text{J} \\
J_E & \ll J_B \\
J_B^+ & \ll J_B
\end{align*}
\]

where \( J = 2.9 \times 10^{-2} \ \text{A/cm}^2 \) is the measured total dark current density at

\( V = V_{OC} = 605 \) mV.
VII. SUMMARY

This work presented new methods for determining the minority-carrier lifetime in narrow regions of solar cells. This leads to a simple analysis which results in determination of recombination currents in each region of the cell. Such an analysis was demonstrated for three different types of cells. The basewidth-modulation (BWM) and the small-signal admittance method involve measurements using very accurate admittance bridges. The accuracy of the BWM method depends on the accuracy with which \( \tau_r \) can be determined from (4). This can be done very accurately for wide regions with a uniform doping. No other material parameter is required to obtain the lifetime from (3) or (8). Additional reasons for the high accuracy of this method are that it is independent of the currents not associated with the region in which the lifetime is measured and that it has a self-consistency check. The accuracy of the BWM method is estimated to be about \( \pm 5\% \).

The lifetime measured by the small-signal admittance method, as determined from (20) or (25), does not require knowledge of any material parameter of the cell. The high frequency capacitance \( C_{HF} \) can be measured at relatively small frequencies (\(~100kHz\)) because of very long lifetimes in the measured cells. This allows measurements on large area devices (\(~1cm^2\)) using commercially available bridges. This method also has a self-consistency check. The total accuracy of this method is estimated to be about \( \pm 10\% \). The dc current method is less accurate than the previous two methods, mainly if the emitter current is dominant.

The determination of lifetimes and recombination currents in the cell allows identification of regions that limit cell efficiency. It will also allow monitoring of fabrication steps and material properties.
REFERENCES FOR CHAPTER 5


FIGURE CAPTIONS

Fig. 1  Basewidth-modulation effects in $n^+\cdot p\cdot n^+$ TJ cell.

Fig. 2  Schematic illustration of (a) $n^+\cdot p\cdot p^+$ BSF solar cell; (b) $n^+\cdot n\cdot p$
HLE solar cell; and (c) the basic structure of the TJ (with floating
front surface), FSF, and IBC cells.

Fig. 3  (a) Schematic diagram of a $n^+\cdot p\cdot p^+$ BSF cell; (b) Qualitative sketches
of minority carrier distribution in dark.

Fig. 4  (a) Schematic diagram of a $n^+\cdot n\cdot p$ HLE cell; (b) Qualitative sketches
of minority carrier distribution in dark.

Fig. 5  (a) $p^+\cdot n\cdot n^+$ BSF cell and a modified transistor-like structure
with a Schottky barrier collector, (b) $n^+\cdot p\cdot p^+$ BSF cell and a modi-
 fi ed $n^+\cdot p\cdot n^+$ transistor-like structure.

Fig. 6  (a) Schematic diagram of TJ cell; (b) Schematic diagram of a $n^+\cdot p$
diode structure obtained from the TJ cell.

Fig. 7  Measured $I_C$, $I_{BT}$, $G_0$, and $G_r$ versus forward bias $V_{BE}$ for $n^+\cdot p\cdot n^+$
TJ cell. The base quasi-neutral current components are indicated
by the dashed lines, $I_{SCR}$ is the extrapolated SCR current component.

Fig. 8  Measured capacitance and conductance versus forward bias $V$ for $p^+\cdot n\cdot n^+$
BSF cell. The quasi-neutral components are shown by the dashed lines,
$G_{SCR}$ is the extrapolated SCR conductance component.
FIGURE 1
Figure 2

(a) p⁺-n-n⁺ BSF cell

(b) n⁺-p-p⁺ BSF cell
\[ I = I_E + I_{\text{SCR}} + \frac{1}{t_n} \int_0^{w_p} N(x) \, dx + I_{B^+} \]

**FIGURE 3**

(a)

(b)
\[ I = I_B + I_{\text{SCR}} + \frac{W_n}{\tau_p O} \int P(x) \, dx + I_E \]

\[ I_E + = q p(W_n) S_{\text{eff}} \]

FIGURE 4
FIGURE 5
FIGURE 6
$n^+ - p - n^+ TJ cell$

$A = 4 \text{cm}^2$

$25^\circ \text{C}$

$I_B \propto \exp \left( \frac{qV}{2kT} \right)$

$I_B \propto \exp \left( \frac{qV}{kT} \right)$

$I_{SCC}$

$I_{BT}$

$G_O$

$G_r$

$V_{BE} (V)$

$10^{-5}$

$10^{-4}$

$10^{-3}$

$10^{-2}$

$10^{-1}$

$10^{0}$

$10^{1}$

$10^{2}$

$10^{3}$

$10^{4}$

$10^{5}$

$10^{6}$

$10^{7}$

$10^{8}$

FIGURE 7
p⁺-n⁻-n⁺ BSF cell
A = 0.7 cm²
25°C

$G_{QN} \propto \exp \left( \frac{qV}{2kT} \right)$

$C_{QN}$

$C_{HF}$

$G_{LF}$

$G_{GAF}$

FIGURE 8
CHAPTER 6

MOS AND OXIDE-CHARGE-INDUCED (OCI) BSF SOLAR CELLS
I. Introduction

The power conversion efficiency of silicon p-n junction solar cells is limited mainly by the recombination currents from highly-doped regions of the cell. The advantages of replacing the highly-doped n⁺-diffused emitter region by an electron accumulation layer was very successfully demonstrated recently in the oxide-charge-induced high-low-junction-emitter (OCI-HLE) solar cell [1].

In this particular cell a thermal oxide layer containing a positive oxide charge induces high-low-emitter junction, which together with the low surface recombination velocity resulting from the oxide layer effectively suppresses the emitter current. As a consequence, silicon solar cells with open-circuit voltages $V_{oc}$ of 650 mV were made, which compares with the maximum value of about 600 mV seen in conventional silicon cells. Another demonstration of the desirability of avoiding a highly-doped n⁺-emmitter region is provided by recent work in n⁺-p MIS solar cells, in which the oxide-charge-induced n⁺ region is an inversion rather than an accumulation region. These devices show a maximum $V_{oc}$ of 655 mV [2].

Fig. 1 shows a schematic diagram of a p⁺-n-n⁺ BSF cell [3]. As was noted above, the limiting factor in determining the cell efficiency of state-of-the-art silicon solar cells, including BSF cell, is the dark recombination current [4,5]. The dark current is a sum of a recombination currents from the quasi-neutral emitter and base regions. For a low-doped base (∼10¹⁰ cm⁻³), typical of BSF cells, the emitter contribution is negligible [5]; the recombination current comes mainly from recombination in the n⁺ region. The n⁺-region current is [6]

$$J_p = \frac{q n_i^2}{N_{DD} W_B} \left[ \frac{1}{\exp(q V/kT)} - 1 \right] \left( \frac{1}{D_p} + \frac{1}{S_{eff}} \right)$$  \hspace{1cm} (1)

where $N_{DD}$ is the doping level in the low-doped part of the base, and $S_{eff}$ is an effective recombination velocity at the n-n⁺ low-high (L-H) boundary [6,7].

In the derivation of Eq.(1) we assumed a long diffusion length of minority holes in the low-doped part of the base: $L_p > W_B$. This is a necessary condi-
tion if the back-surface field is to have any considerable effect [8]. In
addition, in the derivation of Eq. (1), the recombination current in the low-
doped part of the base was neglected. This recombination current will ulti-
mately limit the cell performance, as discussed in Section III. In present-
day $p^+-n^-n^+$ BSF cells of the best quality, in which the $n^+$-region is formed by
phosphorus diffusion, the experimental values of $S_{\text{eff}}$ are about 40 cm/sec [4].
This limits $V_{OC}$ of present cells to about 615 mV at 300K for one-sun AM1 illu-
mination. For this cell, $W_B = 300 \mu$m, $D_p = 40$ cm$^2$/sec, and $\tau_p = 0.7$ msec [5] which
implies that

$$J_p = \frac{q n_i^2}{N_{DD} S_{\text{eff}}} \exp \left( \frac{qV}{kT} \right) - 1 \quad (2)$$

Thus, reduction of $J_p$ in this cell would result if $S_{\text{eff}}$ could be lowered. The
next section describes one approach for doing this.

II. MOS-BSF and OCI-BSF cells

Proposed device structures are shown in Figures 2(a) - (c). Instead of
creating the L-H junction by the diffusion process, we suggest creating an
accumulation layer at the back surface by a MOS gate structure, as in Figures
2(a) and 2(c). In the case of the $p^+-n^-n^+$ structure, the accumulation layer
can alternatively be induced by a positive oxide charge $Q_0$, as was done in OCI-
HLE cell [1], Figure 2(b).

Since the accumulation layer is very thin, it will be essentially trans-
parent to the minority holes (for $p^+-n^-n^+$ structures, for example) which will
recombine at the Si-SiO$_2$ interface, with a surface recombination velocity $S_p$
[1,9]. The electron concentration in the base is shown in Fig. 2(d). The induced
accumulation layer extends several Debye lengths from the surface, and thus
can be as thin as 100 Å. For an electron concentration $N_S$ at the Si-SiO$_2$ inter-
face, $S_{\text{eff}}$ can be written as [6]

$$S_{\text{eff}} = \frac{N_{DD} S_p}{N_S}$$

(3)
As can be seen from Eq. (3), if the ratio $S_p/N_S$ can be made small enough, $J_p$ will be small.

Fig. 3 shows $S_{\text{eff}}$ as a function of $S_p$ for $N_{DD}=6\times10^{14}$ cm$^{-3}$ at 300°K as a function of oxide charge density $Q_0/q$, or equivalent gate voltage $V_G$ for $SiO_2$ thickness of 1000 Å. Values for $N_S$ are calculated using standard MOS theory [10].

From Fig. 3 note that $V_G > 5$ Volts makes $S_{\text{eff}} < 40$ cm/sec even for $S_p$ as large as $10^6$ cm/sec. $S_{\text{eff}} = 40$ cm/sec was the value obtained for diffused $n^+$ regions [5]. The expected values for $S_p$ for oxidized Si surfaces are much below $10^6$ cm/sec. Therefore the MOS gate structure on the back side of the cell is expected to decrease $J_p$ to a larger extent than that achieved in diffused $p^+-n-n^+$ cells. Thus $V_{OC}$ is expected to increase because

$$V_{OC} = \frac{kT}{q} \ln \frac{J_{SC}}{J_{PO}}.$$ (4)

Fig. 4 shows the dependence of $V_{OC}$ on $S_p$ at 300°K, for the proposed structures, calculated from Eqs. (1) and (4), where the $n$-region recombination has been neglected for now) for $J_{SC}=35$ mA/cm$^2$ and $W_B=250$ μm. Values for $V_{OC}$ larger than 650 mV result even for $S_p = 10^5$ cm/sec provided $V_G > 5$ Volts or $Q_0/q > 10^{12}$ cm$^{-2}$. Similar curves can be calculated for $n^+-p-p^+$ structures.

From two sets of experiments [11] with OCI-HLE cells, one which included thermal oxidation (dry and wet) of the front emitter surface at low temperatures (800-900°C) and a second which used chemical-vapor-deposition (CVD) of $SiO_2$ at 400°C, followed by heat treatment in oxygen, it was concluded that $S_p$ for these low temperature oxides is about $10^5$ cm/sec and $(Q_0/q)_{\text{max}} = 7\times10^{11}$ cm$^{-2}$. Low-temperature oxides will have to be used for BSF cells, since high temperature treatments degrade the base material properties, mainly the diffusion length.
Very long diffusion lengths, at least as large as $W_B$, are necessary if the back-surface field is to have any considerable effect \cite{8} and if the total recombination is to be low enough that $V_{OC} \approx 700 \text{ mV}$ is obtained.

Our experiments \cite{11} and other published data indicate that $Q_0/q$ is limited (for the standard process of thermally grown dry oxides followed by heat treatment in oxygen at about 700°C) to about $7 \times 10^{11} \, \text{cm}^{-2}$ for (111) orientation \cite{12,13} and to about $3 \times 10^{11} \, \text{cm}^{-2}$ for (100) orientation \cite{12}. Wet oxides grown at low temperatures (700°-900°C) have $Q_0/q = 5 \times 10^{11} \, \text{cm}^{-2}$ on a (111) surface \cite{13}. CVD $\text{SiO}_2$ prepared at temperatures from 300 to 450°C and evaporated SiO have $Q_0/q$ higher than that for thermally oxidized samples. $Q_0/q$ for these oxides is about $2 \times 10^{12} \, \text{cm}^{-2}$ \cite{2,14}. However, these oxides have a much higher density of surface states, and thus higher $S_p$, than that typical of thermal oxides.

Therefore $p^+ - n^- n^+$ OCI-BSF cell which relies on oxide charge $Q_0$ and is made using the oxidation techniques described above may have $V_{OC}$ limited to about 625 mV. Additional experiments are necessary to determine whether this is a real limitation or whether substantially larger $V_{OC}$ can be obtained by these structures. On the other hand, the MOS-BSF structure, in which we apply a bias voltage to an MOS structure at the back side, has no apparent limitation to prevent achieving $V_{OC} = 700 \text{ mV}$. Notice that for $p^+ - n^- n^+$ cells, one has the choice of using either $Q_0$ or $V_G$ as the origin of the H-L junction. Because $Q_0$ is positive, in an $n^+ - p^- p^+$ cell, the gate-voltage approach is the only feasible one.

### III. Discussion

As discussed in Section II, the recombination current in BSF cell can be very effectively suppressed by a back accumulation region at the Si-SiO$_2$ interface. If the currents in the back accumulation region and the emitter region are low enough, then the recombination currents in the low-doped base region and at the $n^- n^+$ or $p^- p^+$ diffused Ohmic junction will limit the maximum achievable $V_{OC}$ and $n$. 
Based on available experimental data for lifetimes for holes and electrons [5,15,16] we estimate that the base will not be an obstacle in achieving $(V_{OC})_{max} = 700$ mV and $\eta_{max} = 20\%$ for one-sun AM1 illumination. In this calculation, we accounted the high injection condition present in the low-doped base region.

Fabrication of the proposed structures will involve, over a small part of the area, diffusion of $n^+$ or $p^+$-regions to insure good ohmic contact to the base, as shown in Fig. 2. Thus created $n-n^+$ or $p-p^+$ junctions will contribute to the base recombination current. The recombination current density at the $n-n^+$ diffused junction, for example, is

$$J_{nn^+} = q(n_{i1}^2/N_{eff}) (\frac{D_p}{W_{n^+}}) e^{q\phi/kT}$$

where $N_{eff} = 10^{18} \text{ cm}^{-3}$ is the effective doping concentration including the effects of bandgap narrowing [17] due to heavy doping $D_p$ is the average hole diffusivity in the $n^+$ region and $W_{n^+}$ is the thickness of the $n^+$-region. In deriving Eq. (5), we have assumed that the hole diffusion length exceeds $W_{n^+}$ in the $n^+$-region so that the $n^+$-region is nearly transparent to minority holes. From Eq. (5) we find that $J_{nn^+}$ presents no obstacle to obtaining $V_{OC} > 700$ mV provided the area of $n-n^+$ functions is $20\%$ or less.

These predictions did not consider heavy-doping effects [17,18,19] which may occur in very strongly accumulated surfaces. Since the accumulation layer is very thin, these effects will be much less severe than in diffused junctions and are not expected to appreciably change our predictions.

The main advantage of the new MOS-BSF and OCI-BSF cells compared to conventional BSF cells is that using the Si-SiO$_2$ interface instead of an ohmic contact allows very low values of $S_{eff}$ to be achieved at the L-\text{II} back junction, yielding large $V_{OC}$ and improved $J_{SC}$ [8,20]. Another advantage is the possibility of using CVD oxides deposited at low temperatures or evaporated oxides to create the MOS gate. The emitter diffusion in the $n^+-p^+$ BSF cell can be replaced by an induced $n^+$-inversion layer [2,14] which will allow complete fabrication of the cell at very low temperatures, possibly increasing the base lifetime in the finished device.
The disadvantage is that a voltage supply for gate bias $V_G$ is required. No power will be consumed, since the oxide is a very good electrical insulator. The voltage can come from 10 to 30 conventional silicon cells in series, which can supply hundreds of the new proposed cells because no power is consumed by their MOS gate structure. As another disadvantage, additional photoresist steps on the back side are also necessary to define a contact pattern, which raises the cost.

We feel, however, that these disadvantages will be outweighed by increased performance of the cell, even for normal illumination levels. The performance of a BSF cell can improve with increasing of illumination level [5]. For high concentration application the increased cost of production due to additional steps required to produce this new device will become less important, since cost of a cell is very small compared to the cost of an entire system.
REFERENCES FOR CHAPTER 6


Figure Captions

Fig. 1 Schematic diagram of a p$^+$-n-n$^+$ BSF solar cell.

Fig. 2 Schematic diagram of MOS-BSF and OCI-BSF cell structures. (a) p$^+$-n-n$^+$ MOS-BSF cell, (b) p$^+$-n-n$^+$ OCI-BSF cell, (c) n$^+$-p-p$^+$ MOS-BSF cell, (d) concentration profile of minority carriers in the base.

Fig. 3 Effective surface recombination velocity $S_{\text{eff}}$ versus surface recombination velocity $S_p$ for SiO$_2$ thickness of 1000 Å.

Fig. 4 Open-circuit voltage $V_{\text{OC}}$ versus surface recombination velocity $S_p$ for SiO$_2$ thickness of 1000 Å, $J_{\text{SC}} = 35$ mA/cm$^2$ and $W_B = 250$μm.
FIGURE 2
FIGURE 3

- \( V_G = 1.84 \text{V} \) and \( \frac{Q}{q} = 4 \times 10^{11} \text{cm}^{-2} \)
- \( V_G = 4.6 \text{V} \) and \( \frac{Q}{q} = 1 \times 10^{12} \text{cm}^{-2} \)
- \( V_G = 23 \text{V} \) and \( \frac{Q}{q} = 5 \times 10^{12} \text{cm}^{-2} \)
CHAPTER 7
DESIGN OF HIGH EFFICIENCY HLE SOLAR CELLS
FOR SPACE AND TERRESTRIAL APPLICATIONS

1. INTRODUCTION

The purpose of this paper is to discuss design approaches for silicon HLE solar cells. Design of cells for radiation and terrestrial environments are considered. Two main types of HLE cells receive attention: (a) the oxide-charge-induced (OCI) HLE cell, and (b) a new HLE cell having a wide p-epitaxial emitter for which the appropriate choices of emitter width and doping levels in the emitter and base are made to yield both high \( V_{OC} \) and high \( J_{SC} \).

SYMBOLS

\[ \begin{align*}
D_a & \quad \text{ambipolar diffusivity (cm}^2/\text{sec)} \\
D_n, D_p & \quad \text{electron and hole diffusivities (cm}^2/\text{sec)} \\
Q_0 & \quad \text{oxide charge density (C/cm}^2) \\
J_{SC} & \quad \text{short circuit current density (A/cm}^2) \\
J_{n0}, J_{p0} & \quad \text{dark electron and hole saturation current density (A/cm}^2) \\
L_n, L_p & \quad \text{electron and hole diffusion length (cm)} \\
\Delta n, \Delta p & \quad \text{excess electron and hole concentration (cm}^{-3})
\end{align*} \]
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\[ \begin{align*}
&n_i, \quad \text{intrinsic carrier concentration (cm}^{-3}\text{)} \\
n_s, p_s, \quad \text{electron and hole surface concentration (cm}^{-3}\text{)} \\
n_s(Q_0), \quad \text{oxide charge dependent electron surface concentration (cm}^{-3}\text{)} \\
n_{DD}, n_{DD}^+, \quad \text{donor concentration in n and n}^+ \text{ material (cm}^{-3}\text{)} \\
n_{AA}, n_{AA}^+, \quad \text{acceptor concentration in p and p}^+ \text{ material (cm}^{-3}\text{)} \\
n, \quad \text{electronic charge (Coulombs)} \\
S_p, S_{\text{eff}} \quad \text{hole surface recombination velocity (cm/sec)} \\
T \quad \text{effective surface recombination velocity (cm/sec)} \\
V_A \quad \text{temperature (°C, °K)} \\
V_{OC} \quad \text{applied voltage (Volts)} \\
(V_{OC})_B, (V_{OC})_E \quad \text{open circuit voltage (Volts)} \\
W_E \quad \text{open circuit voltage established by base and emitter (Volts)} \\
X_j \quad \text{emitter thickness (cm)} \\
\rho \quad \text{junction depth (cm)} \\
\tau_n, \tau_p \quad \text{resistivity (Ω cm)} \\
p, p^+ \quad \text{lifetime of minority electrons and holes (sec)} \\
n, n^+ \quad \text{associated with p and p}^+ \text{ region} \\
BOL \quad \text{associated with n and n}^+ \text{ region} \\
EOL \quad \text{beginning-of-life} \\
E, B \quad \text{end-of-life} \\
\text{associated with emitter and base} \\
\end{align*} \]

II. OCI-HLE CELL

Fig. 1(a) shows the cross-section of an OCI silicon HLE solar cell. The principles of operation of this cell, which have previously been discussed (1) are illustrated in Figs. 1(a) and 1(b). A positive charge \( Q_0 \), achieved by suitable heat treatment (2,3), induces an electron accumulation and an electric field near the silicon surface which reduces the effective surface recombination velocity for holes \( S_{\text{eff}} \) to (4)

\[ S_{\text{eff}} = \frac{N_{DD}}{n_s} S_p, \quad (1) \]
By solving the hole continuity equation for the desired case, \( W_E < L_p \), and low injection, one determines the hole saturation current \( J_{P0} \) to be (41)

\[
J_{P0} = \frac{q n_i^2}{N_{DD}} \left[ \frac{W_E}{S_{\text{eff}} + \frac{W_E}{\tau_p}} \right] \left[ 1 + \frac{S_{\text{eff}}}{D_p/W_E} \right]
\]

(2)

in which the first term in the numerator accounts for hole recombination at the surface and the second term accounts for hole recombination in the bulk. The current \( J_{P0} \) must be small if high \( V_{OC} \) is to result.

2.1 Beginning of life - (BOL) Design

For BOL, our experiments (1) show that \( S_p < 10^4 \text{ cm/sec} \) can result from the presence of the SiO\(_2\) layer on the illuminated surface. For a wide range of doping levels \( N_{DD} \), the term \( W_E/\tau_p \) in (2) can be made negligible, and the diffusion velocity \( D_p/W_E \) will typically be of the order of \( 10^4 \text{ cm/sec} \). Thus, if \( S_{\text{eff}} \) can be made much less than \( 10^4 \text{ cm/sec} \), then (2) reduces to

\[
J_{P0} = \frac{q n_i^2}{N_{DD}} S_{\text{eff}} = \frac{q n_i^2 S_p}{n_s}
\]

(3)

which also holds for high injection provided \( D_p/W_E \) and \( W_E/(\tau_n + \tau_p) \) are both small compared with \( S_{\text{eff}} \). The functional dependence \( n_s(Q_0) \) is found from standard MOS theory (6).

Because \( S_{\text{eff}} \) can be small, we consider now the value of \( J_{P0} \) for the limiting case \( S_{\text{eff}} = 0 \). Fig. 1(b) shows the minority hole density in the dark cell, resulting from an applied voltage, for the desired condition, \( L_p > W_E \):

\[
J_{P0} = q n_i^2 W_E (N_{DD} \tau_p)^{-1}
\]

(4)

To estimate \( J_{P0} \), we use the empirical data of Kendall (7), which gives, for \( N_{DD} = 5 \times 10^{16} \text{cm}^{-3} \),

\[
\tau_p N_{DD} = 3 \times 10^{12} \text{ sec/cm}^{-3}
\]

(5)
Thus, at $T = 25^\circ C$,

$$J_{p0} = 7 \times 10^{-12} W_E$$ \hspace{1cm} (6)

Thus, if $J_{SC} = 35 \text{ mA/cm}^2 (\text{AMO})$, which was seen in OCI-HLE cells, the open-circuit voltage limit, $(V_{OC})_E = kT/q \ln(J_{SC}/J_{p0})$, established by the emitter current $J_{p0}$ is, for example, 800 mV, 780 mV, and 718 mV for $W_E = 2 \mu m$, 5 \mu m, and 50 \mu m, respectively, independent of $N_{DD}$ (provided low-injection levels are maintained). From a design viewpoint, this demonstrates that $(V_{OC})_E > 700$ mV can be achieved for a wide variety of choices of $N_{DD}$ and $W_E$ provided only that $L_p > W_E$.

### 2.2 End-of-Life (EOL) Design

Radiation damage increase $S_p$ and $Q_0(8)$; it will also reduce $\tau_p (9, 10)$. As a design approach, we choose $W_E$ small compared with anticipated degraded diffusion length to minimize bulk recombination; that is, we require $W_E < L_p$ (after irradiation). Then (2) still applies, and $J_{p0}$ is determined by the velocities $S_{eff}$, $W_E/\tau_p$, and $D_p/W_E$. As a worst-case limit, we consider the case $S_{eff} = \ldots$. Then the transit time $t_t$ for holes to cross the emitter is

$$t_t = W_E^2 / 2D_p$$ \hspace{1cm} (7)

which, for example, is of the order of $10^{-9}$ sec for $W_E = 2 \mu m$. Thus, if $\tau_p$ after irradiation is larger than $10^{-9}$ sec, the emitter will be transparent to holes and (2) reduces to

$$J_{p0} = \frac{q n_i^2}{N_{DD}} \frac{D_p}{W_E}$$ \hspace{1cm} (8)

This worst-case dependence suggests that $N_{DD}$ should be large enough, both to assure small lateral series resistance and to decrease $J_{p0}$, but small enough to avoid heavy-doping degradation. For example, consider a design with $W_E = 2 \mu m$, and $N_{DD} = 10^{18} \text{ cm}^{-3}$. For $T = 25^\circ C$ and $J_{SC} = 25 \text{ mA/cm}^2$, $(V_{OC})_E > 640$ mV. For electron fluences up to $10^{15} \text{ cm}^{-2}$, $J_{SC} = 25 \text{ mA/cm}^2$ is expected if prior to radiation $J_{SC} = 35 \text{ mA/cm}^2 (10)$.

### 2.3 Examples of $V_{OC}$ established by the emitter for BOL and EOL

We have previously discussed $(V_{OC})_E$ for two limiting cases: $S_{eff} = 0$. 
which corresponds to the BOL condition, and $S_{\text{eff}} = \infty$, which corresponds to the EOL condition. We now remove these limiting-case assumptions by considering intermediate values of $S_{\text{eff}}$, as determined by (1) and the condition that $10^3 \text{ cm/sec} \cdot S_p < 10^7 \text{ cm/sec}$. The lower bound on $S_p$ is easily achieved, as is indicated by our experiments for a surface passivated by SiO$_2$ (1). The upper bound is a theoretical limit for a silicon surface (11).

In Fig. 3 we plot $(V_{OC})_E$ as a function of $S_p$ for two values of emitter widths $W_E = 2.5 \mu$m and $15 \mu$m and for emitter doping densities of $N_{DD} = 10^{17} \text{ cm}^{-3}$ and $10^{18} \text{ cm}^{-3}$. Three values of oxide charge densities are considered: (a) $Q_0/q = 4 \times 10^{11} \text{ cm}^{-2}$, which is the order of magnitude obtained in thermally grown dry oxides followed by oxygen heat treatment at about 700°C (2,3) before the irradiation; and $Q_0/q = 1 \times 10^{12} \text{ cm}^{-2}$ and $5 \times 10^{12} \text{ cm}^{-3}$, which is the range of values expected after irradiation (8). As shown in Fig. 3 for BOL with $S_p = 10^3 \text{ cm/sec}$, the emitter recombination is no barrier for achieving $(V_{OC})_E \geq 700 \text{ mV}$ for variety of emitter doping levels and thicknesses. After irradiation, for EOL, $S_p$ is expected to increase significantly (8), but will not be larger than the order of $10^6 \text{ cm/sec}$ (11). But $Q_0/q$ will also increase, as mentioned above, which will increase $n_s$ (6), and $S_{\text{eff}} = N_{DD} \cdot S_p / n_s$ ($Q_0$) will depend on the ratio $S_p / n_s$ ($Q_0$) after the irradiation. It follows from Fig. 3, consistent with our previous worst-case calculation, that $(V_{OC})_E > 650 \text{ mV}$ is still possible at EOL, if $W_E < (L_p/EOL)$. 

2.4 $V_{OC}$ established by the base for BOL and EOL

As shown in Fig. 1(b) for the dark case with applied voltage $V_A$, the quasi-neutral saturation current $J_0$ in low injection, neglecting heavy-doping effects (12), is $J_0 = J_{p0} + J_{n0}$, and the base saturation current is

$$J_{n0} = \frac{q n_0^2 D_n}{N_{AA} L_n}.$$  \hfill (9)

To minimize $J_{n0}$, note that, for $N_{AA} > 10^{17} \text{ cm}^{-3}$, $D_n / N_{AA} L_n$ is a decreasing function of $N_{DD}$ (13), provided heavy doping effects are negligible. As a result, the open-circuit voltage limited by the base $(V_{OC})_B$ is an increasing function of $N_{DD}$ until $N_{AA} = 10^{19} \text{ cm}^{-3}$ ($\rho_{\text{base}} = 0.01 \Omega \text{cm}$) which is a doping level at which the heavy doping effects in p-type material become important (12), as shown in
Fig. 4. The broken line in Fig. 4 shows an experimental dependence of $V_{OC}$ on $N_{AA}$ [14] which peaks at $N_{AA} = 5 \times 10^{17}$ cm$^{-3}$. This is a result of the increasing importance of the emitter current $J_{p0}$, for base dopings larger than about $5 \times 10^{17}$ cm$^{-3}$, in conventional cell where the emitter current is not suppressed by an HLE structure such as that present in the proposed device.

3. Design concepts for space and terrestrial applications

Based on the foregoing analysis we present design concepts for two different types of space cells and for a terrestrial cell.

1) $n^+\text{-n-p OCI-HLE (diffused HLE)}$ space cell

Fig. 5 shows a cell designed for space applications. The p-type base doping is $N_{AA} \approx 5 \times 10^{17}$ ($p \approx 0.1 \text{Ocm}$) which appears to be an optimum value which gives $L_n$ in a range of 85-150 $\mu$m in a finished cell [15]. This long diffusion length, which will assure collection of most of the generated minority electrons, provides a high value of the short circuit current $J_{SC}$. The epitaxial emitter is narrow, about 2 $\mu$m, and highly doped, $N_{DD} \approx 10^{17}$ to $10^{18}$ cm$^{-3}$, to assure low series resistance. The thinness of the emitter offsets, to a large degree, the effects of significant degradation of lifetime in the n-type material after the irradiation [9]. The H-L emitter junction can be achieved using either OCI induced or diffused $n^+$ layer [16].

The following conclusions about this structure can be made based on the discussion in the previous sections:

a) $(V_{OC})_E < 650$ mV at EOL, if $t_t < (\tau_p)_{EOL}$.
b) $(V_{OC})_B$ at EOL will depend on the radiation damage [10]. Since the base is the same as in the conventional n on p cell, results obtained for the conventional cell radiation damage [10] also apply here.
c) $(J_{SC})_{EOL} = (J_{SC})_{\text{conventional}} + (J_{SC})_E$.
d) For an OCI structure, $S_{eff} = N_{DD} S_p/n_s$, where both $S_p$ and $n_s$ increase with radiation, thus tending to keep $S_{eff}$ low. $S_{eff}$ controls $(J_{SC})_E$ and $J_{p0}$.
e) For BOL, with $S_p = 10^3$ cm/sec, $(V_{OC})_E > 700$ mV, and $(V_{OC})_B$ depends on minimizing $D_n L_n N_{AA}$. $(V_{OC})_B$ of the order of 700 mV can be expected for $p_{base} = 0.1 \text{Ocm}$ with $L_n > 75$ $\mu$m.
f) For $q\phi/q > 10^{12}$ cm$^{-2}$, heavy doping effects in the accumulation layer may become important (Fig. 2). However, since the accumulation layer is very narrow, these effects are expected to be very small [17].

g) A structure with a diffused n$^+$-region offers larger flexibility in choosing $N_{OD}$ because of the low shunting resistance of the n$^+$-diffused layer.

2) A wide-emitter p$^+$-p-n$^+$ space cell

We propose a new silicon solar cell structure [18] which is projected to have both high $J_{SC}$ (45 mA/cm$^2$) and high $V_{OC}$ (700 mV) and consequently high $\eta$ (20%, AM0). The new structure is projected to have good performance in radiation as well as non-radiation environments.

The structure is shown in Fig. 6. The qualitative sketches showing the minority carrier distributions in Fig. 1 are valid for this case, too, with hole and electron profiles reversed.

We emphasize some special features of this structure:

a) The surface is passivated with SiO$_2$ on top of which a suitable antireflection (AR) coating is deposited. The H-L emitter junction is achieved by a thin (~0.1 μm) p$^+$-diffused layer resulting in [4]

$$S_{eff} \approx S_n \frac{N_{AA}}{(N_{AA})_{eff}}$$

(10)

where $(N_{AA})_{eff} = 10^{19}$ cm$^{-3}$ is the effective doping in the p$^+$-diffused layer for $N_{AA} = 10^{20}$ cm$^{-3}$ at the surface. An electron recombination velocity at the Si-SiO$_2$ interface on the order of $10^3$ or less can be easily achieved [1]. Therefore, for $N_{AA} = 5 \times 10^{17}$ cm$^{-3}$, $S_{eff}$ is of the order of 10 cm/sec or less; thus $S_{eff} \approx 0$ is a reasonable approximation.

b) As a result of $S_{eff} \approx 0$, and the choice of a 50 μm wide emitter region, about 90% [19] of all available optically generated minority electrons will be collected. Using a 5% loss AR coating and 4% metal coverage the projected AM0 $J_{SC} = 45$ mA/cm$^2$. P-type material is chosen as a region from which the $J_{SC}$ is collected due to smaller sensitivity to the radiation than seen in n-type material [9].

c) The doping level in the n$^+$-base is optimized to be about $10^{18}$ cm$^{-3}$, which is the onset level for heavy-doping effects [17]. The doping
level in the emitter ($\approx 5 \times 10^{17} \text{ cm}^{-3}$) is chosen to minimize $N_{AA} \tau_n$ [13].

d) Using published data for lifetimes for holes and electrons [7,13], we can calculate by use of Eqs. (2) and (9), for structure shown in Fig. 6, that the saturation current $J_0 \approx 7 \times 10^{-14} \text{ A/cm}^2$, implying $V_{OC} = 700 \text{ mV}$ for $J_{SC} = 45 \text{ mA/cm}^2$ at 25°C, and implying $\eta = 20\% \text{ AMO}$.

e) Significant differences exist between this new cell and a previously proposed epitaxial $p^+-p-n$ cell [20]; these are discussed in detail in Ref. 18.

f) An alternative related structure ($p^+-p-n^+$) can be made, which employs an $n-n^+$ low-high junction back-surface-field base [4]. This structure will have higher $J_{SC}$ at BOL due to improved collection of minority holes from the n-region of the base.

3) $n^+-n-p$ OCI-HLE terrestrial cell (Fig. 1)

There are two approaches to minimize the base current in this cell, Fig. 7:

a) Choose $n_{base} = 0.1 \text{ \Omega cm}$ ($N_{AA} = 5 \times 10^{17} \text{ cm}^{-3}$). In this case $L_n \geq 70 \mu\text{m}$ is required for $(V_{OC})_B = 700 \text{ mV} \ 25°C$ and $J_{SC} = 35 \text{ mA/cm}^2$. Such values for $L_n$ can be achieved in finished cells using a low temperature fabrication process [13,15]. Epitaxial growth of the emitter and a high-temperature oxidation required for low $S_p(l)$ may decrease $L_n$ below the 70 $\mu\text{m}$; this would result in $(V_{OC})_B < 700 \text{ mV}$. The largest $V_{OC}$ seen experimentally for a cell with $n_{base} = 0.1 \text{ \mu\Omega cm}$ is 643 mV AMO, at 25°C.

b) A second approach is to use a highly doped p-type ($5 \times 10^{18} - 10^{19} \text{ cm}^{-3}$) base. Note that for $N_{AA} = 5 \times 10^{18} \text{ cm}^{-3}$, for example, $L_n = 2 \mu\text{m}$ is sufficient to achieve $(V_{OC})_B$ of 700 mV. Such values are expected even after the high-temperature fabrication steps. In this second approach, $W_E \approx 50 \mu\text{m}$, since the base will contribute negligibly to $J_{SC}$. Such a wide emitter is required to collect about 90% of generated minority holes. In approach (a), $W_E$ can range from about 10 to 50 $\mu\text{m}$. The largest $V_{OC}$ seen experimentally for a cell with $n_{base} = 0.024 \ \Omega \text{cm}$ ($N_{AA} = 2.5 \times 10^{18} \text{ cm}^{-3}$) is 647 mV AMO, at 25°C.

c) Emitter doping can be chosen from range of about $5 \times 10^{16} \text{ cm}^{-3}$ to about $5 \times 10^{17} \text{ cm}^{-3}$. 
First order analysis of HLE solar cells for BOL and EOL conditions is presented. Based on this analysis and on experimentally measured material parameters, design concepts for both space and terrestrial cells are discussed. The proposed structures include: n⁺-n⁻, CI-HLE space cell, wide emitter p⁺-p⁻-n⁺ space cell, and n⁺-n⁻-p OCI-HLE terrestrial cell. All structures are projected to yield both high $V_{OC}$ and $J_{SC}$. 
REFERENCES FOR CHAPTER 7


Fig. 1. (a) Schematic diagram of a $n^+ - n - p$ p-i-n-L.E cell. 
(b) Qualitative sketches of excess minority carrier distribution in dark with applied voltage $V_h$.

Fig. 2. Dependence of electron surface concentration $n_s$ and effective surface recombination velocity $S_{eff}$ (for $v_b = 10^6$ cm/sec) on emitter doping.
Fig. 3. Dependence of $(V_{oc})_E$ on $S_p$.

$Q_0/q = 4 \times 10^{12} \text{cm}^2$

$Q_0/q = 1 \times 10^{12} \text{cm}^2$

$Q_0/q = 5 \times 10^{12} \text{cm}^2$

$N_0 = 10^6 \text{cm}^{-3}, \psi_E = 2.5 \mu \text{m}$

$N_0 = 10^7 \text{cm}^{-3}, \psi_E = 2.5 \mu \text{m}$

$N_0 = 10^7 \text{cm}^{-3}, \psi_E = 15 \mu \text{m}$

Fig. 4. Experimental and theoretical dependence of $V_{oc}$ on base doping. Best results obtained on OCI-NLE cells are 683 mV for 0.10 cm box resistivity and 647 mV for 0.02 cm box base mobility (measured at NASA Lewis, at 25°C, AM0).

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Fig. 5. Schematic diagram of an $n^+ - n - p$ OCI-NLE (diffused NLE) space cell.

Fig. 6. Schematic diagram of a $p^- - p^- - n^+$ space cell.

Fig. 7. Schematic diagrams of an OCI-NLE terrestrial cells:
(a) $n^+ - n - p$ cell
(b) $n^+ - n - p^+$ cell
CHAPTER 8

SUMMARY

The project "Studies of silicon p-n junction solar cells", sponsored by NASA Lewis Research Center started in June 1974 and ran through December 1979. The project produced two M. S. Theses and three Ph.D. Theses. It also yielded 15 journal papers and 12 conference presentations. All this would have been impossible without the close cooperation of H. W. Brandhorst, Jr., and M. P. Godlewski (Technical Monitor) of NASA Lewis. We also profited from interactions with other NASA Lewis people including C. A. Baraona, D. T. Bernatowicz, R. E. Hart, Jr., C. K. Swartz, and I. Weinberg.

This report summarizes our progress during the period of September 1977 - September 1979. It contains the most significant results of both theoretical and experimental studies done in this period, as follows:

(a) Development and fabrication of an OCI-HLE cell yielding reproducibly $\text{V}_{\text{OC}} = 647 \text{ mV (AM0, 25°C)}$, which is the largest $\text{V}_{\text{OC}}$ observed at NASA Lewis in Si p-n junction solar cells up to date.

(b) Determination of bandgap narrowing as a function of doping density in the emitter in a range of $3 \times 10^{19} \text{ cm}^{-3}$ to $2 \times 10^{20} \text{ cm}^{-3}$.

(c) Development and demonstration of methods for measuring very long diffusion lengths ($\sim 500 \mu\text{m}$) in solar cells and associated
dark recombination currents.

(d) Development of a comprehensive analytic theory for the limit placed on $V_{OC}$ by a heavily-doped emitter region subject to the condition that most minority carriers in the forward-biased nonilluminated emitter recombine at the surface rather than in the bulk.