Comprehensive silicon solar-cell computer modeling
Research Triangle Institute
M.F. Lamorte

Synopsis of Significant Progress

1. Model and analysis of the net charge distribution in quasineutral regions (investigation continuing in collaboration with Professor F. A. Lindholm, University of Florida)

2. Experimentally determined temperature behavior of Spire Corp. n+ pp+ solar cells where n+ emitter is formed by ion implantation of 75As or 31P
(Acknowledgments: M. B. Spitzer, Spire Corp.; and Ward J. Collis, North Carolina A&T State University, Greensboro, N.C.)

3. Initial validation results of computer simulation program using Spire Corp. n+ pp+ cells.

Model and analysis of the net charge distribution in quasineutral regions: a model and a corresponding analysis has been developed that describes the net charge distribution which gives rise to built-in electric fields. Conclusions derived from analysis are:

a. only the redistribution of majority carriers, from their charge neutrality distribution, may affect the establishment of high-intensity built-in electric fields

b. charge neutrality exists in quasineutral regions only for position-independent and exponential doping concentration profiles

c. all other doping profiles produce a net charge concentration distribution

d. new mass action law is developed that applies to quasineutral regions in which charge neutrality is not present.
Application to n+-region:

Electron concentration distribution:
\[ n_n(x) = p_n(x) + N_D(x) - N_A(x) - \Delta N_n(x) \]

Net positive charge concentration:
\[ \Delta n_n = \frac{E}{q} \frac{dE_n}{dx} \]

Mass action law:
\[ p_n = \frac{N_D - N_A - \Delta n_n}{2} \left[ \sqrt{1 + \left( \frac{2n_e}{N_D - N_A - \Delta n_n} \right)^2} - 1 \right] \]

for charge neutrality \( \Delta n_n = 0 \), and \( p_n = \frac{n_e^2}{N_D - N_A} \)

Substitute \( p_n \) into \( n_n \):
\[ n_n = \frac{N_D - N_A - \Delta n_n}{2} \left[ \sqrt{1 + \left( \frac{2n_e}{N_D - N_A - \Delta n_n} \right)^2} + 1 \right] \]

for charge neutrality \( \Delta n_n = 0 \), and \( n_n = N_D - N_A + p_n \)

Application to n+-region with Gaussian Donor Distribution:

Built-in electric field: \( E_n = \frac{kT}{q} \frac{x}{2Dt} \)

\[ \delta = \frac{1}{1 - \frac{N_A - \Delta n_n}{N_D}} \]

Far removed from the depletion region edge: \( \delta \rightarrow 1 \)

\[ E_n = \frac{kT}{q} \frac{x}{2Dt} \]

\[ \frac{dE_n}{dx} = \frac{kT}{q} \frac{1}{2Dt} = \text{position independent} \]

\( \Delta n_n \) - position independent (see Figure 1).
Figure 1. Representation of the Charge Distribution in the Quasi-Neutral n-Type Emitter Region of a Solar Cell that Establishes a Built-In Electric Field Attributed to a Gaussian Donor Concentration Profile.

![Graph showing charge distribution](image)

Experimental Data Obtained from n⁺ pp⁺ Spire Corp. Solar Cells at 28°C

<table>
<thead>
<tr>
<th>Cell #</th>
<th>Ion</th>
<th>Dose (ions/cm²)</th>
<th>LD (µm)</th>
<th>QE (@ 350 µm)</th>
<th>VOL (mV)</th>
<th>JSC (mA/cm²)</th>
<th>FF (%)</th>
<th>EFF (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1B</td>
<td>P</td>
<td>$1 \times 10^{14}$</td>
<td>48</td>
<td>.18</td>
<td>541</td>
<td>20.1</td>
<td>77.1</td>
<td>8.39</td>
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<tr>
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<td>P</td>
<td>$2 \times 10^{14}$</td>
<td>46</td>
<td>.31</td>
<td>577</td>
<td>20.7</td>
<td>77.9</td>
<td>9.28</td>
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<tr>
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<td>P</td>
<td>$4 \times 10^{14}$</td>
<td>46</td>
<td>.44</td>
<td>603</td>
<td>20.5</td>
<td>79.4</td>
<td>9.81</td>
</tr>
<tr>
<td>8C</td>
<td>P</td>
<td>$8 \times 10^{14}$</td>
<td>56</td>
<td>.43</td>
<td>608</td>
<td>21.0</td>
<td>80.1</td>
<td>10.2</td>
</tr>
<tr>
<td>10F</td>
<td>P</td>
<td>$1 \times 10^{15}$</td>
<td>76</td>
<td>.42</td>
<td>610</td>
<td>21.7</td>
<td>81.0</td>
<td>10.7</td>
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<tr>
<td>12C</td>
<td>P</td>
<td>$2.5 \times 10^{15}$</td>
<td>94</td>
<td>.37</td>
<td>610</td>
<td>22.4</td>
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<td>11.0</td>
</tr>
<tr>
<td>14C</td>
<td>As</td>
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<td>37</td>
<td>.31</td>
<td>559</td>
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<td>71.3</td>
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</tr>
<tr>
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<td>As</td>
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<td>41</td>
<td>.42</td>
<td>590</td>
<td>20.6</td>
<td>77.0</td>
<td>9.37</td>
</tr>
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<td>17F</td>
<td>As</td>
<td>$4 \times 10^{14}$</td>
<td>3/</td>
<td>.44</td>
<td>603</td>
<td>20.8</td>
<td>77.5</td>
<td>9.81</td>
</tr>
<tr>
<td>20C</td>
<td>As</td>
<td>$8 \times 10^{14}$</td>
<td>38</td>
<td>.47</td>
<td>605</td>
<td>20.8</td>
<td>79.5</td>
<td>9.91</td>
</tr>
<tr>
<td>22F</td>
<td>As</td>
<td>$1 \times 10^{15}$</td>
<td>40</td>
<td>.46</td>
<td>603</td>
<td>20.8</td>
<td>80.7</td>
<td>10.1</td>
</tr>
<tr>
<td>24C</td>
<td>As</td>
<td>$2.5 \times 10^{15}$</td>
<td>59</td>
<td>.44</td>
<td>595</td>
<td>22.8</td>
<td>74.1</td>
<td>10.1</td>
</tr>
</tbody>
</table>

Notes: cell area = 4 cm². T = 28°C. Insolation was AM1.5, 100 mW/cm². No AR coating.
Figure 2. Experimentally Determined Behavior of Efficiency versus Temperature Obtained from $n^+p^+p^+$ Spire Corp. Solar Cells Which Do Not Have AR Coatings.
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Figure 3. Experimentally Determined Behavior of Open-Circuit Voltage versus Temperature Obtained from n⁺pp⁺ Spire Corp. Solar Cells Which Do Not Have AR Coatings.

LEGEND
- 18
- 8C
- 12C
- 14C
- 20C
- 24C

![Graph showing the relationship between Voc (Open-Circuit Voltage) and temperature (°C).](image-url)
Figure 4. Comparison of Experimental Data and Simulation Results
Describing the Behavior of the Short-Circuit Current Density
Versus Temperatures for n+pp+ Spire Corp. Solar Cell No. 24C,
Which Does Not Have an AR Coating.

Calculated Normalized Temperature Coefficients of Efficiency,
Open-Circuit Voltage, and Short-Circuit Current Density Obtained
from n+pp+ Spire Corp. Solar Cell Experimental Data
Which Do Not Have AR Coatings

<table>
<thead>
<tr>
<th>Figure of Merit</th>
<th>Dose = $1 \times 10^{14}$ cm$^{-2}$</th>
<th>Percent Change</th>
<th>Dose = $2.5 \times 10^{14}$ cm$^{-2}$</th>
<th>Percent Change</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\frac{1}{T} \frac{d \eta}{dT}$</td>
<td>$-4.9 \times 10^{-3}$</td>
<td>$-4.0 \times 10^{-3}$</td>
<td>$-22.5%$</td>
<td>$-4.1 \times 10^{-3}$</td>
</tr>
<tr>
<td>$\frac{1}{T} \frac{d V_{oc}}{dT}$</td>
<td>$-4.1 \times 10^{-3}$</td>
<td>$-3.7 \times 10^{-3}$</td>
<td>$+10.8%$</td>
<td>$-3.4 \times 10^{-3}$</td>
</tr>
<tr>
<td>$\frac{1}{T} \frac{d J_{sc}}{dT}$</td>
<td>$0.9 \times 10^{-3}$</td>
<td>$1.1 \times 10^{-3}$</td>
<td>$-18.2%$</td>
<td>$0.63 \times 10^{-3}$</td>
</tr>
<tr>
<td>$\eta_0$ (Spire Corp)</td>
<td>8.39</td>
<td>8.03</td>
<td>$4.5%$</td>
<td>11.0</td>
</tr>
<tr>
<td>$\eta_0$ (NC A&amp;T)</td>
<td>8.2</td>
<td>7.8</td>
<td>$5.1%$</td>
<td>10.4</td>
</tr>
</tbody>
</table>

*No AR coating
Figure 5. Simulation of Electric Field Distribution in n+ of Spire Corp. Solar Cell No. 24C With Temperature a Parameter.
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Figure 6. Net Charge Distribution in the n⁺-Region of Spire Corp. Solar Cell No. 24C With Temperature a Parameter.
Figure 7. Simulation of Photoexcited Hole Concentration in the 
n⁺-Region of Spire Corp. Solar Cell No. 24C, 
With Temperature a Parameter.
Figure 8. Lifetime and Transit Time Simulations of Holes in the n⁺-Region of a n⁺ pp⁺ Spire Corp. Solar Cell, No. 24C, Under Short-Circuit and 27°C.
Figure 9. Short-Circuit Current Density versus Base Electron Diffusion Length Representing Spire Corp. n⁺pp⁺ Silicon Solar Cells and Computer Simulation Results of Cell No. 24C, no AR Coating, and 27°C.

Figure 10. Behavior of Short-Circuit Current Density versus Base Electron Diffusion Length Obtained from Simulating Cell No. 24C, n⁺pp⁺, Provided by the Spire Corp., no AR Coating, and 27°C.