Objectives and Approach

OBJECTIVES
* To investigate the use of PECVD silicon nitride for passivation of silicon surfaces.
* To investigate measurement techniques for surface recombination velocity.
* To investigate the importance of surface passivation to high efficiency solar cells.

APPROACH

SiN$_x$ FILM DEPOSITION AND CHARACTERIZATION
* Establish PECVD system
* Develop deposition procedures

FILM CHARACTERIZATION
* Optical characterization -- N and K vs. wavelength and deposition parameters.
* Physical characterization

PASSIVATION STUDIES
* Surface state density at SiN$_x$/Si interface for moderately doped silicon substrates.
* Photoreponse of N/P solar cells with PECVD SiN$_x$ films.
* Current-voltage analyses of silicon cells with SiN$_x$ films.
* Rosier measurement
SiN\(_x\) Film Index of Refraction vs Silane-Ammonia Ratio

* SUBSTRATE
  TEMPERATURE = 270 °C
* RF POWER = 1225 W/m\(^2\)

DECREASED POWER AND/OR TEMPERATURE

Optical Constants of SiN\(_x\) Films From Ellipsometry Measurements

*MEASUREMENTS TAKEN ON EQUIPMENT PROVIDED BY BATTELLE NORTHWEST LABORATORIES
Approaches to Investigation of Surface Recombination in Solar Cells

M-Si$_n$-pSi STRUCTURE
High frequency and quasi-static C-V measurements to obtain interface state density.

SOLAR CELL STRUCTURE
Photoreponse at short wavelengths can theoretically yield recombination velocity.

I-V CHARACTERIZATION may allow identification of dominant current mechanisms.

SPECIAL STRUCTURES (ROSIER)
Photoreponse measurement with surface potential varied may allow determination of S.

I-V CHARACTERIZATION with surface potential varied allows detection of surface recombination effects.
Results of Interface State Study of SiNₓ on p-Type Si

<table>
<thead>
<tr>
<th>SURFACE TREATMENT</th>
<th>RF POWER = 212 W/m²</th>
<th>RF POWER = 1225 W/m²</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>SUBSTRATE TEMPERATURE</td>
<td>SUBSTRATE TEMPERATURE</td>
</tr>
<tr>
<td>ABBREV CLEAN</td>
<td>150°C 270°C</td>
<td>150°C 270°C</td>
</tr>
<tr>
<td>RCA CLEAN</td>
<td></td>
<td></td>
</tr>
<tr>
<td>ABBREV CLEAN &amp; NITRIED</td>
<td></td>
<td></td>
</tr>
<tr>
<td>RCA CLEAN &amp; NITRIED</td>
<td></td>
<td></td>
</tr>
<tr>
<td>RCA CLEAN &amp; THIN OXIDE</td>
<td></td>
<td></td>
</tr>
<tr>
<td>RCA CLEAN, THIN OXIDE &amp; NITRIED</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Interface State Density vs. Annealing Temperature for SiNₓ on p-Type Si

○ RCA CLEAN/NITRIED/DEPOSIT @150°C
▼ RCA CLEAN/NITRIED/DEPOSIT @270°C (UPPER LIMIT)
□ RESULTS REPORTED B. HEZEL, ET AL.

![Graph showing Interface State Density vs. Annealing Temperature](image-url)
Internal Photoresponse Analysis

**THEORY**

\[ J_{PH}(x) = S_{INT}(x) \cdot T_e - N_a - q \]

\[ S_{INT}(x) = S_{DEPL} + (S_{EMITTER})_{LENGTH} + (S_{BASE})_{WIDTH} \]

\[ T_e = T_0 \cdot \left( n_{AR} \cdot K_{AR} \cdot n_{SL} \cdot K_{SL} \right) \]

\[ = 1 - R_A - R_L \]

**EXPERIMENT**

**MEASURE:** \[ J_{PH}(x), R_A, N_a \] and \[ K_A \] of \[ S_{INT} \]

**ANALYSIS:** HAVE OBTAINED \[ S_{INT}(x) \] FOR CELLS WITH \[ S_{INT} \] LAYERS. DETERMINED \[ S_e \] ASSUMING A HOMOGENEOUS EMITTER.

**Internal Photoresponse vs Wavelength for S: n-p Cell With 100 Angstroms SiO_2**

**THEORETICAL PARAMETERS:**

- \( L_i = 1.0 \text{ um, } D_i = 3.0 \text{ cm/s} \)
- \( L_s = 150 \text{ um, } D_s = 12.0 \text{ cm/s} \)
- \( X_j = 0.2 \text{ um, } W_i = 0.015 \text{ um, } H = 380 \text{ um} \)
- \( S(0) = 1 \times 10^8 \text{ cm}^{-1} \text{ cm} \text{ (OHMG), Aluminum 85R, } 0.2 \text{ ohm-cm, } n^+ \text{ 3IRpac} \)
Internal Photoresponse vs Wavelength for JPL Cell

**THEORETICAL PARAMETERS:**
- \( L(\gamma) = 1.0 \text{ um}, D(\gamma) = 2.0 \text{ cm}^2/\text{s} \)
- \( L(\beta) = 130 \text{ um}, D(\beta) = 21.0 \text{ cm}^2/\text{s} \)
- \( X_j = 3.5 \text{ um}, W = 413 \text{ um}, H = 210 \text{ um} \)
- \( S(\beta) = 1 \text{E9 (ohmic)}, \text{Aluminum BSR} \)
- \( 2 \text{ ohm-cm N/P Silicon} \)

---

**THEORETICAL PARAMETERS:**
- \( L(\gamma) = 1.0 \text{ um}, D(\gamma) = 3.0 \text{ cm}^2/\text{s} \)
- \( L(\beta) = 140 \text{ um}, D(\beta) = 21.0 \text{ cm}^2/\text{s} \)
- \( X_j = 17 \text{ um}, W = 413 \text{ um}, H = 319 \text{ um} \)
- \( S(\beta) = 1 \text{E9 (ohmic)}, \text{Aluminum BSR} \)
- \( 2 \text{ ohm-cm N/P (111) FZ Silion} \)
**High-Efficiency Silicon Solar Cell Research**

**Illuminated Characteristics of JPL Cells**
*(Fabricated by ASEC)*

<table>
<thead>
<tr>
<th>CELL</th>
<th>ORIENTATION</th>
<th>AR LAYER</th>
<th>AM1* EFFICIENCY [%]</th>
<th>Jsc (mA)</th>
<th>Voc (mV)</th>
<th>FF</th>
<th>TOTAL AREA Jsc (mA/cm²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2-3</td>
<td>(100)</td>
<td>SiO₂</td>
<td>15.2</td>
<td>130</td>
<td>583</td>
<td>.798</td>
<td>32.6</td>
</tr>
<tr>
<td>4-1</td>
<td>(100)</td>
<td>SiO₂</td>
<td>14.7</td>
<td>129</td>
<td>579</td>
<td>.786</td>
<td>32.3</td>
</tr>
<tr>
<td>1-5</td>
<td>(100)</td>
<td>SiNₓ</td>
<td>14.6</td>
<td>130</td>
<td>570</td>
<td>.793</td>
<td>32.7</td>
</tr>
<tr>
<td>2-6</td>
<td>(100)</td>
<td>SiNₓ</td>
<td>14.7</td>
<td>130</td>
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<td>.791</td>
<td>32.7</td>
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<tr>
<td>9-1</td>
<td>(111)</td>
<td>SiO₂</td>
<td>15.0</td>
<td>130</td>
<td>581</td>
<td>.795</td>
<td>32.5</td>
</tr>
<tr>
<td>10-2</td>
<td>(111)</td>
<td>SiO₂</td>
<td>15.7</td>
<td>134</td>
<td>588</td>
<td>.796</td>
<td>33.5</td>
</tr>
<tr>
<td>8-5</td>
<td>(111)</td>
<td>SiNₓ</td>
<td>14.4</td>
<td>128</td>
<td>570</td>
<td>.786</td>
<td>32.0</td>
</tr>
<tr>
<td>9-2</td>
<td>(111)</td>
<td>SiNₓ</td>
<td>14.8</td>
<td>130</td>
<td>573</td>
<td>.792</td>
<td>32.9</td>
</tr>
</tbody>
</table>

*EFFICIENCY MEASURED AT JGS WITH ELH SIMULATOR. THE SIMULATOR HAS BEEN CALIBRATED BY EXCHANGING A REFERENCE CELL WITH SERI.*

**Effect of Reactive Ion Etching Cell Edges**

*JPL1-5-ETCH 9/28/84*  
*ETCHED × SIN*  

**Log (Current) vs. Applied Voltage**

![Graph showing log (current) vs. applied voltage](image)

339
Approach to Dark I-V Analysis

I-V Relationship \( (V_j \gg kT) \)

\[
I_{\text{meas}} = I_j \cdot \frac{V_j}{nkT}
\]

\[
V_j = V_{\text{meas}} \cdot R_S \cdot I_{\text{meas}}
\]

\[
I_j = I_{01} \exp(BV_j) + I_{02} \exp(V_j/nkT)
\]

Fitting Procedure

1. Select \( R_S \) and \( R_{SH} \)
2. Generate \( (I_j, V_j) \)
3. Consider \( (I_j, V_j) \) for Region 1
   \[
   I_j = I_{01} \exp(BV_j)
   \]
   \[
   \log_e(I_j) = \log_e(I_{01}) + BV_j
   \]
   Least squares fit \( \Rightarrow I_{01}, B \)
4. Consider \( (I_j, V_j) \) for Region 2
   \[
   I_{j2} = I_j - I_{01} \exp(BV_j)
   \]
   \[
   = I_{02} \exp(V_j/nkT)
   \]
   Least squares fit \( \Rightarrow I_{02}, B \)
5. Iterate between Regions 1 and 2 until achieve convergence.
6. Carry out steps 1 through 5 for array of \( R_S \) and \( R_{SH} \) values. Select values of parameters which provide best fit to data.
**HIGH-EFFICIENCY SILICON SOLAR CELL RESEARCH**

**Emitter J_0 vs Surface Donor Concentration**
for Shallow-Junction n-p Cell

![Graph showing J_0 vs N_d for different S values](image)

1. J_0 for 2 Ohm-cm N/P CELL WITH THICKNESS OF 15 MILS, L(BASE) = 130 μm, D = 21 cm^2/sec^1 (APPROXIMATE CELLS PROVIDED BY JPL).
2. J_0 for 0.2 Ohm-cm N/P CELL WITH THICKNESS OF 15 MILS, L(BASE) = 150 μm, D = 21 cm^2/sec^-1.

**I-V Parameters for Dark Characteristics**

<table>
<thead>
<tr>
<th>CELL</th>
<th>JCT DEPTH (μm)</th>
<th>BASE RESISTIVITY (Ohm-cm)</th>
<th>MAGNITUDE FOR FIT</th>
<th>AVERAGE ERROR (%)</th>
<th>J_0 (A/cm^2)</th>
<th>n</th>
<th>ACTIVATION ENERGY (eV)</th>
<th>POSSIBLE CURRENT MECHANISM</th>
</tr>
</thead>
<tbody>
<tr>
<td>JPL 6</td>
<td>0.4</td>
<td>2</td>
<td>2.5</td>
<td>0.30</td>
<td>2.1E-11</td>
<td>1.07</td>
<td>0.95</td>
<td>DEPLAYER RECOMB VIA SHALLOW TRAP</td>
</tr>
<tr>
<td>JPL 8-5</td>
<td>0.2</td>
<td>2</td>
<td>2.8</td>
<td>0.20</td>
<td>1.7E-11</td>
<td>1.02</td>
<td>1.00</td>
<td>EMITTER RECOMB WITH S = 10^5 to 10^6 cm/sec</td>
</tr>
<tr>
<td>JPL 9-1</td>
<td>0.2</td>
<td>2</td>
<td>2.8</td>
<td>0.19</td>
<td>3.1E-11</td>
<td>1.06</td>
<td>0.94</td>
<td>DEPLAYER RECOMB VIA SHALLOW TRAP</td>
</tr>
<tr>
<td>JCIGS</td>
<td>0.2</td>
<td>0.2</td>
<td>2.0</td>
<td>0.4</td>
<td>1.3E-12</td>
<td>1.02</td>
<td>1.10</td>
<td>EMITTER RECOMB WITH S = 10^5 to 10^6 cm/sec</td>
</tr>
</tbody>
</table>

**LARGE VOLTAGE MECHANISM**
Analysis of Temperature-Dependent I-V Characteristics of JPL Cell

I-V DATA

ACTIVATION ENERGY ANALYSIS
Theory for I-V Characteristics

1. EMITTER RECOMBINATION CURRENT

\[ J = J_{OE} \left( \exp \left( \frac{V}{nkT} \right) - 1 \right) \]

\[ n = 1 \]

FOR RM TEMP ANALYSIS:

\[ J_{OE} = \frac{qL_0}{N_0 l_{th}} \cdot GF \]

GF IS A FCT OF \( W_H, S_F, D_{PO} \& T_P \)

FOR INTERPRETATION OF TEMPERATURE DEPENDENT DATA:

\[ J_{OE} = J_{00} (T) \exp \left( \frac{-\phi}{kT} \right) \]

\[ \phi = 1.20 - (AE) \quad \text{EMITTER} \]

2. BASE REGION RECOMBINATION CURRENT

\[ J = J_{OB} \left( \exp \left( \frac{V}{nkT} \right) - 1 \right) \]

\[ n = 1 \]

\[ J_{OB} = \frac{qL_0}{N_A} t_n \cdot GF \]

\[ = J_{00} (T) \exp \left( \frac{-\phi}{kT} \right) \]

\[ \phi = 1.20 - (AE) \quad \text{BASE} \]

3. DEPLETION LAYER RECOMBINATION CURRENT

\[ J = J_{OR} \left( \exp \left( \frac{V}{nkT} \right) - 1 \right) \]

\[ n = 1 \quad \text{TO} 2 \]

FOR \( n^2, \phi \approx E_g/2 \)

\[ \phi = (E_i - E_F) \quad \text{OR} \quad (E_C - E_F) \]

\[ \phi \quad \text{TYPICALLY} \quad 0 \quad \text{TO} \quad 0.5 \quad \text{eV} \]

4. TUNNELING/RECOMBINATION

\[ J = J_{OT} \exp (BV) \quad V \gg kT \]

\[ B \quad \text{TEMPERATURE INDEPENDENT} \]

\[ J_{OT} = J_{00} \exp \left( \frac{-\phi}{kT} \right) \]

\[ \phi \quad \text{TYPICALLY} \quad 0 \quad \text{TO} \quad 0.5 \quad \text{eV} \]

5. FIELD EMISSION

\[ J = J_{OF} \exp (C V) \]

\[ C = \frac{1}{nkT} + B \]

\[ J_{OF} = J_{00} \exp \left( -\frac{\phi}{kT} \right) \]

\[ \phi = \frac{f}{n^2} \quad f = n^{-1} \]

6. EDGE LEAKAGE CURRENTS

\[ \text{CURRENT MECHANISMS} \quad (3), (4) \quad \text{OR} \quad (6) \]

\[ \text{USUAL SHUNTING MECHANISM} \]

\[ J_{SH} = V/R_{SH} \]
MINP Cell Concept

MIS CONTACT USING Mg OR Ti

N-TYPE EMITTER
1000 Å TO 2500 Å

P-TYPE BASE
(0.1 TO 2.0 cm)

P+ REGION TO PROVIDE BACK SURFACE FIELD

ALUMINUM BACK CONTACT

Calculated \( J_{ph} \) for Single and Double AR Layers

- Textured (2L-AR)
- Textured (1L-AR)
- Polished

\[ J_{ph} \text{ (mA/cm²)} \]

\[ N_N = 1.3, 1.4, 1.5 \]

\[ L = 500, 150, \text{ and BSF} \]

\[ \text{ACTIVE AM1.5} \]

\[ \text{INDEX OF LAYER ADJACENT TO SILICON} \]
HIGH-EFFICIENCY SILICON SOLAR CELL RESEARCH

Projected Performance

TO ACHIEVE 20%

- MUST REDUCE J0E BY DECREASING Ns AND SP
- NEED SLIGHT IMPROVEMENT IN L

TO ACHIEVE 25%

- NEED F&P DIFFUSION LENGTH
- MUST REDUCE SP TO 10
- WITH THESE VALUES OF L AND SP, J0 WILL BE DECREASED TO 43 x 10^-14 A/cm²
- MUST USE DOUBLE AR WITH TEXTURED SURFACE OR WITH COMPLETE OPTICAL CONFINEMENT

<table>
<thead>
<tr>
<th>Jsc (mA/cm²)</th>
<th>Voc (mV)</th>
<th>FF</th>
<th>J0 (A/cm²)</th>
<th>n VALUE</th>
<th>Ni (cm⁻¹)</th>
<th>10⁴</th>
<th>10⁴</th>
<th>10⁴</th>
<th>10⁴</th>
</tr>
</thead>
<tbody>
<tr>
<td>36.0</td>
<td>630</td>
<td>794</td>
<td>1 x 10⁻¹²</td>
<td>1.0</td>
<td>6 x 10¹⁵</td>
<td>10⁴</td>
<td>10⁴</td>
<td>10⁴</td>
<td>10⁴</td>
</tr>
<tr>
<td>36.0</td>
<td>650</td>
<td>812</td>
<td>4.5 x 10⁻¹³</td>
<td>1.0</td>
<td>4 x 10¹⁵</td>
<td>10⁴</td>
<td>10⁴</td>
<td>10⁴</td>
<td>10⁴</td>
</tr>
<tr>
<td>26.7</td>
<td>670</td>
<td>820</td>
<td>2 x 10⁻¹³</td>
<td>1.0</td>
<td>2 x 10¹⁴</td>
<td>10⁴</td>
<td>10⁴</td>
<td>10⁴</td>
<td>10⁴</td>
</tr>
<tr>
<td>40.9</td>
<td>720</td>
<td>850</td>
<td>3 x 10⁻¹⁴</td>
<td>1.0</td>
<td>2 x 10¹⁴</td>
<td>10⁴</td>
<td>10⁴</td>
<td>10⁴</td>
<td>10⁴</td>
</tr>
</tbody>
</table>

Key Results and Future Work

KEY RESULTS

- ESTABLISHED PECVD SYSTEM.
- DEVELOPED PROCEDURES FOR GROWTH OF SINₓ WITH APPROPRIATE OPTICAL PROPERTIES FOR SINGLE AR COATING.
- DETERMINED APPROACH FOR ACHIEVING SURFACE STATE DENSITY <5 x 10¹⁰ cm⁻² eV⁻¹ ON MODERATELY DOPED SILICON.
- DEVELOPED APPROACH FOR REACTIVE ION ETCHING CELL EDGES TO INCREASE CELL FF VALUES.
- HAVE INITIATED STUDIES ON ROsiER MEASUREMENTS ON SOLAR CELLS.
- CHARACTERIZED CELLS WITH SINₓ AND SiOₓ AR COATINGS WITH I-V ANALYSIS AND PHOTORESPONSE TO OBTAIN ESTIMATED VALUES FOR S.

FUTURE WORK

- INVESTIGATE EFFECT OF SINₓ ON SURFACE RECOMBINATION FOR MODERATELY DOPED N-TYPE MATERIAL.
- INVESTIGATE FEASIBILITY OF ROsiER METHOD FOR MEASURING S ON SILICON SOLAR CELL STRUCTURES.
- INVESTIGATE MINP SILICON SOLAR CELLS.
  - DEVELOP DOUBLE AR AND REDUCE SHADOWING TO ACHIEVE Jsc = 36 mA/cm²
  - REDUCE CURRENT LOSSES SUCH THAT J0 = 5 x 10⁻¹³ A/cm² AND n = 1.0 TO ACHIEVE Voc = 650 mV, FF = 81% and EFF = 19%.

<table>
<thead>
<tr>
<th>BACK SURF</th>
<th>15 mils</th>
<th>15 mils</th>
<th>15 mils</th>
<th>10 mils</th>
</tr>
</thead>
<tbody>
<tr>
<td>OTHIC</td>
<td>OTHIC</td>
<td>BSF</td>
<td>BSF</td>
<td></td>
</tr>
</tbody>
</table>

345