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 FILM DEPOSITION AND CHARACTERIZATION
- ESTABLISH PECVD SYSTEM
- DEVELOP DEPOSITION PROCEDURES

FILM CHARACTERIZATION
- OPTICAL CHARACTERIZATION -- N and X VS WAVELENGTH AND DEPOSITION PARAMETERS.
- PHYSICAL CHARACTERIZATION

PASSIVATION STUDIES
- SURFACE STATE DENSITY AT SIN/SI INTERFACE FOR MODERATELY DOPED SILICON SUBSTRATES.
- PHOTORESPONSE OF N/P SOLAR CELLS WITH PECVD SIN FILMS.
- CURRENT-VOLTAGE ANALYSES OF SILICON CELLS WITH SIN FILMS.
- ROSSIER MEASUREMENT
SiN$_x$ Film Index of Refraction vs Silane-Ammonia Ratio

- Substrate Temperature = 270°C
- RF Power = 1225 W/m$^2$

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-SiNₓ-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 SiN$_x$ on p-Type Si

<table>
<thead>
<tr>
<th>SURFACE TREATMENT</th>
<th>RF POWER = 212 W/m$^2$</th>
<th>RF POWER = 1225 W/m$^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>SUBSTRATE TEMPERATURE</td>
<td>SUBSTRATE TEMPERATURE</td>
</tr>
<tr>
<td></td>
<td>150°C</td>
<td>270°C</td>
</tr>
</tbody>
</table>

- ABBREV CLEAN
- RCA CLEAN
- ABBREV CLEAN & NITRIDED
- RCA CLEAN & NITRIDED
- RCA CLEAN & THIN OXIDE
- RCA CLEAN, THIN OXIDE & NITRIDED

Interface State Density vs Annealing Temperature for SiN$_x$ on p-Type Si

○ RCA CLEAN/NITRIDE/DPOSIT @150°C
▼ RCA CLEAN/NITRIDE/DPOSIT @270°C (UPPER LIMIT)
□ RESULTS REPORTED BY HEZEL, et al.

![Interface State Density vs Annealing Temperature for SiN$_x$ on p-Type Si](image-url)
Internal Photoresponse Analysis

Theory:

\[ J_{PH}(\lambda) = S_{\text{INT}}(\lambda) \cdot T_a \cdot N_a \cdot \eta \]

\[ S_{\text{INT}}(\lambda) = (S_{\text{INT}}^0)_{\text{EMITTER}} + (S_{\text{DEPL}})_{\text{WIDTH}} + (S_{\text{INT}}^0)_{\text{BASE}} \]

\[ T_a = T_s(1 - R_a) \cdot K_a \cdot K_s \cdot K_{SL} \]

Experiment:

Measure: \( J_{PH}(\lambda), R_a, N_a \) and \( K_a \) of \( S_{\text{INT}} \)

Analysis: Have obtained \( S_{\text{INT}}(\lambda) \) for cells with \( S_{\text{INT}} \) layers. Determined \( S_c \) assuming a homogeneous emitter.

Internal Photoresponse vs Wavelength for 
S: n-p Cell With 100 Angstroms SiO\(_2\)
Internal Photoresponse vs Wavelength for JPL Cell

Theoretical Parameters:
- JPL2 Bare
- JPL2 Sin
- S(0) = 1.0E+4
- S(0) = 3.0E+4
- S(0) = 1.0E+5

Theoretical Parameters:
- L(0) = 1.0 um, D(0) = 2.0 cm^2/s,
- L(0) = 130 um, D(0) = 21.0 cm^2/s,
- X = 0.35 um, W = 0.413 um, H = 210 um,
- S(0) = 1E9 (ohmic), Aluminum BSR,
- 2 ohm-cm N/P Silicon

Theoretical Parameters:
- L(0) = 1.0 um, D(0) = 3.0 cm^2/s,
- L(0) = 140 um, D(0) = 21.0 cm^2/s,
- X = 0.17 um, W = 0.413 um, H = 319 um,
- S(0) = 1E9 (ohmic), Aluminum BSR,
- 2 ohm-cm N/P (111) FZ SILICON
**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>Vdc (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>
<td>571</td>
<td>.791</td>
<td>32.7</td>
</tr>
<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 JGSS WITH ELH SIMULATOR. THE SIMULATOR HAS BEEN CALIBRATED BY EXCHANGING A REFERENCE CELL WITH SERI.*

**Effect of Reactive Ion Etching Cell Edges**

![Graph showing the effect of Reactive Ion Etching on cell edges]

JPL1-5-ETCH
9/28/84

* ETCHED
* SIN

**LOG(CURRENT(AMPS))**

**APPLIED VOLTAGE(VOLTS)**
Approach to Dark I-V Analysis

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

\[
\begin{align*}
I_{\text{MEAS}} &= I_j \cdot \frac{V_j}{n k T} \\
V_j &= V_{\text{MEAS}} - R_S \cdot I_{\text{MEAS}} \\
I_j &= I_{01} \cdot \exp(BV_j) + I_{02} \cdot \exp(V_j/n k T)
\end{align*}
\]

**Fitting Procedure**

1. SELECT \(R_S\) AND \(R_{SH}\)
2. GENERATE \((I_j, V_j)\)
3. CONSIDER \((I_j, V_j)\) FOR REGION 1
   \[
   I_j = I_{01} \cdot \exp(BV_j)
   \]
   \[
   \log_e(I_j) = \log_e(I_{01}) + BV_j
   \]
   LEAST SQUARES FIT \(= I_{01}, B\)
4. CONSIDER \((I_j, V_j)\) FOR REGION 2
   \[
   I_{j2} = I_j - I_{01} \cdot \exp(BV_j)
   \]
   \[
   = I_{02} \cdot \exp(V_j/nkT)
   \]
   LEAST SQUARES FIT \(= I_{02}, B\)
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

1. $J_0$ for 2 Ohm-cm N/P cell with thickness of 15 MILS, L(BASE) = 130 $\mu$m, $D = 21$ cm$^2$/sec (approximate cells provided by JPL).
2. $J_0$ for 0.2 Ohm-cm N/P cell with thickness of 15 MILS, L(BASE) = 150 $\mu$m, $D = 21$ cm$^2$/sec.

I-V Parameters for Dark Characteristics

<table>
<thead>
<tr>
<th>CELL</th>
<th>JCT DEPTH (m)</th>
<th>BASE RESISTIVITY (Ohm-cm)</th>
<th>ORDERS OF 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>2.1 E-11</td>
<td>1.07</td>
<td>0.95</td>
<td>DEPL. LAYER 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>1.7 E-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>3.1 E-11</td>
<td>1.06</td>
<td>0.94</td>
<td>DEPL. LAYER RECOMB VIA SHALLOW TRAP</td>
</tr>
<tr>
<td>JCGS 84-2</td>
<td>0.2</td>
<td>0.2</td>
<td>2.0</td>
<td>0.4</td>
<td>1.3 E-12</td>
<td>1.02</td>
<td>1.10</td>
<td>Emitter Recomb with $S = 10^3$ to $10^4$ cm/sec</td>
</tr>
</tbody>
</table>
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**
   \[ J = J_{OE} \exp \left( \frac{V}{n_{OE}kT} \right) - 1 \]
   \[ n = 1 \]
   For room temp analysis:
   \[ J_{OE} = \frac{e^{n_{OE}}}{N_{OE}r_{em}} \cdot GF \]
   GF is a function of W, S, D, D_{PO} & \tau_{P}
   For interpretation of temperature dependent data:
   \[ J_{OE} = J_{OO} (T) \exp \left( -\frac{\phi}{kT} \right) \]
   \[ \phi = 1.20 - (\Delta E) \text{ EMITTER } \]

2. **Base Region Recombination Current**
   \[ J = J_{OB} \exp \left( \frac{V}{n_{OB}kT} \right) - 1 \]
   \[ n = 1 \]
   \[ J_{OB} = \frac{e^{n_{OB}}}{N_{OB}r_{n}} \cdot G_{F} \]
   \[ = J_{OO} (T) \exp \left( -\frac{\phi}{kT} \right) \]
   \[ \phi = 1.20 - (\Delta E) \text{ BASE } \]

3. **Depletion Layer Recombination Current**
   \[ J = J_{OL} \exp \left( \frac{V}{n_{OL}kT} \right) V \gg kT \]
   \[ J_{OL} = J_{OO} (T) \exp \left( -\frac{\phi}{kT} \right) \]
   \[ \phi = (E_{c} - E_{d}) \text{ OR } (E_{c} - E_{d}) \]
   \[ n = 1 \text{ TO } 2 \]
   For \( n^2 \), \( \phi = 0.8 \) eV

4. **Tunneling/Recombination**
   \[ J = J_{OT} \exp (BV) \]
   \[ V \gg kT \]
   B is temperature independent
   \[ J_{OT} = J_{OO} \exp \left( -\frac{\phi}{kT} \right) \]
   \[ \phi \text{ typically 0 TO 0.5 eV} \]

5. **Field Emission**
   \[ J = J_{OF} \exp (CV) \]
   \[ C = \frac{1}{n_{OE}kT} + B \]
   \[ J_{OF} = J_{OO} \exp \left( -\frac{\phi}{kT} \right) \]
   \[ \phi = fV \text{ n}^{-1} \]

6. **Edge Leakage Currents**
   Current mechanisms (3), (4) OR (6)
   Usual shunting mechanism
   \[ J_{SH} = \frac{V}{R_{SH}} \]

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HIGH-EFFICIENCY SILICON SOLAR CELL RESEARCH

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HIGH-EFFICIENCY SILICON SOLAR CELL RESEARCH

MINP Cell Concept

Calculated $J_{ph}$ for Single and Double AR Layers

![Diagram of MINP Cell Concept](image)

- **MIS Contact Using Mg OR Ti**
- **Passivated Surface**
- **Collector Grid**
- **AR Layer**
- **N-Type Emitter**
  - 1000 Å T J 2500 Å
- **P-Type Base**
  - (0.1 to 2 Ω-cm)
- **P+ Region to Provide Back Surface Field**
- **Aluminum Back Contact**

![Graph for Calculated $J_{ph}$](image)

- **0.5 mm Cell Thickness**
  - Phoenix Spectrum
  - $L = 150$, C mic Back Contact
  - $L = 500$, BSF

$N_x = 1.3$, 1.4, 1.5

- **Textured (2L-AR)**
- **Textured 2L-AR**
- **Textured 1L-AR**
- **Polished**
- **Textured (No AR)**
TO ACHIEVE 20% 
- MUST REDUCE $J_0$ 
- BY DECREASING $N_s$ AND $S_p$ 
- NEED SLIGHT IMPROVEMENT IN $L$

TO ACHIEVE 25% 
- NEED F&P DIFFUSION LENGTH 
- MUST REDUCE $S_p$ TO 10' 
- WITH THESE VALUES OF $L$ AND $S_p$, $J_o$ WILL BE DECREASED TO $3 \times 10^{-14}$ A/cm$^2$ 
- MUST USE DOUBLE AR WITH TEXTURED SURFACE OR WITH COMPLETE OPTICAL CONFINEMENT 

<table>
<thead>
<tr>
<th>$J_{sc}$ (mA/cm$^2$)</th>
<th>36.0</th>
<th>36.0</th>
<th>26.7</th>
<th>40.9</th>
</tr>
</thead>
<tbody>
<tr>
<td>$V_{oc}$ (mV)</td>
<td>630</td>
<td>650</td>
<td>670</td>
<td>720</td>
</tr>
<tr>
<td>FF</td>
<td>794</td>
<td>812</td>
<td>820</td>
<td>850</td>
</tr>
<tr>
<td>$J_0$ (A/cm$^2$)</td>
<td>$1 \times 10^{-12}$</td>
<td>$4.5 \times 10^{-13}$</td>
<td>$2 \times 10^{-13}$</td>
<td>$3 \times 10^{-14}$</td>
</tr>
<tr>
<td>n-VALUE</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
</tr>
<tr>
<td>$N_o$ (cm$^{-3}$)</td>
<td>$6 \times 10^{10}$</td>
<td>$4 \times 10^{10}$</td>
<td>$2 \times 10^{10}$</td>
<td>$2 \times 10^{9}$</td>
</tr>
<tr>
<td>SURF REC VEL</td>
<td>10$^4$</td>
<td>10$^4$</td>
<td>10$^4$</td>
<td>10$^4$</td>
</tr>
<tr>
<td>DIFF LENGTH</td>
<td>150</td>
<td>150</td>
<td>200</td>
<td>500 (F&amp;P)</td>
</tr>
<tr>
<td>GRID SHADOW</td>
<td>4%</td>
<td>4%</td>
<td>3%</td>
<td>2%</td>
</tr>
<tr>
<td>CELL THICKNESS</td>
<td>15 mils</td>
<td>15 mils</td>
<td>15 mils</td>
<td>10 mils</td>
</tr>
<tr>
<td>BACK SURF</td>
<td>Ohmic</td>
<td>Ohmic</td>
<td>BSF</td>
<td>BSF</td>
</tr>
</tbody>
</table>

Key Results and Future Work

**Key Results**

ESTABLISHED PECVD SYSTEM.

DEVELOPED PROCEDURES FOR GROWTH OF $SiN_x$ WITH APPROPRIATE OPTICAL PROPERTIES FOR SINGLE AR COATING.

DETERMINED APPROACH FOR ACHIEVING SURFACE STATE DENSITY $<5 \times 10^{10}$ 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 $SiN_x$ AND $SiO_x$ AR COATINGS WITH I-V ANALYSIS AND PHOTORESPONSE TO OBTAIN ESTIMATED VALUES FOR $S$.

**Future Work**

INVESTIGATE EFFECT OF $SiN_x$ ON SURFACE RECOMBINATION FOR MODERATELY DOPED n-TYPE MATERIAL.

INVESTIGATE FEASIBILITY OF ROSIER METHOD FOR MEASURING $S$ ON SILICON SOLAR CELL STRUCTURES.

INVESTIGATE MNP SILICON SOLAR CELLS.

-- DEVELOP DBLAR AND REDUCE SHADOWING TO ACHIEVE $J_{sc} = 36$ mA/cm$^2$

-- REDUCE CURRENT LOSSES SUCH THAT $J_0 = 5 \times 10^{-13}$ A/cm$^2$ AND $n = 1.0$

TO ACHIEVE $V_{oc} = 850$ mV, FF = 0.81 and EFF = 19%.

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