SILICON SURFACE PASSIVATION BY SILICON NITRIDE DEPOSITION

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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

OPTICAL CHARACTERIZATION
• Optical characterization -- N and k vs wavelength and deposition parameters.

PHYSICAL CHARACTERIZATION
• Surface state density at SiN/Si interface for moderately doped silicon substrates.
• Photoreponse of n/p solar cells with PECVD SiN films.
• Current-voltage analyses of silicon cells with SiN films.
• Rosier measurement
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SiNₓ Film Index of Refraction vs Silane-Ammonia Ratio

* SUBSTRATE TEMPERATURE = 270 °C
* RF POWER = 1225 W/m²

DECREASED POWER AND/OR TEMPERATURE

Optical Constants of SiNₓ Films From Ellipsometry Measurements

*MEASUREMENTS TAKEN ON EQUIPMENT PROVIDED BY BATTELLE NORTHWEST LABORATORIES
HIGH-EFFICIENCY SILICON SOLAR CELL RESEARCH

Approaches to Investigation of Surface Recombination in Solar Cells

\[ \text{M-Si:H-Si structure} \]

High frequency and quasi-static C-V measurements to obtain interface state density.

\[ \text{SOLAR CELL STRUCTURE} \]

Photoreponse at short wavelengths can theoretically yield recombination velocity.

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

\[ \text{SPECIAL STRUCTURES (ROSIER)} \]

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 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>150°C</td>
</tr>
<tr>
<td></td>
<td>270°C</td>
<td>270°C</td>
</tr>
</tbody>
</table>

- **ABBREV CLEAN**
- **RCA CLEAN**
- **ABBREV CLEAN & NITRIDE**
- **RCA CLEAN & NITRIDE**
- **RCA CLEAN, THIN OXIDE**
- **RCA CLEAN, THIN OXIDE & NITRIDE**

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

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

![Graph showing interface state density vs annealing temperature](image-url)
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Internal Photoresponse Analysis

**THEORY**

\[ J_{PH}(x) = S_{INT}(x) \cdot T_x \cdot n_x \cdot q \]

\[ S_{INT}(x) = \left( S_{INT}^EMITTER \right) + \left( S_{DEPL} + (S_{INT}^BASE) \right) \]

\[ T_x = T_x(n_{AR}, K_{AR}, n_{Si}, K_{Si}) \]

\[ = 1 - R_x - R_x \]

**EXPERIMENT**

**MEASURE:** \( J_{PH}(x), R_x, n_x, \) and \( K_x \) of \( S_{INT}(x) \)

**ANALYSIS:** HAVE OBTAINED \( S_{INT}(x) \) FOR CELLS WITH \( S_{INT} \) LAYERS.

DETERMINED \( S_x \) ASSUMING A HOMOGENEOUS EMITTER.

Internal Photoresponse vs Wavelength for 
S: n-p Cell With 100 Angstroms SiO2

**THEORETICAL PARAMETERS:**

L(1.0 um), D(1.0 cm=2/s), L(0.1 um), D(1.0 cm=2/s),
X(2.0 um), W(0.015 um), N(380 um),
S(1.0E+4), Aluminum 83K,
0.2 ohm-cm m, 'P' 35% Ion
Internal Photoresponse vs Wavelength for JPL Cell

THEORETICAL PARAMETERS:

JPL-2 BARE
JPL-SIN
S(\nu)=1.0E+4
S(\nu)=3.0E+4
S(\nu)=1.0E+5

THEORETICAL PARAMETERS:

L(\nu)=1.0 um, D(\nu)=2.0 cm\cdot s^{-1},
L(\nu)=130 um, D(\nu)=21.0 cm\cdot s^{-1},
X(\nu)=35 um, W=413 um, H=210 um,
S(\nu)=1E9 (ohmic), Aluminum BSR,
2 ohm\cdot cm N/P Silicon

JPL-5 BARE
JPL-5 SIN
S(\nu)=1.0E+4
S(\nu)=1.0E+5
S(\nu)=1.0E+6

THEORETICAL PARAMETERS:

L(\nu)=1.0 um, D(\nu)=3.0 cm\cdot s^{-1},
L(\nu)=140 um, D(\nu)=21.0 cm\cdot s^{-1},
X(\nu)=17 um, W=413 um, H=319 um,
S(\nu)=1E9 (ohmic), Aluminum BSR,
2 ohm\cdot cm N/P (111) FZ SILICON
Illuminated Characteristics of JPL Cells  
(Fabricated by ASEC)

<table>
<thead>
<tr>
<th>CELL</th>
<th>ORIENTATION</th>
<th>AR LAYER</th>
<th>AM* EFFICIENCY (%)</th>
<th>Isc (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>
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<td>.795</td>
<td>32.5</td>
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<tr>
<td>10-2</td>
<td>(111)</td>
<td>SiO₂</td>
<td>15.7</td>
<td>134</td>
<td>588</td>
<td>.786</td>
<td>33.5</td>
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<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 JCGS 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]
Approach to Dark I-V Analysis

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

\[
I_{\text{MEAS}} = I_j + V_j / nkT
\]

\[
V_j = V_{\text{MEAS}} - R_S I_{\text{MEAS}}
\]

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

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

![Graph showing emitter $J_0$ vs surface donor concentration.]

1. $J_{oc}$ for 2 Ohm-cm N/P cell with thickness of 15 MILS, $L_{base} = 130 \mu m$, $D = 21 \text{ cm}^2/\text{sec}$ (approximate cells provided by JPL).

2. $J_{oc}$ for 0.2 Ohm-cm N/P cell with thickness of 15 MILS, $L_{base} = 150 \mu m$, $D = 21 \text{ cm}^2/\text{sec}$.

I-V Parameters for Dark Characteristics

<table>
<thead>
<tr>
<th>CELL</th>
<th>JCT DEPTH (µm)</th>
<th>BASE RESISTIVITY (Ohm-cm)</th>
<th>ORDERS OF MAGNITUDE FOR FIT</th>
<th>AVERAGE ERROR (%)</th>
<th>$J_0$ (A/cm²)</th>
<th>n</th>
<th>ACTIVATION ENERGY (eV)</th>
<th>POSSIBLE CURRENT MECHANISM</th>
</tr>
</thead>
<tbody>
<tr>
<td>JPL 6 (SiN₅)</td>
<td>0.4</td>
<td>2</td>
<td>2.5</td>
<td>30</td>
<td>2.1 E-11</td>
<td>1.07</td>
<td>0.96</td>
<td>DEPL LAYER RECOMB VIA SHALLOW TRAP</td>
</tr>
<tr>
<td>JPL 8-5 (SiN₅)</td>
<td>0.2</td>
<td>2</td>
<td>2.8</td>
<td>20</td>
<td>1.7 E-11</td>
<td>1.02</td>
<td>1.00</td>
<td>Emitter RECOMB WITH $S = 10^5$ to $10^6 \text{ cm/sec}$</td>
</tr>
<tr>
<td>JPL 9-1 (SiN₅)</td>
<td>0.2</td>
<td>2</td>
<td>2.8</td>
<td>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 MINP 84-2</td>
<td>0.2</td>
<td>0.2</td>
<td>2.0</td>
<td>4</td>
<td>1.3 E-12</td>
<td>1.02</td>
<td>1.10</td>
<td>Emitter RECOMB WITH $S = 10^5$ to $10^6 \text{ cm/sec}$</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
   \[ J = J_{OE} \left( \exp \left( \frac{V}{n_k T} \right) - 1 \right) \]
   \[ n = 1 \]
   For room temperature analysis:
   \[ J_{OE} = \frac{q^2}{N_D} \cdot G_F \]
   GF is a function of \( W_i, S_p, D_p \), and \( T_p \)
   For interpretation of temperature dependent data:
   \[ J_{OE} = J_{OO} (T) \exp \left( -\frac{\phi}{k T} \right) \]
   \[ \phi = 1.20 \times (\Delta E) \text{ EMITTER} \]

2. Base Region Recombination Current
   \[ J = J_{OB} \left( \exp \left( \frac{V}{n_k T} \right) - 1 \right) \]
   \[ n = 1 \]
   \[ J_{OB} = \frac{q^2}{N_A} \cdot G_F \]
   \[ = J_{OD} (T) \exp \left( -\frac{\phi}{k T} \right) \]
   \[ \phi = 1.20 \times (\Delta E) \text{ BASE} \]

3. Depletion Layer Recombination Current
   \[ J = J_{OR} \exp \left( \frac{V}{n_k T} \right) \] for \( V \gg kT \)
   \[ J_{OR} = J_{OO} \exp \left( -\frac{\phi}{k T} \right) \]
   \[ \phi = (E_i - E_g) \text{ OR } (E_c - E_g) \]
   \[ n = 1 \text{ TO } 2 \]
   For \( n^2 \), \( \phi = \frac{\Delta E}{2} \)
   For \( n^1 \), \( \phi = 0.8 \text{ eV} \)

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

5. Field Emission
   \[ J = J_{OF} \exp(CV) \]
   \[ C = \frac{1}{nk T} + B \]
   \[ J_{OF} = J_{OO} \exp \left( -\frac{\phi}{k T} \right) \]
   \[ \phi = fV \text{ } f = n^{-1} \]

6. Edge Leakage Currents
   Current mechanisms (3), (4) or (5)
   Usual shunting mechanism
   \[ f = V_R / f_{SH} \]

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MINP Cell Concept

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

Graph showing active AM1.5 $J_{ph}$ (mA/cm²) vs $N_{i}$, index of layer adjacent to silicon for different AR layer configurations and thicknesses.
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Projected Performance

To achieve 20%:
- Must reduce $J_{sc}$ by decreasing $N_{a}$ and $S_{p}$.
- Need slight improvement in $L$.

To achieve 25%:
- Need F&F diffusion length.
- Must reduce $S_{p}$ to 10$^{-12}$.
- With these values of $L$ and $S_{p}$, $J_{sc}$ will be decreased to $3 \times 10^{-14}$ A/cm$^2$.
- Must use double AR with textured surface or with complete optical confinement.

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 photoreponse 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 $J_{sc} = 5 \times 10^{-13}$ A/cm$^2$ and $n = 1.0$ to achieve $V_{oc} = 650$ mV, $FF = 0.71$ and $eff = 19\%$.