CVD-3 LFSIN
SiNₓ Process

Standard LFSIN Process

<table>
<thead>
<tr>
<th>Top Electrode, °C</th>
<th>Bottom Electrode, °C</th>
<th>Pump to Base Time (s)</th>
<th>SiH₄ Flow</th>
<th>NH₃ Flow</th>
<th>N₂ Flow</th>
<th>HF (watts)</th>
<th>LF (watts)</th>
<th>Pressure (mtoorr)</th>
<th>Deposition Time min:s.s</th>
<th>Pump to Base Time (s)</th>
<th>Wafer Size (in)ᵃ</th>
</tr>
</thead>
<tbody>
<tr>
<td>250</td>
<td>300</td>
<td>120</td>
<td>35</td>
<td>20</td>
<td>1960</td>
<td>0</td>
<td>60</td>
<td>550</td>
<td>Variable</td>
<td>60</td>
<td>0.5-6</td>
</tr>
</tbody>
</table>

- Optical properties
- Growth Rate and Uniformity
- Roughness, Stress, Etch
- Electrical Data – Quantox
- Electrical Data – Probe station
- Elemental Composition
- Baseline Statistics
- Optical Model
- Roughness Data detail
- XRR Data
- Quantox SPV-V/Q-V Curve
- Expanded Probe station data
- Parameter Extraction method (probe station data)

a) Samples smaller than 5mm across will not match the results in this dataset because of edge effects – samples other than whole 6” wafers should be placed on aluminum carrier
## Optical Properties

<table>
<thead>
<tr>
<th>Wavelength, nm</th>
<th>Refractive Index, na</th>
<th>Absorption Coefficient, kb</th>
<th>Transmission</th>
<th>Optical Model&lt;sup&gt;c&lt;/sup&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td>630</td>
<td>1.961</td>
<td>0</td>
<td>TBD</td>
<td>cauchy</td>
</tr>
</tbody>
</table>

<sup>a, b)</sup> Taken from the optical constants vs wavelength curve; Woollam WVASE 32; 300-800nm 3nm steps; 55,65,75°

<sup>c)</sup> Click on link for detailed description of model
Growth Rate and Uniformity: LFSIN

<table>
<thead>
<tr>
<th>Run #</th>
<th>Growth Rate (nm/min)</th>
<th>Std. Uniformity 6” wafer</th>
<th>Max/min Uniformity</th>
<th>Linear or non-linear w/time</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>39.7</td>
<td>1.8 %</td>
<td>6.4 %</td>
<td>linear</td>
</tr>
<tr>
<td>2</td>
<td>41.6</td>
<td>1.7 %</td>
<td>6.1 %</td>
<td>linear</td>
</tr>
</tbody>
</table>

**a)** Run 1 is the first run after a chamber clean, run 2 is a subsequent run.

**b)** Thickness data from Gaertner Scientific single wavelength (632.8nm) scanning ellipsometer using optical data from page 2
- Averaged from 2 wafers from 2 runs

**c)** (1 sigma / mean) × 100 from the 49 point scanning ellipsometer
- Averaged from 2 wafers from 2 runs

**d)** ((Max - Min) / mean) × 100
- Averaged from 2 wafers from 2 runs
<table>
<thead>
<tr>
<th>Stress(^a), MPa</th>
<th>Etch Rate(\text{dil. HF}^b) (nm/min)</th>
<th>Etch Rate BOE 5:1(^c) (nm/min)</th>
<th>Ra(^d) Roughness, nm</th>
<th>Roughness %(\frac{\text{Ra}}{\text{T}} \times 100)</th>
<th>Density g/cm(^3)</th>
<th>Density g/cm(^3) post-anneal(^f)</th>
</tr>
</thead>
<tbody>
<tr>
<td>-770 ± 140</td>
<td>TBD</td>
<td>14 ± 6</td>
<td>0.27</td>
<td>0.026%</td>
<td>2.88(^e)</td>
<td>2.89</td>
</tr>
</tbody>
</table>

\(a\) Measured on FLX-2320-S Thin Film Stress (MET-1) at room temperature using 6” USA ring; compressive

\(b\) Diluted HF solution made by mixing 1 part 49% pure HF with 3 parts DI water (20mL HF + 60mL DI) yielding a HF solution of 15% w/w HF

\(c\) 49 % w/w HF; 3 samples

\(d\) 158nm film; Measured on SPM-5, Veeco NanoMan AFM, tapping mode, standard tip or Optical profiler

\(e\) Measured on a Rigaku Ultima III X-Ray Diffractometer at San Jose State, follow link to report

\(f\) Film annealed at 650C for 4 hours- based off of a thickness decrease of 0.2%
**Electrical Data – Quantox non-contact measurement**

### 150nm SiNx; As-deposited

<table>
<thead>
<tr>
<th>Wafer Type</th>
<th>( Q_{\text{eff}} ) (^{a}) ((\text{e10} \ \text{#/cm}^2))</th>
<th>( V_{\text{fb}} ) (^{b})</th>
<th>( Q_{\text{total}} ) (^{c}) ((\text{e10} \ \text{#/cm}^2))</th>
<th>( V_{t} ) (^{d})</th>
<th>( V_{\text{mid}} ) (^{e}) ((\text{e10} \ \text{#/cm}^2))</th>
<th>( D_{\text{it}} ) (^{f}) ((\text{e10} \ \text{#/cm}^2))</th>
<th>Resistivity (^{g}) ((\text{ohm} \cdot \text{cm}))</th>
<th>( E_{\text{tunnel}} ) (^{h}) ((\text{MV/cm}))</th>
<th>Dielectric Constant</th>
</tr>
</thead>
<tbody>
<tr>
<td>p-type; 11 ohm\cdot cm</td>
<td>750</td>
<td>-25.0</td>
<td>755</td>
<td>-24.01</td>
<td>-0.58</td>
<td>599.2</td>
<td>1.58E+16</td>
<td>6.17</td>
<td>8.11</td>
</tr>
</tbody>
</table>

Data averaged over 13 sites on 3 separate runs

### 150nm SiNx; Annealed – 450 °C 5 hours; forming gas

<table>
<thead>
<tr>
<th>Wafer Type</th>
<th>( Q_{\text{eff}} ) (^{a}) ((\text{e10} \ \text{#/cm}^2))</th>
<th>( V_{\text{fb}} ) (^{b})</th>
<th>( Q_{\text{total}} ) (^{c}) ((\text{e10} \ \text{#/cm}^2))</th>
<th>( V_{t} ) (^{d})</th>
<th>( V_{\text{mid}} ) (^{e}) ((\text{e10} \ \text{#/cm}^2))</th>
<th>( D_{\text{it}} ) (^{f}) ((\text{e10} \ \text{#/cm}^2))</th>
<th>Resistivity (^{g}) ((\text{ohm} \cdot \text{cm}))</th>
<th>( E_{\text{tunnel}} ) (^{h}) ((\text{MV/cm}))</th>
<th>Dielectric Constant</th>
</tr>
</thead>
<tbody>
<tr>
<td>p-type; 11 ohm\cdot cm</td>
<td>54.97</td>
<td>-2.09</td>
<td>-54.68</td>
<td>-1.12</td>
<td>0.00</td>
<td>TBD</td>
<td>1.38E+17</td>
<td>6.21</td>
<td>7.17</td>
</tr>
</tbody>
</table>

Data averaged over 13 sites on 1 run

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Click here for example Q-V and SPV-V Curves

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**Definitions**

- \( Q_{\text{eff}} \) = total charge that acts to shift \( V_{\text{fb}} \) from ideal
- \( V_{\text{fb}} \) = potential where surface photovoltage is zero
- \( Q_{\text{total}} \) = sum of all charges from Si interface through film; charge at \( V_{\text{fb}} \) from Q-V curve
- \( V_{t} \) = Theoretical transistor turn on voltage
- \( V_{\text{mid}} \) = potential at halfway point between max and min SPV voltage
- \( D_{\text{it}} \) = density of fixed charges and non-charge based traps at Si-dielectric interface (negative values imply levels are < \( 1e10 \ \text{#/cm}^2 \))
- Dielectric Resistivity = Oxide is biased then turned off then voltage is tracked as a function of time
- \( E_{\text{tunnel}} \) = similar but not same as breakdown; field where any additional charge on dielectric immediately leaks to silicon

6/9/14

P. de Rouffignac
## Electrical Data – MIS Devices on Probe Station

### Electrical Parameter

<table>
<thead>
<tr>
<th>Parameter</th>
<th>As-Deposited(^b)</th>
<th>Annealed(^c)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Leakage Current Density (A/cm(^2) at 2MV/cm)(^a)</td>
<td>(7.2 \times 10^{-9} \pm 0.1 \times 10^{-9})</td>
<td>(3.4 \times 10^{-8} \pm 0.2 \times 10^{-8})</td>
</tr>
<tr>
<td>Breakdown Field (MV/cm)</td>
<td>8.9 ± 0.2</td>
<td>10 ± 1</td>
</tr>
<tr>
<td>(\varepsilon) (10 kHz)</td>
<td>6.65 ± 0.01</td>
<td>6.38 ± 0.02</td>
</tr>
<tr>
<td>(\varepsilon) (100 kHz)</td>
<td>6.29 ± 0.09</td>
<td>6.40 ± 0.02</td>
</tr>
<tr>
<td>(\varepsilon) (1 MHz)</td>
<td>3.9 ± 1.6</td>
<td>4.10 ± 0.06</td>
</tr>
<tr>
<td>(V_{FB}) (@100kHz)(^d)</td>
<td>-14.6 ± 0.1</td>
<td>-2.68 ± 0.01</td>
</tr>
<tr>
<td>(Q_{eff}) (@100kHz)(^d)</td>
<td>(7.0 \times 10^{-7} \pm 0.1 \times 10^{-7})</td>
<td>(9.2 \times 10^{-8} \pm 0.1 \times 10^{-8})</td>
</tr>
<tr>
<td>(N_{eff}(e10)(^d)</td>
<td>440 ± 5</td>
<td>58 ± 1</td>
</tr>
<tr>
<td>(Q_{m})(^d)</td>
<td>(1.2 \times 10^{-7} \pm 0.1 \times 10^{-7})</td>
<td>(-1 \times 10^{-9} \pm 0.2 \times 10^{-9})</td>
</tr>
<tr>
<td>(N_{m}(e10)(^d)</td>
<td>73 ± 3</td>
<td>0.6 ± 0.2</td>
</tr>
</tbody>
</table>

\(a\) Measured using probe station connected to Agilent 4156c and B1500 analyzers; aluminum pad sizes of 0.0025 cm\(^2\) created using the liftoff technique

– All values listed derived from averages of at least three measurements per sample

\(b\) 1 Wafer batch on 02/13/14; run 12B, deposition time 4 min; 6” p-type prime wafers, HF cleaned; 158 nm

\(c\) Wafer annealed at 425C in forming gas for 4 hours with contact pads present

– aluminum pad sizes of 0.0025 cm\(^2\); backside contact sputtered gold

\(d\) \(V_{FB}, Q_{eff}, N_{eff}, Q_{m}, N_{m}\) calculation method on [Parameter Extraction Method](#) slide

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**More data here**

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# Film Composition and Contaminants

## VPD-ICPMS

<table>
<thead>
<tr>
<th></th>
<th>Al</th>
<th>Ca</th>
<th>Cr</th>
<th>Cu</th>
<th>Fe</th>
<th>Mg</th>
<th>Ni</th>
<th>K</th>
<th>Na</th>
<th>Ti</th>
<th>Zn</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>134.3</td>
<td>50.6</td>
<td>6.6</td>
<td>6.1</td>
<td>38.5</td>
<td>7.9</td>
<td>4.7</td>
<td>9.6</td>
<td>22.9</td>
<td>36.7</td>
<td>67.6</td>
</tr>
</tbody>
</table>

## XPS

<table>
<thead>
<tr>
<th></th>
<th>Si</th>
<th>N</th>
<th>O</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>48.33</td>
<td>49.02</td>
<td>2.65</td>
</tr>
</tbody>
</table>

**SiN$_{1.01}$**

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a) Surface trace metal analysis by VPD-ICPMS; 7mm edge exclusion; values in ppm (by weight)

b) Measured on XPS (05/21/2014), after 45s sputter 200eV (depth profile) using survey results
   – Carbon less than 1 %

6/9/14 P. de Rouffignac
Baseline Statistics

a) d
b) Blue line = running average
c) Red lines = 1 sigma above and below avg

TBD
Optical Model

<table>
<thead>
<tr>
<th>Spectroscopic Ellipsometer Model</th>
<th>An</th>
<th>Bn</th>
<th>Cn</th>
<th>Ideal or non-ideal</th>
<th>MSE</th>
</tr>
</thead>
<tbody>
<tr>
<td>cauchy</td>
<td>1.9238</td>
<td>0.01886</td>
<td>0.000524</td>
<td>non-ideal</td>
<td>&lt; 6</td>
</tr>
</tbody>
</table>

0.3nm SiO2 at interface in the model

- Woollam WVASE 32; 300-800nm 3nm steps; 55,65,75°
a) **Sample**: Run 11a, 2.5 min 104 nm  
   - 6” wafer  
b) **Roughness**, $Ra = 0.27$nm
XRR Data

ANALYSIS CONDITION
Wavelength (Å): CuKa (1.541871)
Divergence (deg): 0.02
2-theta offset (deg): 0.0[--]
Scale factor: 1.113(10)
Background parameter: 1.e-7[--]

<table>
<thead>
<tr>
<th>Material</th>
<th>Thickness (nm)</th>
<th>Density</th>
<th>Roughness (nm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SIN\textsubscript{X}</td>
<td>155.5</td>
<td>2.875</td>
<td>1.11</td>
</tr>
</tbody>
</table>
a) Site (-20,40)
b) Sample 12A (4 min deposition, 150 nm), as-deposited
a) Sample 11B, 109nm

b) X axis of IV curve in MV/cm

c) Annealing has appeared to change the doping at the silicon/film interface from P-type to N-type
   – Could be from diffusion of contaminant ions from film to substrate; LFSIN has the highest concentration of contaminants of the CVD-3 processes

d) Annealing reduced $V_{FB}$ shift, $\Delta V_{FB}$, and frequency related capacitance drop (frequency dispersion)

e) Annealing did not change leakage current density
Parameter Extraction Method

Er vacuum permittivity

d film thickness in meters

A gate area (m²)

Cox Oxide capacitance

ε0 8.854×10⁻¹⁴ F/cm

WMS metal semiconductor work function

VFB Forward flat band voltage

Qeff effective dielectric charge (coul/cm²)

Neff effective charge concentration#/cm²

C FB flat band capacitance

λ Debye length (cm)

εs permittivity of Si (F/cm) 11.7*ε0

A gate area (cm²)

κT thermal energy @ RT (293K*1.3806e-23 J/K)

q electron charge (coulombs)

Nd (Nbulk) Bulk doping concentration (cm⁻³)

Ni Intrinsic carrier concentration (cm⁻³)

Dopetype +1 ptype / -1 ntype'

Nm mobile charge concentration

\[ C_{FB} = \frac{C_{ox} \varepsilon_s A / \lambda}{C_{ox} + \varepsilon_s A / \lambda} \]

\[ \lambda = \left( \frac{\varepsilon_s kT}{q^2 N} \right) \]

\[ W_{ms} = -0.61 - \frac{kT}{q} \ln \left( \frac{N_{BULK}}{N_i} \right) (\text{dopetype}) \]

\[ Q_{eff} = \frac{C_{ox} (W_{ms} - V_{FB})}{A} \]

\[ N_{eff} = \frac{Q_{eff}}{q} \]

\[ Q_m = -\frac{C_{ox} \Delta V_{FB}}{A} \]

\[ N_m = \frac{Q_m}{q} \]

- The flat band capacitance is calculated in order to extract the flat band voltage, \( V_{FB} \), from the experimental C-V curves.
  - Equations 1 and 2
- The forward \( V_{FB} \) is then used to determine the effective charge in the dielectric, \( Q_{eff} \).
  - Equations 3 and 4
- Equation 5 extracts the density (#/cm²) of effective charges from \( Q_{eff} \) and the charge of an electron, \( q \).
- The effective mobile charge, \( Q_m \), in the dielectric is determined using the change in \( V_{FB} \) between the forward and backward CV curves using equation 6.
- The mobile charge density is determined using equation 7.