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Outline

- Introduction
- Thermal Wave Analysis
  - Theory
  - Results
- Measurement System Analysis (MSA)
  - Capability analysis
- Summary & Outlook
Introduction

- Measurement of implant dose (TWIN SC4 system (PVA Metrology and Plasma Solutions GmbH))
  - Measurement directly after implantation. No post-treatment
  - Measurement on productive wafers (compared to 4PP)
Excitation of a sample by local absorption of photons (laser 16mW)

- Generation of carrier wave
  \[ l_P = \sqrt{\frac{2D\tau}{1+\sqrt{1+(\Omega\tau)^2}}} \]

- Generation of thermal wave
  \[ l_T = \sqrt{\frac{2\kappa}{\Omega}} \]

- Tunable modulation frequency \( \Omega \)

Detection of reflected light

- Refractive index \( n(C,T) \)
Thermal Wave Analysis Theory II

- Photothermal response
  - Complex conversion coefficient $K$
  - Superposition of carrier and thermal wave

$$K = \frac{1}{R} \cdot \frac{\delta R}{\delta c} \cdot \hat{C} + \frac{1}{R} \cdot \frac{\delta R}{\delta T} \cdot \hat{T}$$
Effect of implantation on carrier and thermal wave
Thermal Wave Analysis Theory IV

- Excitation → CARRIER WAVE → recombination → THERMAL WAVE → heat dissipation

1. Pure Si with GOX
2. Pure Si with native Oxide
3. B in Si $10^{13}$ Ions · cm$^{-2}$
4. Amorphous layer

Diagram:
- Increase of implant dose
- Non implanted silicon
- 0.1 MHz
- 10 MHz
- Re{K}
- Im{K}
- $|K|$
- $\Psi$

Set date
Optimization of Dose Measurement Parameters - Sensitivity

- Conversion coefficient $K(\Omega)$
  - Amplitude $|K|(\Omega), \Psi(\Omega) \rightarrow \text{Re}\{K\}, \text{Im}\{K\}$

- Recommended procedure
  - Measurement of three wafers (variation of implant dose)
  - Measurement with 19 different modulation frequencies (0.15 MHz – 13.05 MHz)

- Boron implanted wafers. Dose of $d \approx 10^{11}$ ions $\cdot$ cm$^{-2}$, implantation energy $E \approx 160 - 180$ keV
Optimization of Dose Measurement Parameters - Sensitivity

- **Re{K}**
- **Sensitivity** = \(\frac{\text{Observed Change}}{\text{Implemented Change}}\)
- Optimum at \(\Omega = 2.05\) MHz
Optimization of Dose Measurement Parameters - Repeatability

- Point to point repeatability
  - Aging
  - Laser induced annealing
  - Individual measurement spots (integration time vs. micro-scans)
  - Implant uniformity
- New measurement sequence
  - 19 MP → 7125 MP
Optimization of Dose Measurement Parameters - Repeatability/Sensitivity

Optimum at $\Omega = 0.75$ MHz
Requirements

Monitor Process Parameters

Tool Evaluation

Measurement

Sensitivity

Repeatability

Tool Release

Measurement System Analysis (MSA)

Calibration

Capability Analysis

Statistical Process Control (SPC)

✓

✓

✓
Measurement System Analysis (MSA)

- Capability analysis \( %G_r \)

\[
%G_r = \frac{5.15\sigma_r}{USL-LSL} \cdot 100
\]

- \( G_r \leq 10\% \) capable
- \( 10\% \leq G_r \leq 30\% \) conditionally capable
- \( G_r > 30\% \) incapable

5.15 \( \sigma \) at \( G_r = 10\% \)
5.15 \( \sigma \) at \( G_r = 30\% \)
5.15 \( \sigma \) at \( G_r > 30\% \)
Measurement System Analysis (MSA)

- **Impact on process capability ($C_p$)**
  
  - $C_p^* = \frac{USL - LSL}{6\sigma_{Process}^2}$
  
  - $\sigma_{Observed}^2 = \sigma_{Process}^2 + \sigma_{Measurement}^2$
  
  - $C_p = \frac{1}{\sqrt{\frac{1}{C_p^2} + \frac{36 \cdot G_{r&R}^2}{5.15^2}}}$

$C_p^*$...true process capability

$C_p = C_p^* \text{ for } \%G_{r&R} = 0$

![Graph showing process capability ($C_p$) vs. $\%G_{r&R}$]
Capability Analysis
(d \approx 10^{11} \text{ ions} \cdot \text{cm}^{-2}, E \approx 160 - 180 \text{ keV})

\[ \%G_r = \frac{5.15 \sigma_r}{\text{USL} - \text{LSL}} \cdot 100 \]

- Determination of \( \sigma_r \)
- Determination of USL and LSL

<table>
<thead>
<tr>
<th>Modulation Frequency / MHz</th>
<th>USL-LSL / \text{Re}{K}</th>
<th>\sigma_r / \text{Re}{K}</th>
<th>%G_r</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.75</td>
<td>2.8</td>
<td>0.4</td>
<td>8</td>
</tr>
<tr>
<td>2.05</td>
<td>2.4</td>
<td>0.7</td>
<td>14</td>
</tr>
</tbody>
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Measurement System Analysis (MSA)

- Calibration
- Capability Analysis
- Statistical Process Control (SPC)

- Requirements
  - Monitor Process Parameters

- Measurement
  - Sensitivity
  - Repetitability

- Tool Evaluation

- Tool Release
Calibration & SPC

- Calibration Standards
  - No (stable) standard available
    - Self annealing / aging
  - Workaround GOX/Si

- SPC
  - No (stable) standard available
  - Workaround „ancient“ wafers
    - Problematic for new applications
Summary & Outlook

Requirements
- Monitor Process Parameters

Measurement
- Sensitivity
- Repeatability

Measurement System Analysis (MSA)
- Calibration
- Capability Analysis
- Statistical Process Control (SPC)

**Graphs and Equations**

- **Equation:**
  \[ C_p = C_p^{*} \text{ for } \%G_{R\&R} = 0 \]

- **Graphs:**
  - Sensitivity vs. Modulation Frequency
  - Process capability \( C_p \) vs. \( \%G_{R\&R} \)
  - Time series with 16 months data
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