Recent Advances in Implant Metrology with the Shallow Probe LEXES Tool

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Theory of the analytical method: the LEXES technique
Sample Excitation & Detection

Intensity (background subtracted) at Element X-ray position is proportional to **Dose or film thickness**.

**Low Energy X-ray Emission Spectrometry**

- Soft X-rays
- Excited volume 1-700 nm
- 10-100 µm
- Wafer

Wavelength Dispersive Spectrometer
⇒ Rare Overlaps
⇒ Good P/B

Crystal Analyzer

Detector

⇒ Intensity (background subtracted) at Element X-ray position is proportional to **Dose or film thickness**.
Signal Variation with Dose, and illustration of Detection Limit issues. 

*Case of 5keV As implants in Si.*

**Uncertainty on dopant signal:**

\[
\sigma_I (cps) = \sqrt{\frac{P}{t^p} + \frac{B}{t^B}}
\]
LEXES Probing of Nanometric Depths in Silicon

### Electron Range

- **Boron (B Kα: 188eV)** in silicon: Shallow Implants Range
- **Arsenic (As Lα: 1323eV)** or **phosphorous (P Kα: 2145eV)** in silicon: Explored depth in Si wafer (nm)

### Energy Levels

- **Primary Energy**: 0.7keV, 3keV, 5keV, 10keV
- **Depth**: 20nm, 150nm, 300nm, 700nm

### Thresholds

- **B K Threshold**: 0.1
- **As L**
- **P K**

### Graph

- **Explored depth in Si wafer (nm)**
- **Electron Range**

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Quantification Procedure

1. Peak & Background measurements on the **Unknown Sample** at various primary energies

2. Peak & Background measurements on the **Standard** (GaAs, GaP, InP, ...)

3. **Profile Extraction** (Physical Model)

4. **Calibration**

5. **Absolute Dose Determination**
Example of Quantification

As implants to be analyzed

- Experiment (as implanted)
- Simulated (as implanted)
- Experiment (annealed sample)
- Simulated (annealed sample)

As implants

- Implanted
- Annealed sample

5 at/cm² +/- 0.81%
15 at/cm² +/- 1.10%

First estimate of uncertainty $\sigma_{\text{Dose}}$, as follows:

$$\frac{1}{\sigma_{\text{Signal}}^2} = \sum \left( \frac{1}{\sigma_{\text{Intensity}}^2} \right)$$
## Range of Applications

<table>
<thead>
<tr>
<th>Sample Types</th>
<th>Monitored Species</th>
<th>Thickness</th>
<th>Precision (1RSD)</th>
<th>Detection Limits</th>
</tr>
</thead>
<tbody>
<tr>
<td>Implants and diluted species</td>
<td>Dopants (B, N, F, As, P, In, ...) Metals</td>
<td>from Surface (contamination) to 1 µm in-depth</td>
<td>0.1 to 1% for dose (D &gt; 1 \times 10^{15}) at/cm²; 0.5-2% for (1 \times 10^{14} &lt; D &lt; 1 \times 10^{15}) at/cm², 1.5-10% for (D &lt; 1 \times 10^{14}) at/cm²</td>
<td>(5 \times 10^{12} - 1 \times 10^{13}) at/cm²</td>
</tr>
<tr>
<td>Dielectric &amp; Oxide films</td>
<td>N, O, Metals (Hf, Ta, Zr, ...)</td>
<td>Sub-nm to 1µm thick</td>
<td>0.5-2% on nm range thickness</td>
<td>&lt;1/100 monolayer</td>
</tr>
<tr>
<td>SiGe</td>
<td>Ge, B, C, ...</td>
<td>typically nm to 100 nm (or more)</td>
<td>0.1-0.4% on Ge, 0.5-2% for B with dose (&gt; 1 \times 10^{15}) at/cm²</td>
<td>(5 \times 10^{12}) at/cm² for Ge, (5 \times 10^{13}) for B</td>
</tr>
</tbody>
</table>
Shallow Probe System Description

- System configuration
- System performance
System configuration

Must comply with:

- Clean room compatibility
- Full 300 mm wafer analysis capability
- High performance in terms of
  - Precision
  - Accuracy of Quantitation
  - Repeatability & Reproducibility
- High level of automation
- Low cost of ownership
Shallow Probe SP 300:
Instrument Body

- Low Energy Electron column
- 3 X-rays analyzers
- 300 mm analysis chamber equipped with a dry pumping system
- 300mm airlock, with wafer transfer robot. Compatible with FOUP.
Footprint

Physical envelope : 21 ft²
With clearance : 73 ft²
Clean Room Environment

Two control desks

Routine mode

Expert mode

Ethernet

SECS GEM Workstream
Low Energy Electron Column

- Derived from long established Cameca EPMA Expertise
- New Design to achieve Quantitative Electron Probe at very low Energy and high Current. *(patent pending)*
- Electron Beam 0.2 to 10keV, focused on spots 3-100µm. Beam Current from 10nA to 500µA controlled with high performance electrometry.
- Fully Automated (Alignment, Aperture Positionning, Beam Current Monitoring, ..) and embedded as Setup in Analysis Recipes.
Main Features

- **3 WD spectrometers**: Multiplies sensitivity by 3, or allows simultaneous detection of 3 different species.

- WD Spectrometers with large Rowland circle radii (160mm): *high wavelength resolution* and *precise quantification (good Peak/Background)*.

- WD Spectrometers mounted in inclined orientation (40° take-off angle): *strongly reduced sensitivity to sample height variation, which is good for Repeatability*.

- Absolute Positioning thanks to Optical Encoders: *highest Reproducibility*.

- Analyzer design: trace level detection *without saturation from intense matrix signals*. 
System Description

- System configuration
- System performance (Implant Characterization)
Accuracy of Dose determination: comparison with SIMS values

- Although completely independent, SIMS and LEXES typically agrees within 5%, whatever the dopant type and dose.
- Deviation between Implanter tool values and both techniques is about 5-20%.

SIMS data were recorded with CAMECA IMS 6f equipped with Accel-Decel option.

Samples provided by S. Corcoran from Intel Inc. and P. Ronsheim from IBM
Precision per point

Precision of counting as a function of Dose

- 0.1-1% for $D > 1 \times 10^{15}$ at/cm²
- 0.5-2% for $1 \times 10^{14} < D < 1 \times 10^{15}$ at/cm²
- 1-10% for $D < 1 \times 10^{13}$ at/cm²
- Will be further improved!
Resolving dose variations

Arsenic

Shallow Implants

Medium Energy Implants

Shallow Probe easily discriminates dose gradations of 5%. Linearity is maintained even for very shallow implants or highly doped implants (E16 at/cm²).

Uncertainty bars are smaller than the dots (1σ <0.5%).
Characterization of Si-Ge thin films: comparison with XRR

Agreement between LEXES and XRR is typically ~3% for atomic density per area unit. But Spatial resolution is much better with LEXES (test pattern analysis).
Characterization of Si-Ge thin films: Comparison with X-Ray Analysis

Agreement between LEXES and XRR is typically ~5% for thickness determination.
Si$_x$Ge$_{1-x}$ films composition
Comparison with SIMS

Both techniques are matching within 2% (!)

<table>
<thead>
<tr>
<th>LEXES at% Ge</th>
<th>SIMS at% Ge</th>
</tr>
</thead>
<tbody>
<tr>
<td>Patterned Wafers</td>
<td>Non Patterned Wafers</td>
</tr>
<tr>
<td>8.41%</td>
<td>8.90%</td>
</tr>
<tr>
<td>11.30%</td>
<td>11.40%</td>
</tr>
<tr>
<td>14.40%</td>
<td>14.30%</td>
</tr>
<tr>
<td>15.74%</td>
<td>15.70%</td>
</tr>
<tr>
<td>18.55%</td>
<td>19.20%</td>
</tr>
<tr>
<td>20.54%</td>
<td>20.90%</td>
</tr>
<tr>
<td>20.45%</td>
<td>20.80%</td>
</tr>
<tr>
<td>22.73%</td>
<td>23.30%</td>
</tr>
</tbody>
</table>
Boron dosimetry in SiGe films
Comparison with SIMS

Both techniques are matching within 5%

<table>
<thead>
<tr>
<th>LEXES dose (atoms/cm²)</th>
<th>Precision (%)</th>
<th>SIMS dose (atoms/cm²)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Non patterned wafer</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.10E16</td>
<td>0.75</td>
<td>1.17E16</td>
</tr>
<tr>
<td><strong>Patterned wafers</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>9.50E14</td>
<td>0.44</td>
<td>9.43E14</td>
</tr>
<tr>
<td>3.48E15</td>
<td>1.13</td>
<td>3.45E15</td>
</tr>
<tr>
<td>1.58E+15</td>
<td>1.52</td>
<td>1.75E15</td>
</tr>
</tbody>
</table>
Characterization of Low Energy / High Current Implantation Process

**Arsenic.**

<table>
<thead>
<tr>
<th>Range of samples</th>
<th>Nominal dose (atoms/cm$^2$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Si-c(1keV)</td>
<td>1,00E+15</td>
</tr>
<tr>
<td>Si-c(3keV)</td>
<td>1,00E+15</td>
</tr>
<tr>
<td>Si-c(5keV)</td>
<td>1,00E+15</td>
</tr>
<tr>
<td>Si-c(1keV)</td>
<td>5,00E+14</td>
</tr>
<tr>
<td>Si-c(3keV)</td>
<td>5,00E+14</td>
</tr>
<tr>
<td>Si-c(5keV)</td>
<td>5,00E+14</td>
</tr>
<tr>
<td>Si-c(1keV)</td>
<td>5,00E+13</td>
</tr>
<tr>
<td>Si-c(3keV)</td>
<td>5,00E+13</td>
</tr>
<tr>
<td>Si-c(5keV)</td>
<td>5,00E+13</td>
</tr>
<tr>
<td>Si-a(1keV)</td>
<td>1,00E+15</td>
</tr>
<tr>
<td>Si-a(3keV)</td>
<td>1,00E+15</td>
</tr>
<tr>
<td>Si-a(5keV)</td>
<td>1,00E+15</td>
</tr>
<tr>
<td>SiO$_2$(1keV)</td>
<td>1,00E+15</td>
</tr>
<tr>
<td>SiO$_2$(3keV)</td>
<td>1,00E+15</td>
</tr>
<tr>
<td>SiO$_2$(5keV)</td>
<td>1,00E+15</td>
</tr>
</tbody>
</table>

Samples provided by Y. Kataoka from Fujitsu Laboratories Ltd.

Example of LEXES signal from 1 sample set: samples are easily distinguished one another.

![LEXES Signal; As implants in SiO$_2$.](image-url)
Characterization of Low Energy / High Current Implantation Process

Arsenic.

Relative Arsenic Dose as a function of Implant Energy

Ratio between Retained and Nominal dose decreases with decreasing implant energy and increasing implant dose.
Gauge Repeatability & Reproducibility Study

Case of 1 keV Arsenic implants

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</tr>
<tr>
<td>Si-c(1keV)</td>
<td>5,E+14</td>
</tr>
<tr>
<td>Si-c(1keV)</td>
<td>5,E+13</td>
</tr>
</tbody>
</table>

Analysis of Variance (ANOVA method)

Repeatability & Reproducibility

(1 min. analysis time per repeat)
GRR Study; Case of 1 keV Arsenic implants.

Expected & Observed Repeatabilities

Observed Repeatability and predicted Precision match consistently.
Estimated System Throughput
(combined with a 300mm FOUP)

Boron dosimetry in Si, shallow implants, 1E15at/cm², Precision <1%

<table>
<thead>
<tr>
<th>Analysis Type</th>
<th># points /wafer</th>
<th>Run Rate (w/h)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Full Quantitative</td>
<td>1</td>
<td>19</td>
</tr>
<tr>
<td>Full Quantitative</td>
<td>5</td>
<td>8</td>
</tr>
<tr>
<td>Uniformity Check</td>
<td>5</td>
<td>24</td>
</tr>
<tr>
<td>Uniformity Check</td>
<td>25</td>
<td>11</td>
</tr>
</tbody>
</table>

Arsenic dosimetry in Si, 1E15at/cm², Precision <0.5%

<table>
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<tr>
<th>Analysis Type</th>
<th># points /wafer</th>
<th>Run Rate (w/h)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Full Quantitative</td>
<td>1</td>
<td>11</td>
</tr>
<tr>
<td>Full Quantitative</td>
<td>5</td>
<td>4</td>
</tr>
<tr>
<td>Uniformity Check</td>
<td>5</td>
<td>21</td>
</tr>
<tr>
<td>Uniformity Check</td>
<td>25</td>
<td>8</td>
</tr>
</tbody>
</table>

Ge measurement in SiGe box, 20 at%, 100nm, Precision <0.3%

<table>
<thead>
<tr>
<th>Analysis Type</th>
<th># points /wafer</th>
<th>Run Rate (w/h)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Full Quantitative</td>
<td>1</td>
<td>30</td>
</tr>
<tr>
<td>Full Quantitative</td>
<td>5</td>
<td>12</td>
</tr>
<tr>
<td>Uniformity Check</td>
<td>5</td>
<td>27</td>
</tr>
<tr>
<td>Uniformity Check</td>
<td>25</td>
<td>13</td>
</tr>
</tbody>
</table>
Conclusion

- The **Shallow Probe** instrument provides real Quantitative & Elemental information on ULE to ME implants doses >1E14 at/cm\(^2\) (no upper dose limits) with typical accuracy ~3% and 1\(\sigma\) precision ~ 0.1 to 1%. Work is in progress to extend these capabilities to the E13 at/cm\(^2\) range.

- Spatial Resolution (3-100\(\mu\)m) makes the technique compatible with pattern analysis.

- Long Term Reproducibility about 1-2% and easiness of quantitation settings favor its use for Process Matching, especially for Low Energy/High Current Implanters.

- The instrument can be equipped with full wafer capability (up to 300mm) and is designed to be compatible with FOUP operation. High Throughput (10-20 w/h for 25 points mapping) associated with sub\% Repeatability performance make it a serious candidate as an industrial Metrology tool. First 300mm instrument delivery scheduled by next fall.

- Your samples are welcome to evaluate the new tool!