Photoluminescence metrology for global wafer and micro implant and anneal uniformity

Chris Raymond

AVS Junction Technology Working Group
SEMICON West, July 2007
Outline

- Principle of Operation
- PLi Implant and Anneal Metrology
  - As implanted study – dose and energy
  - Anneal process studies
    - Species effects
    - Annealer signatures
  - Laser annealer
  - Measurement precision
- Summary
Predictive Metrics for the Nano World

Principle of Operation

\[ P \approx 7 \text{ mW} \]
\[ R \approx 1 \, \mu \text{m} \]
\[ NF = f(P, R, \lambda) \]

- **Ec**
- **Ev**
- **NF**
- **R_{PL}** - radiative recombination rate
- **R_{SRH}** - SRH recombination rate
- **R_A** - Auger recombination rate

\[ \lambda_1 = 0.532 \, \mu \text{m} \]
\[ \lambda_2 = 0.827 \, \mu \text{m} \]
PL Imaging (PLi)

- Sub-micron-scale spatial resolution
- Rapid macro and micro scans
- Non-destructive and non-invasive
Contamination and Defect Metrology

Macro-mapping + Micro-mapping

Example macro-map of 200mm blanket SiGe wafer showing metallic contamination from epitaxial process

Micro-map of same wafer showing dislocations

Spatial fingerprinting of electrically active defects from wafer-scale to micron-scale
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As-Implanted Capability – Dose and Energy Impact

USJ, B\textsubscript{10}H\textsubscript{14}, equiv. dose and energy – 0.9 to 1.1×10\textsuperscript{15} cm\textsuperscript{-3}, 450 to 550 eV

\[ y = A_1 \exp\left(-\frac{x}{t_1}\right) + y_0 \]
\[ y_0 = 5.092 \]
\[ A_1 = 10.27 \]
\[ t_1 = 0.356 \]

\[ D = 3\sigma/S, \sigma = 0.1\% \]

<table>
<thead>
<tr>
<th>Dose</th>
<th>Energy</th>
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<tbody>
<tr>
<td>(0.9 ~ 1.1 E15)</td>
<td>(450 ~ 550 eV)</td>
</tr>
<tr>
<td>Sensitivity, S:</td>
<td>0.31</td>
</tr>
<tr>
<td>Detectability, D (%)</td>
<td>0.97</td>
</tr>
</tbody>
</table>
As-Implanted Capability: Implanter Signatures

\[ ^{11}\text{B}, \, 1 \times 10^{15} \text{ cm}^{-2}, \, 500 \text{ eV} \]

\[ \text{B}_{10}\text{H}_{14}, \, 1 \times 10^{15} \text{ cm}^{-2}, \, 500 \text{ eV} \]

**Channel Probe**: Contour maps reveal within wafer non-uniformity in the as-implanted USJ wafer from a beam-line system.

**Bulk Probe**: Full wafer maps reveal within wafer non-uniformity in the as-implanted USJ wafer. Substrate features are also exposed.
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### Design of Experiment - Anneal

**Box AA**

<table>
<thead>
<tr>
<th>No.</th>
<th>Split</th>
<th>Activation</th>
<th>Type</th>
<th>Wafer ID</th>
</tr>
</thead>
<tbody>
<tr>
<td>13</td>
<td></td>
<td>600C 1min (SPER)</td>
<td>P</td>
<td>23BKB272MM</td>
</tr>
<tr>
<td>12</td>
<td>Ge 10keV 5E14/cm² + B 0.5keV 1E15/cm²</td>
<td>1000C Spike only</td>
<td>P</td>
<td>23BKB092MM</td>
</tr>
<tr>
<td>11</td>
<td></td>
<td>1000C Spike + FLA</td>
<td>P</td>
<td>23BKB116MM</td>
</tr>
<tr>
<td>10</td>
<td></td>
<td>900C Spike + FLA</td>
<td>P</td>
<td>23BKB114MM</td>
</tr>
<tr>
<td>9</td>
<td></td>
<td>FLA</td>
<td>P</td>
<td>23BKB112MM</td>
</tr>
<tr>
<td>8</td>
<td>As 3keV 1e15/cm²</td>
<td>1000C Spike only</td>
<td>P</td>
<td>23BKB176MM</td>
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<tr>
<td>7</td>
<td></td>
<td>1000C Spike + FLA</td>
<td>P</td>
<td>23BKB108MM</td>
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<td></td>
<td>900C Spike + FLA</td>
<td>P</td>
<td>23BKB173MM</td>
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<td>5</td>
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<td>FLA</td>
<td>P</td>
<td>23BKA066MM</td>
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<td></td>
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<td>P</td>
<td>23BKA067MM</td>
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<tr>
<td>3</td>
<td>B 0.5keV 1E15/cm²</td>
<td>1000C Spike + FLA</td>
<td>P</td>
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<tr>
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<td></td>
<td>900C Spike + FLA</td>
<td>P</td>
<td>23BKB270MM</td>
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<tr>
<td>1</td>
<td></td>
<td>FLA</td>
<td>P</td>
<td>23BKB271MM</td>
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**Box AB**

<table>
<thead>
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<th>No.</th>
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<th>Activation</th>
<th>Wafer ID</th>
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</thead>
<tbody>
<tr>
<td>10</td>
<td></td>
<td>600C 60sec SPE</td>
<td>23BKB272MM</td>
</tr>
<tr>
<td>9</td>
<td>B18Hx</td>
<td>1000C spike only</td>
<td>23BKB092MM</td>
</tr>
<tr>
<td>8</td>
<td></td>
<td>1000C spike + FLA</td>
<td>23BKB116MM</td>
</tr>
<tr>
<td>7</td>
<td></td>
<td>900C spike + FLA</td>
<td>23BKB114MM</td>
</tr>
<tr>
<td>6</td>
<td></td>
<td>FLA</td>
<td>23BKB112MM</td>
</tr>
<tr>
<td>5</td>
<td></td>
<td>600C 60sec SPE</td>
<td>23BKB272MM</td>
</tr>
<tr>
<td>4</td>
<td></td>
<td>1000C spike only</td>
<td>23BKB092MM</td>
</tr>
<tr>
<td>3</td>
<td></td>
<td>1000C spike + FLA</td>
<td>23BKB116MM</td>
</tr>
<tr>
<td>2</td>
<td></td>
<td>900C spike + FLA</td>
<td>23BKB114MM</td>
</tr>
<tr>
<td>1</td>
<td></td>
<td>FLA</td>
<td>23BKB112MM</td>
</tr>
</tbody>
</table>
Bulk Probe Results

B, 0.5 keV, $1.0 \times 10^{15}$ cm$^{-2}$

Flash

900°C Spike + Flash

1000°C Spike + Flash

1000°C Spike

Predictive Metrics for the Nano World

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Bulk Probe Results

Micromapping at X=0 and Y=75 mm; B, 0.5 keV, 1.0×10^{15} \text{ cm}^{-2}

Flash

250×250 \mu m^2

2000×2000 \mu m^2

900^\circ C Spike + Flash

1000^\circ C Spike + Flash

1000^\circ C Spike

nano\text{metrics}

Predictive Metrics for the Nano World

SEMICON West 2007
Bulk Probe Results

As, 3.0 keV, $1.0 \times 10^{15}$ cm$^{-2}$

Flash

900ºC Spike + Flash

1000ºC Spike + Flash

1000ºC Spike

Predictive Metrics for the Nano World

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Bulk Probe Results

Ge, 10.0 keV, $5.0 \times 10^{14}$ cm$^{-2}$ + B, 0.5 keV, $1.0 \times 10^{15}$ cm$^{-2}$
Bulk Probe Results

$B_{18}H_x$, 0.5 keV, $1.0 \times 10^{15} \text{ cm}^{-2}$ (equivalent)
Bulk Probe Results

Impact of implanted specie; Flash annealing

Boron

$B_{18}H_x$

Arsenic

Ge + Boron
Bulk Probe Results

Micromapping at X=0 and Y=75 mm;
Different species; 1000ºC Spike + Flash annealing

250x250 μm²

2000x2000 μm²

Boron
B₁₈Hₓ
Ge + Boron
Arsenic

Predictive Metrics for the Nano World

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Numerical Data

Predictive Metrics for the Nano World

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New vs. Old Heater Design Effects

New Heater

Old Heater

B with FLA

~ 11 units

PLi Units [a.u.]

Position [mm]

New Heater

Old Heater

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Predictive Metrics for the Nano World
Suppression of Flash Lamp Variation Effects by Spike Annealing

Flash

Flash + Spike

B, 0.5 keV, 1.0×10^{15} cm^{-2}

![Graph showing suppression of flash and spike effects](image)

- Flash
- Flash + Spike

- Global 6.4%
- Local 0.8%
- Global 23.7%
- Local 2.1%
PLi Inspection - Damage Recovery

Macro-mapping + Micro-mapping

Spike

Macro-map of 200 mm USJ-implanted wafer showing large scale non-uniformity from spike anneal

Flash

Micro-map showing massive dislocation density from high temperature (1300°C) flash anneal

500 x 500 µm²
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  - **Laser annealer**
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PLi Inspection: Laser 1 Anneal Signature

Laser Anneal Type 1: Correlation Between PLi and Laser Melt

High PLi Regions

Laser Melt Regions
PLi Inspection: Laser 2 Anneal Signature

Laser Anneal Type 2: stripping caused by overlapping

Micro-mapping

Macro-mapping

Beam Height 5.5 mm

9.69 PLi Units

10.46 PLi Units

0.41 mm overlap

Micro-map showing zoomed-in stripping caused by overlap region
Annealing Uniformity and Residual Damage

(a) SPE

D.U.~110

(b) Spike

D.U.~11

(c) Flash

D.U.~5

(d) Laser

D.U.~24

SPE anneal is uniform but it does not remove completely the damage. Spike, flash and laser anneals remove more damage, but exhibit higher non-uniformity than SPE.
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Damage Inspection - Full Wafer Map Repeatability

Boron, $1 \times 10^{15}$ cm$^{-2}$, 500 eV, with FLASH annealing

**Full Wafer Map Repeatability**

- Mean: 54.698
- $1\sigma$: 0.0285
- %: 0.052%
PLi Inspection - Micro Map Repeatability

SPC sample, un-implanted, 10 nm oxide passivated

Micromap Repeatability
Wafer ID: SPC
Mean: 1607 a.u.
σ: 0.285 a.u.
%: 0.018%
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Summary

- Provided an overview of PLi technology
  - Optical set-up and interaction physics
- Demonstrated sensitivity of PLi to dose and energy variation
  - Variety of process conditions
- Data from several experiments indicates:
  - High temperature (1000ºC) Spike or high temperature Spike followed by Flash annealing are the most efficient ways of removing the post implantation damage
  - Flash annealing alone leads to relatively large global and local residual damage variation, while Spike combined with Flash effectively suppresses the variation
  - Flash signature clearly visible for all species studied
  - Annealer heater performance can be optimized with PLi technology
  - Of all species B18 shows best results for damage removal across all anneal methods, but the best removal is obtained with a 900ºC Spike + Flash annealing
Acknowledgements

- John Borland of JOB
- Andrzej Buczkowski, Zhiqiang Li, Dave Doyle of Nanometrics
Annealing Equipment Signatures

**Spike**
- Mean = 10.33 au
- $\sigma = 0.65\%$
- Mean = 9.14 au  
  $\sigma = 0.54\%$

**Laser**
- Mean = 18.99 au
  $\sigma = 1.71\%$
- Mean = 36.65 au
  $\sigma = 4.85\%$

**SPE**
- Mean = 105.8 au
  $\sigma = 4.00\%$
- Mean = 117.5 au
  $\sigma = 4.10\%$
Residual Damage Uniformity Map

Spike Annealed

Sampling size: 6 × 6 mm²

<table>
<thead>
<tr>
<th></th>
<th>Mean</th>
<th>StDev</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>12.11</td>
<td>0.69%</td>
</tr>
<tr>
<td>B</td>
<td>11.26</td>
<td>1.28%</td>
</tr>
<tr>
<td>C</td>
<td>10.40</td>
<td>0.65%</td>
</tr>
<tr>
<td>D</td>
<td>10.10</td>
<td>0.69%</td>
</tr>
<tr>
<td>E</td>
<td>9.43</td>
<td>2.025</td>
</tr>
</tbody>
</table>

Damage Level: Line Profile:
Residual Damage Uniformity Map

Flash Annealed

Damage Level: 3D

Sampling size: 6 × 6 mm²

<table>
<thead>
<tr>
<th></th>
<th>Damage [a.u.]</th>
<th>Residual Damage Uniformity</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>32.67</td>
<td>8.98%</td>
</tr>
<tr>
<td>B</td>
<td>24.70</td>
<td>5.03%</td>
</tr>
<tr>
<td>C</td>
<td>20.46</td>
<td>1.69%</td>
</tr>
<tr>
<td>D</td>
<td>18.86</td>
<td>1.07%</td>
</tr>
<tr>
<td>E</td>
<td>17.25</td>
<td>1.11%</td>
</tr>
<tr>
<td>F</td>
<td>8.09</td>
<td>3.66%</td>
</tr>
</tbody>
</table>

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PLi of USJ Flash Anneal Residual Defectivity

700 Pre : 1250 Peak  700 Pre : 1300 Peak  750 Pre : 1300 Peak  750 Pre : 1350 Peak  (750 Pre : 1300 Peak)

PL

Mean: 2.402 δ: 0.251%
Mean: 36.63 δ: 26.6%
Mean: 2.426 δ: 0.158%
Mean: 9.01 δ: 4.85%

SR

Mean: 28.53 δ: 4.69%
Mean: 11.78 δ: 2.87%
Mean: 9.01 δ: 4.85%
Mean: 55.05 δ: 14.8%
Mean: 36.63 δ: 26.6%

PAI $1 \times 10^{15}$ Ge @ 30 keV
Boron $1 \times 10^{15}$ @ 5 keV

High Damage [ ] Low Damage

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