Background

We have expertise in self-assembled nanostructures that form during strained epitaxial growth, here in $Si_xGe_{(1-x)}$ films on Si.

**QD:** Semiconductor nanostructures that form during strained epitaxial growth, here in Ge/Si(100) system.

**QDM:** A nanostructure comprising of four island ridges (QDs) and a central pyramidal pit; observed in epi-$SixGe(1-x)/Si(100)$ under conditions of limited adatom mobility.
Potential Nanologic Applications

Potential Nanologic Applications Based on Charge and Spin Localizations Inside QDs

Possible Charge Configurations (logic states) of a QDM

Two Key Requirements:
1) Favorable band structure alignments within QDs and QDMs for carrier localization.
2) Doping of QDs and QDMs for the creation of holes.

Spin Exchange Switch (SES)

Majority Gate that implements QDMs


Tang et al, PRL 97, 119903 (2006)

Coherent Spin Switch (CSS)
Key Materials Issues

1) Local Nano-chemistry

Nanochemistry → Electronic Band-Gap → Charge Localization Property

To investigate composition distribution across QDMs

2) FIB Damage

FIB Beam Diameter: Few tens of nm

Ion Current Density: 0.1-10 $A\,cm^{-2}$ (at least three orders of magnitude higher relative to conventional, broad ion beams)

To study structural damage recovery of FIB implanted Si
Goal I: QDM Nano-chemistry
Experimental Measurements

Characterization Technique: Auger Electron Spectroscopy (Resolution: less than 10 nm under optimum conditions); PHI 700

Auger Signal Strength Dependent on:

1. Local surface angle
2. Geometry of the feature

Topography Corrected Auger Signals (TCAS)\(^1\) used to determine variation of c-Si and c-Ge within QDMs.

The TCAS were then suitably converted to composition.

M. Prutton et. al JAP 54 (1), 374 (1983)
Spatial distribution of emitted Auger electrons depends on spatial distributions of primary and backscattered electrons.

**Approach**

**Construction of an AED Function** $j_{Total}$

**Convolution of AED with Model Composition Profiles**

**Comparison of Simulated Profiles with the Experimental Profile**

$$j_{Total} = j_{Primary} + j_{BSE} = \left( \frac{N_e}{\pi \sigma_1^2} \right) e^{-\frac{x^2}{\sigma_1^2}} + \left( \frac{(R-1)N_e}{\pi \sigma_2^2} \right) e^{-\frac{x^2}{\sigma_2^2}}$$

$N_e$: Number of Primary Electrons; $\sigma_1$: Primary Beam; $\sigma_2$: Backscattered Electrons; $R$: Backscattered Electron Correction Factor

Auger Spatial Resolution

\[ j_{Total} = j_{Primary} + j_{BSE} = \left( \frac{Ne}{\pi \sigma_1^2} \right) e^{-\frac{x^2}{\sigma_1^2}} + \left( \frac{(R-1)Ne}{\pi \sigma_2^2} \right) e^{-\frac{x^2}{\sigma_2^2}} \]

Measured on thin sample edges

CASINOv2.42

<table>
<thead>
<tr>
<th>Surface Angle (°)</th>
<th>(\sigma_1) (nm)</th>
<th>(\sigma_2) (nm)</th>
<th>R</th>
<th>(d_0), Effective Spatial Resolution , 80%-20% metric (nm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>11</td>
<td>420</td>
<td>1.33</td>
<td>27</td>
</tr>
<tr>
<td>17</td>
<td>12</td>
<td>440</td>
<td>1.37</td>
<td>31</td>
</tr>
<tr>
<td>28</td>
<td>13</td>
<td>480</td>
<td>1.41</td>
<td>35</td>
</tr>
<tr>
<td>39</td>
<td>14</td>
<td>510</td>
<td>1.45</td>
<td>41</td>
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</table>

FWHM, Primary Beam = \(2.35\sigma_1\) \(\sim d_0\)

BSEs do not significantly degrade the resolution
Pits are the most Ge enriched regions within QDMs. Pit Bases at 17±9 % Si (Leite et al.) Pit Bases at 58±4 % Si (Our Measurement).

Remnant topography effects and potential desorption effects have increased measurement errors inside pits.
Simulations Vs. Experiment

**Profile ID**  
\[ \Delta \% \text{Si} \ (\text{RMS} ) \]

| Profile I (Convoluted) | 0.7 |
| Profile II (Convoluted) | 2 |

*Compositional contrast across the QDM = 12%*

Si Composition continually decreases towards pit cusps starting from exterior edges of QDMs
Goal II: Structural Damage
Recovery of FIB Implanted Silicon
Background

Energy Loss Mechanisms:

- Electron energy loss (EEL) and nuclear energy loss (NEL)

NEL results in interstitials through binary collisions ~13eV needed for lattice atom displacement

Time

Collision cascade, $10^{-13}$ sec

Fast Relaxation of collision cascade, $10^{-11}$ to $10^{-12}$ sec

Slower Relaxation (Thermal)
Fabrication Technique

<table>
<thead>
<tr>
<th></th>
<th>Broad Beam Ion Implanter</th>
<th>Mass Selecting Focused Ion Beam (MS-FIB)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Ion Energy</strong></td>
<td>60keV Si+</td>
<td>30keV Si++ (MS-FIB); 30keV Ge++ (MS-FIB); and 30keV Ga+ (FIB)</td>
</tr>
<tr>
<td><strong>Dose Range</strong></td>
<td>to</td>
<td>to</td>
</tr>
<tr>
<td><strong>Ion Current</strong></td>
<td>1-10 µA</td>
<td>22 pA (Si++); 28 pA (Ge++); and 53 pA (Ga+)</td>
</tr>
<tr>
<td><strong>Beam Diameter</strong></td>
<td>1/2 to 5/8 in.</td>
<td>10s of nm</td>
</tr>
<tr>
<td><strong>Ion Current Density</strong></td>
<td>6-60</td>
<td>0.1 - 10</td>
</tr>
</tbody>
</table>

**MS-FIB Column Schematic**

- LMIS
- Extraction electrodes
- Condenser lens (L1)
- Ion current selection apertures
- Wien filter
- Mass selection apertures
- Blanking plates
- Faraday cup
- Scanning and stigmation octupoles
- Objective lens (L2)
- Sample

- Rensselaer
Raman Spectroscopy (RS) is an optical spectroscopy technique to probe vibrational states in a material.

At sufficiently high implant doses the vibrational density of states would be affected significantly by damage which would produce a noticeable change in Raman signals.

The acquired Raman signals are averaged over the probe depth of the incident laser.

<table>
<thead>
<tr>
<th>From SRIM (Simulations)</th>
<th>Type of Implant</th>
<th>Laser Probe Depth (nm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>60 keV Si</td>
<td>In Crystalline Si</td>
</tr>
<tr>
<td></td>
<td>60 keV Ge</td>
<td>In Amorphous Si</td>
</tr>
<tr>
<td></td>
<td>30 keV Ga</td>
<td></td>
</tr>
<tr>
<td>Ion Range (nm)</td>
<td>88</td>
<td></td>
</tr>
<tr>
<td>Straggle (nm)</td>
<td>33</td>
<td></td>
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</tbody>
</table>

For 405 nm Laser
**Measurement Technique**

RS was used for measurements of structural damage produced by implantation

\[
\text{Structural Damage} = 1 - \frac{H}{H_0}
\]

Stress inferred from peak shifts

Non-amorphizing implants: Fitted by a Voigt function (a mix of Gaussian and Lorentzian functions)

Partially amorphizing implants: Fitted using a combination of 100% Gaussian and Voigt functions

Fully amorphizing implants: Fitted using Gaussian alone
Implant Energy: 60keV
Ion Dose Rates: 10-100 $\mu$A/cm$^2$ (Broad Beam) and 0.1 $\mu$A/cm$^2$ (FIB)
Annealing Conditions: 730 °C, 10 minutes in nitrogen ambient

Si-FIB implants produce a relatively higher damage.

Implantation at a higher dose rate (FIB Vs. broad beam) leads to a greater structural damage in the as-implanted state, but produces a greater structural damage recovery upon annealing.
In the as-implanted state Ge implants lead to a greater structural damage.

Ge implants recover structural damage better upon annealing.

Presumably a higher solid solubility of Ge in Si when compared to that of Ga leads to a higher structural damage recovery during the annealing.
Summary

QDM Nano-chemistry

- QDM pit bases are regions lowest in Si (highest in Ge) with a composition of 58±4 % Si. Holes would localize at pit bases.
- Composition increases monotonically towards pit bases starting from the exterior edges of QDMs.

FIB Damage Recovery in Si

- Relative to broad beam Si implantation, Si-FIB implantation causes a higher structural damage, but, leads to a better damage recovery upon annealing.
- Presumably a higher solid solubility of Ge than Ga in Si aids in the better (100% vs. 63% for the highest dose, $5 \times 10^{15} \text{cm}^{-2}$) structural damage recovery for the former implant upon annealing.
Acknowledgements

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- **Hamed Parvaneh** and **Kiran Sasikumar** at RPI for various discussions