Damage Control by Cluster implantation and heated implantation

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Ion implantation technologies for defect suppression

1. Cluster ion implant

2. Low temp implant
   Thick and fine amorphous, Clear regrowth

3. Heated implant
   Less damages, Enhancing dynamic annealing
Ion Implantation Systems for Damage Control
Cluster ion implanter CLARIS

- High current with precise beam control
- Ultra shallow junction formation
- High activation
- Diffusion suppression
- Damage engineering
- Strain engineering
Cold ion implantation

Precise beam control with high current
0.2 – 7keV with Cluster B
0.24 – 10.5keV with Cluster C

High productivity medium current tool
More than 550 tools installation
3 – 750keV with EX3000AH
3 – 960keV with EX9600A
Cold implant system

- Insitu-cooling (Stable!)
- Batch cooling & warming (Quick & Reliable!)
- Closed cycle cooling
High temperature ion implanter IMPHEAT

- Temperature: up to 500°C
- Energy: 3 – 960keV
- Species: Al, P, B, N, etc.
- High Current Al beam
- Mass production tool for SiC devices

**High Temperature Platen**

Temperature Controlled by TC and feedback

- Wafer
- Ion beams (Scanned horizontally)
- Electrostatic chuck with heater
- Heat shield

Mechanical Scan
Damage Control with Cold and Cluster ion Implantation
Damage control mechanism with cold implant

Ion Implantation at cold substrate

This area remains even if the temperature is zero Kelvin

Dynamic annealing during implant causes thinner amorphous layer

Interstitials and vacancies

Ion Implantation at room temperature substrate
To eliminate EORD not only thicker amorphous layer but also good a/c interface abruptness is required, ideally delta profile is the best.
Amorphous layer thickness
a/c interface abruptness

Damage simulation by Crystal TRIM

Amorphous layer thickness

Amorphous layer: 8 nm
Abruptness: 4 nm/decade

20 nm/decade
10 nm/decade
5 nm/decade

α-Si

Crystal trim
Dr. Matthias Posselt,
Institute of Ion Beam Physics and Materials Research,
Helmholtz-Zentrum Dresden-Rossendorf,
Crystal trim simulation result. A layer with over $2 \times 10^{21} \text{cm}^{-3}$ damage density is defined as amorphous layer.

Experimental result and crystal-Trim simulation result show a good agreement. Crystal trim can estimate the amorphous layer thickness.
Cluster size dependence on a/c interface abruptness

C⁺/C₅⁺/C₁₄⁺
4.5keV 2x10¹⁵ cm⁻²
As-implanted
Wafer -30 deg C

Crystal-Trim can estimate a/c interface abruptness
EORD reduction with a/c interface abruptness

**As-implanted**

- $C^+$
  - 15nm

- $C_5^+$
  - 22nm

- $C_{14}^+$
  - 23nm

**After RTA 800°C 10sec**

- $C^+$
- $C_5^+$
- $C_{14}^+$

$q\quad C^+/C_5^+/C_{14}^+\ 4.5\text{keV}\ 2E15\ \text{at -30°C as-impl and after RTA 800°C 10sec}$
$q\quad \text{Less EOR defects with better a/c interface abruptness}$
Cluster ion size effect

<table>
<thead>
<tr>
<th>Energy</th>
<th>Cluster</th>
<th>Dose</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 keV</td>
<td>C⁺</td>
<td>2x10¹⁵ cm⁻²</td>
</tr>
<tr>
<td>2 keV</td>
<td>C₂⁺</td>
<td>1x10¹⁵ cm⁻²</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5 keV</td>
<td>C₅⁺</td>
<td>4x10¹⁴ cm⁻²</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>14 keV</td>
<td>C₁₄⁺</td>
<td>1.4x10¹⁴ cm⁻²</td>
</tr>
</tbody>
</table>

Equivalent energy and equivalent dose are same

Tilt 0 deg / Twist 0 deg
2 dimension carbon profile and damage profile

1.0 keV (equivalent) $2 \times 10^{15}$ cm$^{-2}$ tilt 0 twist 0

Larger cluster ions make tighter and abrupt damage distribution.
a/c interface abruptness as a function of cluster size

Bigger cluster size makes better a/c interface abruptness
Cluster ion size effect

\[
C^+ < C_2^+ < C_3^+ < \cdots < C_{12}^+ < C_{13}^+ < C_{14}^+
\]

To form steep damage profile, Cluster C is preferable than monomer C.
Lighter cluster ion effect: simulation model

<table>
<thead>
<tr>
<th>Energy 6 keV</th>
<th>Mass</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ge(^+)</td>
<td>72</td>
</tr>
<tr>
<td>Ar(_2)^+</td>
<td>40 x 2 = 80</td>
</tr>
<tr>
<td>Si(_3)^+</td>
<td>27 x 3 = 81</td>
</tr>
<tr>
<td>Ne(_4)^+</td>
<td>20 x 4 = 80</td>
</tr>
<tr>
<td>O(_5)^+</td>
<td>16 x 5 = 80</td>
</tr>
<tr>
<td>C(_6)^+</td>
<td>12 x 6 = 72</td>
</tr>
</tbody>
</table>

Same energy and almost same momentum cluster ions
a/c interface abruptness as a function of ion

2 dimension depth profile and damage profile

6 keV $1 \times 10^{15} \text{ cm}^{-2}$ tilt 0 twist 0

Lighter cluster ions make tighter and abrupt damage distribution.
Relationship between amorphous layer and a/c interface abruptness at same energy and almost same momentum.

Lighter cluster ion makes better a/c interface abruptness at same amorphous layer.
Damage control mechanism of cluster ion mass

Comparing same energy and almost same momentum cluster ions, lighter ion cluster makes better a/c interface abruptness.

\[ \text{Ge}^+ < \text{Ar}_2^+ < \text{Si}_3^+ < \text{Ne}_4^+ < \text{O}_5^+ < \text{C}_6^+ \]
Cold implantation is effective to the damage control. At cold temperature recombination of interstitials and vacancies are suppressed. Therefore cold implantation makes thicker amorphous layer.

End of range defects (EORD) is related to not only amorphous layer thickness but also amorphous crystal (a/c) interface abruptness.

Bigger cluster size ion makes better a/c interface abruptness. 
\[
(C^+ < C_2^+ < C_3^+ < \cdots < C_{12}^+ < C_{13}^+ < C_{14}^+) 
\]

Lighter cluster ion makes better a/c interface abruptness. 
\[
(Ge^+ < Ar_2^+ < Si_3^+ < Ne_4^+ < O_5^+ < C_6^+) 
\]

We can design not only amorphous layer thickness but also a/c interface abruptness using crystal-TRIM simulation.

We can control damage using cluster ion implantation.
High Dose Dopant Implantation to Heated Si Substrate without Amorphous Layer Formation
Motivation

- In Fin-FET structures, SDE ion implantation amorphizes Si Fin. It would be very difficult to recover Si single crystal structure with anneal, especially when Fin width becomes small or amorphization reaches to the Si Fin bottom. Flash memory SDs are the same situation.
- Basic studies for high dose & high activation doping without amorphous formation for advanced device structures by using heated implantation.

Fin FET

- Gate
- Tilt implant
- Si Fin Amorphization
- Si or Si Oxide
- Regrowth from channel
- Regrowth from remained crystal Si or bottom Si sub.

Flash Memory

- STI
- Regrowth from remained crystal Si
- Si sub
Amorphous Si thickness decreases with increasing implant temperature.

Around 300°C is the key temperature for implant damage recovery. Si single crystal structure seems to be maintained at over 300°C.

Critical Amorphization Dose

- BF₂ 20keV 7.0E14/cm²
- P 20keV 1.2E14/cm²
- As 45keV 1.2E14/cm²
XTEM for As implant

- Single crystal structure remains in As as-implanted at higher than 300°C.
- However, many dislocations remain in the crystal structures.

As 45keV 1E15

<table>
<thead>
<tr>
<th>RT</th>
<th>300°C</th>
<th>600°C</th>
</tr>
</thead>
<tbody>
<tr>
<td>[Image]</td>
<td>[Image]</td>
<td>[Image]</td>
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Low temperature long time anneal cannot remove the defects. Only results in growth of the defect size and widens defect formed band width. 

As$^+$ implantation results in the similar defects remained.

BF$_2$ and P  20keV 1E15/cm$^2$ at 300$^\circ$C

- BF$_2$ and P -

(a)BF$_2$ as-impl.  
(b)BF$_2$ after 600$^\circ$C 1H anneal  
(c)P as-impl.  
(d)P after 600$^\circ$C 1H anneal
In order to obtain defects free crystal after annealing,

- Generally used annealing conditions in device manufacturing
- Shallower As profiles for reducing residual defects after anneal; location of defects are close to the surface, and defects could be removed through Si surface.

- As Ion Implantation
  - As 5keV 1.5E15/cm² RT - 550°C
  - As 20keV 1.5E15/cm² 300°C - 550°C

- Anneal
  - Spike RTA 1015°C
There still remains thick density of defects. Size of the defects get larger and defects density become less.

Spike RTA 1015°C also cannot remove the defects in As⁺ 20keV implant.

As 20keV 1.5E15/cm² at 300°C
As 20keV 1.5E15/cm² at 550°C
Crystal structure remains during implant at implant temperature more than somewhere between 300°C-400°C. Many defects, however, remain in crystal Si. The residual defects are removed after 1015°C spike RTA.

- As 5keV 1.5E15/cm² -
High Dose doping without amorphous formation for advanced device structures by using heated implantation has been studied.

1. High dose implantation with keeping single crystal structure has been embodied at implant substrate temperature higher than somewhere between 300°C and 400°C by heated implantation.
2. Many defects remain in as-implanted Si and were eliminated after spike RTA. Lower energy implant realizes defect free doping after anneal.

It has been shown that high dose doping without amorphization and also without defect can be successfully embodied. This technology can be applied to FinFET and memory processes, which prefer doping without a-Si formation.
Thank you for your attention!