Cluster Implant for 32nm

Wade Krull

AVS WCJUG

SemiconWest 08
General Features of Cluster Implant

- High productivity at low energy
- Self-amorphization due to high mass species
- High substitutional placement on anneal
- Elimination of EOR defects
ClusterBoron Implant for 32nm PMOS SDE
45nm & 32nm USJ Requirements

45 nm Node:
- $R_s \sim 1000 \, \Omega/sq$, $X_j < 20\text{nm}$
- $R_s \cdot X_j < 20 \, (\text{k}\Omega\cdot\text{nm})$

32 nm Node:
- $R_s < 1000 \, \Omega/sq$, $X_j < 15\text{nm}$
- $R_s \cdot X_j < 15 \, (\text{k}\Omega\cdot\text{nm})$
### Implant Conditions

- **B$_{18}$H$_{22}$ 500eV (equiv)**
  - 1E15 atoms/cm$^2$

- **BF$_2$ 500eV (equiv)**
  - 1E15 atoms/cm$^2$

Co-implants:
- **C$_{16}$H$_{10}$ 3keV (equiv)**
  - 1E15 atoms/cm$^2$

- **Ge$^+$ 20keV**
  - 5E14 atoms/cm$^2$

<table>
<thead>
<tr>
<th>#</th>
<th>Implant</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>B$_{18}$</td>
</tr>
<tr>
<td>2</td>
<td>B$<em>{18}$ + C$</em>{16}$</td>
</tr>
<tr>
<td>3</td>
<td>B$_{18}$ + Ge</td>
</tr>
<tr>
<td>4</td>
<td>B$<em>{18}$ + C$</em>{16}$ + Ge</td>
</tr>
<tr>
<td>5</td>
<td>BF$_2$</td>
</tr>
<tr>
<td>6</td>
<td>BF$<em>2$ + C$</em>{16}$</td>
</tr>
<tr>
<td>7</td>
<td>BF$_2$ + Ge</td>
</tr>
<tr>
<td>8</td>
<td>BF$<em>2$ + C$</em>{16}$ + Ge</td>
</tr>
</tbody>
</table>
$B_{18}H_{22}$ and $BF_2$ with Co-implants

$B_{18}H_{22}$ with co-implant

$BF_2$ with co-implant

$B_{18}H_{22}$ & $BF_2$ implant - 500eV (equiv), 1e15

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Flash Anneal Conditions

- f-spike 900°C, f-spike 1000°C
- f-spike 1025°C, f-spike 1050°C
- $T_1$-750°C $T_{pk}$ - 1050°C & 1250°C
- $T_2$-900°C $T_{pk}$ - 1250°C & 1350°C
- $T_1$-1000°C $T_{pk}$ - 1250°C & 1300°C

$B_{18}$ and $BF_2$ implants are 500eV per boron atom @ 1e15 atoms/cm$^2$
B_{18} – 500eV, 1e15 (SIMS PROFILE) - FLASH ANNEAL

Sample ID | B_{18} 500eV, 1e15
---|---
Anneal Recipe | Spike 900C | Spike 1050C | T_{i,900C} | T_{i,1000C} | T_{i,1000C}
Rs (Ω/sq) | 1431 | 428 | 562 | 582 | 523
Xj (nm) | 15.4 | 37.8 | 20.4 | 28.0 | 27.9
Rs. Xj / 1000 | 22.0 | 16.2 | 11.5 | 16.3 | 14.6

The Cluster Implant Source

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**f-spike anneal (900°C)**

**B₁₈ with co-implant**

**BF₂ with co-implant**

**Abrupt junction with C₁₆ with co-implants**
**f-spike anneal (900°C)**

With $C_{16}$ co-implant

The pile up due to Ge implants is eliminated with $C_{16}$ co-implant

With $C_{16}$ + Ge co-implants

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**Flash Anneal (f-spike 900°C)**

- BF$_2$
- B$_{18}$
- BF$_2$ + C$_{16}$
- B$_{18}$ + C$_{16}$

**B CONCENTRATION (atoms/cc)**

- $1 \times 10^15$
- $1 \times 10^16$
- $1 \times 10^17$
- $1 \times 10^18$
- $1 \times 10^19$
- $1 \times 10^20$
- $1 \times 10^21$
- $1 \times 10^22$

**DEPTH (Å)**

- 0
- 100
- 200
- 300
- 400
- 500
- 600

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*emEquip*  
*The Cluster Implant Source*

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iRTP 900°C, fRTP $T_i$ 900°C - $T_{pk}$ 1350°C

B$_{18}H_{22}$ co-implant (iRTP 900°C)

High boron concentration at Ge EOR defect region. Reduced concentration with C$_{16}H_{10}$ at iRTP 900°C. The concentration is removed at the higher flash temperature $T_{pk} = 1350°C$. 

B$_{18}H_{22}$ with co-implant (fRTP 1350°C)
**Ti$_{900^\circ C}$ T$_{pk}$ 1350$^\circ C$**

- **B$_{18}$ with co-implant**

  - B$_{18}$
  - B$_{18}$ + C$_{16}$
  - B$_{18}$ + Ge
  - B$_{18}$ + C$_{16}$ + Ge

- **BF$_2$ with co-implant**

  - BF$_2$
  - BF$_2$ + C$_{16}$
  - BF$_2$ + Ge
  - BF$_2$ + C$_{16}$ + Ge

**Abrupt junction with C$_{16}$ with co-implants**

*The Cluster Implant Source*
Ti$_{900}^\circ$C $T_{pk}$ 1350$^\circ$C

**With C$_{16}$ co-implant**

**With C$_{16}$ + Ge co-implants**

Better activation with C$_{16}$ co-implant

The Cluster Implant Source
FLASH Ti _750°C Tpk _1250°C

FLASH T_i_750°C T_pk_1250°C

B CONCENTRATION (atoms/cc)

DEPTH (Å)

B18
B18 + C16
B18 + Ge
B18 (as-implanted)

FLASH T_i_750°C T_pk_1250°C

B CONCENTRATION (atoms/cc)

DEPTH (Å)

BF2
BF2 + C16
BF2 + Ge
BF2 + C16 + Ge
BF2 (as-implanted)

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**R_s \cdot X_j Product: 32 nm Node**

A Measure of Active Carrier Concentration

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**Rs \cdot X_j** product is lowest for the B_{18}H_{22} implant, satisfying the 32 nm requirement.

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For 32nm node:

Rs = 1000 Ohm/sq  
X_j = 15nm

Rs \cdot X_j = 15 k\Omega \cdot nm
**Rs \cdot X_j:** 32 nm Node

**Anneal Conditions for B_{18}H_{22}**

Rs (Ohm/sq) vs Xj (nm) & Rs \cdot Xj (kohm nm)

- B18_Rs
- B18_Xj
- B18_Rs \cdot Xj

Rs \cdot Xj shows that the flash anneal satisfies the 32nm requirement.
XTEM: iRTP 900°C Anneal

With diffusionless anneal, no EOR defects with $\text{B}_{18}\text{H}_{22}$ and $\text{B}_{18}\text{H}_{22} + \text{C}_{16}\text{H}_{10}$. 
XTEM: fRTP ($T_i \, 750^\circ C$ & $T_{pk} - 1250^\circ C$)

**Diffusionless Anneal**

With diffusionless anneal, no EOR defects with $B_{18}H_{22}$. 
XTEM: iRTP 900°C & Flash Anneal

Table I

<table>
<thead>
<tr>
<th>Implant</th>
<th>Anneal (iRTP)</th>
<th>EOR defect</th>
<th>Depth (nm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>B$_{18}$</td>
<td>iRTP @ 900°C</td>
<td>NO</td>
<td>x</td>
</tr>
<tr>
<td>B$<em>{18}$ + C$</em>{16}$</td>
<td>iRTP @ 900°C</td>
<td>NO</td>
<td>x</td>
</tr>
<tr>
<td>B$_{18}$ + Ge</td>
<td>iRTP @ 900°C</td>
<td>YES</td>
<td>35</td>
</tr>
<tr>
<td>B$<em>{18}$ + C$</em>{16}$ + Ge</td>
<td>iRTP @ 900°C</td>
<td>YES</td>
<td>35</td>
</tr>
<tr>
<td>BF$_2$</td>
<td>iRTP @ 900°C</td>
<td>NO</td>
<td>x</td>
</tr>
<tr>
<td>BF$<em>2$ + C$</em>{16}$</td>
<td>iRTP @ 900°C</td>
<td>NO</td>
<td>x</td>
</tr>
<tr>
<td>BF$_2$ + Ge</td>
<td>iRTP @ 900°C</td>
<td>YES</td>
<td>35</td>
</tr>
<tr>
<td>BF$<em>2$ + C$</em>{16}$ + Ge</td>
<td>iRTP @ 900°C</td>
<td>YES</td>
<td>35</td>
</tr>
</tbody>
</table>

Table II

<table>
<thead>
<tr>
<th>Implant</th>
<th>Anneal (iRTP)</th>
<th>EOR defect</th>
<th>Depth (nm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>B$_{18}$</td>
<td>$T_{1,750°C}$</td>
<td>NO</td>
<td>x</td>
</tr>
<tr>
<td>B$_{18}$ + Ge</td>
<td>$T_{1,750°C}$</td>
<td>YES</td>
<td>35</td>
</tr>
<tr>
<td>BF$_2$</td>
<td>$T_{1,750°C}$</td>
<td>YES</td>
<td>5</td>
</tr>
<tr>
<td>BF$_2$ + Ge</td>
<td>$T_{1,750°C}$</td>
<td>YES</td>
<td>32</td>
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</table>

- B$_{18}$H$_{22}$ is the only implant technology with no EOR defects following flash anneal.
- With diffusionless anneal, Ge co-implants are left with EOR defects whereas they are absent with C$_{16}$H$_{10}$ co-implants.
Summary

- 32nm targets are achievable with 500eV equivalent B18 implant and flash anneal
- Boron diffusion observed with 900C spike
  - Amorphous state diffusion
  - Profile tail diffusion driven by EOR damage
- EOR damage not observed for B18 implant even with diffusionless anneal process
ClusterCarbon Implant for NMOS Stressor
NMOS Stressor Requirements

- **Emulate success of PMOS e-SiGe for NMOS**
  - Provide performance boost independent of scaling and gate stack formation
    - *Goal of 10-30% drive enhancement*

- **Si:C materials science very different from SiGe**
  - Epi process chemistry very difficult
  - 1.5-2% limit to carbon fraction in silicon lattice

- **Substitutional carbon required**
  - Interstitial carbon degrades stress

- **Compatible with CMOS integration**
Si:C Stressor Formation:
Selective epi Growth approach

Conventional recess etch and SiC selective epi growth

Challenges:

- Expensive tool
- Narrow process window
- Faceting issue
- Extra etch and cleaning steps
- Difficult to get repeatable carbon incorporation
- Low throughput
Si:C Layer Formation:
ClusterCarbon\textsuperscript{TM} implant approach

Advantages:

- Self-amorphization with cluster implants
- Elimination of extra PAI-implant
- By suitable process sequence, elimination of end of range damage and better recrystallization
- Higher $[C]_{\text{subs}}$ with millisecond anneal
- Better leakage current performance
- Higher throughput
ClusterCarbon Implant Advantages for Si:C Stressor

- Implant approach provides simple and direct process for stressor formation

- Implant provides very accurate control (1%) of carbon concentration
  - Multiple implants at different energies can be used to tailor carbon depth profile

- ClusterCarbon implant - self-amorphization with low crystalline damage below a-Si layer
  - Amorphous layer thickness determines stressor thickness

- Highest substitutional carbon achieved by recrystallation of amorphous layer by millisecond anneal process
ClusterCarbon: $C_7H_7$ from $C_{14}H_{14}$
Cluster Carbon Self-amorphization - $C_5H_5$ vs $C_7H_7$

- Going to a higher mass (from $C_5$ to $C_7$) at same implant condition yields about 25% increase in $\alpha$-Si layer thickness.
UV Raman (363.8nm) Results

C$_7$H$_7$ @ 3e15

Strained layer thickness equal to the amorphous layer thickness for 750°C sample

<table>
<thead>
<tr>
<th>#</th>
<th>Species</th>
<th>Carbon Implant &amp; Anneal</th>
<th>Strained layer thickness from Wafer bow (Å)</th>
<th>Amorphous layer thickness (TEM @6keV)</th>
<th>UV Raman Stress (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>C$_7$H$_7$</td>
<td>6k_3e15_750C</td>
<td>232</td>
<td>220</td>
<td>760</td>
</tr>
</tbody>
</table>

Wavenumber (cm$^{-1}$)

Intensity (a.u.)
Substitutional Carbon Percentage from HRXRD

FIG. 2. XRD rocking scans around the (004) Bragg reflection of three epi layers (dots: measurements, solid lines: simulations). Arrows indicate peak positions corresponding to epi layers with the same C concentrations as given, but assuming a variation of the relaxed lattice constant according to Vegard’s rule between Si and C, and between Si and β-SiC.

Δω vs substitutional carbon percentage

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Substitutional Carbon Percentage from HRXRD Fit for Experimental data

From $\Delta \omega$ we can estimate substitutional carbon percentage

HRXRD Data and Fit (Delta Omega vs Carbon at. %)

$y = 3.1322x$

Experimental Data

Linear (Experimental Data)
Substitutional Carbon Percentage determined with HRXRD

**ECS 2007 – TI, Axcelis, SemEquip**

**VLSI 2007 – pg 44**

Fig. 2 HRXRD rocking curve of the SPE Si:C film ([C]_{sub}=1.65 at.%) grown on (100) Si substrate. The well defined Si:C peak and fringes indicate that the Si:C film is high-quality single crystal.
Chained or Multiple implant – HRXRD Flash Anneal (2k + 5k + 8k) @ 3e15

HRXRD - RC
P082 ( 2k + 5k + 8k _ 3e15) FLASH ANNEAL

P082-1_5 (iRTP 800C)
P082-2_7 (Ti_750C_Tpk_1060C)

1.66% 1.75%
Chained or Multiple Implant – HRXRD
SPE Anneal @ 750°C and 850°C (2k + 5k + 8k) @ 3e15

Chained Implant - HRXRD

Counts/sec

Omega (degrees)

P277_(2k+5k+8k)_3e15_750C
P011_(2k+5k+8k)_3e15_850C

1.55%
1.68%
ClusterCarbon - % $[C]_{\text{sub}}$ vs % $[C]_{\text{atomic}}$

- LASER: $[C]_{\text{sub}}$ increases with dose
- SPE: $[C]_{\text{sub}}$ reaches its solid solubility limit (~1.5%)
% $[C]_{\text{sub}}$ Dependence on $\alpha$-Si Thickness

SIMS PROFILE

$R_p = 32.4\text{nm}$

$C_7H_7 - 10\text{keV}$  
% $[C]_{\text{sub}}$ vs [Amorphous Layer Thickness / $R_p$]

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# HRXRD Results - Substitutional Carbon

<table>
<thead>
<tr>
<th>#</th>
<th>Implant Energy</th>
<th>SIMS plateau depth at 5e20 (atoms/cm³) (nm)</th>
<th>% of Substitutional Carbon for various anneals</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>SPE 750°C - 5sec</td>
</tr>
<tr>
<td>1</td>
<td>2k + 5k + 8k 3e15 + 3e15 + 3e15</td>
<td>41</td>
<td>1.55</td>
</tr>
<tr>
<td>2</td>
<td>3k + 6k + 9k 1.5e15 + 3e15 + 3e15</td>
<td>48</td>
<td>1.66</td>
</tr>
</tbody>
</table>

- Percent of substitutional carbon is highest with MSA anneal
- For SPE, going beyond 850°C reduces the amount of substitutional carbon, confirming the results that carbon is kicked out of its substitutionality beyond 800°C
Summary

- ClusterCarbon provide an approach to NMOS stressor which is simple, direct and inexpensive.
- ClusterCarbon approach demonstrates incorporation of greater than 2% substitutional carbon with millisecond anneals.
- 1.5% substitutional carbon could be achieved just with SPE alone.
- The ClusterCarbon approach eliminates the need for PAI implant that is otherwise required for monomer carbon implants.
- $\% \text{[C]}_{\text{sub}}$ scales with percent of atomic carbon concentration.
- Amorphous layer depth is critical in obtaining higher $\text{[C]}_{\text{sub}}$.
- The heavier the mass of the ClusterCarbon, the better is the $\text{[C]}_{\text{sub}}$ incorporation.