Use of Co-Implantation to Extend Spike RTP to the 65nm Node and Beyond

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Outline

- Introduction – Roadmap
- Fluorine Co-Implantation for PMOS Junctions
- Carbon Co-Implantation for PMOS Junctions
- Carbon Co-Implantation for NMOS Junctions
- Summary and Conclusions
Ultra-Shallow Junction CMOS Device Scaling

**Device Requirements:**
- Increase transistor drive current ($I_{d,sat}$)
- Reduce short channel effects (SCE)
- Decrease power (dynamic and stand-by)

**Process Requirements:**
- Shallow junctions ($X_j$), Abrupt junctions,
- Low sheet resistance, Optimum overlap,
- Junction depth uniformity, Ease of integration

<table>
<thead>
<tr>
<th>Tech. Node</th>
<th>90nm</th>
<th>65nm</th>
<th>45nm</th>
<th>32nm</th>
</tr>
</thead>
<tbody>
<tr>
<td>$X_j$</td>
<td>&lt;250 Å</td>
<td>&lt;170 Å</td>
<td>&lt;120 Å</td>
<td>&lt;90 Å</td>
</tr>
<tr>
<td>$R_s$</td>
<td>&lt;660 Ω/sq</td>
<td>&lt;760 Ω/sq</td>
<td>830 Ω/sq</td>
<td>940 Ω/sq</td>
</tr>
<tr>
<td>Abruptness</td>
<td>4.1 nm/dec</td>
<td>2.8 nm/dec</td>
<td>2.0 nm/dec</td>
<td>1.4 nm/dec</td>
</tr>
</tbody>
</table>

**Anneal**
- Spike
- Transition
- Advanced
Fluorine Co-Implant for PMOS (Boron)
Fluorine Energy Optimization: SIMS Profiles

$Ge/2\text{keV}/5E14 + F/2E15 + B/0.5\text{keV}/1E15 + 1050^\circ\text{C}$ spike

- A steeper profile is formed with F energies from 10 to 20 keV
- 18% decrease in both $X_j$ and $R_s$ and 36% in abruptness over the baseline ($Ge+B$ only)

H. Graoui et al., MRS 2004 proceedings.
Fluorine Energy Optimization: SIMS Profiles

Ge/20keV/1E15 + F/2E15 +B/0.5/1E15 + 1050°C spike

- A steeper profile is formed with F\(^+\) energies from 6 to 20 keV
- Reduction of 22% in \(X_j\), 10% in \(R_s\) and 45% in abruptness over the baseline (Ge+B only)

H.Graoui et al., MRS 2004 proceedings.
Fluorine Energy Optimization: $R_s$ vs. $X_j$

$Ge/20\text{keV}/1E15 + F/2E15 + B/0.5/1E15 + 1050^\circ C$ Spike Anneal

Optimum F energy is 10 keV ➔
An energy ratio of 1-to-20 between the F and B

H.Graoui et al., MRS 2004 proceedings.
Fluorine Dose Optimization: SIMS Profiles
Ge/2keV/5E14 + F/10keV+B/0.5keV/1E15 + 1050°C spike

Optimum F dose is 2E15/cm²; at higher dose the junction diffuses more

H. Graoui et al., MRS 2004 proceedings.
Fluorine Dose Optimization: $R_s$ vs. $X_j$

Ge/2keV/5E14 + F/10keV + B/0.5keV/1E15 +1050°C Spike Anneal

The optimum fluorine dose is 2E15 ions/cm$^2$

H.Graoui et al., MRS 2004 proceedings.
Fluorine SIMS Profiles Before & After Anneal
Ge/2keV/5E14 + F/2E15 + B/0.5keV/1E15 + Spike

- First 10 keV F peak located at B end-of-range and halts B diffusion
- Second F peak located at amorphous/crystalline interface

H.Graoui et al., MRS 2004 proceedings.
Carbon Co-Implant for PMOS (Boron)
Experimental Details

**Implants:**

- **Pre-amorphization (PAI)**
  - Ge for B implants
  - Si for P and As implants

- **Carbon**
  - $1 \times 10^{15}$ cm$^{-2}$ @ 2, 4 and 6 keV

- **Boron**
  - $7 \times 10^{14}$ cm$^{-2}$ @ 500 eV
  - $1 \times 10^{15}$ cm$^{-2}$ @ 500 eV

- **Phosphorous**
  - $7 \times 10^{14}$ cm$^{-2}$ @ 500 eV and 1 keV

- **Arsenic**
  - $7 \times 10^{14}$ cm$^{-2}$ @ 700 eV and 1 keV

**RTP spike anneals:**

- **Spike anneals**
  - 1050°C (P, As) and 1070°C (B)
  - Ramp-up 250°C/s, ramp-down 90°C/s
  - 100% N$_2$ ambient for B and P
  - 10% O$_2$ ambient for As

65nm Ultra-Shallow Junction Solution: Quantum® X Carbon Co-Implant + RadiancePlus™ Spike RTP

- Ge/C/B co-implants of optimal energies and doses with spike anneal meet 65 nm $R_s$ and abruptness requirements
- Junction depth shortfall can be accommodated with offset spacer and halo optimization

IMEC/Philips Research Leuven. Data shown with permission.
PMOS: 0.5keV B in Ge PAI+C Implanted Si

- Shallow, abrupt junctions produced by co-implants of Ge PAI, C, and B
- PAI: Ge 20keV $5 \times 10^{14}$ cm$^{-2}$ (35 nm $\alpha$-layer)
- SPE of $\alpha$-layer will result in substitutional C and improved B activation
- Substitutional C:
  - Suppresses Si interstitial-mediated B diffusion
  - Suppresses defect formation and EOR-damage-driven diffusion
  - Strain-related effects?

### Conditions

<table>
<thead>
<tr>
<th>Condition</th>
<th>$X_j$ (nm) at 1E19</th>
<th>$R_s$ (Ohm/sq)</th>
<th>Abruptness (nm/dec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>B-only</td>
<td>30.8</td>
<td>490</td>
<td>7.2</td>
</tr>
<tr>
<td>B + PAI + C (2keV)</td>
<td>21.2</td>
<td>644</td>
<td>4.5</td>
</tr>
<tr>
<td>B + PAI + C (4keV)</td>
<td>20.6</td>
<td>526</td>
<td>2.7</td>
</tr>
<tr>
<td>B + PAI + C (6keV)</td>
<td>22.3</td>
<td>468</td>
<td>2.3</td>
</tr>
</tbody>
</table>
**PMOS: Annealed Boron/Carbon SIMS Profiles**

- First carbon peak coincides with the carbon projected range and at the end-of-range of the B profile

Carbon Co-Implantation Optimization with 0.2keV B⁺

A variation of 0.5 keV in carbon energy can result in junctions with different junction depths and abruptnesses

H.Graoui et al., European MRS 2005.
Change in Junction Formation by Varying the PAI Depth

Ge PAI energy also has to be optimized

H.Graoui et al., European MRS 2005.
Effect of Different Spike Temperature on Junction Formation

Junction abruptness is constant at 2.5 nm/dec even up to 1100°C, while the junction diffuses and sheet resistance decreases

H. Graoui et al., European MRS 2005.
Junction Depth and Sheet Resistance Trends as Spike Temperature Increases

Junction depth increases exponentially especially above 1050°C, while sheet resistance shows a linear decrease

H. Graoui et al., European MRS 2005.
Simulation of Carbon Co-Implanted Junctions
Synopsys TSuprem-4 Model

Physics-based model shows that at 5keV all implant damage appears to be captured by carbon

H.Graoui et al., European MRS 2005.
Carbon Co-implantation Enables PMOS USJ Formation Down to $X_j = 20$ nm

Junctions as shallow as 20 nm, 573 Ohms/sq and 2.5 nm/decade can be obtained, offering potential solutions for high performance 65 nm transistors

H.Graoui et al., European MRS 2005.
Carbon Co-Implant for NMOS (Phosphorous & Arsenic)
NMOS: 1 keV P in c-Si, c-Si+C, and PAI+C

- Shallow, abrupt junctions produced by co-implants of Si PAI, C, and P
- PAI: Si 25 keV $1 \times 10^{15}$ cm$^{-2}$ (60 nm $\alpha$-Si)
- SPE of $\alpha$-layer will result in substitutional C and improved P activation
- Substitutional C
  - Suppresses Si interstitial-mediated P diffusion at low [P]
  - Enhanced PV$^-$ diffusion at high [P]?
  - Strain-related effects?

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<tr>
<td>P-only</td>
<td>30</td>
<td>411</td>
<td>18.0</td>
</tr>
<tr>
<td>P + C (4keV)</td>
<td>30</td>
<td>392</td>
<td>13.2</td>
</tr>
<tr>
<td>P + C (6keV)</td>
<td>28</td>
<td>349</td>
<td>12.0</td>
</tr>
<tr>
<td>P + PAI + C (4keV)</td>
<td>20</td>
<td>357</td>
<td>3.2</td>
</tr>
<tr>
<td>P + PAI + C (6keV)</td>
<td>20.5</td>
<td>318</td>
<td>3.0</td>
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NMOS: As in c-Si and in PAI+C+P Implanted Si

- Good junction characteristics for single-specie As implant
- Co-implantation drives As deeper
- Reduced As concentration probably due to 100% N₂ anneal conditions

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<td>18.3</td>
<td>480</td>
<td>4.8</td>
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<tr>
<td>As-only (1keV)</td>
<td>18.3</td>
<td>497</td>
<td>4.3</td>
</tr>
<tr>
<td>As (0.7keV) + P + PAI + C (4keV)</td>
<td>23.4</td>
<td>307</td>
<td>3.8</td>
</tr>
<tr>
<td>As (0.7keV) + P + PAI + C (6keV)</td>
<td>23.4</td>
<td>280</td>
<td>3.8</td>
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**NMOS: Comparison of P and As profiles**

- **P and As profiles taken from same wafer**
- **Under single-specie implant conditions**
P and As have different diffusion mechanisms
- **In this experiment junction depth and trailing slope are virtually identical for both species**
- **P diffused deeper than in PAI+C+P case**
- **Activated P concentration higher than As due to its higher solid solubility**

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<td>307</td>
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Summary and Conclusions

- Combination of PAI (Si or Ge) and F or C implant dramatically improves ultra-shallow junction characteristics for both PMOS and NMOS dopants.

- SPE of amorphous layer crucial to provide C on substitutional lattice sites and improve activation of dopants.

- Substitutional C is believed to:
  - Suppress B and P diffusion
  - Suppress EOR damage formation and EOR damage-driven diffusion

- Very similar B, P and As profiles under PAI+C conditions.

- Co-implantation with conventional spike anneal is a very promising candidate for ≤65 nm USJ formation.