Junction Technology Group:
Thurs, July 11, 2013
noon - 4:00 pm
SEMICON West 2013
Moscone Center (San Francisco, CA)

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Advanced Ion Beam Technology
Axcelis
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Nissin Ion Equipment
SEN Corp.
Ultratech

Ion Implantation and Annealing: New Process and Products
Co-Chairs: John Borland & Michael Current

Michael Current of Current Scientific:
"Microwave and RTA annealing of Phos-doped, strained Si(100) and (110) implanted with molecular carbon ions"

Jeff Gelpey of Centrotherm:
"Low temperature oxidation & nitridation process enabling advanced junctions".

Jeff Hebb of UltraTech:
"Laser spike anneals for finFETs".

Gary Mount of EAG:
"Junction evaluation using Electron Beam-Induced Current (EBIC)".

Ice cream break and networking

John Borland of J.O.B. Technologies:
"High mobility Ge channel formation by selective liquid phase epitaxy (LPE) using Ge + B plasma implantation & laser melt annealing".

Yoshiki Nakashima of Nissin:
"Damage control with cluster ions and heated implantation".

Mitch Taylor representing Cameca:
"Advanced metrologies for advanced devices and materials: SIMS, LEXES, ATP".

Dick James of Chipworks:
"Leading edge Si devices: an update".
IIT14 conference: June 29-July 4, 2014:
20th international conference on ion implantation technology, annealing, applications to advanced materials & devices.

Conference venue: Hilton Hotel, Portland OR

Conference chairmen:
Aaron Vanderpool: Intel
Benjamin Columbeau: AMAT/VSEA

Abstract deadline: Feb 7, 2014 (5 days after Superbowl2014)

IIT14 school: June 26-28, 2014: 3-day intensive tutorial on ion implantation machines & process, annealing & process control metrologies. Faculty of international experts, =600 page textbook.
In Memorium: June 2013

James W. Mayer

“Father” of many ion beam technologies. Threshold adjust implants, amorphous-Si regrowth, Rutherford Backscattering Spectroscopy, silicide film growth & characterization, materials science teacher to many at Caltech, Cornell, ASU.

Kenneth G. Stephens

Leader of ion beam technology center at the University of Surrey, Guildford, UK. Teacher to many ion implantation and ion beam physics students. Co-chair of IIT90.
Microwave and RTA Annealing of Phos-doped, Strained Si(100) and (110) Implanted with Molecular Carbon Ions

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Hiroshi Onoda, Karuppanan Sekar,
Nobuhiro Tokoro
Nissin Ion Equipment, Kyoto, Japan

outline:
Comparison of MWA & RTA: Activation & SPE
Experimental details: Implants, MWA, RTA
Results: SIMS, TEM, R_{sheet}, XRD
Summary
What is different about MWA?

<table>
<thead>
<tr>
<th>Light</th>
<th>Wavelength</th>
<th>Frequency</th>
<th>Photon Energy</th>
</tr>
</thead>
<tbody>
<tr>
<td>uv</td>
<td>10-400 nm</td>
<td>30 PHz - 750 THz</td>
<td>124 - 3 eV</td>
</tr>
<tr>
<td>visible</td>
<td>400-750 nm</td>
<td>750 - 400 THz</td>
<td>3.2 - 1.7 eV</td>
</tr>
<tr>
<td>IR</td>
<td>750 nm - 1 mm</td>
<td>400 THz - 300 GHz</td>
<td>1.7 eV - 1.24 meV</td>
</tr>
<tr>
<td>uW</td>
<td>1 mm - 1 m</td>
<td>300 GHz - 300 MHz</td>
<td>1.24 meV - 1.24 ueV</td>
</tr>
<tr>
<td>radio</td>
<td>1 -10^3 m</td>
<td>300 MHz - 3 Hz</td>
<td>1.24 ueV -12.4 feV</td>
</tr>
</tbody>
</table>

- u-wave light has photon energies far below $E_{\text{gap}}$ (Si): no carrier creation.
- u-wave light is absorbed by free carriers with Ohmic heating.
- u-wave heating (phonon generation) from dipole excitations, etc.
- “coherent” excitation (non-thermal) reported in ceramics, chemicals, etc.

MWA Heating

Micro-wave Anneal Chamber:
3 to 5 magnetrons
5.8 GHz
Chamber tuned to minimize static modes
Pyrometer temperature sensor
(line of sight to wafer center bottom)

Wafer temperature depends on:
Magnetron power
Power-on time period
Location of Si and Quartz susceptor wafers

Typical maximum wafer temperature:
350 to 500 C (~300 s)
Minimal dopant diffusion

Fig. 2. Comparisons of temperature profiles versus MWA time at different MWA power. The MWA time was defined as the period when the microwave power was turned on.

Fig. 5. The SIMS profiles of P concentration at a dose of 5×10^{15} ions/cm². The P distribution after the RTA over 800 °C shows deeper dopant diffusion, while the MWA resulted in no significantly dopant diffusion.
MWA vs RTA: Dopant Activation Rate

MWA activates P, As and BF$_2$ implants at $\approx$450 C.

RTA activates dopants at $\approx$570 C.

Implication: c-Si re-growth (SPE) occurs faster and at lower temperatures for MWA than RTA.

Y.J. Lee et al., IIT12
MWA vs RTA: re-growth kinetics

c-Si re-growth (SPE) rates measured for P and As implants are \( \approx 10^3 \) times faster for MWA at \( \approx 450 \) C than thermal rates.

\[
v(\text{cm/s}) = (3.68 \times 10^8 \text{ cm/s}) \times e^{-2.76 \text{ eV/kT}}
\]

Experimental Conditions: \textit{strained nMOS}

\textbf{Implants:} (Nissin CLARIS)
- $\text{C}_7\text{H}_7^+$
  - 10 keV / 3e15 C/cm$^2$
  - 6 keV / 8e14 C/cm$^2$
  - 2 keV / 6e14 C/cm$^2$
- and $\text{P}^+$
  - 15 keV / 4e15 P/cm$^2$

\textbf{Anneals:}
- \textbf{MWA:} (DSG AXOM-300)
  - 3 or 5 Magnetrons, 600s
  - 30 min N$_2$ chamber purge
- \textbf{RTA:} (AllWin 810)
  - 600, 750, 900 C, 30s
  - and 1000 C, 10s

\textbf{SIMS: C}$^\alpha$-Si $\text{C}_7$ implants

\textbf{Carbon Concentration (atoms/cm$^2$)}
- As implanted
- MWA 5P 600s
- RTA 1000$^\circ$C 10s

\textbf{Temperature vs. Time (s)}
- MWA 5P 600s
- MWA 3P 600s
- RTA 1000$^\circ$C 10s
- RTA 900$^\circ$C 30s

\textbf{Depth (nm)}
- 0 to 250 nm
Damage Recovery: C$_7$H$_7$ Implants

MWA at 3P 600s re-grows $\approx 1/3$ of a-Si layer. MWA at 5P 600s re-grows all a-Si.

Both MWA and RTA leave dense “twin-like” dislocations near surface (at regions of high C ($10^{21}$ C/cm$^3$) concentrations).
Carbon Strain: C\textsubscript{7}H\textsubscript{7} implants, XRD

\textbf{Si}(100):

Both MWA (480 - 510 C, 600 s) and RTA (900-1000 C, 10 s) result in high (≈1.5%) substitutional C content.

\textbf{Si}(110):

MWA (480 - 510 C, 600 s) gives lower C\textsubscript{sub} (0.78-0.99%) content than Si(100).

RTA (1000 C, 10 s) results in low (<0.3%) substitutional C content.
C₇H₇ & P implants: SIMS, TEM

SIMS: P
- No substantial P diffusion for MWA.
- Some P diffusion for RTA 1000 C 10 s.

TEM:
- Dense twin-like dislocations seen near surface (high C content) in both MTA & RTA.
Carbon Strain: $C_7H_7$ & P implants, XRD

**Si(100):**

MWA (480 - 510 C, 600 s) with $C_7$ & P implants has lower (1.15-1.3%) $C_{\text{sub}}$ than $C_7$ alone ($\approx 1.5$%).

RTA (1,000 C, 10 s) give only low (<0.3%) substitutional C content.

**Si(110):**

MWA (480 - 510 C, 600 s) gives lower $C_{\text{sub}}$ ($\approx 0.8$%) content than Si (100).

RTA (1000 C, 10 s) results in low (<0.3%) substitutional C content.
Separate MWA after each implant gives high $C_{\text{sub}}$ (1.44%).

RTA gives lower $R_{\text{sheet}}$, but poor $C_{\text{sub}} > 600 \, \text{C}$. 

### Table: $C_{\text{sub}}$ & Sheet Resistance

<table>
<thead>
<tr>
<th>Anneal Method</th>
<th>Anneal Conditions</th>
<th>$C_{\text{sub}}$ (%)</th>
<th>$R_s$ (ohms/sq.)</th>
<th>$C_{\text{sub}}$ (%)</th>
<th>$R_s$ (ohms/sq.)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
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<td></td>
<td></td>
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<tr>
<td>$C_7$ implant, Single anneal</td>
<td></td>
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<td></td>
<td></td>
<td></td>
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<tr>
<td>RTA</td>
<td>900 °C 30s</td>
<td>1.47</td>
<td>na</td>
<td>nm</td>
<td>na</td>
</tr>
<tr>
<td></td>
<td>1000 °C 10s</td>
<td>1.56</td>
<td>na</td>
<td>low (&lt;0.5)</td>
<td>na</td>
</tr>
<tr>
<td>MWA</td>
<td>3P 600s</td>
<td>1.52</td>
<td>na</td>
<td>0.78</td>
<td>na</td>
</tr>
<tr>
<td></td>
<td>5P 600s</td>
<td>1.57</td>
<td>na</td>
<td>0.99</td>
<td>na</td>
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<tr>
<td>$C_7 + P$ implants, Single anneal after both implants are completed</td>
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<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>RTA</td>
<td>900 °C 30s</td>
<td>nm</td>
<td>nm</td>
<td>nm</td>
<td>nm</td>
</tr>
<tr>
<td></td>
<td>1000 °C 10s</td>
<td>low</td>
<td>96.7</td>
<td>very low</td>
<td>134</td>
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<tr>
<td>MWA</td>
<td>3P 600s</td>
<td>1.27</td>
<td>457</td>
<td>0.85</td>
<td>770</td>
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<tr>
<td></td>
<td>5P 600s</td>
<td>1.16</td>
<td>293</td>
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<td>$C_7 + P$ implants, Anneals after each implant</td>
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<tr>
<td>RTA</td>
<td>1000 °C 10s</td>
<td>low</td>
<td>118</td>
<td>low</td>
<td>152</td>
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<tr>
<td>MWA</td>
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<td>1.44</td>
<td>468</td>
<td>0.68</td>
<td>675</td>
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<tr>
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<td>5P 600s</td>
<td>1</td>
<td>300</td>
<td>0.63</td>
<td>634</td>
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<tr>
<td>Extra anneal after $C_7 + P$ implants and MWA (3P 600s)</td>
<td></td>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>none</td>
<td></td>
<td>1.27</td>
<td>457</td>
<td>0.85</td>
<td>770</td>
</tr>
<tr>
<td>RTA</td>
<td>600 °C 30s</td>
<td>1.25</td>
<td>478.9</td>
<td>nm</td>
<td>nm</td>
</tr>
<tr>
<td></td>
<td>750 °C 30s</td>
<td>1.18</td>
<td>237.1</td>
<td>nm</td>
<td>nm</td>
</tr>
<tr>
<td>MWA</td>
<td>3P 600s</td>
<td>1.21</td>
<td>436.1</td>
<td>nm</td>
<td>nm</td>
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<td>Extra anneal after $C_7 + MWA (3P 600s) + P + MWA (3P 600s)</td>
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<td></td>
<td></td>
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<tr>
<td>none</td>
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<td>1.44</td>
<td>468</td>
<td>0.68</td>
<td>678</td>
</tr>
<tr>
<td>RTA</td>
<td>600 °C 30s</td>
<td>1.22</td>
<td>501.3</td>
<td>nm</td>
<td>nm</td>
</tr>
<tr>
<td></td>
<td>750 °C 30s</td>
<td>1.11</td>
<td>260.7</td>
<td>nm</td>
<td>nm</td>
</tr>
<tr>
<td>MWA</td>
<td>3P 600s</td>
<td>1.17</td>
<td>430.4</td>
<td>nm</td>
<td>nm</td>
</tr>
</tbody>
</table>
Extra Anneals: C₇ & P implants, XRD

With a single MWA after C₇ & P implants,

* Additional MWA keeps $C_{sub}$ at $\approx 1.2\%$
* RTA anneal >600 C reduces $C_{sub}$.
$C_{sub}$ is very low after RTA 900 C.

With a separate MWA after each C₇ & P implant,

* Additional MWA reduces $C_{sub}$ from $\approx 1.4\%$ to $\approx 1.2\%$.
* RTA anneal >600 C reduces $C_{sub}$.
$C_{sub}$ is very low after RTA 900 C.
Summary

1. MWA (≈500 C) is more effective than RTA (600-1000 C) for realizing high C strain and P activation for shallow junction (nMOS SDE) formation.

2. Si(100) much better than Si(110) for α-Si re-growth.

3. Dense twin-like dislocations seen near junction surfaces at high C concentrations for both MWA & RTA.

4. Additional RTA anneals >600 C result in lower $R_{\text{sheet}}$ (diffusion) but loss of C strain ($C_{\text{sub}}$).
Key Acknowledgements

Yu-Lun Lu
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