WaferMasters, Inc.

New Technology for Thermal Processing

By John Foggiato

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Outline

• Issues with RTP
• How WaferMasters Addressed the Issues
• Various Characterized Processes
• Future Directions
Dependence of Light Intensity on Temperature

**Heat Source**

**Pyrometer**

Temperature Readout

Temperature (°C)

Intensity (Arb. Unit)

Wavelength

- 3.0 µm
- 0.96 µm
- 5.3 µm

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Filtered IR Image

Si 0.7mm  Si 1.4mm  Si 2.1mm

Pyrometer
3~5.3\(\mu\)m

Heat Source

Filter
Effect of Filters on Temperature Measurement

<table>
<thead>
<tr>
<th>Filter Used</th>
<th>Measured Temperature (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>None</td>
<td>0.96μm 3.0~5.3μm</td>
</tr>
<tr>
<td>0.7mm Si</td>
<td>Detection Limit for 0.96μm</td>
</tr>
<tr>
<td>1.4mm Si</td>
<td></td>
</tr>
<tr>
<td>2.1mm Si</td>
<td></td>
</tr>
<tr>
<td>0.5mm Quartz</td>
<td></td>
</tr>
<tr>
<td>1.5mm Quartz</td>
<td></td>
</tr>
<tr>
<td>5.0mm Quartz</td>
<td></td>
</tr>
<tr>
<td>5.0mm Quartz (Blasted)</td>
<td></td>
</tr>
</tbody>
</table>
Optical Properties of Si

Emissivity

Absorption Coefficient

- Normal spectral emissivity
- Total emissivity
- Absorption coefficient

Lightly Doped Si

Heavily Doped Si
Radiation Spectra from Heated Blackbody

![Graph showing radiation spectra from heated blackbody at different temperatures. The x-axis represents wavelength (µm) and the y-axis represents intensity (Arb. Unit). The graph includes temperature labels for 3000°C, 2750°C, 2500°C, 2250°C, 2000°C, 1500°C, and 1000°C. The intensity peaks at different wavelengths for each temperature.]
Spectral Features in Thermal Processing

Blackbody Radiation

Intensity (Arb. Unit)

Wavelength (µm)

Transmittance (%)

Absorption Coefficient (cm⁻¹)

Wavelength (µm)

Si

Quartz

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Wafer Heating Mechanism
Radiation vs. Conduction

\[ W(T) = \varepsilon \sigma (T_a^4 - T_b^4) \quad W(T) = \lambda (T) (T_a - T_b)/d \]
Impact of 1°C on Wafer Heating

Radiation vs. Conduction

Effect of 1°C on Heat Flux (W/m²) vs. Temperature (°C)

- ε = 1.0
- d = 0.2mm
- ε = 0.7
- d = 0.5mm
- d = 1.0mm
- d = 5.0mm
- d = 10.0mm
Applications of RTP in Semiconductor Device Manufacturing

1. Polyimide Curing
2. Metal Anneal
3. Low-k Interlevel Dielectric
4. Curing of Photo Process Planarization Materials
5. Interlayer Dielectric Densification
6. Silicide Formation
7. Gate Electrode Anneal
8. High-k Dielectric Densification
9. Thin Oxide Growth
10. Ultra-Shallow Junction Activation and Anneal
11. Well Implant Anneal
12. Oxide Trench Fill Densification
13. Trench Oxidation and Corner Rounding
14. SOI Splitting
How WaferMasters, Inc. Addressed Issues

- Isothermal Chamber-No backside pattern effects
- Utilized Natural Characteristics of Wafers’ Thermal Capacity
- Wafer Handling
- Wafer Temperature Control/Uniformity
- No Moving parts-Contamination Control
- Small Footprint and Low Power and Gas Consumption
“Single wafer Rapid Thermal Furnace”

SRTF
Process Module of High Temperature SRTF

- Resistive Heating
- Minimum Aperture (d << W, d << L)
- Nearly Isothermal Cavity
- No Moving Parts
- Zone Temp. Control
- Heat Diffuser
- Wafer Temp. Monitoring
Single Wafer Rapid Thermal Furnace Configuration

AGV Interface

Vacuum Loadlock

Process Chambers

Cooling Stations

New or Processed Cassettes

Robot

Chamber 2

Chamber 1

Vacuum Pump
Configuration of Lower Temperature Chambers

Process Module
- Stacked Hot Plates

Load Port
- Triangular door

Optical Bench
- No adjustment

Vacuum Robot
- Extended z-axis travel

Cassette Stage
- Cooling stations

Vacuum Pump
- Integrated
X-ray Topography with Optimal End Effector

Wafer Processed 5 times at 1100°C, 60s under 1 atm air
System Configurations for Metal Silicide Formation

SRTF-200LP
- No moving parts in process chamber
- Temperature range: 200 – 1100°C

SAO-200LP
- Individually controlled heater element
- Temperature range: 100 – 550°C
Wafer Heating and Cooling Capability

![Diagram showing wafer heating and cooling process time and wafer temperature over time.]

- **Wafer In** and **Wafer Out**
- **Forced Cooling in Cooling Station**
- **Natural Cooling**
- **Process Time**

The graph illustrates the temperature changes over time for wafer heating and cooling, distinguishing between natural cooling and forced cooling in a cooling station.
Low Power Consumption

- **Temperature Set Point (°C)**
- **Power Consumption (W)**

### Zones
- **Zone 1**
- **Zone 2**
- **Zone 3**
- **Total**
Thermal Product Road Map
150 to 300 mm wafers

Temperature (°C)
1200
1000
800
600
400
200
RT

Flash
SRTF
MBF
SAO
DCH

Temperature
1 min
5 min
10 min
20 min
30 min

Process Time

Flash: Flash Annealing System
SRTF: Single Wafer Rapid Thermal Furnace (Sold Through TEL)
DCH: Direct Contact Hot Plate System
SAO: Stacked Annealing Oven
MBF: Mini Batch Furnace

H₂ Anneal
Oxidation
Implant Anneal
USJ Anneal
Nitridation
Glass Reflow
Film Densification
Silicidation (2nd step)
Ta₂O₅ Recrystallization
Silicidation (1st step)
SOI Splitting
Al Sintering
Ta₂O₅ Deposition
Wafer Bumping
SOG/SOD Anneal
Cu Anneal
Photoresist Bake

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**Typical Process Uniformity**

<table>
<thead>
<tr>
<th>Process</th>
<th>Ohm/sq</th>
<th>Change (%)</th>
<th>Temp/Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>TiSi₂ Formation</td>
<td>12.854</td>
<td>2.150</td>
<td>600°C/60s</td>
</tr>
<tr>
<td>Ti₂Si Formation</td>
<td>0.953</td>
<td>1.624</td>
<td>800°C/60s</td>
</tr>
<tr>
<td>Implant Anneal</td>
<td>86.63</td>
<td>0.39</td>
<td>1100°C/35s</td>
</tr>
<tr>
<td>⁷⁵As+ Implant Anneal</td>
<td></td>
<td></td>
<td>75As 70keV 1E15</td>
</tr>
<tr>
<td>Dry Oxidation</td>
<td>2.9</td>
<td>0.67</td>
<td>1000°C/100s</td>
</tr>
</tbody>
</table>

**Notes:**
- TiSi₂ 12.854 ohm/sq, Unif. Change 0.578%
- Ti₂Si 0.953 ohm/sq, Unif. Change 0.151%
- ⁷⁵As 70keV 1E15

**Images:**
- (a) TiSi₂ Formation
- (b) Ti₂Si Formation
- (c) ⁷⁵As+ Implant Anneal
- (d) Dry Oxidation
200mm Stacked Annealing Oven

600mm (W) X 1200mm (D) X 1700mm (H) (2 ft X 5 ft X 6 ft)
Various Characterized Processes

- Ion Implant
  - Boron, BF2 and with amorphization Species
  - Phosphorus and Arsenic
- BPSG Reflow
- Silicide Formation
  - TiSi, CoSi, NiSi
- Low Temperature Anneals
  - Copper
  - SOG
- Film Growth
  - Oxide, Nitride
- Defect Engineering
SIMS Profiles of 35sec Process
Temperature dependence

1KeV, 1E15 ions/cm² 11B+ implant

1KeV, 5E14 ions/cm² 11B+ implant
Ion Implant Anneal Process Window Comparison

Uniformity <0.5% (1σ)

<table>
<thead>
<tr>
<th>Ion Type</th>
<th>Energy (KeV)</th>
<th>Dose (atoms/cm²)</th>
<th>Sheet Resistance</th>
<th>Uniformity</th>
</tr>
</thead>
<tbody>
<tr>
<td>B⁺</td>
<td>50</td>
<td>1E15</td>
<td>&lt;90 (Ω/sq.)</td>
<td></td>
</tr>
<tr>
<td>BF₂⁺</td>
<td>70</td>
<td>1E15</td>
<td>&lt;110 (Ω/sq.)</td>
<td></td>
</tr>
<tr>
<td>As⁺</td>
<td>70</td>
<td>1E15</td>
<td>&lt;92 (Ω/sq.)</td>
<td></td>
</tr>
<tr>
<td>P⁺</td>
<td>70</td>
<td>1E15</td>
<td>&lt;68 (Ω/sq.)</td>
<td></td>
</tr>
</tbody>
</table>
Typical Implant Anneal Process Uniformity

$^{11}\text{B} \ 50\text{keV} \ 1\times 10^{15}$
$1100^\circ\text{C}, \ 35\text{s}$
Ave.$= 86.63\Omega/\text{sq.}$
$1\sigma = 0.95\Omega/\text{sq.}$
Unif.$= 0.39\%(1\sigma)$

$^{31}\text{P} \ 70\text{keV} \ 1\times 10^{15}$
$1000^\circ\text{C}, \ 35\text{s}$
Ave.$= 65.05\Omega/\text{sq.}$
$1\sigma = 0.16\Omega/\text{sq.}$
Unif.$= 0.25\%(1\sigma)$

$\text{BF}_2 \ 70\text{keV} \ 1\times 10^{15}$
$1000^\circ\text{C}, \ 35\text{s}$
Ave.$= 103.19\Omega/\text{sq.}$
$1\sigma = 0.31\Omega/\text{sq.}$
Unif.$= 0.30\%(1\sigma)$

$^{75}\text{As} \ 70\text{keV} \ 1\times 10^{15}$
$1050^\circ\text{C}, \ 35\text{s}$
Ave.$= 89.46\Omega/\text{sq.}$
$1\sigma = 0.37\Omega/\text{sq.}$
Unif.$= 0.41\%(1\sigma)$
Implant Anneal Summary

**Sheet Resistance (Ohm/sq.)**

- **75As⁺**: 70keV 1E15
- **31P⁺**: 70keV 1E15
- **49BF₂⁺**: 70keV 1E15
- **11B⁺**: 50keV 1E15

**Rs Uniformity (%)**

- **75As⁺**: 70keV 1E15
- **31P⁺**: 70keV 1E15
- **49BF₂⁺**: 70keV 1E15
- **11B⁺**: 50keV 1E15
**11B+ Implant Anneal**

**Lamp RTP**

**SWF**

![Graph showing boron concentration depth profiles for Lamp RTP and SWF](image)

**11B+ 50keV, 1E15 cm^-2**

As implanted

- 900°C
  - 10s 236.78 Ω/sq.
  - 150s 158.39 Ω/sq.
  - 1100°C
    - 10s 101.14 Ω/sq.
    - 150s 86.70 Ω/sq.
  - 1000°C
    - 10s 88.58 Ω/sq.
    - 150s 80.69 Ω/sq.

- 1000°C
  - 40s 264.09 Ω/sq.
  - 180s 169.45 Ω/sq.
  - 1100°C
    - 40s 86.92 Ω/sq.
    - 180s 86.94 Ω/sq.
  - 1000°C
    - 10s 88.64 Ω/sq.
    - 180s 86.64 Ω/sq.

**11B+ 50keV, 1E15 cm^-2**

As implanted

- 900°C
  - 10s 236.78 Ω/sq.
  - 150s 158.39 Ω/sq.
  - 1100°C
    - 10s 101.14 Ω/sq.
    - 150s 86.70 Ω/sq.
  - 1000°C
    - 10s 88.58 Ω/sq.
    - 150s 80.69 Ω/sq.

- 1000°C
  - 40s 264.09 Ω/sq.
  - 180s 169.45 Ω/sq.
  - 1100°C
    - 40s 86.92 Ω/sq.
    - 180s 86.94 Ω/sq.
  - 1000°C
    - 10s 88.64 Ω/sq.
    - 180s 86.64 Ω/sq.
$^{49}$BF$_2^+$ Implant Anneal

Lamp RTP

1100°C

SWF

49BF$_2^+$ + 70keV, 1E15 cm$^{-2}$

As implanted

1100°C

10s 109.80 Ω/sq.
25s 130.22 Ω/sq.
40s 146.43 Ω/sq.
70s 194.04 Ω/sq.
110s 207.53 Ω/sq.
150s 215.88 Ω/sq.

1100°C

40s 104.33 Ω/sq.
55s 105.91 Ω/sq.
70s 107.41 Ω/sq.
100s 110.02 Ω/sq.
140s 112.53 Ω/sq.
180s 116.00 Ω/sq.
BPSG Film Densification/Reflow

Maximum density reached with highest shrinkage
Titanium Silicide Formation and Anneal
700 Torr, N₂ Atmosphere, Ti = 35nm
Temperature Sensitivity for CoSi Formation

10nm TiN capped 10nm Co
Annealing time = 120sec
After SPM cleaning

Rs (ohm/sq.)

Temperature (°C)

350 400 450 500 550 600 650 700

0 20 40 60 80 100 120 140 160 180 200

172.0
135.7
84.5
95.2
97.3
92.4
6.7
5.1
Co$_x$Si Formation (10nm TiN capped 10nm Co)

Process conditions: 425°C, 150sec, After SPM cleaning

Slot #01
Average: 74.2 ohm/sq
Maximum: 77.4 ohm/sq
Minimum: 70.6 ohm/sq
Uniformity: 2.25%

Slot #15
Average: 73.6 ohm/sq
Maximum: 79.2 ohm/sq
Minimum: 69.0 ohm/sq
Uniformity: 2.28%

Slot #23
Average: 73.2 ohm/sq
Maximum: 79.0 ohm/sq
Minimum: 69.3 ohm/sq
Uniformity: 2.62%

Wafer to Wafer Repeatability (Max-Min)/2Ave = ±0.68%
Oxide Thickness vs. Oxidation Time

$O_2=0.5$SLM, 760Torr
Typical Thin Dry Oxide Films

1000°C, 100s, 760Torr
O₂=0.3slm, N₂ = 2.7slm
Average = 2.9nm, Unif.= 0.67%

1000°C, 100s, 760Torr
O₂=0.5slm, N₂ = 0slm
Average = 5.3nm, Unif.= 0.91%
1000 Wafer Marathon Run

- Extremely Repeatable
  - Thickness: 0.8% (1σ)
  - Uniformity
Wafer Temperature Ramp Up Profile

- Time (s)
  - 0
  - 60
  - 120
  - 180
  - 240
  - 300

- Wafer Temperature (°C)
  - 0
  - 50
  - 100
  - 150
  - 200
  - 250
  - 300
  - 350
  - 400
  - 450

- Gas Types
  - He
  - Air

- Standoff Height: 8 mm

Diagram shows:
- Hot Plate
- Wafer
- Heater
- Standoffs
SOG Anneal Process Trends

Graphs showing trends of Ave. Thickness Shrinkage (%), Uniformity of Shrinkage (%), Refractive Index, and Uniformity Change (%) with respect to Temperature (°C) for different anneal times (1 min, 3 min, 5 min).
Particle Performance

<table>
<thead>
<tr>
<th>Run Number</th>
<th>No. of Particles Added</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Slot 1</td>
</tr>
<tr>
<td></td>
<td>Slot 2</td>
</tr>
<tr>
<td></td>
<td>Slot 3</td>
</tr>
<tr>
<td></td>
<td>Slot 4</td>
</tr>
<tr>
<td></td>
<td>Slot 5</td>
</tr>
</tbody>
</table>

>0.2µm
Stacked Annealing Oven (SAO-200LP)
for Cu, NiSi and low K Dielectrics Applications

Process Module
- Stacked Hot Plates

Load Port
- Triangular door

Optical Bench
- No adjustment

Vacuum Robot
- Extended z-axis travel

Cassette Stage
- Cooling stations

Vacuum Pump
- Integrated
Surface Response of Rs Reduction Ratio

Cu Anneal in Forming Gas

3 µm

5.5 µm
Cu Grain Growth by Annealing

200°C, 5 min
- Width = 5 um
- Spacing = 4 um

300°C, 5 min
- Width = 5 um
- Spacing = 4 um

400°C, 5 min
- Width = 5 um
- Spacing = 4 um

Cu Thickness = 3.0 µm
1 atm forming gas
NiSi Sheet Resistance Changes between Pre and Post-annealing

- Silicidation in SAO was obtained at temperatures from 350ºC to 550ºC with TiN uncapped samples on as well as capped samples.
- Increasing sheet resistance was observed above 600ºC, 650ºC was already too high to form stable NiSi.
Reflectance Properties of NiSi
After Formation at Various Temperatures

-Reflectance indicates film transformation confirmed by sheet resistance changes.

Showed lowered Rs
Surface Roughness - AFM Image

TiN/Ni(90A)/Si-sub

<table>
<thead>
<tr>
<th>SAO-Capped</th>
<th>200°C→450°C</th>
<th>250°C→450°C</th>
<th>450°C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rs = 8.0 Ω/sq.</td>
<td>Rs = 8.0 Ω/sq.</td>
<td>Rs = 8.7 Ω/sq.</td>
<td></td>
</tr>
<tr>
<td>Unif. = 4.59 %</td>
<td>Unif. = 4.66 %</td>
<td>Unif. = 5.01 %</td>
<td></td>
</tr>
<tr>
<td>Ra = 0.142 nm</td>
<td>Ra = 0.129 nm</td>
<td>Ra = 0.130 nm</td>
<td></td>
</tr>
<tr>
<td>Rz = 1.284 nm</td>
<td>Rz = 1.187 nm</td>
<td>Rz = 1.207 nm</td>
<td></td>
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</tbody>
</table>
Flash Anneal System Concept

• Motivation: USJ formation (Shallow implantation is a must!)
  – Maximum electrical activation
  – Least amount of diffusion

• Light Source: Short wavelength, high intensity light pulse
  – Xe arc lamp
  – Photon energy distribution

• Wafer Temperature: Mainly surface heating
  – Surface vs. Bulk
  – Time dependence
Spectral Emission of Lamps

![Graph showing spectral emission of lamps](image)

- Xe Arc Lamp
- Tungsten-halogen Lamp

- Wavelength (µm)
- Intensity (Arb. Units)
- Absorption Coefficient (α cm⁻¹)

- 3000°C
- 2500°C
- 2000°C
Illustration of Wafer Temperature Profile

- **Surface Temperature vs. Power**
  - Power variations shown with different thresholds (High, Medium, Low)
  - Flash event indicated

- **Bulk Temperature vs. Time**
  - Time progression indicated with $t_1 < t_2 < t_3$
  - Temperature changes at different times
  - Surface, Depth, and Backside temperature profiles compared

[Diagram images of thermal profiles and power events]
Implant Species: $^{49}\text{BF}_2^+$
Implant Energy: 3keV
Implant Dose: $1.0 \times 10^{15}\text{cm}^{-2}$
Surface Condition: 1.0~1.5nm
Chemical SiO$_2$
Amorphized Layer Thickness: ~10nm
USJ Implant Anneal

$^{11}\text{B}^+$, $^{49}\text{BF}_2^+$ Various Implant and Annealing Conditions

Sheet Resistance (Ohm/sq.)

Junction Depth $x_j$ (nm)

Carrier concentration (cm$^{-3}$)

- Crystalline
- Pre-amorphized
- Flash
- Combination

1.0x10$^{19}$
2.0x10$^{19}$
5.0x10$^{19}$
1.0x10$^{20}$
2.0x10$^{20}$
USJ Implant Anneal with Flash
$^{11}$B$^+$ 1keV $1 \times 10^{15}$ cm$^{-2}$

**Lamp Only (CW)**

- 2s, 2748.1 Ω/sq.
- 3s, 1167.6 Ω/sq.
- 4s, 787.2 Ω/sq.
- 5s, 263.3 Ω/sq.
- 6s, 176.1 Ω/sq.
- 7s, 174.1 Ω/sq.

**Hot Plate + Lamp**

- 800°C, 25s, 22906 Ω/sq.
- 1s CW, 1236.5 Ω/sq.
- 2s CW, 402.2 Ω/sq.
- + Flash, 1684.8 Ω/sq.
Summary

• Developed RTP technology based on natural characteristics of wafer
• Demonstrated equivalent processes for ion implant anneal as obtained with lamp based RTP
• System operation insensitive to emissivity characteristics of wafer and wafer surface
• Temperature operation over wide temperature range
• New FLASH technology for USJ demonstrated