Ni$_2$Si and NiSi Formation by Low Temperature Soak and Spike RTPs

Nov. 10, 2005
West Coast Junction Technology Group Meeting

Eun-Ha Kim$^1$, Hali Forstner$^2$, Majeed Foad$^2$, Norman Tam$^2$, Sundar Ramamurthy$^2$, Peter B. Griffin$^1$, James D. Plummer$^1$

$^1$ Stanford University, Stanford, CA
$^2$ Applied Materials, Sunnyvale, CA
Outline

- Background and Motivation
- Experimental Procedure
- Results
  - Soak RTP at 270 °C: Ni$_2$Si growth
  - Soak RTP at 300 °C: Ni$_2$Si-NiSi transformation
  - Spike RTP
- Effective Time Analysis
  - Comparative study for spike and soak anneals
- Summary and Conclusions
## Requirements in Self-aligned Silicide Process

**Silicide**
- Low sheet resistance

**Gate**

**Source**

**Drain**

- Low sheet resistance
- Low junction leakage
- Low contact resistance
- Compatibility with SiGe

### TiSi₂ (C54)

<table>
<thead>
<tr>
<th>RTP 1</th>
<th>RTP 2</th>
<th>NiSi</th>
</tr>
</thead>
<tbody>
<tr>
<td>600-800°C (C49)</td>
<td>700-900°C (C54)</td>
<td>250-350°C (Ni₂Si)</td>
</tr>
<tr>
<td>400-600°C (CoSi)</td>
<td>650-850°C (CoSi₂)</td>
<td>400-500°C (NiSi)</td>
</tr>
</tbody>
</table>

### Adv.
- Modest Si consumption
- Good thermal stability (~900°C)
- Good thermal stability (~1000°C)
- No line-width effect
- Lower Si consumption
- Miscibility with NiGe

### Disadv.
- Line-width dependence → scaling issues
- Gate to S/D silicide bridging
- Larger Si consumption not optimal for shallow junctions
- Low thermal stability (~600°C)
- Increased temperature sensitivity for formation
Challenges of Integrating NiSi

- **Thermal instability**
  - NiSi is stable only up to \( \sim 700 \, ^\circ\text{C} \)
  - Film agglomeration
  - Post-silicide processes will not exceed 450\(^\circ\text{C}\) for the back-end.

- **Defect formation**
  - Epitaxial NiSi\(_2\) formation
  - Careful surface preparation is needed

- **Excessive silicidation**
  - At narrow gates, source and drain regions
  - Accidental fully silicidation of gates
  - Need to Limit the silicide reaction at low temp

Source: A.S.W.Wong et al, APL, 81, 5138 (2002)
Source: V. Teodorescu et al, JAP, 91, 167 (2001)
Two-step RTP Process for NiSi

- Gate stack formation
- Ni/TiN dep
- RTP1 at <300°C
  - Ni-rich silicide

- Selective wet strip

- RTP2 at 400-500°C
  - Low resistance NiSi

2-step anneal process includes:
- RTP1: to control the nickel diffusion at lower temperatures (250~350°C)
- RTP2: to form low resistance NiSi at higher temperatures (400~500°C)
- Effective in preventing the excessive silicidation at the narrow gate/source/drain.

Source: J.P. Lu et al., IEDM 2002
Motivation for This Work

- RTP1 is crucial in limiting the Ni diffusion and the silicidation, since it occurs when the excess Ni is present.

- Low temperature regime of the reaction between Ni and Si needs better understanding.

- Low temperature spike RTP for NiSi process can provide advantages by further controlling thermal budget.
Outline

- Background and motivation
- Experimental procedure
- Results
- Effective time analysis
- Summary and Conclusions
Experimental Details

- Substrate: 8” Si (001) wafers
- Pre-clean: HF-last
- 10nm-Ni/10nm-TiN deposition:
  - Applied Endura ALPS Ni PVD
- RTP1 Silicidation:
  - Applied Centura RadiancePlus RTP
  - Soak anneal: 270, 300°C, 1~300 sec
  - Spike anneal: 300~400°C
- Strip TiN cap, unreacted Ni
- Analysis: Rs, XRD, XRR, TEM
Rs After Soak RTP at 270 and 300°C

- At 270 °C, Rs decreases, then saturates after 45 sec.
- At 300 °C, Rs drops after 60 sec, which is associated with the transformation into NiSi
XRD Spectra from the 270°C Samples

- The decrease in Rs is related to the growth of the Ni$_2$Si phase
Film Thickness: Ni$_2$Si Growth

- XRR was employed to measure the thickness of Ni$_2$Si.
- The Ni$_2$Si thickness is linear with the square root of the anneal time, which suggests that the growth is controlled by the Ni diffusion.
XRD Spectra from 300°C Samples

- The Ni$_2$Si-NiSi transformation is observed at 300°C with increasing the anneal time
- The (121) NiSi peaks decrease, in accordance with the decrease in Rs
- NiSi formation can be confirmed using GI-XRD
Preferred Texture During the Ni$_2$Si-NiSi Transformation

- The sequence includes the initial formation of NiSi and then changes in the alignment of NiSi (121) planes with respect to the Si (001) planes
- Small mismatch between the NiSi (121) and Si (110)
- The preferred texture of NiSi is related with the low resistance phase
Spike RTP: Temperature-time Profile

- Spike RTP anneals use faster rampings to the peak temperature with negligible soak.
- The thermal cycle time is reduced in the spike anneals.
Rs drops between 350 and 370°C, which is associated with the formation of the low resistance NiSi phase.

Compared with the soak RTP for 30 sec, the onset of the Rs decrease shifted to higher temperatures by ~40°C.
The Ni$_2$Si-NiSi transformation is observed from the spike samples with raising the peak temperature.

The spike anneals result in the same sequence in the Ni$_2$Si-NiSi transformation as the soak anneals at 300 °C.
TEM Images from the Series of Spike Samples

- Spike anneal at 310 °C → Mostly Ni$_2$Si
- Spike anneal at 340 °C → Ni$_2$Si and NiSi
- Spike anneal at 370 °C → Mostly NiSi with the thin Ni$_2$Si top layer
- This series of TEM pictures shows the progressive transformation from Ni$_2$Si to NiSi with increasing the peak temperature
Outline

- Background and motivation
- Experimental
- Results
- Effective time analysis
- Summary and Conclusions
Effective Time Approach

\[ t_{\text{eff}} = \int dt' \exp\left[E_a \left( \frac{1}{kT_{\text{ref}}} - \frac{1}{kT(t')} \right) \right] \]


- This provides with a method to convert an anneal with \( T(t) \) to an equivalent anneal at the constant temperature, \( T_{\text{ref}} \).

- To convert, we choose \( T_{\text{ref}} = 300 ^\circ \text{C} \) and \( E_a = 1.8 \text{ eV} \) for the silicide process.

- These two anneals show similar effective anneal time for the silicide reaction.
Spike RTP: Equivalent Anneal at 300°C

- Through the effective time calculation, the spike RTP anneals are compared with the soak RTP at 300 °C.
- For the two RTP schemes, Rs trends are identical with the effective time.
- The effective time is useful to compare anneals with different rampings and temperatures.
### Effective Time, $t_{\text{eff}}$ for Ni diffusion

<table>
<thead>
<tr>
<th>RTP Temperature</th>
<th>Dwell Time</th>
<th>$t_{\text{eff}}$ for silicide reaction ($E_a=1.8\text{eV}$)</th>
<th>$t_{\text{eff}}$ for Ni diffusion ($E_a=0.76\text{eV}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>270</td>
<td>200</td>
<td>~40</td>
<td>109</td>
</tr>
<tr>
<td>300</td>
<td>30</td>
<td>~40</td>
<td>51</td>
</tr>
<tr>
<td>340</td>
<td>0 (spike)</td>
<td>~40</td>
<td>28</td>
</tr>
</tbody>
</table>

- Three anneals are equivalent in terms of the silicide reaction
- The Ni diffusion is a source of silicide related defects and junction leakage currents
- The Ni diffusion can be minimized by using the spike RTP
Outline

- Background and motivation
- Experimental
- Results
- Effective time analysis
- Summary and Conclusions
Summary and Conclusions

- Low temperature reaction between Ni and Si has been investigated using soak and spike RTPs.
- Ni$_2$Si growth is observed at 270 °C with varying the anneal time.
- Ni$_2$Si -NiSi transformation occurs at 300 °C, and its sequence includes the initial formation of NiSi and the change in the alignment with respect to Si substrates.
- Spike RTP follows the parallel trend with soak RTP in terms of the Ni$_2$Si-NiSi transformation.
- With the consideration of lower activation energy for the Ni diffusion, the spike RTP scheme can be effective in preventing the defect formation and the Ni diffusion into the junctions.