High Frequency AC Electromigration Lifetime Measurements from a 32nm Test Chip

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Outline

• Motivation

• Proposed circuit based electromigration characterization technique

• AC and DC electromigration lifetime measurements from 32nm test chip

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Wire Failure due to Electromigration

- Abrupt failure
- Progressive failure

- EM lifetime affected by current density/direction, temperature, and possibly switching frequency

A.S. Oates, et al., TDMR, 2009
• Limitations of traditional probing method
  – Frequency (~5MHz) lower than actual chip clock freq.
  – Unable to generate realistic AC current
  – Large test area due to pads, long test time
Proposed Circuit based Approach

- Advantages of proposed circuit based approach
  - High operating frequency (~GHz)
  - Realistic AC current
  - Small test area due to shared pads, short test time
  - BTI and HCI effects in driver captured \( \rightarrow \) closer to reality

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32nm Test Chip Overview

Heater1  Heater2  Heater3

60 DUTs

Metal gate heaters

220µm

200µm

50nm

Metal gate heaters

350µm

Drivers & switches

Drivers & switches

4 terminal Kelvin measurement via shared pads

EN_A  IN_A

Driver A

EN_B  IN_B

Driver B

Load

EN_B

M1

M2

200µm

50nm
**EM Stress Modes Supported**

<table>
<thead>
<tr>
<th>Stress Mode</th>
<th>Current Waveform</th>
<th>Driver Operation</th>
</tr>
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<tbody>
<tr>
<td>DC</td>
<td><img src="image" alt="DC waveform" /></td>
<td><img src="image" alt="DC driver operation" /></td>
</tr>
<tr>
<td>Pulsed DC</td>
<td><img src="image" alt="Pulsed DC waveform" /></td>
<td><img src="image" alt="Pulsed DC driver operation" /></td>
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<tr>
<td>Square AC</td>
<td><img src="image" alt="Square AC waveform" /></td>
<td><img src="image" alt="Square AC driver operation" /></td>
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<tr>
<td>Real AC</td>
<td><img src="image" alt="Real AC waveform" /></td>
<td><img src="image" alt="Real AC driver operation" /></td>
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</tbody>
</table>

- Supports four different EM modes by configuring driver inputs
Local Metal Gate Heaters

- Local heaters can raise DUT temp. to >350ºC
- Stress temperature is set by adjusting heater voltage until target resistance is reached
More uniform temperature can be obtained using multiple heater voltages (e.g. 28V, 20V, 28V)
Automated EM Testing Flowchart

- Script program with automatic temperature control enables accurate and efficient data collection
32nm Test Chip Die Photo

- Process: 32nm HKMG
- # of DUT: 60
- Stress modes: DC, pulsed DC, square AC, real AC
- Stress current source: On-chip VCO and driver (>3GHz @ RT)
- Stress driver VDD: <1.5V
- Stress/measure temperature: 325/100 ºC
- Stress frequency: <900MHz @ 325ºC
- Heat source: Metal gate heaters
- Test approach: 4 terminal Kelvin measurement
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EM Lifetime under DC

- Results consistent with previously reported data
- Abrupt failure has smaller mean and larger variance
EM Lifetime under Pulsed DC

Possible reasons for ratio > 2:
- Lower $I_{\text{average}}$ $\rightarrow$ less Joule heating $\rightarrow$ lower temperature
- EM self-recovery during off periods
- BTI aging during off period reduces stress current
• Negligible resistance change under both square AC and real AC current from 200 to 900MHz
Alternative Testing Method: Two Phase Stress

- Apply AC stress first and then switch to DC stress*
- DC EM lifetime can reveal AC EM stress impact

* R. Shaviv, et al., IRPS, 2011
EM Lifetime under Square AC + DC

- No apparent difference between pure DC and square AC + DC
- Weak dependence on frequency
EM Lifetime under Real AC + DC

- Real AC pre-stress results in 64-83% longer DC EM lifetime
- Weak dependence on frequency
Possible Explanation for Longer EM Lifetime under Real AC

- Real AC stress may actually make wires more robust
- Additional time may be required for DC EM vacancies to nucleate and evolve
Another Explanation for Longer EM Lifetime under Real AC

- BTI in driver → lower stress current → longer DC EM lifetime
Summary

• EM lifetime measured up to 900MHz from a 32nm test chip
• Square AC did not change DC EM lifetime
• Real AC increased DC EM lifetime
  – Real AC could actually make wires more robust
  – Front end BTI aging may reduce EM stress current