An On-Chip Monitor for Statistically Significant Circuit Aging Characterization

John Keane$^{1,2}$, Wei Zhang$^1$, and Chris H. Kim$^1$

1. University of Minnesota, Minneapolis

2. Now with Intel Corporation, Hillsboro, OR
Outline of Presentation

• Circuit aging
• Motivation for on-chip aging sensors
• Silicon Odometer
• Comparison with alternative circuit methods
• Variation in transistor aging
• 65nm test circuit design & measured results
• Conclusions
Aging Impacts on Circuits

• Bias Temperature Instability (BTI)
  – SRAM SNM degrades; write stability can improve (if NBTI dominant)

• Hot Carrier Injection (HCl) & BTI
  – $F_{\text{MAX}}$ degrades
  – Critical path changes due to asymmetric stress conditions
  – Subthreshold leakage decreases

• Time Dependent Dielectric Breakdown
  – Increased $I_{GATE}$ leads to reduced o/p swing, SNM degradation, etc...
  – Device failure

R. Rodriguez, et al., IEDL, 2002

Breakdowns in different locations in SRAM cell
Motivation for Reliability Monitors

• Shrinking feature sizes, voltage margins

• Process changes improve one metric while perhaps leading to worse aging

• On-chip sensors characterize or trigger compensation schemes for aging mechanisms
  – High frequency shift measurement resolution
  – Fast measurements
  – Automated tests with simple interfaces
  – No expensive probing equipment
  – Test many devices in parallel
Silicon Odometer Beat Frequency Detection

- Two free running ROSCs for beat frequency detection
- Sample stressed ROSC output using reference ROSC
- Measure PC_OUT to determine freq. degradation
- Insensitive to environmental variation

Stressed ROSC (freq = $f_{\text{stress}}$)

Reference ROSC (freq = $f_{\text{ref}}$)

Phase Comp.

PC_OUT

($f_{PC} = f_{\text{ref}} - f_{\text{stress}}$)

Kim, et al., JSSC, 2008
Keane, et al., JSSC, 2010
Beat Frequency Detection

- Operation example:
  - 1% delay difference before stress → $N1 = 100$
  - 2% delay difference after stress → $N2 = 50$
  - $N2$ changes by 50 for 1% change in delay → sub-ps resolution $\Delta f$ measurements
## Comparison of On-Chip Aging Monitors

<table>
<thead>
<tr>
<th>System</th>
<th>1 ROSC T-Counter</th>
<th>2 ROSC T-Counter</th>
<th>Silicon Odometer</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Block Diagram</strong></td>
<td>Stress ROSC → Counter</td>
<td>Ref. ROSC → Counter = Constant N1, Stress ROSC → Counter = Variable N2</td>
<td>Ref. ROSC → Phase Comp. → Stress ROSC</td>
</tr>
<tr>
<td><strong>Benefits</strong></td>
<td>Compact</td>
<td>Simple, Differential</td>
<td>High resolution, Short measurements, Differential</td>
</tr>
<tr>
<td><strong>Issues</strong></td>
<td>External timing reference. Sensitive to temporal variations</td>
<td>Measurement time vs. resolution tradeoff</td>
<td>Resolution degrades with larger shifts</td>
</tr>
<tr>
<td><strong>Meas. time for 0.01% resolution</strong></td>
<td>30 µs</td>
<td>30 µs</td>
<td>0.3 µs</td>
</tr>
<tr>
<td><strong>Meas. error (simulation)</strong></td>
<td>+10.18% / -8.57%</td>
<td>+0.26% / -0.38%</td>
<td>+0.06% / -0.07%</td>
</tr>
</tbody>
</table>

* Theoretical lower limit with ROSC period = 3ns, 65nm technology

** +/- 50mV ΔVCC; 0.4% Δf stress shift; 340ns measurement time
Variability in Transistor Aging

Spread in $\Delta V_{TH}$ increases w/ scaling
S. Pae, et al., TDMR 2008

$\Delta I_{ds}$ variation under NBTI stress
H. Yoshimoto, et al., IRPS 2010

- Finite number and random spatial distribution of discrete charges $\rightarrow$ NBTI & HCl variation
- Inversely proportional to $A_{GATE} \rightarrow$ worse with scaling
- Small number of aging measurements not sufficient to characterize aging
Multiple Odometer System Setup

- Need stressed & reference ROSC frequencies to be close
- Difficult, costly to tune each stressed ROSC
- Use multiple Ref. ROSCs with different frequencies
- Cover the frequency distribution of the stressed array
Reference ROSC Trimming

- **Left:** Fresh full loop frequency distribution for 80 cell array with reference ROSC trimming range

- **Right:** Results from 3 Odometers for 1 ROSC under test
  - Low resolution obvious with an initial count of 41
• Only a section of each ROSC is stressed
• Other control devices are 2.5V thick oxide
• First measure the period of the ctrl loop
• During full loop measurement, cancel out this portion
**Statistical Odometer 65nm Test Chip**

- Measured with LabVIEW & NI DAQ board
- Each reading triggered with a single pulse from tester
- ROSC put back into stress mode before results scan out

### Specifications

<table>
<thead>
<tr>
<th>Process</th>
<th>65nm LP CMOS, 7M</th>
</tr>
</thead>
<tbody>
<tr>
<td>Logic / I/O supplies</td>
<td>1.2V / 2.5V</td>
</tr>
<tr>
<td>Active Area</td>
<td>~257x475μm²</td>
</tr>
<tr>
<td>Total Area</td>
<td>369x493μm²</td>
</tr>
<tr>
<td>Odom. Δf Error Floor</td>
<td>0.07%</td>
</tr>
<tr>
<td>Measure Interrupt</td>
<td>≥1μs</td>
</tr>
<tr>
<td>DUT dimensions</td>
<td>P: 300/60nm</td>
</tr>
<tr>
<td></td>
<td>N: 200/60nm</td>
</tr>
<tr>
<td>σ/μ</td>
<td>1.32% - 1.78%</td>
</tr>
</tbody>
</table>
Si. Odom Measurement Error

- Find the error floor with no-stress experiments
- Typical single-ended ROSC readings on a scope vary with temperature/voltage
- Differential odometer readings cancel common-mode variations, even with fast measurements
- Longer stress interrupt for measurements result in more unwanted recovery
- Recovery is a larger portion of total experiment time at early points
  - Pulls them down $\rightarrow$ steeper slope (i.e., larger $n$)
DC Stress-Induced PDF Shifts

- Fresh and post-stress ROSC frequency PDFs
- No noticeable change in the $\sigma$ of the frequency itself
- Will see that $\sigma$ of the frequency shift increases, though
No significant correlation of the frequency shift with fresh frequency

μ and σ of Δf increase w/ power law behavior
**Frequency Distribution Fit**

- Rauch found that the lognormal overestimated the high tails of his measured $V_{TH}$ shifts (TDMR 2007)
- Our $\Delta f$ measurements fit the lognormal
  - Fischer also found higher tail shift than Rauch (ESSDERC 2010)
Measured AC Stress Results

- Early stress AC results show lower $\Delta f$ than DC due to BTI recovery
- Higher frequency stress results in a significant HCI component that dominates after some time
  - HCI less significant at lower voltage though
Conclusions

• We implemented an efficient statistical ROSC aging measurement system

• 65nm circuit measures $\Delta f$ with an error of $\leq 0.07\%$, and stress interruptions of down to 1$\mu$s

• Fresh frequency and the AC or DC stress-induced $\Delta f$ are uncorrelated

• Both $\mu$ and $\sigma$ of $\Delta f$ increase with stress, and the ratio of $[\sigma(\Delta f) / \mu(\Delta f)]$ decreases with stress time

• Circuits like this can provide valuable reliability learning and aid in areas such as modeling vs. silicon data correlation