On-Chip Silicon Odometers and their Potential Use in Medical Electronics

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Purpose

• Shrinking feature sizes and voltage margins, along with quickly evolving process architecture
  – Designs are susceptible to aging

• Expensive to characterize all aging mechanisms
  – Major consideration in fields such as aerospace and medical

• On-chip sensors characterize or trigger compensation schemes for aging mechanisms
  – High frequency shift & timing resolution
  – Automated tests with simple interfaces
  – Test many devices in parallel
  – No expensive probing equipment
Outline

• Introduction to Circuit Aging
• Overview of Aging Measurement Circuits
• Relevance to Medical Electronics
• Beat Frequency Silicon Odometer
  – Separating BTI and HCI
  – Statistical Odometer
• Array-based TDDB Measurement System
• Summary
Combined Stress in Digital Circuits

**NOTE:** Voltage applied across dielectric ➤ TDBB
Aging Measurement Circuits

- Digital systems for characterization
  - ROSC edge capture (*ISSCC ’10*)
  - Critical path replica ROSC (*VLSI Symp’10*)
  - Starved ROSCs (*ISSCC ‘08 and ‘10*)

- Transistor arrays
  - Smart NBTI array (*IEDM ’11*)

Saneyoshi, et al., *ISSCC ’10*

Hofmann, et al., *VLSI Symp ’10*
Silicon Odometers in Medical Electronics

• Want higher performance and smaller form factors...but reliability is paramount
  – 10+ year lifetime requirements

• Require efficient methods to characterize reliability mechanisms

• Focused on low power and analog space
  – Soft gate breakdown leads to increased power consumption
  – $V_{th}$ shift due to NBTI impacts sensing circuits

• Require precise measurements at low-stress conditions

• High volume to observe distribution tails
Beat Frequency Silicon Odometer

Digital Silicon Odometer Outputs

- With the reference ROSC faster than stressed ROSC, count decreases with stress
- Resolution is highest early in stress
  - Use trimming caps to make $f_{\text{ref}}$ and $f_{\text{stress}}$ close
Odometer Measurement Error

- Measured no-stress (i.e., 0V) characteristics
- Singled ended ROSC varies with environmental conditions
- Differential odometer more immune to variations, and takes fast measurements
The diagram illustrates the operation of the HCI + BTI Silicon Odometer in two modes: Stress Mode and Measurement Mode.

**Stress Mode** (ROSC loops opened)
- BTI_ROSC gated off from supply
- DRIVE_ROSC drives transitions; I/P driven by VCO

**Measurement Mode** (ROSC loops closed)
- Both ROSCs connected to the power supply @ VCC
- Switches between them are opened
Measurement Interface

- All measurements done with LabVIEW & National Instruments data acquisition board
- Each reading triggered with a single pulse from tester
- Low speed digital interface
  - Internal circuits used to minimize BTI recovery time
HCl & BTI Measured Results

- HCl slightly reduced with higher temperature
  - Reduced drain current
- Both mechanisms degrade with stress voltage
  - Point when HCl begins to dominate pushed out in time by >1 order of magnitude at 1.8V vs. 2.4V
Statistical ROSC Aging Odometer

- 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
Stressed ROSC Design

- 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
Measured DC Stress Results

- No significant correlation of the frequency shift with fresh frequency
- \( \mu \) and \( \sigma \) of \( \Delta f \) increase with power law behavior
Automated TDDB Characterization Array

- Gate currents measured with A/D current monitor and on-chip control logic
- 16b results scanned out after each measurement
Array-based design allows us to extract Weibull slope factors with a single stress test

Convenient method to investigate spatial correlation

20x20 Spatial Plot (4.2V)

Positive Correlation

Negative Correlation

30°C

3.8V through 4.3V stress

TBD or TFAIL (ln(a.u.))

ln(-ln(1-CDF))
Summary

- On-chip monitors facilitate:
  - High frequency measurement resolution (< 0.1% with the Silicon Odometer)
  - High timing resolution (sub-μs measurements)
  - Simple, automated measurements
  - Parallel stressing for shortened experiment times

- Data can be used to create/validate models

- Concepts could be extended in to in-situ space, enabling real time system adjustments

- Valuable part of medical technology reliability engineer’s toolkit