Reliability Implications of Bias Temperature Instability in Digital ICs

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Source:
Reliability Implications of Bias Temperature Instability in Digital ICs,
IEEE Design & Test of Computers, Nov/Dec 2009,
Sang Phill Park, Kaushik Roy, Kunhyuk Kang
Agenda

- Introduction
- NBTI mechanism
- NBTI in random logic circuits
- NBTI in 6T SRAM cell
- Reliability-aware circuit design
- Conclusion
Introduction

- SUCCESSFUL DESIGN of Digital ICs
  - Silicon area, speed, testability, design effort, and power dissipation.
- Is the physical and electrical properties of a transistor deterministic and hence predictable over its life time?
- Negative Bias Temperature Instability (NBTI)
  - Negative bias, high temperature, time.
  - PMOS specific transistor aging effect.
  - PMOS biased in inversion.
  - Holes near Si/SiO$_2$ interface.
Is NBTI a major reliability concern?

- Major reliability challenge in nanoscale CMOS technology.
  - Scaling - ultrathin oxide devices and increased electric field.
  - Increased chip operating temperature.
- Results in threshold voltage increase.
- Degrades mobility, drain current, transconductance.
- Introduce extra delay in circuit over its life time.
  - Circuit/system may fail to meet its timing specifications.
  - Max frequency of operation reduces.
  - Reduced life time.
  - Introduce safety concerns in a critical embedded system.
Some NBTI facts ..

- Not yet fully understood!
- 25-30% increase in $V_{TH}$ over 10 years.
- Wide variation depending on specific topology and operating condition.
- Delay between the release of stress and measurement is very important.
NBTI Mechanism

- Reaction diffusion (RD) model.
- Combined effect of electric field, temperature and holes.
- Interaction of inversion layer holes with hydrogen-passivated Si atoms.

\[ Si_3 \equiv SiH \]

- Breaking of Si-H bonds at the SiO\(_2\)/Si substrate.
Reaction Diffusion model

- Holes from the inversion layer under sufficient temperature can break Si-H bonds.
  - Results in dangling bonds or interface traps.
- The H\textsubscript{2} diffuses away from the interface into the oxide or poly-Si gate.
- H\textsubscript{2} diffuse back to the interface when the stress voltage is removed.

\[
\text{Si}_3 \equiv \text{SiH} + H^+ \leftrightarrow \text{Si}_3 \equiv \text{Si} \bullet + H_2
\]
RD based $V_{TH}$ model

- Interface traps increase the device $V_{TH}$.

$$
\Delta V_{TH} \approx \frac{q \cdot N_{it}(t)}{C_{ox}} \\
\approx f_{AC}(S_p) \cdot K_{DC} \cdot t^n
$$

- $N_{it}$ is the density of interfacial traps
- $K_{DC}$ is a technology, VDD, device geometry, oxide nitrogen concentration and temperature dependent constant.
- $S_p$ is signal probability, represents the fraction of time when input is high.
Impact of DC and AC stress on $V_{TH}$

- **DC stress**
  - Power law, $\Delta V_{TH} \sim t^n$
  - On-the-fly measurements: $n \sim 1/6$.
  - Measurements with delay: $n \sim 1/4$.

- **AC stress**
  - Stress phase and Recovery phase.
  - $n \sim 1/6$
  - Degradation scaled by a signal probability dependent function.
NBTI degradation under AC and DC stress

Stress: $V_{gs} = -V_{dd}$
Increase in $N_{it}$ and $V_{TH}$

Recovery: $V_{gs} = 0$
Decrease in $N_{it}$ and $V_{TH}$
NBTI in random logic circuits

- Delay degradation.
- Increased $V_{TH}$ reduces drive current and thus increases individual gate delays.
- In a timing path with rising and falling transitions, the impact of NBTI is less.
6T SRAM cell

- Bit stored in cross coupled inverters.
- Two stable states - 0 and 1.
- In standby, cross coupled inverters reinforce each other.
- Two access transistors.
- Read and write can be done by proper assertion of BL and WL.
  - BL – Bit Line
  - BL_B – not (Bit Line)
  - WL – Word Line

Source: http://www.iue.tuwien.ac.at/phd/entner/node34.html
NBTI in 6T SRAM cell

- Degradation to PMOS.
- Local mismatch among Transistors can lead to failures.
- NBTI degradation can severely damage SRAM read stability.
- Static Noise Margin (SNM) of an SRAM cell decreases.
- Read failure probability increases.
Statistical variation in NBTI

- Transistor mismatch originates from random dopant fluctuation (RDF) as $V_{TH}$ variation.
- NBTI combined with random process variation has greater effect.
- With aggressive scaling of device dimensions, breaking and repassivation of Si-H bonds in the channel experience stochastic fluctuations.

\[ \sigma_{V_{TH}} = \sqrt{\sigma_{\text{RDF}}^2 + \sigma_{\text{NBTI}}^2(t)} \]

- $\sigma_{V_{TH}}$ is the total $V_{TH}$ variation after time $t$.

Degradation Increases

RDF Only RDF & NBTI shift RDF & statistical NBTI
Reliability aware Circuit Design

- Delay guard banding.
- Sizing technique
  - WC sizing method. (Worst case)
  - Optimal sizing – Less area over head.
- Synthesis
  - Worst case NBTI synthesis.
  - Signal probability based synthesis (SP).
- Stand-by VDD scaling – depends on standby time of memory.
- On chip sensors – Area and power over head.
Conclusion

- Successful IC design is a complicated optimization problem and transistor reliability could be an even more severe problem in future technology nodes.
- With Hf based promising high-k dielectrics, PBTI also comes out as a major reliability challenge apart from NBTI and other reliability concerns like Hot Carrier Injection.
- Reliability-aware design of digital circuits and memories is essential for future nanotechnologies to ensure robust and stable products.