Defect–Oriented Degradations in Recent VLSIs:
Random Telegraph Noise, Bias Temperature Instability and Total Ionizing Dose

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Agenda

- Introduction
- RTN: Random Telegraph Noise
- BTI: Bias Temperature Instability
- TID: Total Ionizing Dose
- Summary
Our daily-life highly depends on embedded systems

Big problems when failures happen

- 2 million affected
  - Dec. 2007
  - Trouble on a train system

- 50 planes stopped
  - Jan 2013
  - Trouble on 787 airplane
Reliability Issues in VLSIs

Bathtub Curve
- Infant Mortality failure
- Wear out failure
- Temporal failure

Wear Out (BTI)
- $V_{gs}$
- $V_{ds}$

Temporal (SEE)
- Thermal neutron
- Alpha particle
- High-energy neutron

Infant Mortality
- Voids or Gates
- LER

Error Probability

Kobayashi Lab.
Three Topics Related to Defects

- **Bias-induced Temporal Fluctuation**
  - RTN
    - Random Telegraph (Signal) Noise

- **Stress-induced Aging Degradation**
  - BTI
    - Bias Temperature Instability

- **Radiation-induced Aging Degradation**
  - TID
    - Total Ionizing Dose
Aggressive scaling worsens reliability
Traps (Defects) in Gate Oxide

Silicon Hydrogen Oxygen Hole Oxide Trap/ E’ Center Interface Trap/ Pb Center
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- Charged carriers are captured (trapped) or emitted (detrapped) in oxide traps.
- $V_{th}$ (transistor current) fluctuates temporarily.
- $\tau_e$: time to emission, $\tau_c$: time to capture
- Serious in CCD (Charge Coupled Device)
RTN–induced Drain Current Fluctuation

- Time constant $(\tau_c, \tau_e)$ of RTN strongly depends on gate bias.

\[ V_{gs} = 0.4 \text{ V} \]

\[ V_{gs} = 0.5 \text{ V} \]

\[ V_{gs} = 0.6 \text{ V} \]

\[ V_{gs} = 0.7 \text{ V} \]

\[ V_{gs} = 0.8 \text{ V} \]

\[ V_{gs} = 1.2 \text{ V} \]
Process Variations vs RTN in Scaled Devices

- Large MOSFET: WID variation dominates
- Small MOSFET: RTN can dominate at some realistic $\sigma$ value

$$\Delta V_{thPV} \propto \frac{1}{\sqrt{LW}}$$

$$\Delta V_{thRTN} \propto \frac{1}{LW}$$

Normal distribution for PV
Long-tail distribution for RTN
Introduction
RTN: Random Telegraph Noise
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Summary
NBTI on PMOS and PBTI on NMOS

- Aging degradation by continuous stress

PMOS

NBTI

Negative Bias

VSS

VDD

After 65nm process
SiON gate dielectric

NMOS

PBTI

Positive Bias

VDD

VSS

After 40nm process
Hi-k gate dielectric
BTI (Bias Temperature Instability)

Vth (Threshold Voltage)

0

Stress

Relaxation

Time

Recoverable Component

Permanent Component
Two Models of BTI

- **Reaction Diffusion Model** [Alam, IEDM03]
  - Carriers are trapped by dangling bond (interface trap)

- **Atomistic Trap-based Model** [Kaczer, IRPS10]
  - Carriers are trapped/detrapped in oxide trap (same as RTN)
  - RTN: $\tau_c \approx \tau_e$  
    Carriers repeats capture and emission
  - BTI: $\tau_c \ll \tau_e$  
    Captured carriers are never emitted
BTI Degradation Models

- **Reaction Diffusion Model**
  \[ \Delta V_{TH} \propto t^n \]
  
  - $n=1/4$: atomic H diffusion
  - $n=1/6$: $H_2$ diffusion

- **Atomistic Trap-based Model**
  \[ \Delta V_{TH} \propto \log t \]
Measurement Results

- Stress measurement by Ring Oscillator (RO)
  - Frequency degradation follows log(t)?

VDD 2.0V, Temperature 80°C
Fitting by Two Models

- $\log t$

- $t^n$

Average Error

- 0.53%

- 0.02%

Short-time measurement data matches both models
Long-term Prediction

- $\log t$
- $t^n$

After $10^8$ seconds (3 years), log fitting has a few % degradation, while $t^n$ fitting has 20% degradation.
RTN and BTI

- Large device: smooth degradation by many traps.
- Small device: discrete degradation by several traps.

BTI is caused by oxide traps, not by interface traps.

[IEDM14, 34-6]
RD Model or Trap-based Model

- Hot discussions in IRPS over decades
- Recently, Trap-based model has more supporters
  - How H is diffused back to interface trap on recovery?
  - In RD model recovery depends on stress/relaxation time only
    \[
    \frac{\Delta V_{th}(t_s)}{\Delta V_{th}(t_r)} = \frac{1}{1 + (t_r/t_s)^{1/2}}
    \]

Recovery on RD model

Measurement data on recovery. Dots are measurement data. Lines are predicted by RD model. [Grasser, Trans. ED 2011]
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Radiation Effects in Outer Space

Single events

Displacement damage

Ionising dose

Ions

Cosmic rays

Ions

Solar flares

Protons

Radiation belts

Protons

Electrons
Performance degradation on MOS transistors by protons and electrons

- Thicker field oxide is damaged more than thin gate oxide
- Leakage path between drain and source by charge in field oxide (NMOS only)
- Vth shift like BTI (PMOS dominant)

[Ratti, Ionizing Radiation Effects in Electronic Devices and Circuits]
Both degradations are caused by traps in oxide or interface

- Thicker field oxide is dominant in TID, while thin gate oxide is dominant in BTI
  - No bias in field oxide (No BTI)
  - Thicker oxide is damaged more than thinner oxide by TID

No confirmed theory is established

- Interface traps vs Oxide traps
- How hydrogen is related to degradation
- Still in debates
Reliability issues are hot topics in highly-scaled CMOS circuits

Introduce RTN and BTI in terms of defects (traps)
- Oxide traps and interface traps

RTN is temporal fluctuation of Tr. performance

BTI is permanent (continuous) degradation of Tr. performance. When stress is released, relaxation (recover) starts

TID is also related to defects
- TID is dominant in thicker field oxide
- BTI is dominant in thinner gate oxide

Still in debates about the correct theory
Acknowledgement

- Our lab. members of long-term degradation group
  - Dr. Yabuuchi, Mr. Kishida, Ms. Oshima

- Prof. Takashi Matsumoto of Univ. of Tokyo

- VDEC, RCNP, Renesas Electronics, Synopsys, Cadence & Mentor Graphics for measurement, chip fabrication & EDA tools