Non Volatile Memories
Compact Models
for Variability Evaluation

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Outline

• Reasons to address variability aspects
• Physics based compact models:
  – Charge based
  – Phase change based
• Further effects and model updates
  – Overall concepts
  – Examples
• Applications
  – Flash cell applications
  – Phase Change cell applications
• Perspectives
Reasons to address variability in Memories

• To predict “window budgets”
  – To start the design of sensing circuits
  – To define the ‘correction’ algorithms

• To optimize technology
  – Ranking the sources of variability

• To optimize design algorithms in terms of time/accuracy trade-offs
  – Writing/reading/erasing/verifying
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Non Volatile Memory Compact Models

• Physically based models
  – easier implementation of variability effects
  – correlation directly implemented (e.g. threshold/tox)
  – more accurate extrapolations
  – not easy model implementation
  – model sometimes not completely understood

• Computationally efficient models
  – to allow variability analysis (large number of simulations)
  – coupled with more accurate models - typical of TCAD domain - to maintain physical soundness
Non Volatile Memory Models: Flash cell

- Model developed with “Universita` di Modena e Reggio Emilia” (L. Larcher, P. Pavan)
  - Better description of capacitive couplings: for different operations - Write, Read, Erase - and for the different cells’ writing status.
  - Exploitation of models developed for MOS transistors including their extraction procedures
PCM Working Principle  1/2

- PCM material is the Ge$_x$Sb$_y$Te$_z$ (GST) alloy:

Polycrystalline  Amorphous

Reversible Phase Change

High conductivity  Low conductivity

SET  RESET
PCM Working Principle

PCM cell sketch and symbol

ELECTRICAL pulses

RESET

\[ T_{\text{melt}} \]

\[ t_{\text{QUENCH}} < 10 \text{ ns} \]

SET

\[ T_x \]

\[ t_{\text{QUENCH}} > 100 \text{ ns} \]
The electro-thermal model

ELECTRICAL network

V·I

\[ \begin{align*}
V & \rightarrow R_{GST}(T) \rightarrow I \\
I & \rightarrow R_{HEATER}(T) \rightarrow V \cdot I
\end{align*} \]

THERMAL network

V·I

\[ \begin{align*}
V & \rightarrow + \\
R_{th} & \rightarrow C_{th} \rightarrow T
\end{align*} \]

Room Temperature
SET I-V: Measure and Simulation

![Graph showing measure (pulsed I-V), simulated I-V, and simulated temperature vs. V_PCM and Temperature.](image)

- Measure (pulsed I-V)
- Simulated I-V
- Simulated Temperature

**T_{melt}**

**Temperature [°C]**

**V_PCM [V]**

**I_PCM [μA]**
Geometrical dependence

\[ dR_{GST} = \rho_{GST} \frac{dx}{W(L + 2x \tan \alpha)} \]

\[ R_{GST} = \int_{0}^{t_{GST}} dR = \frac{\rho_{GST}}{2W} \ln\left(1 + \frac{2t_{GST}}{L}\right) \]

\[ R_{HEATER} = \rho_{HEATER} \frac{t_{HEATER}}{WL} \]
Non Volatile Memory Models: PCM

- The full model describes:
  - read
  - set switch
  - reset switch
  - designed to describe partial set
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Variability aspects

• The presented basic models seem a good starting point for the mentioned variability analysis, as relatively accurate and at the same physically based and sound

• Not all the effects are captured: TCAD or more detailed inputs are required to improve such models:

• Some examples…. 
1. FLASH  Discrete nature of charge: sub-poissionsonian-injection statistics

\[ \sigma_{\Delta V_T} = \sqrt{\frac{q}{C_{pp}} \cdot \Delta V_T} \]

\[ \sigma_{\Delta V_T} = \sqrt{\frac{q}{\gamma \cdot C_{pp}} \cdot (1 - e^{-\gamma \cdot \Delta V_T})} \]
2. FLASH

GIANT RTS

Current [µA]

Control Gate Bias [V]

0.0 0.2 0.4 0.6 0.8

0.0 0.2 0.4 0.6

Time [sec.]
2. FLASH  RTS - Doping Dependence

- Doping increase → larger inhomogeneous conduction due to:
  - stronger confinement at the interface
  - more discrete dopants near interface → larger percolation effect
2. **FLASH: RTS - Geometry Dependence**

- Steeper dependence on $W$ than $L$
- $W$ and $L$ independent
2. FLASH: RTS - $\Delta V_T$ Sensitivity Analysis

Single trap $\Delta V_T^{st}$

+ Trap Dens. $N_T$

Switch time $\tau_e, \tau_c$

Experimental $\Delta V_T$

- Increasing $N_T$, RTS distribution rigidly shifts upward
- Increasing $\sigma$, RTS distribution widens
- $\sigma$ key element to assess RTS reliability implications
3. PCM: Drift - Poole/Poole-Frenkel model

\[ \Delta U_{P/PF} = \left( \frac{1}{\Delta U_P} + \frac{1}{\Delta U_{PF}} \right)^{-1} \]

\[ \Delta U_{P/PF} = q \frac{K_P \cdot K_{PF} \cdot V_A}{K_P \sqrt{V_A} + K_{PF}} \]

\[ I_{P/PF} = 2qAN_T \frac{dz}{\tau_0} e^{-\left( \frac{E_A}{kT} \right)} \sinh \left( \frac{q}{kT} \frac{K_P K_{PF} V_A}{K_P \sqrt{V_A} + K_{PF}} \right) \]

Ref: Ielmini, Zhang JAP102, 2007
3. PCM: Drift - Pre-drift and Post-drift

Tech. & Physical parameters

\[ A, dz, E_A, u_a, N_T, \varepsilon_{GST}, \nu \ldots \]

Drift law

\[ R(t) = R(t_0) \left( \frac{t}{t_0} \right)^\nu \]

Graphs showing pre-bake and post-bake conditions.
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NAND Array statistical modeling

IRPS 2010
RESET current distribution

Tech. & Physical parameters

\[ A, dz, E_A, u_a, \tau_0, N_T, \varepsilon_{GST}, \ldots \]

\[ \text{P/PF - model} \quad \Rightarrow \quad \text{Statistical sim.} \]
Technological spreads

\[ \Delta t_{GST} \]

\[ \Delta t_{HEATER} \]

\[ \Delta \rho_{GST} \]

\[ \Delta \rho_{HEATER} \]

Dimensional spreads

\[ \Delta W \]

\[ \Delta L \]
Monte Carlo simulation with only technological spreads is not able to reproduce the experimental SET distribution!
Simulation with BJT selector

- A tighter distribution is obtained by including the BJT selector
  - Better matching of the Gaussian right-side
- But the exponential tail is still unmatched
Spice model

• Exponential tail can be taken into account in Spice model by weighting the full crystallized GST resistance $R_{GST}$ with a logarithmic function:

$$R_{\text{Partial-SET}} \sim R_{GST} \cdot (- \log(\alpha))$$

with

$\alpha = \text{uniform}[0:1]$

✓ In this way the Gaussian technological spreads are combined with the exponential distribution of percolation mechanism
Finite-Element model

- 2-D FE model composed of rectangular GST sub-domains is implemented in order to mimic a partial SET
Complete Spice simulation

- A very satisfactory agreement is obtained between measure and MC simulation
Conclusions and perspectives

- Variability models have been used for:
  - Window budget evaluations
  - Identification of main process steps contributions to distribution width
- Physical models show the advantage of an easier implementation of variability effects
- Various contributions have to be exploited for variability effects evaluation (TCAD, ad hoc characterization)
- Continuously define the trade-offs between accuracy / “physic based models” and speed / model understanding and implementation
- Variability models could be used for algorithms optimization (read / write / verify / read): need to evaluate possible showstoppers.
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References (not complete)
