Flash Memory Cell Compact Modeling Using PSP Model

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Outline

- Motivation
- Background
- PSP-Based Flash cell model
- Characterization procedure
- Simulations
- Conclusions
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Semiconductor memories classification

- Volatile Memories
  - DRAM
  - SRAM

- Non-Volatile Memories
  - Programmable
    - EPROM
  - Permanent Storage
    - EEPROM
    - Flash
    - ROM
Motivation 2/4

Semiconductor memories market

1996
- Total: $36 billion
- Flash → 7%

2000
- Total: $49 billion
- Flash → 21%

2006
- Total: $61 billion
- Flash → 36%
Motivation 3/4

Flash memory cell applications

- Memory cards
- USB flash drives
- Handheld computers
- Digital audio players
- Digital still cameras
- Digital video cameras
- Cellular phones
- Game consoles
Motivation 4/4

Flash memory cell for designers

- To integrate circuit simulators and to perform multi-cell simulations:
  > compact modeling approach
  > adapted and flexible language (Verilog-A)

- To include physical effects appropriate for small component:
  > based on an advanced description (PSP MOS model)

- Accurate electrical behavior for modern technologies:
  > complete characterization procedure
- Motivation
- **Background**
- PSP-Based Flash cell model
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- Conclusions
Flash Memory Cell:
Capacitive structure and injection currents

- Control Gate polySi
- Oxide
- Floating Gate polySi
- Oxide

Source N+
Bulk P
Drain N+
Background 1/4

Flash Memory Cell:
Capacitive structure and injection currents

![Diagram of Flash Memory Cell]

- Control Gate polySi
- Floating Gate polySi
- Source N+
- Bulk P
- Drain N+
- $C_{PP}$
- $C_{OX}$
Background 1/4

Flash Memory Cell:
Capacitive structure and injection currents

![Flash Memory Cell Diagram]
Erased and Programmed modes:

\[ V_T = V_{T_{UV}} - \frac{Q_{FG}}{C_{PP}} \]

\[ V_{READ} \]

\[ \Delta V_t \]

\[ \text{Id}(\llbracket 1 \rrbracket) \]

\[ \text{Id}(\llbracket 0 \rrbracket) \]
Injection Currents : Fowler-Nordheim tunneling

$\begin{align*}
I_{FN} &= \alpha \cdot S \cdot E_{TUN}^2 \cdot e^{-\frac{\beta}{E_{TUN}}} \\
FN &= \text{Fowler-Nordheim tunneling}
\end{align*}$
Injection Currents: Channel Hot Electron current

Negative charge injection into floating gate

\[ I_{CHE} = A_D \cdot I_{AVL} \cdot e^{\frac{-A_D \exp}{E_{TUND}}} \]
Motivation

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PSP-Based Flash cell model

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PSP-based Flash cell model 1/4

The PSP MOS model

- Developed by Philips Research and Penn State University. (first version 2006)

- Compact surface-potential based model.

- Relevant physical effects (mobility reduction, velocity saturation, DIBL, GIDL...)

- Source/Drain junctions are described using the JUNCAP2 diode model.

- Possibility of including temperature and geometrical scaling rules.
PSP-based Flash cell model 1/4

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PSP-based Flash cell model 2/4

Addition of the $C_{PP}$ capacitor using a charge neutrality equation

$Q_{FG} = Q_{GI} + Q_{GS} + Q_{GD} + C_{PP}(V_{FG} - V_{CG})$

- $Q_{GI}$, $Q_{GS}$ and $Q_{GD}$ values are calculated by PSP model.
- They depend on $V_{FG}$, $V_{B}$, $V_{S}$ and $V_{D}$ (Equivalent MOS electrodes).

Implicit computation of $V_{FG}$
PSP-based Flash cell model 3/4
Addition of the injection currents

- From surface potentials, vertical electric fields through tunnel oxide can be computed

Fowler-Nordheim current

\[ I_{FN} = \alpha S E_{TUN}^2 e^{-\beta E_{TUN}} \]
PSP-based Flash cell model 3/4
Addition of the injection currents

- From surface potentials, vertical electric fields through tunnel oxide can be computed

Channel Hot Electron current

\[ I_{CHE} = A_D I_{AVL} e^{E_{TUND}} \]
PSP-based Flash cell model 4/4

Computation scheme

- Static relation
  \[ Q_{FG} = Q_{GI} + Q_{GS} + Q_{GD} + C_{PP} (V_{FG} - V_{CG}) \]

- Dynamic relation
  \[ Q_{FG} = Q_{FG0} + \int (I_{FN} + I_{CHE}) \, dt \]
PSP-based Flash cell model 4/4

Computation scheme

- **Static relation**
  \[ Q_{FG} = Q_{GI} + Q_{GS} + Q_{GD} + C_{PP}(V_{FG} - V_{CG}) \]

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PSP-based Flash cell model 4/4

Computation scheme

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Characterization procedure 1/4

Characterization procedure diagram

- PSP model card extraction on dummy cell (optionally including thermal and geometrical scaling effects)
- Hot carriers injection calibration on dummy cell
  Using $I_g@V_g$ and $I_b@V_g$ characteristics
- Fowler-Nordheim tunneling on a tunnel capacitor
- Inter-polysilicium capacitor characterization
- Checking of the programming window and fine tuning
Characterization procedure 2/4
PSP model card extraction using a dummy cell
Characterization procedure 3/4

Injection current calibration
Characterization procedure 4/4

Fine tuning on real cell characteristics
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Simulations 1/2

Dynamic reliability (example)

- $V_T$ evolutions are compared with a standard programming polarization.
- $V_T$ error after programming < 0.5 V
Simulations 2/2

Overall performances

- Simulation slower than the single PSP model
  
  +5 % for DC simulation
  
  +70 % for transient simulation

- Internal data can be observed (as $V_{FG}$)

- General behavior concords with theory.
Motivation
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Conclusions

The proposed Flash memory cell model:

- is compact to integrate common circuit simulators.
- takes advantage of a MOS channel advanced description (using PSP).
- is written with a flexible code (Verilog-A).
- can perform both DC and transient simulations.
- is adapted for analysis about consumption or injection rates.
Thanks for your attention