Statistical simulations of oxide leakage current in MOS transistor and Floating Gate memories

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INTRODUCTION

• Oxide leakage current is a serious issue for MOS transistor and Floating Gate memories: its characterization and modeling is very important!

• In MOS transistors: 1-2 nm thick gate oxide leads to an exponential leakage current increase
  – The correct understanding of physical mechanisms in oxide degradation is crucial for technology improvement
  – SILC modeling is fundamental to forecast circuit functionality: statistical simulations are required given the large number of devices in modern ICs!
INTRODUCTION

- In Flash memories: the tunnel oxide reduction and the Flash memory scaling are strongly limited by SILC related reliability issues
  - understanding SILC dependencies on process and cell parameters improves Flash memories
  - the large capacity of today Flash devices (up to 512 Mb and increasing) demands for simulation tools with statistical capabilities

资源共享
- Usual testing does not comply properly with SILC statistics, as SILC is either measured on large area capacitors (statistics is neglected!) or derived from $V_{TH}$ measured on Flash cells (the number of samples is limited!)
PURPOSES OF THIS WORK

- Illustrate a physically-based statistical SILC model which allows:
  - to calculate leakage current distributions in gate (MOS) and tunnel (Flash) oxides
  - to evaluate threshold voltage ($V_{TH}$) distributions of Flash cells in reliability (retention) conditions
  - to correlate (statistically) oxide defect characteristics to SILC and Flash memory $V_{TH}$ distributions
  - to predict $T_{OX}$ scaling effects on Flash memory data retention

• Block diagram of model for SILC and $V_{TH}$ simulation
• This model is based on the physical-statistical SILC model [1]
• This model includes a new $V_{TH}$ calculation procedure, allowing to evaluate $V_{TH}$ distribution in retention conditions
SILC MODEL

- Features of the proposed physical-statistical SILC model:
  1. **statistical** computation capabilities
  2. conduction mechanism = *multi-phonon trap-assisted tunneling*: trapped electrons are coupled to oxide phonons, resulting in a series of virtual states broadening the energy trap level
  3. SILC contributions driven by *percolation paths* are taken into account

![Diagram of SILC model](image)
The model calculates the total leakage current by summing SILC contributions driven by every oxide paths formed by one or more aligned traps.

Under steady-state conditions, the rate electrons pass through a $n$-trap paths is

$$R_j = \frac{1}{\max_j (\tau_{c,j} + \tau_{e,j})}$$

$\tau_{c,j}$ ($\tau_{e,j}$) is the time constants of the capture (emission) of electrons by (from) the $j^{th}$ trap.

$$I_{\text{SILC}} = \sum_j q \cdot R_j$$
Capture (emission) time constants are given by the maximum of single phonon time constants, evaluated over discrete energies $E_{j,n} = E_{C,j} + n \cdot E_p$

- $E_{C,j}$ = conduction band when $j = 0$ or $j = \text{trap\_number}+1$
- $E_{C,j}$ = trap energy level when $0 < j < \text{trap\_number}+1$
- $E_p$ = effective phonon energy

$$\tau_{c,j} = \max_n \left( \tau_{c,j,n} \right) = \max_n \left[ N(E_{j-1,n}) \cdot f(E_{j-1,n}) \cdot P_T (E_{C,j} - E_{j-1,n}, F_{j-1,j}, D_{j-1,j}) \cdot C_{a,j,n} \right]$$

$$\tau_{e,j} = \max_n \left( \tau_{e,j,n} \right) = \max_n \left[ N(E_{j+1,n}) \cdot P_T (E_{C,j} - E_{j+1,n}, F_{j+1,j}, D_{j+1,j}) \cdot E_{m,j,n} \right]$$

- $N(E_{j,n})$ = density of states
- $f(E_{j,n})$ = state (Maxwell-Boltzmann) occupation probability
- $C_{a,j,n}$ ($E_{m,j,n}$) = trap capture (emission) rate
- $P_T$ = tunnel probability
The electron tunneling probability $P_T$ is calculated by applying the WKB method. Tunneling through positively charged traps is simply accounted for. The oxide barrier reduction is modeled by a linear decrease of the conduction band profile when the distance from the trap is smaller than its capture radius, $R_T$. 

- $D_{j,i}$ = distance between $j^{th}$ and $i^{th}$ trap
- $F_{i,j}$ = equivalent oxide field between $j^{th}$ and $i^{th}$ trap
STATISTICAL CAPABILITIES

• To enable statistical simulations, a random generator supplying spatial and energy defect coordinates is integrated with the SILC model.

• An ad-hoc procedure calculates leakage current contributions driven by every trap, checking if whatever j\textsuperscript{th} trap belongs to a percolation path:

  1. \( R_{j,anode} \) (i.e. the rate electrons pass from the trap to the anode) is compared to \( R_{j,k} \), \( k \) being the generic trap located between the j\textsuperscript{th} one and the anode.

  2. If \( \text{max}(R_{j,k}) > R_{j,anode} \) \( \Rightarrow \) j\textsuperscript{th} and k\textsuperscript{th} traps belong to the same percolation path.

This procedure is repeated for every trap!
**V_{TH} CALCULATION**

- SILC induced $V_{TH}$ reduction occurring in Flash memories after electrical stress or radiation can be calculated as follows:

1. $I_G$-$F_{OX}$ curves is provided by SILC model, $F_{OX}$ being the oxide field.

2. From the $F_{OX}$-$V_{FG}$ relation (calculated by taking into account both polysilicon depletion and quantization effects), $I_G$-$V_{FG}$ curve is determined.

3. Floating Gate voltage after $t^*$ retention time, $V_{FG,FIN}$, is determined by solving

   \[
   \frac{t^*}{C_T} = \int_{V_{FG,IN}}^{V_{FG,FIN}} \frac{dV_{fg}}{I_G(V_{fg})}
   \]

   $C_T$ and $V_{FG,IN}$ being the total FG capacitance and the initial FG voltage.
4. Final threshold voltage $V_{T,FIN}$ can be calculated from basic FG device equation,

$$V_{T,FIN} = V_{T0} - \frac{V_{FG,FIN}}{\alpha_G},$$

$V_{T0}$ and $\alpha_G$ being the UV threshold voltage and the control gate capacitive coupling

- $V_T$ distribution can be calculated by repeating this procedure for every $I_G$-$F_{OX}$ curve, that are statistically generated in the same defect conditions
SIMULATIONS RESULTS

- Capabilities of the model allowed to successfully simulate:
  - **SILC** on capacitors with different oxide thicknesses ($T_{OX}= 3.3–10.5$ nm)
  - $V_{TH}$ distributions measured on unbiased Flash cells irradiated by heavy ions (Ag, I)
  - $V_{TH}$ distribution in Flash cells that underwent P/E stresses after ten years (retention)
SILC ON CAPACITORS

- **SILC statistical simulations**: $N_T \cdot \text{Area} \cdot T_{\text{OX}}$ defects are randomly generated within the oxide: $N_T=10^{16}$ and $10^{17}$ cm$^{-3}$ are the defect density.
- **Excellent fit** of experimental SILC after CCS!

\begin{align*}
\text{Area} &= 10^{-3} \text{ cm}^2 \quad J_{\text{STRESS}} = 3 \text{ mA/cm}^2 \\
T_{\text{OX}} &= 4.4 \text{ nm} \\
Q_{\text{INJ}} &= C/cm^2
\end{align*}

Lines: simulations  
Symbols: measurements

<table>
<thead>
<tr>
<th>$F_{\text{OX}}$ (MV/cm)</th>
<th>$J_{\text{SILC}}$ (A/cm$^2$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>$10^{-10}$</td>
</tr>
<tr>
<td>3</td>
<td>$10^{-9}$</td>
</tr>
<tr>
<td>4</td>
<td>$10^{-8}$</td>
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<td>$10^{-5}$</td>
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<tr>
<td>8</td>
<td>$10^{-4}$</td>
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</tbody>
</table>
Spatial coordinates and energy levels of defects are generated by assuming a uniform and a Gaussian distribution, respectively:

- $E_T = 2.4\,\text{eV}$ (below the oxide conduction band) and $\Delta E_T = 0.15\,\text{eV}$ are the mean and the standard deviation of the Gaussian energy distribution.

Usually, SILC was simulated by taking into account just the average defect contribution, $N_T \cdot \sigma_T$.

This approach works with large area devices, but it falls when considering small area samples.

With smaller area, total SILC is more sensitive against single spatial-energy trap variations!
SILC ON CAPACITORS /3

- SILC standard deviation increase when device area scales down (device area = 1 $\mu$m$^2$)!
- SILC probability densities are fitted well by a log-normal curve, although tails appear at high $J_{\text{SILC}}$.
Simulations of SILC across a $T_{\text{ox}}=7\text{nm}$ Flash tunnel oxide ($10^3$ simulation trials)

- Mean reproduces accurately experimental curves
- Standard deviation accounts for statistical variations among samples
SILC ON CAPACITORS /5

- **Micro-breakdown current** simulations on $T_{\text{ox}}=3.3\text{nm}$ capacitors agrees nicely with experiments
- Uniform distribution of **neutral traps** are assumed ($\sigma_T=10^{-14}\text{ cm}^2$)

![Graph showing micro-breakdown current simulations versus breakdown field strength.](image-url)

*Symbols: measurements, Lines: statistical simulations*
Flash cells hit by a heavy ion feature degraded data retention properties [2]

- $V_{TH}$ cumulative distribution shows a large tail at low threshold voltage increasing with time
- $V_{TH}$ reduction is driven by defects generated by ion passing through the oxide
- The model is extended to account for the radiation defect generation process
- Defects are concentrated near the ion track, i.e. in a cylinder with a 12 nm diameter [2]

$V_{TH}$ DISTRIBUTION /2

- $V_{TH}$ distribution of unbiased $T_{OX}=10\text{nm}$ Flash after a iodine irradiation (E=286 MeV; LET=64 MeV/cm$^2$mg)
- Nice fitting by assuming 12 defects generated in the ion track, a cylinder with 12 nm diameter
Excellent fitting also with different ions!

Interestingly, defect number (12 for I, 11 for Ag, 5 for Br) depends (as expected) to the ion Linear Energy Transfer.
- The model works well also for Flash cells irradiated by iodine having different $T_{Ox}$!
- **Defect number** (~6 for $T_{Ox}=8.7$nm and ~14 for $T_{Ox}=11.7$nm) depends on the oxide thickness.
This model allows to investigate reliability of Flash subjected to conventional P/E stresses.

Defects are uniformly generated in tunnel oxide to account for the P/E oxide degradation.

Largest $V_{TH}$ reduction (fast/moving bits) could be correlated to defect features ($N_T$, $\sigma_T$, $E_T$, ..).
$V_{TH}$ DISTRIBUTION /6

- $V_{TH}$ distribution (10^6 simulation trials) of 0.18 µm Flash cells left unbiased for 10 years
- Very few cells feature $V_{TH} < 8$V, which is due to the large SILC driven by 3-trap percolation paths
- **Strong $V_{TH}$ degradation** on scaling $T_{OX}$, due to exponential SILC increase
- **Statistical $V_{TH}$ tail increase prediction** helps to scale reliably Flash cells

![Cumulative probability plot](chart.png)

- $N_t = 5 \times 10^{16}$ cm$^{-3}$
- $W = L = 0.3$ µm
- $T_{OX}$ (nm): 7.5, 9, 10.5
Defects can be generated also by a correlated process.

Tails at low $V_{TH}$ strongly increase with the defect Correlation Coefficient, CC.
CONCLUSIONS

• The model presented here is physical and statistical.
• It reproduces very accurately SILC across gate-tunnel ($T_{\text{OX}}=3.3–10.5\text{nm}$) oxides and $V_{\text{TH}}$ in Flash cells after various stresses (electrical, radiation).
• Simulation times are not critical: 2 hours on a Pentium 4 PC for $10^7$ simulation trials.
• It is an important tool for Flash technology improvement as it allows:
  – To correlate defect features to $V_{\text{TH}}$ statistics.
  – To identify physical mechanisms responsible of fast/moving bits.
  – To predict oxide scaling effects.