Unifying the Modeling of Charge Trapping in RTN, 1/f Noise and BTI

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Motivation

• “Traditional / Ideal” MOSFET
  • Deterministic Behavior
  • Distributed quantities (densities)

• “Real” MOSFET:
  • Discrete Quantities (electrons, dopants …)
  • Stochastic Behavior / Variability

• Time Dependent Variability
### Discrete Charges and Traps

<table>
<thead>
<tr>
<th>Technology node</th>
<th>1µm</th>
<th>100nm</th>
<th>40nm</th>
<th>16nm</th>
</tr>
</thead>
<tbody>
<tr>
<td>VDD (V)</td>
<td>3.3</td>
<td>1.2</td>
<td>1</td>
<td>0.8</td>
</tr>
<tr>
<td>width = length in (µm)</td>
<td>1</td>
<td>0.1</td>
<td>0.04</td>
<td>0.016</td>
</tr>
<tr>
<td>EOT / nm</td>
<td>10</td>
<td>2.2</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>specific capacitance (C/nF/cm²)</td>
<td>345</td>
<td>1568</td>
<td>3450</td>
<td>3450</td>
</tr>
<tr>
<td>oxide capacitance Cox (F)</td>
<td>3.45E-15</td>
<td>1.57E-16</td>
<td>5.52E-17</td>
<td>8.83E-18</td>
</tr>
<tr>
<td>Eox at VDD (MV/cm)</td>
<td>3.3</td>
<td>5.5</td>
<td>10.0</td>
<td>8.0</td>
</tr>
<tr>
<td>number of carriers in channel at Eox=5MV/cm</td>
<td>7.1E+04</td>
<td>1.2E+03</td>
<td>345</td>
<td>44</td>
</tr>
<tr>
<td>number of active defects</td>
<td>1000</td>
<td>10</td>
<td>1.6</td>
<td>0.3</td>
</tr>
<tr>
<td>ΔV_{th} for single carrier (mV)</td>
<td>0.05</td>
<td>1.0</td>
<td>2.9</td>
<td>18.1</td>
</tr>
</tbody>
</table>

Useful numbers for some selected technology nodes. Assumption: defect density=10^{11}/cm². [Reisinger, 2014].

\[
\Delta V_{th} = \frac{q}{C_{ox}} \quad \text{with} \quad C_{ox} = \varepsilon \times A / tox
\]

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Modeling Approach

Based on Microscopic (Random) Quantities, instead of distributed (homogeneous) quantities.

1. Charge trapping and de-trapping are stochastic events governed by characteristic time constants, which are uniformly distributed on a log scale.

2. Number of traps is assumed to be Poisson distributed.

3. Amplitude of the fluctuation induced by a single trap is a random variable. If needed, exponential distribution assumed.
BTI \times RTN

\begin{align*}
V_G & \text{ Positive: PBTI} \\
V_G & \text{ Negative: NBTI}
\end{align*}
Traps that contribute to noise are the ones with
\[ \tau_C \cong \tau_E \]
i.e., traps that keep switching state

Traps that contribute to NBTI are the ones with
\[ \tau_C < \tau_E \]
i.e, traps that become occupied
Time x Frequency Domain

\[ S(\log) \]

\[ f(\log) \]

\[ \delta I_d \]

\[ \tau_c \]

\[ \tau_e \]

Current

Time
**Time x Frequency Domain**

RTN and BTI:

$$\Delta V_T(t) = \sum_{i=1}^{Ntr} \delta V_{Ti} S_i(t)$$

$S_i(t)$ is related to the state of the $ith$ trap, which may be empty or occupied and depends on $\tau_{Ci}$ and $\tau_{Ei}$

1/f Noise:

$$S(f) = \sum_{i=1}^{Ntr} \delta V_{Ti}^2 \cdot \frac{\beta_i}{(1+\beta_i)^2} \frac{2}{\pi f_i} \frac{1}{1+(\frac{f}{f_i})^2}$$

$$A_i^2 = \delta V_{Ti}^2 \cdot \frac{\beta_i}{(1+\beta_i)^2}$$

$$\beta_i = \frac{\tau_{Ci}}{\tau_{Ei}}$$

$$N_{tr} = N_{dec}WL \ln(10) \log \left( \frac{f_{max}}{f_{min}} \right)$$

$$N_{tr} = N_{dec}WL \ln(10) \log \left( \frac{t_{max}}{t_{min}} \right)$$

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Phase Noise: Up-converted 1/f Noise
Phase Noise: Up-converted 1/f Noise

[a] Ideal oscillator

Actual oscillator

Frequency band divided in channels

Desired signal
Noise

Signal in nearby channel with phase noise

Haartman and Oestling

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Average Value and Variability

n-MOS, W / L = 25µm / 0.25µm

\[ V_d = 1.0V, V_{g,\text{eff}} = 0.5V \]
n-MOS, $W / L = 2.5\mu m / 0.25\mu m$

$V_d = 1.0V, V_{g,\text{eff}} = 0.5V$
Average Value and Variability

Gate referred voltage noise

\[ [\text{VHz}^{-1/2}] \]

n-MOS, W / L = 0.25µm / 0.25µm

\[ V_d = 1.0V, V_{g,\text{eff}} = 0.5V \]
Logic Gate Delay Variability
Transient Simulation of Ring Oscillators
Period Jitter

- **Period Jitter**
  - Period Jitter is the difference between a clock period and the ideal clock period (it can occur after or before the ideal transition).
Period of a Single Ring Oscillator

Minimum: 3.6784E-11
Máximum: 3.8338E-11
Mean: 3.7370E-11
Std Deviation: 2.06329E-13

Distribution is skewed (not Gaussian)
RTN and Time Domain

Vₜ Fluctuations
$E[Var[\Delta V_T(t)]] = E[N_{tr}]E[A_i^2] \equiv E[V_{T\text{Jitter}}^2]$
Monte Carlo simulation of $V_T$ variation over time due to RTN. Trap occupancy switching leads to discrete fluctuations in $V_T$. Two devices of size 0.03μm x 0.12μm are shown.
**Vₜ Fluctuates Over Time**

Histogram of $V_{Tjitter}^2$ from MC simulations for two different device sizes. Black diamonds show the average $V_{Tjitter}^2$ for each device size. Please note that the y-axis of the first histogram is in log scale.
Variability of $V_T$ Jitter

Each point in the graph is the $V_T$ jitter of a single device. Black diamonds show the average jitter for each area.
RTN: Random Telegraph Noise
Evaluating the Noise Power due to Many Traps

\[ S(f) = \sum_{i=1}^{N_{tr}} A_i^2 \frac{1}{f_i} \frac{1}{1 + \left(\frac{f}{f_i}\right)^2} \]
1/f Noise Statistical Model

- Average Value ($\mu$)

$$
E[S(f)] = \frac{E[A_i^2]N_{dec}WL\pi}{f} \frac{1}{2}
$$

$$
E[N_{tr}] = N_{dec}WL \ln(10) \log\left(\frac{f_{max}}{f_{min}}\right)
$$

- Variance ($\sigma^2$)

$$
Var[S(f)] = \frac{E[A_i^4]N_{dec}WL}{2} \frac{1}{f^2}
$$

$$
E[A_i^2] = E[\delta V_{Ti}^2 \cdot \frac{\beta_i}{(1 + \beta_i)^2}]
$$
RTN Statistical Model

- **Average Value** ($\mu$)
  \[ E[V_{T\text{jitter}}^2] = E[N_{tr}]E[A_i^2] \]

  \[ E[N_{tr}] = N_{dec}WL\ln(10)\log\left(\frac{t_{max}}{t_{min}}\right) \]

- **Variance** ($\sigma^2$)
  \[ \text{Var}[V_{T\text{jitter}}^2] = E[N_{tr}]E[A_i^4] \]
Parameter Extraction \( f \) domain

\[
\frac{\text{Var}[S(f)]}{E[S(f)]]} = \frac{E[A_i^4]}{E[A_i^2] \pi f}
\]

If it is assumed that \( A_i \) is exponentially distributed, \( E[X^n] = n! / \lambda^n \)

\[
E[A_i] = \sqrt{\frac{\pi f \text{Var}[S(f)]}{12 E[S(f)]]}}
\]

\[
N_{\text{dec}}WL = \frac{E[S(f)] f}{E[A_i]^2} \frac{1}{\pi}
\]
Parameter Extraction $t$ domain

\[
\frac{\text{Var}[V_{T_{jitter}}^2]}{E[V_{T_{jitter}}^2]} = \frac{E[A_i^4]}{E[A_i^2]}
\]

If it is assumed that $A_i$ is exponentially distributed, $E[X^n] = n!/\lambda^n$

\[
E[A_i] = \sqrt{\frac{\text{Var}[V_{T_{jitter}}^2]}{12 E[V_{T_{jitter}}^2]}}
\]

\[
E[N_{tr}] = \frac{E[V_{T_{jitter}}^2]}{2E[A_i]^2}
\]
Parameter Extraction $BTI$

- Average Value ($\mu$)

$$E\left[V_{T,BTI}(t)\right] \sim E[\delta V_{Ti}] \ E[N_{tr}(t)]$$

- Variance ($\sigma^2$)

$$Var\left[V_{T,BTI}(t)\right] \sim E[\delta V_{Ti}^2] \ E[N_{tr}(t)]$$

$$E[\delta V_{Ti}] = \frac{Var\left[V_{T,BTI}(t)\right]}{2 \ E\left[V_{T,BTI}(t)\right]}$$
Area Scaling

\[ E[S(f)] \sim \frac{1}{WL} \quad E[V_{Tjitter}^2] \sim \frac{1}{WL} \]

\[ Var[S(f)] \sim \frac{1}{(WL)^3} \quad Var[V_{Tjitter}^2] \sim \frac{1}{(WL)^3} \]
How to statistically describe the noise?

$log[S_{ID}(f)]$ is normally distributed!
How to statistically describe the noise?

- $\sigma[\ln S_{Id}]$ should not and does not follow a $\frac{1}{\sqrt{WL}}$ dependence.

$$Var[\ln S(f)] = \ln \left(1 + \frac{K}{WL}\right)$$

$$K = \frac{2}{\pi^2 N_{dec}} \frac{E[A_i^4]}{E[A_i^2]^2}$$

$V_{GS} = 0.1 \, V, V_{DS} = 1.4$
Conclusion

A microscopic, statistical modeling approach for charge trapping is presented. It unifies the modeling of BTI, RTN and 1/noise, allowing parameter extraction and the investigation of the involved physical mechanisms. It is a statistical model, accounting for the variability among devices and its area scaling. Parameter extraction is discussed.
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- and many others …
Comments / Questions

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A few Refs