Consistent Model for Drain Current Mismatch in MOSFETs Using the Carrier Number Fluctuation Theory

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OUTLINE

- Introduction
- Mismatch Channel Model
- Fluctuation of Charge Density
- Number Fluctuation Model
- Mismatch vs. Inversion Level
- Experimental Results
- Conclusions
Desirable properties of mismatch models: consistency, accuracy, simplicity.

Consistency: series-parallel association

Consistency: contributions of the randomly varying technological, e.g., $V_T$, $C_{ox}$ and geometric ($W, L$) parameters.

Consistency: local fluctuations in $V_T$ rather than total fluctuation (lumped parameter).

Accuracy/consistency: model valid for any bias condition.

Simplicity: simple models, easy-to-extract parameters.
INTRODUCTION

Purpose: A simple one-equation mismatch model for hand analysis & design and circuit simulation.
MISMATCH CHANNEL MODEL

- MOSFET channel splitting
- Transistor equivalent circuit

Basic formulation:

\[ I_D = -\mu \frac{W}{dx} Q'_I \cdot dV_X \]
MISMATCH CHANNEL MODEL

Mismatch results from local current fluctuation ($i_{\Delta A}$) in the small channel element.

\[ \Delta R = -\frac{\Delta x}{\mu W Q_{i}} \]
\[ g_{l} = -\mu \frac{W}{x} Q'_{ix} \]
\[ g_{u} = -\mu \frac{W}{L-x} Q'_{ix} \]

small-signal equivalent circuit
MISMATCH CHANNEL MODEL

- Contribution of local current fluctuation \( (i_{\Delta A}) \) to drain current \( (\Delta I_d) \):
  \[
  \Delta I_d = \left( \frac{\Delta x}{L} \right) i_{\Delta A}
  \]

- The fluctuation of the local charge is the main contribution to mismatch
  \[
  i_{\Delta A} = I_D \frac{\Delta Q'_I}{Q'_I}
  \]

- Total drain current variance is the sum of (uncorrelated) individual contributions
  \[
  (\Delta I_D)^2 = \frac{1}{L^2} \int_0^L \left[ \Delta x (i_{\Delta A})^2 \right] dx
  \]
  \[\uparrow\]
  contribution of the channel element to total current
From UCCM

Local fluctuation of $V_T$ from Pelgrom’s expression

Poisson statistics for depletion charge fluctuations

\[
\frac{\Delta Q'_I}{Q'_I} = \frac{-C_{ox}' \Delta V_T}{Q'_I - nC_{ox}' \phi_t}
\]

\[
\sigma_{VT}^2 = \frac{A_{VT}^2}{LW} \Rightarrow \Delta V_T^2 = \frac{A_{VT}^2}{\Delta xW}
\]

\[
A_{VT}^2 = \frac{q^2}{C_{ox}'} \left( N \cdot x_D \right) = \frac{q^2}{C_{ox}'} N_{oi}
\]

$N_{oi}$: effective number of impurities per unit area of gate
The previous considerations result for the current mismatch in any operating region

\[
\frac{\sigma_{I_D}^2}{I_{D}^2} = \frac{q^2 N_{oi} \mu}{L^2 nC'_{ox} I_{D}} \ln \left( \frac{Q'_{IP} + Q'_{IS}}{Q'_{IP} + Q'_{ID}} \right)
\]

with \(Q'_{IP} = -nC'_{ox} \phi_t\)
MISMATCH vs. INVERSION LEVEL

In terms of inversion level†

\[
\frac{\sigma^2_{I_D}}{I_D^2} = \frac{N_{oi}}{WLN^*} \frac{1}{i_f - i_r} \ln \left( \frac{1 + i_f}{1 + i_r} \right)
\]

where

\[
N^* = -\frac{Q_{IP}'}{q} = \frac{nC_{ox}'\phi_t}{q}
\]

† for long channel MOSFET, from ACM model

\[
I_D = I_F - I_R = I_S (i_f - i_r) \quad I_S = \frac{1}{2} \mu C_{ox} n^2 \phi_t^2 (W/L)
\]
## SUMMARY

<table>
<thead>
<tr>
<th></th>
<th>weak inversion ((i_f &lt; I))</th>
<th>strong inversion ((i_f &gt;&gt; I))</th>
</tr>
</thead>
<tbody>
<tr>
<td>[\sigma_{I_D}^2 \over I_D^2]</td>
<td>(N_{oi} \over WLN*^2)</td>
<td>(N_{oi} \over WLN*^2) (1 \over 1+i_f)</td>
</tr>
<tr>
<td>linear region ((i_f \approx i_r))</td>
<td>(N_{oi} \over WLN*^2)</td>
<td>(N_{oi} \over WLN*^2) (\ln(1+i_f) \over i_f)</td>
</tr>
<tr>
<td>saturation region ((i_f &gt;&gt; i_r))</td>
<td>(N_{oi} \over WLN*^2)</td>
<td>(N_{oi} \over WLN*^2) (\ln(1+i_f) \over i_f)</td>
</tr>
</tbody>
</table>
EXPERIMENTAL RESULTS

Test circuit

\[ V_G \quad V_D \quad I_D \quad I_B \]

\[ M_{REF} \quad M_i \quad V_B \]

Saturation level dependence

Measured: —; Model: ---

Test chip contains 24 NMOS 30µm x 1.2µm transistors in the ES2 1.2µm CMOS DLM process
EXPERIMENTAL RESULTS

Dependence on inversion level

Linear: □ ($V_{DS}=50\text{mV}$); Saturation: ○ ($V_{DS}=1\text{V}$) regions. —; Model

Dependence on bulk-source voltage

$V_{BS}: □ = -1.8\text{V}; \triangle = -1.2\text{V}; \bigcirc = 0\text{V}; \lozenge = +0.3\text{V}$. (Saturation: $V_{DS}=1\text{V}$).

Matching Modeling
CONCLUSIONS

- Physics-based approach (fluctuation in the number of carriers) used for derivation of mismatch.
- Use of ACM model resulted in a compact easy-to-use formula that is continuous in any operating region.
- Experimental results confirmed the accuracy of our model under various bias conditions.
- Useful tool for designers to predict transistor mismatch in an accurate and easy way.
- Single parameter model \( N_{oi} \) to interface foundries and designers.