Self-heat Modeling of Multi-finger n-MOSFETs for RF-CMOS Applications

Hitoshi Aoki and Haruo Kobayashi

Faculty of Science and Technology,
Gunma University

(RMO2D-3)

RFIC – Tampa 1-3 June 2014
Outline

• Research Background
• Purposes of This Work
• Investigation of Self-heating in a Multi-finger n-MOSFET with a 2-D Device Simulator
• Model Derivations
• Measurements and Model Verifications
• Summary and Future Research
Outline

➢ Research Background
   • Purposes of This Work
   • Investigation of Self-heating in a Multi-finger n-MOSFET with a 2-D Device Simulator
   • Model Derivations
   • Measurements and Model Verifications
   • Summary and Future Research
Research Background (1)

• A multi-finger structure is popularly used in MOSFETs for various RF-CMOS circuits including power amplifiers, mixers, and oscillators.

• There is an inconsistency between S-parameters and static drain current simulations despite accurate model parameter extractions.
Research Background (2)

• In bulk MOSFETs for the multi-finger structure, self-heating effect (SHE) may occur especially if shallow trench isolation (STI) technology is adopted.
Research Background (3)

• A sub-circuit based self-heat model does not converge in large circuits

1. Temperature terminals are added to the model equivalent circuit as a sub-circuit

\[ T = T_0 + \left( I_D V_{DS} \right) Z_{th} \]

Rises in device temperature

Ambient temperature

2. Operation temperature

\[ Z_{th} \] : Thermal Impedance

\[ V_{DS}, I_D \] : Drain Voltage and Current

3. Main model circuit simulation
Outline

• Research Background

➤ Purposes of This Work

• Investigation of Self-heating in a Multi-finger n-MOSFET with a 2-D Device Simulator

• Model Derivations

• Measurements and Model Verifications

• Summary and Future Research
Purposes of This Work

• To analyze self-heat mechanisms in multi-finger n-channel MOSFETs

• To develop a general self-heat model without using thermal sub-circuits

• To analyze and modeling fin-number dependencies of thermal resistance with DC and S-parameter measurements and simulations
Outline

• Research Background

• Purposes of This Work

  ➢ Investigation of Self-heating in a Multi-finger n-MOSFET with a 2-D Device Simulator

• Model Derivations

• Measurements and Model Verifications

• Summary and Future Research
Device Simulation of Self-heating Induced Temperature Distribution

- Simulated with a 2-D device simulator (PISCES-2HB)
- A slow pulsed DC source was used for better convergence
Dependence of $\Delta T$ on the number of fins

- The gate width of each fin is 20 $\mu$m
- Simulated $\Delta T$ is obtained at the center fin
- Measurement was made by using DC source/monitor
Outline

- Research Background
- Purposes of This Work
- Investigation of Self-heating in a Multi-finger n-MOSFET with a 2-D Device Simulator

➤ Model Derivations

- Measurements and Model Verifications
- Summary and Future Research
Temperature Dependence on Resistance

The DC and Isothermal current is written as

\[ I_{ds}(V_{ds}, T_{dev}) = I_{iso}\left[V_{ds}, R_{th} \cdot V_{ds} \cdot I_{ds}(V_{ds}, T_{dev}) + T_{dev}\right] \tag{1} \]

\( \Delta T \) is defined as

\[ \Delta T = I_{ds} \cdot V_{ds} \cdot R_{th} \tag{2} \]

\( R_{th} \) can be written as an electrical resistance equation by

\[ R_{th} = \rho \frac{L}{S} \tag{3} \]

Temperature dependence is given by

\[ R_{th}(T_{dev} + \Delta T) = \rho(T_{dev} + \Delta T)\frac{L}{S} \tag{4} \]
Thermal Resistance

Since $\rho$ is linearly proportional to the rise in temperature, we have

$$\rho(T_{dev} + \Delta T) = \rho(T_{dev}) + c \cdot \Delta T$$  \hspace{1cm} (5)

By plugging eq. (5) into eq. (4), we obtain

$$R_{th}(T_{dev} + \Delta T) = R_{th0} + c \cdot \frac{L}{S}(T_{dev}) \cdot R_{th0} \cdot \Delta T$$  \hspace{1cm} (6)

Now we define $K_{th}$ as

$$K_{th} = c \cdot \frac{L}{S}(T_{dev}) \cdot R_{th0}$$  \hspace{1cm} (7)

$R_{th}$ can be simply represented as

$$R_{th} = R_{th0} + K_{th} \cdot \Delta T$$  \hspace{1cm} (8)
Thermal Impedance

For AC analysis, thermal capacitance, $C_{th}$, should be included in parallel with $R_{th}$, which is written as

$$Z_{th} = \frac{R_{th}}{1 + j \cdot \omega \cdot C_{th} \cdot R_{th}}$$  \hspace{1cm} (9)

Now eq. (2) becomes

$$\Delta T = I_{ds} \cdot V_{ds} \cdot Z_{th}$$  \hspace{1cm} (10)
Fin-number Dependence on $R_{th}$

$R_{th}$ is proportional to the number of fins, $NF$, of n-MOSFETs. $R_{th}$ is a linear function as

$$R_{th}^{NF} = A \cdot NF + R_{th}$$  \hspace{1cm} (11)

$Z_{th}$ is replaced with

$$Z_{th}^{NF} = \frac{R_{th}^{NF}}{1 + j \cdot \omega \cdot C_{th} \cdot R_{th}^{NF}}$$  \hspace{1cm} (12)
Drain Current with Self-heating

Temperature dependence of effective mobility is referred as

\[ \mu_{\text{eff}}(T) = \mu_{\text{eff}}(T_{\text{dev}}) \frac{T}{T_{\text{dev}}} \]  \hspace{1cm} (13)

Effective mobility with self-heating can be

\[ \mu_{\text{eff}}(T_{\text{dev}} + \Delta T) = \frac{\mu_{\text{eff}}}{1.0 + \frac{\Delta T}{T_{\text{dev}}}} \]  \hspace{1cm} (14)

Finally, a drain current with self-heating of a multi-finger n-MOSFET is written as

\[ I_{d_{\text{s-th}}} = \frac{I_{ds}}{1.0 + \frac{\Delta T_{NF}}{T_{\text{dev}}}} \]  \hspace{1cm} (15)
Outline

- Research Background
- Purposes of This Work
- Investigation of Self-heating in a Multi-finger n-MOSFET with a 2-D Device Simulator
- Model Derivations
- Measurements and Model Verifications
- Summary and Future Research
BSIM6 Model as a Modeling Vehicle

BSIM6 model

• is continuous in all operation regions
• has accurate derivatives to predict harmonic distortion
• is satisfied both Gummel symmetry and AC symmetry
• has better physical capacitance behavior
• supports Verilog-A code which is supplied by the authors
‘Cold’ DC Measurement (1)

- AC conductance method* with a Network Analyzer (‘Cold’ DC measurement) is developed

\[
\frac{dI_d}{dV_d} = \frac{\partial I_d}{\partial T} \cdot \frac{\partial T}{\partial V_d} + \frac{\partial I_d}{\partial V_d} \bigg|_{T_{dev}}
\]

Can be neglected at high frequencies

‘Cold’ DC Measurement (2)

\[ S_{22} \]

\[ S_{22} - V_d \]

\[ G_{ds} - V_d \]

\[ I_d - V_d \]
Drain current characteristics of 64-fin n-MOSFET

- 'Cold' DC
- PISCES-2HB Simulation
- Static DC
Model Parameter Extractions

1. Input process parameters for BSIM6
2. DC I-V measurement
3. Measurements of $S$-parameters and de-embedded parasitic components, which are used for ‘Cold’ DC calculations and AC parameter extractions
4. Extractions of DC parameters including BSIM6 and SHE parameters
5. AC parameter ($L$, $C$, and $R$) extractions
6. Model verifications with small circuit modules

RFIC – Tampa 1-3 June 2014
DC Drain Current Characterization of 16-fin n-MOSFET

- Measured
- Proposed Model
- BSIM6

$I_d$ [mA] vs. $V_d$ [V]

RFIC – Tampa 1-3 June 2014
DC Drain Current Characterization of 64-fin n-MOSFET

![Graph showing measured and proposed model currents vs. voltage]

- Measured
- Proposed Model
- BSIM6

Integrated Circuits Conference (RFIC) – Tampa 1-3 June 2014
DC Drain Current Characterization of 128-fin n-MOSFET

![Graph showing measured and proposed model for drain current (I_d) vs. drain voltage (V_d). The graph includes data points and lines for measured data, proposed model, and BSIM6 model.]
$S_{21}$ Characterization of 16-fin n-MOSFET

$S_{21}$ [dB]

Measured
Proposed Model
BSIM6

Frequency [GHz]

RFIC – Tampa 1-3 June 2014
$S_{21}$ Characterization of 64-fin n-MOSFET

![Graph showing $S_{21}$ vs Frequency]

- Measured
- Proposed Model
- BSIM6
Characterization of 128-fin n-MOSFET

\( S_{21} \) vs Frequency [GHz]

- **Measured**
- **Proposed Model**
- **BSIM6**

RFIC – Tampa 1-3 June 2014
$S_{11}$ Characterization of 128-fin n-MOSFET

Measurement

Proposed Model

frequency

RFIC – Tampa 1-3 June 2014
Simulation Speed Comparison of n-MOSFETs Ring Oscillators

<table>
<thead>
<tr>
<th># of Stages</th>
<th>17</th>
<th>35</th>
<th>71</th>
<th>143</th>
</tr>
</thead>
<tbody>
<tr>
<td>BSIM6 simulation time [sec]</td>
<td>0.32</td>
<td>2.93</td>
<td>4.81</td>
<td>9.92</td>
</tr>
<tr>
<td>Proposed Model simulation time [sec]</td>
<td>0.34</td>
<td>2.96</td>
<td>4.91</td>
<td>10.86</td>
</tr>
</tbody>
</table>

- HSPICE was used for the simulations on Windows PC (Pentium i5)
- Each stage consists of a 128-fin n-MOSFET
Outline

• Research Background
• Purposes of This Work
• Investigation of Self-heating in a Multi-finger n-MOSFET with a 2-D Device Simulator
• Model Derivations
• Measurements and Model Verifications

➤ Summary and Future Research
Summary

• SHE has been verified with a 2-D device simulator
• The proposed model was implemented into BSIM6 model with the Verilog-A language
• The proposed model has been verified with DC and small-signal S-parameter measurements
• The self-heat model can be applied to other MOSFET models
Future Research

• Since the Verilog-A code itself is not so fast for circuit simulation, the proposed model will be converted to a C code model for practical use.

• Thermal capacitance measurement and the extraction will be developed for more gate fins of multi-finger MOSFETs.

• A temperature-dependent method for circuit simulations will be considered.
APPENDIX
Verilog-A Source Implementations

- **Time dependent heating implementation**

  \[
  T_{dev} = \text{idt}((I_{ds} \times T_e0 / T_{dev} \times v_{ds} - (T_{dev} - T_{e0}) / (R_{TH} + (T_{dev} - T_{e0}) \times K_{TH} \times R_{TH})) + T_{e0};
  \]

- **Small-signal AC simulations**

  ```
  if ((COSELFHEAT == 1) && analysis("ac"))
  begin
    freq = 1.0 / (2.0 * `PI * $realtime());
    cdrain = I_{ds} / (1.0-2.0*`PI*freq*R_{TH}*C_{TH});
  end
  ```