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

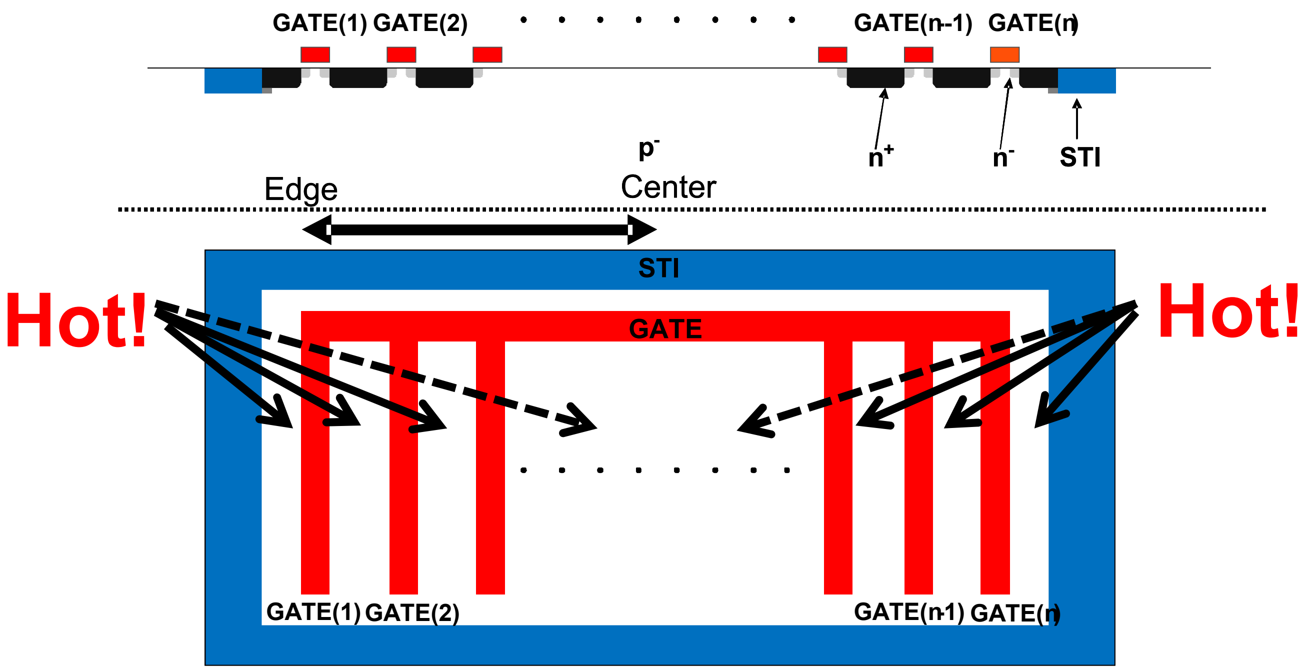
- **Research Background**
- Purposes of This Work
- Investigation of Self-heating in a Multi-finger n-MOSFET with a 2-D Device Simulator
- Model Derivations
- Measurements and Model Verifications
- Summary and Future Research

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)

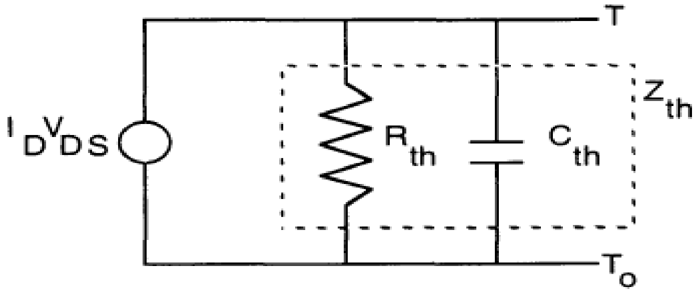
- In bulk MOSFETs for the multi-finger structure, self-heating effect (SHE) may occur especially if shallow trench isolation (STI) technology is adopted



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



Z_{th} :Thermal Impedance

V_{DS}, I_D :Drain Voltage and Current

2. Operation temperature

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

Rises in device temperature

Ambient temperature

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

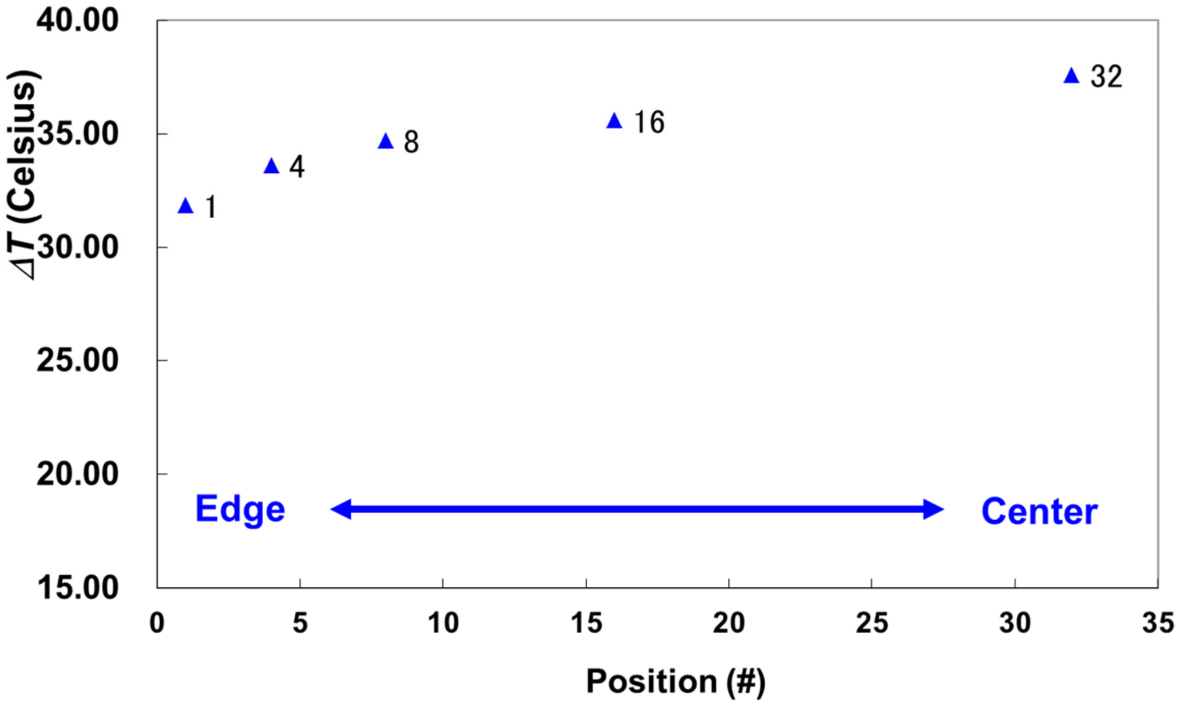
Purposes of This Work

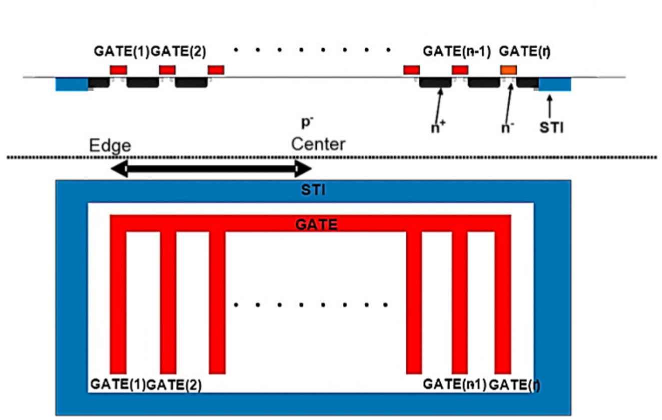
- To analyze self-heat mechanisms in multi-finger n-channel MOSFETs
- To develop a general self-heat model without using thermal sub-circuits
- To analyze and modeling fin-number dependencies of thermal resistance with DC and *S-parameter* measurements and simulations

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

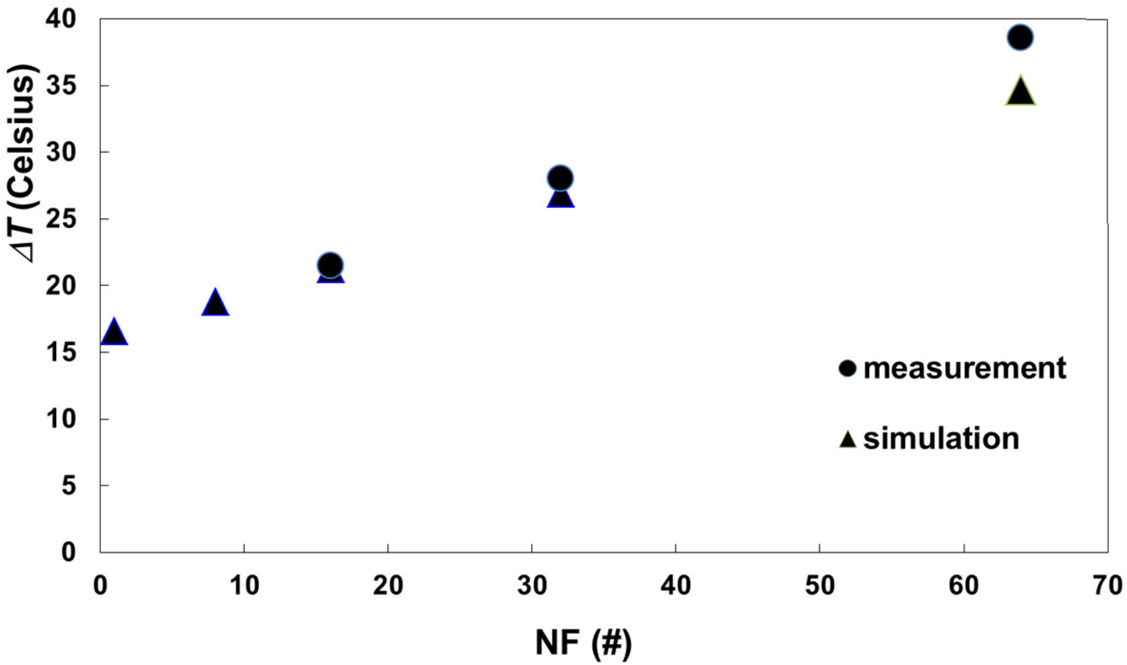
Device Simulation of Self-heating Induced Temperature Distribution

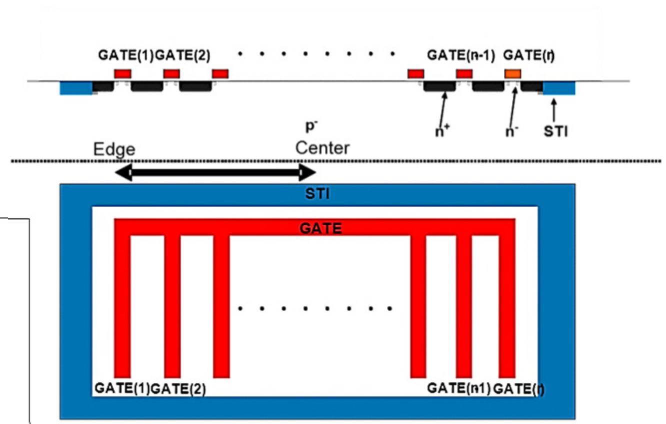




- Simulated with a 2-D device simulator (PISCES-2HB)
- A slow pulsed DC source was used for better convergence

Dependence of *ΔT* on the number of fins





- **The gate width of each fin is 20 μm**
- **Simulated *ΔT* 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

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

***ΔT* is defined as**

$$\Delta T=I_{ds}\cdot V_{ds}\cdot R_{th} \qquad \textbf{(2)}$$

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

$$R_{th}=\rho\frac{L}{S} \qquad \textbf{(3)}$$

Temperature dependence is given by

$$R_{th}\left(T_{dev}+\Delta T\right)=\rho\left(T_{dev}+\Delta T\right)\frac{L}{S} \qquad \textbf{(4)}$$

Thermal Resistance

Since ρ is linearly proportional to the rise in temperature, we have

$$\rho\left(T_{dev}+\Delta T\right)=\rho\left(T_{dev}\right)+c\cdot\Delta T \qquad \textbf{(5)}$$

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

$$R_{th}\left(T_{dev}+\Delta T\right)=R_{th0}+c\cdot\frac{L}{S}\left(T_{dev}\right)\cdot R_{th0}\cdot\Delta T \qquad \textbf{(6)}$$

Now we define K_{th} as

$$K_{th}=c\cdot\frac{L}{S}\left(T_{dev}\right)\cdot R_{th0} \qquad \textbf{(7)}$$

R_{th} can be simply represented as

$$R_{th}=R_{th0}+K_{th}\cdot\Delta T \qquad \textbf{(8)}$$

Thermal Impedance

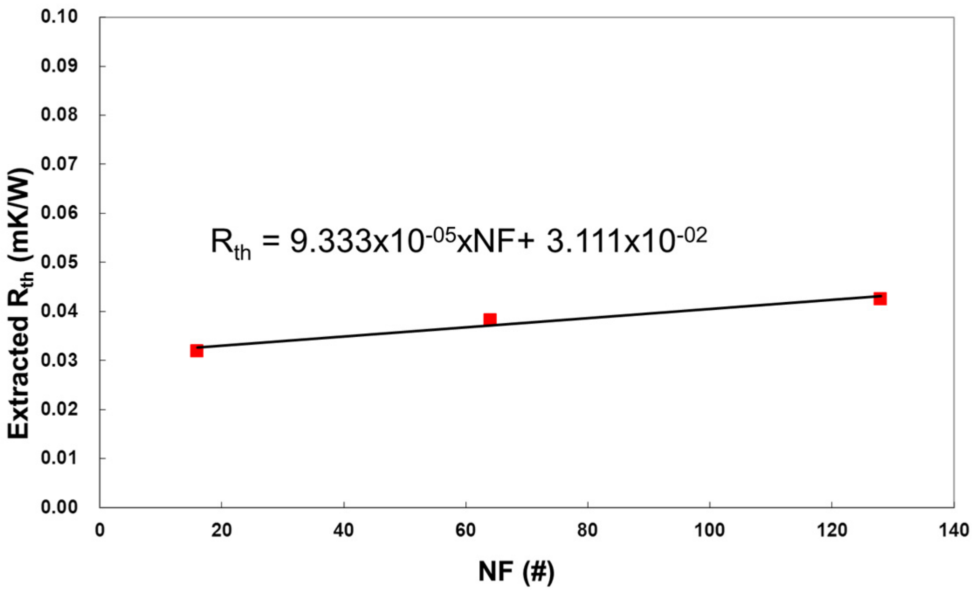
For AC analysis, thermal capacitance, C_{th}, should be included in parallel with R_{th}, which is written as

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

Now eq. (2) becomes

$$\Delta T = I_{ds} \cdot V_{ds} \cdot Z_{th} \qquad \textbf{(10)}$$

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

$$R_{th}^{NF} = A \cdot NF + R_{th} \qquad \text{(11)}$$

Z_{th} is replaced with

$$Z_{th}^{NF} = \frac{R_{th}^{NF}}{1 + j \cdot \omega \cdot C_{th} \cdot R_{th}^{NF}} \qquad \text{(12)}$$

Drain Current with Self-heating

Temperature dependence of effective mobility is referred as

$$\mu_{eff}(T) = \mu_{eff}\left(T_{dev}\right)\frac{T}{T_{dev}} \qquad \textbf{(13)}$$

Effective mobility with self-heating can be

$$\mu_{eff}\left(T_{dev} + \Delta T\right) = \frac{\mu_{eff}}{1.0 + \Delta T / T_{dev}} \qquad \textbf{(14)}$$

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

$$I_{ds\_th} = \frac{I_{ds}}{1.0 + \Delta T_{NF} / T_{dev}} \qquad \textbf{(15)}$$

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

$$\frac{dI_d}{dV_d} = \frac{\partial I_d}{\partial T} \cdot \frac{\partial T}{\partial V_d} + \left.\frac{\partial I_d}{\partial V_d}\right|_{T_{dev}}$$

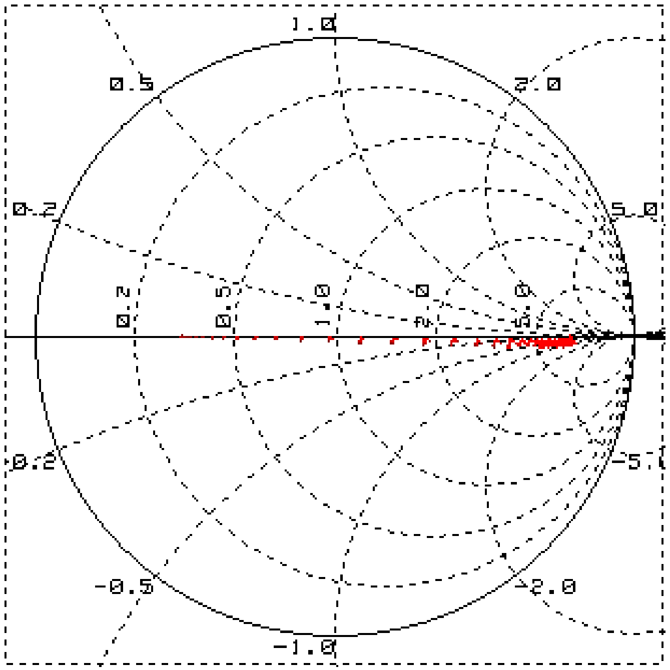
$\gg$

Can be neglected at high frequencies

***R. H. Tu. et.al, IEEE EDL, vol. 16, Feb. 1995.**

'Cold' DC Measurement (2)

S_{22}



Frequency

S_{22} - V_d

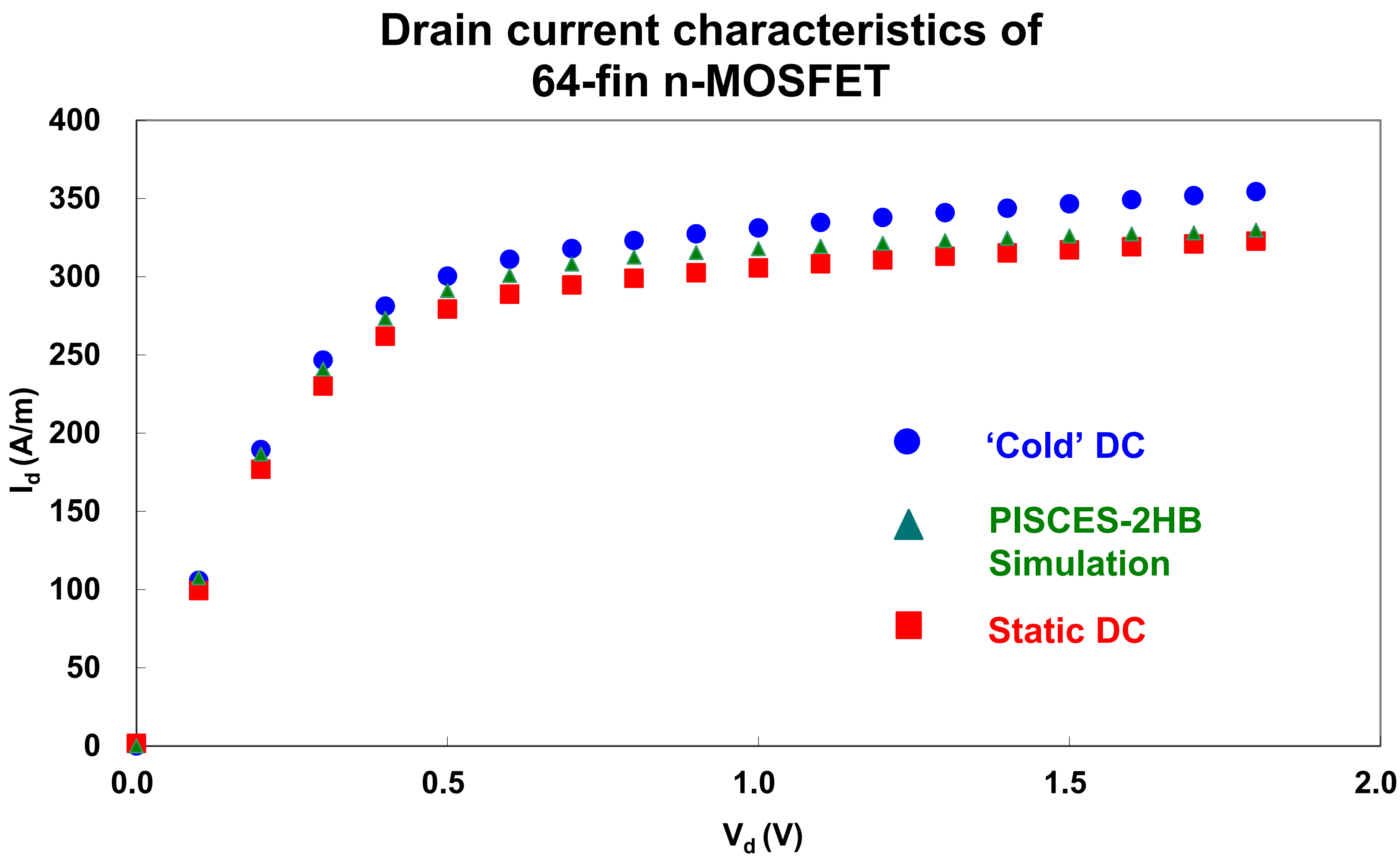
↓

G_{ds} - V_d

↓

I_d - V_d

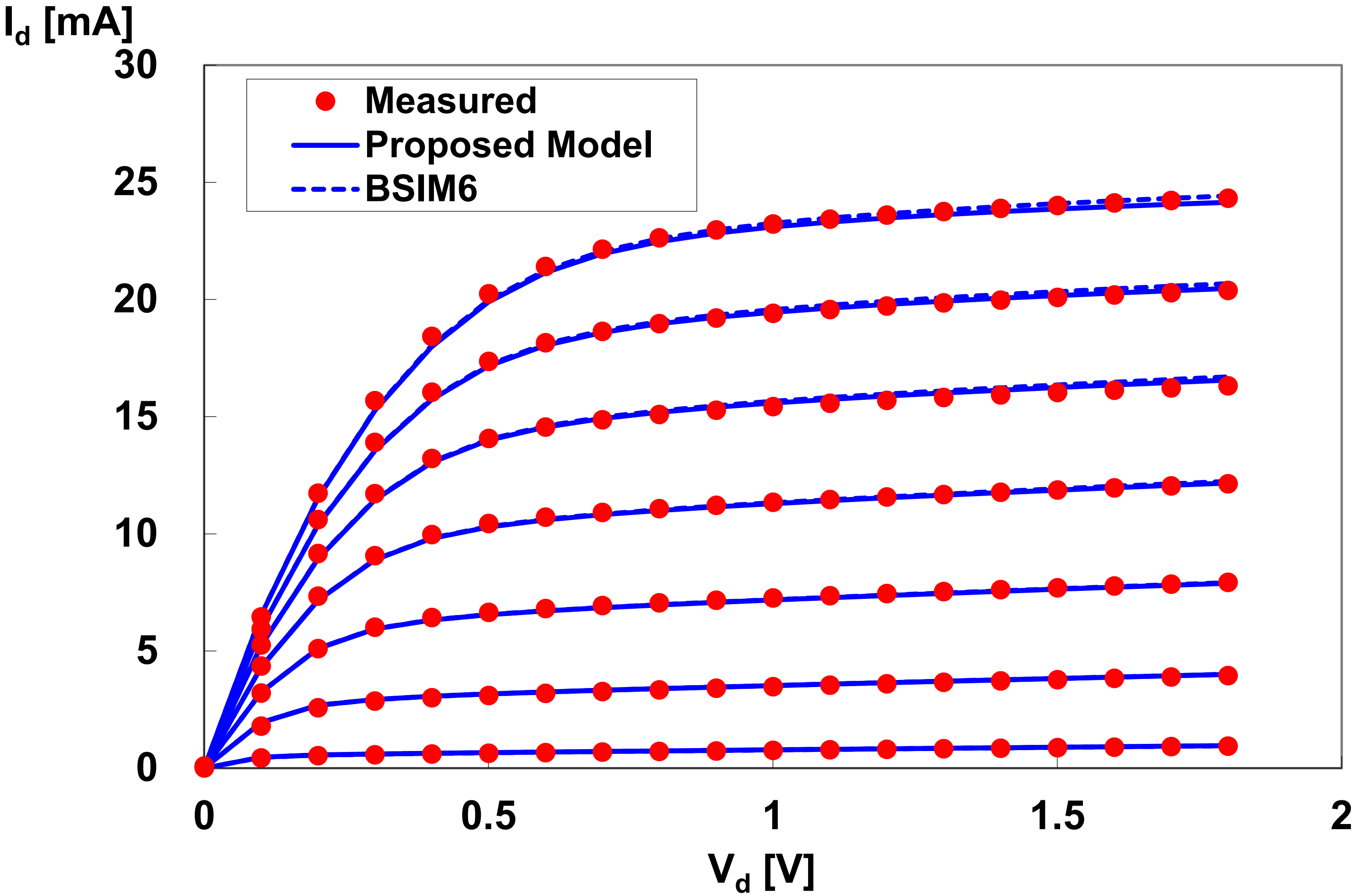
I_d-V_d Measurement



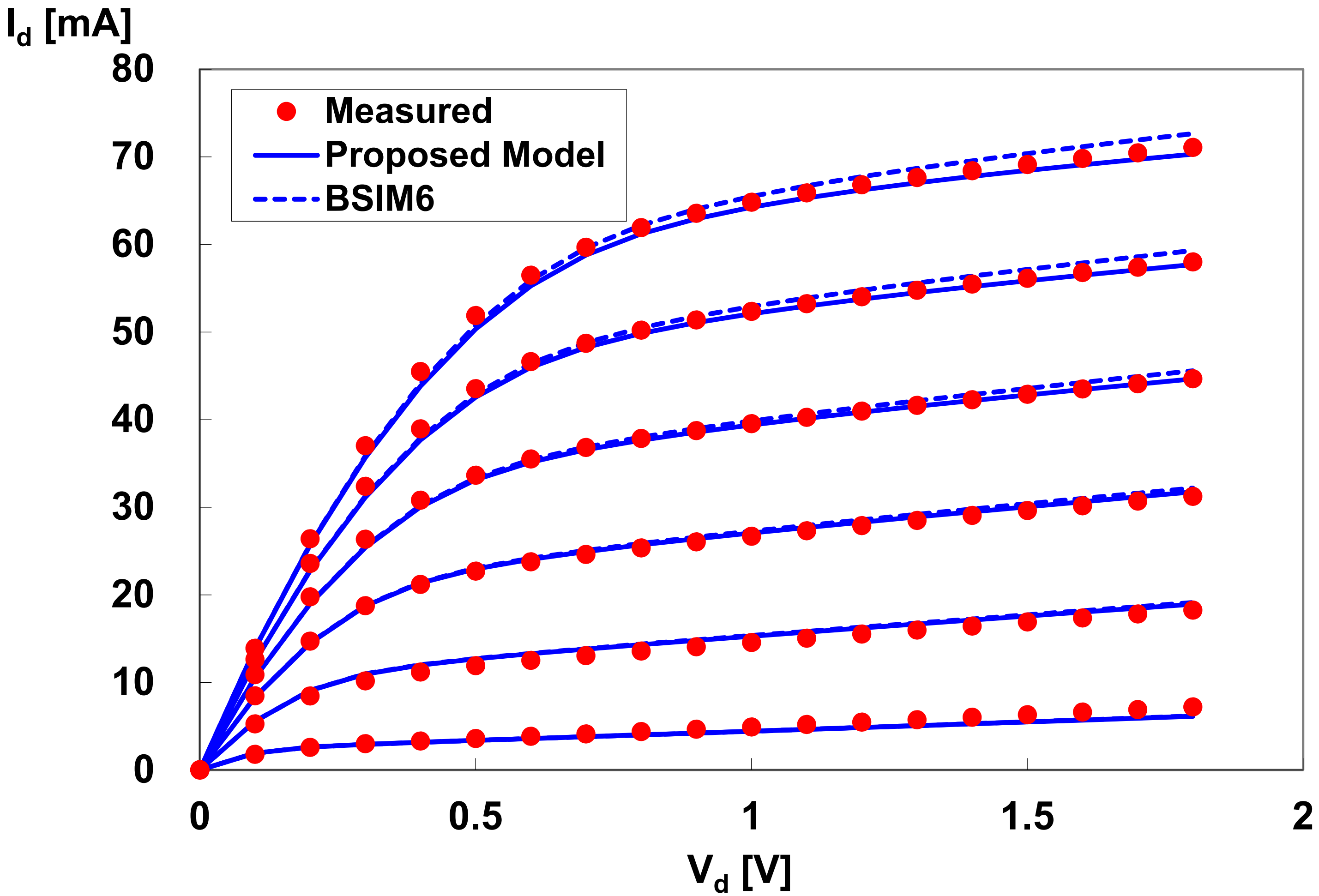
Model Parameter Extractions

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

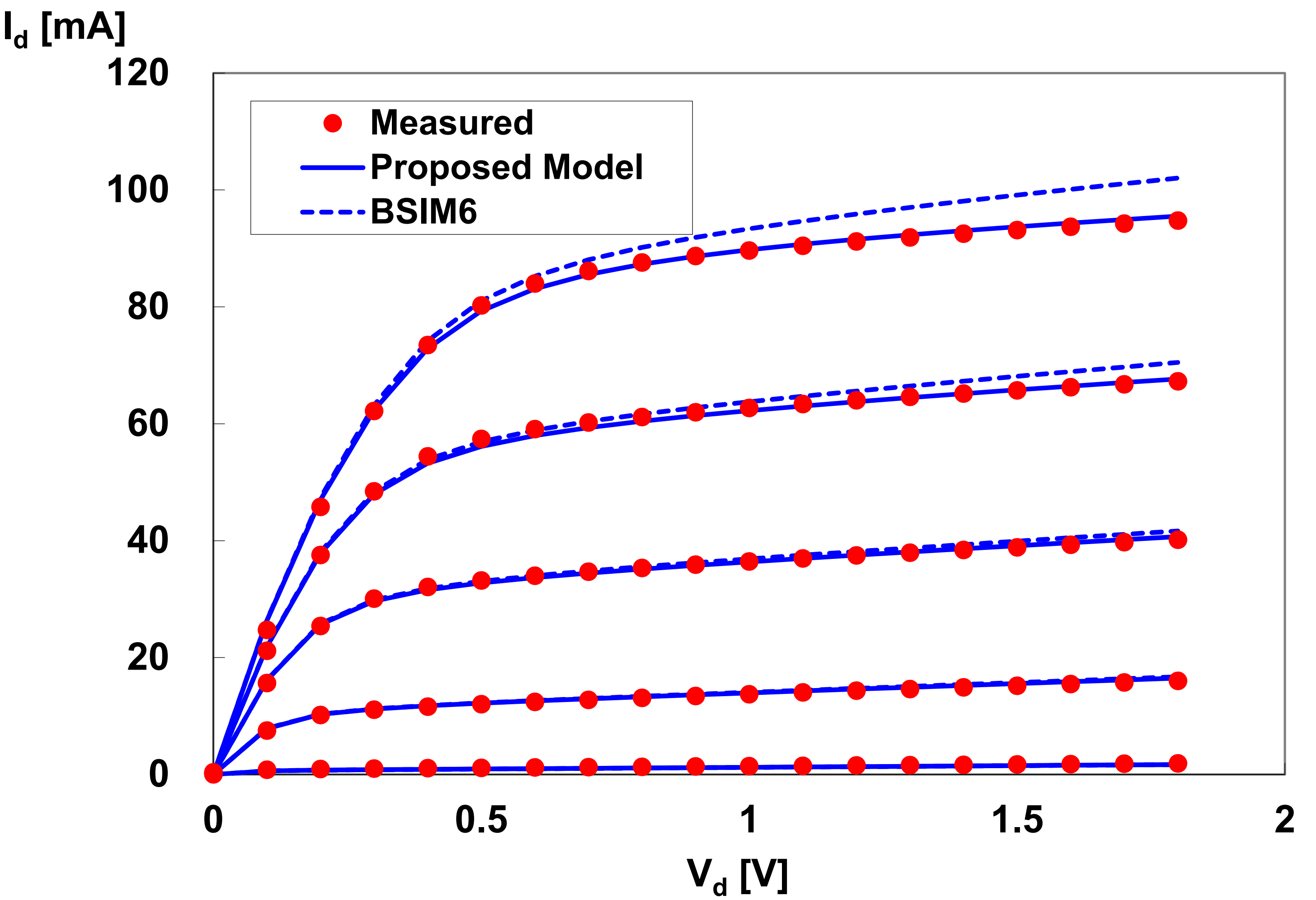
DC Drain Current Characterization of 16-fin n-MOSFET



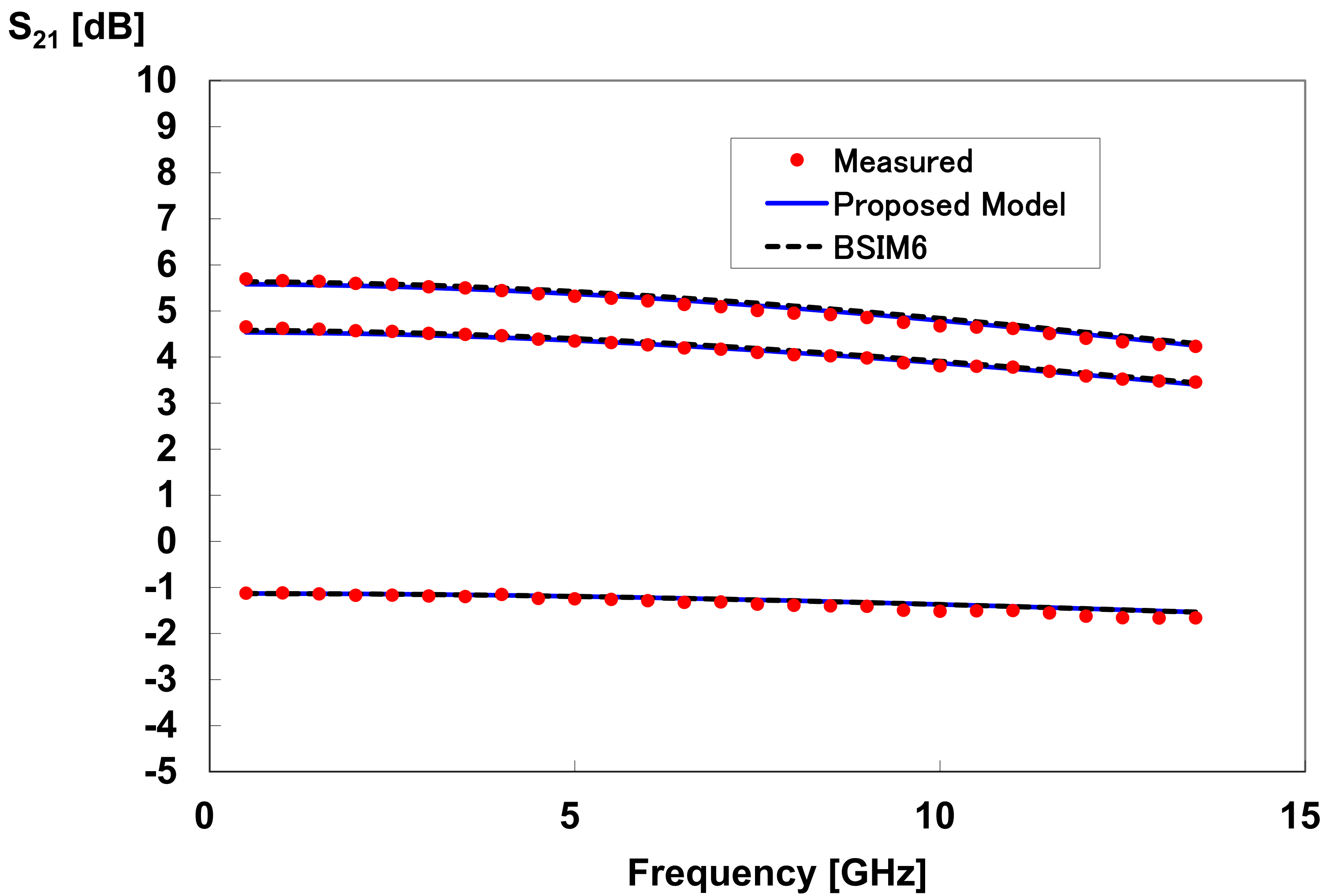
DC Drain Current Characterization of 64-fin n-MOSFET



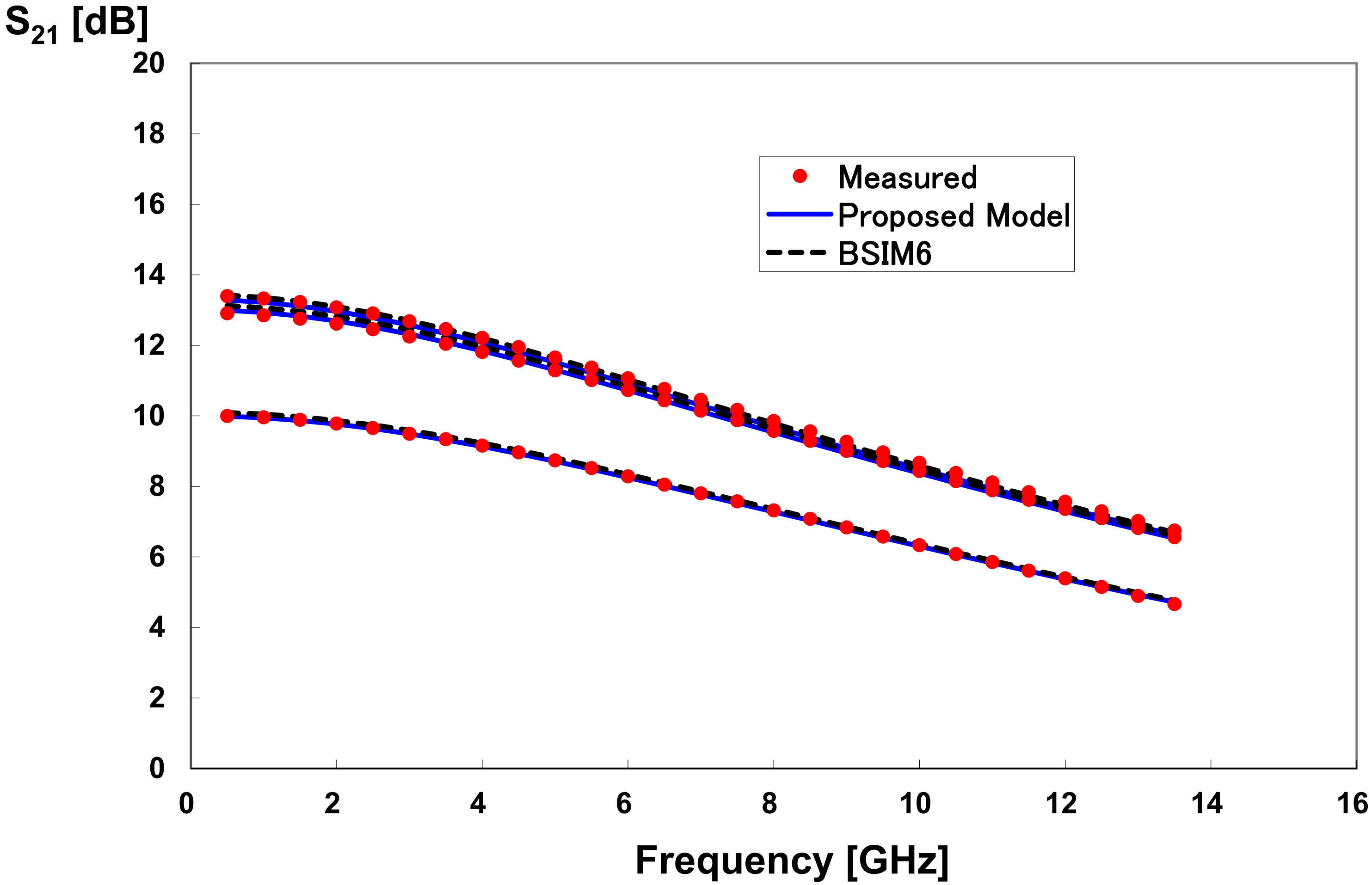
DC Drain Current Characterization of 128-fin n-MOSFET



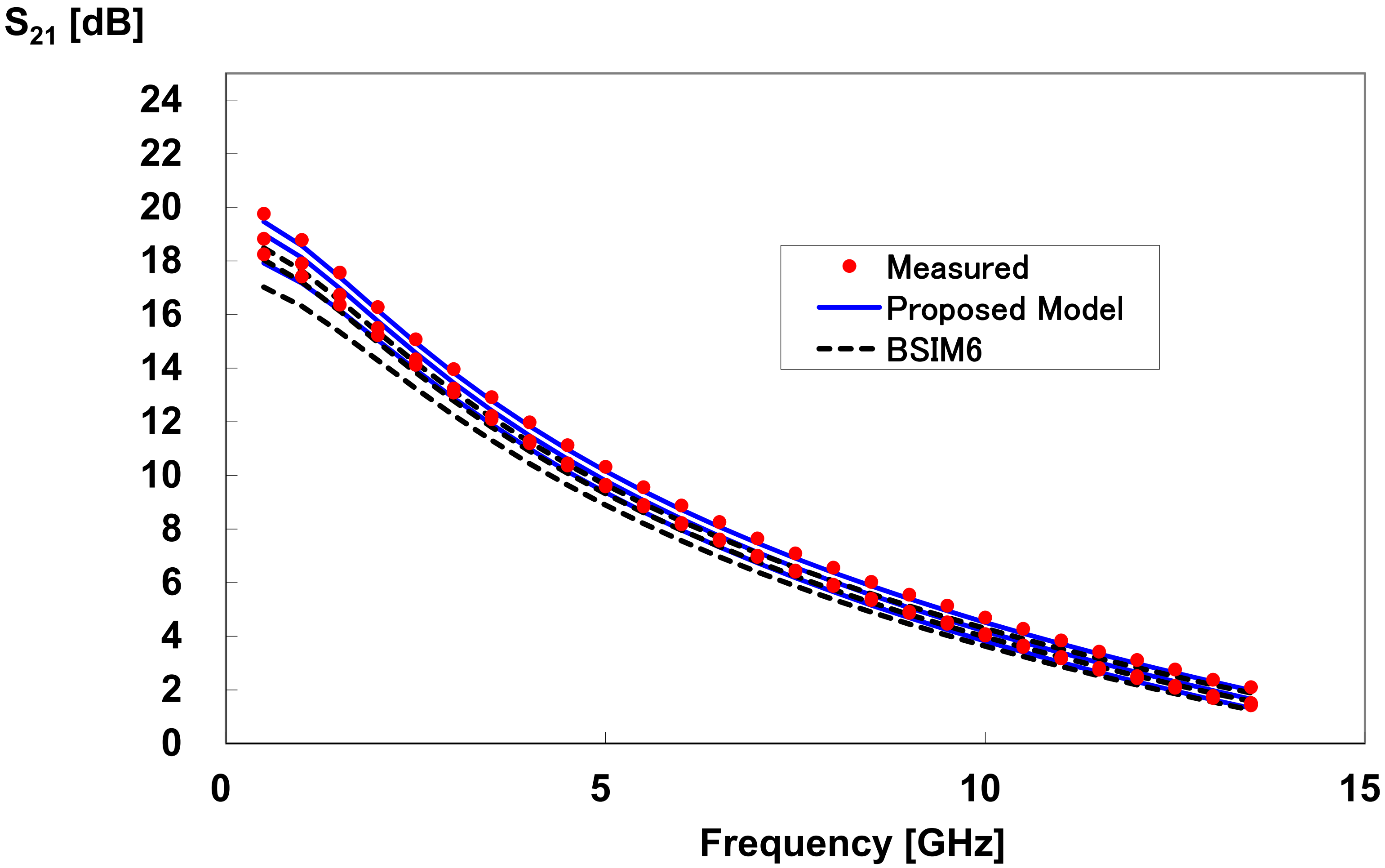
S_{21} Characterization of 16-fin n-MOSFET



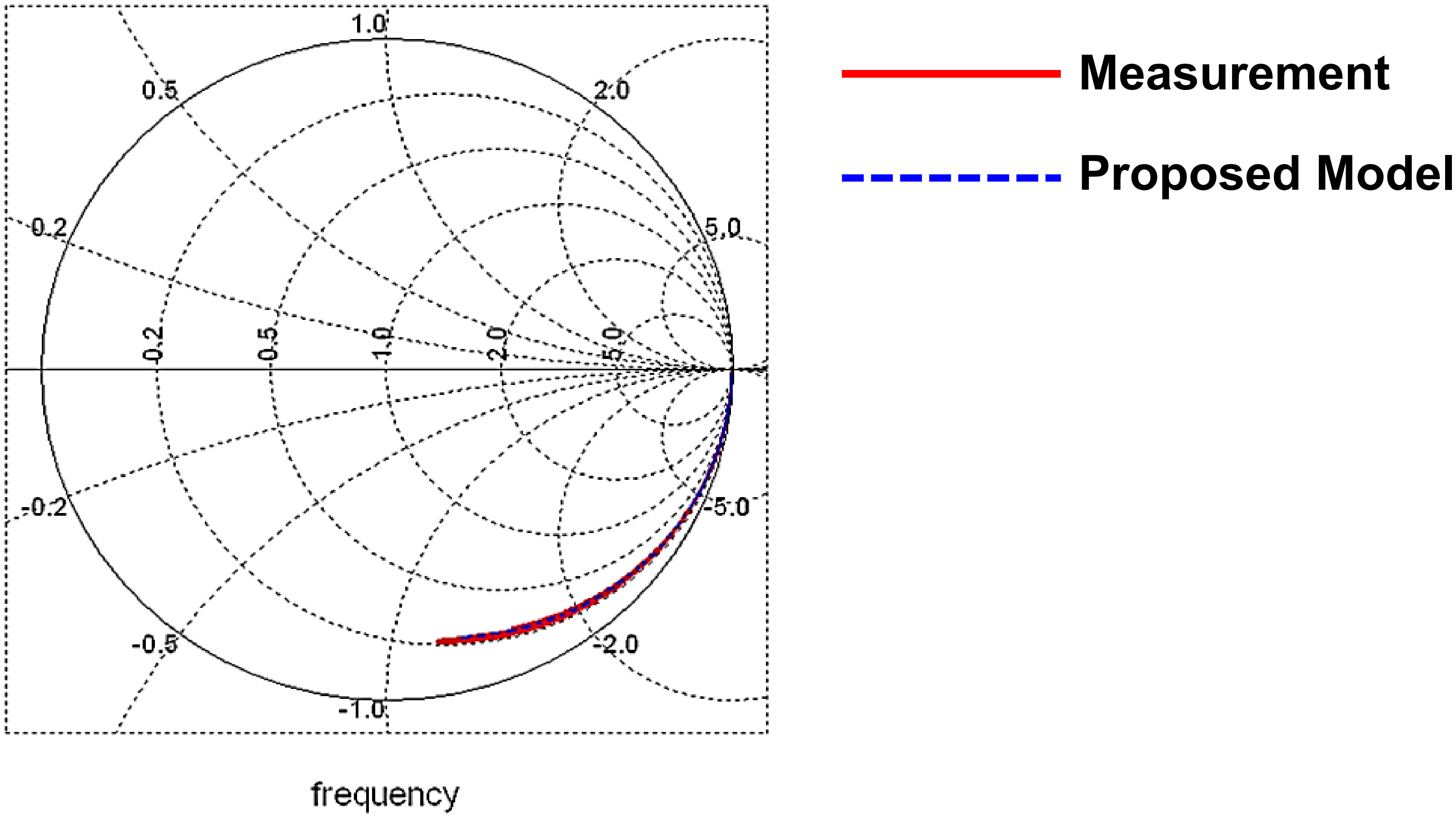
S_{21} Characterization of 64-fin n-MOSFET



S_{21} Characterization of 128-fin n-MOSFET



S_{11} Characterization of 128-fin n-MOSFET



Simulation Speed Comparison of n-MOSFETs Ring Oscillators

# of Stages	17	35	71	143
BSIM6 simulation time [sec]	0.32	2.93	4.81	9.92
Proposed Model simulation time [sec]	0.34	2.96	4.91	10.86

- **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**

```
Tdev = idt((Ids * Tem0 / Tdev * vds - (Tdev - Tem0)
/ (RTH + (Tdev - Tem0)*KTH * RTH)) +Tem0;
```

- **Small-signal AC simulations**

```
if ((COSELFHEAT == 1)&&analysis("ac"))
      begin
       freq = 1.0 / (2.0 * `PI * $realtime());
       cdrain = Ids / (1.0-2.0*`PI*freq*RTH*CTH);
      end
```