Statistical Modeling of Layout-dependent Characteristic Fluctuations for Multi-finger MOSFETs

Chulhyun Park, Junghan Kang, Seong-Ook Jung, and Ilgu Yun

Abstract—Large-signal models using extracted parasitic resistances are proposed for multi-finger MOSFETs and the statistical variations of parasitic resistances are investigated using statistical modeling. The extracted model parameters for the proposed models are verified with measured data. The models can explain the large-signal characteristics of multi-finger MOSFETs. Using the equivalent circuit model, the characteristic variations are statistically modeled with varying the gate layout factors and the extracted parasitic resistances. Based on the results, the gate geometry and extracted parasitic resistances, which are closely related to the source bias, can impact on the characteristic fluctuations of multi-finger MOSFETs.

I. INTRODUCTION

The characteristic fluctuation of multi-finger MOSFETs, which are widely examined owing to the area limitation for MOSFET scaling, is a critical issue recently since the variation is a one of the major problems of the manufacturability for the scaled-down MOS technology [1]. Moreover, research on the large-signal modeling and analysis of multi-finger MOSFETs is on-going process to investigate the relationship between gate geometry and large-signal characteristics such as the threshold voltage (Vth), the saturation voltage (Vdsat), and the saturation current (Idsat). [2] In this paper, the equivalent circuit model for large-signal characteristic of multi-finger MOSFETs is proposed using the parameter fitting analysis based on the measured data with number of finger (Nf) and finger length (Wf). Afterwards, statistical variation of geometry factors for multi-finger MOSFETs is analyzed with additional extracted parasitic resistances. Finally, this paper provide that the method of reducing the characteristic fluctuations and the more accurate characteristic models.

II. TEST STRUCTURE SETS AND FABRICATION

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The test structure SETs are composed of two sets using the design of experiments [3]: SET1 is composed of the test structures where Nf is fixed as 4 and Wf is varied in the values of 25, 37.5, 50 μm and SET2 is constructed with the test structures where Wf is fixed at 50 μm and Nf is varied in the values of 4, 5, and 6. The range of factors and the test sets are summarized in Table I. All of test structures are fabricated by TSMC 0.35 μm process technology in Fig. 1.

![Image of SET structures](image)

Figure 1. Microscopic image of test structures

Using measured data from test structures, the proposed equivalent circuit model parameters are extracted using the circuit simulation tool and statistical variations of MOSFET characteristics are examined using the fluctuation of the extracted parasitic resistances.

III. THE PARAMETER EXTRACTION AND THE EQUIVALENT CIRCUIT MODEL

The parasitic resistances are composed of gate resistance (Rgate), source resistance (Rsource), drain resistance (Rdrain), and substrate resistance (Rsubstrate). Rsource and Rdrain include the metal contact resistances, respectively. Rgate include the silicon oxide (SiO2) resistance. In addition, the substrate of all test structures is tied with the source. Furthermore, the information of gate geometry such as Nf and Wf is included BSIM3v3 as parameters [4]. The value of parameters is optimized to minimize the difference between measured data and simulation data.
The value of $R_{\text{GATE}}$ is unchanged because the gate is almost floated and then, gate leakage is very small in simulation. In addition, $R_{\text{SUBSTRATE}}$ is very large because it is tied with the source. It implies that the substrate leakage current is negligible. However, $R_{\text{SOURCE}}$ and $R_{\text{DRAIN}}$ have little fluctuation. Thus, average values of $R_{\text{SOURCE}}$ and $R_{\text{DRAIN}}$ are set as nominal values for statistical analysis.

The equivalent circuit modeling results are shown in Figs. 2 and 3. It is indicated that the modeling results can explain the large-signal characteristic of multi-finger MOSFETs very well. Therefore, the proposed equivalent circuit model can be used for the statistical analysis.

### IV. STATISTICAL PARAMETER VARIATIONS

For the statistical analysis, $R_{\text{SOURCE}}$ and $R_{\text{DRAIN}}$ are selected as the two process fluctuation parasitic resistances with statistical tolerance to analyze the statistical variation of large-signal characteristic for multi-finger MOSFETs because $R_{\text{GATE}}$ and $R_{\text{SUBSTRATE}}$ have almost no effect on the characteristic fluctuation of multi-finger MOSFETs.

In order to characterize statistical variation of parameters, extracted parasitic resistance values with ±10% variation are considered because the optimized values of parameters have ±10% fluctuation at least. Here, $R_{\text{SOURCE}}^+$ and $R_{\text{DRAIN}}^+$ are denoted as the upper bound values of the source and the drain, respectively, and $R_{\text{SOURCE}}^-$ and $R_{\text{DRAIN}}^-$ are denoted as the lower bound values of the source and the drain, respectively.

The factorial design method is carried out using 4 factors as above state to build a statistical model with analyzing the statistical characteristic fluctuation [3]. Here, each geometric factor ($N_c$ and $W_f$) has 3 levels and each extracted parasitic resistance ($R_{\text{SOURCE}}$ and $R_{\text{DRAIN}}$) has 2 levels, respectively. Here, 9 points are decided by combination between $N_c$ and $W_f$. After that, at each point, the large-signal characteristics are measured for 4 cases which are composed of combination between $R_{\text{SOURCE}}$ and $R_{\text{DRAIN}}$. Thus, the design used in this work required 36 runs.

Even though the threshold voltage is almost unchanged by gate geometry, such as $N_c$ and $W_f$ variations, based on measured data, it is influenced by gate geometry based on the simulation. Furthermore, parasitic resistance, especially $R_{\text{SOURCE}}$, causes the threshold voltage fluctuation. However, it could not be detected in the measured data unless the measurement voltage step is less than 1 mV. From the result shown in Fig. 4, the center value of $V_{\text{TH}}$ is almost unchanged by $R_{\text{DRAIN}}$ value and the variation which is caused by $R_{\text{SOURCE}}$ tolerance is very large. On the other hand, the center value of $V_{\text{TH}}$ has large movement but its fluctuation is very small. That is, $R_{\text{SOURCE}}$ is raised by large $V_{\text{TH}}$ fluctuation compared with $R_{\text{DRAIN}}$. This result is also verified by BSIM3v3 equation [5]:

$$V_{\text{TH}} = V_{\text{TH}}^0 + \delta_{\text{XP}} \left( \Delta V_{\text{T, body effect}} - \Delta V_{\text{T, charge sharing}} \right)$$

$$- \Delta V_{\text{T, DBL}} + \Delta V_{\text{T, reverse short channel}} + \Delta V_{\text{T, narrow width}} + \Delta V_{\text{T, small size}}$$

where the key factor is the threshold voltage fluctuation by the body effect:

$$\Delta V_{\text{T, body effect}} = K_1 \cdot (\sqrt{2\phi} - V_{\text{SB}} - \sqrt{2\phi}) - K_2 \cdot V_{\text{SB}}$$

This effect is related by the voltage between the body and the source. However, the body bias is unchanged because the body is tied as ground and $R_{\text{SUBSTRATE}}$ is very large. Thus, the substrate current is almost equal to zero. On the other hands, the source voltage has the large fluctuation by $R_{\text{SOURCE}}$ and $R_{\text{DRAIN}}$ tolerance. $R_{\text{SOURCE}}$ is impacted on $V_{\text{TH}}$ effectively compared with $R_{\text{DRAIN}}$ because $R_{\text{SOURCE}}$ is directly connected with the source voltage. Therefore, $V_{\text{TH}}$ is so sensitive for $R_{\text{SOURCE}}$ fluctuation.

Based on the measured data, $V_{\text{DStat}}$ is defined as the intersection between the linear and the saturation region in $I_{\text{DS}}$-$V_{\text{DS}}$ curve [5]. Using the definition, $V_{\text{DStat}}$ is influenced by only $W_f$ and it is independent with $N_c$. However, the definition of $V_{\text{DStat}}$ is different in BSIM3 [4]:

$$V_{\text{DStat}} = \frac{E_{\text{sox}} \cdot L_{\text{eff}} \cdot V_{\text{gs}}}{A_{\text{sub}} \cdot E_{\text{sox}} \cdot L_{\text{eff}} + V_{\text{gs}}}$$

$$V_{\text{gs}} = V_e - V_s - V_{\text{TH}}$$
Figure 4. The \( V_{TH} \) fluctuation versus \( N_f \) varying (a) \( R_{SOURCE} \) and (b) \( R_{DRAIN} \) with \( \pm 10\% \) variation

where \( E_{sat} \), \( L_{eq} \), and \( A_{bulk} \) are the critical electric field for carrier velocity saturation, the effective channel length, and the coefficient for bulk state, respectively. In addition, the relationship between parameter tolerance and \( V_{DSat} \) is shown in Eq. 4. When \( R_{DRAIN} \) or \( R_{SOURCE} \) is varied, \( V_{got} \) has variation since \( V_f \) is also varied.

Altogether, \( V_{DSat} \) is decreased when \( N_f \) or \( W_f \) is increased in Fig. 5. It is found from the current-source voltage relationship. When \( N_f \) is increased, the current flowing through the source is also increased because the total width of MOSFET is increased. Thus, \( V_f \) is increased and \( V_{got} \) is decreased (see Eq. 4).

As a result, \( V_{DSat} \) is decreased by Eq. 3. On the other hands, when \( W_f \) is increased, \( V_{TH} \) and \( V_f \) is also increased. Therefore, \( V_{got} \) is decreased by Eq. 4 and \( V_{DSat} \) is also decreased by Eq. 3. From the fluctuation point of view, \( R_{SOURCE} \) is dominant factor to generate the fluctuation of \( V_{DSat} \). From Eq. 3, \( V_{DSat} \) is decided by \( V_{got} \) and \( V_{got} \) is also fixed by \( V_f \) and \( V_{TH} \). Thus, the source voltage is very important. Furthermore, the source voltage is determined by the value of \( R_{SOURCE} \). In consequence, the fluctuation of saturation voltage is more sensitive to \( R_{SOURCE} \) variation than \( R_{DRAIN} \) variation.

Based on the measurement data, the saturation current is influenced by both \( N_f \) and \( W_f \) since the saturation current has the following general form in BSIM3 [5]:

\[
I_{DSat} = W_{eff} \cdot V_{sat} \cdot C_{ox} \cdot (V_f - V_{TH} - A_{bulk} \cdot V_{DSat}) \cdot P_{factor} \\
P_{factor} = A_1 \cdot V_{got} + A_2
\]
Fig. 6 shows that which parameter is more effective factor to cause the saturation current fluctuation. As stated above, the saturation current is increased when \( N_t \) is increased or \( W_t \) is increased. Furthermore, the saturation current is more dependent on \( R_{\text{SOURCE}} \) than \( R_{\text{DRAIN}} \) based on the Eqs. 5 and 6. When \( R_{\text{DRAIN}} \) is decreased, only \( V_{\text{DS},\text{eff}} \) is increased because the drain voltage of core model is also increased. Thus, the saturation current is increased. However, when \( R_{\text{SOURCE}} \) is decreased, both \( V_{\text{DS},\text{eff}} \) and \( V_{\text{GST},\text{eff}} \) are increased because the source voltage of core model is also increased. Thus, \( R_{\text{SOURCE}} \) causes more \( I_{\text{DS},\text{sat}} \) fluctuation, although the value of \( \Delta R_{\text{SOURCE}} \) is the less than that of \( \Delta R_{\text{DRAIN}} \).

V. STATISTICAL VERIFICATION AND MODELING OF CHARACTERISTIC FLUCTUATIONS

Using this statistical analysis, it is determined that the different process factors did significantly impact the characteristic fluctuation of multi-finger MOSFETs.

According to the ANOVA results shown in Table II, a factor to the variation of a characteristic is statistically significant with 95% confidence level when its \( p \)-value is less than 0.05 [3]. These results are equal to explanation in Section IV. Interestingly, both \( R_{\text{SOURCE}} \) and \( R_{\text{DRAIN}} \) did not have a significant effect on the change of \( I_{\text{DS},\text{sat}} \) in the ANOVA results. It is concluded that geometry factors, such as \( N_t \) and \( W_t \), are more effectively impacted on the current fluctuation than parasitic resistances.

<table>
<thead>
<tr>
<th>Factors</th>
<th>( V_{\text{TH}} )</th>
<th>( V_{\text{DS},\text{sat}} )</th>
<th>( I_{\text{DS},\text{sat}} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( N_t )</td>
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<td>0.000</td>
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<tr>
<td>( W_t )</td>
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<td>( R_{\text{DRAIN}} )</td>
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<td>0.814</td>
<td>0.734</td>
</tr>
</tbody>
</table>

Based on the statistical analysis, each characteristic fluctuation is expressed by the function of geometric and extracted parameters. As a result, the proposed statistical models are provided which terms are crucial for large-signal characteristics. Thus, the more accurate equations for large-signal characteristics of the MOSFETs are as follows:

\[
V_{\text{TH,STAT}} = V_{\text{TH}} \pm \sigma(N_t, W_t, R_{\text{SOURCE}}, R_{\text{DRAIN}})
\]
\[
V_{\text{DS},\text{sat,STAT}} = V_{\text{DS},\text{sat}} \pm \sigma(N_t, W_t, R_{\text{SOURCE}})
\]
\[
I_{\text{DS},\text{sat,STAT}} = I_{\text{DS},\text{sat}} \pm \sigma(N_t, W_t)
\]

where \( \sigma(N_t, W_t, R_{\text{DRAIN}}, R_{\text{SOURCE}}), \sigma(N_t, W_t, R_{\text{SOURCE}}), \sigma(N_t, W_t) \) and \( \sigma(N_t, W_t, R_{\text{SOURCE}}) \) express the fluctuation which is composed of combination between the gate layout factors and the extracted parasitic resistances. Thus, the proposed statistical equations are the more adequate to predict the large-signal characteristics of multi-finger MOSFET for circuit design.

VI. CONCLUSION

The equivalent circuit model has been presented using the BSIM3v3 core and 4 parasitic resistances. Large-signal characteristic fluctuation of multi-finger MOSFET was statistically investigated using the proposed MOSFET model with varying \( N_t, W_t, R_{\text{SOURCE}}, \text{and } R_{\text{DRAIN}} \). The fluctuation of MOSFET characteristics, such as \( V_{\text{TH}}, V_{\text{DS},\text{sat}} \text{, and } I_{\text{DS},\text{sat}} \), were examined. The statistical models for characteristic fluctuations are then proposed for accurate prediction. From the proposed statistical model, it was concluded that the characteristics are more sensitive to \( R_{\text{SOURCE}} \) variation than \( R_{\text{DRAIN}} \) variation. Thus, minimization of \( R_{\text{SOURCE}} \) variation and carefully designed gate geometric structure should be required to obtain the smaller fluctuation of the large-signal characteristics for the MOSFETs composed of multi-finger gates with different geometric structures.

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REFERENCES


