Parameter extraction method for ultra-thin oxide MOSFETs using small-signal channel conductance measurement

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Abstract: — In this paper, a simple parameter extraction method based on the relationship between small-signal channel conductance and gate bias is proposed for ultra-thin oxide MOSFETs using small-signal channel conductance measurement. This method extracts the threshold voltage, source/drain series resistance, gain factor, and two gate field related mobility degradation parameters from the measurement of small-signal conductance of a transistor as a function of dc gate bias with zero drain bias. The technique adopts an empirical mobility model accounting for the high gate-field related mobility degradation that is suitable for MOSFETs with ultra-thin oxide in advanced technology. The effective mobility and effective channel length and width can also be obtained by carrying out the extraction method for devices with different geometries. The extracted results of experimental data obtained by the proposed method are compared with those obtained by the other method. In addition, a good agreement of simulated results to the experimental data is obtained by the proposed method.

Key-Words: — Parameter extraction, mobility model, small-signal channel conductance measurement.

1 Introduction
Threshold voltage, effective channel length and width, inversion layer mobility and source/drain resistances are the essential parameters of the submicrometer MOSFET model [1–3]. The extraction methods related to these parameters stand as a critical issue for technology characterization, device design and circuit level simulation [4–6]. In [7], although the proposed technique eliminates the drain bias related effects, i.e., drain-induced barrier lowering effect (DIBL), channel length modulation and carrier velocity saturation, etc, by setting DC drain bias to zero, it would be unable to account for negative transconductance brought about by ultra-thin oxide devices [8], [9]. This is because that the inversion layer mobility model used in [7] did not take into account the strong dependence of the carrier mobility on the surface roughness scattering that is especially remarkable in the ultra-thin oxide MOSFETs. The oxide thickness of test devices in [7] was 10 nm, which is greater than the one in advanced technology. In the paper by Mclarty [10], the proposed extraction method utilized a suitable mobility model for the ultra-thin oxide, but it did not account for the extraction of the series parasitic resistance. Therefore, in this paper, a new parameters extraction method is proposed to effectively extract the critical parameters such as threshold voltage, effective channel length and width, inversion layer mobility and source/drain resistances of the MOS devices. The method is also suitable for the MOSFETs with different gate oxide thicknesses is proposed, even for the ultra-thin oxide devices. The proposed method is based on the small-signal channel
conductance measurement with zero drain bias voltage and the effects relevant to the drain bias such as DIBL and channel length modulation can be eliminated. Further, the extraction method adopts an empirical mobility model to take into account the carrier mobility degradation in the ultra-thin oxide devices owing to the oxide surface roughness scattering. Finally, the comparisons of the simulated results with the experimental data are presented to verify the validity of the proposed extraction method and a close agreement is obtained. This good agreement verifies the validity of the proposed extraction method in the applications of the parameters extraction for the devices with different gate oxide thicknesses and geometries.

2 Extraction Method

The proposed extraction method is based on the relationship between the small-signal conductance \( g_{\text{dom}} \) and dc gate bias. Figure 1 shows the schematic circuit model of a MOS transistor, where \( g, d \) and \( s \) denote the external nodes, while \( d' \) and \( s' \) denote the internal nodes.

![Schematic circuit model of a MOS transistor](image)

The dc drain current and the small-signal source-drain conductance \( g_{\text{dom}} \) of a MOS transistor in the linear region can be expressed as follows [3]:

\[
I_{ds} = \frac{W_{\text{eff}} C_{ox} \mu_{\text{eff}}}{L_{\text{eff}}} \left[ (V_{gs} - V_{th} - \frac{1}{2} V_{ds} - I_{ds}(R + R_s)) \right] \left[ V_{ds} - I_{ds}(R + R_s) \right] \\
= \frac{W_{\text{eff}} C_{ox} \mu_{\text{eff}}}{L_{\text{eff}}} \left[ V_{gs} - V_{th} - \frac{V_{ds}}{2} \right] V_{ds} = \beta_0 \left[ V_{gs} - V_{th} - \frac{V_{ds}}{2} \right] V_{ds}.
\]

(1)

where \( W_{\text{eff}} \) and \( L_{\text{eff}} \) are the effective channel width and length, respectively, \( C_{ox} \) is the gate capacitance per unit area, \( \mu_{\text{eff}} \) is the effective inversion layer mobility, \( \beta_0 \) is the gain factor, \( R_s \) and \( R_d \) are source and drain series resistance, respectively, \( V_{th} \) is the device threshold voltage, \( V_{ds} \) and \( V_{gs} \) are external drain-source voltage and gate-source voltage, respectively (\( V_{ds} = V_{d's'} + (R_s + R_d) I_{ds}, V_{gs} = V_{gs'} + R_s I_{ds} \)). Then, the measured \( g_{\text{dom}} \) at zero drain bias can be expressed as:

\[
g_{\text{dom}} = \frac{1}{R_T + \frac{1}{g_{ds}}} = \frac{1}{R_T + \frac{1}{\beta_0 (V_{gs} - V_{th})}}.
\]

(3)

where \( R_T \) is the sum of the source and drain series resistance and \( g_{ds} \) is intrinsic channel conductance. In SPICE-based model, the gate-voltage dependent curve of the inversion layer mobility \( \mu_{\text{eff}} \) is expressed as follows [11–12]:

\[
\mu_{\text{eff}} = \frac{\mu_0}{1 + \theta_1 (V_{gs} - V_{th}) + \theta_2 (V_{gs} - V_{th})^2}.
\]

(4)

where \( \mu_0 \) is the low field mobility, and \( \theta_1 \) and \( \theta_2 \) are the mobility degradation parameters. The parameter \( \theta_2 \) is used to describe the strong dependence of the carrier mobility on the surface roughness scattering that may result in the decreasing of the drain current and the negative transconductance as gate bias increases. By introducing eqn. (4) into eqn. (3), we have the following expression:

\[
g_{\text{dom}} = \frac{\beta_0 (V_{gs} - V_{th})}{1 + (\theta_1 + \theta_2) R_T \beta_0 (V_{gs} - V_{th}) + \theta_2 (V_{gs} - V_{th})^2}.
\]

(5)

where \( \beta_0 = W_{\text{eff}} C_{ox} \mu_0 / L_{\text{eff}} \). Then, differentiating once and twice results in the first and second order derivatives, which can be expressed as:

\[
F_1(V_{gs}) = \frac{\partial}{\partial V_{gs}} \left( \frac{1}{g_{\text{dom}}} \right) = \frac{\theta_2}{\beta_0} - \frac{1}{\beta_0} \frac{1}{(V_{gs} - V_{th})^2}.
\]

(6)
From eqn. (6), $F_2(V_{gs})$ is a linear function of $V_{gs}$ and it can be used to determine $V_T$ and $\beta_0$ using linear extrapolation approach. For a given device, by the use of a simple straight-line fit to the numerically derived experimental quantity $(\beta_0/2)^{1/3}(V_{gs}-V_T)$ in the plot of $F_2(V_{gs})$ versus $V_{gs}$, $V_T$ and $\beta_0$ can be obtained from the $x$-axis intercept and slope, respectively. According to eqn. (6), the extracted $V_T$ and $\beta_0$ serves to generate a plot of $F_1(V_{gs})$ versus $1/(V_{gs}-V_T)^2$, which can be used to extract $\theta_2$ from the $y$-axis intercept of a best curve-fit of experimental data $F_1(V_{gs})$. After extracting $V_T$, $\beta_0$ and $\theta_2$, the two remaining parameters $R_T$ and $\theta_1$ can be determined by optimization to fit eqn. (5) to the measured data $g_{ds,m}$. By performing the above extraction procedure for devices with several different geometries fabricated by the same technology where, the relationship between parameter $\beta_0$ and $W_{\text{drawn}}$, and the relationship between parameter $1/\beta_0$ and $L_{\text{drawn}}$ can both be obtained [13].

With the standard relationships: $L_{\text{eff}} = (L_{\text{drawn}} - \Delta L)$, and $W_{\text{eff}} = (W_{\text{drawn}} - \Delta W)$ [4], where $\Delta L$ and $\Delta W$ are taken as constant, the parameter $\beta_0$ can be expressed as:

$$\beta_0 = \frac{(W_{\text{drawn}} - \Delta W)}{(L_{\text{drawn}} - \Delta L)} \cdot C_{ox} \cdot \mu_0$$  \hspace{1cm} (8)

From eqn. (8), the plots of $\beta_0$ versus $W_{\text{drawn}}$ and $1/\beta_0$ versus $L_{\text{drawn}}$ can be used to determine the effective values of $W$ and $L$ by linear extrapolation, respectively [13]. Besides, in the plot of $1/\beta_0$ versus $L_{\text{drawn}}$, the $\mu_0$ can also be obtained from the slope of the best-fit linear line for the experimental data.

3 Experimental Results

Fig. 2 shows the linear plots of $F_2(V_{gs})$ versus $V_{gs}$ for devices with different gate oxide thicknesses. In this figure, both $V_T$ and $\beta_0$ can be obtained from the $x$-axis intercept and slope, respectively, of the best-fit straight line of the measured data for each device.

Fig. 3 shows the linear plots of $F_1(V_{gs})$ versus $1/(V_{gs}-V_T)^2$ for devices with different gate oxide thickness. According to eqn. (6), $\theta_2$ can be determined from the $y$-axis intercept of the best straight-line fit of the measured data for each device. With the extracted $V_T$, $\beta_0$ and $\theta_2$, we determine the remaining parameters $R_T$ and $\theta_1$ by optimization to fit eqn. (5) to the experimental data $g_{ds,m}$. Then, by making use of the extracted values $\beta_0$ of devices with different geometries, we can determine the parameters $\Delta L$, $\Delta W$ and $\mu_0$. 

Fig. 3. The plots of $F_1(V_{gs})$ versus $1/(V_{gs}-V_T)^2$ for $n$-MOSFETs with different oxide thicknesses. The
device parameters: \(W_{\text{drawn}} = 10 \, \mu\text{m}, \; L_{\text{drawn}} = 0.5 \mu\text{m}\) and \(V_{\text{ds}} = 0 \, \text{V}\).

Figures 4 shows the plot of effective inversion layer mobility \(\mu_{\text{eff}}\) versus gate bias \(V_{\text{gs}}\) obtained by the proposed method and previous one [7, 10] and [14]. The effective mobility \(\mu_{\text{eff}}\) as a function of gate bias can be extracted from the \(g_{\text{ds}}\) directly [4], where \(g_{\text{ds}}\) is determined according to Eq. (3). From the figure., we could find that the extracted \(\mu_{\text{eff}}\) has a significant raise with reducing \(V_{\text{gs}}\) to just above \(V_T\). This is due to the failure of the approximation of inversion layer charges \(Q_n\) using equation: \(Q_n = C_{\text{ox}}(V_{\text{gs}} - V_T)\) when \(V_{\text{gs}}\) approaches \(V_T\) [4]. Further, in this figure, it is seen that, for 20 Å oxide device, the effective mobility calculated by Eq. (4) in [7] deviates from the one obtained from experimental data by Eq. (2) in [7] as \(V_{\text{gs}}\) increases. Therefore, the mobility model used in [7] cannot well predict the actual carrier mobility in the strong inversion region when the gate oxide thickness is very thin. This is because that the increasing gate electric field as oxide thickness reduces would make the dependence of carrier mobility on surface roughness scattering get stronger and decrease the effective mobility.

In Fig. 5, it is seen that the simulated results obtained by the proposed method agree well with the experimental data of devices with different oxide thicknesses. The simulated results obtained by the previous method in [7] have a significant deviation from the measured data of ultra thin oxide device as gate voltage increases. This is because that it did not account for the strong dependence of the carrier mobility on the surface roughness scattering that is included in the present model through the mobility model. Good agreements between the results obtained from the present model and measured data demonstrate that the proposed model is reliable and suitable for the parameter extractions of MOS devices.

Fig. 5. The curves of the experimental data \(g_{\text{ds}}\) as a function of the gate voltage \(V_{\text{gs}}\) and simulation results calculated by using both two methods for n-MOSFETs with different gate oxide thicknesses.

### 4 Conclusions

A simple parameter extraction method, based on the relationship between small-signal channel conductance and gate bias and use small-signal channel conductance measurement, is proposed for the simultaneous extractions of threshold voltage \(V_T\), sum of drain and source series resistance \(R_T\), gain factor \(\beta_{\text{eff}}\), and mobility...
degradation parameters $\theta_1$ and $\theta_2$ of MOSFETs with different gate oxide thicknesses. By carrying out the extraction method for devices with different geometries, the effective channel length $L_{\text{eff}}$ and width $W_{\text{eff}}$ can be also obtained. The proposed method is shown to provide a good agreement to the experimental data for devices with different gate oxide thicknesses.

References: