STABLE EXTRACTION OF THRESHOLD VOLTAGE USING TRANSCONDUCTANCE CHANGE METHOD

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I. Introduction

Threshold voltage (V_{TH}) is a very important parameter for MOSFET modeling, simulation and characterization. Many V_{TH} extraction method has been proposed [1-2]. Among these methods, only the transconductance change method can yield a result that approaches the classically-defined threshold voltage and eliminate the effects of the mobility degradation and parasitic resistance [3]. However, since in this method the second derivative of drain current (I_{DS}) is required, this method tends to be very noisy [4]. The problem of numerical differentiation is known to be ill-posed in the sense that small perturbations of the function to be differentiated may lead to large errors in the computed derivative. Additionally, in simulation and measurement, most of errors come from round-off and truncation [5]. There is always a trade-off: as nodes are set to be denser, data reflect the rapid variation better while differentiation of the data gets more noise [6]. In this paper, we propose a stable extraction method for the threshold voltage defined bt the transconductance change, using optimized node intervals. Here, "stable" means that small changes in the initial data should give only correspondingly small changes in the final results

Ⅱ. Stable Extraction of V_{TH}

In the transconductance change method, the threshold voltage is defined as the gate voltage at which the derivative of the low drain voltage transconductance dg_m/dV_{GS} ($=g_{m2}$) is maximum. Therefore, a smooth g_{m2} profile without noise leads to the exact threshold voltage.

In the first place, the optimal node interval for g_m will be derived. When the drain current is simulated or measured, some errors result from round-off and truncation. We take them into account by introducing an absolute error δ. The exact drain current becomes $I_{DS} = I_{DSm} + \delta$, where I_{DSm} is extracted drain current. Considering δ, we can get

$$g_m + dg_m = dI_{DSm} / dV_{GS} = d(I_{DS} - \delta) / dV_{GS}$$
$$= dI_{DS} / dV_{GS} - d\delta / dV_{GS}. \quad (1)$$

From (1), it can be shown that

$$dg_m = - d\delta/dV_{GS}. \quad (2)$$

The relative error is derived as below:

$$dg_m / g_m = - (d\delta / dV_{GS}) / (dI_{DS} / dV_{GS})$$
$$= -d\delta / dI_{DS} \approx \Delta\delta / \Delta I_{DS}. \quad (3)$$

It may look problematic because δ is unknown. However, in practice, we can get an error bound for δ, that is, a number β such that $|\delta| \leq \beta$. β represents a characteristic sum of round-off and truncation errors. Eq. (3) becomes

$$dg_m / g_m \approx \Delta\delta / \Delta I_{DS} = 2\beta / \Delta I_{DS}. \quad (4)$$

If we want less than one percent error in g_m, the condition is derived as

$$\Delta I_{DS} \geq 200\beta. \quad (5)$$

For g_m is approximated to $\Delta I_{DS} / dV_{GS}$, from Eq. (5), the optimal interval for g_m is defined as

$$\Delta V_{GS} = \Delta I_{DS} / g_m \geq 200\beta / g_m. \quad (6)$$

Referring to results above, the optimal node interval for g_{m2} is obtained. Assuming $g_m = g_{mm} + \varepsilon$, case is the same. g_m is the true value of dI_{DS} / dV_{GS}, g_{mm} is the dI_{DS} / dV_{GS} from Eq. (1) to Eq. (6) and ε is the calculation error. Note that g_{mm} means g_m in Eq. (1) to Eq. (6). We obtained the optimal node interval for g_{m2} as

$$\Delta V_{GS} = \Delta g_m / g_{m2} \geq 200\gamma / g_{m2}. \quad (7)$$

where γ means an error bound for ε, which requires $|\delta| \leq \gamma$. From the condition of one-percent error above, it is found that γ is equal to 0.01 times g_m. Thus, Eq. (7) can be rewritten into

$$\Delta V_{GS} \geq 2g_m / g_{m2}. \quad (8)$$

To profile g_{m2} with minimum loss of details, condition (6) and (8) should be satisfied at the same time. Finally, the optimal node interval for accurate g_{m2} becomes

$$\Delta V_{GS} \geq \max(200\beta / g_m,\ 2g_m / g_{m2}). \quad (9)$$

By this criterion, g_{m2} is obtained within one percent error.

Ⅲ. Results and Discussion

The condition (9) is applied to simulation by estimating next node interval from g_m and g_{m2} derived referring to previous three data nodes. MEDICI is adopted as a simulator. The error bound β is estimated by preceding calculation results. Fig. 1 shows the key algorithm for optimal node derivation. Adopting the algorithm leads to g_{m2} profile satisfying one-percent noise criterion as shown in Fig. 2. The simulation was done to a 1.5μm channel nMOSFET with 25nm thick gate oxide at 0.1 V drain bias. Considering the noisy profile measured from uniform node interval in the inset figure, the improvement is prominent. V_{TH}(P), V_{TH}(LE) and V_{TH}(TC) represent threshold voltage of classical definition ($\phi_s = 2\phi_f + V_{SB}$), linear extrapolation method and transconductance change method, respectively. V_{TH}(TC) extracted by our algorithm is very close to V_{TH}(P). Our algorithm extracts reliable V_{TH}(TC) with gate length variation as shown Fig. 3.

Ⅳ. Conclusions

We have demonstrated a stable extraction algorithm for g_{m2} by optimizing node interval. With the algorithm, g_{m2} can be extracted within one-percent error, which leads to more exact threshold voltage calculation. It can provide a big help in device characterization.

Acknowledgements

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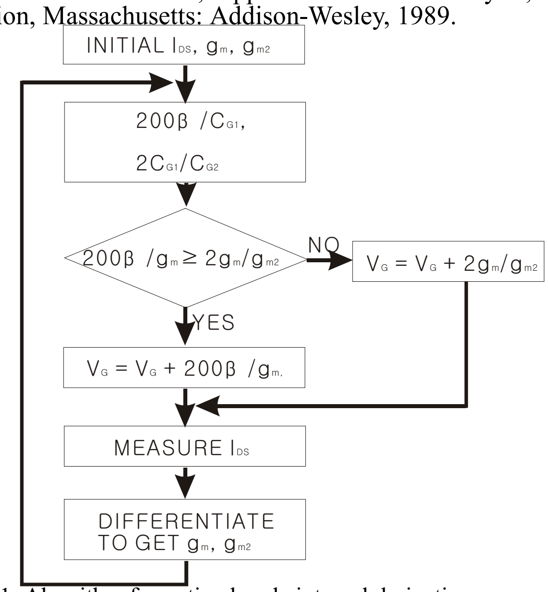

Fig. 1. Algorithm for optimal node interval derivation.

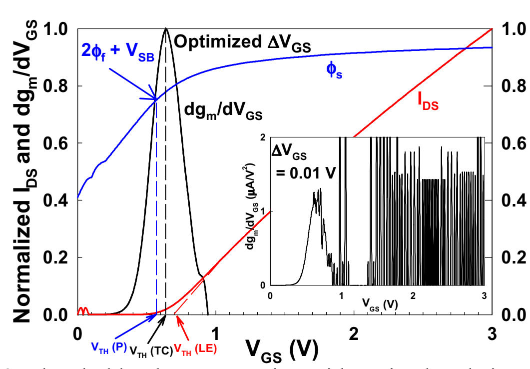

Fig. 2. Threshold voltage extraction with optimal node interval.

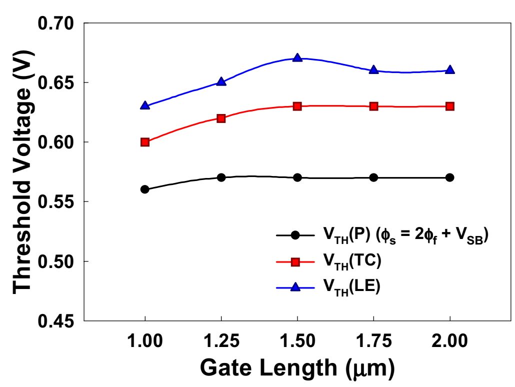

Fig. 3. Comparison of a variety of threshold extraction methods.