# DC MODELING OF COMPOSITE MOS TRANSISTORS

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### Abstract

*Mixed-signal circuit design on sea-of-gates arrays requires the use of composite MOSTs, combinations of in-series and in-parallel connected unit MOSTs. To avoid an increase in circuit simulation complexity these are in general replaced by artificial single MOSTs. The analysis in this paper shows that a straightforward replacement will lead to incorrect results. Series MOSTs (in-series connected unit MOSTs) are essentially different from single MOSTs due to the presence of diffusion areas interrupting the channel at regular distances. The influence of lateral diffusion, charge sharing, and series resistance needs to be reconsidered. The theoretical results are confirmed by measurements on an experimental IC. Parameter decks of existing MOST models for circuit level simulation can be modified easily to reflect the length dependences of composite MOST parameters.*

## Motivation

In mixed-signal designs on digital sea-of-gates arrays, replacements of single wide and long MOSTs in the analog section are obtained by connecting unit MOSTs in-parallel or in-series respectively (see Fig. 1). In general every composite MOST is replaced by an artificial single MOST, with a $W$ and $L$ equal to the summed gate dimensions of the unit MOSTs in the composite MOST (see Fig. 1) [1,2], to avoid an increase in circuit simulation complexity. For accurate results the geometry dependences of device parameters have to be taken into account. On sea-of-gates arrays unit MOSTs are relatively wide, minimum length devices. Therefore the influence of width dependences (narrow-channel effects) is negligible, while that of length dependences (short-channel effects) is considerable. Furthermore, considering the electrical behavior, there are no differences between in-parallel connected unit MOSTs and wide MOSTs, while in-series connected unit MOSTs differ from long channel MOSTs due to the presence of diffusion areas interrupting the channel at regular distances (see

Fig. 1a). For these reasons an interesting subject for study is a comparison between series MOSTs (in-series connected unit MOSTs) and single MOSTs.

## Theory

In a series MOST only the last unit MOST, coming from the source side, may operate in saturation. All other unit MOSTs operate in the linear region. Short-channel effects related to the behavior in saturation are thus related to the drain diffusion of the last MOST and not to the intermediate diffusion areas. Therefore attention is focused on the behavior in the linear region. In this region the behavior of a MOST is described by

$$I_{DS} = \beta\left[(V_{GS} - V_T)V_{DS} - V_{DS}^2/2\right]/\left[1 + \theta(V_{GS} - V_T)\right] \tag{1}$$

where $V_T = V_{T0} + \gamma\left(\sqrt{\phi_B - V_{BS}} - \sqrt{\phi_B}\right)$, $\beta = (W/L)\mu_{so}C_{ox}$ and all parameters have their usual meaning [3]. The intermediate diffusion areas reduce the effective channel length $L$, by lateral diffusion, and introduce additional charge sharing and series resistance.

### Lateral Diffusion

For single MOSTs $\beta$ is inversely proportional to the effective length $L = L_m$-$L_{DT}$. If $1/\beta$ is plotted as a function of the layout mask length $L_m$, the intercept with the horizontal axis yields the lateral diffusion $L_{DT}$ (see Fig. 2). For series MOSTs $\beta$ is inversely proportional to $L = n(L_{mu}$-$L_{DT})$ ($n$: number of unit MOSTs, suffix $u$: unit MOST). Due to the proportional increase in $L_{DT}$, $\beta$ is inversely proportional to the layout length $L_m = nL_{mu}$ (see Fig. 2). For series MOSTs and single MOSTs with identical layout mask lengths, the effective length of the series MOST is shorter.

### Charge Sharing

Charge sharing is the lowering of the effective bulk charge underneath the gate due to the presence of source and drain-bulk junction depletion space charges. For single MOSTs the influence of this effect decreases with increasing effective channel length $L$. The result is an increase in $V_{T0}$ and $\gamma$ with increasing channel length or a decrease in $V_{T0}$ and $\gamma$ proportional to $1/L$. For series MOSTs increasing channel length implies addition of intermediate diffusion areas. The influence of charge sharing is thus independent of channel length. As a consequence $V_{T0}$ and $\gamma$ are constant and equal to the values for unit MOSTs.

### Series Resistance

The effective mobility coefficient $\theta$, incorporates both the influence of the mobility reduction due to the vertical electrical field and the influence of series resistance [4]: $\theta = \theta_0 + \beta R_T$ ($R_T$: total series resistance). For single MOSTs $\theta$ increases proportional to $1/L$ due the $\beta$ dependence. If every unit MOST in a series MOST contributes an identical series resistance $R_{tu}$, an increase in length implies a proportional increase of the series resistance. This results in a constant effective mobility reduction coefficient: $\theta = \theta_0 + \beta_u R_{Tu}$ [5]. Contributions that are length independent, such as resistance due to contacting at the source and drain of composite MOSTs, result in a similar length dependence as for single MOSTs: $\theta = \theta_0 + \beta_u R_{Tu} + \beta R_{T,ct}$.($R_{T,ct}$: contact resistance).

## Experimental Results

An IC has been designed with single and series NMOSTs with layout lengths $L_m$ of 2.5, 7.5, 17.5, and 27.5 μm and a layout width $W_{mu}$ of 13.75 μm. The length dependences are obtained by automated waferscale measurements. The parameters $\beta$, $V_{T0}$, $\gamma$, and $\theta$ are extracted from $I_{DS}$ - $V_{GS}$ characteristics, measured at a low $V_{DS}$ bias. Every data point in Fig. 3, Fig. 4, and Fig. 5 represents the mean value of 180 devices. The error bars indicate the standard deviation.

Expected differences in $\beta$ length dependences (see Fig. 2) are confirmed by the extraction results. The lateral diffusion $L_{DT}$ is 160 nm. The trends in $V_{T0}$ and $\gamma$, plotted in Fig. 3 and Fig. 4 confirm the expected differences in the influence of charge sharing. The differences between long channel series and single MOSTs are relatively small, because the unit MOSTs are relatively long. The trends in $\theta$ plotted in Fig. 5 are explained by the developed theory as well. Layout differences cause the difference in $\theta$ for unit sized series and single MOSTs. Independently obtained data from PCM measurements confirm that for single MOSTs the length dependence in $\theta$ is caused by the total resistance. For the series MOSTs it is only the resistance of the source and drain contacts that contributes to the length dependence in $\theta$.

## Circuit Simulation

In general a parameter deck of a circuit level simulation MOST model specifies device parameters for long channel MOSTs and a set of scaling parameters that represent the influence of device length on the long-channel parameters. Based on the developed theory a parameter deck for composite MOSTs can be obtained easily, by modifying the values of long-channel and the scaling parameters that represent the influence of lateral diffusion, charge sharing, and series resistance.

For instance for a model based on (1) the following modifications should be made. Instead of layout lengths, effective length should be specified. Parameters modeling the influence of charge sharing have to be disabled. $V_{T0}$ and $\gamma$ values of long channel single MOSTs have to be replaced by values of unit sized MOSTs. Long channel values of $\theta$ have to include the series resistance that is identical for every unit MOST. The length dependent part of $\theta$ have to be based on the contribution of the contact resistance.

## Conclusions

For single and composite MOSTs length dependences of the parameters representing the influence of lateral diffusion, charge sharing, and series resistance, are fundamentally different. For the considered process the resulting differences are relatively small, for more state of the art processes these will be significant. A simple method is presented to incorporate these differences in existing MOST models for circuit level simulations.

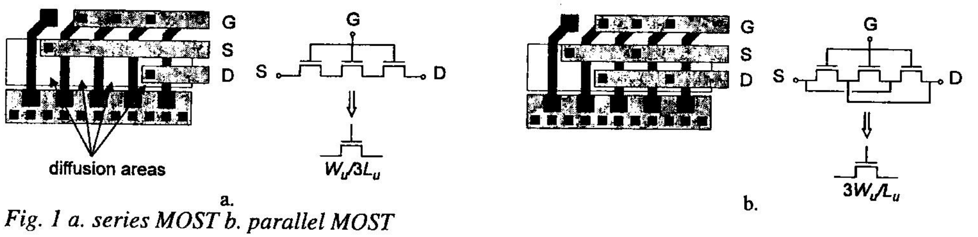
[1] P.P. Duchene, M.J. Declerq, B. Goffart, M. Novak, "Analog Circuit Implementation on CMOS Semi-Custom Arrays", *IEEE JSSC*, vol 28, no 7, pp 872-874, 1993

[2] R. van Dongen, V. Rikkink, "Advanced Analog Circuit Design on a Digital Sea-of-Gates Array", *Proceedings EDT 1994*, pp 70-74, IEEE Press, 1994

[3] Y.P. Tsividis, "Operation and Modeling of the MOS Transistor", McGraw-Hill, 1988

[4] H.C. de Graaff, F.M. Klaassen, "Compact Transistor Modelling for Circuit Design", Springer, 1990

[5] P.E. de Haan, "Analog Circuit Design on Digital Sea-of-Gates Arrays", Ph.D. Thesis, University of Twente, to be published (1995)



a.

b.

*Fig. 1 a. series MOST b. parallel MOST*

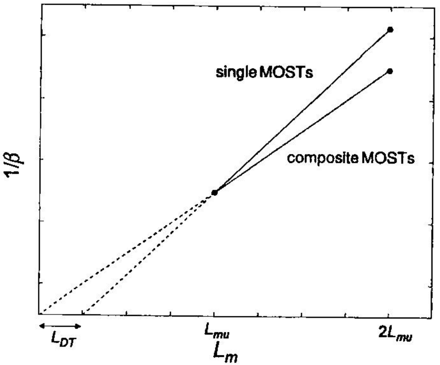


*Fig. 2 β length dependence*

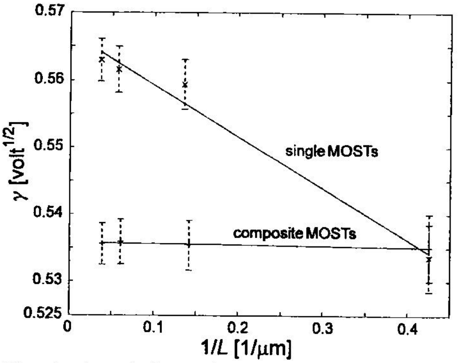


*Fig. 4 γ length dependence*

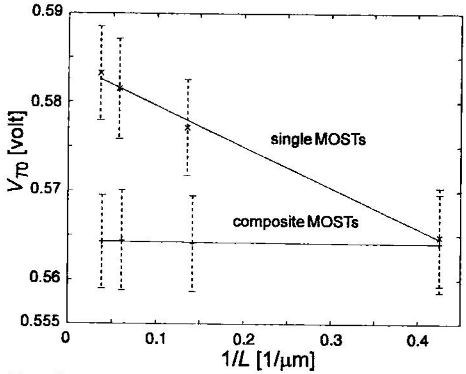


*Fig. 3 $V_{T0}$ length dependence*

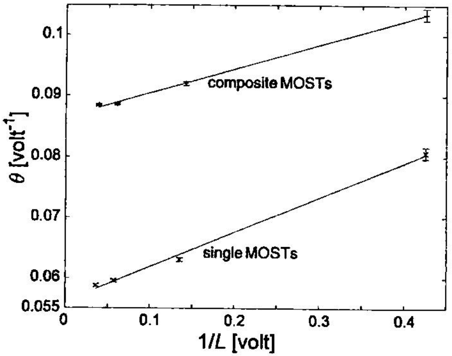


*Fig. 5 θ length dependence*