Tolerances Analysis of MOSFET Integrated Circuits Performances

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Abstract: - In the design and optimization phase of analog integrated circuit conception, a topology is obtained and a value is affected to each parameter of the system yielding the best performance. However, during the manufacturing process the real values of these parameters will deviate in a more or less important way from the computed values, which will produce fluctuations of the performance. Tolerance analysis is needed to estimate the maximum possible fluctuations of the performance, but most of tolerance analysis methods are only applied to systems defined by their electrical parameters, while designers have access only to technological parameters. An efficient and original approach consists in performing the analysis by taking into account tolerances of the technological parameters instead of electrical parameters. This paper presents tolerance analysis method applied to analog integrated circuit realized in CMOS technology, where the maximum fluctuations of the performance are established with respect to tolerances of technological parameters, like dimensions or oxide capacitance.

Key-Words: - Tolerance analysis, Sensitivity, MOSFET, Electrical & technological parameters,

1 Introduction

The precision of electronic systems needs to be the more exact as possible and a small deviation of a circuit performance from its theoretical optimized value may have dramatic consequences on its behaviour. In analog integrated circuits conception, during the phase of design and optimization a topology and a set of component parameters are put in evidence in order to get the best system performance. Unfortunately, there is no guarantee that the real values of the circuit parameters will be the same as the optimized values. Indeed, with the continuous down scaling of circuits, accurate control of every step of the fabrication process becomes more and more difficult and provides differences between computed values and fabricated values. That may affect the performance of the circuit in an unpredictable way. For a device or a circuit manufacturers indicate for each performance, in the best case, the nominal value and the upper and the lower bonds of an acceptability interval. Generally these values are obtained after performing measurement of an important number of samples and not previously computed.

Tolerance analysis is necessary to estimate in which way the fluctuations of the parameters can modify the systems performances. The goal is, considering tolerances on each device parameter in the circuit, to ensure that the circuit performance won't be outside a pre-established interval of acceptability, before manufacturing samples.

Statistical methods have been developed for estimating the circuit performance spread and hence the parametric yield prior to fabrication [1 - 3]. There are methods based on Monte Carlo analysis [4] but time consuming since an important amount of simulation is necessary to produce useful results. Furthermore, statistical methods need also more data like the statistic distribution of each circuit parameter. This is not useful in case of computing the maximum deviations of a performance, which is our goal. Worst-case tolerance analysis may produce interesting results [5 - 6] but presuming the monotonicity between circuit response and circuit parameters it is not appropriate in case of non-monotonicity and therefore deficient.

The major problem is that these methods consider only tolerances of component parameters (resistances, capacitances, etc), which often are elements of equivalent models in which the designer has no direct access. Indeed, he only knows tolerances of the technological parameters (dimensions, charge carriers concentration, etc.) while tolerances of electrical parameters can only be estimated. For a better accuracy of the tolerance analysis, the best way is to consider the technological parameters fluctuations. The idea of taking into account the transistors dimensions in a sensitivity analysis has few been considered [7], but never applied to tolerance analysis.

2 Sensitivity Analysis

An important part of tolerance analysis methods begins with sensitivities computation. Sensitivities are well known for their usefulness in tolerance analysis [1, 6, 8]. Furthermore with sensitivities it is possible to estimate the degree of influence of each parameter in a circuit [9].

2.1 First-Order sensitivity

Consider a circuit having n parameters denoted h_1, h_2 and so on to h_n, and a performance F (for example the gain of a voltage amplifier).

The first-order normalized sensitivity of F with respect to the parameter h_i , denoted S_{h_i} is :

$$S_{h_i} = \frac{h_i}{F} \cdot \frac{\partial F}{\partial h_i} \qquad (1)$$

Generally, a parameter h_i is considered as an influent parameter if the sensitivity S_{h_i} has a magnitude greater than 0.5. If the magnitude of S_{h_i} is smaller than 0.1 the parameter is considered as a few or not influent parameter.

However, the value of the first-order relative sensitivity may be not sufficient to estimate the degree of influence of a parameter h_i, especially when the evolution of the performance leads to an extremum (maximum or minimum) value of F. This case occurs especially after an optimization procedure of the performances. Consequently, the first-order sensitivity is very small but it doesn't mean that the parameter is not influent. Small fluctuations of the parameter around its optimized theoretical value could produce important changes in the performances values.

2.2 Second- and Higher-Order sensitivities

To complete with accuracy the sensitivity analysis, it is necessary to get the second order sensitivity of F with respect to the parameter h_i, noted $S^2_{h_i}$ and given by (2).

$$S^2_{h_i} = \frac{1}{2} \cdot \frac{{h_i}^2}{F} \cdot \frac{\partial^2 F}{\partial {h_i}^2} \qquad (2)$$

This sensitivity is called single second-order relative sensitivity, because computed with respect to a single parameter. In order to get the degree of influence of the parameter h_i, the sensitivities S_{h_i} and $S^2_{h_i}$ are compared. If the magnitude of $S^2_{h_i}$ is very greater than the magnitude of S_{h_i}, it is this second-order sensitivity which has to be considered to establish the degree of influence of the parameter h_i.

Expression (3) is the cross second-order relative sensitivity with respect to two different parameters h_i and h_j ($i \neq j$):

$$S^2_{h_i h_j} = \frac{h_i . h_j}{F} \cdot \frac{\partial^2 F}{\partial h_i \, \partial h_j} \qquad (3)$$

With these second-order sensitivities $S^2_{h_i h_j}$ after comparisons with the other first and single second-order single sensitivities, it should be possible to put in evidence the more important correlations between different parameters of the circuit under study.

2.3 Polynomial approximations of the performances

Knowing the values of the sensitivities allows to build a polynomial approximation of the performance F by the use of the Taylor series development. With fluctuations of the parameters weaker than 20%, one can consider that the second-order Taylor series is a good approximation of the performance behavior around its theoretical value. The expression of the relative fluctuations of the performance F, with respect to the relative variations of the n parameters of the circuit, is obtained from expression (4.a):

$$\begin{aligned} F(h_1 + \Delta h_1, ..., h_n + \Delta h_n) &= F + \Delta F \\ &= F + \sum_{i=1}^{n} \frac{\partial F}{\partial h_i} \Delta h_i + \sum_{i=1}^{n} \frac{1}{2} \cdot \frac{\partial^2 F}{\partial {h_i}^2} \Delta h_i \\ & \sum_{\substack{i=1 \\ j=1 \\ i \neq j}}^{n} \frac{\partial F}{\partial h_i} \cdot \frac{\partial F}{\partial h_j} . \Delta h_i . \Delta h_j \end{aligned} \qquad (4.a)$$

and introducing the sensibilities, we have:

$$\begin{aligned} \frac{\Delta F}{F} &= \sum_{i=1}^{n} S_{h_i} \cdot \left(\frac{\Delta h_i}{h_i} \right) + \sum_{i=1}^{n} S^2_{h_i} \cdot \left(\frac{\Delta h_i}{h_i} \right)^2 \\ &+ \sum_{i=1}^{n} \left(\frac{\Delta h_i}{h_i} \right) \cdot \left[\sum_{\substack{j=1 \\ j \neq i}}^{n} S^2_{h_i h_j} \cdot \left(\frac{\Delta h_j}{h_j} \right) \right] \end{aligned} \qquad (4.b)$$

3 Tolerance Analysis

3.1 Definition

Let us consider an analog integrated MOSFET circuit. This circuit has a target performance noted F.

Each MOSFET is described by its geometrical and technological parameters. The circuit has n parameters (h_1, h_2 and so on to h_n). Each parameter h_i has a nominal value obtained in the design and optimization phase and noted h_{i0}. The actual value of h_i resulting after manufacturing is $h_{i0}+\Delta h_i$, where Δh_i is a positive or negative deviation.

If the nominal value of the performance established during the design and optimization phase is noted F_0, its effective value is $F_0+\Delta F$, ΔF being a positive or negative value.

Tolerance analysis consists, given the maximum deviations $|\Delta h_i|_{max}$ for all the n parameters, to establish the upper- and lower-bond of F, denoted respectively F_{min} and F_{max}. Consequently, it will be possible to ensure that $F_{min} < F < F_{max}$. If the acceptability interval of the performance remains inside this domain, the circuit robustness is guarantee.

3.2 Method

The analysis starts with the computation of all the first- and second-order sensitivities of the performance F with respect to all the parameters. With these results a polynomial approximation of F around its nominal value is available.

The core of the method is an optimization procedure, based on the gradient method [10] and, therefore, an iterative method. If the number of parameters is important, the number of iterations may become important.

In order to reduce the number of iterations we have considered that for an important number of parameters, the monotonic variation of the parameter from $h_i - |\Delta h_i|_{max}$ to $h_i + |\Delta h_i|_{max}$ may produce a monotonic evolution of the performance, increasing or decreasing. These parameters are called monotonic parameters and, if a part of them are previously put in evidence, they won't need to be considered in the gradient method procedure [15].

A parameter h_i is monotonic if the sign of the derivative with respect to it doesn't change. A positive sign of the derivative makes the performance F increasing with respect to h_i. A negative sign makes the opposite. If we consider expression (4.b), we can establish its derivative with respect to $\Delta h_i/h_{i0}$, which is also a polynomial expression given by:

$$\frac{\partial(\Delta F/F_0)}{\partial(\Delta h_i/h_{i0})} = \sum_{i=1}^{n} S_{h_i} + 2.\sum_{i=1}^{n} S_{h_i}^2 \cdot \left(\frac{\Delta h_i}{h_{i0}}\right) + \sum_{i=1}^{n}\left[\sum_{\substack{j=1\\ j\neq i}}^{n} S_{h_i h_j}^2 \cdot \left(\frac{\Delta h_j}{h_{j0}}\right)\right] \quad (5)$$

Each monome of this expression has a minimum and a maximum value. By adding, in one hand, the minimum values and, on the other hand, the maximum values of all the monomes, it's possible to get two values: $D_{h_i}^{min}$ and $D_{h_i}^{max}$, such as $D_{h_i}^{min} < \frac{\partial(\Delta F/F_0)}{\partial(\Delta h_i/h_{i0})} < D_{h_i}^{max}$. Finally, if $D_{h_i}^{min}$ and $D_{h_i}^{max}$ have the same sign, h_i is considered monotonic [15].

The phase of optimization with gradient method is run only on the set of non-monotonic parameters and, consequently, the computation time is significantly shortened. Finally, the values of F_{min} and F_{max} are provided.

In summary, there are three steps:
- computation of first- and second-order relative sensitivities of the performance with respect to all parameters.
- search of monotonic parameters.
- application of iterative gradient method with the remaining parameters.

4 The MOSFET and its parameters

Fig.1 represents a simple 3-D view of the NMOS transistor structure. The PMOS transistor structure is the complementary of Fig.1, N+ region being replaced with P+ region and N zone being replaced with P zone [14].

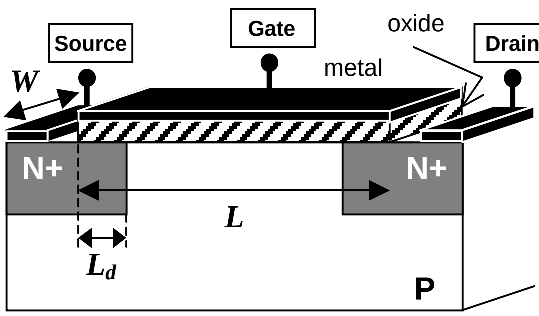

Fig.1 3-D view of the NMOS transistor structure.

The N channel MOSFET is mainly characterized by five technological parameters which are:
- the length of the gate ***L***
- the width of the gate ***W***
- the overlap length L_d
- the oxide capacitance of the gate C_{ox}
- the mobility of charge carriers in the channel μ_n (or μ_p for a P channel MOSFET)

As the access to the mobility of the carriers in the channel is extremely complex, we have chosen to consider this parameter as a constant value. The influence of the substrate and the effects of the source-substrate voltage have been neglected. Therefore, the threshold voltage of the transistor is given as a constant value.

The choice of the transistor or circuit model is depending on its role [11] and also on the wanted precision which can induce resistive, capacitive and inductive elements [12]. We have decided to consider, for the moment, only the case of MOSFET being an active linear component for analog applications, working in the saturation mode.

The drain current of the NMOS transistor is given by expression (6), where $K_{Pn} = \mu_n.C_{ox}$, V_{Tn} is the threshold voltage, V_{GS} and V_{DS} are respectively the gate-source and drain-source voltage, and λ is the channel-length modulation parameter.

$$I_D = \frac{1}{2}.\frac{W}{L}.K_{Pn}.\left(V_{GS} - V_{Tn}\right)^2.\left(1+\lambda.V_{DS}\right) \qquad (6)$$

The employed small signal equivalent model is the most simple [14]. It is presented in Fig.2 and is characterized by four electrical parameters which are:

- the gate-drain capacitance $\boldsymbol{C_{gd}}$
- the gate-source capacitance $\boldsymbol{C_{gs}}$
- the output conductance $\boldsymbol{r_0}$
- the transconductance $\boldsymbol{g_m}$

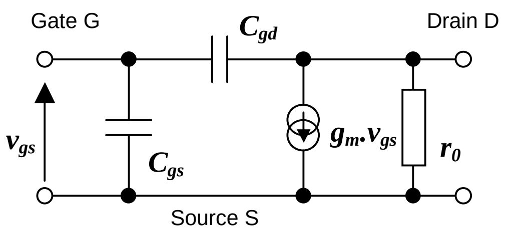

Fig.2 MOSFET small-signal equivalent model.

The links between electrical and technological parameters of the transistor are given by expressions (7) to (10).

$$C_{gs} = \frac{2}{3}.W.(L - 2.L_d).C_{ox} + W.L_d.C_{ox} \qquad (7)$$

$$C_{gd} = W.L_d.C_{ox} \qquad (8)$$

$$r_0 = \frac{1}{\lambda}.\frac{1}{\frac{1}{2}.\frac{W}{L}.K_{Pn}.\left(V_{GS} - V_{Tn}\right)^2} \qquad (9)$$

$$g_m = \frac{W}{L}.K_{Pn}.\left(V_{GS} - V_{Tn}\right) \qquad (10)$$

The simplified equivalent circuit of the MOSFET has been implemented in SAMI, a sensitivities computation software developed in our university [13]. From now on, after having computed the value of the target performance F, it can compute sensitivities with respect to the four electrical parameters of each MOS transistor in the circuit.

In order to take into account the influence of the technological parameters, we have added a module in SAMI. Given the sensitivities with respect to the four electrical parameters of each transistor, it computes sensitivities with respect to the four technological parameters of each transistor.

For example, consider the gate length L of a MOSFET (see Fig.1), we deduce from expressions (7) to (10) the first-order derivatives of C_{gs}, C_{gd}, r_0 and g_m with respect to L.

$$\frac{\partial C_{gs}}{\partial L} = \frac{2}{3}.W.C_{ox} \qquad (11)$$

$$\frac{\partial C_{gd}}{\partial L} = 0 \qquad (12)$$

$$\frac{\partial r_0}{\partial L} = \frac{1}{\lambda}.\frac{1}{\frac{1}{2}.W.K_{Pn}.\left(V_{GS} - V_{Tn}\right)^2} \qquad (13)$$

$$\frac{\partial g_m}{\partial L} = \frac{-W}{L^2}.K_{Pn}.\left(V_{GS} - V_{Tn}\right) \qquad (14)$$

Then, using the relative sensitivities of the performance F with respect to the four electrical parameters ($S_{C_{gs}}, S_{C_{gd}}, S_{r_0}$, and S_{g_m}) given by expression (1), one can deduce (introducing equations (11) to (14)) the expression of the relative sensitivity of F with respect to L:

$$S_L = \frac{L}{F}.\frac{\partial F}{\partial L} = S_{C_{gs}}.\frac{L}{C_{gs}}.\frac{\partial C_{gs}}{\partial L} + S_{C_{gd}}.\frac{L}{C_{gd}}.\frac{\partial C_{gd}}{\partial L}$$
$$+S_{r_0}.\frac{L}{r_0}.\frac{\partial r_0}{\partial L} + S_{g_m}.\frac{L}{g_m}.\frac{\partial g_m}{\partial L} \qquad (15)$$

It's necessary to apply an identical method in order to get the other first-order sensitivities S_W, S_{L_d} and $S_{C_{ox}}$, and the second-order sensitivities.

5 Applications

In order to validate our method, we have chosen to apply it to elementary CMOS analog circuits [16 - 17].

5.1 Common Source Amplifier

The first circuit is the common-source amplifier cell shown in Fig.3 and realized in 1µm technology. It is a NMOS transistor, Q_N, biased with a PMOS transistor, Q_P. Both transistors are biased with respectively a DC gate potential of 1.05V for Q_N

and 3.85V for Q_P. The technological parameters are given in Fig.3. Index n/N is for Q_N and index p/P is for Q_P; gate lengths are the same for both transistors. In Table 1 are given characteristics (bias drain current I_D, oxide capacitance C_{ox}, threshold voltage V_T, C_{gd} and C_{gs} capacitances, output conductance r_0, and transconductance g_m) of Q_N and Q_P. The input resistance R_s is 100kΩ. The frequency is 1kHz.

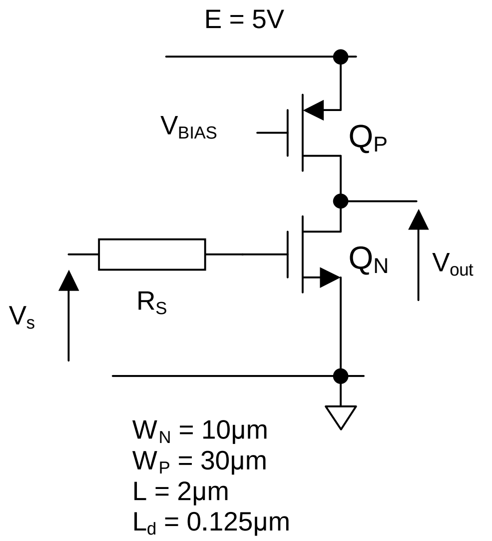

Fig.3 Common-Source amplifier cell.

	Q_N	Q_P
I_D (µA)	19.3	19.3
C_{ox} (fF/µm^2)	1.75	1.75
V_T (V)	0.8	-0.9
C_{gs} (fF)	22.6	67.8
C_{gd} (fF)	2.19	6.56
r_0 (MΩ)	5.33	4.27
g_m (µA/V)	150	150

Table 1 Technological & electrical characteristics of the NMOS and the PMOS transistors.

The magnitude of the voltage gain $\frac{V_{out}}{V_s}$, computed by SAMI, is 347.3, which is about 50.8dB.

The first step of tolerance analysis is the sensitivities computation. In Table 2, are given the first-order relative sensitivities of the voltage gain with respect to the electrical parameters of the circuit. The most influent parameters are the transconductance of Q_N, r_{0n} and r_{0p}. These results are exactly what we expected since the voltage gain expression is about $-g_{mn}.(r_{0n}//r_{0p})$. Note that the weak values of the sensitivities with respect to the internal capacitances (magnitude about 10^{-6} to 10^{-4}) are due to the 1kHz frequency being very smaller than the cut-off frequency. Note also that there is no second-order sensitivity very greater than the most important first-order sensitivities.

Parameter h_i	Sensitivity S_{h_i}
C_{gsn}	-0,70 10^{-6}
C_{gdn}	-0,32 10^{-4}
r_{0n}	0,43
g_{mn}	1
C_{gsp}	0
C_{gdp}	-0,58 10^{-5}
r_{0p}	0,54
g_{mp}	0

Table 2 First-order sensitivities with respect to electrical parameters.

With the previews results the sensitivities with respect to the technological parameters have been established. They are given in Table 3.

Parameter h_i	Sensitivity S_{h_i}
W_N	0,56
L_N	-0,56
L_{dN}	-3,2 10^{-17}
C_{oxN}	0,56
W_P	-0,54
L_P	0,54
L_{dP}	-5,7 10^{-18}
C_{oxP}	-0,54

Table 3 First-order sensitivities with respect to technological parameters.

We have considered ±5% tolerances on L, W, L_d and C_{ox}, which is lightly more than the typical value. The second step of the tolerance analysis has revealed that all the parameters are monotonic parameters and we have established that the value of the voltage gain is inside the domain [-337.7; -356.3]. This represents a maximum voltage gain deviation of 2.8% from the nominal value.

5.2 Differential Amplifier

The second circuit is the differential amplifier shown in Fig.4; this amplifier is biased with a current mirror realized with two PMOS transistors Q_3 and Q_4; the differential pair is formed with two NMOS transistors Q_1 and Q_2. The frequency, the dimensions and the bias current of the previous example have been conserved. Consequently, the technological and the electrical parameters are the same as those given in Table 1. Q_3 and Q_4 are biased with 3.85V gate potential, and since the circuit has a +5V/0V power supply, we consider the gate potential of Q_1 and Q_2 equal to 2.5V. The load is represented by an equivalent resistance R_L.

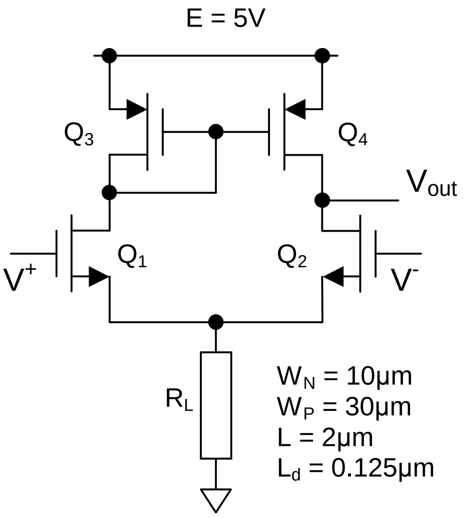

Fig.4 MOS Differential Pair.

The magnitude of the voltage gain $\frac{V_{out}}{V^+ - V^-}$ has the same value (347.3) as the previous example since the expression of the voltage gain is almost identical.

Parameter h_i	Sensitivity S_{h_i}
C_{gs1}	-0.94 10^{-12}
C_{gd1}	-0.49$10^{-12}$
r_{01}	0.0012
g_{m1}	0.31
C_{gs2}	0.19 10^{-11}
C_{gd2}	-0.70 10^{-8}
r_{02}	0.43
g_{m2}	0.69
C_{gs3}	-0.14 10^{-9}
C_{gd3}	0
r_{03}	0.47 10^{-3}
g_{m3}	-0.31
C_{gs4}	0.14 10^{-9}
C_{gd4}	0.43 10^{-7}
r_{04}	0.54
g_{m4}	0.31

Table 4 First-order sensitivities with respect to electrical parameters.

The values of the first-order sensitivities are given in Table 4 (with respect to electrical parameters) and in Table 5 (with respect to technological parameters).

Parameter h_i	Sensitivity S_{h_i}
W_1	0,306
L_1	-0,306
L_{d1}	-5,87$10^{-22}$
C_{ox1}	0,306
W_2	0,259
L_2	-0,259
L_{d2}	-7,04$10^{-19}$
C_{ox2}	0,259
W_3	-0,306
L_3	0,306
L_{d3}	-1,44 10^{-20}
C_{ox3}	-0,306
W_4	-0,237
L_4	0,237
L_{d4}	-4,30 10^{-18}
C_{ox4}	-0,237

Table 5 First-order sensitivities with respect to technological parameters.

We have still considered ±5% tolerances on L, W, L_d and C_{ox}. During the second step most of the 16 parameters were defined as monotonic parameters. Finally, the voltage gain is supposed to vary in the domain [-377.8; -317.4]. This represents a maximum deviation of 8.8% from the nominal value. Note that this value is greater than the tolerances of the parameters and not negligible.

6 Conclusion

Tolerance analysis is efficient if it's performed by taking into account the parameters that the designer can control. We have proved that, by giving the maximum possible fluctuations of technological parameters, we could evaluate the tolerances of analog MOSFET integrated circuits performances without an estimation of the statistics properties.

In order to validate the method, two circuits using a simple model of MOSFET have been analyzed. The results are what we were expecting and validate our approach.

The next step will be to consider a more precise model by taking into account the effects of the substrate, notably the threshold voltage V_T. If the link with electrical parameters is clear, consider the impurity concentration or the carrier mobility as another technological parameter could be possible too.

It will be also necessary to study the influence of the bias potentials of the transistors and the power supply of the circuit, and eventually the connections between elements.

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