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Sensitivity Analysis of an Industrial CMOS Process using RSM Techniques

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Abstract

This paper describes a method to identify the process parameters responsible for the spread in the transistor parameters. The method consists of modeling the response surfaces for the transistor parameters and the correlations between them in terms of process variables. Incorporation of the correlations in the analysis turned out to be essential in order to correctly identify the cause for the fluctuations in the transistor parameters.

I. Introduction

Manufacturability and yield improvement are extremely important in the IC industry. For this purpose, the transistor parameters of MOSFET's in a CMOS production line are constantly monitored. A modern CMOS process consists of a very large number of process steps. Each individual process parameter (e.g. t_{ox}) will contribute to the spread in the transistor parameters (e.g. V_{t}). Identification of the most critical process parameters is extremely important. In this paper, we show that the combination of statistical analysis of the measured devices and Response Surface Modeling (RSM) techniques [1] in a TCAD framework is an extremely powerful tool for modeling the statistics of the transistor parameters. For the first time, we show that correct identification of the most important process parameters is only possible if the correlations between the transistor parameters are explicitly taken into account.

II. Experimental

The DC characteristics of MOSFET's in a CMOS production line were monitored over a long period of time. The MOS-MODEL9 parameters [2] were determined with direct parameter extraction and used for statistical analysis. The database contained more than 11.000 fully characterized sets of MOSFET's. Each set consists of n and p channel devices with various channel lengths. The DC characteristics were modeled using MOS MODEL9. Only the long-channel n and p-channel devices ($W=L=10$ μm) are considered in this paper. The 8 most important transistor parameters and the 6 correlations dealing with the V_{t}'s and the gain factors were chosen for modeling purposes. The spreads of these parameters and the correlations between them form the base of our analysis.

All process parameters are subjected to short-term variations (within one batch) and long-term variations (from batch to batch). In this paper, only the variations around the average values of the parameters of the batches were used in the analysis. We therefore focus on the short-term variations.

III. Simulations

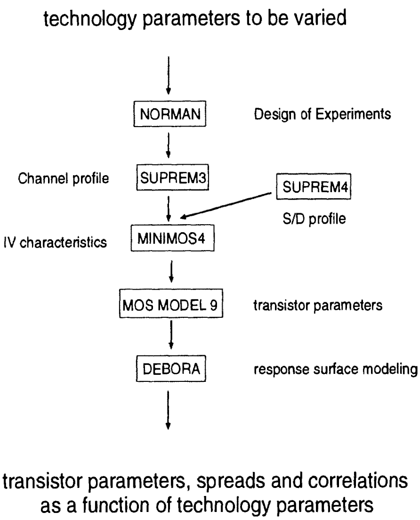

Figure 1: *Simulation chain to simulate the spreads in the transistor parameters and the correlation coefficients.*

The simulation chain is depicted in figure 1. The NORMAN/DEBORA package[3] was used for the modeling of the response surfaces. The doping profile was constructed using SUPREM3 for the channel profile and SUPREM4 for the S/D profile. Since we are interested in the modeling of long-channel devices, we have only taken the variations in the channel profile into account. The S/D profile was assumed to be constant. The 2D S/D profile was merged with the 1D channel profile to obtain a 2D doping profile for the device simulations. The *IV* characteristics were simulated with MINIMOS4, and then the compact model parameters were extracted using MOS MODEL9. In total 15 process parameters were varied. Included were the temperatures of all furnace anneals, the energies and doses of the implantations and the layer thicknesses. In the initial simulations, 1st-order Taylor expansions for the response surfaces were

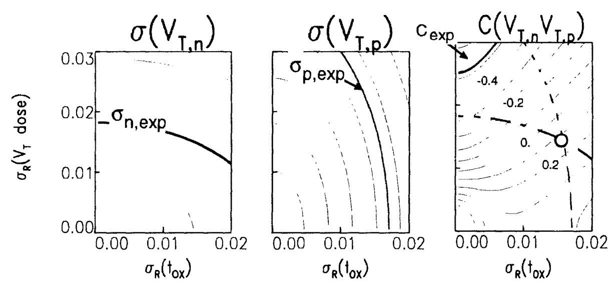

Figure 2: *-The first figure shows the simulated equi-$\sigma(V_{t,n})$ lines. The thick solid line indicates the experimental value. The second figure depicts the same information for $\sigma(V_{t,p})$. The intersection of these two equi-σ lines (for $\sigma(V_{t,n})$ and $\sigma(V_{t,p})$) gives the spread for t_{ox} and the V_t dose. -The last figure shows the equi-$C(V_{t,n}, V_{t,p})$ lines. The two dashed lines are the $\sigma(V_t)$ lines and the intersection is the simulated correlation coefficient. We find $C(V_{t,n}, V_{t,p}) \approx 0.1$, which is completely wrong because the experiments show that $C(V_{t,n}, V_{t,p}) \approx -0.53$*

used to filter out some unimportant process parameters. In subsequent sets of simulations, the response surfaces were modeled with higher accuracy for the remaining process variables using 2nd-order Taylor expansions. These 2nd-order functions were used to model the spreads in the transistor parameters and their correlations.

We were able to identify the five main process parameters responsible for the spreads in the transistor parameters. This is in accordance with principal components analysis on the database with the measured set of devices, which showed that we are dealing with a 5 dimensional parameter space. Some of these parameters are very obvious (e.g. t_{ox}), others are less trivial.

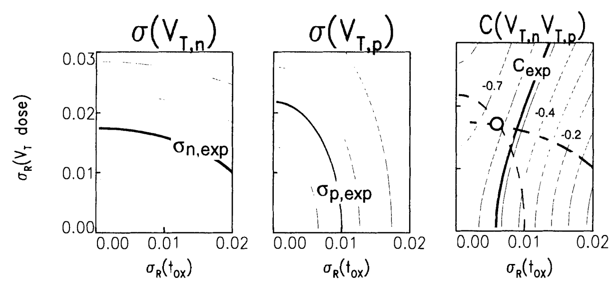

Figure 3: *Situation for the optimum fit. Note that both the experiment as well as the simulations give $C(V_{t,n}, V_{t,p}) \approx -0.53$. In this case we correctly simulate the $\sigma(V_{t,n})$, $\sigma(V_{t,p})$ and $C(V_{t,n}, V_{t,p})$. Each Equi-$\sigma(V_{t,n})$ line represents a 10 % change. For the Equi-$\sigma(V_{t,p})$ lines intervals are 20% changes (same in figure 2).*

The problem we faced was to find a unique description of the statistics in terms of the process parameters. It is not sufficient to fit the simulated spreads in the transistor parameters to the experimental ones. This is illustrated in figure 2, where we briefly discuss the dependence of $V_{t,n}$ and $V_{t,p}$ on t_{ox} and the dose of the V_t implant. This figure depicts the situation were we have fitted the spreads of all parameters, but did not pay any attention to the correlations. The correlation coefficient $C(V_{t,n},V_{t,p})$ belonging to this solution is way off, and this strategy leads to the wrong identification of the critical process parameters. Figure 3, on the other hand, shows the situation where we have fitted the spreads as well as the correlation coefficients to the experiments. In this case we obtain good fit and this leads to different conclusions concerning the process weaknesses. The correlation coefficients are extremely important to take into account, because they are the 'fingerprints' of the process (figures 4 and 5).

It is interesting to look at the $\sigma(V_{t,n})$ and $\sigma(V_{t,p})$ in more detail, because the spread in $V_{t,p}$ is almost twice as much as the one for $V_{t,n}$(figure 4). From our analysis, it is easy to identify the cause of this large spread. In the process under consideration, this spread is caused by the n well construction. This knowledge can in turn be used to minimize the spread in the transistor parameters.

It is also interesting to analyze the variations from batch to batch instead of the short-term variations investigated in this paper. Some of the correlations which exists on a short time scale disappear on a long time scale. The same RSM analysis can be done for the long-term variations. If a self-consistent solution can be found, the outcome will reveal the cause of these long-term fluctuations.

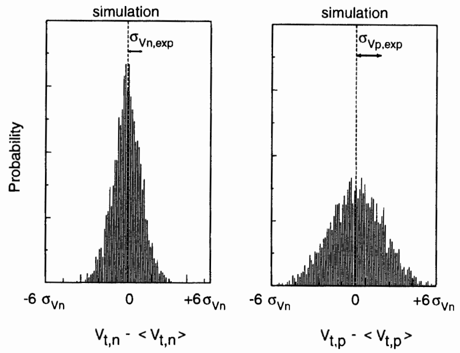

Figure 4: *Simulated distributions for* $V_{t,n}$ *and* $V_{t,p}$. *Note that the spread in* $V_{t,p}$ *is almost twice as large as the spread in* $V_{t,n}$. *These are simulation results. The experimental spreads are indicated in the figure.*

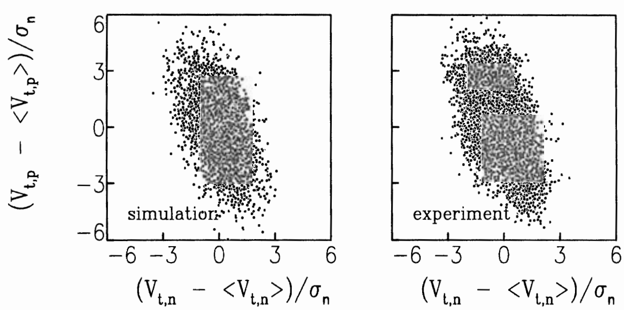

Figure 5: *Simulated and experimental spread in* $V_{t,n}$ *and* $V_{t,p}$. *Good agreement exists between the experiments and the simulations. These plots are the 'fingerprints' of the process.*

IV. Conclusion

In this paper we have shown that the RSM approach can be successfully applied to an industrial environment to simulate the spreads and correlations between the transistor parameters. Modeling of the correlations turned out to be essential in order to reveal the process weaknesses. Furthermore, modeling of the correlations between transistor parameters is also important for circuit designers to improve the design window.

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