Extended Abstracts of the 15th Conference on Solid State Devices and Materials, Tokyo, 1983, pp. 265-268

A Process Variation Analysis Simulator for MOS LSI

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A simulator, CASTAM, is developed to predict MOS process variations by analyzing variations in electrical characteristics of fabricated MOS devices using the Monte Carlo method.

Wafer inspection data for a CMOS pilot line is analyzed with this simulator, and the main cause of threshold voltage variation is pinpointed. Some predictions from the analyzed results are confirmed with additional experimental data, showing that analysis using CASTAM is sufficiently reliable.

1. Introduction.

With all the progress that has been made in the area of LSI, the relationship between process conditions and device characteristics is becoming more complex. It has become difficult to pinpoint the process condition that is the main cause of particular variations in device characteristics. This paper reports development of CASTAM, a Computer Aided STAtistical Modeling simulator. This program makes it possible to predict quantitative variations in process parameters from measured device characteristics, especially for MOS devices. This approach was first reported on by D.P.Kennedy for a bipolar transistor[1].

2. Method of Analysis.

An outline of CASTAM is shown in Fig. 1. The simulator has process models and device models. CASTAM calculates distributions of device characteristics using the Monte Carlo method, assuming variations (standard deviation) in the process parameters. If calculated and measured histograms for device characteristics differ from each other, Monte Carlo simulation is performed again, after changes are made to variances for the process conditions. If both types of histograms then match well, it is assumed that process variations are equal to the real process variations. That is, it becomes possible to quantitatively find process variations that have been difficult to measure directly. The most important step in this task is determining the set of the most suitable measurement items. Variations in many process parameters can be determined from measured data for this set.

In usual process sensitivity analyses, utilizing a process and a device simulator, only $\partial Y/\partial X$ is known, where Y is one of the device characteristics and X is a process parameter. The quantity sought is $A*\partial Y/\partial X$, where A is a variation in a real process line for the process parameter. Value A is estimated from the analysis with CASTAM and realistic process sensitivity $A*\partial Y/\partial X$ is obtained. This is the main feature of this method of clarifying the main cause of device characteristic variation.

The main process models incorporated in the simulator, such as those for oxidation, ion implantation, and diffusion, were chosen to be one-dimensional analytical models to faciliate calculating with a shorter CPU time. Threshold voltage Vt and drain current for long channel MOSFETs were calculated by one-dimensional numerical models to assure accuracy. The model for Vt with short channel MOSFETs was chosen to be an analytical one[2].

These features are summarized in Table 1.

3. Analyzed Results.

CASTAM was applied to a CMOS process pilot line. Measurement items were; threshold voltage Vt under a substrate bias of zero and two volts where gate length was 2 µm and 5 µm each, transconductance Gm for NMOS and PMOS, Vt for parasitic NMOS and PMOS, and the capacitance of MOS capacitor Cox. These data were measured for about 10 batches and analyzed by CASTAM.

The main results are shown in Fig. 2. Measured variances in device characteristics Vt are divided into several types, each of which is determined by the variance for each process parameter, such as oxide thickness Tox, channel length Lg, and implanted dose. From this figure, the following conclusions were derived:

a) The main cause of Vt variation in NMOS is Tox variation.

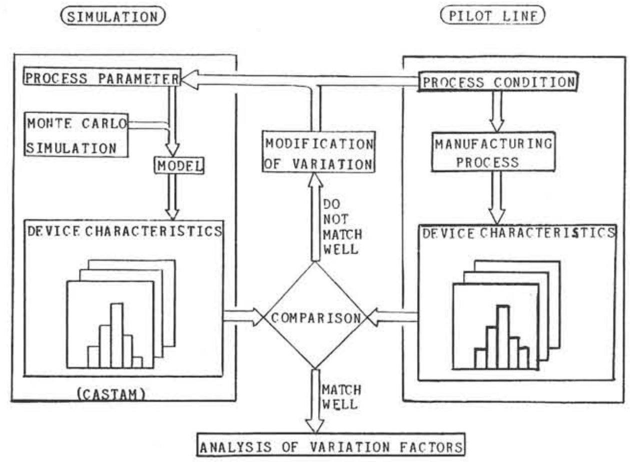

Fig. 1 Outline of CASTAM.

Table 1 Features for a CASTAM simulator.

ITEM	FEATURES
Method	Monte Carlo simulation.
Model	One-dimensional analytical model mainly adopted to calculate with a shorter CPU time.
Measurement	Many device characteristics must be measured to determine variances of many process parameters.
Application	Process sensitivity analysis.

b) Vt variations in short channel PMOS (Lg = 2 µm) are variations in Lg.

c) Vt for a long channel(Lg = 5 µm) PMOS has little dependence on Tox and Lg.

4. Discussion.

Calculated total variances in Vt are usually smaller than measured variances. The difference between calculated and measured total variances are shown in the bottom of Fig. 2(b). There are three possible reasons for appearance of this unknown variance.

(1) Variations of process parameters not included in CASTAM.

(2) Inaccuracy of used process and device models.

(3) Measurement error.

To date, it is not clear which of the above three is the main cause of unknown variance. Notwithstanding this ambiguity, accuracy in analysis is high enough for practical use, because unknown variance is much smaller than measured variance in Vt.

The analyzed results in Fig. 2 lead to the following predictions. First, the Vt of NMOS depends strongly on gate oxide thickness though the Vt of PMOS does not. Second, correlation between the Vt for a 5 µm MOS and a 2 µm MOS is strong for NMOS but weak for PMOS. Additional measurements were made to confirm these predictions. First, dependence of threshold voltage Vt on gate oxide thickness Tox is shown in Fig. 3. This agrees quite well with the first prediction. The work function differences for

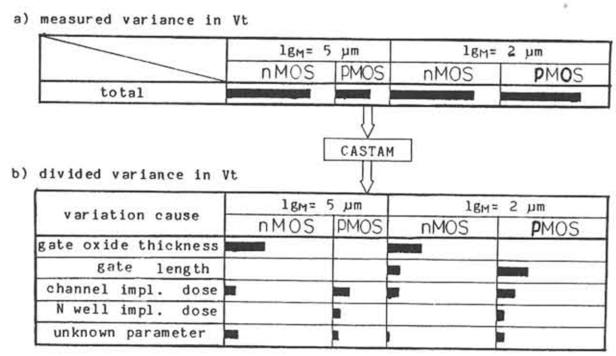

Fig. 2 Analyzed results with CASTAM.

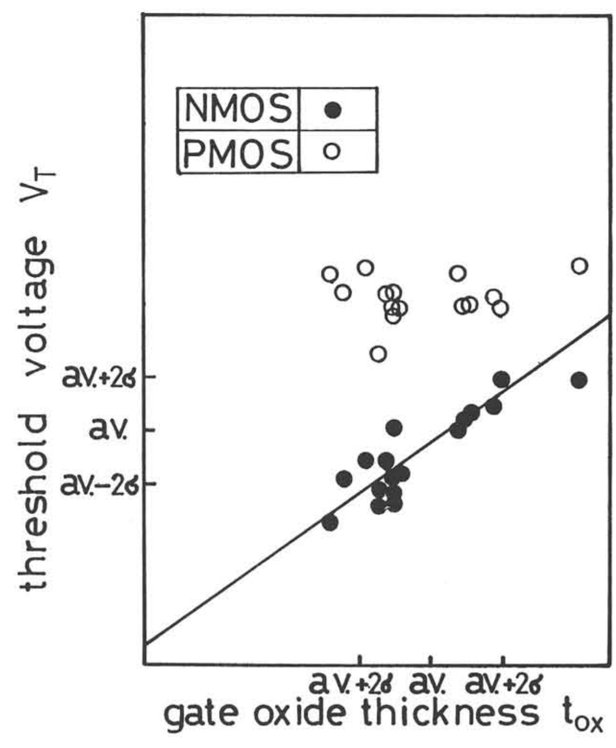

Fig. 3 Gate oxide thickness Tox dependence of threshold voltage Vt.

NMOS and PMOS differ. To make the same Vt for both, NMOS well concentration was made higher than PMOS. This concentration difference may cause the different gate oxide dependence of Vt for NMOS and PMOS. Second, correlation between Vt for a 5 μm MOS and a 2 μm MOS is plotted for measured data in Fig. 4. Correlation coefficient r in NMOS is 0.95 wheras r in PMOS is 0.58. This confirms the second prediction. These good agreements between predictions and measurements show that the results analyzed with CASTAM are reliable.

5. Conclusion.

A simulator which can predict variations in process parameters from measured device characteristics has been developed. This simulator has proven useful in analyzing the cause of device characteristic variations.

[1] D.P.Kennedy et al.;IBM J. 8 (1964) 482

[2] T.Toyabe et al.;IEEE ED ED-26 (1979) 453

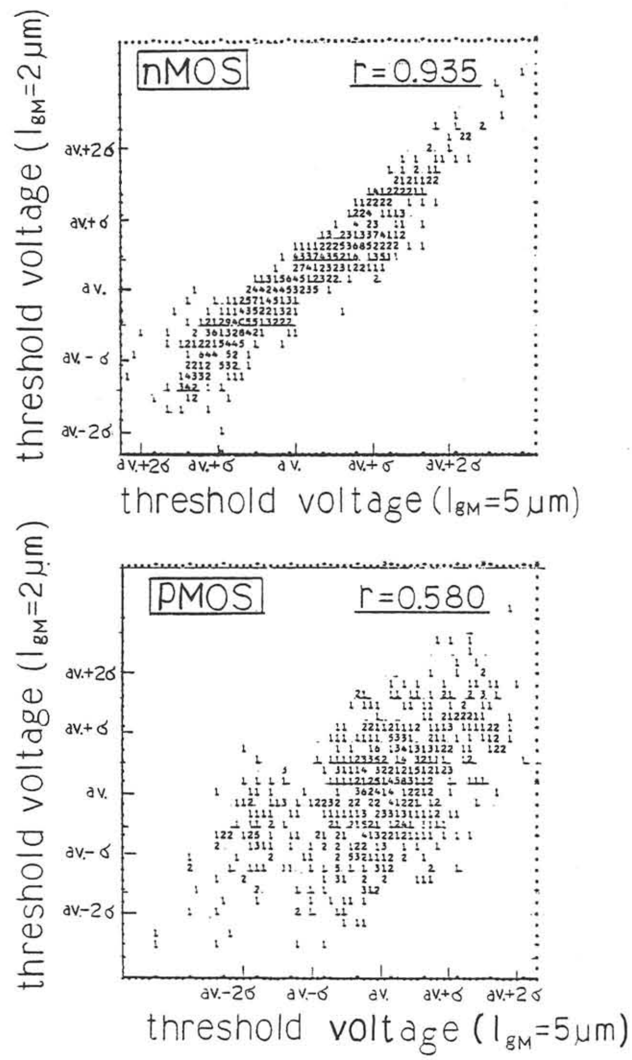

Fig. 4 Correlation between Vt for a 5 μm and a 2 μm MOS.