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DOE Analysis of the Effect of Measurement Setup on Transient Time of Metal-Oxide-Semiconductor Devices

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Abstract— In semiconductor industry, a pulsed metal-oxide-semiconductor (MOS) capacitance-time (C-t) transient response is widely used for investigating the minority carrier lifetime in Silicon. The minority carrier generation lifetime is an important parameter that directly defines the performance of integrated-circuit devices. In this paper we use Design of Experimet (DOE) to study the important parameters that might effect the minority carrier lifetime measurement in a laboratory environment. This information are beneficial for operators while doping measurements.

Index Terms— MOS devices, Transient Response, Carrier Generation, Hold time

1 INTRODUCTION

THE idea behind pulsed metal-oxide-capacitor measurement is creating deficiency of electron hole pairs inside a MOS-C by applying a fast electrical pulse from accumulation to inversion [1], and letting the device return to equilibrium (forming the inversion layer) which is due to generation of electron and hole pirs and watch for the increase of capacitance in respect to time. Therefore the transient time of going from deep depletion to inversion is a direct indication of generation lifetime: The lower the generation lifetime the slower it will saturate [2], [3]. We have a clear idea of how the results should be, though since we are using a sophisticated measuring system, the probable effect of most of measuring parameters is not well known. To do the measurement we use a Probe Station and a HP 4284 LCR meter. Considering the fact that the original wafers are ultra-clean, any mistake in measurement or fabrication will only lead to the reduction of transient time. Therefore, the reasoning is that the longest measured transient time is the most real one [4]. We are after seeing which measuring setting will lead to longest transient time.

We are after seeing which measuring setting will lead to longest transient time. There are three pins available inside the probe station for the measurement where we only use one of them. The probable effect of testing pin is not known to us and it may play a role. Furthermore the measurement is being done by employing an AC signal on top of DC pulse in order to measure the capacitance. We have a wide range of frequency to choose from for our AC signal (From 100 KHz to 1MHz) and following previous literature we use 100 KHz [5]. Though, different probing frequencies may also be of potential importance leading to different answers. Finally, as the last factor we'd like to see the effect of Temperature.

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The general form of the transient response of a MOS-

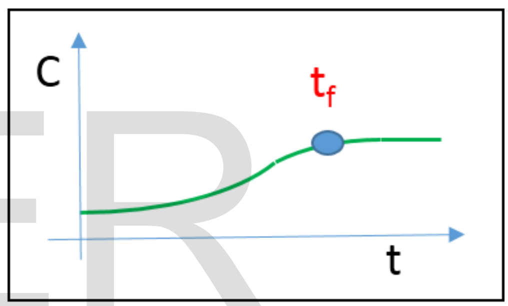

Figure 1. An example of transient response of a MOS device [4].

C device while moving from deep depletion to inversion is shown in Fig A in terms of Capacitance in respect to time. The key element that we have chosen as response is the transient time (t_f) which is the time at which the capacitance reaches saturation. The correlation between t_f and carrier lifetime has been addressed in detail in ref. [4]. Since there are always

TABLE 1. The choice of factors and levels

Factor:	Detail:	Level 1:	Level 2:	Level 3:	Type
A	Testing Pin	Pin #1	Pin #2	Pin #3	Categorical
B	Frequency	100,000Hz	1,000,000Hz	-	Continuous
C	Temperature	60 C	65 C	-	Continuous

noise in such diagrams and in order to be more accurate while reporting the response variable, 90% percentile point of t_f is considered as the true response [5].

2 DESIGN OF EXPERIMENT

2.1 The choice of factors and levels

There are many factors that may affect the transient time. Such factors are Temperature and the wafer on which the MOS-C devices have been fabricated. The transient time is directly proportional to the material (wafer) on which MOS-C

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has been built since lifetime is a property of material. Therefore these two factors will be kept constant during the experiment.

2.2 The selection of response variable

The most suitable factor to study is the transient time, the longer we get the better our test is. So the goal is to get the longest transient time.

2.3 Choice of experimental design

Since C-t measurements are inherently long and time consuming where transient times of hundreds of seconds are expected, and in order to obtain an estimate of pure error, two replicate of the experiment is suggested. Such design will require minimum of 24 runs which includes 2 replicates of each 12 treatment combination.

Since MOS-C that are being studied can be a big source of nuisance variable [6] – based on engineering knowledge- and because there are limited number of tests that can be run on each MOS-C, a good choice of experiment would be to keep MOS-Cs as blocks and run each replicate of experiment on one randomly chosen MOS-C. Therefore total number of 2 MOS-C devices would be required and 12 runs of each replicate of the experiment have to be performed on each of MOS-C (block).

2.4 Desgin Matrix

Below is the JMP [7] suggested design matrix for our factorial experiment [8] with the discussed conditions mentioned above:

Table 2. Desing matrix and measured values

Run Order	Random Block	Pin #	Frquency (Hz)	Temperature (C)	Response - Transient time (s)
1	1	Pin #3	100000	65	797.5
2	1	Pin #2	100000	60	1231.25
3	1	Pin #2	1000000	60	1231
4	1	Pin #2	100000	65	765
5	1	Pin #3	1000000	65	796
6	1	Pin #1	100000	65	785
7	1	Pin #3	100000	60	1192.5
8	1	Pin #1	1000000	65	738
9	1	Pin #3	1000000	60	1110
10	1	Pin #1	1000000	60	1130
11	1	Pin #2	1000000	65	795
12	1	Pin #1	100000	60	1190
13	2	Pin #2	1000000	60	2409
14	2	Pin #3	100000	65	1447.5
15	2	Pin #3	100000	60	2411
16	2	Pin #1	1000000	60	2355
17	2	Pin #3	1000000	65	1457
18	2	Pin #2	100000	65	1439
19	2	Pin #1	100000	60	2408
20	2	Pin #2	1000000	65	1452
21	2	Pin #1	1000000	65	1443.75
22	2	Pin #3	1000000	60	2460
23	2	Pin #1	100000	65	1456
24	2	Pin #2	100000	60	2417.25

The experiment has been performed in a way to eliminate any known nuisance variables such as surface variation or oxide degredation [9] that can not be blocked. In order to do that, one operator has run all of the runs and the runs within each block have been performed in continuous 12-hour shift. The whole experiment was performed in consecutive days in order to avoid any probable changes that may be introduced to the measurement unit by use of other operators.

3 Statistical Analysis of Results

Costume design in JMP has been employed to create the design and Fit Model has been utilized to analyze the results. Both REML and ANOVA methods have been used for analyzing the data. Since we have included random blocks in the design the REML method was used for detailed study of the variance components of the blocks and to form Confidence Interval on it. Though since the design is a balanced design the point estimates from both models are equal. The analysis of the data indicates that the only significant factor is the Temperature.

Before going through the detailed explanation of the analysis, our initial evaluation of the residuals showed issued with the normality and equality of variance. Therefore, BOX-COX method –Figure 3 -was applied to find the right transformation regarding our data to solve those issues. Figure 4 shows relevant plots before and after transformation has been applied. It has been also observed that both R-Square and Adjusted R-Square for the model were increased from 0.94, 0.88 to 0.99 and 0.99 respectively followed the BOX-COX [8] suggested transformation on the data.

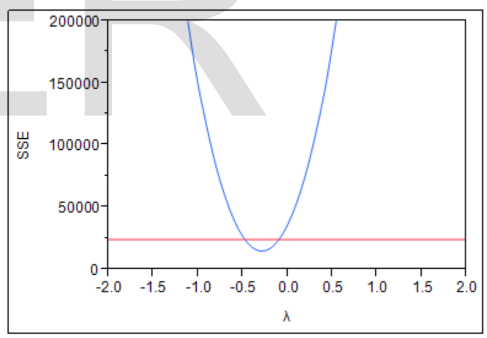

Figure 2. BOX-COX plot for finding Lambda for best transformation

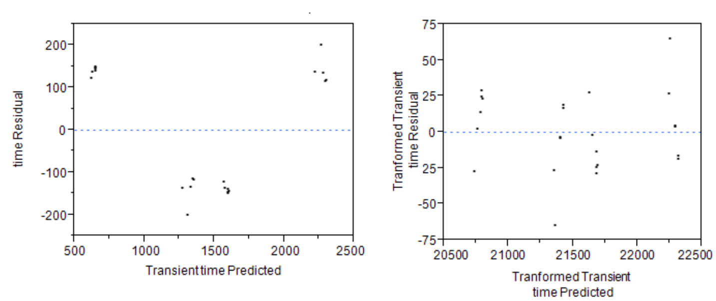

Figure 3. Residual vs. predicted response before and after transformation

The normal probability plot of the residuals after the transformation seems satisfying. Although it is an indication of slightly thicker tails in the distribution of data or in other terms the largest and smallest residuals are slightly larger and smaller than what they have to be a normal distribution. The residual vs. predicted response values shows satisfactory shape after transformation, while it has some aggregation before. Moreover, as can be seen in Figure 4, the Residuals vs. run order plot has an acceptable distribution.
After applying the right transformation and checking for probable issues, as mentioned above, REML method was utilized to analyze the data. Both R-Square and Adjusted R-Square value have satisfactory values. The fit summary is as follows:

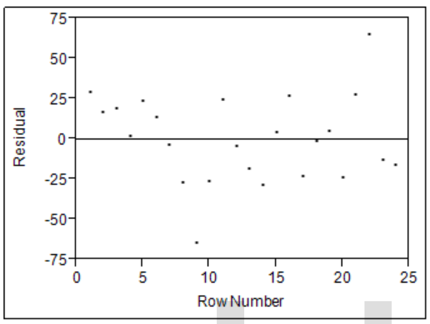

Figure 4. Residual vs. run order

Table 3. Summary of Fit

RSquare	0.997596
RSquare Adj	0.995391
Root Mean Square Error	39.34423
Mean of Response	21529.67
Observations (or Sum Wgts)	24

Table 4. ANOVA Tabel

Source	SS	MS Num	DF Num	F Ratio	Prob > F
Pin	4390.99	2195.49	2	1.4183	0.2831
Frequency(100000,1000000)	1764.65	1764.65	1	1.1400	0.3085
Temperature(60,65)	2272922	2272922	1	1468.326	<.0001*
Pin*Frequency	4433.76	2216.88	2	1.4321	0.2800
Pin*Temperature	3620.09	1810.04	2	1.1693	0.3464
Frequency*Temperature	919.699	919.699	1	0.5941	0.4571
Pin*Frequency*Temperature	577.901	288.95	2	0.1867	0.8323
Random Block&Random	4776287	4776287	1	3085.519	<.0001*

As the analysis reveals, the only significant factor is Temperature and all other factors including their interactions have fairly large P-value and we are in safe region to claim that they have no effect. The random blocks comprise 99% of the total variability in the data which justify the importance of blocking as previous engineering knowledge would also suggest. Furthermore, the variance component for block is 397894.92. This value is the same as the point estimate of block variance calculated from ANOVA from $\sigma_{\beta}{}^{2} = MS_{block} - MS_{E}/12$. Although the confidence interval that has been proposed by REML includes zero, according to portion of variability due to blocks (99%), blocking is necessary. Additionally, checking the ANOVA table below shows also that effect of blocks are significant. Figure 5 also shows the response surface and contour plots with pin level fixed.

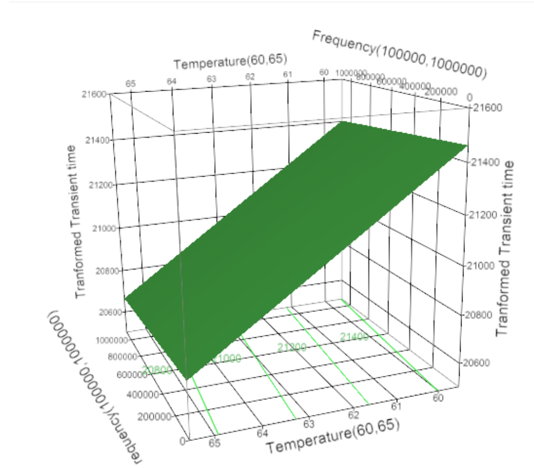

Figure 5. Response surface and Contour plots with Pin#1

4 Conclusion

The practical results of this DOE are really comforting in research. According to previous knowledge we knew there might be an exponential relationship between transient time and temperature which was confirmed by the experiment. What one might be always worried about was the effect of changing frequency and specially pin on the results as it may always happen during an experiment when one of our pins fail and we want to continue with another pin. As the experiment confirms the effect of pin and frequency factors are negligible and there is no interaction of any importance between under-study factors. Consequently working at lower operating temperature range -60 in this case- would lead to longer transient time which is desirable. Furthermore, if less variation in the result is desirable –as in some occasions it may be- we suggest using pins #1 or #2 and lowering the frequency.

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