Analysis and Modeling of Polysilicon Critical Dimensions

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Abstract— **The objective of the project was to evaluate polysilicon CD etch bias as it was affected by etch time, measurement feature within the exposure field, and the product being measured.**

Characterization of the trends has generated a summarizing model that uses etch time, measurement feature, and product type as significant factors in determining polysilicon CD etch bias. Etch time was found to be a continuous factor, while measurement site and product type were categorical. Measurement Site A was found to be independent of measurement Site B, independent of Site C, etc., as well as Product 1 was found independent of Product 2. When tested with JMP Statistical software the generated model produced an R-sq Adj. =0.96. A comparison of modeled values with collected data for several different combinations of conditions showed a maximum difference of 6% on a normalized scale.

I. Introduction

FUNDAMENTAL CMOS technology uses doped polysilicon gate material as a self-aligning mask for source and drain implants. Lithography and subsequent etch processing steps define the critical dimensions of these polysilicon lines, which define the physical parameters of the transistors. Slight variations in these line widths have a direct impact on the electrical performance of the chip. Devices within the same exposure field should have constant CDs; variations, however, in electrical properties indicate a disparity in CD. Of similar concern was a variation between CD measurements of specific features from different product types.

Recent electrical tests have shown variations in several MOSFET devices. Several suspected causes were investigated, with most indications pointing towards gate lengths being off target. The drain current of a transistor in saturation mode is dictated by the equation (1).

$$I_D = \frac{W}{L}\mu_n C_{ox}\left[(V_{GS}-V_T)V_{DSsat}-\frac{V_{DSsat}^2}{2}\right]*[1+\lambda(V_{DS}-V_{DSsat})]. \quad (1)$$

The physical dimensions, length and width, directly impact the drain current capabilities of the device. A review of mid-process polysilicon critical dimensions, however, showed the gate length values to be on target.

The suspected cause of the phenomena is a disparity between mid-process CD test features, which are often in the scribe lines, and intra-field devices. Off-target electrical properties have been found for multiple devices within a given exposure field, with some being high and some being low. Comparisons of the same device from different product types also show variations in electrical properties.

An experiment was designed to test these theories through extensive measurements of photoresist CDs and post etch polysilicon CDs. CD shrinkage thru etch bias was monitored. Several different measurement locations were measured across three different product types.

II. Goal and Objective

A. Goal

The goal of the experiment was to gain an improvement of polysilicon CD control, in the hope that this would improve control on MOSFET drain current and thus bring device parameters closer to the designed values.

B. Objective

The objective of the experiment was to perform an evaluation of polysilicon CD etch bias as it is affected by Etch Time, Measurement Feature, and Product Type.

III. Experimental Procedure

The provided lot of three wafers was processed according to Process-of-Record (POR) specifications up to the polysilicon photolithography step. The wafers were then exposed at the standard illumination conditions with a dose chosen so that a specific resist critical dimension was achieved. On a normalized scale the resist target had a value of 1.00.

CD measurement routines, or jobs, were then created on two different Scanning Electron Microscope tools; the Opal 7830 and the KLA 8250 CD-SEMs. The Opal was used to measure three measurement sites per exposure field: TEST-ISO, TEST-DEN, and ALT-ISO, all of which are scribe-line features. The Opal was set to collect data from 9-fields on the wafer. The KLA

8250 was used to measure six locations per exposure field; the same three scribe-line fields as measured by the Opal, as well as three locations intra-field. These three locations were either LOGIC-ISO, LOGIC-DEN, and SRAM, or SITE-A, SITE-B, and SITE-C. The different product types measured did not all have equivalent LOGIC and SRAM features. The KLA was used to collect measurements at all fields on the wafer.

Data was then collected with both measurement tools. The results from the scribe-line features were then used as a means of comparing the two tools. The Opal 7830 was the tool of record for several CD measurements throughout the fabrication process, and thus it was desired that the KLA 8250 produced similar results. The KLA had greater capabilities, with the most notable being faster data collection times and better pattern recognition capabilities. By adjusting the KLA settings so that it produced comparable results with the Opal it made the systems interchangeable for the measurements in this project, as well as for future measurements.

The wafers were then etched with the standard POR recipe for polysilicon etch, with the exception of the "Etch Time". A 1-variable DOE of Etch Time was conducted with it set at –25%, 0%, and +25%. Following the etch the wafers were moved thru the standard process, which included a wet clean that removed any residual photoresist.

Measurement jobs were created for the post-etch wafers using the same measurement locations as described previously for resist critical dimensions. This round of measurements was collecting data directly from the features in the polysilicon.

Post-etch CDs were collected, and then a comparison of the two CD-SEMs was conducted again. Images of the post-etch measurement sites can be found in the Appendix as Figures 1-8.

CD Bias was then calculated for each measurement location, where

$$\text{Bias} = (polyCD) - (resistCD).$$

All of the resist CD, poly CD, and Bias data was then compiled and stored in one .JMP file for analysis with JMP statistical software.

This entire process was repeated for three different product types: Planet, Product, and Engineering Test Vehicle.

IV. Analysis and Results

The preliminary study of the two measurement tools revealed that for photoresist CD measurements the Opal 7830 and the KLA 8250 were equivalent, but for the poly CDs a significant difference was noted. The normalized data showed a difference of 7.3% between the two systems measurements of TEST-ISO poly CDs, with the KLA values being smaller than the Opal values. The offset setting, which dictates where on a line's slope the KLA will start measuring, was changed slightly to where the normalized error was reduced to 1.4%.

An individual analysis was then conducted for the three data sets, one for each product type. Mean and standard deviation were calculated for each measurement site per wafer. In this manner it was easy to see if the expected trends were present: for resist CD, for a given device, the three wafer means and sigmas were expected to be constant; for poly CD the three wafer means were expected to drop as etch time increased with the sigma holding constant; and the |CD Bias| was expected to increase as the etch time increased. Table #1 below shows an example of this analysis as it was applied to the "Planet" product type.

TABLE I: PLANET MEAN DATA

The CD Bias data for each measurement site, for all three wafers, was then combined into a single file.

Resist CD Mean by Feature by Wafer

Wafer ID	Target	N	TEST-ISO	ALT-ISO	SITE-B
Planet-01	100.00	44	96.70	91.63	93.18
Planet-02	100.00	44	96.80	91.51	94.55
Planet-03	100.00	44	96.50	90.84	93.97

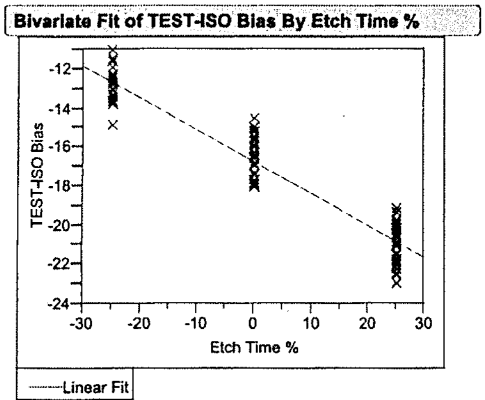
Poly CD Mean by Feature by Wafer

Wafer ID	Etch Time	N	TEST-ISO	ALT-ISO	SITE-B
Planet-01	-25%	44	83.48	77.43	78.07
Planet-02	0%	44	80.44	74.50	76.11
Planet-03	+25%	44	75.36	69.38	72.13

Poy CD - Resist CD Bias by Feature by Wafer

Wafer ID	Etch Time	N	TEST-ISO	ALT-ISO	SITE-B
Planet-01	-25%	44	-12.85	-13.52	-15.28
Planet-02	0%	44	-16.31	-16.99	-18.44
Planet-03	+25%	44	-21.14	-21.46	-21.84

Using JMP software CD Bias was modeled as a linear function of etch time. Six equations were generated, one for each measurement site. An example of the JMP generated analysis is shown below as Fig. 1. The R-sq Adj. Value = 0.92 indicates that the model represents 92% of the data, which is a good fit. The Prob > |t| values show that both the intercept, or offset, and Etch Time parameters are significant factors in the model. Using α=.05, a Prob > |t| value that is less than .05 is statistically significant, which indicates that both of these parameters are significant. The generated equations for each measurement site were then used to calculate projected values across an acceptable range of etch times. A plot of the calculated values shows the fit line, equivalent to the line plotted in Fig, 1. The fit lines for all of the measurement sites are plotted together. Fig. 2 shows this plot for the "Planet" product type. From this representation it is clear that all sites behave with a similar trend, or slope. The offsets do differ however. The TEST-ISO feature is fairly well centered among the group. The ALT-ISO site appears to be a slightly better representative of the group, but the two are very close.



Linear Fit

TEST-ISO Bias = -16.76582 - 0.1636773 Etch Time %

Summary of Fit

RSquare	0.920381
RSquare Adj	0.919608
Root Mean Square Error	0.949677
Mean of Response	-17.3114
Observations (or Sum Wgts)	105

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	1	1073.8433	1073.84	1190.664
Error	103	92.8943	0.90	Prob > F
C. Total	104	1166.7376		<.0001

Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	-16.76582	0.094018	-178.3	<.0001
Etch Time %	-0.163677	0.004743	-34.51	<.0001

Fig. 1: JMP Linear Model of Planet TEST-ISO

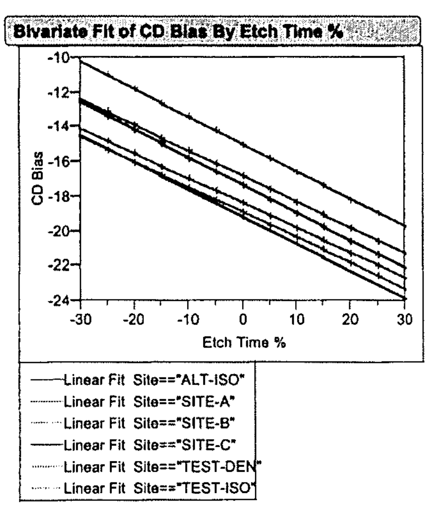


Fig. 2. JMP Plot of All Fit Lines in Planet Lot

A comparison of the trend lines for ALT-ISO from all three product types can be seen in Fig. 3 below. The slopes of the three fit models are close, but a difference in offset is apparent. From this plot it is clear that the suspected variation from product to product does exist.

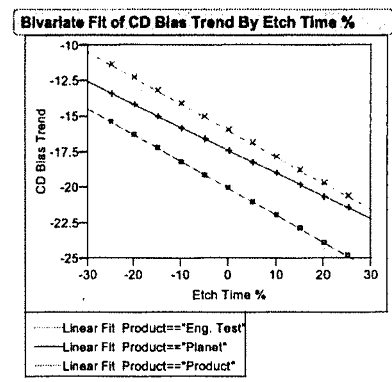
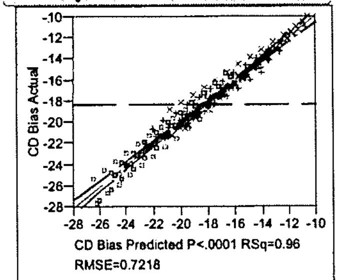


Fig. 3. ALT-ISO Fit Lines for All Product Types

The final step in the analysis process was to put the projected values for all of the measurement sites, for all product types, into one file. This combined data set was modeled using Etch Time, Measurement Site, and Product Type as predictor values. The resulting analysis is shown below as Fig.4.

Whole Model

Actual by Predicted Plot



Summary of Fit

RSquare	0.964498
RSquare Adj	0.962399
Root Mean Square Error	0.721755
Mean of Response	-18.2835
Observations (or Sum Wgts)	198

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	11	2632.3723	239.307	459.3827
Error	186	96.8931	0.521	Prob > F
C. Total	197	2729.2654		<.0001

Parameter Estimates

<table>
<tr><th>Term</th><th>Estimate</th><th>Std Error</th><th>t Ratio</th><th>Prob>|t|</th></tr>
<tr><td>Intercept</td><td>-18.25043</td><td>0.059228</td><td>-308.1</td><td><.0001</td></tr>
<tr><td>Etch Time %</td><td>-0.170263</td><td>0.003244</td><td>-52.48</td><td><.0001</td></tr>
<tr><td>Product[Eng. Test]</td><td>-3.110046</td><td>0.081101</td><td>-38.35</td><td><.0001</td></tr>
<tr><td>Product[Planet]</td><td>0.8287478</td><td>0.102586</td><td>8.08</td><td><.0001</td></tr>
<tr><td>Site[ALT-ISO]</td><td>0.4385844</td><td>0.125641</td><td>3.49</td><td>0.0006</td></tr>
<tr><td>Site[LOGIC-DEN]</td><td>1.112345</td><td>0.162202</td><td>6.86</td><td><.0001</td></tr>
<tr><td>Site[LOGIC-ISO]</td><td>0.72681</td><td>0.162202</td><td>4.48</td><td><.0001</td></tr>
<tr><td>Site[SITE-A]</td><td>2.4388333</td><td>0.217617</td><td>11.21</td><td><.0001</td></tr>
<tr><td>Site[SITE-B]</td><td>-0.973407</td><td>0.217617</td><td>-4.47</td><td><.0001</td></tr>
<tr><td>Site[SITE-C]</td><td>-1.762607</td><td>0.217617</td><td>-8.10</td><td><.0001</td></tr>
<tr><td>Site[SRAM]</td><td>-0.649635</td><td>0.162202</td><td>-4.01</td><td><.0001</td></tr>
<tr><td>Site[TEST-DEN]</td><td>-0.905072</td><td>0.125641</td><td>-7.20</td><td><.0001</td></tr>
</table>

Fig.4. Global Model Analysis

The R-sq Adj. value of 0.96 indicates that the model represents the data well. All of the parameter estimates have a Prob > |t| less than .05 showing that they are significant. It should be noted that each of the measurement site variables, as well as the product type variables, are nominal variables. Each measurement site is unique and independent of the others. The parameter estimates for these variables are treated in a binary manner. The estimated coefficient is only included in the CD Bias calculation when a setting of true is chosen. Only one measurement site parameter can be chosen at a time.

The Prediction Profiler Plot shown below as Figure E was used to verify the validity of the global model. Several combinations of etch time, measurement site, and product type were imputed to compare the prediction with the original data collected for the experiment. A maximum error of 6% on a normalized scale was found between modeled values and actual data.

Prediction Profiler

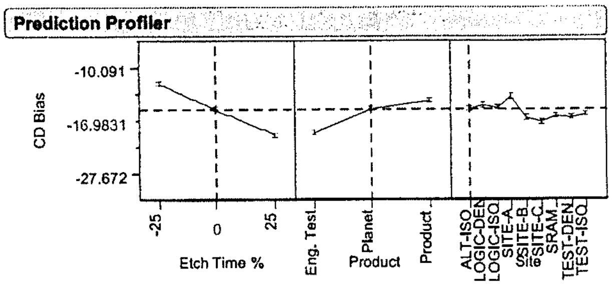


Fig.5. Prediction Profiler

The measured value for ALT-ISO for the "Planet" product type at an etch time of 0% was –16.99. The predicted value given by the global model is –16.983; an error of 0.041%.

V. Conclusions

The presented results, from exhaustive measurements, indicate that suspicions were correct: some features have critical dimensions that are different from the dedicated scribe-line test feature, TEST-ISO. It was found true that certain features do vary from product to product. By analyzing all of the measurement sites for a given product type it can be seen that they all act in a manner similar to the TEST-ISO feature. The offset values may differ, but they all respond to etch conditions in the same way. Although ALT-ISO may yield CDs that are closer to the intra-field devices, the TEST-ISO feature is acceptable because they all react the same way. It is now possible to know how big, or small, intra-field CDs will be by looking at the TEST-ISO value and applying the documented offset value.

The global model that has been generated has been proven to be accurate, as it predicts values very close to the original data. Etch Time, Measurement Site, and Product Type were all found to be significant predictors of CD Bias. This should prove to be a very useful tool for ballpark CD prediction in the future. The desired TEST-ISO poly CD target can be re-evaluated and assigned so as to achieve the optimal results for all intra-field devices, as well as improve the ability to choose an etch time when a specific CD Bias is desired.

Acknowledgment

I would like to thank National Semiconductor for allowing me to perform my Senior Project while on co-op there. Specifically I would like to thank my two mentors Hank Prosack and Pat McCarthy for the countless times they provided assistance, as well as to Scott Kenison and Daryl Batoosingh for helping me get the laboratory experiments completed.

Appendix

Figure #A TEST-ISO, TEST-DEN

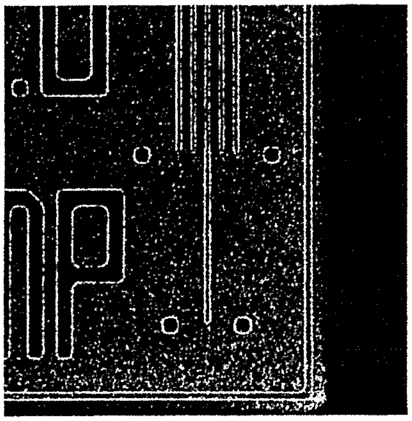


Figure #B ALT-ISO

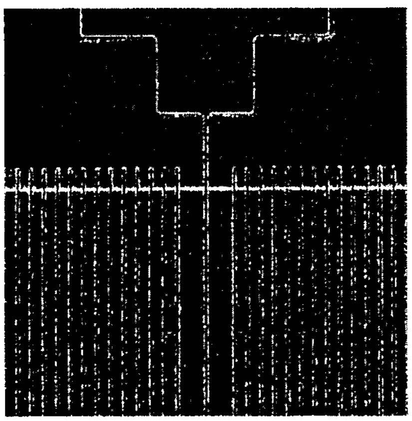


Figure #C LOGIC-ISO

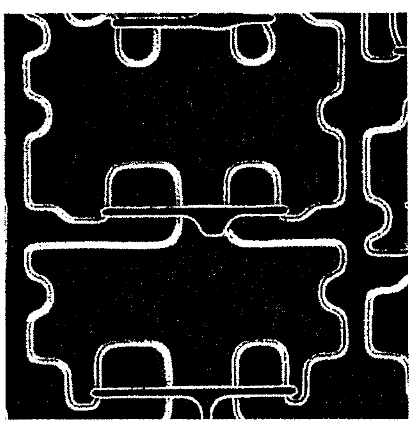


Figure #D LOGIC-DEN

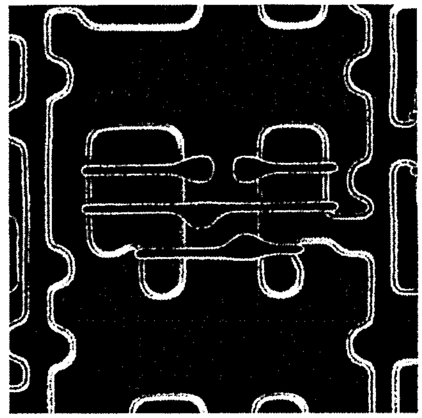


Figure #E SRAM

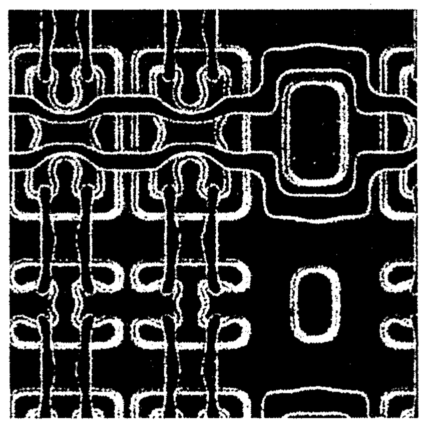


Figure #F SITE-A

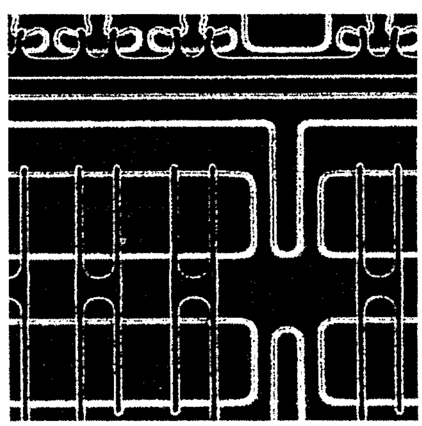


Figure #G SITE-B

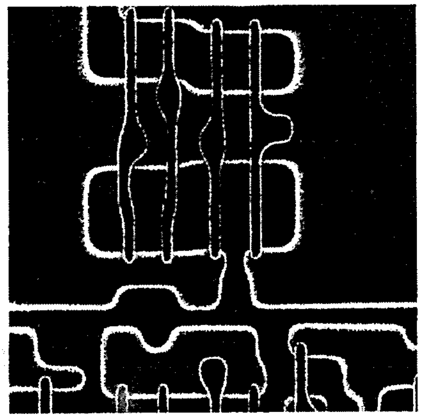


Figure #F SITE-C