# Calibration and Characterization of a Resist Process through Linewidth Measurement on Wafers

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## ABSTRACT

A simple method to evaluate photoresist sensitivity and development/exposure latitude was developed to compare linewidths in positive photoresist under equivalent processing conditions. This method was based on image size measurement by a Nanoline measurement system as a function of exposure and development. In addition, the system was complicated by a variety of materials and a corresponding wide variation in optical parameters, complex refractive indices and thicknesses used in manufacture of integrated circuits. If processing proceeds with controlled oxide thickness, photoresist material, and processing conditions, the linewidth measurements would slightly be affected by the optical variations. It was necessary to calibrate Nanoline measurement system prior to evaluating photoresist performance. The calibration was done by establishing a correlation between the measurements of line/space pair of patterned oxide wafer using Nanoline and scanning electron microscopy (SEM). The calibration yielded a small difference of 0.05 um. between Nanoline and SEM. Also, the Nanoline system was used to measure a mask which was the third order traceable to National Bureau Standard (NBS) to set up the fourth order NBS standard for RIT measurement system. The characterization of positive photoresist and processing by changing exposure and development time were calculated and plotted to obtain a slope of delta linewidth versus wafer processing, which was known as relative process latitude (RPL).

## Introduction

In photolithography, photoresist performance is determined ultimately by how well the size of images can be replicated into a resist coating on a wafer. This task is governed by exposure, development and processing effects which have to be well understood. With this goal in mind, a simple method used for the resist image dimension as a function of exposure/development was developed using a Nanoline critical dimension (CD) measuring system. Furthermore, this method was not destructive as opposed to scanning electron microscopy (SEM) method, where sample preparation and measurement is a very cumbersome and time-consuming task.

The resist image dimension measurements are obtained for the islands (I) or lines and the windows (W) or spaces by computer analysis at 50% line edge profile threshold using the substrate-appropriate software programs provided with the Nanoline system computer. The empirically generated critical dimension parameter, delta, is obtained by subtracting the Nanoline dimension on photomask from that on the wafer. A delta of zero is the desired condition of CD transfer from the mask to wafer, and is a unique relative exposure/development equivalence point for photoresist performance comparison.

With the Nanoline method in mind, the photoresist linewidths were measured on a center die (No 5.) of each wafer under several lithography conditions. A center die was chosen to minimize the variations of Wafertrac as a function of coating, spinning, developer spraying and D.I. rinsing. The die location where measurements taken was shown in Figure 1.

The measurement readings were calculated in delta values relating to optimum condition where the development time and exposure dose were operated at 30 sec. and 60 mJ/cm2, respectively. The delta values were plotted against various exposure doses and linearly fitted by regression analysis to obtain each slope of development time. This slope is known as a relative process latitude (RPL). A low RPL value is desired for the most suitable process because a lower value will slightly suffer from linewidth variation where a higher value indicates more sensitivity by changing process combination.

Prior to the characterization of photoresist performance, it was necessary to have a calibrated Nanoline system. The calibrated measurement system was a fundamental method to detect performance of photoresist and wafer processing. By means of photolithography, the linewidth pattern was transferred on oxide wafer. The measurement of oxide linewidth was performed with Nanoline and on SEM. Then, both data was correlated and a calibration factor was adjusted through Nanoline's calibration program.

A National Bureau Standards (NBS) traceable linewidth standard is widely recognized and used in the semiconductor industries. RIT fab did not have a standard for our measurement system and a third order NBS traceable standard from Digital Equipment Corporation was used to set up that standard. Therefore, our measured linewidths will relatively be the fourth order traceable to NBS. The traceable standard resolution patterns and measurement points are shown in Figure 2.

## Experimental

The experiment was divided into three parts as described below:

1) Nanoline calibration based on SEM result.
2) Set up a correction factor of the fourth order traceable to NBS for RIT Nanoline measurement system.
3) Positive photoresist and wafer processing characterization.

Silicon wafers with approximate 6000 A° of oxide were obtained and measured on Nanospec. The oxide wafers were cleaned with high pressure scrub, coated with positive photoresist and developed to transfer linewidth resist images onto oxide wafers using CGA Wafertrac. A Kasper aligner was used to expose the mask patterns onto the coated photoresist wafers.

### Nanoline Calibration

The calibration approach was to obtain a linewidth patterns on oxide wafer by optimally exposing and developing wafers to obtain a relief image, and etching the photoresist image onto oxide wafer in bufferred HF. The linewidths were measured at 5.0 um on Nanoline. Then, the same set of samples were prepared for SEM to be measured. After both Nanoline and SEM data were obtained, the delta of data was calculated. The Nanoline calibration delta was adjusted through the calibration program (refer to Nanoline user's manual).

A diagram of die locations where measurements were taken.

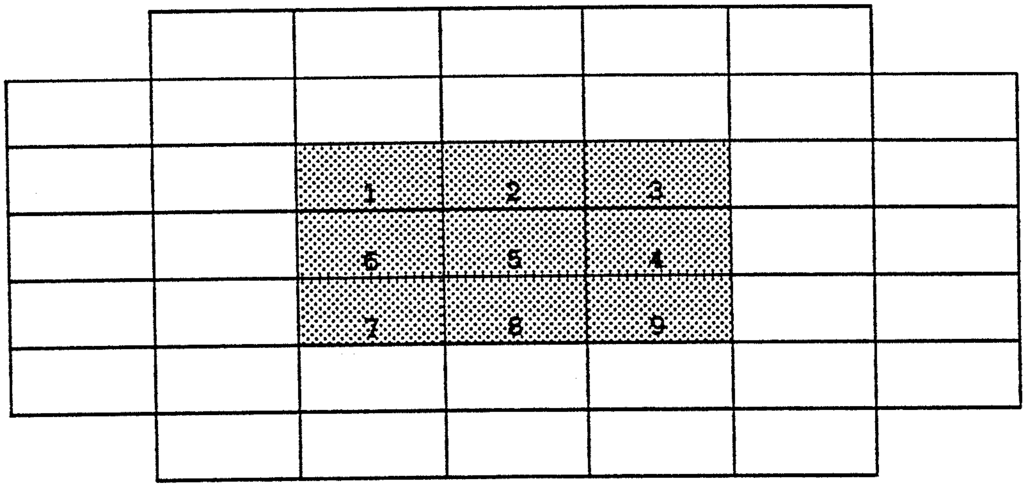


Figure 1

The traceable standard resolution patterns and measurement points

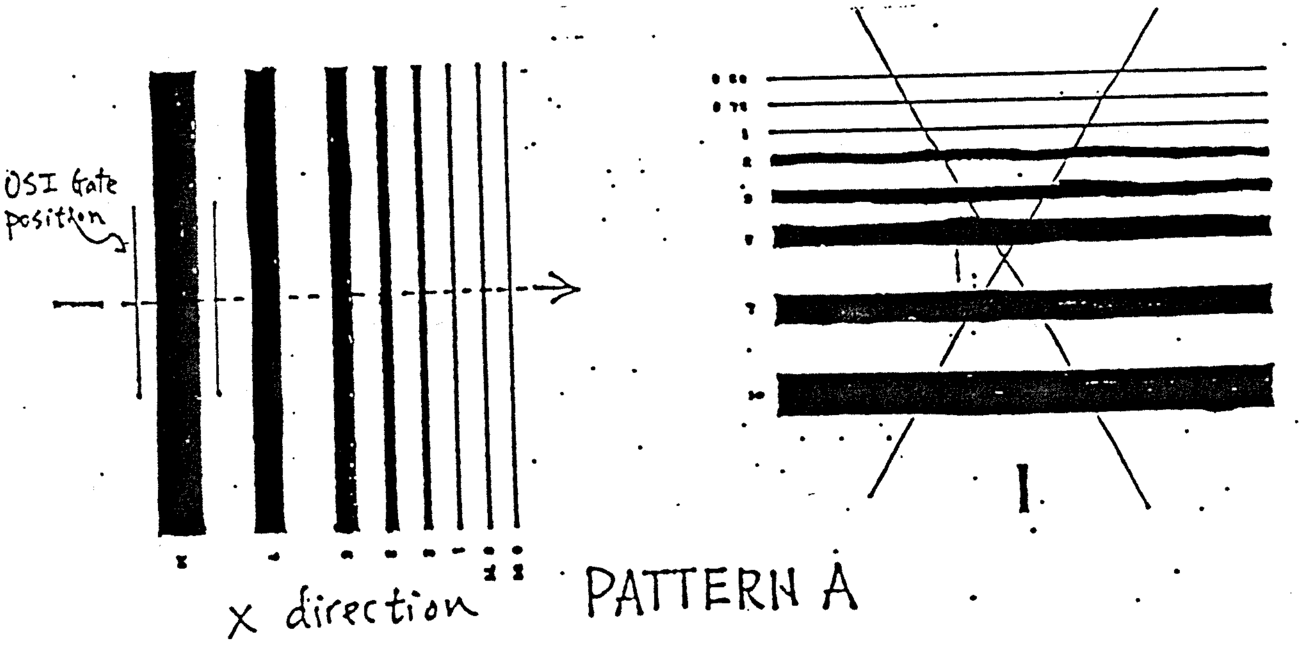


Figure 2

### Set up a correction factor of the fourth order of traceable NBS

The obtained standard mask was third order traceable to NBS. Therefore, Nanoline measurement system can be set up to be the fourth order. By means of measuring the standard mask on Nanoline, the difference (delta) of each linewidth, namely 10, 7, 5, 3, 1 and 0.75, was calculated from Nanoline's and the attached standard data. The correction factor was tabulated.

### Positive photoresist and wafer processing characterization

After the calibration of Nanoline system was established, the characterization of positive photoresist and processing proceeded. The characterization approach was to evaluate the sensitivity of positive photoresist and the effect of wafer processing conditions. While exposure dose was changing, the development time was fixed. For example, the exposure dose would increase in a step of 10 mJ/cm$^2$ from 40 to 80 mJ/cm$^2$ as the development time was fixed at 30 seconds. Then, the development time was changed from the optimum condition of 30 seconds to 20 and 40 seconds respectively, where the exposure dose was varied the same as before.

Having transferred the photoresist images on oxide wafers, the patterned linewidth of positive photoresist was measured on Nanoline. The measurement was made at the die location of 1-9 as shown in figure 1. However, data was calculated from the center die of wafers to plot a slope of delta vs. exposure/development (RPL).

## Results/Discussion

### Table of calibration result of Nanoline based on SEM measurement

| *Measured data from die 1-3, 6-4 and 7-9* | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| **ETM on Nanoline** | | | **Wafer on Nanoline** | | | **SEM picture** | | |
| 4.51 | 4.84 | 4.87 | 4.47 | 4.63 | 4.70 | 4.42 | 4.79 | 4.45 |
| 4.79 | 5.08 | 5.12 | 4.35 | 4.69 | 4.80 | 4.39 | 4.39 | 4.91 |
| 4.92 | 4.99 | 4.84 | 4.25 | 4.58 | 4.61 | 4.52 | 4.88 | 4.73 |

| Delta of Mask to Sem | | | Delta of Mask to Wafer | | | Delta of Wafer to SEM | | |
|---|---|---|---|---|---|---|---|---|
| 0.09 | 0.05 | 0.42 | 0.04 | 0.21 | 0.17 | 0.05 | -0.15 | 0.25 |
| 0.40 | 0.69 | 0.21 | 0.44 | 0.39 | 0.32 | -0.05 | 0.29 | -0.11 |
| 0.40 | 0.11 | 0.11 | 0.67 | 0.41 | 0.23 | -0.27 | -0.30 | -0.12 |
| **Average Delta** | 0.28 | | | 0.32 | | | | -0.04 |

Table I

As it can be seen from the table I, the average delta of wafer to SEM was so small that the value of 0.04 um. was not necessary to recalibrate the Nanoline system. However, according to table I, there was a variation of linewidth involved on 1.56 square inches (1.25"x1.25") of wafer as changed the measured die locations. This is probably the variations as a function of mask, processing and measurement, which was stated in the introduction section.

In addition, if the center die of delta wafer to SEM is considered only, the delta value of 0.29 um should be adjusted to minimize a measurement error through the calibration program in Nanoline system. It should also be noted that the delta of mask to SEM and mask to wafer were much higher than delta of wafer to SEM. It must result from the SEM sample was overetched in bufferred HF where it produced a smaller oxide linewidth.

Table of Nanoline and DEC critical dimension measurement

| Linewidth (um) | Delta of Nano to DEC | | Nanoline readings | | DEC readings | |
|---|---|---|---|---|---|---|
| | *Clear* | *Opaque* | *Clear* | *Opaque* | *Clear* | *Opaque* |
| 0.75 | -0.12 | 0.11 | 0.95 | 0.55 | 1.07 | 0.44 |
| 1.00 | -0.02 | 0.12 | 1.21 | 0.83 | 1.23 | 0.71 |
| 2.00 | -0.12 | -0.10 | 2.14 | 1.70 | 2.26 | 1.80 |
| 3.00 | -0.13 | -0.05 | 3.10 | 2.75 | 3.23 | 2.80 |
| 5.00 | -0.06 | -0.13 | 5.24 | 4.68 | 5.30 | 4.81 |
| 7.00 | -0.09 | -0.21 | 7.23 | 6.62 | 7.32 | 6.83 |
| 10.00 | -0.07 | -0.37 | 10.22 | 9.42 | 10.29 | 9.79 |

Note that DEC mask was the third order tracable to NBS.

Table II

The critical dimension (CD) of the standard mask (the third order traceable to NBS) was measured on Nanoline. The results showed that the delta of Nanoline to standard at spaces and lines of linewidth greater than one micron were smaller. This may be a result of the sensitivity of Nanoline system to detect the sharp edge of spaces and lines on the mask.

The Nanoline system has shown a capability of measuring linewidths at micron and submicron. It can also be seen from the figure 3 that there is a linear correlation of delta CD of lines and spaces measurement. The trend of a delta CD of space plot is approximately stable at 0.1 below x-axis where a line plot indicates a negative slope trend. It may be a linearly accumulation of measurement error of Nanoline system as the linewidth becomes larger. Hopefully, this negative slope of lines will level off at larger linewidths.

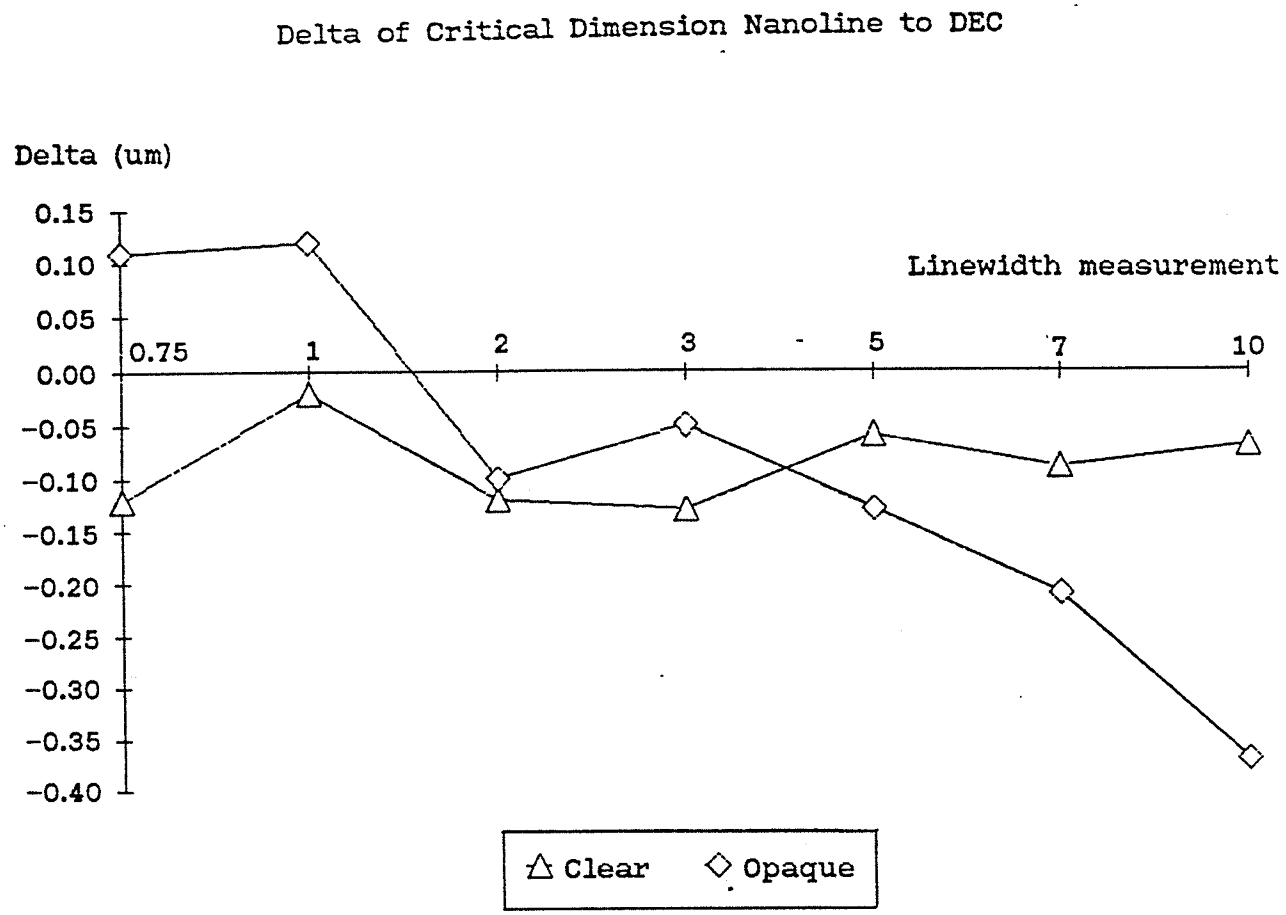

Delta of Critical Dimension Nanoline to DEC

Figure 3

In addition, the Nanoline measurement system is relatively traceable to the fourth order of NBS system. However, to an extent of the standard of Nanoline measurement system, many more measurements should be investigated in future to reconfirm this experiment.

It can be seen from the table III that the average results follow the rule of thumb as increased development time or exposure dose for positive photoresist would decrease linewidth. However, the results showed the linewidth variations across each wafer as the calculated sigma and three sigma indicated in the table. This variations are previously discussed in the calibration.

Table of Nanoline measurement

(The following results were extracted from the original data sheet in appendices).

| Develop time | | 40 mJ | 50mJ | 60 mJ | 70 mJ | 80 mJ |
|---|---|---|---|---|---|---|
| 20 sec. | Avg.line | 5.80 | 5.35 | 5.42 | 5.26 | 4.85 |
| | Sigma | 0.10 | 0.10 | 0.07 | 0.17 | 0.17 |
| | 3 Sigma | 0.30 | 0.30 | 0.21 | 0.51 | 0.51 |
| | Overall average of 3 sigma | | | 0.37 | | |
| 30 sec. | Avg.line | 5.78 | 5.22 | 5.10 | 5.14 | 4.90 |
| | Sigma | 0.14 | 0.10 | 0.15 | 0.20 | 0.08 |
| | 3 Sigma | 0.42 | 0.30 | 0.45 | 0.60 | 0.24 |
| | Overall average of 3 sigma | | | 0.40 | | |
| 40 sec. | Avg.line | 5.24 | 5.04 | 4.89 | 4.69 | 4.50 |
| | Sigma | 0.07 | 0.14 | 0.13 | 0.15 | 0.12 |
| | 3 Sigma | 0.21 | 0.42 | 0.39 | 0.45 | 0.36 |
| | Overall average of 3 sigma | | | 0.37 | | |

Table III.

(Note that the linewidths were measured in micron unit).

The overall average of three sigma of exposure dose and development time were calculated to be 0.37, 0.40 and 0.37 for 20, 30 and 40 seconds respectively. This three sigma average was for 1.56 square inches on wafer which can be used as a photolithography bias at five micron linewidth including the mask, measurement and process errors.

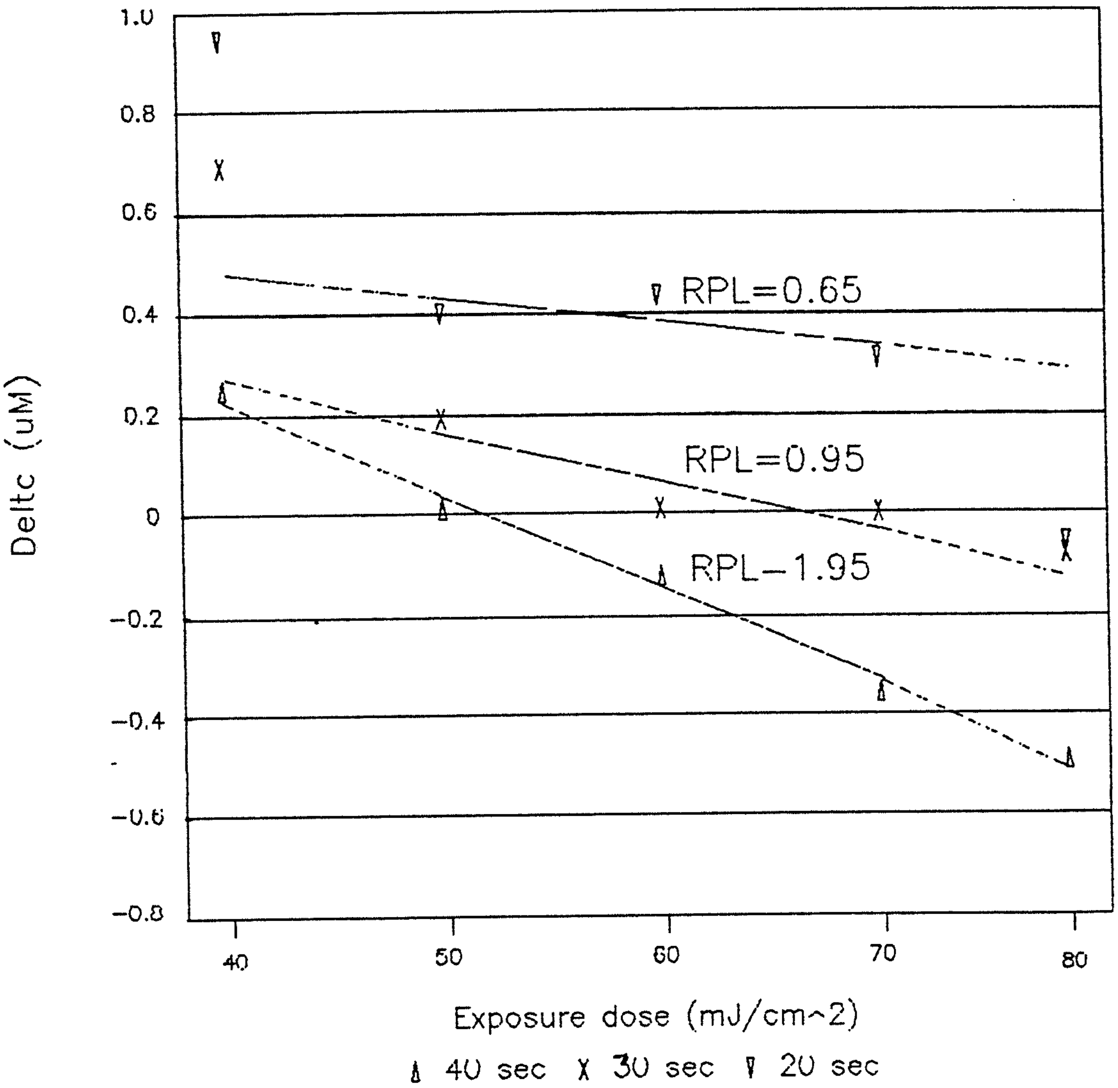
The data was extracted to establish the relative process latitude (RPL). A regression analysis was used to fit linear plots as shown in figure 4. From the linewidth delta versus exposure dose plots, the slope for 20 seconds development showed the least value of 0.65. This resulted in the least sensitive process to linewidth change as the exposure dose was varied from 50 to 80 mJ/cm2. Additionally, the process would use less developer material. It was important to note that at 40 mJ/cm2 dose and 20 seconds development could not be used in the process because wafers produced rings around the edges. Wafers with 30 and 40 seconds of development did not suffer this problem.

# A plot of relative process latitude (RPL)

Regression Analysis equations are shown below:-

@ 20 seconds Y = 0.7566 - 0.0065*X
@ 30 seconds Y = 0.6333 - 0.0095*X
@ 40 seconds Y = 0.9633 - 0.019*X

Delta of 5 uM linewidth VS. Exposure



Noted that at 20 seconds development and 40 mJ/cm2 of dose some rings appeared around wafer edges.

After this relative process latitude (RPL) was established, our optimum wafer processing for 30 seconds development and 60 mJ/cm2 dose was not the least RPL value of 0.95 and economical process. Therefore, according to plot, the 20 seconds development with RPL value of 0.65 should be implemented and used in the CGA Wafertrac instead.

## Conclusion

The calibration of a Nanoline system based on SEM measurement was established. Variations resulted from mask, measurement and process errors. The Nanoline system was set up to be a fourth order traceable to NBS using a standard mask. Our lithography process bias was determined to be approximately 0.38 um. at five micron line/space. Finally, the relative process latitude (RPL) at 5.0 um linewidth versus development time was established using regression analysis. The RPL value of three plots were 0.65, 0.95 and 1.95 for the development time of 20, 30 and 40 seconds, respectively. Because of the least RPL value of a process desired, the 20 seconds development was proved to be not only the best process with a less sensitive to linewidth change but also an economical process as varying exposure doses.

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