Advanced Rinse Process Alternatives for Reduction of Photolithography Development Cycle Defects

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ABSTRACT

As linewidths continue to decrease in size, preventing smaller defects is becoming critical to maintaining yield. Defects that are caused during the development cycle and attach themselves to the BARC surface, such as water spots or photoresist residues, have always been a concern and have been usually removed at the expense of throughput. Various options are available to reduce these types of defects but each has disadvantages. One such example is a double puddle develop process. The disadvantage of this process is that the exposure dose may have to be changed. Another example is increasing the rinse time to several minutes with an associated reduction in throughput. This paper will discuss rinse alternatives that have been able to reduce develop type defects by up to 70% while also reducing the wafer-to-wafer variation by up to 80%. This process may have a dramatic increase in throughput by keeping the total rinse time under 20 seconds and may have minimal (less than 2% change) impact on measured linewidth. These rinse processes utilize a quick succession of changing spin speeds and accelerations that are acceptable for 300-mm wafer processing. Surfactant-containing rinse solutions designed to reduce line collapse in 193-nm photoresists were also investigated to determine their effectiveness in reducing post-develop defects in concert with the newly developed water rinse process. The rinse processes that will be discussed will have the flexibility of integrating the surfactant-containing rinse solution while maintaining the shortest possible cycle time. At the same time these processes will reduce defects and pattern collapse.

Keywords: ArF, KrF, photolithography, BARC, develop, satellite defect, photoresist, bottom anti- reflective coating, surface conditioner.

1. INTRODUCTION

To maintain a competitive edge, companies are striving to improve the manufacturing process to reduce all types of defects at every level. As devices continue to shrink in size, defects that once were not a concern are now considered killer defects. Post-develop defects (PDDs) also known as clear field defects, are one such case. These defects have not affected yield directly but will mask killer defects until the devices are small enough that the residue left from a PDD can be considered an etch block. Therefore, PDDs must be removed before inspection. Increasing cost and yield pressures have raised the urgency to reduce or eliminate PDDs.

The best results to date have been achieved by modifying the photoresist bake and develop process in some way to remove the particles that result in PDDs.[1,2] There are several techniques that are known to reduce PDDs, but all of them have drawbacks. The easiest to implement in production is to extend the rinse time, with the obvious disadvantage of lower throughput. A series of low/high spin speed cycles during the rinse can also reduce the defects, but this still lengthens the rinse cycle. Another drawback to this procedure is that the wafer speed may approach or exceed 3000 rpm during the "high" cycle, which is not conducive to 300-mm wafer processing. Another approach is to puddle fresh developer on the wafer a second time before the rinse begins, which is called "double puddle." This double puddle process requires considerable optimization due to possible exposure dose shifts that could jeopardize CD uniformity across the wafer. In today's newest coater tracks with scanning developer dispense nozzles, the second puddle may be impossible because the proximity of the nozzle to the wafer surface may cause defects while attaching to the nozzle tip, and such defects may transfer to other wafers.

Another defect problem that has become more apparent as 193-nm exposure systems have come on-line is photoresist line collapse. Line collapse is due to surface tension effects as the rinse water dries between the lines and pulls the lines toward each other. The most straightforward way to reduce or eliminate line collapse is to rinse the wafer with water that has a surfactant mixed in the water or use another liquid that has a lower surface tension than that of water. One disadvantage of these solutions is that surfactant or other liquid may leave a residue on the wafer, causing PDDs. A second disadvantage is that if a lower surface tension liquid other than water is used, then the developer process module needs another nozzle to dispense this material along with the developer and DI water.

This study will consider the possibility of reducing or removing the defects by modifying the rinse cycle to maximize agitation of the rinse water on the wafer surface without an increase in rinse time while maintaining wafer speeds below 2000 rpm for 300-mm wafer processing. The new rinse process should also have little or no impact on measured linewidths. The important rinse factors that must be modified to reduce PDDs and maintain all of the attributes just discussed will be identified from a design of experiment (DOE). Also the key parameters involved in removing defects when using the surface conditioner will be discussed with up to an 80% reduction in defects from the worst case to best case scenario.

2. EXPERIMENT

2.1 Dionized (DI) Water Rinse Study

The rinse process was divided into three sections: beginning, middle, and end. A Taguchi L16 screening experiment was designed with eight factors to test factors in all three sections. The other seven factors for screening may represent cross-terms during the analysis step if they are found to be important. The beginning and end factors were spin speed and time. Middle section factors were number of low/high cycles, cycle high speed, and cycle time. Figure 1 shows the process sequence used in this design. The tested factors that are highlighted in Figure 1 are detailed in Table 1, which contains the settings for each factor listed.

A common BARC and a common 248-nm ESCAP photoresist were selected for this study because internal testing of this combination had shown that PDDs were present. All the testing was done on a TEL Mk8 coater track with a 0.26N developer with surfactant. The exposure was done with a broadband exposure source that would expose a square measuring about 110 mm in the center of a 200-mm wafer. A KLA2112 was used at the 1.25 μm pixel size to scan the exposed area for defects.

Several wafers were run before the DOE with just BARC and scanned to check the cleanness of the BARC coating. The average number of defects per wafer from the BARC coating is twelve, averaged from four wafers. Three wafers were coated with BARC and photoresist and were exposed for each of the 15 experimental runs for the DOE. The three wafers were scanned on the KLA after each experimental run. The average and median number of defects per wafer were calculated from the three wafers along with the minimum and maximum number of defects for the wafers. The results from the wafer coating were then analyzed using DesignEase DOE software and are presented here.

It was decided that the three factors of the eight that make the largest contribution to removing defects could be used for further process optimization. Also, with the type of DOE that was used, any factors of the remaining eight that had a contribution greater than any of the three real factors would be considered a nonlinear effect of the three real factors and would be investigated in greater detail with further optimization efforts.

2.2 Surface Conditioner (SC) Rinse Study

The surface conditioner (SC) was installed on one of the E^2 nozzles on a TEL Mk8 Cleantrack. A common 193-nm BARC was chosen for this part of the study because it is in use throughout the industry, and a common 193-nm photoresist known to have PDDs was chosen. As in the DI water rinse study, a Taguchi L16 screening DOE was chosen for its efficiency. The factors and the low/high settings are shown in Table 2, and a schematic of the rinse process is are shown in Figure 2. The testing process was identical to the DI waater rinse portion of the test with three wafers per experimental run and the median and mean defects per wafer statistic used for analysis in the DesignEase DOE software.

3. RESULTS AND DISCUSSION

3.1 DI Water

The most widely held theory for the formation of PDDs in positive photoresists is that the photoresist components of the exposed areas are being removed by the developer but are getting redeposited or adsorbed on the wafer surface during the develop and rinse process. To reduce PDDs, it should be possible to simply rinse off these particles. However, as the resist components fall out of solution and deposit on the wafer or BARC surface, they appear to bond strongly and are not rinsed off easily. The process modifications associated within this DOE were designed to create a large force in a short amount of time to overcome the binding energies from PDDs. The rinse process in this test provides the energy to remove the defects by the cycling of the low/high speed cycles. The changing centripetal forces produced at the transition between the low and high speeds dislodge the particles or prevent their initial deposition. The rapid cycling of the speed does not allow the freed particles to reattach themselves to the BARC surface, much like sugar stays suspended in water as it dissolves in a glass of cold water when stirred.

To create this situation the defect must see a change in momentum in a short amount of time. This can be accomplished by rapid oscillation between two spin speeds during the rinse process. This impulse function can be defined as the force multiplied by the time interval that the force is active. The force is proportional to the velocity squared. Therefore, a small change in spin speed can cause a large change in force. To shorten the time interval between the two spin speeds, a high acceleration and a short spin time should be employed as they were in the DOE. This has the effect of rapidly changing the forces experienced by particles on the BARC and suspended in the rinse water. These changing forces may impart enough energy to dislodge particles from the BARC surface and keep them suspended while the defects are rinsed away.

As stated earlier, the three wafer mean and median results from the experimental runs were input into the software and were analyzed with typical ANOVA techniques to find the relative percent contribution of each factor on the responses. The responses in this work are median, mean, and range of defects for three wafers. In large populations, the mean and median are very close if not identical; with the few wafers coated for each experimental run in this experiment, using both the mean and median statistics would minimize any effect that an outlying data point may have on the mean.

The mean number of defects were examined first. The Pareto chart created from the percent contribution is shown in Figure 3. From left to right the most significant factors are labeled 4, 1, 13, and 2 and correspond to number of cycles, beginning rinse speed, and beginning rinse time. Factor 13 is an unassigned factor in this DOE. Possible reasons for the high significance of this factor are nonlinear effects (multi-factor interactions) that were not taken into account on this DOE, as stated earlier, or the existence of an uncontrolled and unaccounted for factor that varied during the test. The latter is unlikely due to the controls on the TEL Mk8.

The three real factors account for 60% of the total contribution in the Pareto chart, with the number of cycles and the beginning rinse speed making up most of that portion. With regard to the significance statistic of these factors, the number of cycles and beginning rinse speed gave confidence limits greater than 95%. The beginning rinse time had confidence limits of around 80% or less. These data mply that the number of cycles and beginning rinse speed play a large role in reducing PDDs and the beginning rinse time has a smaller role in reducing defects. A rapid drop in the significance statistic implies that all the other factors are very weak and can be ignored in a more detailed study, thus giving confidence in choosing the three largest contributing factors, as assumed initially.

Upon applying the same techniques to the median wafer defect data, it was found that the same named factors are the three highest contributors to the number of defects. In this case, the beginning rinse speed had the highest contribution followed by the number of cycles. Both are still the highest contributors to reducing defects. Factor 13 and Factor 10 (another unassigned factor) were the next largest contributors. The third real factor is beginning rinse time. As before, ANOVA revealed that the number of cycles and beginning rinse speed were significant within 95% confidence limits. The other factors were well below 90% confidence limits.

To ensure the validity of the DOE results, verification runs were designed. Two rinse recipes were created from the DOE, one with the named factors set at the best settings to minimize defects and another at the worst. Two other rinse recipes that are used for internal testing were used to compare the defects associated with typical rinse processes in the industry. Aall the rinse processes are listed in Table 3.

The number of cycles, beginning rinse speed, and beginning rinse time were set to the best and worst settings, and five wafers were coated to verify the results from the DOE. The best rinse settings had a normalized defect average of 1 defects/wafer with a range of .6 defects. The worst settings had an average of 2.5x more defects and a range of 1.5x defects/wafer. The best settings of the rinse process reduced both the average defects per wafer (by 61%) and the range (by about 60%). The rinse time of the best process is 17 seconds, which may be reduced further with further optimization experiments on the three important factors and reduction of the time on other nonessential factors such as the ending rinse time. This time is within the requirement for a rinse time of less than 30 seconds by a very large margin.

The best rinse process was compared to two other rinse processes that are more typical in industry today, as shown in Figure 5. Three wafers were run for each process. The typical rinse process 1 had an average of 3.0 (compared to best rinse) and a large range of 2.5. The typical rinse process 1 with the DOE rinse settings had an average of .7, a reduction of 76%, and much lower range of .14, yielding a reduction in the wafer- to-wafer range of 94%.

The typical rinse process 2 was then compared to the DOE rinse. This time there was no significant defect reduction resulting from the DOE recipe. However the range was reduced by 75% from 1 to .26. Upon examining rinse process 2, the difference between the low and high cycle increases as the rinse process continues, creating a situation like the one described here. The possible energy imparted to the defect increases because the spin speed increases, thus the defects are removed. However this rinse process is 2 seconds longer than the DOE rinse along with incompatible spin speeds for 300-mm wafer processing.

The rinse process as defined by the DOE is a very robust process. When comparing the developer dispense and puddle steps for each process in Table 2, it is easy to spot significant differences. When the defects are compared, the average number of defects are not significantly different and center around 200 defects/wafer. This gives confidence that the process is very robust and will efficiently remove the PDDs regardless of the develop process and will leave behind only the most tightly bound defects. In the case studied here the components from this photoresist adhere very tightly to the BARC surface, and to remove more defects requires additional process modification.

To show the effect the rinse process has on the measured linewidth, the develop steps and exposure dose were held constant and the rinse process was varied. Two wafers were exposed and developed with each rinse process along with a control. The control process dictated the dose to set for the other three rinse processes. Three die on each wafer were measured targeting the 250-nm dense line/space, for a total of six measurements. The data were then plotted in Figure 6 with the range, median, and mean. When the average linewidths of the rinse processes are compared to the control measurements, the difference is less than 2%. The rinse process as defined by the DOE has nearly no impact on measured linewidth when comparing the range of measurements.

3.2 Surface Conditioner

The defects, if any, that are created with these rinse products would be a residue from the surface-active materials in the formulation, or the interaction product between the formulation and photoresist. The analysis of defects was not undertaken; only the process that would remove them is studied here. The developer dispense and puddle process was not changed because that would most likely cause a CD shift. Also the DI water rinse was simplified to only one rinse speed and time, as noted in the DOE, to simplify the analysis of the results.

The results were placed in the DesignEase software, and a Pareto chart of the strength of the factors was made which plotted both the mean defect statistic and the median statistic, as shown in Figures 7 and 8. As with the DI water rinse process, further work should be done to investigate the extent of the process window using the three strongest factors with a more thorough DOE. The results from the median and mean statistics Pareto charts agree reasonably well with the “water rinse spin speed”, the “dry spin speed”, and the “dry time” as the strongest factors. From this it can be stated with some confidence that these three factors will play a large role in reducing the defects associated with the SC. The reason that the results are slightly different between the median and mean statistics Pareto chart is that with only three wafers tested for each experiment, a very high or very low outlier can affect the mean statistic very easily, and then skew the software to reporting false data.

A set of wafers were coated, exposed, and developed under the best and worst process conditions for the three factors previously defined as the strongest. All other factors were set to the low setting to minimize the spin speeds and spin times, and the flow rate was set at 0.8 L/min because of wafer coverage issues. Five wafers were coated, exposed, and developed for each of the two processes. The results are summarized in Table 4. Under the worst DOE conditions, the normalized to average defects was 5.2 with a standard deviation of 0.75. The best condition confirmation run had an normalized average of 1 and a standard deviation of .23, a reduction of 80%.

The dry speed and time still require some optimization because it was noted that the SC was not entirely dry after the 5-second dry time. A test varying the dry spin time was ran to find when the SC dried and what the trend of defects with dry time were. The results are shown in Figure 9. As can be seen an increasing trend of defects with increasing dry spin time is seen. The SC dries somewhere within 15-20 seconds, which is the steepest part if the curve appears to be.

4. CONCLUSIONS

A robust rinse process has been found to reduce the number and the variability of PDDs significantly by using a DOE. The DOE parameters that were found to be significant are the number of cycles during the rinse, the beginning rinse speed, and to a lesser extent, the beginning rinse time. Results from this testing indicate a possible reduction of over 75% can be realized in both average defects per wafer and the range across several wafers. Also, the rinse time has been reduced from the maximum allowed of 30 seconds to 17 seconds. It has also been shown that there is less than 2% difference on measured linewidth for 250-nm dense line/spaces. Three separate develop recipes were considered in this work, and all showed a reduction in variability from wafer to wafer or a reduction in number of defects per wafer, or both. This indicates that the rinse process can be used on any number of developer processes with some positive result. From this work, it is possible to remove unwanted defects that may be considered killer defects and possibly increase yield, at the same time reducing costs by reducing water consumption during the rinse process with the reduction in time needed to remove the defects.

A post-water rinse material to reduce line collapse for 193-nm photoresists was investigated to find the best parameters to change to minimize defects. The parameters for this test were the water rinse speed, dry spin speed and, dry time. From the testing, an 80% reduction in defects was realized from the worst to best process. Further optimization is still required because the SC is not completely dry when the process is completed with the lowest defects.

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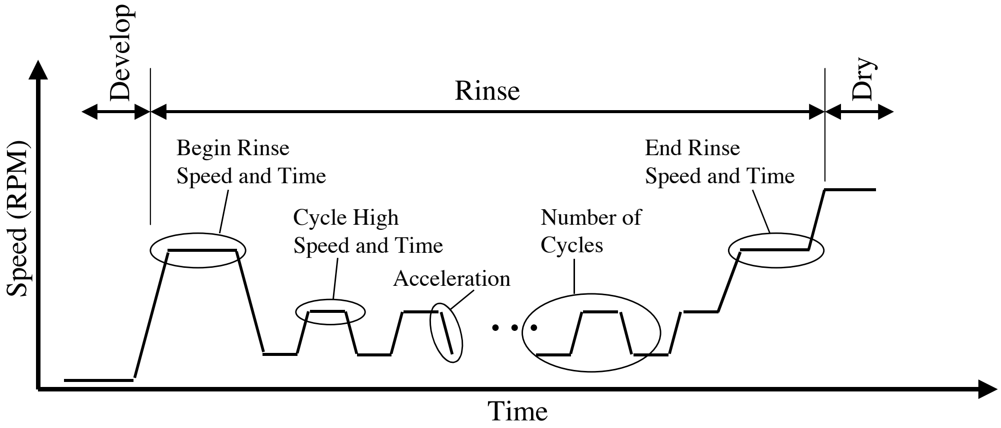

Figure 1. Rinse process sequence and factors.

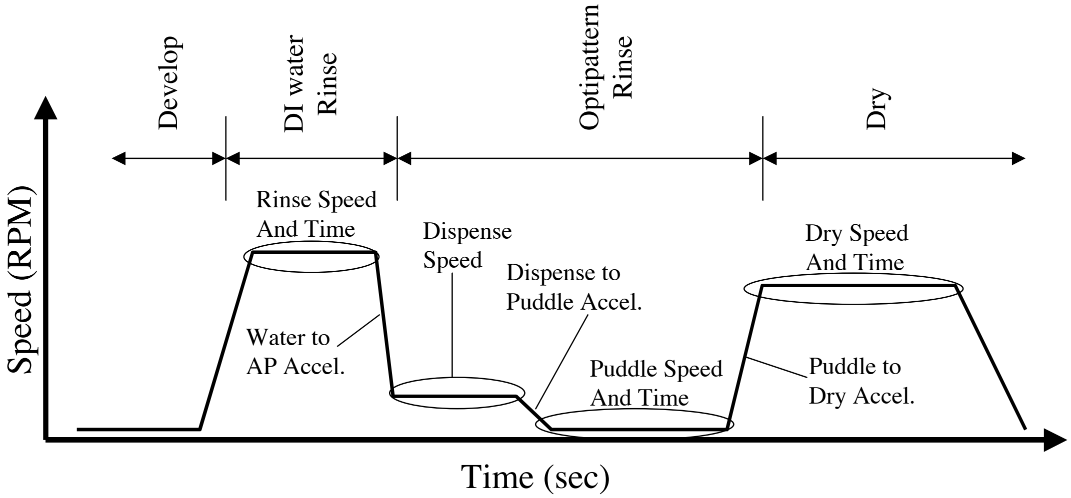

Figure 2. General schematic of the OptiPattern rinse DOE factors.

Factor Number	Factor Name	Low/High Setting
1	Begin Rinse Speed	500/1500
2	Begin Rinse Time	5/10
3	Rinse Acceleration	5000/20000
4	Number of Cycles	10/20
5	Cycle High Speed	600/900
6	Cycle Speed Time	0.1/0.5
7	End Rinse Speed	1000/2000
8	End Rinse Time	5/10
9-15	Used for estimation of nonlinear effects	

Table 1. Experimental design factors. Factor numbers are used in Figures 4 and 5.

Factor Name	Low/High Setting
Water Rinse Spin Speed	500 / 2500 rpm
Water Rinse Spin Time	10 / 40 sec
Water to SC Rinse Acceleration	1000 / 10000 rpm/sec
SC Rinse Dispense Spin Speed	30 / 240 rpm
SC Dispense to Puddle Acceleration	1000 / 10000 rpm/sec
SC Puddle Spin Speed	0 / 200 rpm
SC Puddle Time	1 / 10 sec
SC Puddle to Dry Acceleration	1000 / 10000 rpm/sec
Dry Spin Speed	1000 / 2500 rpm
Dry Time	5 / 20 sec
SC Rinse Flow Rate	0.4 / 0.8 L/min

Table 2. Experimental design factors for OptiPattern rinse DOE with DOE settings.

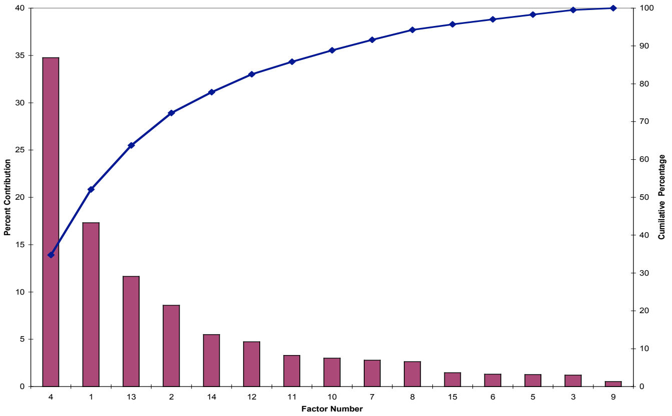

Figure 3. The Pareto chart for the mean number of defects. Factor numbers are listed in Table 1.

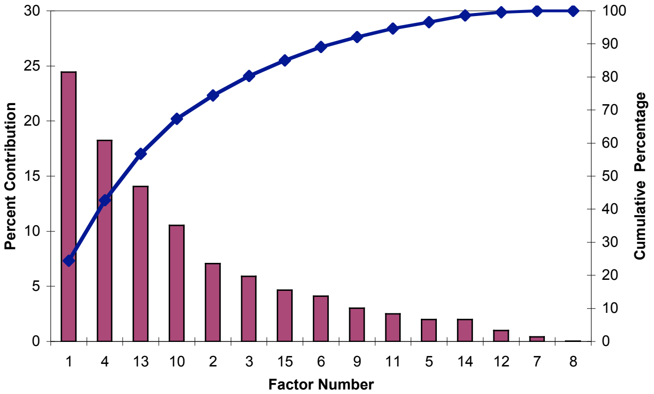

Figure 4. Median number of defects Pareto chart. Factor numbers are listed Table 1.

Rinse Process with best rinse settings.

Time	Speed	Accel	Dispense	Rinse Arm
0.8	0	10000	Developer	Home
1	30	10000	Developer	Home
45	0	10000		Home
5	0	10000		Center
5	500	10000	Water	Center
0.1	500	10000	Water	Center
0.1	600	10000	Water	Center
0.1	500	10000	Water	Center
0.1	600	10000	Water	Center
0.1	500	10000	Water	Center
0.1	600	10000	Water	Center
0.1	500	10000	Water	Center
0.1	600	10000	Water	Center
0.1	500	10000	Water	Center
0.1	600	10000	Water	Center
0.1	500	10000	Water	Center
0.1	600	10000	Water	Center
0.1	500	10000	Water	Center
0.1	600	10000	Water	Center
0.1	500	10000	Water	Center
0.1	600	10000	Water	Center
0.1	500	10000	Water	Center
0.1	600	10000	Water	Center
0.1	500	10000	Water	Center
0.1	600	10000	Water	Center
10	1000	10000	Water	Center
15	4000	10000		Home
1	0	10000		Home

Typical Process #1

Time	Speed	Accel	Dispense	Rinse Arm
0.3	0	10000	Developer	Home
0.3	120	10000	Developer	Home
1	30	10000	Developer	Home
55	10	10000		Home
5	10	10000		Center
10	500	10000	Water	Center
10	2500	10000	Water	Center
10	500	10000	Water	Center
10	2500	10000	Water	Center
20	4000	10000		Home
1	0	10000		Home

Typical Process #2

Time	Speed	Accel	Dispense	Rinse Arm
0.2	400	800	Developer	Home
0.6	400	800	Developer	Home
0.5	60	1700	Developer	Home
1.5	20	100	Developer	Home
3.1	0	200		Home
52	0	200		Home
5	0	200		Center
1.5	1200	1200	Water	Center
4	1200	1200	Water	Center
3	500	1400	Water	Center
3.6	2000	15000	Water	Center
3	500	3000	Water	Center
4.1	3000	25000	Water	Center
10.5	4000	2000		Home
1	0	4000		Home

Table 3. Best process and typical rinse processes with developer dispense steps.

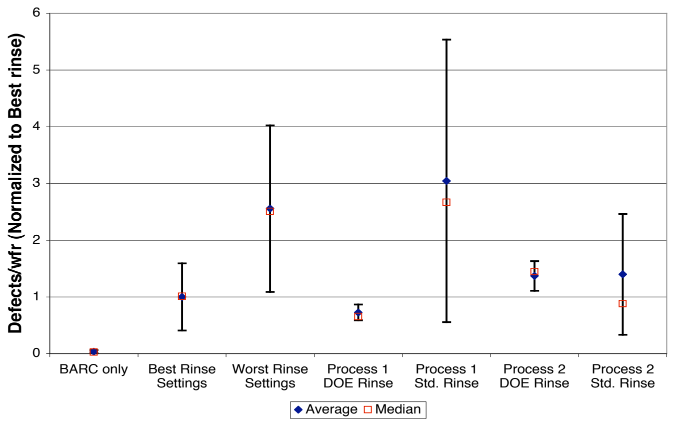

Figure 5. Effect of rinse process on defects with different develop steps.

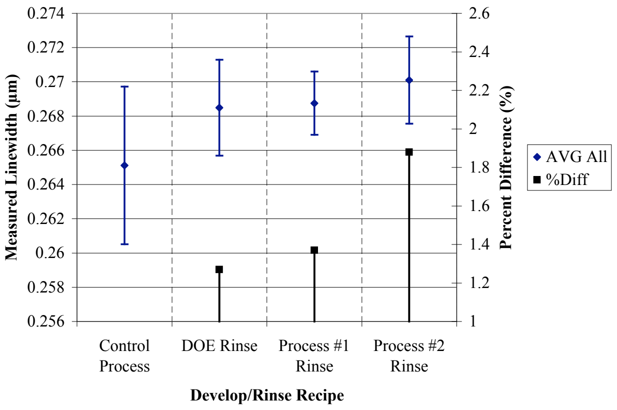

Figure 6. Measured linewidth and percent difference from the control CD.

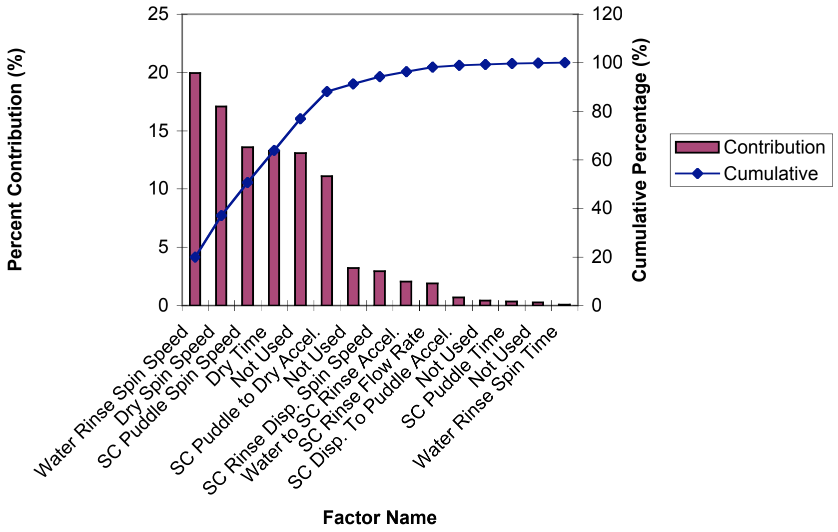

Figure 7. Pareto chart of median defect/wafer statistic for SC rinse DOE.

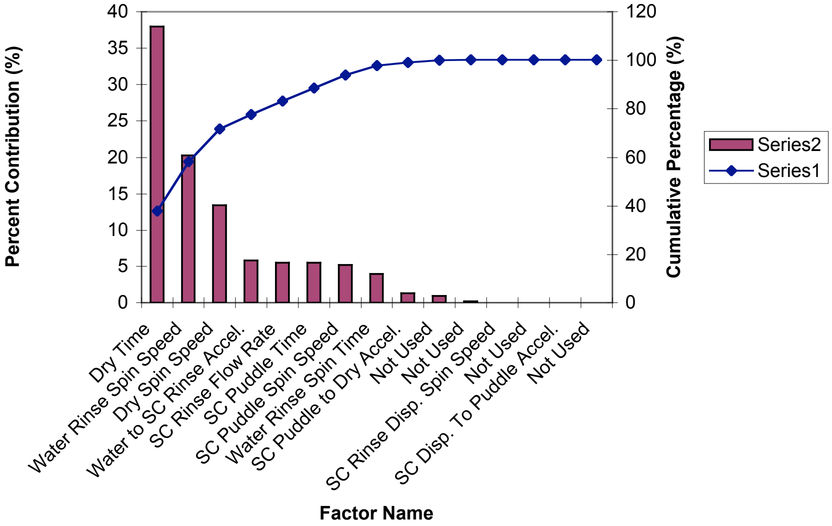

Figure 8. Pareto chart of mean defect/wafer statistic from the SC rinse DOE

Process	Water Rinse Spin Speed	Dry Spin Speed	Dry Time	Average (def/wfer) (Normalized)	Median (def/wfer) (Normalized)	Std. Dev. (1 sigma) (Normalized to Avg.)
Best	2500	1000	5	1	1	0.2
Worst	500	2500	20	5.3	4.4	0.8

Table 4. Summary of OptiPattern DOE confirmation processes and results.

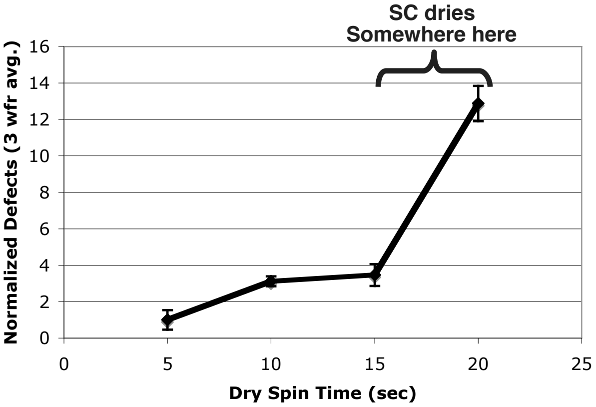

Figure 9. Defect trend with increasing dry spin time. SC dries between 15-20 seconds.