PHOTOMASK

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Second Place Best Paper (PM11)

More than monitoring: Advanced lithographic process tuning

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ABSTRACT

Critical dimensions (CD) measured in resist are key to understanding the CD distribution on photomasks. Vital to this understanding is the separation of spatially random and systematic contributions to the CD distribution. Random contributions will not appear in post etch CD measurements (final) whereas systematic contributions will strongly impact final CDs. Resist CD signatures and their variations drive final CD distributions, thus an understanding of the mechanisms influencing the resist CD signature and its variation play a pivotal role in CD distribution improvements. Current technological demands require strict control of reticle critical dimension uniformity (CDU) and the Advanced Mask Technology Center (AMTC) has found significant reductions in reticle CDU are enabled through the statistical analysis of large data sets. To this end, we employ Principle Component Analysis (PCA) – a methodology well established at the AMTC[1]- to show how different portions of the lithographic process contribute to CD variations. These portions include photomask blank preparation as well as a correction parameter in the front end process. CD variations were markedly changed by modulating these two lithographic portions, leading to improved final CDU on test reticles in two different chemically amplified resist (CAR) processes.

1. Introduction

We continue our investigation into photomask CD signatures using PCA as a probe. The AMTC previously employed PCA to examine resist CD variations of monitoring reticles in advanced positive and negative CAR processes (pCAR and nCAR).[1] Two dimensional representations of the major components of these variations revealed systematic resist CD

Continues on page 3.

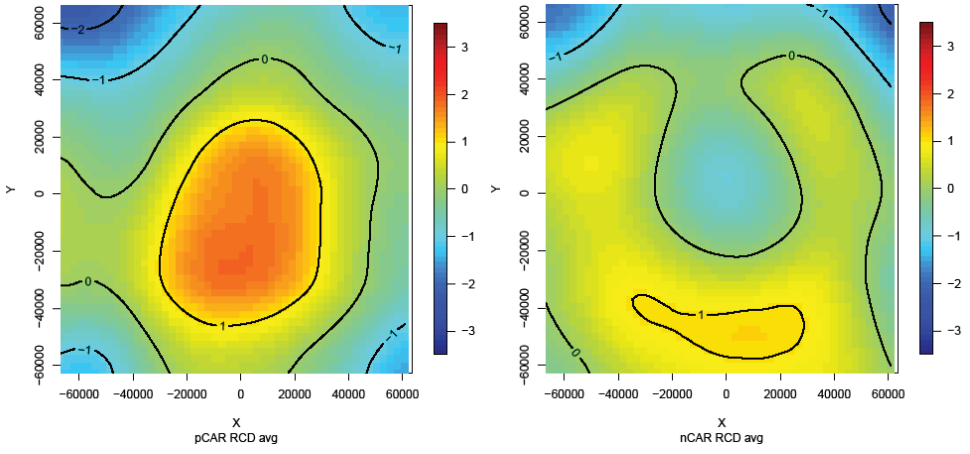

Figure 1. Normalized average resist CDU signatures for pCAR and nCAR processes.

BACUS NEWS

JANUARY 2012
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TAKE A LOOK INSIDE:

SPIE

EDITORIAL

Quality Time

Artur Balasinski, *Cypress Semiconductor Corp.*

As we are taking our first curious peeks into the Year 2012, we are certainly happy that the many challenges of 2011 have been contained. We are happy to carry on with all our conferences, the EML, the SPIE Advanced Lithography, the Photomask Japan, and the SPIE/BACUS Symposium, alive and growing, despite the earthquakes, the economy, and the competition. We also re-elected Wolf Staud for the President of BACUS, added John Whittey as his VP, and the undersigned would carry on in his role as the Secretary. We are also happy to note that mask complexity is growing by leaps and bounds, be it for "More than Moore"- or "No More Moore"-based manufacturing. In fact, the innovativeness, the semiconductor industry at large, and the mask applications related to them, have grown so fast in 2011, that it may be a good time to take a short break this year? Nah. We have to keep up our balancing act, between increasing production volume and keeping the inventories low, between taking on all the possible assignments and taking the time to understand where are we going with all of them, between pushing hard for EUV and looking sideways for the direct write.

I am not big on New Year's resolutions as I do not believe in cheap talk. But one thing seems to me more certain than ever and worth committing to: quality. We have built such a monstrously complex empire of products, processes, and procedures that any rework sets us back well beyond where we want to be. And we keep growing, in the hope that this complexity is still manageable. Yes, but only if we put proper quality checks in place. One little false step and many-a-structure collapses like a house of cards. I just read a reassuring statement that 2011 was the safest year on the record for air traffic. Let's hope this is a meaningful trend, but if it proves to be, we certainly have a good pattern to follow. No bad data for masks! No fab reworks! No poor quality papers! No schedule pushouts! We, as engineers, simply can not afford it if we want to keep improving and growing our reach on everyday's life. I know it sounds like high-school composition but I feel the pressure myself and I am pretty sure many of us feel it too.

How to achieve quality? Here is my favorite: Build state machines for every process we run and follow their flow charts. If A, then B, no excuses or persuasions. Create clear sets of criteria and check your product, be it data, hardware, or an article. Silicon never lies.

Which brings me to the New Year's wishes: May 2012 be a Quality Year for all of us!

BACUS

N • E • W • S

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BACUS NEWS

Table 1. CDU means and standard errors for each CAR process.

CDU [nm 3 σ]	pCAR	nCAR	Tone
Previous, 2010	3.96 ± 0.06	3.16 ± 0.06	Resist
Current, 2011	3.81 ± 0.04	3.05 ± 0.05	Resist
Combined, 2010 & 2011	3.59 ± 0.04	3.70 ± 0.05	Final

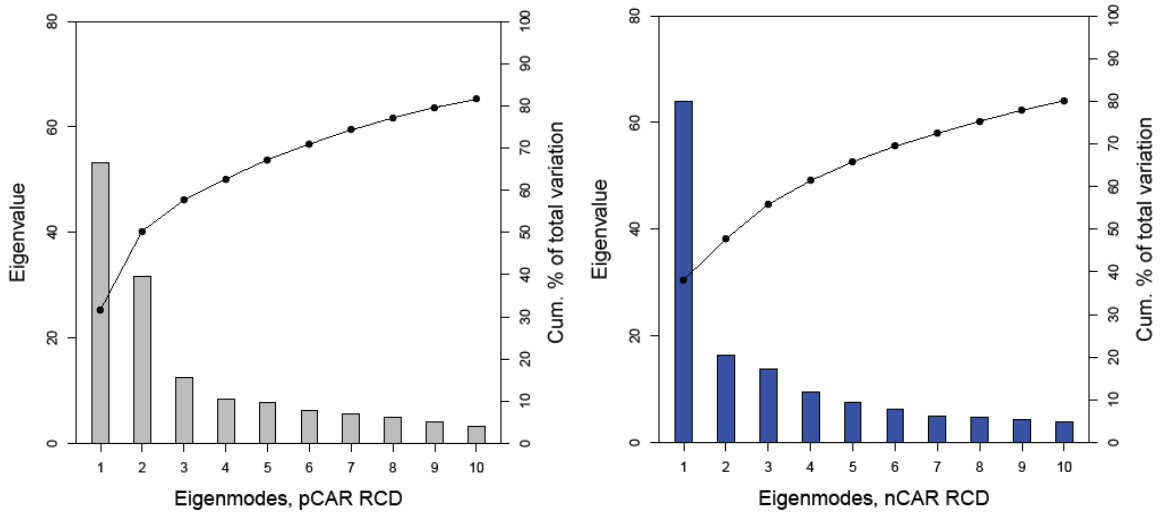

Figure 2. Eigenvalues for the first 10 eigenmodes and cumulative variation percentages for pCAR and nCAR resist CD data sets.

error contributions within the lithographic portion of both CAR processes. In this report we continue to utilize PCA to pinpoint a significant CD error source in each CAR process.

2. Experimental

The AMTC processes test reticles at regular intervals in order to gauge line performance and stability. Commercially available 193nm phase shift blanks with widely used pCAR and nCAR are written with 50kV e-beam (PG) lithography and processed identically to customer reticles, except without the use of feedback compensation strategies. Each test reticle has the identical dense feature layout (560nm pitch) distributed uniformly over ~130mm^2 and 169 measurement points are collected with a CD SEM after the resist develop and final etch processes (i.e., resist and final CD). Resist and final CD measurements of ~100 monitors per CAR process were examined with PCA.

3. Results

3.1 CDU baselines for each CAR process

In Table 1 we compare the average resist and final CDU for each CAR process between our first report (2010) and the current one (2011).

The slight resist CDU improvements between the current and previous report are not statistically significant, meaning no change occurred in resist CDU. Table 1 also provides final CDU for each CAR process which differs significantly from resist CDU. Final CDU for the pCAR process is better than in resist whereas nCAR final CDU is worse. The pCAR result was not expected since etch contributions to the overall CD signature typically degrade CDU performance compared to resist measurements. One reason for these results most likely involves the resist measurement process which uses the top edges of resist profiles for electron beam deflection and signal capturing. This method ignores other resist profile components such as sidewall angle and footing that transfer during the etch process and impact final CD metrology. An alternate reason could be the etch CD error contributions work in an opposite direction to the existing resist CD signature, resulting in an overall better final CDU.

Figure 1 shows the average resist CD signature in each CAR process obtained by normalizing each monitor by its resist CD mean. As in our first report, the dominant pCAR resist CD signature is radial (center fast or hot, with slow or cold corners) while for nCAR a top to bottom resist CD signature dominates (cold top, hot bottom) with an additional radial component (center slow or cold).

Applying PCA to normalized resist CDs provides the modes of data set variation (Eigenmodes) and Eigenvalues or weight of each corresponding Eigenmode. Figure 2 illustrates the first ten Eigenmodes with their associated Eigenvalues for resist CD measurements in each CAR process along with the cumulative variation percentages of each mode. The first 4 Eigenmodes account for >60% of the resist CD variation in each CAR process and Eigenmodes higher than 4 will not be examined in this report.

Figures 3 and 4 plot the Eigenvectors from the first four Eigenmodes against the resist metrology coordinates in each CAR process and provide a spatial representation of these

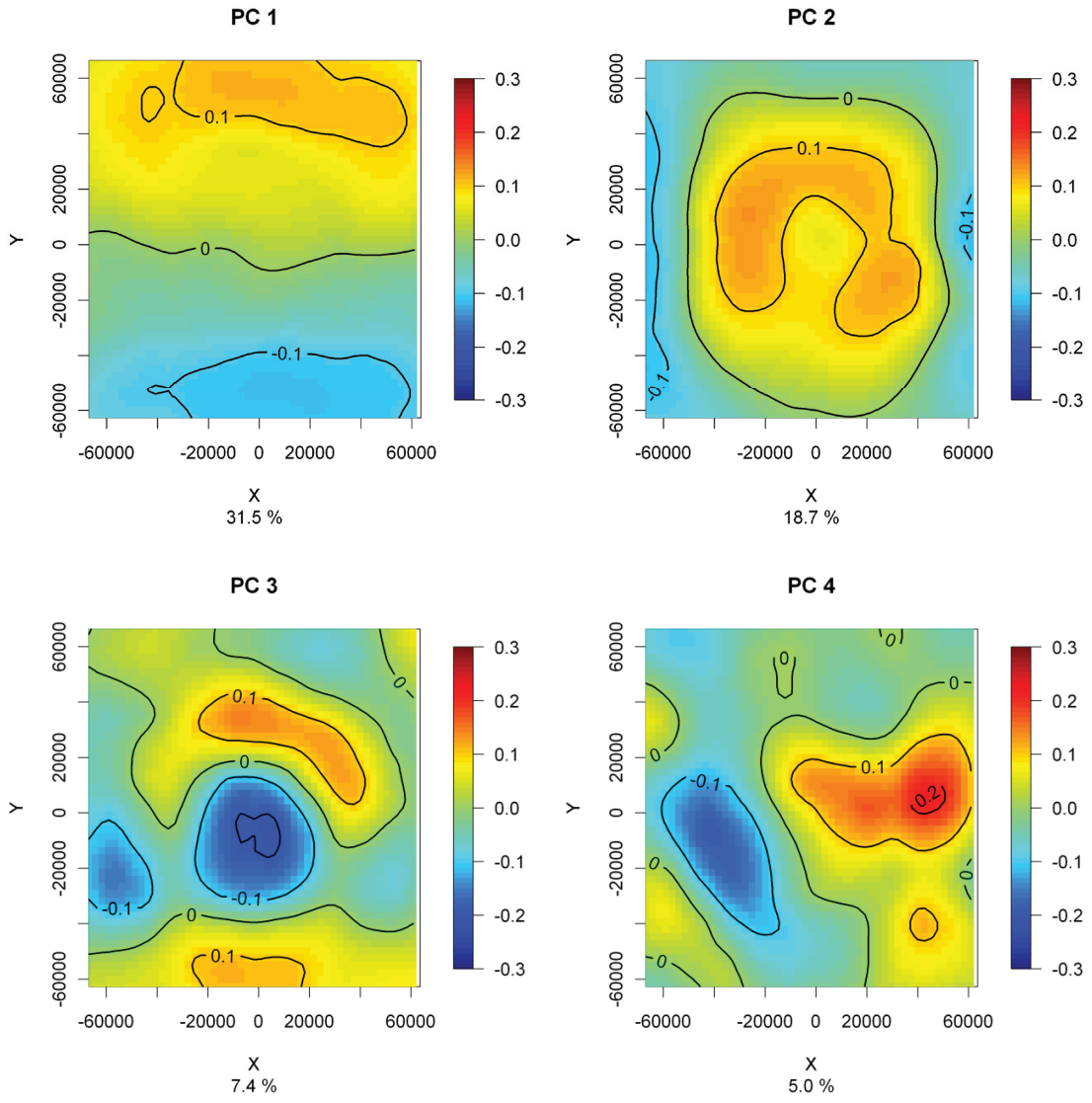

Figure 3. The first four modes of resist CDU variation in the pCAR processes. Collectively, these modes account for ~65% of the variation.

variation modes. As in our first report, both CAR processes have a top to bottom shaped signature as the dominant mode of data variation. Mode 2 variations are also unchanged from our first report for these two CAR processes (radial for pCAR, side to side for nCAR). Modes 3 and 4 are similar for both CAR processes. Mode 3 is radial while mode 4 shows multiple hot and cold radial signatures moving from left to right across the middle portion of the reticle. It is important to note here that signs of Eigenvectors can change without altering the variations they describe.[2]

The present CAR monitor data sets are approximately 50% larger than in our previous report and represent adequate baselines with which to judge the effectiveness of process tuning experiments. The following lithographic experiments within these two CAR processes will be compared to these established baselines.

3.2 Experiment 1: Blank Preparation Impact on pCAR CDU

The large center hot spot that dominates the average pCAR resist CD signature (Figure 1) led us to consider the blank preparation process as a potential CD error source. To this end, two different modifications (A&B) in this process were tested with separate pCAR monitors and Figure 5 shows the resulting resist CD signatures from these two modifications.

Modification A did little to the four cold corners of the average pCAR resist CD signature (Figure 1), but reduced the magnitude of the center hot spot as well as diffused it over a larger area and shifted it downwards on the reticle. Blank preparation B eliminated the bottom right corner cold spot while the bottom left corner was transformed from cold to a hot spot. Modification B enhanced the radial pCAR average signature, with a larger magnitude albeit a smaller area than the pCAR average. Resist CDU for both blank preparations (A=3.6nm, B=3.9nm)

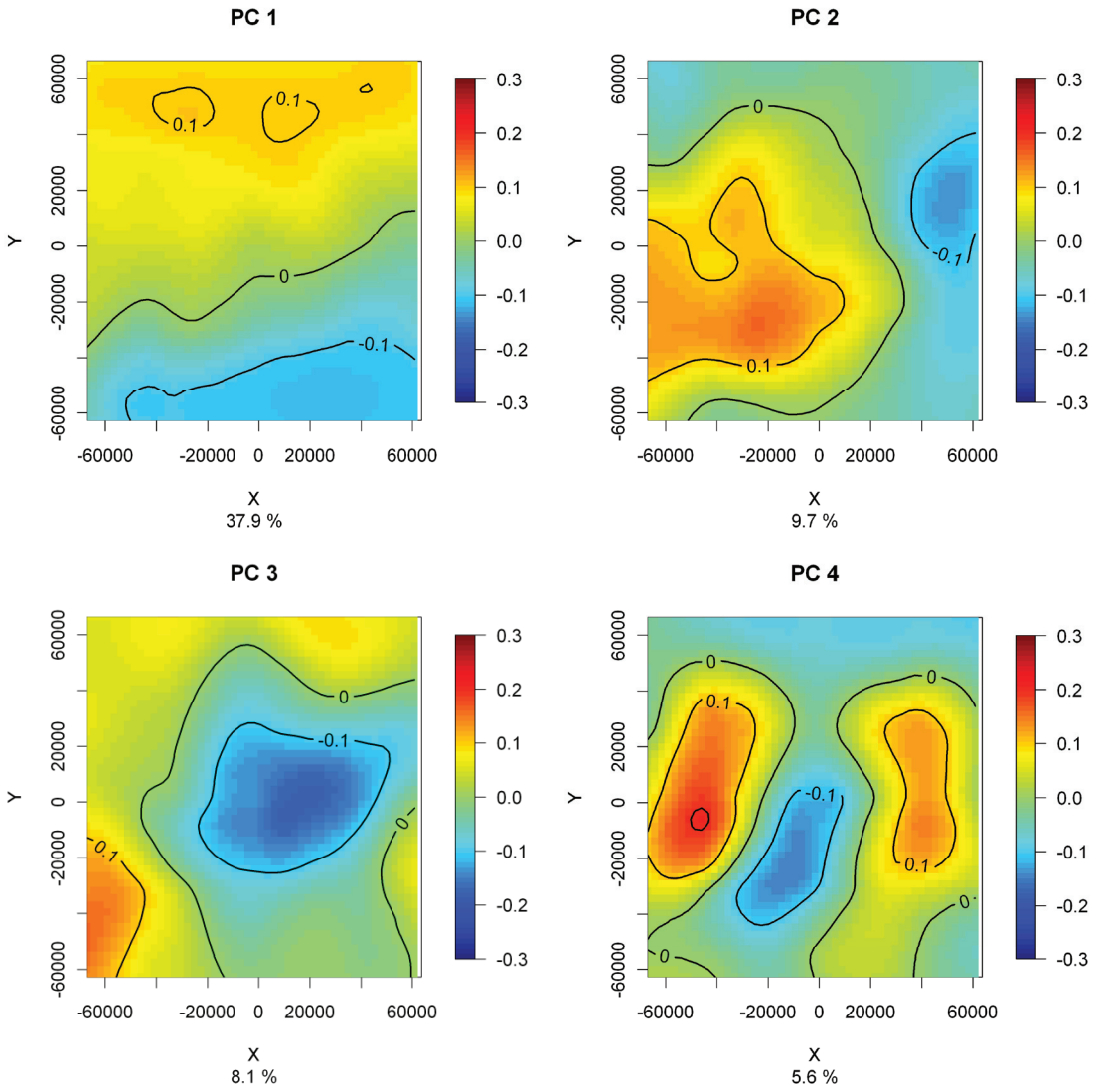

Figure 4. The first four modes of resist CDU variation in the nCAR processes. Collectively, these modes account for ~66% of the variation.

were not drastically different from the pCAR average (3.8nm). Furthermore, PCA did not show any significant changes in the first four resist CD variation modes as evidence by score results in Figure 6. Both blank preparations have score values similar to other pCAR monitors fabricated without these two modifications.

Before abandoning these two blank preparation modifications as potential CDU improvements, final, post etch pCAR monitor data was examined, and Figure 7 displays the pCAR final CD signatures for both modifications. Compared to the average pCAR FICD signature (Figure 8), blank preparation A had a much flatter final CD distribution with an enormous 1.0nm 3σ improvement over the pCAR final CDU average (3.6nm). Compare as well the PCA score results for pCAR final CDU (Figure 9) to the dominant 4 variation modes of pCAR final CDU variation (Figure 10) which indicate that radial variation modes (1 & 3) are different from those without this modification. Figure 10 also represents a dramatic change in the major two variation mode shapes: the dominant two variation modes have traded places. That is, contrary to resist CDU variations (Figure 4), Mode 1 is no longer but top to bottom but radial, while Mode 2 is no longer radial, but top to bottom.

Although modification B yielded a respectable 0.5nm 3σ final CDU improvement, it also contained the characteristic pCAR radial CD signature (hot center) and, as expected, produced score results not very different from pCAR monitors processed without this modification (Figure 9). Thus blank preparation A represents a lithographic process modification that was more successful in improving pCAR final CDU than modification B.

The discrepancy between resist and final CDU in the two blank preparation modifications for pCAR is thought to be related to resist profile changes. These two modifications were presumed to alter resist profiles in a manner that influenced resist measurements (i.e., the tops of resist features), but did not impact final CD metrology when transferred via the etch process.

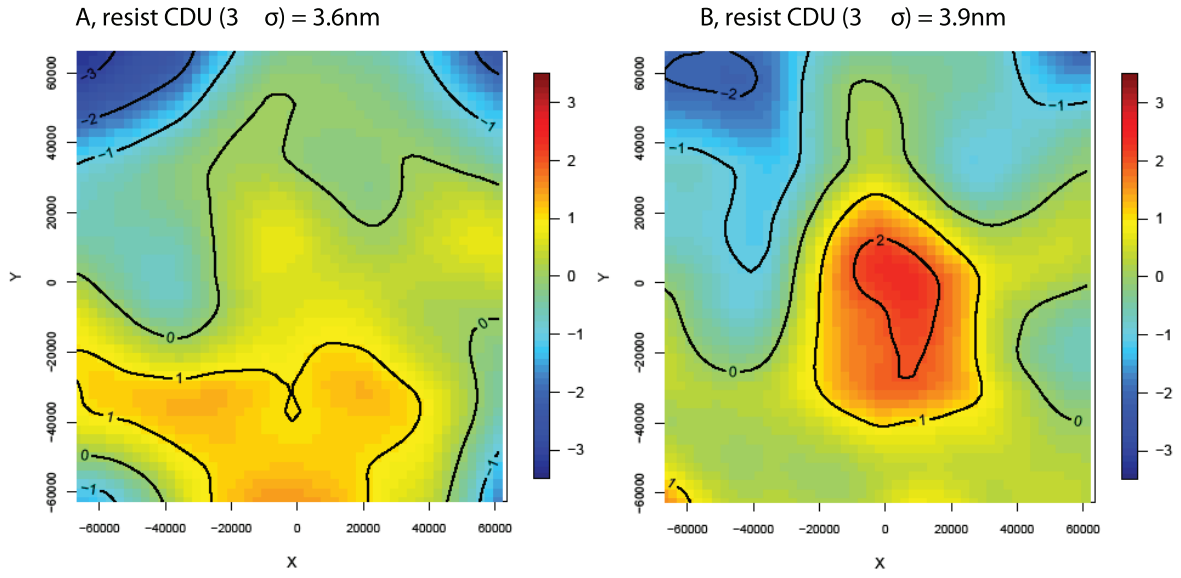

Figure 5. pCAR resist CD signatures for two modifications (A-left, B-right) of the blank preparation process.

3.3 Experiment 2: Front End Correction Parameter

The characteristic top to bottom resist CD signature in nCAR monitors directed attention to a correction parameter (C) in the front end process as a potential CD error source. To this end, an nCAR monitor was fabricated without application of this correction parameter which led to a dramatic impact in the resist CD signature as illustrated in Figure 11.

Instead of the characteristic high-top to bottom-low spatial arrangement (Figure 1), the resist CD signature was inverted in the absence of correction parameter C, with larger CDs at the top, shifting to near on target just before the reticle center, and remaining on target until the lower reticle edge, except for a radial component in the center (cold spot). The center cold radial signature in this experiment is much more pronounced than in the nCAR average (Figure 1).

Spatial representations of the first four variational modes obtained from PCA were not different from those with correction parameter C activated (Figure 4) and are thus not presented here. However, Figure 12 presents score results that show vastly different mode 1 & 2 values for the nCAR monitor fabricated without correction parameter C. The inclusion of this one special nCAR monitor produced a mode 1 (top to bottom) score roughly 30 larger than the average while for mode 2 (radial) this difference was approximately -20. Mode 3 and 4 scores were not significantly different for this nCAR monitor compared to all others fabricated with correction parameter C activated. Both the average nCAR resist CD signature and corresponding score results for this monitor indicate correction parameter C contributes significantly to the overall nCAR resist CD error.

Despite dramatic changes in the nCAR resist CD signature and PCA scores, nCAR resist CDU without correction parameter C was 3.9nm 3σ, about 20% higher than the nCAR average (3.2nm). Again final CDU was examined with PCA but this time for nCAR monitors to ascertain the impact of omitting correction parameter C (Figures 13 and 14). Figure 13 shows deactivating correction parameter C improved final CDU by a substantial 0.8nm 3σ when compared to the nCAR average.

With correction parameter C activated, Figure 14 (left portion) shows the dominant variational mode in nCAR final CDU is radial (mode 1), followed by top to bottom (mode 2) and then side to side (mode 3). As with final pCAR CDU data, the dominant mode of variation in nCAR monitors is no longer top to bottom (as in resist CDU) but radial. When one nCAR monitor without correction parameter C is included in this data set, the dominant two nCAR final CDU variation modes do not change but are visibly altered. In the right portion of Figure 14, mode 1 is still radial but with a stronger top to bottom signature while mode 2 is still top to bottom but with a stronger radial component. Modes 3 and 4 are essentially unchanged without correction parameter C activated.

Score results for nCAR final CDU are presented in Figure 15, with the one monitor processed without correction parameter C indicated in red. Similar to score results from resist CDU (Figure 12), mode 1 and 2 scores show a dramatic change in the nCAR monitor fabricated without correction parameter C. Score results for modes 3 and 4 are similar between resist and final nCAR CDU.

The average nCAR final CD signature, coupled with changes in the major variation modes and dramatic impacts to score values, collectively demonstrate correction parameter C in the front end process can be exploited to improve final nCAR CDU.

4. Conclusions

Monitoring CD data collected at resist and post etch (final) from two advanced CAR processes established baselines with which to assess the CDU impact of lithography process experiments. PCA elucidated potential error sources within the lithographic process by providing the major variation modes in each data set. Two different arenas of the lithographic process were identified as CDU error sources: photomask blank preparation and a correction parameter in the front end process. Both of these were successfully manipulated to improve final CDU in each CAR process.

5. Acknowledgment

AMTC is a joint venture of GLOBALFOUNDRIES and Toppan Photomasks, and gratefully acknowledges the financial support by the Free State of Saxony in the framework of the technology grants based upon European Regional Development Funds and funds of the Free State of Saxony under contract number 12707/2109 (partially funded by KOALA).

6. References

[1] G. R. Cantrell, C. Bürgel, A. Feicke, M. Sczyrba, C. Utzny, "Using Principal Component Analysis for Photomask CD signature investigations", **Proc. SPIE 7823**, 78232O, (2010).

[2] Ramsay, J. O., and Silverman, B. W., [Functional Data Analysis], Springer Texts in Statistics, Springer-Verlag New York, 85-107, (1997).

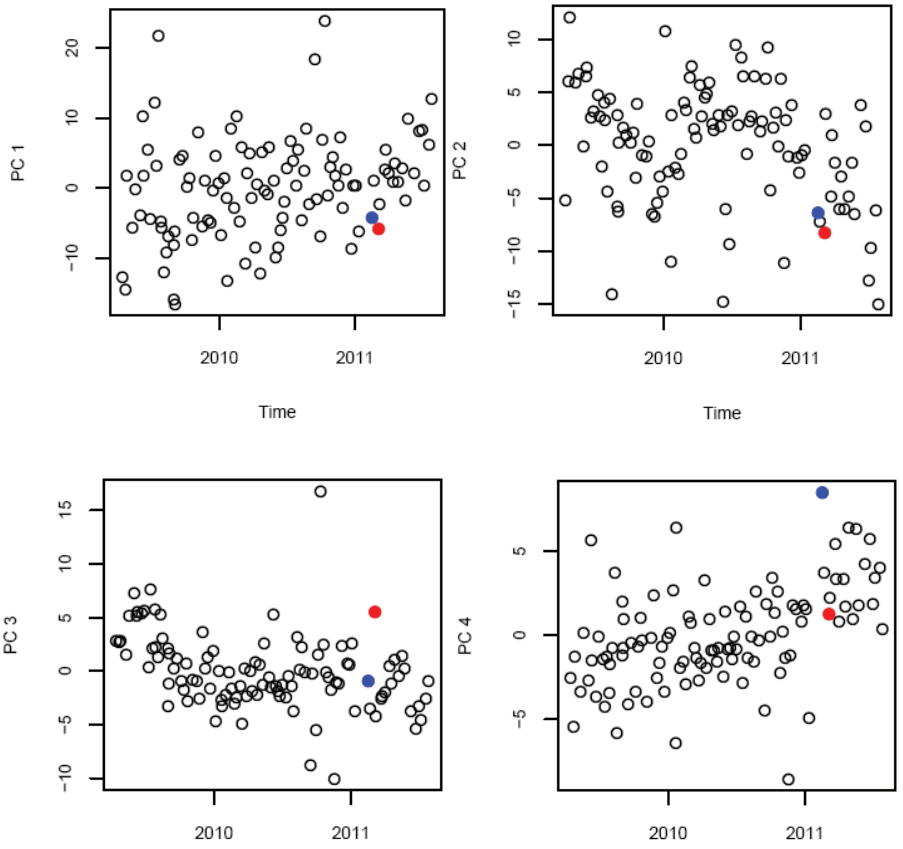

Figure 6. Score versus time plots for the first four resist CDU variation modes in the pCAR process, including A (red) and B (blue) blank preparation modifications.

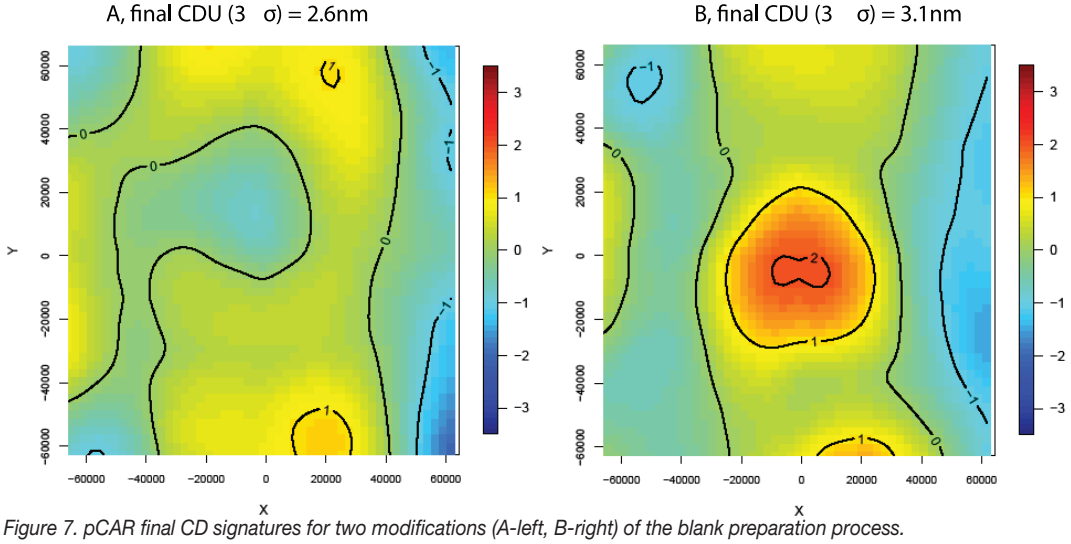

Figure 7. pCAR final CD signatures for two modifications (A-left, B-right) of the blank preparation process.

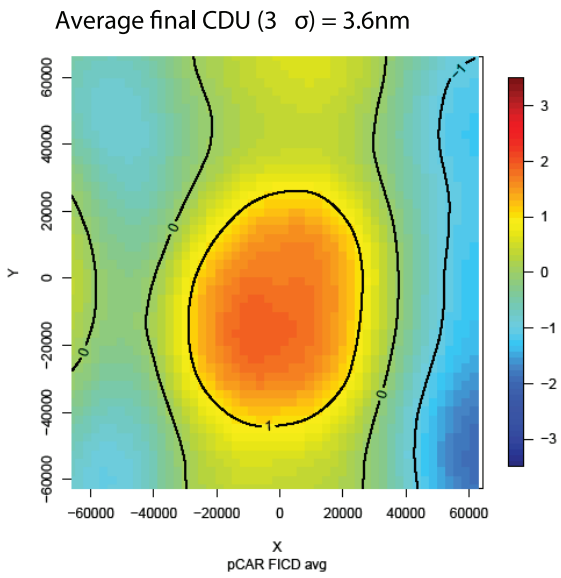

Figure 8. Average pCAR final CD signature without blank preparation modifications.

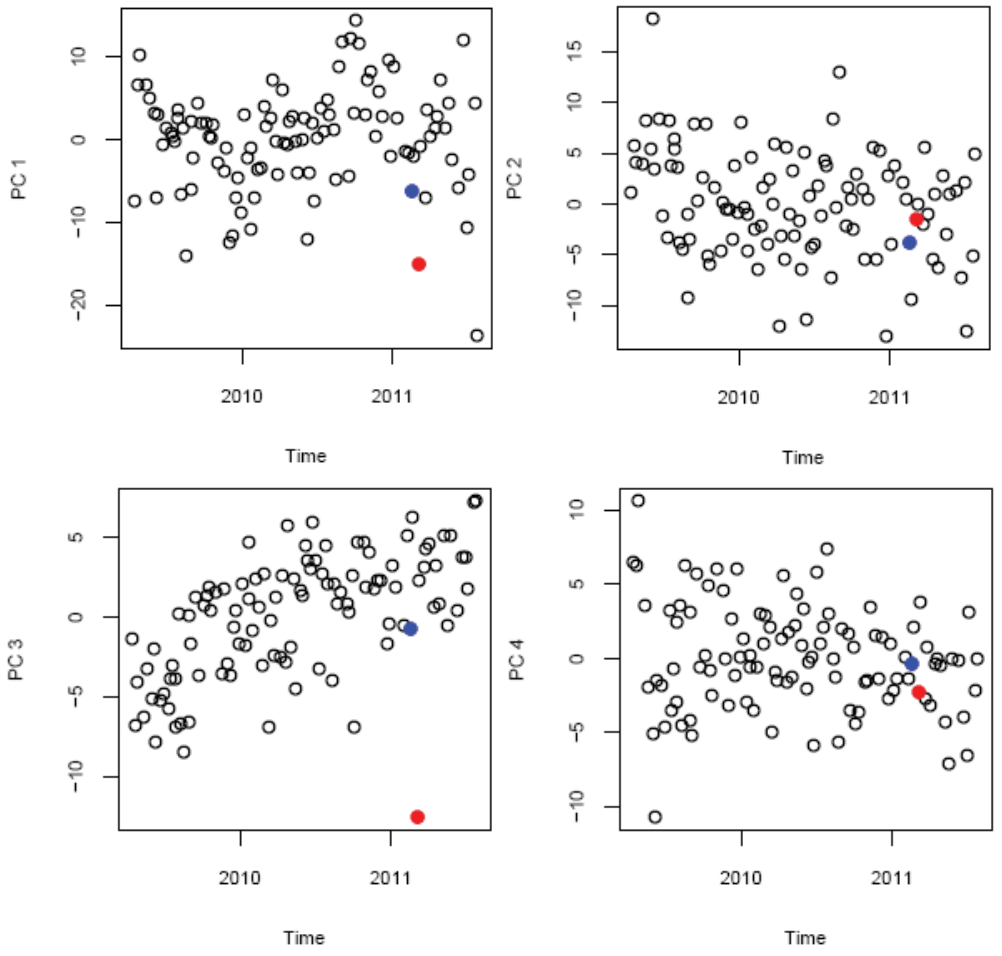

Figure 9. Score versus time plots for the first four variation modes of final CDU from the pCAR process, including A (red) and B (blue) blank preparation modifications.

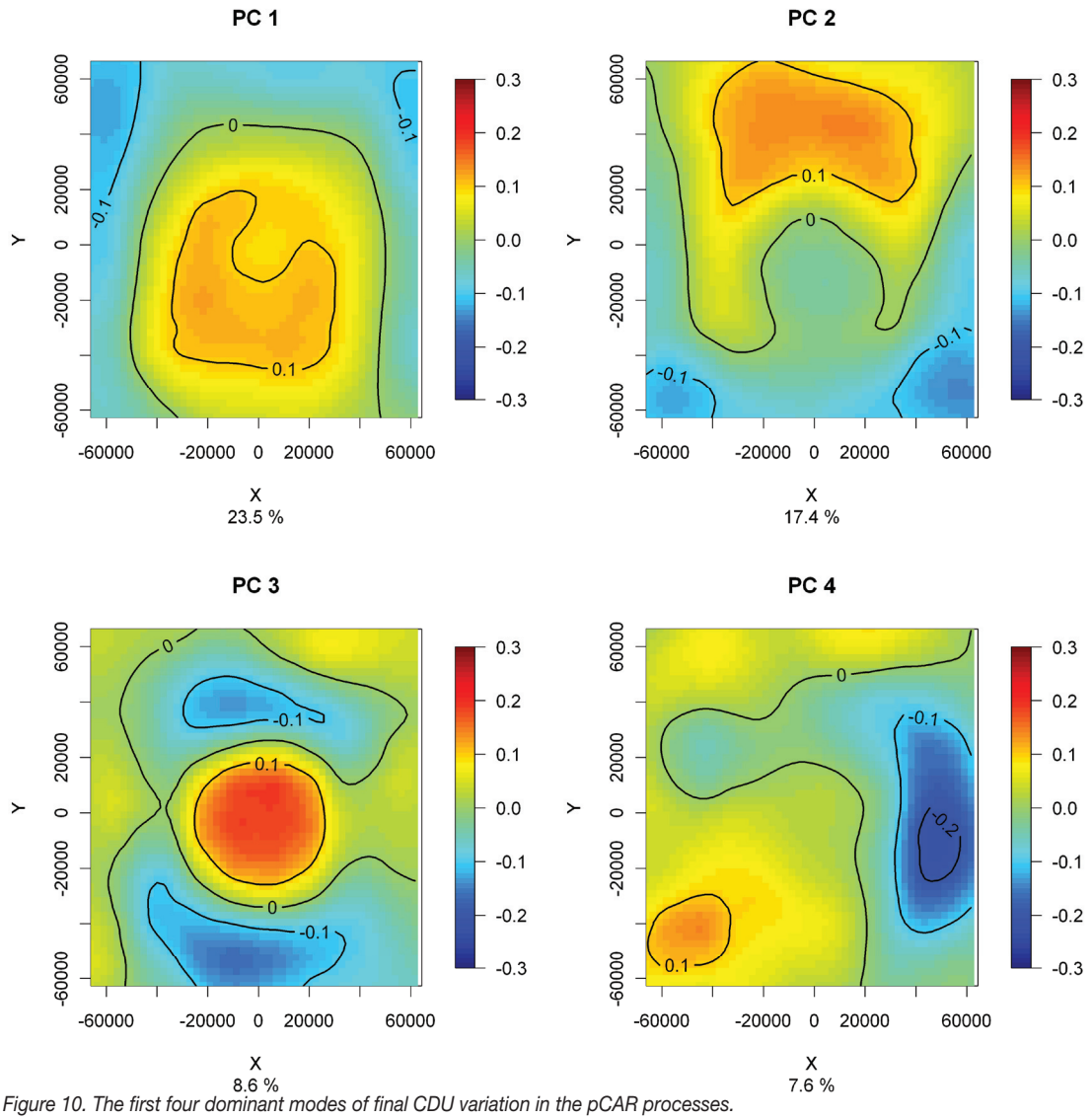

Figure 10. The first four dominant modes of final CDU variation in the pCAR processes.

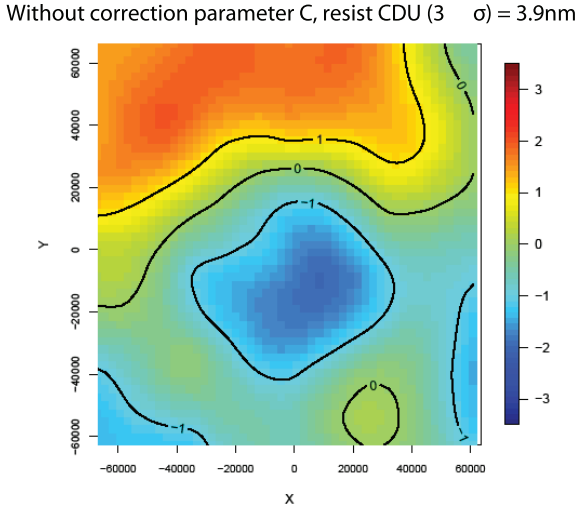

Figure 11. nCAR resist CD signature without correction parameter C.

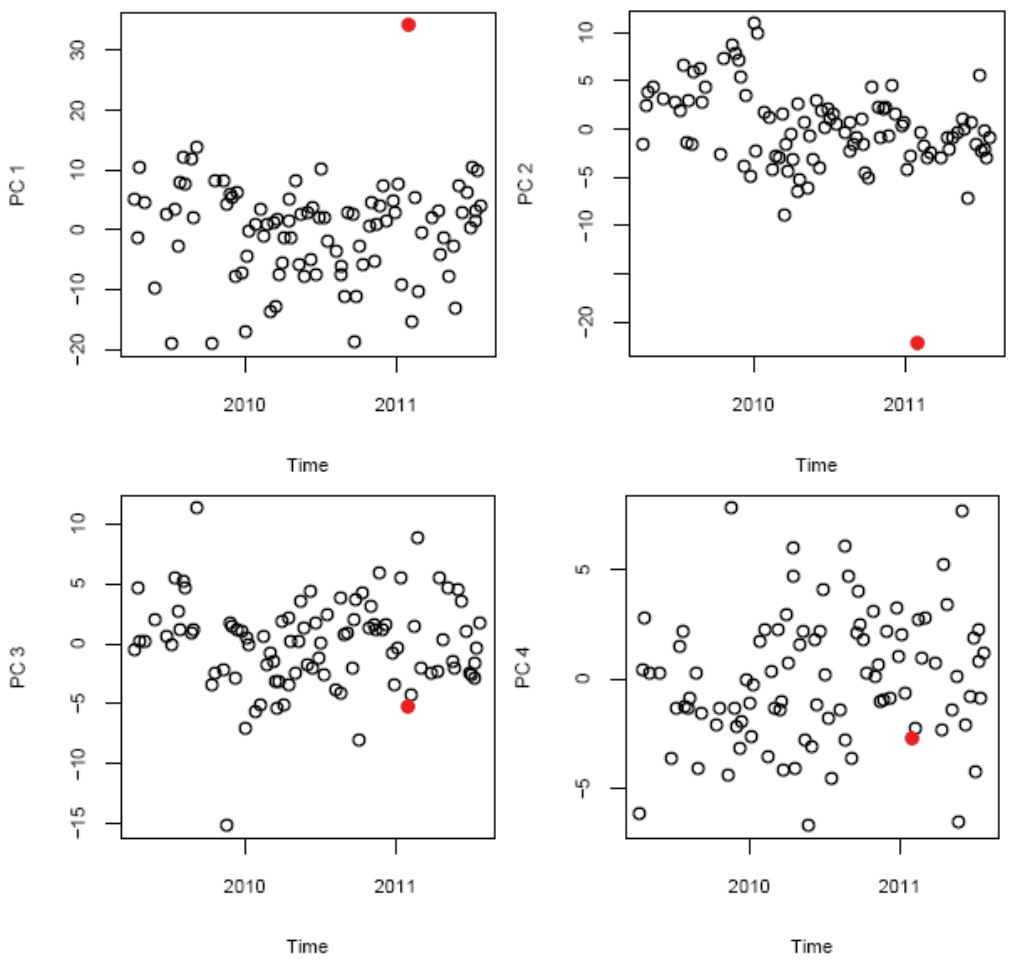

Figure 12. Score versus time plots for the first four variation modes of resist CDU from the nCAR process. Red data point indicates the nCAR monitor processed without correction parameter C.

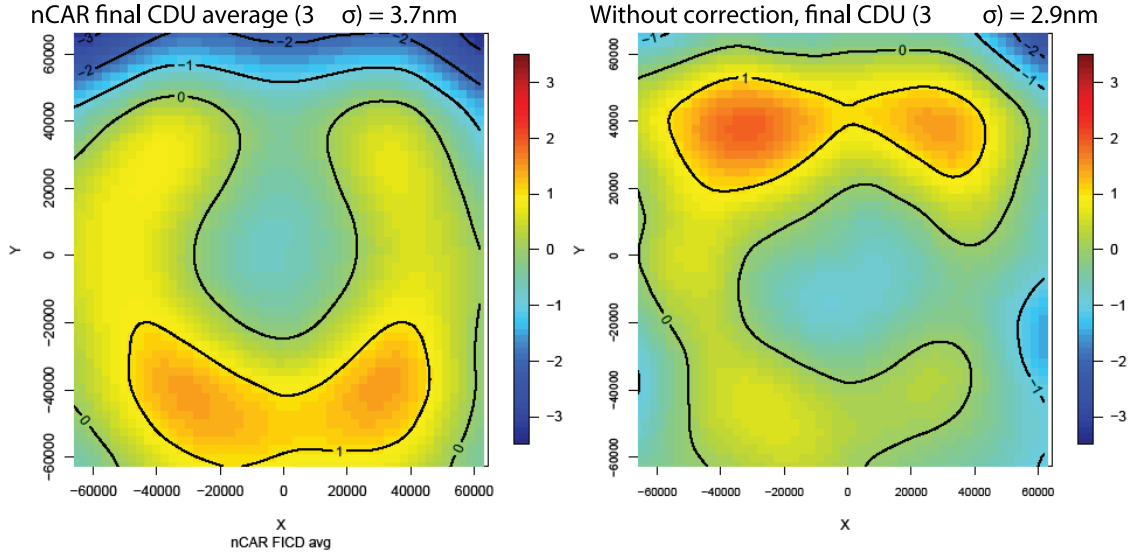

Figure 13. Left: final CDU average, all nCAR monitors processed with correction parameter C activated; Right: final CDU of one nCAR monitor fabricated without correction parameter C.

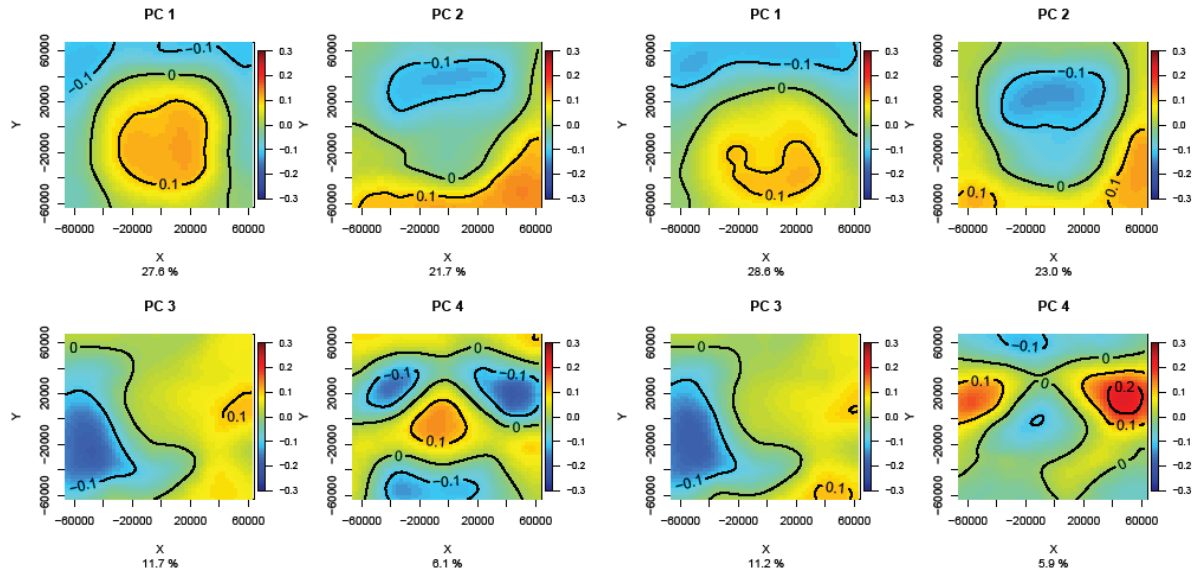

Figure 14. The first four modes of final CDU variation for the nCAR process. Left: all nCAR monitors processed with correction parameter C activated; Right: all nCAR monitors fabricated with correction parameter C absent from one monitor.

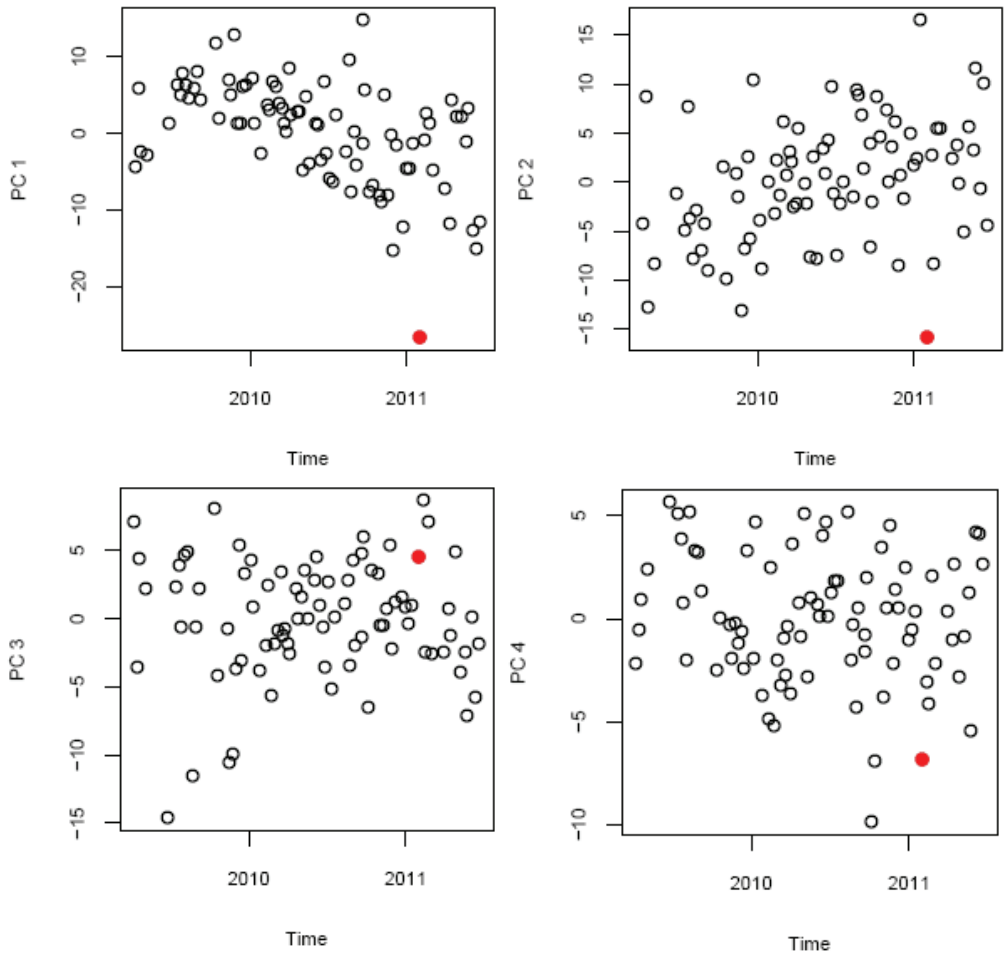

Figure 15. Score versus time plots for the first four variation modes of final CDU from the nCAR process. Red data point indicates the nCAR monitor processed without correction parameter C.

Industry Briefs

New momentum for e-beam writer tools

On December 7, IMS Nanofabrication AG, an Austria-based developer of nanometer scale mask and direct write lithography, announced that Intel Capital and Photronics, Inc. have invested an undisclosed amount in IMS to develop direct-write lithography technology. The funding will be used to complete proof of concept for an electron multi-beam mask exposure tool to support tool characterization, column optimization, and infrastructure enhancements that set the stage for commercialization. "The additional resources will help IMS to demonstrate a 256 thousand e-beam mask writer column with initial exposures by the end of 2011," said Max Bayerl, CEO of IMS. IMS is also developing a direct-write lithography technology called projection maskless lithography. Meantime, Mentor Graphics and electron microscopy company JEOL Ltd. (Japan) are engaged in a research program to demonstrate the feasibility of multi-resolution writing to reduce shot count up to 30 percent over conventional writing. The agreement is focused on developing this technology and providing interfaces between mask preparation and mask process correction software from Mentor (Wilsonville, Oregon) and e-beam lithography mask writing equipment from JEOL.

In a separate effort, SEMATECH has initiated a program to bring together major industry players to fund the development of a multi-beam mask writer tool. This effort is based on their successful EUV Mask Infrastructure (EMI) initiative, which is funding an aerial imaging EUV mask inspection system.

Mask fabrication for future nodes is predicted to require write times of over 24 hours due to the increase in the amount of data that must be transferred. While the current single beam technology has made excellent progress over many generations, with incremental improvements in writing speed to keep pace with industry needs, future nodes will require a significant leap that is not likely to be achieved with a single-beam approach.

Semiconductor process technology challenges at 22nm

Dean Freeman, Research VP, Gartner

December 28, 2011 — According to the Mayan Calendar, the world is supposed to end in December of 2012. The microprocessor will be over 40 years old, and 22nm devices will be ramping in production. 2012 promises much for the semiconductor industry, and the world. The chip industry will see two different device types ramping in 2012: second-generation 2xnm NAND flash, and Intel's 22nm microprocessors. Each of these technologies presents different challenges to manufacture and yield.

In 2012, Gartner expects 22nm technology to account for 24.8 million square inches (MSI) per quarter of the total industry capacity (less than 1% of the total capacity). NAND flash will continue to drive lithography using double- and perhaps triple-patterning. Atomic layer deposition (ALD) will be challenged to deposit films as thin as 4nm to achieve the proper gate dimensions and device electrical characteristics. The number of electrons on the gate continues to shrink, making reliability and repeatability of deposition and etch processes critical to NAND yields. 2xnm and 1xnm NAND are expected to be roughly 4% of the 19,000 Petabytes total production in 2012.

22nm logic will begin to ramp in late 2011 with production-level volumes being reached in 2012 as Intel rolls out the Ivy Bridge products. The trigate transistor brings the third dimension to transistor technology. It presents new etch and deposition challenges to fab equipment. The sidewalls need to be very close to 90° with minimal edge roughness. Sidewall doping needs to be very conformal, which can be accomplished in part with the epitaxial process. ALD uniformity will be necessary for success of the transistor performance. Lithography, while challenging, appears to be a single-pass using immersion -- not quite as complex as the NAND lithography.

For the equipment manufacturer, 2012 is business as usual. For the device manufacturer, it will be about ramping up a learning curve to improve yield, while developing the next generation of technology.

And let's just hope the world doesn't end before we get to 14nm.

Join the premier professional organization for mask makers and mask users!

About the BACUS Group

Founded in 1980 by a group of chrome blank users wanting a single voice to interact with suppliers, BACUS has grown to become the largest and most widely known forum for the exchange of technical information of interest to photomask and reticle makers. BACUS joined SPIE in January of 1991 to expand the exchange of information with mask makers around the world.

The group sponsors an informative monthly meeting and newsletter, BACUS News. The BACUS annual Photomask Technology Symposium covers photomask technology, photomask processes, lithography, materials and resists, phase shift masks, inspection and repair, metrology, and quality and manufacturing management.

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Calendar

2012

Advanced Lithography

12-16 February 2012
San Jose Convention Center and San Jose Marriott
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spie.org/al

SPIE Photomask Technology

10-13 September 2012
Monterey Marriott and Monterey Conference Center
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