Process Window Centering for 22 nm Lithography

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Abstract **- PWC (Process Window Centering) is an efficient methodology to validate or adjust and center the overall process window for a particular lithography layer by detecting systematic and random defects. The PWC methodology incorporates a defect inspection and analysis of the entire die that can be automated to provide timely results. This makes it a good compromise between FEM (Focus Exposure Matrix), where centering is based only on CD (critical dimension) measurements of a few specific structures and PWQ (Process Window Qualification) which provides very detailed defect inspection and analysis, but is more time consuming for lithography centering. This paper describes the application of the PWC methodology for 22 nm lithography centering in IBM's Albany and East Fishkill development facilities using KLA-Tencor's 28xx brightfield defect inspection system.**

I. INTRODUCTION

In the semiconductor industry, there are various methods for determining the optimum lithography exposure and dose condition for qualifying specific mask levels and processes. The most common lithography learning methods are FEM (Focus Exposure Matrix) [1,2] and PWQ (Process Window Qualification) [2-5]. Traditionally FEM utilizes a few locations per die to define the best dose and focus based on CD (critical dimension) measurements analyzed on a Bossung plot. Even though this is a good initial starting point for lithography optimization, the information obtained is limited to specific pre-defined locations in the chip and contains no information on how the pattern on the rest of the die is affected. Thus, pattern defectivity may still exist even under so-called optimum focus and dose conditions. The actual process window after completion of PWC (Process Window Centering) and PWQ is typically much smaller than that predicted using only FEM and CD output.

The PWQ methodology is utilized to provide an extensive defectivity characterization to determine the absolute best conditions for focus and dose. This is achieved by taking into account defectivity in the whole die and capturing all potential systematic defects. PWQ requires unique features of the brightfield (BF) inspector, review and analysis, as well as significant engineering resources in order to determine the optimum lithography conditions. The value of PWQ is in thorough and early detection of systematic defects and process marginalities. Early in process development, however, such thorough characterization is not usually warranted, due to thousands of process marginal defects.

The PWC methodology offers the development engineer a quick solution to this high defect, early learning challenge. The method involves printing unique focus or exposure row striping on a flopdown or short loop wafer and a subsequent inspection measurement of random defectivity. This first order defect approach provides a quick solution in an early development environment and can be initiated any time there is a mask update or process change to ensure the optimum lithography centering is always in use. Thereafter, thorough PWQ characterization is warranted before fully integrated process development continues, and certainly before production ramp. The PWC methodology is one additional tool or method available to the lithographer to better understand and characterize early process windows, and is best inserted between FEM CD characterization and PWQ for systematic defect detection.

Key differences between FEM, PWC, and PWQ are summarized in Table I.

II. PWC METHODOLOGY

FEM

For lithography wafer preparation, the appropriate dielectric stack is built and a photoresist of needed thickness is coated on top of a bottom antireflection coating (BARC). The resist is then exposed with focus steps in one direction and dose steps in the other. A metrology recipe is used to determine the best dose and focus conditions by measuring the respective CDs. The dose and focus conditions for a FEM exposure are selected based on the resist vendor's recommendation. As for the metrology recipe, targets are selected based on the process limiting structures. All process limiting structures should be

TABLE I
COMPARISON OF PROCESS WINDOW TECHNIQUES. ADVANTAGES ARE PRINTED **BOLD**.

	FEM	PWC	PWQ
Exposure	**Focus and dose** variation (one chip per combination)	**Rows** of either focus or dose variation (more data per variation)	Single chips with focus or dose variation on one wafer
Inspection	CD measurement and SEM imaging of selected sites	**Standard** BF inspection and review of **whole chips**	**Sensitive** BF inspection and review of **whole chips**
Detection	Pattern printability and **CD**	**Systematic and random** defects	Systematic defects
Time to results	4 hours	**4 hours (automated processing)**	1-2 days with engineering support
Wafers	**1 (rework possible)**	2 (1 focus + 1 dose)	1

taken in consideration while determining the nominal exposure conditions. Apart from these critical structures, semi-isolated structures are used to determine the best focal point. Minimum pitch structures, based on requirements of the technology, are used for best dose calculation.

PWC

Two wafers are prepared separately; one for focus and the other for dose modulation. On one wafer, the focus is increased in steps from one chip row to the next (Fig. 1) while dose is fixed at the nominal value determined in a previous FEM. On the second wafer, the dose is varied while focus is fixed.

The whole wafer will be inspected with the same sensitivity as the existing standard defect inspection recipe at this step. Each die row and therefore each focus or dose modulation will be set up as a separate test. This allows for separate sampling of defects for SEM review and later analysis per test. The inspection starts with the nominal condition in the wafer center where the lowest defect density is expected. The die rows close to nominal will be scanned next to allow more rows to be scanned before the defect count hits the inspection tool's defect count limit per inspection and the scan aborts. The order of tests is shown in Fig. 1.

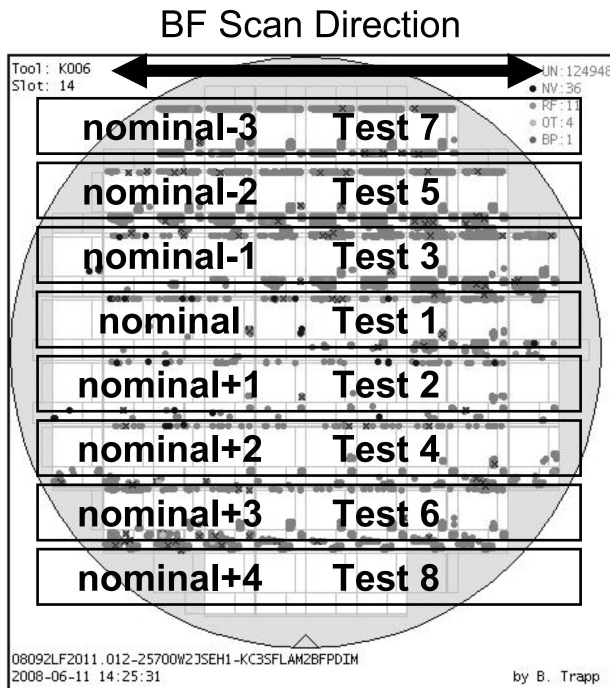

Fig. 1. Focus or dose variation wafer with exposure conditions. Focus or dose increases from top to bottom with nominal conditions in the wafer center. Inspection starts in the center with test 1 and then progresses in the order of tests indicated in the figure.

Automatic SEM review sampling can be done on the inspection tool as part of the recipe. Normally, we sample a set number of defects per die row.

Once the recipes are established, inspection and review can run fully automatically.

PWQ

PWC uses a standard inspection recipe and automated processing. PWQ, on the other hand, uses a dedicated, very sensitive recipe that is optimized separately for each process variation on the wafer. PWQ usually uses a different wafer layout where dose or focus is varied only on single chips.

The analysis follows a multi-step process that first filters out random defects to concentrate on systematics, then prioritizes them. Defects that appear at conditions close to nominal get a high priority and are reviewed. As a result, PWQ is able to detect even small defects caused by mask or OPC (optical proximity correction) and process marginalities [3].

Both the optimization of the recipe and the analysis are done manually by an experienced engineer and are time-consuming. An additional prerequisite for PWQ is stability of the process which is not necessarily the case in the early phase of development.

III. A BRIEF HISTORY OF PWC

PWQ is a good and well-established method to find systematic defects with high sensitivity and to qualify new masks and OPC revisions. However, it requires significant engineering and tool time. If a new mask with already qualified OPC is used, such a thorough analysis is usually not necessary, and if lots have to be processed within a few hours, a faster method is necessary. This is why PWC was developed at IBM and first used in 45 nm technology to define the process window of new masks within 4-8 hours. The methodology and wafer layout was refined on subsequent technology nodes to the one described here and used not only

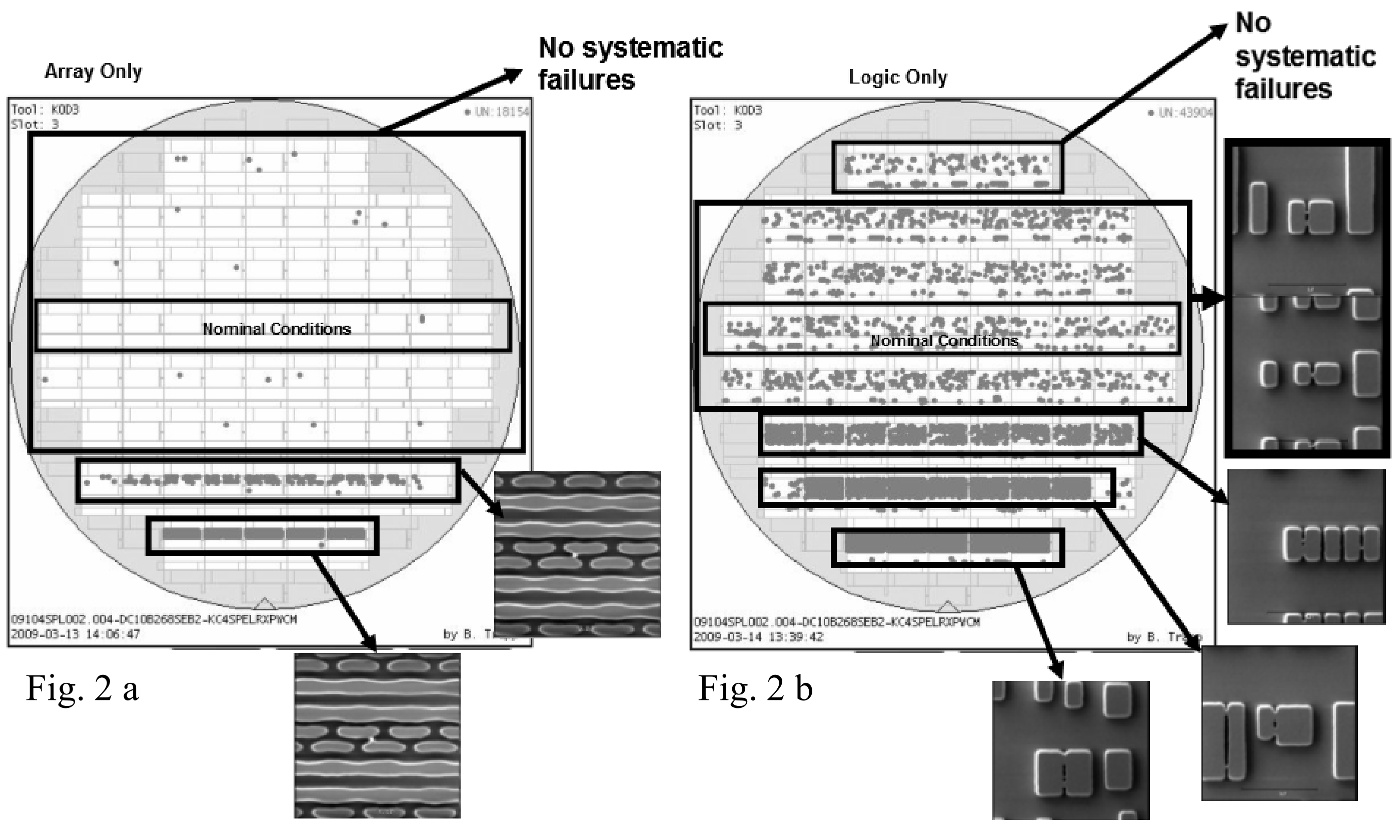

Fig. 2. Display of systematic failure modes on a dose variation wafer at the shallow trench isolation level. Fig. 2 a shows results for the array test: Systematic failures are only observed in the bottom two modulations and are small bridged defects. Fig. 2 b shows results for the random logic: The entire wafer, except the top modulation, has systematic bridging defects. The density of the failures also increases significantly in the bottom two modulations.

to qualify masks and new lithographic materials but also to investigate defect problems that might be caused by process drift.

IV. APPLICATIONS IN 22 NM DEVELOPMENT

In the startup of 22 nm technology development, PWC was used at every critical mask level to supplement FEM and define the best process window. Examples from front end of line (FEOL), middle of line (MOL), and back end of line (BEOL) show different use cases and results of PWC.

FEOL: Shallow trench isolation

For 22 nm FEOL PWC work, SEM sampling is increased considerably over general wafer sampling. SEM sampling is set by-die as opposed to by-wafer. The sampling rate varies depending upon the criticality of the level and for FEOL 22 nm varies between 4 and 10 sampled events per die. This increased sampling allows better visibility to the defect types and structural failures within each lithography modulation on the wafer. This "per die" sampling can be set up for automatic SEM sampling.

For FEOL PWC analysis, SEM images are viewed for each lithography modulation separately. Systematic failures are of most interest and it is desirable to separate these from random defect occurrences. Analysis techniques may vary. FEOL analysis consists of determining systematic failures for each lithography modulation and portraying these alongside the associated wafer defect maps as shown in Fig. 2.

Representative systematic defect failure images are posted next to the die row/lithography modulation where each failure has been observed. Lithography modulations with no systematic failures are also noted.

In the shallow trench isolation level example, the wafers were inspected post etch in order to see the full effect of litho and etch on the final structures. The inspection has been separated into two tests, one array and one logic for increased defect sensitivity. Each test is analyzed separately. In the array example (Fig. 2 a), systematic failures are only observed in the bottom two modulations and are small bridged defects as shown in the associated SEM images. The remainder of the wafer, six modulations, has no systematic failures as highlighted. In the logic example (Fig. 2 b), the entire wafer, except the top modulation, has systematic bridging defects of various structures, as shown in the associated SEM images. Only the top modulation is free of systematic defects. This shows that the logic areas are more sensitive to dose variations and must be taken into account in order to determine the overall process window. The density of the failures also increases significantly in the bottom two modulations as can be seen by the defect density of the dots on the wafer map in these bottom two rows of die. The exact defect density numbers for each modulation can be determined from the raw defect counts from the inspection file as each modulation is inspected as a separate sub-test.

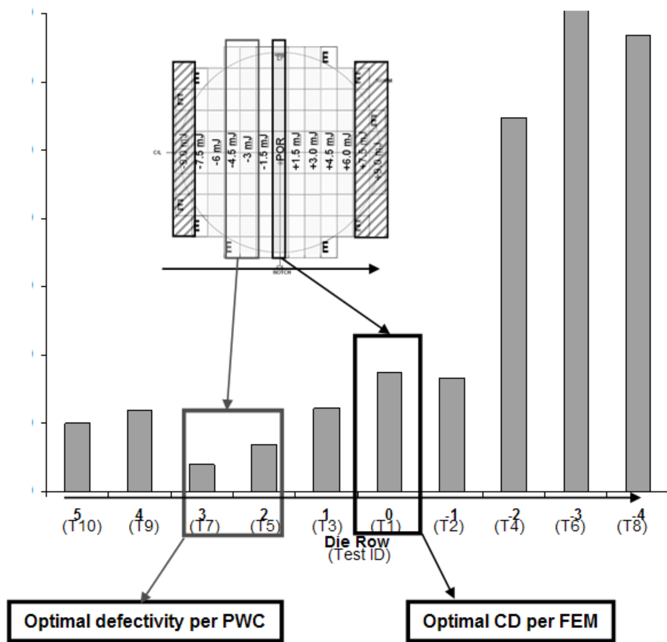

Fig. 3. CA dose PWC results. Best dose for lowest defect density was at lower dose (tests 7 and 5) than best dose for optimal CD (test 1).

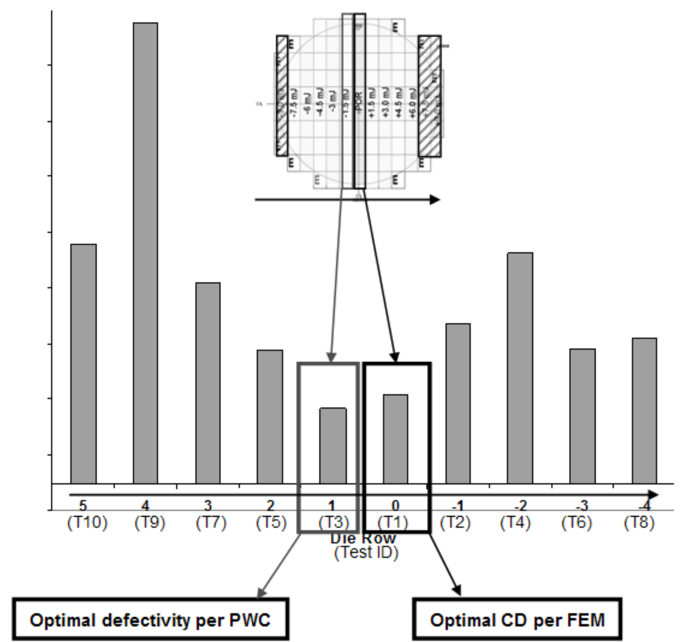

Fig. 4. CB dose PWC results. Best dose for lowest defect density was at lower dose (test 3) than best dose for optimal CD (test 1).

This analysis technique is utilized across all critical FEOL levels where PWC methodologies are employed for 22 nm technologies. The data presented in this manner gives a quick snapshot of systematic defect failures by lithography modulation along with associated representative SEM images of the failure modes.

MOL: Contact level

The contact level is printed with double exposure (CA and CB). Two dose modulation wafers were exposed for the contact processes at CA and CB levels. The initial optimum dose settings were obtained from traditional FEM methodology. The inspection was done after liner/seed deposition in order to obtain the best signal to noise ratio; hence, a good sensitivity of the inspection.

It was found from PWC that the optimum dose derived from the FEM wafers was not optimum for ensuring the lowest defectivity levels. Raw defect density was plotted against dose, and it was observed that the best dose for lowest defect density was different from the best dose for optimal CD (Fig. 3 and Fig. 4). PWC was able to provide additional defectivity data which proved to be critical to determine the overall optimal dose for the lithography process. The result was acceptable critical dimensions with low defectivity for CA/CB levels. Hence, the supplementation of FEM measurements with the PWC methodology is required to ensure that the optimum dose/focus is determined to allow for the printing of structures across the entire die.

BEOL: Photoresist evaluation

PWC was used to evaluate various photoresists for the BEOL at the 2nd metal level.

Usually the PWC inspection in the BEOL is done after liner/seed deposition in order to obtain the best signal to noise

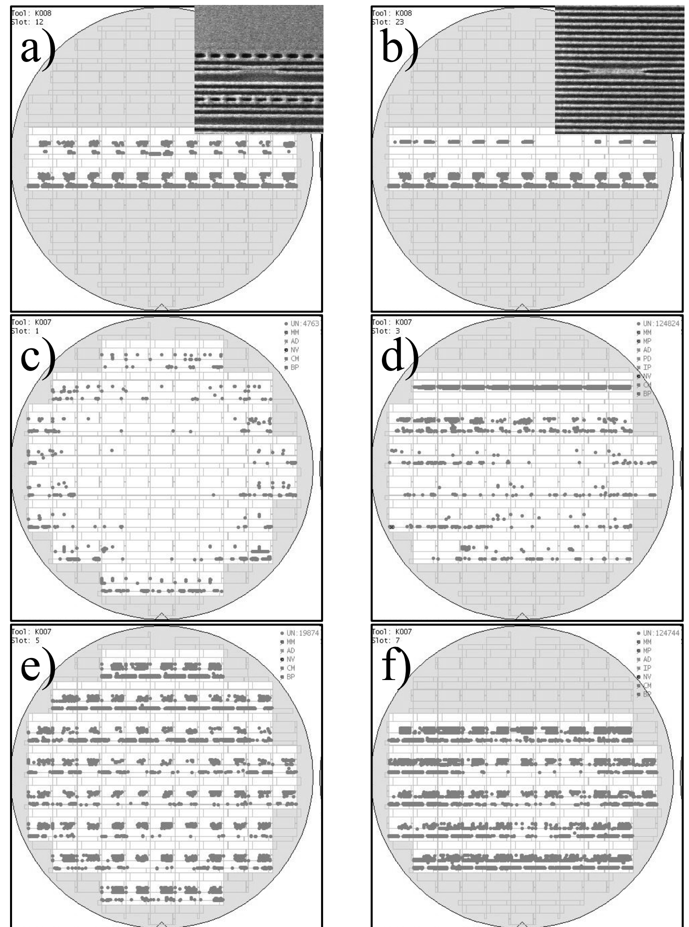

Fig. 5. Defect wafer maps for dose (left) and focus (right) variation wafers processed with Resist 1 (a&b), Resist 2 (c&d), or Resist 3 (e&f).

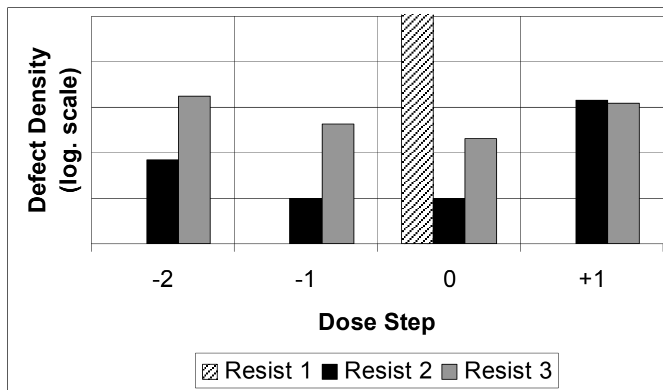

Fig. 6. M2 dose PWC results. Defect density for Resist 1 is out of scale. Best dose for Resist 2 is at step -1 or 0. Best dose for Resist 3 is at step 0 but defect density is higher than for Resist 2.

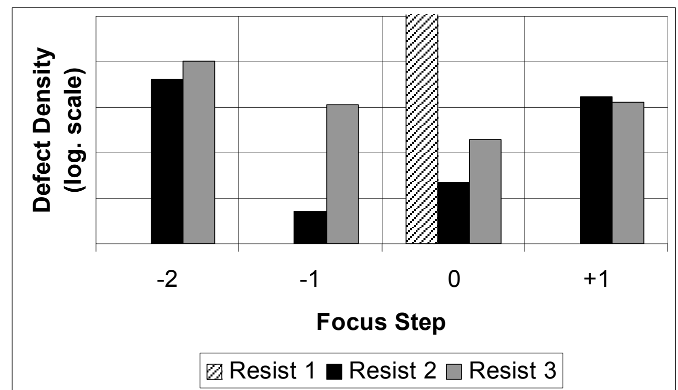

Fig. 7. M2 focus PWC results. Defect density for Resist 1 is out of scale. Best focus for Resist 2 is at step -1. Best focus for Resist 3 is at step 0 but defect density is higher than for Resist 2.

ratio. In the present case, the defect of interest was resist flopover as shown in the insets in Fig. 5. We were able to get excellent signal with relatively low noise source with the brightfield tool directly after lithography. Using shortloop rather than fully integrated wafers helped to further reduce noise. Benefits of inspection after lithography are:

- faster turnaround time because it is not necessary to wait for etch and liner/seed deposition;
- only defects associated with lithography effects are observed, rather than problems caused by subsequent process steps;
- wafers can be reworked.

Wafer maps of the focus and dose variation wafers are shown in Fig. 5. The inspection is supposed to scan the whole wafer, however, if the inspection tool's defect count limit is reached the scan aborts and the wafer map is incomplete.

It is apparent that the wafer with Resist 1 has the highest defect density because inspections on both wafers (Fig. 5 a&b) aborts early.

Resist 2 shows best results: The scan of the dose variation wafer (Fig. 5 c) does not abort at all, and the inspection of the focus variation wafer (Fig. 5 d) aborts several rows away from the center when focus is far off the best condition. This shows a decent process window for this resist.

The process window for Resist 3 (Fig. 5 e&f) looks similar, but defect densities in the scanned area are higher than for Resist 2.

Defect density is plotted against dose in Fig. 6 and against focus in Fig. 7 for conditions near nominal (test 1=step 0). The defect density for Resist 1 is out of scale. Resist 2 has a low defect density near the nominal condition in the center, defect densities increase with increasing distance from the nominal condition. The best dose setting is at step -1 or 0, best focus setting is at step -1. Both settings are close to the nominal settings determined in the FEM. Lowest defect density for Resist 3 is at nominal conditions (step 0 for dose and focus) but defect densities are higher than with Resist 2.

Thus, PWC identified Resist 2 as the best choice along with the best focus and dose conditions for this resist.

V. SUMMARY

PWC is a method to determine the process window more reliably than FEM alone but faster and with less engineering effort than PWQ. It has been successfully used to supplement FEM on critical mask levels in technology development since the 45 nm node.

Examples from 22 nm development that show use of PWC include:

1) Finding systematic defect failures by lithography modulation along with associated representative SEM images of the failures modes in the FEOL;

2) In conjunction with the FEM, determination of the optimum dose and focus settings to result in acceptable critical dimensions with low defectivity in the MOL;

3) Choosing the best resist along with finding the optimum dose and focus settings for this resist in the BEOL.

ACKNOWLEDGMENT

We thank Erin Mclellan and Richard Johnson for the lithography and Dave Horak for the etch work in Albany.

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