Investigation of Hyper-NA Scanner Emulation for Photomask CDU Performance

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ABSTRACT

As the semiconductor industry moves toward immersion lithography using numerical apertures above 1.0 the quality of the photomask becomes even more crucial. Photomask specifications are driven by the critical dimension (CD) metrology within the wafer fab. Knowledge of the CD values at resist level provides a reliable mechanism for the prediction of device performance. Ultimately, tolerances of device electrical properties drive the wafer linewidth specifications of the lithography group. Staying within this budget is influenced mainly by the scanner settings, resist process, and photomask quality. Tightening of photomask specifications is one mechanism for meeting the wafer CD targets. The challenge lies in determining how photomask level metrology results influence wafer level imaging performance. Can it be inferred that photomask level CD performance is the direct contributor to wafer level CD performance? With respect to phase shift masks, criteria such as phase and transmission control are generally tightened with each technology node. Are there other photomask relevant influences that effect wafer CD performance?

A comprehensive study is presented supporting the use of scanner emulation based photomask CD metrology to predict wafer level within chip CD uniformity (CDU). Using scanner emulation with the photomask can provide more accurate wafer level prediction because it inherently includes all contributors to image formation related to the 3D topography such as the physical CD, phase, transmission, sidewall angle, surface roughness, and other material properties. Emulated images from different photomask types were captured to provide CD values across chip. Emulated scanner image measurements were completed using an AIMS™45-193i with its hyper-NA, through-pellicle data acquisition capability including the Global CDU Map™ software option for AIMS™ tools. The through-pellicle data acquisition capability is an essential prerequisite for capturing final CDU data (after final clean and pellicle mounting) before the photomask ships or for re-qualification at the wafer fab. Data was also collected on these photomasks using a conventional CD-SEM metrology system with the pellicles removed. A comparison was then made to wafer prints demonstrating the benefit of using scanner emulation based photomask CD metrology.

INTRODUCTION

The manufacturing process of integrated circuits involves many variables that affect device performance. Each process step is executed under defined specifications that attempt to keep the device operating within certain performance tolerances. One such specification is Across Chip Linewidth Variation (ACLV) that describes the critical dimension (CD) uniformity across a single chip on the wafer. If the CD varies too much within a single chip the electrical performance degrades and the device no longer functions as intended[1]. Complimenting this specification is Across Wafer Linewidth Variation (AWLV) that describes the within wafer variation in CD values. AWLV is typically attributed to process related variances such as PEB temperature, resist thickness, and anti-reflective coating variances. The total CD variation of the manufacturing process can be defined as the sum of ACLV and AWLV results.

It is important to understand the contributors in the manufacturing process that make up ACLV. The contributors that have been identified are typically grouped into two separate categories: photomask variation and imaging variation. Imaging variation includes focus error, dose error, optical aberrations, and flare[2]. Due to the nature of lithography, identifying the amount of imaging variation contributing to ACLV can be difficult. Research has been reported that replaces the wafer with an aerial image sensor. A more realistic approach is to fully characterize the ACLV contribution from photomask variation and subtract that value from the total ACLV to arrive at an approximation for imaging variation.

The photomask variation component of ACLV includes factors such as CD uniformity, phase error, transmission error, sidewall angle deviation, surface roughness, and material properties such as birefringence. Since the photomask is typically manufactured by a vendor, the wafer fab minimizes the photomask contribution to ACLV by specifying strict CD uniformity (CDU) performance when an order is placed. With traditional chrome on glass photomasks a direct relationship between photomask CDU and ACLV was the standard accepted practice. As the resolution limits of optical lithography have been extended with the use of phase shift masks (PSM), reticle enhancement techniques, and optimized scanner illumination patterns the relationship between photomask and wafer results is no longer straightforward. Many more factors are involved in the creation of the image in resist than just the photomask layout and reduction factor of the scanner. When PSM's are ordered additional specifications are requested such as phase and transmission uniformity.

Depending on PSM type (embedded attenuating, alternating aperture, or chromeless) the metrology used to fulfill those specifications is typically done with a variety of methods. Ideally the specifications should be measured using the critical features within the design. The ability to realize this data in a production environment is highly dependent on the metrology methods being used and photomask technology. CD's can easily be measured directly with a CD-SEM on embedded PSM's, but this becomes more difficult on alternating aperture PSM's when the critical feature is straddled by a shallow trench and a deep trench. Current techniques to measure phase require either larger features (> 1.0μm) due to spot size limitations (interferometric) or arrays of repeated structures due to averaging requirements (scatterometry). Phase can also be extrapolated using depth measurements, but is reliant on generic bulk material properties to make the calculation[4]. Besides the inaccuracy due to assumptions, depth measurements using atomic force microscopy or other profilometer derivatives are typically too slow. Transmission measurements of attenuated PSM's also have the problem of relying on measurements of bulk properties.

The question then arises at to whether meeting photomask specifications based on current metrology methods provides a photomask that has the smallest possible impact on wafer ACLV? Viewing the photomask as an optical component of the imaging system, instead of just a simple light filter, changes the relevance of today's specifications. Today's specifications leverage the notion that tight control of CD, phase, and transmission as individual entities will result in low error contribution on the wafer. The problem with this notion is that these variables, along with many more, are the factors when encompassed together contribute to image formation at the wafer level. For example, the issues just described with current metrology methods are compounded when the mask design is corrected with OPC structures. Geometrical shapes on the mask no longer look like the features printing in resist on the wafer. Complex software algorithms manipulate the designer's intent to create patterns that will have sufficient image fidelity after diffraction limited optics project the mask on to the wafer. Progler, et al, have described test cases that exhibit varying sensitivity to the photomask variance properties based on pattern shape and placement[5]. Using scalar approximation is no longer viable due to three-dimensional effects that occur in high numerical aperture imaging situations.

So what approaches are currently used to gain insightful information on photomask performance in relation to wafer ACLV results? Data from photomask CD-SEM's can be used as the input for sophisticated simulation engines for an estimation of the wafer level CD values. This approach is inherently inaccurate due to the large number of assumptions used in the simulation model. For a highly accurate estimation one would be required to input data for sidewall angle, surface roughness, index of refraction, phase at the measurement position, etc. All of the geometric and material values would take an enormous amount of time to capture even if metrology technology was available for everything. The current alternative is to take the finished photomask and run test wafers or short lots to verify the ACLV behavior. This requires a large amount of time and resources (silicon, lithography and metrology tools) that in the end means high costs. It is also impossible to separate the photomask contribution from the resist processing contribution to ACLV. At this point in the process even if a problem is found the photomask would have to be re-ordered.

It is proposed that aerial image based optical metrology of photomasks should be used for a more accurate prediction of ACLV performance. The aerial image is known to be the projected image of the photomask in air at the air/resist interface. Because the optical fidelity of the aerial image is unperturbed by the resist processing steps it is possible to analyze the image formation for optical errors (again treating the photomask as an optical component). Since the projected image incorporates the real three dimensional geometric and material properties of the photomask, the aerial image represents the summation of influences on CD variation.

EXPERIMENTAL

The project described in this paper sets out to evaluate the proposal of using aerial image based optical metrology of photomasks as an effective way of predicting ACLV wafer performance. The experimental plan includes taking a photomask and comparing the mask-level CDU to aerial image based CDU to the wafer-level ACLV. This project concentrated on chromeless phase lithography (CPL) technology. The layout was designed for engineering tests which included evaluating through pitch and across field imaging performance. The design includes 55 measurement locations across a 23.4mm x 27.4mm field. Several sets of line/space structures (5 lines per pitch) with pitches running from 100nm to 960nm are located at each metrology location (Figure-1). Structures included nominal line sizes from 30nm to 80nm as well as several structures that had specific OPC treatments applied. In addition, each set of test structures included a series of varying line lengths with a 20nm gap to allow investigation of line end effects.

The CPL mask was manufactured from an industry standard chrome-on-glass blank. Kasprowicz[6] et al offer process information for CPL technology. The photomask was patterned in resist using a 50keV variable shaped electron beam exposure system. The second level patterning of the CPL mask was done using a laser based writing system. The pattern was transferred into the film stacks using chlorine based (for chrome) and fluorine based (for quartz) chemistries in a plasma etching process. Traditional photomask characterizations were performed including the use of a KLA-Tencor 8100 CD-SEM. Mask level CDU results were obtained by measuring various targets at all 55 cell locations within the layout. Phase angle targeting was verified indirectly using a FEI SNP9000 profilometer to measure the quartz etch depth.

Aerial image CDU measurements were completed using both a Carl Zeiss AIMS™fab193i and an AIMS™45-193i system. The AIMS™fab193i is an ArF (193nm) based optical system for evaluating photomasks utilizing the specific scanner settings of wavelength, numerical aperture (NA), partial coherence of illumination/pupil filling (sigma: σ) and illumination type[7,8]. Both the NA and σ apertures are automatically adjustable to cover a wide range of values. Possible NA settings are $0.6 \leq NA \leq 0.93$ and the range for sigma pupil filling is $0.3 \leq \sigma \leq 0.98$. The AIMS™45-193i utilizes the latest advances in mechanical and optical design to provide aerial image emulation for hyper-NA lithography up to 1.4NA. Highly sophisticated proprietary polarization modes provide full-vector emulation imaging. Environmentally controlled measurement chamber and aberration minimized ArF optics allow the AIMS™45-193i to provide CD metrology tool-like performance. Through-focus aerial images are captured on a CCD camera that can later be evaluated using offline AIMS™ software.

Measurements were taken at multiple sites across the mask for various target and pitch values. For this experiment, a 0.93NA and quasar illumination setting along with a 0.85NA and annular illumination setting was used for aerial image acquisitions. Using the Global CDU Map AIMS™ analysis package the aerial image results were automatically analyzed for CD after a brief setup of the initial measurement location[8]. The software provides a result chart along with graphical maps representing the aerial image based CDU and NILS signatures of the mask.

The wafer exposure and processing experiments were executed on ASML scanners. The first was an ASML TWINSCAN™ XT:1400. Quasar30 Illumination with σ=0.87o - 0.57i, with a numerical aperture of 0.93. The mask type used for exposure was the same CPL phase shifted mask used for the aerial image measurements. Wafer processing was conducted on a Sokudo RF^{3}i inline track. The photoresist used was TOK TArF 6239 with a film thickness of 150nm. JSR topcoat TCX041 and a BARC 1c5d from AZ Electronic Materials with a film thickness of 38nm. All wafer metrology was done on a Hitachi S9380 SEM and process window analysis for experimental data was done using ProData v1.4. Similar processing was completed using a 0.85NA ASML TWINSCAN™ XT:1250.

RESULTS

CD variation within a single chip using all four metrology systems was compared using two different methods. First the CDU was defined as the 3-sigma value normalized to the average CD. Since raw CDU values on the mask and wafer are sensitive to the respective companies this practice provides an alternative for relative comparisons. The second method is a qualitative evaluation of the global CDU maps for a comparison of variation signatures. The mask level CD-SEM results were first divided by 4 to account for the scanner reduction factor and allow the CDU maps to have similar intensity scales. Although this is not representative of the true mask error enhancement factor (MEEF), it *does not effect* the interpretation of the CDU signature.

Shown in Figure-2 are the CDU maps for 70nm main feature targets on a 190nm pitch for both the AIMS™fab193i using 28 measurement sites and a wafer print using 55 sites. It is shown that in both CDU maps there is a low CD area in the upper-right quadrant on the field and high CD areas in a bowl shape at bottom edge of the field. Figure-3 shows a comparison of the measurement results of the same features using mask CD-SEM, AIMS™45-193i and the wafer data. All three data sets use 55 measurement points in the field. The CDU percentage relative to the mean CD is significantly less using the mask level CD-SEM (2.2%) and aerial image (2.0%) than it is for the wafer level ACLV results (3.3%). The difference in CDU values between AIMS™193i and AIMS™45-193I can be attributed to the improvement in measurement accuracy of the AIMS™45-193I. The variation signatures for the AIMS™45-193i and wafer results look very similar to each other. The NILS uniformity map from the AIMS™45-193i for these features is compared to the wafer ACLV map in Figure-4. Here it is shown that the signatures are dissimilar. The NILS results can be used to draw conclusions as to what causes the wafer ACLV. Areas of higher NILS values mean less CD variation would be expected due to process variation. Lower NILS values would cause larger lines to be printed when imaging is executed with some amount of defocus.

Using the same 70nm main feature cells, analysis was done on a slightly larger pitch of 240nm. Figure-5 shows the AIMS™45-193i and wafer CDU result maps using 55 measurement points. The CDU signatures are similar with an area of higher CD values in the upper left corner of the field. Comparing these results with the mask CD-SEM data is shown in Figure-6 along with a table comparing the CDU results of all three. The AIMS™45-193i has significantly lower variation (1.3%) than both the mask (2.4%) and wafer (3.2%) results. Since the signatures of the mask and wafer results are dissimilar, it is believed that other contributors to CDU on the mask offset the CD-SEM CDU results.

Aggressive imaging conditions were explored by measuring 60nm CD targets on the CPL mask using 0.85NA. CDU results were captured for pitch values of 190nm, 230nm, 320nm, 540nm, and 960nm at 15 positions across the field. When the AIMS™45-193i CDU values are compared to the wafer level ACLV values, Figure-7, it is found that there is a significant difference between the two at the extremes of pitch values, 190nm and 960nm. Inside the middle range of CDU signatures, they tend to resemble each other. It should be noted that the 540nm pitch features include a single scatterbar and the 960nm pitch features include a double scatterbar OPC structure.

CONCLUSION

It has been demonstrated through this project that using aerial image based CD metrology of photomasks is a reliable predictor of the mask-contributed component of CDU performance than traditional mask level CD uniformity data. It is possible in today's photomask manufacturing environment to produce PSM's that have very low CD uniformity. It is also possible to provide metrology data for other quality indicators such as phase and transmission although typically on bulk material. In contrast, aerial image based CD metrology provides an accumulative optical result that is more indicative of the behavior of the mask at the wafer level than the individual specifications can hope to forecast. This proposed metrology methodology of using an AIMS™ platform for final mask qualification offers an enhanced benefit to the wafer fab. The AIMS™ global CDU results can be used to better interpret wafer processing trends and shorten yield enhancement activities.

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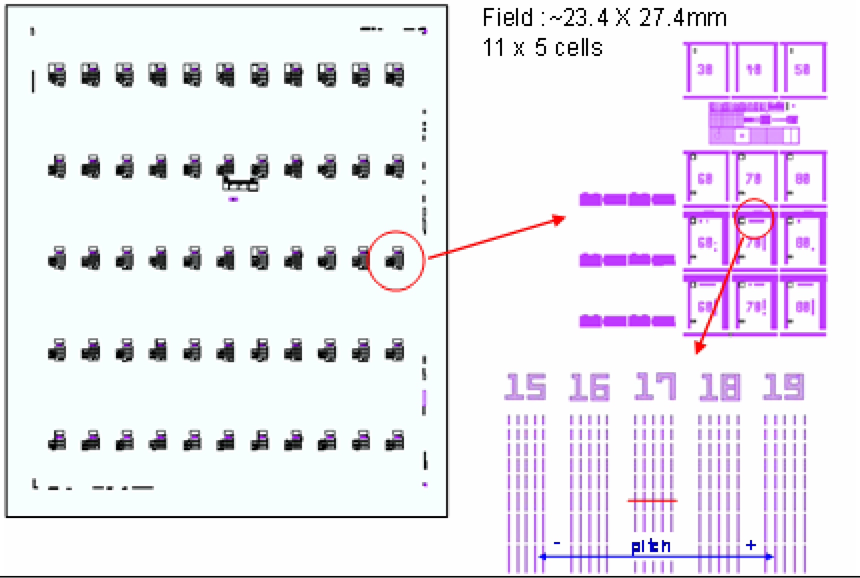

Figure-1: Test Mask Layout

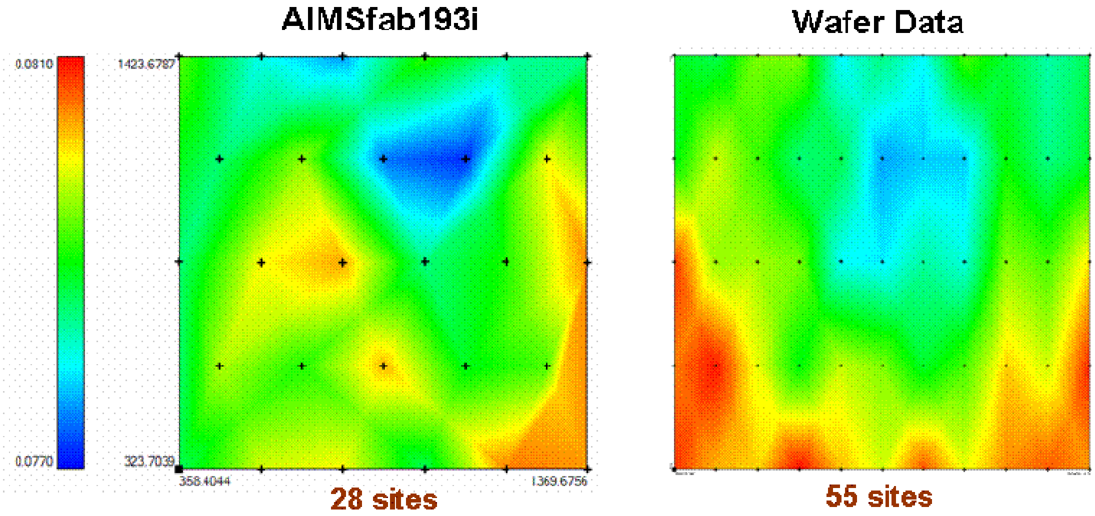

Figure-2: CPL 70nm Main Feature on 190nm pitch AIMS™ versus Wafer CDU

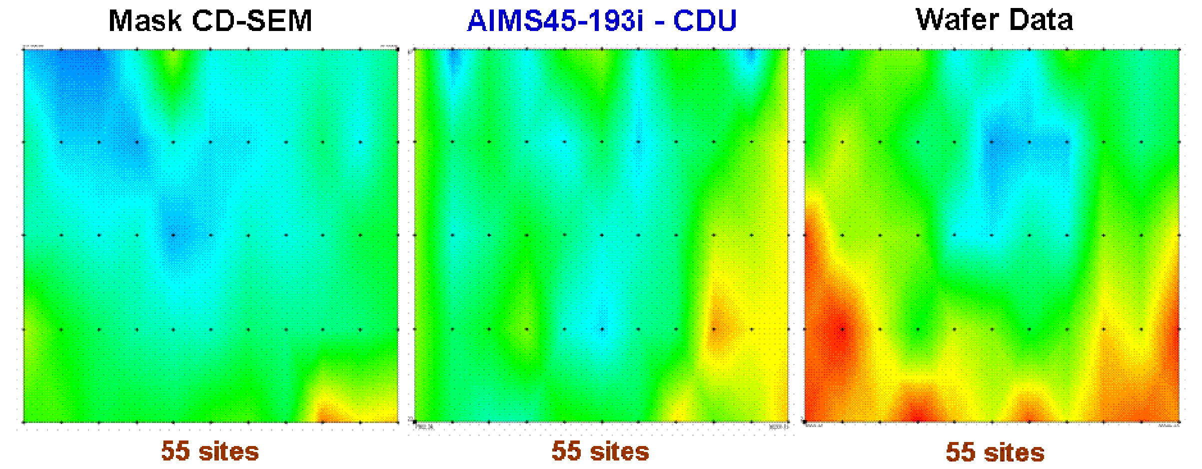

Figure-3: CPL 70nm Main Feature on 190nm pitch CDU Comparison

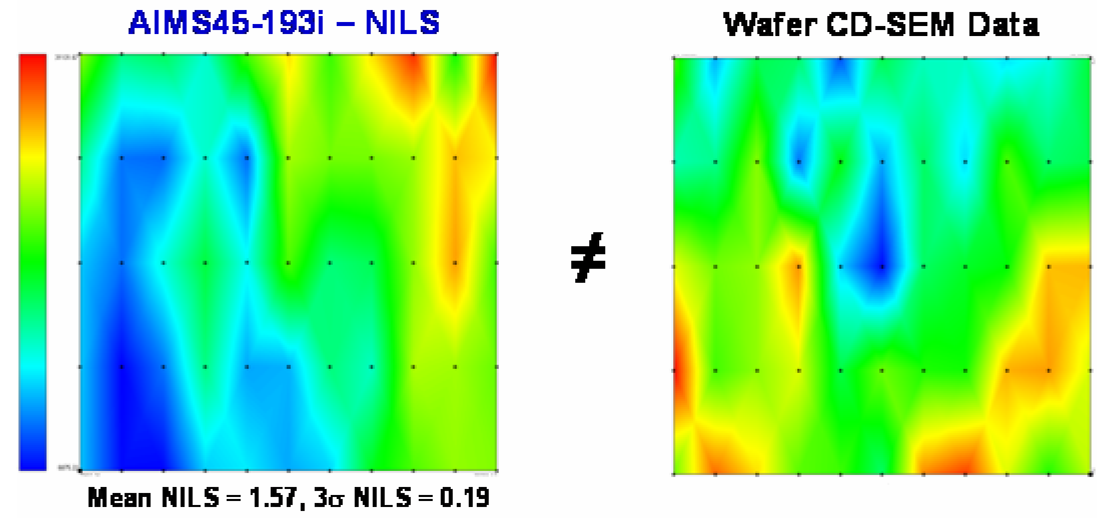

Figure-4: CPL 70nm Main Feature on 190nm pitch AIMS™ NILS map versus Wafer CDU

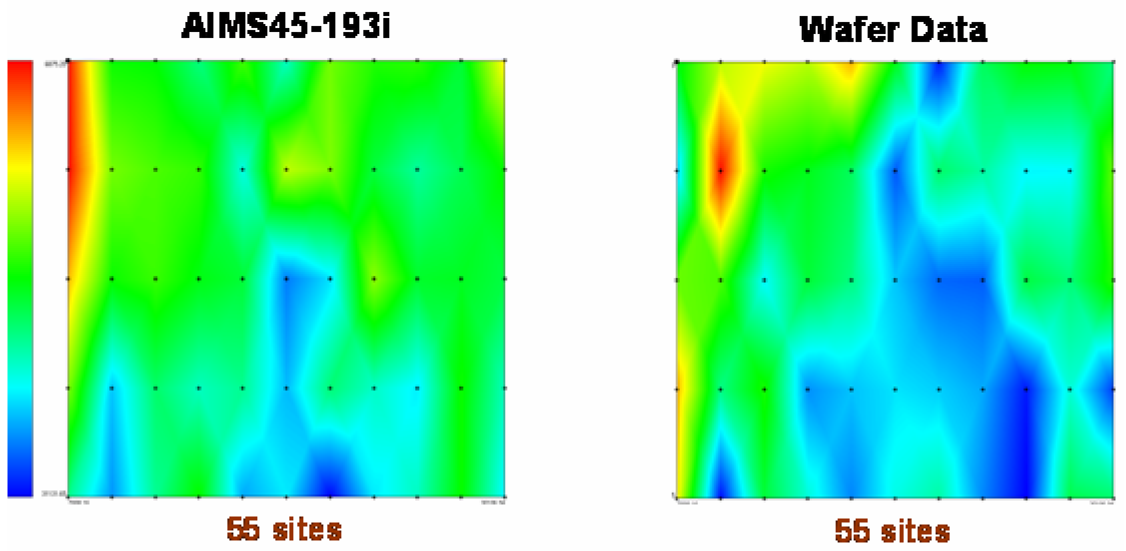

Figure-5: CPL 70nm Main Feature on 240nm pitch CDU Comparison

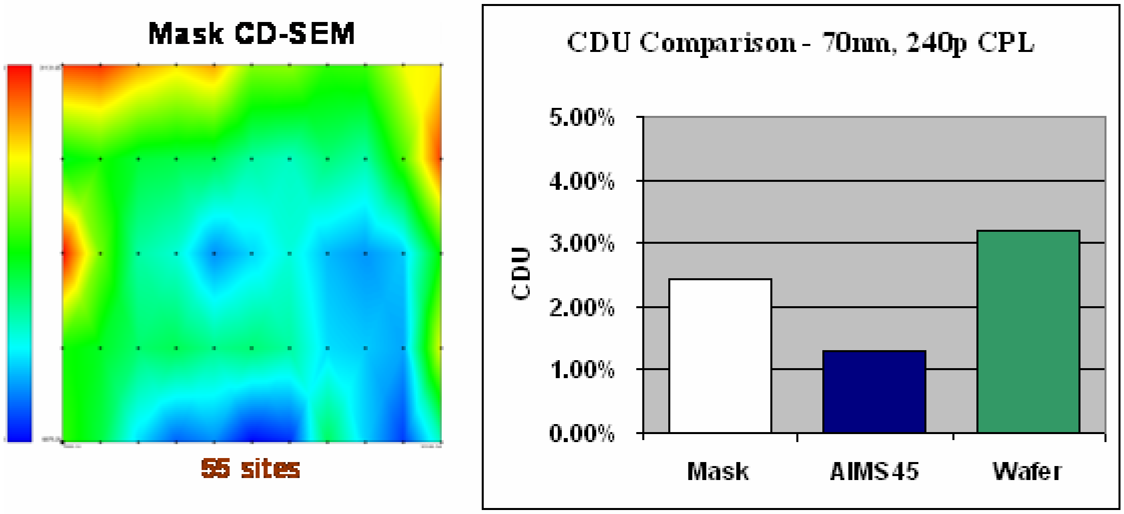

Figure-6: CPL 70nm Main Feature on 240nm pitch CDU Comparison

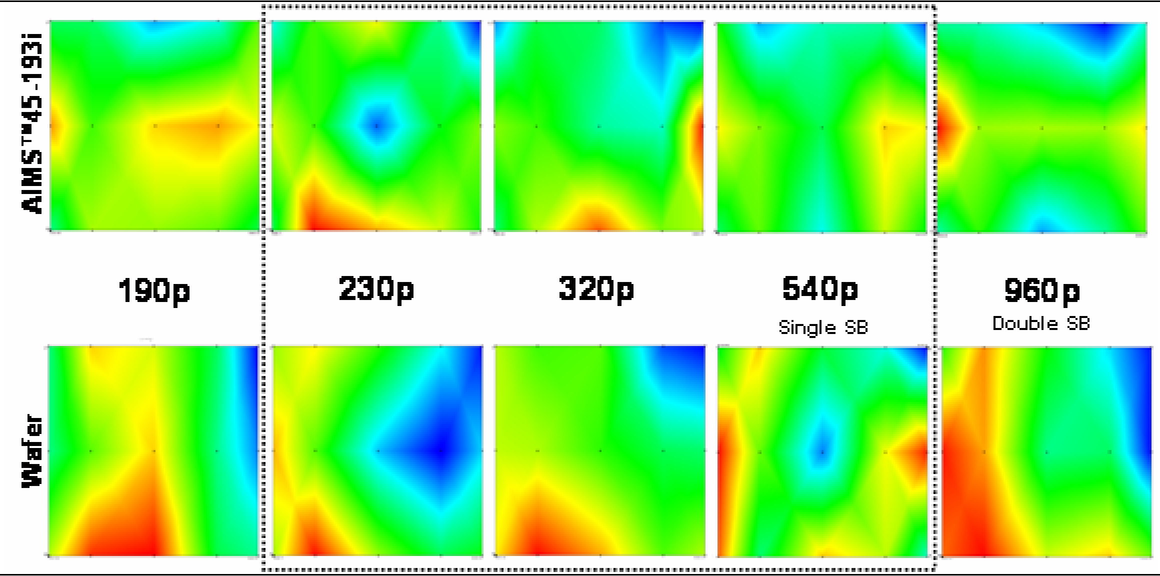

Figure-7: CPL 60nm Main Feature Through-pitch CDU Comparison