Improved prediction of Across Chip Linewidth Variation (ACLV) with photomask aerial image CD metrology

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ABSTRACT

Critical dimension (CD) metrology is an important process step 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 performance 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. At the 65nm node the ITRS roadmap calls for sub-3nm photomask CD uniformity to support a sub-3nm wafer level CD uniformity. Meeting these targets has proven to be a challenge[1]. What can be inferred from these specifications is 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 also tightened with each technology node.

A comprehensive study is presented supporting the use of photomask aerial image emulation CD metrology to predict wafer level Across Chip Linewidth Variation (ACLV). Using the aerial image can provide more accurate wafer level prediction because it inherently includes all contributors to image formation such as the physical CD, phase, transmission, sidewall angle, and other material properties. Aerial images from different photomask types were captured to provide across chip CD values. Aerial image measurements were completed using an AIMS™fab193i with its 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 CD 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 aerial image CD metrology.

INTRODUCTION

Device performance is affected by many variables in the manufacturing process of integrated circuits. Each process step has specifications defined that attempt to keep the device operating within performance tolerances. One such specification is Across Chip Linewidth Variation (ACLV) that describes the critical dimension (CD) uniformity across a single chip. If the CD varies too much within a chip the electrical performance degrades and the device no longer functions as intended[2].

ACLV is a function of the manufacturing process and its magnitude is the culmination of various contributors[3]. The major contributor to ACLV is the lithographic process that includes the photomask, optical aberrations of the scanner, and the resist process. 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. 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[5] 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 a Carl Zeiss AIMS™fab193i 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[6,7]. 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 $0.3 \leq \sigma \leq 0.98$. Through-focus aerial images are captured on a CCD camera that can later be evaluated using offline AIMS™ software. Measurements were taken at 28 sites across the mask for various target and pitch values. For this experiment a 0.93NA and quasar illumination was used for aerial image acquisition. 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 a graphical map representing the aerial image based CDU signature of the mask.

The processing experiments were executed on an ASML TWINSCAN^{tm} XT:1400. Quasar30 Illumination with σ=0.87o - 0.57i, with a numerical aperture of 0.93. The mask type investigated was a CPL phase shifted mask (PSM). 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

RESULTS

The CDU results from the mask level CD-SEM, AIMS™fab193i, and wafer level CD-SEM were compared by 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 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 main features with 70nm targets on a 190nm pitch for both the AIMS™ and wafer CDU results. 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 the mask level CD-SEM CDU map along with a bar chart comparing the CDU results from all 3 metrology techniques. The CDU percentage relative to the mean CD is significantly less using the mask level CD-SEM (2.0%) than it is for the aerial image based CDU (3.5%) and wafer level ACLV results (3.3%).

Using the same 70nm main feature cells, analysis was done on a slightly larger pitch of 220nm. Figure-4 shows the AIMS™ and wafer CDU result maps. Again the CDU signature is similar with a low area of CD in the upper right corner of the field. Comparing these results with the mask CD-SEM data is shown in Figure-5. The AIMS™ and wafer level data have identical CDU values of 3.4% relative to the mean CD. The mask level CD-SEM data is again much lower with a CDU value of 2.2%.

More aggressive resolution conditions were explored by looking at 50nm CD targets on the CPL mask. It should be noted that the mask design for the 50nm cells did not have OPC treatments applied to the data. CDU results were captured for pitch values of 190nm, 240nm, and 255nm. When the AIMS™ CDU values are compared to the wafer level ACLV values (Figure-6) it is found that there is a significant difference between the two. The AIMS™ CDU values are roughly two thirds the amount exhibited once the photomask is exposed into resist. Since the layout was not treated with OPC it is not surprising that the resist process exhibited higher levels of variation on CD. OPC treatments are meant to increase the process window of aggressively sized patterns. With a smaller process window these features would be more sensitive to focus and dose errors in the exposure process. What can be taken away from this data is that the AIMS™ based CDU data can provide the mask contribution to the final ACLV results. The difference between the AIMS™ results and the wafer results would be the exposure/resist process contribution.

CONCLUSION

It has been demonstrated through this project that using aerial image based CD metrology of photomasks is a better predictor of ACLV 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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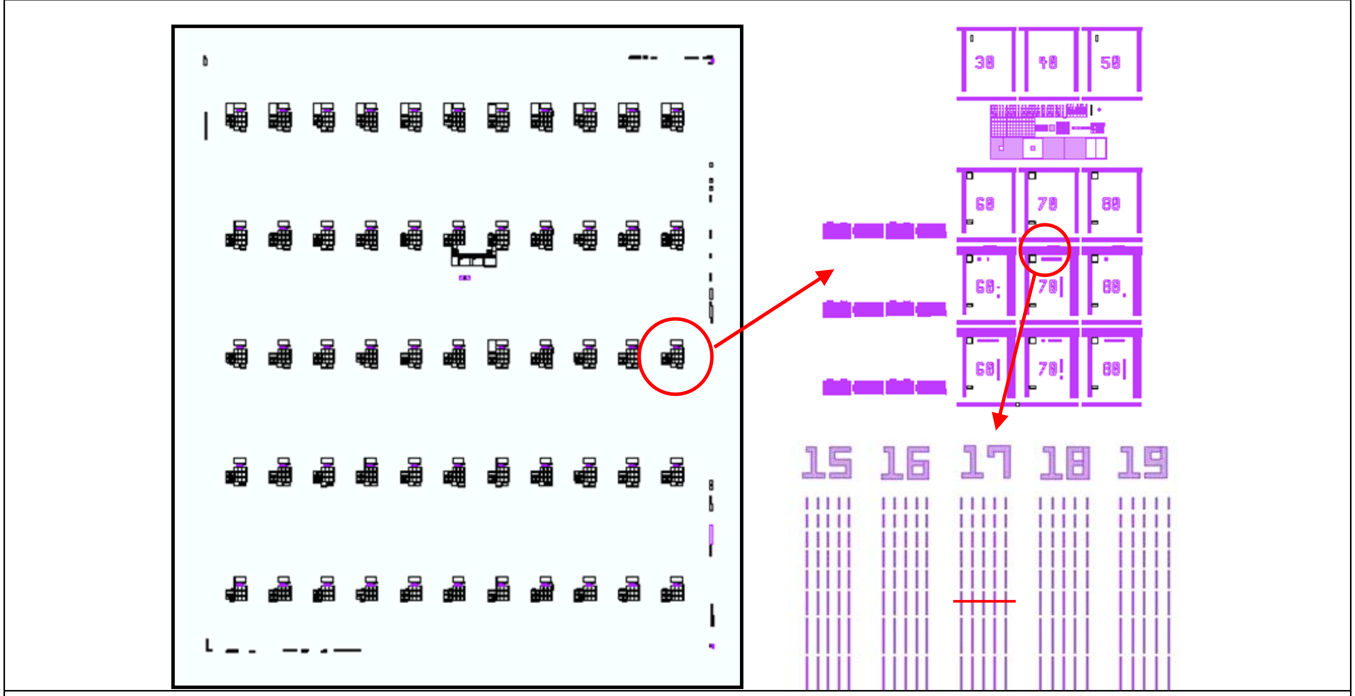

Figure-1: Test Mask Layout

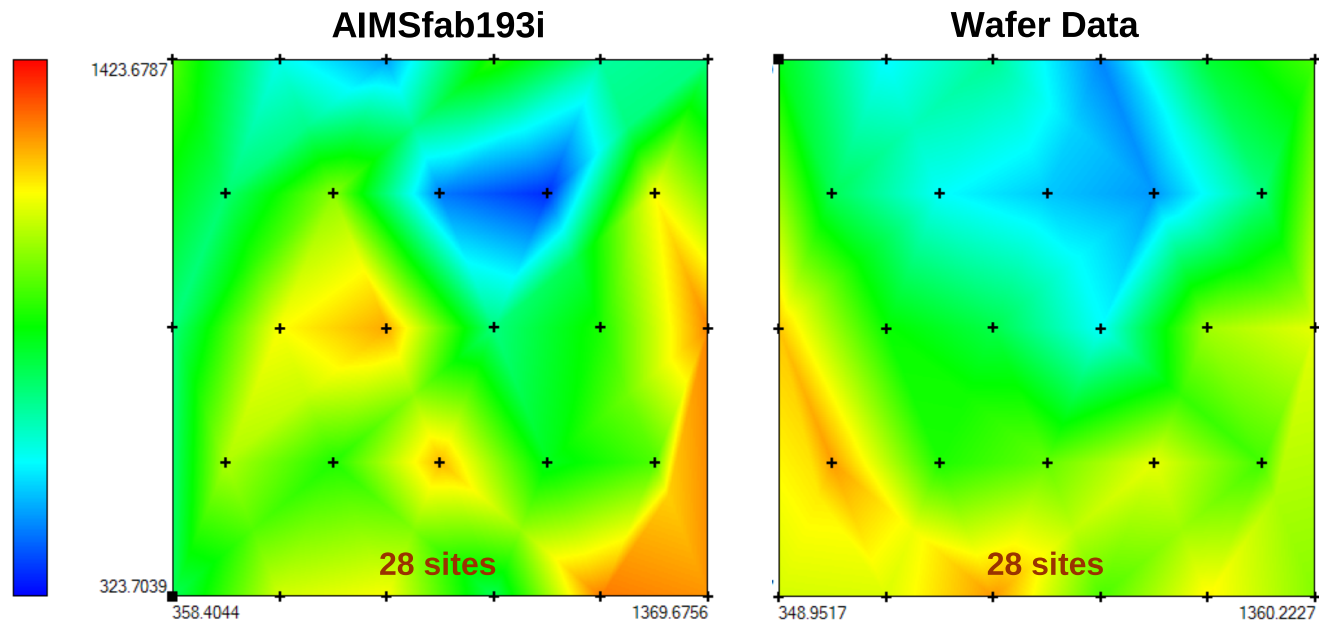

Figure-2: CPL 70nm Main Feature on 190nm pitch AIMS™ versus Wafer CDU

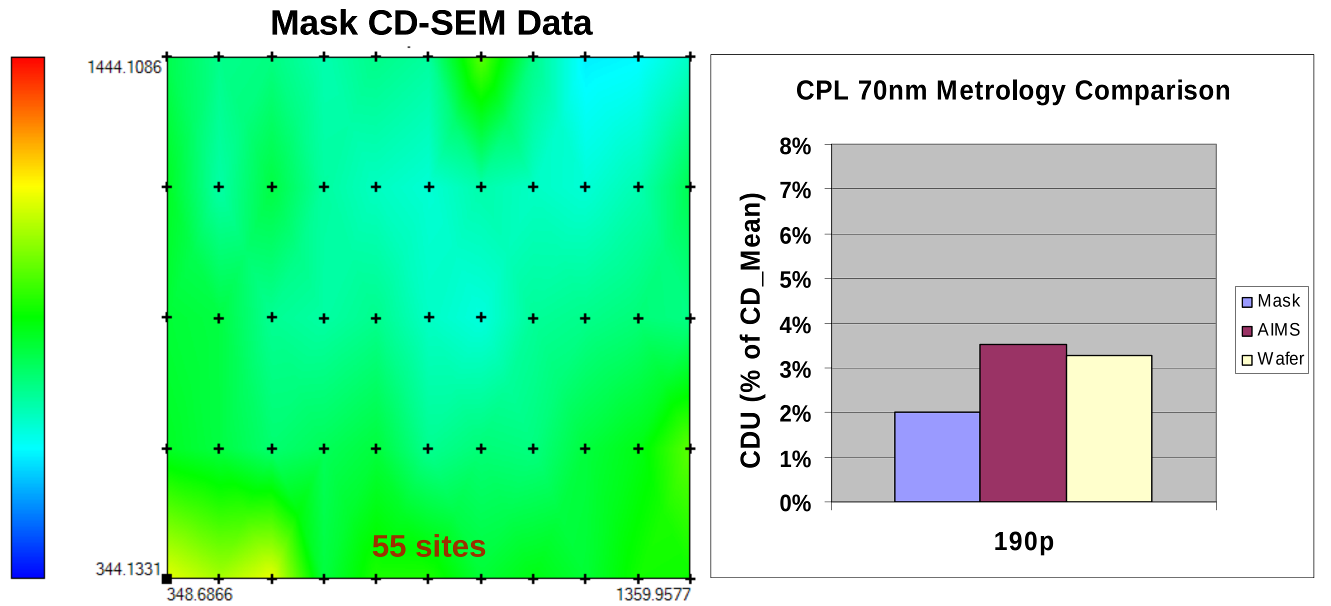

Figure-3: CPL 70nm Main Feature on 190nm pitch CDU Comparison

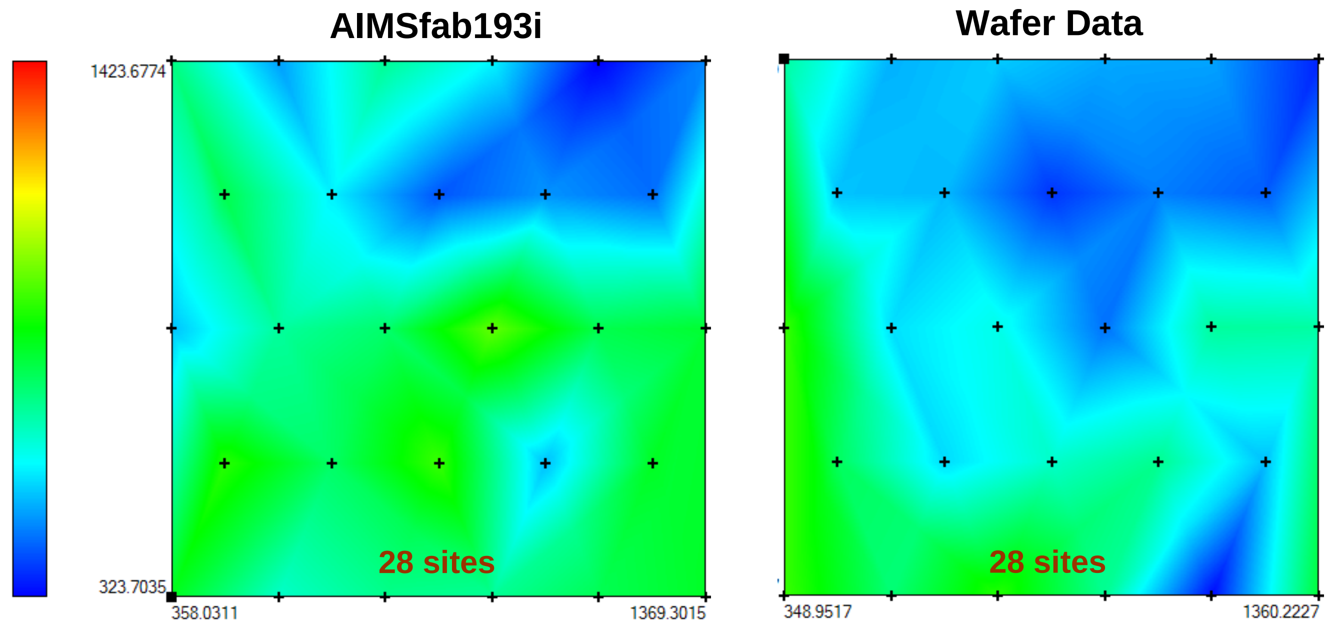

Figure-4: CPL 70nm Main Feature on 220nm pitch AIMS™ versus Wafer CDU

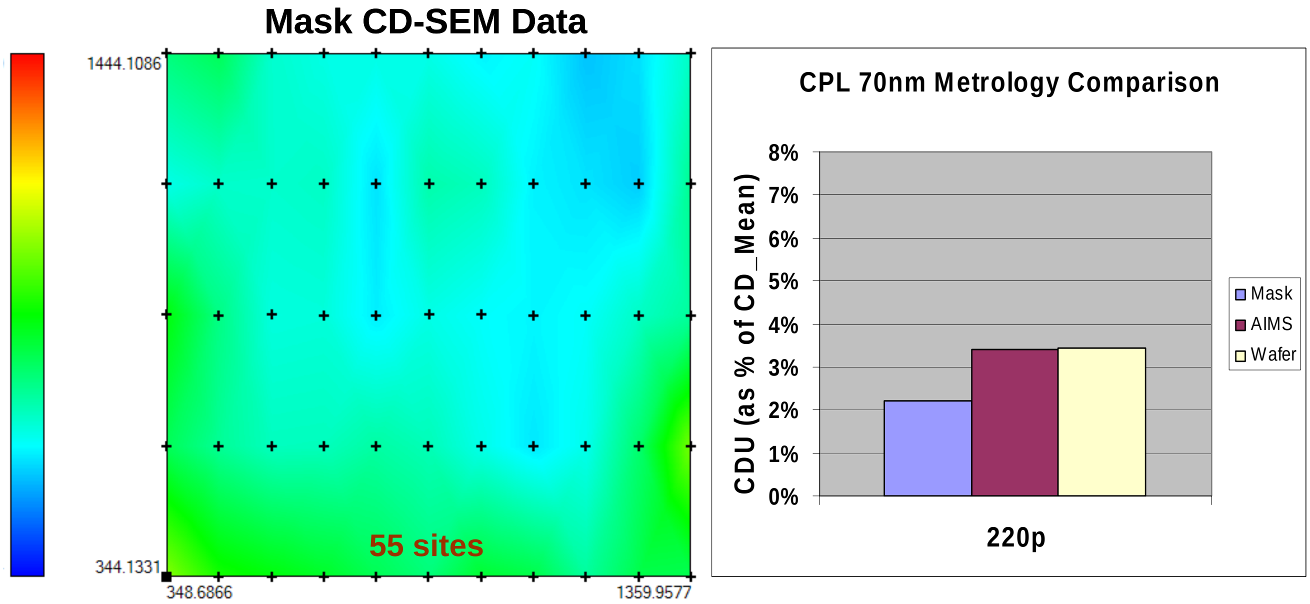

Figure-5: CPL 70nm Main Feature on 220nm pitch CDU Comparison

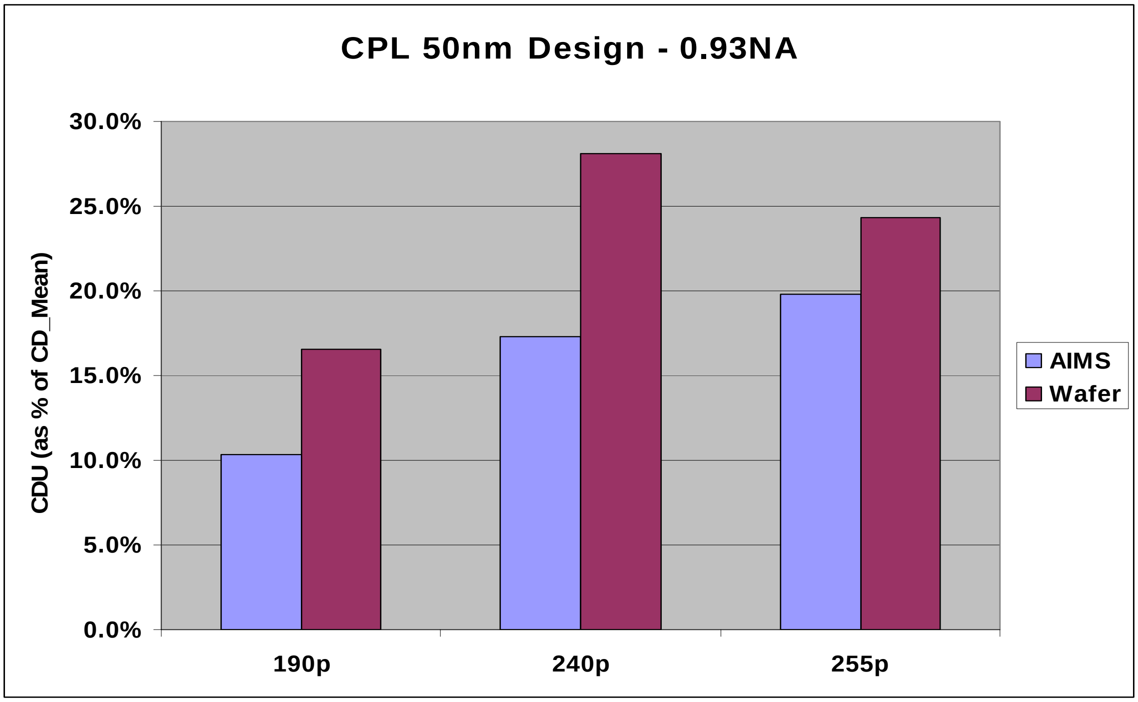

Figure-6: CPL 50nm Main Feature Through-Pitch CDU Comparison