PRIMADONNA: A System for Automated Defect Disposition of Production Masks Using Wafer Lithography Simulation

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ABSTRACT

Today's reticle inspection tools can provide a wealth of information about defects. We introduce here a system called **DIVAS:** Defect Inspection Viewing, Archiving, and Simulation that fully uses and efficiently manages this wealth of defect information. In this paper, we summarize the features of DIVAS and describe in more detail PRIMADONNA, one of its components. Current reticle defect specifications are based, primarily, on defect size. Shrinking design rules, increasing MEEF and use of Optical Enhancement Techniques cause size to be an inadequate criterion for disposition. Furthermore, visual disposition of defects is not automated, strictly reproducible, or directly tied to wafer lithography. To compensate for these inadequacies, reticle specifications are set conservatively adding direct and hidden costs to the manufacturing process. PRIMADONNA, utilizing PROLITH™ as the simulation engine, retrieves all defect and reference images saved from a KLA-Tencor SLF77 inspection tool and processes them through a series of increasingly rigorous simulation stages. These include pre-filtering, aerial image formation, and post filtration. Difference metrics are used to quantify a defect's wafer impact. We will report results comparing PRIMADONNA decisions to manual classifications for a significant volume of inspections. Correlation between PRIMADONNA results and AIMS™ metrology will be presented.

1. INTRODUCTION

1.1 DIVAS system

Reticle inspection tools process vast amounts of optical image information to locate defects. Unfortunately, the processing of defect information has remained a labor-intensive process involving significant manual intervention and human decision-making, thereby making it prone to human error. Furthermore, the sensitivity of reticle defect inspection tools continues to increase to keep up with roadmap requirements. Sub-wavelength resolution lithography increases the MEEF, making visual classification and defect sizing a poor predictor of defect printability.

Traditionally, defect images are manually reviewed and classified at the inspection tool. These images are subsequently reduced to a paper printout (normally referred to as "map") used for mask repair. This defect map contains limited information including defect coordinates, crude sizings, and classification codes. In some cases, a hardcopy of the defect image is provided, but the vast majority of image data is discarded.

We introduce here a system called DIVAS (Defect Inspection Viewing, Archiving, and Simulation) that more completely utilizes and efficiently manages this wealth of defect information. The DIVAS System integrates three Intel Mask Operation (IMO) written software applications (PRIMADONNA, CALLAS and TEBALDI) and PROLITH™ (a product of the KLA-Tencor Process Analysis Division) with the shop-floor control system into the backend of the mask-manufacturing environment. Figure 1 describes the flow of the integrated system. The combined capability automatically processes defect information from inspection and defect metrology tools, using analytical methods. In addition, it makes defect information universally available online and easily quantifiable to mask shop personnel to facilitate defect reduction and continuous improvement.

This Paper will describe in detail the PRIMADONNA application. A brief description of the other applications is provided here, but future papers will describe them in more detail. Note that each of the Intel written applications in the DIVAS system is named after a famous operatic diva. CALLAS is the defect image database and associated GUI. It links defect images and maps with information from the shop control system for a given reticle (lot number, attributes, mask type, specifications, etc.). The application is used extensively on the shop floor to facilitate defect repair, communicate status of repair in real time, and provide an image-based defect repair history. Through the GUI, the CALLAS database is accessible from any networked PC in the mask shop and is a valuable tool for improving defect yield analysis and efficiently evaluating and characterizing defect signatures.

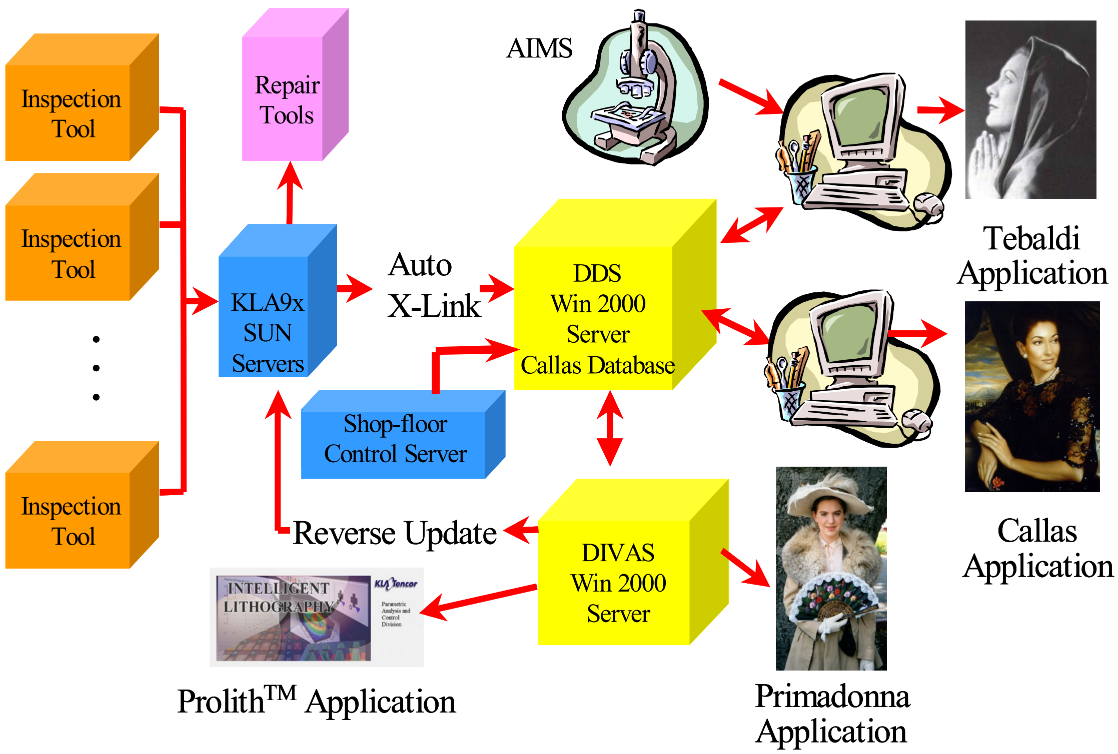


Figure 1: DIVAS system flow diagram

The TEBALDI application quantifies 2D differences between any pair of images. Using this program, the operator can import align and overlay two images, then measure the pattern difference using a variety of metrics. Currently we use this primarily for aerial image microscope (AIM) images of defect sites for post repair verification. However, TEBALDI can also be used to analyze images saved by a SEM, inspection tools and even aerial images generated via simulation. One can use this application to quantitatively measure the wafer impact of mask pattern fidelity differences on complex OPC on any pattern.

1.2 PRIMADONNA

The PRIMADONNA application is designed to automatically quantify severity of defects based upon lithographic impact. The application also determines if repair is required by comparing the severity value to the defect specification of each mask. The advantages of using this system to manage defects are; 1) improved mask quality, and 2) increased efficiency through reduction of repair and manual classification.

More consistent mask quality can be delivered by reducing the risk of human error and establishing defect specifications based upon printability (not simply mask level sizing). It is not a trivial matter to visually classify defects with today's advanced OPC and increasing MEEF. Small or subtle pattern defects can have significant wafer impact in critical areas (see figure 3). Relying upon operators to reproducibly make correct decisions on what is a "false" or "real" defect becomes increasingly risky without an analysis that also includes the geometry surrounding the defect and the actual wafer lithography process used with the reticle. The PRIMADONNA application has demonstrated the ability to accurately assess defect severity without manual intervention, and is not limited to specific geometry (i.e., isolated defects, straight lines, etc.). Automatic classification based upon lithographic significance provides the opportunity to reduce some costs associated with the defect classification and repair. Inspection tool capture sensitivity is based primarily on mask level defect size. With rapidly shrinking design rules and complex geometry, the same size mask defect could have drastically different wafer impact depending upon where it falls in the pattern and depending on wafer lithography process parameters. To ensure mask qualities across all patterns, inspection tool sensitivities are determined by these "high MEEF" locations on the mask (i.e., narrow lines and spaces). Consequently, many defects of similar size are captured in "lower MEEF" locations and have no wafer impact (sub-spec defects). Traditionally, repair is performed on all of the sub-spec defects because of the complexity associated with reliably dispositioning such defects.

2. METHODOLOGY

A KLA-Tencor SLF77 inspection tool was used to process both programmed defect and inline production masks for this study. All inspections performed on these tools were processed through the PRIMADONNA application for a period exceeding 3 months. Accuracy studies were performed on binary DUV critical layer masks using an MSM-100 aerial image microscope (AIMS™) from Carl Zeiss (248nm, 0.68Na). PROLITH™ version 7.1 was used as the simulation engine. The X-link application from KLA-Tencor was used to convert inspection reports and images to KLARF format. Interface software for both PROLITH™ and X-link was tailored by KLA-Tencor to allow these applications to be automated and embedded into the DIVAS environment.

The general outline of the PRIMADONNA data flow is shown in figure 2. Each defect within an inspection report (IR) is associated with a test (defect) image and a reference image. This set of images will be referred to as a test/reference image pair or TRIP. In step 1, a mask is inspected and defect sites are

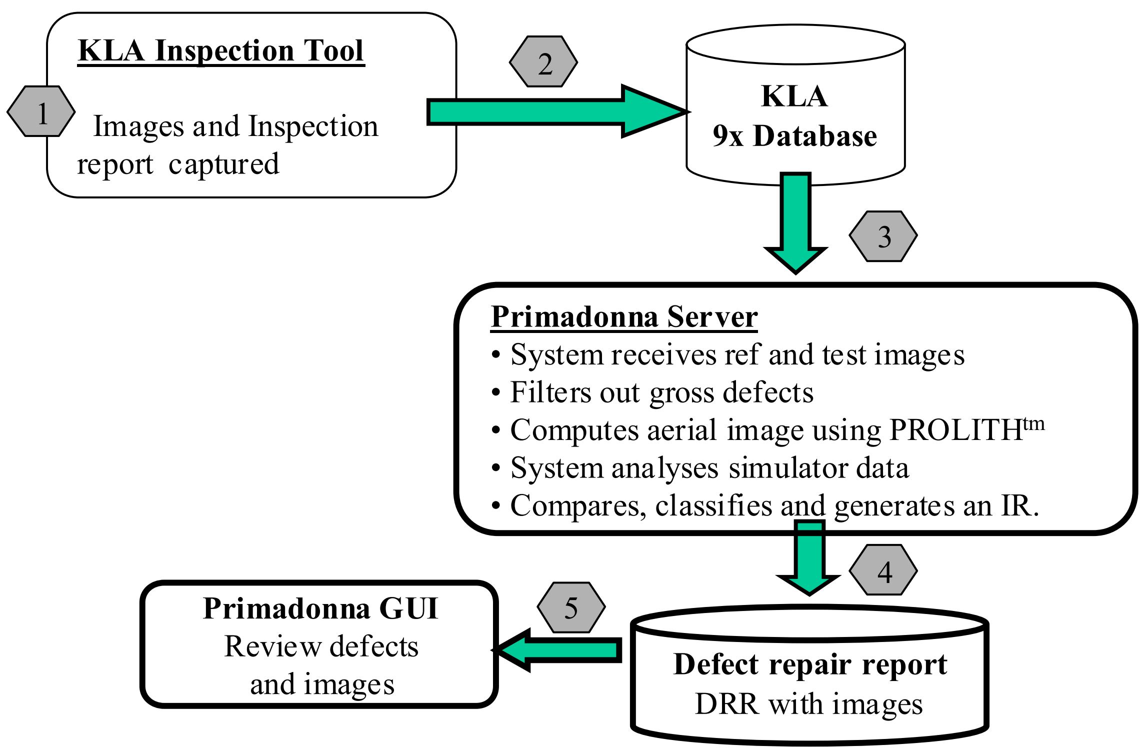


Figure 2: PRIMADONNA application outline

captured in an IR with a TRIP for each defect. During the period of this study, manual classification was performed and the IR that was saved contained the result of the visual classification. In step 2, the IR and images are saved onto the KLA-Tencor 9X database and assigned an identification number. In step 3, the files are automatically converted to a KLARF format which consists of a text file for the inspection report and bitmaps of all the images. This conversion is performed using an automated X-link application from KLA-Tencor and transferred to a database on the PRIMADONNA server. This is also the point at which the IR identification number is associated with the mask specific information from the shop floor management system.

The TRIP for each defect is processed through a series of increasingly rigorous comparison stages. We will not describe in detail the technique or metrics used to quantify the severity and eventually disposition a defect. General methodology is discussed. At each stage, the TRIP is assigned one of three results PASS (not significant), FAIL (significant, needs repair) or Indeterminate (continue to the next comparison stage). The system compares the severity metrics to the defect specification for the particular mask to determine the result for that stage. The first comparison stage can filter out very large (and/or very small) defects by directly comparing the TRIP from the inspection tool. The TRIP is then automatically converted to a MSK file and processed through PROLITH^{TM} to obtain the corresponding aerial images for both the defect and reference images. Simulation parameters specific to the exposure of the mask can be automatically set using input obtained from the shop control system. The aerial images then run through an increasingly rigorous set of comparison stages. This stage of the study is limited to aerial image simulations, however, KLA-Tencor has tailored PROLITH^{TM} to enable PRIMADONNA to automatically simulate the entire process window, including resist profile and through focus and exposure.

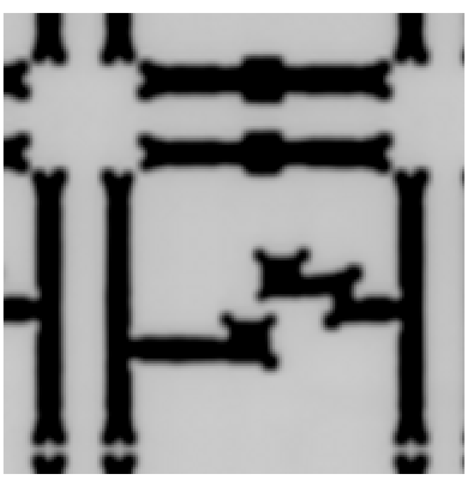
When a decision is made on every TRIP in an inspection report, PRIMADONNA generates a defect repair report and updates the database, step 4. PRIMADONNA output includes the disposition result, quantitative output of the comparison stages, and associated images created. The repair operator can then access the information and images on the database through a PRIMADONNA GUI. The entire process is automated. No manual intervention is required from the time the inspection is saved to the moment the PRIMADONNA decision is made on all defects within an inspection report.

3. RESULTS

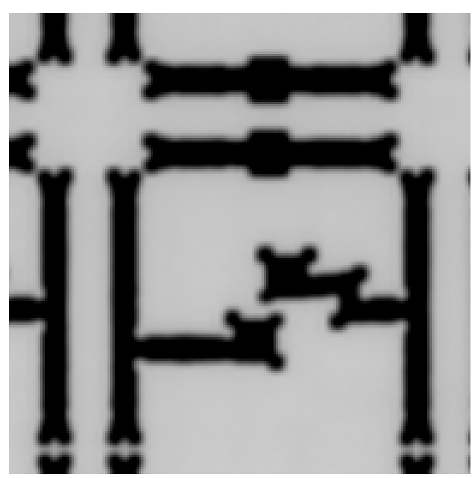
3.1 Example defect

Figure 3 illustrates the dispositioning process for a subtle but significant defect identified during the pilot. This operator understandably classified this defect as false, but the PRIMADONNA application easily identified this defect correctly as being real and out of specification. The defect consists of a circular area where the geometry is over etched. The defect (test) and references images are shown in figures 3a and 3b. Figure 3c and 3d show the magnitude of the intensity difference between the inspection images in gray scale and 3D view. When each inspection image is processed through the aerial image simulator, figures 3e and 3f are produced. Figure 3g shows the intensity magnitude of the difference between the aerial images in 3D view. Under typical wafer exposure conditions, the gate lines for this defect results in partially missing lines.

Figure 3: Example defect image pair as processed through PRIMADONNA (a-g)

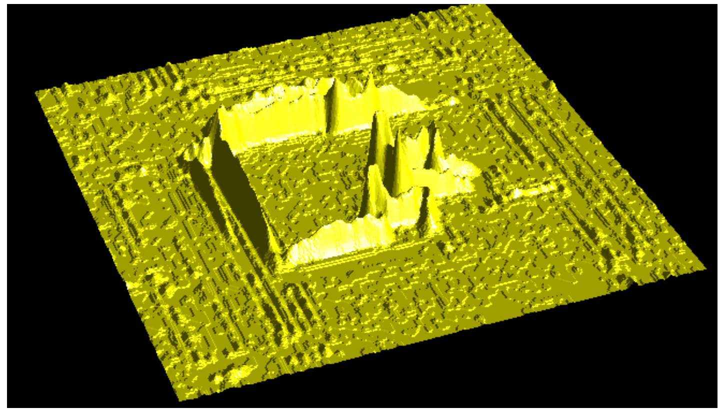


3a) Defect image

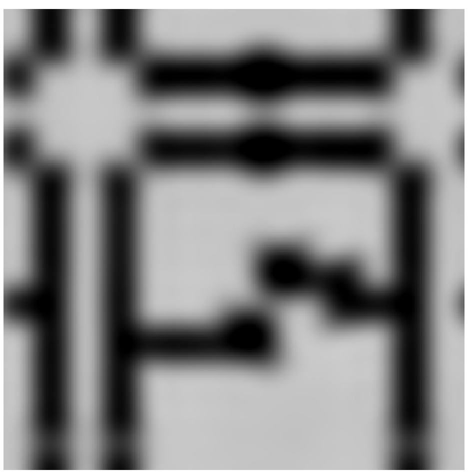


3b) Reference image

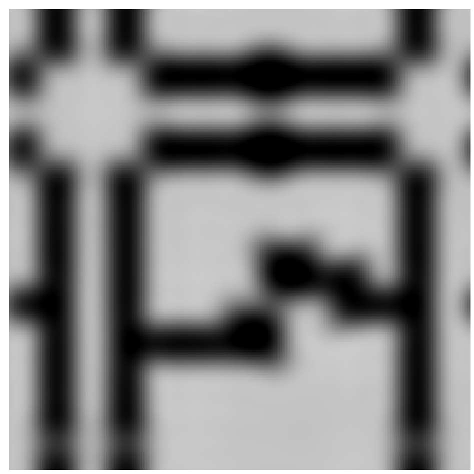
3c) Difference image (Defect - reference)



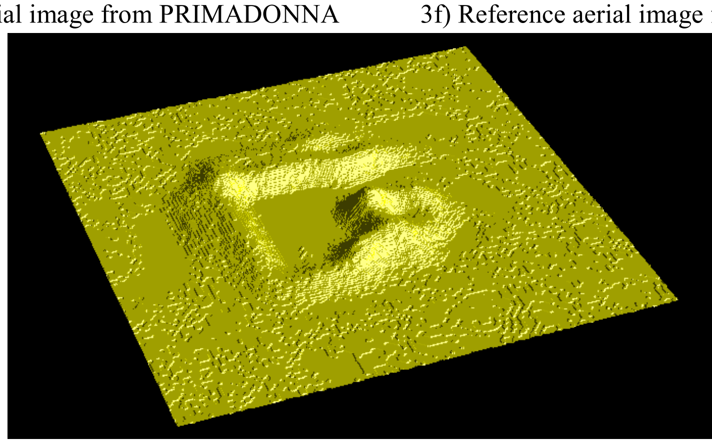
3d) Difference image (z axis is intensity)



3e) Defect aerial image from PRIMADONNA



3f) Reference aerial image from PRIMADONNA



3g) Difference aerial image intensity (3e-3f)

3.2 Accuracy

Figure 4 and 5 shows the results of the PRIMADONNA simulation accuracy study. Experimental aerial images are compared to PRIMADONNA results for 0.13 technology binary programmed defect masks. In figure 4, the line width of the critical dimension is plotted for defects of multiple sizes on gates in different locations. Line widths are measured at the defect site using a simple threshold model for both aerial images from PROLITH™ and the AIM. The direct linear correlation is good over a wide range of line widths and patterns locations.

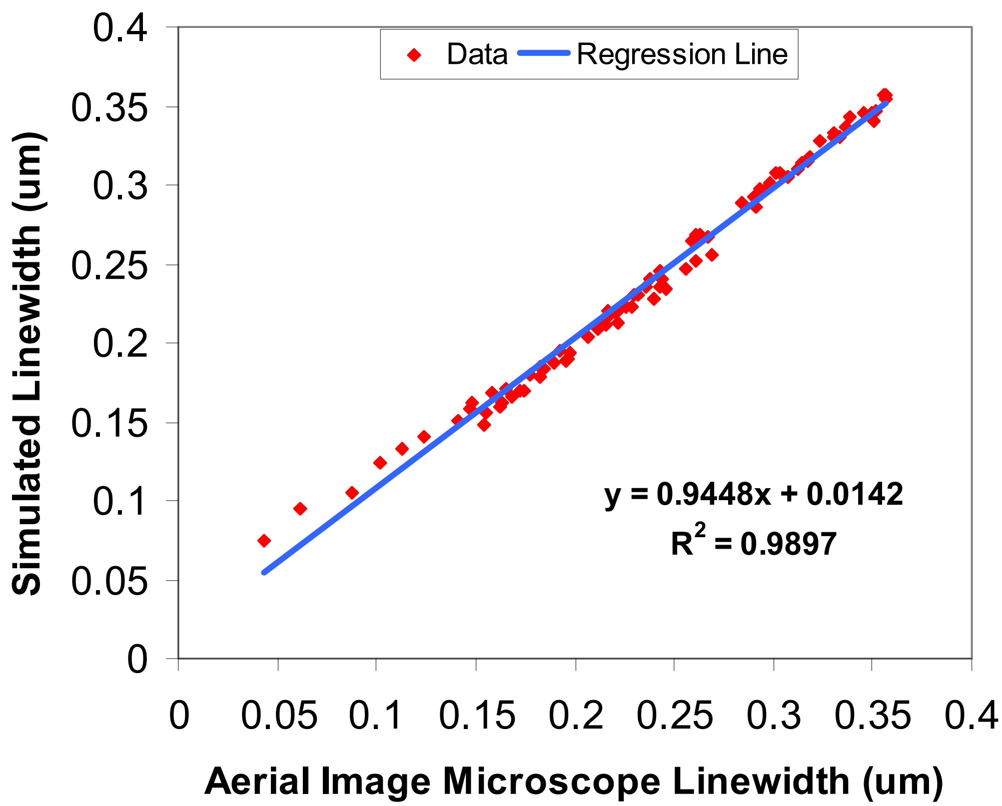


Figure 4: Correlation between simulation and AIM for gate line width

Figure 5 shows accuracy results for two-dimensional (area) difference induced by the programmed defect on the aerial images. The area was determined by applying a simple threshold model to aerial images for both defect and reference images then aligning, and subtracting the respective patterns. The area measurement was performed using the TEBALDI application. This indicates both the accuracy of the simulation engine, and the validity of the approach. Due to location specific MEEF, there is much poorer correlation between defect size on the reticle and aerial image line width. Note the data points for this figure, as in figure 5, were determined through manual analysis from both the PRIMADONNA and experimental aerial images. From the data presented here, we consider the accuracy of the simulation to be as good as (if not better than) the AIM experimental results.

3.3 System reliability and speed

The system has been run on production masks in parallel with manual classification over a 3-4 month period. During the pilot, over 500 inspections have been processed through PRIMADONNA. Less than 1% of the inspections have required manual assistance to process, and no unresolved bugs in the simulation or integration code have been detected.

The speed of the system varies depending upon the number of defects, image size, and fraction that need full simulation comparisons. We use a 4X - 550 MHz Xeon server for the PRIMADONNA application. In general, >90% of the mask inspections take less than 5 minutes to completely process. One programmed defect mask used in the accuracy studies had 371 defects and processed in 45 minutes. That is 742 bitmap images (371 TRIPs) with sizes ranging between 48x48 and 64x64 pixels. Average time to process one defect image pair through simulation comparison to decision is less than 8 seconds. Speed and throughput improvement is achievable by taking advantage of scalable server architecture.

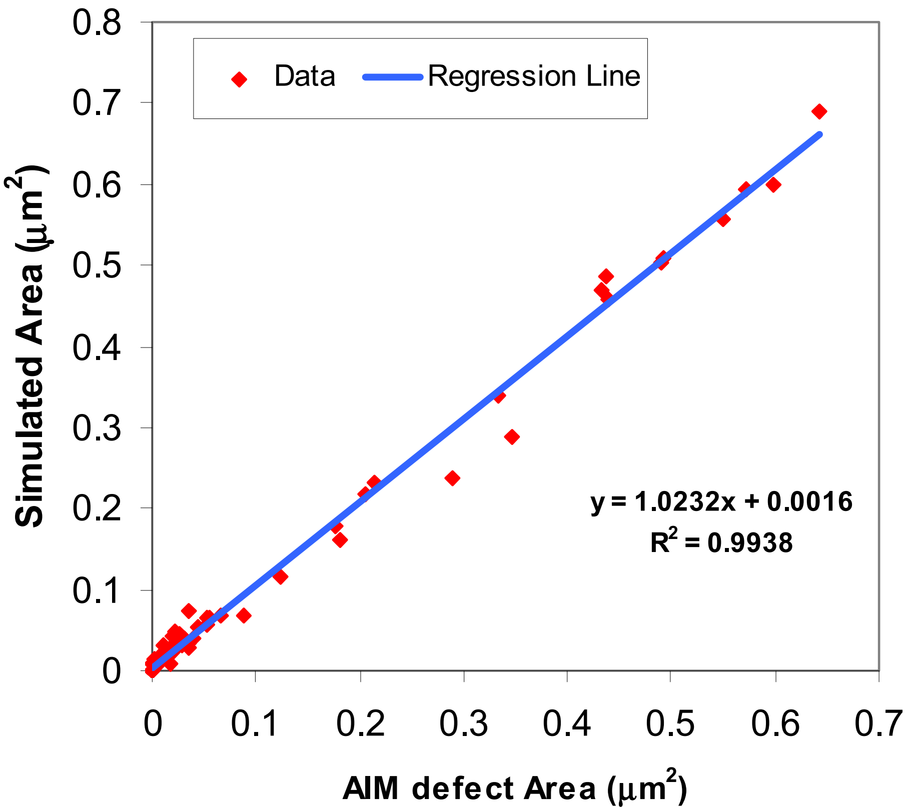


Figure 5: Correlation or defect area between simulation and aerial image microscope

3.4 Comparison with manual classification

For the comparisons to manual classification, we limited the study inspections to binary 0.13 technology masks processed over a 30-day period. This includes both Die to Die (D:D) and Die-to-Database (D:DB) inspections on the KLA-Tencor SLF77 tool. Both real and false defects are included. For each defect, the PRIMADONNA result is either Pass or Fail. Pass indicates the defect (if real) will have little or no impact on the design when printed, also referred to as sub-spec. Fail indicates the defect (if real) will have significant impact on the design when printed. Hard defects are pattern errors that consist of missing or extra chrome on the mask. Soft defects (contamination and particles) are excluded from the analysis because repair is not used to eliminate these. A false defect is one that appears to the operator to be not present (upon visual inspection of the images).

Figure 6 summarizes the results for both real (hard) and false defects. In the current environment, all hard defects are repaired or otherwise dispositioned by metrology tools to meet post repair specifications. The study shows more than 50% of hard defects passed PRIMADONNA criteria and would not have required repair. Similarly, over 75% of the false defects are small enough to be automatically filtered out. Approximately 25% of the false defects fail PRIMADONNA disposition, we will refer to these as false/fail defects. In the vast majority of these false/fail defects, either the defect or the reference image significantly deviates from the "live" image that the operator uses during manual classification. This deviation from the "live" image can be due to image corruption or other issues commonly associated with false defects. In these cases, the defect and reference images are in fact different due to inspection tool issues and tend to have distinctive signatures. Typically, <1% of the false/fail defects are of the type shown in figure 3 where the defect is real and not identified. However, this misclassification error was captured as a false/fail defect. The cost of a single repeating wafer defect caused by misclassification can be very high to a wafer fabrication customer.

In addition to reduction of defect repair, we can roughly quantify the impact to first pass yield (FPY) as the percentage of masks not requiring repair at all. Approximately 50% of the inspections included in this data are pre-repair. If the PRIMADONNA results were used to make repair decisions, additional masks would not have required repair (this is in addition to the FPY masks from manual classification). The data indicates a potential 18% increase in FPY on this limited sample.

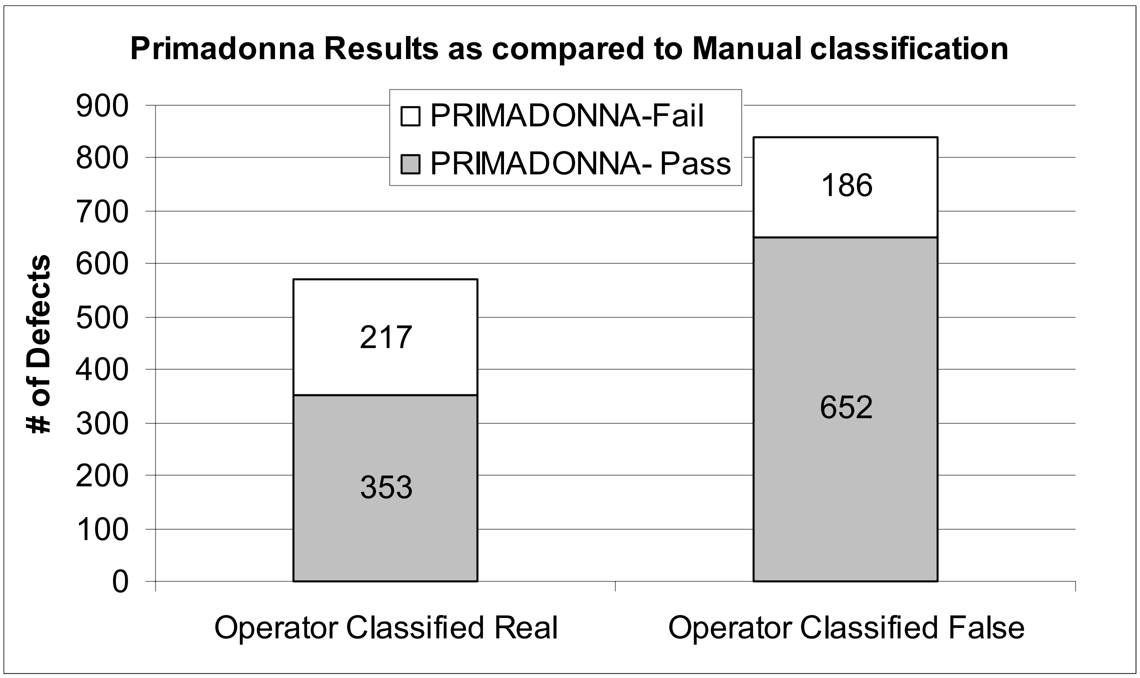


Figure 6: Results of the PRIMADONNA application for defect classification

4. SUMMARY

We have described the DIVAS system for improved mask defect management. We detailed the PRIMADONNA application that automatically classifies defects using wafer lithography simulation. The system has successfully caught manual classification errors and shown good correlation to an aerial image metrology tool. Typical process time of <30min is achieved with good reliability. Use of this system shows promise to reduce mask repair and inspection costs. We demonstrated a significant reduction in required repairs and a potential increase in first pass yield of ~18%.

5. ACKNOWLEDGEMENTS

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