Increasing reticle inspection efficiency and reducing wafer print-checks using automated defect classification and simulation

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Abstract

IC fabs inspect critical masks on a regular basis to ensure high wafer yields. These requalification inspections are costly for many reasons including the capital equipment, system maintenance, and labor costs. In addition, masks typically remain in the “requal” phase for extended, non-productive periods of time. The overall “requal” cycle time in which reticles remain non-productive is challenging to control. Shipping schedules can slip when wafer lots are put on hold until the master critical layer reticle is returned to production. Unfortunately, substituting backup critical layer reticles can significantly reduce an otherwise tightly controlled process window adversely affecting wafer yields.

One major requal cycle time component is the disposition process of mask inspections containing hundreds of defects. Not only is precious non-productive time extended by reviewing hundreds of potentially yield-limiting detections, each additional classification increases the risk of manual review techniques accidentally passing real yield limiting defects. Even assuming all defects of interest are flagged by operators, how can any person's judgment be confident regarding lithographic impact of such defects? The time reticles spend away from scanners combined with potential yield loss due to lithographic uncertainty presents significant cycle time loss and increased production costs

Fortunately, a software program has been developed which automates defect classification with simulated printability measurement greatly reducing requal cycle time and improving overall disposition accuracy. This product, called ADAS (Auto Defect Analysis System), has been tested in both engineering and high-volume production environments with very successful results. In this paper, data is presented supporting significant reduction for costly wafer print checks, improved inspection area productivity, and minimized risk of misclassified yield limiting defects.

Keywords: simulation, inspection, photomask, reticle, defect, disposition, requalification

1. INTRODUCTION

Though a defect on a wafer can sometimes cause a bad die, a defect on a critical layer reticle can repeat in every die, so that whole wafers, in fact a stream of wafers, can all be ruined by a single defect on that reticle. The detection of this kind of problem, and thereafter confirming the exact cause, can take long enough for that stream of ruined wafers to be long and expensive. The many problems and expenses this causes for the fab drive a careful, deliberate process for minimizing the probability that reticles cause repeating wafer defects - reticle requalification.

Reticle requalification has come to have a surprisingly significant impact on several key metrics in a wafer fab and this impact has grown as reticle costs and manufacturing time have gone up, inspection equipment costs have increased, and especially as relevant defect sizes have gotten smaller. Along with these causal factors, interaction and optical physics effects at recent and coming nodes make classification more difficult and its accuracy more critical.

As the limits are pushed to achieve the smaller features in current and coming nodes, the number of defects, and potential defects, goes up - just as the exact printability of these potential defects becomes harder to determine. One strategy is to have backup reticles for these critical layers - but given tight process windows, switching to them brings it's own costs and potential yield issues.

It's easy to project this combination becoming more difficult, not easier - and existing fabs are already pushing their equipment set to their limits. Masks can languish in this “requal” phase for extended, non-productive periods of time. Because this “requal” time is challenging to control, shipping schedules can slip when wafer lots are put on hold until the master reticle is returned to production, or wafer yields can take a hit due to substituted backup critical layer reticles (and the associated scramble to reacquire a process window).

At the heart of this “requal” challenge is the disposition of mask inspections containing hundreds of defects - and the ever-present risk of massive downside if the manual review techniques accidentally pass real yield limiting defects. Further, two types of risk arise in this manual process - was the defect missed? But also - at the margin, will this borderline defect print, or not print? This truly difficult dilemma leads to everyone involved being extremely careful and cautious, so longer times and higher costs result, and are expected to get worse. A powerful tool to aid in this process would bring great value.

This opportunity to bring great value drives the development of a software program to automate defect classification with simulated printability measurement - and thereby reduce requal cycle time and improve disposition accuracy. The product is ADAS (Auto Defect Analysis System), and has shown promise in engineering and high-volume production environments.

Having introduced the issues and opportunity in requal, it is important to be clear on the challenges - this is not an easy or risk-free undertaking.

1. RETICLE REQUALIFICATION CHALLENGES

Over time as reticles are used in production, they receive a cumulative quantity of energy as part of the exposure process. This adds another source of risk of defect origination, biofilms (along with ESD, haze, cleaning damage, etc.) This energy must be tracked, and as the biofilm, and other risks increase, critical reticles must be taken out of production and inspected, contributing to scanner production loss.

In an established fab, with an existing equipment set and a given number of reticle inspection tools, these factors lead to compromise, and potentially lost wafer yield and productivity. The possibility of positively impacting yield for the fab exists if a solution can be found, and inversely the risk of decreased yield grows if a solution is not found.

The good news is that after extensive and in-depth review of months of detailed data for this experiment, operators were found to do a remarkably good job at this tedious and high risk task. Having problems numbering only in the dozens out of over a quarter million defects, when a significant fraction of those many thousands involve extremely fine distinctions, shows the dedication of the (often over-taxed) operators in this area.

But even that tiny fraction of barely discernible mistakes becomes significant when the aforementioned greater cost impacts come into play - and very much worth reducing. In particular, operators occasionally misclassify real defects as false. In the worst case, this increases the chance of killer wafer defects. If a dozen detection machines cost an eighth of a billion dollars, small losses in efficiency of their use are still big numbers, the value of reducing these losses can be a significant number.

Often even more significant is the value, particularly at critical points in the cycle, of shortening time to market and maximizing yield on key products. Knowing that certain errors, like the aforementioned miss-classified killer defects, can lead to printed wafers with problems, and therefore painfully expensive lost production and / or time consuming rework (or disastrous missed deadlines), finding improvements in this process and it's metrics becomes paramount.

What about using AIMS to evaluate the defect's printability? Though a powerful tool, most fabs are not able to send masks to an (expensive, slow) AIMS tool in an economical, convenient time frame.

Two opportunities become clear from these challenges - if one could accomplish what the AIMS tools do in a more local, feasible, and practical way, that would bring great value to a fab. And if that were achieved, and wisely integrated into existing fab process flows to reduce the degree of the aforementioned compromises, even further benefit becomes possible.

Finally, as even smaller features arrive in production at coming nodes, if a solution is not found, the reticle "requal" process (and expected greater number of more difficult inspections / dispositions) could require significant investment to keep from compromising yield beyond workable levels for the fab.

2. AUTOMATED DEFECT CLASSIFICATION SYSTEM

Automated Defect Analysis System (ADAS) automatically classifies all defects in a given reticle inspection. It reads inspections from any reticle inspection tool – KLA-Tencor, Lasertec, AMAT and NuFlare. ADAS has been in continuous development for the last 10 years, and it's being used in production in multiple sites around the world.

The software is run on a server computer in the fab, connected to the fab tool network. It connects to each inspection machine and automatically analyzes new inspections. It saves the inspections onto its local hard drive where operators and engineers can access them remotely (see figure 2.1).

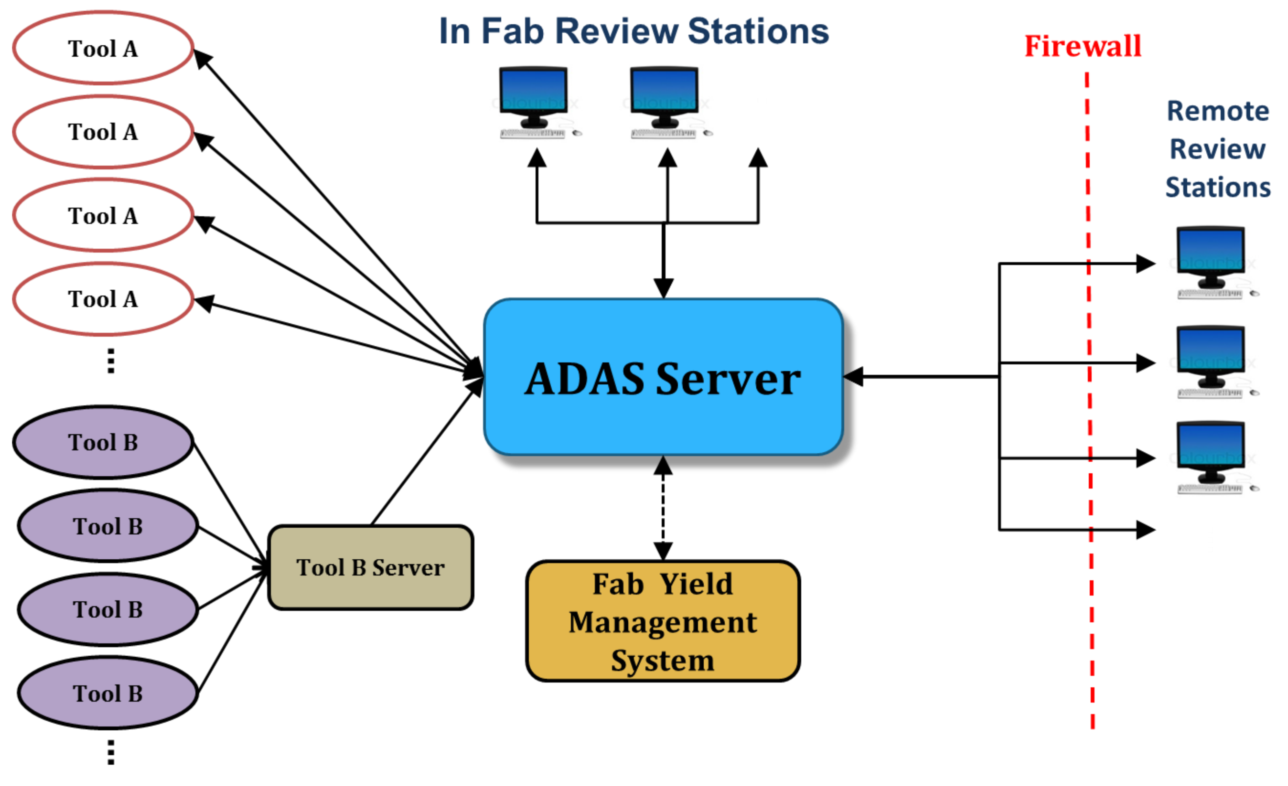

Figure 2.1 – Typical ADAS data flow

ADAS analyzes defects quickly because its method is simple (Figure 2,.2). First, the inspection data and images are imported from the inspection machine database. After alignment and intensity correction, the test images (transmitted and reflected) are subtracted from the reference images, creating a difference image. The location of the defect is determined by finding the area of greatest difference in the difference images. The size of the defect is then measured by calculating the transmitted and reflected intensity differences, and the CD error if applicable. The defect's proximity to the nearest feature edge is also measured (if applicable). Then all those data points (along with a few other, more specific metrics) are used to categorize the defect into one of the reticle inspection area's defect classifications. Generally, those classifications consist of False, White Spot, Focus error, Missing AR, Contam on Dark, Contam on Clear, Contam on Pattern or Edge, Particle, Pinhole, and ESD.

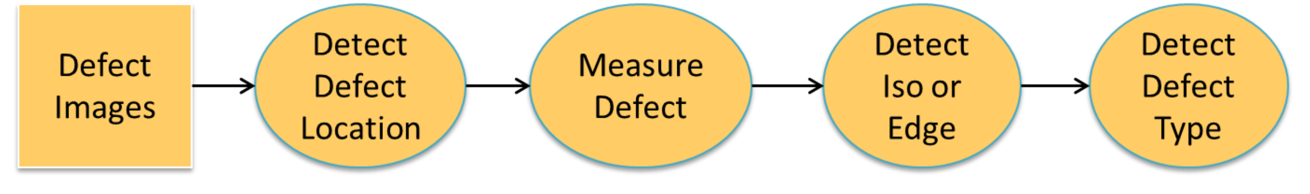

Figure 2.2

There are some other specialized classifications used by the reticle inspection areas of different fabs, but the most important part of classification, and the part that this paper concentrates on, is whether a defect passes or fails – whether it's a real or false defect.

3. EXPERIMENTAL

Four metrics were assessed in this study: Classification accuracy (absolute, and vs. operator), overall inspection machine throughput, repeating wafer defect rate, and simulation accuracy (vs. AIMS). These metrics were assessed over all inspection machines in the reticle inspection area, including machines from several different vendors. A total of 18 months of inspections were included – 9 months before the introduction of ADAS into the production flow, and 9 months after. The pre-ADAS inspection data was taken from the archives on the inspection computer hard drives. With the exception of simulation accuracy, all tests were done with pre-ADAS results as a reference. The simulation accuracy tests were done with AIMS results as the reference. Overall, this study includes the data from over 16,000 reticle inspections.

4. RESULTS

4.1 Defect Classification Results

ADAS software has the ability to analyze thousands of past inspections and report the statistics of how the defects were classified by operators compared to the classification results from ADAS. Figure 4.1.1 below shows the results of analyzing over 16,000 reticle inspections that resulted in over 300,000 defects. The data has been broken down into two main categories – Real and False. Columns one and two show that the inspection tool operators classified 31% of the defects as real and the remaining 69% as false. ADAS automatically classified the same data as 47% real and 53% false shown in columns three and four. Column five shows the number of defects called real by ADAS (16%), but called false by operators, while column six shows the percentage of defects called real by operators (0.3%) but, false by ADAS.

This last category "Found by operators" is critical since if an automatic defect classification system misclassified (passes) Real, printing defects as False, it might create more problems than it solves. Fortunately it will be shown that ADAS never did this in the many thousands of calls made in this study. The benefit of this consistent good performance will be seen as the system's results in real production are examined below. This data will be examined in more detail in the Figures below.

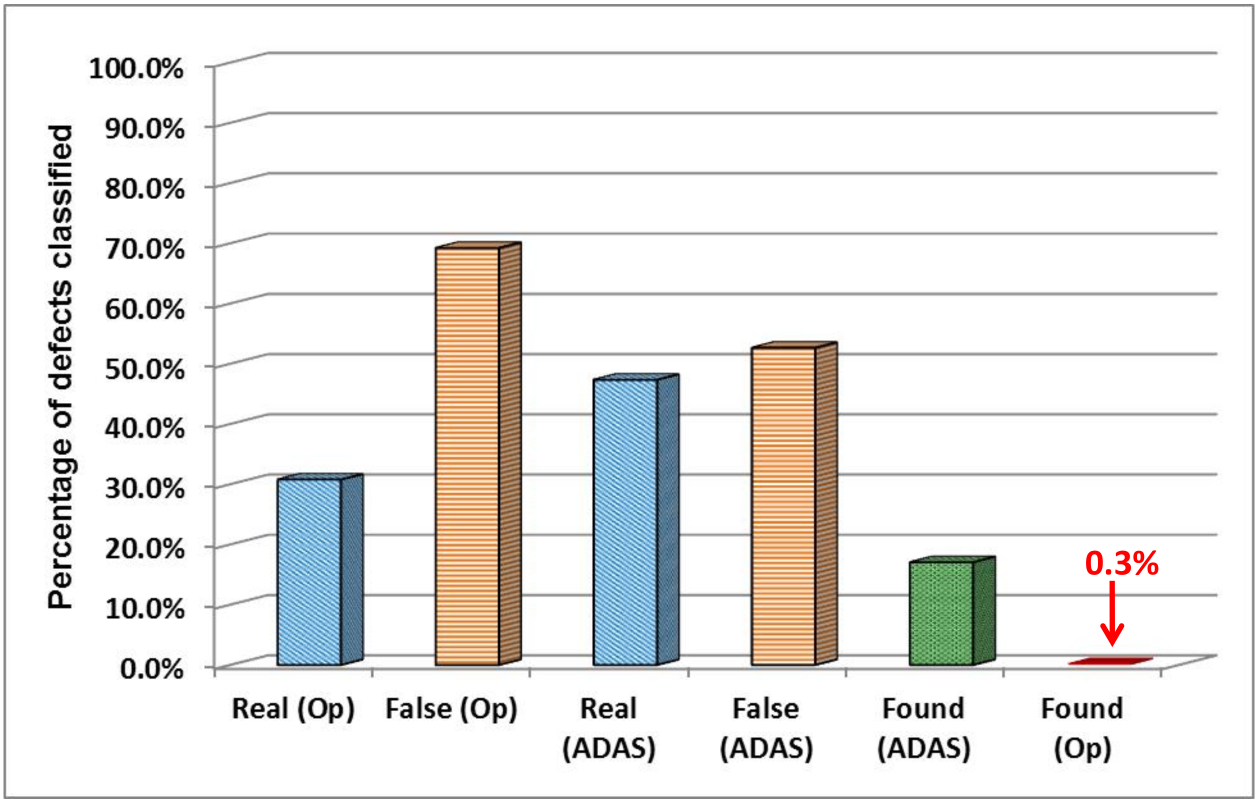

Figure 4.1.1 - Summation of operator defect classifications versus ADAS

Every defect that was “Found by operator” was examined manually in order to ascertain if ADAS actually misclassified any real critical defects as false defects. Figure 4.1.1 shows results from a batch of defect data over time that originally was only classified by operators, and those results are the first two columns.

The same defect data images were subsequently analyzed by the ADAS system, and the two middle columns show its results. ADAS is set more conservatively, and so classified more defects as Real. There are a significant number of defects that an operator's judgment can find as False, but without that the ADAS system is set to find as Real. This difference is reflected in the fifth column, the defects for which ADAS is more conservative than the operators - they are not clearly False, so ADAS keeps them as Real.

Finally, the sixth column shows the tiny number of defects that operators thought were Real, but ADAS called False. Since operators were found to be largely correct, it is very promising that this sixth column is very small. And since there are a few operator misclassifications, even this small number of disagreements with operators overstates ADAS's error rate.

But it's the fourth column that shows the opportunity (once you see that the sixth is very small) - ADAS has dramatically reduced the defects needing review by an operator.

Originally the operators had to weed through a huge number of False defect images, column two, that actually didn't have a problem (along with column one, of course, the Real defects that are the object of the inspection process). After ADAS does an automated first cut, the non-Real defects that operators have to review is only column five (15% as compared to 68% from column two before).

This is the major benefit that ADAS creates directly, and because operators and equipment are more available, there are two follow-on benefits. The shorter disposition process for critical layer masks means the requal cycle times are much less likely to hold up production in the wafer fab. And the automatic reduction of the number of defects to be reviewed by operators gives them a better chance to use their judgment on the close calls, while removing the risk of simple oversights due to fatigue.

Examples of such errors by operators, that become opportunities for improvement through using ADAS, will be illustrated next.

Figure 4.1.2 shows a clearly False defect that operators classified as a Pinhole, but ADAS correctly classified as a white spot. Figure 4.1.3 shows a False defect that operators called contamination, but ADAS again correctly classified false as well.

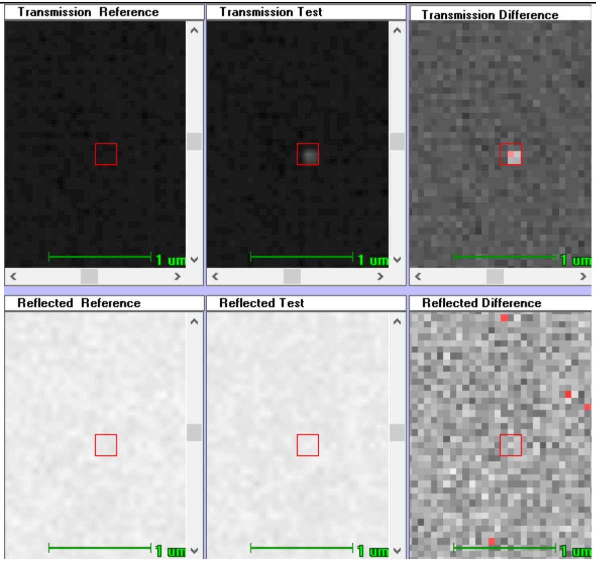

Figure 4.1.2 – False defect (white spot) classified as a pinhole by operator

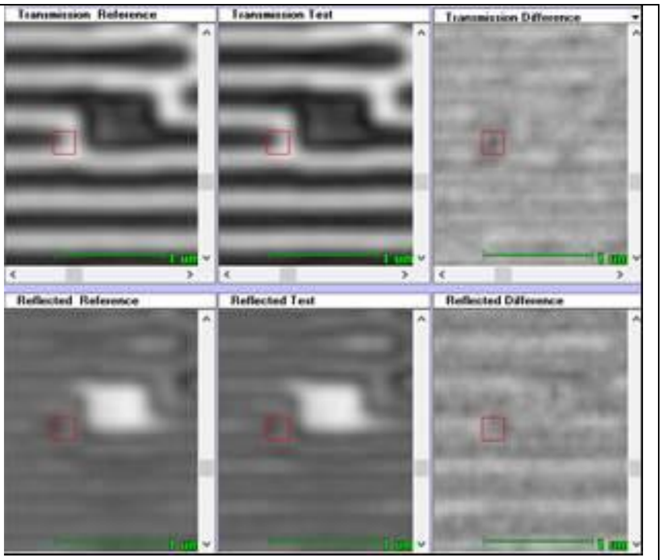

Figure 4.1.3 – False defect called contamination by operator

Figure 4.1.4 shows an example of real contamination, on chrome, that operators classified as False, and Figure 4.1.5 is another example of real contamination that operators called False (note in both cases the Transmission Difference does not show the defect, but the Reflected Difference clearly does).

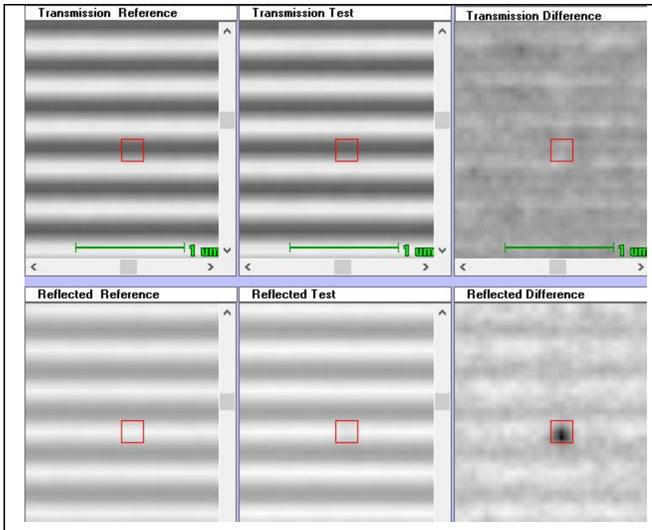

Figure 4.1.4 – Real contamination on chrome found by ADAS called false by operator

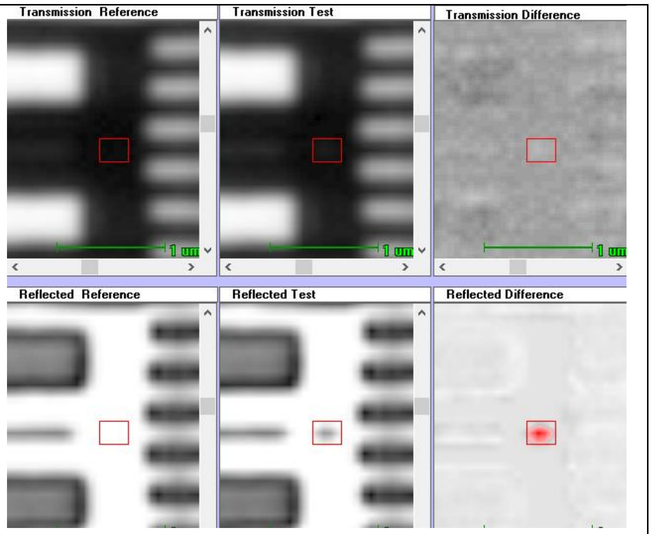

Figure 4.1.5 – Real contamination on chrome found by ADAS called false by operator

While these misclassifications are not catastrophic (they would not immediately print on wafers), they illustrate the advantage of ADAS using an automated process to take care of these categories, freeing the operators to work on other ones and avoid these mistakes. Further, it is better to correctly classify even non-printing defects so that subsequent inspections can take them into account - extra attention can be given to these areas, knowing they can grow or move over time.

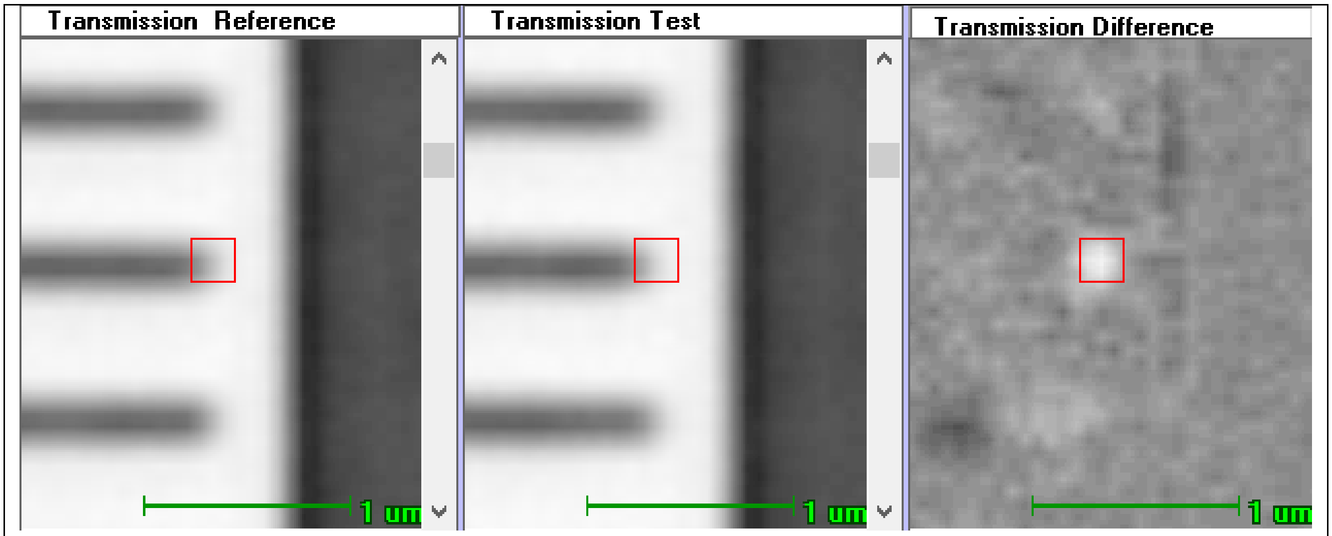

Figure 4.1.6 – Real line-end shortening defect chrome found by ADAS called false by operator

Now in Figure 4.1.6, we see the more alarming case - a Real defect that very well might print on wafers, that operators incorrectly called False. Such line shortening defects can be catastrophic in the fab if they are in critical locations, and finding a way to lower this risk is of great benefit. ADAS did not miss any such defect calls in the over 300,000 defects examined.

This is a key point to consider - ADAS did not miss any Real, critical defects thereby saving operators, and the whole fab, from the severe risk they entail. The consequences of this improvement contribute to the success in improved metrics that will be seen below.

4.2 Simulation Results

In Figure 4.2.1 we see results from 17 individual production reticle defects from different masks/layers that were sent to a physical AIMS tool for analysis compared to the same defects measured using the ADAS defect simulator. The defects were arranged from the smallest to largest percentage CD error as predicted by AIMS.

Two key points can be seen in this figure - first, ADAS is always conservative in giving the same or slightly greater percentage line width change, it never under-estimated the risk by more than 0.5%. And secondly, in the cases under 10%, ADAS was very close to the AIMS results, versus the above 10% cases where ADAS was higher in some cases - but because anything over 10% requires pellicle removal anyway, accuracy for these defects is much less critical.

In the important under 10% cases, ADAS was proven to be very accurate and slightly conservative, as required in the frequent case where AIMS is not available or inconvenient to use.

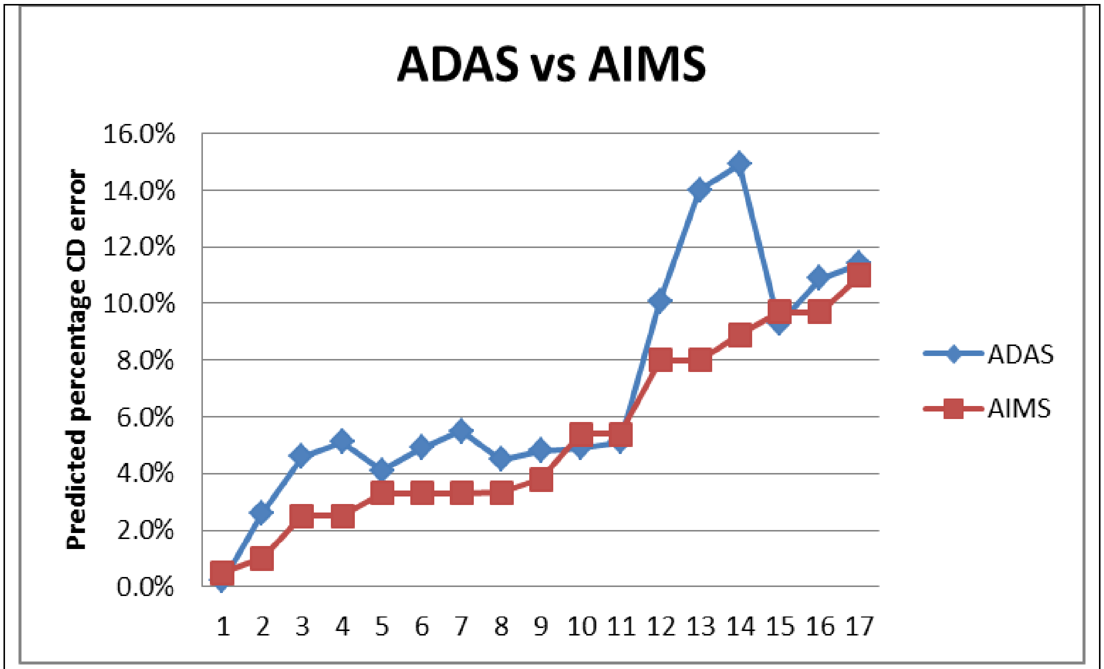

Figure 4.2.1 -

Figure 4.2.2 shows the same data represented in a scatter chart.

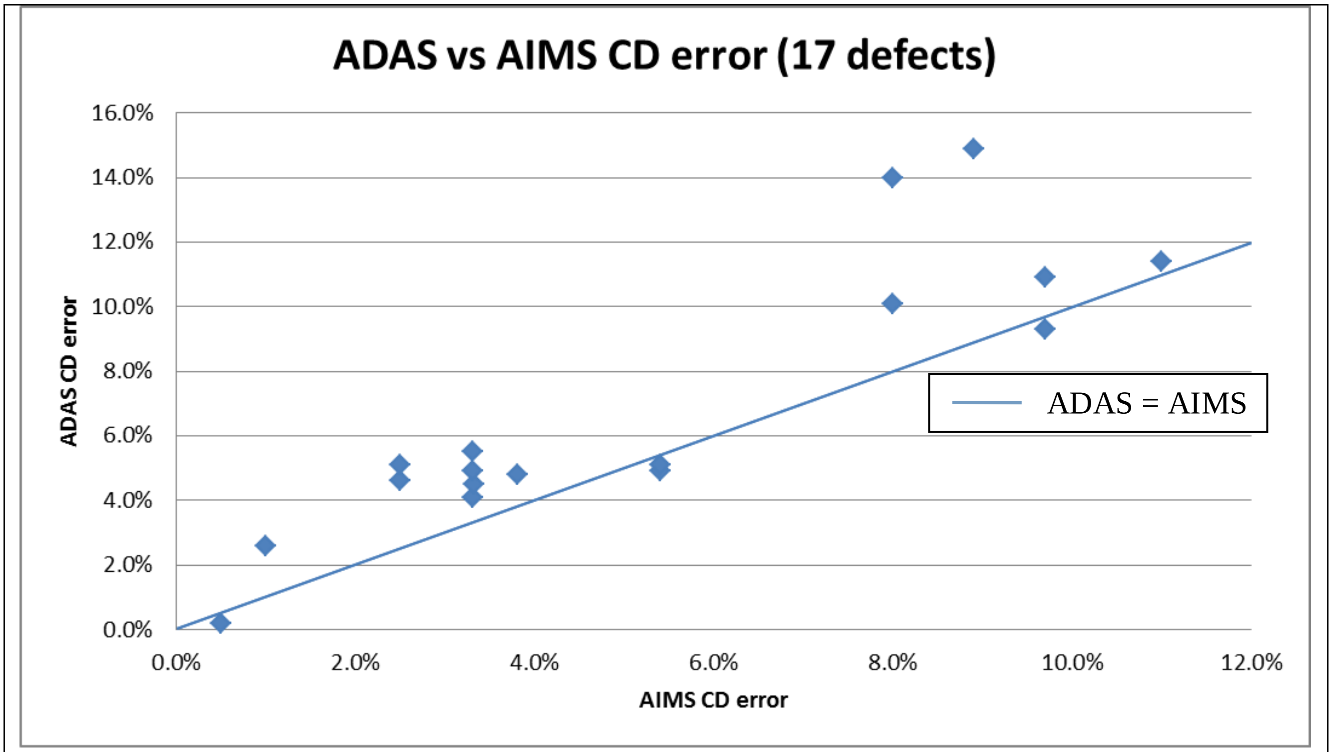

Figure 4.2.2 – ADAS versus AIMS percentage CD error simulation on 17 naturally occurring defects

4.3 Inspection Tool Throughput

Figure 4.3.1 shows the difference in real outcomes, before (left side) versus after (right side) implementation of ADAS in production. The direct benefit of ADAS on inspection tool throughtput is clear and trending higher as operators adapt to its use. An improvement of 8.6% can be seen, and the benefit is trending higher over time with more experience.

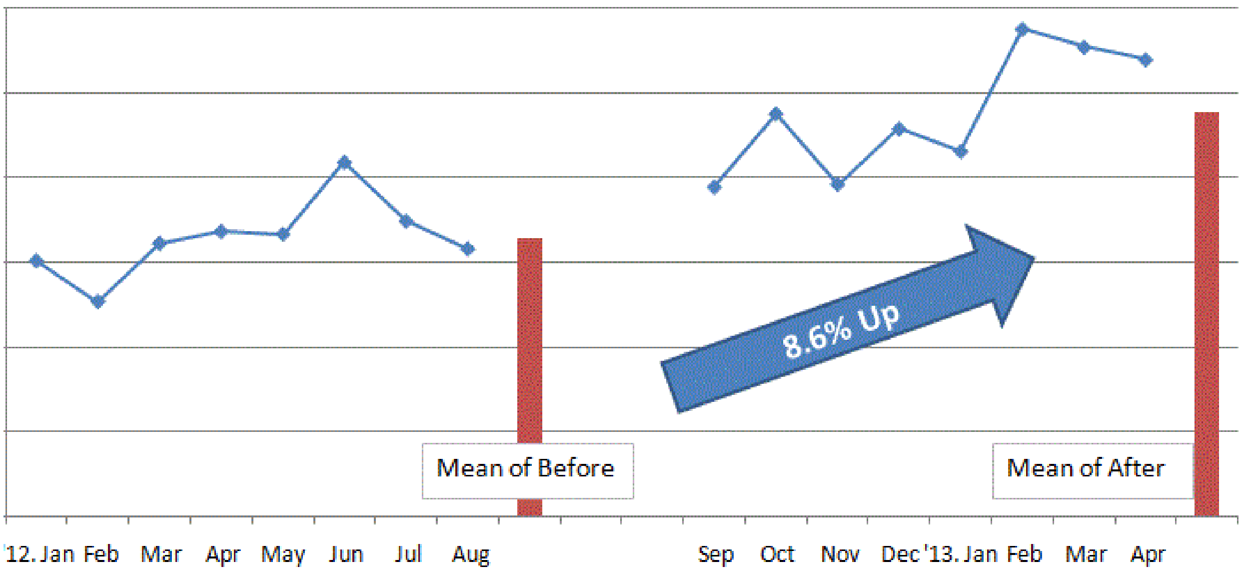

Figure 4.3.1 – Average daily reticle inspection tool throughput before and after ADAS introduction

4.4 Wafer Repeating Defect Rates

In Figure 4.4.1 the even more important result in the wafer fab is shown - ADAS has reduced wafer repeating defects by over 12% as compared to the level before its introduction. This significant benefit shows up in the critical wafer metric, reduced losses due to defects, and shows the substantial benefit of ADAS in the fab.

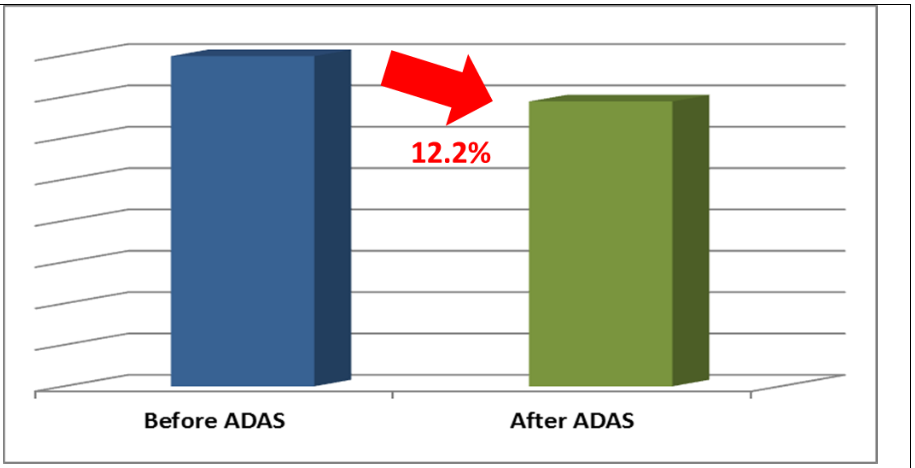

Figure 4.4.1 Average wafer repeating defects before and after ADAS introduction

5. SUMMARY

In this study, we have presented data resulting from the analysis of over 16,000 reticle inspections spanning 9 months before and 9 months after the introduction of an Automated Defect Analysis System (ADAS). The system analyzed over 300,000 defects matching well with operator defect classifications

Since ADAS has been added to production:

- Operators spend less time reviewing defects
- Reticle inspection tools average daily throughput has improved 8.6%
- Initial defect simulation matches well with AIMS
- Repeating wafer defects have decreased 12.2%

These data clearly show that ADAS has provided a significant improvement to the efficiency of the reticle requalification process.

6. FUTURE WORK

We plan to continue studying the effects that ADAS has on the wafer fab reticle requalification area by measuring ADAS's simulation capabilities on 20nm node lithography including free form illumination sources. We also plan to expand the ADAS interface to yield management systems and report on the benefits provided.