An Automated Mask Defect Analysis System for Increasing Mask Shop Productivity

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ABSTRACT

The detection, classification and disposition of defects is an important function that commands significant resources in mask making. Current processes use manual evaluation of defects, which is slow, subject to errors, and provides sparse data for process improvement. The automated defect analysis software described here reads inspection reports from mask inspection tools, classifies each defect, and measures both its size and printability. It combines and compares data from multiple inspections to provide critical process development data. Data from 144 masks is presented showing that the system missed no critical defects found by operators. These inspections also demonstrated numerous occasions for improved classifications compared to that given by the operators. This capability gives improved disposition, an easy path to using simulator based printability for disposition, and significant improvements in mask yield.

1. INTRODUCTION

Most photomask lifecycle costs are expended during process development, while yield is low and engineering costs are high. Defects provide much of the data that indicates what process improvement is needed. Yet current mask inspection processes leave much of the available process information from each mask unused because of manual classification and measurement. This paper discusses a new paradigm for mask defect analysis, and a software tool, the ADAS, which implements it. The new paradigm calls for 1) Complete and accurate classification and measurement of all defects from all inspections, 2) Separate measurements of each defect for process data and disposition, 3) Detection and analysis of all unusual defects and 4) Bringing all defect measurements together on one tool for review and analysis.

The ADAS tool shows great promise for accelerating photomask process development, increasing yield, and improving turn-around on production masks.

This paper discusses defect analysis, based on actual defects reported by inspection tools. It does not discuss any issues of inspection tool capability or sensitivity.

2. CURRENT DEFECT ANALYSIS METHODS

Photomask defect analysis in mask shops and wafer fabs normally starts with the mask inspection. This produces an inspection report that contains defect locations, and in newer tools, defect images. Most defects are then reviewed and classified by an operator. Inspection tools provide significant help for that disposition process, but for each defect it is the operator who makes the decision about the defect type, and whether it needs to be repaired.

A new “100% simulation” method was introduced by Intel in 2002 (2,3) which uses aerial image simulation to determine each defect’s printability, and therefore its disposition. Other companies offer this method as well (4). This 100% simulation method is not discussed further because it does not provide critical process analysis data, and because little production data is available.

3. THE NEED FOR A NEW PARADIGM

The current method of mask inspection can be described as “manual classification”. This method causes problems on process development masks that frequently contain thousands of defects. One problem is that process analysis and the inspection tool must wait for the operator to complete. Another problem is that manual classification of an inspection with hundreds or thousands of defects is usually considered only moderately accurate. This moderate accuracy has been tolerable because the defect classifications are used statistically—the defects are not usually repaired. However, unusual defects are frequently missed in these inspections because they are hidden in the mass of small defects.

Manual classification is seldom a problem on mature masks because those masks have few detectable defects, so the operator attention level remains high and manual classification has a low risk of error. Thus automated classification will have little impact on mature processes.

The biggest problem is with masks in early production. Current procedures in most mask shops are excellent, and printable defects are almost never shipped to customers. The cost of manual disposition on these masks is the high level of management attention (worry) required to attain this required level of quality.

Current defect analysis procedures were developed primarily to deliver “defect free masks”, where the ideal was to produce and deliver masks with no detectable defects. This procedure is characterized by 1) Manual classification, measurement, and disposition and 2) A single classification of each defect combining the information required for repair, fab customers, and process engineering into one of typically 16 categories. This often leads to strategies where inspection tool sensitivity is reduced so that a mask can be shown to be defect-free, and so that there are few enough defects that an operator can reliably classify them.

The current method was developed when there was one write-develop-etch per mask. Photomasks are getting more complicated with the adoption of phase shift technologies, and the patterns are becoming more difficult to image, due to RET techniques.

The result is that sub-spec defects from early production stages frequently become critical defects in later stages. Mask shops are increasingly adding inspections to their processes and these inspections now need to provide information about a range of defect types that previously did not effect the customer, and therefore have not shown up in the classification scheme that was designed primarily to guide disposition and repair.

4. THE NEW PARADIGM: “COMPLETE DEFECT ANALYSIS”

The new “Complete Defect Analysis” paradigm is based on the premise that all detected defects provide data that is vital for process development. Improving the speed, quality, completeness, and reporting of defect analysis will accelerate process development and improve overall mask quality. The new paradigm has four parts: 1) Analyze accurately all defects in all inspections, 2) Perform two different measurements on each defect—one for disposition and one for process analysis, 3) Detect and analyze every unusual defect, 4) Collect all defect data in one place for review and analysis.

There are two key benefits to analyzing every defect. Thorough analysis provides more accurate data for process improvement, and it allows faster response to that data because there is less discussion and hesitation related to wondering about the defects that were not (accurately) analyzed. Thorough analysis is now possible because of improved algorithms and faster computers.

Performing separate measurements for disposition and process is critical for the new paradigm. Disposition decisions are intended to correlate to the printability of a defect. Thus they generally tell more about the pattern around the defect than about the defect. Process analysis requires information about the defect itself, especially under-spec defects which are usually left unclassified or misclassified in current practice. A consequence of performing dual measurements is the production of dual classifications—one for disposition and one for process analysis.

These dual classifications must be reported and recorded, and that requires a new inspection report file type. Fab customers are not affected by dual measurements. They continue to receive classifications related to printability as they have in the past. However defect analysis and process engineers can now have consistent detailed data on every defect.

In addition, the quality of the defect data for process analysis does not change depending on the training of the operator or the disposition specs of a particular mask.

Analysis of unusual defects is important because these defects typically indicate important process problems. Automatic defect classification and measurement allows certainty that all unusual defects will be detected and reviewed. Current analysis methods, using manual classification, commonly force unusual defects into some existing category, and frequently are not reviewed by a process engineer. This is especially true when a defect is below specifications for repair. Analysis of unusual defects usually starts with detailed examination of images from the inspection tool, and frequently leads to examination with other tools, such as AIMS, SEM, or AFM, leading to the fourth part of the new paradigm.

The increased use of additional defect measurement and analysis tools has led to the problem that images and data from each tool come in different formats, and require separate tools to review. The development of improved processes, both in the mask shop and in the combined system of the mask shop and wafer fab depends on accurate data from multiple sources. Therefore collecting the images from all inspections and all tools and making them viewable and comparable with one tool is important. A useful side effect of this is that wafer fabs can have complete data which allows them to improve their mask defect specs, based on detailed analysis of which mask defects cause real problems on the wafer.

5. ADAS IMPLEMENTATION OF THE “COMPLETE DEFECT ANALYSIS” PARADIGM

The AVI ADAS (Automated Defect Analysis System) software runs on a networked Windows computer. It takes inspection reports from inspection tools, computes classifications and sizes of each defect, provides a large tool set for interactive analysis of unusual defects, and writes a range of reports to other tools, customers, and process engineers (fig 1). The automatic classification and measurement is fast, allowing 100% analysis of inspections with up to 10,000 defects in less than one minute.

In addition to fast analysis of individual inspections, the ADAS provides the ability to read and display multiple inspections, and images from multiple sources at the same time. This allows a user to compare defect locations, distributions, types and sizes from multiple inspections. It also allows images from other tools to be compared so that unusual defects can be thoroughly understood.

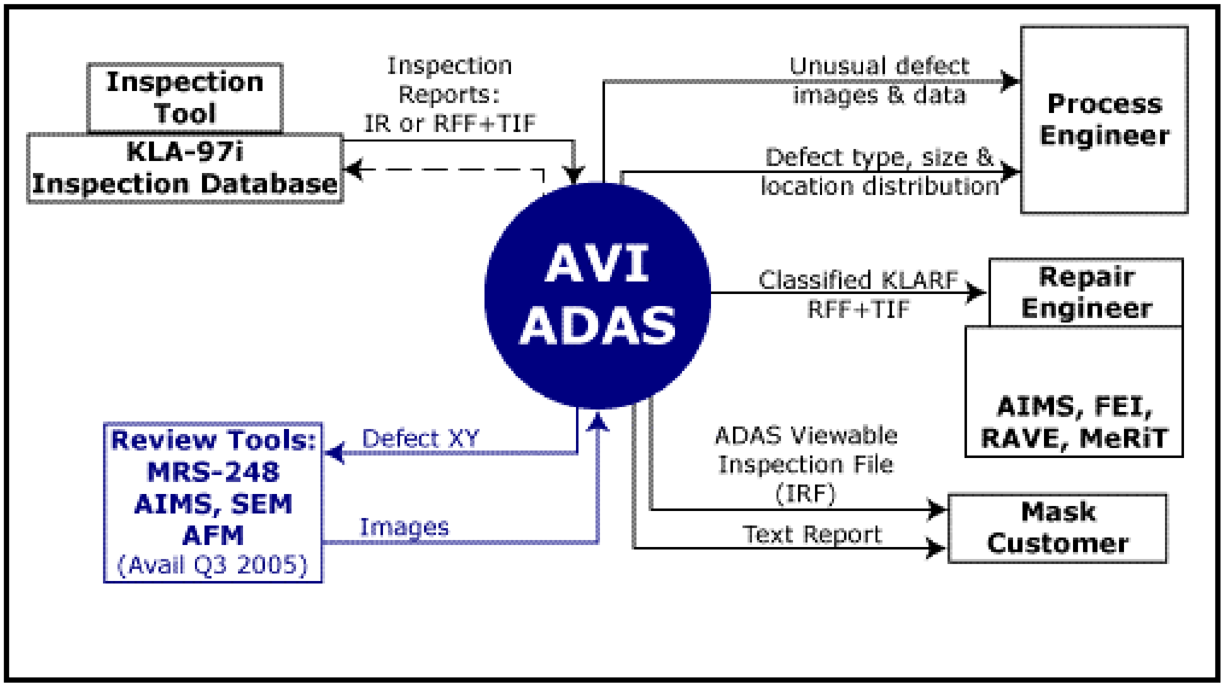


Figure 1: ADAS External Data Interfaces. Inspection reports read from KLA97i to ADAS. Classified inspection reports written to repair tools and AIMS. Printed inspection reports written to customers. Process analysis report (Excel) sent to process engineers

Implementation of the last part of the paradigm, bringing all defect data to one place for review and analysis, is accomplished by use of an extensible public format inspection file (called IRF format). This file can contain multiple inspections as well as images from multiple sources. This allows it to become a vehicle for transferring mask data from mask blank maker to mask shop and mask shop to fab.

6. DEFECT CLASSIFICATION, SIMULATION AND DISPOSITION

The classification rules used are similar to the rules an operator uses, based on images saved by the inspection tool. The ADAS classifications are generally identical to an attentive operator's classifications. All images are used, transmitted and reflected, test and reference, as available. A classification by these algorithms provides more certainty than manual classifications, especially on hard-to-see small defects.

The defect type determines the defect sizing method. For example, chrome defects are measured using the flux-area technique (1), which gives an "effective size" that correspond well to a defect's printability, while chrome on MOSI defects are measured by the area affected.

Defect printability is measured from an aerial image simulation: CD error is measured when possible, on lines and contacts, and edge position error (EPE) is used on other defects. EPE is calculated as the maximum position error between an edge in the test image and the corresponding point in the reference image. The reference image is either provided by the inspection tool or generated from similar patterns in the test image.

Isolated defects require a different printability method because there is no edge to compare. Their printability is measured as the fraction of printable contrast. A defect that gives just enough contrast in the simulation image to be printed is called 100%, and a defect that gives half that contrast is called "50% printable contrast".

The ADAS simulation is not a replacement for AIMS because the source image typically is taken at a different wavelength than the stepper, and there is no information to allow the simulator to estimate the phase and absorption effects of changing to the stepper wavelength. It is commonly agreed that the AIMS can never be fully replaced by simulation for this reason. However ADAS does reduce the number of defects that require AIMS review by reducing the printability uncertainty.

Disposition is accomplished by setting size limits on each defect type. The number of specifications may range from one, which is used for all defects, to thirteen, specifying sizes for each printable type of defect. This allows the disposition algorithm to satisfy the needs of existing mask processes as well as new ones.

The classification system allows initial use of current classes, and smooth development of more sophisticated specification systems as processes are developed and approved. It also enables use of standard classification names between mask shop and fab because the class names and meanings can be customized for any customer.

Accurate and complete reports are customized for the user. Disposition reports are sorted by defect severity so that sub-spec defects are all at the end of the list. Reports include a printability measure for reference, even when there is no printability specification given.

7. COMPLETE DEFECT ANALYSIS IMPROVES PROCESS DEVELOPMENT

Complete and integrated defect analysis provides numerous opportunities for mask shops to accelerate process development, reduce mask rewrites, and produce higher quality masks. Two requirements for rapid process development are accurate data and visualization tools that let engineers see what might be causing quality problems. Although the techniques described here can generally be performed in leading mask shops, the time required to use those tools causes them to be used infrequently.

The ADAS combines complete and accurate defect analysis with speed and simultaneous access to multiple inspections to provide very effective data visualization tools.

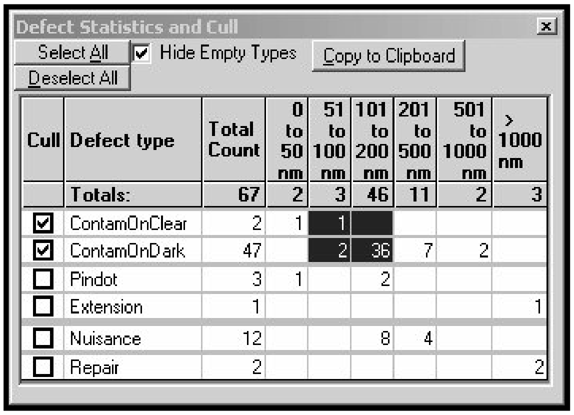
Complete defect analysis is performed on four scales: individual defects, whole inspections, all inspections on a mask, and all inspections for a process. The analysis at these levels includes the following:

Individual defects are measured separately for process information and printability / disposition size. Manual measurements of pixel values, contrast, intensity profile, and CD are also provided.

Whole inspection analysis starts with measurement of all defects as described above, and includes sorting the defects according to severity, and mapping their location, severity, and type. This process insures that all unusual defects are detected and analyzed.

Whole mask analysis includes the above capabilities plus the comparison of defects from each inspection of the mask, frequently including mask blanks at the start, and qualification / requalification inspections at the end. The multiple inspections allow display of new defects, larger, and changed defects, both in table form, and in position maps that show where problems are occurring on the mask.

Whole process analysis is similar to whole mask analysis. Process problems are distinguished from pattern issues by combining and comparing inspections of different masks and noticing the distribution of defects by type, size, and location. Figure 2 shows a table displaying the defect type and size distributions for the combination of two defects. Figure 3 is a development defect map showing the location of above-spec defects.



☑ Hide Empty Types

Cull	Defect type	Total Count	0 to 50 nm	51 to 100 nm	101 to 200 nm	201 to 500 nm	501 to 1000 nm	> 1000 nm
	Totals:	67	2	3	46	11	2	3
☑	ContamOnClear	2	1	1				
☑	ContamOnDark	47		2	36	7	2	
☐	Pindot	3	1		2			
☐	Extension	1						1
☐	Nuisance	12			8	4		
☐	Repair	2						2

Figure 2: Typical defect statistics screen, showing a range of contamination defects selected for display. Defect types with zero defects are shown as thick lines. The distribution of defect types and sizes are shown in the “totals” column and row. The breakdown of counts by size within each type are displayed in the other cells.

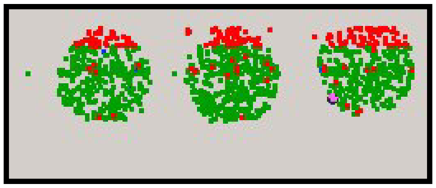
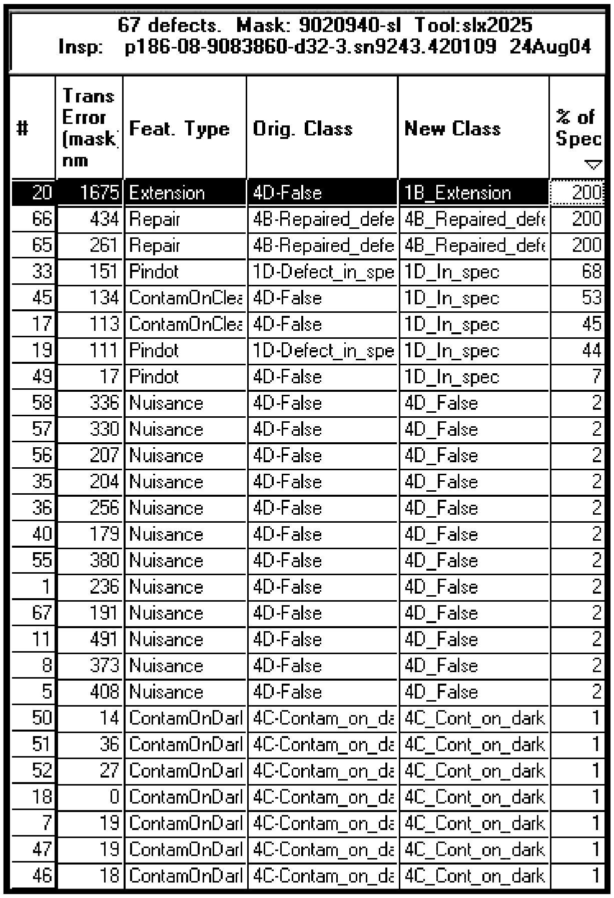


Figure 3: Defect location map showing the distribution of over-spec (red) and under-spec (green) defects.

8. RESULTS

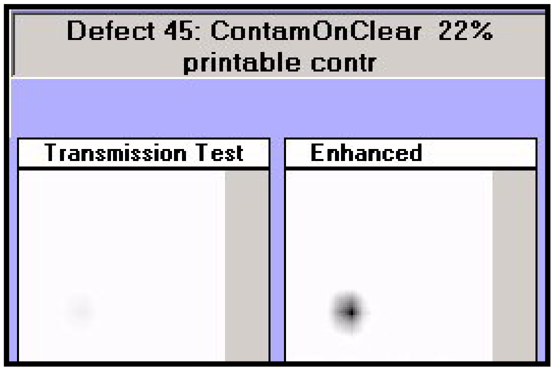
Disposition accuracy was studied with a set of 144 inspections of binary and EPSM masks, containing a total of 17,038 defects that had been previously classified by operators. In this study the ADAS missed no over-spec defects and detected an average of one defect per mask where the classification by the operator could be improved upon by using ADAS.



67 defects. Mask: 9020940-sl Tool:slx2025
Insp: p186-08-9083860-d32-3.sn9243.420109 24Aug04

#	Trans Error (mask nm	Feat. Type	Orig. Class	New Class	% of Spec
20	1675	Extension	4D-False	1B_Extension	200
66	434	Repair	4B-Repaired_defe	4B_Repaired_def	200
65	261	Repair	4B-Repaired_defe	4B_Repaired_def	200
33	151	Pindot	1D-Defect_in_spe	1D_In_spec	68
45	134	ContamOnCle	4D-False	1D_In_spec	53
17	113	ContamOnCle	4D-False	1D_In_spec	45
19	111	Pindot	1D-Defect_in_spe	1D_In_spec	44
49	17	Pindot	4D-False	1D_In_spec	7
58	336	Nuisance	4D-False	4D_False	2
57	330	Nuisance	4D-False	4D_False	2
56	207	Nuisance	4D-False	4D_False	2
35	204	Nuisance	4D-False	4D_False	2
36	256	Nuisance	4D-False	4D_False	2
40	179	Nuisance	4D-False	4D_False	2
55	380	Nuisance	4D-False	4D_False	2
1	236	Nuisance	4D-False	4D_False	2
67	191	Nuisance	4D-False	4D_False	2
11	491	Nuisance	4D-False	4D_False	2
8	373	Nuisance	4D-False	4D_False	2
5	408	Nuisance	4D-False	4D_False	2
50	14	ContamOnDar	4C-Contam_on_d	4C_Cont_on_dark	1
51	36	ContamOnDar	4C-Contam_on_d	4C_Cont_on_dark	1
52	27	ContamOnDar	4C-Contam_on_d	4C_Cont_on_dark	1
18	0	ContamOnDar	4C-Contam_on_d	4C_Cont_on_dark	1
7	19	ContamOnDar	4C-Contam_on_d	4C_Cont_on_dark	1
47	19	ContamOnDar	4C-Contam_on_d	4C_Cont_on_dark	1
46	18	ContamOnDar	4C-Contam_on_d	4C_Cont_on_dark	1

Figure 4: Typical defect list sorted by severity. Shows three classification differences between ADAS and original operator decision. First difference is illustrated in fig 3. "Orig. Class" was operator's classification; "New Class" is ADAS classification.



Defect 45: ContamOnClear 22% printable contr

Figure 5: Defect 45 transmission image: normal and enhanced. This was classified by operator as "False" or not visible. ADAS classified it as sub-spec contamination

8.1.1. Defect size accuracy

The ADAS measures transmission image defect size using the flux-area technique described in reference 1. The repeatability has been measured on a VT5491 mask inspected on a KLA SLF tool as 5% of defect size. This repeatability is worse than that observed with the AVI PDMS system because the PDMS generates reference images from the test images by careful analysis, while the ADAS uses the reference image (die to die or die to database), provided by the inspection tool. Due to physical variations in the optics over time the provided reference images vary in focus and light level, causing variations in the result.

9. CONCLUSIONS

The ADAS implementation of the “Complete Defect Analysis” paradigm promises significant cost savings. It does this by accelerating mask process development, increasing overall mask quality, and reducing production mask manufacturing time. “Complete Defect Analysis” significantly increases the value from the defects now being detected in existing and future mask inspection tools.

The ADAS integration of data from multiple sources allows wafer fabs to better understand the sources of defects on masks. This allows fabs to generate and request more efficient defect specifications. It also allows better utilization of defect review tools. This extra data accelerates the entire wafer process development cycle.

Finally, using the same tool for disposition and process development means that process data is available during production, leading to significantly reduced production costs.

10. ACKNOWLEDGEMENTS

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