Defining Defect Specifications to Optimize Photomask Production and Requalification

Peter Fiekowsky

Automated Visual Inspection, Los Altos, California

ABSTRACT

Reducing defect repairs and accelerating defect analysis is becoming more important as the total cost of defect repairs on advanced masks increases. Photomask defect specs based on printability, as measured on AIMS microscopes has been used for years, but the fundamental defect spec is still the defect size, as measured on the photomask, requiring the repair of many unprintable defects.

ADAS, the Automated Defect Analysis System from AVI is now available in most advanced mask shops. It makes the use of pure printability specs, or “Optimal Defect Specs” practical. This software uses advanced algorithms to eliminate false defects caused by approximations in the inspection algorithm, classify each defect, simulate each defect and disposition each defect based on its printability and location.

This paper defines “optimal defect specs”, explains why they are now practical and economic, gives a method of determining them and provides accuracy data.

Keywords: mask inspection, disposition, defect specs, simulation

[1]

1. Introduction

The ITRS roadmap defines a photomask defect as “any unintended mask anomaly that prints or changes a printed image size by 10% or more.” Defect specs are used to define the maximum allowed defect size in a purchased photomask. Optimum defect specs allow the mask maker to repair all defects that would cause device failure, but no others. At the same time these specs minimize expensive disposition steps, such as measurement of a defect on an AIMS microscope or requesting a repair waiver. The result is significantly reduced mask cost, faster delivery of masks, and reduced frequency of cleaning after requalification inspections.

Defect specs used today are based mainly on defect size in the inspection image and enable a human operator to distinguish all possibly printing defects from false and under-spec defects. However it is well known that many defects that are over-spec by existing definitions are not printable. This results in numerous unneeded repairs and requests for waivers—permission to not repair a particular defect. The repairs are sometimes expensive because they may be difficult and because they can cause fatal damage to the mask. The waivers are expensive because of they cause delay in delivery and use of skilled engineers’ time.

The ideal of using printability specs is accepted—even by the ITRS, but it has seemed impossible because of complexity. Previous attempts to rationalize defect disposition have used a) accurate defect measurement (AVI PDMS), b) simulation on every defect (Synopsys iVSS and KLA ProLith), or binned defects (KLA ReviewSmart). None of these products have significantly changed how defect disposition is prescribed or performed. Intel reported several

---

years ago about their internal project for simulation based disposition, but there was no claim that it replaced manual disposition.

This paper breaks down the problem of automated disposition and implementation of optimal defects into its component parts, shows how each part can be solved through automation, and shows how the AVI ADAS software implements this solution. Later papers will discuss the results of implementations now in progress in fabs and mask shops working on 65 and 45 nm technologies.

1.1. Definitions

Optimal defect specs are defined as defect specifications that allow a mask maker to repair all printable defects, and be required to repair any non-printable defects. It is also allows the mask maker to minimize other expensive operations, such as AIMS measurements or other defect review methods.

The *feature type* is defined on the wafer, not on the mask, because it is only the wafer CD (critical dimension) that is important to the end user. Thus the complex and confusing shapes on RET (resolution enhancement techniques) masks do not need to be considered in this discussion. These shapes include OPC (Optical Proximity Correction) serifs and BARF (bridging assist resolution features).

Significant *feature types* are Iso (isolated clear or dark areas without edges near the defect), edge (referring to a defect on the edge of an active device or line), SRAF (sub-resolution assist features), holes (contacts), spots (gates), border (referring to any edge between clear and dark areas that are both more than 3x the minimum feature size on the mask). The border feature definition includes “dummy” or “fill” areas which are not electrically active, but are required for optical or flatness reasons. An SRAF is any dark or clear feature which is too small to print, but is part of the RET design.

When computing printability from a simulator image the *“printing threshold”* must be determined. This is the exposure which gives the desired linewidth or *CD* on the wafer or simulation image, for a known line. The printing threshold is between 0 and 1, and is typically 30% to 15%, with decreasing values for more advanced masks.

Defect printability is measured in three ways, depending on the feature type: CD error or edge position error for edge defects, and percent of printable transmission for isolated defects.

Edge defect “printability” is defined as the “*percent CD error*”. This is computed on line/space features, holes (contacts), and “spots” (gates) as the maximum CD error divided by the measured CD of the feature in a reference image. For complex shapes on the wafer, where there is no clearly defined CD, the printability is computed by determining the maximum EPE (edge position error) between the defect image and the reference image, and then dividing the EPE by the minimum feature size (node or process size) for that mask.

Isolated defects, which cannot be measured as a percent CD error, are measured as *PPT* or “*percent of printable transmission*”. Which is computed for pinholes by dividing the maximum transmission of the defect in the simulator image by the printing threshold for that mask. For example, a pinhole with simulator transmission of 15% on a mask with a printing threshold of 30% has 50% printable transmission. For a pindot or dark contamination the formula is (1-transmission) / (1-threshold).

SRAF features are treated as both edge and iso defects. They don’t print, but they affect the printing of the nearby “*primary*” feature. For that reason the printability of SRAF defects is measured as the maximum of the CD error of the primary feature and the PPT of the SRAF.

1.2. Defect Analysis Requirements For Disposition and Process Control

Confusion often arises from the fact that most inspections produce one set of defect classifications but those classifications are used for three different purposes: a) Pass/fail disposition of defects for repair, b) Disposition over-spec defects for best repair method, AIMS, or scrap the mask if repair is impossible c) provide process data for front-end process control in a mask shop, or for monitoring haze and crystal growth on masks in a fab.

Optimally there should be two sets of classifications: Disposition classifications that tell what to do with the defect, and Process classifications that describe the defect and suggest its cause. ADAS provides both classifications for each defect.

Dispositioning defects for repair requires only that the printability of that defect be known. Determining the best repair method requires knowing the defect size and type and the feature size and type of over-spec defects.

Process control, such as SPC (statistical process control) requires knowing the defect size and type of all defects on all masks, independent of any defect specs. This is true for mask shop front-end process control and management as well as wafer fab progressive defect management.

An automated defect analysis system must provide all three types of information. If process control data is not provided, then manual review of all defects is still required. In that case the partial automation provides very little net value to the inspection tool owner, as previous tools have demonstrated. For this reason the ADAS is designed to compute and report all these results.

This paper discusses only dispositioning defects for repair. A later paper will discuss the results of using ADAS defect analysis for process control both in a mask shops and wafer fabs.

2. Automated Implementation of Optimal Defect Specs

Measuring defect size or printability is not sufficient for automating defect disposition because a large number of defects detected in production mask inspection tools are actually “false” defects, artifacts of the inspection tool. These false defects are mainly due to failures in the hardware and algorithms that generate and align the reference image to the test image. This bad data must be eliminated before the defects or their printability are measured. Occasionally camera defects cause bad pixels in the test image, and these defects must also be detected and eliminated.

Successful automation of defect analysis starts with detection and elimination of these false defects, classification of the feature type based on its shape, classification of the defect type based on its opacity, size and reflectivity, measurement of the defect’s transmission, transformation of the defect and reference image to simulate the stepper optics, and finally measurement of the CD error and / or transmission error in the simulation images.

Defects are finally dispositioned for repair based on some combination of the defect size, transmission, CD error and simulator transmission error, in conjunction with the feature type.

When using optimal (printability) defect specs only the CD error is required. For isolated defects where there is no CD, the ratio of the simulation image transmission to the printable transmission, or “printing threshold”, is used to determine if the defect will print.

#	Method	Action
1	auto	Acquire Defect Images
2	auto / man	Read simulator conditions and defect specs
3	auto	Identify & eliminate false defects (image errors from inspection tool)
4	auto	Determine feature type
5	auto	Determine defect type
6	auto	Measure defect size and transmission error in mask image
7	auto	Simulate stepper optics in defect and reference images
8	auto	Measure CD error and transmission error in simulator images
9	auto	Disposition defect according to measurements and defect specs
10	manual	Disposition over-spec defects for rework, repair method, or AIMS

Figure 1: Steps in automatic defect analysis

Eliminating false defects is the most critical and difficult part of the process because of the range of causes of false defects. For die-to-die inspections these causes include focus or illumination differences between the test and reference images, warps in the reference image due to alignment, and reversing the reference and defect images. For simultaneous transmitted & reflected inspections the causes include the foregoing plus sharp corners in the image, and for Die-to-Database inspections the causes include the foregoing plus errors in the database-to-image rendering algorithms.

All of these reference image errors must be detected and distinguished from similar looking real defects, such as over-etch. In practice an operator must always be used as a final filter for false defects because each new inspection tool and RET technique generates some new types of false defects.

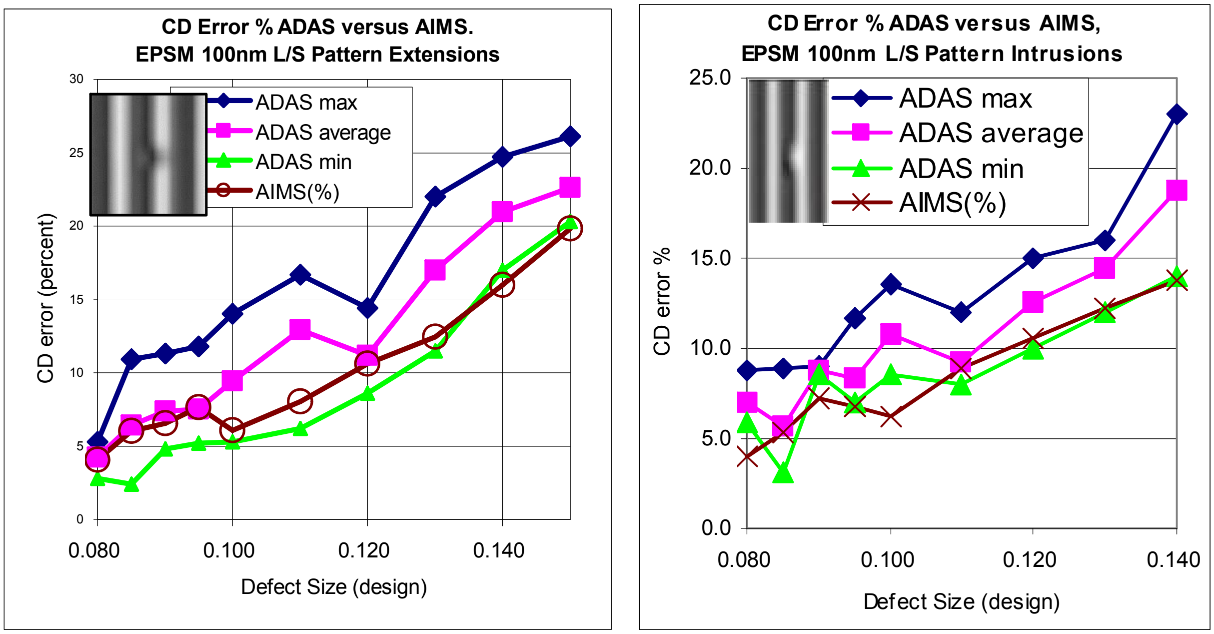
2.1. Efficiency Considerations In Automatic Disposition

All disposition specifications have efficiency implications. Perfect disposition could be achieved by performing test wafer prints on each defect, but that would be too expensive. AIMS analysis could be performed on all defects but that too would be impractical. The goal of optimal defect specs is achieved by using the least expensive tool to analyze or repair each defect. Thus false defects are rejected after discovering that the defect size is approximately zero. The remaining defects have their printability measured after simulation, and the clearly under-spec defects are dismissed. The remaining defects are divided into Over-Spec and Marginal categories. The over-spec defects must be repaired, or waived, commonly because the area is dummy fill.

The marginal defects go through another decision step where the cost of repair is compared to the cost of AIMS. If a defect is determined to be repairable at low risk, then it is repaired. If the repair is considered expensive or risky, then the defect is measured on AIMS, and the defect is judged against the looser AIMS spec.

3. RESULTS

3.1. Simulation Repeatability and Accuracy Compared to AIMS


CD Error % ADAS versus AIMS. EPSM 100nm L/S Pattern Extensions

CD Error % ADAS versus AIMS, EPSM 100nm L/S Pattern Intrusions

Figure 2: Test mask extension and intrusion defects in EPSM 100 nm L/S pattern. ADAS & AIMS

A critical measure of the effectiveness of optimal defect specs is the accuracy of the simulation. Figure 2 compares ADAS simulation CD error measurements and AIMS CD error measurements. Ten inspections of the same defects on a line/space test mask were made on a KLA5xx with 125nm pixel size at DNP and analyzed on ADAS.

The ADAS average CD error measurement is about 5% higher than AIMS, providing a margin of safety if the same printability spec is used on both tools. Thus if the AIMS CD error spec is 8%, then the same 8% CD error spec can be safely used with the ADAS simulator. Note that the largest defects that would be repaired in this high MEEF (Mask Error Enhancement Factor) mask would be between 85 and 120 nm. Most of the defects smaller than 110 nm would be shown to be under-spec. This is in comparison to the 70-80 nm spec normally used with this mask node. Clearly a large number of repairs would be avoided.

It is interesting that the noise in the inspection tool images (KLA5xx) gives a range of +/-5% as well. This must be pixel noise because the same simulation was applied to all ten images of the exact same defect.

The largest accuracy and reproducibility constraint is the line width to pixel size ratio. Thus similar results are expected with a 70 nm line/space pattern using 90 nm pixels, and initial data (unpublished) confirms this.

Previous papers have not discussed the effect of image variations in the simulation results, as seen in figure 3.

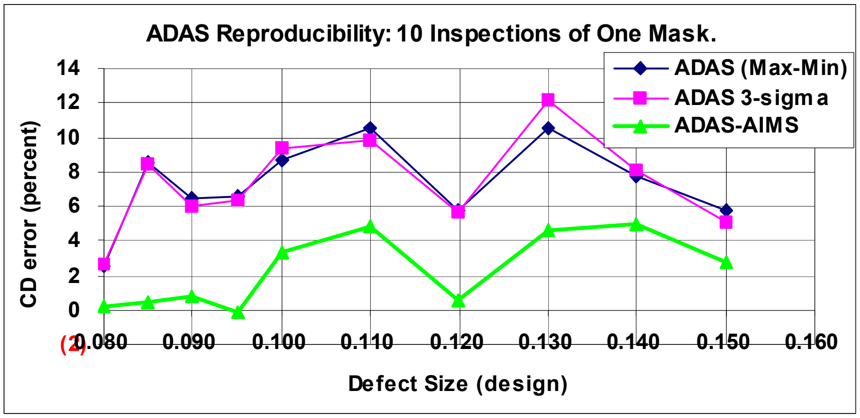


Figure 3: ADAS simulator reproducibility with images from KLA5xx

It can be seen that although simulation algorithm improvements are in process, they will have little impact on the overall efficiency of ADAS with regards to reducing the number of defects repaired or measured on AIMS.

3.2. Simulation Guard Bands Corresponding to Focus / Exposure Latitude and Resist Effects

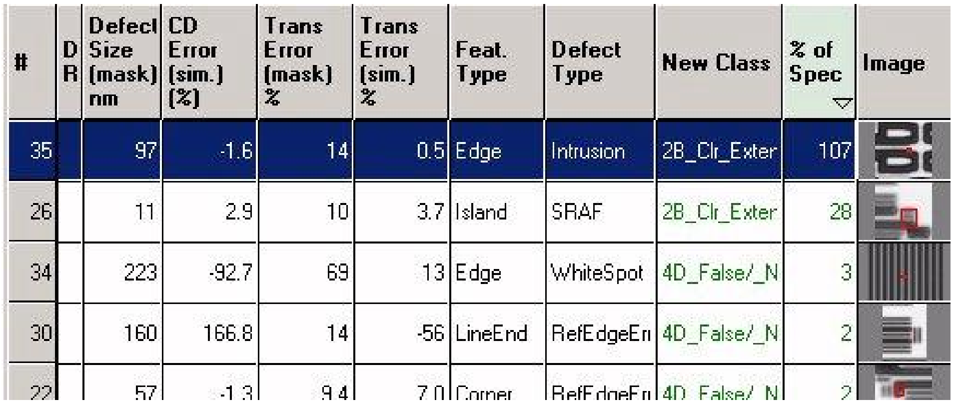
Focus and exposure during projection onto the wafer are controlled only within some range, called the focus-exposure latitude. Defect printability simulation is performed at best focus and exposure on the wafer. Thus it is possible that a defect that is under-spec at best focus and exposure might print over-spec at extreme values of the focus-exposure latitude during production.

For this reason guard bands must be added to the defect specs. For isolated defects one simply subtracts the exposure latitude percentage from the maximum allowed Percent Printable Transmission. Focus latitude is not a factor because any amount of defocus will reduce the real transmission error. For example, if the ultimate PPT spec is desired to be 85%, and the exposure latitude is +/-5%, then the final PPT spec must be 80%.

Adjusting CD error specs for the focus-exposure latitude requires determining the change in a defect CD error as a function of focus change: measure the CD error at best focus, and then at worst focus. This is commonly done on AIMS. Typical values for this difference is 1%. Thus if the maximum CD error on the wafer is 10%, then the maximum CD error on the simulator at best focus must be set to 9%.

Tests on resist effects on CD error are currently in progress.

3.3. Automated Defect Analysis



#	DR	Defect Size (mask) nm	CD Error (sim.) (%)	Trans Error (mask) %	Trans Error (sim.) %	Feat. Type	Defect Type	New Class	% of Spec	Image
35		97	-1.6	14	0.5	Edge	Intrusion	2B_Clr_Exter	107	
26		11	2.9	10	3.7	Island	SRAF	2B_Clr_Exter	28	
34		223	-92.7	69	13	Edge	WhiteSpot	4D_False/_N	3	
30		160	166.8	14	-56	LineEnd	RefEdgeEr	4D_False/_N	2	
22		57	-1.3	9.4	7.0	Corner	RefEdgeEr	4D_False/_N	2	

Figure 4: Sample defect analysis table from ADAS

The table in figure 4 shows how defects are classified by feature type, defect type, and whether they're over-spec. The defects are sorted by decreasing severity, as measured by "Percent of Spec". Percent of spec is the defect size divided by the spec for that defect type. The over-spec defect is at the top of the list, followed by under spec and false defects: a defect on an SRAF (28% of spec), then a White-Spot (unique to KLA-5xx tools) false defect and a focus error false-defect, called "Reference Edge Error".

Notice that the false defects all have large defect sizes and CD errors. Those defects would show up as very over-spec if they had not been detected as false. In this typical inspection 33 of 35 defects reported by the advanced inspection tool are false defects. This suggests that false-defect detection is critical to successful defect disposition automation.

Columns on the left show each defect's size, CD error in the simulator, and its transmission error in the mask image and in the simulator image.

The far left "DR" (D2d Reversed) column appears in die-to-die inspections where the inspection tool sometimes switches the defect and reference images. This column is checked if the defect and reference image have been reversed.

All these classifications and values are computed automatically using advanced and in some cases patented algorithms. Typically only the over-spec defects are reviewed manually for final disposition.

4. CONCLUSION

The results show that significant reduction in the number of defects repairs can be achieved. The minimum defect size requiring repair is increased 50% or more when using printability specs instead of defect size specs. There is also a reduction in the number of defects requiring AIMS analysis, either after repair, or in order to request a waiver.

4.1. Computing Optimal Defect Specification Values

Assuring that no printable defects are sent to the fab could be accomplished by requiring that every defect be measured on an AIMS or a wafer test print. The cost of this is prohibitive, so optimal specs provide a minimum printability spec applied to simulation results, and a looser spec that can be applied to AIMS measurements. Tighter AIMS specs are sometimes used for defects after repair because of subtle damage caused by repairs.

Calculating the printability defect spec does not involve the MEEF because the MEEF is built into the simulation. In fact MEEF values are generally computed from simulation data.

For example, if the CD error spec on the wafer is 10%, then the spec for simulation would be 9%, accounting for the 5% over-estimation of CD error in ADAS, the 5% 3sigma of measurements from inspection tool images, and a 1% allowance for focus/exposure latitude. Marginal defects, with CD error measured on ADAS less than 10%, can be re-measured on AIMS, and if the CD error throughout the focus/exposure latitude is less than 10%, then those defects would be called under-spec.

4.2. Implementing Optimal Defect Specs and Automated Defect Analysis

Mask production and requalification is complicated and expensive and cannot be interrupted for major process changes. With this requirement, implementation of optimal defect specs is expected to be performed in the incremental steps, none of which would cause interruption to the manufacturing process.

Where	Inspection	Why
Fab	Requalification	Internal only: quick response to issues
Fab	Incoming	Low risk. Demonstrate value of optimal defect specs, compare results to conventional specs and possible test wafers.
Mask Shop	Final	Customer is already using optimal specs, avoid expensive re-pels.
Mask Shop	First	Integrate repair / AIMS / rework disposition. Use accurate process data

Fig 5. Suggested integration strategy for Optimal Defect Specs

Implementation is performed first at the fab--in requalification inspections and then in incoming inspection. With the confidence built in the system at that point the specs are implemented in the mask shop at final inspection, and then at first inspection.

Some large mask shops have started implementation of ADAS at first inspection as a pre-filtering step before AIMS and repair. This has allowed them to implement data handling procedures so that the mask shop is ready when the mask customers allow them to shift to optimal defect specs.

5. SUMMARY

It has been accepted for many years that specifying defect printability is better than measuring defect size for photomask defect specs, and many products have attempted to do this, without lasting success.

ADAS now makes optimal (printability) defect specs practical to use for fabs and mask shops. The barriers that have prevented this ideal method from being used have been overcome by automating false defect detection, feature classification, defect classification and sizing, and simulation image measurement. ADAS is in test use in leading commercial mask shops and some advanced memory fabs. Future papers will discuss the results of this use.

This paper has laid out definitions and procedures to use that will allow the automation of this critical aspect of microlithography for new and old technology nodes.

ACKNOWLEDGEMENTS

The author thanks S. Narukawa and T. Kawashima at DNP for their encouragement and valuable reproducibility and AIMS data. Thank you to Andy McDonald and Clare Wakefield at Photronics, Manchester for their extensive testing data on hundreds of masks, S. Nagashige and T. Narita at Toppan for their encouragement and testing on NEC inspection tools, and to K. Nagai at Hoya for valuable test mask and AIMS data.

REFERENCES

1. http://public.itrs.net/
2. P. Fiekowsky, A. Mcdonald, C. Lewis (Photronics) "*An Automated Mask Defect Analysis System for Increasing Mask Shop Productivity*" PMJ 2005 SPIE Int Soc. Opt. Eng 5853-128a (2005)
3. S. Munier et al (Intel), "*DIVAS: Fully Automated Simulation Based Mask Defect Dispositioning And Defect Management",* 22 Annual BACUS Symposium on Photomask Technology and Management, 2004
4. L. Pang (Synopsys) et al**, "***Enhanced defects dispositioning for advanced masks using virtual stepper with improved automated defect severity scoring in a production environment",* Photomask Japan, 2004
5. W. Kim (TI) et al, "*Advanced Reticle Inspection Challenges and Solutions for 65nm-node"*, BACUS 2004

Correspondence for Peter Fiekowsky: Email: peter@aviphotomask.com; www.aviphotomask.com;
Phone 650-941-6871; Fax 650-941-4821; Automated Visual Inspection, 952 S. Springer Road, Los Altos, CA 94024