Auto-classification and simulation of mask defects using SEM and CAD images

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ABSTRACT

Mask defect disposition gets more difficult and time-consuming with each progressive lithography node. Mask inspection tools commonly use 250 nm wavelength, giving resolution of 180 nm, so critical defect sizes are far less than the optical resolution — too small for defect analysis. Thus the rate of false or nuisance defect detection is increasing rapidly and analysis of detected defects is increasingly difficult. As to judging the wafer printability of defects, AIMS (Aerial Image Measurement System) tools are commonly used but are also time-consuming if defect count is high. For improving the efficiency of mask defect disposition, we propose the combination of a SEM defect review tool and defect disposition and simulation software, which use high-resolution SEM images of defects to do defect review, defect disposition, and wafer printing simulation of defects automatically or manually.

The SEM defect review tool, DIS-05 developed by Holon Co. Ltd., is designed for defect review and disposition using reference images derived from e-beam files or CAD database. This tool uses the Automated Defect Analysis Software (ADAS) developed from AVI LLC. to interface the inspection tool and the DIS-05. ADAS detects false defects before SEM imaging and performs aerial image simulation from the SEM and CAD images to estimate the wafer CD error caused by each defect. We report on its speed (>300 defects/hour), classification accuracy and simulation accuracy when used with masks at the 45 nm technology node and beyond. This combination of SEM and ADAS is expected to significantly accelerate process development and production for the 45 and 32 nm nodes. It will also increase the masks-per-day throughput of inspection and AIMS tools by shifting most defect review to ADAS software using SEM images. At preliminary tests showed the combination tool can do auto defect disposition and simulation with promising results.

Keyword: defect, mask inspection, Scanning Electron Microscope (SEM), ADAS, CAD image, Defect Imaging System (DIS).

1. INTRODUCTION

As lithography technology goes to sub-micron node, not only the pattern dimensions on photomasks or reticles shrink considerably, but also many resolution enhancement techniques (RETs) are applied extensively to meet lithography requirements. These RETs including phase shift masks (PSMs), optical proximity correction features (OPC), and sub-resolution assist features (SRAFs) can bring benefits of effectively increasing resolution and depth of focus for lithography engineers to print critical features on wafers with better process control[*1]. However, these RETs combined with smaller features on a reticle may cause a lot of troubles for reticle inspection, such as longer inspection time, higher false or nuisance defect count, longer defect classification time, and lower production throughput. Moreover, as mask features get smaller, tiny defects or contamination may cause catastrophic wafer printing failure due to high mask error enhancement factor (MEEF)[*2]. It is important for mask inspection engineers to detect and classify defects accurately for post defect processing as well as to utilize the inspection tool efficiently due to soaring tool cost.

Figure 1 is a normal flow of mask inspection. Following mask inspection, defect classification and disposition is a crucial step to determine defect types. The information of defect classification is then passed to mask repair engineers for repair or AIMS (Aerial Image Measurement System) verification, or to process engineers for analyzing potential process issues.

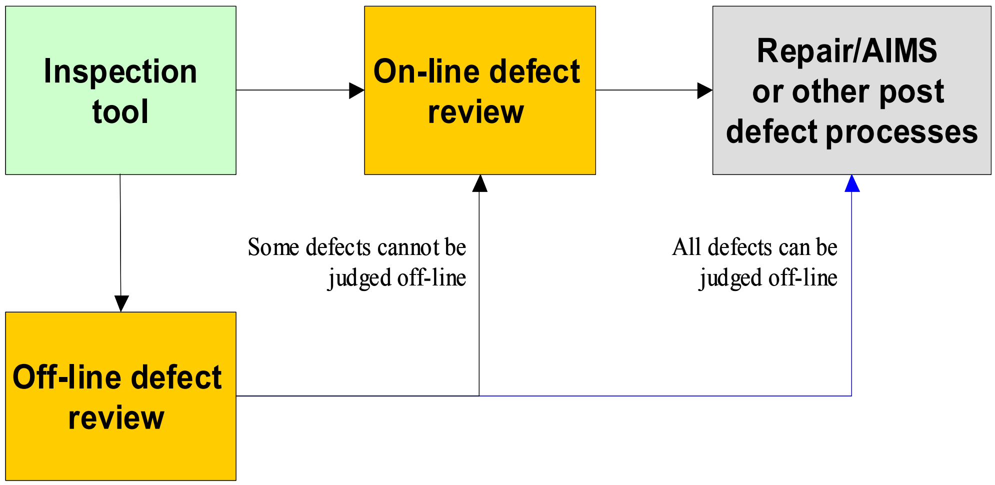


Figure 1: Normal flow of mask inspection

For mask inspection engineers, defect review classification is usually judged by real defect camera images as well as highlight images processed by an inspection tool. However, as defect count increases, defect review could occupy much inspection tool time, which is a big cost concern due to soaring tool price of high-end inspection tools. Defect review may occupy about 30% tool time according to real production statistics[*2, 3]. Many inspection tools provide off-line defect review functions to maximize the utilization of inspection tools on real mask inspections (Figure 2). However, the stored images are frequently not sufficient to judge defect types. For those off-line unclassifiable defects, on-line review is necessary. This on-line review requires expensive inspection tool time. Optical DUV Mask defect review tools have been introduced recently that remove the mask defect review process from the inspection tool and provide higher resolution and through-focus imaging for more accurate classification[*3].

Figure 2: Examples of defects not easily determined off-line

As mask patterns shrink with each new technology generation, even smaller defects can cause catastrophic failure. Due to the limitations of optical tools, however, it is difficult to tell the defect type according to live camera or process highlight images. Incorrect defect classifications confuse mask repair or process engineers, leading to inappropriate repair, and masks being scrapped. Hence high-resolution defects images are essential for accurately classifying defects[*4].

Before hard defects are repaired, repair engineers perform CD error printability measurements on AIMS tools to avoid repairing defects that meet outgoing specifications without repair. When the defect count is high, this verification requires significant AIMS tool time and increases critical TAT. Currently there are some software products on the market to simulate wafer printing results of defects using the processed highlight images of inspection tools. The simulation software can help reduce some tool time loading of AIMS for verifying defects*[5].

For efficiently classifying defects, verifying wafer printing error of defects, and improving the tool time utilization of inspection, repair and AIMS tools, we propose a modified mask inspection flow as shown in Figure 3. In this proposed flow, after mask inspection completes, the inspection report generated by the tool is sent to a high resolution defect review system. The mask being inspected will be transferred to the review tool, which is equipped with powerful software to do defect judgment and classification automatically with manual review. If the level of false or nuisance defects is too high, the software can execute the defect pre-filtering function to filter out those defects. Furthermore, wafer printing simulation can also be predicted by the software. After all information of defects is determined (inside the dash-lined box of Figure 3), the information can be passed to mask repair or other post defect processes.

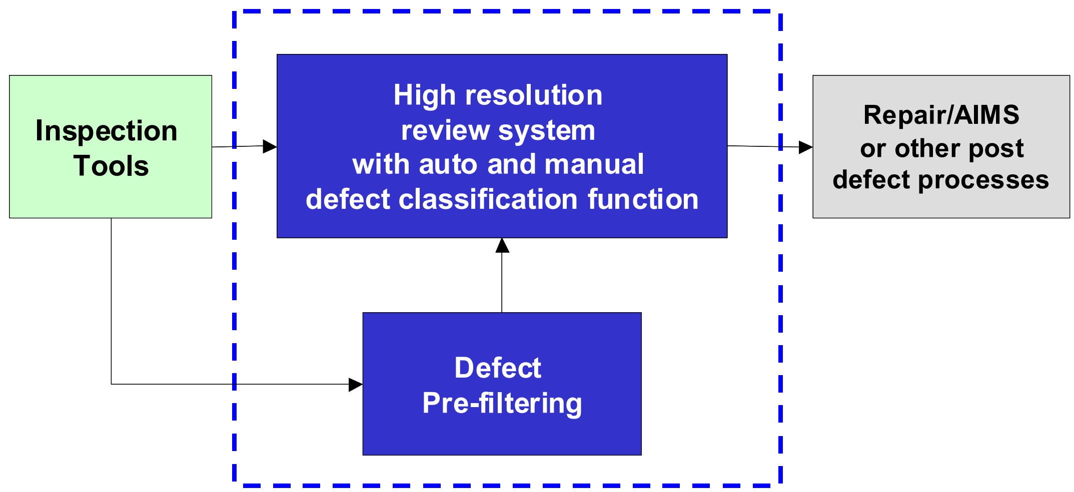


Figure 3: Proposed new inspection flow for improving defect classification and tool utilization efficiency

2. METHODS

For accomplishing the proposed new inspection flow, we combine Holon DIS-05 e-beam mask inspection review tool and ADAS simulation software developed by AVI to form an all-around review tool. The DIS-05 has been developed by HOLON based on the state-of the art technology of Mask CD-SEM, which have two key features. One is low vacuum technology which is very effective for a various kinds of masks measurement with charging free. Another one is an aberration corrector technology to get sharp images with a high resolution. The DIS-05 can also create CAD image from many kind of database format.

The software of ADAS combines defect classification, measurement, simulation and interfaces. It accurately converts the SEM image into a transmission mask-model image, which is then measured, and transformed into an AIMS simulation. It then measures the predicted wafer CD error from the simulation image. ADAS also takes CAD image inputs for reference, and it allows the operator to compare images, measurements, and simulations directly from inspection tool images. The operation procedures are shown in Figure 4.

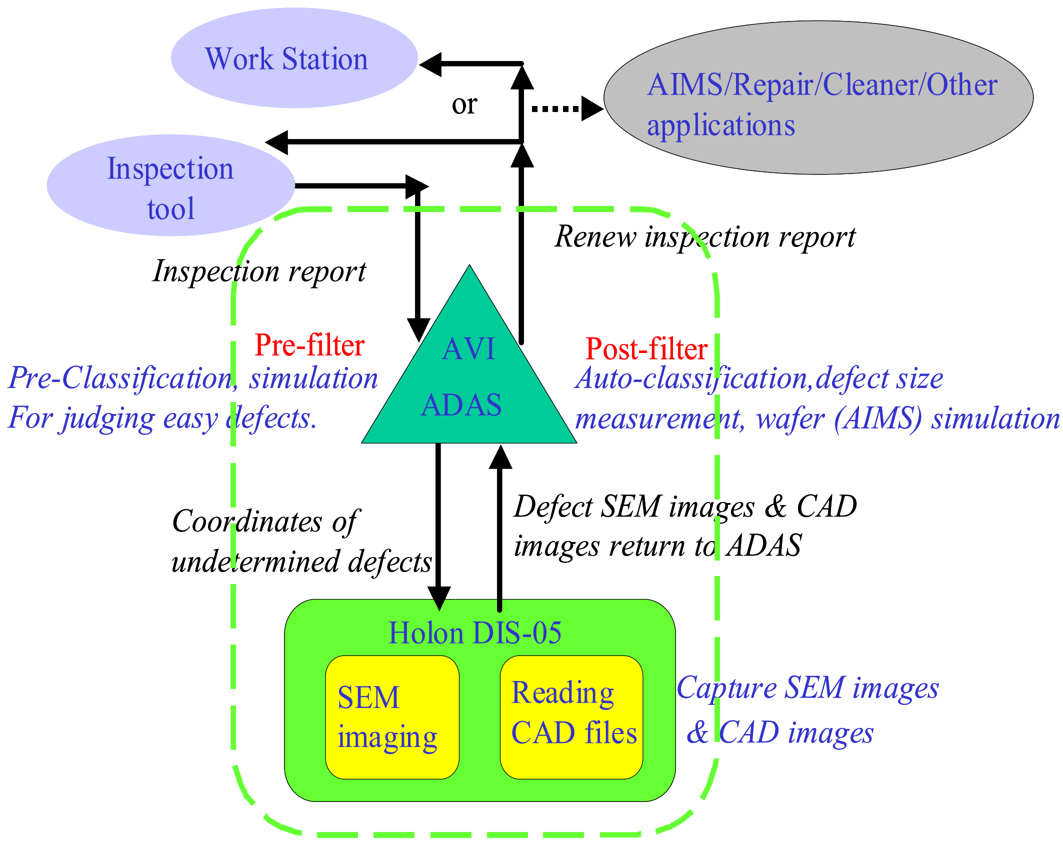


Figure 4: Detailed flow of improving the mask inspection process

The results of the full mask defect inspection are delivered to ADAS through the inspection report. The ADAS pre-filter process identifies false defects such as white spots, and focus errors, and under-spec defects such as SRAF (Sub-Resolution Assist Feature) and isolated defects, and some dummy patterns. ADAS also identifies over-spec defects that do not require further analysis. The remaining unclassified defects must be imaged by the DIS-05, and ADAS sends those defect locations to the DIS-05.

DIS-05 rapidly takes SEM images at each defect position and creates a CAD image for reference. This typically takes ½ hour per inspection. The SEM and CAD images are sent back to ADAS where the post–filter classifies the defect type, measures the defect, does AIMS simulation, and measures the CD and transmission errors in the simulation.

The results of the post-filter are sent to the AIMS and/or repair tool, and /or cleaner. Those defects where repair may cause the mask to be scrapped are sent to AIMS for final disposition.

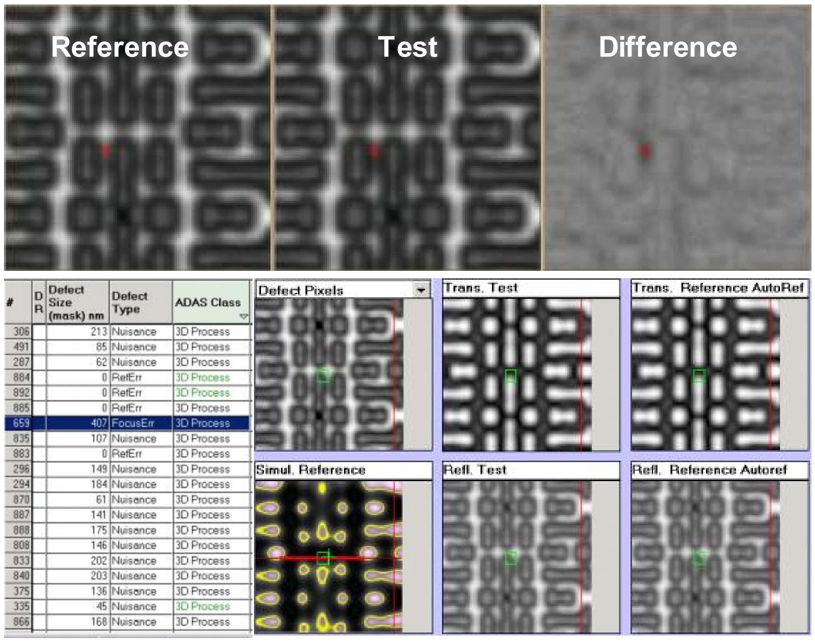
In summary, most defects are classified in the pre-filter stage, but the most difficult defects go through three stages of analysis: Pre-filter using inspection tool images, post-filter using SEM images, and AIMS. It is expected that each stage will filter out more than 90% of the incoming defects, so that less than 1% of defects will require AIMS analysis.

At the preliminary test and verification stage, we tested the following four items to verify the capability and feasibility of the combination of DIS-05 and ADAS: (1) defect pre-filtering for removing false or nuisance defects, (2) auto classification of a line/space mask, (3) auto classification of a contact hole mask with energy flux defect, (4) AIMS simulation of a line/space mask by ADAS.

3. RESULTS

3.1 Defect pre-filtering function

As patterns get smaller and more complex, nuisance or false defect count inevitably gets higher. As nuisance or false defect count is high, defect pre-filtering before SEM imaging is necessary to save the time of the SEM review tool. There are 1009 nuisance or false defects on one of production 45-nm-node line/space mask detected our inspection tool and the defects were classified one by one by a operator. The ADAS can pre-filter 455 nuisance or false defects automatically in a minute before executing the SEM imaging of other defects for classification. The pre-filtering efficiency is about 45% (Figure 5). Further algorithm modifications are ongoing to improve the efficiency



#	DR	Defect Size (mask) nm	Defect Type	ADAS Class
306		213	Nuisance	3D Process
491		85	Nuisance	3D Process
287		62	Nuisance	3D Process
884		0	RefErr	3D Process
892		0	RefErr	3D Process
885		0	RefErr	3D Process
659		407	FocusErr	3D Process
835		107	Nuisance	3D Process
883		0	RefErr	3D Process
296		149	Nuisance	3D Process
294		184	Nuisance	3D Process
870		61	Nuisance	3D Process
887		141	Nuisance	3D Process
888		175	Nuisance	3D Process
808		146	Nuisance	3D Process
833		202	Nuisance	3D Process
840		203	Nuisance	3D Process
375		136	Nuisance	3D Process
335		45	Nuisance	3D Process
866		168	Nuisance	3D Process

Figure 5: Nuisance or false defects detected by an inspection tool (top), and defects pre-filtered by the ADAS (bottom). The pre-filtering was about 45% (455/1006).

3.2 Auto defect classification accuracy – line/space

There are hundreds of programmed defects on the 45-nm-node line/space defect standard mask for verifying the defect defection capability of inspection tools. The total count of detected defects is 320, including pin dots, pinholes, MoSi intrusion, MoSi protrusion, and critical dimension (CD) errors. By traditional defect classification, for example, it is difficult for operators to judge defect types by the highlight or live images provided by inspection tools. An e-beam review tool can provide clear SEM images to operators for judging defects accurately. Figure 6 is an example of a pin dot defect located in dense lines, which cannot be accurately classified using the inspection tool image. However it can be easily classified using SEM images. SEM images can be obtained from the e-beam review tool and can be used for automatic and manual defect classification.

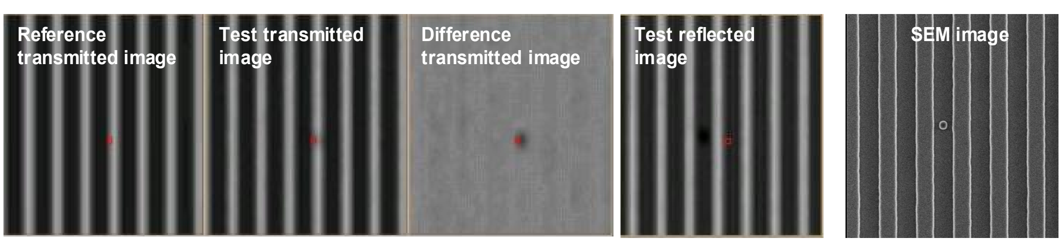


Figure 6: A pin dot defect located in dense lines cannot be easily judged by the inspection tool but can be clearly seen by the e-beam review tool

Having better contrast and resolution than optical ones, SEM images can also be used as input files for defect simulation software to do auto defect classification. There were 315 out of 320 defects accurately classified by the simulation software with 98% accuracy rate. Figure 7 and 8 show parts of auto classification results about pin dot defects (defect code: 2A, number 1~6), MoSi protrusions (defect code: 1A, number 7~12), and pinholes (defect code: 2B, number 19~23).

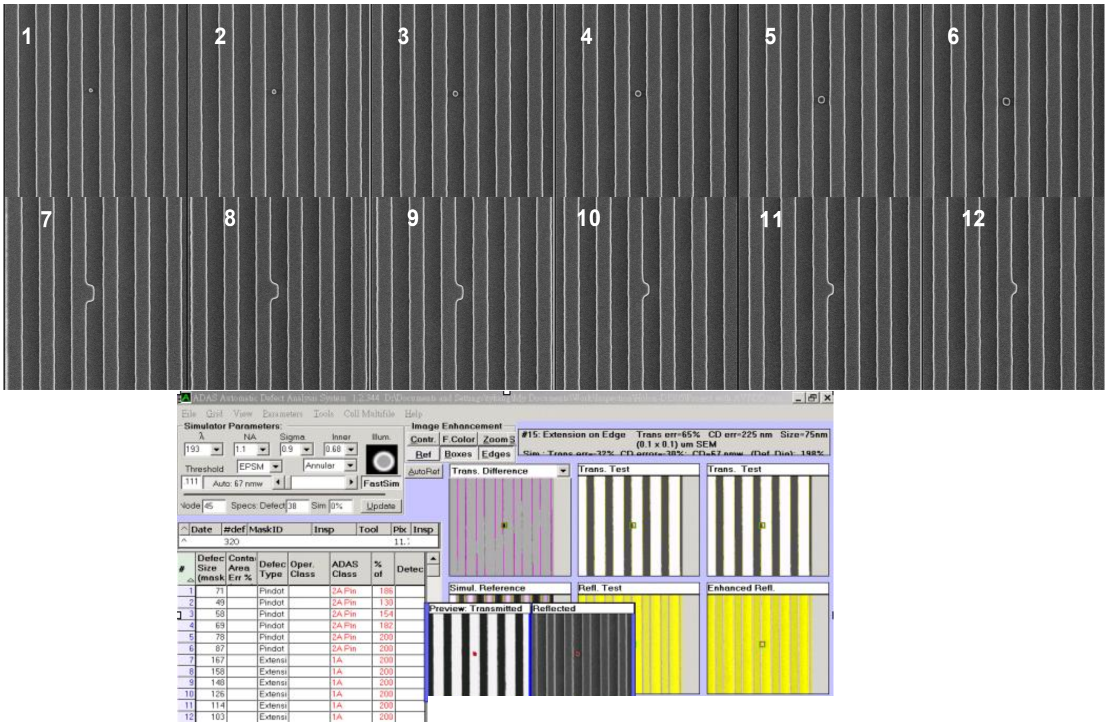


Figure 7: Auto classification of parts of pin dot and MoSi protrusion defects a pin dot defect located in dense lines.

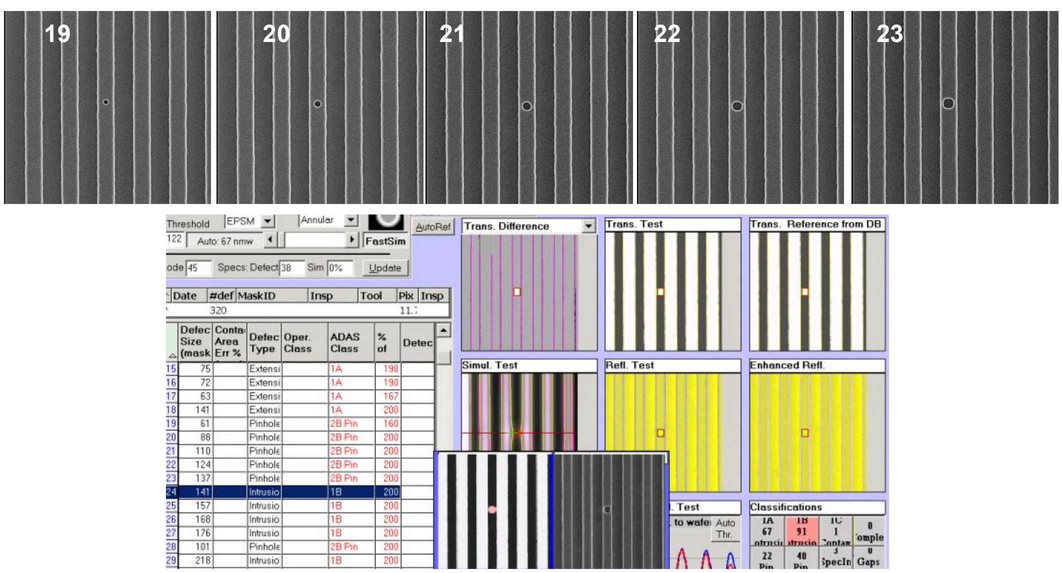


Figure 8: Auto classification of parts of pinhole defects located in dense lines.

As to wrong auto classification, the defects were end-to-end CD errors but were classified as pinholes (Figure 9). Newer software versions have resolved the issue.

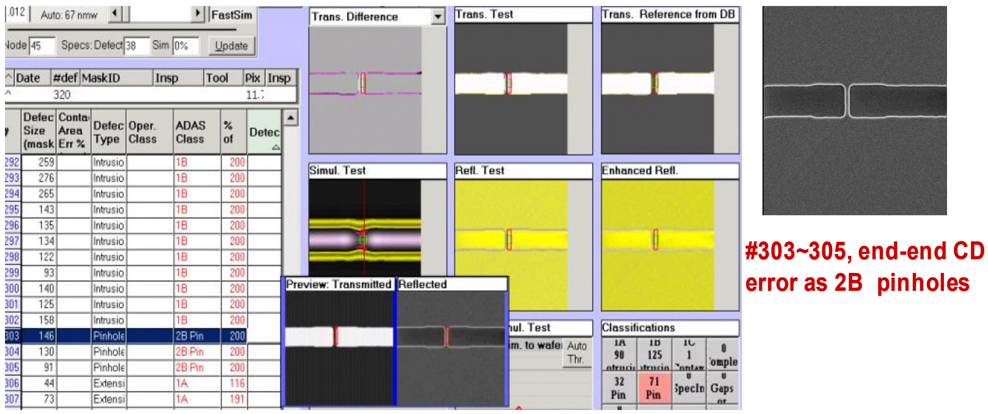


Figure 9: parts of wrong-auto-classified defects

3.3 Auto defect classification accuracy – contact holes

As for contact hole mask inspection, the most annoying defects are energy flux defects, which are more difficult to be judged than hard or soft defects located in holes. Especially for die-to-die inspection, it is tough to tell which die has energy flux error as the inspection tool flags energy flux defect. Practically, the AIMS measurement of two defect dies with additional reference die is required to determine which die is defective. The flow takes a long time. DIS-05 captures the SEM images of the two dies and the corresponding die information of the original e-beam files (CAD image), then sends them to ADAS to do the hole area difference calculation between SEM and CAD images automatically. According to our previous study, hole area difference smaller than 2.2% can meet our AIMS measurement specification and no more defect repair is required[*4]. On our 45-nm-node contact hole production mask are 265 energy flux error defects. Our classification approach was applied and there is no defect out of the specification (Figure 10). The AIMS measurement of the most defective defect shows it still meets the specification. It can verify and reconfirm our approach is practical.

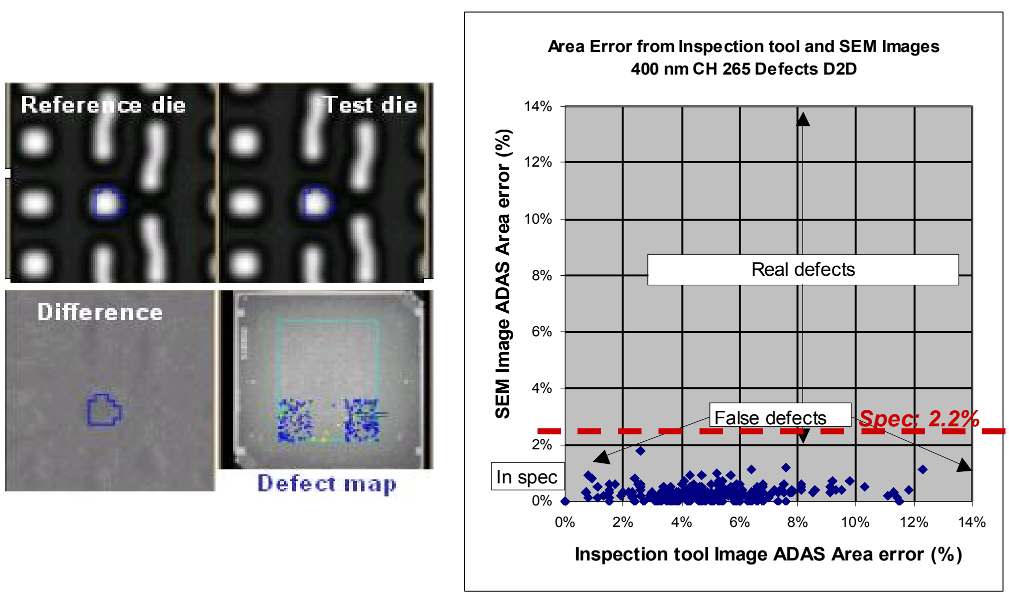


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Figure 10: Energy flux defects detected by the inspection tool (left) and auto classification results of die-to-die contact hole energy flux error (right). All defects are in the specification verified by area difference calculation and AIMS measurement.

3.4 AIMS simulation by ADAS – line/space

ADAS not only classifies defects but also simulates wafer printing behavior affected by different sizes of defects (Figure 11). The prediction of ADAS on MoSi intrusion defects located in the minimum pitch of the 45-nm-node line-space mask was compared with AIMS measurement and actual wafer printing results under the same lithography conditions. As Figure 12 shows, the prediction of ADAS has similar trend with AIMS and actual wafer printing. ADAS also shows good prediction on other types of defects. If more data are collected in the future, a new spec based on ADAS could be established to filter out most of defects to skip AIMS measurement for saving tool cost.

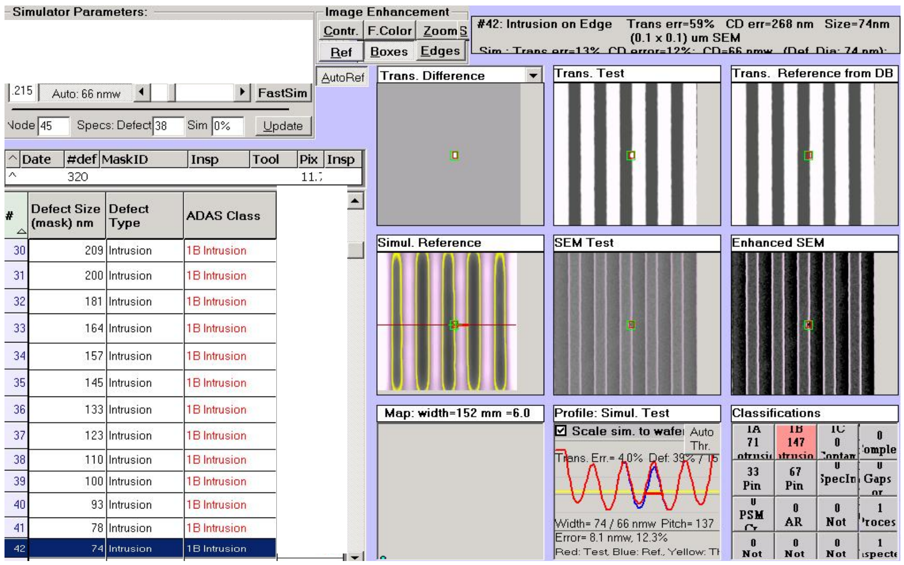

Figure 11: ADAS can also predict wafer printing behavior.

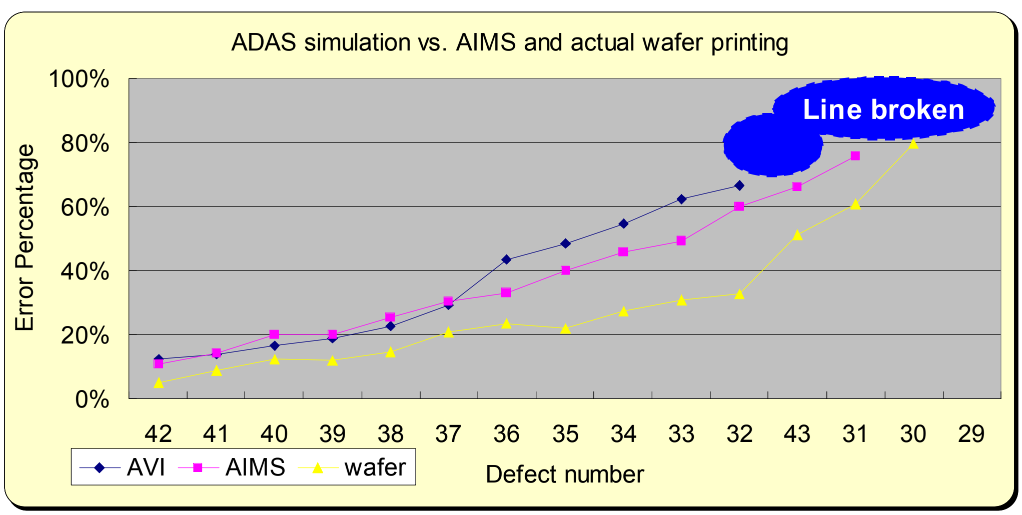

Figure 12: ADAS shows good prediction on the wafer printing behavior of MoSi intrusion defects with variable dimensions.

4. SUMMARY

The traditional flow of mask inspection and defect disposition occupies a lot of precious machine times of mask inspectors and AIMS tools. In addition, defect types cannot be easily determined due to the limitation of optical resolution of mask inspection tools. The combination of the high-resolution SEM review tool Holon DIS-05 and the defect simulation and disposition software AVI ADAS is proposed to utilize machine time more efficiently and to benefit accurate defect classification and judgment by using SEM and CAD images of defects. At preliminary test stage, the combination of DIS-05 and ADAS proves that defects on masks can be classified automatically with high accuracy 98%. As to pre-filtering nuisance or false defects, the pre-filtering rate was about 45% and can be further improved. Wafer printing simulation of defects classified by the combination of DIS-05 and ADAS was matched well with that of AIMS measurement. More data collection is ongoing to verify the repeatability and feasibility.

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