EUV Photomask Defects: What prints, what doesn't, and what is required for HVM

Jed Rankin[a], Zhengqing John Qi[a] , Mark Lawliss[a], Eisuke Narita[b], Kazunori Seki[b], Karen Badger[a], Ravi Bonam[c], Scott Halle[c], Christina Turley[a]
a GLOBALFOUNDRIES, 1000 River St., Essex Junction, VT 05452
b Toppan Photomasks Inc., 1000 River St., Essex Junction, VT 05452
c IBM Research, 257 Fuller Road, Suite 3100, Albany, NY, USA 12203

ABSTRACT

As Extreme Ultraviolet (EUV) lithography has matured, numerous imposing technical challenges have been the focus of intense scrutiny, including the EUV radiation source, reflective optics, and fundamental mask fabrication. There has been a lurking question on the state of mask defectivity that has been almost unanswerable until the recent relative maturation of the rest of the infrastructure. Without readily available actinic blank or patterned inspection systems, EUV blank and mask manufacturers must continue to rely on relatively low resolution optical systems for blank characterization.

Despite best efforts, detectable defects still exist; these can be classified into three types: large defects that can be avoided through pattern-shift, medium defects that can be repaired, and small defects which must be suppressed during manufacture. To successfully intercept high-volume-manufacturing (HVM) for the 7nm node, aggressive, continued industry focus is required to ensure that these three defect types are addressed.

Without actinic mask inspection, an unknown element with EUV lithography continues to be the presence of non-detected printable defects – defects that print on wafer despite being undetected during mask or blank fabrication. Another risk is that until recently, focus has been on developing techniques to identify catastrophic defects, while past manufacturing experience tells us that much more subtle defects (<10% CD variation) can have significant impact on yield and performance.

Using information from many characterization sources, including blank inspections, patterned inspection, atomic-force microscopy (AFM), scanning-electron microscopy (SEM), as well as 36nm and 32nm pitch wafer printing results, we will try to address what the real current state of mask defectivity is. We will discuss techniques to answer the key questions of: "What defects print, what defects do not, and what might our inspections methods be missing?" From this vantage point, we will analyze the current mask defectivity rates and sources, and assess the gap in capability to support full HVM support.

Keywords: EUV, EUV Masks, blank inspection, defect transfer rate, patterned inspection, pattern shift, HVM.

1. INTRODUCTION

Since the introduction of Extreme Ultra Violet Lithography (EUVL) at 13.5nm wavelength radiation for semiconductor patterning, "defectivity" has been one of the key items identified for learning as part of the "EUV infrastructure" activities[1,2]. The term "defectivity", however is broad and captures many aspects of the blank manufacture, mask manufacture, mask repair, and even mask shipment and wafer usage.

There have been countless innovations made in all aspects of the EUV infrastructure with respect to reducing the defectivity. These include improvements in polishing techniques for creating the Ultra-Low-Expansion (ULE) blanks[3], developing new deposition techniques for creating the multilayered Bragg Reflector mirror, minimizing drop-on-defects in the lithography scanner[4], and also repair technology for defects generated during mask manufacture. The key to all of these reduction activities, and ultimately to ensuring low enough defectivity levels to support High-Volume-Manufacturing (HVM), is having appropriate inspection capabilities to detect *defects that matter*. As shown below in Figure 1, for the subset of the EUV mask manufacturing infrastructure from blank manufacture through usage, there are at least eight critical inspection steps, some of which are part of both feed-back, and feed-forward loops. To bring EUVL mask manufacturing to a maturity level high enough to make defect-free masks, both the processes that these inspections support, and the inspections themselves must continue to mature.

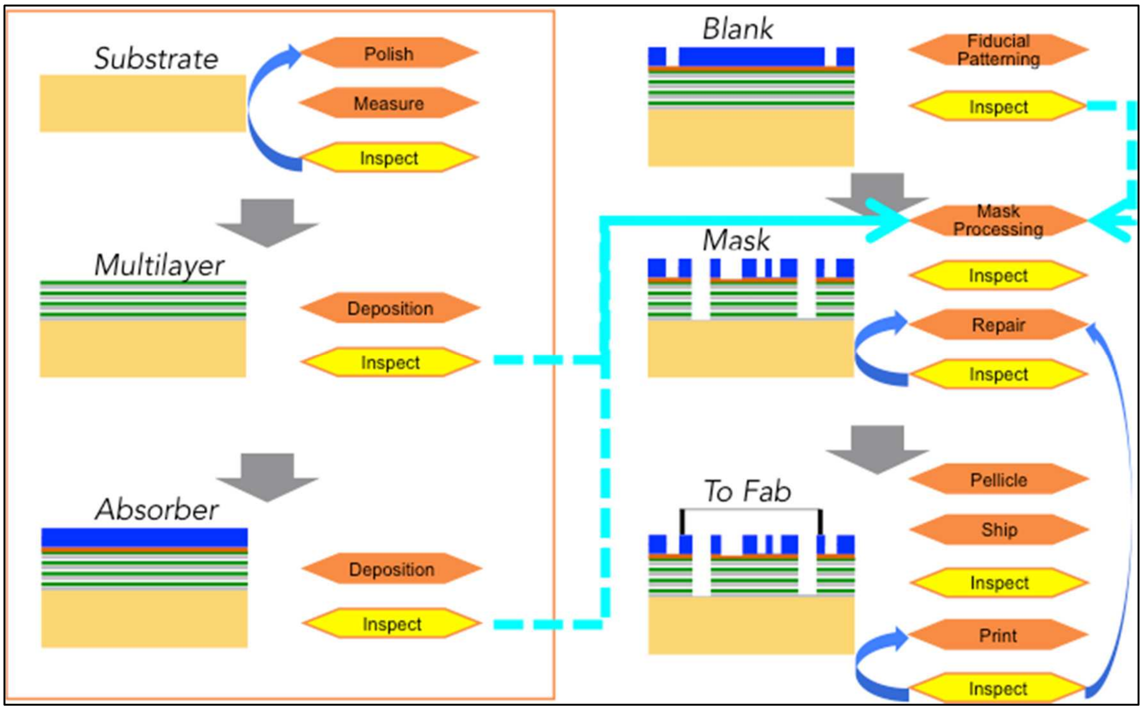


Figure 1: A high level schematic of mask blank and mask manufacturing showing a minimum of eight inspection steps, where many are iterative, and many less critical inspection steps are not shown. Curved arrows indicate feedback loops, and dotted, straight arrows indicate feed-forward (for pattern-shift)

We will discuss the capabilities and limitations of both the Process Of Record (POR) in use, and the current Best-Known-Methods (BKM) for many of the key inspection steps where substantial learning is ongoing, or where extensive continued development is still in progress. Where possible, we will augment the *at-level* inspections capabilities with studies of the *on-wafer* results to validate the required sensitivity for each *at-level* inspection. From this vantage point, we can assess the viability of HVM EUV mask manufacture with both the current POR and BKM processes in time to meet 7nm manufacturing requirements.

2. EUV MASK DEFECTS

For EUV Masks, defects can be grouped into four types, corresponding to the manufacturing process during which the defect is generated; for each of these defect types, inspection systems and feedback loops have been established to provide the earliest detection, and most accurate quality information for feed-forward. These defects are described in table 1.

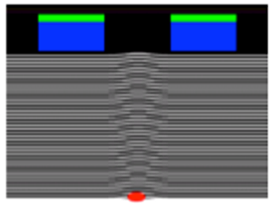
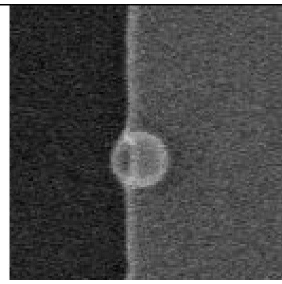
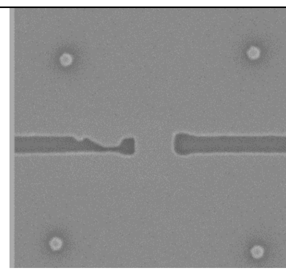
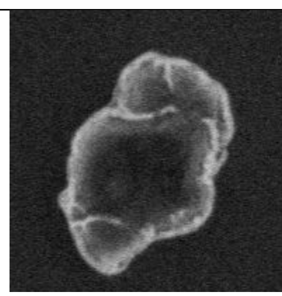
Type	Image	Earliest Detection	Mitigation Strategies and location
Multilayer		Blank Fab	Pattern Shift (in Mask Fab) Repair (in Mask-Fab)
Absorber		Blank Fab	Repair (in Mask Fab)
Process		Mask Fab	Repair (in Mask Fab)
Particle		Wafer Fab	Dual Pods (shipping) Pellicle (in Mask Fab) Cleaning (in Wafer Fab)

Table 1: Four EUV mask defect types as grouped by manufacturing process

2.1 Overall Defect Management Strategy

Despite these varied sources of defects, many have analogous counterparts in optical mask manufacturing, with the exception of *multilayer defects*. Depending on when the defects occur in the manufacturing process, they can cause errors to both the phase and the amplitude of the light reflected from the multilayer Bragg reflector[5]. It is generally believed that sufficient defect free blanks will not be available in time for HVM. There are three categories representing how the defects seen on blanks must be dealt with to support HVM defect free reticles despite this limitation.

- Large defects must be eliminated by the blank manufacturer

- Medium sized defects must be avoided through pattern-shift defect mitigation
- Small defects must be repaired.

Conceptually, this strategy seems to define a clear path, however it has long been shown, that with the complexity of the reflective nature of the mask, the sensitivity of the multilayer mirror to dimensional changes, and the resolution of the EUV optics, this strategy may require more refinement. Figure 2 shows that with the current distribution of defect sizes, there are still too many small and medium sized defects to be accounted for during mask manufacturing.

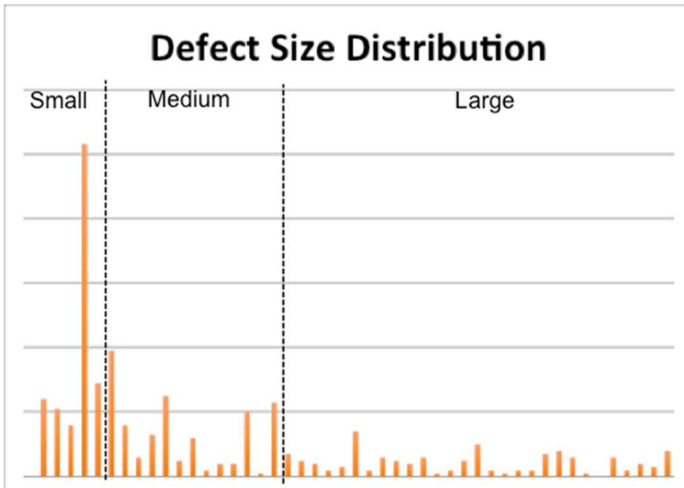


Figure 2: A histogram showing the distribution of defects versus size, with Small, Medium, and Large defect regions identified which correspond to the mitigation strategies of repair, avoid, and eliminate, respectively

2.2 Defect Detection Challenges

As described above, the prevailing philosophy for the defect management is dependent on classifying the defects first by size, then assigning a mitigation strategy. Figure 2 demonstrates that the number of defects requiring action may challenge mask manufacturers ability to avoid medium sized defects, and repair small sized defects. To this end, additional characterization information, beyond size is being extracted from the defect detection or analysis systems to augment the classification, such as intensity or intensity change, phase, or from post-processing analysis such as Histogram of Oriented Gradients (HOG)[6].

2.3 Refined Defect Management Strategy

Using these extra characteristics, the refined defect management strategy hopes to reduce the number of defects requiring repair or avoidance from the native distribution (shown in Figure 2) to a more manageable quantity using a relationship like that described in Figure 3. In this example, only small defects with low intensity would be candidates for repair, whereas similar size defects, with higher magnitude may require avoidance; a risk is that due to shallow penetration of the non-actinic light, the size of the defect on the surface may be considerably smaller than the perturbation deep in the multilayer[7].

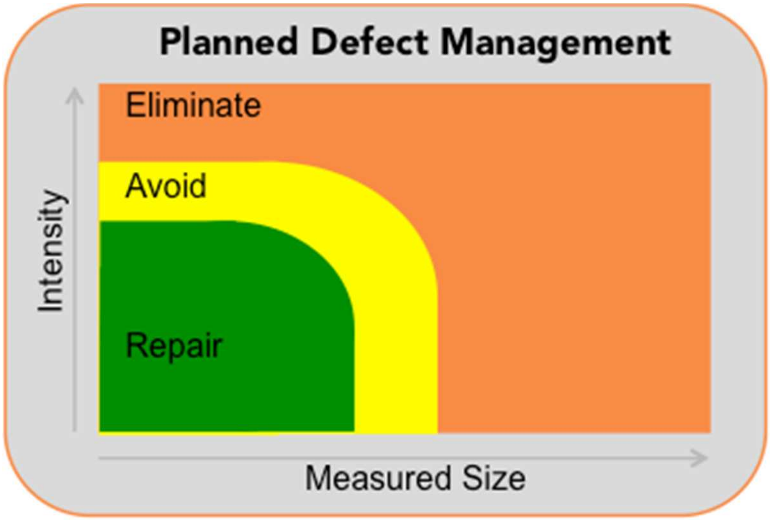


Figure 3: The modified Defect Management Strategy includes both size and other characteristic parameters. Shown here the y-axis is intensity, but it may differ depending on the inspection or analysis characteristics used.

Most EUV mask manufacturers use a combination of inspection systems using both Mid-UltraViolet (MUV) and Deep-UltraViolet (DUV) light, rather than the 13.5nm EUV light required for actinic inspection. With the wavelength mismatch, further refinement of the relationship between detected defect, and lithographic consequences must be made. It has been proposed that using a combination of detected size, intensity and phase may add predictability[8]. Additionally, secondary or tertiary characterization techniques, such as Atomic Force Microscopy (AFM) or Scanning Electron Microscopy (SEM) may improve this predictability[9].

Despite the challenges noted above, successful execution of the three mitigation strategies have been demonstrated[8,9,10]. The question remains of whether the industry learning rate for minimizing defect generation and characterizing defects will be compatible with the groundrules and lithographic requirements for the first HVM technology node[8].

3. EUV MASK INSPECTION CAPABILITY

Inspection techniques have been developed to help blank, mask, and wafer manufacturers identify, quantify, characterize, and reduce the four key defect types shown in Figure 1. Results can only be as good as the measurement system, so it is imperative to continually question if there is a mismatch between the inspection capability and the requirements; we must ensure that we understand not only the limits of the inspection systems being used, but what the limits of the mask in use are as well.

3.1 Wafer Printability

Lacking actinic inspection systems, either scanning or large-field, EUV mask development has had to rely on actinic microscopy, or more often, early lithographic scanner systems to provide a measurement of the impact of the defects that are characterized on the mask. Given the size of the early defects, and the immaturity of the patterning solution (scanner, resist, etch, inspection), the criteria used to assess mask defect impact has been "printability". Printability is most often used to describe catastrophic failure (opens or shorts), as the lithographic capability of 13.5nm light has outpaced some of the other parts of the system (resist, optical-inspection systems). It is important to remember however, that for EUV to be successfully inserted into HVM succeeding 193-immersion lithography, it must exceed the capabilities of 193 for resolution, and variability, including the impact of defects. Printing a 36nm half-pitch grating requires mask features of approximately 72nm. Catastrophic failure may not be detected until the aerial image of a half-pitch feature is nearly 50% perturbed, which is 9nm 1X, or 36nm on mask! For comparison, 14nm mask CD control requirements are already less than 2nm, and are expected to approach 1nm 3-sigma by the 7nm node[1]. From another perspective, post-repair intensity and CD are required to match neighboring features with less than 5-8% deviation [REF ITRS]; assuming unity contrast, this corresponds to 3.5-5.7nm for a 72nm mask feature. Using only catastrophic criteria risks underestimating the impact of the defects on the lithography system. For comparison, the current POR inspection strategy and approximate capability is listed in Table 2. Sensitivity ranges indicated represent different capability depending either on specific equipment differences, local geometric printing differences, or defect-type differences.

	POR	Sensitivity
Qtz / ULTEM Inspection	Darkfield MUV	~50-35nm
Multilayer Blank Inspection	Darkfield MUV/ DUV phase	50-60nm / 25x5nm
Absorber Inspection	Darkfield DUV / DUV Phase	50-60nm / 25x5nm
Pattern Inspection	DUV	30-40nm
Post Repair Verification (AIMS)	SEM and/or Scanner	4-10nm
Particle Inspection	DUV	30-40nm

Table 2: Current "POR" sensitivities for blank and mask inspection.

In the sections below, we will focus on what the current POR sensitivity is as it corresponds to the known "defects that matter" and to lithographic printing for Multilayer, Absorber, Pattern, and Repair Verification.

3.2 Multilayer Inspection

For EUV masks, the Multilayer structure, which is composed of a Bragg reflector is perhaps the most crucial part of the photomask as an optical element. Due to the short wavelength of EUV (13.5nm), almost all materials absorb, rather than transmit or reflect EUV radiation; any deformation of the 40 pairs of multilayer films which compose the reflector can quickly change the multilayer from being a mirror to an absorber (amplitude defect), or change the depth of the primary reflection (phase defect)[5].

Multilayer Defects are also the most difficult type to characterize and repair, thus they are the focus of pattern-shift defect avoidance protocols[8]. Since most mask-fabs currently have only laboratory level access to actinic inspection equipment, defect are only detected when they cause surface or gross reflectivity differences. Using light such as DUV or MUV, which penetrate only between 2 and 13 multilayers[11], it is impossible to know with confidence the depth or lateral extent of the multilayer defect[5].

The criticality, and elusiveness of characteristics of multilayer defects make them the most important, and most challenging defects to inspect. To form a full photomask, a capping layer (generally Ruthenium), and an absorber layer (Tantalum based) must be deposited on top of the multilayer reflector. Generally these films are all deposited in the blank fab. Ideally, to minimize defects, vacuum would never be broken from the beginning of the multilayer deposition through the absorber coating, but since tool configuration must be updated for depositing different films, and to guarantee interim quality, the blanks are removed from the deposition systems and inspected for defects. Currently, the most widely available inspections are based on MUV radiation, using darkfield optics. While relatively quick, the sensitivity of these systems is limited to ~50nm with high detection repeatability.

To perform pattern-shift, makers must first identify which defects will potentially cause problems, thus need to be avoided, then determine the precise location of the defects, and finally adjust the placement and orientation of the pattern with respect to these defects[12]. Blank Fiducials, or common reference marks for inspection and patterning are most often used for this. To minimize blank defectivity, and maximize positional accuracy during inspection and writing, fiducials are often formed in the absorber, rather than the multilayer. This has two consequences; 1) the multilayer inspection done during blank manufacture has no high-accuracy positional information 2) the mask-fab must re-inspect after forming the fiducials to define the defect locations (and type).

In the mask-fab, two inspection techniques are commonly used for this post-fiducial inspection: MUV darkfield, or DUV phase. In either case, the inspection is at best, a proxy, as neither wavelength radiation will penetrate the absorber to allow direct characterization. Several experiments were performed to help quantify the value of an inspection on the absorber for identifying multilayer defects.

In the first experiment, a comparison was done between the MUV darkfield multilayer inspection, and an MUV darkfield absorber inspection. It was hoped that the absorber inspection would be able to identify the Multilayer defects with unique characteristics.

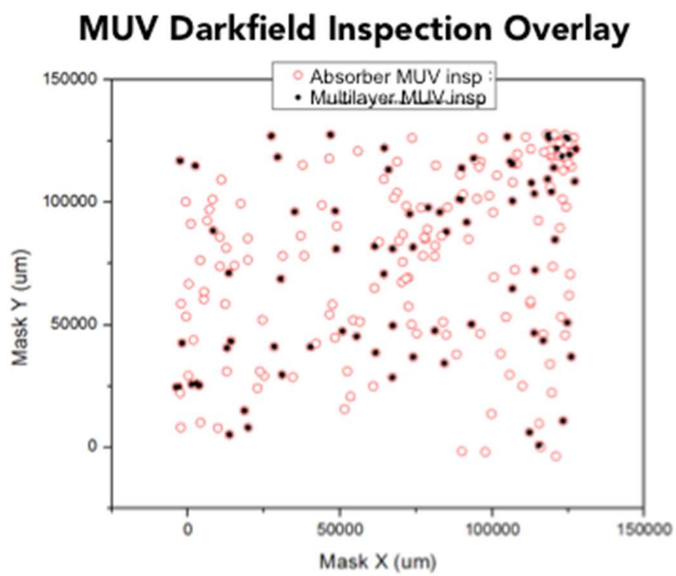


Figure 4: Overlay of Absorber and Multilayer MUV inspections. Open circles represent the defects identified during the absorber inspection, and solid marks indicate defects identified during multilayer inspection

This experiment demonstrated that defects visible in the multilayer generally propagate through the absorber, such that 100% of the multilayer detected defects were also detected in the absorber; every solid marker in Figure 4 has a corresponding open mark, indicating detection at both inspection steps. While this is promising for using absorber-based inspections for identifying the multilayer defects, these common stops only represented approximately one-third of the absorber stops. Furthermore, even with secondary and tertiary characterization by SEM and AFM, the "multilayer only" population could not be discriminated from the "absorber only". Finally, and most problematic was that some of the "absorber only" defect were later proven to be in fact multilayer defects by post-patterning characterization.

In the second experiment, many aspects of experiment 1 were repeated, but with a DUV phase differential inspection system. Since a DUV phase multilayer inspection was not available, the experiment was run in reverse; the absorber inspection was executed, after which the absorber was stripped, and the multilayer was re-inspected directly.

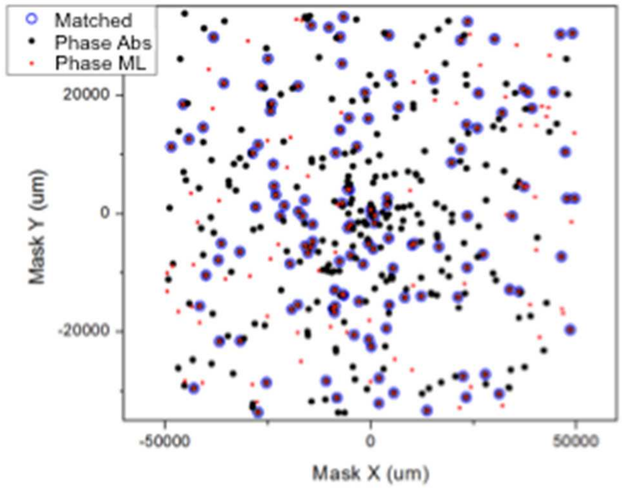


Figure 5: Overlay of Absorber and Multilayer DUV inspections

The results of the second experiment shown in Figure 5 had both similarities and differences from experiment 1. Most notably, with DUV inspection, only about 65% of the defects identified on multilayer were also detected at the absorber inspection. This may be indicative of either different inspection capabilities, or artificial multilayer detections induced by the absorber removal process. There were several types of defects identified though which appeared to be true multilayer based defects, based on shape consistent of buried multilayer inclusion, as measured with AFM, and based on chemical composition as identified by EDX.

Finally, using the results of these two studies, a final experiment was performed where "probable multilayer" defects were identified using MUV, DUV, SEM, and AFM characteristics. These defects were used as part of a native-defect printing study where contact-hole and line-space patterns were placed on or near the potential defects. After patterning the mask, SEM and AFM classification of the size, height, and placement of the defects were noted. Finally, the mask was exposed on a EUV scanner, and SEM was used to detect the lithographic impact[9].

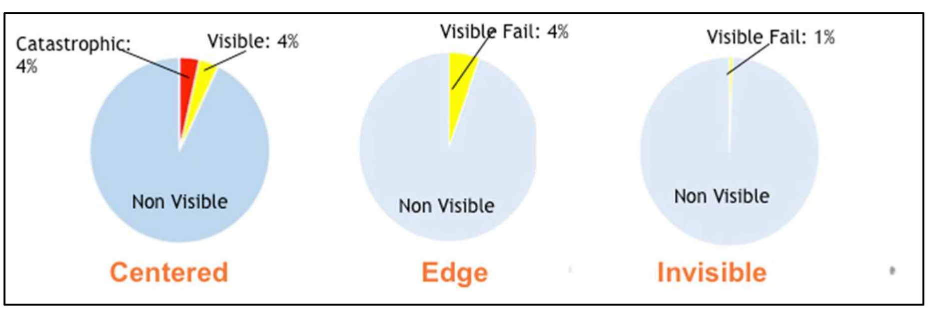


Figure 6: Results from printing "probably multilayer" defects grouped by position as measured by SEM on mask.

An initial review of the results suggest that concerns over multilayer defectivity may be exaggerated, as only 3% of the defect caused lithographically detectable defects, with barely 1% causing catastrophic failure, as shown in Figure 6. The challenge however, is that even with the characterization techniques described above, it has proved impossible to define characteristics unique to these printable defects. Using the "3x3 residual", or maximum difference in 9 adjacent pixels, does yield a relationship which allows differentiation of the probably printing defects from non-detectable defects, seen in Figure 7.

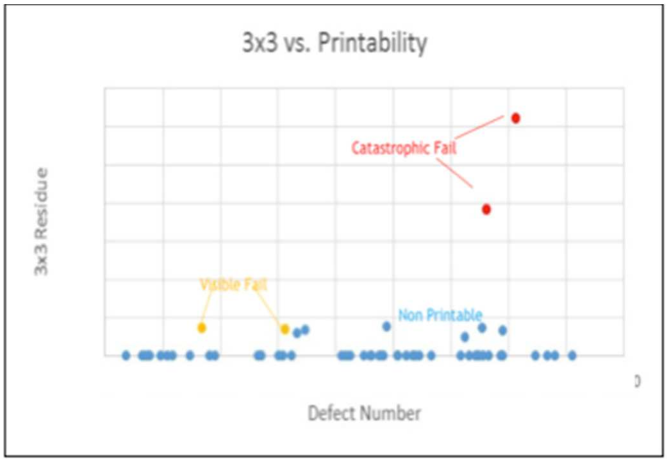


Figure 7: A plot showing the relationship between 3x3 residual and printability.

While some non-printable defects share the 3x3 residual with the visible-fail defects, culling only the defects with 3x3 residual will greatly reduce the number of possible lithographically significant defects. It must be noted, however, that the analysis was qualitative, not quantitative, so "failure" as characterized here represents a qualitative failure only (see discussion in section 3.1).

The discussion that precedes has focused on generally available DUV and MUV inspections; for the last several years, EIDEC has led a program to develop an Actinic Blank Inspection (ABI) systems specifically for inspecting unpatterned mask blanks using actinic (13.5nm) light to identify only lithographically significant defects[13]. Jonckheere has shown that an ABI inspection can accurately detect defects smaller than 2 nm in height and 20 nm in diameter that impact the lithographic image. Clearly this exceeds the capability of MUV and DUV tools, but is not yet generally available.

3.3 Absorber Inspection

As discussed above, MUV darkfield inspection is often used in both the blank-fab and the mask-fab for absorber inspection, as well as DUV phase inspections. Figures 4 and 5 have shown that inspections of the absorber identify both real "absorber only" defects and in the case of MUV, can identify multilayer defects that have been *decorated* by the absorber deposition process. Referring to the optical properties of most mask materials (Si, SiO2, Mo, Ta, and compounds) at 13.5nm, almost all are strong absorbers of EUV radiation; any defects in the absorber composed of these materials will have minimal impact on the lithographic performance of the mask unless they exceed 40-50nm[14]. Inclusion defects of foreign materials may interfere with the RIE etch transfer process, however micromachining repair techniques can shape the defects to match the desired shape. Reviewing Figures 4 and 5, we see that only 20-50% of the defects identified, represent non-fixable multilayer defects, but identifying which are multilayer defects, and which are nuisance absorber defects has proved elusive.

Although effective at characterizing multilayer defects, ABI systems provide little benefit for absorber inspections. The absorber performs as required, and prevents the actinic 13.5nm light from penetrating, leaving multilayer defects invisible.

The largest value of absorber inspection, as previously discussed, is to provide positional information for defects relative to absorber-patterned fiducials.

3.4 Pattern Inspection

Patterned EUV mask inspection is currently performed with two techniques: DUV systems developed primarily for 193i applications, or e-beam inspection systems. While DUV systems have proved invaluable for optical mask production, the industry has demonstrated the need for actinic inspection at every wavelength change. One of the primary limitations to DUV inspection is the pixel size in relation to EUV feature size.

To pattern 32nm half-pitch features, mask features (4x) can be as small as 50-70nm for line-space gratings, and as small as 40 nm for corner-to-corner and tip-to-tip. By contrast, the smallest available pixels used for DUV inspections range from 50-60nm. For dynamic inspection, peak sensitivity is achieved for features larger than 2 inspection pixels, with hypersensitivity when pixel and feature size match[15]. These optical limitations result in MRC (Mask Rule Check) requirements that significantly hamper the EUV mask design to maintain inspectability.

Patterned inspection with e-beam based systems has been demonstrated for EUV masks[16,17]. While sensitivity has been shown as low as 5-6nm, there is risk of *oversensitivity*; in some cases, severe defects identified by mask SEM have little to no impact to the lithographic image[18]. Referring to section 3.2, we have also demonstrated inconsistent results between mask-SEM visible defects and lithographic impact.

Even if these sensitivity challenges were overcome, process noise, specifically with respect to pattern fidelity, or Line Edge Roughness (LER) prevent performing patterned inspections at full sensitivity.

The future of patterned inspection is unclear. There are schools of thought that thorough actinic characterization of the blank prior to use obviates the need for actinic patterned inspection, but for mask makers and mask users to accept this will require a paradigm shift in a decade-old mask fabrication model.

3.5 Post Repair Verification Inspection

All of the inspections discussed to this point have been focused on inspecting the entire mask. There is one additional inspection technique used during mask-manufacture which must be considered as part of the EUV mask lithography infrastructure; Post-repair verification inspection. For DUV masks, actinic small-field aerial-image collection tools are used to simulate the conditions of mask usage on the scanner. For EUV, until recently, actinic aerial systems have not been available, so repair verification was either done through SEM of mask, SEM of printed masks on wafer, or by collecting aerial simulations in a laboratory environment.

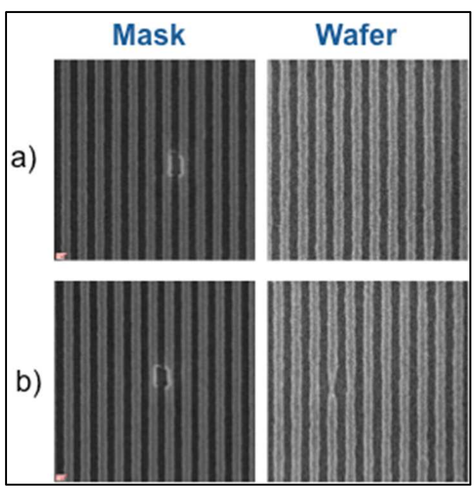


Figure 8: Two mask repairs on 32nm HP patterns with the respective on-wafer results.

Although SEM characterization has sub-1nm resolution, the results are not always predictable. Figure 8 shows two mask repair images which are similar on mask, but have drastically different results on wafer. It is almost universally accepted that actinic aerial imaging systems with sub 5% CD resolution will be required to support HVM mask manufacture. Although verification of repairs through wafer imaging is technically possible, two factors limit it's success: 1) the turn-around-time associated with extending a feedback loop to the fab, 2) the increased level of noise in the results due to other processing.

4. SUMMARY AND CONCLUSIONS

The decades of diligent research and hard work to bring EUV from a concept, to a research project, to a viable manufacturing technology are beginning to pay off. Despite the technical challenges, both the technical aspects of EUV masks, and limited actinic inspection systems, the defectivity focused elements of the EUV infrastructure are coming to maturation. Undoubtedly, the implementation for EUV masks include new elements compared to optical masks, such as the multilayer Bragg reflective mirror, pattern-shift defect avoidance, blank fiducials, and compensational repair. EUV mask infrastructure has required development and implementation of new inspection and analysis systems for both blank and mask manufacturers. Analysis suggests that the newly developed techniques and equipment, in conjunction with furious defectivity learning will result in a high probability of creating high-confidence defect free masks for the 7nm node.

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