The door opener for EUV mask repair

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ABSTRACT

The EUV-photomask is used as mirror and no longer as transmissive device. In order to yield defect-free reticles, repair capability is required for defects in the absorber and for defects in the mirror. Defects can propagate between the EUV mask layers, which makes the detection and the repair complex or impossible if conventional methods are used. In this paper we give an overview of the different defect types. We discuss the EUV repair requirements including SEM-invisible multilayer defects and blank defects, and demonstrate e-beam repair performance. The repairs are qualified by SEM, AFM and through-focus wafer prints. Furthermore a new repair strategy involving in-situ AFM is introduced. We will apply this new strategy on real defects and verify the repair quality using state of the art EUV wafer printing technology.

Keywords: EUV, defect-free reticle, multilayer defect, blank defect, compensation repair, e-beam repair

1. INTRODUCTION

Driven by the consumer market and keeping pace with Moore’s law, integrated circuit components are continuously shrinking in dimension. To make smaller circuit features, the microelectronic industry is developing next-generation extreme-ultraviolet (EUV) lithography for high-volume chip manufacturing. The technology’s 13.5nm wavelength imposes very strict requirements on the quality of the involved optical elements, such as the light source, mirrors, and masks.

For reticle production mask repair has become a fundamental part of the production process. In switching from the transmissive 193nm optics used in conventional photolithography to reflective EUV optics, the mask architecture has had to evolve. EUV masks include a multilayer Bragg mirror onto which an absorber pattern is defined. This transition has dramatic challenges for performing successful mask repair. Since the EUV-photomask is used as a mirror and no longer as a transmissive device the severity of different defect types has changed significantly. The EUV-photomask material stack is much more complex than the conventional 193 nm photomask. Defects can arise in these masks from multiple sources: optically imperfect mirrors that lead to pits and bumps, wrongly written absorber patterns, and even dust particles lying on the mask. Repair capability is required for defects in the absorber layer and for defects in the mirror. This expands the field of critical defect types even further and requires not only repair capability for smaller defects but also for new material stacks and multilayer defects. A tighter interconnection is also necessary between different mask writing levels: blank inspection1, pattern generation2, pattern mask inspection, repair, final inspection.

One of the most promising concepts for EUV photomask defect repair is focused electron beam induced processing3. This technology employs a high resolution electron beam to induce a local chemical reaction on the EUV mask surface. A suitable precursor gas is dispensed through a nozzle in close vicinity to the incident beam. A reaction is induced by the electrons. Depending on the precursor chemistry, either a deposition is caused by fragmentation of precursor molecules, or a reaction between the adsorbed molecules and the substrate material results in volatile products and thus etching of the substrate material. The reaction is confined to the area exposed by the electron beam, so this technique allows for high resolution nanostructuring.

From a repair point of view, a EUV mask can be separated into 3 layers: absorber, capping layer and multilayer. Unlike defects on 193 nm photomasks, defects on EUV masks can propagate through these layers. This makes the detection and
the repair difficult or impossible if conventional methods are used. A review of different defect types shows that, from a repair point of view, all defects fall into two categories. One is a defect in the EUV absorber itself. This is almost impossible to repair if 193 nm e-beam mask repair technology is applied, because parasitic degradation and collateral damage of the capping layer are caused by the 193 nm repair method. The second defect type is a distortion in the blank mirror. Such a defect has two delicate implications. First, until today the direct repair of a EUV mirror has not been demonstrated successfully, although several concepts were proposed. Then, the defect is almost invisible in scanning electron microscopy (SEM) review.

In this paper we give an overview of key features of our e-beam based repair tool, discuss EUV repair requirements and demonstrate current repair performance. We show the methodology, with which the smooth multilayer defects can be visualized and located. Furthermore the repair strategy is demonstrated on natural defects. The repair quality is verified by wafer prints. This work is a further development on previously reported first results. On the one side, we had shown the through-focus reparablebility of ML-based “pits” and “bumps”, and had stressed out the importance of accurate repair shape positioning for successful compensation. On the other side, we had reported simulation results for absorber-free ML “pits” and “bumps”, and their effects on reflectivity loss and through-focus printing effects.

A mask for production must be free of defects, both at blank level and absorber pattern level, so that they do not kill yield of the fabricated integrated circuit. EUV masks require a perfect “blank” and a defect-free patterning. In reality, even when meeting very strict quality standards, a certain number of defects can generally not be avoided. Some of the known blank defects can be covered by absorber material by using smart patterning. But some small blank-related defects can be unnoticed until wafer printing. The patterning cannot be made free of a few errors either. The final defect map usually contains blank-related- as well as absorber-related defects. The repair strategy must thus be able to cope with small amounts of both defect types. Firstly, the absorber-related defects must be repaired, either by etching away opaque defects or by adding absorber on clear defects. Secondly, the structures patterned on non-removable blank defects must be edited or compensated in order to present lithographically acceptable process windows.

2. EXPERIMENTAL

2.1 EUV reticles

The mask patterns used consist of lines and spaces in vertical direction, all across the exposure field. Through the correlation of multiple inspection techniques the total set of known printing defects was determined. The ML-defects within this set have been identified and many were visualized by AFM. This investigation was an ideal baseline for a first experimental study of the compensation repair of natural ML-defects. Wafer printing is used to determine the success rate of the repairs. The 40 nm pitch masks were exposed on the ASML EUV Alpha Demo Tool (ADT), and the 32 nm pitch mask on the ASML NXE:3100 tool at IMEC. For the 32 nm node reticle, the available inspection results were obtained from M1350 blank inspection and from KLA 2835 wafer inspection on NXE:3100 exposed wafers.

2.2 E-beam mask repair tool

Repairs are performed using the electron beam based Carl Zeiss MeRiT® repair technology. Gas-assisted focused electron beam induced processing is a well-established technology for nano-structuring by locally depositing or etching materials from the processed samples, which are respectively used for repair of clear and opaque absorber defects. Subsequent to adsorption of precursor molecules at the surface, for the former, deposition is realized by e-beam induced reaction and immobilization of the precursor. For the latter, etching is initiated by the e-beam induced reaction of the precursor with the material on the mask surface. Its application to photolithographic mask repair has become the state-of-the-art method for high-yield production of defect-free masks with critical dimensions from 65 nm in 2006 down to the present 32 nm.

2.3 AFM analysis

The commercial MeRiT® mask repair tool from Carl Zeiss SMS has been refined to support EUV mask repair. One requirement is to rapidly locate and visualize the mask defects before the actual repair. Since shallow defects like those present on the EUV blanks can be invisible to top-view SEM, a combination of optical and scanning probe methods is necessary. An atomic force microscope (AFM) compatible with the vacuum environment and the used process gases was developed as an upgrade for the MeRiT® HR platform, and integrated into the vacuum chamber. The design allows for
rapid and accurate switching between SEM and AFM imaging as well as nano-processing using either the SEM or AFM mode over the whole surface of a photolithographic mask. Probe exchange can be conducted automatically, using a robotic handling system, without breaking the vacuum in the chamber.

In the course of our process development, AFM results on EUV masks had been gathered also with a commercially available atmospheric-pressure AFM. This allowed us to cross-check the obtained results and offered easier access during the hardware development phase. Some of the AFM results shown in this paper originate from this external AFM, operated under ambient conditions. Only the results labeled as “vacuum-AFM” were obtained with the AFM that is integrated in the MeRit® tool.

3. EUV ABSORBER DEFECT REPAIR

The SEM review of the two 40 nm node reticles resulted in a series of 30 opaque absorber defects (distributed equally on both masks), and 29 clear absorber defects. Among the real opaque absorber defects, most (29 out of 30) were of a “complex bridge or extension over one space” type, only one of them extending over 3 spaces. All of the addressed defects were repaired successfully, so that no more CD deviations could be observed on the printed wafers at the repair locations. The exposure was performed after several days and after cleaning the repaired mask, which did not affect the print results. Typical results are presented in fig. 1.

![40 nm real defects](image1)

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Figure 1. Example repair results for real opaque absorber defects on two representative 40 nm reticles. (Left) MeRit® SEM top views of the defects and SEM views of ADT wafer prints from the defect areas. The ADT print images are displayed with horizontal mirroring for easier comparison. (Right) MeRit® SEM top views and SEM views of the ADT-printed wafers from the same areas after repair.

The SEM review of the 32 nm node reticle gave a series of over 50 absorber-related defects, all of which were opaque absorber defects. A representative subset of 30 real defects was selected and repaired with a single process recipe, consisting of 4 multi-line defects, 8 partial height defects, 14 complex bridges and extensions (mostly extending over a single space), and 4 double-extensions. The average time necessary per etch repair using standard process conditions was...
20 minutes. For the partial-height defects (classified as such by SEM), no AFM information was necessary since the process stops on the Ru-cap: the shorter process duration, 50 to 75% of that needed for full-height defects, reflected the reduced absorber thickness. Typical repair results are shown in fig. 2. Anticipating the difficulties to locate well-repaired defects on the wafer prints in the absence of markers, 16 of the 30 defect locations were marked by cutting away short pieces of a line, at 3 spaces distance ("cut-markers", not shown).

![32 nm real defects](image)

**Figure 2.** Example repair results for real opaque absorber defects on a 32 nm reticle. (Left) MeRiT® SEM top views of the defects and SEM views of NXE:3100 wafer prints from the defect areas. The NXE:3100 print images are displayed with horizontal mirroring for easier comparison. (Right) MeRiT® SEM imaging and SEM views of NXE:3100 wafer prints of the same areas after etch, demonstrating successful repair.

A substantial repair yield was obtained. Under the qualification conditions used, only a single defect, bridging over 8 lines, did show appreciable CD variation on the wafer print (in the form of larger spaces). This extra-large defect would have required a different process recipe, and will be used as a learning example for future repairs. Among the other defects, either no CD variation was visible in the area between the printed cut-markers, or the repaired defect location could not be recognized on the prints.

### 4. EUV MULTILAYER DEFECT CHARACTERIZATION AND REPAIR

#### 4.1 ML defect characterization

The above shown defects are located in the layers above the capping layer of the EUV mask. State of the art repair tools can address these for repair. Yet the defect origin in a EUV mask is additionally between the LTEM substrate and the capping layer as shown in fig. 3. EUV mask defects can roughly be divided into two classes. One class contains all the "classical" clear and dark defects located above the capping layer. The other class contains the defects that cause a multilayer distortion.
A first requirement for a successful repair is to see the defects. For conventional repair of absorber defects typically the flaw of the absorber pattern can be fully visualized by SEM. AFM information can be helpful to repair clear absorber defects, since shallow thickness variations would be unnoticed by SEM. For ML-defects, at least the ones that risk to be missed by blank inspection are typically shallower than approximately 5 nm. Under the usual mask-compatible imaging conditions, these are not visible in SEM (see fig. 4). The limited accuracy of the available defect maps (in our experience typically still up to 1 µm, due to positioning mismatch between several tools) does not yet allow the user for a successful “blind” navigation to a defective space. Since the multilayer distortion causes a change of the aerial image an obvious process would be to make distortion visible using AIMS. Using the EUV AIMS it should be easy to calculate the difference of the so determined aerial image and the intended wafer design. This calculated difference can then be used by the repair tool to compensate for this defect. Since the EUV AIMS is not available right now an alternative solution is required in the meantime.

AFM has proved very successful in finding, locating and measuring such occurrences of shallow ML-defects by the analysis of the surface of the ML.

![Defect types and repair solutions](image)

**Figure 3.** The mask repair tools work only effective above the capping layer whereas the possible defect origin of defects which is addressed by the mask repair tool is located between the LTEM substrate and the surface.

**Figure 4.** Estimation of the need for AFM input for the repair of different EUV-specific defects.

<table>
<thead>
<tr>
<th>Defect type</th>
<th>Example</th>
<th>Repair solution</th>
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<td>Opaque absorber defects</td>
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<td><strong>MeRiT® HR EUV etch</strong></td>
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<tr>
<td>Clear absorber defects</td>
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<td><strong>MeRiT® HR EUV depo:</strong> AFM input is helpful to determine deposition height</td>
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<tr>
<td>Multilayer „pits“ and „bumps“</td>
<td><img src="image" alt="Multilayer pits and bumps" /></td>
<td>Compensational repair: AFM input is mandatory for repair shape placement</td>
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The SEM review of the two 40 nm node reticles resulted in a series of over 50 ML-related defects. A representative series of 44 defects, equally distributed on both masks (25 vs. 19), was investigated. One of the masks had predominantly “bumps” (23 out of 25), while the other had predominantly “pits” (18 out of 19).

The limit for SEM visibility of ML defects is around 5 nm thickness. After having located a defect by AFM, the SEM imaging parameters can be optimized to try and increase the contrast. In particular by fine-tuning the beam acceleration conditions, some of the larger “bumps” and “pits” can show a faint contrast (see fig. 5). However, this would not have allowed for unambiguous location of the defects without AFM cross-check. The ML defects of interest for repair (i.e. the smaller ones, susceptible of being missed by blank inspection) will hence further be considered as “SEM-invisible”.

![Figure 5. Example characterizations by SEM and AFM of multilayer-based defects on EUV reticles with 40 nm L&S. (left box) SEM top-view and AFM 3D view, of a raw ML “bump” (height 5 nm, full width 70 nm). (right box) SEM top-view and AFM 3D view, of a raw ML “pit” (depth 3 nm, full width 130 nm).](image1)

The in-situ AFM option of the MeRiT® HR tool series is designed to allow for SEM and AFM imaging in a single tool. Applied to EUV reticles, its scope is to locate ML defects easily and rapidly, as a step in the repair workflow. This relies on an accurate positioning of the AFM with respect to the e-beam. This capability and the imaging performance of the in-situ AFM are demonstrated in fig. 6. The AFM image was taken in 5 minutes. A previously compensated 40 nm EUV ML bump with height 15 nm still SEM visible and width 100 nm is clearly located and imaged at the bottom of the space.

![Figure 6. Imaging of a EUV ML defect by the MeRiT® HR in-situ AFM. (Top left) Schematic drawing of the two imaging modes in a single vacuum tool. (Top right) MeRiT® top-view SEM imaging of previously compensated bump. (Bottom) MeRiT® vacuum AFM imaging of the same defect, with cross-sectional profile along the defect space shows a clearly resolved 15 nm high ML bump at the bottom of the space.](image2)
4.2 ML defect compensation repair

The basic principle is depicted in fig. 7. Due to the multilayer distortion the light is scattered. As a consequence the dose in the space stays below the dose to clear limit and the space is not resolved. This reflectivity loss from ML defects can be compensated in the EUV scanner by removing absorber around the defective area\(^6\). The intensity can be increased by removing absorber material around the distortion. The shape of the distortion must be done in a way that the areal image is reconstructed. With the so achieved increased intensity, the open mirror spaces print acceptably, while the narrower lines do not affect the diffraction-limited photoresist image. Repair examples on a real pit (resp. bump) are shown in fig. 8 and fig. 9).

Figure 7. This series shows a simulated aerial image when absorber material is removed around the multilayer distortion. Without modification the distortion causes an insufficient dose to clear in the space during the wafer exposure process which causes that the line bridge. The more material is removed from the absorber around the distortion the more light gets into the space.

Based on the AFM input, a repair shape can be satisfactorily positioned over the defect area. A multilayer pit and a multilayer bump, both previously printing with a strong dependency on the focus setting during wafer printing, were successfully compensated over 200 nm focus range. Although it can be expected from previous simulation studies\(^1\), that the effect of absorber removal should be a CD shift of the same magnitude within all focal planes, it turns out that the experimental results do not show any measurable residual dependency of CD on focus. This had been noticed on previous compensation tests of real defects, although to a lesser extent\(^6\). One of the reasons could be that the assumptions used in the simulations do not describe accurately enough the ML profile obtained in reality. These results show that printable multilayer pits and bumps can both be successfully compensated.
Figure 8. Demonstration of a successful through-focus compensation repair on a real ML pit in 40 nm L&S. (Top) Reticle AFM imaging of the defect before and after repair (performed with two different AFM tips, which yielded different cross-sectional edge profiles). (Top right) MeRiT® top-view SEM imaging after repair. Notice that the ML pit is almost invisible. (Bottom) SEM views of the ADT-printed wafers before and after repair, at different focus positions around best focus (BF), as a reminder to a previous publication.

Figure 9. Demonstration of a successful through-focus compensation repair on a real ML bump in 40 nm L&S. (Top) Reticle AFM imaging of the defect before and after repair (performed with two different AFM tips, which yielded different cross-sectional edge profiles). (Top right) MeRiT® top-view SEM imaging after repair. Notice that the ML bump is almost invisible. (Bottom) SEM views of the ADT-printed wafers before and after repair, at different focus positions around best focus (BF).
4.3 32 nm blank-level defect repair

The 32 nm reticle was inspected at the blank vendor’s site level by a M1350 blank inspection tool, and resulted in 36 blank-level defects. The correlation of the known blank defects with the defects found by KLA 2835 wafer inspection of the NXE:3100 prints highlighted 18 printing defects. These were reviewed in the MeRiT® by SEM. Among the 18 defects, 12 were large. These were interpreted as “research-class blank” defects, classified as non-repairable, and are of the type that must be avoided preferably during blank manufacturing. From the remaining 6, one appeared as an absorber-embedded particle, but 5 were repairable ML-related defects (4 of which were SEM-visible, and a single one was SEM-invisible). The SEM-visible defects were repaired or compensated. Repair results are shown in fig. 10.

![32 nm blank-level defects](image1.png)

### 32 nm blank-level defects

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<td>BF -60 nm</td>
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Figure 10. Review and repair of reticle defects detected by blank inspection. (Left). MeRiT® SEM top-view imaging of the defects, at the locations indicated by wafer inspection, with corresponding SEM views of the NXE:3100 printed wafers. (Right) MeRiT® SEM top-views of the same areas after repair or compensation.

The blank-based particle (top row in fig. 10) led to a non-conformal absorber deposition. Etching the half of the particle which lied in the space was enough to provide a printing-defect-free area. Two solid blank defects, assumed to be ML defects, could be successfully compensated, one of which was lying almost centrally in the space, the other one buried under an absorber edge. The through-focus prints reveal a slight residual printing behavior besides the best focus, which indicate that these defects are probably at the limit of what can be compensated under the imaging conditions in use. Still, this represents the first qualification of a compensation repair strategy on 32 nm structures as printed with the NXE:3100 scanner. Further investigations will involve AFM characterization and compensation of the less solid, SEM-invisible ML defects present on this mask.

A criterion for reparability of blank defects can be proposed based on these results. In view of the further development of blank inspection tools, it is considered a good approach to restrict the technique of compensation repair to the less solid ML defects, i.e. the ones that are more likely missed by state-of-the-art blank inspection. Based on the repair and compensation possibilities offered by e-beam mask repair, defects found at a late point in the reticle manufacturing process might be less severe than those found early. The latter consist of those found by generations of inspection tools nowadays recognized as less performing. To avoid the need for wafer printing before mask qualification, the printability of the defects, before and after repair, will be qualified in a closed-loop approach with the AIMS™ EUV tool presently under construction.15
5. SUMMARY, CONCLUSIONS

This paper showed the performance of the MeRiT® HR mask repair tool to repair EUV real defects on 40 nm as well as 32 nm node reticles. The defects were classified as classical “absorber-level” defects or mirror distortion “multilayer-level” defects. The e-beam mask repair technique is ready to repair both classes of defects. Successful repairs have been presented for both cases. The need for AFM input for the successful compensation of multilayer-based defects was highlighted. To cover this need, an optional AFM system was implemented in the tool. Its principle was explained. Experimental results obtained with the in-situ AFM system on the EUV reticles were presented and showed good performance in terms of positioning accuracy, resolution, and scanning speed.

A series of absorber-based real defects and blank-based real defects was reviewed by SEM, AFM, and EUV printing. Successful e-beam-based repair and compensation over the whole focal range were demonstrated on significant numbers of typical EUV-specific real defects on 40 nm and 32 nm pitches. This is a first qualification of the compensation repair strategy under state-of-the-art lithographic imaging conditions at the NXE:3100. The e-beam mask repair technique thus offers a solution to close the quality gap in the EUV mask manufacturing chain.

REFERENCES