Evaluation of multilayer defect repair viability and protection techniques for extreme ultraviolet masks

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Abstract. A variety of repairs were conducted on extreme ultraviolet (EUV) multilayer, including protection against pattern degradation in manufactural use, in order to evaluate feasibility of multilayer repair and subsequent protection schemes. The efficacy of postrepair protection techniques is evaluated to determine the lifetime of multilayer repairs. Simulations were used to select the optimal material thicknesses for repair protection, and the simulation results are verified with the lithographic results. The results showed a high correlation coefficient. Finally, all repaired sites were cleaned multiple times to quantify repair durability and impact on wafer critical dimension (CD). Aerial imaging of the repair sites before and after cleans showed a dramatic degradation of wafer CD. However, we show that applying a surface protection material after multilayer repair successfully mitigates the influence of multilayer degradation during extensive manufacturing operations. © 2016 Society of Photo-Optical Instrumentation Engineers (SPIE)

Keywords: extreme ultraviolet; absorber stacks; mask defect repair; repairability; printability.

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1 Introduction

Owing to the decades of manufacturing experience coupled with the simple stack structure used in fabricating deep ultraviolet (DUV) photomasks, conventional mask blanks have routinely been free of defects.1 However, as device scaling continues to drive innovative patterning solutions, extreme ultraviolet lithography (EUVL) has begun to receive industry-wide acceptance to complement and likely replace DUV lithography.2 Due to the considerable absorption of EUV radiation, the lithography system is based completely on reflective rather than refractive optics. This reflective design introduces a new class of defects not seen in previous mask technologies.3–9 As such, EUV mask defectivity remains a persistent obstacle that must be addressed in order to enable EUVL high-volume manufacturing (HVM).

Various defect-mitigation strategies have been demonstrated in order to reduce the prevalence of native blank defects.10,11 However, the presence of unavoidable defects motivates the need for a robust mask-repair solution for native blank defects. There have been tremendous advancements in absorber repair and compensation methods; for example, the demonstration of selective absorber removal with 10-nm resolution represents great promise for eliminating process defects. Micromachining was introduced to address multilayer defects and attempts to correct for the phase effect by judicious removal of multilayer material.12–15

Despite promising results from prior studies, considerations for HVM and lifetime durability of micromachined repair sites have remained largely unexplored. In particular, exposed multilayer sidewalls have been shown to significantly degrade after several mask cleans.16 In order to quantify any potential imaging impact from cleans, a variety of repairs, guided by rigorous three-dimensional (3-D) electromagnetic field (EMF) simulations, were performed on the EUV multilayer, and actinic aerial image critical dimensions (CDs) before and after cleans were experimentally measured and compared. Several protection methodologies were experimentally evaluated to quantify their effectiveness in preventing degradation from cleans. The work here focuses important attention on the lifetime durability of micromachining mask repair and demonstrates promising protective techniques to address degradation concerns during extensive manufacturing operations.

2 Methods

In order to replicate repair methodologies assuming the presence of a multilayer defect, we adopted micromachining repair to excavate the EUV multilayer. Then, a protective layer treatment was applied to the exposed multilayer postmicromachining. Analysis and comparisons were studied between pre- and postcleans. The EUV blank used for this study was built with the standard film structure: 60 nm of absorber layer, 2.5 nm of Ru-capping layer, 40 pairs of Mo/Si bilayers on the substrate and backside film of CrN. The mask patterning processed 180-nm hole arrays in order for better control of the repair process. Figure 1 shows repair and treatment processes for sample creation. In order to follow the way of improving wafer print quality,17 an electron beam (EB) repair tool was used to widen the absorber pattern at first and then a nanomachining repair tool was used to excavate various amounts of multilayer. The dimension of absorber repair defined as D is targeted 60 nm in lateral direction. The dimension of multilayer repair defined as X is from 45 to 90 nm in lateral...
The dimension of multilayer repair, defined as Z, is from 35 to 70 nm in depth, follows previous work. After applying the repair process to the pattern, three kinds of protective layer treatments were performed in order to protect the exposed multilayer from degradation due to cleans. The protective treatment thickness used for subsequent experiments was selected via rigorous 3-D EUV mask simulations to help threshold the lithographic imaging degradation. Here, the finite-difference time-domain method was used for 3-D EMF modeling, following prior computational work on multilayer defect compensation. Generally, as the postrepair protective layer increases in thickness, the more wafer CD loss occurred due to the increase in absorption of EUV light from a thicker protective layer. In manufacturing operations, the thickness of post-treatment must minimally impact wafer CD change. The treatment thickness used for our subsequent experiments is targeted to maintain imaged lithographic CD, as compared to a nontreatment site.

To characterize the mask, the repaired sites were measured for CD, depth, and cross-section profile by means of scanning electron microscope (SEM) and atomic force microscope (AFM). An EUV microscope enables the capturing of aerial images with the same illumination setting (NA, source) as an EUV scanner. To simulate wafer printability, aerial image CD was measured by defining a certain threshold to the intensity profile generated from microscopic aerial image. Measured value on the mask pattern is used for building a simulation model. Simulated wafer CD is compared to EUV microscope aerial CD in order to validate the simulation model.

The mask was cleaned over 30 times to accelerate potential pattern degradation and to replicate conditions of a pellicle-less mask in normal fab operations. We compared mask characteristics and wafer printability between pre- and postcleaning to evaluate how much cleaning degrades the repaired sites and which postrepair treatment method is the most protective in minimizing pattern degradation. Transmission electron microscope (TEM) was used to obtain cross-sectional views of the repair sites, allowing for a detailed comparison of the cleaning impact on sites with and without postrepair protection.

3 Results and Discussions

3.1 Multilayer Repair Simulation

3.1.1 Treatment thickness simulation

Since the influence of applying a postrepair protective treatment on wafer CD was unclear, we determined the optimum treatment thickness by means of simulation. Figure 2 shows simulation results of the postrepair treatment’s influence on wafer CD change. The horizontal axis indicates treatment thickness. The vertical axis indicates wafer CD reduction rate as compared to an untreated site. Each treatment result showed linearly proportional tendencies.

The specification was set at 5% change in wafer CD as an acceptable baseline, and the maximum thickness of each treatment was determined form this baseline. Along with each protection methodology, the thickness of acceptable treatment varied. The thickness of treatment A was determined to be limited to ≤6 nm, treatment B is limited to ≤1 nm, and treatment C is limited to ≤5 nm. It should be noted that thicker treatments could be used if the repaired dimension is appropriately compensated.

3.1.2 Correlation result between actual and simulation

In order to confirm reliability of the simulation, we verified between simulated results and experimental results including both of treated and untreated repair sites. Figure 3 shows aerial CD correlation result between an EUV microscopic aerial image (quasar illumination at 0.33 NA) and simulation. The horizontal axis indicates repaired site aerial CD, as measured by the EUV microscopic. The vertical axis indicates repaired site aerial CD, as measured from lithographic simulation images. The correlation coefficient was >0.9, illustrating high confidence in the simulated model. Therefore, it was concluded that the current simulation model is very reliable for evaluating multilayer repair and represents a valuable tool for predicting target repair geometries.

Fig. 1 Process of repair and postrepair treatment.

Fig. 2 Simulated influence of postrepair protective layer treatment versus wafer CD change.
3.2 Cleaning Impact on Multilayer

3.2.1 Target repair size dependency and treatment type comparison at single focus image

To understand impact of cleaning, some repaired samples were measured by EUV microscope, AFM, and SEM, and analyzed between pre- and postcleaning. The EUV microscope can provide wafer performance characteristics, while AFM and SEM allow for mask characterization.

To characterize the change between pre- and postcleaning, we compared results from the viewpoint at both the mask- and wafer level. In order to assess the impact of cleaning, Fig. 4 provides a comparison between pre- and postcleaning characteristics via aerial imaging as well as mask-level metrology. For this particular repair, target sizes were $D$ (lateral direction on absorber) = 60 nm, $X$ (lateral direction on multilayer) = 90 nm, $Z$ (depth direction in multilayer) = 70 nm, and no treatment was applied. Both EUV microscopic imaging [Fig. 4(a)] and the mask AFM profile [Fig. 4(b)] showed that cleaning degraded the initial pattern shape of the repair site.

To understand the dependency of target repair size on CD change due to cleans, we measured the CD difference from both the aerial image and physical mask measurement result. The repair target sizes of the intended samples were from 45 to 90 nm in $X$, and 35 to 70 nm in $Z$. $D$ is consistently 60 nm for all samples. Figure 5 shows the cleaning influences as a function of target repair size. The horizontal axis indicates repair target size in absorber and multilayer. The vertical axis on left indicates CD change in the aerial CD due to cleans. The vertical axis on right indicates mask-level CD change due to cleans, as measured by SEM. The result showed that as the repair target size gets bigger, the repaired site tends to be influenced more greatly by repeated cleans. In particular, the wider ($X$ and $Z$) the repair, the greater the influence of cleans on aerial CD change.

To quantify the impact of CD change on repairs with a protective treatment, we measured the CD difference from both the aerial imaging and physical mask measurement result. The repair target sizes of the intended samples were consistently 60 nm in $D$, 90 nm in $X$, and 70 nm in $Z$. Figure 6 shows the postrepair treatment comparison result. The horizontal axis indicates the type of repair treatment used. The vertical axis on left indicates change in aerial axis on left indicates CD change in the aerial CD due to cleans. The vertical axis on right indicates mask-level CD change due to cleans, as measured by SEM. The result showed that as the repair target size gets bigger, the repaired site tends to be influenced more greatly by repeated cleans. In particular, the wider ($X$ and $Z$) the repair, the greater the influence of cleans on aerial CD change.

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CD due to cleans. The vertical axis on right indicates CD change on the physical mask due to cleans, as measured by SEM. The results showed that the greatest amount of CD change due to cleans was from the repair without any prior treatment, while protection methodology A, B, and C showed the mitigation of CD impact, both physically on the mask and also in the aerial CD.

3.2.2 Treatment type comparison through-focus image

In order to better understand the impact of postrepair treatment, through-focus aerial image evaluation was performed. The repair target sizes of the intended samples were consistently 60 nm in D, 90 nm in X, and 70 nm in Z. Figure 7 shows each of postrepair treatment comparison image expanding through-focus. Every treatment result captured both best-focus aerial image, and positive and negative focus.

The graph in Fig. 8 shows the pre- and postcleaning aerial CD impact through several focus planes. The horizontal axis indicates focus offset in mask units. The vertical axis indicates CD changes in the aerial image. At best focus, the result showed that repair without treatment had a 22% aerial CD degradation postcleaning. Treatment A showed an 18% aerial CD degradation, whereas treatments B and C showed a 9% and 3% reduction, respectively. Through-focus results of aerial CD change showed that repairs without treatment suffered from increasing CD degradation through positive and negative defocus. However, the curves remained relatively flat for repair sites with treatment, indicating that the impact of cleans on depth of focus was mitigated by the use of a protective treatment.

3.2.3 Transmission Electron Microscope cross section image

In order to confirm how postrepair treatment protects the exposed multilayers from cleaning chemistry, we obtained cross-sections by TEM. Figure 9 shows TEM images of repair sites with and without treatment, postcleaning. Images are magnified on the repaired sites to compare between treatment and no treatment. The repaired site without treatment [Fig. 9(a)] showed degradation and undercutting of the multilayer due to the impact of cleans. The degradation also showed the etching of molybdenum, as comb-like silicon fingers can be seen in the middle of side wall, consistent with past observations. The repaired site with treatment [Fig. 9(b)] showed reduced degradation as compared to the untreated result.

4 Summary

A variety of repairs on EUV multilayer, including protection against pattern degradation, were conducted on 180 nm contact holes using nanomachining and EB repair technologies. The repair target was guided by past work. Rigorous
simulations were also used in order to target the amount of postreparative protective surface treatment to apply so that protected repaired sites can maintain its reflectivity. The simulation results were verified with the experimental lithographic results from an EUV microscope. Correlation coefficient between simulated and experimental aerial CD showed more than 0.9, indicating that simulations represent a promising tool to predict wafer characteristics for multilayer repair, impact of surface treatment on multilayer repair, and provide guidance on life-time degradation mitigation techniques. Durability and lifetime of multilayer repairs were tested by subjecting the repaired sites to multiple cleans and experimental aerial imaging between pre- and postcleaning was captured. Cleaning impact on the repaired site was assessed by change in aerial CD, which showed roughly 20% reduction in CD. A trend emerged showing that as the repair target size increased, the repaired site was increasingly affected by a repeated cleans process. It was found that by applying a postrepair surface protection layer, aerial image CD degradation due to cleans was minimized from 3% to 9% aerial CD reduction. TEM imaging showed that the cleaning process degrades the postrepair cross section. In summary, we have demonstrated that there may be significant degradation on any repairs penetrating the capping layer if the mask was to receive multiple cleans after fabrication. As a countermeasure, postrepair treatment techniques on the exposed multilayer will be needed to prevent such degradation.

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References


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