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EUVL mask repair: expanding options with nanomachining

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ABSTRACT

Mask defectivity is often cited as a barrier to EUVL manufacturing, falling just behind low source power. Mask defectivity is a combination of intrinsic blank defects, defects introduced during the mask fabrication and defects introduced during the use of the mask in the EUV exposure tool. This paper works towards minimizing the printing impact of blank defects so that the final EUVL mask can achieve a lower defectivity. Multilayer defects can be created by a step or scratch as shallow as 1nm in the substrate. These small defects create coherent disruptions in the multilayer that can generate significant variations in mask reflectivity and induce clearly-defined, printable defects. If the optical properties of the defect can be well understood, nanomachining repair processes can be deployed to fix these defects. The purpose of this work is to develop new nanomachining repair processes and approaches that can repair complex EUVL mask defects by targeted removal of the EUVL mask materials. The first phase of this work uses nanomachining to create artificial phase defects of different types and sizes for both printability evaluation and benchmarking with simulation. Experimental results validate the concept, showing a reasonable match between imaging with the LBNL Actinic Inspection Tool (AIT) and simulation of the mask topography measured

Continues on page 3.

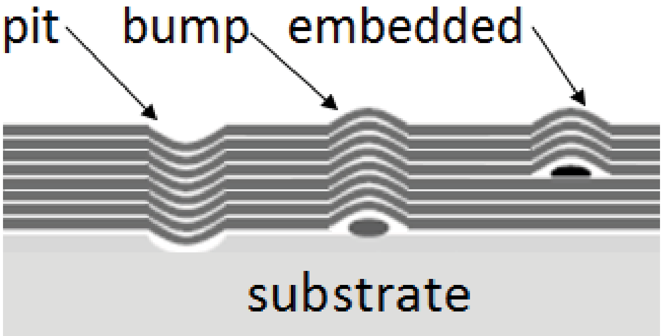

Figure 1. A schematic diagram of multilayer defects illustrates a pit, a bump and an embedded particle.

TAKE A LOOK INSIDE:

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EDITORIAL

It is a Matter of Size ...

Frank E. Abboud, Intel Corp.

Our mask industry continues to be at the center of almost every controversial lithography issue. I could not help but notice the amount of chatter these days regarding the reticle size. A great deal of technical discussions also center on the need for a higher magnification factor that would drive the mask size to a larger form factor, like 9x9 or larger. I listened to a few technical arguments and all the points actually connect. If the need for higher NA EUV scanner is real, then higher magnification, like 6x or 8x, is needed to maintain optical efficiency; therefore a larger mask is needed to, in turn, maintain throughput. Of course, the question that follows this is: will the mask industry be able to adopt the new requirement and not be an obstacle?

I have to say this brings memories of the mid-nineties, where conference after conference talked about the imminent next generation mask size of 9x9. I even attended some of those conferences! Those of us in the mask business during the nineties can also recall the multiple working group meetings that resulted in industry standards that were written on 9x9. The necessity for 9x9 was so certain, tool makers were told that new platforms must be designed to handle the next generation reticles. Just to make the point, I found an industry survey conducted by PMJ in 1995 in which more than half the participants predicted that 6x6x.25 will not be the reticle size for the high volume manufacturing of the 1 Gbit DRAM. The survey listed a choice of 7x7, 8x8 or 9x9. Needless to say 9x9, was the most popular. Well as you all know, 6x6x.25 not only made the 1Gbit DRAM but I think is also currently making the 32~ 64Gbit.

Our mask industry is not opposed to change. Actually we embrace change. The mask size has changed multiple times since the early days of 2x2, in the sixties to 3x3, and then 4x4 in the late seventies. In the early eighties, there were a number of sizes, including a 7x7 that was used for 1x printing. The reticle was held vertically and little or no consideration for sag or bow due to glass thickness was given. With the introduction of the 5x steppers, mask size of 5x5x0.09 became the industry standard. However, with pressure for larger field size and the need for better accuracy, the 6x6x0.25 reticle was born in the late eighties. It was a good compromise of a larger field and increased thickness for better flatness. I also must mention that today, a large number of 5x5 reticles are still being produced, although all the high end is using 6 inch. Over time, there have been many attempts to change the reticle size (7x7, 6x9, 8x8, 9x9 ...etc.) But the question of why we have not made the change still remains.

Well, we know the lack of change is not attributable to technology. Actually, going to a larger substrate and increasing the magnification to 6x or 8x would take us back to the days of the "mask makers vacation," when 1x steppers were replaced with 5x. Granted, the larger substrate would introduce mechanical challenges to equipment makers, and probably handling and defect issues at the mask shop, but these are engineering problems that we can overcome. Today, the fundamental challenge in mask making is the ever shrinking feature size and associated CD and registration control. With higher magnification, the feature size would reset to something from one or two previous nodes. The key issue is really economics; in the nineties the reason the industry did not switch to 9x9 was primarily driven by the choice of Lithography solution. Usually one of two things happened either the assumptions do not materialize or a better (cheaper) Lithography solution ends up winning. It is really all about return on investment. When larger reticles are proven to provide a competitive advantage and/or lower cost, the mask industry (equipment makers and mask makers) can move quickly and lead the transition. We have seen this time and time again. Meanwhile, stay tuned to all the chatter and the conferences as we try to learn from the past but not be encumbered by it. I will be looking forward to a talk by Dr. Harry Levinson at SPIE Advanced Lithography at the end of February and also the Large Glass Panel Discussion at SPIE Photomask in Monterey, September.

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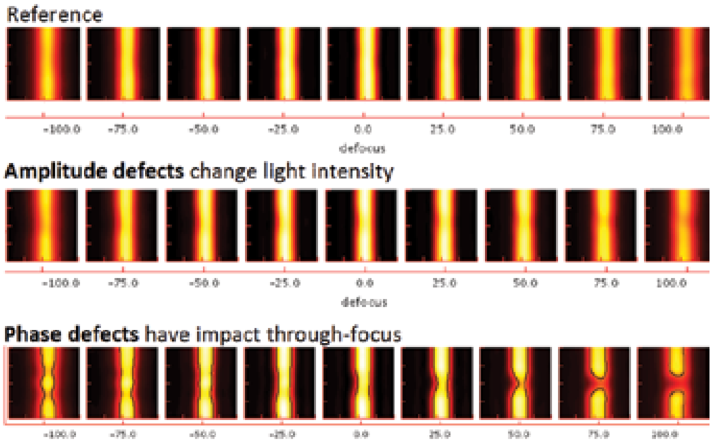

Figure 2. Illustration of near field aerial image of a clear EUV mask line as it is imaged through focus. The top row is the no defect reference case. The middle row illustrates how amplitude defects create a localized change in intensity. The bottom row shows the asymmetric impact of a phase defect through focus.

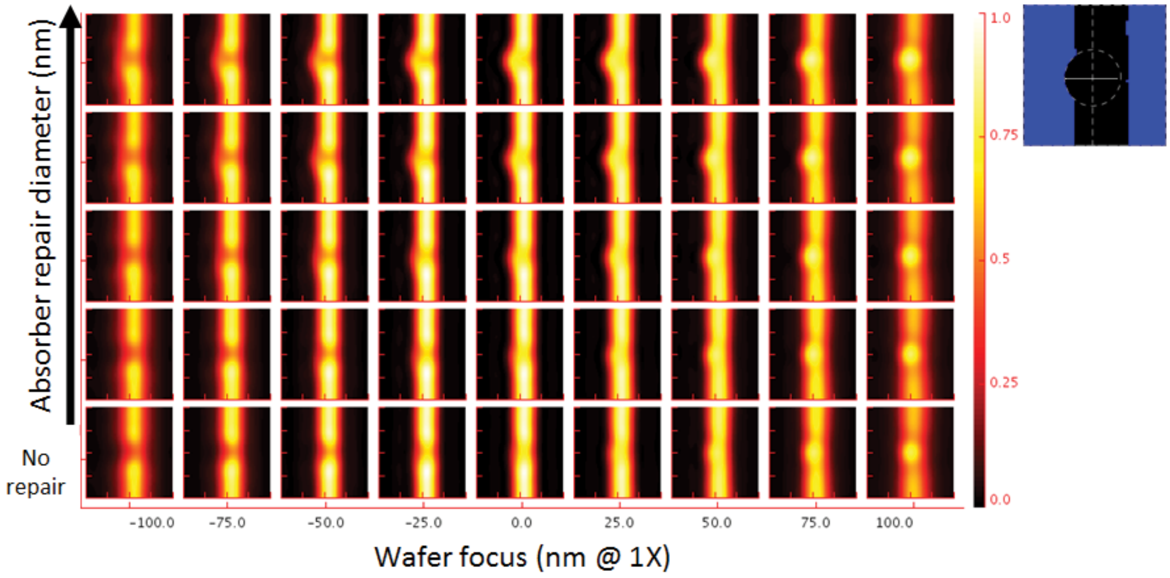

Figure 3. Near field aerial image of a clear EUV mask line as it is imaged through focus. The five rows correspond to different absorber repair conditions. The bottom row is the no repair reference and subsequent rows have increasing amounts of absorber removed. The repair pattern is illustrated at the upper left in a top view that shows a circle centered The top row is the no defect reference case. The middle row illustrates how amplitude defects create a localized change in intensity. The bottom row shows the asymmetric impact of a phase defect through focus.

by AFM. Once the printability of various nanomachined structures is understood, the second phase of the work aims to optimize the process to repair real EUVL mask defects with surrounding absorber patterns.

1. Introduction

EUV mask defectivity is one of the top technology barriers to introducing EUV lithography into manufacturing. Mask defects fall into several categories depending on when they originate. Some defects fall onto the mask or are created by damage during handling, shipping and use. Other defects are generated during mask fabrication and consist primarily of differences between the actual mask pattern and the intended design. The third category of defects is created during the mask blank fabrication. Clearly the most insidious defects are those that are generated at the beginning of the process, during blank fabrication, but are not detected until wafers are printed from the completed mask. This is

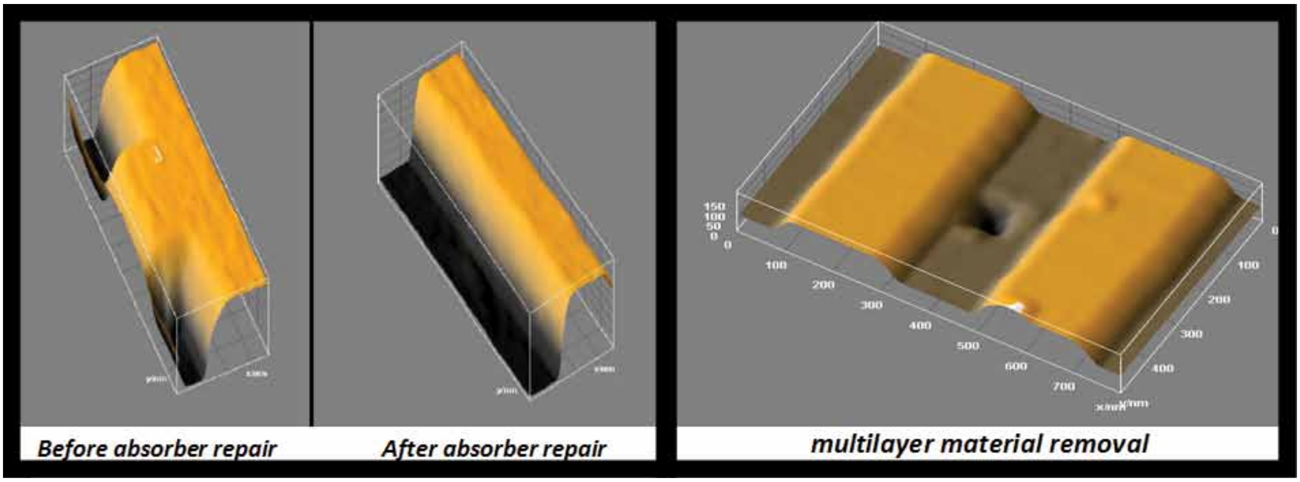

Figure 4. Two AFM scans of nanomachining repairs are shown: TaBN absorber edge defect is shown before and after repair (left) and a multilayer 100 x 100 x 89 nm repair in 200nm space (right).

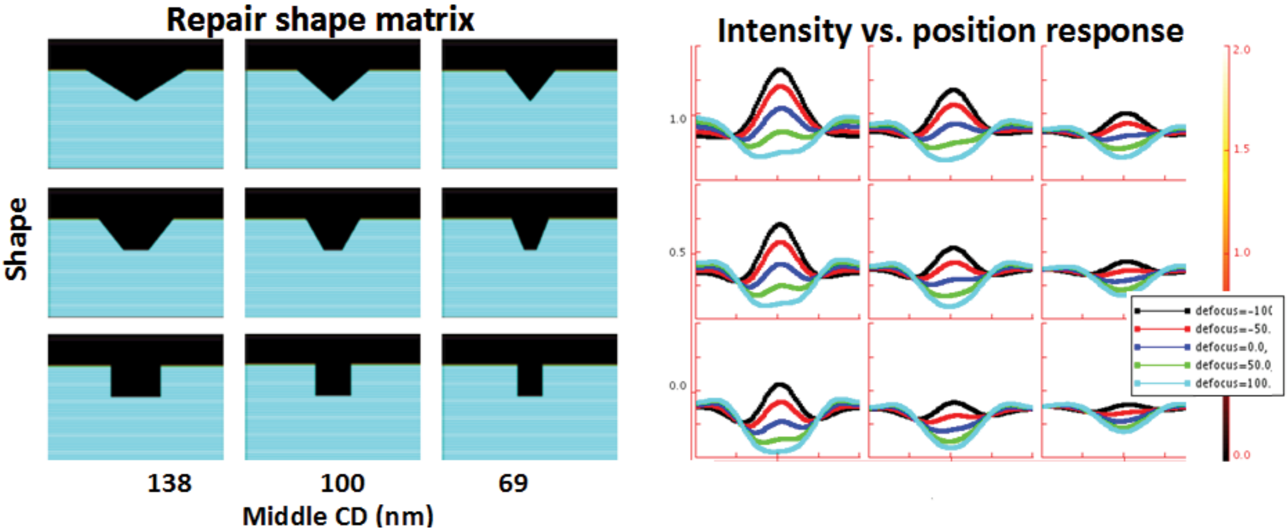

Figure 5. Matrix of multilayer repair shapes is illustrated on the left. All have 90nm depths and the middle CD was varied as labeled. Nine corresponding plots of intensity vs. position as a function of defocus are shown on the right.

exactly what occurs with certain types of blank defects in the multilayer and repairing these is the focus of this paper.

The EUV mask blank consists of an ultra low thermal expansion substrate with a backside film for conductivity and front side multilayer for reflectivity. The multilayer is composed of 40-50 bilayers of Mo and Si that create a Bragg mirror. The Si layers are low absorption spacers and the high absorption Mo creates an interface to reflect the 13.5nm EUVL exposure wavelength. The blank is completed with a Ru capping layer to protect the multilayer during mask and with an absorber layer that will be removed selectively to create the final mask pattern. The multilayer defects can also be broken into categories as is illustrated in Figure 1. A defect can result from conformal coating of a pit in the substrate, conformal coating over a bump in the substrate, or from a particle embedded in the multilayers. All three types of defects will create an imperfection in the multilayer's reflective properties. While these defects can be minimized by improving the blank process, or avoided by shifting the absorber pattern to cover them, some will be discovered after the mask is completed. At this point, the only options are to rebuild the mask on a new substrate or to repair the defect.

Others have recognized the need to develop a multilayer defect repair method. In the early 2000s, researchers and Lawrence Berkeley National Laboratories and Lawrence

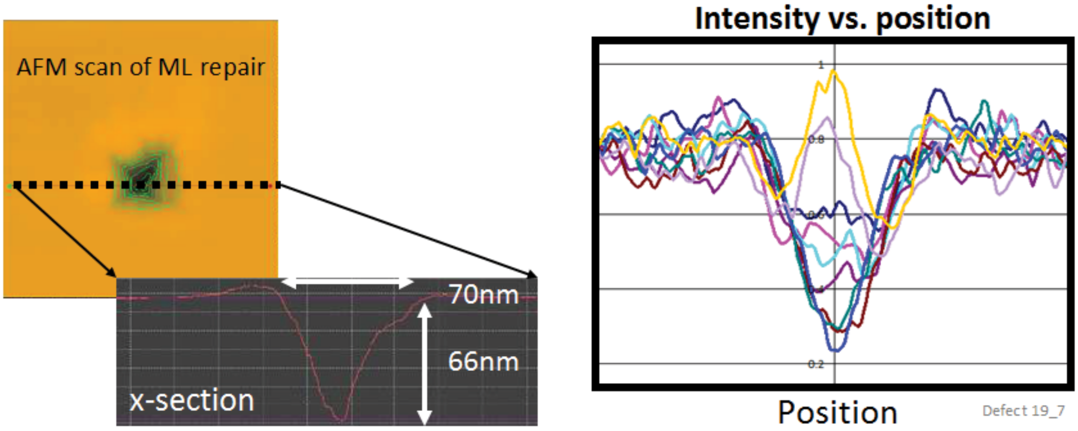

Figure 6. A pit was nanomachined into a multilayer. The AFM scan from the top and side are shown on the left. Measured EUV intensity vs. position is on the right as a function of focus position.

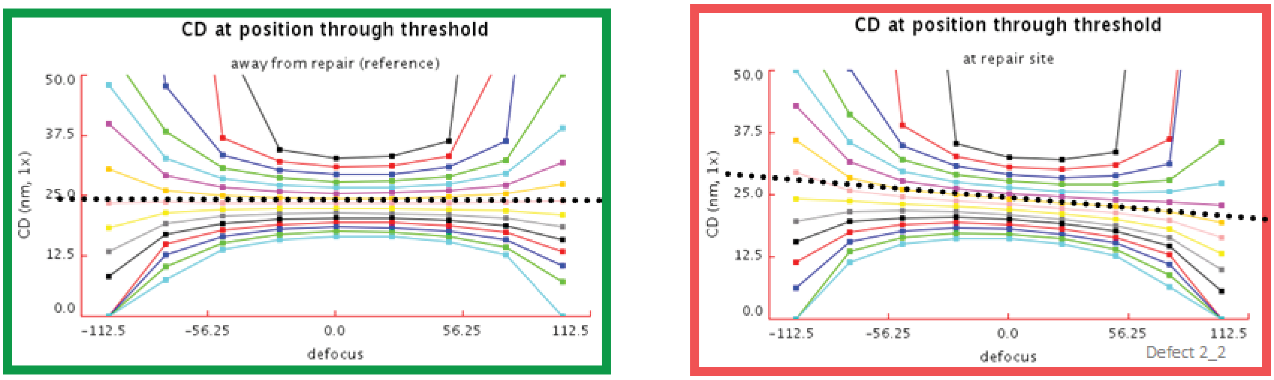

Figure 7. Simulated Bossung plots of a 160nm line/space pattern. Dotted lines indicate the iso-focal curve. The reference plot (left) has a flat iso-focal line, but the nanomachined pit (right) created the desired iso-focal tilt.

Livermore National Laboratories focused on improving the quality of the EUV multilayers by repairing the intrinsic blank defects.[1,2] They described the defects in two ways: defects occurring near the substrate create a phase response in the reflected light, while defects occurring nearer to the surface have an amplitude response.[2,3] This work was limited to blank studies and the concepts were not reduced to practice on finished masks. More recently there has been an effort to compensate for multilayer defects by modifying the absorber. [4,5] This method can work well for the amplitude response of a multilayer defect, but will never be able to compensate for all of the phase implications. This paper will explore a new method of repairing multilayer defects using nanomachining techniques that addresses both the amplitude and the phase nature of a multilayer defect.

2. Absorber Repair of Multilayer Defects

Before repairing a mask defect, it is important to understand how it prints. A flexible, fast way of generating illustrative examples is to move to the simulation space. For all the simulations in this paper, a rigorous finite difference time domain (FDTD) models are used. The mask is assumed to have 40 bilayers of Mo/Si, a 2.5nm Ru cap, and a Ta-based absorber stack that has a total height of 70nm. A 13.5nm plane wave exposes the mask at an angle of 6 degrees and the near field light intensity is taken as the output signal. An example of is shown in Figure 2 to illustrate how the amplitude and phase components of a multilayer defect differ. An amplitude defect simply changes the intensity in the vicinity of the defect throughout the focus window. A phase defect has an asymmetric response through focus. Most defects create both phase and amplitude responses to varying degrees.

Since multilayer defects have both a phase and an amplitude response, we do not anticipate that changing the absorber shape alone will restore the near-field imaging of the mask. To explore the effectiveness of an absorber-only repair, a bump defect was simulated in the center of a 200nm clear line. Absorber repairs were simulated by removing all of the absorber described by a virtual circle

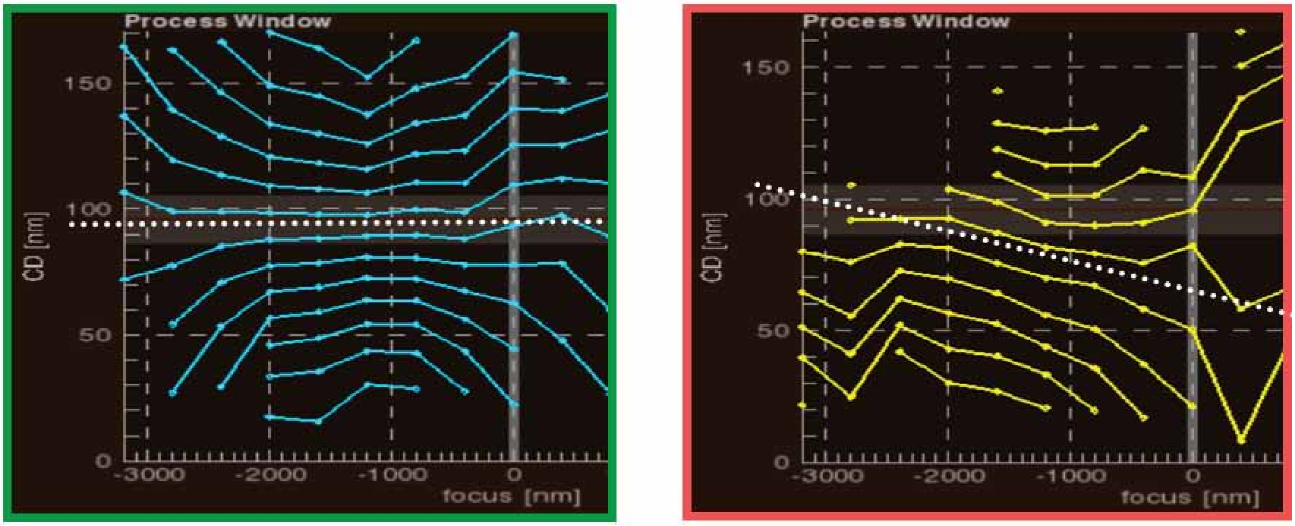

Figure 8. Measured Bossung plots of a 160nm line/space pattern. Dotted lines indicate the iso-focal curve. The reference plot (left) has a flat iso-focal line, but the nanomachined pit (right) created the desired iso-focal tilt. Match to the simulated results is excellent.

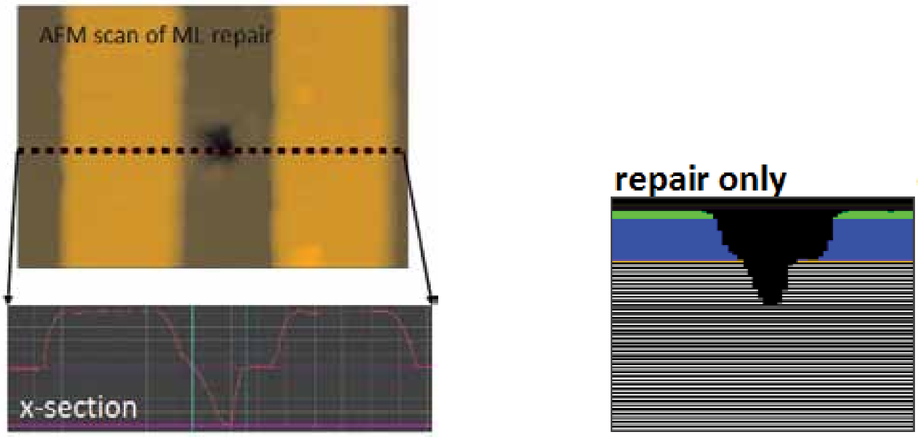

Figure 9. An AFM scan of the 82x82 nm test repair in a 200nm space (left) and the simulated version of the repair (right).

centered 67nm from the absorber edge. The diameter was increased in increments to 100nm. Figure 3 shows the series of near field images associated with this repair series. While it is possible to increase the line width in the vicinity of the repair, the focus extremes illustrate the inadequacy of the repair to correct the phase response. We can conclude that absorber biasing does not restore through-focus image fidelity and must consider a more complete solution.

3. Nanomachining Repair Options

A complete repair solution must provide a means for modifying both amplitude and phase. A family of nanomachining technologies can modify mask topography precisely, and is a good candidate for both repair requirements. All begin with an Atomic Force Microscope (AFM). The defect and surrounding pattern is scanned in a non-contact mode. Once the topographic references are defined, the tool shifts into a contact mode and removes unwanted material using a cold mechanical process until the topographic targets for the repair are reached. Nanoparticles are naturally generated as part of the nanomachining process in the vicinity of the repair. These particles are readily removed with standard cleans: wet clean, cryogenic clean, or selective removal using BitClean® on the Merlin tool itself.

Nanomachining technologies routinely repair absorber type defects and this has been reported.[6] Additionally, EUV multilayer repair has been demonstrated using both nanomachining and Ga+ FIB technologies.[6,7] This paper extends nanomachining to phase-matched multilayer repairs. In principle, the technology is relatively insensitive to

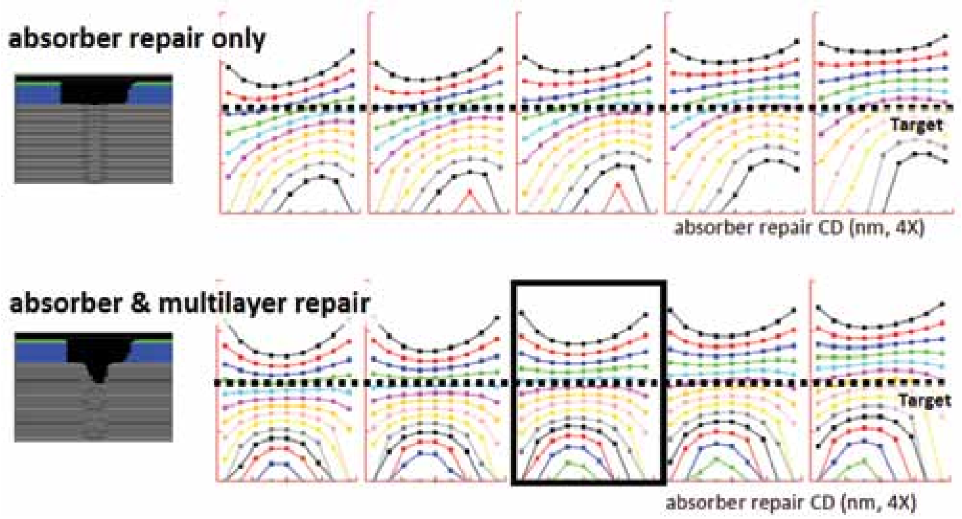

Figure 10. Bossung curves are plotted in a series for a 200nm clear space with a multilayer bump defect. The absorber repair bias is increased from left to right. The top row only includes this absorber repair. The bottom row combines the absorber repair with a pit repair to achieve the completely repaired condition highlighted by the box.

the targeted material. An example of what can be achieved for both types of repairs is shown in Figure 4.

Confirming that multilayer material can be removed in the required dimensions is only part of the challenge, it must also be demonstrated that a multilayer pit creates a phase response, and that the phase response can be applied to compensate for a multilayer defect. Through simulation, the presence of a phase response can be verified quickly. A matrix of three different shapes was generated in a standard Mo/Si multilayer blank. Each pit shape was simulated at three different critical dimensions (CDs) as measured half way down the pit: 69, 100 and 138nm. All pits were 90nm deep. The mask blank shapes and the simulated phase response at EUV exposure is illustrated in Figure 5. In simulation space, the desired phase response is achieved.

The next step is to measure the phase response of a pit created on an EUVL mask. In a clear area of the mask, a large area of exposed Ru-capped multilayer, a 70nm square pit was nanomachined to a depth of 66nm. The AFM scan of the pit is shown in Figure 6. This location was subsequently imaged on the Actinic Inspection Tool (AIT) at Lawrence Berkeley National Labs. The measured phase response is also shown in Figure 6. Good qualitative agreement can be seen between the simulated intensity response and the measured one through focus. It appears that nanomachining has potential to influence phase, but to be sure, mask patterns must be introduced.

4. Pattern Simulation and Measurement

Mask patterns exist to create images on wafer. To understand how these images print, it is logical to introduce Bossung curves to characterize the image.[0] In simple terms, the Bossung plot is CD vs. defocus for a number of different doses. The simple description belies the information conveyed by this plotting method, the standard method for illustrating lithographic process window. The iso-focal line describes the best operating point for depth of focus and occurs at the boundary between the dose lines that curve up and those that curve down. In practice, the mask bias is adjusted so that the target CD occurs as close to the iso-focal curve as possible. Modifying mask bias shifts the curves up and down. Tilted Bossung curves indicate that a phase error is present because the CD is changing asymmetrically through focus.

Armed with this information, the purpose of the repair will be to first restore symmetry in the Bossung curves with a multilayer repair, then shift the curves up and down with absorber bias to restore CD. This is important because repair does not mean removing a defect; it means that the mask must be changed to produce acceptable imaging through the anticipated ranges of focus and dose. In other words, the imaging must be maintained through the process window.

The possibility of tilting Bossungs with a repair was explored by nanomachining a series of pits in clear lines of a linespace pattern. All sites were scanned with the AFM. The scans could then be converted to the simulation domain to create an anchored starting point for the simulation. This method creates a realistic, flexible way of probing the influence of the nanomachined pits on printed line space patterns. One example will be described here for illustration. A 160nm nested line/space was used for the base pattern. A shallow pit was nanomachined in the center of a clear line: 50nm x 36nm square and 27.5nm deep. An AFM scan of this region was simulated and compared to an untouched reference. In both cases, the resulting Bossungs were simulated from the mask AFMs and are shown in Figure 7. The iso-focal line is indicated by a dotted line and shown clearly that the presence of the nanomachined tip tilts the Bossung curves as desired. The next question is whether this can be measured directly from the mask itself.

The same mask was measured on the AIT microscope at Lawrence Berkeley Laboratory. The exposure conditions were the same as those used for the simulations: 0.33NA, degree angle of incidence at 13.5nm. The resulting Bossung curves are shown in Figure 8 for the same two locations just described. The tilts are visually similar. For this example, the measured slope on both AIT and simulation is ~0.04nm CD/nm defocus in wafer dimensions.

5. Feasibility of a Complete Repair

A 200nm line/space base pattern was selected to demonstrate a complete repair example. An 82nm deep pit was nanomachined into the clear area and cleaned using BitClean®. An AFM scan of the repair is shown in Figure 9 along with the same repair in simulation space. In simulation, it is possible to surgically add and subtract both the defect and repair to isolate the impact of each. The progressive simulation tested four cases: reference, multilayer bump defect only, nanomachined repair only, and finally the combined defect and repair. Adding a bump defect tilts the Bossungs so that the CD is larger at positive focus. The repair in the absence of a defect has the opposite effect, the CD prints smaller at positive focus. In other words the repair only pit creates Bossungs that tilt down to the right. Combining these two effects could potentially cancel the response to restore ideal imaging.

Finally, we have enough background to simulate the full repair on a bump defect in the substrate, centered on a 200nm space. The efficacy of an absorber-only repair is explored first and is shown on the top of Figure 10. The absorber repair is increased moving from the left Bossung to the right. A clear shift in the Bossungs is seen as expected, but the tilted phase response is not corrected. This is not a complete solution. The lower row of Figure 10 includes a constant phase repair (pit) coupled with the same absorber repairs. Now, the Bossung tilt is restored to flat while the absorber repair shifts the Bossungs so that the iso-focal curve coincides with the target.

6. Conclusions

Multilayer defects have both amplitude and phase impacts on printed images. If the phase response is strong, a complete mask repair must include compensation that goes beyond an absorber bias. Merlin® nanomachining removes material without etch stops, heat or gases and can modify the absorber to change amplitude and remove multilayer to adjust phase. This paper demonstrated the potential of using nanomachining through both simulation and AIT microscope measurements. This proof of concept is very encouraging and points to much more that should be explored. Planned work includes: extending to contact features, applying the method to naturally-occurring defects, and testing the nanomachined repairs for durability. This is an exciting area to explore and one which could have a large impact on the industry's ability to deliver defect-free masks.

7. Acknowledgments

The authors would like to acknowledge IBM's mask house engineering and manufacturing teams for mask builds and processing, Sematech for Actinic Inspection Tool (AIT) time and Kenneth Goldberg (CXRO) and Iacopo Mochi (CXRO) for AIT support and insight into the analysis.

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Industry Briefs

Intel Looks to Emerging Markets in Phone Push

Eva Dou, Wall Street Journal

Intel Corp.'s processors may be ubiquitous in personal computers world-wide, but the world's biggest chip maker has had to aim much more modestly in its late entry into the smartphone market. The two phones launched this month that run its newest low-cost mobile chip are regional offerings for Kenya and Thailand.

Intel Given Green Light to Build $4 billion 14nm Chip Plant in Ireland

Shawn Knight, TechSpot

Intel has been itching to start construction on a new chip plant in Ireland to build future 14-nanometer microprocessors for some time but before anything could be done, they needed final approval from officials in the region. Fortunately for Intel, the lead planning agency in Ireland has given the $4 billion project the green light. Intel confirmed plans for the Ireland plant in May of 2012 and the Kildare County Council approved plans for the facility back in August 2012. Intel was ultimately met with an appeal from An Bord Pleanála, Ireland's lead planning agency, which delayed construction. Intel received word that the agency had given them the final go-ahead, albeit with a few updated conditions. The Leixlip plant will be one of three global sites used to produce Intel's next generation 14-nanometer chips; the other two locations are in Arizona and Oregon. It will be built alongside existing infrastructure and buildings at Intel's manufacturing complex and will consist of 244,819 square meters of floor area.

ASML Expects Slow Start to 2013

January 2013

ASML closed out its fiscal 2012 with annual sales of €4.7 billion – in line with expectations but down from the record-breaking 2011 figure of €5.7 billion. "2012 fourth-quarter and full year sales and profit came in as expected, making the year our second best ever," reported Eric Meurice, CEO at the market-leading lithography firm, in its full-year results. "We plan net sales for 2013 at a similar level to that of 2012, with a slow Q1 start, recovering in Q2 and a relatively large second half." That prediction is based on an expected transition to more lithography-intensive 14-20 nm foundry and logic nodes as 2013 unfolds, driven by the requirements of next-generation portable devices. ASML plans to implement sufficient improvements to EUV power levels over time so that its customers can produce 70 wafers per hour with the tools by mid-2014. But in ASML's investor call to discuss the 2012 results and outlook, Meurice admitted that the company had missed performance targets for the EUV light source last year. "What should have happened in the summer happened in the winter," said the CEO of recent engineering problems. To support the transition to EUV, ASML is also preparing to acquire key light source supplier Cymer. Although approval from several regulatory authorities, as well as the Cymer shareholders, is still required – ASML says that clearance for the deal has been granted by the US Committee on Foreign Investment in the United States (CFIUS) and Germany's anti-trust authorities. "We continue to expect the transaction to close in the first half of 2013," said the firm, expecting to post EUV tool sales of around €700 million this year.

GloFo, Samsung in Race to 14 nm

Rick Merritt, EE-Times

Globalfoundries and Samsung are in a dead heat to get their first 14 nm production wafers out before the end of the year, aiming to beat rival Taiwan Semiconductor Manufacturing Co. by as much as a year. Meanwhile, an IBM building in New York sits empty, waiting for an extreme ultraviolet (EUV) lithography machine to light the way to the industry's longer-term future. The companies said they now expect EUV will not be ready until the 7-nm node. It remains their primary bet on the future of chip making, but it will require advances in physics on several fronts to succeed, said a top IBM technologist. "We're in the most complex business in the history of human kind," said Mike Noonen, vice president and marketing at sales at Globalfoundries.

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About the BACUS Group

Founded in 1980 by a group of chrome blank users wanting a single voice to interact with suppliers, BACUS has grown to become the largest and most widely known forum for the exchange of technical information of interest to photomask and reticle makers. BACUS joined SPIE in January of 1991 to expand the exchange of information with mask makers around the world.

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