Bringing mask repair to the next level

K. Edinger[*], K. Wolff, H. Steigerwald, N. Auth, P. Spies, J. Oster, H. Schneider, M. Budach, T. Hofmann, M. Waiblinger

Carl Zeiss SMS GmbH - Industriestraße 1, 64380 Roßdorf, Germany

ABSTRACT

Mask repair is an essential step in the mask manufacturing process as the extension of 193nm technology and the insertion of EUV are drivers for mask complexity and cost. The ability to repair all types of defects on all mask blank materials is crucial for the economic success of a mask shop operation. In the future mask repair is facing several challenges. The mask minimum features sizes are shrinking and require a higher resolution repair tool. At the same time mask blanks with different new mask materials are introduced to optimize optical performance and long term durability. For EUV masks new classes of defects like multilayer and phase defects are entering the stage. In order to achieve a high yield, mask repair has to cover etch and deposition capabilities and must not damage the mask. These challenges require sophisticated technologies to bring mask repair to the next level. For high end masks ion-beam based and e-based repair technologies are the obvious choice when it comes to the repair of small features. Both technologies have their pro and cons. The scope of this paper is to review and compare the performance of ion-beam based mask repair to e-beam based mask repair. We will analyze the limits of both technologies theoretically and experimentally and show mask repair related performance data. Based on this data, we will give an outlook to future mask repair tools.

Keywords: focused electron beam, focused ion beam, e-beam based mask repair, beam induced processing, mask damage, process resolution

1. INTRODUCTION

In order to keep pace with the semiconductor industry roadmap future mask repair tools are facing several challenges such as shrinking minimum repairable feature size, robust process capabilities for an increasing number of mask materials with a large process window in order achieve high repair yields and a high tool availability. In terms of repair technology these requirements translate into a high processing resolution, versatile and efficient absorber removal processes for a large variety of mask types and a dependable and predictable technology. In order to evaluate potential future technologies and access their strength and weaknesses, we will start with a brief introduction into the factors that determine process resolution for a focused particle beam based repair technology. These are mainly: a) the spot size of the focused primary beam, b) the interaction area around the impact point of the primary particle at the surface of the material to be processed and c) in case of beam induced chemistry, the precursor dynamics at the surface.

1.1 Spot size

In the operation regime currently used for mask repair the primary spot size of both focused electron beams is typically on the order of 1 nm and is not limiting the size of the obtained microstructures. However, if the beam energy is reduced considerably, the spot size increases due to chromatic aberrations requiring design modifications of the optical system. Gas field ion source based focused ion beam systems are employing an atomically sharp emitter for the ionization of gas atoms in a high electric field. Due to the small virtual source size and the low energy spread of the ion beam, those systems can achieve spot sizes down to 0.5 nm and below[1]. Due to the physical principle of source operation only certain gas species with a relatively high ionization potential can be used. In addition, the source requires low temperatures, ultra pure gases and frequent reconditioning of the emitter. Due to this complexity the technological risks are expected to be higher compared to the mature electron emitter technology.

---

[*] Further author information: klaus.edinger@zeiss.com; phone +49 6154 803836; fax +49 6154 803880; www.zeiss.com/sms

1.2 Substrate interaction

For the deposition of materials as well as for enhanced removal of materials with high selectivity focused electron or ion beam based nanostructuring typically employs beam induced chemistry. Here, a suitable precursor gas is dispensed through a nozzle in close vicinity to the incident beam. The dispensed precursor molecules adsorb at the surface and a reaction is induced by the energetic particles incident at the surface. 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. For both ion and electron beam induced chemistry this process is mediated by the substrate. While the incident primary particle is traveling through the substrate, scattering events take place and secondary electrons are created. Depending on the depth where these electrons are created and their energy they can reach the surface at a certain distance away from the primary impact. If a precursor molecule is adsorbed at this emission site a chemical reaction can be induced. For focused electrons, backscattered primary electrons (BSE) also contribute to the induced reactions. Since our current repair tool operates at a primary energy of about 1 keV the radius around the focal spot from where secondary and back scattered electrons are emitted can be reduced by decreasing the electron energy. In figure 1 a simulation of the trajectories of the scattered primary electrons is shown. For a 1000 eV beam radius of the area where back scattered electrons are emitted is around 18 nm. It decreases to 7 nm for a 500 eV beam and 2 nm for a 200 eV beam.

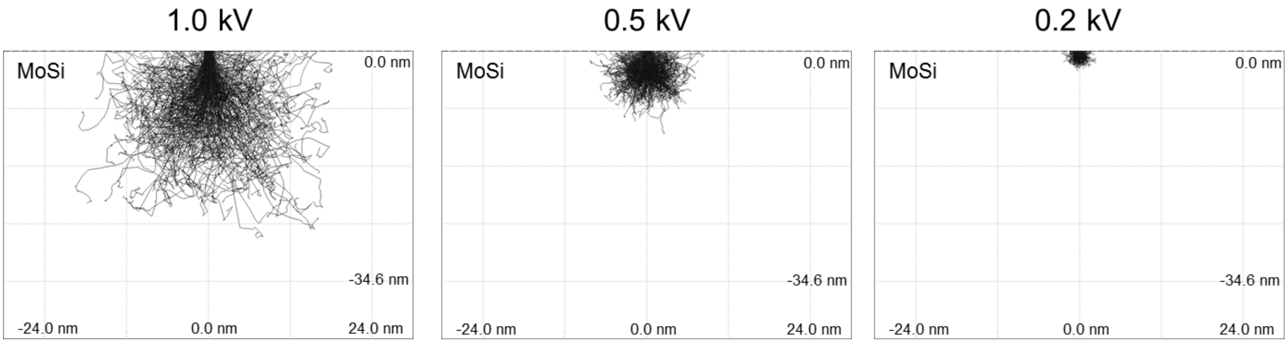

Figure 1: Comparison of electron/solid interaction volumes at different primary beam energies as simulated by Monte Carlo calculations (software: CASINO). The solid is a MoSi absorber material, while the beam radius was set to 1 nm.

For focused ion beams the situation is more complex, since in addition to electronic energy loss, the incident ions also loose energy by collision events with substrate atoms. These collisions can displace the lattice atoms causing in turn new collisions with other lattice atoms which can eventually re-coil to the surface leading again to chemical reactions of the absorbed molecules or the ejection of substrate atoms. In the latter case material is removed by pure physical sputtering without the need for dedicated precursor chemistry. As a consequence, in analogy to the focused electron beam case, the process resolution can be improved by either reducing the primary energy of the ions or by increasing the depth where most of the ion energy is deposited. This can be achieved by either increasing the energy of the ion beam or by using light ions such as Helium. Due to their low mass and consequently low momentum transfer, He ions are penetrating very deep into the substrate before they loose the majority of their energy and become finally implanted into the substrate. Typical values for the first 2 periods of the periodic table are listed in **Error! Reference source not found.** together with simulation of the scattering events.

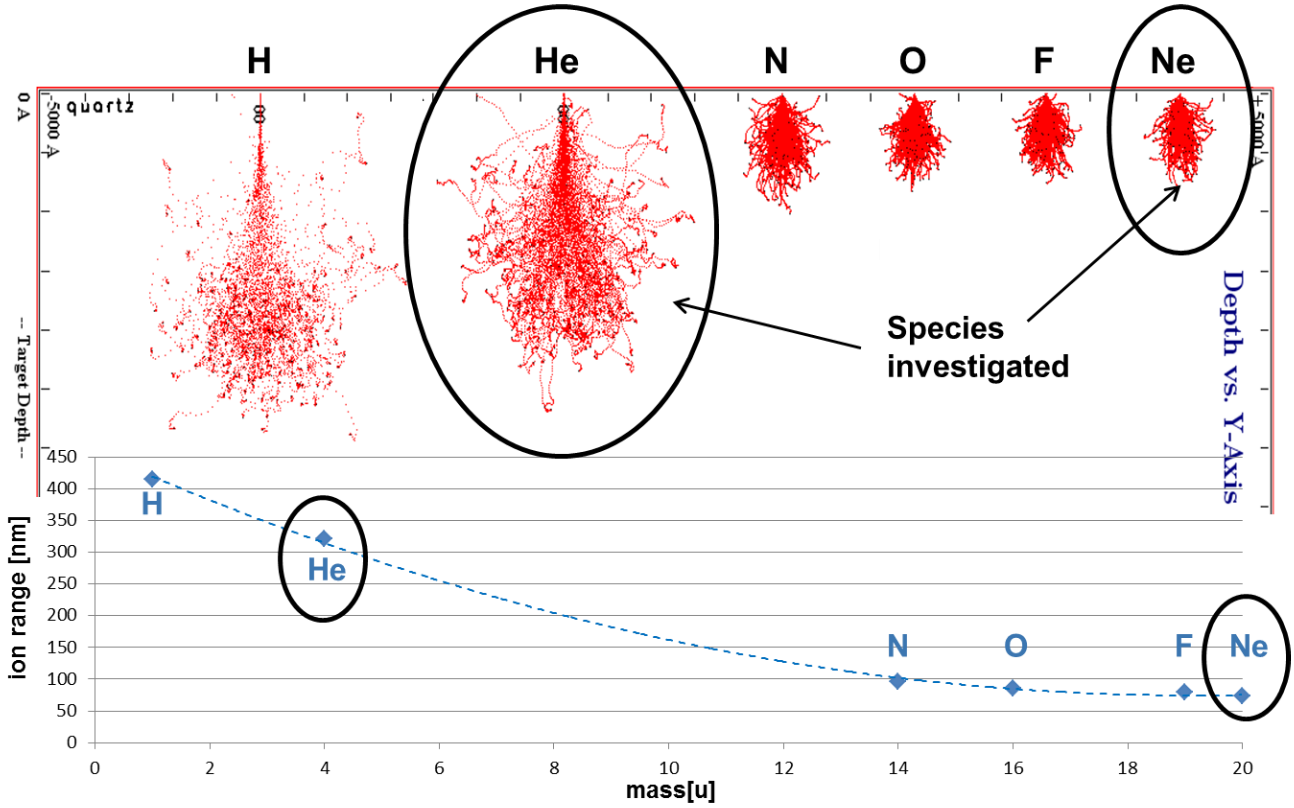

Figure 2: SRIM Monte Carlo simulation of scattering events and corresponding ion ranges for various light ions[2].

1.3 Precursor supply

A further well documented factor limiting the process resolution in beam induced chemistry is the depletion of precursor molecules under the incident beam. Above a certain beam current density to precursor gas flux ratio, adsorbed precursor molecules consumed by beam induced reactions cannot the replenished fast enough from the gas phase. In this case the main route of replenishment under beam exposure is surface diffusion. Since the molecules travel from the periphery into the reaction zone, this dynamic effect modifies the spatial distribution of available precursor molecules and leads to a reduced process resolution[3]. For highly focused electron or ion beams operated in the precursor limited regime, the resolution is in fact limited by this effect. The process resolution can therefore be improved by optimizing the gas flux to secondary electron emission ratio. This can be achieved by either improving the precursor delivery or by reducing the electron emission flux. The latter depends on the properties of the primary beam and can be reduced by lowering the beam current, reducing the beam dwell time or reducing the secondary electron yield using higher beam energies. However, reducing the electron emission flux will also lower the throughput and are therefore not the preferred way to increase the resolution.

In conclusion, from a theoretical point of view the resolution of current e-beam based mask repair tools operating around 1 keV is not limited by the primary spot size which is on the order of 1 nm. For those highly focused beams, the interaction area around the incident beam together with the gas supply dynamics determines the achievable process resolution. This area can be reduced by either lowering the primary beam energy or by moving the main beam–solid interaction away from the surface and deeper into the substrate. In terms of technology, both low energy electrons as well as light ions from a gas field ion source have the potential to achieve the resolution needed for future mask repair applications. Over the last years ZEISS has conducted a feasibility study of both technologies, in order to evaluate their capabilities and explore their potential risks.

2. EXPERIMENTAL

The study has been performed at our research facility in Rossdorf using a focused ion beam system based on a ZEISS ORION Helium Ion Microscope (HIM) modified to operate with other gases such as Neon and a ZEISS MERLIN e-beam column modified for low voltage operation. Both systems were laboratory tools without standard mask handling and stage and had not been optimized concerning thermal, acoustical or vibrations isolation. Mask repair related performance of both systems in terms of imaging and process resolution, as well as invasiveness and process stability have been evaluated using a variety of different mask types including binary and PSM photo masks, imprint templates (NIL) and EUV multilayer masks.

2.1 Imaging resolution

As expected the imaging resolution of the GFIS system for both Helium and Neon was found to be in the order of 1 nm or below. Also the MERLIN e-beam column showed a resolution around 1 nm at 1 keV. To operate the column at lower voltages we have modified the nozzle design to reduce the working distance resulting in an extended operating range down to 500 eV. Typical resolution images are shown in Figure 3 for a MERLIN column operated at 1000 eV (left) and 500 eV (center) respectively. Also included is a resolution image at 100 eV (right) using a dedicated ultra-low energy electron column developed by ZEISS. This microscope uses a novel design based on magnetic beam separation with an electron mirror to correct aberrations and an electron spectrometer to collect secondary and backscattered electron with high efficiency and high energy resolution. This concept has the potential to allow electron beam induced processing at energies below 100 eV with ultra-high resolution using BSE electrons for process control and clearly demonstrates the extendibility of e-beam based mask repair. Zeiss Microscopy is currently developing a commercial version of this column.

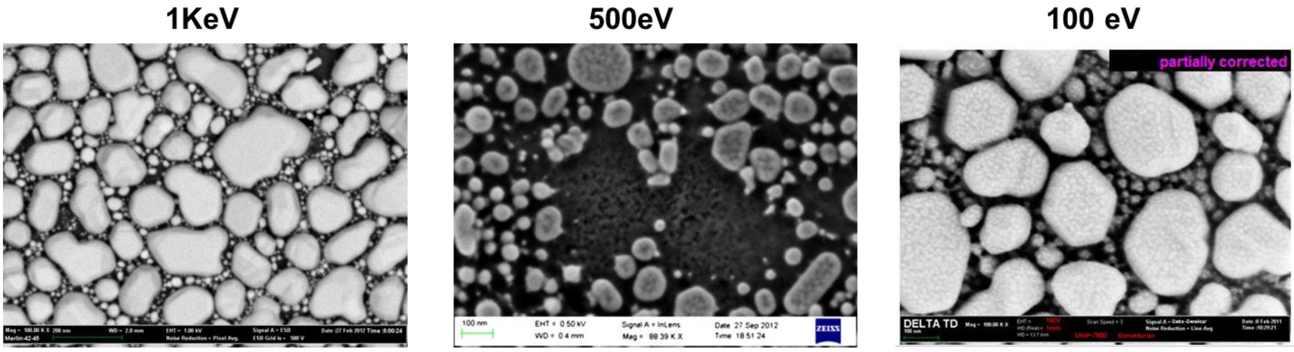

Figure 3: Representative Gold on Carbon resolution samples for a MERLIN e-beam column at 1000 eV (left) and 500 eV (center). A aberration corrected image taken at 100 eV using a dedicated low-voltage microscope from Carl Zeiss Microscopy is shown on the right.

2.2 Process resolution and minimum feature size

As discussed before, for state of the art focused electron beam systems with beam spot sizes on the order of 1 nm the achievable process resolution in electron beam induced chemistry is determined by the precursor flux to secondary electron emission ratio. Consequently the best results have been achieved using short dwell times and low beam currents as well as slightly elevated beam energies (most likely due to a reduction in the secondary electron yield). All process resolution tests have been performed on an amorphous quartz substrate (NIL template) using a XeF_2 based etch chemistry to exclude inhomogeneous etch effects cause by the crystalline microstructure of certain absorber materials. Under those settings an etching resolution of 10 nm could be achieved for a dense line and space pattern (left and center in **Error! Reference source not found.**). Additional tests are currently underway to improve the resolution further by optimizing the nozzle geometry for higher gas fluxes. A preliminary result showing a resolution of 9 nm is also presented in **Error! Reference source not found.** (right). Similar resolution limits have been obtained for focused ion beam induced chemistry indicating that indeed the resolution is determined by the gas supply. This conclusion is also supported by the fact that a minimum line width of 5 nm was observed if the line was milled with a He ion beam by pure physical sputtering alone and line widths between 5 and 10 nm have been found for partially gas enhanced processes. While this indicates that focused ion beam milling can improve the resolution, this might be of limited use for an application such as mask repair. Here, a good selectivity between the removal rate of the absorber versus the underlying substrate is desired to improve over-etching and thus the process window. While in principle, tailored chemistries can be developed to improve this selectivity in the case of beam induced chemistry, in ion beam milling the removal rate of different atoms mostly depends on the difference in their mass (Z value). For materials typically used on photo masks the removal rate of the absorber versus the underlying substrate is not expected to show a significant difference. In addition, beam chemistry will still be required for the deposition of material.

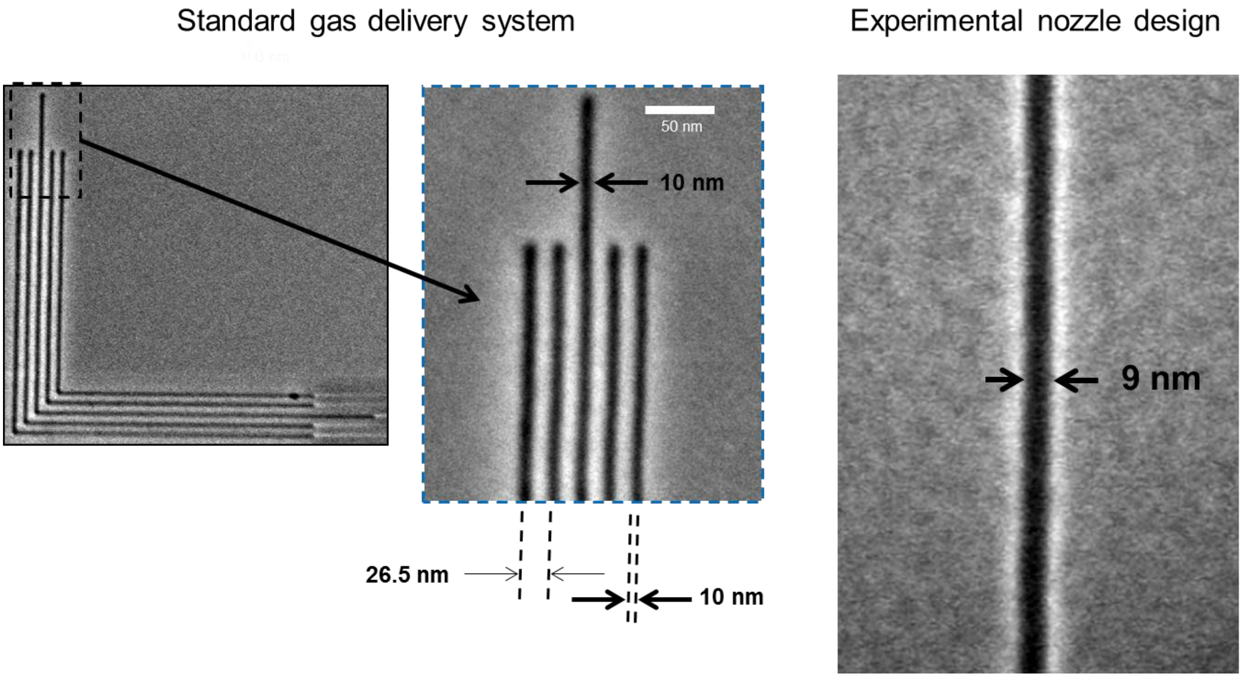

Figure 4: A dense line and space pattern was etched into quartz material by e-beam induced processing. An etching resultion of 10 nm could be achieved. For an optimized nozzle design the resolution was about 9 nm.

While the process resolution by writing single lines or spots is certainly a good indication for the capability of a nanostructuring technique, usually the performance in a mask repair application is specified by the minimum feature size that can be repaired. In the case of opaque defects where absorber has to be removed, the typical defects usually have an edge bordering uncovered quartz substrate. In this case, the primary electrons or ions that are scattered while they travel through the substrate can exit the absorber at this edge and re-enter into the bordering quartz substrate, causing severe damage such as riverbedding. To avoid this problem the beam steering system keeps the incident beam far enough away from the edge, by applying a bias on the order of the scattering width. Since this width directly scales with the primary beam energy the necessary bias can simply be reduced by reducing the beam energy. This situation is depicted in **Error! Reference source not found.** for an isolated defect, calculated using the software CASINO. Since this kind of defect has an edge all around, the beam can only expose the area in the center and therefore the minimum defect size where there are still pixel left that can be exposed is twice the bias. As can be seen in **Error! Reference source not found.** there is a direct relation between the beam energy and the minimum repairable feature size.

This direct relation has also been demonstrated experimentally for two complementary cases: The repair of a too short line that has been extended by 15 nm (**Error! Reference source not found.**) and the removal of a 16 nm extension shown in **Error! Reference source not found.**. The test system again was an imprint template etched with XeF_2 and no bias was applied. This test clearly demonstrated the potential of reduced voltage operation, since in this case no further enhancement due to differences in etch rates between absorber and substrate are present. For the removal of absorber material with a good selectivity with respect to the quartz substrate there is an increase in the process window and we expect that even smaller defects can be removed.

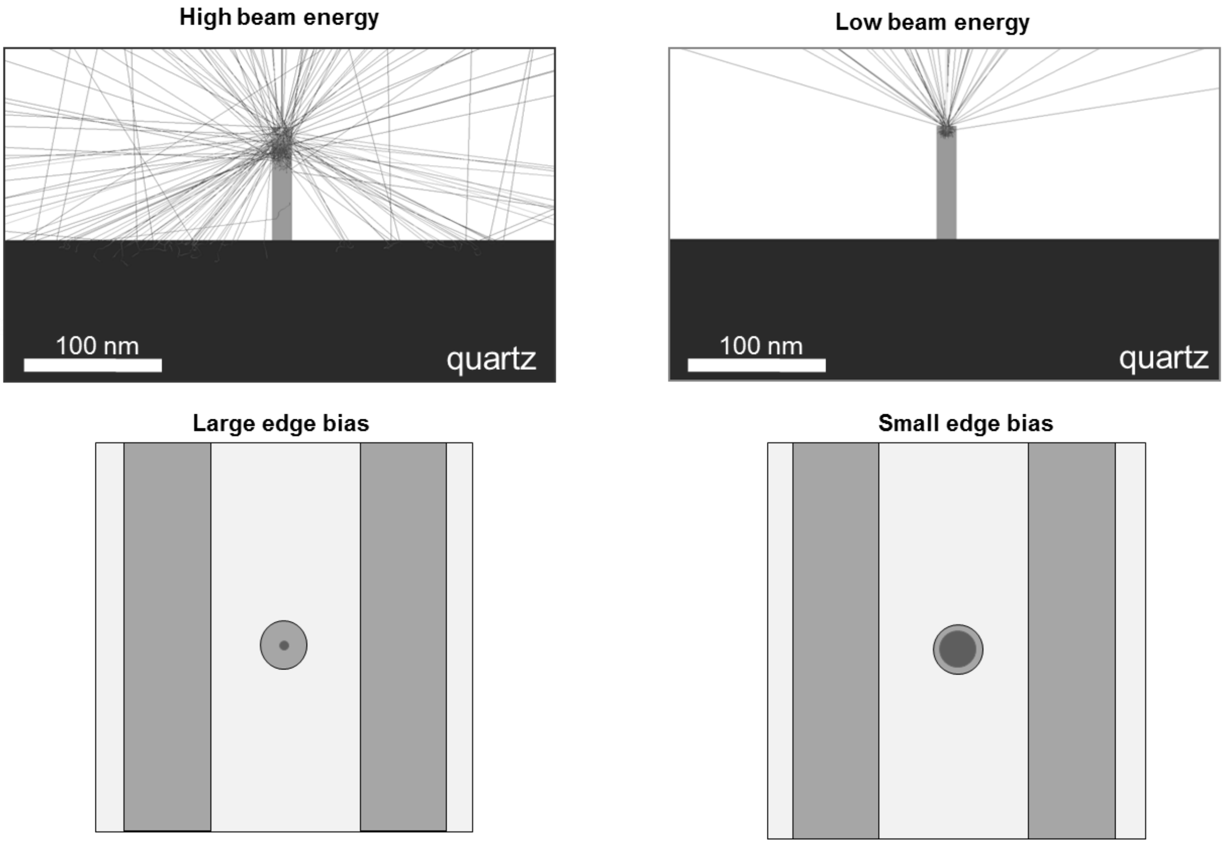

Figure 5: Upper part: Simulation of the electron trajectory for an isolated defect in cross section. The lower part shows a top view of the defect with the area exposed by the electron beam in a darker shade. This demonstrating a direct relation between the beam energy and the minimum repairable feature size defined by the smaller process bias

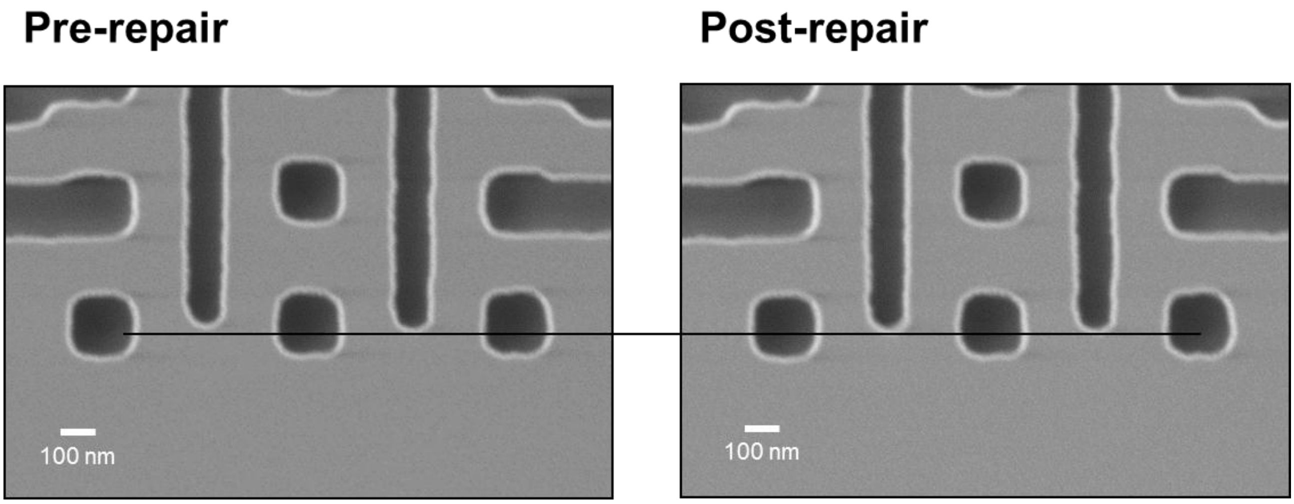

Figure 6: A 15 nm line shortening defect was repaired successful by applying a low energy e-beam based repair process

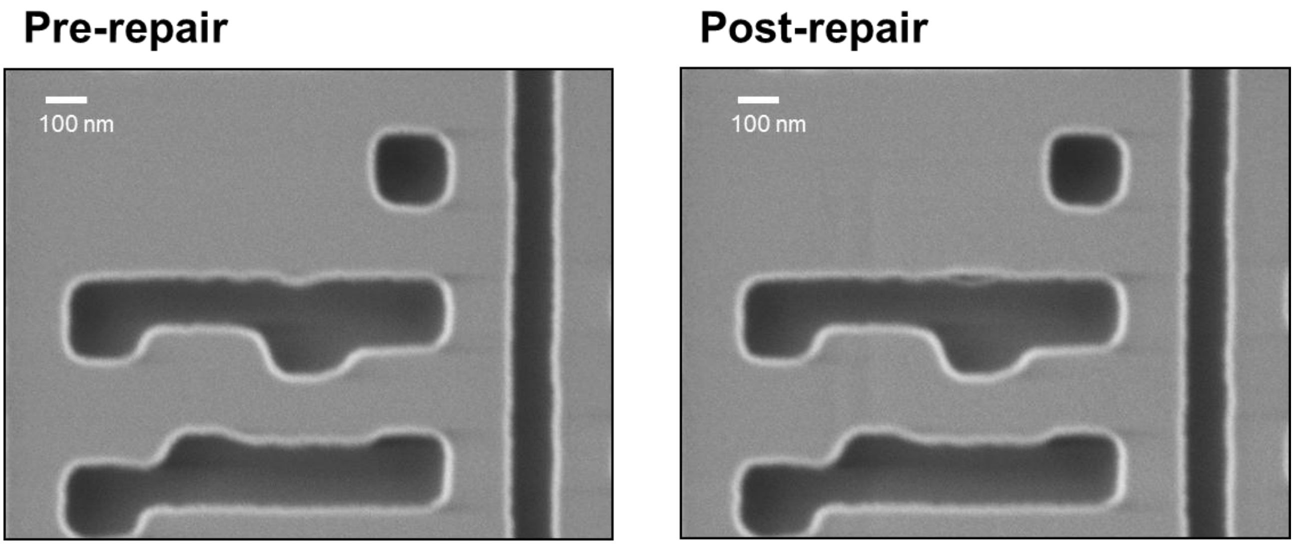

Figure 7: A 16 nm extension defect was repaired successful by applying a low energy e-beam based repair process

2.3 Invasiveness

When using a charged particle beam there is always a potential for substrate damage which must be carefully considered. Especially for an application such as mask repair, the invasiveness of the repair technology is of critical importance, since the mask must remain intact in its entirety with no degradation in its optical properties during exposure. We have investigated the dose dependent effects of beam exposure for 193nm optical masks as well as of EUV multilayer masks and found two types of defects.

For 193nm masks an energy dependent compaction of the quartz substrate was observed for both electron and ion beams. In the case of ion exposure the effect was also strongly influenced by the ion mass. An increase in density of the quartz substrate upon energetic beam exposure has been reported in the literature before and has been attributed to a reorganization of the amorphous silicon oxide network[4,5]. This effect is energy depended and saturates at 2% densification. The total effect of this densification accumulates over the effected volume. This volume correlates directly with the range over which the energetic particle loses its energy while it travels through the solid. As can be seen in figure 1 and 2 this range is largest for light ions at high primary energies. Consequently, we have found the largest recess of the quartz surface due to quartz densification of up to 17 nm for 25 keV Helium beam. This value was observed for doses above $3x10^{16}$ ions/cm^2, but even for lower doses such as $1.5x10^{15}$ ions/cm^2 equivalent to 1-2 imaging frames a significant recess of 3 nm has been observed. As expected the effect decreases with lower energy for both ions and electrons and the smallest impact with a saturation level of the recess of just 1 nm has been found for a 1 keV electron beam as typically used for mask repair applications.

Another well documented effect only observed for exposure with light ions such as Helium and Neon is the formation of sub-surface bubbles[6]. We have observed bubble formation both for He and Neon ion beams on various mask materials such as PSM and binary masks as well as EUV multilayer masks. The effect is dose dependent with a threshold of about $1x10^{17}$ ions/cm^2 for Neon ions and $1x10^{18}$ ions/cm^2 for Helium ions. While this threshold is typically acceptable for imaging, it will be relevant for repair applications.

Because of the sensitivity of the multilayer structure, EUV masks are especially susceptible to beam induced damage. While we found no effects of electron beam exposure under typical repair conditions, for Helium as well as for Neon ion beam exposure, compaction as well as bubble formation was observed. CD measurements of the exposed mask using wafer prints revealed CD changes of up to 7 nm even for a relatively small dose of $2x10^{15}$ ions/cm^2 (comparable to one image frame). Severe degradation of the EUV multilayer under ion beam exposure has also been observed by other groups[7,8].

2.4 New HD MoSi materials

One of the challenges of mask repair is to adapt existing processes to novel blank materials. The most recent challenge is the introduction of high durable PSM materials ("HD-MoSi"). These blank types have been developed to harden the light absorbing mask layers against mask cleaning and DUV radiation to ensure productivity of future manufacturing nodes. Zeiss developed a new and versatile process to perform repairs on this class of blanks. Kanamitsu et al. presented repairs on commercially available HD-MoSi during PMJ 2014 showing in spec results and a selectivity comparable or better than known for standard MoSi material[9]. Over the last years, Zeiss established close collaborations with the photo mask blank vendors. Thus we have conducted studies regarding the versatility of the new HD-MoSi recipe against different material compositions of PSM masks of both vendors. Figure 8 shows a representative result on one of the new generation blanks. The novel recipe is able to etch the new generation materials with a selectivity better than 4:1, in some cases even better than 5:1. On programed defect masks we have demonstrated in spec results on various defect types on high end nodes. These materials are still in development and not commercially available. Therefore detailed results of the repairs are considered proprietary and can currently not be disclosed.

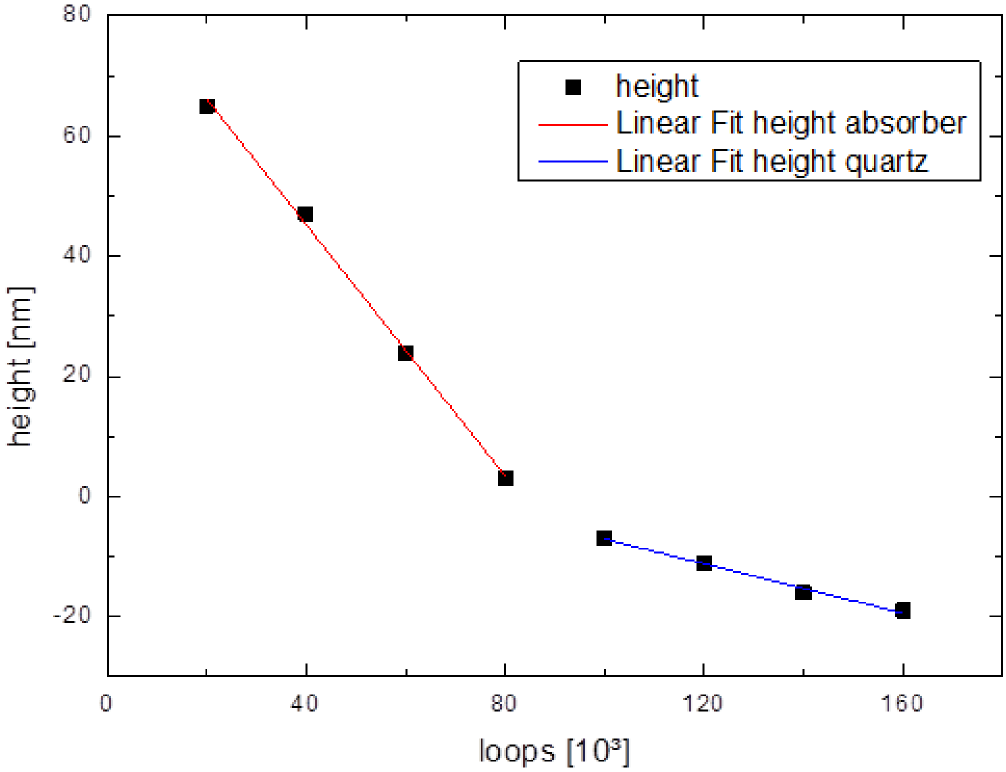

Figure 8: Selectivity data on next generation HD MoSi

3. CONCLUSION

We have evaluated the performance of GFIS based mask repair and low energy electron mask repair. Both technologies achieve superior imaging resolution and have high potential to meet the resolution required for future mask repair applications. For the GFIS technology several potential issues have been identified. Beside the GFIS source stability and complexity, ion solid interaction effects such as quartz compaction, micro bubble formation and degradation of the EUV multilayer have been observed. These effects are negligible for low energetic electron beam based processing.

REFERENCES

[1] Notte, J., Ward, B., Economou, N., Hill,R., Percival, R., Farkas, L., and McVey, S, “An introduction to the Helium Ion Microscope”, AIP Conference Proceedings 931 489 (2007)

[2] www.srim.org

[3] Utke, I., Friedli, V., Purrucker, and M., Michler, J., “Resolution in focused electron- and ion-beam induced processing”, J.Vac Sci. Technol. B25, 2221 (2007)

[4] Devine, R., “Macroscopic and microscopic effects of radiation in amorphous SiO_2”, Nucl. Instr. and Meth. In Phys. Res. B 91, 378-390 (1994)

[5] Stevens Kalceff, M.A., Phillips, M.R. and Moon, A.R., “Electron irradiation-induced changes in the surface topography of silicon dioxide”, J. Appl. Phys. 80 (B), 4308-4314 (1996)

[6] Livengood, R., Tan, S. and Greenzweig, Y., “Subsurface damage from helium ions as a function of dose, beam energy, and dose rate”, J. Vac. Sci. Technol. B, Vol. 27(6), 3244-3249 (2009)

[7] Gonzalez, C., Timilsina, R., Li, G., Duscher, G., Rack, P., Slingenbergh, W., Dorp, W., De Hosson, J. Klein, K., Wu, H. And Stern, L., “Focused helium and neon ion beam induced etching for advanced extreme ultraviolet lithography mask repair”, J. Vac. Sci. Technol. B, Vol. 32(2), 021602 (2014)

[8] Gonzalez, C.; Slingenbergh, W.; Timilsina, R.; Noh, J.-H.; Stanford, M.; Lewis, B.; Klein, L.; Liang, T.; Fowlkes, J.; Rack, P., “Evaluation of mask repair strategies via focused electron, helium, and neon beam induced processing for EUV applications”, Proc. SPIE 9048, 90480M (2014)

[9] Kanamitsu, S., Morishita, K., Hirano, T., “Application of EB repair for high durable MoSi phase shift mask”, PMJ 2014