Photomask repair using low energetic electrons

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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. We will demonstrate in this paper that low energetic electron-beam (e-beam)-based mask repair is a commercially viable solution. Therefore we developed a new repair platform called MeRiT® neXT to address the technical challenges of this new technology. We will analyze the limits of the existing as well as lower energetic electron induced repair technologies theoretically and experimentally and show performance data on photomask reticles. Based on this data, we will give an outlook to future mask repair technology.

Keywords: low energetic electron, focused electron 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. These are a shrinking minimum repairable feature size, robust process capabilities with a large process window for an increasing number of mask materials in order to 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 as well as 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. The different aspects of mask repair with ions have been discussed before[10]. In this work we will focus on electron-based mask repair and its advantages over ion-based mask repair with respect to substrate damage.

1.1 Spot size

In the operation regime currently used for mask repair the primary spot size of electron beams is typically in the order of 1 nm and does not limit 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 electron optical system.

1.2 Substrate interaction

For the deposition of materials as well as for enhanced removal of materials with high selectivity focused e-beam-based nanostructuring employs beam-induced chemistry. In this case, 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

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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 e-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 they can reach the surface at a certain distance away from the impact of the primary beam. 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.

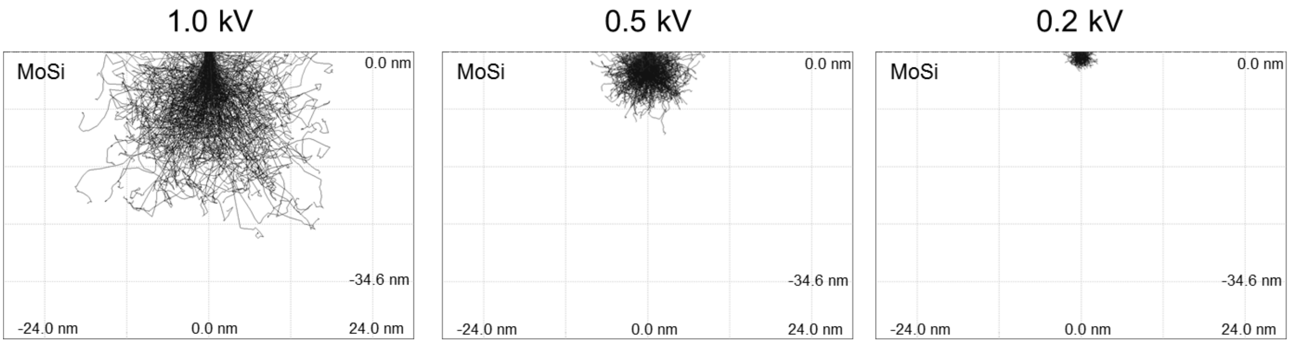

Figure 1: Comparison of electron/solid interaction volumes at different primary beam energies as simulated by Monte Carlo calculations (software: CASINO). The solid is a MoSi absorber material, while the beam radius was set to 1 nm.

1.3 Precursor supply

A further well documented factor limiting the process resolution in beam-induced chemistry is the depletion of precursor molecules under beam irradiation. Above a certain beam current density to precursor gas flux ratio, adsorbed precursor molecules consumed by beam-induced reactions cannot be 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 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. 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 also lowers the throughput. Therefore it is 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 in 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 hence deeper into the substrate.

2. EXPERIMENTAL

The study has been performed at our research facility in Roßdorf and on our manufacturing site in Jena using focused e-beam systems based on a ZEISS Merlin column modified for low voltage operation. Two systems are used for this study. One is a laboratory tool without standard mask handling and stage which has not been optimized concerning thermal, acoustical or vibration isolation. The other type is an engineering version of the next generation mask repair tool called ZEISS MeRiT neXT (Figure 2). 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 phase shifting photomasks (PSM), binary masks, imprint templates (NIL) and EUV multilayer masks.

Figure 2: ZEISS developed a new repair platform. This system hosts a new low energetic e-beam column integrated in an advanced gas injection system and support electronics

2.1 Imaging resolution

As expected 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 e-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. Carl ZEISS Microscopy is currently developing a commercial version of this column.

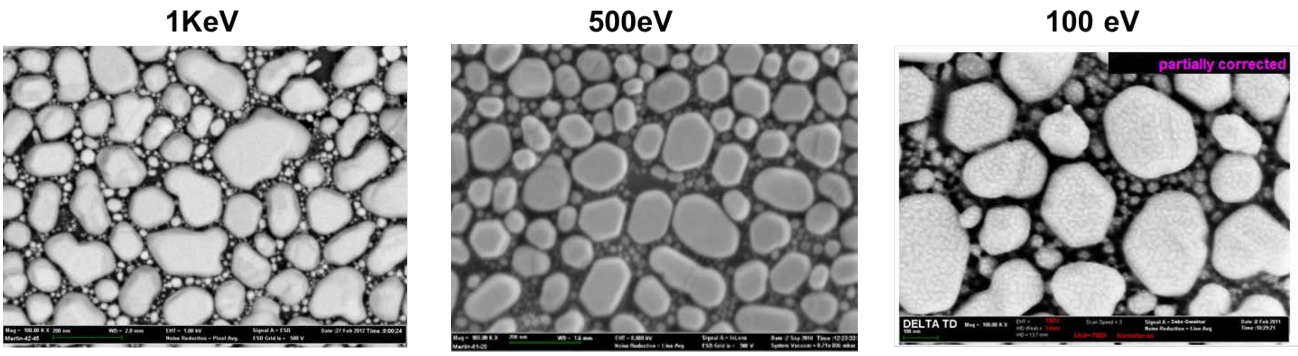

Figure 3: Representative gold on carbon resolution samples for a MERLIN e-beam column at 1000 eV (left) and 500 eV (center). An aberration corrected image taken at 100 eV using a dedicated low-voltage microscope from Carl Zeiss Microscopy is shown on the right.

2.2 Process resolution and minimum feature size

As discussed before, for state of the art focused electron beam systems with beam spot sizes of 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. With those settings an etching resolution of 10 nm could be achieved for a dense line and space pattern (left and center in Figure 4). 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 Figure 4 (right).

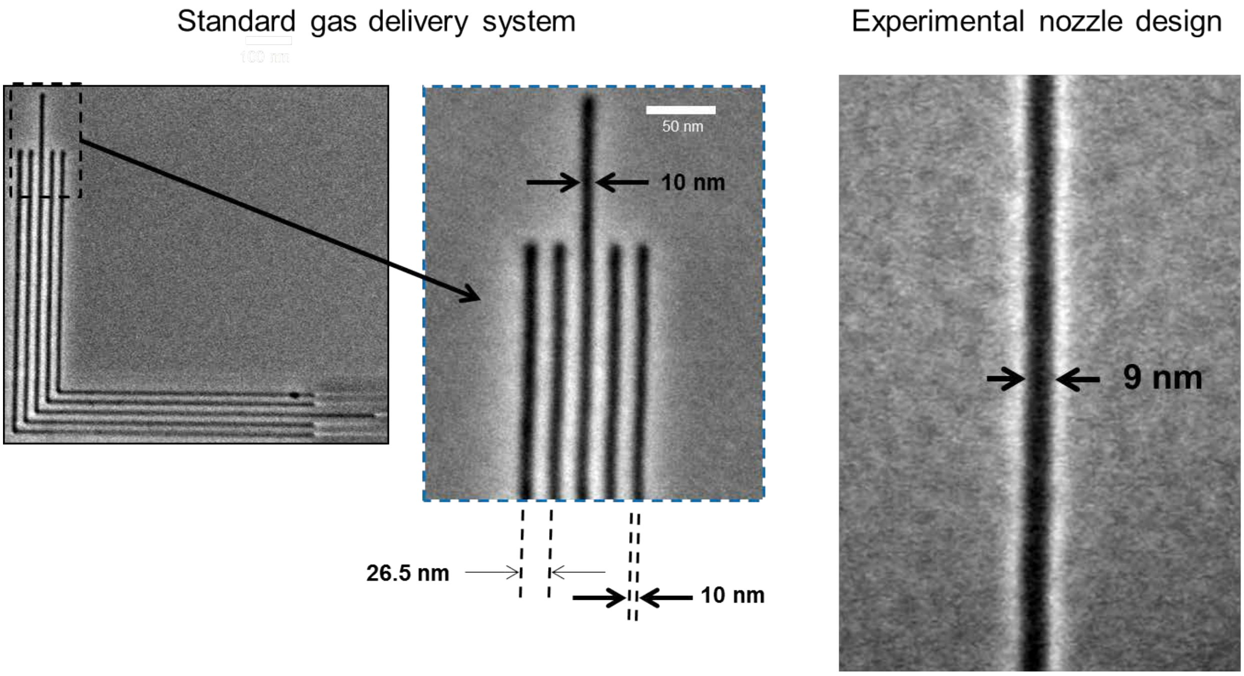

Figure 4: A dense line and space pattern was etched into quartz material by e-beam-induced processing. An etching resolution of 10 nm could be achieved. For an optimized nozzle design the resolution was about 9 nm.

The process resolution for writing single lines or spots is certainly a good indication for the capability of a technique for nano structuring. However, the performance in a mask repair application is usually 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 river bedding. 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. Simulations, calculated with the software CASINO and visualizing this situation, are depicted for an isolated defect in Figure 5. Since this kind of defect has an edge all around, the beam can only expose the area in the center. Therefore the minimum defect size at which there are still pixels left that can be exposed, is twice the bias. Figure 5 reveals the direct relation between the beam energy and the minimum repairable feature size.

This direct relation has also been demonstrated experimentally: The repair of a too short line that has been extended by 15 nm (Figure 6). 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 is 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.

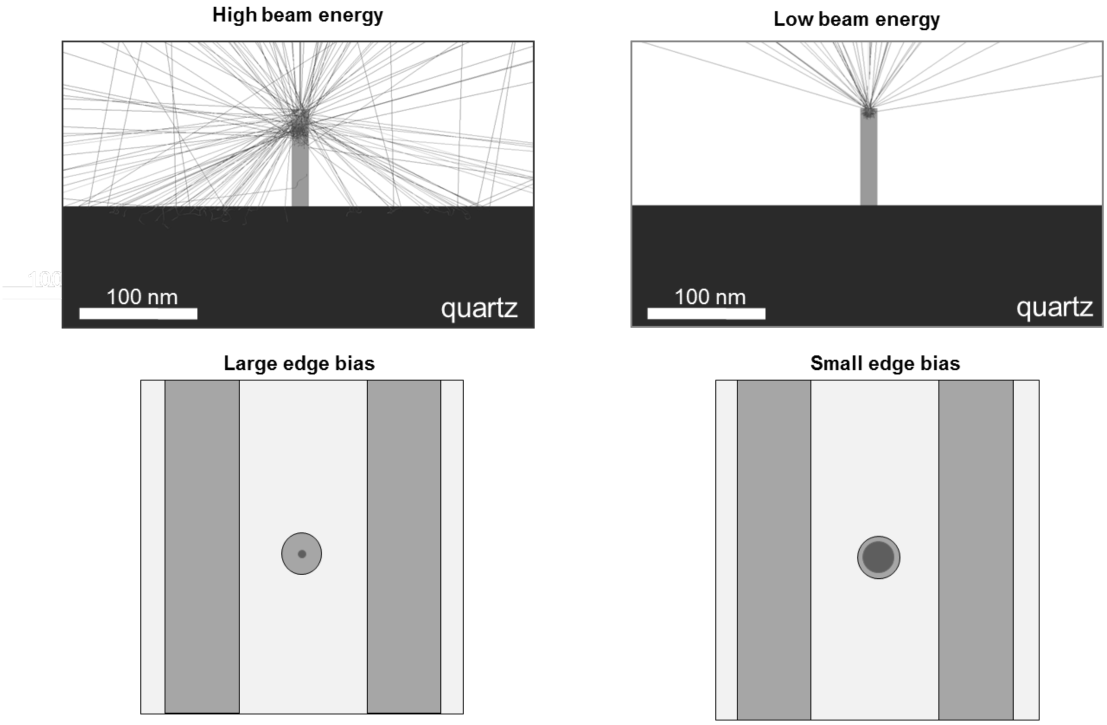

Figure 5: Upper part: Simulations of the electron trajectory for an isolated defect in cross section for a high (left side) and low beam energy (right side), respectively. Lower part: Top view of the defect with the area exposed by the electron beam in a darker shade. This demonstrates a direct relation between the beam energy and the minimum repairable feature size defined by the smaller process bias

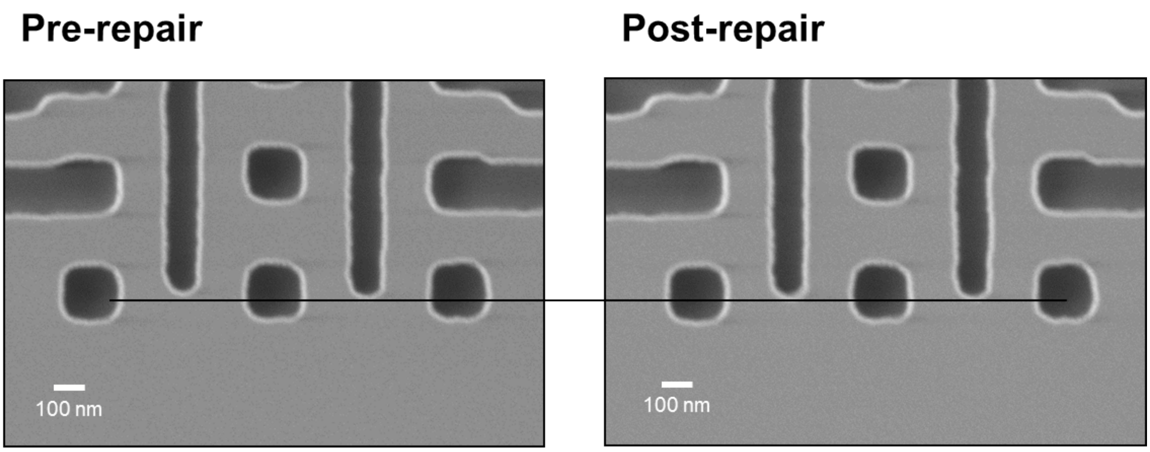

Figure 6: A 15 nm line shortening defect was successfully repaired by applying a low energy e-beam-based repair process

2.3 Invasiveness

For charged particle based mask repair there are two classes of species which can be used: ions and electrons. 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. The 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 types of photo masks 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 like A6L2. 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. For mask repair, 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. In principle, tailored chemistries can be developed to improve this selectivity for beam induced chemistry. However, in the case of ion beam milling the removal rate of different atoms mostly depends on the difference in their mass (Z value) and so only e-beam-induced chemistry provides a promising solution for this approach. For materials typically used on photo masks the removal rate for ion milling of the absorber versus the underlying substrate is not expected to show a significant difference.

Since high durable material is robust against chemical modification induced by cleaning and DUV irradiation, this material is robust against e-beam induced chemical reactions as they are used for the repair of standard materials. ZEISS developed a new and versatile process to perform such repairs. First repair results on A6L2 have been presented by Kanamitsu et al. during PMJ 2014[9]. Over the last years, ZEISS established close collaborations with the photo mask blank vendors. Thus we have conducted studies regarding the versatility of further improving the A6L2-MoSi etching recipe. The aim was to find a new chemical composition which allows an e–beam-induced chemical reaction which has a preferred reaction path with the high durable phase shifting material but not with the quartz. Figure 7 shows as representative result of the novel recipe, employing a new precursor combination, the etching depth as a function of the etching time. The achieved selectivity is better than 10:1.

Figure 8 shows an example of a complicated defect with the dimension of 10 nm x 500 nm on an A6L2 reticle. The upper left part shows a SEM image of the defect before repair. To prove that this defect is really printing we applied AIMS measurements and analyzed the data using repair verification (upper right part). The AIMS analysis predicts a ΔCD of 8.6% which typically drives a photomask out of specification. In the lower left part a post repair image is depicted. The defect is not visible anymore. Furthermore no collateral damage at the quartz side is visible. In the lower right part the results of the AIMS measurement performed after the repair are presented. The measured ΔCD is below 2.5%. This can be clearly rated as successful repair.

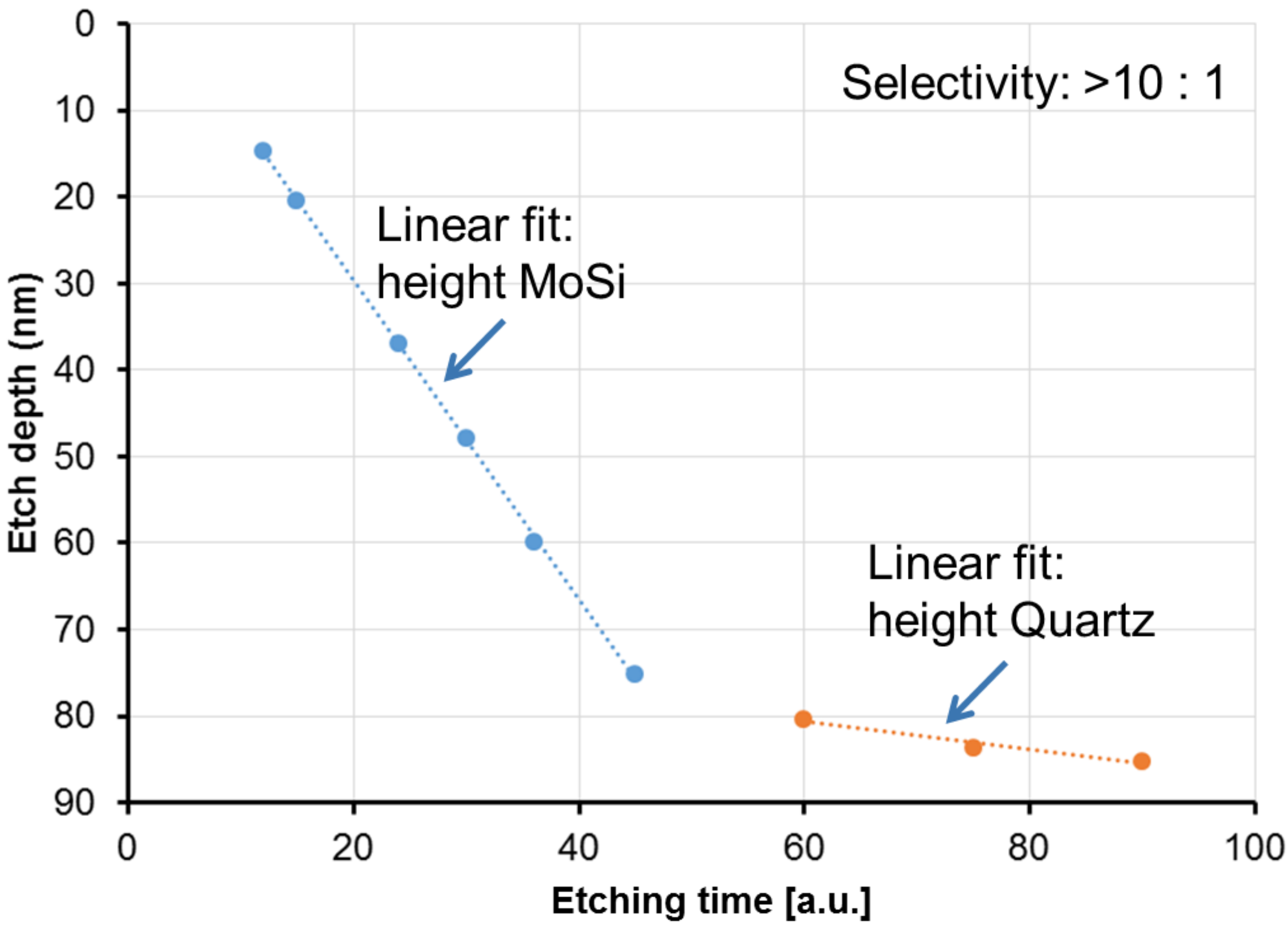

Figure 7: Selectivity data for the high durability MoSi A6L2. A selectivity between MoSi and Quartz of more than 10:1 was achieved

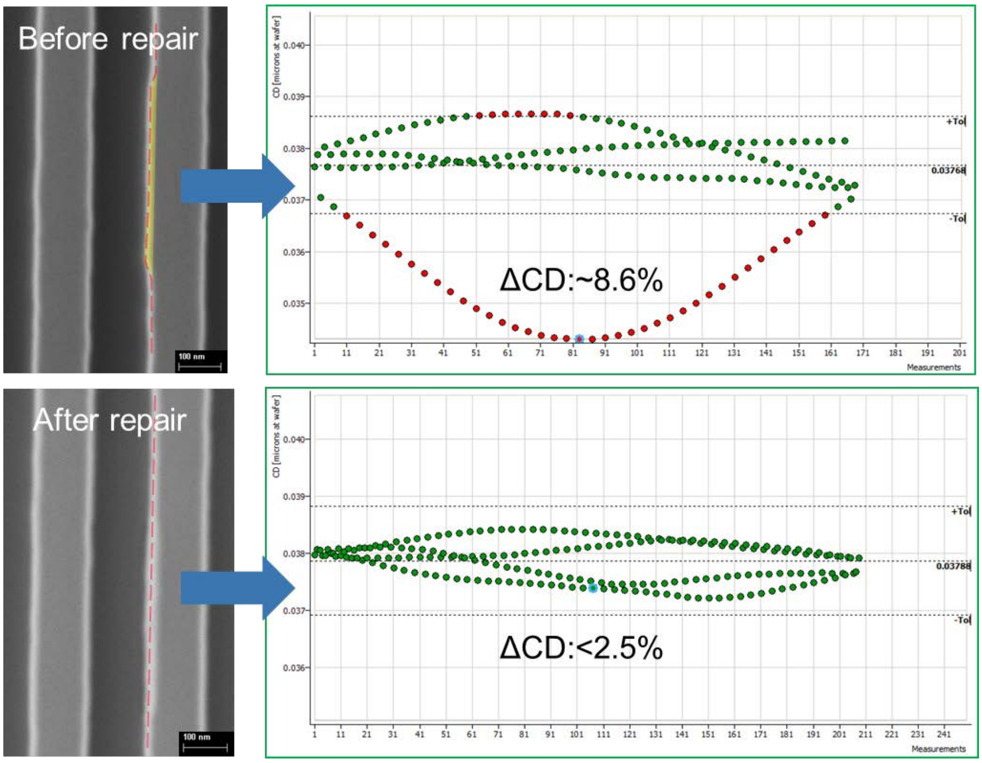

Figure 8: Example of complicated 10 nm x 500 nm defect on an A6L2 reticle. Upper left: SEM image before repair. Upper right: AIMS measurement is predicting a delta CD of -8.6 %. Lower left: Post repair SEM image. Lower right: same AIMS measurement was performed. The measured delta CD is below 2.5% which means a successful repair.

3. CONCLUSION

In this study the limits of today's charged particle based mask repair are evaluated. The impact and influence of repair process resolution by the primary beam spot size, substrate interaction and precursor supply are discussed. Further we establish the possibility to shrink the minimum feature size of repairs by reducing the primary electron beam energy. Etches on a NIL template show this experimentally and simulations illustrate the interplay between the beam energy and the process resolution. In addition, we report about a new chemical etch process, which allows to perform repairs of seminally high durable A6L2-MoSi materials with a very high selectivity of more than 10:1 and to repair complicated defects down to a dimension of 10 nm x 500 nm, using low primary electron beam energies. It has recently been developed by Carl Zeiss and can be carried out with the new tool generation MeRiT neXT being already successfully introduced into the market.

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