Mitigation of EUV Mask Blank Substrate Pit and Scratch Defects by Accelerated Neutral Atom Beam (ANAB) Processing

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ABSTRACT

EUV mask blank substrates will be subject to extraordinarily demanding requirements upon flatness, smoothness and absence of residual defects. To date, no combination of available surface preparation techniques has been able to produce essentially perfect substrates with zero residual defect populations. A critical problem yet to be resolved involves small numbers of nanoscale divots and scratches which are generated by the operations used to meet smoothness requirements. A new non-contact surface sputtering technique known as accelerated neutral atom beam (ANAB) shows promise for mitigating the divot and scratch defects without increasing surface roughness and without altering flatness and planarity. This paper describes a mask blank substrate study which has been conducted to demonstrate the ANAB defect mitigation capability.

Key Words: EUV mask blank substrate, accelerated neutral atom beam, ANAB, lateral sputtering

1. INTRODUCTION

Ability to manufacture defect-free mask blanks must be established before EUV lithography can be implemented into production. Challenging problems exist in achieving mask blank substrates able to satisfy defined requirements including surface flatness and roughness while also being entirely free of residual scratches, bumps and embedded particles. No combination of available surface preparation techniques has been found capable of accomplishing all of the flatness, roughness and residual defect demands. Extensive development efforts employing combinations of surface preparation techniques have been conducted under the direction of SEMATECH and have resulted in mask blank substrates approaching the defined goals, but a fully complete and practical solution has to date not been demonstrated. Substrates which meet flatness and roughness requirements can be produced but they still invariably exhibit non-zero counts of shallow pits and scratches having dimensions sufficient to produce printable defects on completed masks.

Exogenesis Corporation has introduced a new surface modification technique known as Accelerated Neutral Atom Beam (ANAB) processing which shows promise for being able to remove from mask blank substrates the residual defects that other techniques have not been able to eliminate. ANAB is conducted under vacuum by a beam of electrically neutral argon gas atoms which have average energies of a few tens of electron volts. ANAB can remove material by sputtering under conditions which inherently cause nanoscale bumps, scratches and pits to be diminished as the removal action proceeds. When used to sputter material from an extremely smooth surface, ANAB can remove a precisely controllable and uniform thickness of material without resulting in any increase of roughness. In the case of a mask blank substrate already planarized and polished by CMP, without creating any additional surface roughness, ANAB is capable of removing a sufficient depth of material so as to eliminate all residual pits and scratches.

Exogenesis and SEMATECH have collaborated to conduct an initial demonstration of feasibility of using ANAB for defect correction on EUV mask blank substrates. A representative mask blank substrate was characterized by

SEMATECH to identify the location and nature of residual pit defects to be re-examined following processing by ANAB. Punch marks were added to mark the pit locations. The substrate was processed at Exogenesis on an nAccel 100™ ANAB system using different ANAB doses on quadrant areas of the surface so as to remove 20, 40, 80 and 160 nm thick layers from respective quadrants and then using conditions to remove 40 nm uniformly from the entire surface. Post processing examination of the substrate at SEMATECH showed that all marked pit defects initially present had been eliminated. Surface roughness after processing was measured to be 0.160 nm RMS, essentially unchanged from the initial value of 0.151 nm RMS. These results indicate the potential of ANAB as the solution for the residual defect mitigation required in order to produce defect-free mask blank substrates. Additional development is in process.

2. ACCELERATED NEUTRAL ATOM BEAM (ANAB) TECHNIQUE

ANAB is a surface modification technique in which processing is done in high vacuum by a high intensity directional beam of electrically neutral energetic gas atoms which have been accelerated so as to have average energies in the range between 10 and 100 eV per atom, the ideal range for producing ultra-shallow surface interactions. The technique has been previously described [1]. Most applications are performed using Ar gas atoms, but beams can be produced using almost any source gas. Because the beams contain only electrically neutral atoms, they are not subject to space charge effects which limit low energy ion beam transport and which normally require active neutralization of target surfaces.

To create an ANAB neutral atom beam, a beam of accelerated gas cluster ions is formed first by expanding appropriate source gas through a small nozzle into vacuum, using electron bombardment to ionize emerging gas clusters, and then accelerating the ionized clusters through a high potential of tens of kilovolts. Figure 1 shows a typical system configuration. Immediately after acceleration, collisions of accelerated gas clusters with gas atoms present within the gas stream transfer energy into the clusters, causing them to become thermodynamically unstable so as to disrupt weak van der Waals bonds between atoms, and causing large numbers of constituent atoms to be released. Unbonded released atoms continue to travel collectively with the same velocities that they had before being released. An electrostatic deflector is then used to eliminate from the beam residual charged clusters and other charged species which might be present. As an example, a representative singly-charged gas cluster ion comprised of 1000 Ar atoms and accelerated through 30 kV can be predicted to lose up to 350 atoms as a result of a single gas collision. Each of the released neutral atoms in the resulting ANAB stream will have an energy of 30 eV. The average energy of ANAB atoms can be controlled by varying the cluster ion acceleration potential or by altering the size distribution of clusters emerging from the source gas nozzle. To illustrate the typical effect of ANAB on a target surface, Figure 2 shows a TEM image of the extremely shallow uniform amorphous layer left on a silicon surface after sputter removal of 100nm of material from the surface

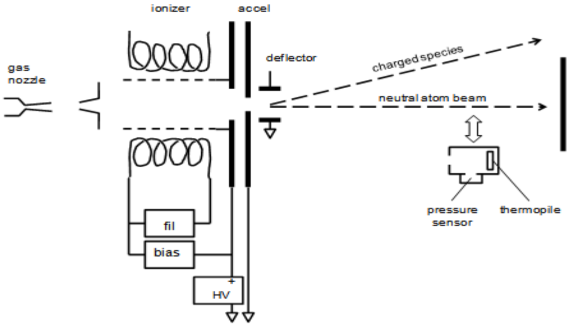


Figure 1. Typical accelerated neutral atom beam configuration

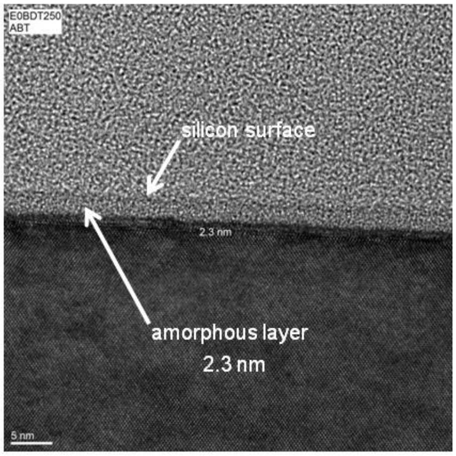


Figure 2. TEM Image of amorphous layer in Si after removal of 100 nm by ANAB

3. ANGSTROM SCALE SMOOTHING WITH ANAB

ANAB Ar atoms have average energies of a few tens of eV, values which are typically very close to the sputtering thresholds of most target materials. At these energies, atoms sputtered from a target surface are found to have directional distributions quite different from those normally associated with sputtering by ions at higher incident energies. Where higher energy ions tend to cause ejection primarily normal to the target surface, the much lower energy ANAB neutral atoms cause ejection primarily toward shallower angle directions. This behavior, which is referred to as lateral sputtering, is also a well-known characteristic of sputtering by gas cluster ions which are the ANAB parent species [2]. Figure 3 shows an experimental example of the angular distribution of sputtering from a Cu target by Ar ANAB.

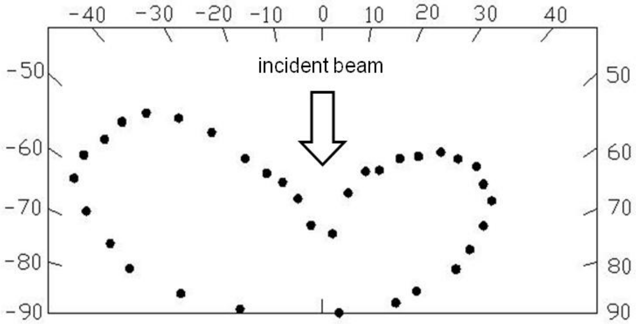


Figure 3. Angular distribution of sputtering from a Cu target by Ar ANAB.

Due to its characteristic lateral sputtering behavior, ANAB has an inherent ability to cause smoothing of surfaces on virtually any material provided that the material has sufficiently good initial quality. As a result of the laterally directed components of the sputter ejection distributions, a mechanism exists which slightly enhances effective removal rates from surface high regions and slightly decreases corresponding removal rates from valleys and divots. These actions are most effective when the initial surface is already of good quality with only small scale local defects and deviations. As representative examples, Figures 4 and 5 show atomic force microscope images of quartz and high-quality sapphire surfaces before and after smoothing by Ar ANAB.

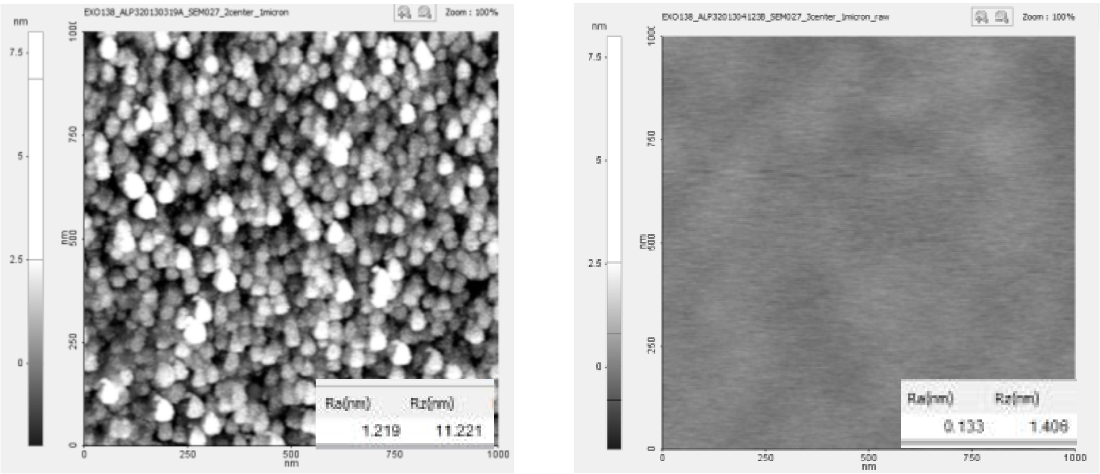


Figure 4. quartz unprocessed (Ra = 12.19Å), and processed with ANAB (Ra = 1.33Å)

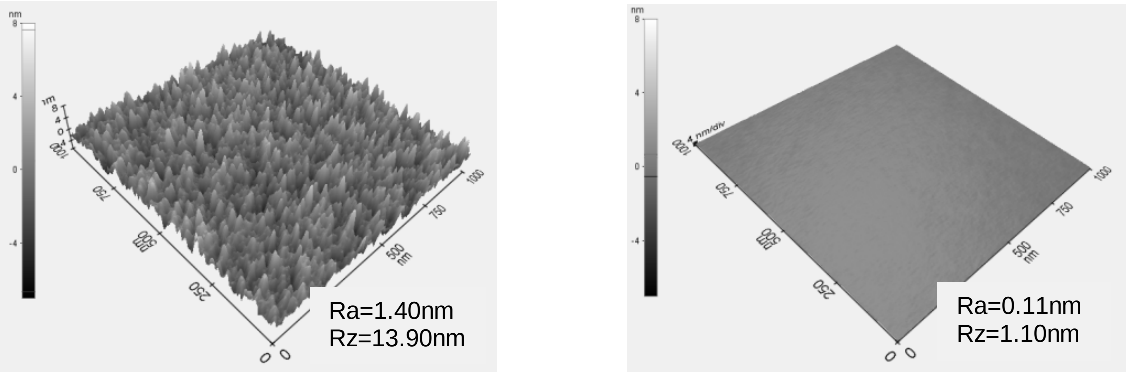


Figure 5. Sapphire unprocessed (Ra =14.00Å), and processed with ANAB (Ra = 1.10Å)

Lateral sputtering by ANAB not only reduces the roughness of a surface; it also enables the removal of nanometer sized divots and scratches. ANAB is a non-contact process so there are no normal forces applied to the surface of the material being processed. These normal forces which are used by traditional polishing techniques such as chemical mechanical polishing (CMP) can create sub surface damage [3]. These normal forces can be iteratively reduced, but inevitably result in a compromise between ultimate smoothness and induced defects. ANAB is a dry non-contact process which does not possess the mechanism for creating subsurface damage.

An additional advantage of ANAB as an atomic level smoother and defect removal technique is that it is a “dry” technology; there are no fluids or compounds that are used with ANAB. ANAB processing takes place in an ultra-pure high vacuum chamber. Traditional techniques such as CMP and MRF require various chemical fluids and compounds to enable the polishing results. These fluids and compounds carry the burden that they must be removed and properly disposed of. In addition, substrates processed with these fluids require cleaning steps to completely remove the remnants of these various chemicals. These aggressive cleaning techniques have been shown to enable subsurface damage to migrate to the surface [3].

ANAB is performed by mechanically scanning of the target material through a stationary beam. An automated X-Y scanner controlled by a raster scan algorithm provides uniform removal across the entire surface plane while not affecting the planarization. The ANAB is Gaussian in distribution with a full width at half maximum (FWHM) of approximately 10mm. The scanning algorithm employs a 2mm scan pitch and complete beam over-scan. As an example; a 150mm x 150mm sample would receive 80 scans of 160mm in distance. The scan distance is calculated by adding one beam radius for the top over-scan, then adding the size of the material, and then adding another beam radius for the bottom over-scan. See Figure 6 showing a typical scanning pattern of a material that is 150mm x 150mm.

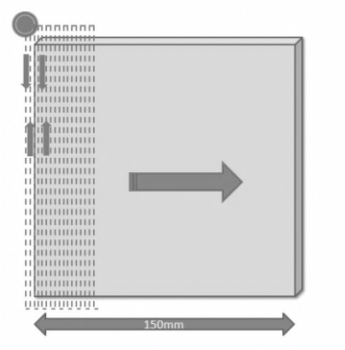
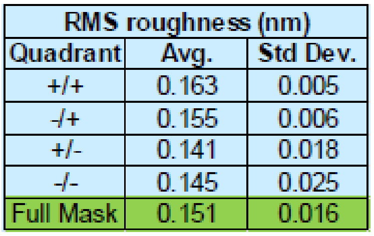


Figure 6. A typical scan pattern with 2mm pitch and full beam over-scan

4. ANAB TO MITIGATE DEFECTS ON EUV MASK BLANKS

ANAB has been shown to remove nanometer sized pits and scratches from EUV mask blank substrates without affecting the surface roughness. In collaboration with SEMATECH a test was designed to show the viability of ANAB to remove surface defects without negatively affecting the surface roughness. SEMATECH selected a test mask blank substrate to be used for the evaluation. The mask blank substrate was characterized for different nanometer scratch and divot defects, and surface roughness. The scratches and divots were quantified, cataloged, and physically punch-marked to archive their specific location for the post process evaluation of each exact defect. See Figure 7 Pre-process roughness for the AFM roughness quantification. The mask blank substrate was shipped to Exogenesis' facility and was processed with Exogenesis' nAccel-100 processing tool. The ANAB technology has been described in a previous section. A unique processing technique was engineered in an effort to determine the proper processing time needed to successfully remove the defects. This technique divides the mask blank substrate into quadrants, and removed a different thickness of material in each quadrant by varying the ANAB exposure times of each quadrant. The final step was designed to apply a uniform process to the entire mask blank substrate. After the mask blank substrate was processed, it was re-packaged and returned to SEMATECH for post-process evaluation.

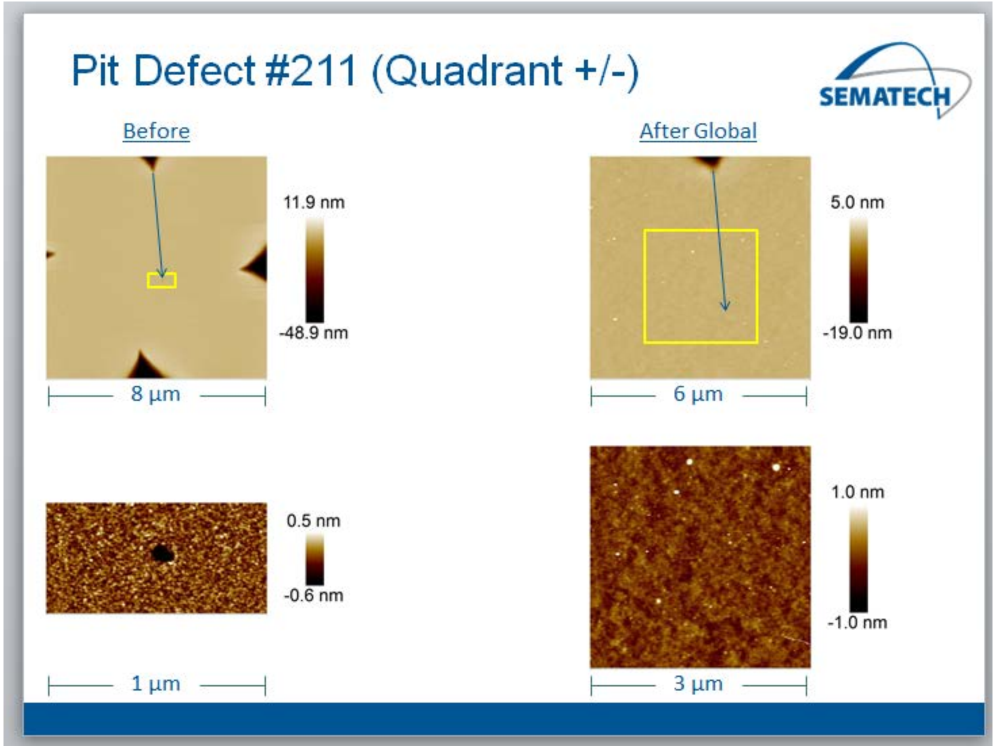


RMS roughness (nm)		
Quadrant	Avg.	Std Dev.
+/+	0.163	0.005
-/+	0.155	0.006
+/-	0.141	0.018
-/-	0.145	0.025
Full Mask	0.151	0.016

Figure 7. Pre-process roughness

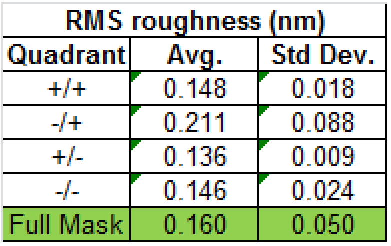
5. RESULTS OF TEST

After the final evaluation it was shown that the pits and scratches on the mask blank substrate were completely removed, and the surface roughness was not increased. Four of the sixteen pre-characterized defects were post process analyzed. See Figure 8 Pre and post defect example for an example of the typical results of pit removal with ANAB. The figure shows the pre-Exogenesis-process analysis (*Before*) on the left side of the figure and the post-Exogenesis-process (*After Global*) on the right side of the figure. The location punch marks were used to enable the equipment operator to return to the exact nanometer defect. An AFM was used to confirm the defect was completely removed, and that the surface roughness was not increased. See Figure 9 Post-process roughness for the quantification of the roughness after the mask blank substrate was processed by Exogenesis.



Pit Defect #211 (Quadrant +/-)

Figure 8. Pre and post defect example



RMS roughness (nm)		
Quadrant	Avg.	Std Dev.
+/+	0.148	0.018
-/+	0.211	0.088
+/-	0.136	0.009
-/-	0.146	0.024
Full Mask	0.160	0.050

Figure 9. Post-process roughness

6. SUMMARY

ANAB is a novel surface modification technique that has been shown to be effective in angstrom level smoothing of various materials, with concurrent removal of surface defects such as nanometer divots and scratches. ANAB is a non-contact, dry process that does not use normal forces in conjunction with fluids or compounds to smooth substrates. For these reasons, ANAB is being further studied to understand its impact on sub surface damage; it does not possess the mechanisms for creating subsurface damage, and therefore it should also be a viable technique for removing existing subsurface damage while concurrently polishing the surface. The results of this study confirm that ANAB is viable for removing nanometer sub surface defects while not increasing surface roughness on EUV mask blank substrates.

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