Investigation of Nanomachining as a Technique for Geometry Reconstruction
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ABSTRACT

Nanomachining is a relatively new technique to the semiconductor industry. This technique utilizes the positional control of an atomic force microscope coupled with RAVE LLC’s nanomachining head to perform material removal with nanometer level precision. This paper discusses the benefits of that technology as applied to photomask repair. Specifically, we will show the capability of the RAVE nm1300 to reconstruct completely missing contacts on 193 nm - 6% MoSi phase shift material utilizing both symmetric and asymmetric NanoBit tips. Wafer print test data confirmed the MSM-193 (AIMS)TM data that symmetric NanoBit tips have the ability to consistently produce contacts with through focus critical dimensions within 15 nm (1x) of unrepaired contacts. Experiments show that in order to reproduce the correct through focus behavior, the nanomachined depth into the quartz substrate must be controlled to within 5 nm on the photomask. In addition, 193 nm AIMS data show that placement errors of the reconstructed contacts are less than 15 nm (1x). Throughput and tip lifetime for both tip types on these repairs will also be examined.

1. INTRODUCTION

Photomask repair technology has lagged well behind the capability requirements listed in the International Technology Roadmap for Semiconductors. The lack of this necessary capability has led to reduced yields on high end product and, as a result, diminished on-time delivery of photomasks.

Additionally, the need for sub-wavelength resolution has driven the implementation of phase-shifting photomasks for critical layer processing. The increased complexity of these layers has, in turn, dramatically increased mask costs and cycle time. Advanced alternating phase shift masks may cost in excess of $50,000 U.S. and take five or six times as long to deliver as a standard photomask.

Typically, there is significant difficulty in getting these masks through front end processing with any predictability. To make matters worse the write times are long, so rewrites have a pronounced impact on operating costs and write-tool availability. Once a mask successfully completes front end processing, therefore, it is extremely desirable to be able to repair any existing defects.

Until recently, there were only two options for photomask repair: focused ion-beam (FIB), or laser. While each technique has its advantages and unique capabilities, each is also limited in its ability to perform production repairs on attenuated phase shift materials. Specific limitations include imaging, substrate damage control, edge placement, and transmission of repaired areas.

A third photomask repair option is the RAVE LLC nm1300 (Figure 1). The system is based on Atomic Force Microscopy (AFM) techniques to produce a three-dimensional rendering of the surface at a defect location. This is done by first driving to the defect site using high NA 100x optics, then scanning the surface with the NanoBit. The same NanoBit is then used to complete the repair by physically removing the defect by nanomachining. This process generates some nanometer-sized debris, which is subsequently cleaned off using a cryogenic cleaner.

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By using sub-nanometer control afforded by AFM technology the nm1300 employs a subtractive photomask repair technique. The current system is focused on meeting the SIA Roadmap requirements for the 130-nanometer design rule node, but the technique is extendable to the 100 nm node, NGL, and beyond. For the purposes of this paper, we will focus on contact hole reconstructions on 6% 193 nm MoSi attenuated phase shift material.
The concept of attenuated phase shifting masks was originally developed in the early 1990's.\textsuperscript{1, 2} The fundamental principle being that a partially transmitting 'shifter' layer can be used to phase shift light 180 degrees out of phase from light traveling through a quartz opening defining a feature on the wafer (Figure 2). Light diffracted from the quartz opening into the phase shifted area destructively interferes with light from the phase shifted area, improving image contrast.\textsuperscript{3} One important element of this technology is the sidewall profile of the shifter material. When the RAVE nm1300 is used to repair a contact it creates a sidewall profile angle that is less than 90 degrees. The angle of the tip relative to the substrate is 65 degrees and 83 degrees for symmetric and asymmetric NanoBits, respectively. Decreasing the sidewall angle from 90 degrees incurs a phase error in the light traveling through the partial height shifter material. The phase error due to light passing through the partial height attenuating layer, which results in an incomplete phase cancellation with the light traveling through the quartz opening. There are two consequences of this phase error, one is a loss of contrast, the second is a shift in depth of focus or through focus behavior of the repaired feature. In principle, a feature with perpendicular shifter sidewall angles has a symmetric through focus behavior. This means conjugate focal planes have equivalent critical dimensions (CD's). However, when the sidewall angle is decreased the through focus behavior of the feature becomes asymmetric about best focus, resulting in larger CD's at positive depths of focus compared with those at negative depths of focus.

![Figure 2. Simplified graphical representation of attenuated phase shift mask.](image-url)
In the case of contacts, the issue becomes even more crucial because four sidewall angles are used to define the feature, making contacts twice as susceptible as line/space patterns to through focus issues caused by non-perpendicular sidewalls. In the course of repairing completely missing contacts, matching through focus behavior, as well as CD targeting and contact placement, can become very difficult. One way to compensate for the phase error created by decreasing the sidewall angle profile is to remove (overcut) a portion of the quart substrate (Figure 3).

![Figure 3. Graphical representation of sidewall angle profile and overcut into quartz substrate as a means of compensation.](image)

This overcut essentially restores the relative phase shift between the light passing through the shifter layer and that passing through the quartz to 180 degrees. We have developed a process with the RAVE nm1300 utilizing the symmetric tip type that balances the phase error created by the decreased sidewall angle with the phase error created by removing the quartz substrate.

3. RESULTS

Results for this paper are divided into 4 sections. The first section will show process development for reconstructing isolated contacts using the RAVE nm1300 with the symmetric NanoBit type. The second section describes reconstruction of isolated contacts on the RAVE nm1300 with the asymmetric NanoBit type. Section 3 will deal with reconstruction of nested contacts with symmetric NanoBits. Section 4 discusses repeatability, throughput time (TPT), and tip wear. All CD data given in this paper is taken directly from wafer print tests.

3A. Nanomachining Isolated Contacts with Symmetric NanoBits

In figure 4 (below) a plot of through focus delta (TFD) vs. overcut depth into the quartz substrate is shown. Through focus delta (TFD) is defined as the difference of a reference contact CD at negative defocus and RAVE nanomachined contact CD at the same negative defocus minus the difference in reference CD at positive defocus and RAVE CD at that same positive defocus (Eq. 1).

\[
\text{Through Focus Delta (TFD)} = (\text{Ref CD}_n - \text{RAVE CD}_n) - (\text{Ref CD}_p - \text{RAVE CD}_p) \quad \text{Eq. 1}
\]

For our purposes in this paper negative defocus is defined as 0.2 um into the wafer resist from the best focus and positive defocus is defined as 0.2 um out of the wafer resist. Through focus delta will be used as the primary success criteria for whether or not a RAVE nanomachined contact matches reference contacts on the wafer. The data in Figure 4 shows a linear relationship between TFD on the wafer and cut depth into the quartz substrate for a
particular contact size on the mask. Since, the TFD is normalized to reference contacts the desired TFD for process development is zero. Data in Figure 4 shows the optimum cut depth into the quartz substrate for this contact size is 22 nm.

![Through Focus Behavior as a Function of Overcut Depth for Symmetric NanoBit](image)

Figure 4. TFD for symmetric NanoBits and simulation as a function of nanomachined depth into the quartz substrate.

Simulations were performed to substantiate that the quartz nanomachined depth was indeed compensating for the sidewall angle profile (Figure 4). Symmetric NanoBit tip angles are approximately 68 degrees relative to the substrate. From this, it can be inferred that the sidewall angle of reconstructed contacts produced by the symmetric tip should be on the order of 65 degrees. A rudimentary geometry calculation, shows that \( \tan \theta = \frac{\text{shifter height}}{\text{width of shifter left at the quartz shifter interface}} \). (Figure 5, left)

![Graphical Representations of RAVE Nanomachined Contact (Left) and Structure Used for Simulation (Right).](image)

Figure 5 Graphical Representations of RAVE Nanomachined Contact (Left) and Structure Used for Simulation (Right).

For the nominal 70 nm 6% MoSi shifter thickness, the width of the shifter left at shifter/quartz interface is \( \sim 35 \) nm. For simplicity we have replaced the sloping sidewall with a block of shifter 35 nm wide (Figure 5, right). This creates a 35 nm rim just inside the perimeter of the contact hole, which is assumed to have 50% transmission relative to quartz and a 90 degree phase shift. The simulation results, shown in Figure 4, match the wafer data trend, and predict an overcut depth of 17 nm will be necessary to compensate for the sidewall profile created by the RAVE. The agreement between the wafer and the simulated data from this simple model suggests that the quartz overcut depth is compensating for the phase error incurred by the sidewall profile.
3B. Nanomachining Isolated Contacts with Asymmetric NanoBits

The RAVE nm1300 can also perform removals with an asymmetric NanoBit. The advantage to using an asymmetric tip is that the angle of the tip relative to the substrate increases from 65 degrees to 83 degrees. This would suggest that with an asymmetric tip that a smaller quartz overcut depth could be used because there is far less sidewall angle profile requiring compensation. Figure 6 compares the asymmetric and symmetric NanoBit data.

![Graph showing through focus behavior as a function of overcut depth for asymmetric NanoBit.](image)

Figure 6  TFD for symmetric and asymmetric Nanobits as a function of nanomachined depth into the quartz substrate.

The data in figure 6 clearly shows that this assessment is true. Where a contact nanomachined with a symmetric tip requires an overcut depth of 22 nm, a contact nanomachined with an asymmetric tip requires an overcut of only 5 nm into the quartz substrate. This evidence again points to the fact that the overcut into the quartz substrate is compensating for the sidewall profile left by the NanoBit.

3C. Nanomachining Nested Contacts with Symmetric NanoBits

The interdependence of nested features to produce desired CD's on the wafer affects not only the phase error produced by the sidewall profile but also the phase compensation from the overcut depth. For this reason the pitch for a pair of nested contacts can have some influence on the optimum overcut depth. If both contacts in a nested pair are nanomachined by the RAVE nm1300, the interplay between the phase error created by the shared sidewall and the phase compensation effect from the overcut depth both contacts becomes difficult to comprehend. The wafer print test data shows a decrease in the overcut depth necessary to compensate for the sidewall profile of the primary contact and the additional phase error due to the sidewall angle of the adjacent contact. Figure 7 shows that in nested geometry the overcut depth must be on the order of 10 nm to compensate for the sidewall profile of both contacts, in comparison to the 22 nm necessary in the isolated case.
3D. Repeatability, Placement, Throughput Time, and Tip Wear

Though often overlooked in the world of mask repair, repeatability is equal in significance to capability. Table 1 shows repeatability data for 10 contacts nanomachined with symmetric Nanobits by the tool over a five-day period.

<table>
<thead>
<tr>
<th>Site #</th>
<th>Wafer CD Delta 1x (nm)</th>
<th>Through Focus Delta (nm)</th>
<th>Worst Placement (nm)</th>
<th>Overcut Depth (nm)</th>
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<tr>
<td></td>
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<td>Best Focus</td>
<td>Positive Defocus</td>
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<td>-1</td>
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<td>19</td>
<td>15</td>
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</table>

Table 1 Repeatability and placement data for 10 contacts nanomachined with multiple symmetric tips over a 5-day period. Positive CD deltas correspond to contacts smaller than a reference CD, negative CD deltas correspond to contacts larger than a reference CD.
The data shows the average CD delta at negative, best and positive focus with respect to a reference contact site is 2, -2, and -3 nm respectively, which indicates the tool has good mean to target performance through focus. The worst 3σ value of 20 nm, will give a process capability (Cp) = 1 for a defect specification of ±20 nm through focus. For the .13 um node this corresponds to a 15% defect specification. For the .09 um node this is a 22% defect specification.

Contact placement, which was collected as an absolute value with no relation to the direction of the misplacement, shows that on average the 10 contacts exhibit a misplacement by 7 nm. It should be noted that there appears to be no indication of a directional dependence in the placement data with respect to operator or NanoBit utilized. Since, the placement data was collected as an absolute value, a standard deviation of the placement data is not relevant. However, assuming a worst-case scenario, that the two worst placements were in opposite directions, the range would be 20 nm. Assuming this as a reasonable 3σ value gives a Cp = 1 resulting in a for a defect specification of ±20 nm. This is equivalent to the CD delta specification.

The consistency of the quartz nanomachine depth is also shown for the 10 contacts in table 1. The target overcut depth for these contacts was 15 nm. The average quartz nanomachined depth for the 10 contacts in this study was 13 nm, which corresponds to a -2 nm in mean to target performance. The standard deviation of these 10 sites was 2.7 nm, 3σ = 8 nm. Assuming a good mean to target depth, as was observed in this study, figure 4 predicts the range in the TFD one could expect to see is 15 nm (±7 nm from matching the reference contact).

Average throughput time (TPT) for the 10 contacts nanomachined with symmetric NanoBits, see Table 1, was ~1.5 hrs/contact. This includes overhead time such as mask loading, mask alignment, scans of reference sites, tip changes, and Eco-snow post-repair treatment. Six contacts (Table 1 Sites 3-8) were nanomachined on the same plate with only one mask load, one mask alignment and minimal reference scans in 6.5 hours, which corresponds to a TPT of ~1.1 hrs/contact. None of these contacts required further repair. In comparison with Laser or Focused Ion Beam (FIB) tools, RAVE's TPT is definitely slow. However, there are a number of factors, which make this TPT more reasonable. First, RAVE exhibited a good first pass yield. Though only 10 data points have been collected here, the FPY for these 10 sites is 90%. Second, Eco-snow post-treatment requires only five minutes, after which a repair site can be evaluated using an AIMS™ tool. Though a wet clean is required at some point after Eco-snow, it is not necessary to perform this step before the repair site can be dispositioned.

The TPT for the 6 contacts nanomachined with asymmetric NanoBits was ~3 hrs/contact. The larger TPT can be attributed to the fact that the mask had to be removed from the tool, rotated, and realigned four times, once for each sidewall profile. The only other solution is to use 4 asymmetric NanoBits, one for each sidewall being nanomachined, which requires 4 tip load/unload cycles. This issue not only makes the process with asymmetric NanoBits longer but also much less manufacturable.

In all for the study, 22 contacts were nanomachined with 2 symmetric tips (15 with the first tip and 7 with the second). Note the second tip used was not worn out when the experiments were completed. It should be noted here that MoSi is a fairly soft material in comparison to other materials that the RAVE nm1300 may be used to remove. Thus, the defects repaired/tip for this particular material may not be consistent with that of other materials. Another tip-related issue has been the concern of how tip to tip variation affects CD's and overcut depth. No discernable difference in either of these metrics could be found between the two tips used in this study, nor was any difference found during the use of either tip. However, it was quite obvious when tips dulled, due to rounding of the top and bottom edge of the contacts being nanomachined.
4. Conclusion

This study has determined that it is possible to nanomachine completely missing contacts on 6% MoSi attenuated phase shift masks utilizing both symmetric and asymmetric NanoBits on the RAVE nm1300. Repairs performed with a symmetric NanoBit exhibit good targeting and placement, while minimizing through focus delta (TFD). The key to this process is compensating for the sidewall profile angles on contacts repair by the RAVE nm1300 by overcutting the quartz substrate. Through focus delta (TFD) with respect to quartz overcut depth for symmetric NanoBits were consistent with simulation data for a simplified structure. Contacts nanomachined with asymmetric NanoBits show equivalent performance to those nanomachined with symmetric NanoBits, but are much more time consuming and less manufacturable. First pass yield for the 10 repairs performed with a symmetric NanoBit at the correct target and overcut depth was 90% and the tool should have a $C_p = 1$ for a $± 20$ nm specification. Tip to tip variation as well as tip wear after numerous repairs did not affect the performance of the tool.

5. Acknowledgements

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6. References

