Simulation of Quartz phase etch affect on performance of ArF chrome-less hard shifter for 65-nm technology

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Abstract

The Cr-less Phase Shift Mask (CLPSM) has been considered as one of the most practical resolution enhancement techniques (RET) solution providing low Mask Error Enhancement Factor (MEEF) for low k1 geometries for memory and logic semiconductor devices. There are several papers that show the advantages of the CLPSM compared to the other types of RET. Also the required design changes have been widely studied.

Manufacturing of CLPSM requires quartz etching additionally to the COG mask process. Contrary to CLPSM, the required characteristics of the quartz etching process for altPSM are well specified. However, the required quality of the etching process for the CLPSM has not been sufficiently evaluated yet.

In this paper, the impact of imperfections of the mask manufacturing process, like the effect of quartz sidewall profile, etch depth deviation and quartz trenching during quartz dry etching on mask imaging performance is investigated. Simulations were performed using Solid-CTM to investigate these effects for both mesa and trench type CLPSM for different pitches. A CLPSM mask was manufactured at AMTC to confirm the validity of the simulation through comparing the contrast deviation on various mesa and trench sizes. AIMS measurements have been performed for this purpose.

Key Words: Chrome-Less PSM (CLPSM), NA, AIMS, AltPSM, MEF, RET, Cr-less, quartz trenching, sidewall profile

Introduction

An essential part of the CLPSM mask manufacturing process is the quartz etch step. Here the 180 degree phase shifting areas are etched into the quartz. This step is done using either the photoresist covered chrome or only the chrome as blocking layer for the quartz dry etching process. After quartz etching the remaining chrome is removed to open the 0 degree phase quartz background area which results in a mask pattern that transmits 100% light everywhere. The transmitted light forms dark lines by destructive interference along the phase edges.

Since the quartz dry etching is used to define the 180 degree phase-shifting areas, this process is being considered as critical for CLPSM manufacturing1, 2. As a consequence, a large effort has been spent to improve the quartz dry etching process. The most important characters to be controlled are the phase uniformity, micro-trenching, sidewall profile and the etch depth linearity, the so called RIE lag.3,4

The quartz dry etching process is expected to deliver vertical sidewalls and a flat bottom fit in the etched area. However, it is difficult to establish a dry etching process that gives vertical sidewall profiles and flat micro trenching for different pattern sizes and loads on both, global and local areas, meeting all other critical characteristics under control at the same time. The major parameters that control the dry quartz etching are the bias power, the source power, the gas mixture and the pressure. However, these conditions do not provide a unique solution for all key characteristics. Often, they drive the characteristics in different direction like a lower pressure improves uniformity while resulting in poor sidewall profiles. On the other hand, a lower bias power causes less micro trench but sacrifice of the uniformity.

Some of these major etching characteristics, e.g. the sidewall profile and micro trench of the bottom pit of the etched quartz, are not easy to measure during the etching process. This is due to limited tool capabilities for measuring these
characters for an individual product without destroying the photomask. Therefore, a vertical sidewall angle and minimal micro trench is considered as a prerequisite on the quartz dry etch process development. Although the vertical sidewall profile is the ultimate goal for dry quartz etch process development, it is more preferable to sacrifice the sidewall profile and/or micro trench for a better uniformity and RIE lag. To know the impact of the sidewall profile and the micro trenching on the imaging properties of the mask helps to balance better all mask parameters for an optimal imaging performance of the mask.

In Fig. 1 the cross-sections of quartz-etched areas are shown. The photos show clearly non-vertical sidewall profiles and a tendency to the micro-trenching at the bottom corners of the etch profile.

**Figure 1.** Cross section profile of quartz dry etched pit.

Intention of this paper is to investigate the impact of sidewall angle variations and micro-trenching on the imaging properties of Crless masks. The simulations presented here were performed using SOLID-CTM. Lines/Spaces pattern with varying pitches for both, mesa and trench-style Crless masks have been considered. For various pitches the impact of feature width and etch depths on contrast was determined and at a pitch of 150nm the influence of imperfections of the etch profile on the wafer CD has been studied. One sample CLPSM photomask was provided to verify the validity of the simulation. The 180 degrees etch was performed by three iterative dry etch processes. Various mesa and trench type patterns have been used to evaluate the optimum contrast. A Zeiss AIMS193Fab tool has been used for experimental verification of the simulated data. Crless features with a pitch of 150nm were measured using .85NA and a dipole illumination source (sigma= 0.25).

**Simulations**

Simulations were performed to study the impact of errors in the quartz etch process on the lithographic performance of a Crless mask. For this purpose the optimal etch profile, i.e. width and depth of the etched feature, for masks with different pitches were determined. Considering this as the “perfect Crless mask” at the given pitch, a certain threshold results in a CD equal to the half-pitch. The response of the CD at this threshold on deviations from the perfect mask geometry was studied. The investigations focused on the impact of a non-vertical sidewall profile and micro-trenches at the bottom of the etched area. Also these effects were studied as function of the defocus in the imaging process.

A Crless mask can be produced in two different types, the mesa- and the trench-style Crless mask. In the case of a mesa-style mask the main part of the pitch on the mask is etched away, whereas in the other case only small trenches are etched into the quartz. Both cases were considered in the simulations. Fig. 2 shows the basic geometry.

**Figure 2.** Design for simulation (2d-cross-section): mesa style (left) and trench style (right).
As the size of the mesa or the trench feature, $a$, is varied the two types merge. The optimal geometry for either of the two styles can be determined by varying the size $a$ and the etch depth $d$ at a given pitch until a maximum in contrast is reached. Then the geometry found can be considered as the “perfect Crless mask” for this pitch. In Fig. 3, simulation results are shown for a mesa-style Crless mask. Plotted there is the contrast as a function of the mesa size and the etch depth for various pitches. The illumination source used for the simulations was a disar with a sigma of 0.2 and an offset of 0.86 at a numerical aperture of NA=0.85 and an illumination wavelength of 193nm.

![Figure 3. Contrast vs. mesa size and etch depth for a mesa-style Crless mask at various pitches.](image)

The results for the optimal values of feature size and etch depth are summarized in Tab. 1. As shown in the graphs, for a mesa-style mask the geometry depends only very little on the pitch, whereas for the trench-type the width of the trench shows stronger variations with the pitch. Another remarkable point is that the etch depth does not depend on the pitch but on the type of mask. For a trench style mask the etch depth is 2nm smaller than for mesa style. Also, Tab.1 shows that the contrast for a trench style mask is higher than for a mesa style mask. For both types it gets reduced as the pitch decreases.
Figure 4. Contrast vs. trench size and etch depth for a trench-style Crless mask at various pitches.

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Table 1. Optimal feature size and etch depth for mesa- and trench-style Crless mask for various pitches.

For a pitch of 150nm the simulation results for the contrast are compared to AIMS measurements. This is shown in Fig. 5. The simulations were done at an etch depth of 48nm.

One can see that the optimal mesa sizes are well reproduced by the simulations. Nevertheless, the absolute values of measurements and simulations do not match very well. The origins of this are deviations of the real geometry of the area that has been quartz etched and flare that is known to reduce the contrast of AIMS measurements. The impact of flare has not been taken into account in the simulations presented here.

Figure 5. Comparison of the simulated and the AIMS-measured contrast vs. mesa size at pitch=150nm.

After having determined the geometry of the “perfect Crless mask” one can study the impact of deviations from this geometry. The first type of deviation considered here is a non-vertical shape of the sidewalls of the quartz trenches. In
Fig. 6 the geometry used for the simulations is shown. As is illustrated in Fig. 7 a non-vertical etch profile shifts the optimal contrast to higher values of the mesa size without changing the absolute values of the contrast. This is due to a reduced width of the non-etched (mesa-style) or etched (trench-style) area and, thus, a smaller effective feature size.

**Figure 6.** Geometry of the etch profile used to study the impact of a sidewall angle for mesa (left) and trench style Crless (right).

**Figure 7.** Influence of a sidewall angle of the quartz profile on the contrast at pitch=150nm.

Due to the change of contrast at given mesa size for various sidewall angles, it can be expected that, the CD at a certain threshold changes with the sidewall angle. To investigate this effect a threshold was determined at which the “perfect Crless mask” yields a CD equal to the half pitch. At this threshold the CD was measured for various sidewall angles and the deviation to the target was determined. Also the influences of changes of the etch depths and the mesa size for various sidewall angles have been investigated. The results of the simulations are shown in the Figures 8 and 9. As can be derived from the graphs a sidewall angle of 5 degrees leads to an overall increase of the CD variations as response on changes in feature width and etch depth. This effect is more pronounced for trench-style masks. By keeping the feature width and the etch depth at the optimal values a change of the sidewall angle to 5 degrees results in a CD change of 1.5nm for the mesa-type and –3.5nm for the trench-type. The (etch depth dependent) impact of CD on changes of the feature is almost not affected by the sidewall angle. For a vertical etch profile of the mesa type the CD change is about 0.5nm for a 1nm offset of feature width to the optimal value. A sidewall angle of 5 degrees leads to the same value. The trench style mask yields a value of 0.7nm for a 1nm deviation from the optimal trench width, also almost independent of the sidewall angle. However, this behavior also depends on the etch depths. An increase of the etch depths results in a lower sensitivity of the CD on deviations of the feature size, for both sidewall angles investigated here. On the other hand, a decrease of the etch depth results in an increase of this sensitivity. In Fig. 9 the change of the CD is plotted for various sidewall angles, ranging from 0 to 10 degrees for both types of mask at a pitch of 150nm. An interesting effect can be seen there. Whereas for a trench-style mask the CD always decreases from the target for all feature sizes and sidewall angles investigated here, the mesa type shows an increase for some
feature sizes and a decrease for others. The change from the increasing to the decreasing behavior occurs continuously with increasing mesa size.

(a) Mesa-Style Crless Mask, Sidewall angle = 0°  
(b) Mesa-Style Crless Mask, Sidewall angle = 5°

(c) Trench-Style Crless Mask, Sidewall angle = 0°  
(d) Trench-Style Crless Mask, Sidewall angle = 5°

**Figure 8.** Impact of Mesa/Trench width and etch depth variations on wafer CD for various sidewall angles at pitch=150nm.

(a) Mesa-Style Crless Mask  
(b) Trench-Style Crless Mask

**Figure 9.** Effect of Sidewall angle on CD for various feature sizes for mesa-style (left) and trench-style masks (right) at pitch=150nm.

The investigation of the impact of a non-vertical etch profile shown here indicate that there is only a small impact of the sidewall angle on the CD. All the results shown so far were obtained assuming the imaging in the best focus plane. Now the impact of defocuse on the image for various sidewall angles is discussed. In Fig. 10 the CD deviations from the target
are plotted for different sidewall angles and different defocus setting. Plotted here are the deviations of CD normalized to the through-focus deviations of the CD of the “perfect Crless mask”, i.e. all differences are due to the sidewall angle.

(a) Mesa-Style Crless Mask

(b) Trench-Style Crless Mask

Figure 10. Effect of Defocus on CD for various sidewall angles for a mesa-style (left) and trench-style masks (right) at pitch=150nm.

Note, that the CD deviations out of the best focus plane increase strongly but at least for moderate sidewall angles of less than 5 degrees the variation is still small. For the mesa type at a defocus of 0.3µm and a sidewall angle of 5 degrees the CD deviation is less than 4nm. The trench type shows under the same conditions with less than 1.5nm an even smaller value.

In summary it can be concluded, that simulations indicate a very small impact of the sidewall angle on the CD. For sidewall angles less than 5 degrees the maximum deviation of the CD from target is 4nm but in a strong defocus setting of 0.3µm off the best focus. The effect of small deviations in feature size and etch depths for the same range of sidewall angles was shown to be less than 3nm for a deviation of 1nm in feature size and etch depth. Also it turned out that trench-style Crless masks are more sensitive to these imperfections in the manufacturing process in best focus. Beside the sidewall angle there is another critical deviation from the “perfect Crless mask”: the bottom profile of the etched areas. Especially micro-trenching, i.e. the over-etch at the edges of the profile is a major concern. Micro-trenching is shown in Fig. 1 as a triangular shaped area in the cross-section just in the bottom corner of the quartz trench. As discussed in the introduction there is always a trade-off between sidewall angle and micro-trenching when setting up a quartz etch process. For that reason it is necessary to investigate the impact of micro-trenching on the imaging performance of the mask and compare it to the effect caused by sidewall angle imperfections.

In order to do so, a triangular over-etch has been added to the perfect profile and its impact on the CD response has been determined. The geometry used is shown in Fig.11.

(a) Mesa-Style Crless Mask

(b) Trench-Style Crless Mask

Figure 11. Geometry used to model the impact of micro-trenching, mesa type (left) and trench type (right).

Micro-trenching can be modeled by adding a rectangular triangle with equal legs at each bottom corner of the etch profile. The sidewall angle was always kept to be vertical.
Using this geometry the CD was determined at a threshold that for the “perfect Crless mask” yields a CD equal to the half-pitch. The results are shown in Fig.12 where the CD deviation from target is plotted against the size of the micro-trench. This has been done for various feature sizes at the optimal etch depth.

![Figure 12. Effect of micro-trenching on CD for various feature sizes for a mesa-style (left) and trench-style masks (right) at pitch=150nm and vertical etch profile.](image)

From the curves it can be concluded that micro-trenching has only a very limited impact on the printed CD on the wafer. By using the feature width and the etch depth of the “perfect Crless mask” the CD deviation is 0.3nm for a micro-trench size of 5nm (wafer-scale!) for the mesa type. For the trench type the CD deviation is less than 0.1nm at the same micro-trenching. The simulations suggest that a trench style mask is less sensitive to micro-trenching than the mesa type. In general, Fig.12 shows that micro-trenching has an almost negligible impact on CD.

So far the impact has only been studied for imaging at best focus. Fig. 13 shows the CD deviations versus defocus. Again, the deviations shown here are already normalized to the CD deviations in defocus of the mask without micro-trenching.

As illustrated in Fig.14 the impact of micro-trenching remains negligible even for a strong out-of-focus imaging. The maximum CD deviation for a mesa type mask is less than 1nm and slightly higher than 1nm for the trench-style mask at an defocus of 0.3µm.

![Figure 13. Effect of defocus on CD for sizes of micro-trenching for a mesa-style (left) and trench-style masks (right) at pitch=150nm and vertical etch profile.](image)

**Conclusion**

Simulation results were presented here which analyzed the impact of imperfections in the etch profile of the quartz phase-shifting areas on the wafer CD. Namely studied were the impact of a non-vertical sidewall angle and micro-trenching. The study was performed using 150nm as pitch for both: mesa and trench style Crless masks. The simulations
indicate that such imperfections have a very small impact on the CD for imaging in best focus. It has been shown that the 1nm mesa size and phase depth error cause 0.4nm CD variation on wafer. The trench type is more sensitive to errors in the targeting of the feature size but less to the etch depth errors. In general, the results presented here show that sidewall angle variations and micro trenching are not likely to result in a strong impact on wafer CD. Although the ultimate goal for the quartz dry etch process development is providing vertical profile and flat bottom pit, these results suggest that one could put more effort on improving uniformity and other process characters than vertical sidewall angle and flat bottom pit.

The simulation results of contrast deviation presented here were compared to AIMS measurements. The confirmation of the simulation results on wafer printing is left for a future study.

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Reference