Optimized Processes and Absorber-Stack Materials forEUV Masks

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ABSTRACT

Currently, EUV lithography targets for sub-50 nm features. These very small feature sizes are used for reflective illumination and impose great challenges to the mask maker since they do not allow a simple downscaling of existing technologies. New material combinations for absorber and buffer layer of EUV masks have to be evaluated and fundamental material limits have to be overcome. We report on optimized absorber-stack materials and compare in particular the performance of chrome and tantalum nitride for such small nodes. Tantalum nitride shows similar or even better properties than standard chrome, above all with respect to etch bias. Further investigations have to be done but this material is a promising candidate for feature sizes in the sub-50 nm range.

Keywords: EUV lithography, mask, tantalum nitride, etching, etch bias, etch uniformity

1. INTRODUCTION

1.1. Challenges of the EUV technology

EUV lithography is the most widely accepted technology beyond optical lithography. With an exposure wavelength of 13.5 nm it targets for sub-50 nm features. The exposure wavelength is strongly decreased and falls below 1/10 of the wavelength used in optical technologies. This allows doing lithography with a wavelength smaller than or similar to the exposed feature size for the first time after more than 15 years. However, life gets not really easier. EUV radiation is strongly absorbed by virtually all materials. Thus, masks as well as optics have to be reflective, and exposures are done in vacuum. The strong absorbance also means that no pellicle will be available. Since the critical dimension (CD) target is becoming smaller and smaller, smaller defects also become more critical. The required, very low defect level (with a critical size of 35 nm and below [1]) is one of the expected main issues for the EUV technology. Furthermore, a tight image placement is required which translates into the use of low-thermal expansion substrates and a flatness specification of the mask substrate of 50 nm peak-to-valley [1].

While many of these requirements are not specific to the mask shop, manufacturing of the very small feature sizes on mask is. There is no simple downscaling of existing technologies since new layer functionalities are introduced and the physical limit of current material is approached. Thus, new material combinations for the absorber, buffer and capping layer have to be investigated and the resolution capability needs to be proven.

1.2. Layer sequence of EUV blanks

EUV blanks consist of various layers for different purposes distinct of those for optical lithography. A schematic drawing of the layer sequence is given in Fig. 1.

First of all, the substrate is no longer quartz but a low-thermal expansion material to avoid image distortion by mask heating. A multilayer of usually 40 bilayers molybdenium/silicon is coated on the substrate which reflects the incident EUV radiation. On top of the multilayer stack is a capping layer for environmental protection. In addition this layer acts as an etch stop during mask fabrication and should have a low EUV absorption. The stack is finalized by a buffer layer (e. g. SiO_2) and an absorber layer (e. g. Cr) which define the dark and bright features.

The mask features are patterned in the absorber and buffer layer on top of the capping layer. This is done by coating a resist on the absorber, writing the pattern with e-beam or laser exposure and a subsequent etching of the absorber. The

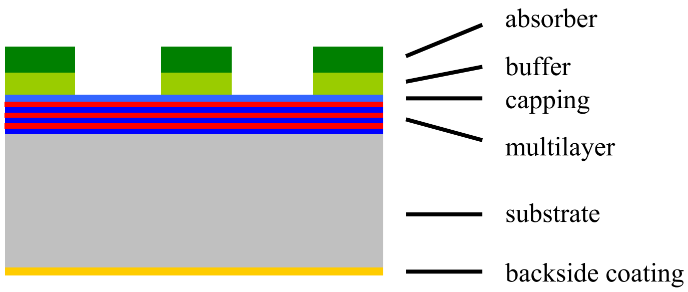


Fig. 1. Schematic cross section through an EUV blank.

etch process should stop on the buffer layer below. Finally, the buffer is aimed for protection of the sensible multilayer during the absorber repair and is etched through after this has been done.

The complete mask blank may include a conductive backside coating for electrostatic chucking. Owing to the intact multilayer on the frontside and the conductive coating on the backside, EUV masks are not transparent for both EUV and optical light once the mask layers are completely deposited.

2. OPTIMIZATION OF THE ABSORBER STACK

2.1. Limits of conventional materials

Currently, the standard absorber material for binary masks is chrome. Chrome has been used for a long time and its behaviour in wet and dry etch processes is well understood and under mature control. It exhibits a sufficient absorption in the EUV and has successfully used for printing [2].

The primary disadvantage of chrome dry etching is the need of oxygen in the plasma to build the volatile CrO_2Cl_2. This etch mechanism causes an etch bias of several tens of nanometers. For wide features this etch bias can be compensated by advanced manipulation of the mask layout. For small features targeted by EUV lithography, corrections in the order of the feature size itself would be necessary which is not possible. Therefore new absorber materials have to be evaluated.

On the other side, the specific etch requirements of the chrome etch (need of oxygen, low power) ensure a high selectivity to many other materials which may be advantageous for certain stacks.

2.2. Absorber stacks of the study and relevant properties

In this study, we focus on tantalum nitride (TaN) as a promising absorber candidate for an optimized EUV-mask material stack. Optimization means first a small etch bias for the absorber and second a suitable patterning process for the absorber/buffer combination. Other topics of interests in this work are the dependence of the etch bias on the feature size, etch selectivity between absorber/buffer layer and buffer/capping layer and CD uniformity over the reticle area.

The experiments were done on square 6-inch quartz blanks. We have investigated the etch behaviour of two different TaN-based absorber layers and compare these results to standard chrome material. The etch processes for TaN are still under development, however, the results are promising. For Cr dry etching we used a standard Cl_2/O_2 etch process.

Since the final mask performance is a result of the combined absorber/buffer etch process, we also investigate both silicon dioxide and chrome as buffer material together with a tantalum nitride absorber and silicon dioxide buffer with chrome absorber for reference. The capping is a thin silicon layer.

2.3. ITRS requirements for EUV masks

The ITRS Roadmap 2003 defines requirements of EUV masks for the 45-nm technology node and beyond. Table 1 gives a short overview of some relevant properties demonstrating the goals of our development. In general, considerable effort is necessary to move the frontiers of current technologies to these values.

Table 1. EUV mask requirements as defined in the ITRS 2003 [1].

Requirements	45-nm node	32-nm node
Wafer min. half pitch	45 nm	32 nm
Wafer min. line (in resist)	25 nm	18 nm
Wafer min. contact hole (in resist)	55 nm	40 nm
Magnification	4×	4×
CD uniformity (3σ)		
Isolated lines (MPU)	2.0 nm	1.3 nm
Dense lines DRAM	9.0 nm	5.5 nm
Contact /vias	6.5 nm	3.5 nm
Linearity	6.5 nm	4.5 nm
CD mean to target	3.0 nm	2.0 nm
Minimum printable defect size	32 nm	23 nm
Mean peak reflectance	66 %	67 %
Peak reflectance uniformity (3σ absolute)	0.54 %	0.42 %

3. ETCH PERFORMANCE OF TaN-BASED ABSORBERS

3.1. Resolution and etch profile

The test masks used in this study contain a number of structures which occur in various sizes. Figure 2 - 4 show dense lines and contact holes in the absorber, respectively, with a nominal CD of 125 nm at mask level for the different absorber materials. This corresponds to a feature size required for the 32-nm node. The chrome absorber as benchmark has been etched with our standard Cr process in an chlorine/oxygen athmosphere while we have applied a pure chlorine chemistry for the TaN based materials.

Let us start discussing the chrome benchmark (Fig. 2). The Cr absorber with a 50% overetch of the main etch time shows approximately a 1:1 pitch for the dense lines although the layer is not fully etched through. A footing is clearly visible. With a longer overetch time, the footing was removed and straight side walls have been achieved. However, the line width is considerably reduced by the isotropic etch component and no equal line/space width is obtained. These problems become even more pronounced if the simultaneous etch of contact holes with the same CD is considered. The contact holes need a much longer overetch than dense lines for a comparable etch profile. The optimal overetch time is also dependent on the feature size which is known as the RIE lag effect (RIE - reactive ion etch).

The results of the two different TaN-based absorbers are given in Figs. 3 and 4 for the same features. They show virtually no change in CD with a variation of the overetch time for both dense lines and contact holes. No footing is observed. One of the materials has some bowing in the side wall whereas an excellent side wall is achieved with the

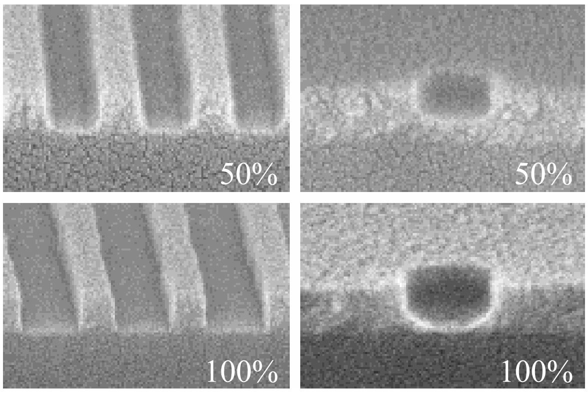
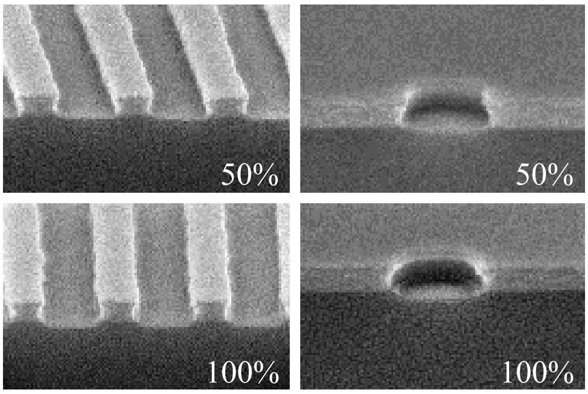
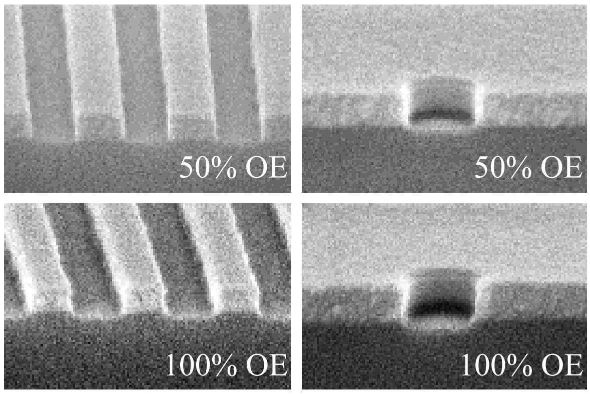


Fig. 2. Cross sections of 125 nm dense lines and contact holes in Cr absorber (roughly 32 nm on wafer level). The different overetch times (OE) for dense lines and contact holes as well as and the strong etch bias is clearly visible.





Figs. 3+4. Cross sections of 125 nm dense lines and contact holes in two different TaN absorbers (roughly 32 nm on wafer level). Although both materials show different side-wall profiles, they have a strong tolerance with respect to overetch time.

second absorber. The etch processes for both TaN absorbers are still preliminary and give opportunity for further improvement. These results already show the potential of tantalum nitride for the 32-nm node and beyond as a possible successor of standard chrome. The following sections further underline the favourable properties of this material.

3.2. Etch bias

In a next step, the etch bias of the various absorbers have been determined in dependence of the feature (dense lines and contact holes) and feature size. The final CD of the structures is influenced not only by etching but also by the electron-beam writing and resist process. The absorber CD after etching is substracted from the CD in the developed resist giving the influence of the etch process. A positive etch bias thus means a widening of a full space. The various measurements are summarized in Fig. 5.

For the chrome benchmark, the etch bias starts in the order of +30 nm for 1000-nm space and gradually decreases to approximately half of that. This dependence is again a consequence of the strong RIE lag. The etch bias for contact holes is somewhat smaller but follows basically the same behaviour. If the overetch time is increased to 100%, the etch bias grows considerably and varies between +25 nm and +50 nm. Moreover, we find a large difference in the etch bias for dense lines and contact holes for small features. Both, the RIE lag and the strong CD variation with the overetch time makes the fabrication of qualified EUV masks very difficult.

In comparison, we obtain a completely different behaviour for tantalum nitride regardless of which of the two different layers is used. First of all, there is no dependence of the etch bias on neither the feature size nor the sort of the feature. This allows a considerable process tolerance for a feature variation on the same mask. Additionally, the etch bias does

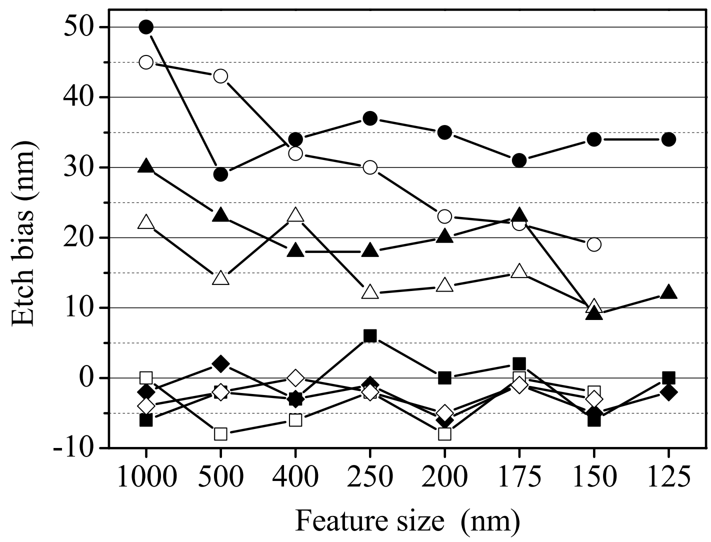


Fig. 5. Etch bias vs feature size for the various absorbers. The full symbols denote the values for dense lines, hollow symbols for contact holes (circles: Cr with 100% OE; triangles: Cr with 50% OE; squares: TaN with 50% OE)

not significantly deviate from zero. We find values in a range between -5 nm and +5 nm. The negative values might occur due to the uncertainty in the measurement of the resist CD or weak polymerisation during the absorber etch. Nevertheless, the etch bias is below 5 nm and underlines again the capability of the TaN material. The results hold also after the buffer etch.

3.3. CD uniformity

The absorber etch process is not only required to achieve a high resolution for EUV masks. There is furthermore the need for a narrow and uniform distribution of the critical dimension over the mask. We thus have measured the CD of 400 nm dense lines (mask level) on a 11×11 grid filling the 130×130 mm^2 quality area of the mask. The reference values of the Cr absorber is 9.8 nm (3σ) and 12.3 nm total range for a 100% overetch. The uniformities measured on a mask with the two TaN-based absorbers down to 8.3 nm / 8.1 nm (3σ) and a total range of 11.5 nm / 9.9 nm, respectively. In comparison to Cr, an overetch of 50% only were sufficient for a fine etch profile. The TaN performance found is slightly better than that of the reference material. With respect to the ITRS roadmap 2003 (see Table 1), the achieved results already fulfil the requirements of the 45-nm node. The TaN etch process is not yet optimised giving hope for even better uniformities.

4. OPTIMIZATION OF THE COMPLETE ABSORBER STACK

Beside an accurate patterning of the absorber, the etch selectivity between absorber and buffer is an important issue for the complete process. We therefore did the absorber etch with a subsequent buffer etch in a two-step process. The Cr/SiO_2 reference stack can be patterned with an excellent selectivity to the buffer. The Cr etch process with a Cl_2/O_2 chemistry is very unique to this material so that we achieve a selectivity better than 100:1. The SiO_2 buffer etch is carried out with a fluorine based quartz etch process of phase shift masks. It has an excellent selectivity to the patterned absorber but not to the capping layer. However, test masks with Cr absorber have successfully been fabricated.

Doing a chlorine-based etching of the TaN absorbers without oxygen results in a very selective process on Cr buffer. This buffer is then etched with the standard chrome process stopping selectively on the Si capping and leaving the TaN absorber unaltered. Test masks with this absorber/buffer combination have also been completed succesfully. The same

TaN process etches the SiO_2 buffer with a similar rate. The problem is not so much the poor selectivity to the buffer layer since the buffer is for protection of the multilayer during repair and will be removed in the next step anyway. Merely, the fluorine chemistry of the SiO_2 buffer etch reacts very effectively with the TaN absorber, i. e. both TaN absorber and SiO_2 buffer are etched by the same processes. Our process development is under way to overcome this issue.

5. SUMMARY

In summary, tantalum nitride based absorber layers have shown to be promising candidates for EUV masks. Features corresponding to the 32-nm nodes could clearly be resolved. The advantage of TaN in comparison to the standard Cr absorber is a large overetch tolerance. Excellent etch profiles for dense lines and contact holes were achieved simultaneously indicating a suitable common process window. Moreover, there is a neglectable etch bias for the TaN material (if reliably detectable at all) which is independent on the feature size. The achieved CD uniformity with our process is 8.1 nm and 8.3 nm (3σ) for the TaN material versus 9.8 nm for Cr. This uniformity already fulfils the requirements for the 45-nm node although the process is not yet optimised. The basic etch properties of TaN thus reach or supersede the performance of chrome.

We also have fabricated complete test masks with both Cr and TaN absorbers. The use of chrome in the stack (either as absorber or buffer) facilitates the manufacturing because of its very selective etch process. Nevertheless, the combination of TaN-based absorber with SiO_2 buffer seems feasible with further process development being done.

6. ACKNOWLEDGEMENTS

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