Challenges of the Mask Manufacturing Approaching Physical Limits

Pavel Nesladek
Advanced Mask Technology Center, Rähnitzer Allee 9; 01109 Dresden, Germany

ABSTRACT

Over the past 25 years, following the International Technology Roadmap for Semiconductors[1], the main feature size of integrated circuits has decreased from approximately 3µm to 70nm. With feature sizes well below the exposure wavelength of the stepper, resolution enhancement features such as serifs, scatter-bars, and hammer heads are added to the mask design. Given a 4:1 reduction from mask to wafer, the resolution enhancement features, such as scatter bars, are roughly the same size as main features on the wafer.

Recently, with the reduction of mask feature size, mask manufacturing technology faces several problems in satisfying customer needs for resolution, CD uniformity, and CD linearity. The problems result, in part, as the legacy of material and process choices made in the early days of mask making. For example, the use of chrome as an absorber was suitable material choice for wet etch binary mask processes, but this material is now seen as problematic current dry etch process. Another general source of problems for the mask industry is its small size relative to wafer manufacturing. As a result, vendors focus material and equipment development efforts on wafer, and then make adaptations to fit mask making requirements.

Nowadays the patterns of high end lithographic masks are written by variable shaped beam 50kV e-beam writers with minimum beam size of as little as few nm. However the latent pattern after writing differs significantly from the final pattern on the mask due to interactions during post exposure bake, resist development, and etch processes so the final pattern is a convolution of these effects.

The parameters of interest are resolution, critical dimension uniformity (CDU), pattern fidelity, CD-linearity, iso-dense as well as clear-dark bias, transmission of the transparent substrate and absorber, and birefringence. Besides these requirements, there are implicit not specified expectations the mask has to fulfill. To this group of parameters belongs for example reflectivity of the surface, chemical and environmental stability of the mask, and mechanical properties.

This paper will present some issues which must be solved in order to satisfy future needs for lithographic masks. The focus of the presentation is to examine shortcomings of materials used in today's technology and provide a description of the properties needed for future materials.

Keywords: Photomask manufacturing, semiconductor technology limits

INTRODUCTION

The mask manufacturing process is historically connected to Cr layer as absorber material for binary masks and 1st level for half-tone phase shift masks. Reason for utilization of Cr can be found in its good properties for the PVD Cr deposition process, it's chemical and environmental stability, and its etchability by wet chemistry (cerium ammonium nitrate).

Resists used in mask manufacturing were developed accordingly to the exposure process, starting with resists capable for g- and i-line exposure tools and wet etch process only, proceeding to Novolak resin based resists with higher plasma resistance and further to more complex resist types like ZEP-poly(methyl-chloroacrylate-co-methyl-styrene) usable for e-beam writing and exhibiting high plasma resistance. Recently the high end masks are manufactured using one of widely used chemically amplified resist families such as REAP, FEP, FEN, etc.

These resist types were, however, mainly developed for use in waferfabs and are usually highly sensitive to environmental contamination by e.g. amines. The major improvements expected by introducing chemically amplified resists are the reduction of the writer dose leading to a decrease of the pattern generator relevant pattern misplacement (registration), lower resolution limit leading to small features manufacturable on the mask, and last but not least reduction of the writing time, which directly decreases costs of the writing process.

Wet etch was the only etch process for mask manufacturing until the end of the 1990s and is still common for low end masks manufacturing. On top of the Cr layer a CrO_x antireflective coating with gradient composition towards Cr base material is deposited. Positive side effects of the approx. 1998 introduced dry etch process were among others reduction of the CDU and higher process stability when compared to the formerly used wet etch process.

RESOLUTION

Resolution limit is understood as the smallest stable manufacturable feature. Since any photomask contains several feature types, which differs significantly in their stability and manufacturability, the resolution limit has to be estimated for each of them separately. We will discuss some of the feature types:

- isolated dark line (iso-dark)
- isolated clear space (iso-clear)
- dense-dark line + dense-clear space
- contact hole + contact dot.

Isolated dark line is typically the smallest stable feature type written on positive resist. The in resist resolution limit is given by the convolution of the exposure beam edge shape and the resist contrast – resist development rate as function of writing dose and can be further influenced by post exposure bake settings and the resist development chemistry and process. The resolution limit for isolated dark features is shifted towards smaller values by etch process. The thinning of the dark features is equal to the etch bias. (Fig.1a)

Isolated clear space resolution limit is significantly higher that the of isolated dark feature due to the fact, that the feature size is given by sum of the resist resolution limit and the etch bias, which is always positive for Cr etch process.[3] In addition the isolated clear feature on positive resist has to be written by higher dose in order to resolve the feature and so its size is further increased. (Fig.1b)

Dense lines and spaces are structures connected to each other in resolution limit by their nature. The physical limits for resolution are given already at resist development, during which the capillar force pulls the lines to each other leading to the collapse of the lines above the resolution limit for isolated dark feature. This effect is, however, aspect ratio dependent and so thinner resist leads to lower resolution limit. After etch process the duty cycle – the ratio between the line and space width is changing. When

1:1 duty cycle is requested on the mask, the width of the dark features in design has to be increased by so called process bias – the sum of biases of all manufacturing steps. (Fig.1c)

Contact holes have the highest resolution limit. This feature type has the disadvantages of the clear features. In addition the processes at contact holes exhibit lower etch rates possibly due to higher O_2 consumption at surrounding resist or slight shift to transport limited regime in comparison to other feature types, further decreasing the Cr/resist selectivity and so shifting the resolution limit.

Contact dots behave comparably to isolated or dense dark lines, leading to lower resolution limits, their pattern fidelity is slightly better than contact holes.

One important parameter influencing the resolution limit is resist thickness; lower resists thickness increases the resolution due to the reduction of the aspect ratio, increases stability of the developed structures (Fig.2), and reduces electron scattering within the resist layer. Unfortunately the resist thickness can not be easily reduced. The minimum resist thickness is given by the resist consumption at the absorber etch process. There is also limit for the remaining resist thickness after the absorber etch process preventing pinholes creation.

The usage of O_2/Cl_2 etch gas necessary to build the volatile Cr etch product CrO_2Cl_2 increases the resist consumption especially in combination with high plasma power. In order to reduce the resist consumption, either the Cr-to-resist selectivity has to be raised significantly or the Cr layer thickness has to be reduced.

Improved selectivity as measure of the ratio between vertical Cr and resist etch rate reduces slightly the etch bias as well and further improves the resolution. However this parameter is strongly linked to several customer related criteria as CDU and CD linearity. Increase of selectivity by process change only and so reduction of the etch bias is typically connected to increase of CDU or some of its components (radial footprint, loading effect etc.). Since the CDU is the most critical parameter with tightest specifications, this approach is not viable. The more promising way to solve the problem and get out of the trade off is design of new resist with higher plasma resistance. The goal is significant reduction of the sensitivity of resist to O_2 plasma and so significant increase of the Cr-to-resist selectivity.

CD UNIFORMITY

CDU, The most critical factor directly affecting the performance of the device manufactured using the lithographic mask is specified as tightly as possible. CDU is understood as 3x standard deviation of the feature measured across the mask. Since any front end process contributes to and influences the final CDU performance, the processes are optimized separately to provide minimum CDU and high CDU stability. Particular processes contribute to different CDU component accordingly to footprint, so their contributions have to be measured and evaluated differently. Modern unit processes provide almost flat CDU footprint and the final CDU contains a relatively large amount of non systematic scattering with respect to spatial distribution, which can change from mask to mask. The root cause of this scattering is difficult to identify.

The main systematic effects identified and classified by their CDU footprint contribution are:

- radial effect – center slow or center fast circular symmetrical footprint
- linear footprint – side to side or front to back effect
- loading effect – dependent on distribution of pattern density averaged over particular range
- mask edge effect – CD change when approaching mask edge
- fogging effect, proximity effect – effects connected to exposure of neighbor area by forward scattered /back scattered beam

Besides the systematic CDU effects listed above, the CDU contains some “noise” like short range non systematic variation of the CD across the mask. This can be partly introduced by the metrology tool during the measurement as uncertainty of the single point measurement, however, a big part of the scattering remains even when averaging several measurements (Fig.3).

We assume the remaining scattering to originate from one of following effects:

A, local CD variation (LCD)

B, pattern placement error from pattern generator when measured on indirectly written features

C, line edge/ line width roughness introduced by resist (LER)

A, is caused by minor variation in the pattern generator process, possibly also due to resist thickness variation and misplacement during multiple pass writing when a feature is created by several shots of the writer. Slight improvement can be reached by increase of the settling time, however, the significant cost increase due to lower throughput has to be taken into account.

B, Placement Error increases significantly CDU of indirectly written features. Whereas the directly written feature type for example space on positive resist type is written by single shot, indirectly written feature as dark line on positive resists type is written by at least 2 shots along the feature. This effect is demonstrated in Fig.4 and is obvious reason for systematic CDU difference between directly and indirectly written features (E.g. clear features at positive resist type and dark features at negative resist type exhibit better CDU performance than their indirectly written counterpart).

The root cause for LER is not fully understood. The effect can be observed as line edge variation along the line. The LER shows spectral properties and can be described as wave function by frequency/ wavelength and intensity spectrum. The origin of LER is most probably in the resist – the LER intensity and spectrum is varying from resist to resist. One of the possible explanations is, that the LER is created during development process by washing out the resist macromolecules, leaving the surface structure formed by the shape and orientation of the not removed resist macromolecules. Taking into account the size of polymer macromolecules in current resists, this theory only partially explains the effect. Very obvious differences in LER can be observed between non-CAR and CAR resists. A likely explanation for higher LER at CAR resists may be the diffusion length of the photo-acid generated by the writing process during the post exposure bake, when the temperature exceeds 100°C. However the significant differences in the processes do not allow us to reach this conclusion. (Fig.5,6)

Another source of the LER can be found in the absorber material itself. Polycrystalline material can be etched away preferentially along the grain boundaries and introduce roughness into the side wall corresponding to the grain boundary shape. In order to clarify the absorber contribution to the LER, detailed study of the structure of the absorber material as well as the variation of the LER in dependence on the etch parameter is needed.

In case of single crystal preferential etch direction can be explained by anisotropy, but since the materials used in mask making process are not single crystals, we will not discuss this hypothesis.

In order to enable the study of LER, reliable and reproducible and very sensitive LER measurement has to be established[5]. Since the LER contribution to the overall CDU in many cases exceeds the systematic footprint, optimization for the factors influencing LER becomes necessary if future specifications according to the ITRS roadmap are to be reached. Some improvements can be expected, when resists without footing and minimum side wall variation will be available.

LINEARITY

CD Linearity is measured by means of CD SEM as the deviation of the feature size from the target, plotted as function of the measured feature size or target size for each feature type: isolated-clear, isolated-dark, dense-clear, and dense-dark. An ideal CD linearity is flat across the whole feature size range. The CD linearity measured on real masks differs from ideal one significantly especially at low feature size as shown in Fig.7. The clear features are getting smaller with decreasing feature size. The dense dark feature linearity is opposite to the of dense clear feature and has the same amplitude. These two features have to have numerically the same CD linearity; otherwise the CD pitch is not correct. The mismatch can be caused by CD measurement as well. The linearity of isolated dark feature is typically above the dense clear linearity curve, but is slightly negative as well.

The shape of CD linearity curves has two main contributors – lithography and absorber etch. After resist development the CD linearity is usually better than after the etch process. The linearity of clear structures is slightly negative, the linearity of dark structures is positive.

During the etch process the clear structures becomes wider because of the etch bias; however, widening of small structures is significantly smaller that widening of big structures. This is valid for both isolated and dense clear structures. Small dense dark structures shrink less than big dense dark structures due to the fact that the small clear neighbor are widening slower than the big clear neighbor of dense dark structure. Isolated dark structures keep approximately the resist CD linearity.

In order to explain the effects described, we have to think about the driving force of the etch process. The widening of the clear structures is caused by lateral etch of the resist trench. This process is limited by the reaction rate on the surface, but increasing aspect ratios shift the process to diffusion limited, as can be demonstrated by longer etch process for significantly smaller feature sizes. Some contribution can be expected from the difference in the resist shape between broad and narrow spaces. This effect is illustrated in Fig.8. Small structure exhibits significantly bigger resist footing, which further reduces the widening of the structure when etched in parallel to big structures. As already mentioned, we assume the etch rate is limited by aspect ratio in resist. This fact provides us additional benefit if the resist thickness necessary for etch can be reduced significantly.

CONCLUSIONS

The presented work summarizes and illustrates the challenges of the mask manufacturing in the near future. Performed analyses show that the customer related parameter of the mask cannot be optimized independently, due to strong cross linking between process parameters. Some data identify interaction between litho and etch processes as expected. Major problems which have to be solved during the process development for next technology node are resolution, CDU, etch bias and CD linearity of the mask.
CDU is linked to systematic and non systematic effects such as loading effect and LER; some of these effects are well understood and there is solution possible, when material properties will be changed appropriately. Few parameters are not well understood yet and a lot of effort needs to be spent in order to investigate them.

In order to get out of the trade off between the resist thickness and many important parameters, either change of the absorber material or improvement of the plasma resistance of the photo resist is necessary. Reduction of the resist film thickness may relax many current critical issues of the photomask technology.

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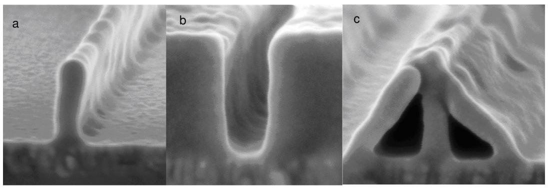

Fig.1 – shape of structures near resolution limit for **a**, isolated line **b**, isolated space **c**, dense lines and spaces

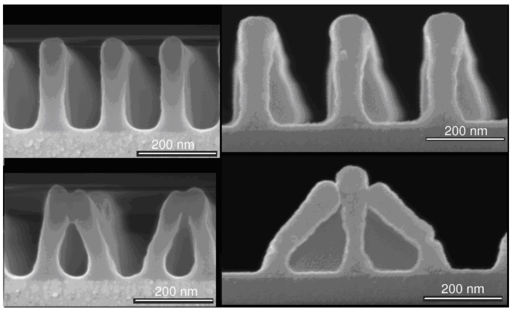

Fig.2 – Comparison of resolution limit for different resist thickness; on the left hand side the resolution limit at standard productive resist thickness of 200nm; right hand side resolution limit at 30% increased resist thickness. Upper row shows feature above the resolution limit – ca. 160 nm pitch for standard resist thickness, and ca. 240 nm pitch for thicker resist.

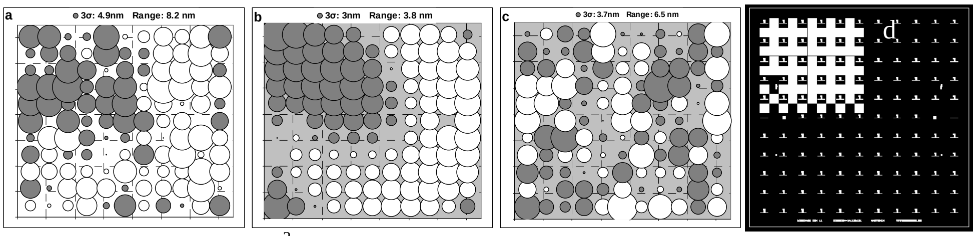

Fig.3 - **a**, CDU plot of a 132x132 mm^2 mask design – dark circles represent feature bigger than the mean, white circles feature small than the mean **b**, fit of the CDU footprint assuming linear, radial and loading effect; the major contributor to CDU is the loading effect expressed as higher CD value in the upper left corner of the mask. **c**, residuals – spatial distribution of the difference between CDU raw data and fit. **d**, design of the mask. Please note the difference between the raw CDU data, the CDU fit and the residuals. By optimization of the CDU footprint the overall CDU performance can be reduced from 4.9 to 3.7 nm 3σ.

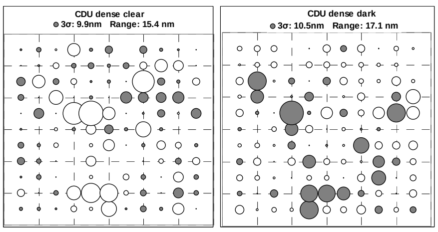

Fig.4 – demonstrates effect of directly-indirectly written feature - CDU comparison of directly (left) and indirectly (right) written features on positive resist type measured in resist. The dark features (indirectly written) exhibit slightly higher CDU due to shot placement error.

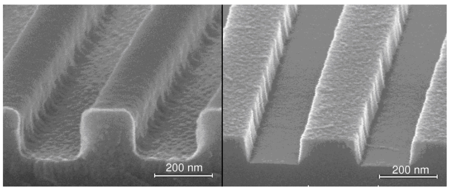

Fig.5 – LER as observed in SEM cross sections. Left picture shows the LER in resist, right hand picture demonstrates transformation of the resist LER into Cr layer.

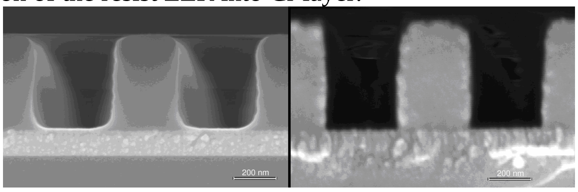

Fig.6 - Footing observed at positive CAR resist types due to poisoning of PAG on Cr surface - left. Barrel like side wall slope observed at negative CAR resists - right.

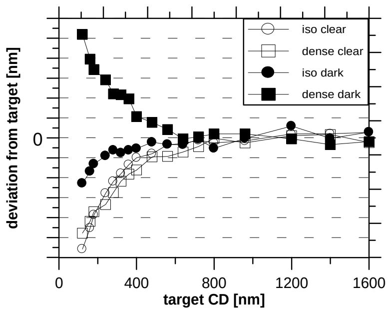

Fig.7 – CD linearity curves for iso-clear, dense-clear, iso-dark, and dense-dark features.

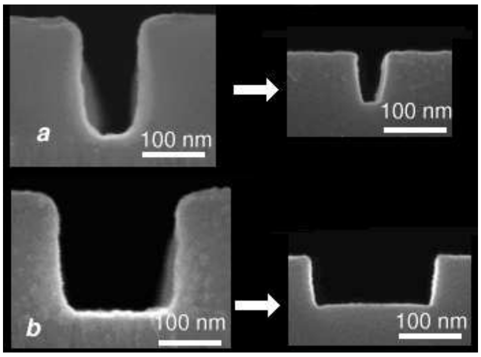

Fig.8 Comparison of the development of isolated space during the etch process. **a**, for small features **b**, for big features. Pictures on the left hand side show the side wall shape after resist development, picture on the right hand side show the side wall shape after Cr etch.