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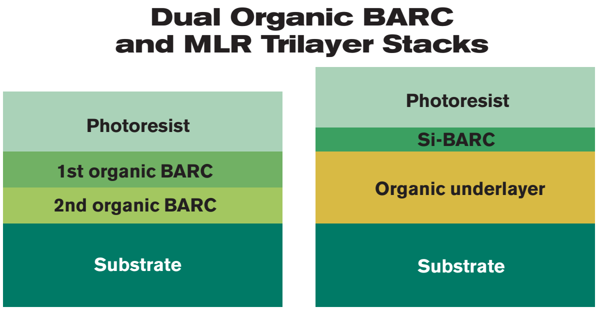
Silicon-Containing Materials for Sub-65 nm Etch

The use of silicon-containing materials in future lithography schemes should provide etch-resistant options, while depth of focus and photoresist film thicknesses continue to decrease.

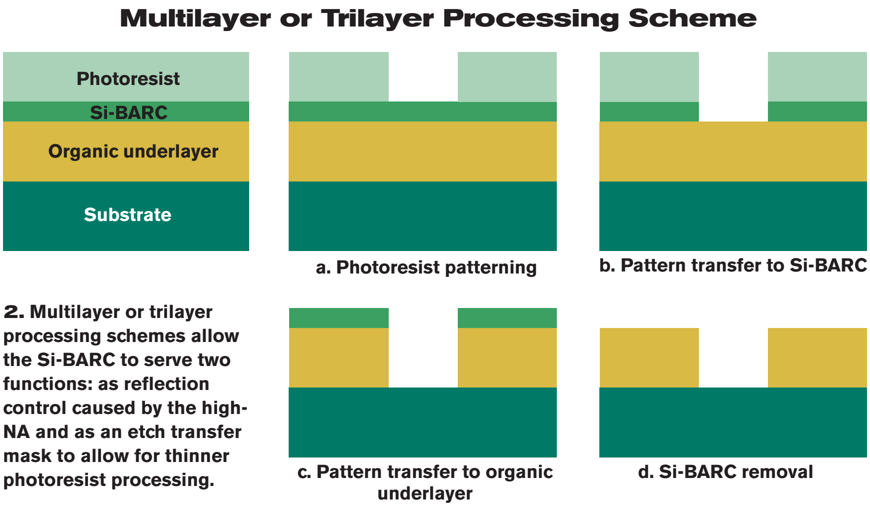
E.S. Moyer, J. Bremmer, C. Brick, P.F. Fu, A. Shirahata, S. Wang and C. Yeakle,
Dow Corning Corp.,
Midland, Mich.,
www.dowcorning.com

Advanced immersion technology extends 193 nm optical lithography to feature sizes of 45 nm and beyond by increasing the numerical aperture (NA) of photoresist exposure systems, but it comes with new challenges requiring new materials for cost-effective device fabrication. Thin imaging layers with increased etch selectivity in pattern transfer are required to deliver high-resolution and sufficiently wide process windows. Silicon-containing materials — whether used in multilayer resist (MLR) or bilayer resist (BLR) process schemes — are emerging as leading solutions for thin imaging layers.



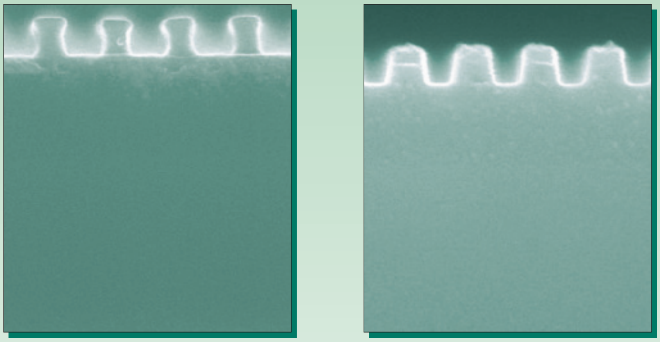
1. With high-NA immersion lithography, reflectivity must be controlled over a large range of angles, raising the need for two BARC layers.

Several different types of processing schemes have been proposed to meet the increased etch-resistance demands, including MLR and BLR. One of the most desirable aspects of the MLR process is that it typically uses a single-layer resist for imaging. An underlying, ultrathin silicon-containing layer acts as a hard mask during the etch pattern transfer step. This hard mask layer can be a spin-coatable polymer or a film created by chemical vapor deposition (CVD). The third layer is typically an organic film. The key disadvantages to MLR approaches are the complexities that arise from the need for three separate layers and the requirement to integrate processing steps for good imaging and pattern transfer. However, with the uncertainty of extreme ultraviolet (EUV) development and the increased probability of implementing double-patterning techniques to continue Moore's Law into the future, spin-coatable silicon-containing hard masks that also act as antireflective layers may become important as alternative material choices.



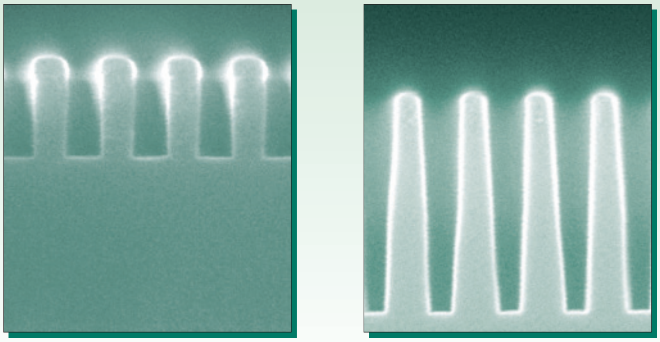
a. Photoresist patterning
b. Pattern transfer to Si-BARC
c. Pattern transfer to organic underlayer
d. Si-BARC removal

2. Multilayer or trilayer processing schemes allow the Si-BARC to serve two functions: as reflection control caused by the high-NA and as an etch transfer mask to allow for thinner photoresist processing.



After image development

After Si-BARC etch



After carbon hard mask etch

After SiO_2 500 nm etch

3. Image transfer process through a trilayer stack and into a SiO_2 substrate (Film stack; Resist/Si-HM/C-HM/SiO_2/Si: Thickness; 120 nm/50 nm/300 nm/500 nm). *(Source: TOK)*

Multilayer resist scheme

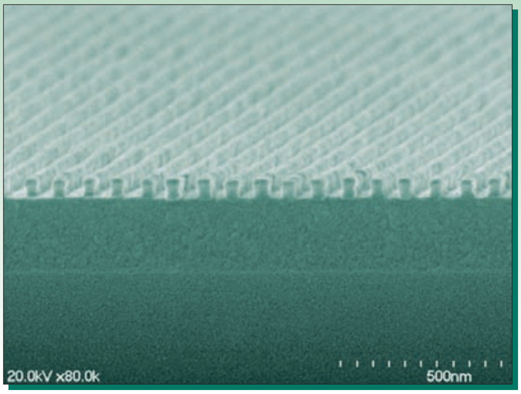
The increased NA of immersion lithography results in an overall smaller depth of focus (DoF), requiring the use of thinner and thinner photoresists. Often these thin photoresist layers do not have enough etch resistance to effectively transfer the pattern to subsequent layers. Therefore, new processing schemes requiring higher etch-resistant layers have been proposed, such as MLR processing schemes.

Another driving force for MLR schemes is the need for dual-layer bottom antireflective layers. One of the biggest challenges caused by increased NA is the control of reflectivity over an increased range of angles. As the NA of tools moves above 1, a traditional single organic bottom antireflective coating (BARC) may not be sufficient to keep the reflection below 1% at all the incident angles.[1] Therefore, it has been proposed that there is a need for "dual BARC" layers to keep the reflection under control. A few studies using various lithography modeling programs have demonstrated that multilayer or dual-layer BARCs are capable of suppressing reflectivity through a wide range of incident angles.[1,2] These dual BARC processing schemes can use either two organic BARCs or an inorganic and an organic BARC stack (Fig. 1).

Because the thickness of photoresist films continues to be reduced caused by the reduced DoF on high-NA exposure tools, etch resistance also becomes a challenge. It has been predicted that resists for the 32 nm half-pitch node will have to be 100 nm thick or less to allow for accurate imaging in a reduced DoF condition. In addition, pattern collapse must be avoided with the increase in aspect ratio. Photoresists have typically accounted for the majority of etch mask properties, and BARCs have been used only for controlling the reflection and subsequent standing waves. Some work has focused on developing faster-etching organic BARCs to leave the remaining photoresist to act as a mask for the underlying layers.[3] However, another approach has focused on increasing the etch selectivity of the BARC by incorporating silicon into it. Incorporating silicon into the upper BARC material results in an ARC that can also be used as an effective etch mask.[2,4] Where a thin silicon-containing BARC (Si-BARC) is used, the underlying organic BARC is often thicker for better reflection control and also functions as an etch-transfer mask. This approach is often labeled a "trilayer" imaging scheme.

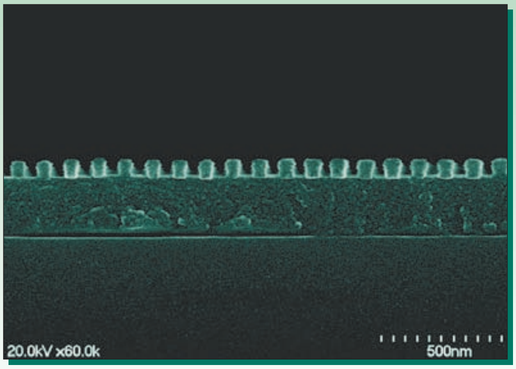
Many factors must be considered when designing and optimizing an appropriate trilayer processing scheme. Si-BARCs must be carefully designed to meet all of the requirements for both the optical and material properties. To begin with, they must have optimized silicon content that provides the appropriate level of etch selectivity toward both the photoresist on top and organic layer below. For the silicon materials to have a greater etch selectivity than the photoresist on top, >30 wt% silicon is desirable. This increases the etch rate of the CF_4-containing reactive ion etch (RIE) process for the silicon materials above the etch rate of the organic-based photoresist that the pattern is being transferred from. After pattern transfer, the Si-BARC must have sufficient silicon content to resist oxygen RIE long enough to allow the pattern to transfer to the organic layer below. This trilayer scheme is outlined in Figure 2.

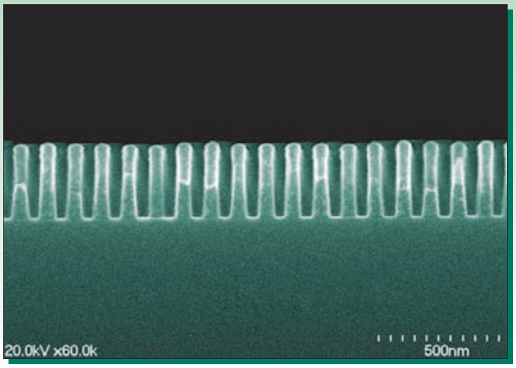
Other requirements of the Si-BARC — besides being a hard mask for etch transfer — are the correct optical properties, such as refractive index (n) and extinction coefficient (k). The



4. 45 nm l/s pattern using dual-beam interference exposure system (calculated NA=1.07).

refractive index should be as close as possible to matching both the photoresist above and the organic-based underlayer below. The extinction coefficient can be optimized by using appropriate lithographic modeling software to minimize the amount of reflection of the entire trilayer stack.[1] The extinction coefficient of Si-BARCs can be optimized by controlling the amount of dye incorporated into the polymer; for 193 nm, the dye can be a simple phenyl group. Other requirements of Si-BARC systems include a low-temperature cure of <250° C in 60 sec that allows for sufficient throughput in a typical photoresist spin track, compatibility with the photoresist on top of the Si-BARC, and the ability to be reworked after the Si-BARC has been coated and cured.





5. 55 nm l/s pattern after first layer patterning and etch.

These few requirements necessitate a balance of the composition to allow for the presence of low-temperature cure, photoresist compatibility and rework capabilities all at the same time. Development of an appropriate spin-coatable Si-BARC material that provides both excellent pattern fidelity and transferability has been a topic of many recent studies.[2,4] The photoresist image is free from any defect, such as “scumming” and “footing,” thanks to the optimization of the silicon resin and formulation.[4] This pattern can be effectively transferred into the Si-BARC by a RIE pattern-transfer step (Fig. 3). After etch transfer of the photoresist to the Si-BARC, the pattern can be transferred into the organic layer by changing the etch recipe from a CF_4-based process to an oxygen-based RIE process. One of the more challenging requirements for Si-BARC materials is to achieve a shelf life similar to that of the photoresist, which can typically withstand room temperatures for at least three months without any change in performance. This can only be accomplished with careful design and control of the silicon-containing resin used in the Si-BARC formulation.

Bilayer scheme

Bilayer photoresist is another type of silicon-containing material that may be useful in future high-NA lithography. This material has been a topic of many R&D projects because of its simpler lithography requirements, compared with those of multilayer or trilayer schemes.[5,6] The difficulty has been developing a silicon-containing photoresist that has the same resolution as a single-layer resist, but is etch resistant after the pattern has been developed to allow for pattern transfer to the organic underlayer. Effective bilayer photoresists have been developed that allow for 35 nm l/s pattern resolution. Figure 4 shows a 45 nm l/s pattern using a dual-beam interference exposure system with an NA=1.07. These materials have also been shown to be effective in pattern transfer, and have no silicon outgassing when exposed to 193 nm light.[5,6] Figure 5 shows an effective 55 nm l/s pattern after the first layer patterning and etch transfer to the bottom organic-based underlayer.

More recently, it has been reported that the hydrophobicity of silicon-containing photoresist could be a useful attribute in immersion lithography, where it could reduce leaching of the photoacid generator into the water within the immersion lithography tool.[7] The intrinsically hydrophobic silicon-containing photoresist would be in direct contact with the immersion fluid, acting as an effective leaching barrier. It may be possible, therefore, to avoid the usual requirement for a resist topcoat for the exposure step. One limitation of the bilayer approach for hyper-NA immersion lithography is that silicon-containing photoresist requires a dual-organic BARC to effectively control the reflection of 193 nm light, as with the other systems. This requirement effectively makes bilayer schemes into trilayer schemes in hyper-NA exposure tools. However, for double-patterning technology, bilayer solutions might offer a promising, cost-effective lithography approach without the need for two BARC layers.

Double patterning considerations

Extreme ultraviolet (EUV) lithography has been studied for some time now. However, before real device production can begin, many problems need to be solved, such as the development of new resist materials, effective mask and mirror fabrication, and a good power source. Until then, immersion lithography and double patterning approaches are emerging as potential interim solutions to allow the resolution limit of 193 nm lithography to be lowered well below current constraints.[8-10] In fact, the updated 2006 International Technology Roadmap for Semiconductors (ITRS) includes double patterning technology as an alternative lithography scheme for below

32 nm half-pitch lithography. Yet, while double patterning technology offers a promising solution for future lithography needs, its resolution enhancement will require complex lithographic schemes that increase the overall number of processing steps. Double patterning technology entails numerous additional processing steps, including two photoresist and Si-BARC depositions and more etching steps. In addition, it must overcome many topology problems caused by the need for a second pattern and etch on top of already etched profiles. Many device fabricators are looking at how new materials, such as Si-BARCs, can reduce the number of processing steps and still allow cost-effective lithography schemes despite double patterning complexities. Therefore, processes requiring CVD hard masks are likely to be replaced with more cost-effective spin-on materials that serve both hard mask and antireflective functions, and can be deposited using the same spin track used for the photoresist.

Conclusions

As feature sizes continue to shrink to 45 nm and below, exposure tools and processes are being optimized to allow for the continuation of Moore's Law. Along with the various lithographic tool options, various techniques are being considered to extend the use of 193 nm dry and wet lithography to allow for cost-effective manufacturing. These techniques are especially important considering the significant technology challenges that continue to face next-generation lithography technologies, such as EUV. New materials, such as silicon-containing bilayer photoresist and silicon-containing antireflective coatings, are being developed to help simplify these complex lithographic processing schemes.

Acknowledgements

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Eric S. Moyer *is the global thin-film product platform manager for Dow Corning Electronics Solutions. He has a Ph.D. from Virginia Polytechnic Institute and State University, and has been working in the electronic materials area for over 20 years.*

Jeffrey Bremmer *is the global market manager of Silicon Lithography Solutions for Dow Corning Electronics. He has a M.S.E. from the University of Michigan and an M.B.A. from Michigan State University.*

Chad Brick *is an associate research specialist for Dow Corning Electronic Solutions. He received his Ph.D. in chemistry from the University of Michigan.*

Peng-Fei Fu *is a senior research specialist at Dow Corning Electronics Solutions. He received a Ph.D. in chemistry from the University of Oklahoma and did postdoctoral work at Northwestern University.*

Akihiko Shirahata *is a technology leader for Dow Corning Electronic Solutions. He received a Ph.D. in chemistry from Tohoku University in Sendai, Japan.*

Sheng Wang *is a research specialist at Dow Corning Electronic Solutions. He received a Ph.D. in chemistry from Virginia Polytechnic Institute and State University.*

Craig Yeakle *is a senior development chemist for Dow Corning Electronic Solutions. He received a B.S. in chemistry from Central Michigan University.*