Recent progress in electron-beam resists for advanced mask-making

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Resists for advanced mask-making with high-voltage electron-beam writing tools have undergone dramatic changes over the last three decades. From PMMA and the other early chain-scission resists for micron dimensions to the aqueous-base-developable, dry-etchable chemically amplified systems being developed today, careful tuning of the chemistry and processing conditions of these resist systems has allowed the patterning of photomasks of increasing complexity containing increasingly finer features. Most recently, our research efforts have been focused on a low-activation-energy chemically amplified resist based on ketal-protected poly(hydroxystyrene). These ketal resist systems, or KRSs, have undergone a series of optimization and evaluation cycles in order to fine-tune their performance for advanced mask-fabrication applications using the 75-kV IBM EL4+ vector scan e-beam exposure system. The experiments have led to an optimized formulation, KRS-XE, that exhibits superior lithographic performance and has a high level of processing robustness. In addition, we describe advanced formulations of KRS-XE incorporating organometallic species, which have shown superior dry-etch resistance to novolak-based resists in the Cr etch process while maintaining excellent lithographic performance. Finally, current challenges facing the implementation of a chemically amplified resist in the photomask manufacturing process are outlined, along with current approaches being pursued to extend the capabilities of KRS technology.

Introduction

Optical lithography continues to be the mainstream technology used in the semiconductor industry for the fabrication of silicon devices at the current 180-nm design rules. Furthermore, it is forecast that through the use of resolution-enhancement techniques (RETs), such as off-axis illumination (OAI), optical proximity correction (OPC), phase-shifting masks, and exposure wavelength reductions, optical lithography will be capable of extension below 100-nm design rules. However, in order to meet the mask error budgets required at these smaller feature sizes, improved resolution and more accurate control of the

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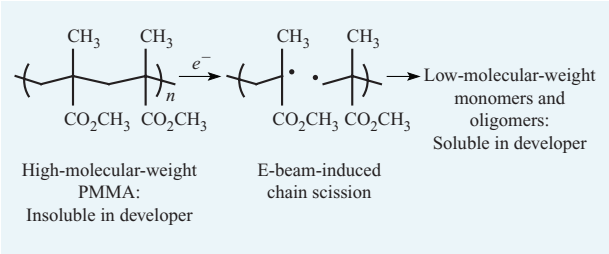


Scheme I

Poly(methylmethacrylate)—the original e-beam resist.

photomask critical dimensions (CDs) are required. The 1999 version of the Semiconductor Industry Association's *International Technology Roadmap for Semiconductors* [1] projects that the required CD uniformity on the mask will have to have a $\pm 3\sigma$ variation of 10 nm for 130-nm design rules and $\pm 3\sigma$ of 7 nm for 100-nm design rules. In addition, mean to nominal variation and CD linearity on the mask will have to be 10 nm and 20 nm per unit dose, respectively, for 130-nm design rules, and 8 nm and 14 nm per unit dose, respectively, for 100-nm design rules.

Because of the introduction of phase-shifting masks and OPC, the complexity of the mask-making process has increased dramatically in the past few years and will continue to become more challenging as dimensions and error budgets continue to contract. The causes of mask CD errors have two primary sources: the process (resist, develop, etch) and the writing tool. Over the past few years, the mask industry has been focused on migrating to dry-etch processes in order to obtain better CD control during the Cr patterning [2–5]. However, to achieve better resolution and to improve the CD uniformity of resist images, photomask manufacturing will require the use of higher-energy e-beam exposure systems. Each of these improved specifications has required in the past and will require in the future a reevaluation of the resist systems being used, since the performance of the resist will be one of the most important factors in meeting advanced mask-fabrication specifications. **Table 1** summarizes the current criteria necessary for a production-worthy electron-beam resist for advanced mask-making.

Electron-beam resists for mask-making: A brief history

The development of electron-beam resist systems used for photomask fabrication has been focused on improving the sensitivity, resolution, and etch resistance of the resist materials [6]. Among the first resists used for this application were members of a family of positive-tone resists that undergo chain scission. Chain-scission resists operate on the basis of a radiation-induced reduction in the molecular weight of the comprising polymer; this reduced molecular weight results in a solubility differential in the appropriate developing solution, usually an organic solvent. The first and classic example of a chain-scission resist for e-beam applications is poly(methylmethacrylate), or PMMA, as shown in **Scheme I**. This simple resist material has been shown to provide resolution that is among the highest for any resist for any lithographic application; it has been the touchstone in the development of all e-beam-sensitive materials since its initial use in the late 1960s [7–9]. Numerous publications have reported on the optimization of PMMA-based resists [6, 9]. Of particular note is the incorporation of highly electron-withdrawing groups, such as halogens, at the α-position of the acrylate moiety to assist in the stabilization of a free radical, the first intermediate in depolymerization or chain unzipping [10–12]. In the 1970s, such structural modifications led to PMMA derivatives that afforded resist formulations with sensitivities as low as 1 μC/cm^2 at 10 kV [13]. Despite their excellent sensitivity and resolution, however, PMMA-type resists suffer from poor resistance to corrosive etching conditions, and alternative materials were sought.

Another example of chain-scission resists is poly(1-butene sulfone), known as PBS (**Scheme II**), which was developed concurrently at Bell Laboratories, RCA, and IBM [14–16]. These resists exhibit e-beam sensitivity of ~3 μC/cm^2 at 10 kV and have been used with a Cr wet-etch process to produce photomasks. PBS has been widely used in photomask manufacture since

Table 1 Requirements for a production-worthy electron beam for advanced mask-making.

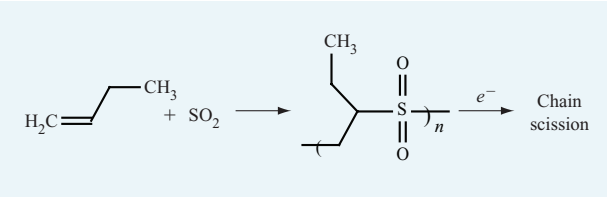
Resist parameter	*Requirement for 4X photomask fabrication*
Resolution	130 nm
Dose	<20 μC/cm^2 at 50 keV
Contrast	>5
Post-apply bake/post-exposure bake latitude	<1 nm/°C
Post-coat delay stability	>1 month
Cl_2/O_2 etch resistance	Comparable to DUV resist

the 1970s and 1980s because it affords resolution down to ~500 nm. However, as the industry began migrating to dry-etch processing of the Cr as well as smaller feature sizes, a new resist was needed because the performance of PBS was no longer acceptable with regard to etch resistance, resolution, and CD linearity and uniformity.

One approach to improving the etch resistance of PBS-type resists was the incorporation of novolak resins into the formulation, as in the poly(methylpentene sulfone) (PMPS) resists developed at Bell Laboratories and the sulfone/novolak system (SNS) resists developed at IBM in the 1980s [17–19]. The inclusion of novolak not only decreased etch rates, but it also allowed aqueous base development of the patterned resist, because the olefin sulfone acted as a dissolution inhibitor in the unexposed regions, while the unzipped polymer allowed solubilization of the phenolic matrix in the base. Ultimately, however, the SNS materials were less sensitive than PBS, since a large degree of the incoming energy of the exposing electrons is absorbed by the novolak matrix and thus is unavailable for chain-scission reactions by the olefin sulfones. A bilayer resist approach developed at IBM was also used for the manufacturing of masks in the late 1980s [20]. This approach involved the use of a polysiloxane as the imaging top layer. After exposure and development, the pattern was transferred using dry development techniques. However, research continued on a lower-cost, simpler single-layer resist approach.

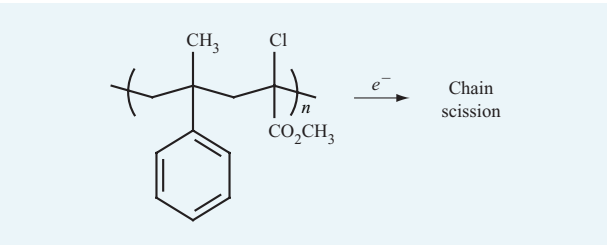
In response to the limitations of PBS and SNS, a new chain-scission positive-tone resist was developed in the mid-1990s that was based upon poly(methyl-α-chloroacrylate-co-α-methylstyrene), as shown in **Scheme III** [21, 22]. This new resist, ZEP from Nippon Zeon, has found wide acceptance and is currently being used in 180-nm device design rule mask production at doses of ~8 μC/cm^2 on 10-kV exposure systems [2, 8]. The implementation of a dry Cl_2/O_2 etch process with high etch anisotropy allowed for high-fidelity image transfer of mask images with dimensions as small as 250 nm. However, despite the widespread acceptance and use of ZEP, it does not fully satisfy all of the industry's current and future requirements; some desirable enhancements as the industry begins to migrate toward higher-voltage exposure systems include improved contrast (>2) [9], enhanced RIE resistance (>2:1 resist/Cr etch ratio), and improved sensitivity (<8 μC/cm^2 at 10 kV or <25 μC/cm^2 at 50 kV).

Higher-voltage e-beam exposure systems are believed to be the best solution for meeting the resolution and accuracy requirements of advanced masks because of their finer beam profile compared to the 10-kV exposure systems that have been used in the mask-making industry



Scheme II

Poly(1-butene sulfone) (PBS) resist.



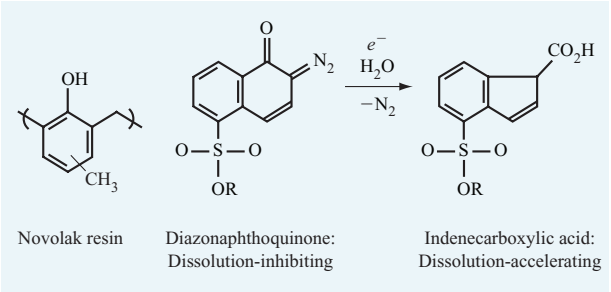
Scheme III

Poly(methyl-α-chloroacrylate-*co*-α-methylstyrene), the polymer comprising ZEP resist.

for many years.[1] The finer beam profileresults from the reduction in electron forward scattering in the resist layer at higher accelerating voltages. New raster-scanning tools such as the MEBES X[1] are moving toward a 50-kV accelerating voltage, and 50-kV vector scan systems have also been reported in the fabrication of advanced masks [23–25]. However, the higher accelerating voltages of these systems lead to lower resist sensitivity because fewer electrons are absorbed in the resist layer, being instead absorbed in the underlying quartz substrate. For example, the 8-μC/cm^2 dose required to expose ZEP at 10 kV would increase by more than five times in the move to a 50-kV system, where the dose required would be ~40 μC/cm^2. Increased electron absorption by the quartz substrate can in turn lead to significant heating of the mask [26] during e-beam exposure, causing CD errors. Therefore, higher-sensitivity resists are needed to reduce the amount of beam heating and increase the mask fabrication throughput of the vector-scan tools. Higher sensitivity is also of significant importance in the development of resists for electron-beam projection lithography (EPL)—a potential next-generation lithography solution [27, 28].

The use of diazonaphthoquinone (DNQ)/novolak-based resists, the workhorse materials for the lithographic imaging of semiconductor devices using G-line (436-nm)

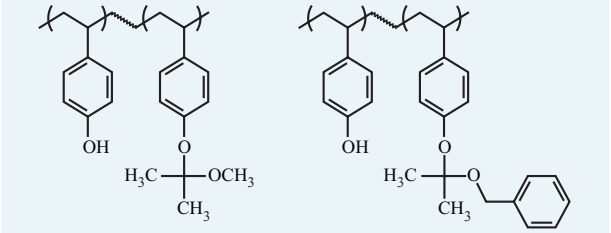
[1] MEBES X Mask Writer manufactured by ETEC Systems.



Novolak resin | Diazonaphthoquinone: Dissolution-inhibiting | Indenecarboxylic acid: Dissolution-accelerating

Scheme IV

Chemical structures of novolak and DNQ resist components.



2-methoxypropyl-protected PHS (MOP) (a) | 2-benzyloxypropyl-protected PHS (BOP) (b)

Scheme V

Early versions of the ketal resist system (KRS): (a) KRS-MOP; (b) KRS-BOP.

and I-line (365-nm) exposure wavelengths, has found some applications in mask-making. The chemical structures of novolak and DNQ are shown in **Scheme IV**. These materials exhibit some processing advantages, since they are not dependent on organic solvents for development, but instead use more environmentally benign aqueous-base developers and have perhaps the best dry-etch resistance of all conventional resist materials. Resists of this type are based on the solubility of the novolak film modulated by the radiation-sensitive DNQ molecule. In the unexposed areas, DNQ acts to inhibit the aqueous-base solubility of novolak, while in the exposed regions, DNQ is transformed to the solubility-enhancing indenecarboxylic acid. Sensitivity of ~20 μC/cm^2 at 10 kV is typical for the DNQ/novolak systems. While these resists offer specific advantages, they are ultimately unable to satisfy the high-performance requirements necessary for advanced mask-making.

Chemically amplified resists

Recently there has been significant interest in the use of chemically amplified (CA) resists for e-beam writing applications because of their high resolution, high sensitivity, high contrast, and good etch resistance [29–32]. Positive-tone CA resists usually function by means of the acid-catalyzed cleavage of labile blocking groups that "protect" the acidic functionalities of an inherently base-soluble polymer. Acid is generated in the exposed regions of the resist by radiation-sensitive photoacid generators (PAGs). Resists of this type are widely used in KrF (248-nm) and ArF (193-nm) lithography and are generally regarded as the most promising candidates for next-generation lithography strategies such as extreme ultraviolet (EUV) and EPL, as well as for F_2 (157-nm) optical lithography.

The advantages of using CA resists over conventional e-beam resists for photomask-making have recently been demonstrated. Since many positive-tone CA resists developed for KrF lithography are also imageable with e-beam radiation, examples of the use of these systems with e-beam radiation abound in the literature. For example, it was recently reported that 120-nm equal line and space arrays were printed with an e-beam dose of 50 μC/cm^2 at 50 kV with Shipley UV-5 resist [33]. Additionally, researchers have reported that resolution of sub-50-nm relaxed-pitch lines was obtained with Shipley UV-III with a dose of 60 μC/cm^2 at 100 kV [34]. In the recent literature [29–33], comparative evaluation of some CA resists with conventional chain-scission resists has demonstrated several advantages of using the amplified systems. These findings are characteristic of conventional positive-tone CA resists in that a number of issues remain to be addressed before widespread acceptance in mask-making is established. Among the more significant of these concerns are the stability of CA resists to environmental contaminants such as airborne amines, sensitivity to post-apply and post-exposure bake (PAB/PEB) temperature variations, and post-coat and post-exposure delay stability.

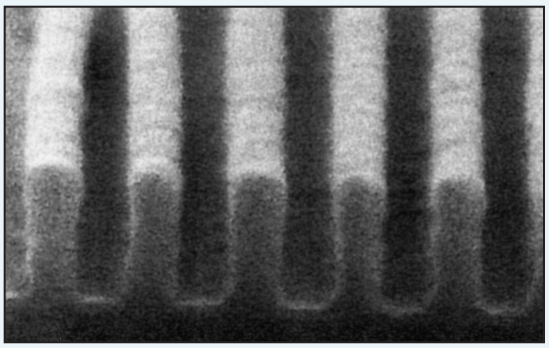
To address the environmental concern, carbon filtration of the clean-room environment has been used to remove airborne contaminants in resist-processing areas [30]. However, the sensitivity to PAB/PEB temperature variations is perhaps the most critical concern for mask fabrication, since the quartz substrates require a long ramp time to achieve a constant temperature across the surface, and temperature uniformity often varies by more than ±2°C. To address this issue, two main approaches have been taken: designing precision hot plates that can achieve temperature variation of less than ±0.5°C across the mask surface, and tailoring the resist to have reduced thermal and environmental sensitivities. One approach to

the latter that has proven successful in our laboratories has been the incorporation of a low-activation-energy-protecting group as the "deblocking" strategy [35].

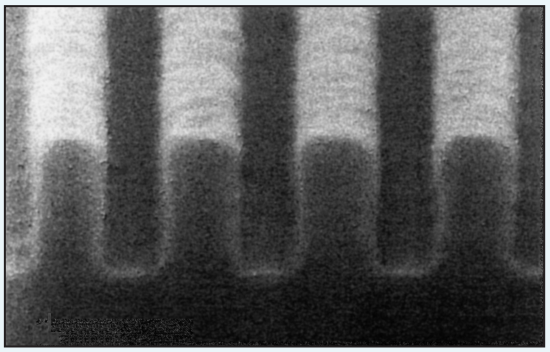
Low-activation-energy resist for mask-making

We have previously reported that an environmentally stable CA resist called KRS containing a partially ketal-protected poly(*p*-hydroxystyrene) (PHS) has exhibited excellent resolution (<100 nm), high sensitivity (~12 μC/cm^2 at 50 kV), and high contrast (>10) without the need for PEB processing [35–39]. However, this original formulation of KRS, based on PHS protected with 2-methoxypropene (MOP) [**Scheme V(a)**], was found to have low thermal stability, excessive outgassing (*vide infra*) during exposure, and insufficient inhibition to development in the standard aqueous-base developer, 0.263 N tetramethylammonium hydroxide (TMAH). To alleviate these shortcomings in the original KRS formulation, larger protecting groups were sought; after several iterations, new formulations have been developed using less volatile protection groups. For example, ketal-protected PHS using 2-benzyloxypropene (BOP) [**Scheme V(b)**] has been examined, and the lithographic performance of these materials has been reported [38]. An improved KRS resist discussed below, KRS-XE, is based on a novel ketal-protecting group that is also significantly less volatile than MOP [39]. Results have shown that these new resist systems can exhibit excellent resolution (<60 nm), are robust with respect to airborne contaminants, exhibit large PAB/PEB latitude, and are compatible with 0.263 N TMAH aqueous-base developer. Furthermore, these resists have demonstrated dry-etch resistance comparable to that of the best DUV resists. The excellent resolution of this resist is illustrated in **Figure 1**.

As mentioned previously, KRS-XE is based on partially protected PHS. The ketal protecting group is derived from a carefully selected enol ether to which the phenolic hydroxyl is added under acidic conditions (**Scheme VI**). The low-activation-energy ketal offers several distinct advantages over conventional positive-tone CA resists. Most notable is the insensitivity displayed by KRS-XE to a broad range of variations in both PAB and PEB temperatures. It has been shown that this resist may be post-apply baked at temperatures ranging from 90 to 110°C without significant performance deviation, as shown in **Figure 2**. Even more significant is the invariance observed with changes in PEB temperature. Because deprotection can occur at room temperature in this system, a PEB is not essential for imaging. Thus, it has been shown that KRS-XE performs almost identically with or without a PEB over the temperature range of 80 to 110°C, as shown in **Figure 3**.



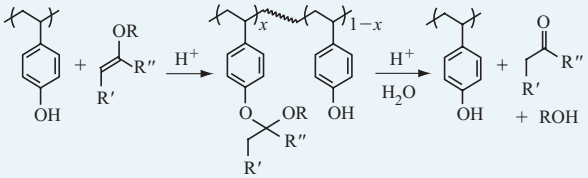
(a)



(b)

Figure 1

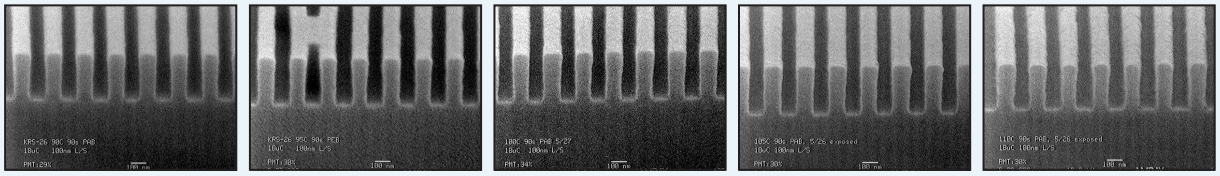
SEM images of KRS-XE exposed on a 75-kV EL4+ exposure tool: (a) 55-nm equal lines and spaces; (b) 100-nm lines and 50-nm spaces.



Scheme VI

Schematic showing synthesis of KRS-XE polymer and acid-catalyzed deprotection to PHS.

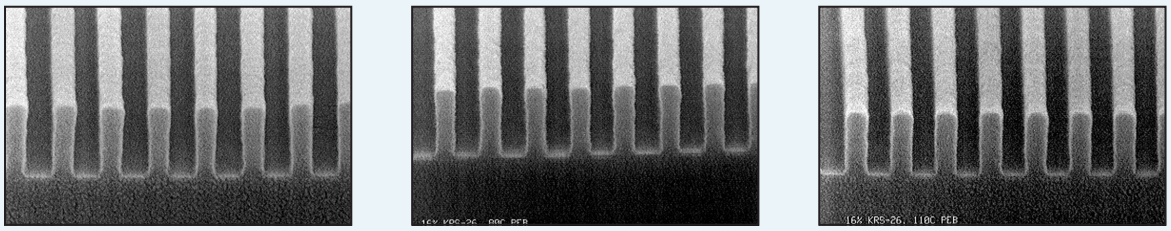
For mask-making applications, the quartz plates usually require more than six hours of exposure time using a MEBES exposure system and ZEP 7000 resist. The introduction of CA resists is expected to reduce the exposure time to three to four hours with a 75-kV mask



(a) (b) (c) (d) (e)

Figure 2

Insensitivity of KRS-XE image quality to variation in PAB temperature (100-nm equal lines and spaces): (a) 90°C; (b) 95°C; (c) 100°C; (d) 105°C; (e) 110°C.



(a) (b) (c)

Figure 3

SEM images of 100-nm lines and spaces of KRS-XE: (a) no PEB; (b) 80°C PEB; (c) 110°C PEB.

writer. The often-observed vacuum effect, in which the CD of a feature varies in response to the time spent under high vacuum after exposure, has been decreased significantly by the adoption of more sensitive CA resists. It is still important that a resist be stable in vacuum for more than eight hours. Therefore, we have investigated KRS-XE linewidth stability in vacuum for more than twelve hours. As shown in **Figure 4**, the change in CD is very small.

While the performance of KRS-XE demonstrates how a positive-tone CA resist can be tuned for the specific requirements of mask-making by addressing the concerns that have accompanied CA resists since their invention, this relatively new application for these materials introduces a new set of challenges that may not have been considered previously. For example, in contrast to device manufacturing on silicon substrates, coated films on mask blanks are often required to withstand prolonged storage prior to exposure and subsequent processing. Current common practice suggests that the storage lifetime of a coated mask blank should range from three to six months. The high sensitivity of CA resists makes them somewhat more susceptible to a variety of airborne contaminants including acids, bases, and moisture, as well as to fluctuations in temperature when stored for a prolonged period. Current approaches being investigated to address the storage criterion include modification of the KRS-XE formulation to reduce contamination susceptibility as well as the use of appropriate packaging protocols to further extend the shelf life of coated mask blanks. Other high-performance demands being placed on resists for mask-making are similar to those being encountered with conventional photoresists for semiconductor device manufacture. These issues include enhanced sensitivity, improved etch resistance, reduced resist outgassing, and challenges associated with image quality such as higher resolution, image collapse, and line edge roughness. The remainder of this paper outlines some of these issues as they relate specifically to mask-making resists and describes our recent approaches to addressing these concerns by modifications of the formulation, composition, and processing of KRS-XE.

Future challenges for high-performance CA resists for mask-making

Etch resistance

One of the key components that will drive next-generation mask-making is the necessity for delineation of subresolution OPC features on the photomask. High-resolution imaging (100 nm and below) coupled with excellent CD control and process latitude will clearly be required. It is very likely that thin resists will have to be developed to provide such performance while avoiding the image collapse often observed in high-resolution imaging with aspect ratios greater than 3 to 4. The implementation of thin resists will require significant enhancement of the dry-etch resistance of conventional single-layer resists or a migration to a more complex thin-film imaging technique.

The etch resistance to Cl_2/O_2 plasma of KRS-XE has been shown to be comparable to that of most conventional DUV resists currently being used in KrF lithography, but it is still considerably less than that of novolak resists. One approach to enhancing etch resistance in resists has been the incorporation of organometallic species into the resist composition. It has been proposed that the products of plasma etching of organometallic species (namely metal oxides, halides, and oxyhalides) are generally low-volatility materials that assist in the retardation of etch rates and in some cases may actually form a hard mask *in situ*, thereby essentially reducing the etch rate to near zero. We have successfully implemented this approach using two distinct mechanisms of metal incorporation: direct covalent attachment of organometallic substituents to the polymer matrix and the blending of organometallic additives into the conventional resist formulation. Both techniques have resulted in enhanced etch performance in Cl_2/O_2 plasma while maintaining excellent lithographic performance.

In earlier studies [40, 41], the covalent incorporation into resist materials of organometallic functionalities containing, for example, silicon or tin was shown to enhance etch resistance in a variety of systems. This is a particularly attractive approach for mask-making applications in which contamination of semiconductor devices by metallic impurities is not an issue, as it is in device manufacture. Our approach to this method involved electrophilic substitution of the phenolic ring of PHS with 4-trimethylgermylstyrene under acidic conditions, as outlined in **Scheme VII**. This germanium-containing polymer, containing ~5 wt% Ge, was then successfully protected with a ketal protecting group to afford an imageable CA polymer matrix. After polymer composition and resist formulation optimization, a system emerged that demonstrated ~10% reduction in Cl_2/O_2 etch rate as compared to the non-germanium-containing material, while maintaining excellent lithographic performance (**Figure 5**).

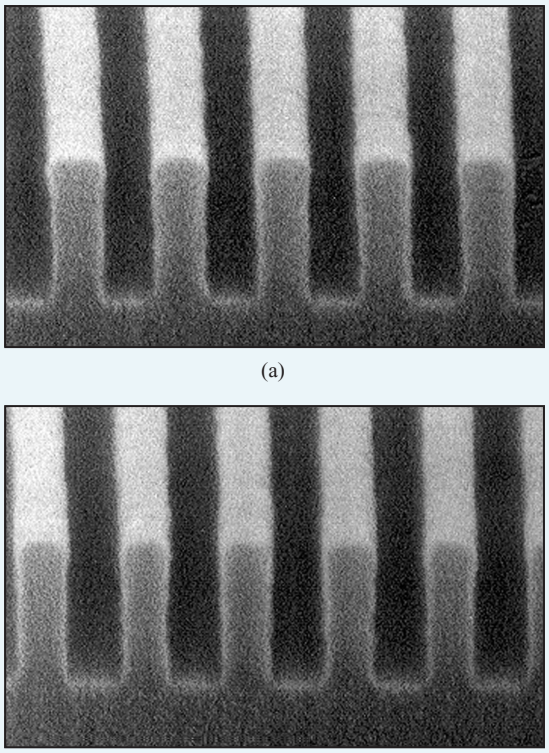
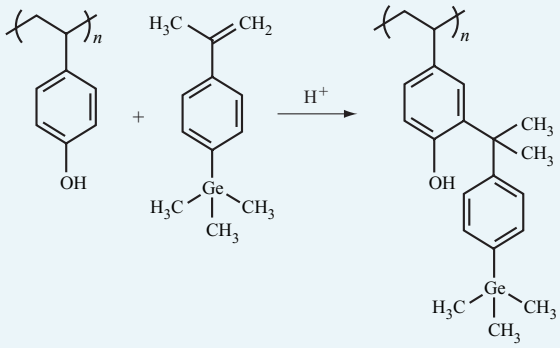


Figure 4

Vacuum delay stability of KRS-XE: (a) 12 hr in vacuum; (b) 0 hr in vacuum (100-nm lines and spaces).



— For position only —

Scheme VII

Method for the incorporation of germanium into PHS using electrophilic aromatic substitution.

Another approach to increased etch resistance through the use of metals involved the blending of a proprietary

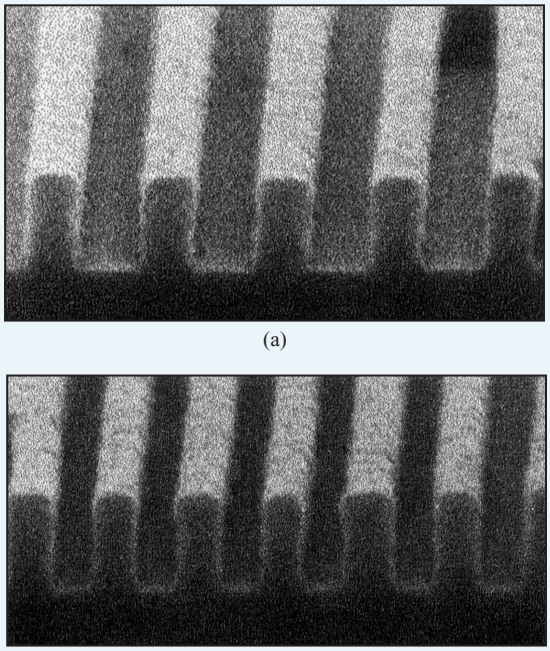


Figure 5

SEM images showing high resolution attainable with germanium-modified KRS-XE: (a) 100-nm lines and spaces, 14 μC/cm^2; (b) 75-nm lines and spaces, 15 μC/cm^2.

organometallic additive with the standard KRS-XE formulation. The miscibility of this additive with KRS-XE allowed for more than 5 wt% of a transition metal to be incorporated into the formulation without indication of phase separation or any noticeable impact on lithography (**Figure 6**). This approach has led to high-performance formulations having etch rates even lower than that of novolak resin, and nearly half that of the standard KRS-XE formulation.

Sensitivity

In addition to improved dry-etch resistance, improved sensitivity will be required in order to reduce write times and in turn enhance throughput. This clearly has a direct and significant influence on the final mask cost. As previously described, the migration of mask-writing tools to higher accelerating voltages necessitates higher sensitivity both to improve production throughput and reduce beam-induced resist heating [42, 43].

Our current research is involved in optimizing the sensitivity of this resist by modification of the radiation-active component. The current formulation of KRS-XE

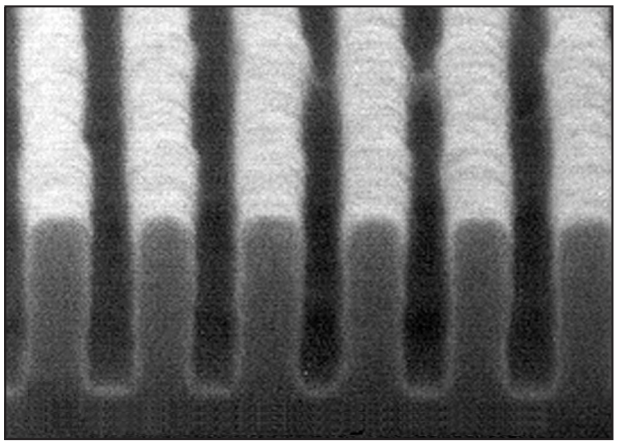


Figure 6

150-nm-pitch 2:1 lines and spaces in KRS-XE containing etch-resistance-enhancing additive.

has a sensitivity of 18 μC/cm^2 at 75 keV base dose, with proximity correction, for dimensions of 100 nm and greater. For 75-nm resolution, the dose is ~21 μC/cm^2. Early investigations suggest that sensitivities as low as 3–5 μC/cm^2 are attainable by adjusting the loading of the PAG, as is shown in **Figure 7**. However, more effort is needed to fully understand the processability and shelf life of formulations containing higher PAG loading.

There has been very little research associated with the design of PAG materials specifically for electron-beam applications. A recent report by Ocola and colleagues suggests that more than 99% of the energy deposited within a resist film during high-energy e-beam exposure is initially captured by the polymeric matrix [44]. Thus, to rationally develop a radiation-sensitive material specifically for e-beam applications, it is critical to first understand the energy- or electron-transfer mechanism between the polymer matrix in an excited state and any radiation-sensitive components, e.g., PAGs, in the resist composition. This area of research is ripe for future investigation and should provide insight into e-beam resist sensitivity.

Resist outgassing

Resist outgassing is an issue that is frequently raised when a CA resist is being developed for e-beam applications, particularly a low-activation-energy resist such as KRS-XE [45, 47]. It has been suggested that the room-temperature deprotection leads to a high propensity for these materials to outgas the low-molecular-weight byproducts of the deprotection reaction during exposure. The presumption that all low-activation-energy CA resists outgas to a high degree is largely based on the observation

of mass loss and subsequent film thickness shrinkage experienced with certain resists exposed with DUV radiation. Our approach to understanding outgassing, particularly in regard to the performance and room-temperature deprotection of KRS-XE, was to undertake a series of experiments involving DUV and e-beam exposure systems, various spectroscopic techniques, and thermal analysis. These studies have allowed the qualitative identification of the products of deprotection and their relative propensity of volatilization from the resist film under a variety of different conditions, as well as the quantitative assessment of the extent of outgassed material per electron. The result of these experiments may be summarized in two general statements. First, the propensity of a photoresist film to outgas can be directly controlled by careful selection of the protecting group. Second, the relative humidity of the environment under which the photoresist film is exposed directly influences the extent to which the deprotection reaction occurs, and therefore dictates the amount of outgassing. Since virtually no moisture is present in the high-vacuum environment of an e-beam exposure system, the subsequent acid-catalyzed hydrolysis is delayed until the external post-exposure processing, in which ambient moisture is allowed to participate in the deprotection reactions. The results of these findings have been published in detail elsewhere but are generally summarized by the data in **Table 2**, which demonstrates the low degree of resist outgassing in KRS-XE with a lithographically relevant dose of e-beam radiation as compared to more conventional high-activation-energy materials [46]. It should be noted that in all cases the primary outgassing products are not attributable to the products of deprotection, but rather are the consequence of PAG photolysis.

Conclusions

Superior mask-making resists are vital to semiconductor lithography, and over the last thirty years these materials have advanced significantly. By rational structural design of all components of the resist compositions and stringent attention to the effects of process variations, high-performance resists capable of enabling high-resolution optical proximity correction and assist features on state-of-the-art photomasks has emerged. While many of these accomplishments resulted from applying the lessons learned in the development of resists for semiconductor device manufacture, the unique requirements of photomask-making also required application-specific solutions. The ever-increasing demands imposed by the next generation of photomasks, including phase shifting as well as the new substrate materials that may be encountered in masks for next-generation-lithography technologies such as EUV and 157-nm lithography, will continue to produce a variety of innovations in the coming years.

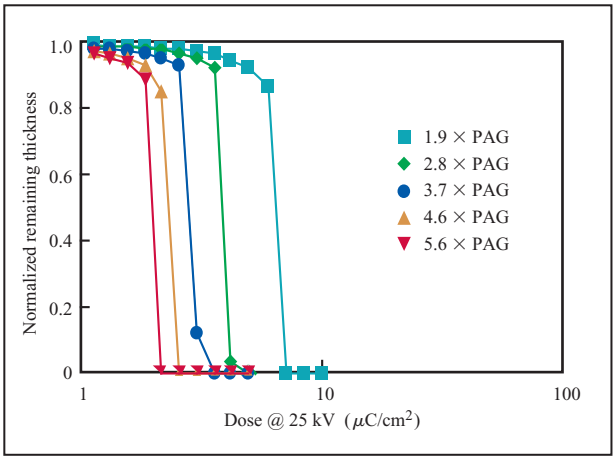


Figure 7

Sensitivity enhancement of KRS-XE by increased PAG loading.

Table 2 Outgassing of chemically amplified resists with e-beam (10-kV) exposure as measured by quadrupole mass spectrometry at MIT Lincoln Laboratories.

Resist	*Molecules/electron*
KRS-XE	3 ± 1
High E_a PHS-based	0.9–1.3
High E_a acrylate-based	10–20

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