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Extendibility of 193nm immersion lithography

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To achieve smaller feature sizes, 193i systems need to increase the refractive indices of their immersion fluids, lenses, and resists. Sixth and final article in a series.

There are now commercially-available 193nm water immersion scanners with numerical apertures (NAs) of 1.3 or 1.35. They can provide lithography solutions for line-and-space features as small as 45nm half-pitch. Can they be extended to provide 32nm half-pitch lithography? A simple k_1-calculation suggests that a 193nm scanner with NA at least of $\sim$1.65 is needed to print 32nm dense lines in which the width of the lines and spaces between them are equal (i.e., 1:1). A further increase of NA beyond 1.35, however, is limited by the refractive index (RI) of the system's lens, fluid, and resist. Therefore, the development of high-RI materials is key. Here, we will discuss the requirements for each material in more depth after discussing the scanner system as a whole.

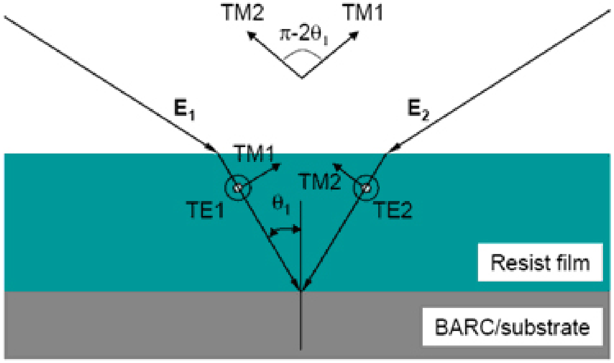

Figure 1. *Optical path of two exposure beams (E_1 and E_2) that interfere in a resist film with high refractive index (RI). The higher the RI of the resist, the smaller the refractive angle θ_1, and the more efficient the interference of TM1 and TM2. TM: transverse magnetic polarization. TE: transverse electric polarization. BARC: bottom anti-reflection coating.*

System issues

Currently, the bottom projection lens in one of these scanners is made of fused silica, which has an RI of 1.55 at 193nm. The conventional resists used at this wavelength have a refractive index of $\sim$1.7. The replacement of water (which has an RI of 1.44) with a high-RI immersion fluid would be the first step towards achieving high-RI 193nm immersion lithography (193i+). However, this is not sufficient to create a scanner with an NA of 1.65. The fused silica lens must also be replaced by a new material with an RI larger than 1.65.

Table 1 summarizes the possible combinations of high-RI immersion fluid, lens material, and resist. It also shows the theoretical NAs that can be achieved. Recently, a second-generation (G2) fluid with a high RI of 1.60–1.65 has become available for early imaging tests.[1] The implementation of a G2 fluid with current lens material should lead to the development of a full-field scanner with an NA of $\sim$1.5.

Various potential lens materials have been screened for high-RI values, which we discuss later. In addition, several basic-research organizations are exploring ways to increase the RI of the resist polymer. We hope this will lead to the design of a resist platform with a refractive index of 2.0. Combined with a G3 fluid with an RI of 1.8 and a high-RI lens, we hope that a scanner with an NA of $\sim$1.8 will be possible.

Two other issues to consider are the optical design and overall risk of pursuing 193i+ lithography. The RI values of the lens, fluid, and resist are not the only determinants of the system's NA: the design of the projection optics also affects it. One approach that avoids the high-RI lens material instead uses a design with a curved final lens, which can provide large incident beams. The disadvantage of the curved lens is that the exposure beam must then travel 20–50 times as far in the immersion fluid, which imposes additional requirements on the fluid, including extremely low absorption.

Finally, we acknowledge that adoption of this approach is not certain. The 193i+ roadmap is full of technical challenges. Another layer of risk is added by the possibility that the worldwide

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Table 1. *Possible combinations of high-RI immersion fluid, lens material, and resist.*

NA	Immersion Fluid	Lens material	Resist	Resolution capability
≤ 1.35	Water (1.44)	Fused silica (1.55)	Methacrylate (1.70)	45nm half-pitch node
≤ 1.5	*High-RI fluid (∼1.60)*	Fused silica (1.55)	Methacrylate (1.70)	
≤ 1.6	*High-RI fluid (∼1.65)*	*High-RI material (∼2.0)*	Methacrylate (1.70)	32nm half-pitch node
≤ 1.8	*Third-generation fluid (∼1.8)*	*High-RI material (∼2.0)*	*High-RI resist (∼2.0)*	

Numbers in parenthesis are the RI. Cells in italics indicate risk. NA: numerical aperture.

lithography community, in a push towards sub-32nm resolutions, may adopt a different solution such as double patterning or extreme UV lithography. Nevertheless, let us consider the requirements for each high-RI component of a 193i+ scanner, beginning with the immersion fluid.

High-RI immersion fluid

In addition to offering a high-RI value (>1.44 at 193nm wavelength), the immersion fluid has to fulfill numerous other requirements. The best way to assess an immersion fluid is perhaps to compare it with water. Table 2 summarizes the performance parameters of water as an immersion fluid at 193nm. Water is very transparent at this wavelength: its absorption coefficient is about 0.036 cm^{-1} (base 10, i.e., $I = I_0 e^{-\alpha x}$). The RI of water is ∼1.44 with a temperature sensitivity of $dn/dT = -10^{-4}/^{\circ}\text{C}$. This means that a temperature fluctuation of 0.01°C will cause a refractive index change of 10^{-6}, which in turn will lead to a defocus of ∼1nm at a working distance of 1mm. Water is also familiar to the integrated circuit (IC) manufacturers; and it has been used to quench development and rinse the resist patterns. The water molecule does not change when exposed to 193nm radiation, so it provides very good photostability during exposure.

A tentative specification for the high-RI immersion fluid recommended by Sematech is included in Table 2.[2] Except for the RI value, specifications were obtained simply by compromising the water performance. The absorption coefficient of $<0.15/\text{cm}$ is chosen to ensure acceptable transparency to exposure light and also to limit fluid heating during exposure. The low viscosity of the fluid is important for the meniscus to move with the exposure head across the wafer. Because the high RI fluid may have different components, a light scattering 'specification' is imposed to control flare.

How can we develop high-RI fluids that meet these specification? An initial approach involves doping water with high-RI organic or inorganic additives. For example, adding an inorganic heavy-metal salt to water can increase its refractive index. This approach can take advantage of some favorable properties of water (including density and viscosity). However, the inorganic metal salt has very low solubility in water, which limits the RI increase. Adding crown ethers to water enhances the solubility of metal salt. With this approach, an RI of 1.6 was obtained with the water solution of dCl_2.[3] The high concentration of heavy-metal-salt-water solution is very toxic, however, which is not a production-preferred solution. Non-toxic inorganic metal salts of $BaCl_2$ and $CaCl_2$ were also tested. Adding crown ethers improves solubility, but the increase in the RI was very limited. Increasing the additive concentration in water also tends to increase the absorbance of the solution.[4]

Dispensing transparent high-RI nano-particles in a liquid host is another way to make a high-index fluid.[5] For high transmission, the particle size must be smaller than 5nm, and for high RI the particle loading must be more than 50%. However, nanoparticles and metal oxides can damage the lens. The accurate control of the additive concentration is another challenge because small variations in concentration cause fluctuations in the index.

The dominant approach is to design single-component organic fluids with high RI. For example, JSR has announced the availability of two sample fluids (HIL-1 and HIL-2)[6] that are thermally stable over 200°C, and can be stored at room temperature for more than one year without significant change in quality. However, the contact angle of the high RI fluid on a typical methacrylate ArF resist is around 22°, which is too small for practical use in a production tool. Use of a specially-designed topcoat may be required to control the contact angle.

Other specifications are also important for the fluid including it's ability to leach components from the resist, swell the resist, break down when exposed to UV light, and hold dissolved gases. Leaching of the resist into high RI fluid seems a slow process, slower than that of water. On the other hand, most organic fluids can dissolve or swell photoresist film significantly. The assessment of a high RI fluid must include measurement of the resist film thickness before and after it is immersed in the

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Table 2. *Performance of water as an immersion fluid at 193nm and possible requirements for a high-RI immersion fluid*

	Water	High-RI fluid (G2)
Refractive index (n) at 193nm wavelength	1.44	1.60–1.65
Variation of RI with temperature fluctuation (dn/dT)	$-10^{-4}/°C$	$\sim 3\times10^{-4}/°C$
Absorption coefficient (α)	$0.036cm^{-1}$	$<0.15cm^{-1}$
Viscosity at 20°C (μ)	1.002cP	<2.0cP
Light scattering	<0.03%/mm	<0.2%/mm
Chemical compatibility with resist and lens	Good!	No negative impact
Chemical stability under 193nm irradiation	Stable	Not photoactive or degradable
Environmentally begin	Excellent	No negative impact
Cost-of-ownership		< $1 per layer

fluid. Photostability is another unique test for a high RI fluid: first, the fluid is exposed to a high dose of 193nm radiation, then the RI and k of the fluid is monitored to seek signs of decomposition. Finally, the solubility of air is also an important parameter because the more soluble to air the fluid is, the shorter the lifetime of bubbles. This could reduce the number of micro- or nanobubbles in the fluid, and thus decrease their related defects.

High-RI lens material

Meanwhile, the search for a new lens material continues. The key specifications for a high RI material have been suggested by Sematech.[2] These include a target RI of 1.7 at 193 nm, a small intrinsic birefringence (IBR) of <10nm/cm, stress birefringence of 1nm/cm, and a clear path to volume manufacturing. Sematech also specifies an absorption coefficient of <0.01/cm, which means means that >90% of the exposure light can pass through a lens 3cm thick. The material also must be homogeneous and capable of being formed into large lenses.

Theoretically, large-bandgap materials with high ionicity have high transmission and large polarizability, which produce high RI values. These predictions narrow the searching area towards group-II and metal-oxide materials. Currently, several candidates have been identified: $BaLiF_3$, ceramic spinel, LuAG, and germanate garnets.[7] $BaLiF_3$ has the highest transmittance and a smaller IBR at 193nm than the other candidates, but its RI of 1.6 is smaller than required.[8] Ceramic spinel ($MgAl_2O_4$) has no IBR problem, however, it has high absorption and poor RI uniformity that, due to its polycrystalline nature, is very hard to improve. LuAG ($Lu_3Al_5O_{12}$) has a high RI (∼2.1) but high IBR (3× the specification), which also cannot be easily corrected.[9] Finally, germanate garnets ($X_3Y_2Ge_3O_{12}$) have potential and investigation of these materials continues.

Another approach to producing a high-RI lens material is to dope fused silica with La.[10] Since the silica glass is the standard lens material used in scanners now, doping may allow us to retain some of the its preferred characteristics. The La dopant forms La_2O_3 in the glass, leading to a RI value of ∼1.6. Work continues on improving the doping process and developing a high-purity raw material.

High-RI resist

The highest system NAs are only possible if we combine a new immersion fluid and lens with a new, high-RI resist. The goal for such a resist polymer is an RI of 2.0, as well as imaging, etch, and cost properties similar to current 193nm 'dry' resists. Reports in the literature indicate that introducing sulfur, bromine, or aromatic groups into a polymer structure increases its RI. But some of these routes cause other problems: phenyl groups show relatively strong absorption at 193nm and therefore must be avoided. Similarly, bromine poses problems associated with contamination of the silicon wafer. Hence, of the three possibilities mentioned, a sulfur-containing polymer is the most promising choice.

A model has been developed to predict the RI of monomers and polymers.[10] This model used nine descriptors of the RI: heat of formation; translational entropy; minimum partial charge of a carbon atom; relative number of sulfur atoms; relative number of fluorine atoms; minimum bond order of a carbon atom; relative hydrogen donor-charged surface area; polarizability; and total enthalpy.

$$RI = \sum_{i=1}^{9} (k_i \cdot \text{Descriptor}_i).$$

This predictive model allows the candidate polymers to be assessed before they are synthesized, so that only those molecules with the desired properties need be prepared. This both accel-

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erates the development cycle and reduces costs. Resist samples with sulfur content of 14.7wt.% to 29.4 wt.% were designed and tested.[11] In general, the RI of a polymer increases with sulfur content in the polymer, but the molecular structure sometimes alters the RI value.

In addition to enabling a large NA, a high-RI resist can enhance the aerial image contrast. Under the same exposure conditions, the aerial image contrast is higher in a high-RI film than a conventional resist film, because in the former, the two beams interfere more efficiently. An exposure beam arrives at the resist surface with the incident angle of the NA. The higher the RI, the smaller the refractive angle; and the transverse magnetic polarized (TM) component of the exposure light interferes better and leads to better image contrast.[12] Figure 1 shows the optical path of two-beam interference in the resist film. In a high-RI resist film, the refractive angle θ_1 is smaller, leading to better interference of TM1 and TM2. The improvement of image contrast is very pronounced at large NAs. Also, reflection is reduced at the interface between the resist and the bottom anti-reflection coating because the incident angle is small in a high-RI resist.

Polarization and masks

In addition to the development of high-RI materials, other issues become more important as we move from 193i to 193i+ lithography, such as control of the polarization of the exposure light. When the incident angle of exposure beams in the resist surface approaches 45°, the TM component of the exposure beams cannot interfere and the imaging contrast is reduced. Therefore, control of the illumination polarization is increasingly important. This has been introduced on dry 0.93 NA tools, but will become critical for a 193i+ tool. This polarization control will impose constraints on the pattern design and layout.

Mask-induced polarization gets more pronounced at small feature sizes. At the exposure reduction factor of 4×, a minimum half-pitch of 128nm is needed in the mask to print 32nm half-pitch features in the wafer. For half-pitches smaller than the wavelength, the intensity of diffraction orders becomes a strong function of polarization. Masks made of different stacks (Cr, MoSi, Ta/SiO_2, and so on) demonstrate different transmissions for different polarized illumination light.[13] For example, a Cr-based binary image mask (BIM) appears to give better aerial image contrast than that of a regular MoSi attenuated phase-shift mask. This is because the Cr wall absorbs the TM-polarized light and acts like a TE-polarizer; while the MoSi sidewall reduces the transmittance of TE-polarized light and acts like a TM-polarizer. The mask stack must be optimized for 193i+ lithography.

We have covered some of the issues involved in pushing immersion lithography scanners to higher NAs, including development of high-RI immersion fluids, lenses, and resists. More work remains before we can extend 193i+ lithography to smaller and smaller feature sizes.

Author Information

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