# Lithography Simulation of Sub-0.30 Micron Resist Features for Photomask Fabrication using I-line Optical Pattern Generators

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The inorganic antireflection coating (AR3-chromium oxide) commonly used on photomask blanks was designed to minimize flare in h-line (405 nm) lithography steppers. The reflection of light (flare) off this coating (air-photomask) increases with shorter exposure wavelengths. High levels of flare occur in 248 nm and 193 nm IC steppers due to reflections off of the photomask surface. The reflections (standing waves) in photomask resists also increase during exposure using lower wavelengths of light. Lithography simulations and photomask manufacturing trials have led to resist processes that can generate sub-0.30 micron resist features on photomasks with I-line optical pattern generators (ALTA 3500). Lower developer concentration, higher exposure doses and the minimization of standing waves by incorporating a post-exposure bake and/ or organic antireflection coatings (ARC) maximizes resolution. High resolution photoresists show standing waves on photomasks fabricated with optical pattern generators. Low contrast resist processes show only small standing waves or in certain cases resist "footing." The use of organic antireflection coatings can minimize standing waves and allow the use of high contrast resist processes.

ARCs reduce the swing ratio, which improves linewidth uniformity. ARCs also improve the adhesion of the resist to the photomask surface. Simulations reveal that the optimal ARC coating thickness is around 46 nm for typical I-line systems and around 50 nm for 257 nm non-chemically amplified photomask resists. Preliminary I-line photomask manufacturing trials have been done with bottom antireflection coatings at the DPI Reticle Technology Center. The first process trials reveal that the standing waves in high resolution resists were reduced but not removed. Very precise control of the ARC thickness must be exercised to completely extinguish standing waves and careful film thickness optimization appears to be necessary to minimize these reflections.

**Keywords:** lithography simulation, photomask, photoresist, anti-reflective coatings

## 1. INTRODUCTION

Industrial photomask trials have demonstrated that a post-exposure bake allows the use of high contrast resist processes that improve resolution and process latitude. Realistically, the infrastructure for a post-exposure bake is not in place for full scale photomask fabrication. Organic antireflection coatings might be an easier option that current mask fabs can utilize immediately to improve resolution.

Organic antireflection coatings are used to minimize standing waves and maximize resolution in I-line and DUV IC processes. Organic antireflection coatings can also be used in photomask fabrication with optical pattern generators. Organic antireflection coatings provide the flexibility for minimizing reflections with both 365 nm and 257 nm optical pattern generators. Simulation was used to determine the optimal ARC thickness needed to minimize reflections at the ARC-resist interface. Simulation reveals that the resist film thickness and ARC thickness need to be simultaneously optimized to determine the overall resist swing curve reflectivity minimum (air-resist interface) as well as the ARC-resist reflectivity minimum. This can be done by simulation based on index of refraction measurements and experimentally by reflectivity measurements with different resist and ARC film thickness. The simulation is not absolutely precise because the reflectivity of the chromium layer can not be modeled exactly. This layer has a graded composition varying from pure chromium near the quartz interface to high concentrations of non-stoiciometric chromium oxides at the surface. The Cauchy coefficients derived for variable wavelength ellipsometry are therefore not exact [1].

High resolution non-chemically amplified and chemically amplified resists show large changes in dissolution rate with small changes in exposure dose. Reflections off of the photomask substrate create oscillations in dose in the resist. The high contrast/ resolution resists are sensitive to small changes in dose and create resist features with "standing waves". These standing waves seriously degrade resolution and create scumming problems. The use of antireflection coatings can theoretically preclude the need for a post-exposure bake for non-chemically amplified resist processes. Reflectivity calculations and simulations were used to explore the potential of organic antireflection coatings for optical photomask applications

## 2. THEORY

### 2.1 Organic ARC Reflectivity Calculations

Organic antireflection coatings (ARCs) minimize reflections at the ARC-resist interface through destructive interference (Figure 1). Light reflecting for the resist-ARC interface needs to be 180 degrees out of phase (destructive interference) with the light that propagates through the ARC (layer 2) and reflects off the photomask (layer 3) and then back up to the top of the ARC layer. The reflectivity at the resist-ARC interface can be calculated from the index of refraction and thickness of each layer.

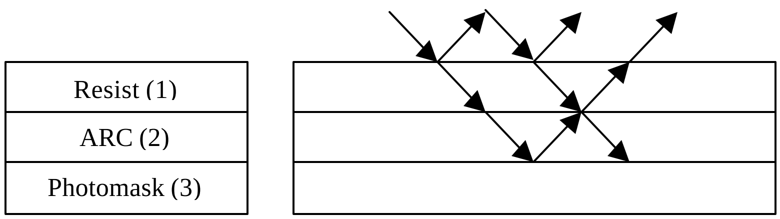


Figure 1: Optical Film Stack with the use of an Antireflection Coating

The total reflectivity in the ARC layer depends on the sum of the reflection and transmittance that occurs at each interface in the film stack. The reflection and transmittance coefficients for light propagating through each interface (from layer i to j) are shown in Equations 1 and 2, respectively. Others have completed a detailed analysis on this phenomenon [2,3].

$$r_{ij} = \frac{\tilde{n}_i - \tilde{n}_j}{\tilde{n}_i + \tilde{n}_j} \qquad (1)$$

$$t_{ij} = \frac{2\tilde{n}_i}{\tilde{n}_i + \tilde{n}_j} \qquad (2)$$

where

$r_{ij}$ = reflectance coefficient at the interface between layers i and j
$t_{ij}$ = transmittance coefficient at the interface between layers i and j
$\tilde{n}_i = n_i - i k_i$ (real and imaginary index of refraction)

The transmittance through the thickness of the ARC is described by Equation 3.

$$t_D = e^{-i2p\tilde{n}_2 D / l} \qquad (3)$$

where

$t_D$ = internal transmittance through the ARC film
$l$ = wavelength of light
$D$ = the thickness of the ARC

The reflectivity in each layer can be determined through the summation of the reflections at all of the interfaces in the resist-arc-photomask film stack. The total reflectivity in the arc film is calculated from the square of the total reflection coefficient in the ARC film defined from the film stack described in Figure 1 (Equation 4).

$$R_{total} = |\boldsymbol{r}_{total}|^2 = \left| \frac{\boldsymbol{r}_{12} + \boldsymbol{r}_{23}\boldsymbol{t}_D^{\,2}}{1 + \boldsymbol{r}_{12}\boldsymbol{r}_{23}\boldsymbol{t}_D^{\,2}} \right|^2 \qquad (4)$$

In order to minimize standing waves in the resist layer, the total reflectivity in the arc layer ($R_{total}$) must be minimized. The total reflectivity is minimized by solving equation 4 for the case when Rtotal equals zero.

$$R_{total} = 0 \text{ when } \boldsymbol{r}_{12} + \boldsymbol{r}_{23}\boldsymbol{t}_D^{\,2} = 0 \qquad (5)$$

The total reflectivity becomes zero when the light reflecting from of the arc-substrate interface of the arc ($\boldsymbol{r}_{23}$) is 180 degrees out of phase ($\tau_D^2 = -1$) with the light reflecting from the top interface of the arc ($\boldsymbol{r}_{12}$). This is a simplified case where the resist and photomask are not absorbing at the exposure wavelength. When the resist and chromium do absorb, simulation is required to minimize the reflectivity. Simulation is used to determine the ARC thickness that will minimize reflectivity for a given set of refractive indices.

## 3. SIMULATION RESULTS

### 3.1 Photomask Reflectivity and Optical Properties of Resist Materials

The reflectivity as a function of wavelength was measured by ellipsometry on a Hoya photomask. The chromium oxide layer thickness appears to be optimized to reduce reflections at 405 nm (Figure 2). The reflectivity increases from around 10% at 365 nm to around 17% at 257 nm

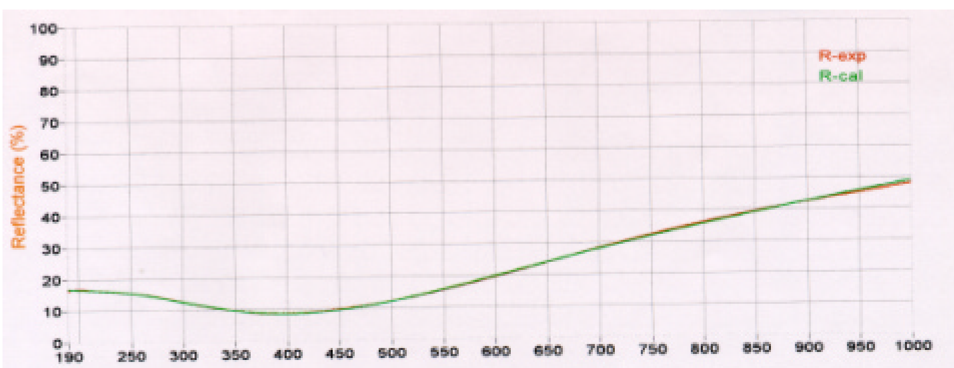


Figure 2: Reflectivity on Hoya AR3 photomask coatings as a function of wavelength

In the absence of an arc layer, the magnitude of the reflections from the resist-photomask interface determines the magnitude of standing waves in the resist. These reflections are dependent on the index of refraction of each layer. The index of refraction for common resists, organic antireflective coatings and a Hoya photomask substrate are in Table 1.

Table 1: Index of Refraction for Resist Materials at both 365 nm and 257 nm

| | n (365 nm) | k (365 nm) | n (257 nm) | k (257 nm) |
|---|---|---|---|---|
| iP3600 | 1.69 | 0.03 | | |
| Exp. NCA | | | 1.83 | 0.05 |
| Exp. CA | | | 1.62 | 0.02 |
| AZ Barli | 1.64 | 0.31 | 1.70 | 0.23 |
| AZ Barli II | 1.62 | 0.28 | 1.67 | 0.15 |
| Hoya Mask | 1.38 | 0.44 | 1.82 | 0.63 |

**3.2 Organic ARCs for I-line Optical Pattern Generators**

The reflections at the resist-arc interface were calculated for Barli II as a function of ARC thickness. Simulation of iP3600 on Barli II predicts that an ARC thickness of 46 nm reduces the reflections near zero for 365 nm exposure (Figure 3). The reflections are reduced from around 2.5% to nearly zero.

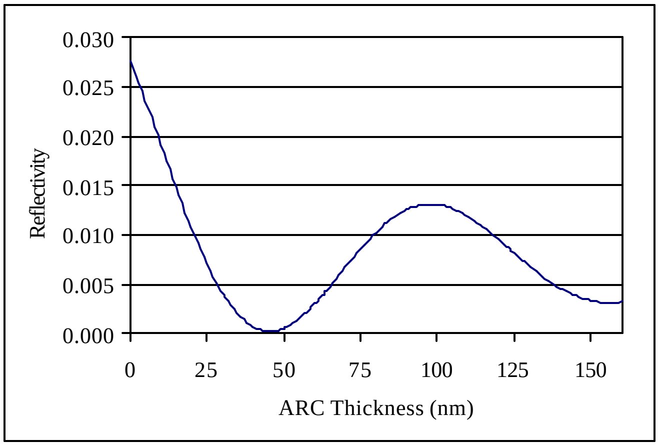


Figure 3: Simulation of the optimal ARC thickness to minimize reflectivity for IP3600 at 365 nm

The use of antireflection coatings also decreases the change in reflectivity from the resist with changes in resist thickness (swing ratio). Swing curves simulated for IP3600 with and without an ARC (46 nm of Barli II) at the optimal ARC thickness of 46 nm are shown in Figure 4.

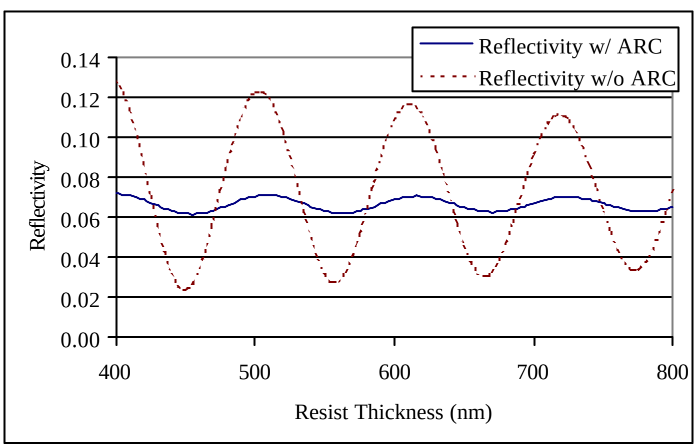


Figure 4: Simulation of the swing ratio reduction for IP3600 using the optimal Organic ARC thickness for 365 nm

### 3.3 Organic ARCs for 257 nm Optical Pattern Generators

There is substantial reflectivity from the Hoya chromium film stack at 257 nm. Barli I was chosen as the organic antireflection coating since it minimizes reflectivity for resists at 257 nm. A simulation of the reflectivity at the resist-Barli I interface for our experimental 257 nm NCA resist and for a typical CA resist are shown in Figure 5. Simulations reveal that the optimal Barli I thickness for the NCA resist is 50 nm and for the CA resist is 39 nm at 257 nm. These thicknesses are of course unique to the specific ARC, chromium layer and resist.

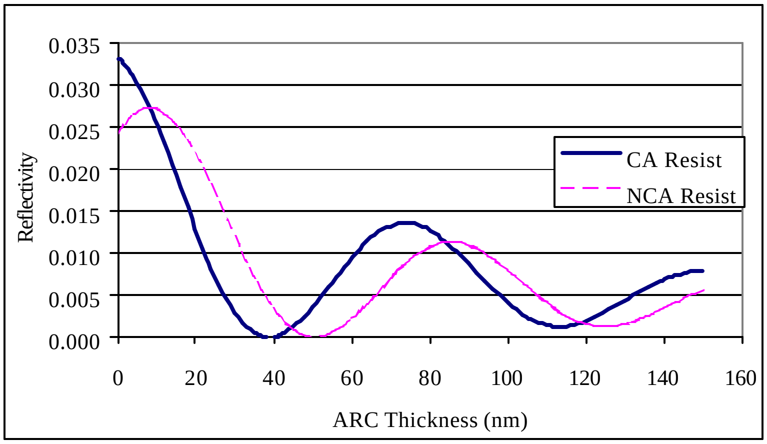


Figure 5: Simulation of the optimal ARC thickness to minimize reflectivity for a NCA and CA resist at 257 nm

The Barli I coating also efficiently minimizes the swing ratio at 257 nm as shown in Figure 6.

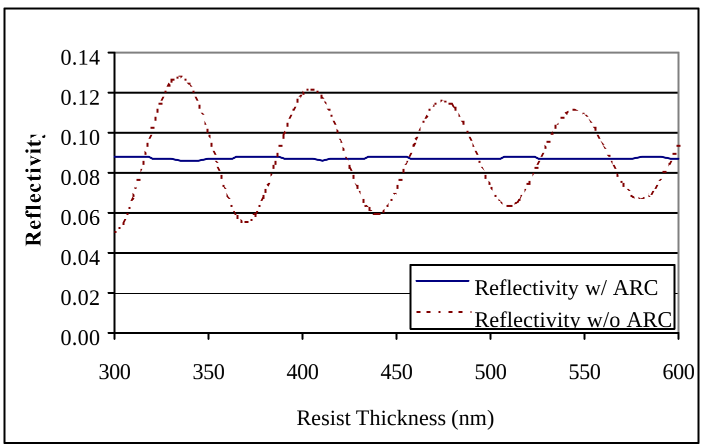


Figure 6: Simulation of the a NCA resist with and without an organic ARC at 257nm

### 3.4 Resist sensitivity to standing waves

Resist processes that have a high dissolution contrast (sharp change in dissolution rate with dose) provide steeper wall profiles and higher resolution but the high contrast also makes these systems more sensitive to standing waves. Previous simulations and manufacturing trials showed that high exposure doses and lower developer concentrations improve resolution for optical photomask processes at the cost of resolving larger standing waves [1]. Scanning electron micrographs (SEMs) of TOK resist IP3600 (500 nm X-features) show that resists developed with a lower developer concentration of 0.20N TMAH resolve larger standing waves compared to resist features developed with 0.26 N TMAH without a post-exposure bake (Figures 7 and 8). A post-exposure bake of 5 minutes at 120 °C removed the standing waves for IP3600 developed with the lower normality developer (Figure 9). The standing in the Sumitomo PFI88A3 resist become so pronounced with a lower developer concentration that even a 5 minute, 120 °C post-exposure bake would not fully diffuse the PAC. Scanning electron micrographs of the Sumitomo resist developed with a 0.23 N TMAH developer (TOK NMD-W) show worse standing waves than some resist processed under the same conditions developed with a 0.26N TMAH developer (TOK NMD-W) even with the same PEB conditions (Figures 10 and 11). Both resist processes with lower developer concentrations and high exposure doses have been able to produce high resolution features by using a post-exposure bake to remove standing waves.

Sumitomo resist (PFI88A3) has demonstrated very high resolution (0.27 micron isolated resist space) when processed with a 0.26 N TMAH developer concentration and a 120 °C post-exposure bake (Figure 12). However, lower developer concentration (0.23 N TMAH) did not further improve the resolution due to the formation of pronounced standing waves, even after a post exposure bake. The potential for still higher resolution can not be realized unless the standing waves are removed. An organic arc could be used to reduce standing waves and exploit the full potential of these resist processes.

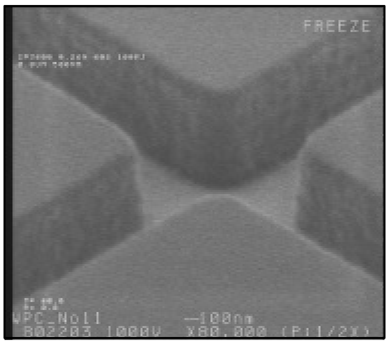

Figure 7: IP3600/ 0.26N / No PEB

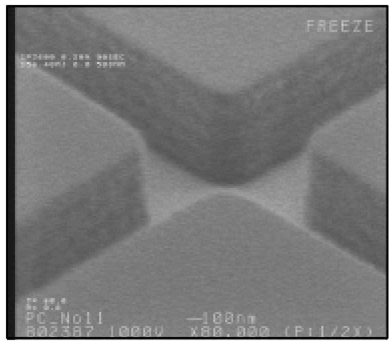

Figure 8: IP3600/ 0.20N/ No PEB

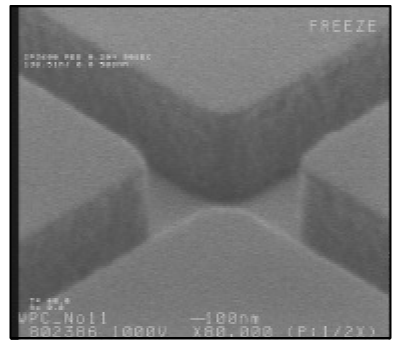

Figure 9: IP3600/ 0.20N/ PEB

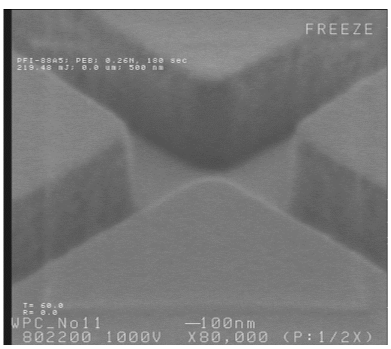

Figure 10: PFI88A3/ 0.26N/ PEB

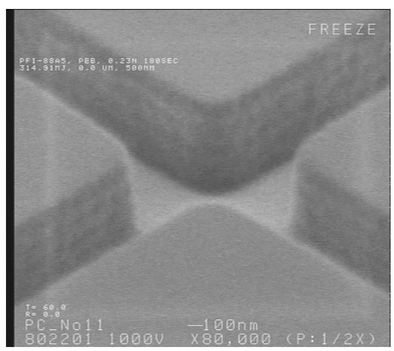

Figure 11: PFI88A3/ 0.23 N/ PEB

Figure 12: PFI88A3/ 0.26N/ PEB

**3.5 Dissolution rate analysis for resist processes that contain standing waves**

The techniques for extracting the optical and dissolution properties of photoresists have been previously discussed [1,4,5,6]. Higher contrast resists have a steep slope in the R(m) curve at the threshold PAC concentration where the onset of dissolution occurs. The R(m) curves for the higher contrast PFI88A3 resist and the lower contrast IP3600 resist using a 0.26 N TMAH developer are shown in Figure 13. There are significant differences in these response functions. The region near the onset of solubility (the dissolution notch) is particularly important. The Shipley i120 and Sumitomo PFI88A3 resists have steepest contrast in this region. The sharp dissolution change with PAC concentration leads these resists to be more sensitive to the oscillating distributions in PAC that result from standing waves.

The Sumitomo PFI88A3 resist has demonstrated optimal resolution when the steep dissolution notch was matched to the optimal exposure dose (over 200 mJ/cm$^2$) that provided the steepest PAC gradient. Shipley resist i120 has been characterized to determine if the same high resolution can be achieved at a lower dose around 125 mJ/cm2 which is closer to current IP3600 processes used in mask fabs. The i120 R(m) curve reveals that the onset of dissolution will occur at a lower dose (m = 0.65) than the PFI88A3 resist (m = 0.55) at the same developer concentration of 0.26 N TMAH. The i120 resist also has a larger notch in the R(m) curve that indicates that the resist has higher contrast than PFI88A3. It is important to understand the tradeoff between resist contrast and dose influence on PAC gradient.

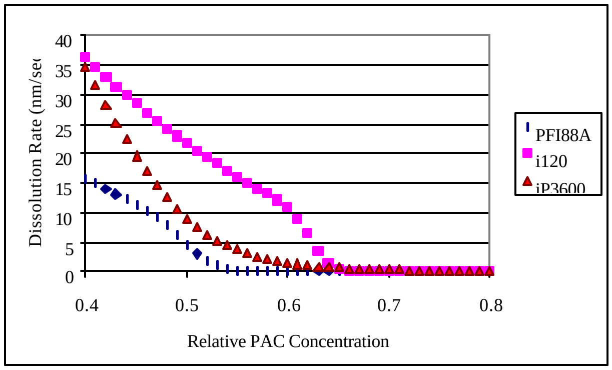


Figure 13: Dissolution Rate model for three I-line photoresists

### 3.6 I-line Photoresist Processes on an Organic Antireflection Coating

AZ Barli II (viscosity for 90 nm) was diluted 55 % by weight with an ethyl lactate based thinner provided by Clariant. The diluted ARC was coated and baked to a film thickness of 55 nm at a spin speed of 2000 rpm. While the ARC thickness of 55 nm was not optimum (target of 46 nm), simulation revealed that it still reduces the reflection by an order of magnitude as shown in Figure 3. The ARC was baked for a total of 15 minutes on hot plates set at a temperature of 200 °C. The target ARC thickness changes slightly for each resist system due to the slight difference of index of refraction between the resists. The target ARC thickness was 42 nm for i120, 46 nm for iP3600 and 45 nm for PFI88A3. A simulation of a 0.5 micron space in IP3600 developed with a 0.20 N TMAH developer for 180 seconds without a PEB shows standing waves (Figure 14). A simulation of IP3600 using PROLITH 6.05b on a 46 nm organic ARC (Barli II) under the same process conditions shows a major reduction in the standing waves (Figure 15).

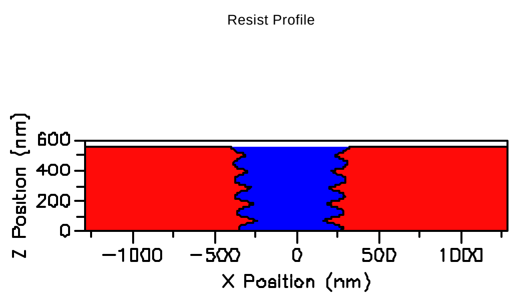


Figure 14: IP3600 resist profile without an organic ARC

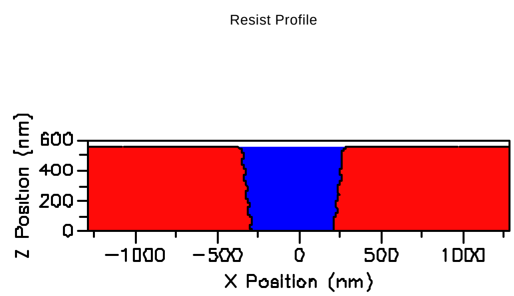


Figure 15: IP3600 resist profile with an organic ARC

The organic arc films only had very few visual defects at a film thickness of 55 nm. The resist coated normally on the ARC. There was no beading or layer intermixing between the ARC and resist.

The IC industry has demonstrated that high resolution processes can be run on Barli II antireflection coatings. The ARC should also improve adhesion between the resist and photomask. More work is needed to dimension the coating uniformity, defect propagation , impact on CD uniformity and etchability of organic ARCs on photomask blanks.

In preliminary manufacturing trials conducted at the DPI reticle technology center in Austin, resist profiles were fabricated on photomasks coated with organic antireflection coatings. Sumitomo resist PFI88A3 and Shipley resist i120 were coated at a target film thickness of 570 nm on 55 nm organic ARC coatings. The two resists were post-application baked for 15 minutes at a hot plate setting of 100 °C. PFI88A3 was developed with a 0.23 N TMAH (TOK NMD-W) developer for 180 seconds. I120 was developed with a 0.20 N TMAH (TOK NMD-W) developer for 180 seconds. Both resists were also post-exposure baked for 5 minutes at 120 °C to provide a comparison to previous experiments without an ARC. Scanning electron micrographs of 500 nm X-features were taken to reveal the level of standing waves (Figures 16 and 17). The i120 resist sized with an exposure dose of 134 mJ/ $cm^2$ and the PFI88A3 resist sized with an exposure dose of 175 mJ/$cm^2$. The standing waves were reduced but still exist in both the i120 and PFI88A3 resists even with the use of an ARC. The i120 resist which had the highest dissolution contrast (large notch) shows slightly more pronounced standing waves than the Sumitomo resist.

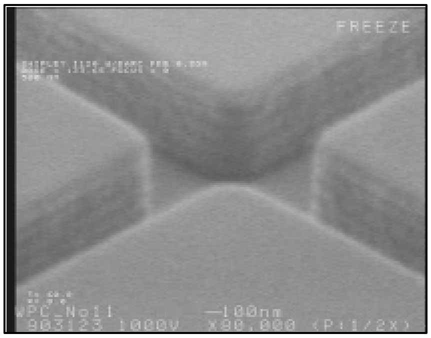


Figure 16: i120/ 0.20 N/ ARC/ PEB

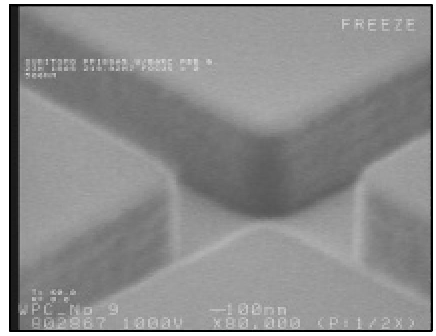


Figure 17: PFI88A3/ 0.23 N/ ARC/ PEB

These very high contrast resists still show standing waves, because the actual ARC coating thickness (55 nm) was slightly thicker than the 46 nm optimum. It is also possible that the simulated target ARC thickness is not exact due to the difficulty of making index of refraction measurements of the chromium oxide layer.

### 3.7 Organic ARC and photoresist thickness optimization

The thickness of both the organic arc and photoresist need to be simultaneously optimized to reach the global reflectivity minimum. A simulation of the resist reflectivity of our non-chemically amplified 257 nm resist as a function of resist thickness and organic ARC (AZ Barli I) thickness reveals that the overall global reflectivity occurs at an ARC thickness of 50 nm and a resist film thickness of 420 nm (Figure 18). The swing curve of the resist is dependent upon the ARC thickness. The reflectivity minimum moved from a resist thickness of 440 nm to 420 nm with the use of the ARC. The second diagram in Figure 18 and Figure 6 both show that there is very little dependence of the reflectivity of light on the resist thickness at an ARC thickness of 50 nm. Similar simulations can also be done for I-line processes.

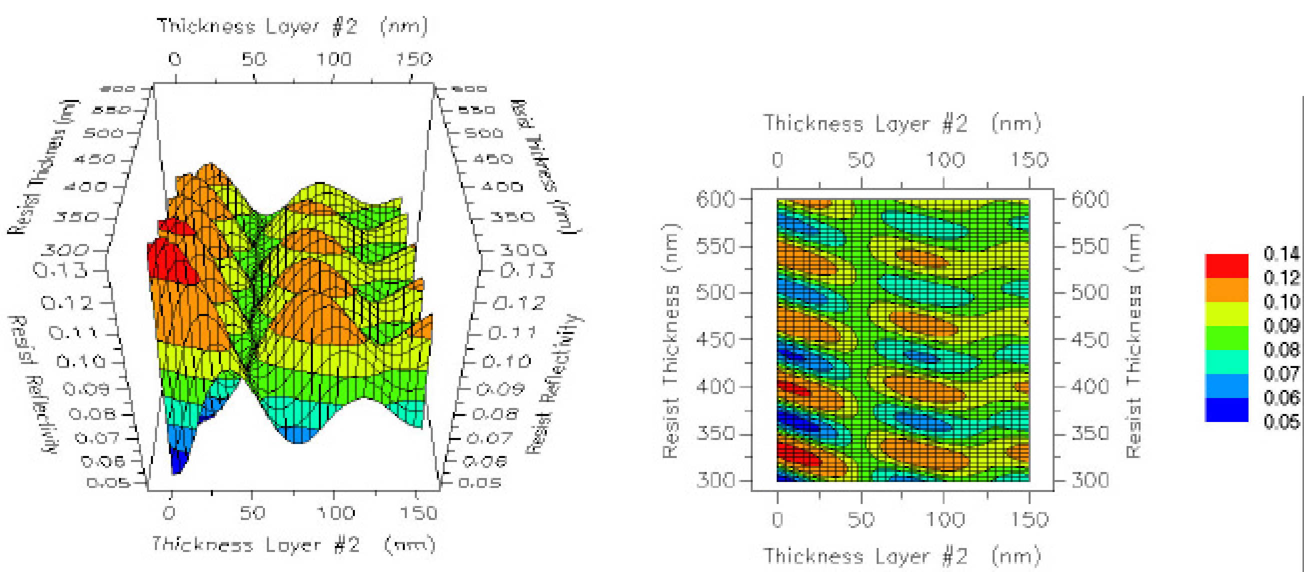


Figure 18: Resist reflectivity as a function of ARC and photoresist thickness for a 257 nm NCA resist process

The optimal resist thickness and ARC thickness apparently needs to be determined experimentally. The reflectivity as a function of resist thickness and arc thickness at the exposure wavelength (365 nm or 257 nm) can be measured to determine the overall global reflectivity minimum. A statistical design of experiments will be necessary to determine overall reflectivity as a function of both layer thicknesses. Simulation should be used to get good estimates of the optimal layer thickness. Furthermore, experimental CD measurements should be made as a function of resist thickness to determine the swing curve of the resist since exposure changes the index of refraction of a bleachable resist, influencing the optimal resist thickness.

### 3.8 Organic Antireflection coatings for the Photomask Industry

The importance of organic antireflection coatings will increase with the introduction of a 257 nm optical pattern generator. Non-chemically amplified 257 nm resists may be optimized with an organic ARC potentially without the use of a post-exposure bake. The most important application of organic ARCs will arrive with the introduction of chemically-amplified resists for 257 nm optical pattern generators. Chemically amplified resists are very high contrast, which results in the resolution of small changes in dose throughout the resist thickness. Chemically-amplified resists will most likely require an organic antireflection coating and post-exposure bake to optimize performance.

## 4. CONCLUSIONS

High contrast resists show standing waves on photomasks fabricated with I-line optical pattern generators. The use of high exposure doses and low developer concentration improves contrast but resolves more standing waves that are not easily removed even with the use of a post-exposure bake. ARCs can theoretically minimize standing waves, reduce the swing ratio and increase adhesion between the photomask and resist. Organic antireflection coatings can potentially be utilized to remove the standing waves in high contrast resists without the use of a post-exposure bake. We have demonstrated that organic ARCs can be coated on photomasks and photoresists can be normally patterned on the organic ARC layer. High contrast photoresists like chemically amplified resists will potentially require an organic ARC at 257 nm. More work is still required to experimentally determine the optimal ARC and resist thickness to provide a global reflectivity minimum at the exposure wavelength. Experimental CD swing curve experiments will also be necessary to fully dimension the optimum thickness for a bleachable resist. More work is also necessary to dimension the effects of defects and ARC dry-etching on photomask fabrication.

## 6. ACKNOWLEDGEMENTS

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