

Practical resolution enhancement effect by new complete anti-reflective layer in KrF excimer laser lithography

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ABSTRACT

A new complete anti-reflective layer (ARL) for KrF excimer laser lithography, which become a excimer laser lithography to a practical mass production tool beyond 0.35 μ m rule devices, is developed. This new ARL, whose material is a type of hydro silicon oxynitride film (SiOxNy:H), can be applied to tungsten silicide (W-Si) and even to aluminum silicon (Al-Si) substrates by controlling deposition conditions in plasma enhanced chemical vapor deposition systems. Using this SiOxNy:H film with 30nm and 25nm thicknesses on W-Si and Al-Si substrates respectively, critical dimension (CD) variations for both substrates are drastically reduced to within 0.02 μ m for 0.30 μ m imaging. On actual device structures, with these SiOxNy:H film as an ARL, notching effects by halation are completely reduced. Moreover, these SiOxNy:H film can not only be deposited with topographically uniformity but also etched with conventional SiO₂ etching conditions. Another advantage with ARL is a depth of focus enhancement effect. With a SiOxNy:H film, depth of focus for the critical dimension is enlarged more than 23% for 0.35 μ m line and space patterns. Accordingly, practical resolution is enhanced. From the above effect, the limitations of KrF excimer laser lithography for ideal substrate conditions are considered from the point of view of optimal projection lens NA for various feature sizes.

1. INTRODUCTION

The current status of KrF excimer laser lithography indicates that the laser[1], the illumination system[2], the projection lens[2], and photoresist[3] have already reached the practical application level. When exposure wavelengths are shorter in order to obtain higher resolution, reflection from the interface between the photoresist and substrate are seen to be stronger as shown in Table 1. As a result, thin film interference effects in photoresists are the most serious issues for device production with deep UV lithography[4]. These effects change the fraction of the energy available for photoresist absorption and subsequently causes serious line width fluctuation. Thus, accurate line width control requires the reduction of these effects. Although some methods has been proposed to reduce these effects such as using a broad band exposure system[5], enhancement of optical contrast[6], adoption of high absorption but low resolution photoresists[7], using high performance anti-reflective layers[8,9,10], the most realistic candidate from the point of view of device mass production with actual deep UV lithography is the development of high performance anti-reflective layers. High performance anti-reflective layers for transparent and high resolution photoresists in deep UV region, which can absolutely reduce thin film interference effects in photoresists and be easily matched with actual device processes, have not yet been developed.

This paper describes a newly developed high performance ARL for KrF excimer laser lithography. With this new ARL, the above issues can be solved, and simultaneously KrF excimer laser lithography will become a practical mass production tool for beyond 256MDRAM or 64MSRAM class devices.

2. NEW ARL DESIGN

In this section, we describe our theoretical method for anti-reflective layer (ARL) optimization[11]. In particular, complete ARL's optical conditions for tungsten silicide (W-Si) and aluminum silicon (Al-Si) substrates, which minimize the energy absorption fluctuation in photoresists for photoresist thickness

variations, are investigated using a multi thin films interference simulator. Then, we propose new and practical ARL materials, which are types of hydro silicon oxynitride films (SiOxNy:H), for W-Si and even for Al-Si substrates. Expected performance with optimized SiOxNy:H films as an ARL are described.

2.1. Design concept

Considering current photoresist performance, photoresist absorption fluctuation tolerance is required to be $\pm 3\%$ or less for $\pm 5\%$ line width control at K1 level of 0.6 as shown in Table 2. Therefore, a high performance ARL is needed to satisfy this tolerance level for any highly reflective substrates. In the design of an ARL, the following basic concepts must be taken into consideration.

1. For 3 layers structures (photoresist/ARL/high reflective substrate), the optimized ARL cancel both reflective light from the interface between the photoresist and the ARL and from the interface between the ARL and the substrate in optical amplitude and phase as shown in Figure 1 (a).
2. For 4 layers structures (photoresist/clear inorganic film such as SiO_2 /ARL/high reflective substrate), the optimized ARL cancel reflective light from the interface between the photoresist and the clear inorganic film, and from the interface between the clear inorganic film and the ARL, and from the interface between the ARL and the substrate in optical amplitude and phase as shown in Figure 1 (b).
3. As a result, photoresist absorption are expected minimum values for any photoresist thicknesses with complete ARL, because effective light for chemical reaction in photoresist are only incident light.
4. Accordingly, the optimal optical conditions for the ARL, refractive index n (real part), k (imaginary part), and thickness d , are defined as those values that cause minimal energy absorption in photoresist for any photoresist thickness.

To consider the above concept, the following methodology was adopted for finding the optimal optical conditions for an ARL.

1. For a given photoresist and ARL thickness, calculate the energy absorption in the photoresist as a function of the continuously varying values of the complex refractive index of the ARL
2. Change the values of the photoresist thickness and perform part 1 again
3. Compare plots of equi energy absorption contours for the various photoresist thicknesses, and obtain common regions or closest points where the difference in energy absorption are low.
4. Carry out parts 1 to 3 for other ARL thicknesses.
5. Determine the optimal refractive indices n and k for various ARL thicknesses d .

This method gives one direction for optimizing an ARL for some target substrate. Using this method, for any given substrates and ARL thicknesses, the optimal optical conditions as an ARL for a target substrate can be determined. Moreover, even if exposure wavelengths are changed, the optimization method does not change. For this case, the values of refractive indices of the substrates, photoresist, and various films need only be determined and the calculations once again performed with these new parameters.

As an application of this method, optimal optical constants as a complete ARL for both W-Si and Al-Si substrates were optimized. Imaging on W-Si substrates require high quality imaging, because gate pattern using W-Si materials are most important for device electronic characterizations. Additionally, imaging on Al-Si substrates are difficult due to strong reflection with light diffusion and by high steps. For the calculation, refractive indices of W-Si, Al-Si substrates, and Wako WKR-PT1 chemically amplified positive photoresist at 248nm were measured using a spectroscopic ellipsometer as shown in Table 3. Figure 2, 3 shows the optimal ARL optical conditions for W-Si and Al-Si substrates respectively. Therefore, materials, which are on optimal optical constants curves in Figure 2, 3 are appropriate materials as a high performance ARL for W-Si and Al-Si substrates.

2.2. Establishment of new ARL material.

New and practical materials for optical lithography were established. SiOxNy:H films are an appropriate material as an ARL for W-Si and Al-Si substrates in KrF excimer laser lithography.

Figure 4 shows refractive indices of the SiOxNy:H film dependence on plasma enhanced CVD conditions. Parallel-plate plasma enhanced CVD system with SiH₄ and N₂O gas are used. At the 248nm, the real part of the refractive indices (n) are constant values of about 2.1 for deposition conditions. On the other hand, the imaginary part of the refractive indices (k) were strongly affected by flow ratio of SiH₄ gas. These refractive indices characteristics are convenient for using as an ARL. Because n values are independent of plasma enhanced CVD conditions, optimal thickness d for n values can be automatically defined from Figure 2, 3 for W-Si and Al-Si substrates respectively. Furthermore, optimal k value for optimal thickness d which satisfy n values also can be defined from Figure 2, 3 for W-Si and Al-Si substrates respectively. With the above procedure, optimal optical condition as an ARL for W-Si covered with 170nm of SiO₂ film and Al-Si substrate can be obtained. n=2.12, k=0.54, d=29nm, and n=2.09, k=0.87, d=24nm were adopted as a practical optimal ARL conditions for W-Si and Al-Si substrates respectively.

Figure 5 shows calculated photoresist absorption with and without SiOxNy:H films for W-Si in (a) and Al-Si in (b) substrates respectively. Without ARL, photoresist absorption variations caused by thin film interference effects in photoresists are about $\pm 21\%$ and $\pm 46\%$ for W-Si and Al-Si substrates respectively. On the other hand, using these SiOxNy:H film with 30nm and 25nm thickness for W-Si and Al-Si substrates respectively, that variations are drastically reduced within only $\pm 1\%$ for each substrate. Therefore, SiOxNy:H film are appropriate materials as a high performance ARL for W-Si and even for Al-Si substrates.

3. EVALUATION OF SiOxNy:H FILM

In this section, we describe evaluation results for the optimized SiOxNy:H film as an ARL for W-Si and Al-Si substrates using KrF excimer laser stepper Canon FPA-3000EX1 (NA=0.45, 28.2mm diameter lens) equipped Cymer ELS-4000 series laser and Wako WKR-PT1 chemically amplified positive photoresist.

3.1. ARL performance on W-Si substrate

The optimal optical condition for a W-Si substrate covered with a 170nm SiO₂ film were n=2.12, k=0.54, with d=29nm. This optical condition can be obtained with a SiH₄/N₂O flow ratio of 1.14 in the deposition chamber. Figure 6 shows the actual SiOxNy:H film performance as an ARL for a flat W-Si substrate covered with 170nm SiO₂ film. The figure shows photoresist thickness versus critical dimension for a nominal 0.35 μ m line and space in (a), 0.30 μ m line and space in (b) with and without the SiOxNy:H film. In the figure, black circles indicate without SiOxNy:H film, and black squares indicate with SiOxNy:H film. With the SiOxNy:H film, critical dimension variations were reduced negligibly, as shown in Table 4.

Figure 7 shows line width uniformity on wafer for with and without the SiOxNy:H films. The figure shows measured pattern positions versus critical dimensions for a nominal 0.35 μ m line and space in (a), (b), and 0.30 μ m line and space in (c), (d) with 0.84 μ m photoresist thickness. The tested wafer has a 8.9nm SiO₂ thickness variation range. The distribution of SiO₂ film thicknesses indicates they are most thin in the wafer center, and most thick near the wafer orientation flat. Without the SiOxNy:H film, critical dimension varied by 0.064 μ m for 0.35 μ m line and space pattern, and 0.078 μ m for 0.30 μ m line and space pattern for a 8.9nm SiO₂ thickness variation. Because thickness variations of SiO₂ films cause optical phase changes, the available energy for photoresist absorption subsequently fluctuated. Even for these substrates, critical dimension variations can be reduced to within 0.02 μ m for both geometries with the SiOxNy:H film, because optical constants of the SiOxNy:H films were tuned for canceling reflective light from the interface between the photoresist and SiO₂ film, from the interface between SiO₂ film and the SiOxNy:H film, and from the interface between SiOxNy:H and substrate in optical amplitude and phase.

Figure 8 shows ARL performance for actual 0.35 μ m rule 16MSRAM gate patterns with and without the SiOxNy:H film. This gate structure, which has a 200nm LOCOS step, was used 170nm offset SiO₂ film over gate material (W-Si). With the SiOxNy:H films, gate patterns can be resolved without halation or scum. Figure 9 shows uniformity of gate pattern on wafer. Highly uniform images can be obtained with the SiOxNy:H films. Figure 10 shows the cross section of a gate pattern profile after SiO₂, SiOxNy:H, W-Si, and Poly-Si etching. Etching conditions for the SiOxNy:H film are the same as that of SiO₂ film as

shown in Table 5. Favorable images can be obtained without stringers by SiOxNy:H film etching. Critical dimension changes caused by etching were within $0.02\mu\text{m}$ as shown in Table 6. Therefore, with SiOxNy:H film as an ARL for W-Si substrate, a $\pm 8\%$ geometry control can be achieved all over the wafer even for actual device structure including step and SiO₂ thickness variations.

3.2. ARL performance on Al-Si substrates

This SiOxNy:H film also can be applied to Al-Si substrates by controlling deposition conditions. The optimal optical constants for Al-Si substrates were $n=2.09$, $k=0.87$, with $d=24\text{nm}$. This condition can be obtained with a SiH₄/N₂O flow ratio of 1.85 in the deposition chamber.

Figure 11 shows the imaging result on a grainy Al-Si substrate for $0.35\mu\text{m}$ line and space pattern with and without the SiOxNy:H film. Without the SiOxNy:H film, a usable image can not be obtained due to both the substrate's high reflectivity and graininess which causes strong light diffusion. Even for these substrates, high quality images can be obtained with the SiOxNy:H film.

Figure 12 shows ARL performance for critical dimension variations caused by thin film interference effects in photoresists. The figure shows photoresist thicknesses versus critical dimension for nominal $0.35\mu\text{m}$ line and space pattern in (a) and $0.30\mu\text{m}$ line and space pattern in (b) with the SiOxNy:H film. With the SiOxNy:H film, even for $0.30\mu\text{m}$ geometries on grainy Al-Si substrates, critical dimension variations were negligible.

Figure 13 shows SiOxNy:H film performance as an ARL for grainy Al-Si substrate with 1100nm step. Without halation or scum, a $0.40\mu\text{m}$ line and space pattern can be acceptably resolved using the SiOxNy:H film. These results indicate that SiOxNy:H film as an ARL for Al-Si substrate can become a promising candidate for 256MDRAM or 64MSRAM device processes which require under $0.40\mu\text{m}$ metallization technology in mass production with KrF excimer laser lithography.

3.3. SiOxNy:H film deposition tolerances

To apply this new ARL to mass production level, besides performance of reduction effects for thin film interference effects in photoresists, performance of step coverage and uniformity of optical constants and film thickness should be satisfied. This SiOxNy:H films can be deposited with topographically conformal using a plasma enhanced CVD system. Furthermore, this SiOxNy:H film has wide margin for uniformity of optical constants and film thicknesses which depend on deposition stability.

Figure 14 shows SiOxNy:H film performance over steps. In this figure, step height is $1\mu\text{m}$. Even for steep and high step substrates, this SiOxNy:H film can be deposited with topographically conformal.

Table 7 shows SiOxNy:H film uniformity in terms of optical constants and thickness. Variations of optical constants n and k in wafer are within 0.02 and 0.16 respectively. Thickness variations on wafer are within 2.1nm. For these variations, photoresist absorption fluctuations calculated by thin film interference simulator were within $\pm 3\%$. This $\pm 3\%$ photoresist absorption fluctuation satisfied the tolerance level mentioned in section 2.1.

4. RESOLUTION ENHANCEMENT EFFECT

In this section, we report practical resolution enhancement effect by reduction of thin film interference effects in photoresists. Then, we investigate limitation of KrF excimer laser lithography in ideal substrate conditions from the point of view of optimal projection lens NA for various feature sizes.

Other advantage with optimized ARL are depth of focus enhancement effect. Figure 15 shows results of depth of focus with and without optimized ARL for W-Si substrates. The figure shows depth of focus versus feature size. Depth of focus was defined as a $\pm 10\%$ variations in critical dimension for each geometry. With optimized ARL, depth of focus was increased 23% for $0.35\mu\text{m}$ line and space pattern. This effects indicate that degradation of inhibitor concentration in photoresist caused by reflective light from substrate, especially in defocus region, was decreased with optimized ARL. Thus, the practical resolution is enhanced by the increased depth of focus.

Figure 16 shows optimal projection lens NA for various feature sizes for ideal substrates conditions. From the figure, maximum depth of focus for $0.35\mu\text{m}$, $0.30\mu\text{m}$, and $0.25\mu\text{m}$ geometries were $1.91\mu\text{m}$, $1.40\mu\text{m}$, and $0.97\mu\text{m}$ with 0.45, 0.50, and 0.60 projection lens NA respectively.

Figure 17 shows required resolution from device fabrication versus maximum depth of focus with the optimal projection lens NA. Accordingly, assuming that required depth of focus in mass production is 1.0 μ m, 1.25 μ m, 1.5 μ m without phase shift or oblique illumination technology, the limitation of KrF excimer laser lithography for ideal substrates is 0.26 μ m, 0.29 μ m, 0.31 μ m with 0.59, 0.53, 0.48 projection lens NA respectively as shown in Table 8.

5. CONCLUSION

To control thin films interference effects in photoresists effectively, we developed hydro silicon oxy nitride film (SiOxNy:H) as a high performance ARL for KrF excimer laser lithography with our original optimization methodology. Even if high transparent photoresists were used for imaging 0.30 μ m level geometries on W-Si and even for Al-Si substrates, the high performance ARL shown here can absolutely reduce both thin film interference effects in photoresists and notching effects by halation, and be easily matched to actual device processes. Furthermore, optimized ARL can enhance the practical resolution, because reflected light from substrate causing degradation of inhibitor concentration in photoresist can be decreased. With the SiOxNy:H film, depth of focus is increased more than 23% for 0.35 μ m line and space patterns. Assuming that required depth of focus in mass production is 1.0 μ m, 1.25 μ m, 1.5 μ m without phase shift or oblique illumination technology, the limitation of KrF excimer laser lithography for ideal substrates is 0.26 μ m, 0.29 μ m, 0.31 μ m with 0.59, 0.53, 0.48 projection lens NA respectively. Therefore, we confirm that, by using SiOxNy:H film as a high performance ARL, excimer laser lithography will become a practical mass production tool for 256MDRAM or 64MSRAM level devices which required less than 0.30 μ m level fabrication.

6. ACKNOWLEDGEMENTS

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7. REFERENCES

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Table 1. Reflectance at the interface between photoresist and substrates.

Substrates	Reflectance		
	@248nm	@365nm	@436nm
Si	53%	41%	24%
W-Si	35%	31%	31%
Al-Si	92%	91%	90%
Poly-Si	47%	36%	31%

Table 2. Tolerance of variation in photoresist absorption for feature size.

Resolution (K1 unit*)	0.847	0.677	0.593
CD Specifi- cation (%)	± 5.0	± 5.0	± 5.0
Resist Absorption Tolerance (%)	± 6.5	± 4	± 3

* Resolution= $k_1\lambda/NA$

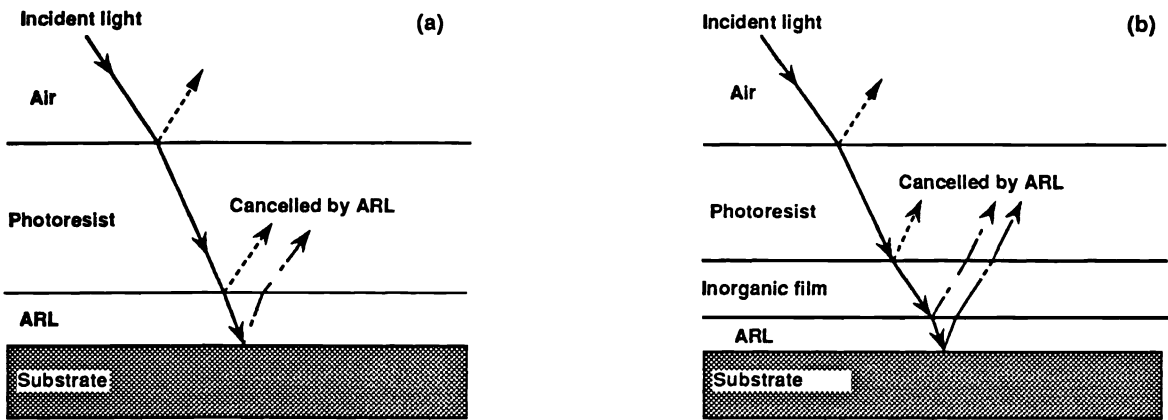


Figure 1. Schematic illustration of anti-reflective mechanism for 3 layer structure (Photoresist/ARL/Substrate) in (a), and 4 layer structure (Photoresist/Inorganic film/ARL/Substrate) in (b).

Table 3. Refractive indices of photoresist, SiO2, W-Si, Al-Si at 248nm.

Materials	Photoresist	SiO2 film	W-Si	Al-Si
Real part of refractive index (n)	1.801	1.518	1.930	0.089
Imaginary part of refractive index (k)	0.011	0.000	2.730	2.354

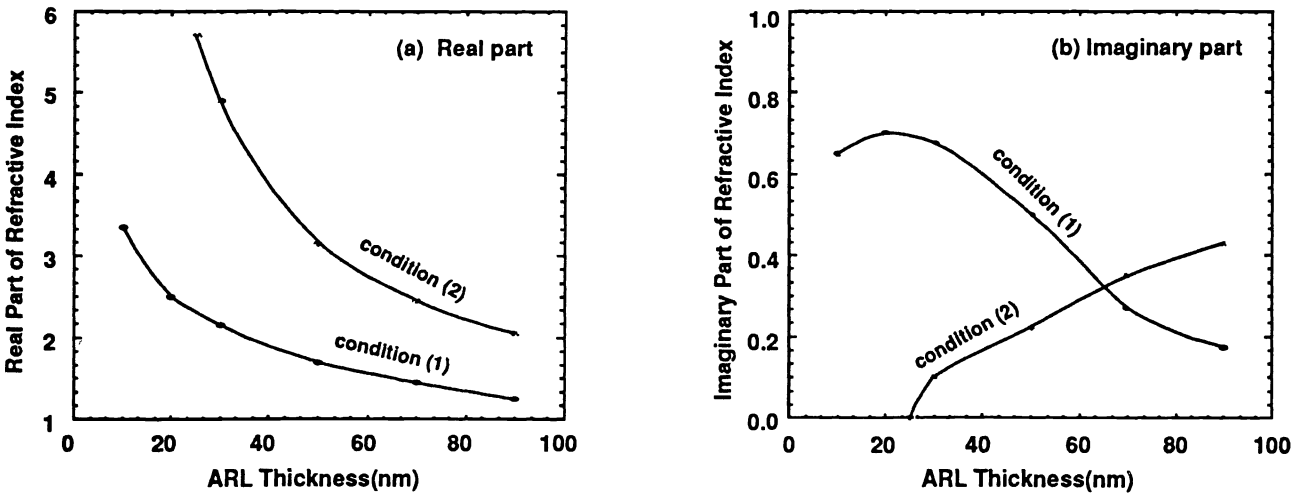


Figure 2. Optimal refractive indices versus ARL thicknesses for W-Si substrate, real part in (a), and imaginary part in (b).

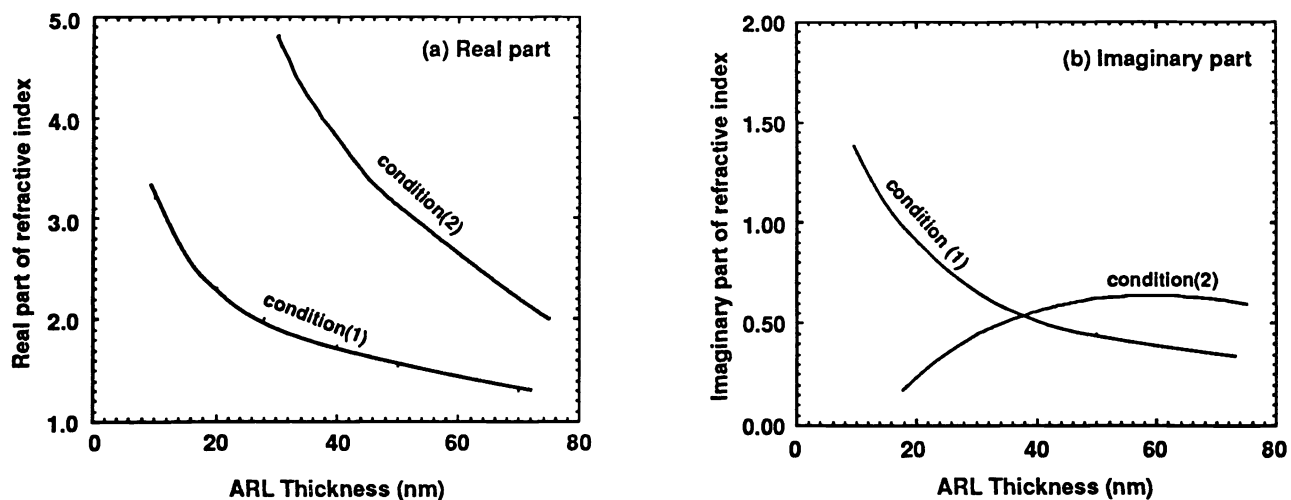


Figure 3. Optimal refractive indices versus ARL thicknesses for Al-Si substrate, real part in (a), and imaginary part in (b).

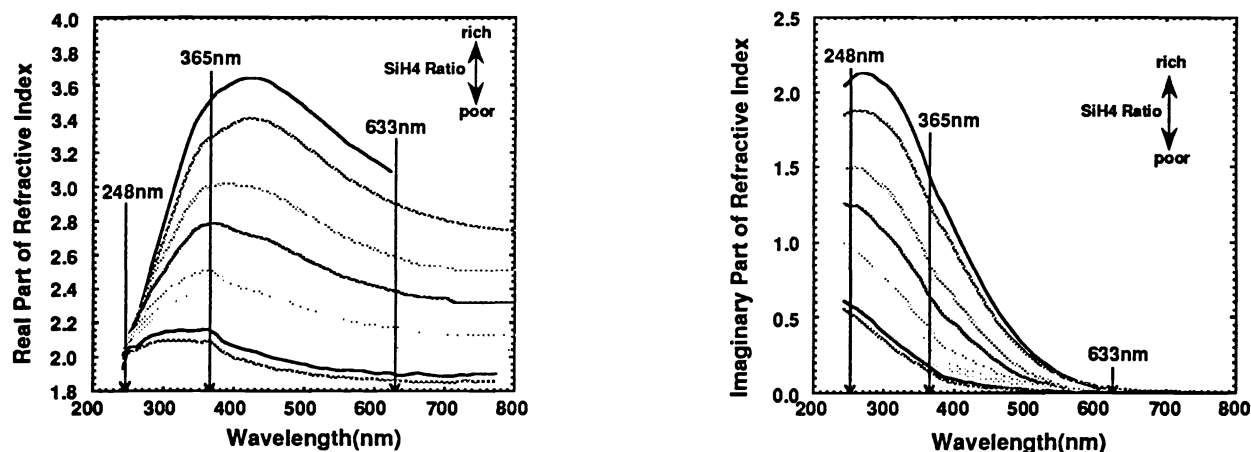


Figure 4. Optical characterization of SiO_xN_y:H film versus deposition conditions

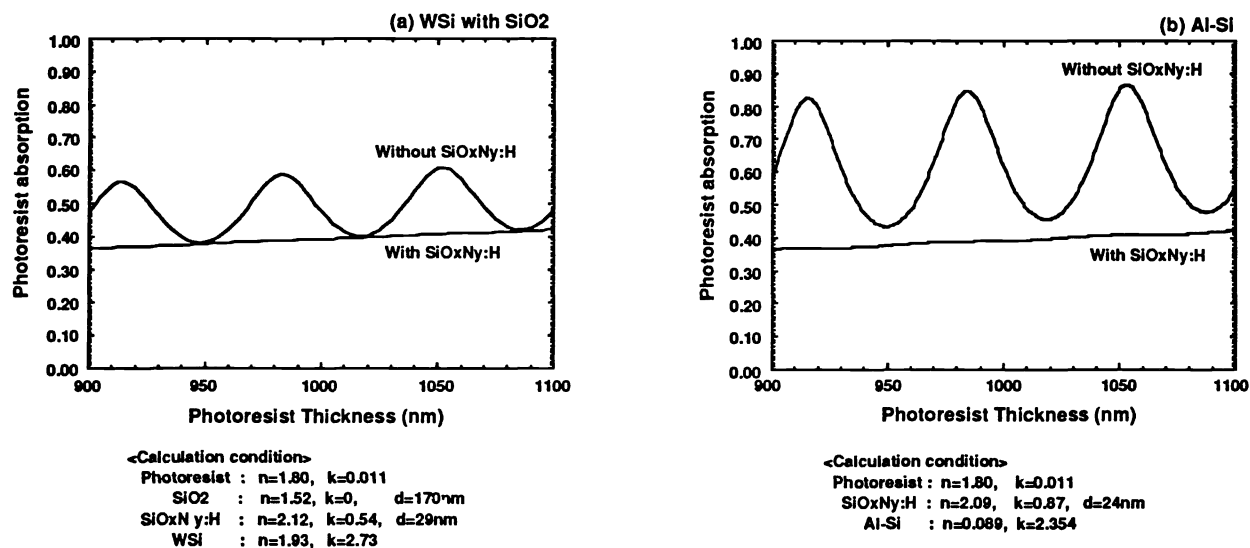


Figure 5. Expected performance of SiO_xN_y:H film as an ARL for W-Si substrate in (a), and for Al-Si substrate in (b).

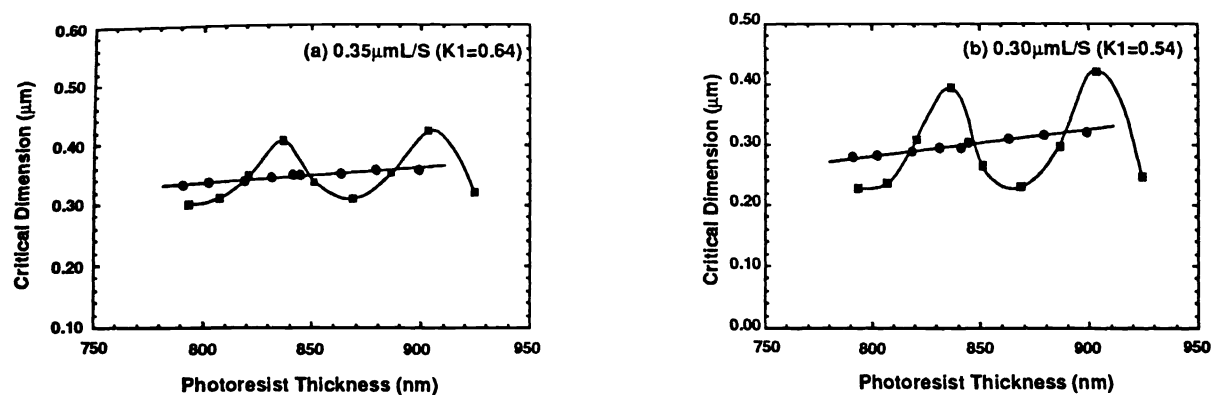


Figure 6. Photoresist thickness versus critical dimension for with and without SiOxNy:H film, 0.35 μ mL/S in (a), 0.30 μ mL/S in (b). In these figures, black circles indicate with 29nm SiOxNy:H film condition, and black squares indicate without SiOxNy:H film condition.

Table 4. SiOxNy:H performance as an ARL for W-Si substrate.

Geometry (K1 value)	CD variations caused by thin film Interference effects	
	Without SiOxNy:H film (1)	With SiOxNy:H film
0.35 μ mL/S (K1=0.64)	0.120 μ m	Only bulk effects
0.30 μ mL/S (K1=0.54)	0.195 μ m	Only bulk effects

(1) peak to valley values

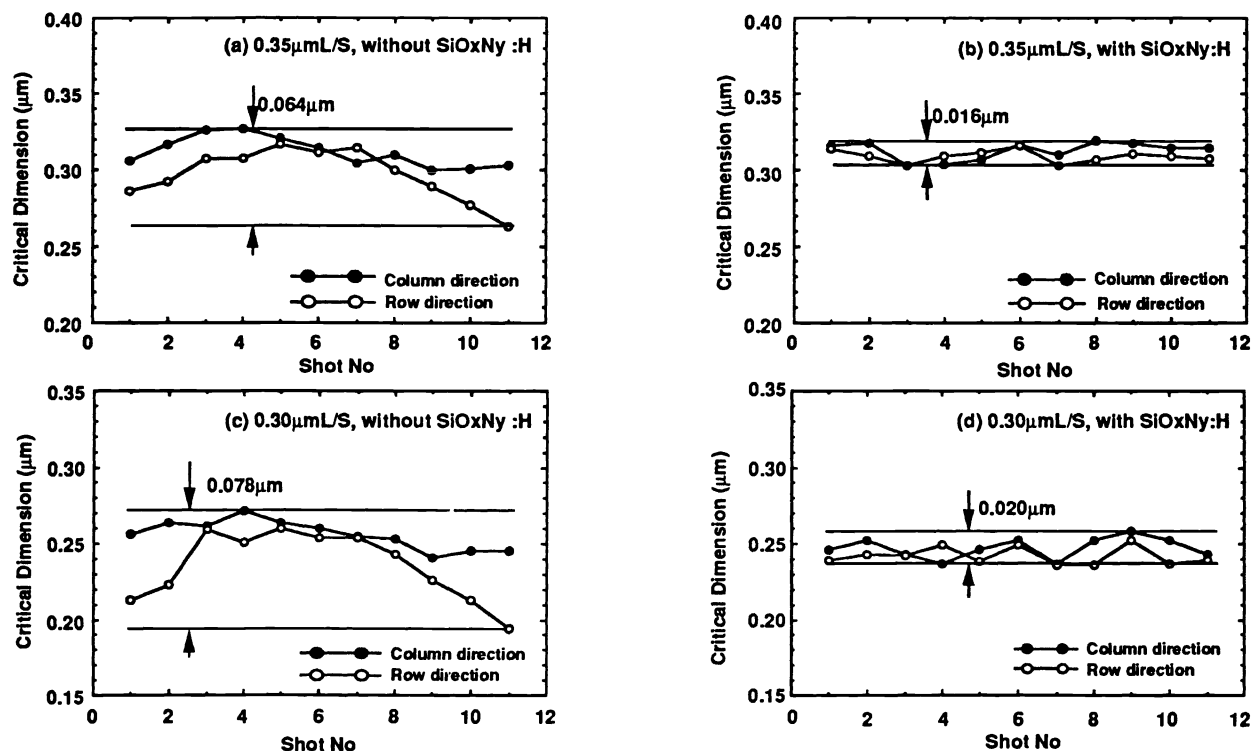
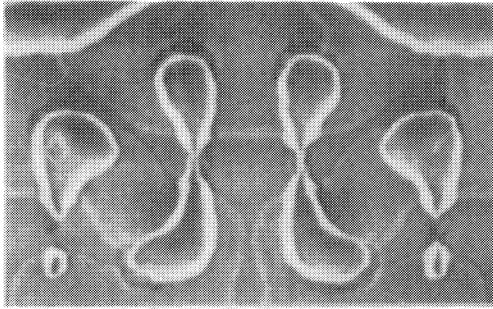
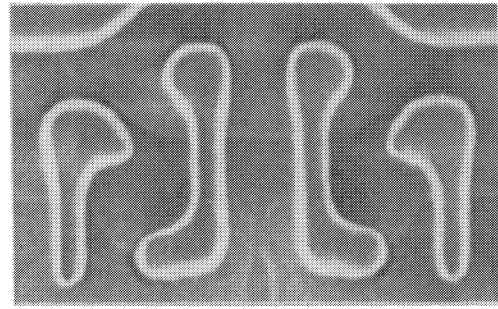


Figure 7. CD variations in wafer caused by SiO₂ thickness uniformity with and without SiOxNy:H film, 0.35 μ mL/S in (a), (b), 0.30 μ mL/S in (c), (d).

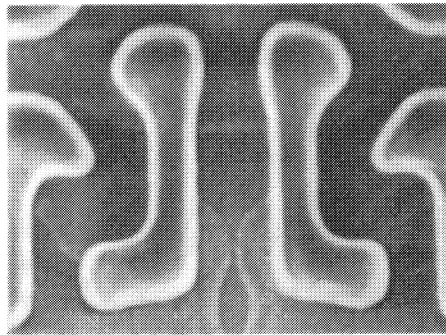


without SiOxNy:H

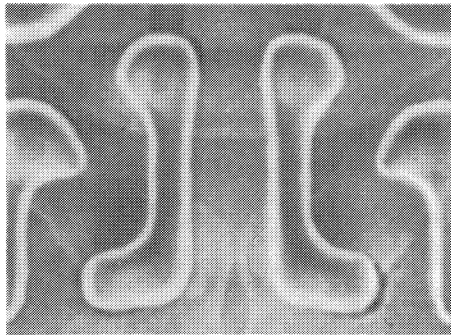


with SiOxNy:H

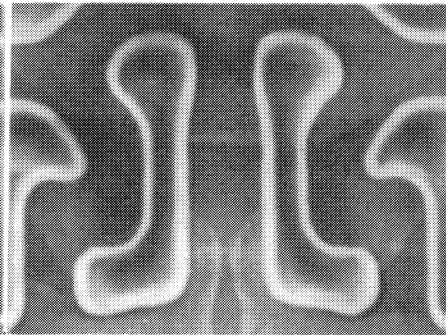
Figure 8. SiOxNy:H film performance for 0.35μm rule 16MSRAM gate patterns, without SiOxNy:H film in (a), with SiOxNy:H film in(b).



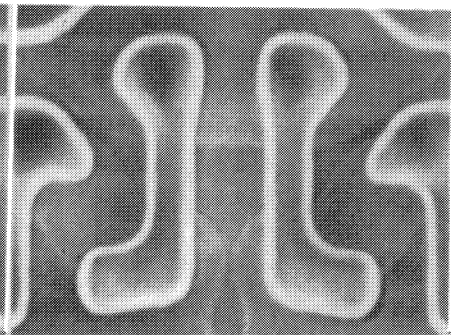
Upper



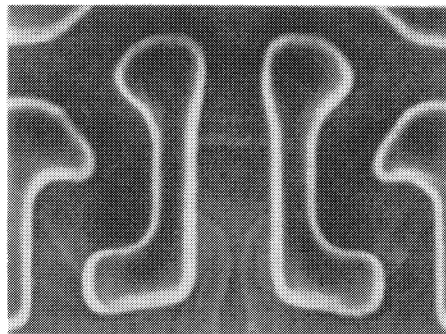
Left



Center



Right



Lower

Figure 9. SiOxNy:H film performance for imaging uniformity on wafer.

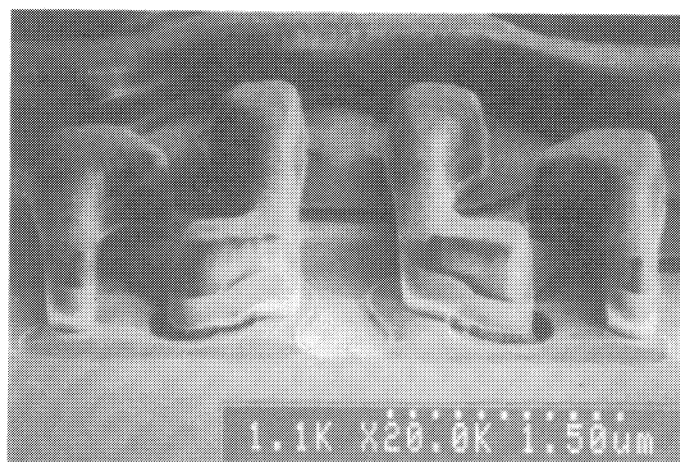


Figure 10. Image quality after SiO₂, SiO_xNy:H, W-Si, and Poly-Si etching.

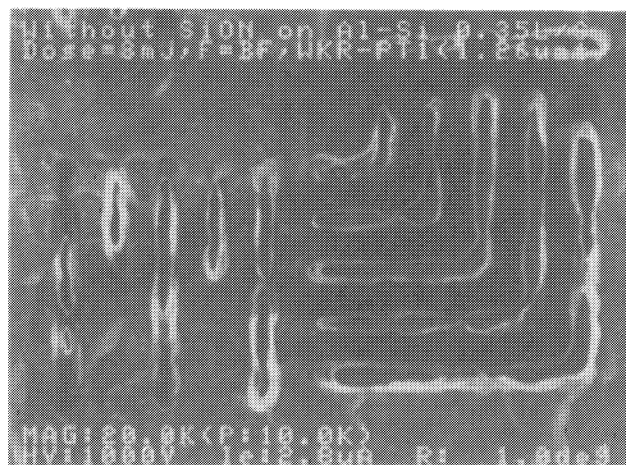
Table 5. Etching conditions for image transfer.

	SiO ₂ , SiO _x Ny:H	W-Si, Poly-Si
System	RIE	ECR
Gas	CHF ₃ /O ₂	Cl ₂ /O ₂
Pressure	0.67Pa	0.40Pa
Microwave		850W
RF	1150W	40W
Temperature	Room temperature	30deg

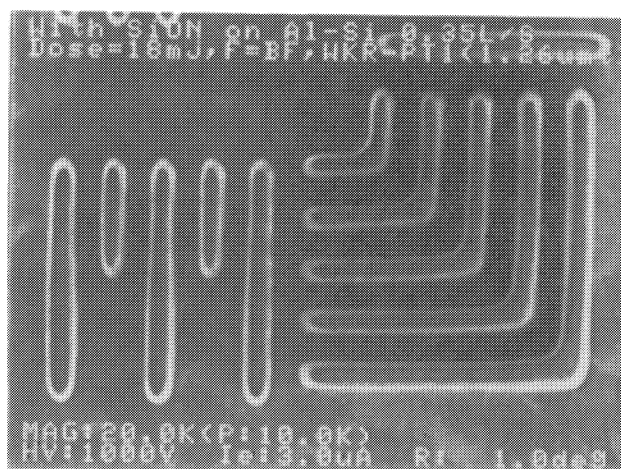
Table 6. CD uniformity in wafer after imaging and etching.

	After imaging	After etching		CD changes
		SiO ₂ and SiO _x Ny:H	W-Si and Poly-Si	
Mean CD (n=21 points)	0.374	0.358	0.355	-0.019
3sigma	0.037	0.054	0.056	

(unit : μm)



Without SiO_xNy:H film



With SiO_xNy:H film

Figure 11. 0.35 μm imaging results on grainy Al-Si substrate with and without SiO_xNy:H film.

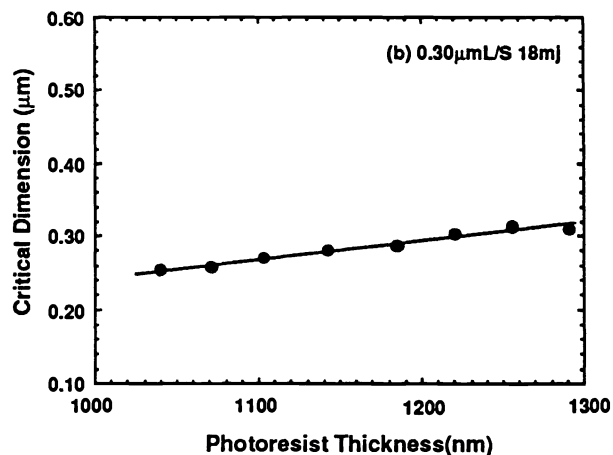
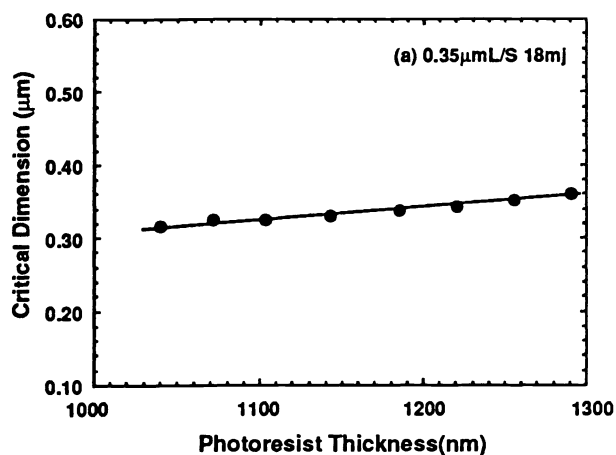


Figure 12. Photoresist thickness versus critical dimension with SiOxNy:H film as an ARL for Al-Si substrate, 0.35μmL/S in(a), 0.30μmL/S in(b).

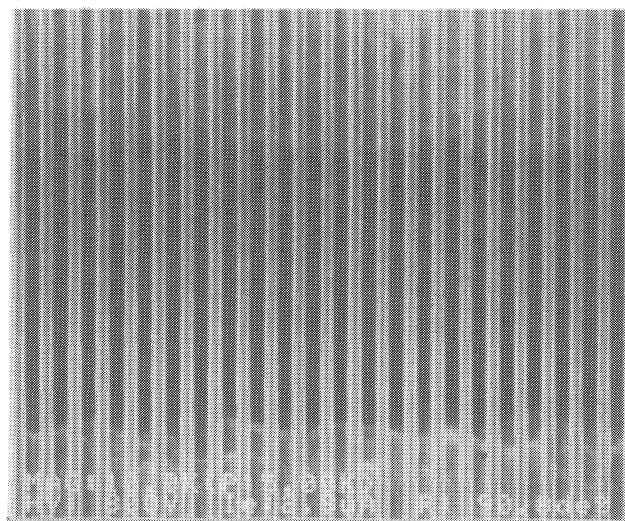


Figure 13. SiOxNy:H film performance as an ARL for 0.40μm imaging on 1.1μm step grainy Al-Si substrate

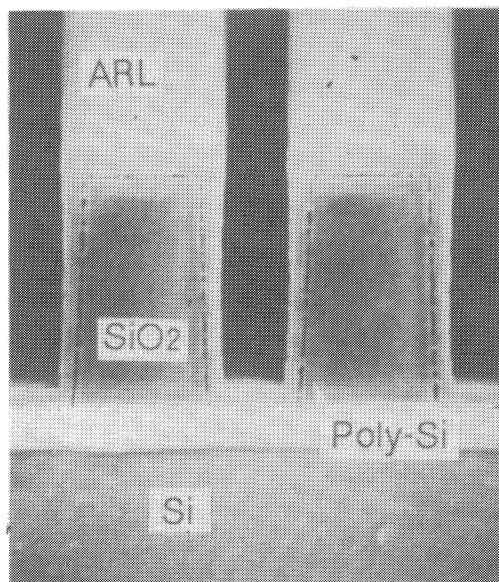


Figure 14. Step coverage of SiOxNy:H film on steep and high step substrate.

Table 7. Variation of SiOxNy:H film uniformity in wafer for ARL performance.

	measurement position in wafer				
	Center	Right	Left	Upper	Lower
Real part n	2.12	2.13	2.14	2.13	2.13
Imaginary part k	0.54	0.68	0.70	0.66	0.66
Thickness d (nm)	29.0	30.4	30.2	30.9	31.1
Swing ratio of photoresist absorption (%)	±0.36	±2.95	±3.06	±2.77	±2.95

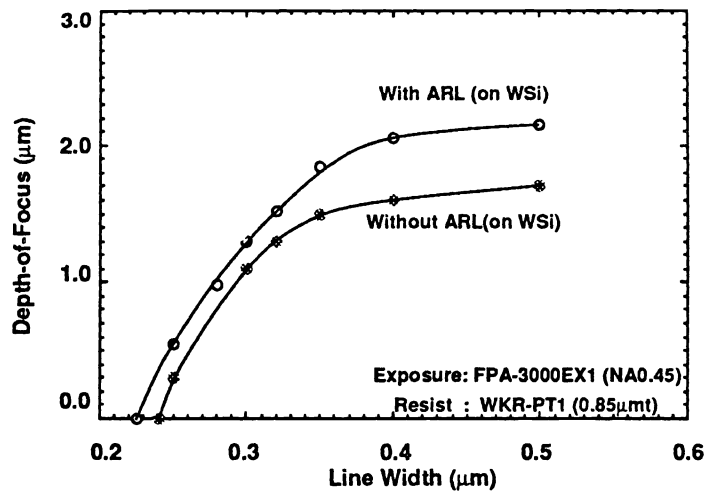


Figure 15. Line width versus depth of focus for with and without ARL.

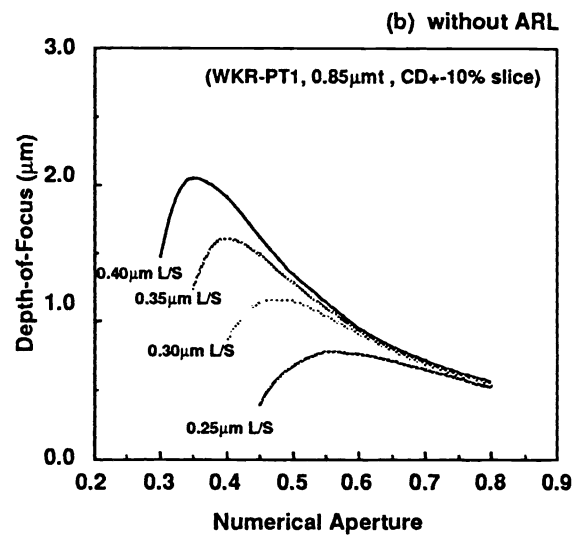
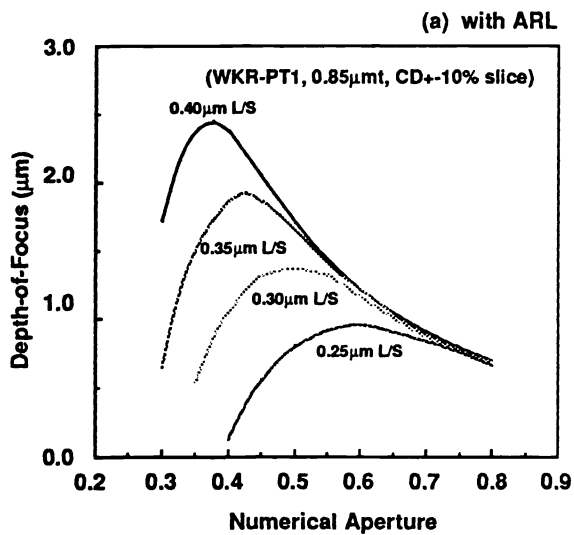


Figure 16. Optimal projection lens NA with (a) and without (b) anti-reflective layer.

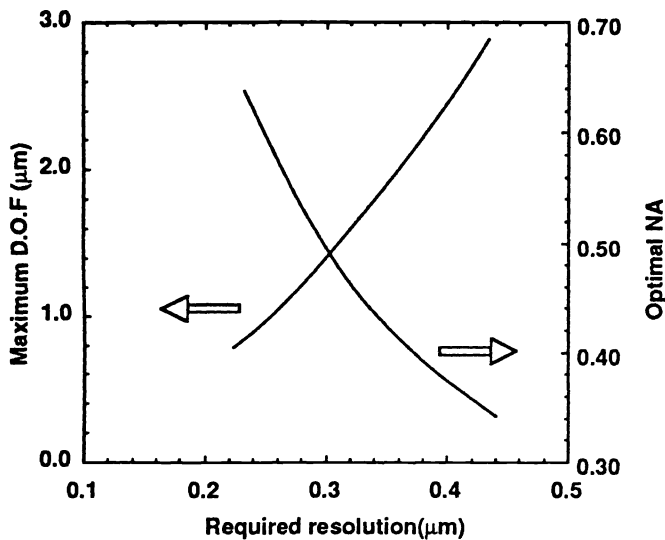


Figure 17. Maximum depth of focus with optimal projection lens NA.

Table 8. Limitation of KrF excimer laser lithography with ideal substrates.

Required D.O.F	Resolution	optimal NA
0.75	0.22	0.72
1.00	0.26	0.59
1.25	0.29	0.53
1.50	0.31	0.48



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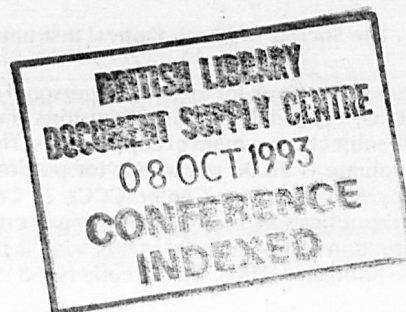
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