Lithographic Effects of Metal Reflectivity Variations

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ABSTRACT

This paper examines the effects of specular and diffuse reflectivities, both empirically and theoretically, on the imaging process for highly reflective substrates. Aluminum (Al) and Titanium Nitride (TiN) wafers were used extensively in this study. TiN wafers were prepared with varying specular reflectivities and virtually no diffuse reflectivity. Dose to clear on TiN wafers was found to increase linearly with specular reflectivity in the absence of any diffuse component. Aluminum wafers were prepared with high specular reflectivity and varying diffuse reflectivities. On these Al wafers, the increase in diffuse reflectivity decreased the dose to clear in a nonlinear fashion. A theoretical explanation for the observed phenomenon is presented based on the interaction of thin film interference effects with diffuse scattering. Modelling results based on this theory are shown to be in good agreement with the experimentally observed data. Based on these results, a method for the generation of specification limits for the allowable variations in specular and diffuse reflectivities are also presented. Also discussed are the tools and methods used for measuring substrate reflectivity to obtain these specification limits.

1. INTRODUCTION

The effects of substrate reflectivity on photoresist range from reflective notching of the patterned image, to critical dimension (CD) control issues where reflectivity changes may cause a shift in the absolute energy required to hit CDs. These effects on large features are relatively small, when compared to the associated large CD tolerances, and have not required close control of substrate reflectivity. But the effects can not be ignored on small geometries and have resulted in the use of anti-reflective coatings on highly reflective substrate levels such as metal. Even though anti-reflective coatings on metal, such as TiN, offer a substantial reduction in substrate reflectivity, the effects of reflectivity on CDs are still seen.

Substrate reflectivity can be divided into two components, namely, specular and diffused. Specular reflectivity is the light reflected from a flat or polished surface (for example, a mirror). Diffuse reflectivity, on the other hand, is the scattering of light encountered from an uneven surface (for example, a grainy metallic film). Both specular and diffuse reflectivities play a part in the lithographic process and are most pronounced when using high reflectivity films such as metals (TiN, Al, etc.). It is not only important to understand the impact of substrate reflectivity on the resist image but to develop methods to measure and track reflectivity. In this paper the effects of both specular and diffuse reflectivity on an imaged resist feature are studied. The methods and tools used in this study are presented along with a theoretical explanation for the observed results. Also included is a method to generate specification limits for the allowable variations in reflectivity needed for fab line control.

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2. EXPERIMENTAL

2.1 Wafer preparation

Al wafers were prepared on the Varian 3290 sputter deposition tool. The deposition conditions were varied so the wafers would have an expected range of specular reflectivity. The TiN wafers were deposited in a multi - chamber single wafer deposition system. The flow rates were adjusted to vary the film stoichiometry for an expected range of diffuse reflectivity. The processing parameters for the 75 wafers used in this study were obtained through experimental designs.

2.2 Reflectivity measurements

Reflectivity data was taken using three different reflectivity tools, the Varian Cary 2200, the Nanometrics 216S, and the Censor ANS-100. The Varian tool is capable of measuring both specular and diffuse light independently for a range of user chosen wavelengths. This tool uses a specific density of barium sulfate powder as a calibration standard. Wafers are manually loaded with the wafer surface directly contacting the mounting stage and individual readings are taken near the wafer center. A quick hardware reconfiguration is required when switching from the specular to diffuse light measuring modes. The Nanometrics 216S is a film thickness and reflectivity measuring tool. Measurements are taken using either three user chosen wavelengths or using the scanning mode for the set wavelengths of 200 to 800nm. The Censor ANS-100 is a surface defect inspection tool that uses light scattering of a laser light source to characterize the wafer surface. On this tool, surface roughness is measured as "Haze" which is essentially the diffuse reflected light from the wafer. Both the Nanometrics 216S and the Censor ANS-100 are completely automated tools made for use in the semiconductor manufacturing environment. Both tools also are capable of reading multiple sites for full wafer characterizations. For this experiment a bare silicon wafer was used as a reference for the 216S and the ANS-100.

Measurements were taken on all 75 wafers using both the specular and diffuse modes on the Varian. Total reflectivity for most of these wafers was measured on the Nanometrics tool, and a smaller set was measured on the Censor tool for diffuse reflectivity values. For the Varian and the Nanometrics the light wavelength was targeted at 365nm with an argon laser light source being used for the Censor. The data was recorded for each tool in units relative to the calibration standard used for that tool.

2.3 Lithography testing

Three well known commercially available i-line resists (A, B, and C) were used for wafer imaging using the supplier recommended process for each resist. These three resists were being used to support the SEMATECH facility and their three respective processes were fully characterized and stable. Resist-coated wafers were exposed on a GCA .48NA i-line stepper. A focus/exposure matrix of 0.70μm grouped features as well as an open frame exposure matrix were imaged on the wafers before developing. The energy-to-clear values (E0) for each wafer were read and recorded as the exposure time needed to completely remove all the resist from the exposed area. The 0.70μm grouped features were used to determine the dose to size. This test was repeated for the three resists on the same wafer set, exposing a separate area of each wafer when a new resist was processed. This procedure avoided patterning over areas where the metal may have developer induced micro-etching that could change the substrate reflectivity. Resist A was processed twice, omitting the post-exposure bake portion of the process for the second processing run.

2.4 Modeling tools

PROLITH/2v2.2 (FINLE Technologies) was used to simulate the effects of specular reflectivity variations on the dose to clear for resists processed with and without a post-exposure bake. The resist used for this simulation was a typical positive resist with generic properties. The goal of these simulations was to verify the observed trends, and no attempt was made to match the resist being simulated with the resist used in the experiment. The parameters used for these simulations are listed in Table I. To generate E0 versus reflectivity plots, a film stack was created with a reflectivity which was extremely sensitive to film thickness, Since a polysilicon on oxide on silicon stack is very sensitive to poly thickness variations at g-line, variations on the polysilicon thickness of 30 to 50nm changed the reflectivity from 70% to 5%. Since PROLITH/2 allows easy simulation of dose-to-clear as a function of polysilicon thickness, a plot of dose to clear versus film stack reflectivity can be obtained.

3. RESULTS

3.1 Reflectivity versus wafer preparation conditions

A wide range of reflectivites were observed on the metal wafers. An example data set, showing 34 of the 75 wafers tested, is summarized in Table II for each measurement tool. As expected, Al wafers showed the highest reflectivity. The Al wafers had a Varian measured range of specular (20% - 95%) and diffuse (0.03% - 46%) reflectivities. For the TiN wafers, the specular reflectivity ranged from 19% to 50% while the diffuse reflectivity was essentially zero (0.03% - 0.14%).

3.2 E0 versus reflectivity

The raw data for the lithographic imaging is also shown in Table II. Since the diffuse reflectivity was essentially zero for the TiN wafers, it was possible to study the isolated effect of specular reflectivity on wafer imaging. Figure 1 shows a plot of E0 versus specular reflectivity for the TiN wafers. To observe the effects of diffuse reflectivity, wafers with a consistent specular and varying diffuse reflectivity were studied. In Figure 2, E0 is plotted versus diffuse reflectivity when the specular reflectivity is greater than 92% (for aluminum wafers measured on the Varian tool).

4. DISCUSSION OF RESULTS

4.1 Imaging versus specular reflectivity

From figure 1, a change in specular reflectivity is shown to have little or no effect on the energy to clear for resists A and C, but for resist B an increase in E0 is seen as specular reflectivity increases. This result may be caused by the photo active compound (PAC) being bound to the resist resin in resist B so it is not free to diffuse during a post exposure bake (PEB) operation. To confirm this, resist A was processed without a PEB limiting PAC diffusion after exposure. In the absence of a PEB, resist A also shows an increase in E0 with an increase in specular reflectivity. Modeling results from PROLITH/2 further confirm this trend. Figure 3 shows a PROLITH/2-generated plot for energy-to-clear versus substrate reflectivity where one sample used a PEB and the other did not. This plot matches the response seen experimentally for resist B, showing an increase in energy required for exposure as reflectivity increases.

Wafers patterned with 0.70µm grouped lines were inspected using an off-line SEM to determine the dose to size. This dose (exposure time) was recorded for each measured sample and is included in Table II. An example of two TiN wafers patterned with resist B is shown in Figure 4 where the diffuse reflectivity is essentially zero. The Varian-measured specular reflectivity on these wafers was 20.2% and 48.3% for a required exposure time of 0.24 and 0.30 seconds respectively. These two wafers show the same trend as seen with the E0 testing where the higher reflectivity requires more exposure energy for imaging.

A proposed reason for the observed reaction to specular reflectivity could be related to standing waves, and the development rate of the resist. An illustration of this is shown in Figure 5 where two standing waves are plotted as development rate versus depth into the resist, and could represent resist B used in this experiment. The standing waves with the large and small amplitudes would be representative of high and low reflectivities respectively. As the resist is developed, the rate of development will change depending on the depth into the resist (position on the standing wave). Even though resist is developed at a fast rate at the maximums of the standing wave, the overall development rate would be controlled by the minimums where the rate is slower. For the plots shown in Figure 5, the standing wave that represents low reflectivity would have an overall faster development rate than the standing wave representing the high reflectivity. This in turn means more exposure energy would be required for the high reflective sample if the develop times were held equal for both samples. The observed difference between resist A processed with and without a PEB may also be explained by using Figure 5. The PAC diffusion, when using a PEB on resist A, may be explained as a "smoothing out" of the standing wave. This could be visualized as the large amplitude standing wave being smoothed out to resemble the small amplitude standing wave.

4.2 Imaging versus diffuse reflectivity

In the case of resist B, the E0 decreases with an increase in the diffuse reflectivity (see Figure 2). A similar relationship is observed for resist A in the absence of a PEB but does not hold true for resist C. The CD measurements for 0.7 micron grouped lines confirmed this trend as shown in Figure 6. This figure shows SEM photos of wafers with essentially equal specular reflectivities but differing diffuse reflectivities. The diffuse reflectivity of these wafers were 41.4% and 0.04% requiring a dose-to-size of 0.18 and 0.26 seconds respectively. An increase in the exposure energy with decreasing diffuse reflectivity is opposite to the reaction seen with specular reflectivity.

The proposed reason for this observed effect is also related to the standing waves and development rate of the resist. Figure 5 could be used to illustrate this effect. As the diffuse reflectivity increases, there is less light left to be reflected in the specular mode. This would cause a general shift of the development rate for the standing wave. This shift would been seen as an up or down movement on the Y axis of Figure 5 depending on the change in diffuse reflectivity. If diffuse reflectivity goes up, these standing waves would shift upward on Figure 5, speeding up the overall development rate. This in turn means less exposure energy would be required for the high reflectivity sample if the develop times were held constant.

4.3 Practical application of the observed trends

With the known effects of reflectivity on resist CD, specification limits for wafer metal reflectivity can be determined. From the E0 data measured on resist B a model was generated in the statistical data analysis software RS/1. The specular reflectivity data and corresponding E0 values from the TiN wafers were used to predict the change in E0 when specular reflectivity is changed. From this model, 95% confidence intervals were generated so that spec limits may be drawn. Figure 7 shows this RS/1-generated model with an example of the spec limits drawn in. The exact spec limits would be chosen by the process engineer and would depend on the CD budget that is allocated for reflectivity variations.

A comparison of the reflectivity measurements were made for the respective measurement tools. Figure 8 shows the correlation between specular reflectivity as measured on the Varian and the total reflectivity measured by the Nanometrics 216S on the same wafers. In this plot, wafers that measured a high diffuse reflectivity on the Varian are separated from those that measured a low diffuse reflectivity. For the wafers where diffuse reflectivity is low there is a good correlation between the Varian specular measurements and the Nanometrics readings. Since the Nanometrics will detect portions of the diffuse light as well as the specular reflections, the correlation is good only for the wafers with the low diffuse reflectivity.

Figure 9 shows the correlation between diffuse reflectivity as measured on the Varian and the haze value measured by the Censor ANS-100 on the same wafers. A general trend is seen between the two tools showing the possibility that the haze value may be used to characterize diffuse reflectivity. These haze values were taken with no attempts to calibrate the Censor to read data for detecting diffuse light. It is likely that a closer correlation could be achieved with calibration work.

5.0 CONCLUSION

This study has shown the profound effect that substrate reflectivity can have on CD control. The effects of specular and diffuse reflectivity are shown to have opposite effects on critical dimension sizing as the two respective reflectivities increase. However this is true only for certain resists, and for resists where no PEB is used. A post exposure bake will substantially reduce these effects on CD by diffusing the photo active compound in the resist, but will have no effect for resists where the PAC is bound and not free to diffuse. Modeling tools are available that can help in understanding the general trends in the relationship between reflectivity and resist imaging. The definite relationship between reflectivity and CD variations found experimentally can be used for setting process controls (spec limits) for a manufacturing environment. With the knowledge that required spec limits on incoming reflectivity are much tighter for certain resist processes (for example where no PEB is used), a process may be chosen to minimize these effects.

Tools are available to measure both specular and diffuse reflectivity to help determine and monitor specification limits for wafer production. It is important to measure diffuse and specular reflectivity separately to insure proper understanding of the lithographic response. This study has shown that diffuse reflectivity must be low, and specular reflectivity must be constant, in order to measure the effects of specular and diffuse reflectivity on lithography respectively. Without some means for separate specular and diffuse reflectivity measurements, a lithographic response (CD shift) may be seen without a corresponding shift being seen detected by the reflectivity measuring tool.

Projection System:	Resist System: Positive
Wavelength = 436.0nm	Thickness = 1.000μm
Bandwidth = 0nm	Layer #1: Polysilicon
Numerical aperture = 0.45	Thickness = 30 to 50nm
Partial coherence = 0.50	Layer #2: SiDioxide
Linewidth = 0.700μm	Thickness = 40nm
Pitch = 4.000μm	Substrate: Silicon
Mask bias = 0.000μm	
Focal position = 0.00μm	Resist Parameters:
Fixed defocus = 0.00μm	$A = 0.6\mu m^{-1}$
Image flare = 0.020	$B = 0.05\mu m^{-1}$
	$C = 0.015 cm^2/mJ$
Prebake conditions:	$n = 1.68$
not used	

Table I
PROLITH/2 input Parameters used for modeling the reflectivity effects on E0 and for generating the standing wave curves.

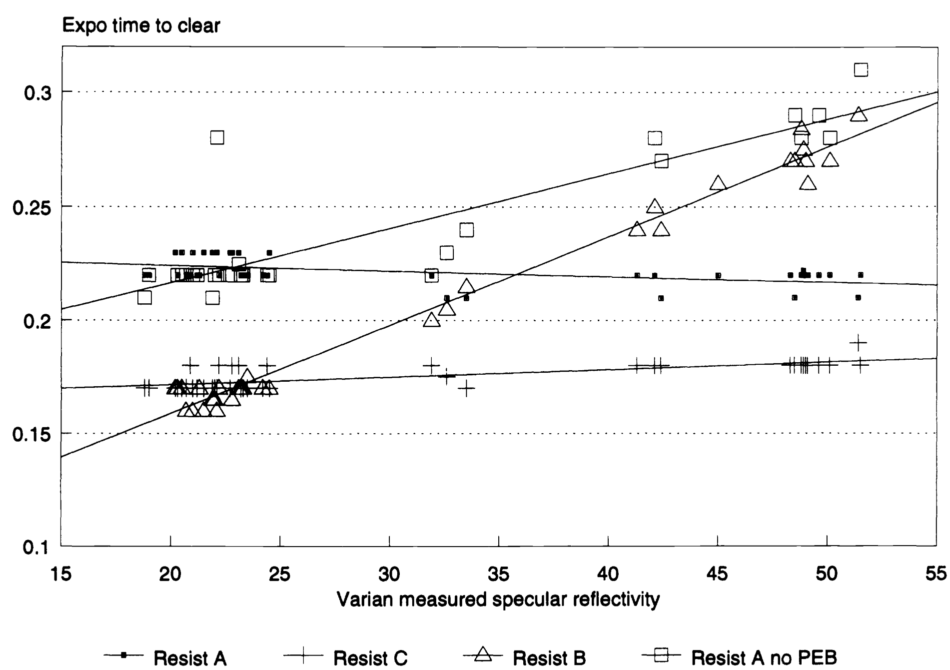


Figure 1
Specular reflectivity effects on exposure to clear for the various resist processing runs on TiN substrate. Data values measured on the Cary 2200 where diffuse reflectivity is less than 1%.

Wafer Type	Varian Cary 2200 Specular	Diffuse	Nanometrics 216S	Censor ANS-100	Exposure time (in seconds) for E0 A	B	C	A - no PEB	0.70um images Resist	Exposure	CD
TiN	20.9	0.03	34.2		0.22		0.18		A	0.25	0.691
TiN	21.5	0.03	46.5		0.22	0.16	0.18		A	0.25	0.689
TiN	49	0.08	83.8		0.22	0.27	0.18		A	0.23	0.698
TiN	41.3	0.05			0.22	0.24	0.18		A	0.25	0.687
Al	94.13	13.09	143		0.2	0.145	0.16		A	0.2	0.684
Al	93.96	24.39	128.4		0.21		0.18		A	0.2	0.695
Al	91.8	41.4	96.67		0.19	0.12	0.15		B	0.18	0.685
Al	90.79	0.4	151.4		0.23	0.25	0.18		B	0.26	0.689
TiN	48.3	0.07			0.22	0.27	0.18		B	0.3	0.695
TiN	20.2	0.08			0.23	0.17	0.17		B	0.2	0.685
Al	91.78	0.38	153		0.21	0.275	0.18		B	0.45	0.687
TiN	22.8	0.08	36.7		0.23	0.165	0.18		C	0.31	0.734
Al	94.06	25.25	120		0.2		0.17		C	0.23	0.706
TiN	49	0.07	84.4		0.22	0.26	0.18		C	0.31	0.702
Al	43.18	7.09	69.1	873.8	0.2	0.135	0.15	0.2			
TiN	21.9	0.08	84.4	0.481	0.22	0.165	0.17	0.22			
Al	21.35	11.53	24	4004	0.21	0.13	0.14	0.18			
Al	93.91	12.12	143	5602	0.25	0.145	0.16	0.24			
TiN	49.6	0.1	84.4	8.979	0.22		0.18	0.29			
Al	21.25	10.73	23.78	3777	0.19	0.18	0.14	0.17			
Al	20.9	9.84	24.32	3375	0.19	0.19	0.14	0.17			
Al	91.78	0.38	165.27	215.9	0.21	0.275	0.18	0.29			
Al	93.77	12.32	150.13	5989	0.2	0.145	0.17	0.24			
Al	92.25	20.93	84.17	6368	0.19	0.13	0.15	0.22			
TiN	48.5	0.04	85.55	2.533	0.21	0.27	0.18	0.29			
Al	92.53	20.62	117.98	6345	0.21	0.135	0.14	0.2			
Al	89.1	0.65	151.4	184.2	0.22	0.15	0.18	0.22			
TiN	51.4	0.03	87.2	0.854	0.21	0.29	0.19				
TiN	48.9	0.14	83.3	0.833	0.22	0.275	0.18				
TiN	20.5	0.01	38.7	1.545	0.23	0.17	0.17	0.22			
TiN	33.5	0.07	56.5	1.318	0.21	0.215	0.17	0.24			
TiN	24.5	0.03	47	0.515	0.23	0.17	0.17	0.22			
TiN	20.7	0.04	34.2	0.498	0.22	0.16	0.17	0.22			
TiN	21.3	0.04	38.7	0.669	0.22	0.17	0.17	0.22			

Table II
Example data set, showing 34 of the 75 wafers tested, results for reflectivity, E0 and 0.70μm imaging results.

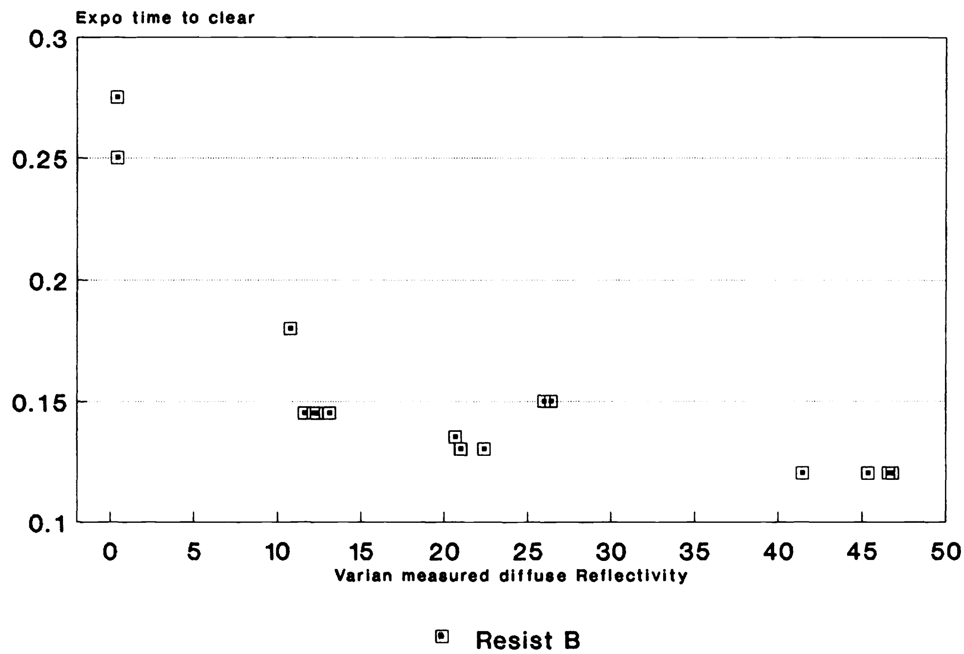
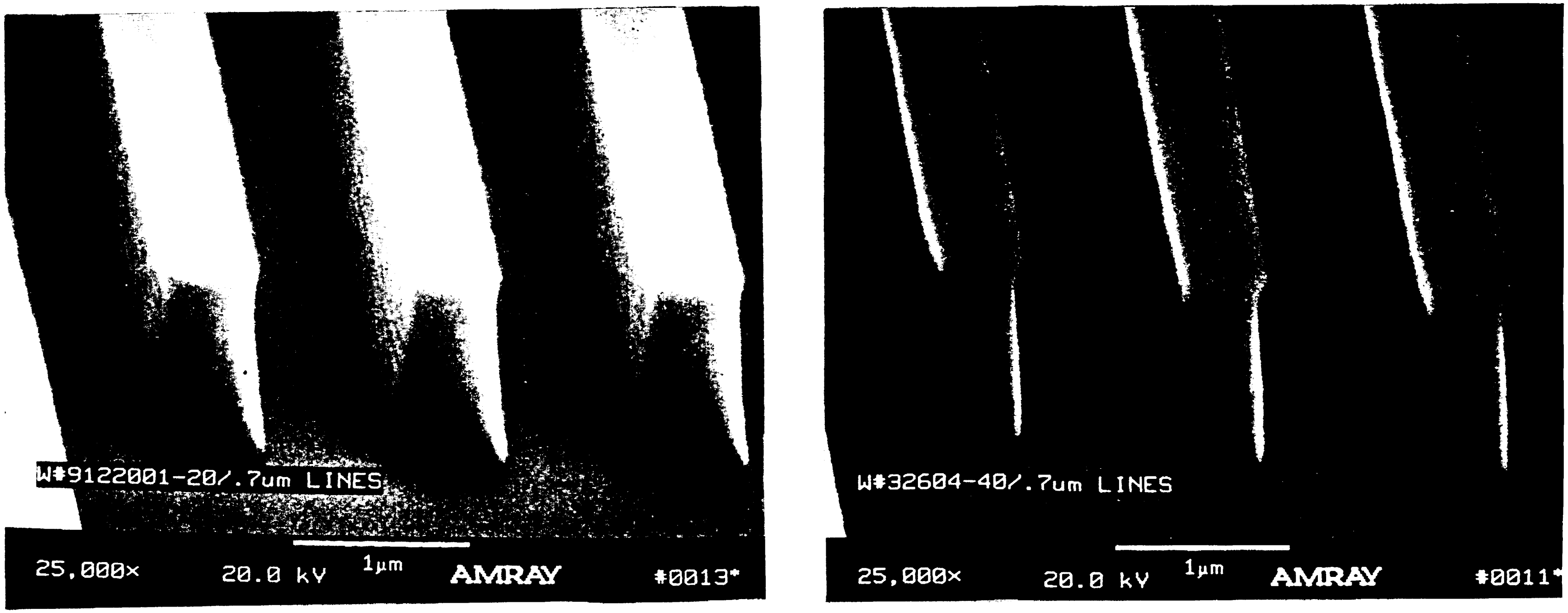


Figure 2

Diffuse reflectivity effects on exposure to clear for resist B on Aluminum substrate. Data values measured on the Cary 2200 where the specular reflectivity is greater than 92%.

Figure 3

Effect of PEB on E0 variation from PROLITH/2 simulations using the input parameters listed in Table I.



Specular = 20.2
Diffuse = 0.08
Exposure = 0.24

Specular = 48.3
Diffuse = 0.07
Exposure = 0.30 sec

Figure 4
Resist B patterned with 0.70µm grouped lines on TiN wafers. The exposure dose was varied to image the 0.70µm features to size.

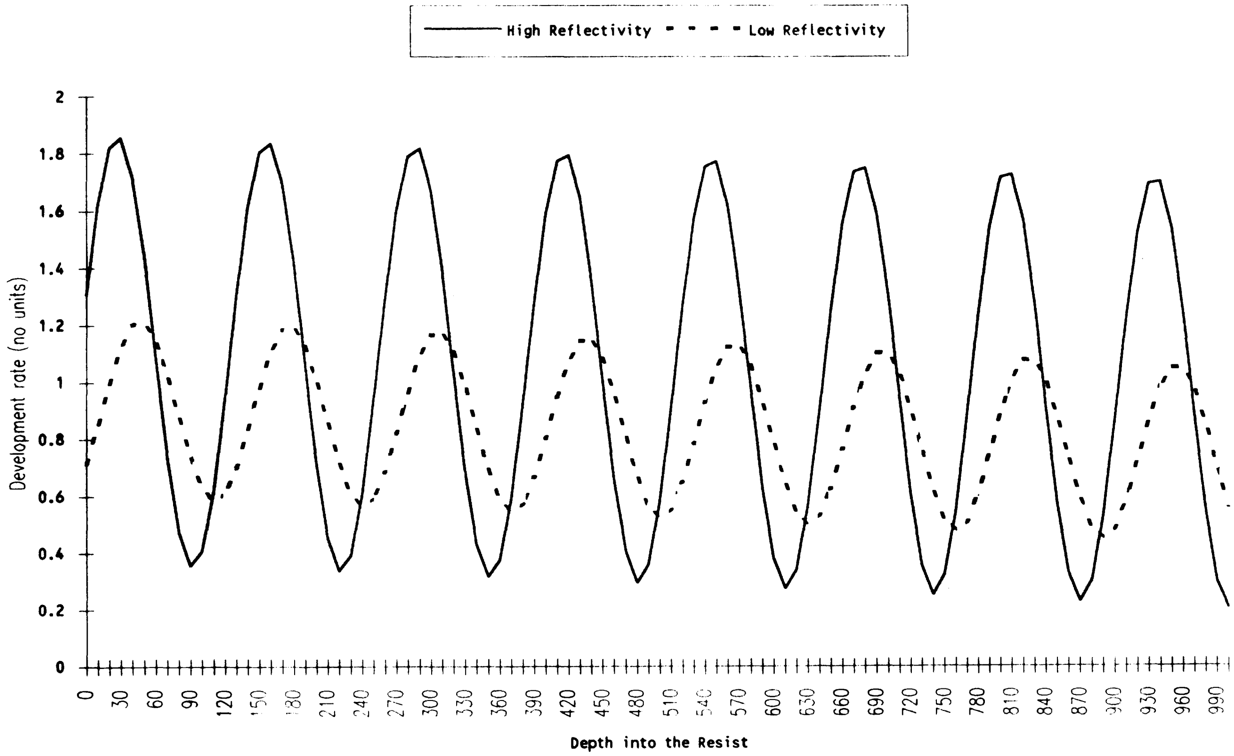


Figure 5

PROLITH/2 simulated standing waves of development rate versus developed depth into the resist. Variation in the polysilicon thickness in Table I was used to create the two standing waves.

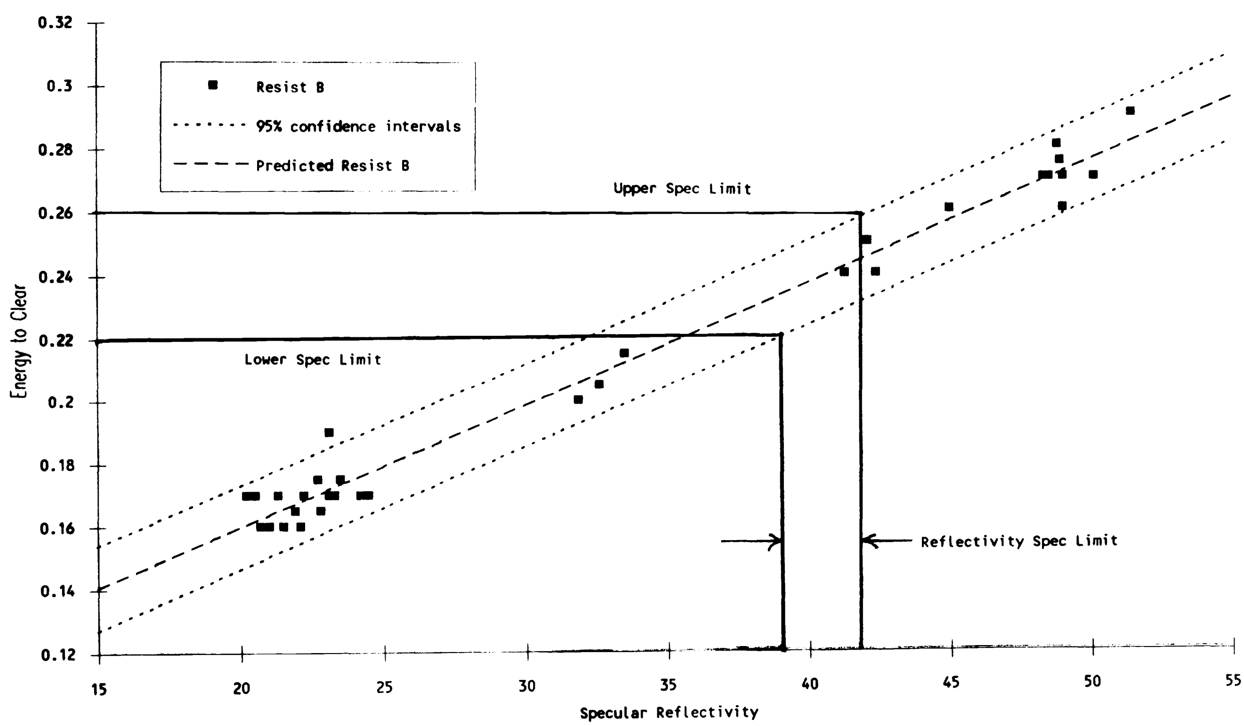
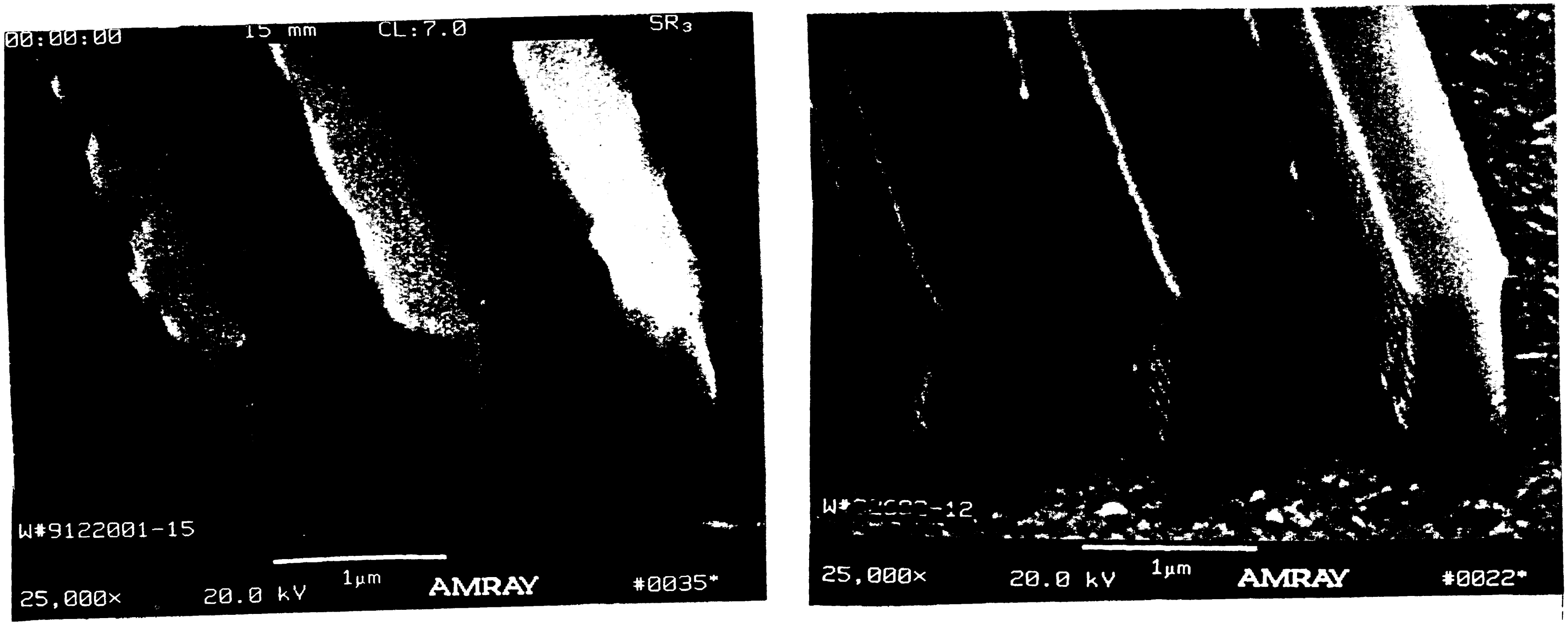


Figure 7

RS1 generated graph with predicted values from the model and the actual data. Example spec limits are shown, using the RS1 generated 95% confidence limits from the predicted values, as a guide.



Specular ▪ 91.8
Diffuse ▪ 41.4
Exposure ▪ 0.18 sec

Specular ▪ 90.8
Diffuse ▪ 0.04
Exposure ▪ 0.26

Figure 6
Resist B patterned with 0.70μm grouped lines on Al wafers. The exposure dose was varied to image the 0.70μm features to size.

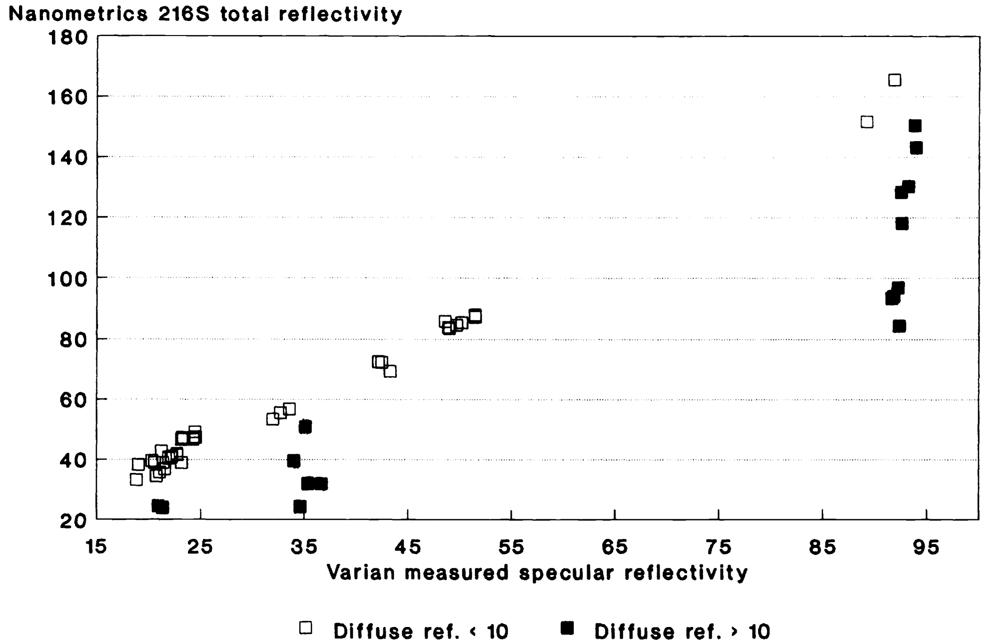


Figure 8
Comparison measurements of total reflectivity from the Nanometrics versus specular reflectivity from the Varian. A good correlation is seen for wafers where the diffuse reflectivity is less than 10%.

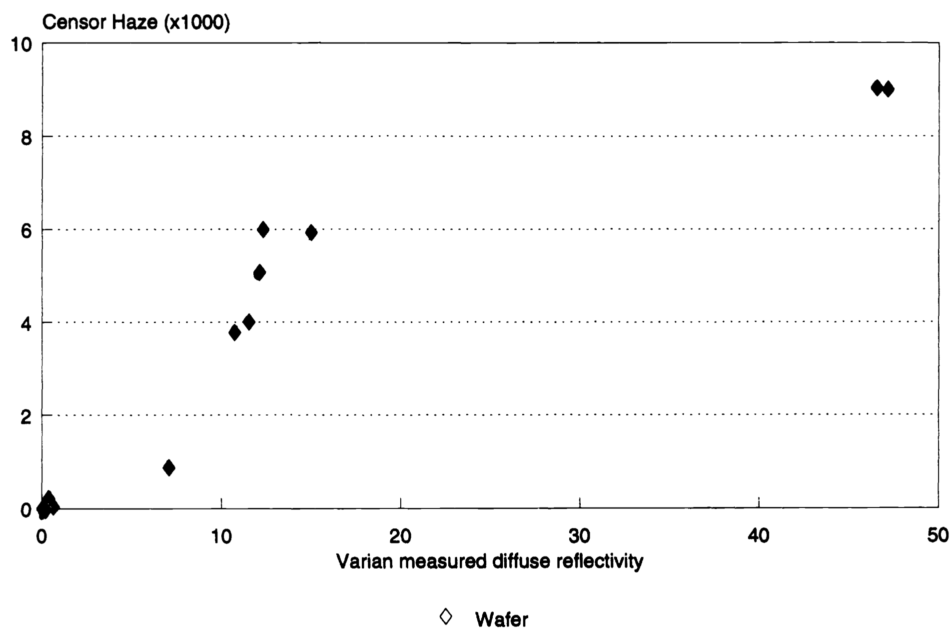


Figure 9
Comparison measurements of Haze values from the Censor versus diffuse reflectivity from the Varian.