Investigation of Tantalum Silicon Oxide as an Attenuated Phase Shift Masking Material for 157nm Lithography

Matthew Malley
Microelectronic Engineering
Rochester Institute of Technology
Rochester, NY 14623

Abstract- As the microelectronics industry trends toward 157nm lithography and device geometries shrink below 0.1μm, it seems more than likely that phase shift masking will be necessary as a means of optical enhancement. The attenuated phase shift mask is an attractive tool by which lithographers hope to push their art to its limits. However, potential materials for use as the attenuating film at wavelengths as low as 157nm have yet to be determined. There are several requirements that must be met by a material before it will be considered seriously for use on attenuating phase shift masks. One material that shows promise as a possible attenuating film is a compound film of tantalum silicon oxide, $Ta_xSi_yO_z$. The rationale behind the selection of $Ta_xSi_yO_z$ as a material worthy for use on the technology in question will be presented, as will a preliminary overview of the characterization of the film's constituents, SiO_2 and Ta_2O_5. The process by which a composite film with varying levels of Ta_2O_5 incorporation can be sputter deposited will be shown. Work that will have to be performed before the adoption or rejection of TaSiO as an APSM film will be discussed.

1. INTRODUCTION

The desire to push the limits of optical lithography has become more prevalent with the advent of 248 and 193nm systems. With the impending inception of 157nm lithography, the need to produce the dimensions necessary for advanced semiconductor technologies has facilitated the use of resolution enhancement techniques. One such technique is the phase shift mask, a subset of which is the attenuated phase shift mask (APSM). The latter has gained more attention in recent years because of the added ease of manufacturing over standard, alternating phase shift masks. The idea behind attenuated phase shift masking is a simple one, and yet the technique is very effective. This film is etched using a reactive ion etching process, creating a pattern analogous to that of a binary mask. However, the region shadowed by the attenuating film allows some amount of radiation to leak through, with transmission in the range of around 5-15%. This film also serves the purpose of the phase shifter by being engineered to a thickness that will create a π-phase shift between unobstructed and attenuated radiation from the source. It is this phase shift that produces very sharp, dark edges to features, allowing for increased resolution capabilities by taking the guesswork out of line/space differentiation by the resist. A graphical representation of what occurs as exposing radiation passes through the mask, is collected by the lens, and is sensed by the resist is shown in Figure 1. The APSM has also been shown to provide a significant increase in the useful depth of focus, which is a distinct benefit due to the trend toward shorter wavelengths and higher numerical aperture steppers.

A. Requirements of an APSM Film

The first and most elementary requirement for a phase shift masking film is that it deliver the desired 180° phase shift. The current tolerances on this requirement may be less than 1°. Assuming that the film is exactly the right thickness and understanding that the phase shift is therefore controlled by the refractive index of the phase shifting material, the requirement on refractive index control must be better than 0.6%[3]. This requires tight deposition condition restraints and etch rate/selectivity requirements. The attenuating film must also deliver the appropriate transmission characteristics. Again, this is an issue with producing a film that has the desired composition, since absorption, and therefore transmission, relies on the extinction coefficient of the composite film at a given wavelength. Both the phase shifting capabilities and the transmission properties of the APSM film must be controlled in order to deliver an aerial image to the resist that displays the characteristics of a maximizing image log slope while at the same time minimizing the printability of residual "lobes" in the areas shadowed by the attenuating

film. It is also desirable that the film reflectivity be kept below 15%. This reflectivity can be minimized by ensuring that the material in the composite film with the lower of the two refractive indices be the last to be deposited [4].

The ability of an APSM film to be patterned using reactive ion etch (RIE) techniques is another requirement. As device geometries are steadily being scaled down, the mask geometries must keep in step, requiring CD and uniformity control across the mask that is becoming more and more stringent. This points to plasma processing rather than wet etch techniques. The elimination of chrome from the mask, which is a distinct benefit of APSM over binary and alternating phase shift masks, makes this possible. The attenuating material must exhibit high etch selectivity between the film itself and the underlying substrate so that phase shifting requirements can be maintained, preserving the functionality of the system. Work that has been done previously on the etch characteristics of various APSM films will be presented in the section covering the feasibility of using TaSiO as an APSM material.

The chemical and radiation stability of the film to excimer laser exposure is a requirement that must be met by an aspiring APSM film. Any chemical or physical alteration that results from extended exposure to excimer laser radiation can eliminate a material for consideration in attenuating phase shift masking schemes. These alterations will most likely lead to changes in the optical properties of the film, an unacceptable situation for a mask with such tight restrictions set on its performance. When testing the radiation stability of the masking material, the attenuating film is subjected to pulsed radiation from an excimer laser (Ar ion laser in the case of 157nm). This is done for a long enough period of time that the test can effectively approximate the amount of radiation that the mask would see in a lifetime of heavy use. In order to isolate the effects of radiation damage, the transmittance and reflectance of the film is measured using ellipsometric techniques before and after the exposure. Tolerable exposure-induced transmission modification is near 0.5% [3], allowing very little room for chemical or physical change within the film to effect its optical properties.

B. The Selection of $Ta_xSi_yO_z$ as an APSM Film

Previous experiments have been performed at 248 and 193nm wavelengths on films that were chosen as potential candidates for APSM films. Among them were metal-rich metal nitrides (Zr/ZrN and Al/AlN), silicon-rich nitrides (Si_xN_y), nitride composites (TaN/Si_3N_4), and molybdenum silicon oxides (MoSiO). Tests were done on each of these to determine how suitable they would be for use as deep UV attenuating films. Reactive ion etch conditions were developed and analyzed for each. The radiation stability of these films in relation to the preservation of their optical properties was also explored.

Plasma RIE processes were previously explored for a number of materials for use at 193nm, among which were MoSiO and TaSiO, which etch in nearly the same way due to their similar compositions. Etch conditions were investigated using SF_6 and/or CF_4 with oxygen [2]. In the case of MoSiO etching, the chemical reaction that takes place involves the generation of volatile $MoOF_4$ and $SiOF_6$. Similar conditions could be used to etch TaSiO with the etch by-products being TaF_8 and $SiOF_6$, both of which are volatile at standard etch pressures and temperatures. The tantalum film exhibited higher selectivity to fused silica than the molybdenum film due to the greater transparency of Ta_2O_5 and the resulting lower SiO_2 content within the film. This ease of etching and relatively high etch selectivity of the TaSiO film makes it an attractive option for APSM applications from the RIE perspective.

The radiation stability of many of the films mentioned before have been previously investigated for applications at 248 and 193nm. It can be claimed that if a film does not meet stability standards set at these wavelengths, that they can provisionally be rejected from use at shorter wavelengths, since more damage is likely as wavelength decreases. The most common causes of radiation-related breakdown are cumulative damage mechanisms and oxidation effects within the film. It has been shown that metal-rich metal nitrides have a tendency to oxidize quite easily, greatly altering the optical properties of the material. In fact, after the pulsed laser test, the Zr/ZrN film was closer related to ZrO than ZrN when analyzing reflectance spectra. Past radiation damage experiments on a number of materials have led to one very important conclusion; understoichiometric metal nitrides, oxides, or oxynitrides are inherently unstable and prone to excessive oxidation [3]. The resulting transmission properties of the film are altered and this is intolerable. A material that proved to hold up to the pulsed laser experiment was the composite TaN/ Si_3N_4 film. No significant modification to the film's optical properties was observed. This film is deposited as a multilayer stack of stoichiometric TaN and Si_3N_4, which is the cause of its relative stability. Films that are stoichiometric in nature, such as the multilayer stack of tantalum and silicon nitride, are inherently less prone to damage, which can be predicted from analysis of the film's individual constituents [3]. Another benefit of the multilayer stack is the use of individual layer thicknesses that are significantly below the wavelength of exposing radiation. The components that make up the multilayer stack are deposited in thin (10Å or less) layers as the wafers pass under the target in the sputtering system. There is also some amount of interdiffusion that takes place on the wafer after layers are deposited on top of one another. The

result is a film that exhibits homogeneous optical behavior, which is often not the case with understoichiometric compounds. Extolling the benefits of multilayer stacks has a purpose, in that TaSiO is deposited in this manner. Something on the order of a single atomic layer of SiO_2 is deposited on each layer of Ta_2O_5, resulting in a homogeneous film. It would be expected that a film of TaSiO would exhibit high stability to laser radiation because of the nature of the materials that compose it. This presents another benefit of using TaSiO as the attenuating film for phase shift masking applications; it can (more than likely) hold up against the day to day rigors of being subjected to excimer laser radiation.

Further benefits of selecting TaSiO as an APSM material involve its control of transmission properties. The transmission of the resulting composite film is manipulated by simply adjusting the sputter deposition conditions to tailor the amount of Ta_2O_5 incorporated in the film [1]. As more Ta_2O_5 is added to the film, the transmission decreases as a result of increased absorption from the higher extinction coefficient of the composite. If the sputter deposition used for putting down TaSiO is well controlled, the percent incorporation of Ta_2O_5 can be changed by simply calculating the power distribution needed at each of the targets. This also adds flexibility to the mask design, if it is discovered for instance that different transmission characteristics are desirable for specific structures.

2. EXPERIMENT AND RESULTS

Prior to an attempt to deposit a composite film, it was necessary to characterize the deposition process and optical properties of the constituent films. Blanket films of SiO_2 and Ta_2O_5 were deposited on bare silicon wafers for this purpose. A Perkin Elmer rf magnetron sputter system, PE 2400 was used at a power of 500W. The deposition was carried out in an oxidizing ambient of 30sccm Ar with 10sccm O_2. Pure targets of silicon and tantalum were used. In both cases, a base pressure of 1E-6Torr was achieved before flowing gas and performing the deposition. A fifteen minute pre-sputter was done to clean the targets prior to deposition as well. The deposition pressure was 4-5mTorr The films were deposited for 30 minutes. The film samples were then analyzed for optical properties using VUV spectroscopic ellipsometer. The data collected was then analyzed using WVASE software, with which the resulting film thicknesses, refractive indices, and extinction coefficients were determined. The SiO_2 thickness was found to be 241Å and the Ta_2O_5 thickness was found to be 192Å, corresponding to deposition rates of 8.7Å/min and 6.4Å/min, respectively. The refractive index of SiO_2 was determined to be 1.690, with an extinction coefficient of 0.005 at a wavelength of 157nm. The refractive index and extinction coefficient of Ta_2O_5 at 157nm were found to be 1.921 and 0.574. Plots that show the refractive indices and extinction coefficients of these two films as a function of wavelength can be found in Figures 2 and 3. These films were then combined within WVASE using an effective media approximation (EMA). A simulation of the film characteristics of an arbitrary combination of these two materials could be generated with this technique. Percent Ta_2O_5 incorporation in the sputtered SiO_2 film was varied from 0-100%. The response of interest here was the resulting transmission of the composite film.

The theoretical refractive index (n) and extinction coefficient (k) of each composite film was extracted from the simulation. These values were then used to determine the theoretical thickness (t) at which the film would cause a π-phase shift, the absorption of the film (α), and the resulting transmission (T) [1]. This was done using the following equations:

$$t = \lambda / 2(n-1)$$
$$\alpha = 4\pi k / \lambda$$
$$T = e^{-\alpha t}$$

Table 1 contains selected theoretical $Ta_xSi_yO_z$ film compositions that would result in transmission values between 1% and 41%, more than encompassing any films that would be considered for attenuated phase shift masking applications.

Theoretical deposition conditions for a range of attenuating films were determined. These can be found in Table 2

3. CONCLUSIONS

An investigation was performed to determine the feasibility of using a tantalum silicon oxide film as an attenuating film for phase shift masking applications. The constituent films, SiO_2 and Ta_2O_5, were deposited by sputtering metal targets in an oxidizing ambient and these films were analyzed using VUV ellipsometry. Theoretical composite films were simulated and their resulting optical properties were extracted. Theoretical deposition conditions were also determined

ACKNOWLEDGEMENTS

The author would like to acknowledge Bruce Smith for his help in devising the idea for the project and for providing some excellent research material. Further thanks go out to Matthew Lassiter, Michael Cangemi, and Anatoli Bourov, all of whom had a hand in instructing the author on machine operation necessary for the experiment.

REFERENCES

[1] B.W. Smith, S. Butt, Z. Alam, S. Kurinec, and R.L. Lane, "Attenuated Phase Shift Mask Materials for 248 and 193nm Lithography" J. Vac. Sci. Technol. B 14(6), Nov/Dec 1996, pp. 3719-3723.

[2] B.W. Smith, C. Fonseca, L. Zavyalova, Z. Alam, and A. Bourov, "Plasma Reactive Ion Etching of 193nm Attenuated Phase Shift Mask Materials" J. Vac. Sci. Technol. B 15(6) Nov/Dec 1997, pp. 2259-2262.

[3] B.W. Smith, L. Zavyalova, A. Bourov, S. Butt, and C. Fonseca, "Investigation into Excimer Laser Radiation Damage of Deep Ultraviolet Optical Phase Masking Films" J. Vac. Sci. Technol. B 15(6) Nov/Dec 1997, pp. 2444-2447.

[4] B.W. Smith, L. Zavyalova, S. Butt, A. Bourov, N. Bergman, C. Fonseca, and Z. Alam, "The Effects of Excimer Laser Radiation on Attenuated Phase-Shift Masking Materials" SPIE vol. 3051 1997.

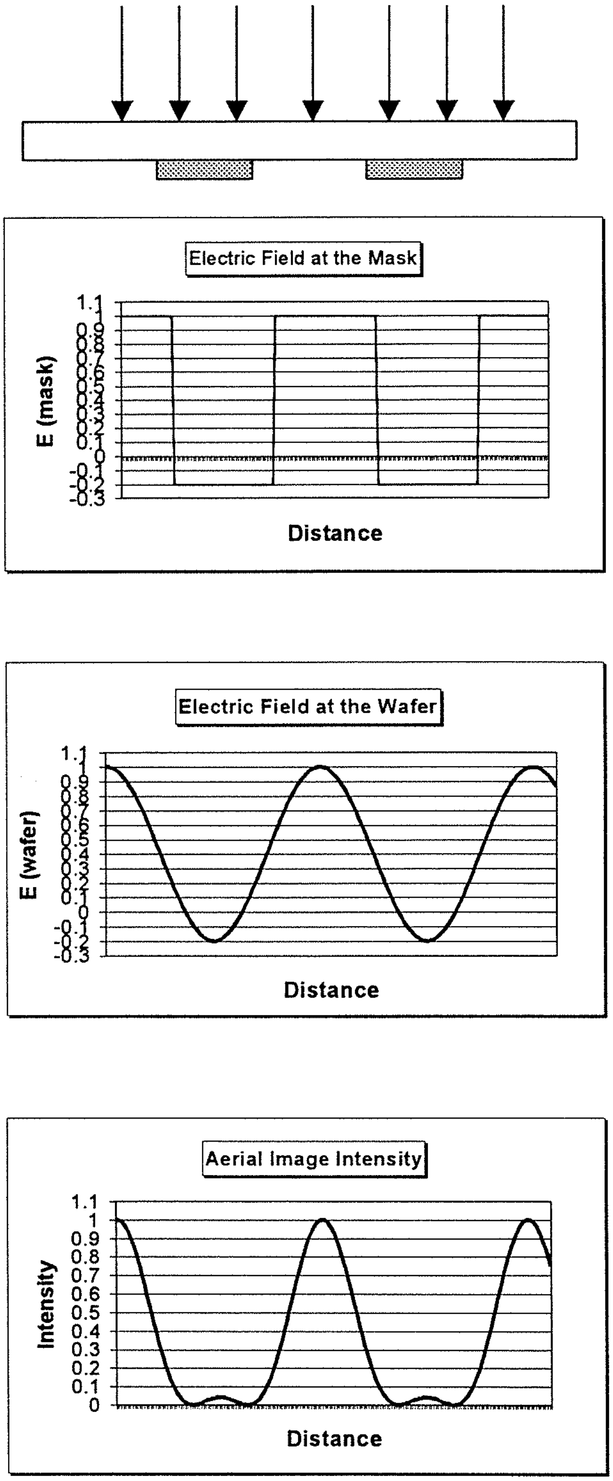

Figure 1. The three plots above demonstrate the way in which the attenuated phase shift mask takes radiation at the mask and delivers it to the resist.

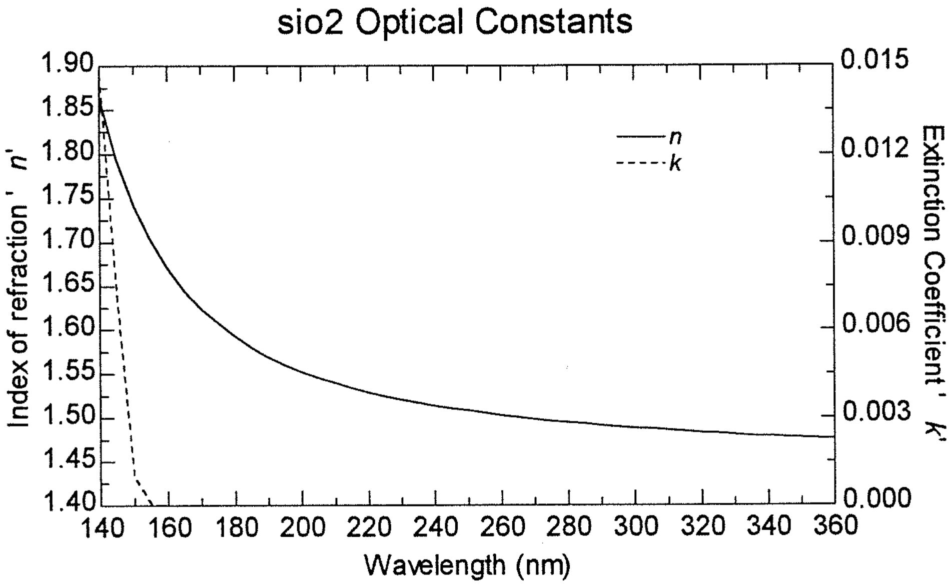

Figure 2. Refractive index and extinction coefficient as a function of wavelength for an SiO_2 film.

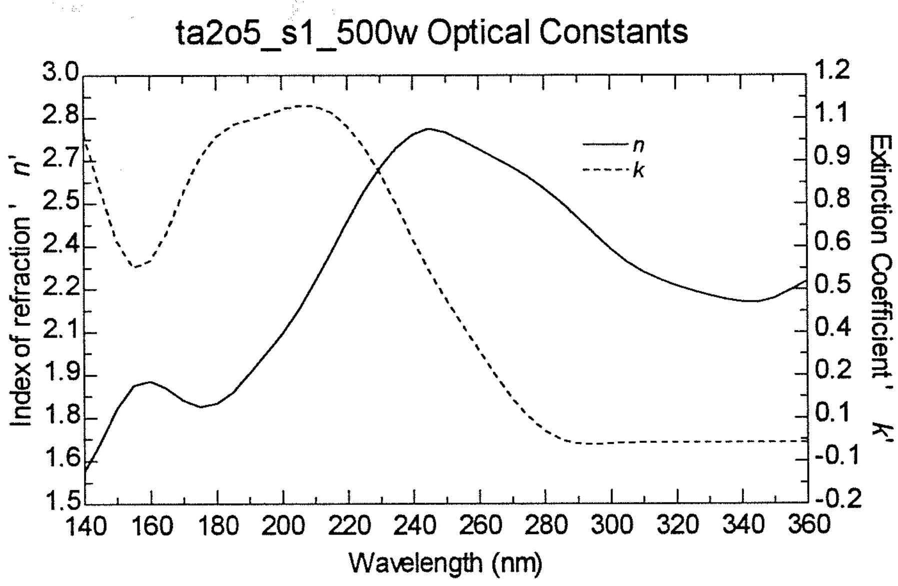

Figure 3. Refractive index and extinction coefficient as a function of wavelength for a Ta_2O_5 film.

%SiO2	%Ta2O5	n	k	Thickness for 180° Phase Shift (Å)	Transmission
88	12	1.719	0.068	3275.4	41.01%
87	13	1.721	0.072	3266.3	39.02%
86	14	1.725	0.078	3248.3	36.28%
85	15	1.727	0.084	3239.3	33.66%
84	16	1.731	0.089	3221.6	31.74%
83	17	1.734	0.096	3208.4	29.15%
82	18	1.736	0.101	3199.7	27.44%
81	19	1.738	0.107	3191.1	25.50%
79	21	1.741	0.117	3178.1	22.58%
78	22	1.744	0.123	3165.3	21.05%
77	23	1.747	0.13	3152.6	19.39%
75	25	1.753	0.141	3127.5	17.12%
73	27	1.755	0.152	3119.2	15.00%
71	29	1.762	0.163	3090.6	13.32%
68	32	1.767	0.18	3070.4	10.95%
66	34	1.773	0.192	3046.6	9.62%
65	35	1.775	0.197	3038.7	9.11%
61	39	1.785	0.219	3000.0	7.21%
55	45	1.797	0.251	2954.8	5.14%
46	54	1.818	0.306	2879.0	2.94%
27	73	1.86	0.419	2738.4	1.01%

Table 1. TaSiO composite film composition for selected transmission values between 1 and 41%. the thicknesses shown are for the second π-phase shift thickness (total phase shift of 540°)

%Transmission	Target Thickness	SiO2 fraction	Ta2O5 fraction
25.50%	3191.1	0.81	0.19
19.39%	3152.6	0.77	0.23
15.00%	3119.0	0.73	0.27
9.62%	3047.0	0.66	0.34
5.14%	2955.0	0.55	0.45

SiO2 thickness	Ta2O5 thickness	SiO2 time (at 500W)	Ta2O5 time (at 500W)
2584.8	606.3	297.1	94.7
2427.5	725.1	279.0	113.3
2276.9	842.1	261.7	131.6
2011.0	1036.0	231.2	161.9
1625.3	1329.8	186.8	207.8

Power Ratio (SiO2:Ta2O5)	Si Target Power	Ta Target Power	New SiO2 Dep Rate (Å/min)
3.14	1568	500	27.3
2.46	1231	500	21.4
1.99	994	500	17.3
1.43	714	500	12.4
0.90	899	1000	15.6

New Ta Dep Rate (Å/min)	Combined Dep Rate (Å/min)	Dep Time (min)
6.4	33.7	94.7
6.4	27.8	113.3
6.4	23.7	131.6
6.4	18.8	161.9
12.8	28.4	103.9

Table 2. Deposition conditions that would produce films with transmission values of 5, 10, 15, 20, and 25% at thicknesses that would exhibit the desired phase shifting characteristics.