Amorphous Silicon for 157nm Lithography

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Abstract - Amorphous silicon (α-Si) was investigated as a potential masking material at 157nm wavelength. Characterization of α-Si included film deposition on CaF_2 (calcium fluoride) substrates through reactive sputtering, spectroscopic ellipsometry in the UV range, reflection and transmission at 157nm wavelength, and extraction of optical constants (n&k) with a commercial software package. Experimental results suggest that α-Si films deposited at RIT have similar optical constants as published values in the UV range. Simulation work suggests that a 50Å silicon nitride film can be used as an anti-reflective layer to minimize reflections at the a-Si / air boundary. Consequently, silicon nitride films were also investigated in this work. Since these films (stack) must be patterned for mask applications, proper dry etch selectivity among these materials must be achieved.

I. INTRODUCTION

As optical lithography below 193 nm is explored, materials issues become more challenging. The challenge lies in obtaining materials whose optical properties allow them to be applied as masking layers, optical layers, antireflective layers (AR), and phase-shift masking at 157nm, or at other potential VUV wavelengths. Historically, chromium has been used as a masking material at g-line, i-line, and 193nm lithography. Its optical properties (high absorption and adequate optical density) at UV wavelengths have been the main reason why chromium is the preferred choice as a masking material. The problem with using chromium at shorter wavelengths is that its extinction coefficient (k) is relatively lower than other materials at 157nm, thus resulting in a lower absorption coefficient (α). Figure 1 shows the absorption of several materials as a function of wavelength. Furthermore, chromium may not meet optical density (OD) requirements at a film thickness < 1000Å as a masking material at 157nm to give adequate modulation (aerial image contrast). A film thickness <1000Å is desired in order to meet industry standards and to provide satisfactory etched profiles at projected aspect ratios.

Masking material alternatives do exists at 157nm. One such alternative is amorphous silicon (α-Si). As shown in Figure 1, amorphous silicon has a higher absorption coefficient than Chromium at 157nm. Consequently, α-Si exhibits an optical density of 5.0 at 157nm at a film thickness less than 1000Å. However, other considerations such as mask reflectivity at 157nm must be taken into account. The reflectivity of α-Si is relatively high at 157nm. The use of an anti-reflective layer may be required with α-Si as a masking layer. This work investigated thin film deposition, etch considerations, and optical characterization (simulation and experimental data) of amorphous silicon with an AR layer.

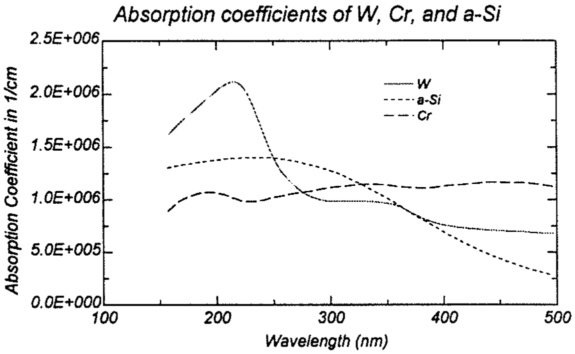

Figure 1: Absorption coefficient for several materials.

II. BACKGROUND

To set a starting point for this project, theoretical calculations for film thickness were employed with the use of fundamental physical equations and industry standards. Equations 1-3 can be used to determine the theoretical film thickness that meets OD requirements. Industry has set OD values of about 3 to 5 as adequate measures for opaqueness of the masking material.

$$OD = -\log(T) \qquad \text{(Eq -1)}$$

$$T = (1-R_1)(1-R_2)\,e^{-\alpha t} \qquad \text{(Eq - 2)}$$

$$R = \frac{(n_1 - n_2)^2 + k_1^2}{(n_1 + n_2)^2 + k_1^2} \qquad \text{(Eq - 3)}$$

Using published optical constant values for the materials of interest at 157nm wavelength, the required film thickness can be calculated. Table 1 shows the published optical constants for α-Si, CaF_2, and quartz (SiO_2).

Material	n @ 157nm	k @ 157nm
α–Si	0.6749	1.6277
CaF_2	1.5678	0
SiO_2	1.6895	0

Table 1: Published optical constants for several materials.

Figure 2 presents a theoretical plot of transmission vs. film thickness for α-Si at 157nm wavelength. This graph suggests that a 60nm film thickness can provide an OD value of about 4. An OD of 4 was arbitrarily chosen since it is in the middle of the range for standard OD values. These theoretical values were verified on RIT's lithography research web-site. (http://www.rit.edu/~635dept5).

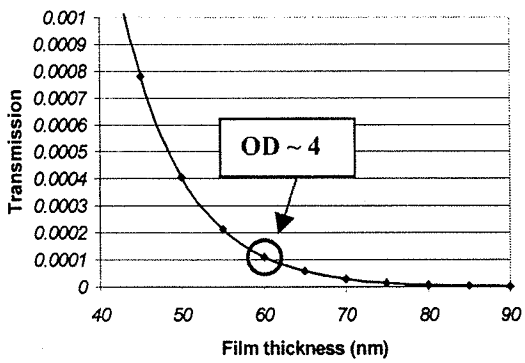

Figure 2: Transmission of α-Si film thickness at 157nm.

Since about 50% reflection is expected (Eq –3) at the α-Si/air boundary, simulation and modeling for an A.R. layer were also carried out. Previous knowledge and suitability of certain materials allows for choosing adequate materials as A.R. layers. Silicon nitride (Si_3N_4) was chosen for investigation as depicted in Figure 3.

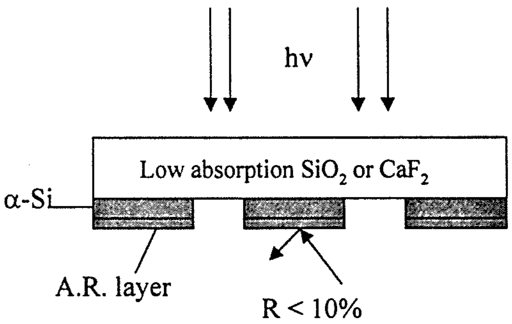

Figure 3: α-Si masking scheme with A.R. layer.

Simulation was performed using PROLITH software program and published optical constants (Palik) for Si_3N_4 at 157nm wavelength (n = 2.6750, k = 0.9236). The simulation results indicate that a 50Å nitride film can minimize reflection down to about 4% and a large process latitude can be achieved in terms of the extinction coefficient (k) as shown in Figures 4 and 5, respectively.

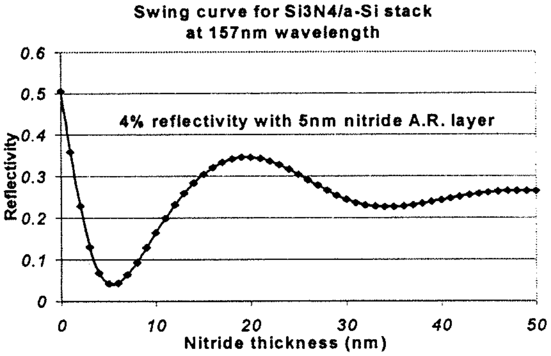

Figure 4: Swing curve for Si_3N_4/α-Si film stack.

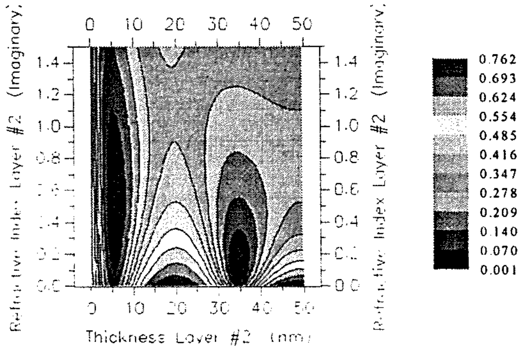

Figure 5: α-Si reflectivity as function of A.R. layer thickness and extinction coefficient.

The goal of this project was to identify or extract the optical constants of deposited films. More specifically, in order to justify the use simulation results, the optical constants must be verified by comparison of extracted values and published values. The procedure for extraction of optical constants is described in the following section.

III. EXPERIMENTAL

Film deposition was executed by reactive sputtering in a Perkin Elmer 2400 sputter system. Thin films were deposited on CaF_2 substrates and thickness measurements were done with profilometry technique (Tencor stylus). The deposition parameters for α-Si and Si_3N_4 are given below. Chamber conditions and preparation can greatly impact the quality of the films. One way to ensure high quality films is to achieve a low chamber base pressure (~10^{-7} Torr). This was typically achieved in the Perkin Elmer system by a minimum of a 6-hour pump down.

α-Si Process conditions:
- 1000Watts
- 30 sccm Ar
- rotation mode
- deposition rate = 12.5 Å/minute

Si_3N_4 Process conditions:
- 1000Watts
- 30 sccm Ar / 10 sccm N_2
- rotation mode
- deposition rate = 5Å/minute

Plasma etch studies

Since ultimately the stack must be patterned with an anisotropic dry etch process, this work also investigated etch selectivity among the different materials under investigation. For these studies, α-Si and Si_3N_4 films were deposited on thermal oxide substrates. The etch recipes are given below

α-Si Etch conditions:
- 40 Watts
- 42 sccm SF_6
- 400 mTorr

Si_3N_4 Etch conditions:
- 50 Watts
- 30 sccm SF_6 / 7.5 sccm O_2
- 300 mTorr

Extraction of optical constants

The extraction of optical constants consisted of obtaining **a)** ellipsometric data (Δ and Ψ) in the UV wavelength range and **b)** transmission and reflection at 157nm wavelength. Ellipsometric data was obtained with a variable angle spectroscopic ellipsometer operating from 190nm to 800nm. Using a software program called WVASE™ (Woollam Variable Angle Spectroscopic Ellipsometry), the ellipsometric data was fitted to a model in which the expected optical constants (as a function of wavelength) were those of the published values. In addition, the transmission and reflection data at 157nm was to be used to extract n & k down to 157nm. The 'goodness' of fit was then reported as a mean square error (MSE).

It is expected that some differences may be observed between the optical constants of deposited films at RIT and the published values. However, the closer the films exhibit n &k values as expected, a higher confidence exists in the stack masking performance as expected from the simulation work.

IV. RESULTS AND DISCUSSION

Figure 6 and 7 show the extracted and expected optical constants for α-Si and Si_3N_4, respectively. Relative good fits were observed in both plots. The α -Si film exhibited a better fit (MSE = 0.7) than the silicon nitride film (MSE = 5.4). More importantly, a better fit was observed in the UV region for the α–Si film than in the longer wavelength region. This is critical to the studies since the focus of this work concentrates on the optical constants in the VUV region. Note that no optical constants were extract down to 157nm. Due to time constraints, transmission and reflection data could not be obtained in a timely manner prior to the authoring of this report. Therefore, realize that until this data has been received from outside laboratories, more fitting will be performed and extraction of optical constants down to the VUV region is expected. However, it is worthwhile to emphasize that because of such great fit in the UV region, a similar fit is expected once the transmission and reflection data is used. Verification of expected results will be published in a future progress report.

The poor fit in the longer region for the α–Si film may be attributed to a crystalline silicon behavior. Another reason could be that some impurities (i.e., Argon, residual oxygen, etc.) might have been incorporated during film deposition. Thus, adequate deposition conditions are desired in order to obtain highest quality films as possible. Similarly, the nitride film exhibited large differences in the optical constants. For this material, it is believed that difficulty in obtaining stoichiometric Si_3N_4 films is responsible for the differences in optical constants. In general, a MSE of 5.4 is regarded as a good fit for this type of film.

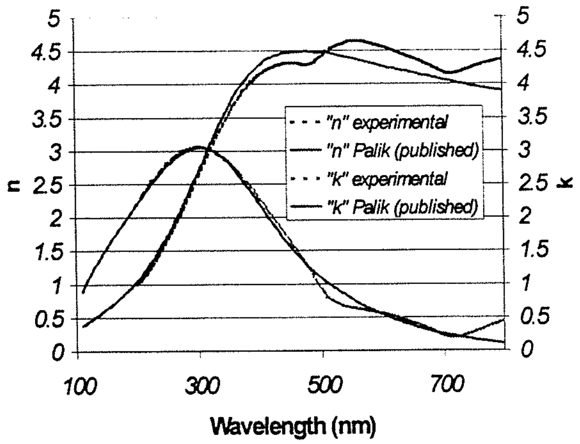

Figure 6: Amorphous silicon optical constants. (MSE = 0.7)

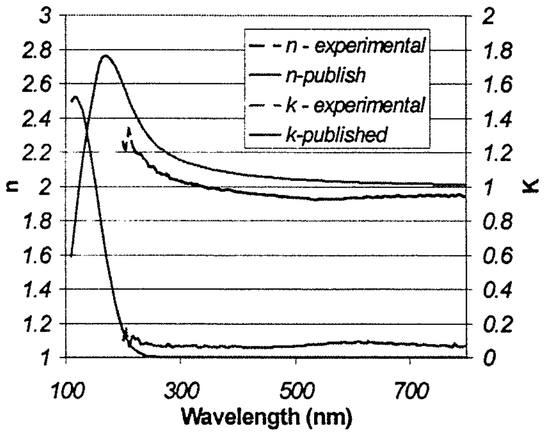

Figure 7: Silicon nitride optical constants. (MSE = 5.4)

Plasma etch results

High etch selectivity to oxide were achieved for both etch processes. High selectivity to oxide is desired because it implies that minimal etching will occur in the quartz substrate (mask). Ultimately, an etch-stop layer may be required in order to attain the highest selectivity as possible. Etching into the substrate is a concern as non-uniform etching could lead to mask defects and unwanted phase transitions in the electric field.

As it can be seen in Table 2, a relative high selectivity of about 10 (α-Si:Si_3N_4) was achieved. In contrast, an etch selectivity of about 0.5 (Si_3N_4:α-Si:) was achieved with the silicon nitride etch recipe (Table 3). The goal is to achieve a 1:1 etch selectivity between the amorphous silicon and silicon nitride. A single or uniform etch rate is desired while etching through the stack because it leads to better end-point determination. This 'homogeneity' can be achieved by proper adjustments to the etch process (i.e. gas flows, pressures, power, etc.). The nitride etch process could allow for an optimum process and thus further investigation could prove beneficial.

Material	Etch rate (Å/minute)	Selectivity (a-Si : material)
Amorphous Silicon	4,540	-
Silicon Nitride	480	9.5
Oxide (SiO_2)	224	20

Table 2: Amorphous silicon etch results.

Material	Etch rate (Å/minute)	Selectivity (Si_3N_4 : material)
Amorphous Silicon	4,300	0.5
Silicon Nitride	2,160	-
Oxide (SiO_2)	246	9

Table 3: Silicon nitride etch results.

V. CONCLUSIONS

Optical characterization, by means of extraction of optical constants, for amorphous silicon and silicon nitride films has been successfully assessed in the wavelength region of 200nm to 800nm. Although extraction of optical constants down to 157nm could not be assessed at this time, due to time constraints, very good fits in the UV region were observed for both amorphous silicon and silicon nitride films deposited at RIT. Thus, similar results are expected once data at 157nm is incorporated to the model. Plasma etch results indicate that a 1:1 etch selectivity between the amorphous silicon and silicon nitride may be feasible to achieve with a SF_6 and O_2 chemistry. Additionally, an etch-stop layer may be required to minimize substrate etching.

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