Reactively-sputtered Silicon-oxynitride Films and Filters

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ABSTRACT

Thin film optical filters depend on the properties of the coating materials. For a particular application, proper selection of the coating materials is important not only for the final filter performance, but also because this affects the complexity of the filter design and its manufacture. Ideally all the refractive indices would be available in the widest possible range. However, traditional coating materials such as oxides, metals, etc. only offer discrete choices. Silicon oxynitrides are interesting because their refractive indices can be made to vary continuously. In this paper, we present our recent work on the deposition and characterization of this material. The thin films are made in an AC magnetron sputtering system using pure silicon targets in an argon, oxygen and nitrogen gas mixture. By controlling the oxygen and nitrogen content in the sputtering environment, the silicon oxynitride layers range from pure silicon nitride to pure silicon dioxyde. Homogeneous and inhomogeneous silicon oxynitride layers are characterized ex-situ by ellipsometric and spectrophotonic measurements. Results on the fabrication of inhomogeneous interference filters are also shown.

INTRODUCTION

Silicon oxynitride has been extensively studied for different types of applications. In the area of optical coatings, it has been applied to rugate and broad band AR filters [1-4]. One of the benefits of this material is that a wide range of refractive indices can be achieved from a single deposition source by simply varying the deposition conditions. In the reactive sputtering process, any refractive index between those of SiO_2 (1.47 at 550 nm) and Si_4N_3 (2.03 at 550 nm) is possible just by changing the gas environment in the deposition chamber. Other processes such as PECVD, etc. yield similar results. Figure 1 shows the dispersive refractive indices of the two extreme silicon-oxynitride recipes achieved by reactive sputtering in our laboratory, namely silicon oxide (SiO_2) and silicon nitride (Si_3N_4).

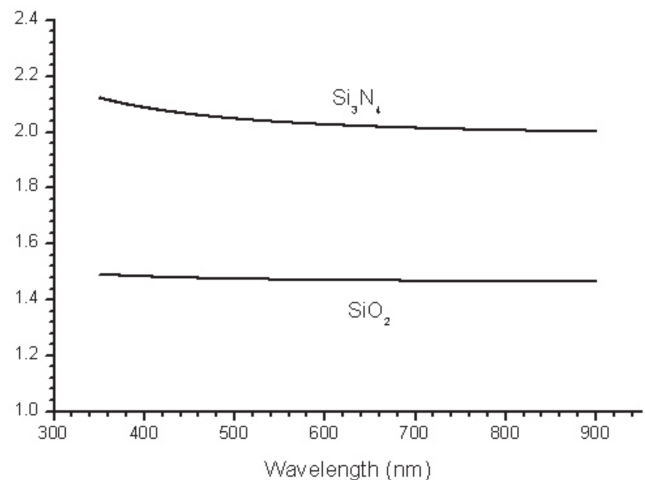

Figure 1: Refractive indices of SiO_2 and Si_3N_4 deposited by reactive AC magnetron sputtering.

Silicon oxynitrides are well suited to the realization of inhomogeneous filters but fabrication is challenging. An accurate knowledge of the refractive indices and deposition rate as a function of the deposition conditions is essential. The realization of complex filters requires advances in thin film monitoring technology and simulation software. Ideally the software should be able to acquire the material indices and the deposition rate continuously in real time. The advantage of the sputtering process is its relatively good repeatability and predictability in terms of deposition rate and refractive index. Therefore, with proper calibration, it is possible to fabricate fairly complex inhomogeneous coatings without a complicated monitoring system. In the following we report our recent results on the deposition and characterization of homogeneous silicon-oxynitride films, and their application to inhomogeneous filters.

DEPOSITION AND CHARACTERIZATION OF HOMOGENEOUS SILICON OXYNITRIDES

All the films discussed in this paper are deposited in a dual magnetron sputtering system fitted with pure silicon targets. AC power supplies drive the magnetrons at 40 kHz. The base pressure is about 5×10^{-8} Torr. Argon, nitrogen and oxygen are fed in the chamber through mass flow controllers that maintain the total gas pressure at 3.00 mTorr. In all cases, the O_2 flow is

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programmed according to the desired refractive index profile, while the Ar and N_2 gas flows are adjusted so that the total pressure is constant.

A series of homogeneous SiN_xO_y layers are deposited on quartz, BK7 glass and silicon substrates. The transmittance at normal incidence and ellipsometric data at several angles of incidence are measured ex-situ using a Lamda 900 spectrophotometer and a J. A. Woollam variable-angle spectroscopic ellipsometer (VASE). The relationship between the deposition conditions and the refractive indices is established by fitting the measured data to a dispersion model. Figure 2 shows the refractive indices as a function of O_2 flow. The dependency is more or less linear for low flows and becomes nonlinear as the flow increases, that is, when the film composition approaches SiO_2.

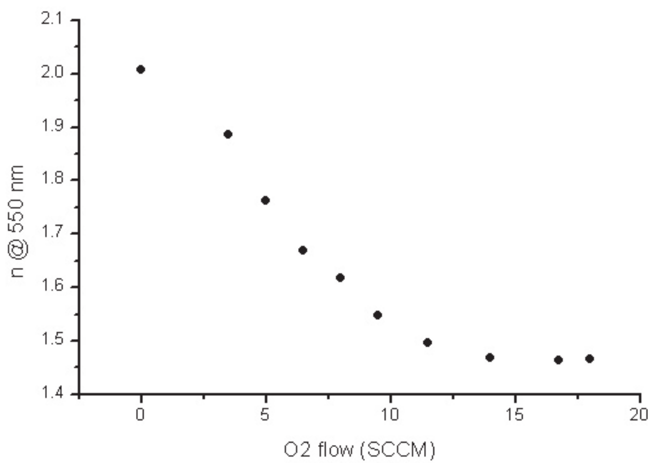

Figure 2: Refractive index of homogeneous SiNxOy films as a function of oxygen flow. The total pressure and the ratio between the Ar and N_2 gas flows are constant.

INHOMOGENEOUS COATINGS USING SILICON OXYNITRIDES

Our first test for the accuracy of the refractive-index calibration described in the previous section is a simple graded layer coated on a silicon wafer. Figure 3a shows the variable O_2 gas flow – a linear ramp from 3.0 to 11.0 SCCM with flat sections at each end. Figure 3b shows the refractive index profile generated using the calibration data. The indices are shown at the reference wavelength 550 nm. The optical performance of the coating was measured by ellipsometry in the spectral range 350-900 nm. For clarity, only partial data is plotted in Figure 3c. Specifically the ellipsometric □ parameter is shown for two angles of incidence. The solid lines in Figure 3c are calculated using the refractive index profile in Figure 3b. The calculation involves the fitting of only one parameter, the total coating thickness. The fitted thickness is within 1% from the original one. The small discrepancy can be interpreted as a result of a variation of the deposition rate during the deposition and/or small calibration errors. The fit between the measured and calculated data is excellent, including for data that is not shown in the figure, namely the ellipsometric parameter Ψ and other angles (55, 65, and 75 degrees). This suggests that the accuracy of the calibrations and the system stability are quite acceptable for this application.

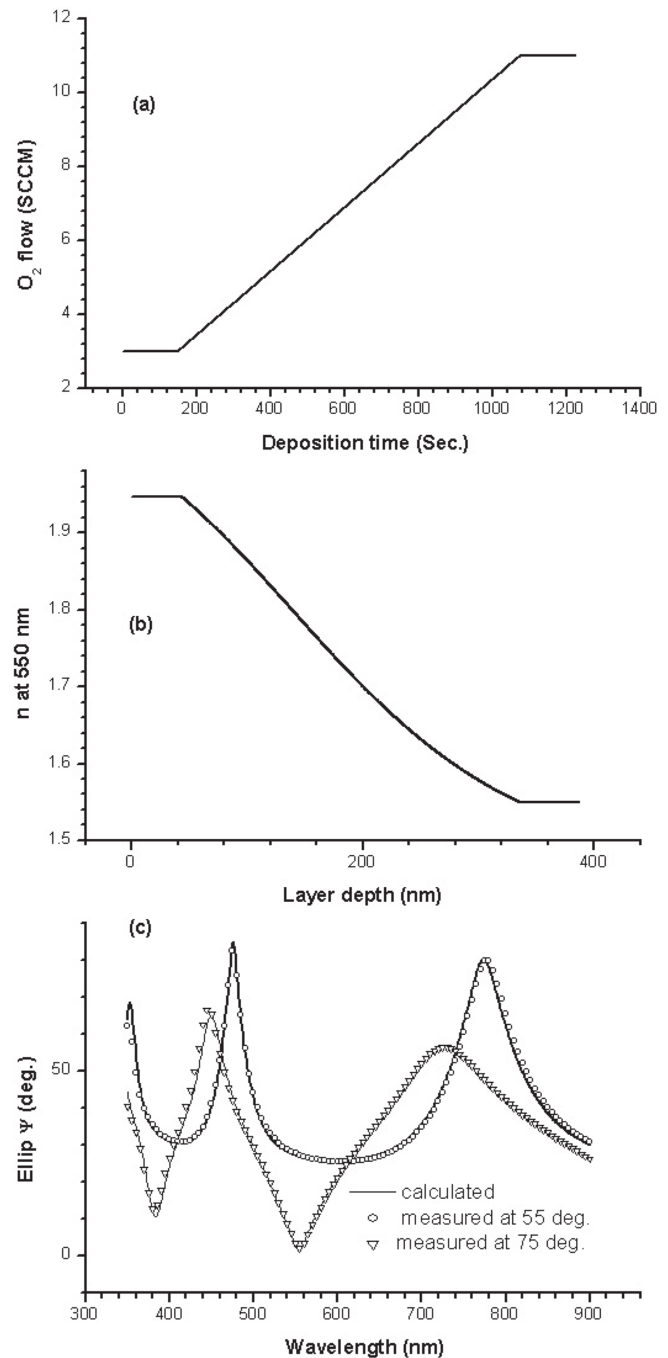

Figure 3: Simple SiN_xO_y coating generated by a linear O_2 gas flow. (a) O_2 gas flow profile. (b) Refractive index profile computed from the calibration data. (c) measured ellipsometric parameter Ψ and values calculated from the index profile in (b).

A more complex rugate-type filter was also made. Figure 4a shows its refractive index profile calculated from the O_2 flow, at the reference wavelength 550nm. The O_2 flow has the following format:

$$n=n0-d(D-d)A \sin(2\pi fd+C),$$

where d is the metric depth within the inhomogeneous layer starting at the substrate interface. A, f and C are adjustable parameters optimized so that the reflectance in the rejection band is as high as possible and the ripples elsewhere as small as possible. Figure 4b shows that the measured transmittance less that 1.5% in the rejection band and the ripple is less than 5%.

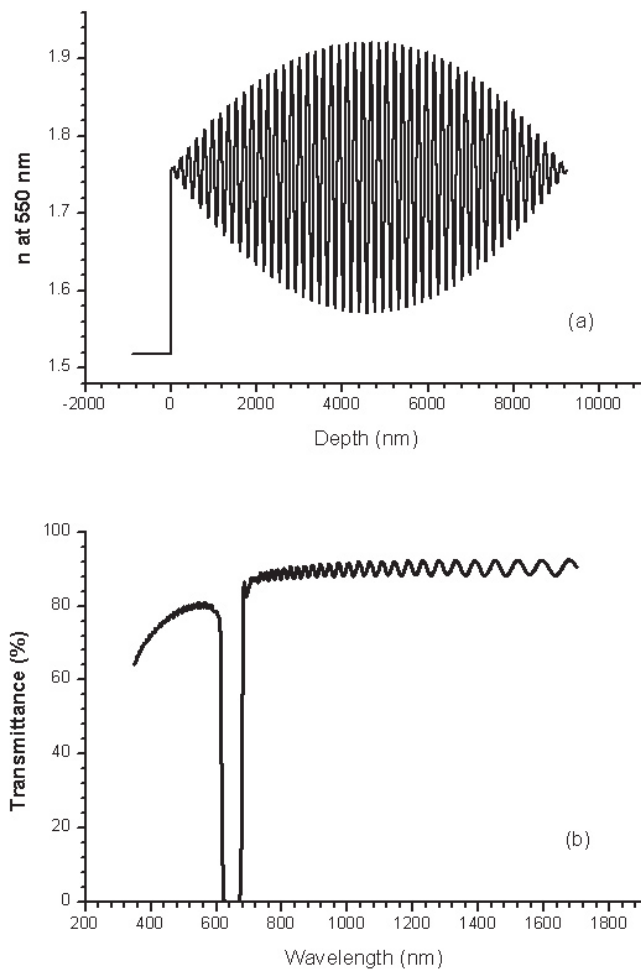

Figure 4: SiNxOy rugate filter. (a) O_2 gas profile. (b) Measured transmittance.

CONCLUSION

Homogeneous and inhomogeneous Silicon oxynitride films were reactively deposited in a dual magnetron sputtering system. The dependence of the refractive indices and deposition rates of homogeneous SiNxOy layers were systematically studied and the results applied to the fabrication of more complex rugate filters. The stability of the sputtering process made possible the realization of the inhomogeneous coatings without the need for an elaborate monitoring system. Further studies are under way and will be reported in future publications.

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