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CHARACTERIZATION OF SILICON NITRIDE WAVEGUIDE PRODUCED BY R.F. SPUTTERING TECHNIQUE

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ABSTRACT

Silicon nitride thin film is produced by radio frequency (R.F) Magnetron sputtering technique as an alternative to familiar chemical vapor deposition (CVD) technology. Rather than the conventional sputtering deposition parameters (i.e. r.f. power, sputtering gas pressure and sputter gas flow rate), in this work, the influence of distance between target to substrate was investigated. Experimental results show that target to substrate distance has a significant effect on growth rate and surface morphology of deposited thin films. Silicon nitride films deposited at target to substrate distance of 14 cm show the minimum surface roughness of 0.7 nm and high average transmission of 95% in the visible range. The deposited films exhibit the amorphous nature when characterized through XRD technique. The transparency of silicon nitride thin films in visible region points out its potential as an optical waveguide.

Keywords: magnetron sputtering, thin film deposition, silicon nitride.

INTRODUCTION

Waveguide based biosensors are becoming popular due to its non-contact detection. Waveguides are composed of high refractive index materials surrounded by low refractive index material (Kozma *et al*., 2014). Oxide/nitride/oxide (ONO) waveguides are under consideration for last two decades (Heideman *et al*., 1991). Recent advances in ONO waveguide only concentrates on the sensitivity and specificity but less attention being paid on fabrication technique. As an efficient thin film deposition process, low pressure chemical vapor deposition (LPCVD) is widely employed as a main technique to fabricate ONO waveguide (Nabok *et al*., 2003).

However the disadvantages of this technique lie in the hydrogen impurity incorporation which has a significant effect on the properties of waveguide material. An annealing process, normally at higher than 600 ^{0}C is inevitable to solve this problem (Sharma *et al*., 2014). These processes however cause thermal induced stress or surface roughness. Therefore sputtering technique can be suited as an alternative for thin film deposition at room temperature (Samavati, *et al.,* 2015). Sputtering technique is getting popular due to the availability of all types of target material which varies the selection of thin film coating.

Although thin film deposition by sputtering technique is not new, however the process parameters are not fully explored especially for specific application. Among the typical sputtering parameters are RF power, sputtering gas pressure and gas flow rate, the distance between target to substrate also plays an important role in thin film properties variation. To our knowledge, this parameter is not widely explored in the literature. In present study, the characterization of silicon nitride is done in order to investigate the effect of target to substrate distance. The deposited silicon nitride is run through elemental and structural analysis, growth rate study, morphological changes as well as the effect on optical properties specifically for waveguide applications.

EXPERIMENT

Preparation of silicon nitride films

Single sided polished P-type boron doped silicon wafer (with thickness 500 um and orientation <100>) were used as substrate. These substrates were coated first with 1.5 µm thick silicon oxide. All substrates were cleaned using organic solvents acetone and isopropyle alcohol (IPA) for ten minutes in ultrasonic bath then washed with de-ionized (DI) water (18 MΩ, Millipore USA) and dried with industrial grade nitrogen gas. In order to perform the spectroscopic investigation, the deposition was carried out on microscopic glass slides.

Silicon nitride thin films were deposited using RF magnetron sputtering system (Syntek, Korea) at room temperature. A stoichiometric Si_3N_4 circular target (Taewon Scientific, Korea) of 3” diameter and 3mm thickness was mechanically clamped to the water cooled R.F. electrode. The sputtering chamber was evacuated to 4.5×10^{-6}Torr to get high purity in thin films. It was achieved from a vacuum turbo molecular pump and backed by rotary mechanical pump. Argon (Ar) gas with 99.99% purity was introduced in the chamber as sputtering gas with a constant pressure of 5 mTorr. Ar flow rate was fixed at 80 sccm. R.F. power was kept constant at 300 W.

A pre-sputtering process of 3 minutes was performed before each deposition to clean the target prior to deposition. At this stage, substrate was covered to avoid any deposition. A series of experiments were performed at different target to substrate spacing ranging from 8cm to 14 cm. Table 1 shows the growth rate and average surface roughness of deposited thin films at various target to susbtrate distance.

Table-1. Numerical values of growth rate and average surface roughness at various target to substrate distance.

Sr. No	Target to substrate distance (cm)	Growth rate (nm/min)	Surface roughness (nm)
1	8	13.3	1.9
2	10	12.2	2.0
3	12	9.0	1.3
4	14	6.5	0.7

Characterization of silicon nitride films

The elemental analysis was carried out by energy dispersive x-ray (EDX) spectroscopy. The structure was investigated by X-ray diffraction (XRD) technique. Average growth rate was found by measuring thickness by surface profiler then divided by deposition time and the surface morphology was found by atomic force microscopy (AFM) technique. Spectroscopic measurements were done by UV-Vis spectrophotometer.

RESULTS AND DISCUSSION

X-ray diffraction analysis was performed with PanAlytical X-pert[3] X-ray diffracto-meter using Cu Kα radiation to investigate the crystal structure of deposited silicon nitride thin films.

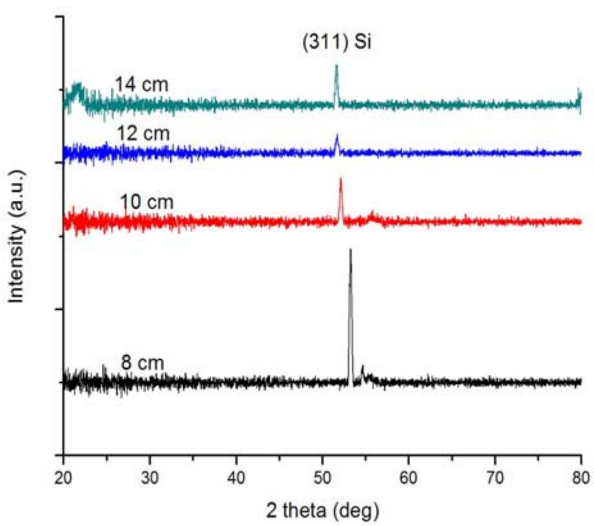

Figure-1. XRD results of silicon nitride thin films at various target to substrate distance.

Figure-1 shows the results for deposition at different target to substrate spacing. Only one peak was appeared which corresponded to (311) plane of bulk Si because for <100> wafer the (311) planes are oriented at approximately 55/2 = 27.5^0 from the wafer surface (Weiss *et al*., 2013). This shows that silicon nitride thin films are amorphous. The silicon nitride thin films were expected to amorphous as the deposition was carried out without any external heating. The weakly crystalline structure was observed in literature when the substrate was heated to 300 ºC (Tiwari and Chandra, 2011) while very high temperature i.e. >1000 ºC is required to produce crystalline (α-Si_3N_4) structure (Vila *et al*., 2003).

The confirmation of nitrogen content present in the samples was carried out with EDX analysis. Figure 2 shows the EDX result of silicon nitride thin films deposited at target to substrate spacing of 14 cm. The nitrogen peak confirms the formation of silicon nitride. The oxygen peak is due to the presence of silicon oxide buffer layer.

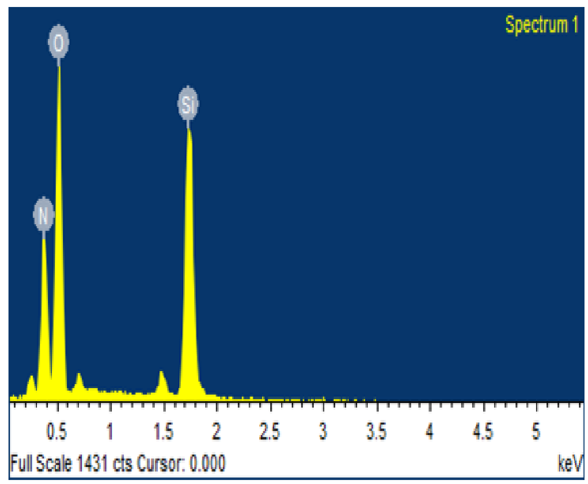

Figure-2. EDX plot of silicon nitride waveguide at target to substrate distance of 14 cm.

There is small variation observed in nitrogen percentage at different target to substrate distance as shown in table 2 revealing that film composition is dependent on target to substrate distance. More nitrogen content is detected at smaller target to substrate distance. At larger target to substrate distance not much difference was found in nitrogen content.

Table-2. Weight percentage of nitrogen in silicon nitride thin films at various target to substrate distance.

Sr.No	Target to substrate distance (cm)	Nitrogen %
1	8	14.2
2	10	10.34
3	12	7.55
4	14	8.16

Figure-3 shows the deposition growth rate as a function of target to substrate spacing. Growth rate was found to increase with decreasing target to substrate distance.

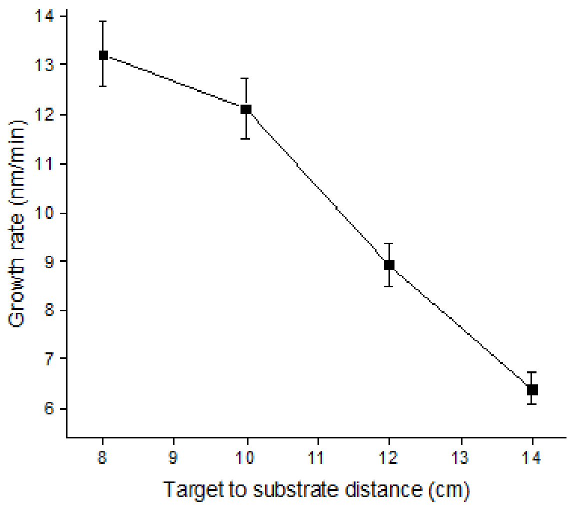

Figure-3. Growth rate of silicon nitride thin films at different target to substrate spacing.

This is due to increase in mean free path of sputtered atoms which enable them to reach the substrate with minimum collisions and higher kinetic energy. On the other hand, as the target to substrate distance increases the probability of scattering or back diffusion increases due to small mean free path i.e more number of collisions with Ar^{+} ions which results in energy loss of sputtered particles (Thaveedeetrakul *et al*., 2012).

Figure-4 shows the 3D surface images of silicon nitride thin films at various target to substrate distance. The measurements were done on the scan area of 3 µm x 3 µm. From the images, it is clearly seen the larger target to substrate distance produces the smoother surface.

Figure-5 shows the average surface roughness of deposited thin films as a function of target to substrate distance. As depicted from film growth rate, the variation in target to susbtrate distance at a fixed sputtering power changes the mean free path which effect the energy of sputtered atoms. The higher kinetic energy of sputtered atom enables them to improve their mobility which results in more homogenous and smooth surfaces.

At smaller target to substrate distance, more number of sputtered atoms reaches together at the substarte and instead of producing homogenous and smooth surface, the clusters formation is observed that increases the surface roughness.

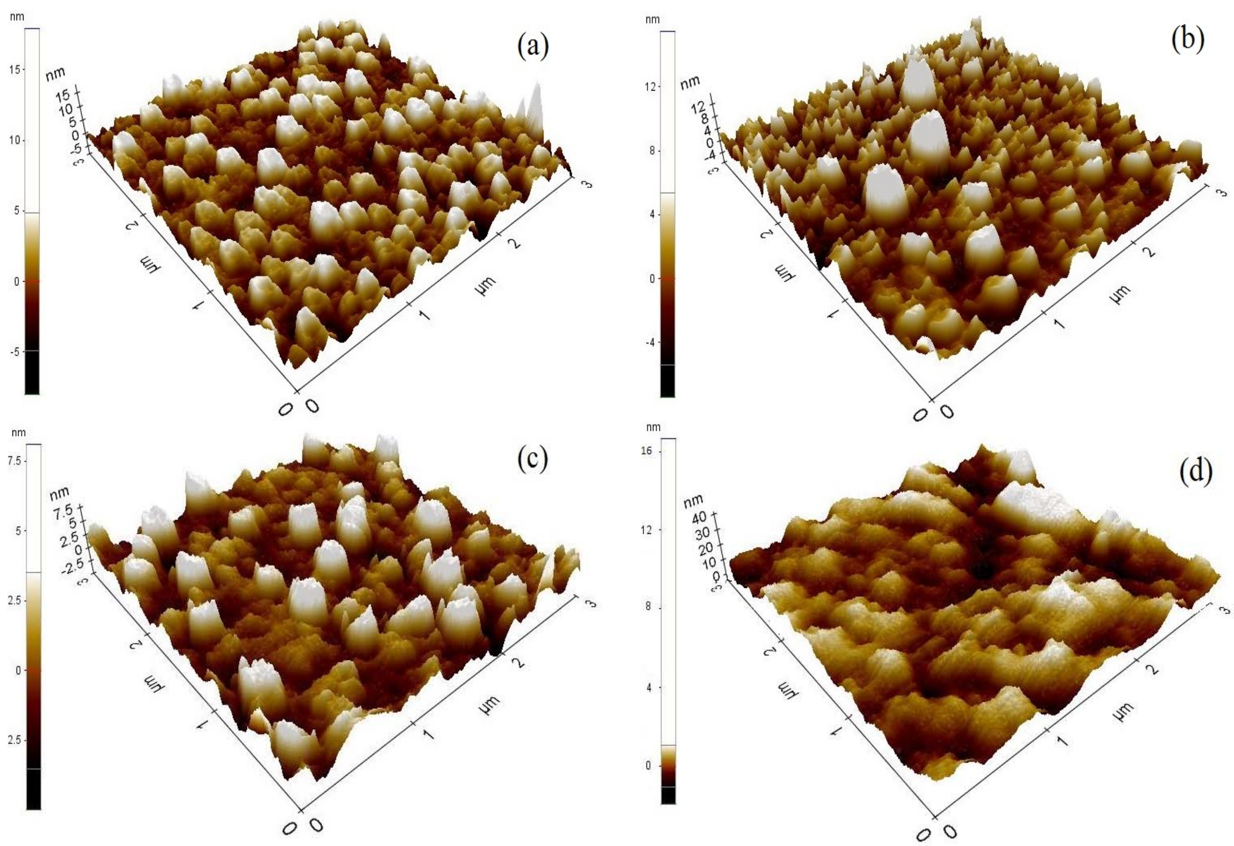

Figure-4. Surface morphology at various target to substrate spacing: (a) 8 cm (b) 10 cm (c) 12 cm (d) 14 cm.

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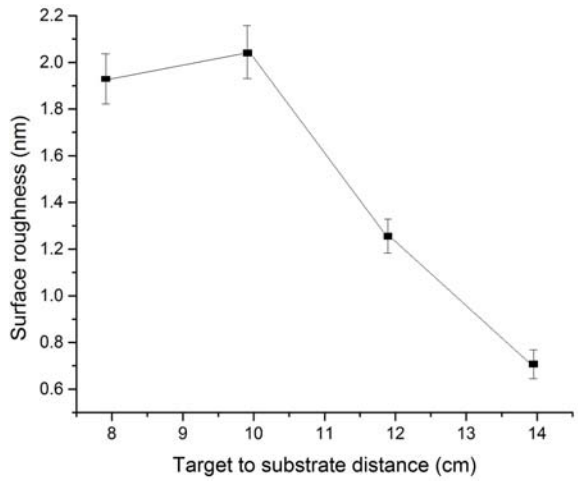

Figure-5. Average surface roughness of silicon nitride thin films at various target to substrate distance

High optical transmission in wavelength range of 400-700 nm agreed with the potential of deposited thin films for optical waveguide applications as shown in Figure-6. To achieve the transmission spectrum, clean glass slides were placed first in the spectrophotometer (Shimadzu, UV-1800) to subtract the transmission spectra from susbtrate.

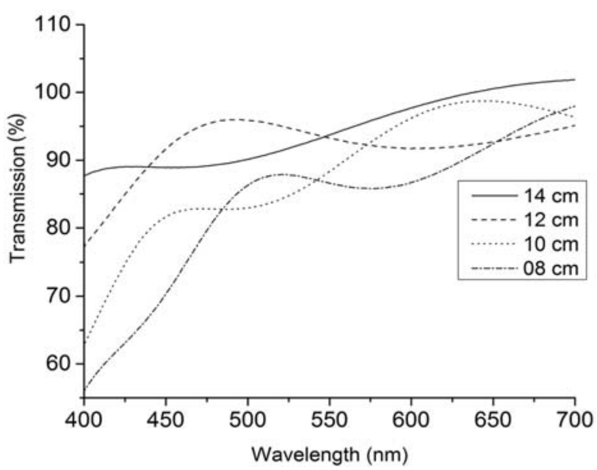

Figure-6. Transmission spectra at various target to substrate distance (a) 8 cm. (b) 10 cm (c) 12 cm (d) 14 cm

After that the transmission spectra of each deposited film was recorded which revealed the highest transmission from silicon nitride films deposited at the target to substrate distance of 14 cm. The relative high transmittance indicates low surface roughness and good homogeneity of thin film (Nair *et al*., 2011). It shows agreement with afm results.

CONCLUSIONS

Silicon nitride thin films were deposited by r.f magnetron sputtering technique as an alternative to conventional CVD technology. Rather than the conventional sputtering deposition parameters i.e. r.f. power, sputtering gas pressure and sputter gas flow rate, target to substrate spacing was varied and its influence was investigated for waveguiding applications. The elemental analysis confirmed the existence of silicon and nitrogen proved that the deposited thin film is silicon nitride.

XRD analysis revealed the amorphous nature of thin films independent of target to substrate spacing. Growth rate was found to be improved at lower target to substrate spacing. However, the surface roughness has the inverse relationship with target to substrate distance. Smoothest film have average surface roughness value of 0.7 nm was observed at largest target to substrate distance of 14 cm. Similar film showed the highest transparency in visible region.

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