Material Characterization of Silicon Dioxide Cladding for Photonic Devices

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ABSTRACT

The top cladding is an important factor when designing photonic devices. It has implications on waveguide properties such as mode guidance and optical loss. Silicon dioxide (SiO_2) is a commonly used cladding material for photonic devices as it has low optical loss and also enables a large refractive index contrast between the waveguide core and cladding. We performed an investigation into the material properties of SiO_2 thin films deposited by different methods, namely, plasma-enhanced chemical vapor deposition (PECVD) undoped silicate glass (USG), high density plasma (HDP), PECVD tetraethyl orthosilicate (TEOS), and low pressure chemical vapor deposition (LPCVD) TEOS. Material properties including refractive index, surface roughness, absorption, and film stress were characterized for the different SiO_2 cladding samples. Our results show that the surface roughness of HDP films was around 55 times better than that of USG films. In terms of film stress however, USG films had the lowest, whereas PECVD TEOS films were found to have the highest film stress, more than twice of that of the USG films. These findings indicate that when deciding on a particular deposition method for the SiO_2 cladding, besides considerations of thermal budget and device application, an equally important compromise needs to be made to give a balance among the various material properties.

Keywords: silicon dioxide, top cladding, material characterization

1. INTRODUCTION

Silicon dioxide (SiO_2) is a commonly used cladding material for photonic devices as it has low optical loss and enables a large refractive index contrast with commonly used materials such as silicon, silicon nitride. The large refractive index contrast allows for the smaller bend radii to achieve more compact devices. It has a large transparency window between 200 nm and 3500 nm [1], making it suitable for photonic devices operating in the ultraviolet and near-infrared applications.

The common methods of SiO_2 deposition for waveguide top cladding includes PECVD [2, 3], LPCVD [4], HDP [5]. These films are mainly silane-based, and TEOS-based. The different deposition method such as deposition temperature, gas precursors and their ratio, can affect the properties of the SiO_2 films. LPCVD films can offer good high quality conformal films with good sidewall coverage [6]. The wafers are deposited in batches and therefore have a high wafer throughput. However, it is a high temperature process (~800 °C) [7] and has a slower deposition rate. So LPCVD SiO_2 is not suitable as a top cladding material for actives devices with metal or implanted layers. On the other hand, PECVD can be performed at low temperature (<400 °C) and produces conformal and good quality films [8], making it more compatible and popular as a top cladding for various device applications. HDP [9] also has lower deposition temperature. The high-density plasma generated during HDP deposition allows for good gap filling. However it may also cause bombardment to the surface of the underlayer [10].

Other deposition methods of SiO_2 and engineered SiO_2 films have also been reported such as sputtering [11] and sol-gel [12]. There have also been reports of hydrogen-free silicon dioxide for top cladding as hydrogen bonds in SiO_2 can cause absorption loss and increase propagation loss of waveguides [13]. They used hydrogen free precursors such as $SiCl_4$ [14] and deuterated silane [15].

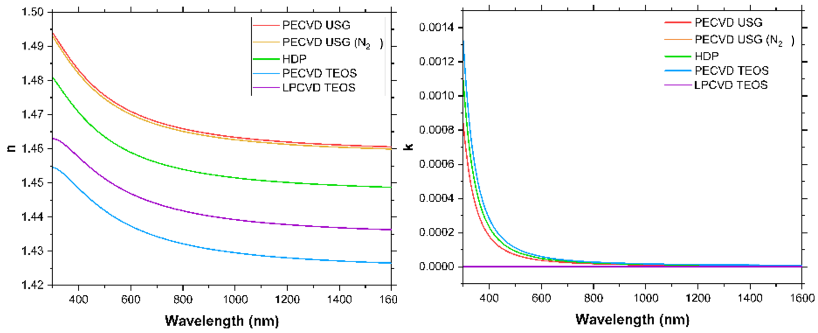
In this study, we investigated SiO_2 thin films deposited by five different methods on Si substrate; PECVD USG (two different type, one with extra N_2 as precursor), HDP, PECVD TEOS, and LPCVD TEOS. The refractive index, extinction coefficient, surface roughness, film stress, wafer bowing and absorption spectrum were evaluated to determine the most suitable SiO_2 deposition method for the top cladding of photonic devices.

2. RESULTS

2.1 Refractive Index and Extinction Coefficient (*n*, *k*)

The refractive index (*n*) and extinction coefficient (*k*) of the SiO_2 films were extracted from the ellipsometry measurements. Fig. 1a and b shows the *n* and *k* of the films between 300 nm and 1600 nm modeled using the Cauchy model for transparent films. The refractive index of the two PECVD USG films showed the highest refractive index of ~1.46 at 1550 nm, whereas the TEOS-based films had the lower refractive index of ~1.43 at 1550 nm. LPCVD TEOS and N_2O PECVD USG films also had the lowest *k*, as shown in Fig. 1c.

Using a higher refractive index top cladding gives a lower refractive index contrast between the waveguide core and cladding and can therefore reduce the scattering loss caused by the surface roughness of the waveguide. A lower refractive index contrast can also improve the coupling efficiency from the waveguide to an optical fiber. On the other hand, higher refractive index contrast allows for better mode confinement within the waveguide to achieve a smaller device footprint and higher integration density.



SiO_2 Film	n @ 1550 nm	k @ 1550 nm
PECVD USG	1.46068	5.67E-6
PECVD USG (N_2)	1.46003	0
HDP	1.44885	7.37E-6
PECVD TEOS	1.42665	8.92E-6
LPCVD TEOS	1.43641	0

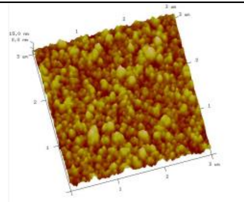
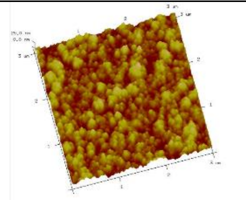
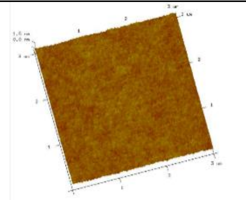
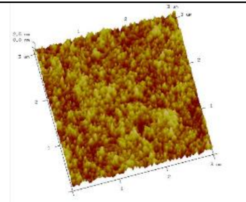
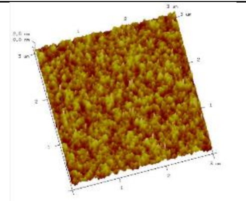
a) b) c)

Figure 1. a) Refractive index (*n*) and b) extinction coefficient (*k*) of SiO_2 between wavelength range of 300 - 2300 nm and c) *n* and *k* at 1550 nm.

2.2 Surface Roughness

Another material property investigated was the surface roughness; it is important as it may cause scattering loss. The surface roughness of the SiO_2 films was measured using an atomic force microscope (AFM) over a 1 µm by 1 µm scan area. The root mean square (rms) surface roughness results in Table 1 show that HDP films and PECVD USG have the lowest and highest surface roughness among the films studied, respectively, with that for TEOS films in between. This matches with previous report of similar films [16].

Table 1. rms surface roughness of the SiO_2 films measured using AFM (1 µm by 1 µm scan area)

PECVD USG	**PECVD USG (N_2)**	**HDP**	**PECVD TEOS**	**LPCVD TEOS**
2.56 nm	4.67 nm	0.085 nm	0.392 nm	0.468 nm
				

2.3 Film Stress and Wafer Bowing

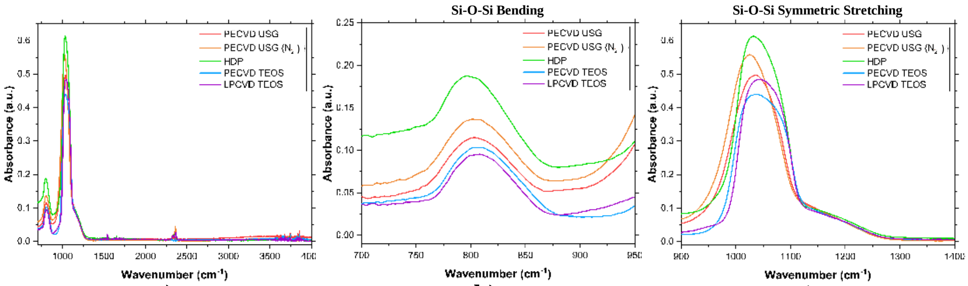
Film stress and wafer bow measurements were performed on the deposited thin film using a film stress measurement system, shown in Table 2. Four line scans were taken across the diameter of the wafer. The film stress of PECVD TEOS was found to be nearly twice that of PECVD USG films. The negative bow height indicates that the films stress is compressive. For LPCVD TEOS, the stress was lowest and the bow height was positive. However, this is not representative of the actual film stress as the LPCVD process deposits the film on both sides of the wafer, and therefore balances out the film stress. To accurately determine the LPCVD film stress, the film on the back side of the wafer has to be removed. The higher film stress of HDP and TEOS films may indicate a higher density film. However higher top cladding film stress may affect the birefringence of the waveguide.

Table 2. Stress and wafer bowing measurements of the different SiO_2 thin films (over four line scans across the diameter of the wafer)

SiO_2 Film	**Stress (MPa)**	**Bow Height (µm)**	**Bow Radius (m)**
PECVD USG	92.81	-42.53	117.98
PECVD USG (N_2)	72.17	-52.39	95.51
HDP	115.40	-20.29	248.43
PECVD TEOS	242.57	-175.93	28.43
LPCVD TEOS	7.90	24.71	204.16

2.4 Absorption Spectrum

Material absorption contributes to higher propagation loss in a waveguide. Fourier transform infrared spectroscopy (FTIR) was used to determine the bond absorption of the SiO_2 films between 700 cm^{-1} and 2000 cm^{-1}. The main absorption bonds observed in Fig. 2 were Si-O-Si bending (peak at around 798 cm^{-1} [17]) and Si-O-Si symmetric stretching (peak at around 1030 cm^{-1} [17,18]). PECVD TEOS films were observed to have the low absorption for these two absorption bond, whereas HDP films showed the highest. The peaks observed at around 2330 cm^{-1} are believed to be due to defect in our FTIR tool. A Si-O-Si peak at around 1080 cm^{-1} is indicative of a stoichiometric SiO_2 film [19], Fig. 2c shows that LPCVD TEOS film had better stoichiometry than the other films.



a) b) c)

Figure 2. FTIR absorption spectrum of the SiO_2 films a) between 700 cm^{-1} and 4000 cm^{-1}, zooming into the two main observed absorption bonds b) Si-O-Si bending bond and c) Si-O-Si symmetric stretching bond

3. CONCLUSIONS

We have investigated the material properties of five SiO_2 thin films deposited by different methods. Material properties including refractive index, surface roughness, absorption spectrum, and film stress were characterized. Our findings indicate that when choosing among SiO_2 cladding deposition method, besides traditional considerations such as thermal budget and device application, achieving a balance among the various material properties is equally imperative.

ACKNOWLEDGEMENTS

We acknowledge the funding support from Agency for Science, Technology and Research (C220415015).

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