Integrated Photonic Devices with Silicon Oxycarbide

Faisal Ahmed Memon*[a,b,c], Francesco Morichetti[a,c], Andrea Melloni[a,c]
[a]Dipartimento di Elettronica, Informazione e Bioingegneria (DEIB), Politecnico di Milano, via Ponzio 34/5, 20133 Milano Italy; [b]Dept. of Telecommunications Engineering, Mehran University of Engineering & Technology, Jamshoro 76062, Pakistan; [c]Polifab, Politecnico di Milano, via Giuseppe Colombo 81, 20133 Milano Italy

ABSTRACT

In this paper, we report on the potential of silicon oxycarbide (SiOC) for integrated photonic applications. SiOC films are developed by reactive radio frequency magnetron sputtering from a silicon carbide (SiC) target in the presence of argon and oxygen gases. The optical properties of the developed SiOC film are characterized with spectroscopic ellispometry over a broad wavelength range 300-1600 nm. The refractive index n of the SiOC film is 2.2 at wavelength λ = 1550 nm and the extinction coefficient k is estimated to be less than 10^{-4} in the near-infrared region above 600 nm. The topography of SiOC films is studied with AFM showing very smooth surface, with rms roughness of 0.24 nm. SiOC film with refractive index n = 2.2 is then patterned by direct laser-writing lithography and etched with reactive ion etching to realize high contrast SiOC core optical waveguides for integrated photonics applications. The waveguide losses are characterized at telecommunication wavelength λ = 1550 nm. As an example of photonic integrated devices integrating SiOC films, a microring resonator is fabricated where a SIOC layer is used as a coating material for the core of a silicon oxynitride (SION) waveguide.

Keywords: Silicon oxycarbide, spectroscopic ellispometry, thin films, optical materials, high contrast optical waveguides, integrated optics, RF sputtering

1. INTRODUCTION

Materials whose refractive index can be tailored by changing fabrication process parameters are of great interest for photonics applications. However, dielectric platforms such as SiO_2, SiON and SiN are limited in their refractive index tunability. Silicon oxycarbide (SiOC) is a glass compound that has a potential of wide refractive index tunabilty extending from silica (n = 1.45) to silicon carbide (n = 3.0). A high refractive index is useful for the large integration scale of photonic devices on a single chip as the light can be tightly confined in waveguide core, thus enabling smaller bending radii[1]. SiOC has received significant attention in the scientific community and it has been studied for a variety of applications including Li-ion batteries[2], photoluminescence[3], electroluminescence[4], and low-k interlayer dielectric[5]. Despite excellent material qualities, SIOC is yet not explored for realizing passive devices for integrated photonics.

In this paper, SiOC films are developed with radio frequency magnetron sputtering from a SiC target in the presence of argon (Ar) and oxygen (O_2) gases at room temperature. The prepared films are characterized with variable angle spectroscopic ellipsometry, atomic force microscopy and scanning electron microscopy. The refractive index n of the deposited SiOC films increases from 1.8 to 2.2 at 1550 nm as a function of deposition conditions. The extinction coefficient k of all the deposited SiOC films is estimated to be less than 10^{-4} above λ = 900 nm. SiOC films with n = 2. 2 and thickness = 175 nm were used to fabricate high contrast optical waveguides using direct laser-writing lithography and reactive ion etching (RIE) techniques. The optical waveguides are covered by PECVD SiO_2 (n = 1.45). The optical waveguides are characterized at standard telecom wavelength λ = 1550 nm, demonstrating the suitability of sputtered SiOC for integrated optics applications. Further, we demonstrate the possibility to integrate SiOC technology in photonic integrated devices by realizing a microring resonator employing a silicon oxynitride (SiON) waveguide coated with a SiOC film.

*faisalahmed.memon@polimi.it; phone +39 392 787 1498; photonics.deib.polimi.it

2. FILM DEPOSITION AND CHARACTERIZATION

2.1 Film Deposition by Sputtering

SiOC films have been developed by RF magnetron sputtering from a silicon carbide (SiC) target. Figure 1 shows the schematic of the sputtering deposition technique, which is widely used to develop high quality films with good adhesion on substrates[6]. Bombardment of argon (Ar) ions results in the ejection of Si and C atoms that react with oxygen (O_2) gas to yield SiOC molecules. These molecules accumulate on Si substrate surface and form a thin SiOC layer.

SiOC thin films were deposited on silicon (100) with 6 μm SiO_2 substrates. The chemical composition, and hence the refractive index, of SiOC films is tuned by controlling the O_2 gas flow in the sputter chamber by mass flow controller; the deposition rate can be adjusted by optimizing the RF power (in the films discussed in this contribution RF power is 350 W). Further details on deposition process and the obtained deposition rate of sputtering are reported in previous contributions[7-10].

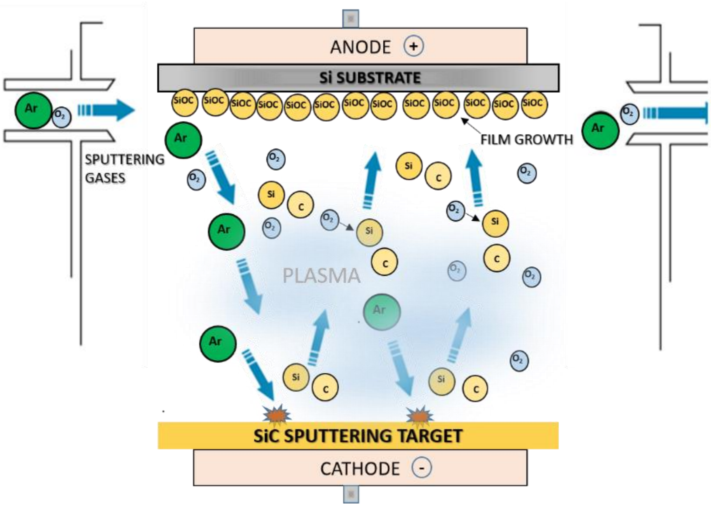

Figure 1. Reactive RF magnetron sputtering scheme for the deposition of SiOC films.

2.2 Ellipsometry

The optical properties of the deposited SiOC thin films were investigated with variable angle spectroscopic ellipsometer (VASE J. A. Woollam Inc. USA). The ellipsometric data are acquired at multiple incidence angles (65°, 70° and 75°) with a wavelength step size of 10 nm over a broad spectrum from 300 nm to 1600 nm. The ellipsometry measures the change in polarization state of the light reflected from the surface of the film/substrate under investigation. The measured quantities are represented as ψ and Δ angles, which define the ratio of Fresnel reflection coeffcients R_p and R_s for parallel (p) and normal (s) polarized light as[11],

$$\frac{R_p}{R_s} = \tan\psi \exp(i\Delta). \tag{1}$$

Ellipsomteric measurements from the sample were carried out considering the possible depolarization originated by thickness non-uniformity and surface roughness. Since ellipsometry is an indirect technique, an optical model is necessary to obtain optical constants of the film/substrate. A four-layer film/substrate stack including surface-roughness, SiOC thin film, SiO_2 layer, Si substrate as shown in Fig. (2) was used as a model for our samples and to extract the optical constants

n and k of the SiOC films. The measured ψ and Δ spectra were fitted in a commercial WVASE32[12] software using the optical model. A Tauc-Lorentz (TL) model[13] , which is intrinsically Kramers-Kronig[12,13] consistent, was used to represent the SiOC film and extract the extinction coefficient k and refractive index n.

Since ellipsometry is sensitive to surface roughness conditions, surface roughness layer was added to improve fit and MSE. The surface roughness SR layer based on effective medium approximation (EMA)[12] composed of 50 % material and 50 % voids is used to simulate the surface roughness on SiOC films. The SR layer is ellipsometry equivalent of AFM in a way that it gives peak-to-valley roughness. The tabulated optical constants of Si substrate and SiO_2 were used from the WVASE® database[12]. The parameters of the Tauc-Lorentz oscillator were declared fit in the model and regression analysis algorithm was run to minimize the global mean squared error (MSE).

The refractive index n and extinction coefficient k spectra of SiOC film are reported in Fig. 3. The refractive index spectral curve is decreasing as a function of wavelength from UV to near-IR region, as expected from a typical dielectric medium. The refractive index of SiOC film at telecom wavelength $\lambda = 1550$ nm is $n = 2.2$. The extinction coefficient k is less than 10^{-4} above $\lambda = 600$ nm in all the SiOC films as can be seen in Fig. 3. The ellipsometric measurement cannot provide a more accurate evaluation of the material loss; yet, from this information we can infer that material absorption $\alpha = 4\pi k/\lambda$ is less than 10 dB/cm, suggesting the possibility to use this material for guided wave applications. Further the refractive index can be varied over a wide range, enabling the possibility to tune the refractive index of the waveguide for specific applications. The energy band gap E_g of SiOC film has been determined by using absorption spectra measured with spectroscopic ellipsometry and applying Tauc relation $(\alpha h\nu)^2 = h\nu - Eg$, where α is absorption coefficient, $h\omega$ is photon energy[14]. The direct bandgap of the silicon oxycarbide film is calculated as $E_g = 3.4$ eV.

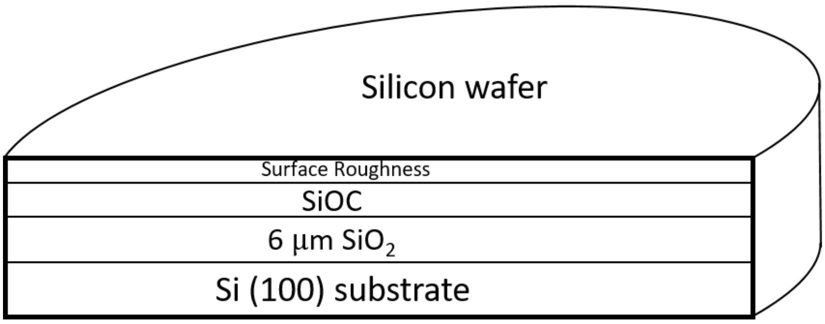

Figure 2. Optical model used for fitting ellipsometric data and deriving SiOC optical constants.

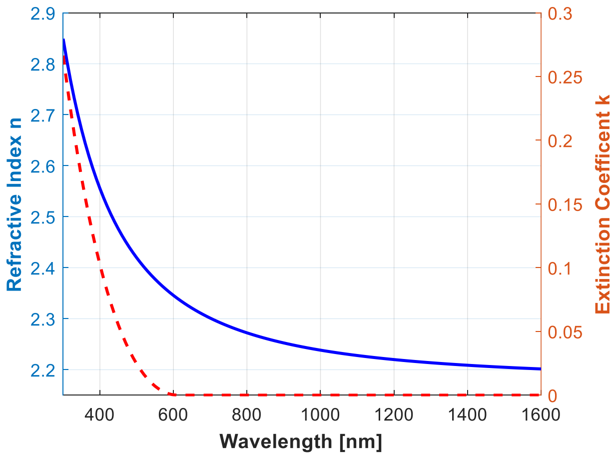

Figure 3. Refractive index n and extinction coefficient k spectra of SiOC film extracted from ellipsometric measurements.

2.3 Film Structure

Morphology of the SiOC film and waveguides cross section was analyzed with scanning electron microscope (SEM, LEO 1525). Being a dielectric material, the SiOC film was coated with thin layer of metal (≈ 2 nm) to avoid electrons charging effect. High-resolution images were captured by accelerating electrons at a voltage of 5 kV and collected signal from in-lens detector while keeping the distance around 6 mm between the SiOC sample and the electron gun. Figure 4(a) shows the cross sectional SEM micrograph of the SiOC film, which looks compact and with no porosity.

The film topography was investigated with tapping mode atomic force microscopy (Keysight 5600LS AFM system). The SiOC film surface was probed over an area of 25 µm^2 to quantify the rms roughness. Figure 4(b) shows the AFM 2D image of the SiOC film with n = 2.2. The rms roughness of the film is measured as 0.24 nm, that is comparable to substrate roughness. In comparison to [11], SiOC film structure and roughness is improved.

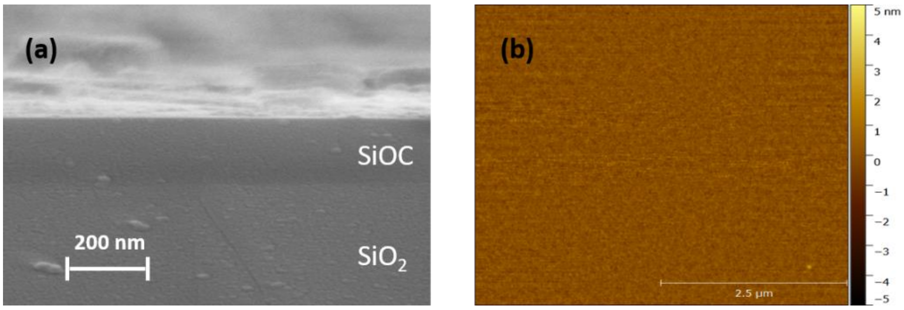

Figure 4. a) SEM micrograph and b) AFM 2D image of silicon oxycarbide film with n = 2.2.

3. INTEGRATED DEVICES FABRICATION AND ANALYSIS

3.1 Photonic Devices Fabrication and Characterization

SiOC films deposited on Si with 6 µm SiO_2 substrate were used for realizing photonic waveguides. The deposited film has a refractive index n = 2.2 at wavelength λ = 1550 nm and thickness = 175 nm. The waveguides in SiOC were patterned using direct laser-writing lithography and reactive ion etching (RIE) processes as follows. First, the SiOC sample was spin coated with photoresist AZ 5214 E at a speed of 6000 rpm for 72 s and soft baked on a hot plate at 110 °C for 50 seconds. Then the sample was placed in Laser Writer (Heidelberg MLA100) and exposed with a high-power light source operating at wavelength λ = 365 nm. For the inverse lithography, the photoresist was baked at 125 °C for 55 s and then exposed using I-line 365 nm mercury arc lamp emitting power of 1000 W for 80 s. The waveguide patterns were developed in AZ MIF 726 developer to remove the photoresist from the unwanted parts. A controlled ICP-RIE etching process using gas chemistry of CHF_3 (100 sccm) and O_2 gases (5 sccm) was used to transfer the pattern to SiOC film. The chamber pressure was set at 5 mTorr with a gas mixture of CHF_3 (100 sccm) and O_2 (5 sccm). ICP power was set at 250 W with RF power at 50 W. The SiOC was etched for 20 minutes and the obtained etching rate was 9 nm/min. The fabricated SiOC waveguides were covered with 2 µm PECVD silica.

Figure 5 shows the cross section and SEM micrograph of uncovered SiOC photonic waveguide. The rectangular core section has dimensions of the width = 2.72 µm and height = 175 nm. To evaluate the optical properties of the SiOC waveguides, several waveguides with different widths from 2 to 4 µm were fabricated and measured. The losses were characterized for TE and TM polarizations with cut back technique. A light wave from a tunable laser source operating around the telecommunication wavelength 1550 nm was coupled into waveguides by using tapered lensed fibers and the output power was measured with an optical power meter. The polarization state of the light wave was selected with an external polarization controller. The propagation losses of TE and TM polarizations estimated are around 2 dB/cm.

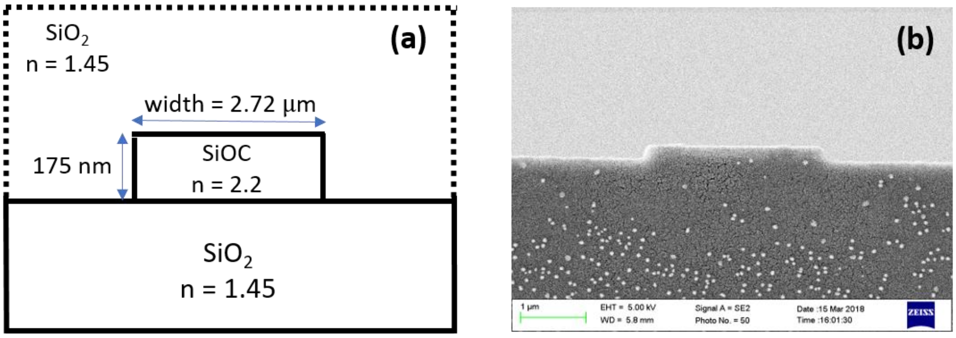

Figure 5. a) cross section and b) SEM image of SiOC core (n = 2.2) on a Si substrate with 6 µm SiO_2, before upper cladding deposition.

To realize etch-less ring structure, SiOC layer with n = 2.2 was deposited by RF sputtering on a silicon oxynitride (SiON) core micro-ring resonator. Figure 6(a) shows the cross section and optical photograph of SiON ring resonator coated with SiOC layer. The SiOC layer has thickness of d = 60 nm and width of sidewalls are about 40% of the top layer. The SiON[15] is a rib shaped core with width = 2.5 µm, height = 1.8 µm and rib height = 0.4 µm. The radius of the ring is 555.3 µm, coupler length is 260 µm and the length of the ring cavity is 4.009 mm. After coating with SiOC layer, the sample was covered with PECVD silica. The SiOC coated SiON ring resonator was measured across a 10 nm spectrum from 1545 nm to 1555 nm as shown in Figure 6(b). The free spectral range of SiOC coated SiON ring is 380.7 pm and the group index is n_g = 1.57. The SiON ring resonator without SiOC layer had a FSR of 400 pm and n_g = 1.5[15]. Therefore, the SiOC layer deposition has significantly increased the group index and changed the FSR of ring resonator.

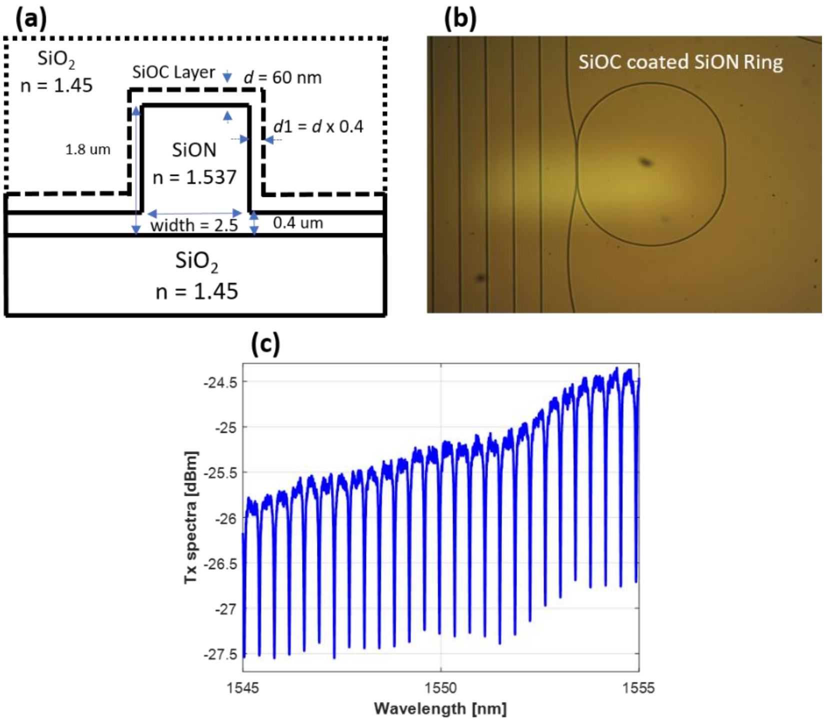

Figure 6. a) Cross section, b) SEM picture and c) spectral response of SiOC coated SiON Ring resonator.

4. CONCLUSION

In conclusion, we have presented a study on the characteristics of silicon oxycarbide film and devices. The optical properties of SiOC film are reported and SiOC film with refractive index *n* = 2.2 has extinction coefficient well below 10^{-4} above the wavelength of 600 nm. The SiOC film shows good transparency in near-infrared region that indicates the potential of SiOC for photonics integration applications. The structure and roughness of the deposited film has been improved. We have demonstrated for the first time the sputtered SiOC core photonic waveguides with *n* = 2.2. The propagation losses of SiOC waveguides are characterized, which exhibit similar propagation losses for TE and TM polarized light of 2 dB/cm. SiOC coated SiON ring resonators are also demonstrated.

ACKNOWLEDGEMENT

F. A. Memon acknowledges the financial support in his PhD from European Union under Erasmus Mundus 'LEADERS' project. This work was supported in part by Fondazione Cariplo under Project Advanced Control Technologies for Integrated Optics (ACTIO) – Rif. 2016-0881. This work was partially performed at Polifab, the micro- and nanofabrication facility of Politecnico di Milano (www.polifab.polimi.it).

REFERENCES

[1] Melloni, A., Costa, R., Cusmai, G. and Morichetti, F., "The role of index contrast in dielectric optical waveguides," Int. J. of Materials and Product Technology, 34, 4 (2009)

[2] Pradeep, V. S., Graczyk-Zajac, Riedel, M. R. and Soraru, G. D., "New Insights in to the Lithium Storage Mechanism in Polymer Derived SiOC Anode Materials," Electro. Acta, 119, 78-85 (2014).

[3] Peng, Y., Zhou, J., Zheng, X., Zhao, B. and Tan, X., "Structure and photoluminescence properties of silicon oxycarbide thin films deposited by the rf reactive sputtering," Int. J. Mod. Physics B, 25, 2983 (2011).

[4] Ding, Y., Shirai, H., and He, D., "White light emission and electrical properties of silicon oxycarbide-based metal–oxide–semiconductor diode," Th. Sol. Films, 519(8), 2513-2515 (2011).

[5] Kim, H. J., Shao, Q. and Kim, Y.-H., "Characterization of low-dielectric-constant SiOC thin films deposited by PECVD for interlayer dielectrics of multilevel interconnection," Sur. and Coat. Technology, 171, 39-45 (2003).

[6] Ryan, J. V. and Pantano, C. G., "Synthesis and characterization of inorganic silicon oxycarbide glass thin films by reactive rf-magnetron sputtering," J. Vac. Sc. & Technology A, 25, 153-159 (2007).

[7] Memon, F. A., Morichetti, F., Abro, M. I., Iseni, G., Somaschini, C., Aftab, U. and Melloni, A., "Synthesis, Characterization and Optical Constants of Silicon Oxycarbide," EPJ Web Conf., 139, 00002 (2017). DOI: 10.1051/epjconf/201713900002

[8] Memon, F. A., Morichetti, and Melloni, A., "Waveguiding Light into Silicon Oxycarbide," Appl. Sci., 7(6), 561 (2017). DOI: 10.3390/app7060561

[9] Memon, F. A., Morichetti, and Melloni, A., "Silicon Oxycarbide Waveguides for Photonic Applications," Journal of Physics Conference Series 961(1), (2018)

[10] Memon, F. A., Morichetti, and Melloni, A., "Exploring silicon oxycarbide films for photonic waveguides," 15th IBCAST Conf., Islamabad, 43-44, (2018), doi: 10.1109/IBCAST.2018.8312182

[11] H. Fujiwara, [Spectroscopic Ellipsometry: Principles and Applications], Wiley, West Sussex, UK, (2007).

[12] "Guide to using WVASE® spectroscopic ellipsometry data acquisition and analysis software," J. A. Woollam Co., Inc., chap. 4, 16-20 & chap. 17, 21-31 (1994-2012).

[13] Jellison, G. E. and Modine, F. A., "Parameterization of the optical functions of amorphous materials in the interband region," App. Phys. Letters, 69, 371-373 (1996), Erratum, App. Phys. Letters, 69, 2137 (1996).

[14] J. Tauc., "Optical properties and electronic structure of amorphous Ge and Si," Mat. Res. Bull. 3, 37-46 (1968).,"

[15] A. Melloni, R. Costa, P. Monguzzi, and Mario Martinelli, "Ring-resonator filters in silicon oxynitride technology for dense wavelength-division multiplexing systems," Opt. Lett. 28, 1567-1569 (2003).