MJFAS MALAYSIAN JOURNAL OF FUNDAMENTAL AND APPLIED SCIENCES
PRINT ISSN: 2289-5981 | ONLINE ISSN: 2289-599X

RESEARCH ARTICLE

Introducing SiOC as novel dielectric platform for photonic integration

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Article history
Received 4 March 2019
Revised 28 May 2019
Accepted 1 August 2019
Published Online 2 February 2020

Abstract

In this paper, we explore the potential of silicon oxycarbide (SiOC) as a novel dielectric platform for integrated photonics and present photonic waveguides. The interesting features of SiOC are its wide tunable window of refractive index and low absorption, that are considered key for large scale photonic integration. It is possible to tune SiOC refractive index from silica glass (1.45) to silicon carbide (3.2) that allows to realize a myriad of photonic passive devices. We have prepared SiOC thin films by employing reactive RF sputtering technique and examined their structural and optical properties using several techniques such as SEM, AFM, ellipsometry, profilometry, and prism coupling. For the first time, SiOC thin films with index of refraction of 1.554 at the standard telecom wavelength 1.55 µm are exploited for the fabrication of photonic waveguides and the propagation losses around 0.37 dB/mm are measured. SiOC photonic waveguides exhibit relatively higher index contrast with silica cladding when compared to traditional Ge-doped silica platform.

Keywords: Silicon oxycarbide, sputtering, photonic waveguides, integrated photonics.

INTRODUCTION

Integrated photonics has progressed at an exponential rate over the last few decades. Photonics is considered as the central player for robust, reliable, and ultra-high-speed telecommunications. Besides, it has pushed forward several other fields including entertainment, biomedical, sensing, and agriculture. Several materials have been exploited to realize photonics devices and circuits. However, the mature platforms namely silica, silicon nitride, silicon, and indium phosphide have majorly limited refractive index tunable window. Although Ge-doped silica platform is a well-known optical material for its lowest absorption in the telecom window, its refractive index is limited between 1.45 and 1.47 yields large footprint integrated circuits. Silicon oxynitride (SiON) anther material platform has been demonstrated to have tunable refractive index (n) between silica glass and silicon nitride. Unfortunately, the scientists have encountered two drawbacks of this material: (1) SiON exhibits large peak of absorption in the third optical communication window at 1510 nm, and (2) fractures are observed as refractive index n gets larger than 1.5 which confine its use to low index material similar to silica glass [1-4]. Silicon oxycarbide (SiOC), a novel glassy compound, has potentially wider refractive index tunable window that extends from silica glass to a-SiC [5,6]. The continuously tunable refractive index window is essential from the point of view of large-scale integration of devices on a chip. Since the light wave can be bound in small core of waveguides with higher contrast, this allows it to have very small bending radii [7]. Fig. 1 portrays the picture of the state-of-the-art of material platforms used in photonics with SiOC highlighted as a promising candidate.

SiOC has attracted significant attention from the scientific community around the world. With versatile material properties, SiOC has been exploited in several applications that range from Bloch multilayer EM structures [8], photo-luminescence [9], lithium-ion batteries [10], to inter-layer dielectric for micro-electronics [10]. However, SiOC with appealing material properties has not been tested for photonic integration applications.

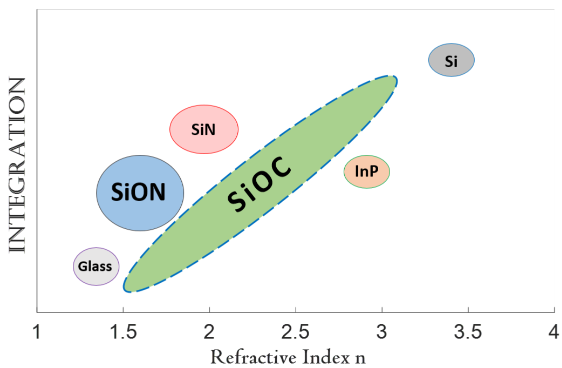

Fig. 1 State-of-the-art of photonics technologies including silicon oxycarbide (SiOC) that is highlighted as a potential candidate.

In this paper, we have deposited SiOC thin films using reactive RF magnetron sputter technology. Sputter-deposited SiOC thin films were characterized using several techniques to analyze the optical and physical properties. SiOC thin films were further exploited and used as core for the demonstration of photonic waveguides with a higher refraction index of 1.554 surrounded by silica cladding. The propagation losses of the SiOC photonic waveguides have been measured by standard cut-back technique using a precise optical setup at standard telecom wavelength of 1550 nm.

This paper is organized as follows: Section 2 describes the preparation of SiOC films and waveguides, and their characterization setup; Section 3 presents the obtained results and discusses in details the properties of SiOC films and waveguides; the conclusions are presented in Section 4; and the references are listed in Section 5.

MATERIALS AND METHODOLOGY

Thin films preparation and characterization techniques

SiOC thin films were produced with reactive RF magnetron sputter technique by sputtering silicon carbide (SiC) target in the presence of plasma i.e. Argon (Ar) and reactive gas i.e. oxygen (O_2). The scheme of reactive RF magnetron sputter is illustrated in Fig. 2 (a). The SiC target mounted on cathode was biased negatively with supply of RF power in the range from 150 W to 450 W. The partial pressure of Ar and O_2 gases in the chamber was controlled by regulating mass flow controllers. Si and thermally-oxidized Si substrates were placed on anode at a suitable distance directly above the SiC target. The ejected Si and C atoms from SiC target surface due to bombardment with Ar ions react with O_2 gas atoms and accumulate on substrate surface to form SiOC layer. An example of the SiOC layer deposited on four inches thermally-oxidized Si wafer is shown in Fig. 2 (b). SiOC thin films with varying index of refraction were sputter-deposited by increasing RF power between 150 W and 450 W and keeping Ar and O_2 gases flow at 60 sccm and 2.6 sccm, respectively. The SiOC thin films that were sputtered on thermally-oxidized Si substrates were further used to pattern photonic waveguides.

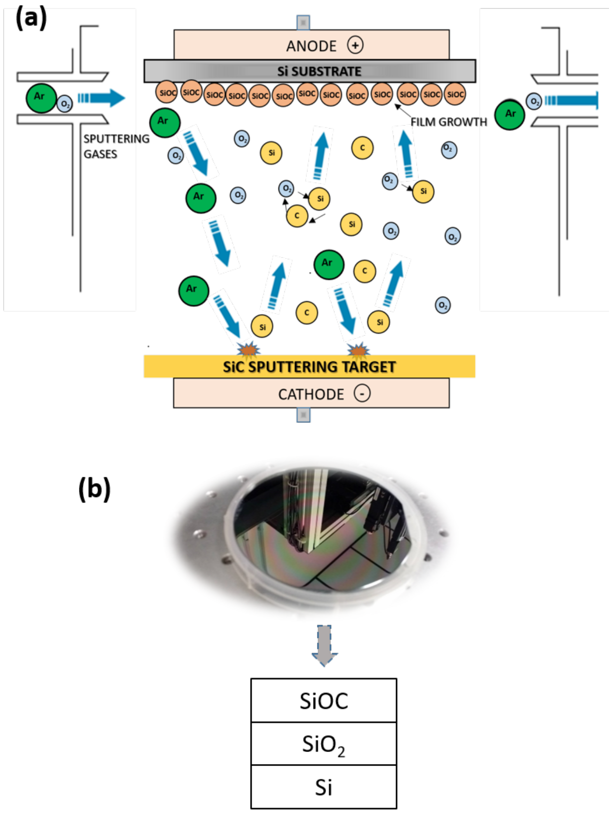

Fig. 2 Reactive RF magnetron sputtering of SiC target in the presence of Ar and O_2 gases to deposit SiOC films. RF power was applied to SiC target to change the refractive index of the SiOC films.

Characterizations of the SiOC thin films were performed to analyze the effect of sputtering conditions and attain the required physical and optical properties. Roughness profile of the SiOC thin films that is considered a major parameter was estimated using atomic force microscopy (AFM by Keysight Tech.) by probing the film surface in tapping mode. The morphology of SiOC thin films was carefully examined by imaging cross section with scanning electron microscopy (SEM) and measuring the thickness. To capture high resolution images of SiOC films, a thin metal layer was sputtered to avoid charging effect and the electrons were accelerated at a high voltage of about 20 kV. The output signal collected from in-lens detector by keeping a minimum gap of around 6 mm between the electron gun and the SiOC chip. The stress analysis of the sputtered SiOC thin films on thermally-oxidized Si wafer was performed using profilometry and considering Stoney's equation [11]. The stress evaluation of thin film is an important parameter as it induces birefringence in the waveguides.

The optical properties including index of refraction n and extinction coefficient k of SiOC thin films were studied with Metricon 2010M prism coupler [12] and spectroscopic ellipsometer (VASE J.A. Woollam Inc., USA) [13] in the near-IR wavelength region with central wavelength around 1550 nm. Prism coupler measures the absolute refractive index n of the film brought in close contact with higher index prism and further matched with ellipsometry. The accuracy of the prism coupling method is 10-4. The extinction coefficient k was determined with ellipsometer by modeling the experimental data [13].

Waveguide fabrication and losses characterization setup

The micro-photonic waveguides in SiOC film with n = 1.554 were patterned with UV photolithography and reactive ion etching (RIE) techniques. Firstly, a photoresist layer was coated on the SiOC film using spinner. Secondly, the coated photoresist was soft-baked on hot plate and exposed using mask aligner in hard contact mode with photo mask. The photo mask used for photolithography consisted of several waveguides with different widths between 2 and 4 microns. After lithography, the patterned photoresist layers were etched using RIE process of Fluoroform (CHF_3) and O_2 gases mixture to transfer the strip waveguiding structures in the SiOC film. The produced SiOC strip waveguiding structures were later buried under thick layer of silica cladding with n = 1.444 that was deposited by a plasma-enhanced chemical vapor deposition (PECVD) process.

The losses of SiOC photonic strip waveguides were assessed on the optical setup through end-to-end coupling with optical fibers having small core diameter as illustrated in Fig. 3. Further index matching oil was used to reduce the gap and precisely align the SiOC waveguides facets with optical fibers having mode field diameter MFD ≈ 3.6 µm. Tunable laser source operating at central optical wavelength λ = 1550 nm was used to launch light in the photonic waveguides. The output from the photonic waveguides was measured with power meter. Fiber polarization controller was used to select between TE and TM polarization states of the light signal.

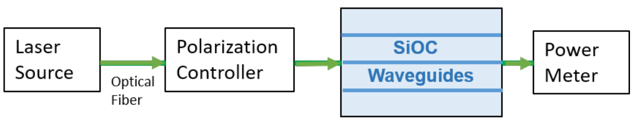

Fig. 3 Optical setup for silicon oxycarbide (SiOC) waveguides propagation losses assessment.

RESULTS AND DISCUSSION

SiOC film characterizations

The optical parameters (n and k) of the sputtered SiOC thin films deposited on Si (100) substrate under varying deposition conditions have been characterized by employing prism coupling method and spectroscopic ellipsometry. Fig. 4 shows the measured refractive index n of the SiOC thin films sputtered by enhancing RF power from 150 to 450 W. The refractive index n was measured at infrared wavelength λ = 1.554 µm with prism coupler. The refractive index n increases proportionally under the influence of deposition conditions. The refractive index n shown in Fig. 4 matched well with the values acquired with ellipsometer. The extinction coefficient k of sputtered SiOC thin films with different index of refraction was less than 10-4 in the near-infrared spectral range. SiOC films exhibited lower extinction coefficient that is fundamental to the realization of low loss photonic devices.

The roughness profile of the sputtered SiOC thin films was quantified with AFM. The film surface was scanned over an area of 5 by 5 µm^2 by AFM tip in tapping mode. Fig. 5 (a) shows the 2D AFM image of the SiOC film having refractive index n around 1.554 attained by optimizing the sputter process. The rms roughness evaluated from AFM measurements was around 0.9 nm, that is considered atomically flat to fabricate photonic waveguides.

The roughness profile is important in waveguiding applications as it causes light to scatter out from the optical waveguide and contributes to the losses. The cross-section image of the deposited SiOC film captured with SEM is given in Fig. 5 (b). The thickness d of the sputtered SiOC film is estimated about 400 nm. The morphology of SiOC thin film was observed to be compact and suitable for waveguides.

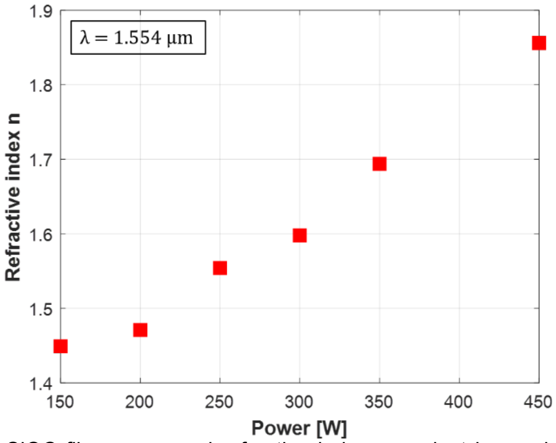

Fig. 4 SiOC films measured refractive index n against increasing RF power at λ = 1554 nm.

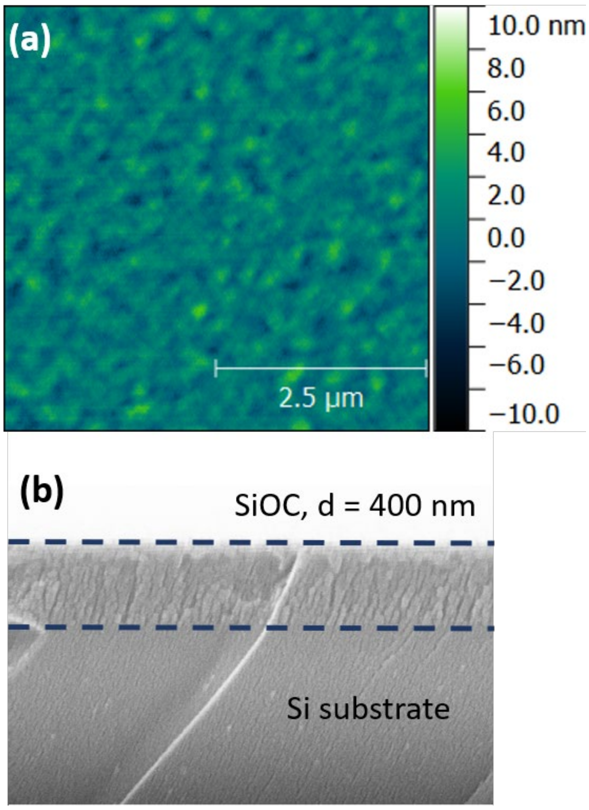

Fig. 5 (a) AFM 2D scan of SiOC film surface to quantify rms roughness; (b) cross-section image of SiOC film having thickness d of about 400 nm.

Stress analysis was performed from the curvature measurement of 4 inches SiOC/SiO_2/Si (measured by profilometer before and after the SiOC deposition), by using Stoney's equation [11]. The residual stress of SiOC film deposited was found to be compressive and equal to -194 MPa. The stress level of sputtered SiOC films is less than PECVD SiON and SiN films and better for photonics waveguides fabrication.

The chemical analysis of the deposited SiOC films was performed using energy dispersive spectroscopy (EDS). The sputtered SiOC films were observed to include silicon, carbon, and oxygen as constituent elements with no impurities, for example hydrogen. Analysis of SiOC films with refractive index of 1.554 showed the presence of silicon, carbon, and oxygen with atomic percent of 40%, 16%, and 44%, respectively.

SiOC waveguides characterizations

Fig. 6 shows the SEM image of SiOC photonic waveguide with core refractive index n = 1.554, width = 3.7 μm, and height = 0.4 μm before upper cladding deposition [14]. Photolithography and RIE processes were optimized to attain waveguides with smooth side walls and near-vertical profile. The SiOC channel waveguides sandwiched between 8 microns thick upper and lower SiO_2 clad (n = 1.444) were designed to have single-mode operation at 1.55 μm wavelength. The effective index neff of fundamental TE and TM modes, which were computed with a mode solver based on beam propagation method (BPM) are 1.4558 and 1.4582, respectively [14].

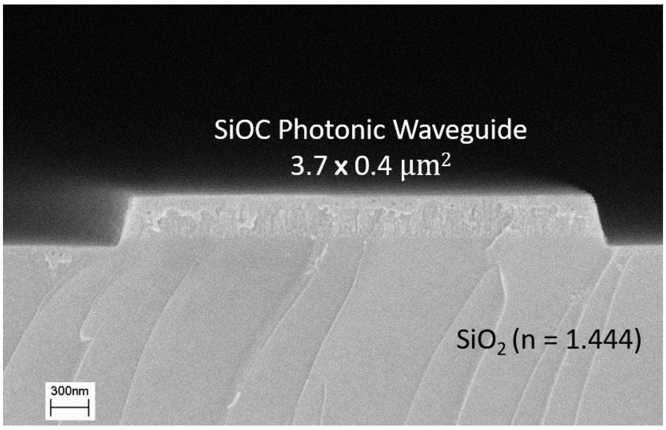

Fig. 6 SEM image of silicon oxycarbide (SiOC) waveguide with refractive index n = 1.554 and silica cladding (n = 1.444) [14].

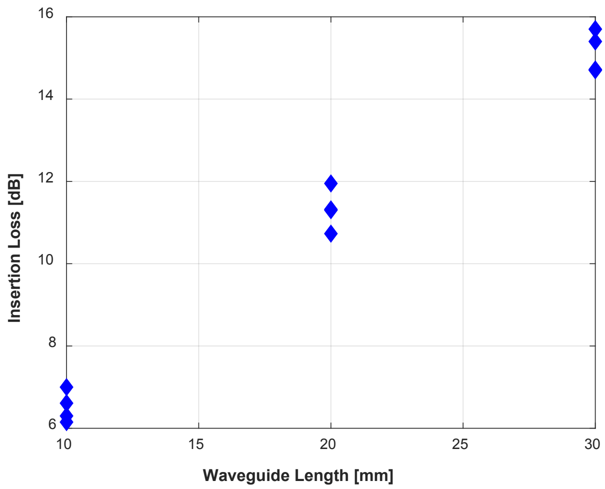

Fig. 7 Assessment of propagation losses of SiOC photonic waveguides with different lengths [14].

As reported in the cut-back measurements of Fig. 7, loss measurements were carried out for photonic waveguides having length between 10 mm and 30 mm, respectively. Propagation losses of SiOC waveguide with core index of 1.554 are estimated to be 0.37 ± 0.05 dB/mm for both TE and TM polarizations [14].

The thermo-optic coefficient (TOC) of the SiOC waveguide with refractive index of 1.554 was evaluated. The optical setup shown in Fig. 3 was used with peltier cell to heat up the integrated chip. The spectral response of the SiOC waveguides was recorded at different temperatures between 25 °C and 35 °C. The SiOC waveguides exhibited TOC of 1.5×10^{-5} RIU/°C that is almost two times higher than Ge-doped silica platform. This work underlines the importance of SiOC as a potential platform for integrated photonics applications. The photonic waveguides in SiOC with larger index (n > 1.55) are being developed and will be demonstrated.

CONCLUSION

In conclusion, we have demonstrated for the very first time photonic waveguides based on SiOC core layer. The SiOC thin films were deposited by reactive RF sputtering of SiC target in the ambient of plasma (Ar) and reactive (O_2) gases. The refractive index of sputtered SiOC thin films was tuned over a large window between 1.45 and 1.86 under the influence of process parameters. Then, the SiOC waveguides were fabricated using photo-lithography and RIE processes. The fabricated SiOC micro-photonic waveguides exhibited a high index contrast of 8% with silica claddings (n = 1.45). The SiOC waveguides propagation losses were assessed on a controlled optical setup using cut-back technique. The propagation losses around 0.39 dB/mm have been achieved that demonstrates the possibility of SiOC as a potential dielectric for low loss integrated photonics applications. Higher contrast and complex photonics structures such as couplers and ring resonators are under fabrication process and will be demonstrated in future study

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