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RESEARCH ARTICLE

Laser annealing of SiO_2 film deposited by ICPECVD for fabrication of silicon based low loss waveguide

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Abstract Laser annealing of silicon dioxide (SiO_2) film formed by inductively coupled plasma enhanced chemical vapor deposition (ICPECVD) is studied for the fabrication of low loss silicon based waveguide. The influence of laser annealing on ICPECVD-deposited SiO_2 film is investigated. The surface roughness, refractive index, and etch rate of annealed samples are compared with those of SiO_2 film obtained by thermal oxidation. It is demonstrated that the performance of ICPECVD-deposited SiO_2 film can be significantly improved by laser annealing. Al_2O_3/SiO_2 waveguide has been fabricated on silicon substrate with the SiO_2 lower cladding formed by ICPECVD and laser annealing process, and its propagation loss is found to be comparable with that of the waveguide with thermally oxidized lower cladding.

Keywords laser annealing, waveguide loss, silicon dioxide, inductively coupled plasma enhanced chemical vapor deposition (ICPECVD)

1 Introduction

Silicon dioxide (SiO_2) films are extensively used in the fabrication of microelectronic and optoelectronic devices due to its outstanding characteristics including high electrical resistivity, excellent chemical stability and mechanical strength, as well as low optical absorption in the near infrared wavelength range [1–3]. For low loss waveguide fabricated on silicon substrate, thick SiO_2 lower cladding of several microns is considered necessary to reduce the substrate leakage loss [4]. Usually, thermal oxidation is the preferred method to form SiO_2 film on silicon substrate, as low optical absorption can be ensured. However, this process is highly time-consuming for thick SiO_2 film formation. For example, it takes about 86 hours to form a 5-μm-thick SiO_2 by wet thermal oxidation at 1000°C on a (100) orientated silicon wafer, and 122 hours for 6-μm-thick SiO_2 [5]. As a result, other methods for SiO_2 formation such as chemical vapor deposition (CVD) [6], sputtering [7], and sol-gel [8] are developed. CVD is widely used in semiconductor industry for thin film fabrication, and the properties of CVD-prepared SiO_2 films, including surface roughness, refractive index, and absorption spectra, have been investigated by atomic force microscopy (AFM), ellipsometry, and Fourier transform infrared spectroscopy (FTIR) [9–13]. And it has been reported that CVD-deposited SiO_2 films exhibit lower density and higher absorption around 1.55 μm than those of thermally oxidized silicon [13].

In this paper, CO_2 laser annealing is employed to improve the performance of inductively coupled plasma enhanced chemical vapor deposition (ICPECVD) deposited SiO_2 films. The effects of laser annealing on film properties are investigated, such as surface roughness, etch rates of wet and dry etching, as well as film thickness and refractive index. Furthermore, the material loss is characterized by the propagation loss of Al_2O_3/SiO_2 waveguides fabricated by laser annealing process.

2 Experimental procedure

A 5-μm-thick SiO_2 film is deposited on a (100) single polished silicon wafer using a Sentech Instruments SI 500D deposition platform. The gas flow rates of O_2, Ar, and SiH_4 are 13, 125, and 130 sccm, respectively. The film is deposited at 230°C and 2 Pa chamber pressure, with an inductively coupled plasma (ICP) power of 178 W.

After deposition, the SiO_2 sample is attached to an aluminum platform and scanned with a pulsed CO_2 laser,

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similar to the method demonstrated in Ref. [14]. A Coherent C-30 CO_2 laser is adopted in our study. The focused laser output exhibits a nearly Gaussian profile with a beam diameter of 120 μm. The scan speed along *x*-direction is 2 mm/s with 1 kHz pulse reputation rate, while the displacement step along *y*-direction is 5 μm. The average output power of the laser is controlled by pulse width modulation (PWM).

The refractive index and thickness of the SiO_2 film are measured with a Sopra GES5 ellipsometer, and a Veeco AFM nanoscope V system is used to characterize the surface morphology. The etch depth by either wet etching or dry etching is determined by a Veeco Dektak 150 surface profiler.

3 Result and discussion

The thickness and refractive index of the deposited SiO_2 film after annealing under different laser power are plotted in Fig. 1. It is found that the refractive index of the annealed film increases with the laser power. On the other hand, the thickness reduces as the annealing laser power increases. These data leads us to the conclusion that increasing the laser power results in increased film density. Actually, it has been reported that CVD deposited SiO_2 films are of a sparser structure as compared with thermally oxidized silicon. Annealing by high power laser helps condense the film, which explains the increased refractive index and reduced film thickness.

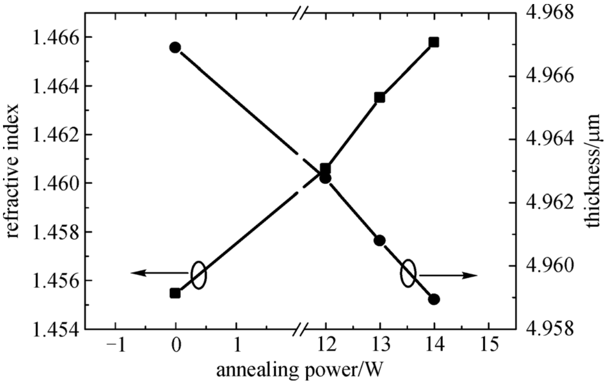


Fig. 1 Refractive index and thickness of the ICPECVD-SiO_2 film vs. annealing laser power

To confirm the above analysis, the behavior of the annealed SiO_2 samples under dry plasma etching and wet chemical etching is investigated. Dry etching of the SiO_2 samples by SF_6 plasma is performed in a reactive-ion etching (RIE) reactor with AZ5214 photoresist as the mask. The gas flow of SF_6 is 50 sccm at a chamber pressure of 10 Pa and a radio frequency (RF) power of 200 W. Figure 2 shows the etch rates of samples annealed with different laser power, and that of thermal-oxidized SiO_2 film is plotted for comparison. The etch rates of the laser annealed samples range between 37.1 and 38.5 nm/min, which are slightly higher than that of the thermal oxidation one.

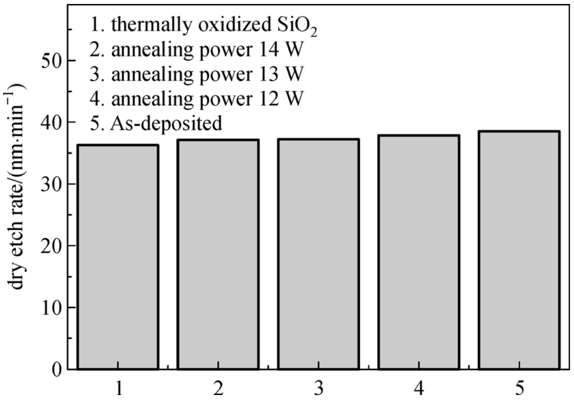


Fig. 2 Etch rates of SiO_2 samples by SF_6 plasma

Wet etching of the samples in buffered HF is also carried out, and the results are shown in Fig. 3. The as-deposited SiO_2 film exhibits a etch rate as high as 12.7 μm/min, revealing the sparse nature of the as-deposited SiO_2 film. In contrast, significant reduction in etch rate is observed for the laser-annealed samples. For the sample annealed with a laser power of 14 W, the etch rate in buffered HF is reduced to 0.133 nm/min, which is on a par with that of the thermal oxidation sample (117 nm/min). It is well known that wet etch rate is an important parameter to evaluate the film compactness. The above experimental results confirm that laser annealing improves the density of ICPECVD deposited SiO_2 films, and the density of samples annealed with high laser power is on a similar level with that of the film obtained with thermal oxidation.

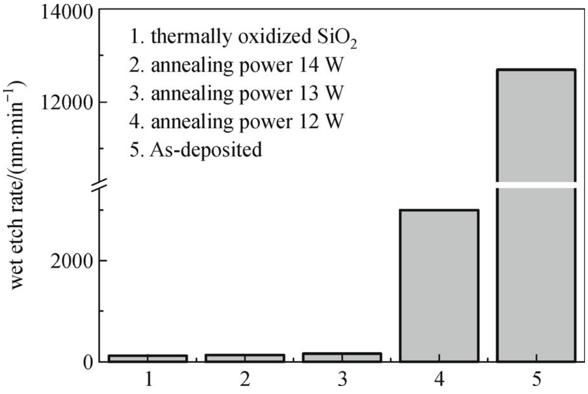


Fig. 3 Etch rate of SiO_2 samples in buffered HF

Scanning electron microscope (SEM) is adopted to study the surface morphology of the samples before and after dry/wet etching. Nodular-like features are found on the surface of as-deposited SiO_2 film, as shown in Fig. 4 (a1). Such features become less discernable as the annealing laser power increases. On the other hand, the thermal oxidized sample exhibits a fairly smooth surface. In Fig. 4, the most obvious feature is that the as-deposited sample suffers from significant surface roughness degradation after wet etching in buffered HF. This degradation in surface roughness becomes undiscernible as the laser power increases above 13 W.

The cross section images of the samples are shown in Fig. 5. Columnar structure with voids can be readily observed in the as-deposited SiO_2 film, but disappear as the annealing laser power increases to 14 W.

The surface morphology of the samples measured with AFM is plotted in Fig. 6, and the root-mean-square (RMS) roughness of the samples is summarized in Fig. 7. According to Fig. 7(a), there is only moderate improvement in the surface roughness after laser annealing. The RMS roughness reduces from 2.7 nm for the as-deposited film to 2.0 nm for the sample annealed with 14 W laser power, which is still much higher than that of the thermal oxidation film (0.34 nm). But the RMS roughness of all samples becomes more or less similar after SF_6 dry etching, as shown in Fig. 7(b). On the other hand, Fig. 7(c) reveals that the surface roughness after wet etching in buffered HF reduces significantly as the annealing laser

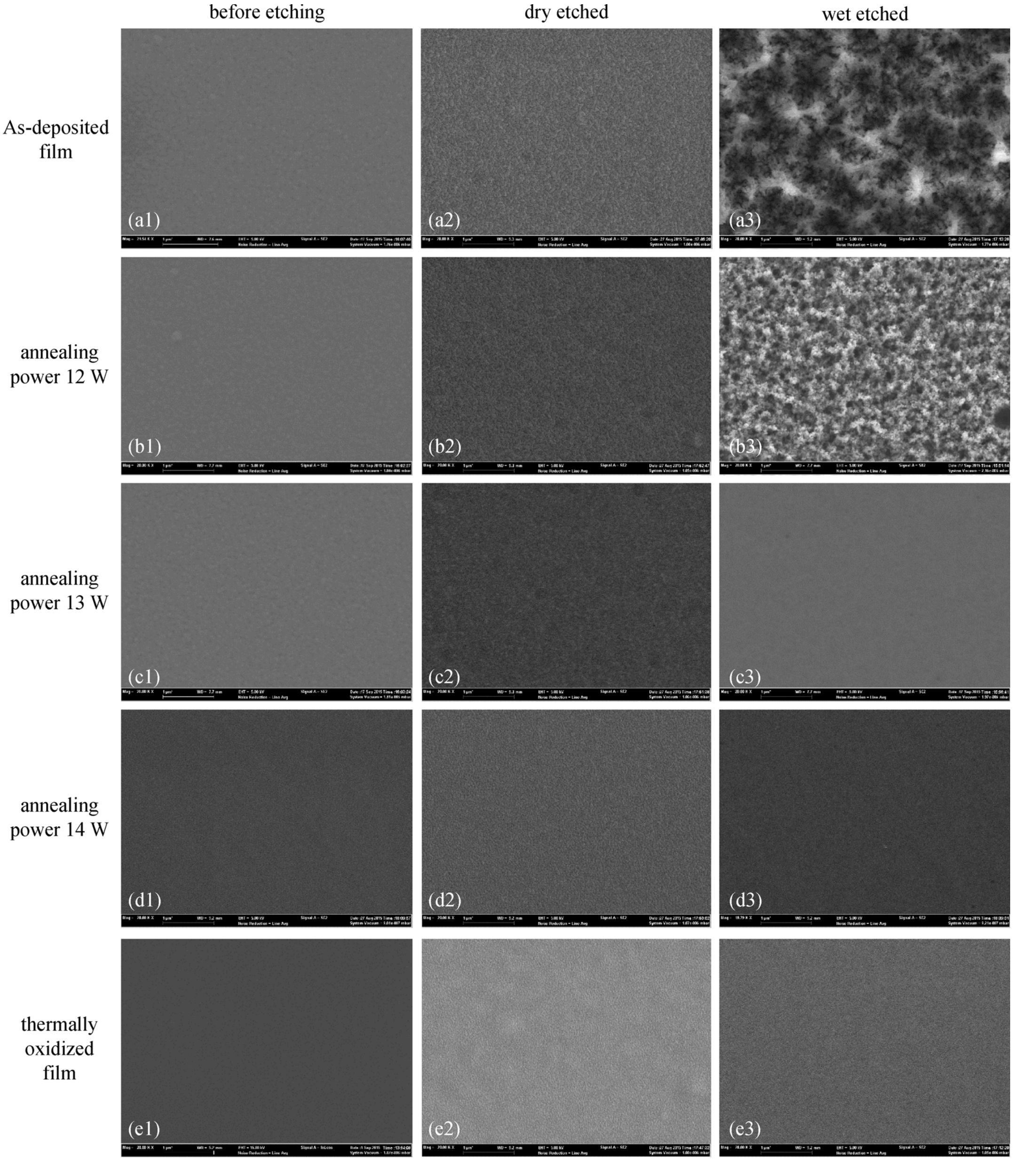
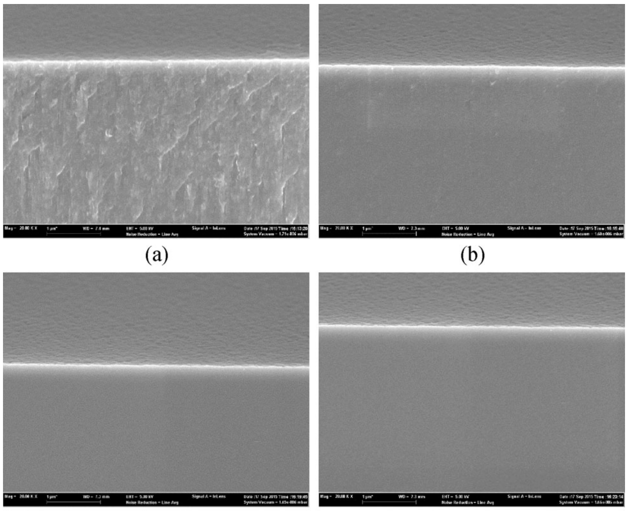
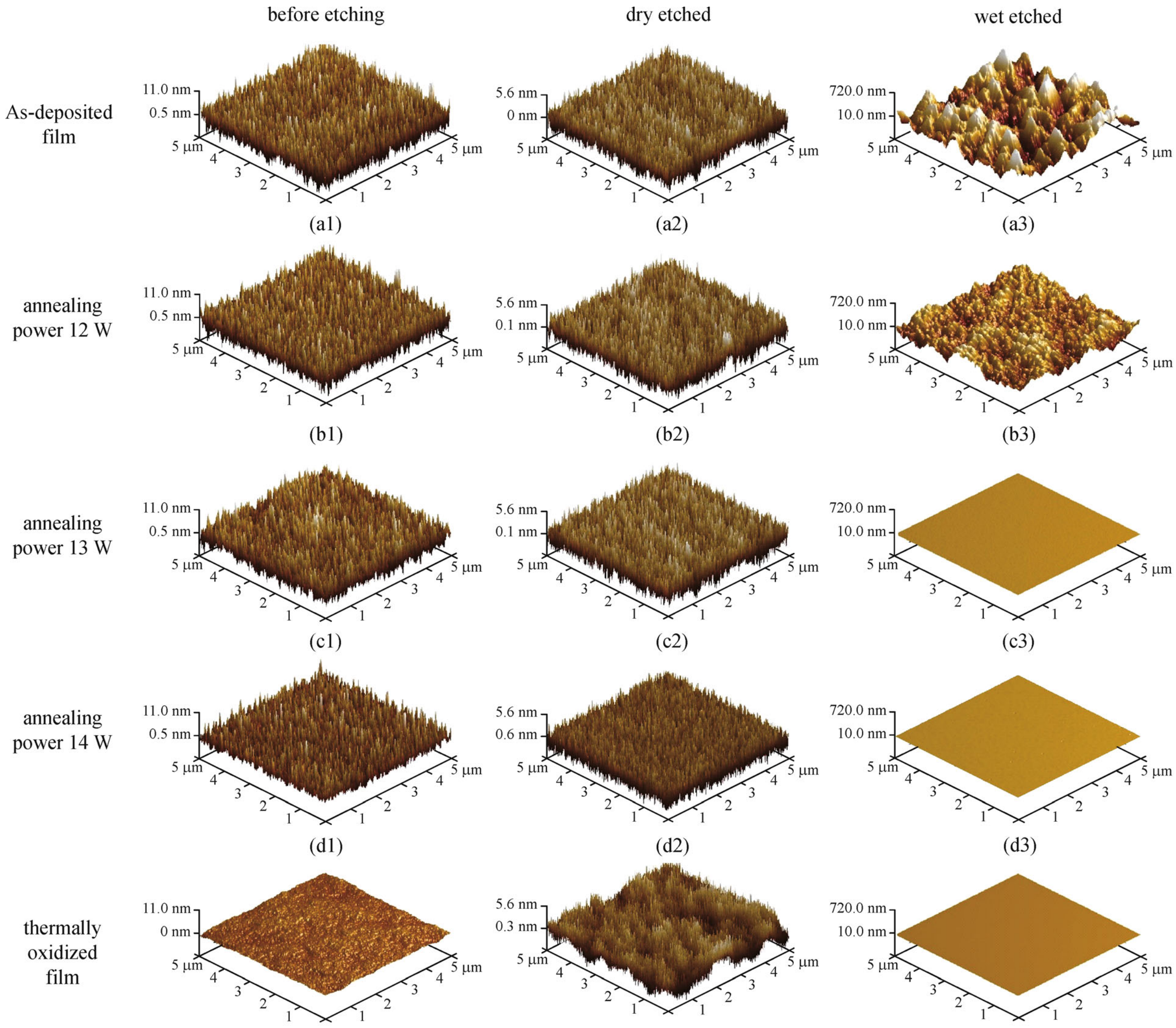


Fig. 4 SEM images of SiO_2 samples before and after dry etching with SF_6 plasma or wet etching in buffered HF


(a) (b)

(c) (d)

Fig. 5 Cross section SEM images of (a) as-deposited and annealed samples with (b) 12 W, (c) 13 W, and (d) 14 W laser power



(a1) (a2) (a3)

(b1) (b2) (b3)

(c1) (c2) (c3)

(d1) (d2) (d3)

(e1) (e2) (e3)

Fig. 6 AFM images of sample surfaces before and after dry etch in SF_6 plasma and wet etching in buffered HF power increases. The RMS roughness after wet etching is 220 nm for as-deposited film, but reduces to 1.23 nm for the sample annealed with 14 W laser power.

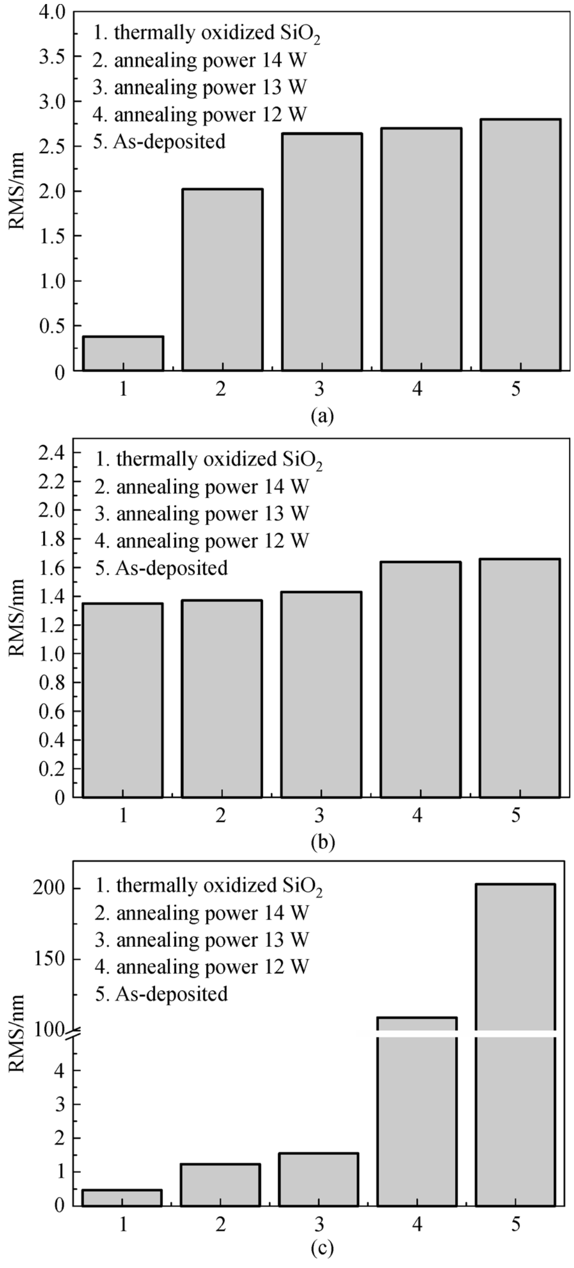


Fig. 7 RMS surface roughness of the samples (a) before etching, (b) after SF_6 dry etch, (c) after wet etching in buffered HF

In order to study the material loss of the deposited film, single mode Al_2O_3/SiO_2 optical waveguide is fabricated. A 5-μm-thick SiO_2 lower cladding is chosen so as to ensure a leakage loss lower than 0.05 dB/cm. Three different fabrication procedures are adopted to form the 5-μm-thick SiO_2 lower cladding, namely by thermal oxidation, ICPECVD deposition, and ICPECVD followed by 14 W laser annealing, respectively. A 500-nm-thick Al_2O_3 acting as waveguide core is then sputtered onto the samples and patterned into 3-μm wide stripe by ICP dry etching in a Sentech Instruments SI 500 system. To complete the waveguide structure, a 3-μm thick SiO_2 upper cladding is deposited by ICPECVD.

The propagation loss of the Al_2O_3/SiO_2 waveguide at 1.55 μm wavelength is characterized by cut-back method. For the waveguide with as-deposited SiO_2 lower cladding, the losses for fundamental transverse electric (TE) and transverse magnetic (TM) modes are 7.8 and 6.4 dB/cm, respectively (see Table 1). For the sample with laser annealed lower cladding, the losses of TE and TM modes reduce to 6.4 and 5.6 dB/cm, which are almost the same as for the waveguide with thermal oxidized lower cladding. The relatively large residual loss of the waveguides with annealed or thermal oxidation lower cladding is attributed to the scattering loss due to the sidewall roughness of Al_2O_3 core as well as the material loss due to the SiO_2 upper cladding deposited by ICPECVD. Nevertheless, it is evident that the material loss of the CVD deposited SiO_2 is effectively reduced by laser annealing, and the laser annealed SiO_2 lower cladding is as effective as the thermal oxidation film in reducing the waveguide loss. As a result, we believe that laser annealing offers an efficient way for low loss waveguide fabrication as compared with conventional time-consuming thermal oxidation. Low loss waveguide with both upper and lower SiO_2 cladding fabricated by laser annealing will be the focus of our next step work.

Table 1 Correlation between the lower cladding and propagation loss

lower cladding	propagation loss/($dB\cdot cm^{-1}$)	
	TE mode	TM mode
As-deposited	7.8	6.4
annealed with 14 W power	6.4	5.6
thermal oxidation	6.4	5.4

4 Conclusion

The influence of laser annealing on ICPECVD-SiO_2 film is investigated. It is experimentally verified that proper laser annealing conditions helps increase the film density and reduce the material loss. Single mode Al_2O_3/SiO_2 rib waveguide has been fabricated by lasing annealing process, and it is found that the laser annealing is an effective method to reduce the material loss of ICPECVD-SiO_2 film.

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References

1. Bhatt V, Chandra S. Silicon dioxide films by RF sputtering for microelectronic and MEMS applications. Journal of Micromechanics and Microengineering, 2007, 17(5): 1066–1077
2. Zheleva T, Lelis A, Duscher G, Liu F, Levin I, Das M. Transition layers at the SiO_2/SiC interface. Applied Physics Letters, 2008, 93 (2): 022108-022108–3
3. Kawachi M. Silica waveguides on silicon and their application to integrated-optic components. Optical and Quantum Electronics, 1990, 22(5): 391–416
4. Bauters J F, Heck M J R, John D, Dai D, Tien M C, Barton J S, Leinse A, Heideman R G, Blumenthal D J, Bowers J E. Ultra-low-loss high-aspect-ratio Si_3N_4 waveguides. Optics Express, 2011, 19 (4): 3163–3174
5. Ghandhi S. VLSI Fabrication Principles Silicon and Gallium Arsenide. New York: J. Wiley and Sons, 1994, 452–482
6. Gherardi N, Martin S, Massines F. A new approach to SiO_2 deposit using a N_2-SiH_4-N_2O glow dielectric barrier-controlled discharge at atmospheric pressure. Journal of Physics D: Applied Physics, 2000, 33(19): L104–L108
7. Santamaria J, Iborra E, Quesada F S, Diaz G G, Vidal M R. Sputtering of SiO_2 in O_2-Ar atmospheres. Thin Solid Films, 1986, 139(2): 201–208
8. Duran A, Serna C, Fornes V, Navarro J M F. Structural considerations about SiO_2 glasses prepared by sol-gel. Journal of Non-Crystalline Solids, 1986, 82(1-3): 69–77
9. Zúñiga-Segundo A, Ruiz F, Vázquez-López C, González-Hernández J, Torres-Delgado G, Tsu D V. Characterization of SiO_2 layers on Si wafers using atomic force microscopy. Journal of Vacuum Science & Technology, 1994, 12(4): 2572–2576
10. Chen X Y, Lu Y F, Tang L J, Wu Y H, Cho B J, Xu X J, Dong J R, Song W D. Annealing and oxidation of silicon oxide films prepared by plasma-enhanced chemical vapor deposition. Journal of Applied Physics, 2005, 97(1): 014913
11. Ay F, Aydinli A. Comparative investigation of hydrogen bonding in silicon based PECVD grown dielectrics for optical waveguides. Optical Materials, 2004, 26(1): 33–46
12. Boogaard A, Kovalgin A Y, Brunets I, Aarnink A A I, Holleman J, Wolters R A M, Schmitz J. Characterization of SiO_2 films deposited at low temperature by means of remote ICPECVD. Surface and Coatings Technology, 2007, 201(22-23): 8976–8980
13. Bauters J F, Heck M J R, John D D, Barton J S, Bruinink C M, Leinse A, Heideman R G, Blumenthal D J, Bowers J E. Planar waveguides with less than 0.1 dB/m propagation loss fabricated with wafer bonding. Optics Express, 2011, 19(24): 24090–24101
14. Armani D K, Kippenberg T J, Spillane S M, Vahala K J. Ultra-high-*Q* toroid microcavity on a chip. Nature, 2003, 421(6926): 925–928

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