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# Asymmetrical single-mode silica waveguide deposited by PECVD

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**Abstract** Silicon oxynitride (SiON) layer and $SiO_2$ buffer layer were deposited on silicon wafers by PECVD technique using $SiH_4$, $N_2O$ and $N_2$. The refractive index of SiON films measured at a wavelength of 1552 nm using a prism coupler, could be continuously varied from 1.4480 to 1.4508. Optical planar waveguides with a thickness of 6 $\mu$m and a refractive index contrast ($\Delta n$) of 0.36% have been obtained. In addition, etching experiments were performed using ICP dry etching equipment on thick SiON films grown on Si substrates covered with a thick $SiO_2$ buffer layer. In order to measure optical properties, a polarization maintaining single-mode fiber was used for the input and a microscope objective for the output at 1.55 $\mu$m. A low-loss and low propagation SiON-based waveguide was fabricated with easily adjustable refractive index of core layer.

**Keywords** Plasma enhanced chemical vapor deposition · Silicon oxynitride · Optical planar waveguide · ICP dry etching

## 1 Introduction

The integration of planar optical waveguides on silicon substrates with micro-mechanical components has many application areas, such as integrated sensors, micro-actuators and optical communication [1]. Low-index contrast silica bench technology referred to as planar lightwave circuit (PLC) or silicon optical bench (SiOB), has gained widespread usages in fabricating passive integrated optical components due to its uses of well-tested integrated-circuit industry manufacturing processes and technologies [2]. Large silica waveguide cross sections offer low fiber-to-chip coupling and propagation losses. A major drawback of SiOB technology is the relatively large component size, where a critical factor is the minimum waveguide bend radius. This radius is large (normally in millimeters) in the low-index contrasts ($\Delta n\% =$ 0.25–1.5%) in silica [3, 4]. An important property of these waveguides and devices are the slight variation in the refractive index over their cross-sections, typically an order of 1% or less.

Many different kinds of fabrication technologies have been developed for optical waveguides on silicon substrates, including plasma enhanced chemical vapor deposition (PECVD) [5, 6] and flame hydrolysis deposition (FHD) [7, 8]. Most of the published works which refer to waveguide structures are based on depositing pure silica ($SiO_2$) for the buffer layer and doped silica, silicon oxynitride (SiON) and silicon nitride (SiN) for the core layer, respectively [9–12]. Combining these waveguides with silicon micro-machining technology is very attractive, because it offers many major advantages over previously developed or currently competing technologies, such as ion-exchanged glass waveguides, $LiNbO_3$, or III–V technologies using GaAs and InP components [13].

The PECVD technology is considered as a lucrative method for the planar waveguide fabrication because of its easy controllability of the film thickness, refractive index, and excellent surface roughness. This work has focused on developing high quality $SiO_2$ and SiON layers for the application of silica waveguide that can fulfill needed requirements and map these into the relevant parameters, such as refractive index, etching profile, and mode images.

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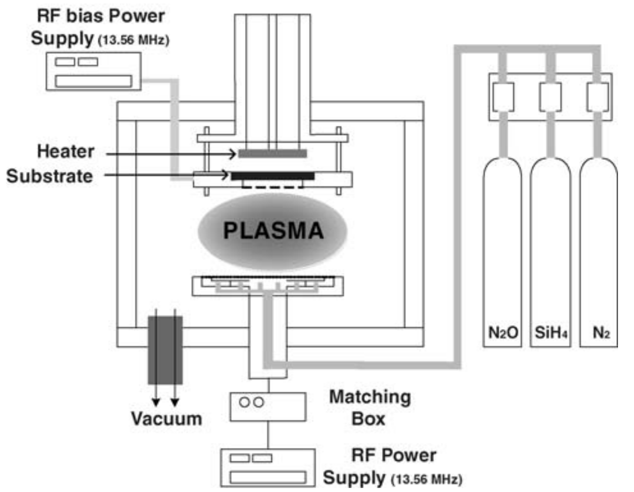


**Fig. 1** A schematic diagram of the RF PECVD equipment

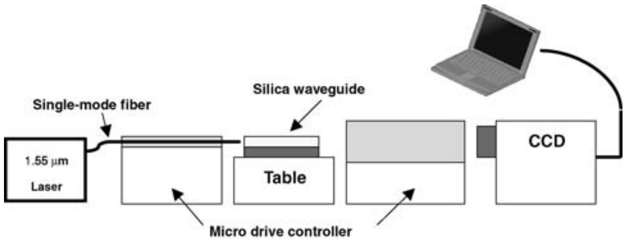


**Fig. 2** A schematic setup diagram for silica waveguiding measurement

**Table 1** The process conditions used for the deposition of $SiO_2$ and SiON films.

| Sample | Gas flow ratio | rf power | rf bias power (W) |
|---|---|---|---|
| $SiO_2$ | $N_2O / SiH_4 = 8$ | 120 W | 0 |
| | | | 25 |
| | | | 50 |
| | | | 75 |
| | | | 100 |
| SiON | $SiH_4/ (N_2 + N_2O) = 0.17$ | 120 W | 0 |
| | | | 25 |
| | | | 50 |
| | | | 75 |
| | | | 100 |

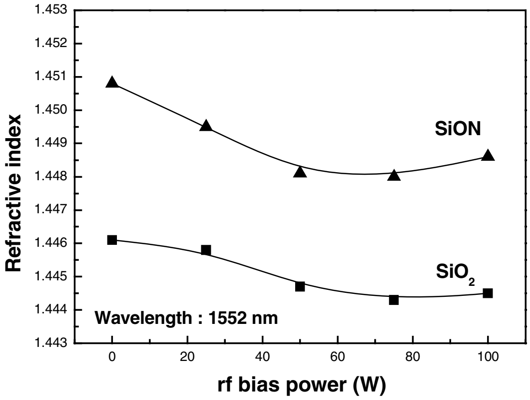


**Fig. 3** The refractive index of $SiO_2$ and SiON films as a function of the rf bias power

## 2 Experimental procedure

$SiO_2$ and SiON films as buffer and core layers, respectively, were deposited by PECVD technique using appropriate gaseous mixtures of silane ($H_2$ 90% dilution, $SiH_4$), nitrous oxide (99.999% $N_2O$), and nitrogen ($N_2$). The schematic diagram of the rf PECVD equipment is shown in Fig. 1. The reaction system is a parallel planar discharge type, which is using a rectangular rf (13.56 MHz) electrode (lower) and a rf bias electrode (upper). The upper electrode supporting the substrate, is connected to a 13.56 MHz rf bias power supply. The substrate is placed on a tray with the surface to be coated facing downward, so that the possible depositions of dust particles and flakes can be minimized. The p-type Si wafers with (100) orientation were used as substrates. Before the deposition, we performed a short *in-situ* pre-cleaning of the wafers to improve the film adhesion to the substrate using $N_2$ discharge at an rf power of 100W. After the deposition of the $SiO_2$ and SiON films, the films were annealed at 800°C in nitrogen atmosphere for 3hrs to prevent optical absorption. This paper mainly focused on investigating the influence of rf bias power during the fabrication of $SiO_2$ and SiON films based on the process conditions as given in Table 1. The pressure (0.9 torr) and the substrate temperature (320°C) for all the sample conditions were held constantly. After two (the buffer and core) layer depositions, an inductively coupled plasma (ICP) system was used to etch core (SiON) layers at a thickness range of 6 and 8 $\mu$m. The etching gases used in this process were $CF_4$ and $CHF_3$ to obtain clean etch profiles.

The refractive index was measured using a prism coupler (METRICON 2010) operating at a wavelength of 1552 nm. The cross-sections of multilayer films and etched surfaces were observed by a scanning electron microscopy (SEM). A waveguide having three different layers ($SiO_2$/SiON/$SiO_2$) was fabricated, and the waveguide intensity mode profiles and propagation losses for the straight and Y-branch waveguides were measured by the experimental setup as shown in Fig. 2. A polarization maintaining single-mode fiber was used for the input and a microscope objective for the output at 1.55 $\mu$m. The input fiber was butt-coupled to the cleaved endface of the waveguide. To measure mode images, the light intensity scattered out of the waveguide plane, which is proportional to the guided intensity, was recorded by a video camera.

## 3 Results and discussion

Figure 3 shows the variations of refractive indexes of $SiO_2$ and SiON films as a function of the rf bias power. As the rf

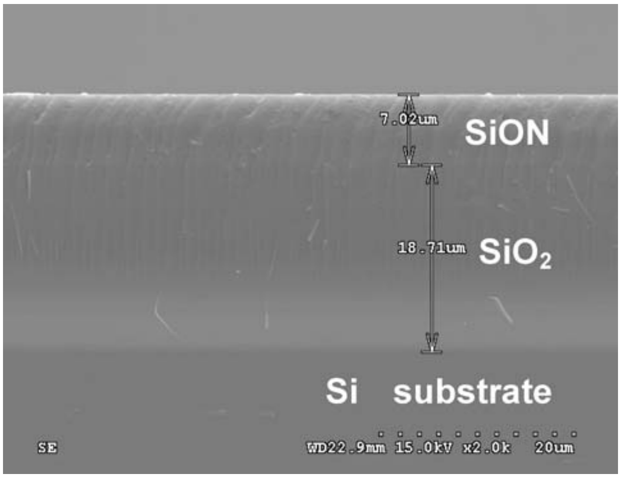


**Fig. 4** Cross-sectional SEM image of SiON/$SiO_2$ multilayer grown by PECVD

bias power increases, the refractive index for SiON films decreased reaching a minimum value of 1.4480 at rf bias power of 75 W, and then increased up to 1.4486. It is well known that silane radicals react preferentially with oxygen radicals rather than with nitrogen radicals because the electronegativity of oxygen is greater than that of nitrogen [5]. Therefore, Si-H, Si-NH and Si-OH bonds are formed in the solid phase only when all the oxygen radicals have been consumed in the reaction. These bonds could be largely reduced after annealing for 3 hrs at 800°C in a nitrogen flow. The increase of rf bias power during the deposition of $SiO_2$ films may produce a similar effect on the refractive index as that of SiON films. The refractive index value was measured as 1.4461 for no rf bias, while it is 1.4443, close to that of thermally grown silicon dioxide, for rf bias power of 75 W.

For typical waveguides, the buffer layer must be thick enough to prevent absorption of the guided light by the high refractive index of Si substrate. Figure 4 shows a cross-sectional SEM image of the prepared SiON ($\sim$7 $\mu$m)/$SiO_2$($\sim$18 $\mu$m) multilayer structure on Si substrate. The $SiO_2$ and SiON films were deposited at rf bias power of 75 W and 25 W, respectively. A $SiO_2$ thick film with refractive index 1.4443 (at $\lambda = 1552$ nm) was used to avoid any generation of leaky modes into the substrate. It has been calculated that, for a refractive index difference of 0.36% between the core and the buffer layer, a 17$\mu$m-thick buffer layer is sufficient to reduce losses to $<$0.01dB/cm. This kind of $SiO_2$ film is sufficient to use as a buffer layer to fabricate planar optical waveguides.

Figure 5 exhibits SEM images of 0.36% etched core layer by ICP etching on a 6 $\mu$m SiON (a) cross-section, (b) straight waveguide, and (c) Y-branch waveguide. From the top view of the ridge region as shown in Fig. 5, a very smooth surface can be seen, which is very important for device applications.

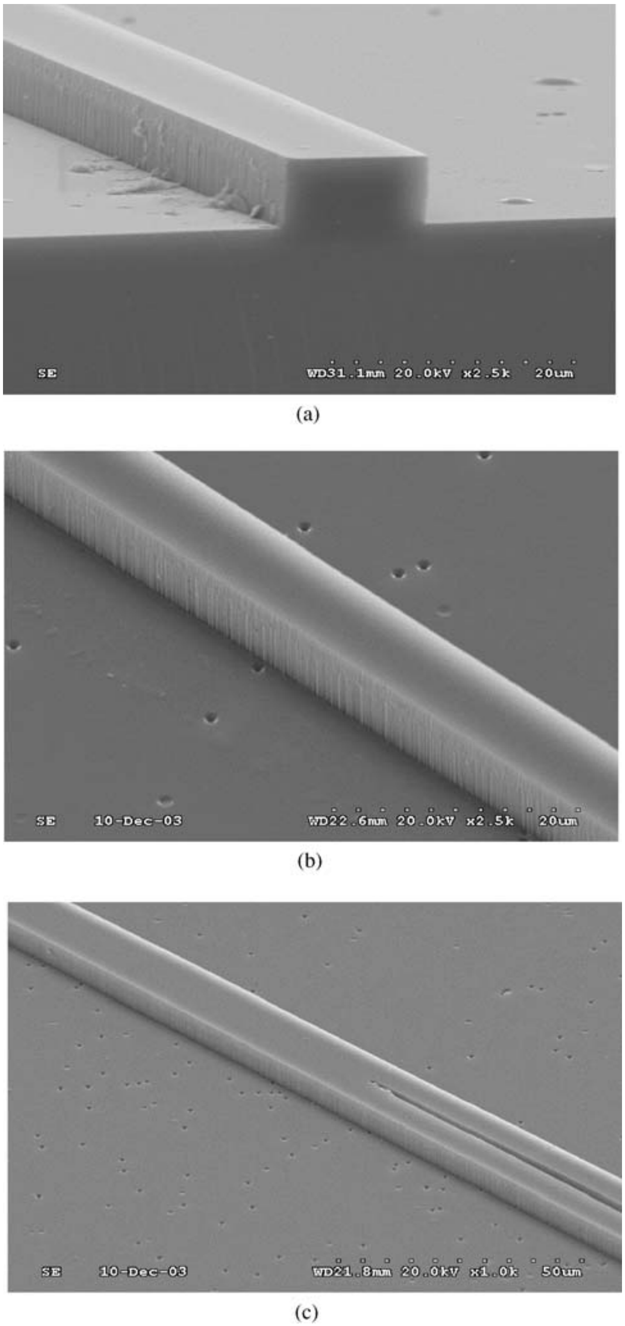
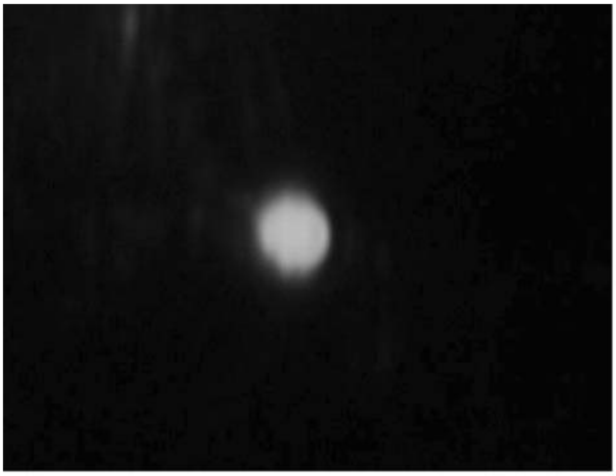
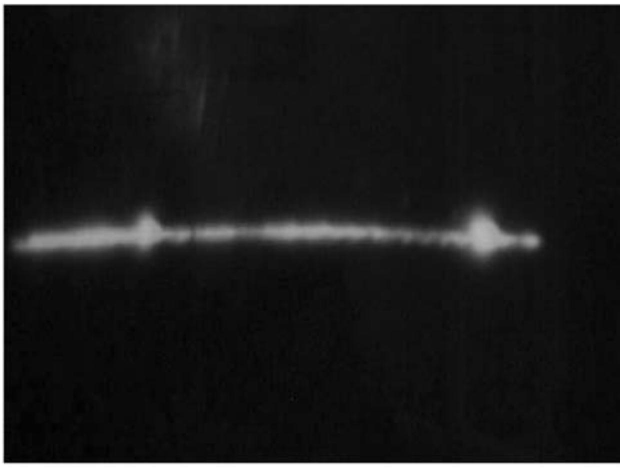


**Fig. 5** Etching profiles of SiON films: (a) cross-section, (b) straight waveguide, and (c) Y-branch waveguide

Figure 6 shows the near-field output pattern of (a) straight waveguide, and (b) Y-branch waveguide taken by an infrared camera. If the fiber spot size is well matched to that of the fiber and also optimally aligned well with the waveguide, there is minimal mismatch between the fundamental modes of the fiber and the waveguide having transmission losses typically around 0.1 dB or less. However, if the fiber and the waveguide spot sizes are offset or tilted, the transmission loss will be considerably high. This result illustrates that the mode of output is a waveguiding single-mode.



(a)



(b)

**Fig. 6** The input near-field output pattern taken by the display monitor of an infrared camera: (a) mode image of straight waveguide, and (b) mode image of Y-branch waveguide

## 4 Conclusions

Silicon dioxide ($SiO_2$) and silicon oxynitride (SiON) thick films have been synthesized by plasma enhanced chemical vapor deposition (PECVD). $SiO_2$ and SiON films having excellent characteristics for the application of planar optical waveguides were obtained at low temperatures. As the rf bias power increases, the refractive index of SiON films decreases to 1.4480 with the increase of the rf bias power from 0 to 75 W and again increases to 1.4486 at the rf bias power of 100 W. The stoichiometric and optical properties of the films were strongly influenced by the rf bias power used during the deposition process, which was confirmed from prism coupler, SEM, and mode images. SiON films presenting a $\Delta$ 0.36% are required for the fabrication of a planar optical waveguides, and such devices were successfully fabricated. The uniformity of the refractive index was well controlled and concentration of a planar optical waveguide could be precisely controlled through the exact mode images.

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