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Research Report

High-Contrast and Low-Loss SiON Optical Waveguides by PECVD

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Abstract

PECVD SiO_xN_y waveguides on SiO_2-cladded Si substrates were fabricated with an effective refractive-index contrast of approximately 0.02. After annealing, an optical propagation loss of 0.10 dB/cm is measured in the wavelength window of 1540–1580 nm using prism coupling. Systematic evaluation is done as a function of PECVD process conditions, and a comparison of as-grown and annealed films is made. Single-mode waveguide channels with a lateral width of 3 μm are made using RIE, and subsequently overgrown with SiO_2 by PECVD. Curved waveguide segments with bending radii down to 1 mm are optimized for low-loss transmission.

I. INTRODUCTION

Future photonic lightwave circuits (PLC) have to meet the following requirements: (i) low propagation losses within the waveguiding structures, (ii) small size, (iii) compatibility with silicon IC techniques, and (iv) low manufacturing cost. Plasma-enhanced chemical vapor deposition (PECVD) techniques are well suited to meet these requirements: thus it is interesting to exploit this technique for the fabrication of SiON-based waveguiding structures, as alternative to the well-known flame-hydrolysis deposition (FHD) techniques for depositing Ge-doped SiO_2 waveguiding films [1]. The refractive index of SiON thin films can be varied from 1.46 (SiO_2) to 2.02 (Si_3N_4), which provides a large flexibility in waveguide design, both for the index of the guiding layer as well for the index step to its embedding layers. Our attention focuses primarily on the telecommunication window region around 1550 nm, in which optical amplification is possible.

The successful realization of such waveguiding materials as described above will allow the development of a class of integrated optical devices.

II. GROWTH AND FABRICATION TECHNIQUES

The SiON waveguide structures are manufactured onto thermal oxide buffer layers (SiO_2) of 7 to 8 μm thickness on silicon wafers. The thin films (approximately 2.0 μm thickness) are grown by PECVD using 2% SiH_4 in He, N_2O, N_2 and NH_3 as gaseous precursors. Films with refractive indices between 1.46 and 1.70 are deposited by varying the 2% SiH_4 in He, to N_2O, to NH_3 gas ratios. The higher indices result from the nitrogen content in the film. In order to optimize the PECVD growth, several growth modes with plasma frequencies of 13.56 MHZ (HF) and 100 kHz (LF), with and without additional NH_3, have been investigated in detail. Using optical techniques, a first analysis is made after the deposition of the SiON films (see below). Further evaluations of the SiON films are performed (i) after annealing and (ii) after processing the unannealed material into channel waveguides by reactive-ion etching (RIE) and PECVD overgrowth with 5 μm of SiO_2. Annealing of the SiON films is done at 1140 °C for one hour in an N_2 atmosphere. Ridge channel waveguides are defined by photolithography and etched by RIE using CHF_3 and O_2. A SEM micrograph of an overgrown channel structure is shown in Fig. 1 together with all relevant parameters.

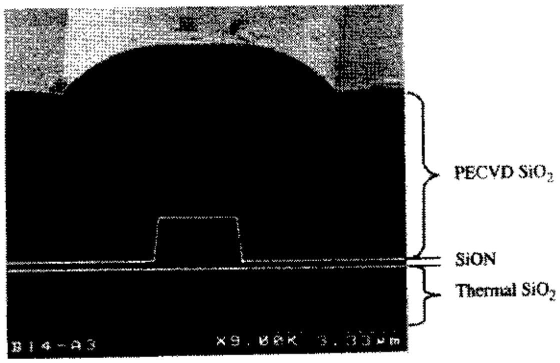

FIG. 1. SEM micrograph of an overgrown waveguide structure. SiON core thickness: 2 μm; etch depth: 1.3 μm; waveguide width: 2.5 μm. The SiON and SiO_2 refractive indices are 1.499 and 1.450, respectively, at 1550 nm. The interface between core and cladding layers is indicated by white lines.

III. CHARACTERIZATION AND ANALYSIS

PECVD growth is optimized by using various techniques: ellipsometry at 633 nm and prism coupling (PC) are used to determine the refractive index and film thickness, the PC technique employing both 633 and 1550 nm wavelengths. This technique is also used to measure the optical propagation loss in the range of 1480–1580 nm by means of using a tunable diode laser, with typical prism separations between 5 and 25 mm.

Fast Fourier Transform Infrared Spectroscopy (FTIR) is used to determine the chemical bonds in the SiON films, such as Si–H and N–H absorption bands [2,3]. From the infrared spectra (Fig. 2a), we observe that annealing greatly reduces the hydrogen content of the films. The as-deposited film displays the N–H stretching mode at 3375 cm^{-1}, the Si–H stretching mode at 2205 cm^{-1}, and the well-documented Si–O–Si features at 500, 820 and 1100 cm^{-1}, but shifted slightly and broadened by the presence of Si–H and Si–N. In the optical loss spectra (Fig. 2b) the as-deposited waveguide layers exhibit a large absorption band that peaks near 1510 nm owing to the N–H bonds. After annealing, the Si–H and N–H peaks disappear in the FTIR spectra, and the Si–O–Si stretching vibration at 1100 cm^{-1} undergoes a shift to higher energy, owing to an increase in oxygen bonded directly to silicon. High-temperature annealing results in lower waveguide losses by reducing the number of Si–H and N–H bonds as well as the materials defects. After annealing, there are no major differences in the properties of the SiON films grown with the four deposition modes (LF, HF, with and without NH_3), and no cracks are found. The optical loss in the 1550-nm window after annealing decreases considerably compared to the as-deposited material: by a factor of 10 and 4 for the regions at 1510 and 1550 nm, respectively (Fig. 2b). We find a very low propagation loss of less than 0.10 dB/cm in the wavelength region of 1540–1580 nm. Note that this value is obtained with an effective refractive index contrast of 0.02 and is, to our knowledge, among the lowest values reported for this contrast in SiON waveguide materials.

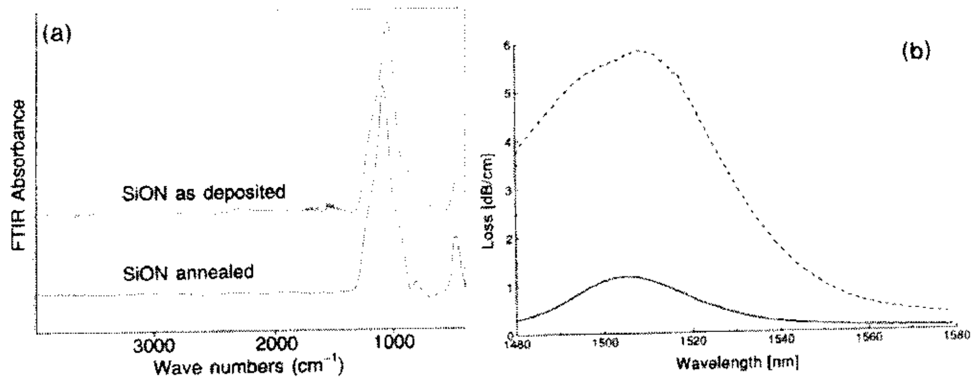

FIG. 2. (a) Infrared absorbance spectra of a PECVD SiON film before (top) and after (bottom) annealing at 1140 °C. Curves are offset for clarity. (b) Optical loss spectrum of a planar waveguide grown by LF PECVD without NH_3, unannealed (dashed) and after annealing at 1140 °C (solid).

IV. BEND WAVEGUIDE OPTIMIZATION

The high-contrast SiON waveguides allow small bending radii [4,5]. To optimize these bending losses for the optical waveguide structure described, beam propagation modeling (BPM) tools are used.

There are two contributions to the losses in bends: (i) the radiation loss occurring in the bend sections owing to radiation of the fundamental mode, and (ii) the transition loss occurring at the interface between straight and curved sections owing to the mismatch of the modal field distributions. The field mismatch is minimized by optimizing the width of the bend section or the waveguide offset at the straight-to-curved interface. Using the overlap function between the connected waveguide segments of a conventional BPM program [6], we obtain a first estimate for the offset and waveguide width in the bends. Radiation losses are further analyzed using an extended BPM program [5]: these simulations indicate that in our structure bend radii of 1 mm are feasible. We implemented these variations in a mask design, as shown in Fig. 3. The mask consists of a series of straight waveguide sections connected to bend sections with radii varying between 0.1 mm and 5 mm, while the total waveguide length is kept constant so that a direct comparison of the results is possible. Offset or width are varied appropriately for a fixed radius between the optical guides. Characterization of two runs processed with the mask shown in Fig. 3 confirms the modeling expectations. Bending radii of 2 mm show only little radiation losses. For smaller radii, the radiation losses increase substantially, which makes proper selection of the waveguide width and offset more important [7]. Even for bending radii as small as 1 mm, 90° bending losses of less than 1 dB were measured.

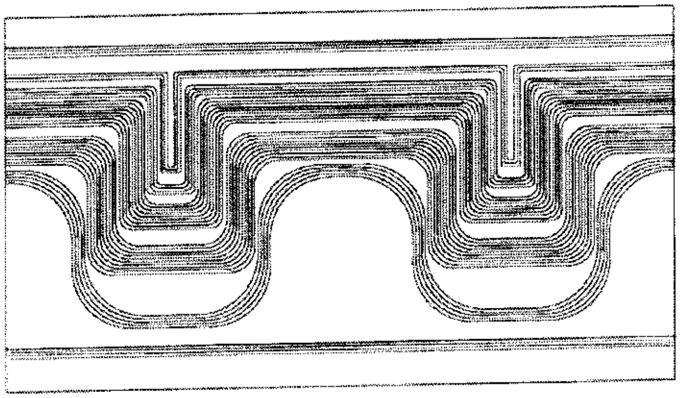

FIG. 3. Mask layout for bend waveguide testing. Radii of 0.1, 0.5, 1, 2, and 5 mm were tested by appropriately varying bend width and offset for each radius.

The dependence of the optical throughput on the waveguide width in the bend is shown in Fig. 4. It clearly reveals two regimes: for small bend widths no light is guided through, owing to strong radiation losses, while for broader guides higher-order modes are excited. Consequently, the field mismatch results in higher losses at the interfaces to straight sections.

In conclusion, our results on high-contrast SiON optical waveguides grown by PECVD are a prerequisite for the fabrication of even more compact, low-loss devices.

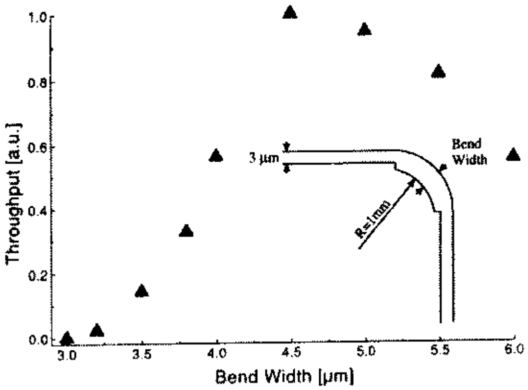

FIG. 4. Measured optical throughput versus bend width for the 1-mm-radius bends.

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