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Influences of silicon nano-crystallized structures on the optical performance of silicon oxynitride rib-type waveguides

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Abstract

Silicon oxynitride (SiON) films were deposited on p-type (100) silicon substrates by plasma enhanced chemical vapor deposition (PECVD), at the temperature of 300 °C, using silane (SiH_4), nitrogen (N_2), ammonia (NH_3) and laughing gas (N_2O) as gas precursors. The effects of the processing gas ratio of $N_2O/(N_2+NH_3)$ on the optical properties, microstructure and chemical bonding evolutions of SiON material, and the influences of silicon nano-crystallized structures on the optical performance of SiON-based rib-type optical waveguides were studied. Microstructure evolutions analysis and optical measurements indicated that the refractive index and the extinction coefficient could be precisely determined by controlling the $N_2O/(N_2+NH_3)$ ratio and the thermal annealing process. A greater density and dimension of silicon nano-crystallized structures resulted in more optical scattering effect phenomena occurring between the interface of silicon nano-crystallized structure and SiON matrix and more optical propagation loss.

Keywords: Waveguide; Silicon oxynitride; PECVD; Optical properties; Optical communication

1. Introduction

In the last few years, following the rapid development of the Internet and multimedia services, the demand for transmission capacity has increased tremendously. This creates a big challenge for the information transmission capacity of the optical fiber network between metropolises and that of the long distance main optical line already set up. Dense wavelength division multiplexing (DWDM) technology is responsible for the original type of transmission capacity variation, and thus enables the capacity of the broadband to increase greatly. Arrayed waveguide grating (AWG) plays a key role in the DWDM system because of its flexibility, low-cost mass production, manufacturing processes similar to VLSI, and ease of integration with other optical electronic ICs.

The optical waveguide can be divided into two main categories in material selection. One is a low index contrast (LIC), such as using silica-based waveguides with a silica cladding [1] and other LIC optical materials [2,3], with low insertion loss performance. However, because of its larger dimension, its application scope is limited. Another is a high index contrast (HIC), such as using silicon waveguides with a silica cladding (silicon-on-insulator, SOI) [4] and other HIC optical materials [5,6]. Silicon oxynitride (SiON), which is considered the candidate material for LIC and HIC optical waveguides, possesses the properties of low residual stress, variations of refractive index controlled by adjusting $N_2O/(N_2+NH_3)$ ratio, and low absorption phenomena for infrared regions [7].

However, the role of Si nano-crystallized structures in SiON film needs to be further clarified. Therefore, the effects of the processing gas ratio of $N_2O/(N_2+NH_3)$ on the optical properties and microstructure evolutions of SiON material, and the influences of silicon nano-crystallized structures on the optical performance of SiON-based, rib-type optical waveguides were investigated.

2. Experimental

2.1. Structure simulation

The schematic structure of a rib-type waveguide was adopted by following Pogossian's single-mode model [8], with indexes

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of 1.50 SiON and 1.45 SiO_2 films as core and top/bottom cladding layers, respectively, as shown in Fig. 1(a). The beam propagation method (BPM), with launch position and optical waveguides length variations for connecting optical fiber and optical waveguides, was studied to achieve reasonable coupling and propagation losses, respectively. Based on the simulation results, the quartz glass masks for AWG devices and straight optical waveguides pattern were designed and manufactured. These straight optical waveguides in the optical mask were used to measure the coupling and propagation losses.

2.2. Fabrication processes

In order to obtain the designed optical properties of SiON film, variations of $N_2O/(N_2+NH_3)$ ratio, in the range of 0.2~ –2.0, were adopted to deposit a 3000 nm thickness of SiO_2 and 6000 nm thickness of SiON single layer films on the D263T quartz glass. The ICP-PECVD system was used, with a radio-frequency (RF) of 13.56 MHz at the substrate temperature of 300 °C with the SiH_4 flow rate of 25 sccm, the NH_3 flow rate of 25 sccm, the N_2 flow rate of 75 sccm, the N_2O flow rate in the range of 20~ –200 sccm, and RF power wattage of 100 W with an operating vacuum pressure of 253 Pa, respectively. The thickness was monitored in-situ by quartz oscillation equipment. The optical transmittances of SiO_2 and SiON single layer films were determined by a Hitachi U-4100 scanning spectrophotometer in the wavelength region of 350–2000 nm. The refractive index and the extinction coefficient were determined by the Swanepoel [9] reported method and obtained a reasonable $N_2O/(N_2+NH_3)$ ratio to fabricate the designed waveguide. Therefore, we used the obtained $N_2O/(N_2+NH_3)$ ratio to deposit a 3000 nm thickness of SiO_2 and 6000 nm thickness of SiON films on the six-inch diameter, p-type (100) silicon wafer, respectively. We then proceeded with the optimum photolithography and reactive etching (C_4F_8/O_2) processes, by using the ICP-RIE system with a radio-frequency of 13.56 MHz at the temperature of 300 °C and using the C_4F_8 flow rate of 45 sccm, the O_2 flow rate in the range of 4–8 sccm, RF power wattage of 2500 W with an operating vacuum pressure of 0.67 Pa, respectively, to investigate the effects of etching reactant ratio (C_4F_8/O_2) on the profile and sidewall roughness of SiON optical waveguides. Subsequently, we annealed the determined etched bi-layer films in a thermal furnace with an oxygen atmosphere at the temperature of 1050 °C and operating pressure of 10,133 Pa for 4 h, respectively, to reduce the N–H bonds of SiON film. We deposited a 3000 nm thickness of SiO_2 to serve as the top cladding for the optical waveguides. Finally, we performed cutting, grinding, and polishing processes to finish the rib-type waveguides, and the optical characteristics of optical straight waveguides were measured by the auto optical coupling stage system, as shown in Fig. 1(b).

Surface roughness of the films was measured below the 5000 nm×5000 nm size by using an atomic force microscope (AFM, Solver Scanning-probe-Microscope SPM-P7LS). Cross-sectional transmission electron microscopy (XTEM) samples were prepared by cutting, mechanical grinding, chemical mechanical polishing, and ion-milling (Gatan Duo-mill) to an electron transparency. High-resolution transmission electron microscopy (HRTEM) was used to observe the cross-sectional microstructure of the SiON core layer, with a JEOL JEM-4000EX type electron microscope operated at a voltage of 400 kV. The density and dimension of silicon nano-crystallized structures in the amorphous SiON optical films were quantitatively calculated with at least 5 TEM images. Optical waveguides profile analysis of the core layer was performed by scanning electron microscopy (SEM, JSM-6400).

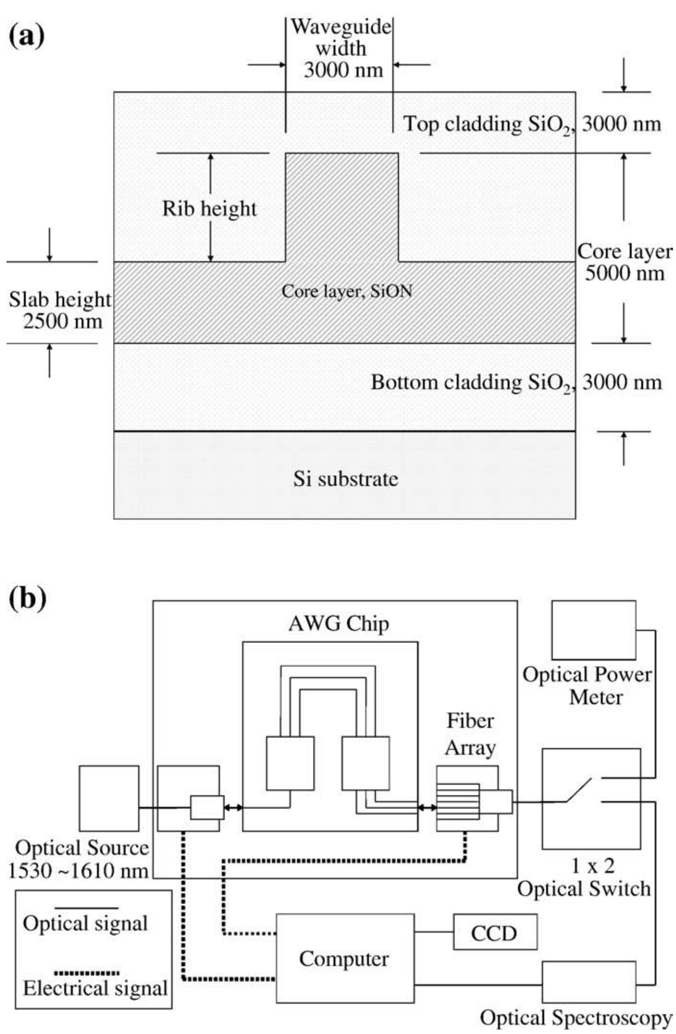

Fig. 1. (a) Schematic structure of small rib-type AWG with an index of 1.50 SiON and an index of 1.45 SiO_2 used as core and top/bottom cladding layers, respectively. (b) Schematic features of auto optical coupling stage system.

3. Results and discussion

3.1. Simulation results

Optical waveguides, with the width of 5000 nm, the height of 6000 nm, the slab height of 4000 nm, and the length of 20 mm, revealed reasonable spectral performance by 3-dimension (3D) simulation, as indicated in Table 1. The waveguide of the smaller dimension, rib-type waveguide design, with an index of