Planar optical waveguides fabricated by sol-gel derived inorganic silicate glass

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Optical waveguide slabs are synthesized using germano-silicate glass by the sol-gel process. A systematic study of the design of the low-loss material is presented. A propagation loss of <0.5 db/cm at 1550 nm has been achieved.

Keywords: Germano-silicate, sol-gel, optical waveguides.

Introduction

It is well known that the sol-gel method allows the synthesis of homogeneous materials at low temperatures and offers control of chemical purity and ease of multi-dopants mixing. In a sol-gel process, the formation of amorphous materials is by chemical means at low temperature as opposed to a physical route where an abundance of energy is consumed in the process. For example, in process like CVD, substrates have to be kept at an elevated temperature typically above 500^{o}C and FHD where flame temperature is above 1000^{o}C. In addition, plasma and vacuum equipment for these other methods often incur huge overhead and maintenance costs. Among the different systems which can be obtained by the sol-gel route, the binary $GeO_2 – SiO_2$ material has been recognised as being excellent for obtaining lightwave waveguides in films with controllable refractive index [1],[2]. As well, the photosensitivity of $GeO_2 – SiO_2$ based materials [3],[4] gives another good reason for further study. Silicate-based glasses provide a material for waveguides with optimum compatibility with single-mode fibre and very high stability.

In this work, a systematic study for the design of Germano-silicate planar waveguide is carried out resulting in a low-loss waveguide. Optimisation of chemistry process, with annealing temperature and deposition parameters were achieved.

Experimental Procedure

Figure 1 schematizes the sequence of the different synthesis steps. A detailed outline of the preparation of the germano-silicate sol has been documented elsewhere [5]. In this experiment, high purity alkoxide precursors were used (99.999% TEOS by Aldrich and 99.99% Germanium isopropoxide by Chemat Technology Inc.). Once the sol has been aged to a spinnable state, it was deposited onto a 10-micron-thick SiO_2 on a silicon substrate by a syringe. Then, a thin layer of xerogel film (~200 nm) was formed by spin-coating at 1500 rpm for 30 s followed by a thermal treatment of 900^{o}C in a rapid thermal processor for 10 s under oxygen atmosphere. In order to build a waveguiding structure, a high-index, core layer typically requires a thickness of, at least, several microns. Hence, an iterative thin film deposition routine was carried out until the desired thickness was achieved. One distinct advantage of such method is that residual organic solvents and OH/H_2O content can be driven off before each thin layer is deposited, making the removal of such detrimental matter much easier than other waveguide fabrication technique. Lastly, the densified multi-layer germania doped silicate was consolidated in electric furnace at 1100^{o}C in air for one hour. By subjecting the sample to an extended and elevated thermal treatment, the purpose of this consolidation step is to equilibrate the optical properties of each successively coated layer.

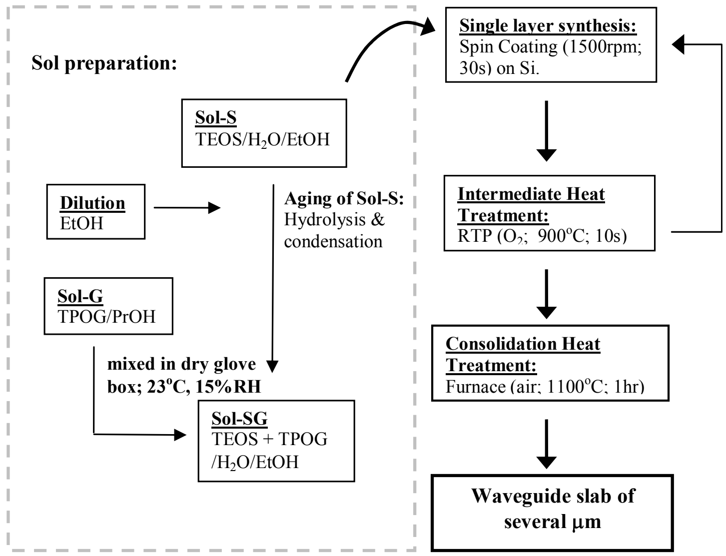

Figure 1: Schematic diagram of the process flow.

Results and discussion

Before proceeding to the multi-layer thick film, single layer films were studied extensively to ensure a material of optical quality with minimal loss of light due to absorption and scattering. As proposed in [5], 20 mol% Ge doped silicate yields the highest index for this material system while reducing the likelihood of nano-dimension Ge clusters or crystals. And at a processing temperature of greater than 800^{o}C, porosity and OH content are both minimized as suggested by a refractive index of close to 1.47 at 1550 nm. The FTIR spectra in Figure 2 show the signature absorption of OH related bonds for the sample annealed at 500^{o}C but absent in 900^{o}C samples. Furthermore, from the same figure, the absence of Ge-O-Ge linkages (2 peaks between 860 – 980 cm^{-1} [6]) can be viewed as the onset of Ge-O clustering or phase separation. In the inset of Figure 2, one can note that the Ge-O-Ge presence in the 20 mol% Ge annealed at 900^{o}C is substantially less than that of the 30 mol% Ge sample. Secondly, the Ge-O-Si absorbance as seen as shoulders indicated by an arrow in Figure 2. The presence of such linkages (960 – 1020 cm^{-1} [6]) suggests the homogeneous incorporation of the GeO_2 into the SiO_2 host network.

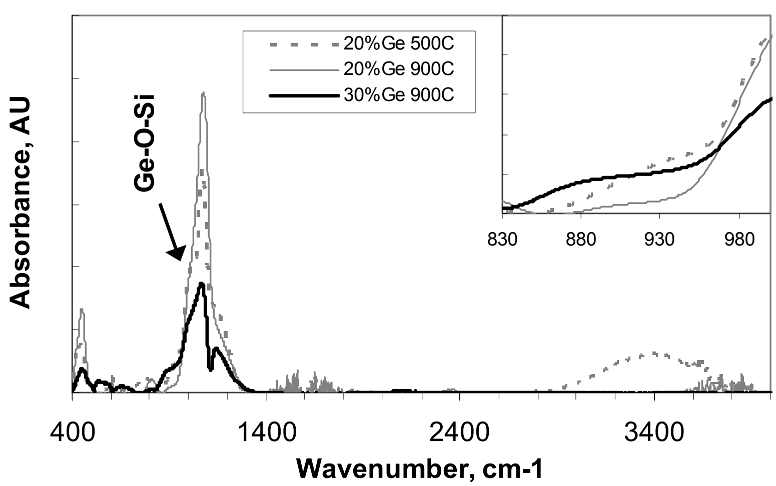

Figure 2: FTIR spectra for 20 mol% and 30 mol% Ge doped single-layer films

Micro-Raman and XRD have been used to confirm the amorphous state of the thin films. No crystallinity was observed. The TEM micrograph as shown in Figure 3, shows that no Ge-concentrated clusters larger than 20 nm are visible. Inherent to the sol-gel spin-coating technique is that surface roughness is less than 1 nm even for the multi-layer as measured by AFM. Such surface smoothness contributes to a low-loss waveguide.

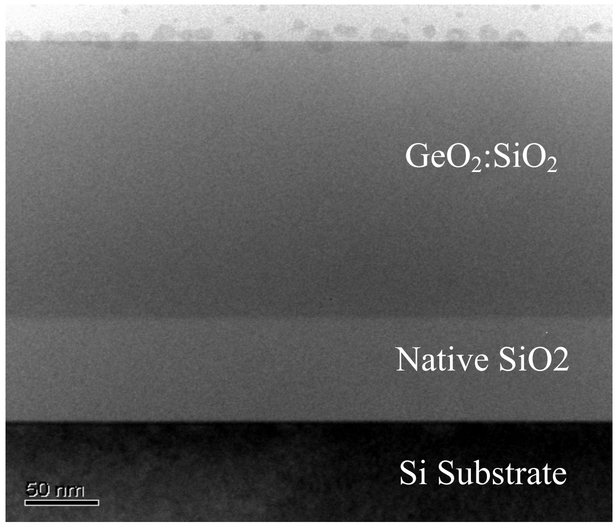

Figure 3: TEM Micrograph of a 20 mol% Ge single-layer sample annealed 1 hour under 1100^{o}C in air.

Once the necessary parameters for single layers have been determined, the multilayer film was fabricated. It was then characterized by a prism-coupler equipment (Metricon 2010) with an He-Ne laser at 632.8 nm and a semiconductor diode laser at 1550 nm. The result for a sample is summarized in Table 1. The uncertainties accompanying the optical values are standard deviations of a number of readings carried out at different locations of the sample. From the fact that indices for TM waves and TE waves closely match each other, one can infer that birefringence is insignificant.

Table 1: Derived optical properties of the multi-layer and single-layer films

<table>
<tr><td rowspan="2"></td><td colspan="2">21-layer</td><td colspan="4">1-layer</td></tr>
<tr><td>632.8 nm</td><td>1550 nm</td><td colspan="2">RTA900^{o}C</td><td colspan="2">RTA900^{o}C/FA1100^{o}C</td></tr>
<tr><td>Thickness (μm)</td><td>4.97 ± 0.05</td><td>4.97 ± 0.06</td><td colspan="2">0.269</td><td colspan="2">0.240</td></tr>
<tr><td>Number of modes</td><td>4</td><td>2</td><td colspan="2">--</td><td colspan="2">--</td></tr>
<tr><td rowspan="2">Refractive index (TE)</td><td rowspan="2">1.4830 ± 0.0002</td><td rowspan="2">1.4687 ± 0.0002</td><td>632.8 nm</td><td>1550 nm</td><td>632.8 nm</td><td>1550 nm</td></tr>
<tr><td>1.4816</td><td>1.4663</td><td>1.4836</td><td>1.4685</td></tr>
<tr><td>Refractive index (TM)</td><td>1.4835 ± 0.0005</td><td>1.4694 ± 0.0005</td><td colspan="2">--</td><td colspan="2">--</td></tr>
<tr><td rowspan="2">Attenuation coefficient (dB/cm)</td><td rowspan="2">1.27 ± 0.2</td><td rowspan="2">0.3 ± 0.2</td><td>632.8 nm</td><td>1550 nm</td><td>632.8 nm</td><td>1550 nm</td></tr>
<tr><td>0.36</td><td>0.06</td><td>0.36</td><td>0.06</td></tr>
</table>

Following the same analysis as [7] to account for the loss in our GeO_2-SiO_2 system, assuming an invisible separation of Ge-O clusters of 20 nm occupying a volume fraction of 10%, the Rayleigh-Mie scattering losses are ~ 0.51 and 0.01 dB/cm at 632.8 and 1550 nm respectively. From these figures, one can see that a significant portion of the loss is due to other foreign particles introduced to the system during the process. Our waveguides can therefore be improved through better precaution to prevent other particles falling to the sample especially during spin-coating.

For a comparison, the optical properties of single layers deposited on an Si substrate were derived from reflectance measurements. One sample was subjected to 1 cycle of rapid thermal annealing (RTA) at 900°C whereas another was subjected to 21 cycles of RTA followed by furnace annealing (FA) at 1100°C. The Lorentz oscillator model (LOM), as before [5], was used to model the reflectance data taken from a Filmetrics F20. The results are also tabulated in Table 1. An expected reduction in thickness corresponds to an increase in refractive index between the two single-layer samples. The average thickness of the consolidated single-layer sample of 0.240 μm seems to concur with the average 1-layer thickness of 0.237 μm for the multi-layer sample. The attenuation coefficients (α) were estimated by using $\alpha = 4\pi k/\lambda$ (λ refers to wavelength of probing photons), from the extinction coefficient (k) from the LOM. These values are found to be less than the measured values which make physical sense as the single-layer film should be more homogeneous and defect free than the multi-layered film. We should stress that these derived α values are only as good as the LOM can model the real material. However, these values do suggest that the LOM parameters found represent a reasonable optical model for our analysis.

Conclusion

A birefringence-free optical waveguide fabricated using germania doped silicate materials by the sol-gel process has been demonstrated. With a propagation loss of less than 0.5 dB/cm, our planar waveguide is suitable for realizing high performance polarization-independent optical devices. The optical properties of the multi-layer slab correspond very well with the single layer properties illustrating the effectiveness of the consolidation step to eliminate differences of the optical properties between layers of the multi-layer stack formed by the iterative deposition and annealing process.

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