Low Loss Chalcogenide Glass Waveguides Fabricated By Thermal Nanoimprint Lithography

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Abstract: Low loss thermally nanoimprinted chalcogenide waveguides are demonstrated for the first time, uniquely using a soft PDMS stamp. Losses of 0.24dB/cm at 1550nm limited by Rayleigh scattering were achieved and embossing of As_2S_3 also demonstrated.

OCIS codes: (130.2755); Glass waveguides, (190.4390); Nonlinear optics, integrated optics

1. Introduction

A chalcogenide glass is one containing one or more of the chalcogen elements (S, Se or Te) as a substantial constituent. The chalcogen element(s) are covalently bonded to network formers, typically Ge, As, Ga, or Si to form an amorphous glass with unusual and sometimes remarkable properties. Chalcogenides have found widespread application as phase change materials for optical data storage media (DVDs) and non-volatile random access memories (PRAM), as lens materials for thermal infrared imaging, as photovoltaic cells, and recently as promising candidates for integrated non-linear optic devices due to their large non-resonant non-linearity and low linear and non-linear losses, e.g. [1,2]. The extraordinarily wide transmission (out to 20μm in some cases) of chalcogenides has also sparked a lot of interest in using them for mid-infrared integrated optical processing for defense and chemical and bio-sensors, as most chemicals and biological materials/toxins have their spectral fingerprints in this region.

Against this plethora of opportunities is the need to fabricate low loss waveguides from chalcogenide materials. Many methods have been used, the best results to date coming from plasma etching with losses of 0.05dB/cm reported for waveguides with ~7μm^2 mode areas, and ~0.2dB/cm at 1550nm for devices with ~1.7μm^2 mode areas [3]. These results however have not come easily as chalcogenides are readily attacked by chemicals used in standard photolithography, and often by any gas in plasma form. This requires very careful process design and results in a complex process with more steps and less control than the ideal, especially for the fabrication of low cost devices.

Thermal nanoimprint technologies on the other hand are well known for their capability in making nanometer sized features [4], require no use of chemicals, and are extremely fast and low cost, requiring only a single step to fabricate the device layer. Several groups have demonstrated the possibility of molding chalcogenide glasses [5,6], but to date the only waveguide result exhibited unacceptably high propagation losses of 2.9dB/cm at 1550nm [6].

In this paper we report the fabrication of the first low loss hot embossed chalcogenide waveguides. Remarkably, this was accomplished with a soft PDMS stamp in contrast to all previous results, which used hard stamps. Losses as low as 0.24dB/cm at 1550nm (limited by Rayleigh scattering in the glass films) were achieved in waveguides up to 8cm long in the highly non-linear glass $As_{24}S_{38}Se_{38}$. Embossing of As_2S_3 glass was also demonstrated.

2. Fabrication Method

Films 1μm thick of $As_{24}S_{38}Se_{38}$ glass were deposited by thermal evaporation on 100mm <100> silicon wafers with 1.5μm of thermal oxide as under cladding. Instead of then following the established hard stamp hot emboss route we chose to modify the process demonstrated previously for ultraviolet nanoimprint lithography of polysiloxane waveguides [7], as the $As_{24}S_{38}Se_{38}$ has a low glass transition temperature at about 120C. Thus a 100mm diameter PDMS stamp was prepared by standard methods [7] with 0.5μm deep “cladding ribs” and waveguide widths from 1.3 to 3.3μm. To ensure flexibility and conformal molding to the substrate surface, the stamp was made with a thickness of 1-2mm. Before first use the stamp was vacuum cured at 160C for ~4 hours to ensure the PDMS was fully cured and would not undergo permanent deformation in the emboss process. The stamp was used in a home built thermal imprint tool where the wafer with stamp sat on a hotplate with an elastic membrane suspended above it, this being vacuum sealed back to the hot plate surface. Another sealed chamber was above the membrane. By evacuating both chambers and keeping the upper one at lower pressure, the membrane bows up and all air can be removed from the stamp. The hot plate was then heated to 190C, and 1-2 atmospheres of pressure applied to the upper chamber. The membrane then elastically deforms applying the pressure isobarically to the stamp for the imprint process. After 20 minutes the hot plate was flash cooled at ~40C/min rate by forcing compressed air through a cooling cool soldered to the bottom surface of the hot plate. Upon cooling below the glass transition temperature, both chambers were vented and the sample removed. The stamp was de-embossed by simply peeling it off by hand, the radically different compositions of the stamp and the films plus the low surface energy of PDMS ensuring there was no adhesion of the stamp. A layer of RPO Pty Ltd IPG^{TM} spin on polymer upper cladding was then applied and cured, and end facets hand cleaved o the chip with a diamond scriber. Fig. 1 shows some typical SEM images of the imprinted waveguides and it is clear that very smooth sidewalls have been attained.

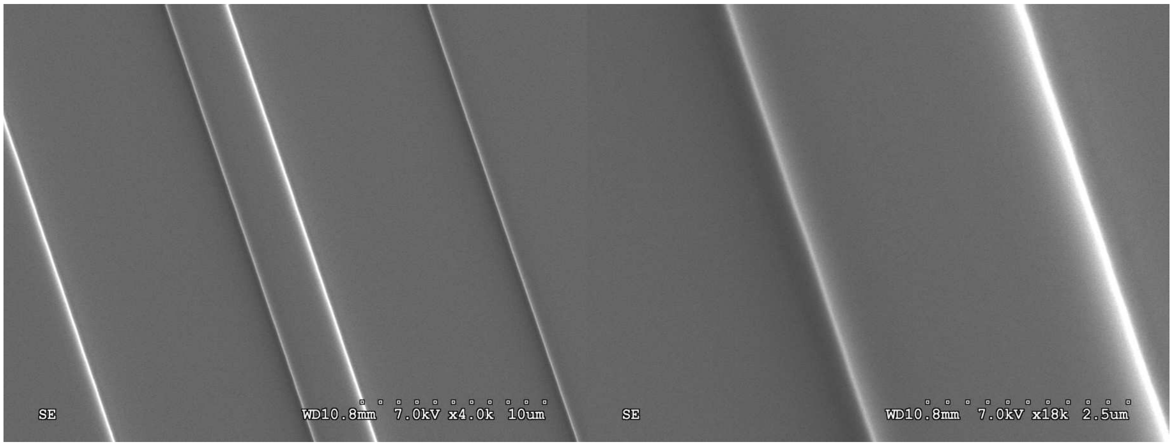

Fig. 1. SEM Images of embossed rib waveguide core

3. Characterisation

Measurements of the imprinted waveguides were made using the cut back technique, here measuring the full sample and then cleaving this into two pieces constituting 1/3 and 2/3 the original length. Measurements were performed using lensed fibres with a 2.5µm 1/e^2 mode field diameter to couple to the sample, and were taken at each length with a laser and power meter, and at several lengths with a fibre coupled arc lamp source and optical spectrum analyzer to obtain the wavelength dependent propagation loss. The waveguides displayed considerable amounts of mode beating which manifests as a strong random (from waveguide to waveguide) wavelength dependence of the insertion loss. The laser-based measurements were therefore taken by sweeping the laser over ~100nm and reading the minimum loss, and the OSA data were taken with a 10nm resolution bandwidth to try and average out the effects. Fig. 2 shows the cut back results for launched TE and TM modes in 5 waveguides of 3.3µm width.

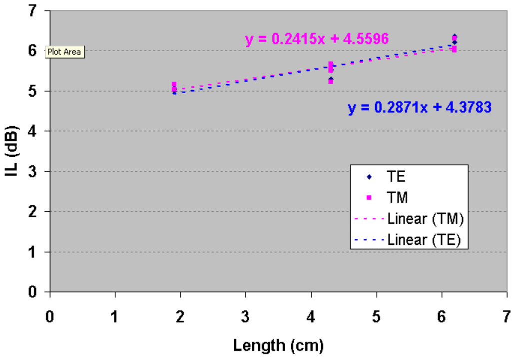

Fig. 2. Cut back results for 3.3µm width waveguide

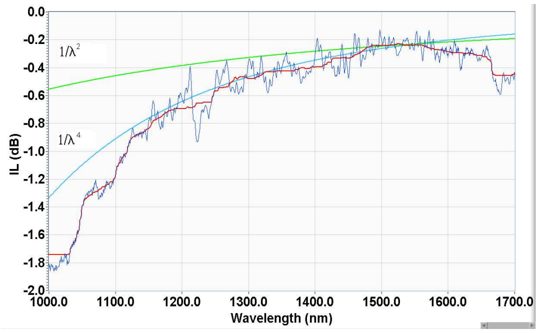

Fig. 3. Spectral dependence of propagation loss

A loss of 0.24dB/cm was obtained, more than an order of magnitude lower than previous results [6], and given the estimated mode area of ~1.5µm2 comparable with the best etched results [3]. The spectral dependence of the propagation loss was also calculated from spectra taken from the long and short lengths. Fig. 3 shows the result for a 3.3µm wide waveguide. Also plotted on Fig. 3 are $1/\lambda^2$ and $1/\lambda^4$ curves representative of waveguide sidewall scattering and Rayleigh scattering in inhomogeneous media respectively. It is clear from the SEM images of Fig 1. and the wavelength dependence of the loss that the mechanism in play here is in fact Rayleigh scattering in the film. This implies that even lower losses are possible with appropriate film deposition conditions.

We also sought to fabricate devices from As_2S_3 for comparison due to its common usage as the "work horse" material of chalcogenide glasses and the known absence of Rayleigh related effects in thermally evaporated thin films. In contrast to the $As_{24}S_{38}Se_{38}$ glass, As_2S_3 has a glass transition temperature of ~180C thereby necessitating a higher imprint temperature. Previous studies [5,6] used a temperature of 240C for embossing with hard stamps. We determined that a temperature of 250C was in fact superior for the stamping method used here, and sought to fabricate devices at this temperature. Fig. 4 shows an optical micrograph cross-section of an embossed As_2S_3 waveguide with ~1µm^2 mode area.

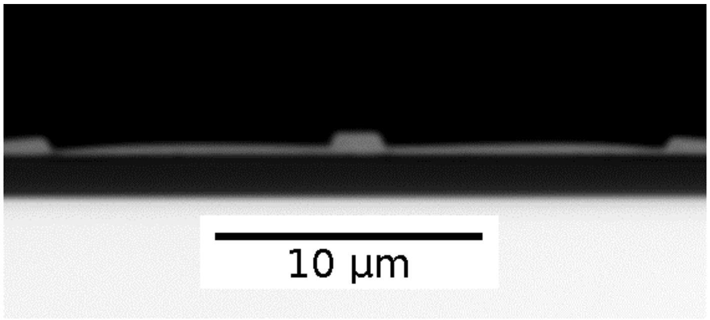

Fig. 4. Optical Micrographs of 1.7µm wide 0.85µm high imprinted As_2S_3 waveguide

Despite the somewhat higher temperature, it is clear that the waveguide was successfully embossed. The stamp was not degraded and could be reused repeatedly. Insufficient time was available to characterize this device before the submission deadline, full optical results will be presented at the conference.

4. Conclusions

We have demonstrated the first low loss chalcogenide glass waveguides fabricated by hot embossing techniques, here using $As_{24}S_{38}Se_{38}$ glass. A soft PDMS stamp was used in contrast to previous works using hard stamps and was shown to be capable of providing sufficient performance. Losses as low as 0.24dBcm at 1550nm were demonstrated, the limit appearing to come from Rayleigh scattering in the thin film itself rather than from the imprint process. Imprinting in As_2S_3 glass using a soft stamp was also demonstrated successfully with the same technique.

5. Acknowledgments

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6. References

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