Rapid Prototyping of Planar Infrared Waveguides

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***Abstract*—A method for creating planar As_2S_3 waveguides with a minimum of processing steps is proposed, and the resulting waveguides have been characterized. When the processing parameters are optimized, the losses are low enough for practical use. The authors demonstrate this by creating serpentine waveguides with multiple bends and lengths in excess of 23cm.**

Keywords-component; chalcogenide glass; optical waveguides; rapid prototyping; infrared.

I. Introduction

Planar optical waveguides offer a great deal of flexibility in terms of the incorporation of active elements[1], coupling of multiple waveguides[2], multiplexing / demultiplexing[3] and so on. Currently though, while planar waveguides based on SiO_2 and certain polymers are relatively common[4,5], waveguides operating in the infra-red are less well-developed. This lack of development is of particular importance for chemical sensing; many common analytes have absorbances in the infra-red, allowing them to be effectively characterized, but current technology makes analysis on a planar waveguide device difficult.

We present the development of a method for the rapid prototyping of optical waveguides based on amorphous arsenic trisulfide (As_2S_3), a chalcogenide glass. This material has several useful properties, such as transparency from 650 to 12000nm and photosensitive changes in refractive index, solubility and optical absorption. This method exploits the change in solubility to employ the As_2S_3 both as photoresist and as the waveguiding material itself, significantly reducing the time and number of processing steps required to create an infra-red waveguide over existing methods[6].

II. Results and Discussion

Previous literature results suggest that annealing of As_2S_3 waveguides unavoidably leads to cracking, and hence poor performance of the waveguide[7]. We have determined that cracking can be eliminated in almost all cases if the waveguides are cooled sufficiently slowly after annealing, on the order of 20°C / hour. We have used this discovery, along with the fact that our waveguides are fully etched, as opposed to the more common shallow rib waveguides, to remelt the waveguides into a hemispherical cross-section with very smooth side-walls (see Figure 1).

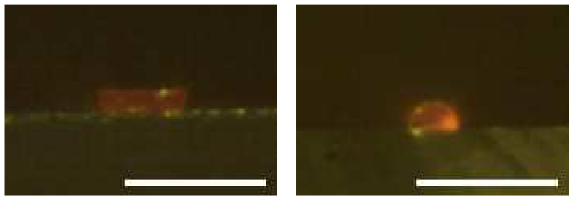

Figure 1. Unmelted and melted waveguides. The unmelted waveguide on the left (annealed at 230°C) retains its rectangular cross-section whereas the waveguide on the right, annealed at 290°C, has a hemispherical cross-section.

The waveguide dimensions were optimized by manufacturing large numbers of waveguides with different thicknesses and widths and measuring the transmission losses. It was found that the losses were not particularly sensitive to waveguide thickness, provided that they were not so thin that the waveguide partially evaporated during annealing (<4µm when annealed at 260°C) or that the aspect-ratio was too high (thicknesses >11µm combined with widths <10µm). The optimum thickness appeared to occur at approximately 8.5µm, although thicknesses between 4 and 10µm were acceptable.

The loss measurements were similarly insensitive to waveguide widths (under current processing parameters); provided the waveguides were between 9 and 33µm wide, there appeared to be little difference in the loss values.

The losses were found to be much more sensitive to annealing temperature; all annealing tests were performed for 2 hours under nitrogen atmosphere. The glass-transition temperature for As_2S_3 is approximately 180°C; waveguides annealed at 170°C had losses on the order of 2-3dB/cm, compared to approximately 5-10dB/cm for unannealed waveguides.

Increasing the annealing temperature unexpectedly increased the waveguide losses; when inspected under a microscope, these waveguides appeared to be darker in places. This was attributed to a roughening of the surface. The origin of this effect is not clear, but we hypothesize that it is due to microscopic inhomogeneities in the glass leading to either localized remelting on a nanoscopic length-scale, or partial microcrystallisation. With more time, this phenomenon would be investigated further. Once the annealing temperature passed 260°C though, the roughening was no longer observed. At temperatures on the order of 290°C and above, partial evaporation of the waveguides was observed, placing an upper limit on the practical annealing temperature when performed at ambient pressure.

The optimum waveguides were found to be those with thicknesses of 8.5μm, widths of 9μm, and which were annealed at 260°C for two hours under nitrogen atmosphere before being cooled slowly; losses were found to be on the order of 1.2±1dB/cm.

Several different structures were created using the waveguides outlined above. Firstly, waveguides bends were demonstrated. Since the waveguides are fully-etched, the lateral confinement is very good. Waveguides with bend radii of >4mm were found to have almost negligible increase in loss over that of a straight waveguide, although smaller bend radii were still possible; radii < 1mm had appreciable additional losses, but these appeared to be limited to approximately 6dB/cm for a 287μm bend radius. Utilising these bends, a serpentine waveguide with a total length of 238mm was created; waveguiding was demonstrated over the whole length.

Y-splitters were also created, and light coupled into the input waveguide could be observed in both arms of the output waveguides. The design splitting ratio was 1 : 1, but the measured ratio was found to be between 1 : 1.6 and 1 : 8.8.

III. Experimental

As_2S_3 was synthesized from a mixture of arsenic (99.9999%, ABCR) and sulfur (99.9995%, Alfa Aesar) in the correct stoichiometric ratio. The elements were sealed in a quartz-glass ampoule, heated to 750°C for 12 hours in a rocking furnace to ensure a homogenous melt, and then cooled rapidly by removing the ampoule from the furnace and immersing it in water. The As_2S_3 glass was removed from the ampoule and broken into small lumps. These lumps were then placed in a molybdenum evaporation boat which was, in turn, placed in a vacuum chamber for thin-film deposition.

A series of glass microscope slides were cleaned by immersion in aqua regia for 12 hours, followed by immersion in a solution of Decon 90 (Decon Laboratories Ltd.) for 1 hour and rinsing in distilled water. The slides were then dried with a stream of compressed nitrogen. They were mounted in a rotating sample holder in the vacuum chamber, and a thin layer of As_2S_3 deposited by Joule heating of the molybdenum boat. Deposition rate and thickness were monitored by a film thickness monitor.

Once the slides had been removed from the vacuum chamber, they were placed in a custom-built direct-write laser system and a series of optical waveguide designs were written into the thin film by exposure to a tightly-focussed laser spot (532nm continuous-wave frequency-doubled Nd:YVO, lasing at 100mW with a spot size of approximately 10μm). The spot size could be controlled by defocusing the laser from a diffraction-limited spot to approximately 500μm diameter, and changing the laser power to maintain the same fluence.

Once laser-writing was complete, the slides were placed in an etching solution of 3.5×10^3M diisopentylamine in dimethyl sulfoxide[8] and etched until the surrounding unexposed regions had completely dissolved (20-30 minutes at room temperature and pressure). The slides were then washed in dichloromethane to remove any excess etchant and left to dry. Finally, the slides were heated in a nitrogen atmosphere for 2 hours to anneal the waveguides.

Transmission losses were characterized using the method of Okamura, Yoshinaka and Yamamoto[9]. Briefly, infra-red light is coupled into one end of the waveguide and the waveguide is imaged from above. Assuming the density of scattering centers in the waveguide is constant, the intensity of light scattered from the waveguide is proportional to the intensity of light in the waveguide itself, and hence by plotting the intensity of scattered light versus the distance along the waveguide and fitting to an exponential decay, the waveguide losses in dB/cm can be calculated independently of coupling losses.

IV. Conclusions

We have demonstrated a method for the creation of fully-etched As_2S_3 waveguides that requires a minimum of processing steps, yet yields waveguides with low losses and very strong confinement. We have used this method to create waveguides with lengths in excess of 23cm as well as with several bends and splitters, demonstrating the practical application of our method. Further details can be found in [10].

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