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Abstract: A rapid thermal reflow technique is applied to high-index-contrast, sub-micron waveguides in As_2S_3 chalcogenide glass to reduce sidewall roughness and associated optical scattering loss. Up to 50% optical loss reduction after reflow treatment is achieved.

OCIS codes: (160.2750) Glass and other amorphous materials; (130.3120) Integrated optics devices; (230.7390) Waveguides, planar; (240.5770) Roughness.

1. Introduction

Chalcogenide glasses (ChG's) have recently emerged as a promising material candidate for high-index-contrast (HIC) photonic devices, featuring almost unlimited capacity for composition and property tailoring, wide infrared transparency, and high Kerr nonlinearity accompanied with low two photon absorption (TPA) [1]. However, despite the tight optical confinement in HIC waveguides and the ensuing integration benefits, HIC waveguides typically suffer high propagation loss, mainly due to increased optical scattering from sidewall roughness, which scales with the square of refractive index contrast [2]. We showed that optical scattering arising from sidewall roughness is the dominant source of optical loss in HIC chalcogenide strip waveguides [3], and such high scattering loss is a major hurdle to performance improvement of HIC photonic devices in chalcogenide glass.

In this letter, we present rapid thermal reflow as an effective approach for sidewall roughness and optical loss reduction in HIC chalcogenide waveguide devices. In analogy to a fiber drawing process, the action of surface tension leads to elimination of roughness and hence negligible scattering loss. Thermal reflow has been shown to effectively decrease optical loss in silica glass [4]; and this is the first report of applying the reflow technique to chalcogenide glasses to the best of our knowledge. Compared to silica glass reflow process, chalcogenide glass reflow does not require thermal processing at elevated temperature given the lower softening temperature of chalcogenides. Such a tolerant thermal budget, compatible with CMOS backend processes, and imposing minimal adverse effects on other on-chip devices, is particularly advantageous for electronic and photonic integration.

2. Device fabrication and characterization

The chalcogenide glass bulk preparation and film deposition process are described elsewhere [5, 6]. Strip waveguides with a width of 800 nm and a height of 400 nm in thermally evaporated As_2S_3 film (n = 2.37) are patterned via lift-off in this study. The entire patterning process has been carried out on a 500 nm CMOS line [3]. Thermal reflow of the as-patterned waveguide devices is carried out at different temperatures (± 5 ºC) on a pre-heated hotplate in a nitrogen filled glove box (oxygen and water vapor impurity < 1 ppm). After heat treatment, the samples are immediately transferred onto an aluminum heat sink held at room temperature to minimize dwelling time at intermediate temperatures. Before optical characterization, a 3 μm thick layer of SU8 polymer is spin-coated onto the waveguides to prevent oxidation. Cavity quality factors (Q-factors) of racetrack micro-resonators, comprising As_2S_3 strip waveguides with a bending radius of 50 μm, are measured using a fiber end-fire technique. The corresponding optical loss in the waveguides is calculated based on critically coupled resonator Q factors.

3. Results and discussion

Figure 1 shows the surface morphology of chalcogenide glass waveguides (a) before and (b) after reflow at 230 ºC for 15 s. The sidewall roughness is significantly reduced after reflow, and the waveguide cross-sectional geometry is modified towards a dome shape due to surface tension. RMS sidewall roughness values of As_2S_3 waveguides plotted in Figure 2a confirm that roughness decreases as reflow temperature increases, given the reduced viscosity of As_2S_3

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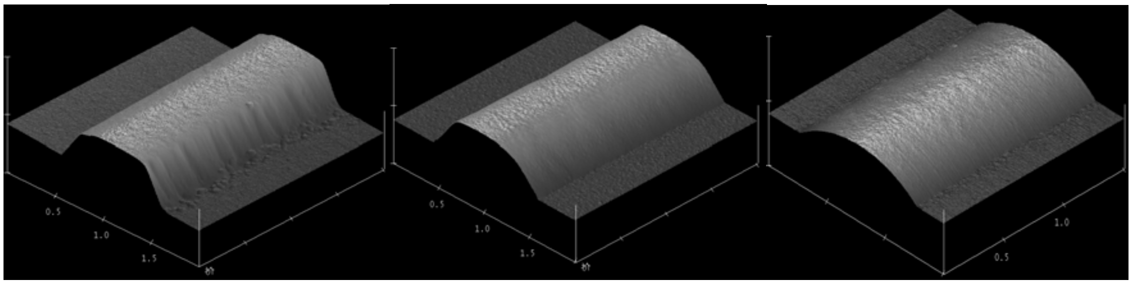
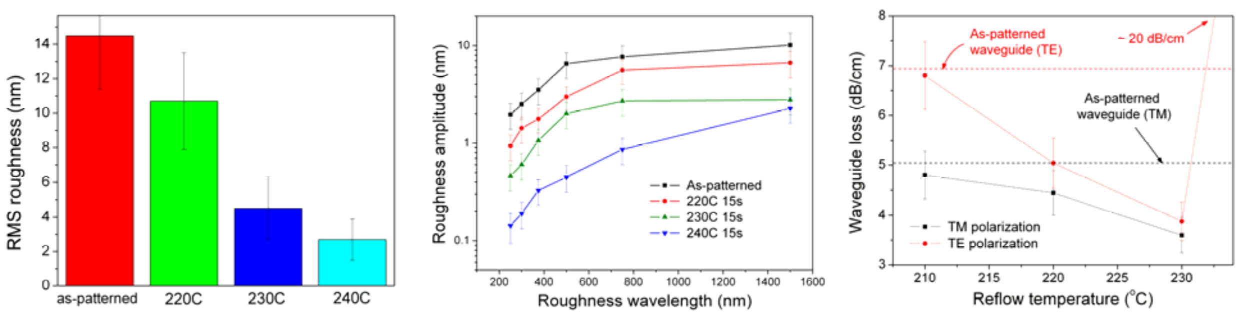
glass at higher temperature. Power spectral density functions of waveguide sidewall roughness are shown in Fig. 2b. Generally the roughness amplitude diminishes with the roughness wavelength, a trend observed in waveguides fabricated in other material systems [7]. Further, roughness with smaller spatial wavelength exhibits a more significant amplitude reduction. Such an observation will be discussed and consistently explained within the framework of a kinetic theory.



(a) (b) (c)

Fig. 1. Surface morphology of As_2S_3 waveguides: (a) as-patterned; (b) reflowed at 230 ºC for 15 s; and (b) reflowed at 240 ºC for 15 s.

Figure 2c plots the transmission loss in As_2S_3 waveguides after reflow treatment at different temperatures. The optical loss decrease after 15 s reflow from 210 ºC to 230 ºC is consistent with the trend of sidewall roughness smoothing, and thus can be associated with the scattering loss reduction. However, despite the continuing trend of roughness reduction at increased reflow temperature, optical loss in As_2S_3 waveguides sharply increases to ~ (20 ± 6) dB/cm after 15 s reflow at 240 ºC. Based on material and device characterization results, we attribute the loss increase to the partial evaporation of As_2S_3 glass, which leads to waveguide thickness reduction and hence increased bending loss and modal mismatch loss between the straight and bent sections in a racetrack resonator. The evolution of optical loss in As_2S_3 is also investigated using waveguide modal analysis and good agreement between simulation and measurement is confirmed.



(a) (b) (c)

Fig. 2. (a) RMS waveguide sidewall roughness; (b) waveguide roughness amplitude as a function of roughness wavelength and (c) optical transmission loss in racetrack resonators for different reflow temperatures.

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