High-quality Mid-infrared Chalcogenide Ring Resonator

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Abstract: We report $Ge_{23}Sb_7S_{70}$ chalcogenide ring resonators with up to 8×10^4 quality factors operating around 3.6 µm wavelength fabricated through e-beam lithography. Their rib waveguide geometry can be engineered to support close-to-zero dispersion modes needed for mid-infrared microcomb generation.

Chalcogenide glasses are attractive platform for linear and nonlinear optics in the mid-infrared (MIR) due to their vast transparency window and high nonlinearity. In addition, chalcogenide planar waveguides and ring resonators can be integrated on-chip with sources and detectors for compact spectroscopic sensing. There have been steady efforts to advance the quality of chalcogenide-based MIR photonic devices in recent years [1-3], but a dispersion controlled low-loss microresonator platform suitable for microcomb generation is yet to be demonstrated. Among chalcogenide glasses, $Ge_{23}Sb_7S_{70}$ is transparent between 0.6 to 22 µm and has low toxicity compared to arsenic-based chalcogenide glass system. It is easy to deposit via thermal evaporation and its glass transition temperature of 311 ℃ ensures material stability during high-intensity light propagation [4]. In this paper, we present a highly repeatable fabrication process and thorough characterization of $Ge_{23}Sb_7S_{70}$ ring resonators with high quality factors up to $\sim 8 \times 10^4$. Also, the rib waveguide geometry of the ring cross-section offers plentiful degrees of freedom for dispersion engineering, which could be used to achieve a close-to-zero dispersion needed for frequency comb generations at mid-infrared.

The $Ge_{23}Sb_7S_{70}$ ring resonators were fabricated through a combination of thermal evaporation, electron beam lithography (EBL), and inductively coupled plasma (ICP) reactive ion etching (RIE). First, a $Ge_{23}Sb_7S_{70}$ chalcogenide film was thermally evaporated on a MgF_2 substrate that was dehydrated at 400 ºC for 15 hours in an N_2 environment to remove all physically and chemically adsorbed water [5]. Next, the film was annealed at 265 ℃ to promote adhesion between the chalcogenide and MgF_2 while reducing thermal stress. EBL was then performed to pattern double coated, micron-thick e-beam resist which was also used as an etch mask for the following dry etch process as shown in Fig.1(a). We first explored an ICP dry etch of $Ge_{23}Sb_7S_{70}$ chalcogenide with a BCl_3/Cl_2 chemistry established for a similar chalcogenide, [1] but results produced extremely rough sidewalls. After a comprehensive etching study, we found that Cl_2 prohibits the formation of passivation layer during the ICP etch, which is essential for achieving smooth sidewalls. Thus, we adapted to a Cl_2-free etch chemistry with BCl_3/Ar and further optimized the etch condition to achieve smooth and vertical sidewalls as shown in Fig.1(b). The etch depth was deliberately set to be slightly smaller than the $Ge_{23}Sb_7S_{70}$ film thickness to avoid exposing MgF_2 substrate to air. It is critical to fully remove the hardened e-beam resist after ICP etch with a short Ar plasma ash followed by 1 hour soaking in 75 ºC N-Methyl-2-pyrrolidone (NMP) based solvent and 30 seconds of sonication. The short sonication process will efficiently remove any passivation overgrowth on the etched sidewalls without delaminating the $Ge_{23}Sb_7S_{70}$ devices.

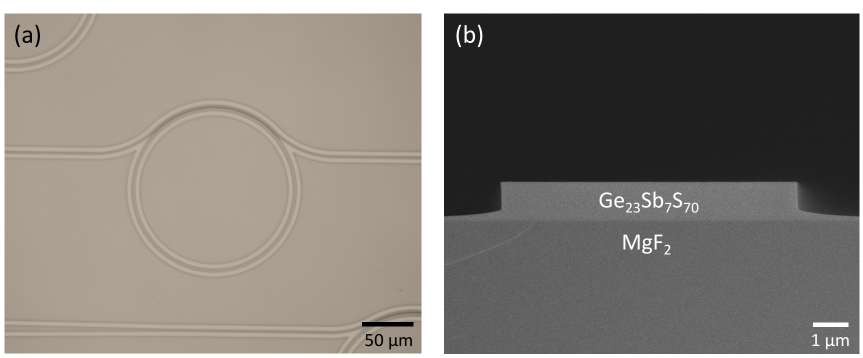

Fig. 1. (a) Optical microscope top-view image of the e-beam resist pattern on $Ge_{23}Sb_7S_{70}$ film for 100 µm-radius ring resonators coupled with a tapered bus waveguide. (b) Scanning electron micrograph of the cross-section of a $Ge_{23}Sb_7S_{70}$ bus waveguide etched by BCl_3/Ar chemistry inductively coupled plasma reactive ion etching.

Finite element analysis simulation was performed to engineer the dispersion of the fabricated waveguide using the optical constants measured by MIR ellipsometry. By tuning the width of the rings, we achieve close-to-zero total dispersion for various radiuses. Finite-Difference Time-Domain (FDTD) simulations were then performed to design pulley couplers for coupling to the dispersion controlled TE_{00} mode. The bus waveguides were tapered to 8 μm wide at the cleaved facets for efficient free-space coupling. The optical transmission spectra of the ring resonators were measured using an Argos Aculight Model 2400 CW optical parametric oscillator (OPO), Bristol 671 wavemeter, and two PbSe AC coupled amplified detectors. Asphere lenses (NA 0.56) were used for free space coupling into and out of the chip. The wavelength of the OPO was tuned continuously following procedures outlined in [6]. Transmission spectra of the resonances were fitted to a Lorentzian lineshape to identify loaded quality factors Q_l, and the intrinsic quality factor Q_i was calculated from the measured coupling depth, as shown in Fig.2(a). To characterize the dispersion, resonant frequencies were identified over a wide range of wavelengths and the integrated dispersion was then extrapolated from the changes in free spectral range, as shown in Fig.2(b,c). As designed, the resonator exhibited a flat and close-to-zero dispersion near 3600 nm. Near the edges of the measured wavelength range, the measured dispersion deviates from the design due mainly to the limited number of data points available. This mismatch is expected to be greatly reduced when a wider wavelength scan is performed.

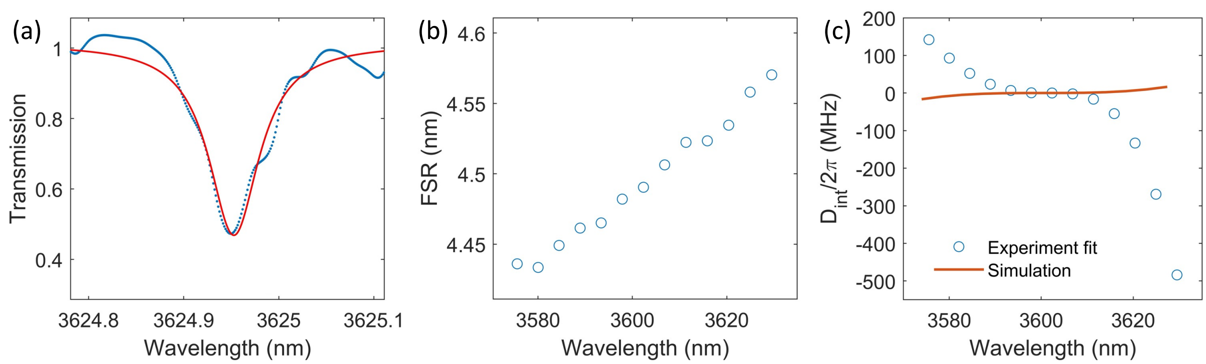

Fig. 2. (a) Transmission spectrum of a 200 μm-radius $Ge_{23}Sb_7S_{70}$ ring resonator around 3.6 μm wavelength. The measured quality factor is $Q_l = 6.44 \times 10^4$, and the intrinsic quality factor is calculated to be $Q_i = 7.64 \times 10^4$. (b) The measured free-spectrum-range (FSR) spectrum of the ring resonator measured from a wideband transmission scan. (c) Fitted integral dispersion D_{int} spectrum compared to the simulation of the $Ge_{23}Sb_7S_{70}$ ring resonator's TE_{00} mode.

From the intrinsic quality factor, we calculated the propagation loss to be 2.1 dB/cm. Given our optimized etch condition, we believe that remaining sources of loss can be attributed to atmospheric degradation and absorption in the substrate. Therefore, continuing work will investigate fabrication with substrate options, such as Al_2O_3 (sapphire) substrates that is free from water absorption, as well as thick claddings, such as Al_2O_3 chemical vapor deposition (CVD), to prevent device exposure to atmosphere.

In conclusion, we present high-quality $Ge_{23}Sb_7S_{70}$ ring resonators in the mid-infrared region. Scattering losses were reduced by an optimized BCl_3/Ar etch chemistry that enabled vertical and smooth sidewalls, as well as a short sonication process to remove passivation overgrowth. Dehydrating the MgF_2 substrate significantly reduced absorptive losses compared to the previous works [1]. These combined efforts produced ring resonators with Q_i up to $\sim 8 \times 10^4$ which is among the best reported in chalcogenide material systems. These resonators are a great platform for cavity-enhanced MIR spectroscopy. Further improvement in quality factor will enable $Ge_{23}Sb_7S_{70}$ resonators as a promising integrated system for mid-infrared nonlinearities such as micro-comb generation, due to its low-loss propagation and dispersion engineering capability.

References

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