Quaternary Semiconductors for Integrated Nonlinear Optics

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Abstract:

We propose strip-loaded and nanowire waveguides on quaternary III-V semiconductor InGaAsP for integrated nonlinear optics. III-V Quaternary semiconductors have been widely used for laser sources and multilayer mirrors such as Bragg reflectors. However, their nonlinear optical properties yet remain unexplored, while the materials definitely hold promise for nonlinear photonics on-a-chip, since III-V compounds tend to exhibit high values of the nonlinear optical susceptibilities, while the nonlinear absorption in these materials can be minimized in the wavelength range of interest through a proper selection of the material composition. We designed waveguide structures based on InGaAsP and show that the effective mode area as small as 1.0 µm² can be achieved through the optimized design. We also present fabrication process for these waveguides and optical transmission loss measurements along with self-phase modulation data are also presented.

Summary of Research:

All-optical wavelength conversion can be achieved through nonlinear optical effects, such as four-wave mixing, cross-phase modulation, or a two-step χ(2) process involving a difference-frequency generation followed by a sum-frequency generation [1]. Several material platforms have been used to demonstrate all-optical wavelength conversion and other operations of optical signal processing. Among these materials, III-V semiconductor compound, such as, aluminum gallium arsenide (AlGaAs), demonstrated the best potential for nonlinear photonic devices [2]. In the present study, we extend the quest for suitable nonlinear optical materials to III-V quaternary semiconductor: indium gallium arsenide phosphide (InₙGaₗAsₘPₙₘ), whose relative composition (x and y) add another degree of freedom (compared to tertiary semiconductors, such as AlGaAs) to control optical linear and nonlinear properties.

InGaAsP passive nonlinear waveguides can be used in combination with integrated InGaAsP lasers to extend their range of operation to longer wavelengths (2 µm and beyond). Such sources can be of interest in spectroscopy and environmental sensing, specifically for lab-on-chip applications that are of interest specially for biosensing [3]. This motivates our studies on the nonlinear optical performance of InGaAsP.

Designs of the material composition and waveguide geometry were optimized to achieve high confinement, while being suitable for epitaxial growth on lattice-matched substrates, indium phospide in this case. For high confinement, material compositions with high refractive index contrast between core and cladding layers was selected. Numerical simulations of the Eigenmode were performed using finite-difference Eigenmode method. Figure 1 shows a schematic of the designed strip-loaded waveguide along with wafer composition. Simulated effective modal area of this waveguide design was 1.0 µm².

Figure 1: Schematic of InGaAsP waveguide with wafer composition.
Strip-loaded InGaAsP waveguides were fabricated with waveguide widths ranging from 1.5 µm to 1.9 µm. Wafer was grown by a commercial vendor using molecular beam epitaxy. 250 nm of silica was deposited by plasma enhanced chemical vapor deposition, followed by 50 nm of chromium deposited using electron-beam evaporation. Negative tone e-beam resist HSQ was spin-coated and patterned using 100 kV JEOL electron beam lithography system. Waveguide pattern was etched into chromium layer using inductively coupled plasma reactive ion etching (ICP-RIE) to generate mask for etching silica layer. Silica layer was then etched using another ICP-RIE to form silica mask, which was finally used to etch InGaAsP. Scanning electron microscopy images of fabricated structures are shown in Figure 2.

Fabry-Perot method was used for measuring propagation losses [4]. Measured propagation loss for 1.7 µm wide waveguide was 1.5 dB/cm, which is lower than any published data for InGaAsP waveguides, to the best of our knowledge. To demonstrate nonlinear optical process in such waveguides, self-phase modulation measurements were performed using setup shown in Figure 3, spectral broadening is shown in Figure 4, showing power in waveguides in watts (W) and also approximate nonlinear phase shift. These measurements hint at efficient nonlinear effect in InGaAsP waveguides, detailed measurements to determine quantitative efficiency are in progress.

This study demonstrates InGaAsP as a suitable candidate for integrated nonlinear optics targeting optical applications in mid-infrared band. Low propagation losses were achieved using our fabrication process and self-phase modulation was demonstrated.

References: