Suspended Membrane InGaAs Photonic Crystal Waveguides for ammonia sensing at λ=6.15µm

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Abstract: Fully suspended InGaAs waveguide devices with holey photonic crystal waveguides (HPCWs) are designed for mid-infrared sensing at λ=6.15µm in the low index contrast InGaAs-InP platform. We experimentally detect 5ppm ammonia in 1mm long suspended HPCWs. © 2019 The Author(s)

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Due to its distinctive features, mid-infrared (MIR) photonics research has intrigued great interest for various applications in civilian, military and security domains. Among them, MIR trace-gas sensing applications have been vigorously developed based on molecular absorption spectroscopy and the fundamental vibration signatures of chemical bonds in the MIR region, known as “molecular fingerprints”. Although silicon is the most prevalent material for the passive photonic devices, it is not applicable to wavelengths λ > 6µm because of its high intrinsic material loss (~0.25dB/cm at λ=6µm, exceed 2dB/cm after λ~7µm). Several alternative low-loss material platforms such as Ge-GaAs, GaAs-AlGaAs, InGaAs-InP can cover the entire molecular fingerprint region from λ=3-15µm [1,2]. Furthermore, to ameliorate current bulky and expensive commercial systems, integrated photonic circuits have shown its promising potential in terms of light-weight, alignment-free, compact and high sensitivity.

In this paper, with regard to monolithic integrated circuits, we also take the light sources and detectors into account which are primarily in the form of quantum cascade lasers (QCLs) and quantum cascade detectors (QCDs) in the MIR region. Since the most efficient room temperature QCLs presented till date are InP-based material, we chose the InGaAs-InP platform to fabricate fully suspended InGaAs membrane waveguides, and eventually to integrate the passive devices with QCLs and QCDs in future work. Previously, it has been demonstrated that slow light enhanced slotted photonic crystal waveguides (SPCWs) and holey PCWs (HPCWs) can effectively reduce the optical absorption path length due to slow light effect, and increase the light-matter interaction length by enhancing the in-plane evanescent optical mode overlap within the low-index etched holes of the photonic crystal (PC) lattice; as a result, significantly higher detection sensitivities are achieved for the targeted gas detection [3-7]. Our previous research elaborated that the peak electric field enhancement factor in the SPCWs was better than that for the HPCWs; on the other hand, the propagation losses for the HPCWs were 3× lower than that for the SPCWs [3]. Since the guided light in 2D PCWs is confined out-of-plane by total internal reflection, an index contrast at least Δn~1.5 is required between the core and the substrate to ensure an appreciable band gap for guiding slow light. In the InGaAs-InP material system, we therefore sacrificially etched away the lower cladding InP to build suspended membrane waveguides to ensure Δn~2.3 to ensure slow light PC guiding. In this paper, we experimentally study fully suspended InGaAs HPCWs at λ=6.15µm, for sensing ammonia which has a peak absorbance at this wavelength.

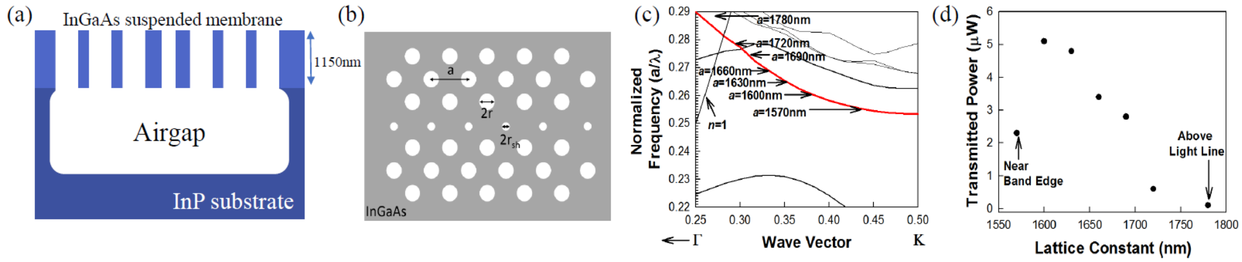

Fig. 1. (a) Schematic of the fully suspended InGaAs HPCWs cross view. (b) Schematic of the InGaAs HPCWs membrane, which is formed by etching a row of smaller air holes with radius r_s=0.5r in the center of the PCW. (c) 3D plane-wave expansion (PWE) dispersion diagram of HPCWs in suspended membrane InGaAs in (b); devices were made with various lattice constants ‘α’ to probe the guided mode (red) using a single wavelength external source at λ=6.15µm for optical characterization. (d) Optical transmission characteristics versus lattice constant. Ammonia sensing is done with suspended membrane InGaAs SPCW device with α=1600nm in (c).

At λ=6. 15μm, a single fundamental transverse-electric (TE) polarized mode is allowed only in a waveguide with heights h_{InGaAs}=1.15μm with air cladding as shown in Fig. 1. (a). A schematic of the InGaAs HPCWs membrane is shown in Fig. 1. (b); the HPCWs device comprises a W1 PCW with a single missing row of holes along the Γ-K direction in a hexagonal lattice of air holes in InGaAs with lattice constant α. In the center of the PCW, a row of smaller holes with radius r_s=0.5r, where r=0.315α is the radius of the holes in the bulk lattice; W1 indicates that the width of the PCW is $\sqrt{3}$α. Fig. 1. (c) shows simulated dispersion diagram of the HPCWs in suspended membrane InGaAs. Since devices were to be characterized using a single wavelength external source at λ=6.15μm, similar to our previous measurements [1], several 1mm long devices were made with increasing lattice constants to probe the guided mode dispersion diagram from the stop band edge to above the air light line. Optical transmission measurements in Fig. 1. (d) show the variation in transmitted power as a function of lattice constant. Group index of the guided mode (in red) is maximum at the band edge and reduces with increasing lattice constant farther from the band edge. As a result, transmitted power increases with increasing lattice constant away from the band edge. The optimized structure was designed to ensure a large guiding band-width for the propagating PCW guided mode as well as a large electric field overlap with the analyte. It is also necessary to ensure the existence of a sufficiently wide stop gap to enable a more accurate determination of the slow light guiding transmission regime of the guided mode. We simulated bandwidth and stop gap variations versus r_s/r ratio as well as the peak electric field enhancement factor and electric filed overlap percentage in small air holes in the center of the PCW, as a function of r_s/r. Accordingly, we choose r_s=0.5r, r=0.315α and α=1600nm at λ=6.15μm as our optimized design, considering the above design constraints.

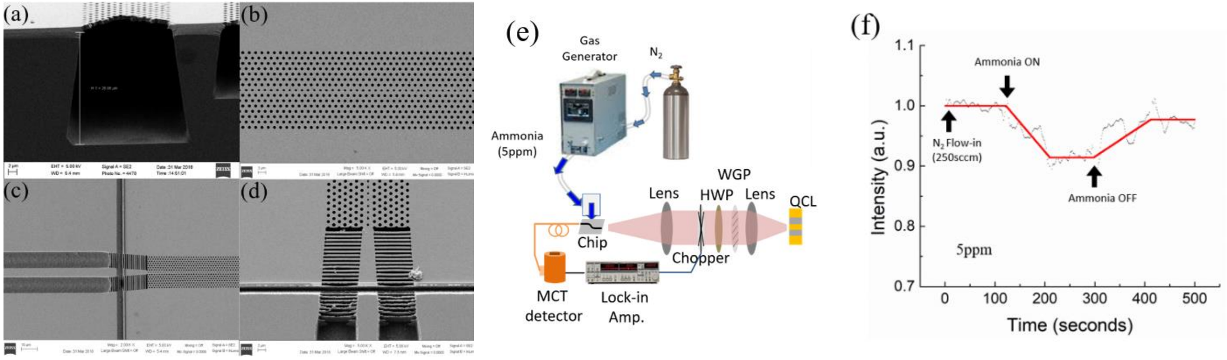

Fig. 2. (a) Cross view SEM images of the fully suspended HPCWs. (b) Top view of the fully suspended HPCWs. (c) Top view of the fully suspended HPCWs and Strip WG-Sub-waveguide Gratings (SWGs)-HPCW interface; only SWGs and HPCWs are suspended. (d) Oblique view of the strip WG-SWGs-HPCWs interface. (e) Schematic plot for testing setup. (f) Ammonia detection result at 5ppm with TE polarized light. The off state normalized transmission is 91.4%.

Fig. 2. (a)~(d) show cross and top view SEM images of fabricated devices. The devices are cleaved and characterized with end-fire coupling setup as shown in Fig. 2. (e). By measuring the output power versus time, in the presence and absence of ammonia flow from a calibrated Kintek vapor generator, we successfully detected ammonia at 5ppm, as shown in Fig. 2. (f). The slopes observed during ammonia On/Off are related to the lag time of ammonia flow from the vapor generator via tubing to the surface of our chip. We have demonstrated elsewhere using computational fluid dynamics (CFD) simulations that the gas concentration on the surface of the chip under the tubing outlet is equal to the gas concentration delivered by the vapor generator. The higher turn-off slope is possibly related to trapped ammonia under the suspended membrane which takes a longer time to escape than in unsuspended structures. Detailed characterization is in progress.

In summary, suspended InGaAs HPCWs were fabricated and experimentally characterized for operation at λ=6.15μm at the absorbance peak of ammonia. We experimentally detected 5ppm ammonia from 1mm long suspended InGaAs HPCWs. The research was supported by Army (ARO) SBIR Contract # W911NF-18-C-0085.

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