Monolithic Suspended Optical Waveguides for InP MEMS

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***Abstract*—We present a novel waveguide design for InP microelecromechanical systems. The substrate is removed from underneath the waveguide by sacrificial etching, and the suspended waveguide is supported by lateral tethers. This allows segments of the waveguide to be moved and prevents substrate leakage loss in the fixed segments of the waveguides. A single-mask fabrication process is developed that can be extended to more complex devices employing electrostatic actuation. Fabricated suspended waveguides exhibit a loss of 2.2 dB/cm and tether pairs exhibit 0.25-dB additional loss.**

***Index Terms*—III–V semiconductors, indium phosphide (InP), InP microelecromechanical systems (MEMS), waveguides.**

I. Introduction

MICROELECROMECHANICAL systems (MEMS) have experienced rapid growth in optical systems over the past decade. To date, the majority of optical MEMS have been free-space devices utilizing actuated micromirrors and lenses to direct light. Free-space optical MEMS were originally pursued due to their potential for dense channel integration and flexibility. The drive for small size, low cost, integrated optical circuits, however, has led to new interest in confined optics such as waveguide MEMS.

Optical waveguide MEMS provide several distinct advantages over free-space optical MEMS. With high-contrast waveguides, light is tightly confined and propagates in the plane of the wafer, allowing dense integration, monolithic fabrication, small size, and low cost and increased manufacturability due to decreased assembly and packaging requirements [1]. There have been several optical waveguide MEMS devices implemented in silicon [1], which provides an excellent mechanical material, however, these devices are limited to passive optics due to the indirect bandgap in silicon. Gallium arsenide (GaAs) waveguide MEMS have also been demonstrated [2], but GaAs is not compatible with active operation at 1550 nm, the wavelength for minimum transmission loss in optical fibers. Indium phosphide (InP) material is ideal for active operation at 1550 nm, allowing integration of InP MEMS with active and passive optical communication systems.

We have previously characterized InP mechanically as a MEMS material and found that, although it is brittle, it is suitable for the small displacements required by waveguide MEMS [3]. Fabricating movable InP optical waveguides presents several further challenges due to optical device constraints, such as low sidewall roughness, optical index contrast, and leakage loss to the substrate. To overcome these challenges, we have developed a novel waveguide design that removes the substrate from the entire waveguide by including lateral tethers for mechanical support. This allows both movable segments and low-loss fixed waveguides to be fabricated monolithically. Here we present the design, fabrication, and testing of laterally suspended waveguides as a platform technology for InP optical MEMS.

II. Device Description

In order to incorporate optical waveguides in MEMS devices such as switches and tunable filters, it is necessary to be able to actuate the waveguides, either laterally in plane, or vertically out of plane. This actuation requires a free-standing section of the waveguide that is released from the substrate. Surface micromachining, a common MEMS fabrication technique, uses a sacrificial layer beneath the device that can be selectively etched away. In order to obtain a single-crystal growth, it is necessary to incorporate a sacrificial layer that is both selective and lattice-matched to the substrate and waveguide layers. Several options exist in the InP material system. InP and InGaAsP are 100% selective in several wet etchants, but thick layers of InGaAsP with large gallium and arsenic mole fractions are prone to spinodal decomposition, resulting in compositional nonuniformity [4]. InP and InGaAs also provide 100% selectivity, however, lattice-matched InGaAs has a bandgap wavelength of 1627 nm and will absorb light at 1550 nm.

Suitable wave-guiding and etch selectivity properties can be attainted by using an InP waveguide structure with a InGaAs sacrificial layer. However, with a refractive index of 3.5, the InGaAs sacrificial layer will couple optical power from the InP waveguide ($n = 3.195$) causing large leakage loss. To overcome this substrate leakage, our waveguides utilize a design that allows removal of the entire InGaAs sacrificial layer, resulting in a monolithically substrate removed low-loss waveguide with both fixed and movable portions.

To provide support after the InGaAs is removed, pairs of lateral tethers are incorporated at regular intervals along the length

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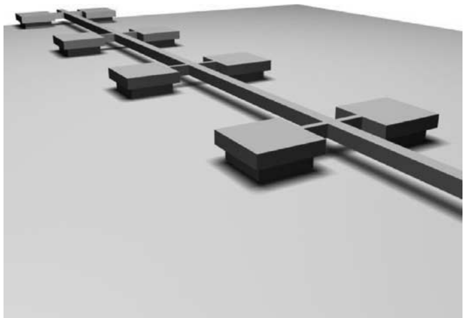

Fig. 1. Schematic of suspended InP waveguide showing lateral tethers and anchors to the substrate through unetched InGaAs sacrificial layer.

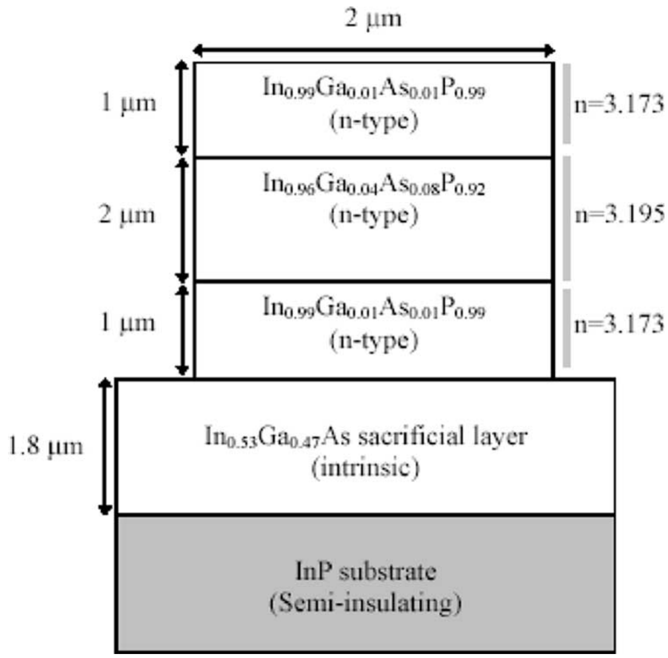

Fig. 2. Material layer structure for InP suspended waveguides. All layers are epitaxially grown and lattice matched or nearly lattice matched to the substrate wafer.

of the waveguide. The tethers extend from the side of the waveguide and anchor to the substrate through the unetched InGaAs. This design is shown in Fig. 1.

For our initial devices, the tethers are 1.5 μm wide to ensure adequate mechanical strength while maintaining low loss. Although these tethers cause additional optical losses due to beam expansion and mode mismatch, analytical simulations based on a lateral Gaussian beam expansion within the tether predict the loss to be about 0.24 dB/tether—far less than the leakage and absorption losses caused by retaining the InGaAs sacrificial layer. To further reduce additional loss due to the tethers, long waveguide lengths can be supported between tethers, so only a small number of tethers are needed to support waveguides. We have demonstrated suspended waveguide lengths up to 2.5 mm between tether pairs.

III. Layer Structure and Fabrication

The material structure of our device is shown in Fig. 2. All layers are grown using solid-source molecular beam epitaxy and are designed to be lattice matched or nearly lattice matched to the (100) InP substrate misoriented 4° toward (111). The InGaAsP ($n = 3.195$) core of the waveguide is 2×2 μm. The slight gallium and arsenic mole fractions are incorporated in order to provide the desired refractive index contrast and to incorporate very slight tensile strain ($\varepsilon < 0.05\%$). This prevents the waveguides fixed at both ends from buckling, which occurs when doubly clamped beams exhibit compressive stress, but still allows low-voltage actuation of the waveguides. The upper and lower cladding are 1 μm thick and consist of InGaAsP ($n = 3.173$).

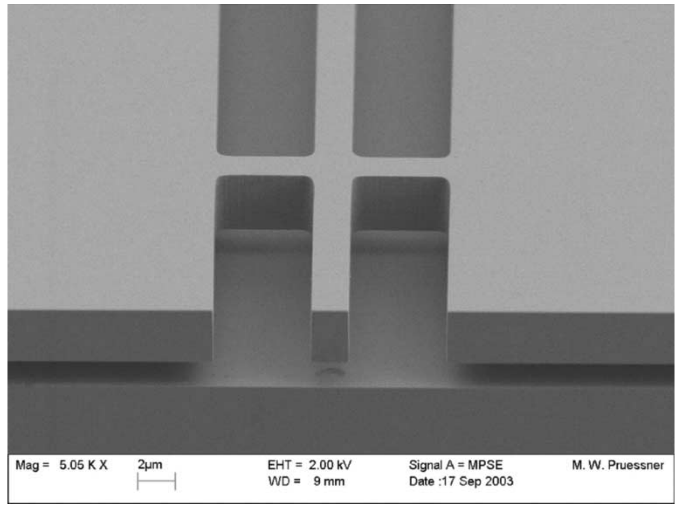

Fig. 3. Scanning electron microscope micrograph of released InP waveguide, tether pair for lateral support, and cleaved facet. The waveguide is 2 μm wide and the tethers are 1.5 μm wide and 5 μm long. The high quality sidewalls show that the waveguide layers were not attacked by the sacrificial etch.

The waveguide core is designed to be large in order to relieve tolerances on waveguide-to-waveguide axial alignment for first-generation waveguide MEMS devices. This results in a multimode structure, but the dimensions can be decreased for single-mode operation in subsequent devices. By keeping the gallium and arsenic mole fractions in the waveguide layers low, the material and chemical properties of InP are retained and selective etchants can be used. A 1.8-μm InGaAs sacrificial layer is grown beneath the waveguide for the release. To allow electrostatic actuation of the waveguides for future devices, the InP layers are doped n-type while a semi-insulating InP substrate is used.

Fabrication of the suspended InP waveguides involves only a single lithography step followed by three etch steps. First, a 7000-Å SiO_2 masking layer is deposited using plasma-enhanced chemical vapor deposition. Next, the devices are patterned using a $5\times$ optical stepper to expose 1-μm-thick positive photoresist. The pattern is then transferred into the SiO_2 hard-mask using a reactive ion etch (RIE) in CHF_3–O_2 plasma. To obtain highly vertical optical-quality sidewalls in InP, a multistep RIE process was used. The first step of the process is an InP etch using a CH_4–H_2 plasma. The second step is removal of the polymer by-product from the sidewalls in a short O_2 plasma. This process is repeated to an etch-depth of 5 μm to ensure the waveguide layers have been etched through. Next, the sample is cleaved to expose the waveguide end facets. Finally, the sacrificial InGaAs is removed in $HF:H_2O_2:H_2O$ $(1:1:8)$ followed by supercritical drying in CO_2 to prevent stiction to the substrate. Fig. 3 shows a released waveguide, tether pair, and end

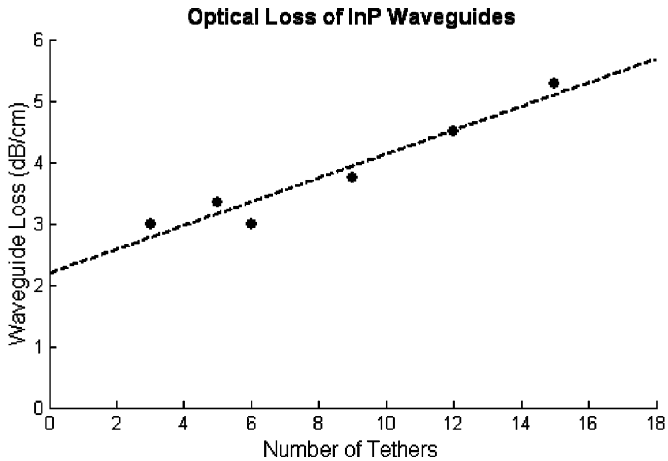

Fig. 4. Measured waveguide loss versus total number of tethers for released InP suspended waveguides. Y-intercept of the interpolated line is the waveguide propagation loss without tethers.

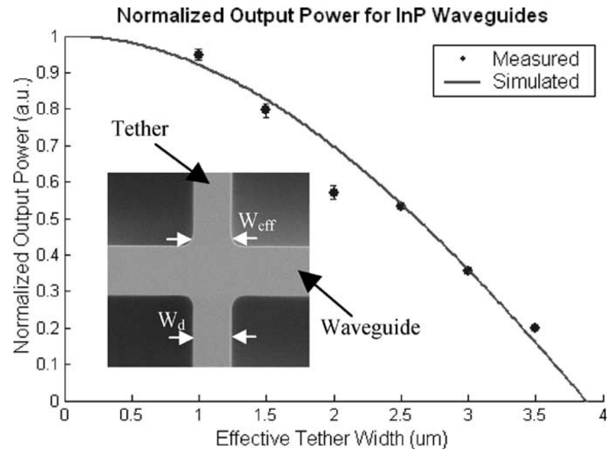

Fig. 5. Normalized waveguide output power versus effective tether width for InP suspended waveguides. Inset shows the curvature in concave corners that causes an approximately 0.5-μm-larger effective tether width ($W_{\rm eff}$) than the designed tether width (W_d).

facet. It can be seen from the quality of the facet that the sacrificial etch does not chemically attack the InP, even with the low content of gallium and arsenic.

IV. Device Characterization

An optical setup consisting of two movable conical-tipped fibers and a stationary waveguide stage was used to test the fabricated waveguides by coupling light from a tunable laser into the input facet and collecting the output through the second fiber. Fabry–Pérot contrast analysis [5] and relative power measurements are used to determine waveguide propagation loss and the optical loss per tether pair. Measurements were performed both before and after the sacrificial release to establish the leakage and absorption loss caused by the InGaAs sacrificial layer.

Isolating the waveguides from the substrate proved to be necessary, with a 17.3-dB gain in power achieved by removing the InGaAs. With the sacrificial layer removed, the waveguide propagation loss was determined to be 2.2 dB/cm (Fig. 4). The loss per tether pair was measured to be 0.25 dB, very close to the simulated value of 0.24 dB. Normalized output power with respect to effective tether width is plotted in Fig. 5 for waveguides with 15 tether pairs. This agrees well with the simulated output power for a Gaussian beam expansion within the tethers where there is no lateral confinement. The effective tether width is about 0.5 μm larger than the designed tether width due to lithography limitations at the corners, as shown in Fig. 5. The results show that decreasing the tether design width from 1.5 to 0.5 μm would result in up to 0.16 dB per tether decrease in loss, yielding 0.09-dB loss per tether while maintaining structural support.

V. Conclusion

We have demonstrated monolithically fabricated suspended InP waveguides for use in optical waveguide MEMS. These waveguides integrate movable and fixed portions with a single lithography step, allowing both optical routing and MEMS functions such as switching and attenuation to be performed laterally on the same chip. The waveguide propagation loss is 2.2 dB/cm and the novel tethers used to support the waveguide have been shown to induce 0.25 dB of loss per pair with waveguide lengths up to 2.5 mm supported between tethers. Additionally, future devices could decrease the tether loss to 0.09 dB per tether by using 0.5-μm tethers. We are currently developing and testing a MEMS waveguide evanescent coupler which employs electrostatic actuation of suspended InP waveguides and has demonstrated 1-kHz switching frequency with low-voltage actuation. Other applications include 1×2 optical switches and Fabry–Pérot tunable filters. By providing good optical confinement and low-loss propagation as well as the ability for in-plane electrostatic actuation, suspended InP waveguides can bridge the gap between InP waveguide optics and InP MEMS devices, positioning them as an enabling technology for InP waveguide MEMS.

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