Mid-infrared Suspended Waveguide Platform and Building Blocks

(Invited paper)

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ABSTRACT

In this work we present our recent progress in the development of a platform for the mid-infrared wavelength range, based on suspended silicon waveguide with subwavelength metamaterial cladding. The platform has some intrinsic advantages, which make it a very promising candidate for sensing applications in the fingerprint region. Specifically, it can cover the full transparency window of silicon (up to a wavelength of 8 µm), only requires one lithographic etch-step and can be designed for strong light-matter interaction. Design rules, practical aspects of the fabrication process and experimental results of a complete set of elemental building blocks operating at two very different wavelengths, 3.8 µm and 7.67 µm, will be discussed. Propagation losses as low as 0.82 dB/cm at λ_o=3.8 µm and 3.1 dB/cm at λ_o=7.67 µm are attained, for the interconnecting waveguides.

Keywords: Integrated optics, Subwavelength structures, Mid-infrared, Waveguides, Optical devices.

1. INTRODUCTION

The Mid-InfraRed band (MIR, wavelengths from around 2 to 20 µm) is an especially interesting wavelength range because it includes the molecular fingerprint spectral region. Each substance is uniquely identified by a specific absorption spectrum. By measuring these spectra, it is possible to determine the presence and concentration of substances as diverse as greenhouse gases, explosives, food, petroleum products, polluting substances, plastics or even human tissues, among others. Regardless of the final application, to operate with a high degree of integration it is necessary to provide the most appropriate platform for this new band of wavelengths. One of the most successful platforms in the communications band (around 1.55 µm), Silicon-on-Insulator (SOI), could only be used up to a wavelength of 4 µm, given the strong absorption of silicon dioxide at longer wavelengths. Therefore, to be able to increase the wavelength and cover the full range of the MIR band, it is necessary to develop new platforms. The different alternatives that are currently being considered in the bibliography can be grouped into two different types: i) Platforms that combine materials with a greater range of transparency, including, silicon on sapphire, silicon on silicon nitride, chalcogenide crystals, germanium on silicon nitride or germanium on silicon (a summary of their attainable propagation loss can be found in [1]); and ii) Suspended platforms that are based on the selective elimination of the oxide on which silicon rests, producing waveguides known as suspended silicon. In this way, the complete transparency of silicon, up to 8 µm, could be covered, while still benefiting from the consolidated SOI manufacturing processes.

There are two alternatives to achieve the suspension: i) using an array of holes away from the core waveguide, yielding silicon membrane waveguides [2], and ii) using periodic subwavelength metamaterial cladding [3] [4]. In this work we will only focus on the latter, reviewing the current state of development. The operation principle of the elemental suspended waveguide, practical issues and experimental results of essential building blocks (interconnecting waveguides, bends, grating couplers and MMIs) operating at two different wavelengths, 3.8 µm and 7.67 µm, will be covered throughout the present work.

2. THE SUSPENDED SILICON WAVEGUIDES

A schematic representation of the suspended silicon waveguide is shown in Figure 1(a). As can be seen, it is composed of a silicon core of width W_{wg} and thickness t_{Si} which is anchored to the unsuspended lateral silicon areas making use of a subwavelength (SWG) pattern of silicon bars. The periodic cladding thus works as an equivalent homogeneous medium, by means of which it is possible to control the lateral refractive index contrast required for optical waveguiding (see Figure 1(b)). The SWG cladding must also perform two additional crucial functions: i) to have enough mechanical stiffness to support the weight of the wider and therefore heavier waveguides present in the circuit and ii) to allow the flow of the hydrofluoric acid (HF) through the holes to remove the buried oxide layer. This makes the design process to determine the adequate dimensions more intricate than that of conventional photonic waveguides, because each one of the aforementioned functions imposes its own constraints, and, unfortunately, their respective optimum values move towards opposite directions. Table 1 summarizes towards what values the different geometrical parameters should move to better satisfy the respective constraints imposed by the fabrication process, the optical waveguiding and the mechanical stability. The final chosen values of the interconnecting waveguides at the two operating wavelengths, 3.8 μm and 7.67 μm, are also indicated in Table 1.

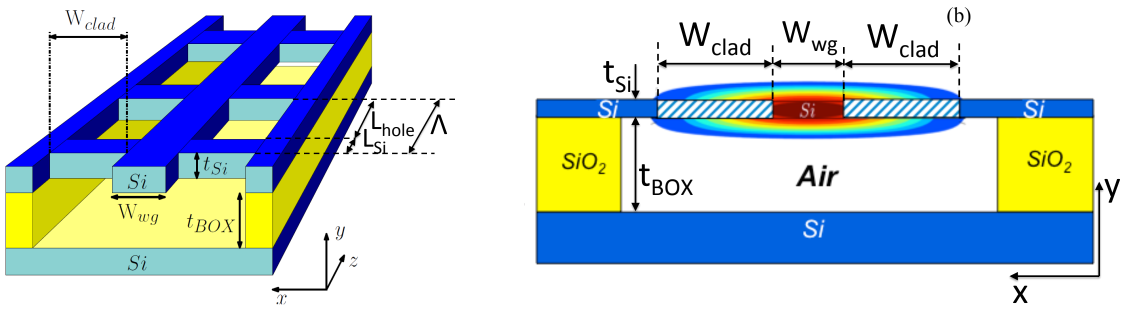


Figure 1. (a) 3D schematic of the suspended silicon waveguide; (b) 2D cross view and electric field spatial distribution of the fundamental mode associated with a specific value of the equivalent metamaterial cladding.

TABLE 1. SUMMARY OF CONSTRAINTS AND FINAL SELECTED VALUES AT λ = 3.8 μm & λ= 7.67 μm.

Parameter	A high value (↑) is good …	A small value (↓) is good…	Selected values at	
			λ= 3.8 μm	*λ=7.67μm*
W_{clad}	• to reduce the lateral leakage	• to reduce the mechanical torque	*2.5 μm*	*3 μm*
W_{wg}	• to reduce the lateral leakage	• to reduce the weight of the waveguide • to avoid the second order horizontal mode	*1.3 μm*	*2.9 μm*
t_{Si}	• to reduce the vertical leakage	• to reduce the weight of the waveguide • to avoid the second order vertical mode	*0.5 μm*	*1.4 μm*
t_{BOX}	• to reduce the vertical leakage		*3 μm*	*3 μm*
L_{Si}	• to assure the mechanical stability	• to increase the lateral index contrast and so reduce the lateral leakage. • to operate in the SWG regime	*0.1 μm*	*0.25 μm*
L_{Hole}	• to facilitate the flow of HF • to increase the lateral index contrast and thereby reduce the lateral leakage	• to operate in the SWG regime	*0.45 μm*	*0.9 μm*

3. FABRICATION

The fabrication process of any device in the proposed suspended platform requires the well-known dry etch to transfer the pattern to the silicon layer plus an additional wet etch to locally remove the BOX. This consists in dipping the chip into a 1:7 HF bath to remove the BOX. The difficulty arises from the required immersion time, which, as is shown in Fig. 2(a), is greater for wide waveguides (e.g. Multimode Interference devices, MMIs) than for narrow ones (e.g. interconnecting waveguides). Although the HF acid is highly selective and, in theory, it should not affect the silicon, in practice the silicon is slightly affected, suffering an over etching which produces a reduction in both the thickness and width of the nominal dimensions (see Fig. 2(b)). This silicon over etching can have dramatic consequences not only in the performance of the device but also in its mechanical stability. To compensate for this effect, required biasing for the dry etch must be accurately known in advance. Figures 2(c) and 2(d) show the effects of the dip time: when it is too short, the BOX is not completely removed, and when it is excessive, the over etching is so large that it ends up breaking the silicon bars. Figure 2 (e), in turn, shows the results of a more optimized dip time.

4. EXPERIMENTAL RESULTS

A complete set of essential building blocks operating at the wavelengths of 3.8 μm and 7.67 μm, respectively, have been designed, fabricated and characterized. Table 2 shows their SEM images and summarizes their dimensions and attained performance.

5. CONCLUSIONS

We have presented and reviewed the current state of a recent platform for the Mid-Infrared band, the suspended silicon waveguide, which would allow us to extend the usage of silicon photonics up to wavelengths of 8 μm. The first results at 3.8 μm and 7.67 μm in waveguides, bends, MMIs, and interferometers are very promising.

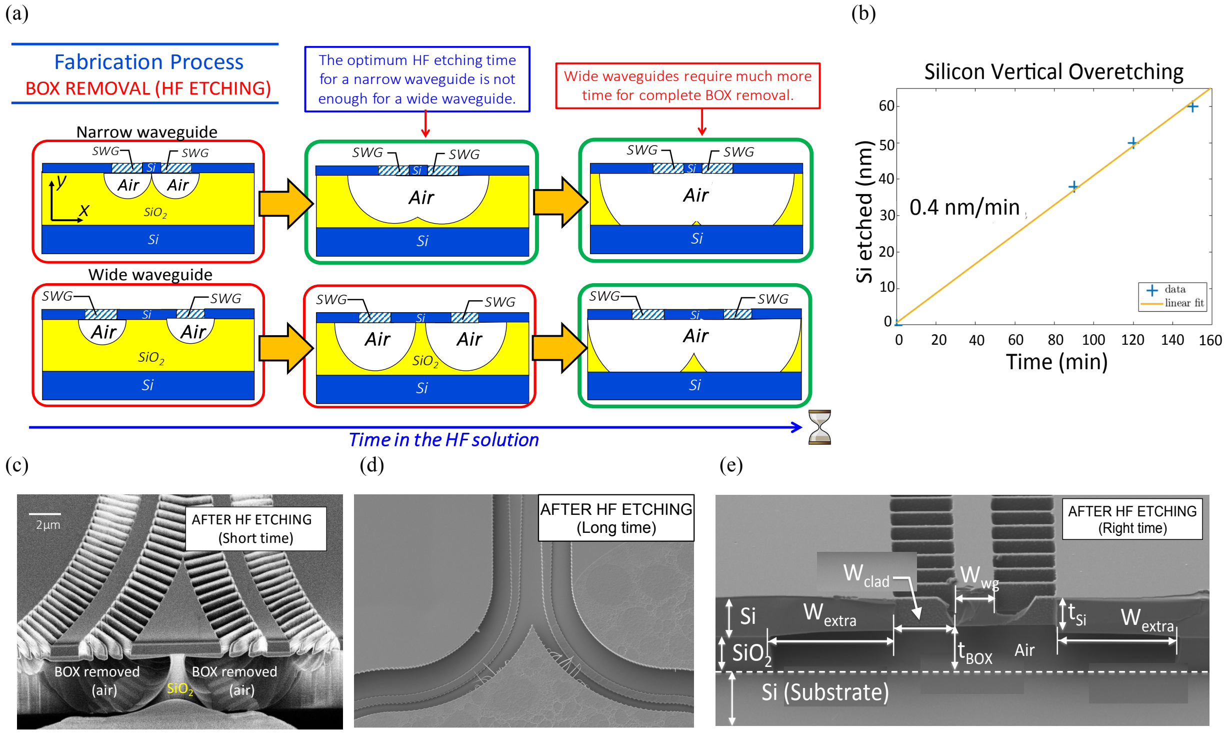
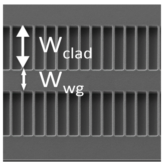
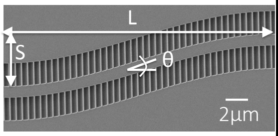
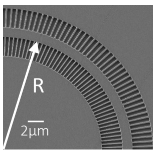
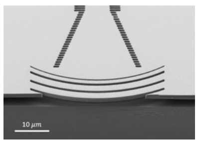
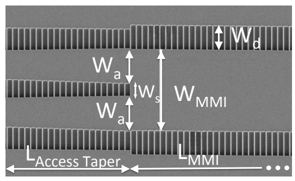


Figure 2. (a) Graphical illustration of the wet etching process to remove the BOX beneath the devices; (b) Undesired reduction of the vertical silicon thickness as a function of the immersion time into the HF acid dissolution; SEM images of fabricated interconnecting waveguides when the immersion time is c) too short; d) too long and e) optimized.

TABLE 2. PERFORMANCE SUMMARY OF SOME BASIC BUILDING BLOCKS AT λ = 3.8 μm & λ= 7.67 μm.

Straight waveguides	S-bends	90º-bends	Focusing grating coupler	MMI
				
@ λ = 3.8 μm W_{wg}= 1.3 μm W_{wg}= 2.5 μm Loss: 0.82 dB/cm	**@ λ = 3.8 μm** S= 7 μm; L= 41 μm; θ = 15º Loss: 0.01 dB/bend	**@ λ = 3.8 μm** R=16 μm; Loss:0.02dB/bend	Not available	**@ λ = 3.8 μm** **(no-biasing was applied)** W_a = 3.1 μm; W_S = 1.3 μm W_d = 2 μm; W_{MMI}= 7.1 μm L_{Taper} = 40 μm; L_{MMI}= 71.5 μm ExcessLoss & Imbalance <0.3 dB (minimum shifted to 3.71 μm)
@ λ = 7.67 μm W_{wg}= 2.9 μm W_{wg}= 3 μm Loss: 3.1 dB/cm	**@ λ = 7.67 μm** S= 5 μm; L= 75 μm; θ = 6º Losses: 0.06 dB/bend	**@ λ = 7.67 μm** R=35 μm; Loss:0.08dB/bend	**@ λ = 7.67 μm** (simulated, fabricated but not yet characterized) Coupling efficien.: 58% $Bandwidth_{1dB}$ = 230 nm Back-Reflections: 0.1% Radiation angle: 19.3º	**@ λ = 7.67 μm** (simulation results, under fabrication) W_a = 5.9 μm; W_S = 1.84 μm W_d = 2 μm; W_{MMI}= 13.38 μm L_{Taper} = 30 μm; L_{MMI}= 136.9 μm ExcessLoss & Imbalance <0.3 dB

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