

Study of Ridge Waveguide Based on Porous Silicon Layers at 7.8 μm

A. Gutierrez-Arroyo*, J. Lemaitre, P. Girault, M. Guendouz, N. Lorrain, L. Bodiou and J. Charrier*

FOTON -UMR-CNRS 6082, ENSSAT BP80518, F-22305 Lannion Cedex, France

*gutierre@enssat.fr, *joel.charrier@univ-rennes1.fr

The implementation of a Mid-InfraRed (MIR) silicon photonics transducer with broad transparency (up to 8 μm) is a challenge that could find applications in spectroscopic sensing and environmental monitoring. Due to silica absorption above 3.6 μm , the conventional silicon-on-insulator platform, used in the near infrared (NIR) wavelength range, is not adapted for MIR broadband silicon photonic integrated circuits. Another approach is to use silicon-on-sapphire or silicon pedestal structures [1]. A waveguide using porous silicon (PSi) layers was also proposed for MIR devices, in which the guiding layer is a silicon layer and the waveguide cladding is a PSi layer created by high-energy proton beam irradiation and electrochemical etching [2]. However, high propagation losses were measured in these structures at 3.39 μm . Several photonic integrated circuits based on PSi were demonstrated in the NIR wavelength range [3, 4]. However, in the MIR, only PSi optical rugate filters with reflectance peaks matching specific spectral features of molecules in the region from 4 to 8 μm have been fabricated so far [5].

This work demonstrates for the first time to our knowledge, the use of an electrochemically prepared optical ridge waveguide based on PSi operating at MIR spectral region (up to 7.8 μm).

The PSi layers were obtained by electrochemical anodization of p-type doped (100)-oriented silicon wafer (4-6 $\Omega\cdot\text{cm}$). The electrolyte was composed of HF(50%):H₂O:ethanol (7-1-2). The refractive indices and porosities of single layers were studied by reflectometry. The thickness of each porous layer (guiding and cladding) was controlled by the anodization time. The guiding (upper) and cladding (lower) layers were formed by successively applying two current densities in order to obtain porosities about 59% and 62% respectively (sample A) or about 59% and 65% respectively (sample B). Lastly, PSi waveguides (sample C) were also fabricated from p-type heavily doped (100)-oriented silicon wafer (5 m $\Omega\cdot\text{cm}$). The thicknesses of the guiding and cladding layers were equal to 2.7 μm and 6 μm respectively for samples A and B. The thickness of the cladding layer was chosen to avoid radiative losses. The ridge waveguides (Figure 1a) were subsequently patterned using standard i-line photolithography and fluorine-based reactive ion etching.

To demonstrate the capacity of these PSi waveguides for MIR spectroscopic sensor application (2-8 μm), QCL light at 7.8 μm was coupled in a single-mode chalcogenide fiber- and injected into the waveguide. The intensity of the light at the waveguide output was collected with a MIR objective and imaged on a digital camera. MIR propagation was observed in samples A and B, whereas for sample C, no propagation was observed. The heavily doping of the silicon substrate could explained the

absorption of this last PSi waveguide because of the free carrier absorption in the MIR. Lastly, the guided light power at the output of waveguides A and B was attenuated by the water presence on the surface of the sample due to the water absorption in the MIR.

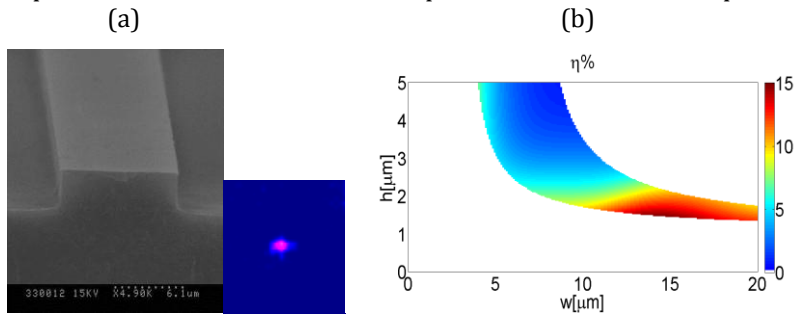


Fig. 1. (a) SEM image of a ridge waveguide made of PSi layers and the Propagation-mode near-field in this ridge waveguide at $\lambda=7.8 \mu\text{m}$. (b) Evanescent power factor η for TM polarization as a function of the geometrical parameters (width (w) and height (h)) of single-mode PSi ridge waveguides respectively for sample B.

The transducer will use the volume detection of the target molecules due to opened pores but also the evanescent wave. To design a MIR sensor with an important sensitivity, the evanescent power factor η was calculated. Using the PSi layers refractive indices, simulations based on the effective index method were performed in order to determine the geometrical parameters (waveguide width and height) allowing single-mode propagation in a ridge waveguide at 7.8 μm. A field analysis tool was also used to calculate the transverse profile of the electromagnetic field associated with the single propagated mode. From these calculations, the evanescent power factor η for potential sensor applications were obtained as a function of the ridge waveguide geometrical dimensions (Figure 1b).

The first optical results obtained from p-type PSi ridge waveguides at 7.8 μm are very promising. Such waveguides can now serve as a building block to develop more complex passive and active MIR devices for spectroscopic sensor applications (3-8 μm). This passive platform will be used as transducer in the fields of sensors thanks to their opened pores and their wide internal surface. This study is completed by their optical loss measurement and the demonstration of the fabrication of PSi passive devices such as beam splitter, bend and spiral waveguides.

References

- [1] P. T. Lin, V. Singh, Y. Gai, L. Kimerling and A. Argarwal. *Air-clad silicon pedestal structures for broadband mid-infrared microphotonics*. Optics Letters, 38, 1031-1033, 2013.
- [2] B. U. King and M. J. Sailor. *Medium-wavelength infrared gas sensing with electrochemically fabricated porous silicon optical rugate filters*. Journal of Nanophotonics, 5, 051510, 2011.
- [3] P. Pirasteh, J. Charrier, Y. Dumeige, S. Haesaert and P. Joubert. *Optical loss studies of porous silicon and oxidized porous silicon planar waveguides*. Journal of Applied Physics, 101, 083110-1 083110-6, 2007.
- [4] P. Girault, N. Lorrain, J. Lemaitre, L. Poffo, M. Guendouz, I. Hardy, M. Gadonna, A. Gutierrez, L. Bodiou and J. Charrier. *Racetrack micro-resonators based on ridge waveguides made of porous silica*. Optical Materials, 1-8, 2015.
- [5] G. Z. Mashanovich, M. M. Milosevic, M. Nedeljkovic, N. Owens, B. Xiong, E. J. Teo and Y. Hu. *Low loss silicon waveguides for the mid-infrared*. Optics Express, 19, 7112-7119, 2011.