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Study of optical ridge waveguide based on porous silicon layers at 7.8 µm

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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 porous silicon (PSi). However, if several photonic integrated circuits based on PSi were demonstrated in the NIR wavelength range [1, 2], only few structures have been implemented in the MIR. A waveguide 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 was proposed [3]. However, high propagation losses were measured in these structures at 3.39 µm. PSi optical rugate filters with reflectance peaks matching specific spectral features of molecules in the region from 4 to 8 µm have also been fabricated [4]. This work demonstrates, for the first time to our knowledge, the implementation, at MIR wavelength (up to 7.8 µm), of an optical ridge waveguide where both guiding and confinement layers are fabricated by electrochemically-prepared PSi layers.

The PSi layers were obtained by electrochemical anodization of p-type doped (100)-oriented silicon wafer (4-6 Ω.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 mΩ.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 to the substrate. The ridge waveguides (Figure 1a) were subsequently patterned using standard i-line photolithography and fluorine-based dry etching.

To demonstrate the capacity of these PSi waveguides for MIR spectroscopic sensor application (2-8µm), 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 bolometric camera. MIR propagation was observed in samples A and B (Figure 1b), whereas for sample C, no propagation was observed. Free carrier absorption in the MIR related to the heavy doping of the silicon substrate could explain the absorption of this last PSi waveguide. 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.

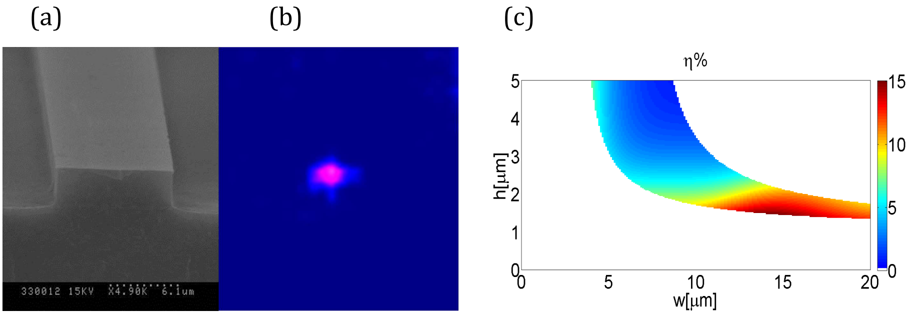

Fig. 46. (a) SEM image of a ridge waveguide made of PSi layers, b) recorded near-field intensity mode profile in this ridge waveguide at λ=7.8 µm, and (c) evanescent power factor η for TM polarization as a function of the geometrical parameters (width (w) and height (h)) of single-mode PSi ridge waveguides for sample B.

The transducer will use the volume detection of the target molecules infiltrated into opened pores of the ridge waveguide, 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 1c).

These 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 optical loss measurements and by the demonstration of the fabrication of PSi passive devices such as beam splitter, bend and spiral waveguides.

References

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