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Surface wave photonic device based on porous silicon multilayers

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Abstract

Porous silicon is widely studied in the field of photonics due to its interesting optical properties. In this work, we present theoretical and first experimental studies of a new kind of porous silicon photonic device based on optical surface wave. A theoretical analysis of the device is presented using plane-wave approximation. The porous silicon multilayered structures are realized using electrochemical etching of p^+-type silicon. Morphological and optical characterizations of the realized structures are reported.

Keywords: Surface wave; Photonic crystal; Porous silicon

1. Introduction

Optical surface waves are very interesting for sensing applications. Most of surface wave's applications are used in surface plasmon devices [1,2]. One limitation of the surface plasmons is the absorption loss of the metals at optical wavelength. This is why an alternative approach based on dielectric photonic crystals (PC) can be quite useful. It is well known that a finite 1D PC can sustain surface waves [3,4]. These surface waves are different in nature from surface plasmons polaritons in the sense that they do not exist due to strong coupling between photonic mode and material excitation. They are ensured by the finite size of the PC, breaking down the translation symmetry. They are the analogue of Tamm surface states [5] in solids.

Porous silicon is chosen for the realization of such photonic structures. Porous silicon is an ideal candidate for this kind of application, since it allows the fabrication of photonic structures with a continuous control of the refractive indexes [6,7]. Moreover, we can easily obtain an important contrast of the refractive indexes, for example $\Delta n \approx 1$ [8].

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2. Modeling

Our surface wave structures are based on 1D dielectric multilayers. We have chosen refractive indexes that can be reasonably reached by electrochemical etching of silicon, namely $n_1 = 2.5$ and $n_2 = 1.5$. Thicknesses of the layers are $\lambda/4n$.

Calculations with plane wave's method [9] were performed in order to obtain the dispersion relations in reduced coordinates:

$$\frac{\omega a}{2\pi c} = \frac{a}{\lambda} = f(k), \tag{1}$$

where a is the period of the crystal.

Dispersion dependences calculated for TE waves in a PC ended by a high-refractive-index layer are reported in Fig. 1a. The thickness of this surface layer is included between 0 ($\sigma = 1$) and $\lambda/4n_1$ ($\sigma = 1$). One can see the photonic band gap and notice the appearance of the defected states located below the light line in this band gap. Consequently, such states are evanescent both in air and in the PC and correspond to surface waves. Moreover, they are strongly dependent on the termination of the PC [10] and this phenomenon can be exploited for sensing.

In the case of an experimental device, a way for surface wave excitation should be carefully chosen. We use two approaches: (i) prism coupling (Kretschmann

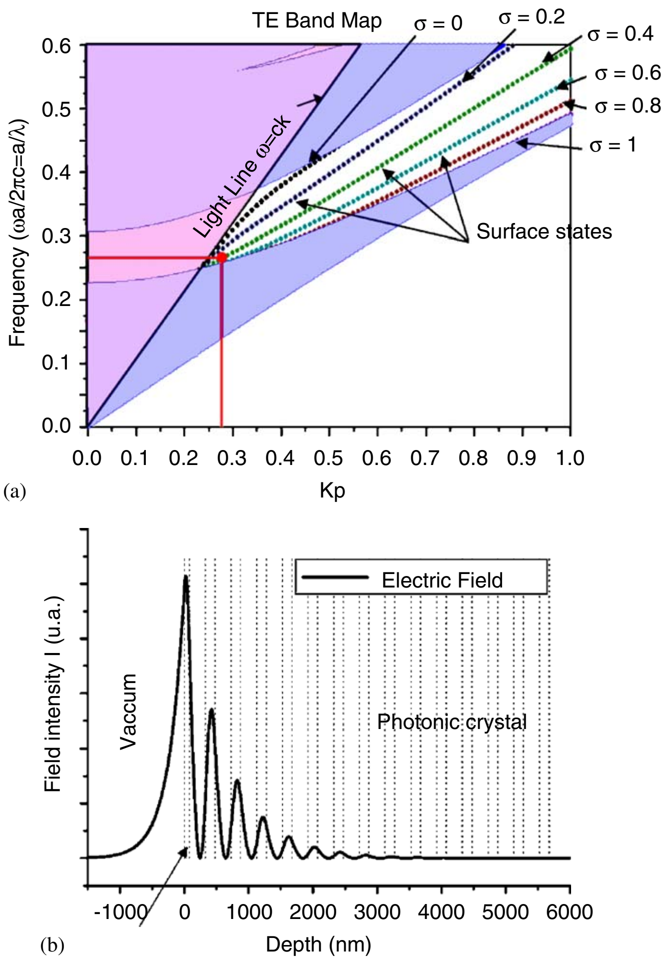

Fig. 1. (a) Dispersion relations in reduced coordinates of the surface wave device. The dotted lines represent the surface states for various surface layers' thicknesses (from 0 ($\sigma = 0$) to $\lambda/4n_1$ ($\sigma = 1$)). (b) Electric field intensity versus the depth for a surface wave device operating at the wavelength $\lambda = 1500$ nm and terminated by a high-refractive-index layer with $\sigma = 0.5$, and a coupling angle of $\theta = 18.67°$.

configuration) [11] or (ii) guided wave configuration [3]. In both cases, theoretical calculations using the transfer matrix method have been performed for a 14-period structure with $\sigma = 0.5$ at a wavelength $\lambda = 1500$ nm. The point reported in Fig. 1a corresponds to this structure, for which $a/\lambda = 0.27$.

Coupling angle for the Kretschmann configuration in the case of a silicon coupling prism was calculated. We have assumed that there are no intrinsic absorption losses within the material. Fig. 1b shows the intensity of the electric field confined in the top guiding layer as a function of the depth for a coupling angle θ around 18.7°. The angular half width of the angular reflectivity is found to be around $\Delta\theta = 5 \times 10^{-4}$deg. This value is directly related to the linking of the surface mode to the silicon substrate.

Effective refractive index n_{eff} and losses α for the surface mode in the case of the guided wave configuration were also calculated. The obtained results are: $n_{\text{eff}} = 1.128$ and $\alpha = 2.5$ dB/cm for the 14-period structure. Theses propagation losses are directly related to the number of Bragg periods, and they decrease exponentially with the number of periods because they correspond to the states within the band gap of the PC. Therefore, porous silicon multilayer structures with 25 periods were realized by electrochemical etching procedure, in order to have a negligible loss level (below 2×10^{-3} dB/cm).

3. Experimental results

In this study, our porous silicon samples are realized on highly boron-doped p^+-type, $\langle 100 \rangle$-oriented silicon substrates with a resistivity of 0.01 Ω cm. Silicon is electrochemically etched at −40 °C in 25% hydrofluorhydric acid solution diluted with water and ethanol.

The etching rate and the porosity of the porous samples versus current density are calibrated using infrared reflectivity at normal incidence of single layers [7]. The corresponding calibration curves are given in Fig. 2.

Then, the current density and etching time values are chosen in order to obtain the photonic structures described before.

First of all, a Bragg mirror test structure terminated by a high-refractive-index layer with a thickness of $\lambda/4n_1$ was fabricated. The period of the multilayer $a = 455$ nm is deduced from an SEM image given as inset in Fig. 3. By fitting the reflectivity spectrum of this structure (see Fig. 3), one can deduce the parameters of high-refractive-index layers ($d_1 = 109$ nm and $n_1 = 2.15$), and those of low-refractive-index layers ($d_2 = 346$ nm and $n_2 = 1.39$) of the multilayer. These refractive indexes and thicknesses are different from those deduced previously from calibration curves on single layers. This is most probably due to the influence of the multilayer with different porosities on the etching kinetics [7].

For the surface wave structure with $\sigma = 0.5$, at $\lambda = 1500$ nm ($a/\lambda = 0.29$), the resulting surface wave is slightly

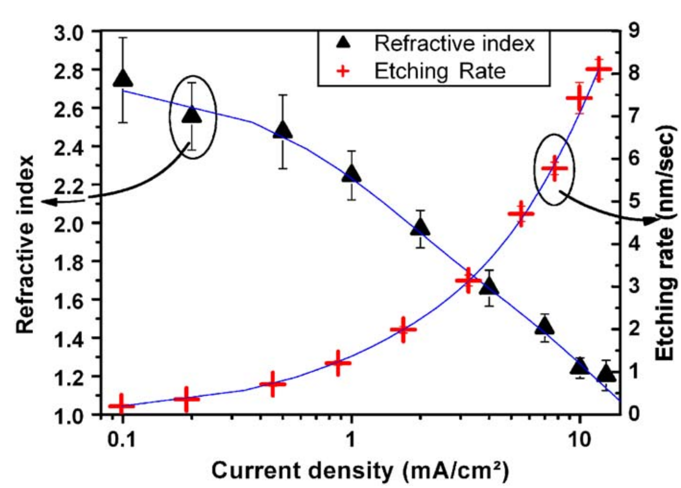

Fig. 2. Refractive index and etching rate formation of the porous silicon versus the applied current density.

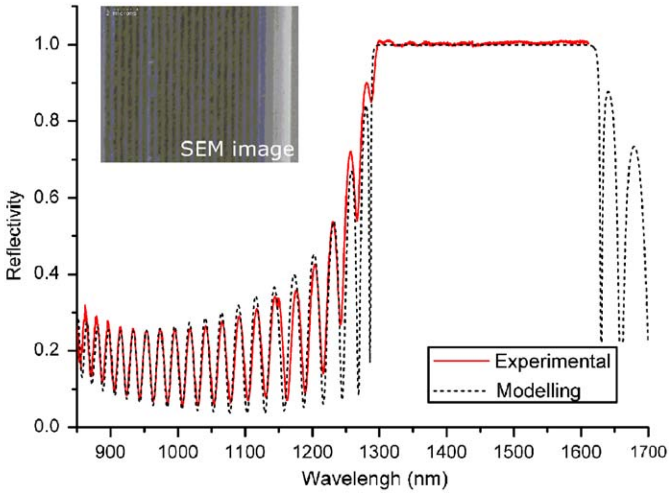

Fig. 3. Experimental and simulated reflection spectra of a 25-period Bragg mirror. The inset shows the SEM image of the structure.

confined and, therefore, has a high level of loss ($\alpha = 1580\,\mathrm{dB/cm}$). However, a well-confined surface wave for $\lambda = 1300\,\mathrm{nm}$ ($a/\lambda = 0.35$) is present for a coupling angle $\theta = 17.52^{\circ}$. Experiments are now carried out directly to the evidence of this surface wave existence.

4. Conclusion

A possibility to generate surface optic waves in a porous silicon multilayer structure has been theoretically demonstrated. Calibration curves allowing porous silicon multilayer formation and experimental conditions to realize surface wave devices were presented. Finally, a Bragg mirror and a surface wave structure were realized. Optical studies are in progress in order to show the surface waves existence in this type of photonic device at the wavelength $\lambda = 1300\,\mathrm{nm}$.

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