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Bending properties in oxidized porous silicon waveguides

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Abstract

The greatest limit in high-speed communications between different circuit blocks is due to the delays introduced by metal interconnections. Knock-down wire communication bottleneck is, therefore, one of the best goals that current research could reach in the field of fast electronics. A possible solution is to build fast optical links and even better if the technology is based on silicon. To attain these ends, we have made studies into possibility to fabricate optical waveguide based on oxidized porous silicon. In the last few years, such a device was realized and characterized. Waveguiding in the visible and in the near infrared was demonstrated, with propagation losses of about 3–5 dB/cm for a light with a wavelength of 632.8 nm. Moreover, a design feature of an integrated waveguide based on oxidized porous silicon is that it offers a spontaneous bending of the waveguiding layer at its ends. The edge bending is provided by a convex camber of a leading edge of forming porous silicon. This bending can be exploited to promote a vertical light output with no use of any additional devices. The paper discusses the properties of edge bending, evaluation of the light losses depending on the radius of curvature, and analysis of possibilities to reduce these losses.

Keywords: Waveguides; Porous silicon; Coupling; Bending

1. Introduction

Optical technologies are becoming increasingly important in areas that were traditionally the domain of electronics. In particular, silica-based optical waveguide fibers are used in long-distance telecommunications and local networks. Recently, important developments have been made on smaller scale in optoelectronics integrated circuits in which planar optical waveguides on a semiconductor substrate are employed for optical interconnections between active devices (e.g. lasers, detectors, light-emitting diodes, etc.) and also in passive devices (e.g. splitters, filters, couplers, etc).

High-speed and high-density devices are rapidly increasing for the development of ultra-large-scale integration (ULSI) with large numbers of circuit blocks. The area of ULSI chip is at least 1 cm^2, and the communication between the different circuit blocks of the multi-chip modules need long interconnection paths of about 1–10 cm. These metal wires occupy the majority of wafer's area. The signal delays due to the charging of the high capacitance for interconnections between the metal lines become a significant part of delay in integrated systems, and thus attenuate the frequency of the system [1,2]. Also the mutual coupling and the power dissipation to transmit bits are becoming a serious bottlenecks. Furthermore, in [3] is illustrated that electrical connections can perform relatively well where distance is less than 1 mm, such as within chips. Where the distance are greater than 1 mm as between chips, multi-chip module, boards, or frames, one of the ideas to solve the metal interconnection problem is to use photons instead of electrons.

Following such a purpose, in the last few years we realized and characterized oxidized porous silicon waveguides. These waveguides showed guiding properties in

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the visible and near-infrared range with propagation losses of 3–5 dB/cm with a wavelength of 632.8 nm [4–6] where silicon photodetectors can be used.

The fabrication process of the waveguide introduces a natural bending of the guiding layer at its ends. In this work we present a first characterization of the properties of these bendings.

2. Experimental

The starting material for the fabrication of the waveguides were p-doped silicon with 0.01 Ω cm resistivity. Porous silicon channels were obtained by selective anodization of silicon wafers in HF/alcohol solution using a silicon nitride mask, which was removed after the electrochemical process. Then thermal oxidation of the porous waveguides was performed in a furnace by a three-step process.

Figs. 1 and 2 illustrate schematic views of the waveguides. As can be seen from the figures, the waveguide presents two 90° bending near the terminal parts of the mask used during the anodization step. These bendings can be exploited to perform vertical input and output coupling of light. As an example we can use in input a vertical cavity surface emitting laser (VCSEL) and in output a silicon photodetector (PD).

The propagation losses were determined by a statistic elaboration on a set of measures made by cut-back method. The losses for the waveguide under test are 13.10 ± 0.50 dB. In Fig. 3 we present the simplified model of the waveguide used to determine the vertical bending losses where we consider:

- L is the length of the waveguide.
- P_1 is the optical power that enters the waveguide. Having performed the input coupling of light in the same conditions for both the bending waveguide and the one used for the cut-back measurements, we assume that the power is the same in the two measurement conditions.
- P_2 is the optical power inside the waveguide at a distance "L" from the input section. It is the power entering the bending part of the waveguide. This power could not obviously be measured, so it has been determined by measuring the power P_B at distance L_B and knowing the propagation losses α_p we obtain

  $$\log(P_2) = \log(P_B) - \alpha_p[(L - L_B)/10]. \quad (1)$$
- P_C is the optical output power of the bending part of the waveguide.

In all measurements, the waveguide was excited by end fire coupling.

The source was an argon laser beam with a wavelength of 488 nm. The coupling was performed with a lens to focus the laser radiation on the input of the waveguide. The vertical output power was collected by a fiber probe and measured with a pyrometer using a lock-in technique to improve the signal-to-noise ratio.

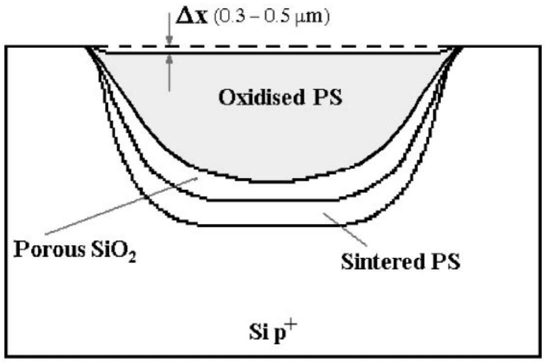

Fig. 1. Transverse section of the waveguide.

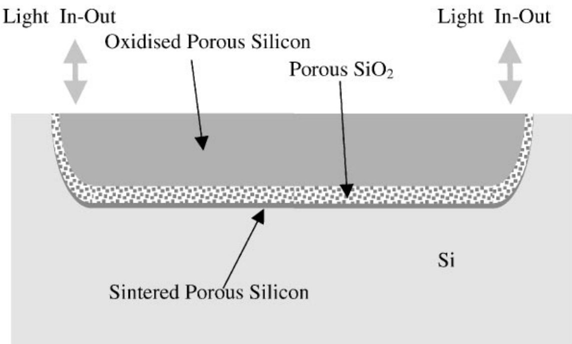

Fig. 2. Longitudinal section of the waveguide.

The measured power P_C was low, in the range of nanowatts, for this reason we could not ignore the optical power measured when the laser source was not coupled with the waveguide, it was necessary to take into consideration the radiant beam of the laser on the surface of the silicon wafer.

P_C is determined as the difference between the power revealed by the pyrometer in coupling conditions (P_{CC}) and in non coupling conditions (P_{CNC}) where only the radiant laser beam was under the fiber probe.

For both P_{CC} and P_{CNC} 30 measurements have been performed varying the chopper frequency.

On this set of measurements a statistical analysis has been carried out.

This analysis showed that both P_{CC} and P_{CNC} have a Gaussian distribution as P_C, being a linear combination of the two, obtaining

$$P_C = P_{CC} - P_{CNC} = 1.55 \pm 0.278\,\text{nW}.$$

From this value of P_C and using (1) to determine P_2 we can finally evaluate the bending losses α_B:

$$\alpha_B\,(\text{dB}) \equiv 10 \log(P_2/P_C) = 31.10\,\text{dB}.$$

The bending losses depend on some parameters of the waveguide, such as the curvature radius, the refractive

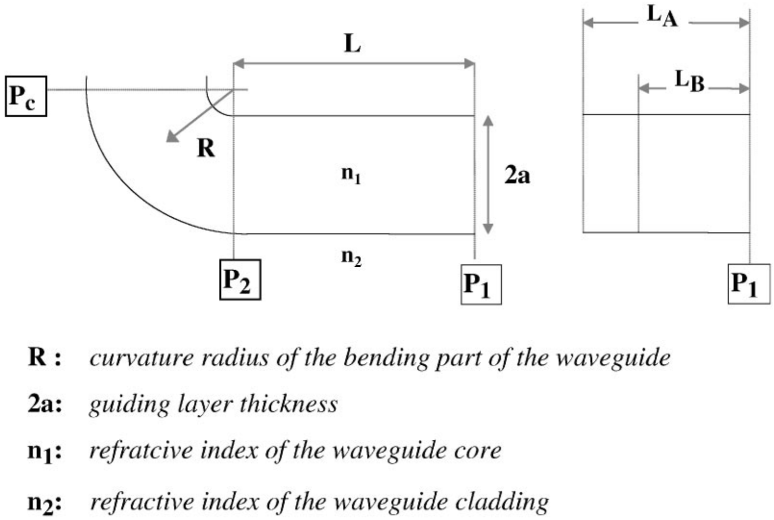

Fig. 3. Schematic view of the bending part of the waveguide.

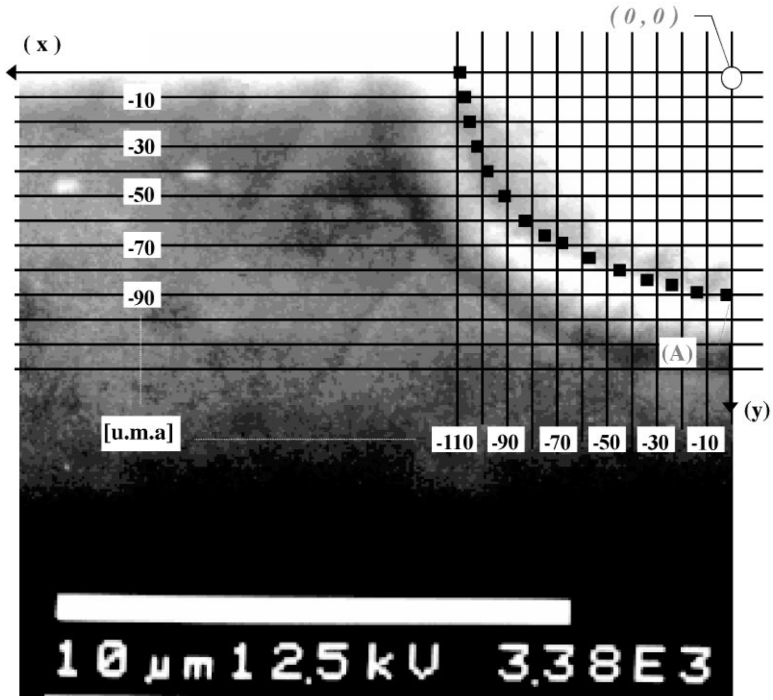

Fig. 4. SEM photograph of the bending part of the waveguide.

index profile and the thickness of the guiding layer. An expression that shows the relation existing between this parameter and the bending losses, is as follows [7]:

$$P_C = P_2 - P_2\alpha = P_2(1-\alpha) = P_2\alpha_B, \quad (2)$$

$$\alpha = C\exp\left[-R(n_1^2 - n_2^2)/a\right], \quad (3)$$

where R is the curvature radius, n_1 and n_2 are the values of the refractive index in the waveguide core and cladding, and "a" is half the thickness of the guiding layer.

Eq. (3) permits to calculate the curvature losses knowing geometric parameters as curvature radius and guiding layer thickness and refractive index profile and does not consider the losses due to substrate radiation. This is achievable if the buffer layer between the guiding layer and the substrate is sufficiently thick.

Fig. 4 shows a SEM photograph of the bending part of the waveguide and it is used to evaluate the curvature radius of the bending and the thickness of the guiding layer. To perform an evaluation of the curvature radius R we fixed 15 points placed on the bending. These points should be part of a circle with radius r. We looked for a circle tangent to the x-axis on point A and with center on the y-axis that best approximated the 15 points. This task was performed minimizing the error function

$$E = \sum_{i=1}^{15} e_i^2 = \sum_{i=1}^{15} \left[x_i + \sqrt{(y_0+90)^2 - (y_i - y_0)^2} \right]^2. \quad (4)$$

The function $E(y_0)$ is plotted in Fig. 5. The radius r of the circle corresponding to the minimum of the error function is 5.6 μm. This radius has been calculated with points placed on the deepest part of the bending, while we need the value of the radius referred to the central part of the guiding layer. This value is given by

$R = r - a = 3.4$ μm.

The refractive index profile for the waveguide was previously measured and it is presented in Fig. 6. As can be seen from the figure, the refractive index n_1 at the surface is 1.46, approximately the same as SiO_2, while at the end of the guiding layer the refractive index has a value $n_2 = 1.446$.

Introducing this values in (3) we determined the constant $C = 1.064$.

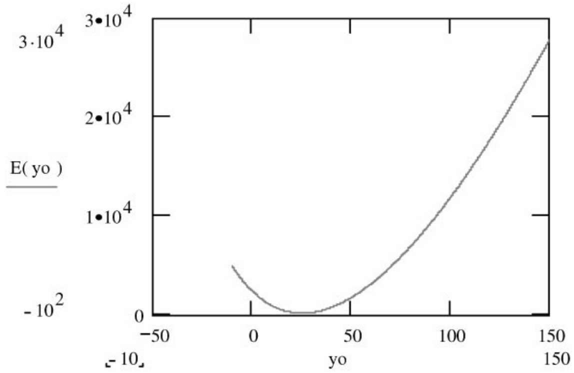

Fig. 5. Error function $E(y_0)$ graph.

3. Discussion

Using Eq. (3), we can calculate new values for the bending losses varying the refractive index or the difference of refractive index (Δn) of the cladding layer and varying the geometric parameters of the waveguide as the curvature radius and the guiding layer thickness.

The bending losses calculated are shown in Table 1.

As can be seen from the table, it is possible to change the value of the bending losses in a wide range. As expected, the bending losses fall when we increase the curvature radius, but it is not easy to increase the curvature radius very much and, furthermore, such an increase would introduce a subsequent increase of the guiding layer thickness.

Nevertheless, looking at the table, we can see that it is possible to reduce the bending losses increasing the refractive index difference between the core and the cladding of the waveguide. Such variations are possible as both the parameters can be controlled during the anodization process.

The values of the parameters used in Table 1 are technologically achievable for our waveguides. So we think we can reach bending losses below 5 dB and an acceptable value would be less than 3 dB.

Furthermore we have to say that all the preceding considerations were made neglecting the thickness of the buffer layer between the waveguide core and the substrate. In effect, part of the losses is due to radiation towards the substrate and can be considerably reduced

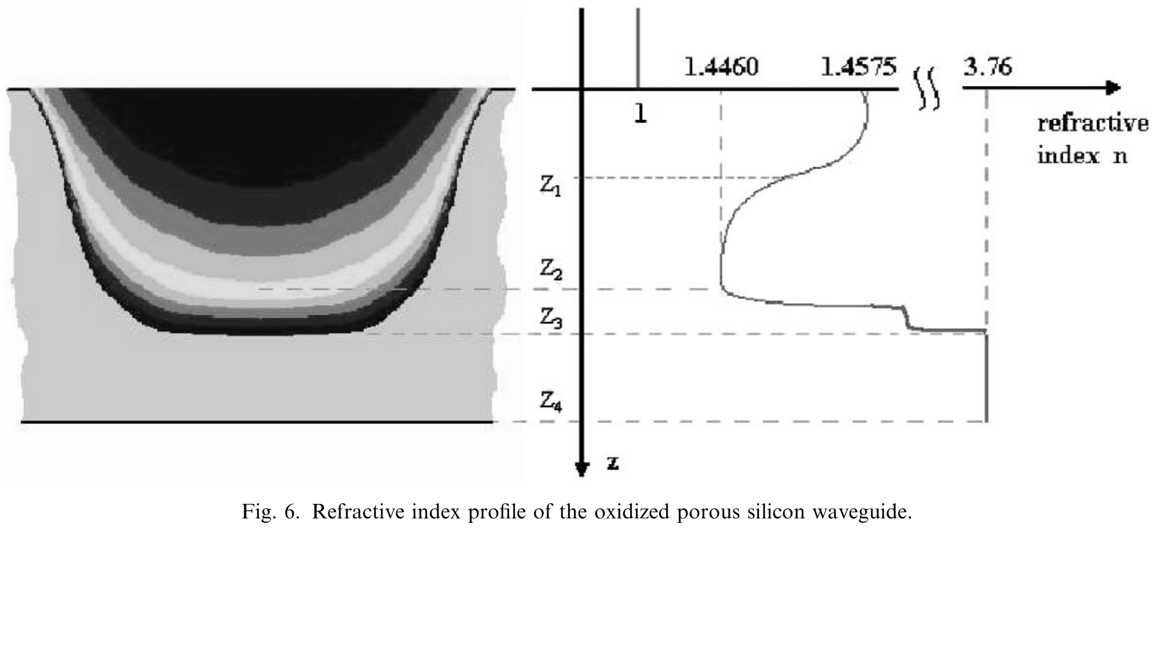

Fig. 6. Refractive index profile of the oxidized porous silicon waveguide.

Table 1
Calculation of bending losses

Vertical bending losses α_B (dB)	R	a	Δn
31.10	3.4	2.2	0.014
20.47	3.4	1.94	0.014
10.18	8.8	2.2	0.014
6.51	3.4	0.44	0.014
4.78	8.1	0.70	0.014
12.00	3.5	2.38	0.03
2.28	8.0	1.20	0.05
7.15	4.0	2.48	0.06

increasing the buffer-layer thickness. This task is also achievable varying the parameters of the anodization process.

4. Conclusions

In conclusion, we have for the first time investigated the bending properties of oxidized porous silicon waveguides. As we said, these waveguides present a characteristic 90° bending at its ends, which can be exploited for the coupling of light. After the first investigation we measured a bending loss of about 31 dB introduced by the bending. From theory we were able to see how to reduce these losses varying some waveguide parameters such as refractive index profile and guiding layer and buffer layer thickness. Furthermore, an increase of the refractive index difference between the guiding and the buffer layer would reasonably produce also a reduction of the propagation losses.

Acknowledgements

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