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Optical properties of erbium-doped porous silicon waveguides

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Planar and buried channel porous silicon waveguides (WG) were prepared from p⁺-type silicon substrate by a two-step anodization process. Erbium ions were incorporated into pores of the porous silicon layers by an electrochemical method using ErCl₃-saturated solution. Erbium concentration of around 10²⁰ at/cm³ was determined by energy-dispersive X-ray analysis performed on SEM cross-section. The luminescence properties of erbium ions in the IR range were determined and a luminescence time decay of 420 μs was measured. Optical losses were studied on these WG. The increased losses after doping were discussed.

Keywords: Porous silicon; Waveguide; Erbium

1. Introduction

Erbium-doped optical waveguide (WG) amplifiers on silicon are of growing interest due to their potential integration as loss-compensating devices [1]. In optical telecommunication application, using porous silicon (PS) material to form doped optical WG is an attractive solution [2]. In fact, porous silicon offers a large range of refractive indices and presents a high specific surface for erbium incorporation. The Er³⁺ rare-earth element has an incompletely filled inner 4f shell and exhibits optical intra-center transitions. The main transition (⁴I_{13/2} → ⁴I_{15/2}) occurs at 1.53 μm, almost independent of the host material because of the strong localization of the 4f states and their excellent screening by the outer valence electrons [3,4]. Erbium is introduced in the porous silicon layers by different methods such as ion implantation [5], spin-on technique [6], electrochemical method [7] and immersion technique [8]. The electrochemical method has the advantage of deeper Er penetration and simplicity of processing.

In the present work, planar and channel porous silicon WG were prepared by varying the anodization current density during the formation of PS. Erbium was then

incorporated by an electrochemical method. The concentration profile of Er in the planar and channel WG was determined by energy-dispersive X-ray (EDX) analysis. The photoluminescence of Er³⁺ ions in the IR range were shown. The decay curve of the 1.53 μm emission peak was characterized. Optical loss measurements at 1.55 μm were investigated by measuring the light streak scattered out of the upper surface of the WG.

2. Experimentation

The porous silicon WG structures were elaborated using (1 0 0)-oriented Si substrate. The resistivity of the p⁺-type wafer was 4–6 mΩ cm. The anodization was performed in a (HF 50%, C₂H₅OH, H₂O:2:2:1) electrolyte. By varying the current density of anodization, layers of different refractive indices were obtained. Two current densities of 50 and 80 mA/cm² were successively applied to respectively form guiding and cladding layers (CLs). The thickness of layers was fixed by the anodization time equal to 3 and 5 μm, respectively. To form buried channel WG, porous silicon layers were formed locally by using lithographic technique [9]. These channel WG were elaborated under the same experimental conditions as those of planar WG. The characteristics of both types of WG are reported in Table 1.

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Table 1
Characteristics of planar and channel WG after heat treatments

	Currents density (mA/cm ²)	Thickness (μm)	Porosity (%)	Refractive index
Guiding layer	50	3	31	1.35
Cladding layer	80	5	43	1.26

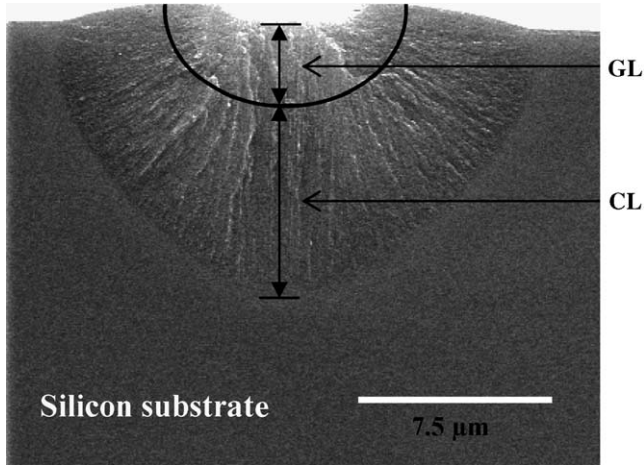


Fig. 1. Cross-sectional SEM micrograph of a channel WG after heat treatments.

In order to dope the porous silicon layers, the HF electrolyte was then replaced by a $\text{ErCl}_3\cdot 6\text{H}_2\text{O}$ /ethanol-saturated solution. Erbium ions were electrochemically deposited in the porous silicon WG at a constant current density (0.1 mA/cm² for the planar WG and 0.75 mA/cm² for channel WG) at different times (10 min for the planar WG and 5 min for the channel WG). Thermal treatments of the obtained porous silicon WG were performed using a three-step process. First, the porous silicon structures were stabilized by low-temperature annealing at 300 °C for 1 h in wet O₂. Then, an oxidation step at 900 °C for 1 h was performed in wet O₂. Finally, the temperature was raised to 1000 °C for 2 h in a N₂ gas in order to optically activate the erbium ions. Fig. 1 shows a typical SEM micrograph of a channel WG cross-section after thermal treatments. The guiding layer (GL) and the bottom (CL) are clearly distinguished.

In order to estimate the Er³⁺ concentration in the porous layers, SEM observations coupled with EDX analysis were performed on the sample cross-section. The infrared photoluminescence (IR-PL) obtained from Ar⁺ laser excitation at 488 nm, was performed using a Jobin–Yvon monochromator and an InGaAs photodiode. For the time decay measurement, the 488 nm beam whose power was equal to 125 mW was chopped with an acousto-optic modulator. The time decay signal was monitored and recorded with a digital oscilloscope. Optical losses were studied by measuring the light streak scattered out of the upper surface of the WG by using an infrared digital camera for detection at 1.55 μm [10].

3. Results and discussion

In order to investigate the incorporation of Er ions in the two layers, EDX analysis was performed in different regions of the WG. The Er concentration as a function of the distance from the surface deep into the substrate for the planar and channel WG is reported in Fig. 2. In the case of planar WG, the Er concentration is nearly constant in the GL and drastically decreases in the CL. The value of Er concentration in the GL is around 2.5 at% which corresponds to approximately 10²⁰ at/cm³. On the other hand, the Er concentration in the channel WG is lower (1.5 at%) than the previous one and is nearly homogeneous inside the two porous silicon layers. Although cathodic current density is higher in the case of channel WG than in the planar WG, the erbium concentration is lower in the first case. The difference between the two Er concentrations is due to the longer cathodization time for the planar WG. The doping of the channel WG is performed through the openings in the mask (width of 6 μm) in the opposite of planar WG. We have noticed that the Er deposition is more homogeneous in the case of channel WG.

Fig. 3 shows IR-PL spectra at room temperature for planar and channel WG after thermal treatments. The position of the 1.53 μm peak is typical of the $^4I_{13/2} \rightarrow ^4I_{15/2}$ transition between internal energy levels in Er³⁺ ions. The two spectra have the same shape, but the PL intensity is higher in the planar than in the channel WG because of the higher Er concentration in the planar WG. This PL intensity difference could be also explained by the fact that the analyzed surface for the channel WG has a small size. The highly developed surface of porous silicon is expected to enhance the diffusion and interaction of different impurities, in particular, Er and O₂. Erbium ions are chemically combined with the surface states of porous silicon at high temperatures. Then, these ions are excited by

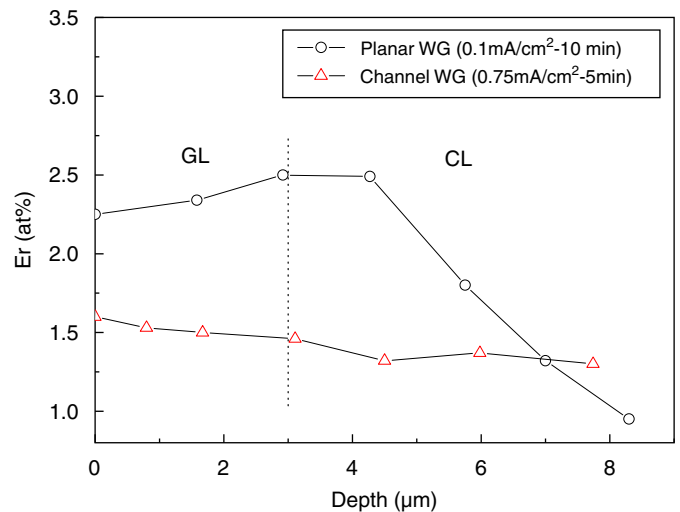


Fig. 2. Er concentration profile as a function of the waveguide depth (GL and CL), open circles for planar WG and open triangles for channel WG.

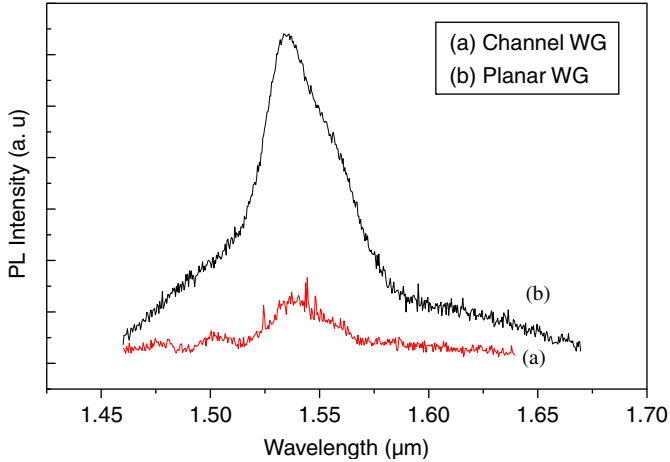


Fig. 3. Room temperature photoluminescence spectra relative to the ${}^4I_{13/2} \rightarrow {}^4I_{15/2}$ transition of Er^{3+} for planar and channel WG after thermal treatments.

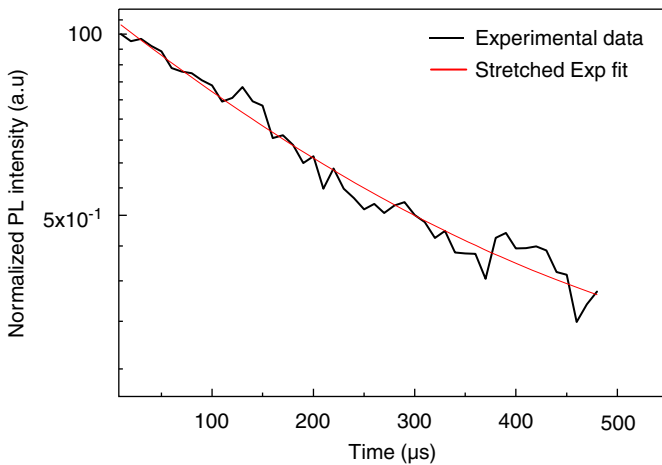


Fig. 4. Time decay curve of the 1.53 μm emission at room temperature for planar WG.

the recombination energy of electrons and holes, which are generated in the surface region of Si nanocrystals [11].

The time decay measurement of the 1.53 μm emission, measured at room temperature from erbium-doped planar WG is shown in Fig. 4. The decay curve is expressed approximately by a stretched exponential. The measured lifetime is equal to 420 μs . This value is lower than 1 ms reported for p-type porous silicon [12]. We believe that this lower value is due to the three steps of thermal treatments.

So far, only the confinement and propagation of light inside a WG have been considered. The intensity of propagated light decreases exponentially in the WG according to the equation: $I(z) = I_0 e^{-\alpha z}$, where $I(z)$ is the intensity of light at position z , I_0 is the intensity of light at $z = 0$ and α (cm^{-1}) is the attenuation coefficient.

The propagation losses measured at 1.55 μm in the planar and channel WG are given in Table 2. The value of losses for the planar WG is 0.7 dB/cm for the undoped sample and increase to 1.1 dB/cm for the doped sample. The same behavior is observed for the channel WG, the

Table 2

Optical losses for planar and channel WG at 1.55 μm

	Planar WG (dB/cm)	Channel WG (dB/cm)
Undoped	0.7	2.6
Er^{3+} -doped	1.1	4.4

losses were increased from 2.6 to 4.4 dB/cm. The propagation loss measurements for Er-doped buried channel WG was lower than the value (~ 7 dB/cm) reported by Balucani et al. [13]. This loss increase is essentially due to Er^{3+} absorption at 1.53 μm , which has been confirmed by PL measurement. Furthermore, interfacial scattering can play a significant role in the losses at this wavelength. The difference in optical losses between the doped and undoped WG is higher in the case of channel WG, whereas the erbium concentration is lower. We have noted a few erbium aggregates on the surface of WG. The quantity of these aggregates is more important in the channel WG which may be due to the low reactive surface dimension. So, we attribute this loss difference increase to a rise of the surface scattering.

By comparing the losses between the two undoped samples, we can notice that they are higher in the case of the channel WG. These values were comparable to those reported in Refs. [14]. These losses can be explained by surface scattering which plays a significant role in the losses associated with a WG. The scattering occurs through roughness at material interfaces. This phenomenon is more significant in channel WG because the pronounced roughness of its interfaces than in planar WG.

4. Conclusions

A study of erbium-doped planar and channel porous silicon WG was presented. A relatively uniform incorporation of erbium ions in the porous layers of the WG was shown by EDX analysis. Er incorporation was found to be rather different for channel and planar WG. However, in the two cases the electrochemical doping method is very efficient. PL emission at 1.53 μm was detected in Er-doped WG and a lifetime of 420 μs at room temperature was determined. Optical losses measured at 1.55 μm for Er-doped planar and channel WG were equal to 1.1 and 4.4 dB/cm, respectively. These values were higher than those obtained for undoped WG realized in the same conditions. This is mainly due to optical absorption of erbium. These results confirm the effective incorporation of Er in the porous layers as already obtained by EDX analysis and prove their efficient optical activation. In order to enhance the efficiency of luminescence co-doped erbium-ytterbium channel WG are now currently investigated. Another task, to which we have to address is to demonstrate the optical amplification in such structures.

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