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Porous Silicon Optical Waveguides with an Extremely High Contrast of Refractive Index

Morio Takahashi and Nobuyoshi Koshida

Department of Electronic and Information Engineering, Faculty of Technology,
Tokyo University of Agriculture and Technology, Koganei, Tokyo 184-8588, Japan
Phone: +81-42-388-7128, Fax: +81-42-385-5395, E-mail: morio@cc.tuat.ac.jp

1. Introduction

By making use of the refractive-index-controllable nature of luminescent porous silicon (PS), it is possible to fabricate mode-selective waveguides [1] and tunable cavities [2] on silicon wafers. For further developments of these PS devices into photonic integration, the optical functions of PS should be clarified for a well-controlled device configuration.

We present here that three-dimensionally buried PS optical waveguides with active core layer can be fabricated by monolithic process. It is shown that owing to an enhanced confinement of electromagnetic field in the core layer, visible lightwave can be propagate.

2. Experimental

A possible fabrication process flow for a buried PS waveguide is shown in Fig. 1. The starting p-type (100)-oriented silicon wafer (8–12 Ωcm) was first oxidized to form a masking SiO_2 layer for ion implantation in an H_2O vapor. The SiO_2 layer thickness was $\sim 1\,\mu m$. Following a stripe-geometry patterning by photolithography, boron ions were implanted into the silicon substrate in order to form the low-resistivity region ($\sim 0.01\,\Omega cm$). The accelerating voltage and the ion dose was 200 kV and $10^{15}\,cm^{-2}$, respectively. After masking SiO_2 layer are removed by an HF-etchant, the substrate was annealed in an Ar ambient at 1100 °C for 1 h. From estimation based on the LSS theory, the in-diffused thickness of the implanted low-resistivity layer was $\sim 2\,\mu m$ under these conditions. Next, the anodization was carried out in the dark at a constant current density of $20\,mA/cm^2$ for 2 min in a mixture of ethanol and 55 wt % HF (1:1). As a result of this one-step continuous anodization, the high-porosity cladding layer was automatically formed around the low-porosity core layer as the fourth step in Fig. 1. Finally, the device was thermally oxidized in a dry oxygen gas at 1000 °C for 4 h in order to reduce an internal absorption loss for lightwave with visible wavelengths. The resultant partially oxidized PS operates as blue-PL-emissive active core layer.

To confirm the possibilities of the fabricated device as a optical waveguide, fundamental properties were evaluated in terms of propagation losses and polarization mode including related theoretical analyses. In most of these evaluations, a part of the active core layer was excited by a He-Cd (325 nm) laser, and output light emitted from a cleaved edge was measured.

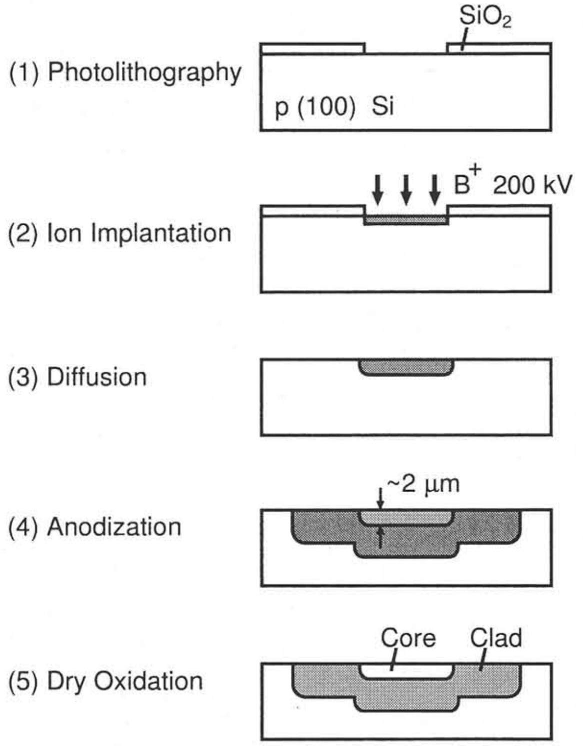

Fig. 1 A schematic fabrication process flow of a three-dimensionally buried porous silicon optical waveguide. The usual silicon process technologies were used to form a core region.

3. Results and Discussion

A scanning electron microscopy (SEM) cross sectional view of the fabricated optical waveguide is shown in Fig. 2. This waveguide was designed such that a core width and a thickness were $15\,\mu m$ and $2\,\mu m$, respectively. It is clearly observed that the core layer is buried in the cladding layer as designed, although the core width is widened from $15\,\mu m$ to $20\,\mu m$ by the diffusion process.

It should be noted that the three-deminsionally buried structure was self-reguratedly formed by one-step anodization at a constant current density. This is due to that the growth rate and porosity of PS increases and decreases, respectively, with increasing doping concentration. In accordance with optical measurements car-

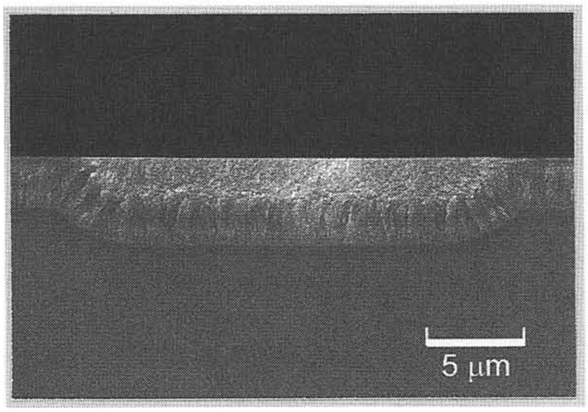

Fig. 2 The SEM cross sectional view of the PS optical waveguide without thermal oxidation.

ried out separately, refractive index value of partially oxidized PS varies in an extremely wide range of about 1.4 to 2.5. In the case of oxidized PS waveguide, the refractive indices of the core and cladding layer are 2.31 and 1.46, and the calculated specific refractive index contrast is remarkable high value of 53 %.

When excited by a He-Cd laser (325 nm), a blue PL generated in the core layer was efficiently confined there. It was also confirmed that the generated lightwave propagated along the waveguide and was emitted to outside from a cleaved facet. To verify the availability of the fabricated waveguide, the propagation losses were estimated by varying a waveguide length which was distance from the cleaved edge to the He-Cd excited point. Figure 3 (a) shows the edge emission spectra as a function of the waveguide length. The intensity decreases with increasing the propagation length. Correspondingly, the peak wavelength shows a slight red shift, since the propagation losses become high in shorter wavelengths. The wavelength dependence of propagation losses are calculated from these spectra as shown in Fig. 3 (b) (the solid curve). The losses in longer wavelengths (650–850 nm) shown by dashed curves were estimated by using a slab PS waveguide [3]. Obviously, the propagation loss increases with decreasing the wavelength in a range from 10 dB/cm to 60 dB/cm. This is suggests that the major origins of the losses are Rayleigh scattering and self-absorption caused by remaining silicon skeletons.

As for bending losses, optical waveguiding was observed in the PS waveguide with a curvature radius of 250 μm. The polarization characteristic was also evaluated, the edge-emission lightwave was polarized in transverse electric (TE) direction, which could be expected by theoretical analysis based on the Maxwell equation treatment.

4. Summary

Three-dimensionally buried optical waveguides for visible wavelengths using luminescent PS was fabricated on silicon substrates by continuous processing. The device operates as an multi-mode optical waveguide with blue-PL-emissive active core layer. These results suggest that functional integration of optical components is possible on a basis of monolithic silicon technology. Also, the device presented here has made it possible to study the detailed optical properties of PS in a well-controlled system.

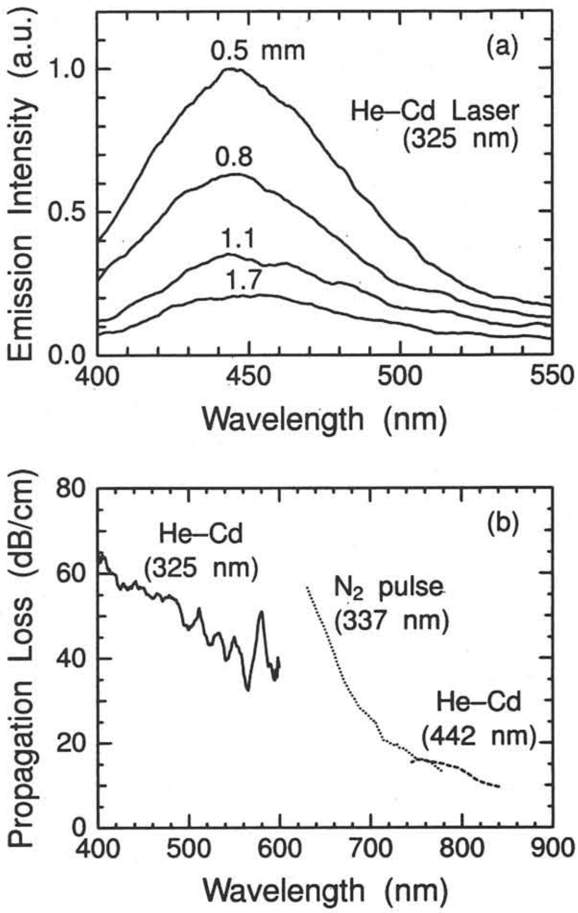

Fig. 3 (a) The observed edge emission spectra as a function of the propagation length. (b) The wavelength dependence of the attenuation losses.

Acknowledgments

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References

1) M. Araki, H. Koyama and N. Koshida: Appl. Phys. Lett. **68** (1996) 2999.
2) M. Araki, H. Koyama and N. Koshida: J. Appl. Phys. **80** (1996) 4841.
3) M. Araki, M. Takahashi, H. Koyama and N. Koshida: Mat. Res. Soc. Symp. Proc. **486** (1998) (in press).