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Sculpting of three-dimensional nano-optical structures in silicon

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Separation by IMplantation of OXygen (SIMOX) based process has been developed to sculpt three-dimensionally integrated nano-optical waveguiding structures in silicon. An approach, based on the implantation of oxygen ions into a silicon substrate, patterned with thermal oxide, has been adopted to synthesize low loss buried rib waveguides in a single implantation step of thickness 286 nm and widths varying from 2 μm to 12 μm. These waveguides show propagation losses in the range of 3–4 dB/cm. The capability of the process to sculpt three-dimensional (3-D) structures has also been demonstrated by defining rib waveguides on the top silicon layer. © *2003 American Institute of Physics.* [DOI: 10.1063/1.1634384]

Vertically integrated optical structures have received considerable attention in recent years in the context of microring/microdisk resonators, mode expanders, and other complex integrated circuits.[1–3] Vertical integration allows for the fabrication of densely integrated three-dimensional optical structures, enhancing the functionality of the optical chip. Apart from this inherent advantage, vertical integration offers the prospect of accurate control of critical dimensions of the structure. The control over the critical dimension is more precise than laterally patterned structures, where the limit is set by the photolithography and etching processes. Thus, more complex optical circuitry with accurately controlled evanescent coupling between devices is possible by employing vertically integrated optical structures.

Optical miniaturization, employing nano-photonic devices such as ring and disk resonators and 2-D photonic crystal cavities, requires tight confinement of the optical field within these tiny structures. This necessitates the use of high index contrast (Δn) material systems such as those provided by Si/SiO$_2$ with a Δn of 2. A silicon-on-insulator (SOI) structure provides an excellent platform for the fabrication of a variety of integrated optical structures, with the prospect of full integration of electronic and optical devices on the same substrate.[4] In this paper, we report on the use of SIMOX (Separation by IMplantation of Oxygen) process for fabricating 3-D integrated photonic structures. Buried waveguides, fabricated using a single implantation step, are reported. These waveguides exhibit the lowest losses ever reported for SIMOX devices.

SIMOX process involves the implantation of oxygen ions into a silicon substrate, followed by a high temperature (around 1300 °C) anneal of the substrate in order to cure the implantation damage and to effect SiO$_2$ formation. The thickness and the depth of the buried oxide layer are, respectively, determined by the implantation dose and energy. It has been observed that in order to achieve good quality buried oxide and to keep the defect densities in the range of $<10^5/\text{cm}^2$, implantation dose should be in the range of 1×10^{17}–9×10^{17} ions per cm^2, with implantation energies in the range of 40–200 KeV.[5] The process is conventionally used to obtain thin silicon layers (of the order of 3000 Å) on top of a buried oxide layer of thicknesses of the same order of magnitude. There has been an attempt previously to fabricate 3-D structures in SOI wafers using the SIMOX process, combining it with the epitaxial growth of silicon.[6] The complete process involved two implantation steps and two epitaxial growths in order to grow vertically integrated SOI waveguides. The waveguides fabricated in this case were planar in nature with a guiding layer thickness of 2 microns.

A method, utilizing the implantation of oxygen ions into a masked SOI substrate, is proposed in this paper to realize buried rib waveguides of submicron dimensions. Figure 1 depicts the process flow of the fabrication of vertically integrated structures using the SIMOX process. The implantation of oxygen ions is performed on a SOI substrate that has been patterned with thermally grown oxide. The thickness of the oxide mask may be chosen suitably to decelerate the oxygen ions that penetrate into the area underneath the mask. The angled side-wall of the buried rib waveguide formed after the high temperature anneal arises due to the lateral straggle of the implanted oxygen ions. After the anneal, rib waveguides may be defined on the top layer using conventional lithography and etching process, as shown in Fig. 1. This process may be utilized in fabricating laterally patterned ring or disk resonators with SIMOX defined SiO$_2$ spacers to accurately provide the vertical coupling between them, as shown in Fig. 2. The figure also depicts the extension of this idea to fabricate WDM filters. In the SIMOX process, there occurs an inherent sidewall smoothening due to the lateral straggle of the oxygen ions, which helps in the formation of high quality waveguides and high Q cavities.

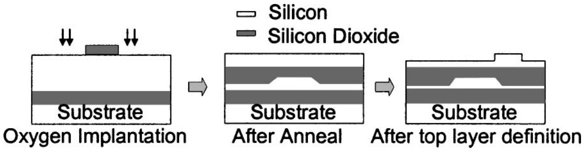

FIG. 1. Process flow for the SIMOX fabrication of 3-D structures (cross-sectional view).

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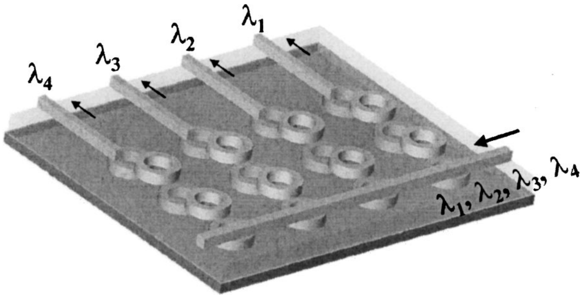

FIG. 2. Example of laterally patterned resonator rings and WDM filter with vertical coupling.

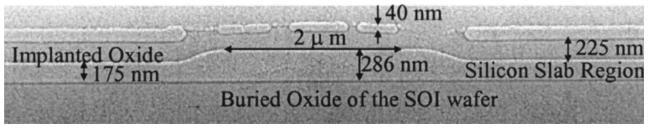

FIG. 3. SEM picture of the buried waveguide fabricated using the SIMOX process. The grainy surface is due to the gold sputtered prior to SEM photography.

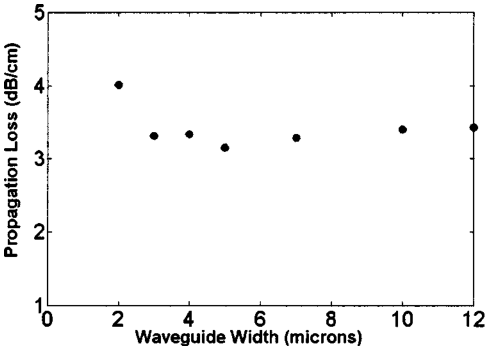

FIG. 4. Variation of propagation loss with waveguide width.

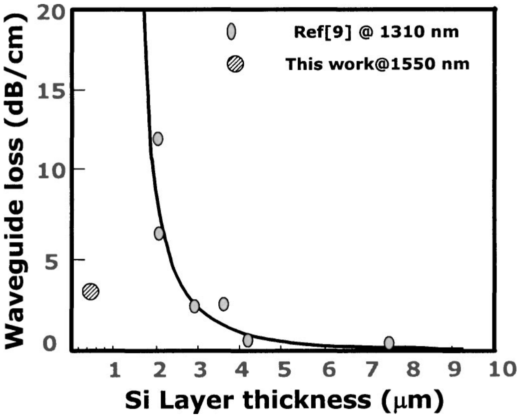

FIG. 5. Loss comparison with wet etched SOI waveguides.

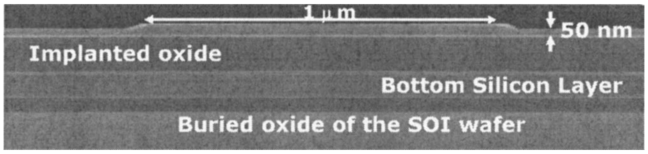

FIG. 6. Rib waveguides fabricated on the top layer of a two-layer SIMOX structure.

A SOI wafer (made by SOITEC Inc.) with 0.5 μm of silicon on top of a buried oxide layer of 3 μm thickness was oxidized and patterned using reactive ion etching process to form oxide stripes of thickness 0.15 μm, with widths varying from 2 μm to 12 μm. The patterned wafer was then implanted with oxygen ions with a dose of 9×10^{17} ions per cm^2, at energy of 80 KeV. The implanted wafers were then annealed at 1320 °C for 7.5 hours in an ambient of argon, with 1% oxygen, to cure the implantation damage.

Figure 3 shows the SEM photograph of a buried rib waveguide structure that was fabricated employing the aforementioned technique. It may be seen from the figure that the process has resulted in the formation of rib waveguides with submicron core thickness, in a single implantation step, and with excellent uniformity for the buried oxide. It has been observed that, under nonideal conditions, the SIMOX process can result in the formation of high density of silicon islands inside the buried oxide.[7] The optimized SIMOX process employed in this work has been successful in preventing the formation of these islands that degrade the quality of the buried oxide. It may also be seen that the interface of the formed buried oxide with the bottom silicon layer is smooth. The discontinuities in the top layer silicon directly above the rib structure could be due to volume expansion of the formed SiO_2, and the stress generated inside as a consequence of this expansion. Further process optimization is under progress in order to overcome these issues.

Cutback measurements were performed on these rib waveguides to measure the propagation loss. The loss as a function of the width of the waveguide is plotted in Fig. 4. It is seen that losses are in the range of 3–4 dB/cm, with the lowest measured loss of 3.2 dB/cm. This, to our knowledge, is the lowest reported loss for waveguides fabricated using the SIMOX process, previously reported lowest loss being 6 dB/cm in a planar waveguide structure,[8] as opposed to the laterally confined optical structures fabricated in this work, employing the SIMOX process. A comparison of this loss value with the reported losses for rib waveguides fabricated in SOI, using anisotropic wet etch,[9] reveals that for the same value of the silicon layer thickness, the current method has resulted in waveguides with losses lower by an order of magnitude, as may be observed in Fig. 5. Rib waveguides fabricated on silicon surface, with 0.8 dB/cm propagation loss, have been reported recently in SOI.[10] However, the waveguide fabrication in this case involved a multi-step process, consisting of an etch step to define the waveguides followed by an oxidation smoothening step to reduce the sidewall roughness.

The feasibility of 3-D integration is demonstrated by defining a rib waveguide on the top silicon layer. These structures were defined using a photoresist mask and reactive ion etching, the results of which are shown in Fig. 6 (the buried waveguide on the bottom layer is not shown in the picture). The ability to fabricate waveguides on two different layers paves the path for future monolithically fabricated, vertically-coupled photonic devices on silicon.

In conclusion, a SIMOX based process has been developed to fabricate three-dimensionally integrated nano-optical waveguiding structures in silicon. This approach has been adopted to synthesize low loss buried rib waveguides in a single implantation step, with propagation losses as low as 3.2 dB/cm for 286 nm thick waveguides. The proposed technology has the capability to sculpt 3-D low-loss silicon nanophotonic structures in a standard silicon foundry.

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