Vertically-coupled micro-resonators realized using three-dimensional sculpting in silicon

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(Received 15 March 2004; accepted 12 June 2004)

A modified separation by implantation of oxygen process has been developed to sculpt vertically coupled microdisk resonators in silicon. The approach involves the implantation of oxygen ions into a silicon substrate, patterned with thermal oxide, to define waveguides on the bottom silicon layer, and photolithography and reactive ion etching to define the microdisk resonators on the top silicon layer. The top and the bottom silicon layers are separated by the oxide layer that was formed after the oxygen implantation. Fabricated microdisk resonators show resonances with a *Q* value of 10 300 and a free spectral range of 5.4 nm. © *2004 American Institute of Physics*.
[DOI: 10.1063/1.1781370]

Optical microcavities are versatile devices, with applications ranging from add-drop WDM multiplexers, optical filters, to microdisk lasers. Fabrication of vertically coupled microring/microdisk resonator structures has received considerable attention in recent years.[1–3] Vertical integration allows for the fabrication of densely integrated three-dimensional optical structures, enhancing the functionality of the optical chip. Apart from the inherent advantage of achieving densely integrated three-dimensional (3D) optical structures, vertical integration offers the prospect of precise control of coupling coefficient in vertically coupled devices.[1] Here, the control over the critical dimension is more precise than laterally patterned structures, where the limits are set by the photolithography. Thus, complex optical circuitry with accurately controlled evanescent coupling between devices is possible by employing vertically integrated optical structures.

Optical miniaturization, employing nanophotonic devices such as ring and disc resonators, and two-dimensional 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. 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] There have been reports of laterally patterned ring resonators in SOI substrates with Q values greater that 3000.[5] The tight confinement of the field in SOI-based waveguides also leads to an enhancement of optical nonlinearities in silicon. This has been utilized in demonstrating nonlinear Raman effects such as, stimulated Raman amplification and Stokes to anti-Stokes wavelength conversion in silicon waveguides.[6,7] We have previously reported the fabrication of 3D integrated nanooptical structures in SOI substrates, including low-loss buried waveguides, using a modified process of separation by implantation of oxygen (SIMOX sculpting).[8] This letter reports the demonstration of vertically coupled microdisk resonator structures on silicon substrates. More significantly, these vertically integrated structures are realized through a monolithic fabrication process. This is considerably simpler than the wafer bonding technique that was previously employed in fabricating vertically coupled devices on III-V substrates.[1,2]

The 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 $<10^5/cm^2$, implantation dose should be in the range of $1-9\times10^{17}$ ions/cm^2, with implantation energies in the range of 40–200 keV.[9] 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 3D structures in SOI wafers using the SIMOX process, combining it with epitaxial growth of silicon.[10] 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 μm.

A method, utilizing the implantation of oxygen ions into a masked SOI substrate, is employed to realize buried rib waveguides of submicrometer dimensions. Figure 1 depicts the process flow of the fabrication of vertically integrated structures using the SIMOX process. Implantation of oxygen ions is performed on an 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

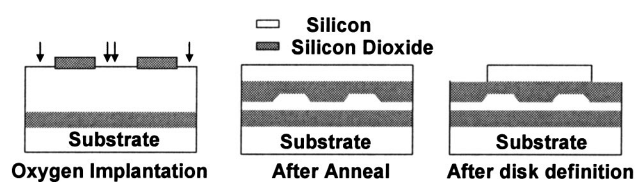

FIG. 1. Process flow for the SIMOX fabrication of microdisk structures (cross-sectional view).

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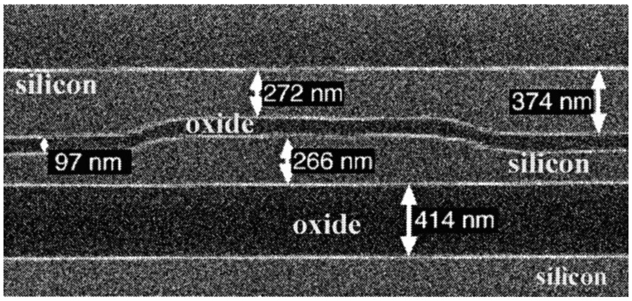

FIG. 2. SEM picture of buried waveguide structure fabricated using SIMOX 3D sculpting.

penetrate into the area underneath the mask. The angled sidewall 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, microdisk structures may be defined on the top layer using conventional lithography and an etching process, as shown in Fig. 1. 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.

A SOI wafer (made by SOITEC Inc.) with 0.6 μm of silicon on top of a buried oxide layer of 0.4 μm thickness was oxidized and patterned using a reactive ion etching process to form oxide stripes of thickness 0.06 μm, with widths varying from 2 to 12 μm. The patterned wafer was then implanted with oxygen ions with a dose of 5×10^{17} ions/cm^2, at energy of 150 keV. The implanted wafers were then annealed at 1320 °C for 7.5 h in an ambient of argon, with 1% oxygen, to cure the implantation damage.

Figure 2 shows the SEM photograph of a buried rib waveguide structure that was fabricated employing the aforementioned technique, the dimensions of which are shown in the figure. It may be seen from the figure that the process has resulted in the formation of submicron rib waveguides in the bottom silicon layer, separated from the continuous silicon layer on the top by the oxide layer formed after the oxygen implantation and subsequent anneal. These buried waveguides act as bus waveguides to the microdisk that is fabricated on the top silicon layer. The buried oxide that was formed after the implantation and anneal is found to be very uniform, which is very important in achieving accurate control of evanescent coupling from the rib waveguides to the devices on the top silicon layer. It has been observed that, under nonideal conditions, the SIMOX process can result in the formation of a high density of silicon islands inside the buried oxide.[11] 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.

A silicon nitride layer of thickness 0.1 μm was deposited, and patterned using standard lithography and reactive ion etching to form circular discs of radii 23 μm, straddling two adjacent buried bus waveguides. The substrate was then oxidized to remove the silicon on the top layer, everywhere except underneath the circular silicon nitride disks. This results in the formation of a microdisk structure on the top silicon layer that is coupled vertically to the buried waveguides in the bottom silicon layer through the oxide layer formed after the oxygen implantation. Figure 3 shows the SEM photographs of the microdisk resonator on the top layer of silicon, straddling the buried bus waveguide. The silicon nitride disk used as the oxidation mask is also seen in the picture, on top of the microdisk. It may be noted here that the silicon dioxide that was formed after the oxidation, and the buried oxide layer formed during the implantation, were removed to obtain scanning electron microscopy (SEM) photographs that clearly illustrate the structure of the device.

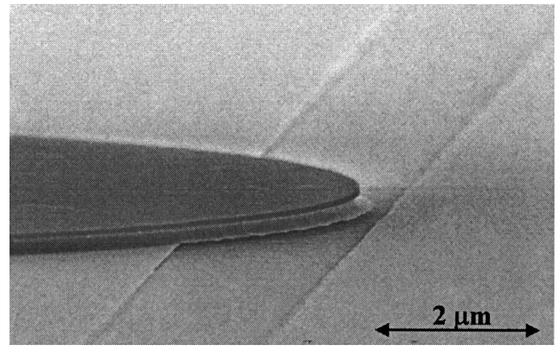

FIG. 3. SEM picture of the fabricated microdisk resonators of radius 23 μm on the top silicon layer with bus waveguides underneath.

Figure 4 shows the transmission properties of the throughput port of the resonator, characterized using an amplified spontaneous emission (ASE) source, for the TE polarized light. The unpolarized light from the ASE source was passed through an inline fiber polarizer (General Photonics make, extinction ratio 40 dB) and a polarization controller (General Photonics make, extinction ration 30 dB), that can rotate the state of polarization of the light to any desired state. This polarized light was coupled into the bus waveguides using a tapered fiber that has a spot diameter of 2 μm. The light output from the throughput port of the resonator was collected using a tapered fiber, similar to the one used at the input. For a power of 1 mW coming out the input fiber, 1 μW of power was measured after the output fiber, corresponding to a fiber-to-fiber insertion loss of 30 dB for the setup. This includes the mode mismatch loss and reflection losses at the input and the output facets of the device, and the propagation losses in the waveguides. The collected light was observed using an optical spectrum analyzer (ANDO Model: 6319) that can measure power levels as low

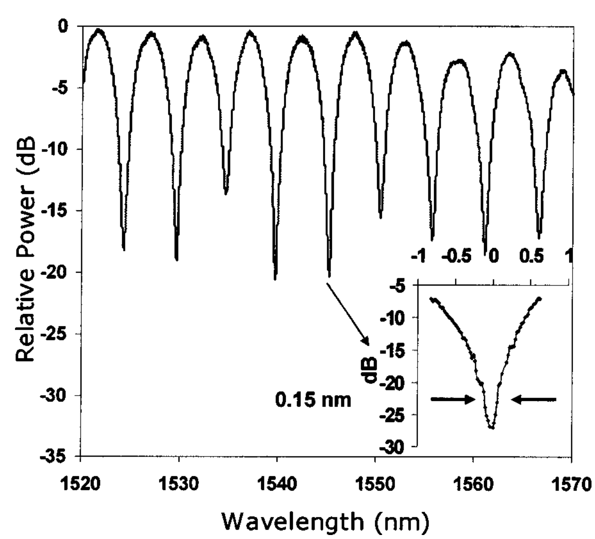

FIG. 4. TE polarized transmission characteristics of the fabricated microdisk resonator.

as 1 pW. The spectrum displayed in Fig. 4 is normalized with respect to the maximum transmission of the throughput port, after correcting for the spectral shape of the ASE source. Sharp resonances are observed with a free spectral range of around 5.4 nm, with the narrowest resonance observed showing a full width of half maximum of 0.15 nm, centered at 1545 nm. This corresponds to a Q value of 10 300, with attenuation greater than 20 dB for the throughput signal at the resonant wavelength. This is a high value of Q for microresonators in Silicon.

In conclusion, a modified SIMOX-based process has been developed to fabricate vertically integrated microdisk resonator structures in silicon. These vertically integrated structures are realized through a monolithic fabrication process that is considerably simpler than the wafer bonding technique that was previously employed in fabricating vertically coupled devices on III-V substrates. Fabricated disk resonators, of radii 23 μm, exhibit resonances with a free spectral range of 5.4 nm and a Q value of 10 300.

The authors would like to thank Koichiro Kishima for his assistance. This work was performed under the CS-WDM program funded by the MTO office of DARPA. The authors would like to thank Dr. Jag Shah of DARPA for his support.

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