Add-drop filters utilizing vertically coupled microdisk resonators in silicon

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Add-drop filters, based on vertically coupled microdisk resonators, have been realized in silicon, using a modified separation by implantation of oxygen process. Buried rib waveguides in the bottom-layer silicon, of a two-layer structure, are coupled to microdisk resonators in the top-layer silicon through a silicon dioxide layer formed by oxygen implantation. The radii of the microdisk structures were varied suitably to obtain resonators with slightly shifted resonance wavelengths. The average adjacent channel crosstalk suppression of these filters exhibits an upper limit of 12.11 dB and a lower limit of 6.2 dB over the wavelength band under consideration. © *2005 American Institute of Physics*. [DOI: 10.1063/1.1873064]

Optical microcavities are versatile devices, with applications ranging from add-drop wavelength division multiplexers and optical filters to microdisk lasers. Fabrication of vertically coupled microring/microdisk resonator structures has received considerable attention in recent years.[1–5] Vertical integration allows for the fabrication of densely integrated three-dimensional (3-D) optical structures, enhancing the functionality of the optical chip. Apart from the inherent advantage of achieving densely integrated 3-D optical structures, vertical integration offers the prospect of precise control of coupling coefficient in vertically coupled devices. 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.

Silicon-on-insulator (SOI) material system, with its high index contrast (Δn) of ~2 between Si and SiO_2, provides an excellent platform for the fabrication of a variety of nanophotonic structures, with the prospect of full integration of electronic and optical devices on the same substrate.[6] We have previously reported the fabrication of low loss waveguides and vertically coupled microdisk resonators on SOI substrates using a modified process of separation by implantation of oxygen (SIMOX 3-D sculpting).[7,8] This letter reports a realization of add-drop multiplexers based on vertically coupled microdisk resonators in silicon, using the technique of SIMOX 3-D sculpting. It is worth mentioning here that these vertically integrated structures are fabricated through a monolithic process that is completely compatible with complementary metal-oxide semiconductor processing techniques.

The process of SIMOX 3-D sculpting has been discussed in detail elsewhere.[7,8] Briefly, the method involves the implantation of oxygen ions into an SOI substrate patterned with thermal oxide to create buried rib waveguides. After the implantation, and subsequent high-temperature anneal to cure the implantation damage, microdisk structures are defined on the top layer using conventional lithography and etching process. In this work, microdisk structures were defined on the top silicon layer by thermal oxidation, using a patterned silicon nitride layer as the mask for the oxidation process. These microdisk resonators on the top silicon layer are coupled vertically to the buried waveguides in the bottom silicon layer through the oxide layer formed after the oxygen implantation. Figure 2 shows a cross-sectional schematic of the coupling region between the buried rib waveguide, and the region of the microdisk resonator immediately on top of the buried rib waveguide. These buried waveguides act as bus waveguides to the microdisk that is fabricated on the top silicon layer. In this case, the SOI substrate was implanted at 150 KeV, with an oxygen ion dose of $5\times10^{17}/cm^2$. The offset (dx in Fig. 2) between the edge of the buried waveguide and the edge of the microdisk resonator is an additional design parameter that may be used to engineer the coupling between the disk and the waveguide.

Figure 3 shows the scanning electron micrograph (SEM) photographs of the microdisk resonator on the top layer 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 SEM photographs that clearly illustrate the structure of the device. Figure 4 shows the top view of a 1×3 drop filter fabricated using this process. Disks of radii 20, 20.5, and 21 μm were used to obtain resonators with slightly shifted resonance wavelengths.

Figure 5 shows the experimental set up used to characterize the fabricated add-drop filters. Unpolarized light from an amplified spontaneous emission (ASE) source was passed through an in-line fiber polarizer (General Photonics, extinction ratio 40 dB) and a polarization controller (General Photonics, extinction ratio 30 dB), that can rotate the state of

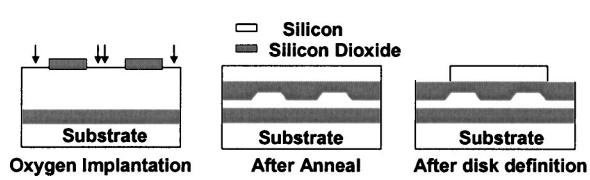

FIG. 1. Process flow for the SIMOX fabrication of microdisk structures (cross-sectional view).

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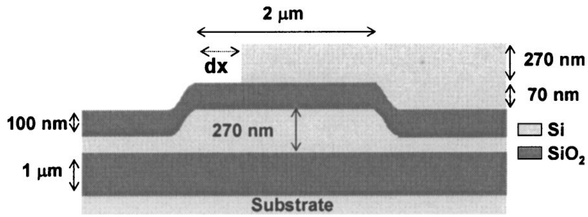

FIG. 2. Cross-sectional schematic depicting the coupling region between a buried waveguide and a microdisk resonator.

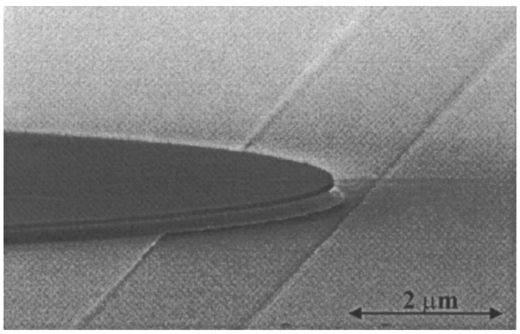

FIG. 3. SEM picture of the fabricated microdisk resonators on the top silicon layer with bus waveguides underneath.

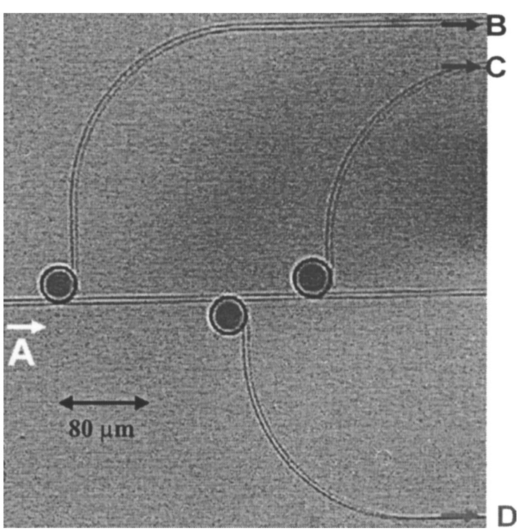

FIG. 4. Top view of the fabricated 1×3 add-drop filter.

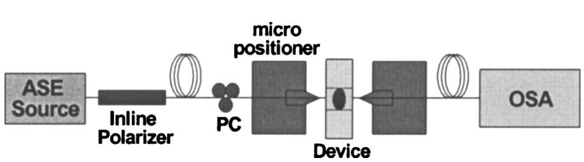

FIG. 5. Experimental setup used to characterize the add-drop filter.

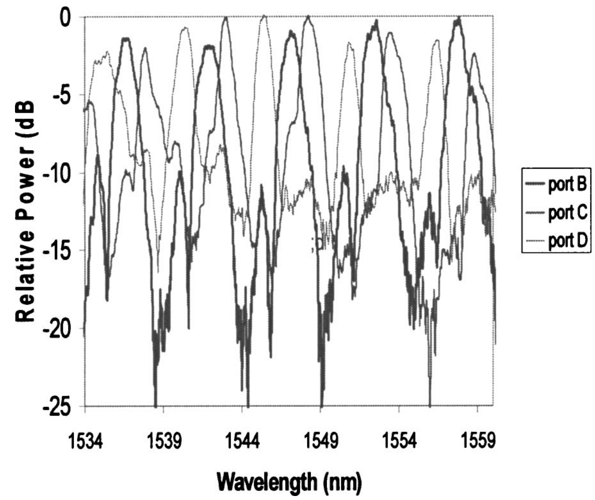

FIG. 6. Filter characteristics of the fabricated add-drop filter.

polarization of the light to any desired state. This polarized light was then coupled into the bus waveguides using a tapered fiber that has a spot diameter of 2 μm. The light output from the drop ports of the filter was collected using a tapered fiber, similar to the one used at the input. The fiber-to-fiber insertion loss of this setup was found to be ~30 dB. 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 as 1 pW.

Figure 6 shows the drop port responses of the filters, characterized by launching optical power at port A and observing the drop port optical spectra at ports B, C, and D. The spectrum displayed in Fig. 6 is corrected for the spectral shape of the ASE source. Fabricated disks show a free spectral range of around 5 nm. The adjacent channel wavelength separation between port B and port C is approximately 1.0 nm, whereas that of port B and port D is around 1.5 nm. The average value of adjacent channel crosstalk suppression, over the wavelength band of 1534–1560 nm, was found to be 12.1 dB for channels dropped at port D. At ports B and C these values were found to be 8.3 and 6.2 dB respectively. The device characteristics may further be improved by optimizing the processing conditions, and also using multistage microdisk resonators.

In conclusion, SIMOX 3-D sculpting process has been utilized to fabricate 1×3 add-drop filters on silicon. These filters utilize monolithically integrated microdisk resonators that are vertically coupled to the bus waveguides, through a buried oxide layer that is formed through the SIMOX process. Disks of radii 20, 20.5, and 21 μm were used to obtain resonators with slightly shifted resonance wavelengths. These disks show a free spectral range of ~5 nm. The average adjacent channel crosstalk suppression exhibits an upper limit of 12.1 dB and a lower limit of 6.2 dB over the wavelength band under consideration.

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