Silicon-on-Insulator Spectral Filter With CMOS Technology

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Abstract—We give an overview of recent progress in passive spectral filters and demultiplexers based on silicon-on-insulator pho- tonic wire waveguides: ring resonators, interferometers, arrayed waveguide gratings, and echelle diffraction gratings, all benefit from the high-index contrast possible with silicon photonics. We show how the current generation of devices has improved crosstalk levels, insertion loss, and uniformity due to an improved fabrica tion process based on 193 nm lithography.

Index Terms—Arrayed waveguide grating (AWG), echelle grat ing, nanophotonics, photonic wire, planar concave grating (PCG), ring resonator, silicon-on-insulator (SOI), silicon photonics.

I. INTRODUCTION

SILICON photonics has become one of the focus technology platforms for photonic integration in the last ten years. This can be mainly attributed to the combination of a very high-index contrast (and thus strong miniaturization) and the compatibility with CMOS fabrication technology [1], which allows the leverage of existing investments in electronics fabrication facilities. As we will discuss extensively in this paper, silicon passive waveguide technology has been steadily improving in terms of performance, uniformity, and reproducibility [2]–[4]. In addition, over the past years, there have been many demonstrations of integrated active devices, including modulators [5], Germanium-based photo detectors, and even III–V integrated sources and detectors.

The essential components we will discuss here are, different types of wavelength filters or spectral filters. With such filters, one can separate a broad spectrum into wavelength channels.This is essential for wavelength division multiplexing (WDM) communications, but it can find also important applications in sensing or spectroscopy. Silicon photonic wires confine light in a submicrometer waveguide core, enabling sharp bends, and thus, compact components. Compared to silica waveguide technologies or even many III–V semiconductor waveguides, the reduction in chip real estate for a given function is reduced with several orders of magnitude. Put differently, silicon photonics can integrate more components on the same chip area [1]. The high index and sharp bends also reduce the footprint of many wavelength filtering components, such as ring resonators or wavelength demultiplexers based on arrayed waveguide gratings AWGs) or planar echelle diffraction gratings.

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In addition, we have standardized on the use of two different etch layers to incorporate waveguide structures with both a high- and a low-lateral-refractive index contrast. The shallow etch is also used to define diffractive gratings, which are used for coupling light in to and out of the chip. We discuss basic photonic wire waveguides for on-chip interconnections, and the implication for spectral filters. The obvious performance metric here is the waveguide loss, but also some essential components, such as low-loss crossing and splitters are being discussed.

We take a quick look beyond the performance of a single device and into the reproducibility of device functionality from wafer to wafer, as well as uniformity within a wafer. This is essential for the filter components discussed here, as the optical length of delay lines must be controlled to a very high accuracy. We will show that IMEC's advanced CMOS technology is capable of supporting very stable processes for nanophotonic devices with linewidth uniformities down to a few nanometers. While this might seem much for wavelength selective components, this is a remarkable technological feat on an industrial platform used to tolerances of 10% (5% for the more recent deep submicrometer nodes). Also, the spread in CDs is sufficiently low to enable low-power tuning of the optical length of delay lines using thermal or carrier-based effects.

II. SPECTRAL FILTERING

A. Principles

Spectral filters (wavelength filters) are used for functions such as multiplexing many frequency channels into one waveguide, selecting one or multiple channels from an incoming bundle, equalizing channel powers, and dispersion compensation. Linear wavelength filters work by interference of multiple light paths, which experience a phase delay with respect to each other that is usually a multiple of a certain unit delay. The interfering paths can be spatially separated waveguides, giving a feed forward mechanism, or self-interfering paths in a resonant optical structure, giving a feedback mechanism. Multimode interference in a single (waveguide) structure is also a possible approach. Feed forward and feedback filter stages can be combined to yield more complex devices with a larger degree of freedom in design. Note that the properties of feedback and feed forward filter stages are very different, for instance with respect to group delay. Only with suitable feed forward filters, it is possible to achieve linear phase behavior (and then only if they are designed for that purpose).

The choice for a filter architecture depends very much on the application, which can traditionally be found in optical communications, but is now being used increasingly for spectral sensors or spectroscopy. In some cases, a single large demultiplexing device, such as an AWG may be ideal, while in other cases, for instance, when much more fine-grained control is needed, multistage filters are necessary.

III. FABRICATION AND CHARACTERIZATION

A. Fabrication With CMOS Technology

We fabricate our devices using industrial CMOS tools suitable for 130 and 90 nm transistors. This includes the same optical lithography as used for the fabrication of CMOS electronics. In contrast, with most research groups in silicon photonics, we make use of optical projection lithography instead of e-beam writing. Originally, we used 248 nm deep UV lithography for the photonic circuit definition, but recently we have switched to the higher resolution of 193 nm lithography. The waveguides are made in SOI, where a 220-nm-thin silicon layer with refractive index n = 3.45 acts as a waveguide layer, separated from the silicon substrate by a 2 µm buried oxide cladding layer (n = 1.45).

B. Deep and Shallow Etch

Photonic wires, with their large index contrast, enable sharp bends and compact interconnects. However, in some cases, a lower index contrast is desirable. This can be achieved by using a shallow etch, which results in an effective lateral index contrast of 2.8 to 2.5. To combine these low-contrast waveguides with photonic wires, we use two etch layers. First, shallow-etch regions (70 nm etch depth) are defined, followed by the deeply etched waveguide trenches. This is shown in Fig. 3. With this dual index contrast, we can make very compact devices without some of the penalties that come with the high-contrast photonic wires. Overlay alignment accuracy between the two etch layers is better than 20 nm, due to the wafer-scale alignment functions in the lithography steppers. To couple from a photonic wire with a 450 nm width to a low-contrast rib, we use the transition in Fig. 4. The deep-etch waveguide is flared out over a length of a few micrometers. Inside this deep-etch taper, we etch the shallow waveguide. As the deep taper expands, the shallow waveguide will take over the confinement of the light.

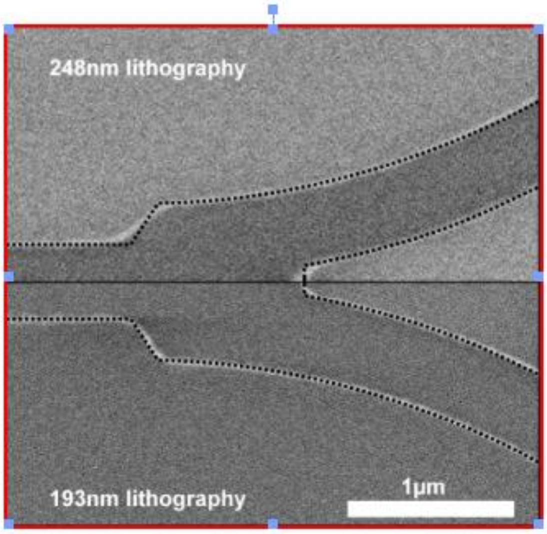

Fig. 2. Improvement in fabrication fidelity from 248 nm lithography to 193 nm lithography.

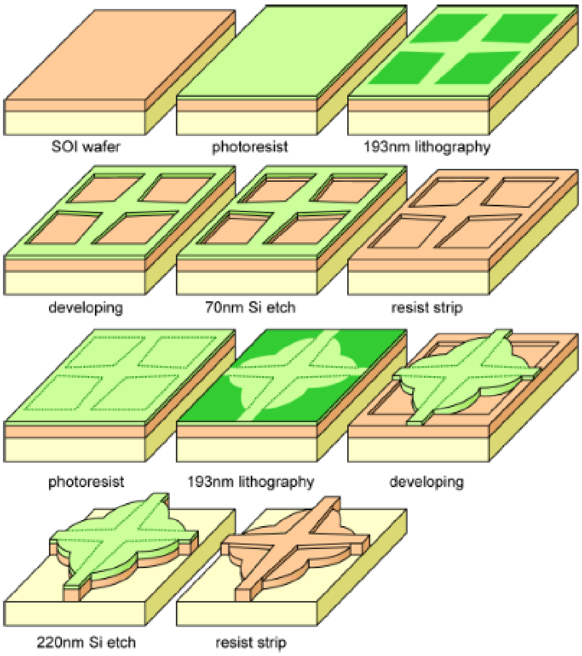

Fig. 3. Fabrication process for passive silicon nanophotonic waveguide components, illustrated with the waveguide crossing in Fig. 7. Two etch layers are used. First, as shallow-etch layer is patterned, which contains diffraction grating couplers and low-contrast rib waveguides. After that, the deep-etched regions, such as the waveguide trenches, are defined.

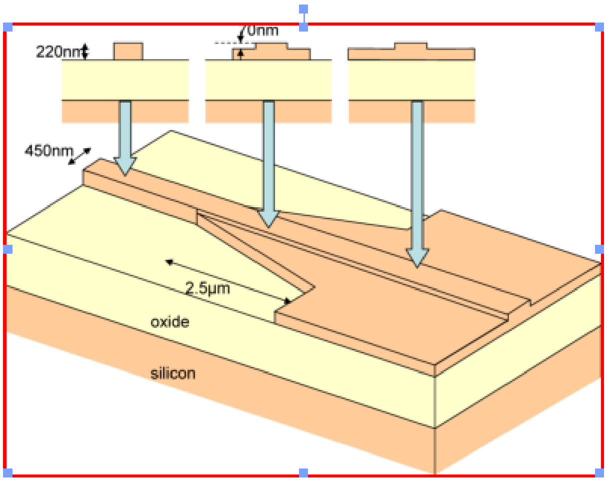

Fig. 4. Transition between a photonic wire and a lower contrast rib waveguide.

VII. CONCLUSION

We have discussed recent progress on spectral filters in SOI nano photonic waveguides, fabricated with advanced CMOS tools. Due to improved processing, using 193 nm lithography compared to 248 nm lithography [1],the performance of the devices has significantly improved compared to previous device generations. The new process results in better pat- tern fidelity, higher efficiencies, lower insertion losses, and very good uniformity and reproducibility. Waveguide losses are below 3 dB/cm (from 7 dB/cm) with low bend losses. Using the combination of a deep and shallow etch, we managed to make standard building blocks like crossings and splitters with an ex- cess loss of about 0.15 dB. We have shown ring resonators with good drop efficiency and quality factor of about 15 000, well- balanced MZ filters, and demultiplexers with insertion losses as low as 1.1 and −25 dB crosstalk. Especially, these wavelength filters will benefit most from the improved processing, as they are exceptionally prone to imperfections.

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