Fabrication of Uniform Photonic Devices Using 193nm Optical Lithography in Silicon-on-Insulator

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Abstract: *We report sub-nanometer linewidth control in high index contrast photonic devices using CMOS fabrication tools. A linewidth uniformity of 20pm and 0.1nm is achieved over a distance scale of 25μm and 10,000μm respectively. Over a 200mm wafer, we have achieved linewidth uniformity of 99.55% for a 450nm photonic wire.*

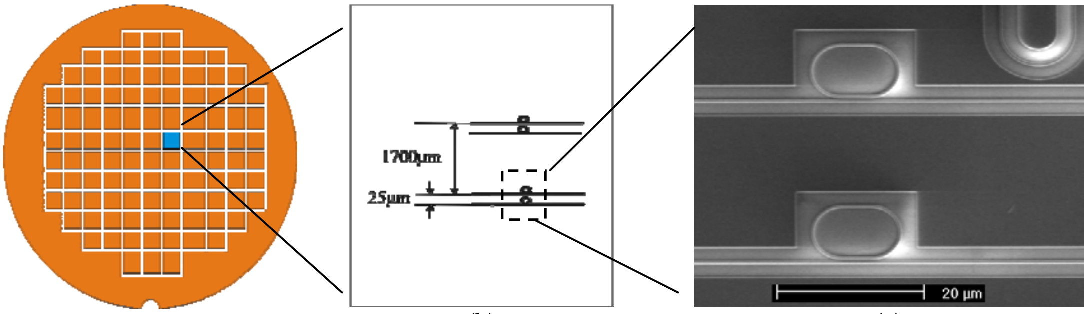
Introduction

High index contrast material technology is an attractive platform for making compact and high density photonic integrated circuits[1]. However, the spectral characteristics of these high index contrast devices, especially SOI based circuits, are very sensitive to very small dimensional variations. This does not only hold for circuits as a whole but also for parts of devices, such as an individual ring in a multi-ring demultiplexer [2]. Making identical photonic circuits or devices is a technological challenge in high-index contrast systems. Each step in the fabrication process can give rise to dimensional variations. Starting from mask fabrication till device measurement small variations in dimensions and material properties can induce a change in the spectral response of the device. The device dimensions - width and layer thickness - have to be controlled in the order of few nanometers (or even below 1nm), which requires a high resolution fabrication process. Fortunately, advanced CMOS fabrication processes allows for such high resolution and stable fabrication process.

In this paper, we present our recent results on device uniformity achieved using 193nm optical lithography and dry etching. All the processes were carried out using 200mm CMOS high volume manufacturing tools. Over a 200mm wafer, we have achieved a linewidth uniformity of 99.55% and 99.44% after optical lithography and dry etching respectively, for isolated lines. This high uniformity encouraged us to fabricate wavelength selective devices such as ring resonators and mach-zehnder interferometers. For these devices, we obtained a fabrication accuracy better than 20pm for short range device-to-device separations (25μm) and 0.1nm for long range device-to-device separations (10,000μm).

Design and fabrication

To test the uniformity within a die and between dies, identical wavelength selective components were arranged in a particular fashion (Fig. 1a). We use all-pass racetrack ring resonators and 1X1 mach-zehnder interferometers (MZI) as wavelength selective test devices for characterizing the device uniformity over short (25μm) and long distance range (1700μm). Each device was repeated 4 times in pairs of 2 (twins). The racetrack ring resonators were designed with a wire width of 450nm, coupling gap of 180nm, coupling length of 4μm and a ring radius of 4μm. The MZI's were designed with a delay length of 50μm in one of the arms.



(a) (b) (c)

Fig. 1 (a) Die layout in a 200mm wafer , (b) Device layout in a die and (c) SEM picture of the ring pair

A 200mm SOI wafer was patterned with the mask containing the test devices described above (Fig. 1a). The fabrication was done in a CMOS pilot line at IMEC, Leuven, Belgium. We used 193nm optical lithography (ASML/1100) and dry etching to define our circuits. For comparison, we have also used 248nm optical lithography [3] and etching to compare the process with our new 193nm lithography process [4]. Fig.1b depicts one of the fabricated pairs of ring resonators. During the fabrication process the linewidths were measured at two stages, first, the resist linewidth after optical lithography and then the silicon wire width at the end of the fabrication process. Accurate linewidths were measured using critical dimension scanning electron microscope (CD-SEM). The linewidth measurement was done at 175 locations in a 200mm wafer. For a 450nm photonic wire, a standard deviation (1σ) of 2nm and 2.6nm was obtained after optical lithography and etching respectively. Table 1 summarizes the linewidth measurements statistics. A 15nm increase in the mean linewidth value after etch is due to the sloped sidewalls obtained after etching, which increase the photonic wire linewidth measured from the top. There is also a slight increase in the standard deviation after etch, which is associated with a non-uniform plasma distribution over the wafer, which subsequently increases the linewidth non-uniformity.

Table 1

Linewidth statistics after 193nm optical lithography and dry etch

Target linewidth = 450nm

	After Lithography	After Etch
Mean linewidth (nm)	450.92	464.77
Intra wafer stand. deviation (nm)	2.01	2.59
Intra wafer range (nm)	5.50	7.50
Intra wafer stand. deviation (%)	0.45	0.56
Intra wafer range (%)	1.22	1.61

Device characterization

The fabricated devices were optically characterized by coupling in TE polarized light from a broadband light source and measuring the output from the devices through a spectrum analyzer with a resolution of 0.12nm. Grating fiber couplers [5] were used for in and out coupling of light. The measurement spectrum was limited to the 1550nm telecom wavelength range (1520nm-1600nm). The spectral response of the ring resonators and MZI's was obtained to analyze intra (within) die and die-to-die uniformity.

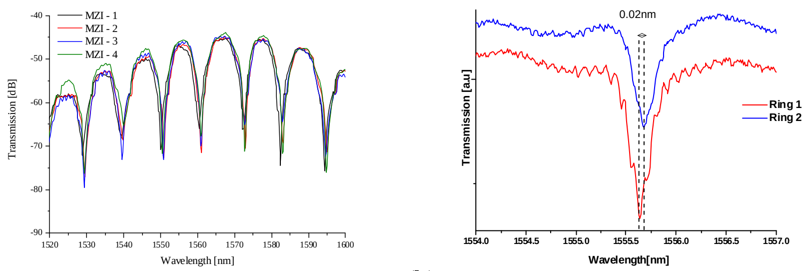
Intra Die Uniformity

Each die contains two pairs of ring resonators and MZI's as shown in Fig.1. Fig 2a shows the spectral response of four MZI's within a die, which were separated by 25µm (MZI-1,2 and MZI-3,4) and 1700µm (MZI-1,3 and MZI-2,4). Similarly, ring resonators were characterized (Fig. 2b). The measurements are summarized in Table 2. It can be clearly seen from Table 2 that the wavelength shift increases with an increase in the distance between the devices. This shift is more apparent when using 248nm lithography. Even though we used the same mask for 193nm and 248nm illumination, the linewidth variation using 248nm lithography is much higher than for 193nm lithography. These measurements clearly demonstrate the need for high resolution optical lithography for fabricating photonic devices.

From the measurements, we observed that the wavelength shift in the short distance range (25µm) ring resonator was below the resolution of our spectrum analyzer (0.12nm). Therefore, a tunable laser was used to characterize the resonance wavelength shift. With a sampling period of 10pm, we observed a peak shift of 20pm. This indicates an average linewidth offset of 20pm between the two ring linewidths. Fig.2b depicts the spectral response of two closely placed ring resonators. This short range linewidth uniformity achieved is comparable with matched ring resonators fabricated in SiN using e-beam lithography [2].

Table 2
Within Die/Chip device uniformity

Distance between the devices (Within Die)	Average resonance wavelength shift obtained using 193nm litho		Average resonance wavelength shift obtained using 248nm litho	
	Ring resonator	MZI	Ring resonator	MZI
25µm	0.15nm	0.2nm	0.3nm	0.7nm
1700µm	0.55nm	0.6nm	7.8nm	7.3nm



(a) (b)

Fig. 2 (a) Spectral response of 4 MZI's within a die,
(b) Spectral response of two racetrack ring resonators which are 25µm apart.

Die-to-Die Uniformity

Die-to-die or chip-to-chip uniformity is the device uniformity between two normally identical chips within a wafer. Die-to-die uniformity falls under long distance scale uniformity, at least few 10's of millimeter. Thus device uniformity is more complex than within a die. There are various factors (lithography tool etch, resist thickness, Si layer thickness, etc) contributing to the device non-uniformity and discriminating the contribution requires a detailed study of the different factors.

Table 3 shows the summary for 3 dies of the die-to-die measurements on ring resonators and MZI's. The average wavelength shift was calculated from 12 ring resonators and 12 MZI's (Fig. 3). A wavelength shift as low as 0.1nm was observed for ring resonators on immediately adjacent dies and 1.5nm for the next farthest die. From these measurements, we observe a strong correlation of wavelength shift over each die (not shown here), which could be related to the mask or the lithography tool. More extensive experiments and analysis are necessary to draw further conclusions however.

Table 3

Die-to-Die device uniformity using 193nm optical lithography

Distance between the devices (Die-to-Die)	Average resonance wavelength shift obtained		Smallest resonance Wavelength shift obtained	
	Ring resonator	MZI	Ring resonator	MZI
10,000μm	1.3nm	1.08nm	0.1nm	~0nm
20,000μm	1.8nm	1.73nm	1.5nm	1nm

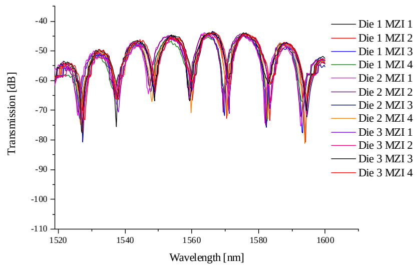


Fig.3 Spectral response of 12 MZI's from 3 different Dies

Conclusion

Highly uniform high index contrast silicon-on-insulator photonic devices were demonstrated. Device uniformity within die and die-to-die showed linewidth uniformity as low as 20pm and 1.5nm respectively. The results obtained are a good indication of the high resolution fabrication possible using CMOS fabrication tools. An extensive study on the non-uniformity is necessary to understand and improve the accuracy further.

Acknowledgments

We acknowledge the Smartmix Memphis and the ICT WADIMOS projects for supporting this work

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