Trimming of silicon ring resonator by electron beam induced compaction

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Abstract - *We present a technique to trim the resonance of silicon ring resonators. The cladding oxide is compacted by electron beam bombardment, causing strain in the silicon lattice, which leads to a 5 nm resonance shift.*

Introduction

Silicon-on-insulator (SOI) is gaining interest as preferable material system for future ultra-compact integrated photonic components. The main advantages of this material system are firstly the high refractive index contrast between silicon (core) and oxide or air (cladding) enabling small bend radii and dense integration, and secondly mature fabrication facilities thanks to the electronics industry. One of the applications aimed at by the telecom industry is optical filtering for wavelength (de)multiplexing. SOI is the ideal platform to make these filters compact and low-cost. Several geometries, such as ring resonators [1] and photonic band gap materials [2] have good filtering characteristics. However, most of the demonstrated filters were fabricated with electron beam lithography, which is a serial fabrication technique and therefore unattractive for mass fabrication. In previous work we have demonstrated that these filters can also be fabricated in a parallel way, with 248 nm or 193 nm Deep-UV lithography (DUV) in a standard Complementary Metal Oxide Semiconductor (CMOS) facility [3]. However, variations of the critical dimensions of devices fabricated by optical lithography are inevitable. These variations can be caused by wafer non-uniformity, by e.g. varying layer thicknesses on wafer edges, or by non-uniformity within one chip, mainly caused by lithography imperfections near mask edges. A way to assess critical dimension variations in a photonic circuit is to evaluate the resonance wavelength shift of identically designed ring resonators, dispersed over a wafer. These resonators are fabricated with Q-factors of about 10^4 [1], or a 3 dB bandwidth of 0.15 nm. In practice the resonance wavelength shifts exceed 1 nm, which is unacceptable for many applications. The most common solution for this is active thermal tuning [4], however, when many resonators have to be integrated on a single chip, this would lead to high power consumption and important device complexity. Another approach to circumvent these process variations is trimming of the devices after fabrication. In this paper we present a technique to locally and independently trim the resonances of ring resonators on a silicon chip. This allows for complete compensation of resonance wavelength variations on silicon photonic integrated components.

Experiment

The resonance wavelength of a ring resonator is trimmed by changing the optical path length of the resonator, in our case by varying the effective index of the guided mode and

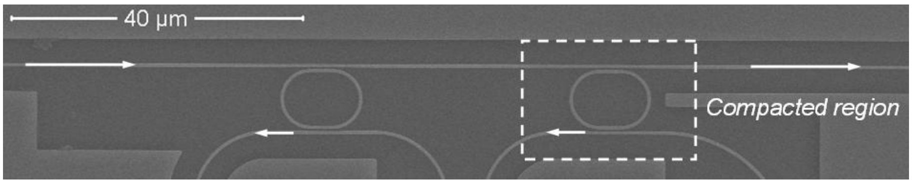

Figure 1: Overview of the experiment: the right ring is trimmed by electron beam compaction; the left one is kept original as a reference to exclude temperature or ambient variations.

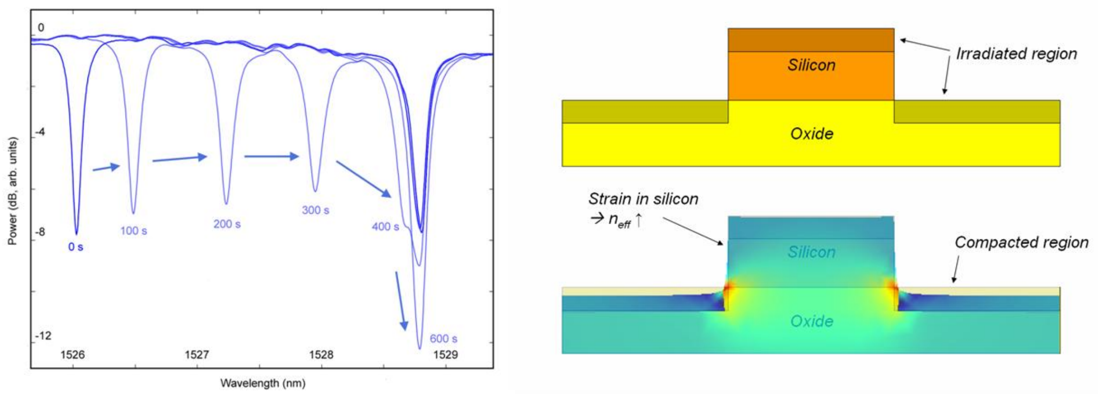

Figure 2: Left: The resonance wavelength of a ring is red shifted to equate that of the reference ring. One can notice a slight decrease of the Q factor. Right: Cross-section of the 220 nm thick silicon ring resonator. The 2 keV electrons penetrate 70 nm into silicon and oxide, and lead to volume compaction only in the oxide. This effect generates a tensile strain in the silicon, parallel to the substrate. The effect of silicon strain dominates the refractive index change. In the bottom drawing the first principal strain obtained from a finite element simulation was overlaid.

not the length of the ring. An increase in effective index causes a red shift of the resonance wavelength. This was demonstrated in several (low to medium index contrast) material systems such as silica glass [5] and SiN/SiON [6]. In SOI, the preferable material system for future industrial deployment, the core material is silicon, which can not be compacted by either UV or electrons. Only the SiO_2 cladding is susceptible to compaction. Due to the imaging capabilities and the ease to precisely control the irradiation dose and energy we have used an electron beam (from an FEI Nova 600 scanning ion/electron microscope) to compact the SiO_2 cladding layer. The resonance frequency of silicon ring resonators is extremely sensitive to changes of temperature and of the surrounding medium; rings are therefore attractive as sensors. However, in this experiment we want to exclude all external factors and investigate the resonance shifts caused only by electron beam irradiation. Therefore we have fabricated a sample with two rings, with different resonance wavelengths, serially connected to the same waveguide, as depicted in Figure 1. Only one of these rings is irradiated by imaging it with a scanning electron beam. The transmission spectrum features two superimposed ring spectra. By evaluating only relative peak shifts between the two ring spectra the external influences are excluded.
The experiment was performed in situ, inside the vacuum chamber of a scanning elec-

tron microscope, by providing it with vacuum fiber feedthroughs. The optical input and output signals are transported by single mode fibers, glued (with UV-curable glue) in a near-vertical position above grating couplers. The optical circuit, with grating couplers, waveguides, tapering sections, and ring resonators, was fabricated by DUV lithography in a CMOS pilot line [3]. Light was generated by a super luminescent LED with center wavelength at 1530 nm and detected by a spectrum analyzer with a resolution of 60 pm. The graph in Figure 2 shows part of the experiment. The left transmission dip - belonging to the right ring from Figure 1 - is trimmed to equate the resonance of the other ring. In this graph a resonance wavelength red shift of about 3 nm is shown. This part of the experiment was performed with a 0.84 nA beam, by scanning it over the ring resonator for 400 s. Figure 2 shows a slight decrease of the Q factor. The original position of the resonance was around 1523.9 nm, so in the complete experiment a total resonance shift of 4.91 nm was obtained.

Discussion

Two distinct physical processes cause the effective index change of the mode in the silicon ring resonator, as depicted in Figure 2. The first is a larger refractive index of the oxide cladding due to volume compaction; the second is the stress this oxide compaction induces in the silicon lattice. In our experiment we have worked with 2 keV electrons, which have a penetration depth of about 70 nm in Si and SiO_2 (this was calculated with Monte Carlo simulations, and confirmed by [7]). The silicon ring is 220 nm thick, on top of a 2 μm oxide layer; therefore the electrons can not penetrate the silicon. The mode overlap with the compacted oxide is lower than 1.5%, as was calculated with a mode expansion tool. From [7, 8] we have estimated the maximum amount of refractive index change lower than 3% (i.e. for a compaction of about 10%), with a total irradiation dose of 2.8 x 10^{23} keV/cm^3 (the total dose in our experiment). This can not lead to more than 0.5 nm shift in resonance wavelength. We can thus conclude that the largest fraction of the observed resonance wavelength shift is caused by strain in the silicon lattice. Finite elements simulations were used to evaluate this effect, as is shown in Figure 2. The overlay picture illustrates the deformed mesh (with a scale factor of 2) and the first principal strain in the case of a 10% compacted oxide layer with a thickness of 70 nm. Since a complete study was beyond the scope of this work, we have chosen to estimate the influence of compaction induced stress on the effective index of the supported modes without detailed simulations of the optical mode profile in the strained lattice. We have therefore calculated the average silicon strain in the dominant direction: perpendicular to the waveguide propagation direction and in the plane of the substrate surface. The resonance wavelength shift was calculated by using only the p_{11} component of the silicon elasto-optical tensor. This shift is calculated for varying oxide compaction rates and for different compacted layer thicknesses. The results of this simulation support the fact that tensile strain in the silicon waveguide can account for the observed resonance wavelength shift of more than 5 nm. Although all experiments in this report were performed with an electron beam, they can in principle be repeated with UV since the penetration depth at wavelengths between 200 nm and 400 nm is sufficiently low to create compaction induced strain. Ring resonators in other semiconductor materials can be compacted in a similar way, as well as other kinds of cavities, such as photonic crystal cavities. It can be argued that this method is too slow for mass fabrication purposes. However, we believe that it can be accelerated by using higher beam currents. Furthermore, realistic shifts will not often exceed 1 nm. This makes that a typical trim will be performed in seconds. Specifically in combination with vertical grating couplers and in situ readout, this technique is suited for rapid and automatic trimming of devices before packaging and on wafer scale.

Conclusion

We report on the trimming of a silicon ring resonator by electron beam irradiation. The oxide cladding is subject to volume compaction, causing tensile strain in the silicon lattice. Both effects generate an increase in refractive index, generating a red shift in resonance wavelength. The dominant effect is the tensile strain in silicon. In our experiment we have measured a maximum resonance wavelength red shift of 5 nm, which would be sufficient to compensate for variations on wafer scale and on chip scale due to optical lithography imperfections.

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