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SPIE.

Event: SPIE OPTO, 2011, San Francisco, California, United States

Micro-cavities based on width modulated SOI waveguides

Stefan Meister^{*a}, Aws Al-Saadi^a, Bülent A. Franke^a, Shaimaa Mahdi^a, Mirosław Szczambura^a, Berndt Kuhlow^a, Ulrike Woggon^a, Lars Zimmermann^b, Harald H. Richter^b, David Stolarek^b, Sigurd K. Schrader^c, Hans J. Eichler^a

^aTechnische Univ. Berlin, Institut für Optik und Atomare Physik, ER1-1,
Str. des 17. Juni 135, 10623 Berlin, Germany;

^bInnovations for High Performance microelectronics (IHP) GmbH, Im Technologiepark 25,
15236 Frankfurt (Oder), Germany;

^cTechnische Fachhochschule Wildau, Institut für Plasma- und Lasertechnik, Bahnhofstr.
15745 Wildau, Germany

ABSTRACT

We have designed, fabricated and investigated one-dimensional (1D) micro-cavities in Silicon-on-Insulator (SOI) waveguides. The single mode waveguides are fabricated in a 220 nm silicon device layer. The 1D micro-cavities in Fabry-Perot structure consist of two Bragg-mirror regions formed by a sinusoidal modulation of the waveguide width. The mirror regions are separated by a sub-micron spacer.

The SOI photonic structures are produced in a CMOS environment using 248 nm DUV lithography. The waveguides as well as the width modulated mirror regions are designed using a single mask and are fabricated in a shallow trench process.

The transmission spectra of these width modulated micro-cavities with different mirror reflectivities and cavity lengths are investigated. Q-factors up to 855 could be observed at 1550 nm wavelength with low insertion loss of 1.9 dB.

The width modulated micro-cavities, including the mirror regions, have lengths of less than 20 microns and widths of maximum 450 nm. These small foot-print cavities act as band pass filters and can be used as resonators for laser or electro-optic modulation of light.

Keywords: silicon photonics, SOI waveguides, micro-cavity, micro-resonators, band pass filter, CMOS

1. INTRODUCTION

Silicon photonics, especially based on silicon-on-insulator (SOI) attracted great attention in the last years. With an intrinsic bandgap of 1.1 eV silicon is transparent at wavelengths typically used for optical communication transmission, i.e. 1270 nm – 1625 nm. In addition, the possibility to produce silicon photonics devices in a complementary metal oxide semiconductor (CMOS) environment offers an opportunity for very low-cost photonic solutions. Furthermore, the ability to integrate silicon photonic devices with electronic control functions opens a wide range of applications from telecommunications to chip-to-chip interconnects¹, on-chip communication as well as possible applications in emerging areas such as optical sensing and biomedical devices².

Ultrasmall cavities play an important role in photonic integrates circuits (PIC) by controlling light for trapping and emission of photons³, lasing⁴, switching, and optical filtering. Most popular structures are ring resonators⁵ and photonic crystal micro-cavities^{6,7}. One-dimensional (1D) micro-cavities have a very small footprint and are, therefore, well suited for highly dense packaging.

In this paper, the characteristics of 1D micro-cavities based on width modulated SOI waveguides are investigated, which are fabricated in a CMOS environment. The micro-cavities act as band pass filters. The filter design parameters, e.g. number of modulations, cavity length, etc., are systematically changed to investigate the limits of such 1D micro-cavities.

*smeister@physik.tu-berlin.de; phone: +49-30-31426227; fax: +49-30-31426888

2. DESIGN OF THE MICRO-CAVITIES

The filters here are designed for the telecommunication wavelengths range around 1550 nm. The 1D micro-cavities in Fabry-Perot structure consist of two Bragg-mirror regions separated by a sub-micron spacer. The two mirror regions are formed by modulation of the waveguide width. In the design, the mirror regions are defined by pairs of so called half-holes on both sides of the waveguide. The centers of the holes are placed on the edges of the waveguides. Figure 1 shows the basic structure and parameters of the width modulated micro-cavities.

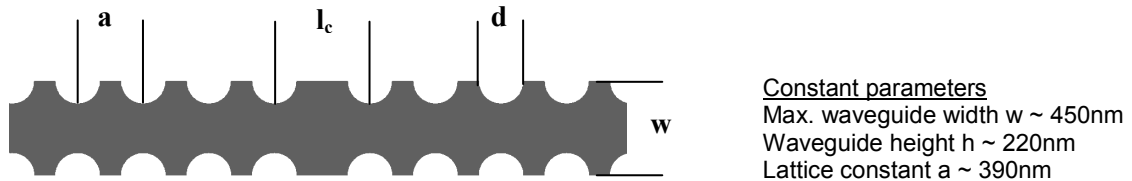


Figure 1. Basic design structure and parameters of the width modulated micro-cavities.

The lattice constant a and cavity length l_c are both measured from center to center between neighboring half-holes. The rectangular waveguides (also called nanowires) are fabricated in the 220 nm thick silicon device layer of the SOI substrate. Therefore, the waveguide height is fixed to $h = 220$ nm. The micro-cavities are written in singlemode waveguides of 450 nm width.

The fixed lattice constants $a = 390$ nm have been chosen for all mirrors, see figure 1. Different half-hole diameters between $d = 160$ nm and $d = 220$ nm were realized in the mask design. The micro-cavities were designed with two mirror regions of 10 or 20 half-holes pairs, e.g. 20+20 half-holes pairs. The half-hole diameter as well as the number of half-holes will change the mirror reflectivity and therefore the filter bandwidth. For the first order cavity filters, three different cavity lengths l_c were introduced, ranging from $l_c = 570$ nm to 600 nm in steps of 15 nm. The cavity length has an influence on the wavelength of the transmission peak.

3. FABRICATION OF WIDTH MODULATED MICRO-CAVITIES

The SOI photonic structures are produced in a $0.13\mu\text{m}$ SiGe BiCMOS environment at IHP GmbH, Frankfurt (Oder), Germany. The photonic devices were fabricated in 200 mm SOI wafers using a 248 nm DUV lithography. Waveguides as well as the width modulated micro-cavities are designed using a single mask and fabricated in a shallow trench process. The waveguides as well as the width modulated micro-cavities are etched completely down to the BOX layer, which has a thickness of $2\mu\text{m}$.

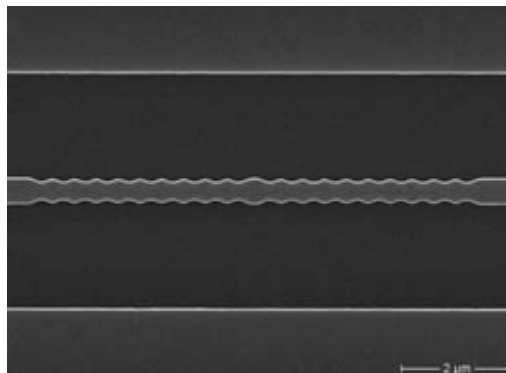


Figure 2. SEM image of a 1D width modulated micro-cavity with 10 designed half-hole pairs in each of the two mirror regions (10+10) and a sub-micron spacer in the center of the cavity.

Physically, the waveguides were formed by inserting two parallel running grooves into the Silicon surface, which distance to each other define the waveguide width. These lateral trenches are wide enough to prevent waveguide leakage into the surrounding intact top SOI areas.

The SEM image in figure 2 shows a top view of a 1D micro-cavity. The two width modulated mirror regions were designed with 10 half-holes each. Between the mirror regions is seen the slightly wider spacer. Also seen are the two etched trenches forming the waveguide. The higher magnification in figure 3 shows that the waveguide between the designed half-holes are rounded due to fabrication process leading to a sinusoidal modulation of the waveguide width. Also the sub-micron spacer in the center of the images is rounded. The designed half-hole diameters of the structure shown in figure 3a was 160 nm, which results in a slightly width modulated micro-cavity. The 220 nm designed half-hole diameters of the structure shown in figure 3b leads to a comparable strong modulation of the waveguide. In both cases, the modulation of the waveguide width is sinusoidal.

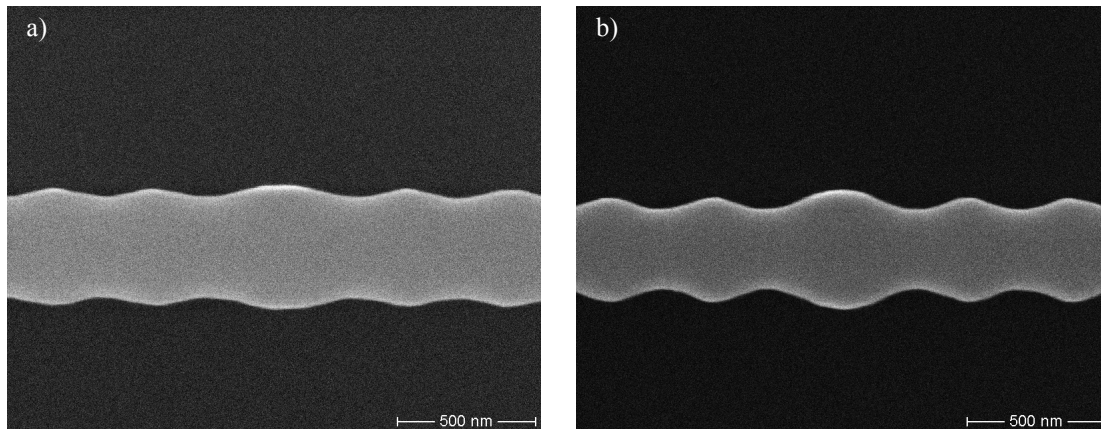


Figure 3. SEM images of the center part of width modulated micro-cavities, including the sub-micron spacer, etched in a SOI waveguides. a) The designed half-hole diameter was 160 nm. b) The designed half-hole diameter was 220 nm.

4. EXPERIMENTAL DETAILS FOR OPTICAL CHARACTERISATION

Figure 4a shows the experimental setup for optical characterization of the 1D width modulated micro-cavities. The samples to be tested were fixed on a specially constructed vacuum chuck with integrated temperature control on top of a translation stage. Coupled SLEDs, providing a broad spectral range of 1200 nm – 1700 nm, serve as white light (WL) sources for transmission measurements. The light was coupled into the SOI waveguides via a tapered optical fiber (OZ Optics), see figure 4b. The tapered fiber has a focal diameter of 2.5 μm and a working distance of 14 μm .

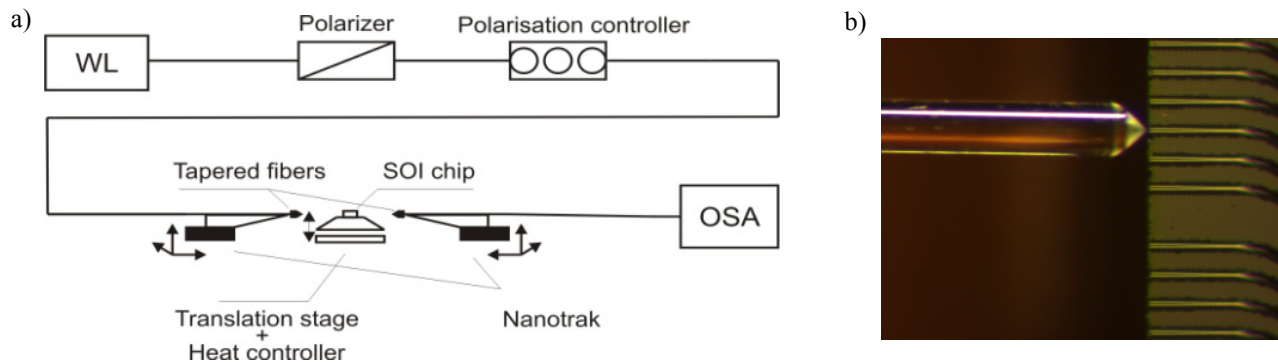


Figure 4. a) Experimental setup for optical characterization of the width modulated micro-cavities. b) Tapered fiber which couples the light in a SOI waveguide.

TE polarization (E-field along the wider waveguide side) is necessary to excite the cavity modes. In order to achieve TE polarization at the waveguide input, a fiber optical polarizer followed by a polarization controller⁸ was inserted. The output light of the SOI waveguide was collected by a second (identical) tapered fiber. Both tapered fibers were mounted on a piezo controlled translation stage (NanoMax TS3), respectively. The output light was measured by an Optical Spectrum Analyzer (OSA). A resolution bandwidth of 0.2 nm was selected in the measurements.

5. RESULTS AND DISCUSSION

As reference for the transmission measurements, dummy waveguides without micro-cavities were used, which had the same physical dimensions as the waveguides carrying the micro-cavities. Most of the induced losses can be assigned to coupling losses from mode mismatch between the fibers and the SOI waveguide.

The transmission of width modulated micro-cavities, formed by two identical Bragg-mirror regions are investigated in dependence on the number of the designed half-holes. Furthermore, the cavities are of first order, which means the cavity length l_c has the shortest possible length for a certain transmission peak wavelength. In a classical Fabry-Perot, this would correspond to an optical spacer thickness of $\lambda/2$, if λ is the center wavelength in the transmission band of the filter. Figure 5 shows the transmission spectrum of a width modulated micro-cavity filter with 10+10 designed half-holes, in a) logarithmic and b) linear scale, respectively. The diameter of the designed half-holes was $d = 180$ nm and the cavity length $l_c = 600$ nm.

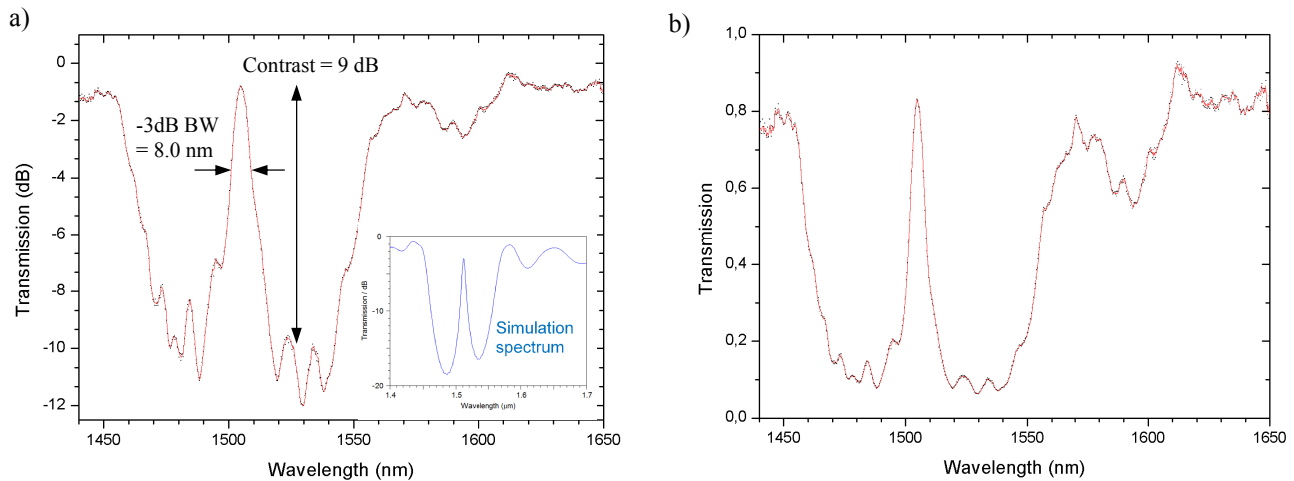


Figure 5. Transmission band of a width modulated micro-cavity filter with 10+10 designed half-holes a) Logarithmic scale, b) linear scale. The hole diameter was 200 nm and the cavity length was $l_c = 570$ nm.

The transmission spectrum of the micro-cavity exhibits a stop band from 1460 nm to 1550 nm with low transmission. Due to the relative low index contrast in the mirror regions, the width of the low transmission range is relative narrow. The transmission peak of the filter is located in the center of the stop band. The -3dB bandwidth of the transmission peak is 8.0 nm, which corresponds to a quality factor of $Q = 188$. The filter contrast is about 9 dB for wavelengths 10 nm off to the filter peak. The 0.8 dB insertion loss of the filter is very low.

The insertion in figure 5a shows a simulated spectrum of this filter structure. In the simulation, using a Finite-Difference-Time-Domain (FDTD) method, the chosen grid introduces virtual roughness to the sinusoidal width modulated waveguides, which lead to calculated scattering losses. Hence, the simulated filter losses are higher than the measured losses in the real waveguides.

If the number of designed half-holes in the mirrors is increased to 20, the reflectivity of the Bragg mirrors will be higher. The transmission spectrum of a 20+20 width modulated micro-cavity is shown in figure 6, in a) logarithmic and b) linear scale, respectively. The diameter of the designed half-holes was $d = 180$ nm and the cavity length $l_c = 600$ nm.

Due to the higher mirror reflectivity the -3dB bandwidth of this filter is narrowed to 1.8 nm, which corresponds to a quality factor of $Q = 855$. The filter contrast is increased to 13 dB for wavelengths 6 nm off the filter peak. The 1.9 dB insertion loss is low for such a filter.

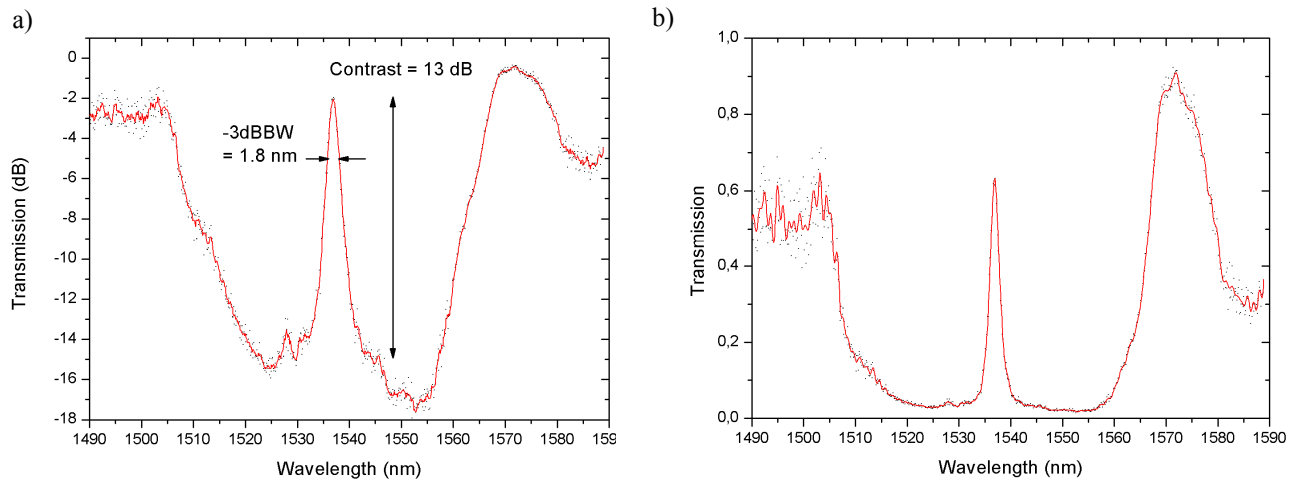


Figure 6. Transmission band of a width modulated micro-cavity filter with 20+20 designed half-holes a) Logarithmic scale, b) linear scale. The hole diameter was 180 nm and the cavity length was $l_c = 600$ nm.

By changing the cavity length l_c , in combination with the right choice of the lattice constant a , the peak wavelength of the filter can be tuned. For 1D photonic crystal micro-cavities⁹, the ratio between single order cavity length l_c and lattice constant a should be around $l_c/a = 1.5$. In accordance with this relation, the cavity length of the width modulated micro-cavities is designed around 585 nm for the chosen lattice constant of 390 nm. Figure 5 and 6 show that the transmission peaks with these parameters are located in the center of the low transmission region of the filters. This proves that the rule for 1D photonic crystal micro-cavities is also applicable for the width modulated micro-cavities.

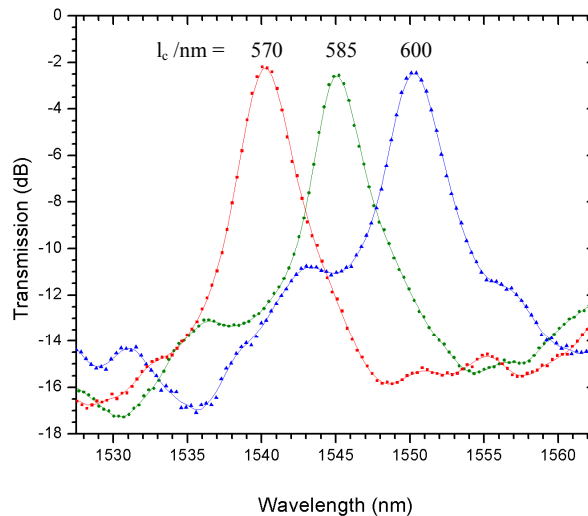


Figure 7. Transmission spectra of width modulated filters with three different cavity lengths $l_c = 570$ nm, 585 nm, and 600 nm. The designed half-hole diameters of the 20+20 micro-cavities were 180 nm.

Figure 7 shows transmission spectra of filters with different cavity lengths l_c . It is evident that an increasing cavity length will shift the filter peak to longer wavelengths. This behavior is shown for three cavity length $l_c = 570$ nm, 585 nm, and

600 nm. The obtained wavelength shift per cavity length yields nearly constant $\Delta\lambda/\Delta l_c = 0.33 \pm 0.05$ in the considered limited range of cavity lengths.

Furthermore, the center-wavelength of the transmission peak of the filters shifts if the designed half-hole diameter d_{hh} and therefore the modulation depth change. The wavelength shift was determined to be $\Delta\lambda/\Delta d_{hh} = -0.98 \pm 0.01$.

6. SUMMARY

Design, fabrication, and optical characterization of 1-D micro-cavities in SOI waveguides fabricated in a CMOS environment using a 248 nm DUV lithography have been presented. The Bragg-mirror regions of the micro-cavities are formed by a modulation of the waveguide width. It was shown that the waveguide between designed adjacent half-holes is rounded by the fabrication process leading to a sinusoidal modulation of the waveguide width. Also the sub-micron spacer in the center of the images is rounded.

The transmission peak of a width modulated micro-cavity with 20 modulations in each of the two mirror regions (20+20) and 180 nm designed half-hole diameter has a -3dB bandwidth of 1.8 nm, which corresponds to a quality factor of $Q = 855$. The filter contrast was 13 dB for wavelengths 6 nm off the filter peak. The determined insertion loss of the filter was only 1.9 dB.

ACKNOWLEDGEMENT

This work is supported by BMBF/VDI in the frame of project 13N9732.

We thank Christian Meuer from Institut für Festkörperphysik of TU Berlin for his support.

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