Functional Silicon Wire Waveguides

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Abstract: We will demonstrate recent progress in Silicon nanowire based devices such as AWG's and lattice filters and show their performance is rapidly reaching a level useful for practical applications. Next we will show how the functionality of the passive nanowires can be improved by different approaches including heterogeneous integration with InP-based materials and different overlays such as liquid crystal and colloidal nanocrystals.

1. Introduction

Silicon wire waveguides form a very interesting platform for fabricating extremely compact photonic integrated circuits (PIC). They are typically fabricated from an SOI-wafer consisting of a thin silicon layer (200-300nm) on top of a thick buried oxide layer (>1um), which shields the waveguide layer from the under laying silicon substrate. Depending on the width and the top cladding (air or SiO_2), the single mode width varies from 300nm to 600nm. Losses for such waveguides vary, depending on the quality of the waveguide fabrication process and the waveguide width, from 2dB/cm to 4dB/cm [1][3][4][5][6][7][8]. Recently also low loss waveguides fabricated from an amorphous Silicon layer deposited using a low temperature PECVD process where demonstrated [2].
Most research groups use an optimized ebeam-litho process for the definition of the waveguides. To overcome the slow ebeam writing process we developed a mask-based process using DUV-lithography, for which we made use of the CMOS research facilities of IMEC, Belgium. The structures are fabricated on 200mm silicon-on-insulator wafers with a silicon top layer of 220nm and a buried oxide of 1µm. The patterns were defined with 248nm deep UV lithography, and transferred into the silicon using ICP-RIE etching. The fabrication process is described in detail in [1].

2. Basic Waveguide Properties

Before designing more complex devices it is important to characterize and optimize the characteristics of basic components such as straight waveguides, bends, couplers and crossings. We demonstrated propagation losses as low as 2.4dB/cm for 550nm wide waveguides. Due to the high index contrast, silicon wire waveguides allow for an extremely short bend radius. We have characterized the loss using spiral waveguides with various bend radii, various length (up to 20mm) and a number of bends varying from 1 to 550.

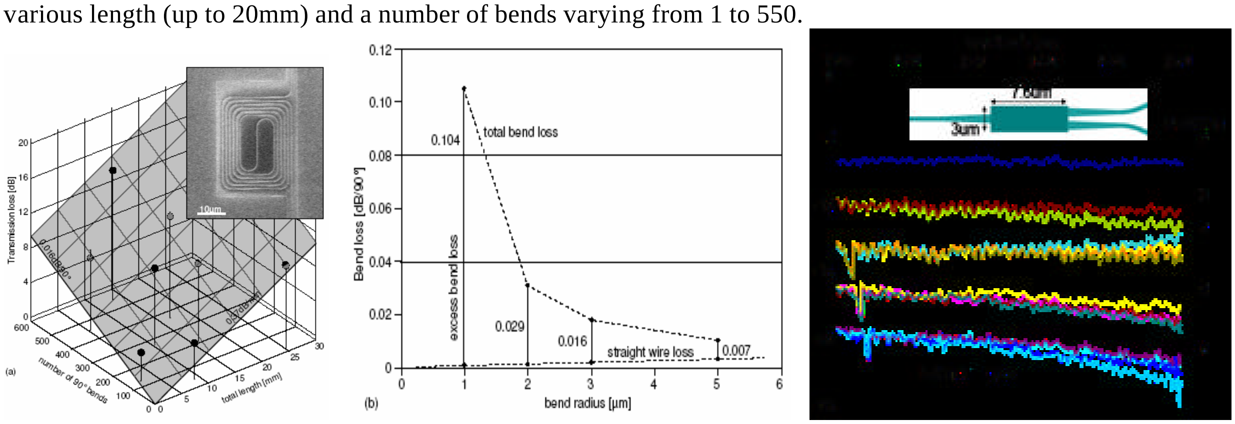

Fig. 1 a Transmission for different spiral waveguides with 3um bends. b) Bend loss as function of radius. c) Transmission as function of wavelength through increasing number of concatenated MMI-splitters.

In Fig. 1a we plotted the transmission for such a set of spirals with a 3um bend radius as a function of both the total waveguide length and the number of 90degree bends, which allows to extract both the propagation loss of straight waveguides and the excess loss per 90degree bend. The results are shown in Fig. 1b. Similar values for bend losses have been reported in literature [3], although measured on much fewer bends. Also 3D-FDTD simulations predict similar losses. To characterize the loss of compact MMI-splitters (3um x 7.6um) we measured the transmission through an increasing number of splitters concatenated in series. The results as function of wavelength are shown in Fig. 1c. The excess loss per splitter was smaller than 0.3dB.

3. Fiber-chip couplers

For an optical waveguide platform to be practically useful, efficient fiber-chip couplers are needed. These couplers should be easy to manufacture, show low coupling loss and broad band operation. The two most promising approaches described in literature today are based on the inverted taper or on a short grating. In the inverted taper approach the silicon wire waveguide is narrowed down and the optical mode is pushed upwards to a polymer or SiN waveguide integrated on top of the Silicon layer (Fig. 2a, left). Low loss coupling (<1dB) and broadband operation (>100nm) has been demonstrated [5][3]. The drawback is that coupling to standard single mode fiber remains difficult (typically lensed fibers or high NA-fibers are used) and that extremely narrow taper tips are required (80nm), which cannot be fabricated using standard 248nm DUV-lithography. The latter is overcome in a new approach we recently demonstrated [8] and which is illustrated in Fig. 2a, (right). A thin spacer layer is introduced between the polymer waveguide and the Silicon wire waveguide. This relaxes the requirements on the width of the taper tip: a width of 150nm is now sufficient to allow low loss coupling. We measured a coupling loss of 1.5dB.

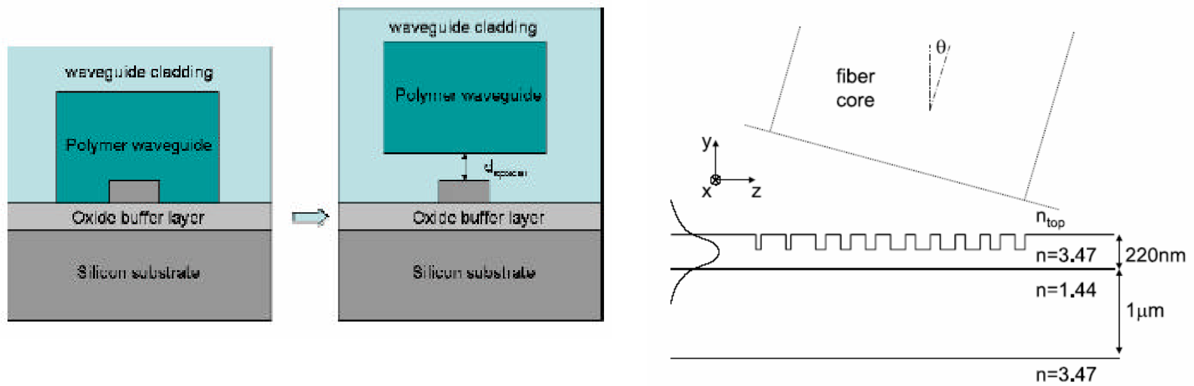

Fig. 2 a) Inverted taper fiber coupler. b) Grating based fiber coupler

Short grating couplers form an interesting alternative for efficient fiber-chip coupling [12]. A grating coupler matching the dimensions of a standard single mode fiber core (12um x 12um) is used to couple light from the silicon waveguide to a fiber placed under a slight angle on top of the grating. Due to the short grating length broadband operation (1dB width >40nm) is obtained. Measured coupling efficiency for uniform grating couplers is better than 30% and matches well theoretical predictions. By apodising the grating as illustrated in Fig. 2b, the profile of the field coupled out of the waveguide will better match the gaussian fiber mode and the efficiency can be increased to 60%. A further improvement (to >90%) can be obtained by integrating a DBR-mirror below the grating.

4. Arrayed Waveguide Gratings

Early Arrayed Waveguide Grating (AWG) demultiplexer devices fabricated using silicon wire waveguides showed high insertion losses (>8dB) and unacceptable crosstalk performance (-7dB). A series of improvements have led to a dramatically improved performance however. By introducing shallowly etched tapers in the star coupler the largest loss origin (reflection losses at the high-contrast star coupler) was overcome and total insertion loss was reduced to -2.2dB. By widening the waveguides, the effect of phase noise was reduced and crosstalk improved to -19dB. Results are shown in Fig. 3.

5. Heterogeneous integration with InP based components

We recently demonstrated a new approach for integrating III-V based optoelectronic devices with silicon nanowire circuits. In this approach III-V dies are bonded on top of the SOI-circuits. Following removal of their substrate these are then processed to functional devices. Fig. 4 shows a series of detectors integrated on top of grating couplers connected with a wavelength demultiplexer [9] and an electrically connected mikrodisk laser [13]

6. Conclusion

We have demonstrated that the silicon wire platform shows a performance which is rapidly reaching that of more established platforms based on InP, SiN or even SiO_2 waveguides. By integrating the waveguides with III-V devices, now also active devices are within reach.

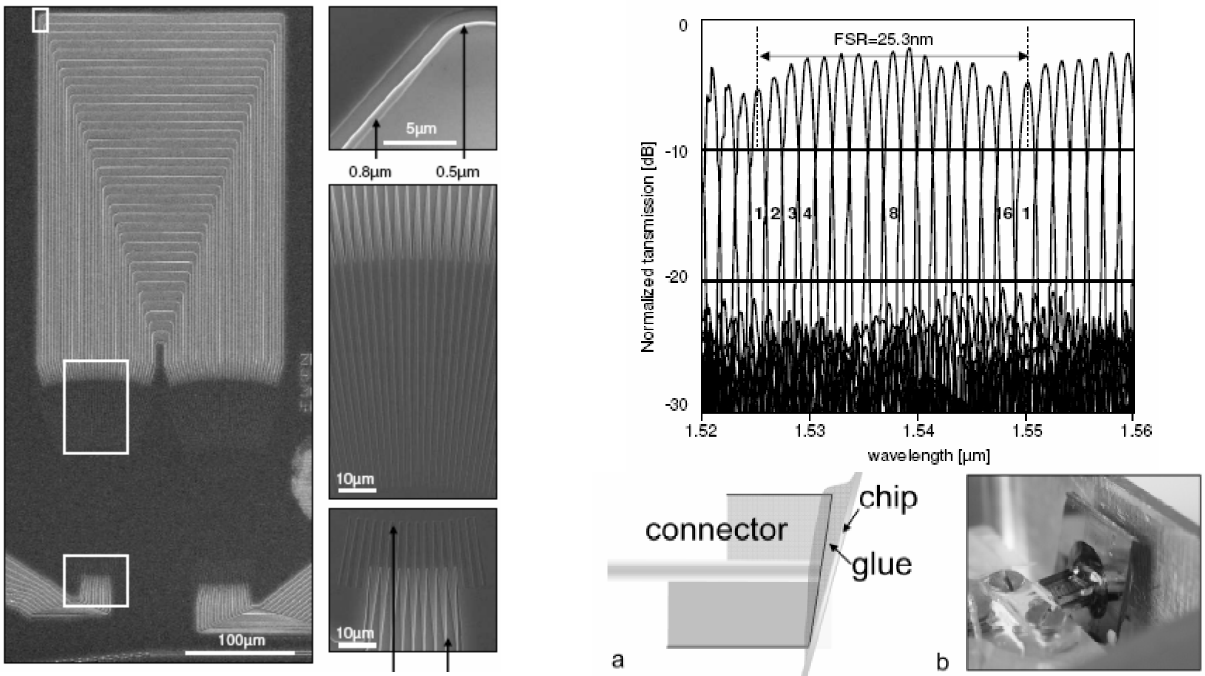

Fig. 3 a) SEM picture of SOI-based AWG device. b) Measured transmission. c) Packaged 4x4 router device

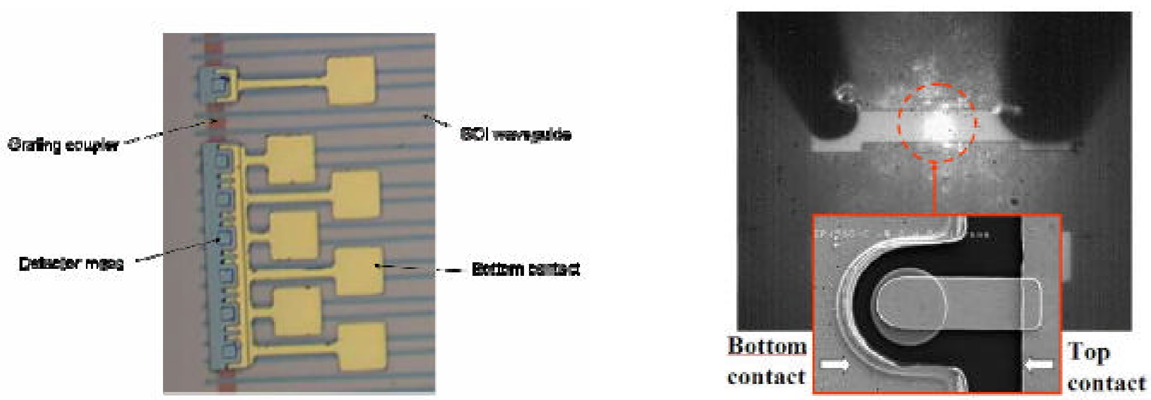

Fig. 4 a) Detectors integrated on Silicon wire waveguides. b) Electrically contacted mikrodisk laser

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