

# Silicon Based Double-layer 1x12 Multimode Interference Coupler for Three-dimensional Photonic Integration

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**Abstract**—We present a scheme for fabricating on-chip vertically integrated three-dimensional (3D) photonic integrated circuit (PIC). Double-layer 1x12 multimode interference (MMI) couplers with low excess loss and uniform outputs are fabricated on double-bonded silicon-on-insulator (SOI) wafer.

**Keywords**—Multimode Interference; Three-dimensional

## I. INTRODUCTION

Three-dimensional (3D) integration of multiple layers of silicon Photonic Integrated Circuits (PICs) can address the bottleneck of limited number of photonic components on single layer silicon PIC [1]. To date, deposited polysilicon has been used for its applicability in 3D photonic integration [2]. However, the lowest reported propagation loss for sub-micron size polysilicon single mode waveguides is 6.45dB/cm [3]. Waveguides with similar geometries in crystalline silicon show only ~1dB/cm propagation loss [4].

In this paper, we demonstrate a 3D photonic integration of self-aligned structures on two-layer crystalline silicon membranes using double-bonded silicon-on-insulator (SOI) wafers. Double-layer 1x12 Multimode Interference (MMI) couplers are fabricated for scheme demonstration. This scheme can be applied to other devices including waveguide arrays, MxN MMI couplers and arrayed waveguide gratings (AWGs) to significantly increase on-chip integrated photonic components count.

MMI couplers can be used as efficient on-chip beam splitter with optimized design techniques described in [5]. We choose the multimode waveguide width,  $W_{\text{MMI}}=60\mu\text{m}$  and the corresponding multimode waveguide length,  $L_{\text{MMI}}=664\mu\text{m}$ . The input and output access waveguide width,  $W_w=2.5\mu\text{m}$ , matches the mode size of the input/output lensed fiber. We fabricate two self-aligned 1x12 MMI couplers on two vertically

stacked crystalline silicon membranes using one lithography process followed by a single etching step. The schematic of self-aligned waveguide structure is shown in Fig. 1(a). The thickness of both silicon layers are  $h_1=h_2=1.3\mu\text{m}$ , and the thickness of two buried silicon oxide (BOX) layers are  $2.0\mu\text{m}$ .

## II. DEVICE FABRICATION

The double-bonded SOI wafers are fabricated using fusion bonding and etch-back [6]. The devices are patterned using electron beam lithography. A chromium lift-off process defines the hard etching mask. The pattern is then transferred to both silicon layers using one  $\text{SF}_6/\text{C}_4\text{F}_8/\text{Ar}$  based Deep Reactive-Ion-Etching (DRIE) step in Plasma-Therm's Versaline system. The DRIE process consists of ~1000 iterations of a two-step polymer deposition/etching cycle. At the end, the chromium mask is removed.

The fabricated MMI access waveguides are  $2.0\mu\text{m}$  and  $2.9\mu\text{m}$  wide on top and bottom layers, as shown in Fig. 1(b), which correspond to transverse electric (TE) fundamental mode effective refractive indices of 3.410 and 3.419, respectively. The undercut to the top silicon layer is due to the ~40 minutes etch time of the BOX layer [7]. We notice that due to the large thickness of the silicon layers, the effective index changes negligibly with variations in the waveguide width. Fig. 1(c) shows a microscope image of the overall double-layer MMI coupler.

## III. DEVICE CHARACTERIZATION

A six-axis automated aligner system with a 50nm precision in movement is used to couple TE polarized light at  $1.55\mu\text{m}$  from a polarization maintaining lensed fiber (PMF) with a  $2.5\mu\text{m}$  output mode diameter into the waveguide inputs. An IR CCD camera connected to a variable objective lens captures the top-down near field

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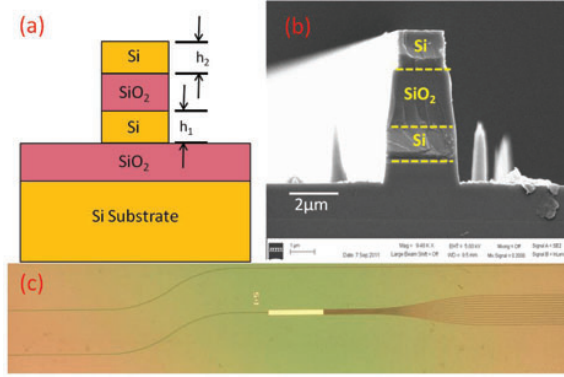


Figure 1. (a) A schematic of the self-aligned waveguide structure. (b) SEM image of MMI access waveguide cross-section. (c) Microscope image of double-layer MMI

images of the output facets. In order to visually resolve the 12 output spots, a waveguide fanout design is used to increase the separation of each adjacent channel to  $30\mu\text{m}$ . To better demonstrate the performance of the double-layer device using top-down IR images, we separate the outputs in the bottom layer from those in the top layer so that two device layers terminate at two different locations as shown in Fig. 2(a). Fig. 2(b) and 2(c) show results of the excitation of top and bottom layer MMI couplers, respectively. The results show the ability to selectively couple to each layer without cross talk. This is due to the thick oxide layer ( $2\mu\text{m}$ ) between the two layers. Fig. 2(d) shows results of the simultaneous excitation of top and bottom layer MMI couplers by putting the input fiber at the middle of two layers.

We characterize the MMI couplers on both layers by fiber scanning as described in [8]. The uniformity of an MMI coupler is defined as  $10\log(I_{\max}/I_{\min})$ , where  $I_{\max}$  and  $I_{\min}$  are the maximum and minimum intensities of the MMI output channels. The excess loss of an MMI coupler, which excludes the fiber-to-waveguide coupling loss and the waveguide propagation loss, is defined as  $-\log[(\sum I_m)/I_{in}]$ , where  $I_m$  is the intensity of the  $m^{\text{th}}$  output channel, and  $I_{in}$  is the output intensity of a reference waveguide on the same chip with the same cross-section dimension as the MMI access waveguides. The top layer MMI coupler has an excess loss of 0.48dB and a uniformity of within 1.1dB fluctuation, and the bottom layer MMI coupler has an excess loss of 2.9dB and a uniformity of within 1.7dB fluctuation. Since the measured MMI performance metrics on both layers are close to those of single layer  $1 \times N$  MMIs fabricated on a 230nm thick silicon nanomembrane (vertically single mode) [8], we conclude that the input power is mostly coupled to the  $\text{TE}_{00}$  mode with the optimized input coupling condition, where the effects of the higher order modes are suppressed.

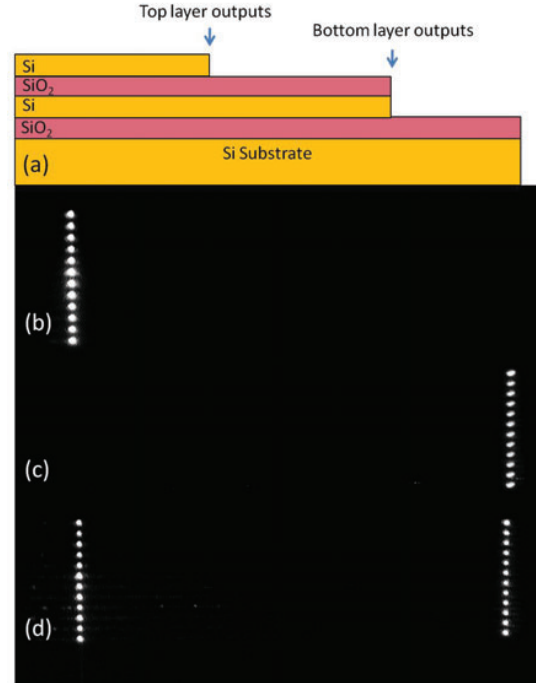


Figure 2. (a) Schematic of separated outputs on top and bottom layers. (b) Excitation of the top layer MMI. (c) Excitation of the bottom layer MMI. (d) Simultaneous excitation of top and bottom layer MMIs.

In summary, we present the double-layer  $1 \times 12$  MMI couplers with low excess loss [0.48dB (top) and 2.9dB (bottom)] and uniform outputs [within 1.1dB (top) and 1.7dB (bottom)] on the vertically integrated two-layer low loss crystalline silicon membranes.

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