Low-Loss Silicon Wire Waveguides with 3-D Tapered Couplers Fabricated by Self Profile Transformation

Ming-Chang M. Lee[1], Wei-Chao Chiu[1], Tse-Ming Yang[1], Chin-Hung Chen[1], and Ming C. Wu[2]

[1]Institute of Photonics Technologies, National Tsing Hua University, Hsinchu 30055, Taiwan
E-mail:mclee@ee.nthu.edu.tw
[2]Department of Electrical Engineering and Computer Sciences, University of California, Berkeley, USA
E-mail:wu@eecs.berkeley.edu

Abstract: A novel low-loss silicon wire waveguide as well as 3-D tapered couplers is demonstrated by self profile transformation for the first time. The preliminary experimental results show the propagation loss is 2 dB/cm and the coupler loss is 2.7 dB.

OCIS codes: (130.3120) Integrated optics devices; (230.7370) Waveguides

1. Introduction

Sub-wavelength silicon wire waveguides fabricated on silicon-on-insulator (SOI) are attractive to realize highly integrated, ultrasmall optical devices[1]. Typically, the core area is only about 0.1 μm^2 for supporting a single guided mode due to high refractive index of silicon. Such a small dimension is desirable for exhibiting nonlinear optical effects of silicon[2] because the power density can be enhanced by scaling down the core area. This enhancement facilitates observations on silicon nonlinear optics with relatively low pump power. However, in practical applications, the required pump power has to be increased to compensate two major losses in silicon wires. One is high propagation loss resulting from sidewall surface roughness created during etch processes. The other is low coupling efficiency between fibers and the wires due to severe mode mismatch. Although the roughness can be reduced to be 5 nm by state-of-the-art complementary metal-oxide-semiconductor (CMOS) technologies and the coupling efficiency can be improved by adding extra couplers, the fabrication steps become complex and critical.

Here, we present a low-loss silicon wire waveguide, which is fabricated on SOI via self profile transformation induced by hydrogen annealing[3]. Silicon atoms tend to migrate along the surface in high-temperature hydrogen ambience. Due to surface tension, the sidewall roughness is dramatically reduced to 0.26 nm [3] and a silicon wire as well as a 3-D tapered coupler can be formed simultaneously in this single process step. .

2. Device Structure and Fabrication

Fig. 1 illustrates the fabrication process of silicon wires. First, a 5-μm high SOI was etched to form a high-aspect-ratio silicon slab. Hydrogen annealing and thermal oxidation were then applied to transform the rectangular tip into a circular wire coated with silicon dioxide as cladding. The core area of silicon wires is about 0.1 μm^2 and the thickness of coated SiO_2 is 500 nm. A 3-D tapered coupler was simultaneously developed at the two ends of the waveguide if the hydrogen annealing was applied on a laterally tapered structure, as shown in Fig. 2(a). The optical wave is initially launched at position A. As it propagates, the lateral spot size reduces through the taper part. Ultimately, the wave is squeezed to the top circular profile defining the silicon wire waveguide. The SEM images of profiles at position A and C in a fabricated device are shown in Fig. 2(b) and 2(c), respectively.

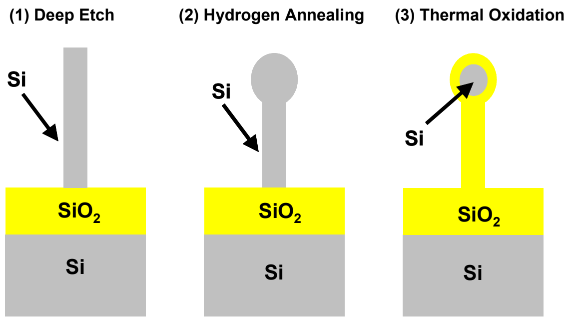

Fig. 1 Schematic illustration of fabricating silicon wire waveguides (cross sections)

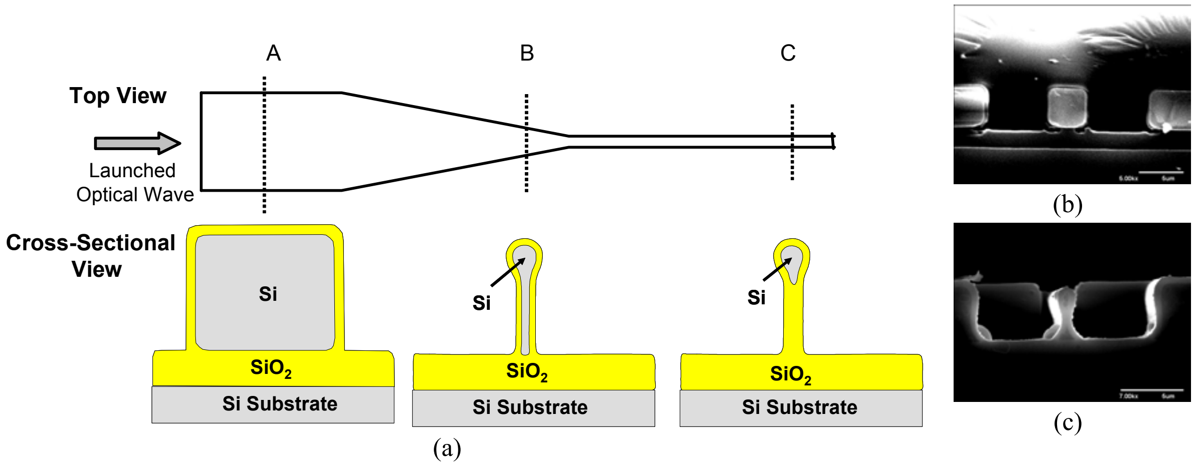

Fig. 2 (a) Schematic illustration of a 3-D tapered coupler, (b) SEM image of the profile at position A, and (c) SEM image of the profile at position C.

3. Measurement

The propagation loss of silicon wires was measured by the cutback method with launched wavelength of 1550 nm. Two single-mode fibers were aligned to the input and output couplers respectively. Fig. 3 presents the insertion losses versus wire lengths with a fixed taper length of 2 mm. The insertion loss includes the fiber-waveguide coupling loss, the reflection loss at the silicon-air interface, coupler loss and the waveguide loss. The fiber-to-waveguide loss should be further improved by using lensed fibers. The preliminary data shows the absorption coefficient is about 2 dB/cm by curve-fitting. We believe the actual value, limited by the precision of alignment, could be even small. To examine the coupling loss of tapered couplers, we fist obtained the losses from the silicon-air reflection and fiber-waveguide coupling by referring a bare silicon channel waveguide with the core dimension of 5 μm for calibration, which is equal to the size of the input end of couplers. By subtracting the propagation loss from silicon wires and other losses, the coupler loss can be calculated. The minimum coupling loss of tapered couplers is 2.7 dB for a taper length of 0.2 cm. In addition, we also investigated the coupling loss varied with the taper length. The result is shown in Fig. 4. The coupling loss increases as the taper length decreases.

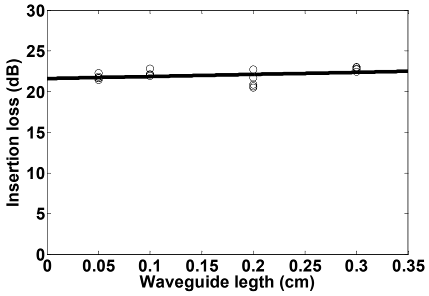

Fig. 3 Insertion loss as a function of waveguide length.

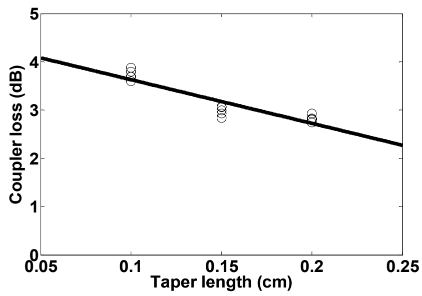

Fig. 4 Coupler loss versus coupler length

4. Summary

We have demonstrated a novel Si wire waveguide with 3-D tapered couplers fabricated on SOI substrate by the hydrogen annealing process. The core size of silicon wire is measured to be 0.1 μm^2. The sidewall roughness can be controlled to be very small and a 3-D taper coupler can be formed through this single process step. Preliminary measurements show the propagation loss and coupler loss are 2 dB/cm and 2.7 dB, respectively.

5. Reference

[1] A. Vlasov Yu and S. J. McNab, in *2005 Optical Fiber Communications Conference Technical Digest (IEEE Cat. No. 05CH37672). IEEE. Part Vol. 3, 2005, pp.1 pp. Vol. 3. Piscataway, NJ, USA.*

[2] H. Yamada, M. Shirane, T. Chu, et al., Japanese Journal Of Applied Physics Part 1-Regular Papers Brief Communications & Review Papers **44**, 6541 (2005).

[3] M. C. Lee and M. C. Wu, Journal of Microelectromechanical Systems **15**, 338 (2006).