Extended Abstracts of the 2016 International Conference on Solid State Devices and Materials, Tsukuba, 2016, pp129-130

C-1-04

Mirror Based Surface Optical I/O Technology with Precise and Arbitrary Coupling Angle for Silicon Photonics Application

Akihiro Noriki[1,2], Takeru Amano[1,2], Masahiko Mori[1,2] and Yoichi Sakakibara[1,2]

[1] National Institute of Advanced Industrial Science and Technology
Central 2, 1-1-1 Umezono, Tsukuba, Ibaraki 305-8568, Japan
Phone: +81-29-862-6383 E-mail: a-noriki@aist.go.jp
[2] Photonics Electronics Technology Research Association (PETRA)

Abstract

Mirror based surface optical input/output technology allowing precise and arbitrary control of coupling angles was demonstrated for silicon photonics application. The mirrors were integrated into 3x3 μm-square single-mode silicon oxynitride optical waveguides on Si substrates, and far field patterns of optical beams output from the mirrors were measured to evaluate the coupling angles. Controllable range of the coupling angle was achieved to be more than 20 degrees. Coupling angle error was less than plus or minus 1 degree.

1. Introduction

Surface optical input/output (I/O) will be required for low-cost, compact, dense, and accurate packaging of silicon photonics chips. As shown in Fig. 1, the surface optical I/O, using flip-chip bonding technology, allows simultaneous optical and electrical connection for many optical and electrical I/O ports of future silicon photonics chips. Thus, assembling cost per each optical I/O port can be greatly reduced. Such flip-chip bonding technology is also attractive for low cost, compact, dense, and accurate packaging. The surface optical I/O can also realize wafer-level testing, and testing cost can be reduced dramatically.

Currently, many kinds of grating couplers have been proposed and demonstrated as attractive components for the surface optical I/O [1-5]. However, coupling efficiency of the grating coupler depends on wavelength and polarization. In addition, coupling angle cannot be determined arbitrarily. It would be more than ~10° to achieve efficient optical coupling [1]. To overcome these problems, we integrated 45-degrees mirrors into Si-rich silica optical waveguides on a Si substrate [6]. The 45-degrees mirrors were fabricated by dicing and polishing processes and efficient, broadband and polarization-independent surface optical coupling was demonstrated.

In this work, we evaluated coupling angle accuracy of the surface optical I/O using our mirrors, since accurate coupling angle is necessary for efficient and repeatable single-mode optical coupling. We also evaluated controllable range of the coupling angle. The controllable range of the angle would be very important factor to cover various packaging demands.

2. Experiments

We integrated the several angle mirrors into optical waveguides on Si substrates. In this work, the mirrors were integrated into 3x3 μm-square single-mode silicon oxynitride (SiON) optical waveguides which were assumed to be optical waveguides for spot-size converters.

Shape of the mirrors was formed by cutting the SiON waveguides at wafer dicing step using common automatic dicing saw as shown in Fig. 2. After dicing, rough and fine polishing of the mirror facets were performed with diamond slurry. Cross-sectional microscopic image just after polishing is shown in Fig. 3(a). Owing to the polishing process, smooth mirror surface was obtained. Finally, the polished mirror surface was covered with 200 nm-thick Cu film by using RF magnetron sputter. A cross-sectional scanning electron microscope (SEM) image of the fabricated mirror is shown in Fig. 3(b), and it was confirmed that the mirrors were fabricated without any mechanical damages.

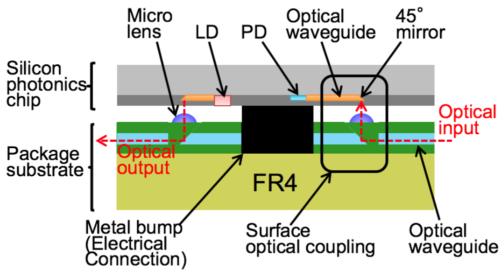

Fig. 1 Schematic cross-sectional image of flip-chip bonded silicon photonics chip with surface optical coupling.

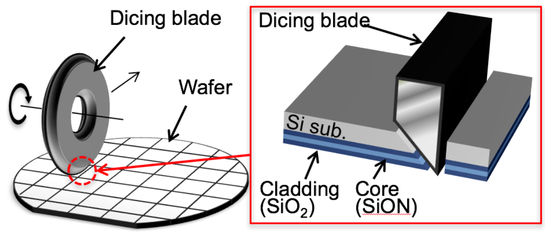

Fig. 2 Schematic image of mirror fabrication with dicing technique.

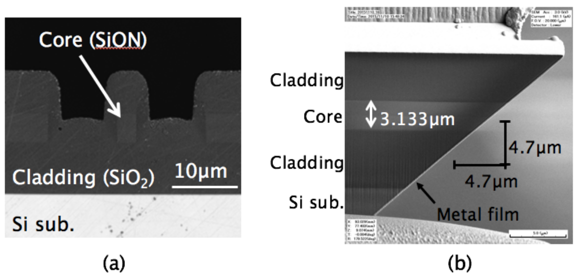

Fig. 3 (a) Microscopic image of mirror surface just after polishing process and (b) cross-sectional SEM image of fabricated mirror.

3. Evaluations

Using 1.55-µm laser light, near field patterns (NFPs) and far field patterns (FFPs) of optical beams from the fabricated mirrors were measured. The NFP and FFP of 45-degrees mirror are shown in Fig. 4 (a) and (b), respectively. High quality gaussian-like single-mode beams with the almost same mode field diameter (MFD) as that of the SiON waveguides (~3.6 µm) were obtained. 5% half-angle of the FFP was ~21.4 degrees which corresponds to NA of ~0.37. The NFPs and FFPs of the other mirror angles were also same quality as that of 45-degrees mirror. The MFDs were 3.6-3.9 µm and 5% half-angles were 20.4-25.3 degrees (NA: 0.35-0.43). Thus, we successfully fabricated different angled mirrors without affecting any characteristics of the output optical beam.

The coupling angles, defined as tilt angles from normal output (see Fig. 5), were evaluated by measured FFPs and plotted in Fig. 5. The 5% half-angle of the FFPs were also shown in Fig. 5. As shown in this figure, the coupling angles were successfully controlled over a wide range from -16 to 8 degrees with stable 5% half-angle of the FFPs. For example, the mirror with 45-degrees angle, fabricated for perfect vertical coupling, had the coupling angle of 0.1 degrees. Perfect vertical output, which is impossible by using the grating coupler, was successfully demonstrated. In Fig. 5, fitting curve for measured results is also represented as a solid line. The fitting equation was derived from geometric optics and Snell's low as below.

$$\theta_b = 2\times(45 - \theta_a)\times n_{SiO_2} \qquad (1)$$

θ_a is the mirror angle, θ_b is the coupling angle, and n_{SiO_2} is refractive index of SiO_2. The measured results were well fitted by equation(1) with appropriate n_{SiO_2} of ~1.5. The coupling angle mismatches between measured results and fitting curve were less than 1 degree. Considering the obtained fitting curve, the coupling angle would be controlled with very small error of ~0.3 degrees, since the mirror angle would be potentially fabricated with 0.1-degrees increment by our equipment. Thus, the mirror based surface optical I/O, fabricated by our dicing and polishing processes, realizes accurate and arbitrary coupling angle for surface optical coupling of silicon photonics.

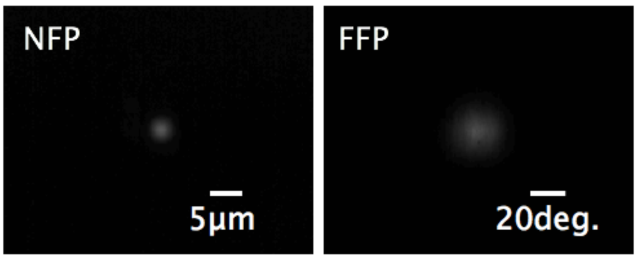

Fig. 4 NFP and FFP of optical beam output from 45-degrees mirror. MFD was ~3.6 µm, and 5% half-angle of FFP was ~21.4 degrees (NA ~0.37).

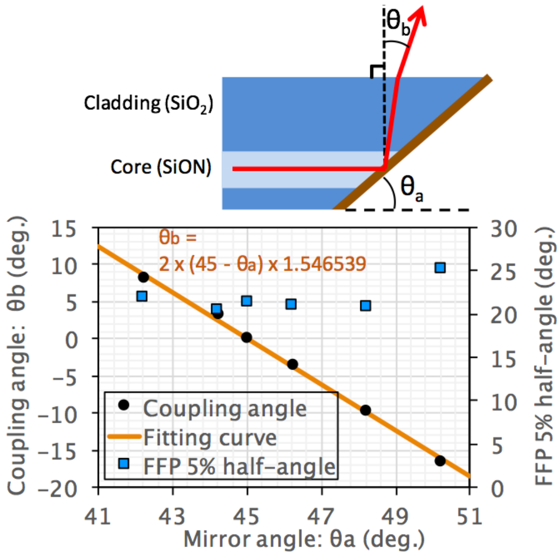

Fig. 5 Measured coupling angle and 5% half-angle of FFPs vs mirror angle. Fitting curve for measured coupling angle is also shown. Top illustration shows definition of mirror angle (θ_a) and coupling angle (θ_b).

4. Conclusions

For mirror based surface optical I/O technology which leads broadband and polarization-independent surface optical coupling, the coupling angle controllability was evaluated. The mirrors were integrated into single-mode SiON optical waveguides of Si substrates by dicing and polishing processes. The coupling angle was controllable from -16 to 8 degrees with the error less than ± 1 degree. Regardless of the coupling angle, same characteristic optical beams were obtained and they were good quality as single-mode optical beams. The coupling angles of the fabricated mirrors were agreed with the theoretical estimation based on geometric optics and Snell's low. Thus, not only wavelength and polarization independence, the mirror based surface optical I/O realizes accurate and arbitrary coupling angle including perfect vertical coupling, all of which are difficult by the grating coupler.

Acknowledgements

This research is partly supported by New Energy and Industrial Technology Development Organization (NEDO).

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