Analysis of Optical Coupling for SOI Waveguides

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Abstract—Optical coupling loss and alignment tolerance between SOI waveguides and laser diodes were investigated. It was found that the minimum optical coupling loss was about 1.6 dB and alignment tolerance was about ±0.7 µm. An optical input/output interface for optical fibers was also proposed and investigated the coupling loss characteristics.

1. INTRODUCTION
Photonic integrated circuits (ICs) based on silicon-on-insulator (SOI) waveguides are attractive for applying future ultra-high speed optical networks or ultra-high speed data communications in clustering computers. Thus far, various optical device functions have been demonstrated on the SOI waveguides [1-6]. Those devices can be extremely small compared with silica based waveguide devices because sharp bend is possible for the SOI waveguides [7, 8] and the crosssection of the waveguide is extremely small. Furthermore, integration with electronic circuits is also possible because those optical devices are fabricated with conventional CMOS fabrication process which makes electronic circuits. Monolithic integration of photonic circuits and electronic circuits eliminates wiring between photonic IC chips and electronic IC chips, and it makes possible ultra-high speed signal processing.

However, there are few reports for integrating light sources on the SOI waveguides. Integration of laser diodes (LDs) or photo diodes (PDs) with passive optical components on the same chip is essential for realizing compact and low-cost photonic ICs. LDs or PDs are made of compound semiconductors, and it makes difficult to integrate them with SOI waveguide devices on the same chip.

There are several approaches to integrate light sources on the SOI wafer. As practical methods, thermal bonding [9] or BenzoCycloButene (BCB) bonding [10] of compound semiconductor wafers and Si substrates with optical waveguides is studied. However, sufficient operation properties for practical use in actual systems have not yet been obtained.

Optical input/output (I/O) interface for optical fiber or external optical components is also required for the photonic ICs. Thus far, in-plane coupling type I/O with beam spot-size-converters (SSC) [11] and vertical coupling type I/O with grating coupler [12] were demonstrated for the SOI waveguides. However, there are still difficulties to practical use of them. For example, optical fibers must be tilted to obtain high optical coupling efficiency for the grating coupler type interfaces, and it makes complex for the structure of optical connectors.

Based on these backgrounds, we studied a method for integrating LD chips on the waveguides and analyze optical coupling loss between the waveguides and LDs. We also proposed an optical I/O interface for single mode optical fibers (SMFs), and investigated the coupling efficiency.

2. INTEGRATION OF LDS ON SOI WAVEGUIDES
Our studied method is mounting LDs with flip-chip bonding on the SOI substrate as shown in Fig. 1. Light output from LDs is butt-joint coupled to the optical waveguides with spot-size converters. The alignment accuracy of commercially available flip-chip bonders is about ±1 µm. Therefore, more than 1 µm of alignment tolerance for optical coupling is required. We investigated the alignment tolerance for the optical coupling between conventional LDs and Si photonic-wave waveguides with horizontal taper type beam SSCs.

Figure 2 shows a schematic view of the SSC. BPM method was used for calculating the coupling loss for the SSC. In the analysis, total coupling loss is comprised of three loss factors; i.e., mode conversion loss in SSC, mode-mismatch between beam spot-size of LD light output and mode profile in the SSC, and reflection loss at the end facet of the SSC. Taking into account these loss factors, we calculated the coupling loss.
Figure 3 shows calculated coupling loss as a function of misalignment in $x$-direction (a) and $y$-direction (b). The coupling losses were calculated for the different $W$ values from 2 $\mu$m to 5 $\mu$m. It is found that minimum 1.6 dB of coupling loss can be achieved provided that both end facets of LD and SSC contact each other without air gap. We also found that the alignment tolerance for maintaining less than 3 dB optical coupling loss is about $\pm 0.7 \mu$m when the SiO$_x$ layer width is around 2 $\sim$ 3 $\mu$m.

We measured optical coupling loss between Si photonic-wire waveguides and LDs to verify the analytical results. First, we put an LD chip on an $x$-$y$-$z$ moving stage in order to measure the optical coupling loss and the alignment tolerance for $x$ and $y$ directions. Fig. 4 shows measured coupling losses normalized at just aligned position for $x$-direction (a) and $y$-direction (b). If we assume the distance between the end facet of LD chip and the SSC was 10 $\sim$ 15 $\mu$m, the measurement results is in good agreement with the calculation.

Figure 1: Flip-chip bonding of LD on SOI substrate.  
Figure 2: Schematic view of spot-size-converter.

Figure 3: Calculated coupling loss as a function of misalignment in (a) $x$-direction and (b) $y$-direction.

3. OPTICAL I/O INTERFACE FOR EXTERNAL OPTICAL COMPONENTS

An optical input/output (I/O) interface for external optical components was also proposed. The interface consisting of a grating coupler can introduce light signal from vertical direction to the substrate although grating couplers reported so far must be used for tilting optical fibers from the vertical direction in order to obtain high coupling efficiency [12].

Figure 5 illustrates the structure. Light input signal irradiated from vertical direction to the substrate is diffracted for both right and left directions by the grating, and the diffracted light signals are combined with 3 dB coupler. We calculated coupling loss for SMFs with 3D FDTD method. Fig. 6 shows calculated optical coupling efficiency as a function of wavelength. It is found that about maximum 50% of coupling efficiency can be obtained with the interface and enough wide bandwidth for operating wavelength can be expected. We also investigated misalignment tolerance of input light beam, and found that the interface have enough tolerance for misalignment and tilt of input beam.
Figure 4: Measured coupling loss as a function of misalignment in (a) $x$-direction and (b) $y$-direction.

Figure 5: Proposed optical I/O structure for vertical coupling.

Figure 6: Calculated coupling efficiency.

4. CONCLUSION

We investigated optical coupling loss between LDs and SOI waveguides with BPM method, and found that about 2 dB of minimum coupling loss can be attained. Enough alignment tolerance was also confirmed for the flip-chip mounting of LD chips on the SOI waveguide substrates. Optical I/O interface for vertical coupling was also proposed and investigated the optical coupling efficiency with 3D FDTD method. It was found that maximum 50% of coupling efficiency can be obtained.

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