Vertical Trident Coupler for 3D Optical Interconnection

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***Abstract*—A vertical trident coupler for 3D optical circuit was demonstrated. This is novel interlayer directional-type coupler between crystalline Si and amorphous-Si:H wire waveguides. The trident structure can manage both easiness of fabrication and high coupling even with relatively thick interlayer distances. In experiment, this trident coupler realized low coupling loss (coupling efficiency) of 0.58dB (87%) at 1550 nm wavelength and almost constant coupling loss of around 0.5dB within the wavelength range from 1530 nm to 1610 nm**

Keywords-Silicon photonics, trident, a-Si:H waveguide, multi-layer, vertical coupler

I. INTRODUCTION

Optical interconnection is recently considered an indispensable technology for realizing larger-capacity and higher-speed data transmission in comparison with conventional electrical wiring. Especially, silicon photonics has attracted worldwide attention due to its potential for providing high-density optical interconnection with high index contrast structures, as well as its compatibility with CMOS fabrication process [1].

Recently, in order to realize higher density 3D optical circuits, an adoption of hydrogenated amorphous silicon (a-Si:H) has been investigated [2], [3]. Because a-Si:H can be deposited on Si at relatively low temperature (less than 300 °C), it can be stacked with no damage of underlayer such as CMOS as a back-end process repeatedly and can be applied to 3D integration easily.

In such 3D integration approach, one of key components is vertical interlayer transition (VIT) device. So far the main topic of VIT is a grating coupler. A high-efficiency grating coupler with a metal mirror was demonstrated that enabled transmission with an arbitrary interlayer thickness and even with several μm of thickness [3], [4]. However, this requires an accurate formation of the grating and several mask processes including metal deposition processes. On the other hand, there is directional-type couplers which use an adiabatic coupling. a directional-type coupler with the interlayer thickness of 200 nm was reported [5]. It can be fabricated easily and achieves high coupling efficiency due to simple structure, but it has a drawback of long device length, especially for thick interlayer distances. For example, about 1 cm device length is required when the interlayer thickness is 1 μm.

In this paper, we propose Si-based vertical trident coupler, which has both a simple fabrication process and applicability to interlayer transmission across relatively thick interlayer distances. In the following section, we report design and experimental results of the trident coupler with 1-μm interlayer thickness.

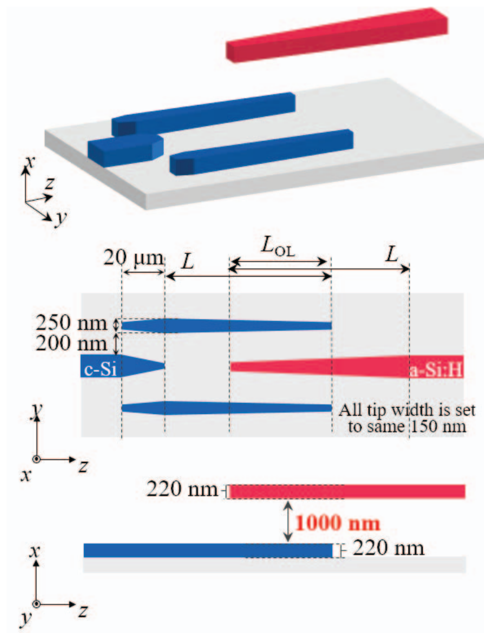


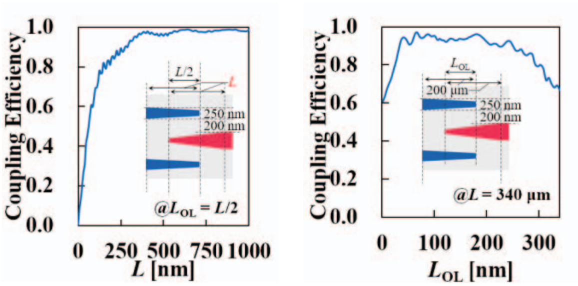
Fig. 1. Schematics of trident coupler.

II. DEVICE STRUCTURE & FABRICATION

On the premise of a device design, we assumed that 220-nm high and 450-nm wide c-Si (refractive index: 3.48) or a-Si:H (refractive index: 3.58) waveguides are buried in SiO_2 (refractive index: 1.44). Under such conditions, we designed structures at a wavelength of 1.55 μm and TE mode using Eigen mode expansion method and finite-difference method (FDM)

The schematic of the interlayer trident coupler is shown in Fig. 1. The trident structures have parallel waveguides, which are located around two connected waveguides that taper. The trident waveguides can realize larger mode field than the single taper waveguide with the same device length. As a result, we can expect the trident structure can realize shorter length to achieve high coupling efficiency when the interlayer distance D is large. In this work, D is set to 1 μm by considering the cross talk between vertically stacked layers [2].

Fig. 2(a) shows the taper length L dependence of the coupling efficiency when the overlap length L_{OL} is $L/2$. This figure shows that the coupling efficiency is higher than 95% if $L > 340$ μm. Thus, L is set to 340 μm. Fig. 2(b) shows the L_{OL} dependence when $L = 340$ μm. For a small footprint, L_{OL} is set to 170 μm, and the coupling efficiency of 95%



(a) (b)

Fig. 2. (a) L dependence of coupling efficiency when overlap length L_{OL} is $L/2$, and (b) L_{OL} dependence of coupling efficiency.

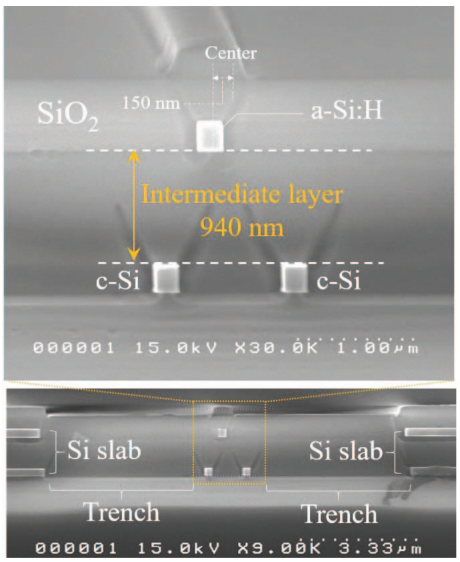


Fig. 3. Cross-sectional view of interlayer-type coupler.

can be obtained. Total coupler length is as short as 530 μm, which is ~20 times shorter than that for conventional one, for the interlayer distance of 1 μm

The fabrication process of this trident interlayer coupler is as follows. First, on a silicon-on-insulator (SOI) with a 220-nm-thick top silicon layer, 3-μm-thick buried oxide layer, and alignment marks were formed by EBL and metal evaporation (20-nm Ti/100-nm Au). Next, a ZEP520A-C_{60} resist [6] was spin-coated, and a c-Si waveguide was patterned by EBL and inductively coupled plasma reactive ion etching (ICP-RIE) with CF_4/SF_6 mixed gas. After that, an interlayer of 1.5-μm-thick SiO_2 was deposited by PECVD and flattened by a chemical mechanical polishing (CMP) process to obtain a thickness of 1 μm by using an *ex-situ* thickness monitor. Then 220-nm-thick a-Si:H was deposited using PECVD, and a-Si:H waveguide was formed in the same way. Finally, SiO_2 was deposited as a cladding layer.

Figure 3 shows the cross sectional SEM image of the fabricated device. This figure confirms the fabrication of the parallel waveguides, but a-Si:H waveguide deviated from the center by 150 nm caused by mistake during the patterning process, which can be solved by modifying CAD.

III. Measurements

Figure 4 shows wavelength dependences of the coupling loss; experimental and numerical results. . As can be seen in

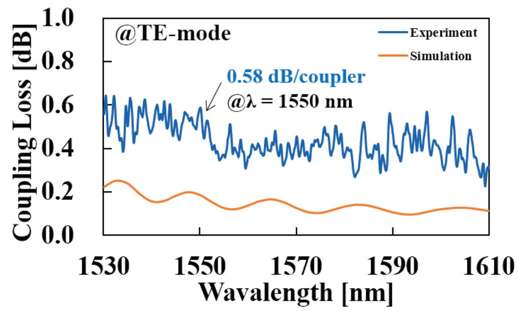


Fig. 4. Wavelength dependence of coupling loss.

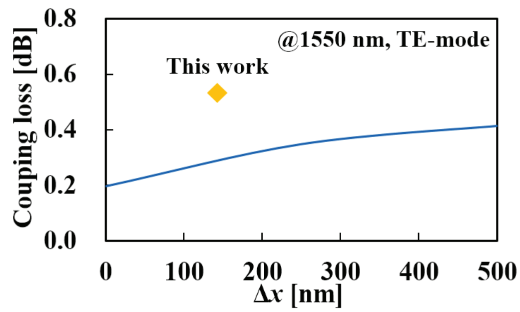


Fig. 5. Misalignment dependence of coupling efficiency for misalignments to x direction (Δx).

this figure, the coupling loss seems to be more or less constant and is around 0.5dB for measured wavelength range from 1530 nm to 1610 nm. Fabry-Pérot resonance between facets caused fine ripples because there was no anti-reflection coating on the facet. Figure 5 shows coupling efficiency dependence on the misalignment along x-direction. From this figure, main cause of the drop in coupling efficiency compared with the simulation is not only the offset of the a-Si:H waveguide. We assume that there is light leakage into the side Si slab area as shown in Fig. 3. This slab area remained just for reducing exposure time of EBL, so we can increase trench width in the future.

IV. Conclusion

We demonstrated a novel interlayer trident type coupler between c-Si and a-Si:H wire waveguides. The trident structure can manage both easiness of fabrication and coupling between long distance by only forming additional two side waveguides. Experimentally, the trident coupler achieved coupling efficiency (coupling loss) of 87% (0.58dB) per coupler and almost flat property in C- /L-band.

Acknowledgment

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References

[1] B. Jalali *et al., 2010 IEEE Photinic Soc. 23rd Annu. Meet.*, vol. 24, no. 12, pp. 489–489, 2012.
[2] J. Kang *et al., Proc. SPIE*, vol. 8630. pp. 863008–863012, 2013.
[3] J. Kang *et al., Appl. Phys. Express*, vol. 032202, pp. 5–8, 2014.
[4] M. Sodagar *et al., Opt. Express*, vol. 22, no. 14, p. 16767, 2014.
[5] R. Sun *et al., Opt. Express*, vol. 16, no. 16, pp. 11682–11690, 2008.
[6] K. Inoue *et al., Jpn. J. Appl. Phys.*, vol. 48, no. 3, p. 208, 2009.