Compact InP-based 1×2 MMI Splitter on Si Substrate with BCB Wafer Bonding for Membrane Photonic Circuits

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***Abstract* — Ultra-low power and compact optical interconnects can be realized with III-V-based membrane photonic intergrated circuits (PICs) on Si platform. This study focused design and fabrication of the III-V-based passive components of the PICs, especially, a compact 1×2 multimode interference (MMI) splitter with SiO_2 buried GaInAsP wire structure. The calculated excess loss was as low as 0.28dB in the optimized structure, and the structural tolerance obtained was as low as 0.05dB, when MMI width W_{MMI}, length L_{MMI}, output gap Y were changed in range of ± 50 nm. The footprint of the MMI region was only 1.4×1.5 μm^2. In the spectral range of 1548-1552 nm, the average excess loss measured was around 3dB and the average imbalance between the outputs was 0.5dB allowing the compact size and light splitting function.**

***Index terms* — Multimode ineterference (MMI), III-V-based passive components, membrane photonic integrate circuits(PICs), optcal beam splitters.**

I. Introduction

The processing speed in large-scale integrated cirtuits (LSIs) is being limited by the RC time constant and the power consumption on the global electrical wires [1-2]. As one solution, optical on-chip interconnects have been proposed with the replacement of the copper wiring in Si-LSI [3-4]. To realize them, we proposed the concept of membrane photonic integrated circuits (PICs) such as shown in Fig. 1, which consist of the thin III-V-based PICs with high index-contrast structure of the semiconductor core layer sandwiched by SiO_2 or air claddings [5-6]. The strong optical confinement to the core layer in the membrane structure leads to ultra-compact footprints and low-power dissipation. For integration technique of III-V/Si, a Benzocyclobutene (BCB) adhesive wafer bonding was used to realize the membrane PICs by the way of backend process after the CMOS process [7]. For such III-V PICs, we have reported membrane lasers [8] and photo-detectors [9] as active components. InP-based wire waveguides on the Si substrate was also reported with a propagation loss of 4 dB/cm [10].

For membrane PICs, passive devices for splitting and coupling of the optical signals are necessary. As such a beam splitter, N×N multi-mode interference (MMI) devices have been extensively investigated due to its simple structure and large fabrication tolerance [11-12]. So far, an InP-based 1×2 MMI splitter on Si substrate was reported, but the footprint was rather larger to 2.75×6.64 μm^2 [13].

One of the advantages of this index contrast membrane

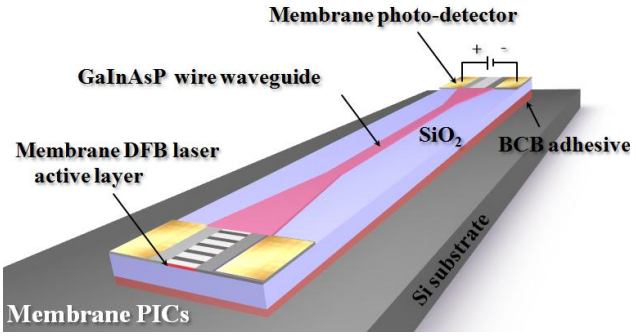


Fig. 1 Schemetic representation of a membrane photonic integrated circuits consisting of the membrane DFB laser, the GaInAsP wire waveguide and the membrane photo-detector.

structure is the compactness of components. A 1×2 MMI splitter on Si-on-insulator (SOI) substrate was reported with its compact size (1.8×2.6 μm^2) and low excess loss (0.45dB) structure [14]. Since the index contrast of our InP-based membrane structure is comparable to SOI, similar size InP-based MMI splitter should be realized.

In this study, we focused on design and fabrication of an ultra-compact (to extent of the MMI on SOI) GaInAsP 1×2 MMI splitter with SiO_2 buried wire structure which can be integrated wih the light sources for membrane PICs.

II. Design

A 3dB splitter, 1×2 MMI structure consisting of one input waveguide, one MMI region, and two output waveguides was theoretically investigated, where the GaInAsP 1×2 MMI splitter was assumed to be buried in 1.5-μm-thick SiO_2 upper and bottom claddings on Si substrate by BCB wafer bonding as shown in Fig. 2 (a).

In the calculation, finite difference method (FDM) was used by assuming transverse electric (TE) polarization with the wavelength fixed at 1550 nm. The refractive indices of GaInAsP and SiO_2 were assumed to be 3.35 and 1.45, respectively. While the size of MMI region was designed for compact and low-loss structure, the sizes of the input and the output waveguides were set to be 500-nm-wide and 150-nm-thick, satisfying the singlemode condition at 1550 nm wavelength with the equivalent refractive index n_{eq} 2.0 of the GaInAsP wire waveguide. Figure 2(b) illustrates a top view of the MMI splitter model used for the FDM

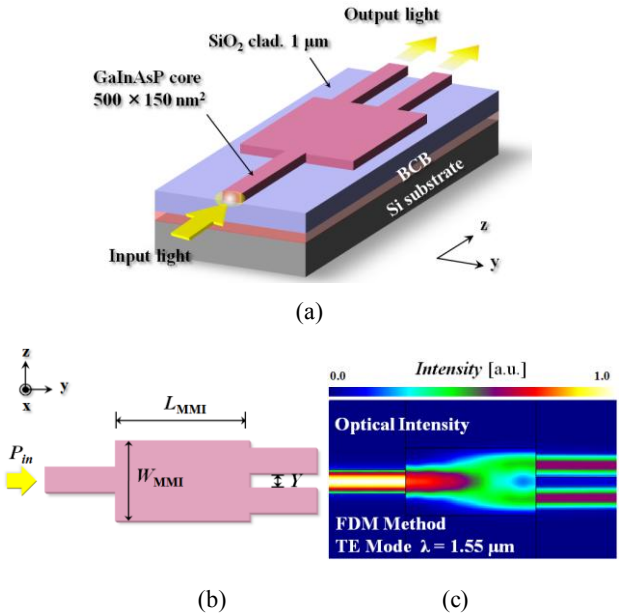


Fig. 2 (a) Schematic structure of the MMI splitter; (b) Top view of the FDM calculation model; (c) launched TE polarization optical intensity.

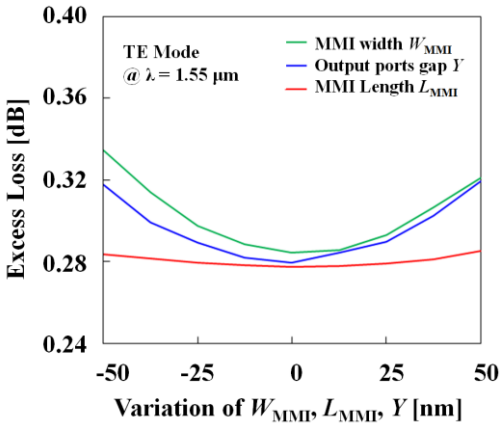


Fig. 3 Estimated structure tolerance by considering excess loss versus MMI width W_{MMI}, output ports gap Y and MMI length L_{MMI}.

simulation. The parameters of MMI region were set as MMI width W_{MMI}, length L_{MMI}, and the gap between output ports Y. The excess loss of 1×2 MMI was calculated from the ratio of total output power of both ports to the input power. By changing the above mentioned parameters, 1×2 MMI structure for compact and low-loss property was investigated. The minimum excess loss of 0.28dB was obtained when the parameters were W_{MMI} = 1.41 μm, L_{MMI} = 1.54 μm, and Y = 0.20 μm. Figure 2(c) shows the calculated optical intensity with TE polarization, which was launched into the input GaInAsP wire waveguide of the MMI splitter with the optimized structure.

Considering fabrication error caused by process variations, the fabrication tolerance was also estimated by changing each parameter in the range of ± 50 nm (which can be regarded as the maximum deviation of our fabrication process by using an electron-beam-lithography followed by

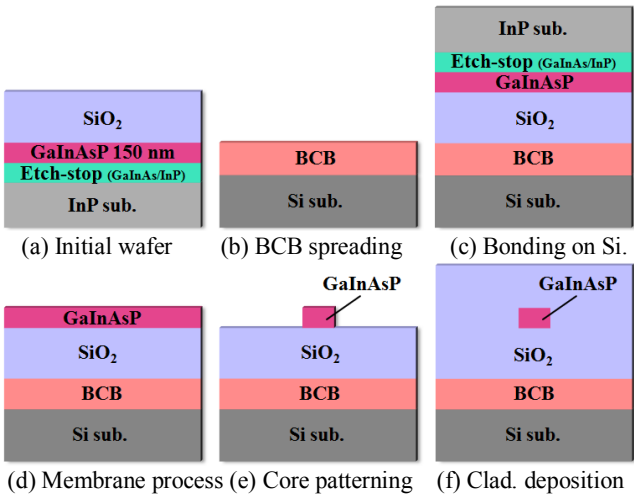


Fig. 4 Schematics for fabrication process with GaInAsP membrane structure on Si substrate using BCB adhesive wafer bonding.

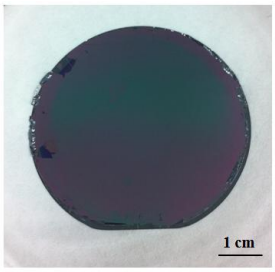
a dry etching) from the optimized structure. Figure 3 shows the excess loss as a function of the deviation from the optimum value of each parameter. As can be seen, the excess loss variation was only 0.05dB when the width was changed, and was 0.04dB when output ports gap was varied in the range of ± 50 nm. At the same time, the increased excess loss was as low as 0.01dB during MMI length was also changed in the range of ± 50 nm. The 1×2 MMI splitter size and the excess loss calculated are comparable to the value of the MMI splitter with Si wire waveguide on a SOI substrate, hence compact and low-loss optical elements could be fabricated even in the GaInAsP membrane circuits.

III. Fabrication

The device fabrication process was performed by the following steps as illustrated in Fig. 4, and comprised of two main steps; a BCB adhesive wafer bonding and a device structure fabrication.

For the BCB bonding process, organo-metallic vapor-phase epitaxy (OMVPE) was used to grow an initial GaInAsP/InP wafer which consists of a 150-nm-thick $Ga_{0.21}In_{0.79}As_{0.46}P_{0.54}$ (λ_g = 1.22 μm) core layer on top of two etch-stop layers (InP/GaInAs). Then, as shown Fig. 4(a), a 1.5-μm-thick SiO_2 bottom cladding layer was deposited on the GaInAsP/InP wafer by plasma-enhanced chemical-vapor deposition (PECVD). Meanwhile, BCB was spin-coated onto the Si wafer, and then, it was thermally pre-cured for its polymerization in N_2 environment at 210°C. Both wafers were bonded with a bonding pressure of 5.9 kPa at 130°C, and completely solidified by hard-curing at 250°C under N_2 atmosphere. With selective wet etching, the InP substrate and two etch-stop layers were removed, then GaInAsP membrane was formed on the Si substrate. Figure 5 shows the GaInAsP membrane of 2 inch wafer formed after BCB bonding and membrane process.

Next, in order to fabricate waveguides, a SiO_2 hard mask



Layer	Thickness [nm]
GaInAsP core	150
SiO_2	1500
BCB	1200
Si sub.	150 μm

Fig. 5 Image of 2-inch GaInAsP membrane surface on a Si substrate after BCB adhesive wafer bonding and selective wet-etching of the InP substrate and etch-stop layers.

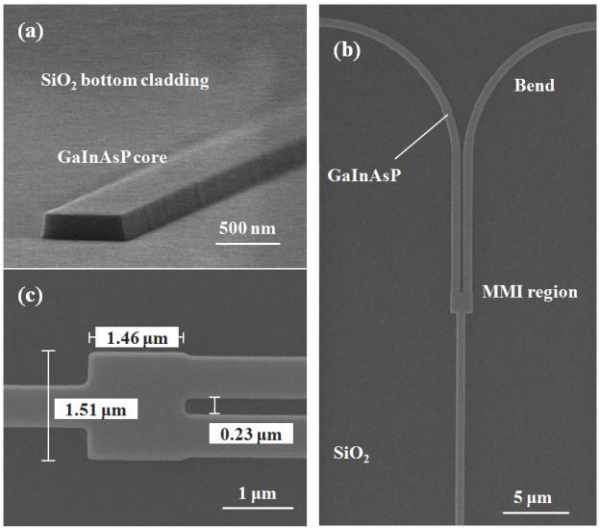


Fig. 6 SEM image of the MMI splitter (a) input waveguide on cross-sectional; (b) the MMI region and (c) enlarged micrograph on top view.

was deposited by PECVD and electron beam resist (ZEP520A/ZEP-C_{60} double layer) was spun onto the GaInAsP membrane on the Si substrate. After forming the mask pattern using electron beam lithography, the SiO_2 mask was transferred by reactive-ion etching (RIE) using CF_4 gas. And then, the GaInAsP core layer was etched by inductively-coupled plasma RIE (ICP-RIE) using a mixture of CH_4 and H_2 gas. After each etchig process, the surface was cleaned by O_2 plasma ashing, and SiO_2 mask was removed with BHF solution. Finally, to obtain the complete device structure, a 1.5-μm-thick SiO_2 upper cladding was deposited by PECVD. Figure 6 represents the scanning electron microscope (SEM) images of 1×2 MMI splitter fabricated; (a) side view of input portand (b) and (c) top view of device body. The width W_{MMI}, length L_{MMI} and the gap of output ports Y of the fabricated MMI were 1.46 μm, 1.51 μm, and = 0.23 μm, respectively. The width and the thickness of the input and output ports were 0.49 and 0.15 μm, respectively.

IV. Measurements

The measurement of fabricated MMI splitter was carried

Fig. 7 Near field pattern of MMI splitter at wavelength 1.55 μm.

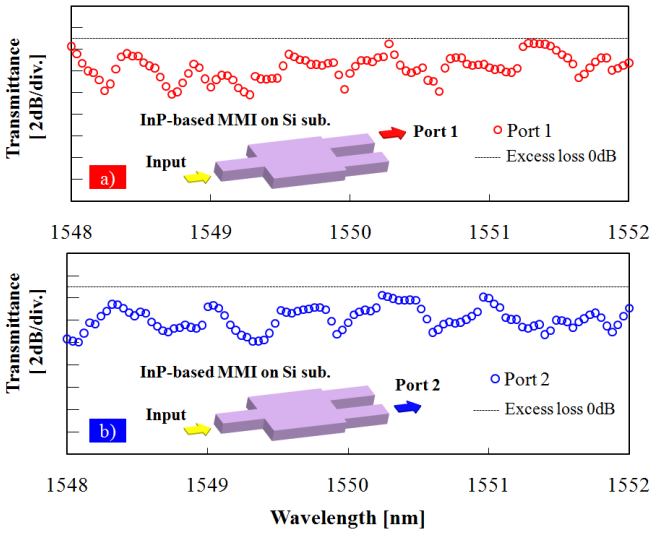


Fig. 8 Transmission of MMI splitter on Si substrate; (a) output port 1 and (b) output port 2.

out in the way that the input and outputs light beams on cleaved facets were coupled to each of the waveguide using spherical-lensed single mode fibers (mode field diameter of ~1.0 μm). Transmission measurement was performed with a wavelength tunable laser. The light transmitted through the device was coupled to the other spherical-lensed single mode fiber and projected on an optical power detector. A polarization controller was used to maintain the transverse electric (TE) incident polarization of the input light from the light source.

Figure 7 indicates the near field pattern on cross-sectional view of upper port and lower port at 1.55 μm wavelength.

Figures 8 shows the transmission of the output port 1 and port 2 of the MMI splitter. The wavelength of input light was swept and the average excess loss was obtained to be 3dB in the range of 1548-1552 nm. The average imbalance, which definded as the power ratio of the output ports was 0.5dB in the spectral range of 1548-1552 nm. The deviation of the excess loss value from the theoretical calculation is considered to be due to the displacement of the device sizes, and imperpect symmetric structure fabricated.

V. Conclusion

In conclusion, we designed and fabricated an ultra-compact and low-loss 1×2 MMI splitter with SiO_2 buried GaInAsP wire structure on a Si substrate by BCB

adhesive wafer bonding. The excess loss of calculated MMI was as low as 0.28dB in optimized structure, and this structure had a good fabrication tolerance of 0.05dB when W_{MMI}, L_{MMI}, and Y were changed in range of ± 50 nm. The footprint of fabricated 1×2 MMI splitter was as small as 1.51×1.46 μm^2; in consequence, this device is about 9 times smaller than the reported InP-based 1×2 MMI splitter [13]. The average excess loss was 3dB in C-band and the imbalance between output ports was 0.5dB, but it can still be improved by reduction of its displacement and imperpect summetry of device structure . It is confirmed that compact optical element with low-loss property can be realized even in the GaInAsP membrane circuits.

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