Optical Interconnection between III-V Chips on Si by using Photonic Wire Bonding

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Abstract— We connected two III-V laser and photodiode chips on Si substrate by using three-dimensional polymeric wires based on two-photon polymerization. We achieved an enhancement of the transmitting efficiency through PWB compare to the free-space transmission.

I. INTRODUCTION

Optical interconnects will provide significant performance improvement and power savings over conventional copper-wire-based solutions in large-scale integrated circuits (LSIs) [1]. From the viewpoint of CMOS technology, photonic integration of various optical functionality on Silicon-on-insulator (SOI) platform is now being focused for intra-chip interconnects. However, the realization of light source in SOI platform by using CMOS process still remain a challenge since the group IV elements such as silicon and germanium are well-known indirect transition semiconductor. To overcome this obstacle, research activities in this field primarily concentrated on the heterogeneous integration technologies of silicon and III-V based photonic components such as adhesive bonding and direct bonding [2][3]. However, either of them suffers from the structure restriction, which tend to be the barrier of wide-range application.

In this research, we considered to introduce a newly-emerging technology named photonic wire bonding (PWB) --- three dimensional freeform polymeric waveguide based on two-photon polymerization to achieve efficient optical interconnection between each component [4]. Here we demonstrate direct optical interconnection between a GaInAsP/InP lateral-current-injection (LCI) laser and a detector [5][6] which were mounted on Si substrate by Benzocyclobutene (BCB) adhesive bonding and succeeded 150-µm optical transmission via PWB with connection loss around 10dB.

II. NUMERICAL SIMULATION

Fig. 1 provides the concept of optical interconnection based on PWB and details of the designed coupling structure between PWB and the LCI laser. The LCI laser is one key object we have studied toward the demand of ultralow power consumption device regarding on-chip optical interconnection [5]. Here we chose SU-8 (n = 1.57) as the polymer material of PWB in terms of two photon polymerization. We also assumed a circular cross section similar to the optical fiber and calculated the mode characteristic of the PWB as a function of its diameter, which result indicated that single-mode propagation condition could be fulfilled when the diameter of the SU-8 wire is smaller than 1.5 µm. However, during the

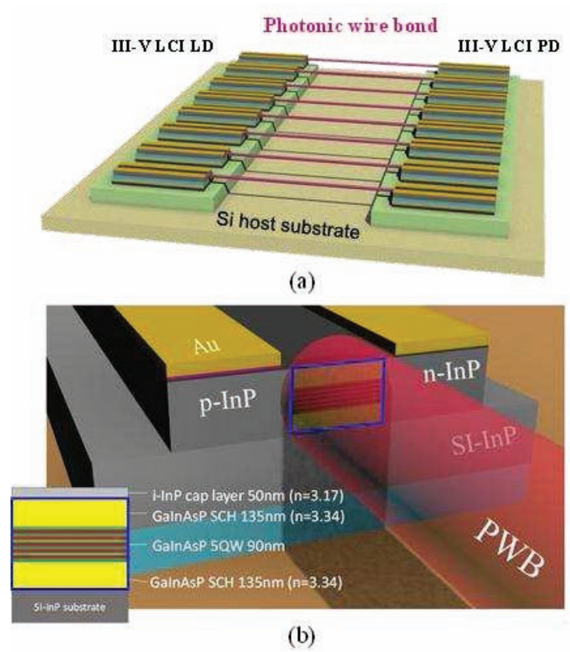

Fig. 1 (a) Concept of optical interconnection between two LCI optical chips based on photonic wire bonding. (b) Details of the transition section between the LCI laser and PWB.

calculation of the coupling loss between PWB and LCI laser we still chose the aspect ratio of the cross section of PWB as one parameter in consideration of the physical limitation of the focus spot of femtosecond laser during two photon polymerization. The cross-sectional structure of the core layer of the LCI laser is also illustrated in Fig. 1(b). In terms of the coupling structure, we considered an end face contact between the PWB and the core layer of the LCI laser for higher coupling efficiency.

Fig. 2 provides the calculation results of the coupling loss together with the tolerance characteristic of this structure. The horizontal ordinate represent the displacement of the center of PWB and the core layer of the LCI laser in transverse and vertical directions. The asymmetry of the coupling loss in vertical direction is mainly caused by the asymmetric mode distribution of the laser as that of our previous device [6] because of the refractive index difference of the upper air cladding layer and the bottom semi-insulator host substrate. The minimum coupling loss of 1.7dB can be obtained when there is 300 nm displacement in vertical direction between the laser and the PWB with aspect ratio of 1:1.

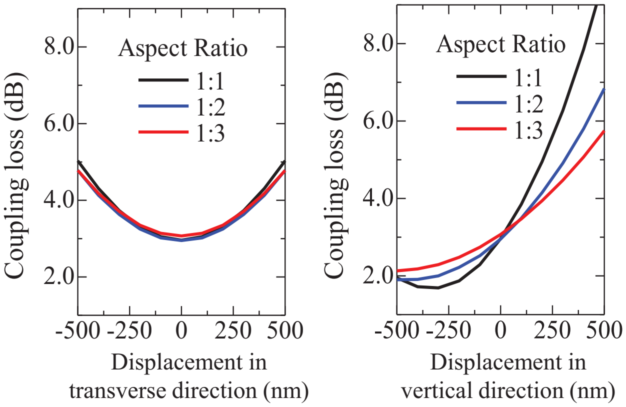

Fig. 2 Calculation result of the mode coupling loss between PWB and LCI laser regarding different aspect ratio with tolerance characteristic in both direction.

III. Exprimental Result

A microscopic view of a completed sample is shown in Fig. 3(a), where two III-V LCI optical chips [6] with the same structure are located on the Si substrate by BCB adhesive bonding and connected by the PWB. 1.5 μm-wide-PWB with an aspect ratio of 1:3 was fabricated when we used the objective lens with NA of 0.95 and set the power of femtosecond laser to be 88mW during the lithography. We are now still trying to figure out a better fabrication condition for lower aspect ratio PWB (e.g. adjusting exposure speed). To make a comparison of the optical transmission characteristics between laser and detector chips with and without being connected by PWB, we measured the photocurrent I_{pd} of the photodiode regarding the current I_1 injected into the laser (the measured light output P_1 of this laser is also provided in Fig. 3(b) for reference). According to the experimental result, the threshold current of the laser (25 mA) was consistent with the rise up current of the photodiode, and a significantly enhancement of the transmitting efficiency through PWB was obtained compare to the free-space transmission.

The concrete coupling loss between PWB and these two III-V optical components were estimated according to the following steps (see Fig. 3(c)). Firstly the light output P_2 trying to get into the PWB can be theoretically calculated according to P_1 because the ratio of light output from both facet mainly relies on the reflection ratio of each facet mirror. Next, the photosensitivity of the photodiode was measured by the incident light P_4 entering the facet without PWB, which is nearly 0.09 A/W according to the result embedded in Fig. 3(b). The light power P_3 absorbed by the photodiode can be estimated through the photocurrent I_{pd} and the photosensitivity. The total coupling loss between the PWB and laser/photodiode chips can be assessed by comparative analysis of P_2 and P_3 (i.e. 10log (P_3/P_2)). As a result, 10dB of the loss was estimated, which means roughly 5dB for each side. Regarding the PWB with an aspect ratio of 1:3, we considered the experimental result to be compatible with the simulation result shown in Fig. 2 to some extent. And the scattering loss induced by the bonding angle and the reflection

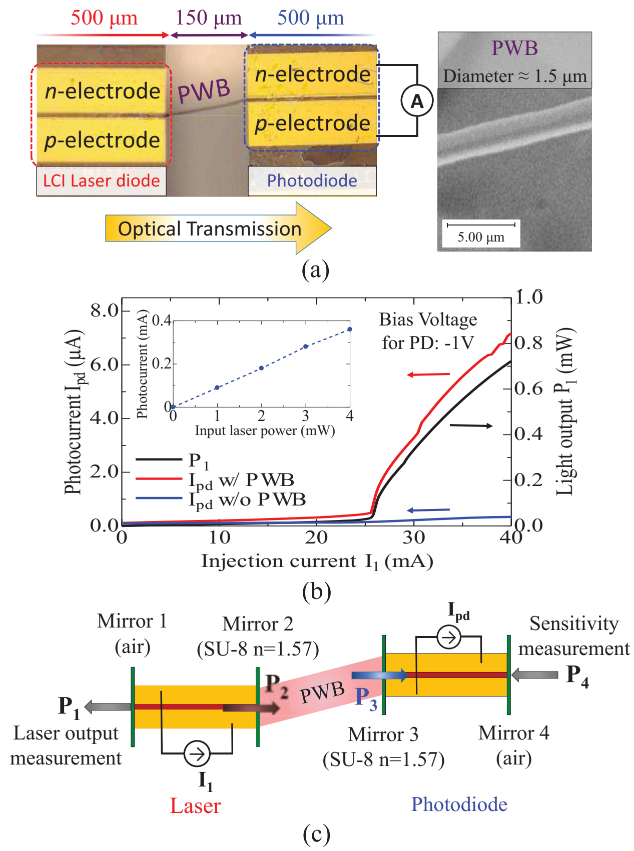

Fig. 3 (a) Optical microscope image of the completed sample. (b) Measured photocurrent I_{pd} of the photodiode regarding of the injection current to laser I_1 together with the laser I-L characteristic. The inset shows the property of an individual PD. (c) The schematic figure of optical transmission between laser and photodiode chips.

loss between the PWB and optical chips are considered to be the main reason of the discrepancy. As the future work, we intend to introduce anti-reflection coating between PWB-photodiode and reduce the bonding angle by adjusting the scanning path during the fabrication to suppress the reflection and scattering loss, respectively.

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