Hybrid photonic integration based on flip-chip bonding combined with vertical coupling

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***Abstract*—Hybrid photonic integration based on flip-chip bonding combined with vertical coupling is proposed, which shows excellent alignment tolerance by simulation.**

Keywords—hybrid integration, flip-chip bonding, vertical coupling, photonic integration

I. Introduction

Si photonics has made rapid progress in modulators, tunable lasers, LIDAR and so on [1], urgently needing to be integrated with active devices in subsequent development. Especially with the development of the communication industry, coherent optical communication has become increasingly critical. The integration of light source and passive devices such as silicon-base devices is an essential factor limiting its development. At present, the hybrid integration schemes mainly include wafer bonding [2], micro-transfer printing [3] and flip-chip bonding [4]. Each scheme has its characteristics, based on which new schemes are proposed [5].

This paper presents a new hybrid integration scheme based on flip-chip bonding and vertical coupling. The finished single laser chip is soldered into the pre-set cavity of the passive chip. The coupler is designed based on the offset quantum well integration platform and is completed using only the existing technologies. It can maintain the high performance of the laser and has an oversize tolerance. The scheme's feasibility is analyzed by taking the Silicon-On-Insulator (SOI) as an example. The lateral coupling tolerance of 90% efficiency is ±1.5 μm, and the longitudinal tolerance is much larger than this. The production tolerance is also sufficient. This scheme will be used to fabricate modulators with integrated light sources and silicon-based tunable lasers to promote the development of photonic integration.

II. Scheme Details

A. Overall Structure

Taking SOI as an example (the other materials are similar), vertical couplers, multiple mechanical stops and Au-Sn alloys for bonding are designed respectively on the laser and SOI, as illustrated in Fig. 1. The finished single laser chip is inverted in the pre-set cavity of the SOI so that the vertical couplers of the two can be closely contacted and aligned. Therefore, the alignment error in the vertical direction is tiny, which is one of the advantages of this scheme over the integration scheme of butt coupling. Au and Sn in the structure are used to bond and inject current. Au is deposited on the ridge waveguide and the side walls at both ends of the laser. Au-Sn alloys are also deposited on the corresponding places of the SOI. Some mechanical stops in the laser and the SOI can support the device while the Au-Sn alloys melt. The positive electrode of the laser is bonded to the alloy corresponding to the ridge waveguide in the SOI. The negative electrode is the back electrode, similar to the standard semiconductor laser. The whole scheme has few changes to the laser, which will not affect the performance of the laser. In particular, it can still maintain the same heat dissipation performance as the ordinary laser.

After the accuracy of the vertical direction is guaranteed, the primary alignment error is the two dimensions of the horizontal direction. Since the vertical coupler is longer, it is easy to tolerate ±10 μm or more in the longitudinal direction. A lateral tolerance of ±1.5 μm is also possible with appropriate design. This tolerance is much larger than the error of the current alignment equipment. The specific design will be introduced in detail in the third part.

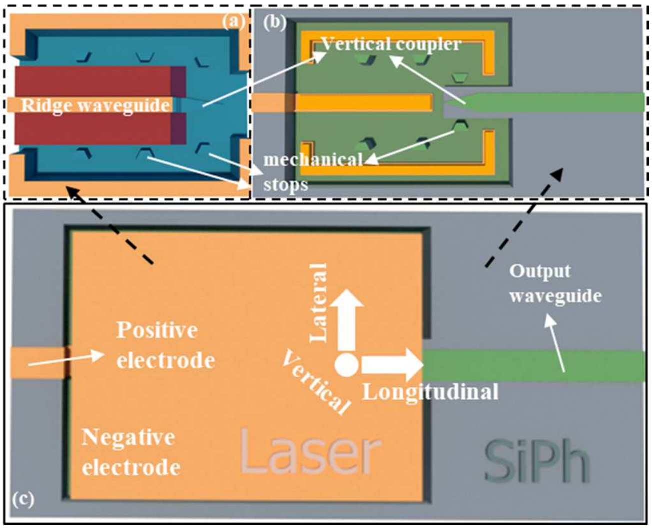

Fig. 1. Schematic diagram of the laser(a), SOI(b), and the whole(c).

B. Laser Structure

As shown in Fig. 1 (a), the laser is divided into an active region and a coupling region. Usually, the optical field of the laser is below the ridge waveguide. It cannot easily be coupled upward, so the ridge waveguide and quantum well layer in the coupling region need to be removed. The laser in this scheme adopts the offset quantum well structure to lower the light field [6], which has low transition loss and makes it easier to achieve a high output power. In the vertical coupler, the cover layer's thickness dramatically influences the coupling effect. To control the InP cover layer accurately, adding the InP wet-etched stop layer to the secondary epitaxial structure of the laser is necessary. The vertical coupling structures and

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mechanical stops are then etched together to ensure they have the same height. The entire laser requires only minor changes in the actual process, rather than the need to develop a new process, which is much less complicated than micro transfer-printing and wafer bonding. Therefore, realizing the integration of active and passive devices in mass production is more accessible.

C. SOI Structure

The structure of SOI is divided into two parts: cavity region and coupling region, as shown in Fig. 1 (b). The silicon waveguide layer and silicon oxide layer are removed in the cavity area, and Au-Sn is alternately deposited on the Si substrate. By controlling the height of the laser ridge waveguide or the thickness of silicon oxide in the SOI, the couplers can also contact each other when the ridge waveguide touches the substrate during bonding. The gold corresponding to the ridge waveguide in the SOI can be used for heat dissipation to ensure the device's thermal performance.

III. Scheme Verification

The structure of the coupling region is the primary design difficulty of this scheme, whose goal is to achieve maximum tolerance. The tolerance of alignment affects whether the scheme can be massively produced. For the alignment equipment with known accuracy, the larger the alignment tolerance, the easier to achieve a high-quality rate. The current equipment can achieve 0.3 µm alignment accuracy. On these premises, the coupler in this hybrid integration scheme is designed and schematically shown in Fig. 2.

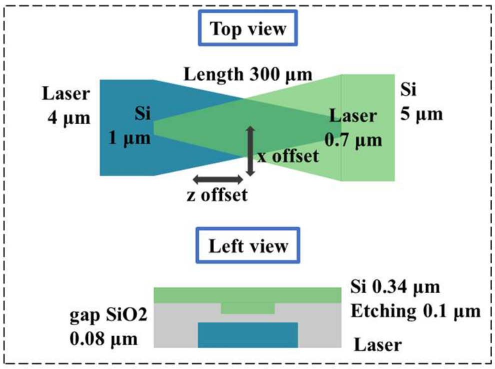

Fig. 2. The schematic diagram of the coupler structure.

In the coupling region, the laser waveguide is composed of the 1.1Q passive waveguide layer and the upper and lower InP cladding. The SOI waveguide consists of the silicon waveguide and the upper and lower silicon oxide cladding. The thickness of the passive waveguide, determined by the design of the laser, is 0.3 µm, and the upper InP cover is also 0.3 µm-thick. The thinning of the InP cap layer facilitates coupling but increases the loss from the source region to the coupling region. For easy coupling and single mode output, the 0.34 µm Si waveguide is etched 0.1 µm to form ridge waveguide. The thickness of the silica cap has a significant influence on the coupling. The thin silicon oxide makes the two waveguides not independent, which makes it easy for light to vibrate back after coupling. Thick silica makes it difficult for light to couple. Finally, the thickness of silica is selected as 0.08 µm after careful consideration. Then the taper is designed to achieve the adiabatic coupling effect.

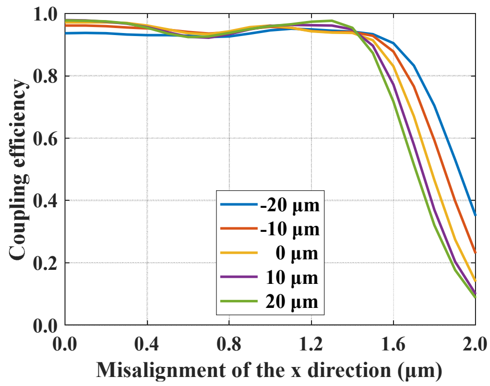

Fig. 3. Tolerances in the x and z directions.

Tolerances in the x direction are calculated under different z offsets, as shown in Fig. 3. It can be seen that the tolerance is ±1.5 µm in the x direction and larger than ±20 µm in the z direction with 90% efficiency as the limit. The longitudinal tolerance is much greater than the transverse tolerance because of the properties of the adiabatic coupler. The tolerance of the length of the coupler is shown in Fig. 4. The longer the coupler, the better the coupling, which means the device is longer and the transmission loss is larger. The coupling tolerance decreases obviously when the length is less than 200 µm. The tolerance of the silicon oxide cap thickness is shown in Fig. 5. Based on the current structure, the thicker the thickness, the smaller the coupling tolerance. The two waveguides interact when the thickness is small, and the coupling efficiency is very low when the error is small. In actual production, the thickness is controlled by plasma enhanced chemical vapor deposition (PECVD), which can achieve nm precision control.

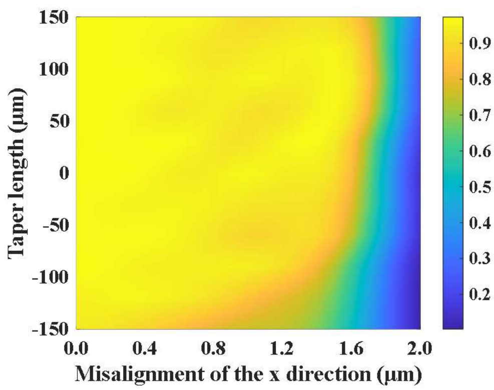

Fig. 4. The tolerance in x direction varies with the length of the coupler.

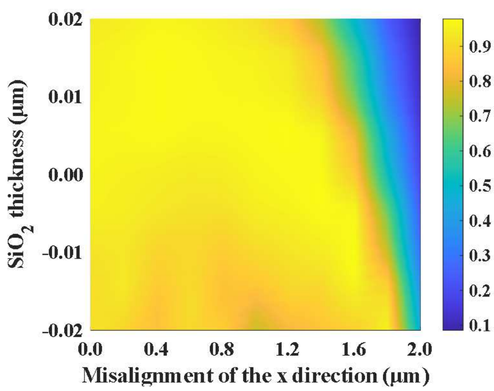

Fig. 5. The tolerance in x direction varies with the silica cap's thickness.

IV. CONCLUSION

This paper proposes a new hybrid integration scheme based on flip-chip bonding and vertical coupling. The hybrid integration scheme is elaborated on and compared with the existing schemes. A suitable coupler is designed to verify the feasibility of the scheme. Simulations show that a lateral tolerance of ±1.5 μm is obtained for the designed coupler, and the longitudinal tolerance is much larger than the lateral tolerance. Through the proposed scheme, the light emitted from the semiconductor laser can be coupled to the passive waveguide such as SOI, providing the light source for passive optical devices to make optical chips with excellent performance. In addition, the proposed scheme has a large tolerance and thus is easy to manufacture, which makes it a good solution for mass production.

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