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Passively Aligned Flip-chip Laser Diodes using Multi-axial Slide-stop Guided Design and Laser Assisted Bonding (LAB) on a CMOS-based Optical Interposer™

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Abstract
The incorporation of rectangular slide-stop structures improve post-bond accuracy by 1.6X achieving a best-in-class relative axial offset of 0.13μm. High-precision bonder with laser-assisted bonding capability enables heterogeneous integration of optical components with higher packing density due to a small heat-affected zone radius of 280μm.

Introduction

Silicon photonics (SiPh) has been considered the mainstay for the development of 800G and beyond optical communication technology [1]. As such, SiPh has seen increasing demand for applications in on-chip signaling and data processing. This is in part, due to its low latency, CMOS-compatibility, near-zero electromagnetic interference and the potential for large bandwidth.

To date, most photonic integrated circuits can be broadly classified to be homogenously or heterogeneously integrated. The former includes the epitaxial growth of III-V semiconductors or layer transfers on a Si substrate. So far, fabrication efforts have been hampered by defect dislocations brought forth by lattice mismatch and carrier annihilation. On the other hand, heterogeneously integrated systems appear to be more promising in the near term. Typically, singulated known good chips i.e. laser diode, modulators, etc. are "pick and place" assembled onto an interposer platform [2]. One main challenge for heterogeneous integration is the requirement for sub-micron alignment and post-bonding accuracy [3]. Our Optical Interposer solution presented here alleviates these challenges through the use of multi-axial self-guided slide-stop pedestals and precisely designed on-wafer fiducials.

Typical heterogeneous integration processes employ thermomechanical compression of a die onto a substrate. Thermal energy is supplied by both the bond tool and the bottom chuck. In this configuration, the entire Si substrate is generally heated at elevated temperature, near to that of solder melt temperature, for an extended time until bonding has been completed. As such, bonded temperature-sensitive materials could be prone to thermal-induced infantile failure.

Consequently, laser-assisted bonding (LAB) techniques have been increasingly adopted by photonics backend integrators [4]. This is driven by 1) shorter exposure time to elevated temperature and thermal shock and 2) minimal heat-affected zone (HAZ). As such, LAB can overcome bonding issues of materials with large thermal expansion coefficients and challenging thermal reliability.

In this work, we showcase using a multi-axial slide-stop guided design and LAB to accomplish flip-chip bonding of P-down passively aligned directly modulated laser (DML) diode array onto the world's smallest transmit and receive CMOS-based optical interposer™.

Results and Discussion

Approaches for passive placement of optical Components: Misalignment would often lead to coupling loss, stray light, and unwanted localized heating due to the need to increase input power for compensation. While it is a necessity in the case of imperfect bonding, the production of excess heat contributes to issues of lower-than-expected thermal rollover. One critical step to achieve passive placement of optical components is the use of precisely designed on-wafer fiducials coupled with an ultra-high precision die bonder as shown in Fig 1. The flip chip die re-place functionality during placement is strategically achieved by backside-frontside fiducials correlation.

Consistent sub-micron accuracy is demanded for the integration of laser diodes onto a photonic circuit. Subsequently, light produced by the laser is launched into a waveguide. Due to the waveguide design, as shown in Fig 2, misplacement of the laser in the lateral plane (x-axis offset) would cause significant coupling loss. In this case, a slide-stop guided design has been incorporated to address lateral offset (Fig 1D).

Minimising Heat Affected Zone (HAZ): Materials are differentially affected by heat [5]. During thermomechanical heterogeneous integration, components are typically integrated in

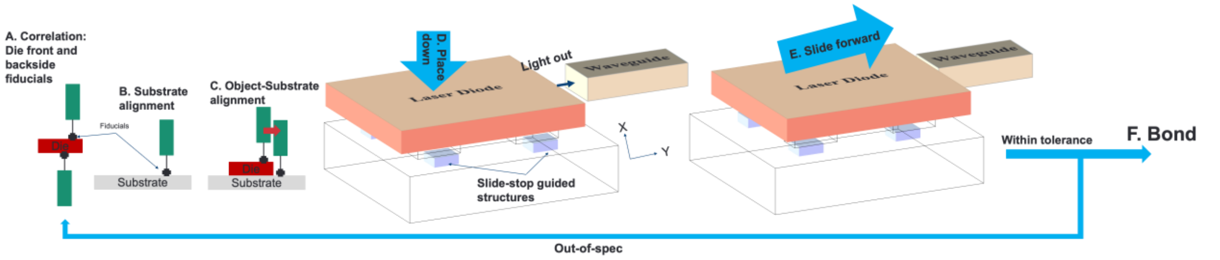

Figure 1 A-C,F) Bonding concept of a high-accuracy bonder with re-place capability in the case of out-of-spec, D-E) Guide-slide-stop design to improve passive alignment and bonding

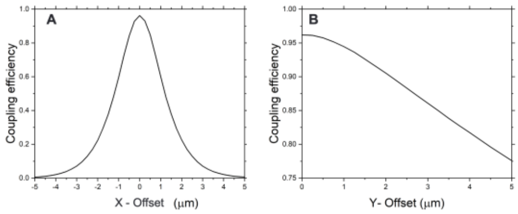

Figure 2 Simulated laser to waveguide coupling efficiency with respect to deviations from A) optical axis in X-axis and B) laser to waveguide gap

Specifically, the slide-stop guided design comprises a rectangular pedestal and a complementary cavity on the interposer and die, respectively. The design confers more confinement in the X- than the Y-direction. The snug fit along the x-axis is to prevent unintentional lateral movement during the place and bond steps. Furthermore, the snug-fitting design is to align the laser ridge to the waveguide to ensure the maximum launching of light into the waveguide. On the contrary, the additional space in the Y-direction allows 1) smoother glide-in during die placement while 2) enabling scrub motion to reduce solder voids and 3) facilitate laser diode slide-forward towards the waveguide to improve coupling efficiency (Fig 1E and Fig 2B). Finally, it is designed with to align the optical axis of the die in the Z-direction for efficient edge-coupling of light launched into the waveguide.

Equally important, the use of highly contrasted and precisely designed fiducials is of paramount importance (Fig 3). During die placement, the front fiducial will not be visible. However, the backside fiducial can be observed to determine the placement accuracy. Finally, the bonding process will proceed if the placement tolerance is within the intended specification.

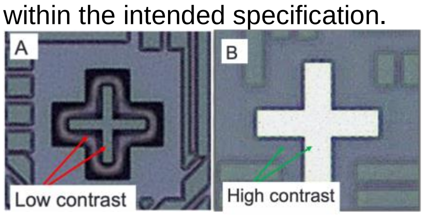

Figure 3 A) Low contrast and B) high contrast fiducials which can affect placement and bonding outcomes

descending order of thermal budget. To overcome this constraint, tightly confined HAZ can be achieved using LAB. It can be seen in Fig 4, for the processing of AuSn solders, the HAZ was confined to a region of approximately 280 μm in radius. The adjacent solder pad was unaffected by the zone heating. Also, the simulated heat spread profile confirms the result and shows the laser bars can be packed more closely together with spacing tolerance <300 μm to decrease the overall form factor. Moreover, the bonding time of LAB (<10s) is a fraction of thermomechanical bonding (1-3 min) thus mitigating the risk of thermal-induced infantile failure.

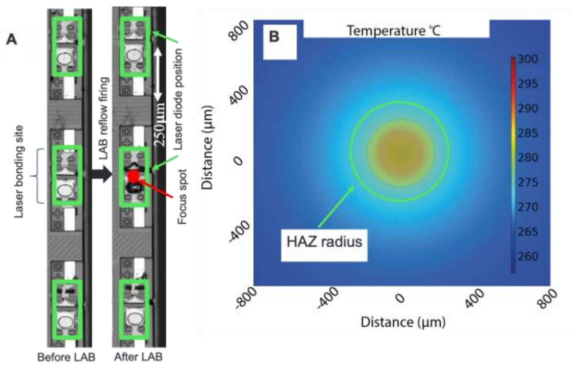

Figure 4 HAZ A) before and B) after melt test showing unaffected adjacent solder pads and C) simulated thermal gradient showing HAZ of radius 280 μm

Placement & Post-bond Accuracy Evaluations: To demonstrate the capability, the placement and post-bond alignment accuracy of approximately 600 devices are shown in Fig. 5. The placement accuracy spread of the laser diodes, with reference to "Unconfined_Place_X", was measured to be about 0.43 μm. With the incorporation of the slide-stop guide, the placement accuracy spread was improved to 0.27 μm.

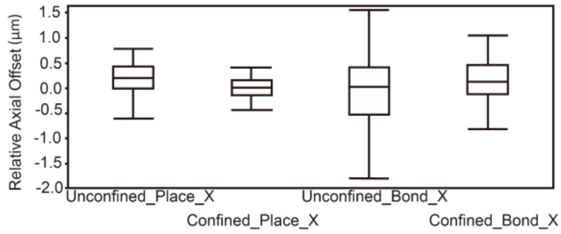

Figure 5 Improvement of placement and bonding accuracy in the absence (unconfined) and presence (confined) of the guide-slide-stop design by a factor of 1.7X.

Coupled with a smaller confined HAZ than thermocompression, the post-bond accuracy spread is enhanced by a factor of 1.6X. As shown in Fig. 6, with the multi-axial slide-stop guided design, the bonded laser diodes have demonstrated a median relative offset value of $x = 0.13\ \mu m$, $y = 0.09\ \mu m$ and $\theta = 0.007^o$.

A one-way ANOVA analysis has been carried out. Objectively, it is to understand the significance of the guide-stop design for die place and bond accuracy. It is shown that there is statistical significance between place and bond accuracy in the absence of the slide-stop structures ($p<0.0001$). On the contrary, a p-value of 0.08 suggests that the place and bond accuracy is not statistically significant with the incorporation of the slide-stop guided design.

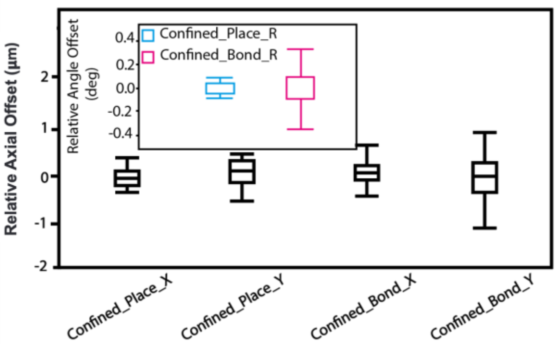

Figure 6 Achieved tolerance between pre- and post-bond in the X, Y and θ axes.

The alignment of the bonded laser optical axis to that of the waveguide is important for coupling efficiency. Thus, bonded lasers have been ion-milled to verify their siting above the guide-stop structure. As shown in Fig 7, the laser device is positioned perfectly on the slide-stop guided structure without measurable gap. Aside from that, the shear mode of a bonded sample indicated properly solder wetting.

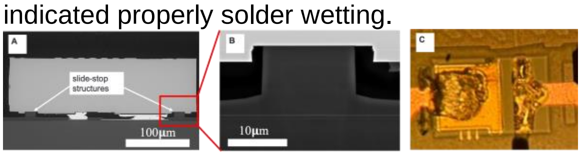

Figure 7 cross-section of bonded die-substrate and D) high-resolution image of guide-slide-stop with Z-height control.

To demonstrate the robustness of the multi-axial slide-stop guided design, DMLs (250 um x 150 um) have been bonded onto a transmit engine.

Product Demonstration: A DML diode array is depicted in Fig 8A. As shown, eight laser diodes are passively bonded onto a CMOS-based optical interposer™. Subsequently, the optical outputs of these laser diodes are analysed with a probe system. During testing, the samples are sited on a copper block and held at 50ºC. As shown in Fig 8B, the DMLs have coupled output power of approximately 4 mW at 50 mA. The performance of bonded samples has exceeded the requirement of -3.5dBm launch minimum power as spelled out in the multi-source agreement [6].

The measured optical output, without thermal rollover despite small form factor, suggests good bonding interfaces (electrical and thermal contact) between the laser diode and the optical interposer.

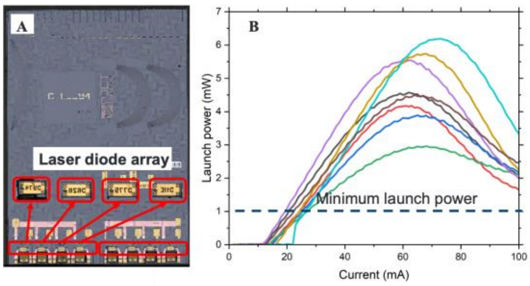

Figure 8 A) Bonded laser bank of eight diodes for long reach communication and B) measured optical performance of the mounted diodes

Conclusion

In this work, passively aligned flip-chip laser array of up to eight laser diodes has been bonded onto an optical transmit engine. This is made possible by the incorporation of a multi-axial slide-stop guided design. The bonding accuracy spread is improved by at least 1.6X. This demonstration illustrates the robustness of a slide-stop design when used in conjunction with an ultra-precision die bonder and with small confined zonal heating from LAB, a high bonding accuracy of active devices with a small form factor can be achieved without the need for active alignment.

Acknowledgements

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