Self-aligned Fiber Attach on Monolithic Silicon Photonic Chips: Moisture Effect and Hermetic Seal

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Abstract: We report a study on moisture effect on optical performance of monolithic silicon photonics technologies featuring V-grooves for self-aligned fiber attach. Chip-level hermetic sealing was achieved by implementing moisture barrier for the fiber coupler. **OCIS codes:** (130.3120) Integrated optics devices; (250.5300) Photonic integrated circuits; (250.3140) Integrated optoelectronic circuits.

1. Introduction

Silicon photonics (SiPh) leveraging mature CMOS manufacturing lines is the most competitive technology to deliver photonic integrated circuits (PIC) at large scale with low cost. GLOBALFOUNDRIES Fotonix™ platform has qualified two leading 300-mm monolithic SiPh technologies: 90WG and 45SPCLO [1]. The optical I/Os developed for these technologies are fiber couplers featuring V-grooves and meta-material spot-size convertors (SSC), which enables self-aligned fiber attach with low loss and high efficiency [2, 3]. An array of fibers can be passively attached to and simultaneously aligned with the PIC in parallel. This significantly reduces packaging complexity and improves manufacturing throughput. In the meantime, device and assembly reliability is critical in ensuring product long term stability, of which moisture impact is of particular interest as humidity is an inevitable environmental exposure for products deployed in field. Here we report a study on moisture effect on the fiber couplers on a 12-V-groove block where different fiber-to-PIC alignments can be controlled through varying V-groove widths. The high performance of the fiber couplers is then demonstrated on a product-like PIC with large sample size, followed by a rigorous test of implemented moisture barrier (MB) with excessive stress in ensuring technology robustness and high volume manufacturing (HVM) readiness.

2. Result and Discussion

The fiber coupler used in the monolithic platforms comprises a V-groove for self-aligned fiber attach and a meta-material SSC for minimized loss [2-4]. Fig. 1(a) shows the top-view schematic of a fiber in V-groove interfacing the fiber coupler. Two columns of vent holes are used to create undercut beneath the SSC to avoid optical leakage through the substrate. The meta-material SSC in-between the vent holes contains sub-wavelength silicon structures to achieve adiabatic mode conversion and improved fiber-to-PIC alignment tolerance [2]. Fig. 1(b) shows the cross-sectional schematic of the fiber coupler region with a fiber aligned with the SSC achieved by the V-groove with precise dimensions. Also shown is a MB that seals the cladding of the SSC, which is a critical layer to ensure the fiber coupler long term stability. The undercut below the SSC is subsequently filled with optical adhesive during packaging to further enhance optical performance. Fig. 1(c) is an SEM image of a V-groove interfacing a suspended coupler, and Fig. 1(d) shows a module with a fiber array passively attached to a 12-V-groove block on a SiPh chip.

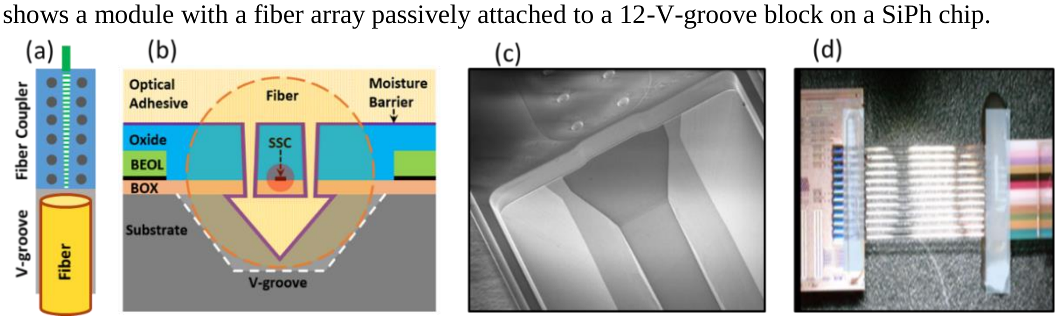

Fig.1. (a) Schematic of a fiber in V-groove interfacing with a fiber coupler with meta-material SSC. (b) Schematic of cross-sectional view of the coupler with the V-groove and the attached fiber. (c) SEM image of a V-groove and a suspended fiber coupler. (d) Optical image of a fiber array attached in a V-groove bank on a SiPh chip.

Moisture ingress into the cladding of SSC can cause refractive index (RI) shift hence performance degradation. The bottom cladding of the SSC is the buried oxide (BOX) which is a dense thermal oxide less vulnerable to moisture ingress. The oxide cladding above and surrounding the SSC is, however, a plasma enhanced chemical vapor deposition (PECVD) oxide due to temperature limitation in post BEOL processes, where tetraethyl orthosilicate (TEOS) is most commonly used for its fast deposition rate. It is known that PECVD oxide absorbs moisture which can cause refractive index (RI) shift [5, 6]. Fig. 2(a) shows RI distribution of a 200 nm TEOS film measured from 49 evenly distributed sites across a 300-mm wafer, characterized using ellipsometry at 1310 nm wavelength. The wafer was stored in a lab environment with ambient humidity for weeks before the measurement. A bake at 300°C for 2 hours was then performed to drive out potential absorbed moisture in the TEOS film during storage, followed by re-measuring the RI distribution. An average of 0.0067 reduction in RI was observed in post-bake measurement, indicating statistically significant sign of moisture absorption of the TEOS film during storage. This could have negative impact on fiber coupler performance if the TEOS cladding is left unprotected after deposition. Fig. 2(b) shows the wafer map of the measured post-bake RI, where a wafer center to edge distribution can be observed. Nevertheless, the distribution is remarkably tight. A range of 1.442±0.002 for the TEOS RI was achieved on the entire wafer.

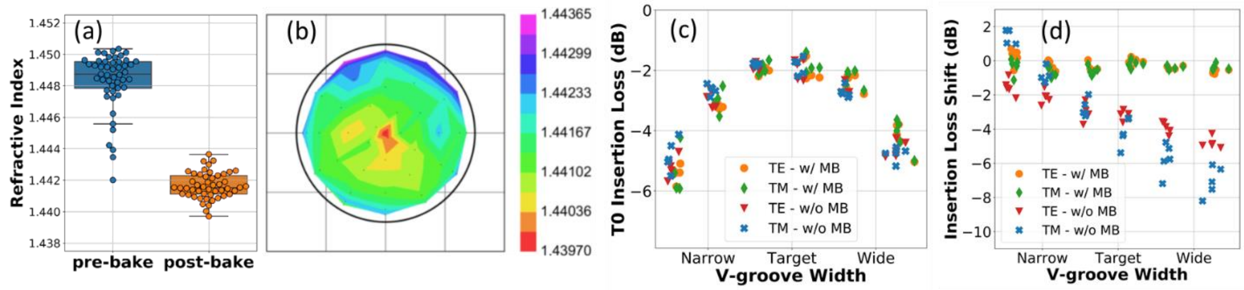

Fig.2. (a) RI of a TEOS film on a wafer measured before and after bake. (b) Wafer map of the RI post bake. (c) T0 IL for V-groove pairs with different widths. (d) IL shifts after 250 hours of damp heat stress.

To systematically study the moisture impact on fiber coupler performance, characterizations were conducted on a 12-V-groove block forming 6 loopbacks with varied V-groove pair widths, with 3 pairs narrower than target width and the other 3 wider than target. With passive fiber attach, the 3 narrower V-groove pairs would have fiber center higher than SSC center, defined as positive z-offset, whereas the 3 wider V-groove pairs would have negative z-offset. Samples with and without MBs were prepared for damp heat stress (85°C, 85%RH). Fig. 2(c) presents the O-band T0 insertion loss (IL), where both TE and TM show expected trend: larger z-offset yielding worse coupling loss. No clear difference was observed between samples with and without MB, suggesting the presence of MB has negligible impact on the T0 optical performance. Fig. 2(d) shows the IL shift after 250 hours of stress. Significant change was observed in samples without MB, with the widest V-groove pair having the largest IL shift. The degradation generally decreases with reduced V-groove width for both TE and TM polarizations. It is interesting to note that a slight improvement in IL was observed in the narrowest V-grooves for TM mode. On the contrary, no IL degradation was observed in samples with MBs, clearly demonstrating the effectiveness of MB in protecting the devices from moisture.

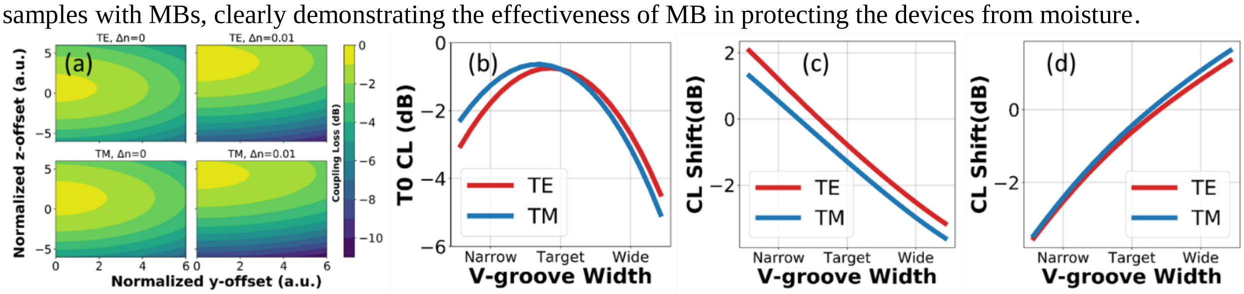

Fig.3. FDTD simulation result. (a) Fiber-to-PIC coupling loss simulation at different offsets. (b) Simulated coupling loss (CL) with different VG widths when $\Delta n = 0$. (c) Simulated CL shift when $\Delta n = 0.01$. (d) Simulated CL shift when $\Delta n = -0.01$.

To comprehend the observation, finite-difference time-domain (FDTD) method was employed to simulate the fiber-to-PIC coupling at different alignment offsets. Fig. 3(a) shows the simulation results. We assume $\Delta n = 0$, i.e., TEOS RI matching with BOX, at T0, and $\Delta n = 0.01$, i.e., TEOS RI increased by 0.01, after stress. At T0, the best coupling position is close to perfect alignment with targeted V-groove width. Deviation from that width would result in poor coupling, generating inverted U-shape curves shown in Fig. 3(b). It is consistent with experimental data in Fig. 2(c). A zero y-offset was assumed in this simulation. When TEOS RI increases, the optimal coupling position shifts up. As a result, the wider V-grooves with negative z-offsets, would have further coupling degradation, whereas the narrower V-grooves would benefit and show coupling improvement. This could explain the experimentally observed IL improvement in narrowest V-grooves. Also, this leads to increased degradation in coupling loss in wider V-grooves, as shown in Fig. 3(c), which is consistent with the experimental data in Fig. 2(d), except that the measured IL degradation is significantly larger than model prediction. Besides uncertainties introduced from the modeling assumptions, other source of discrepancy may include conversion loss from transmission through SSC, which is not captured in the fiber-to-PIC interface coupling model. Nevertheless, the model predicted a general trend consistent with experimental data. With moisture ingress, one can expect that the conversion loss would degrade overall, resulting in larger IL degradation for wider V-grooves than improvement in narrower ones, as observed in experimental data. In comparison, Fig. 3(d) plots the simulated coupling loss shift when the TEOS RI decreases by 0.01, where curves with positive slopes were generated. This trend is opposite to the experimental data, verifying that the moisture soak of TEOS film without MB protection caused RI increase instead of decrease, which is consistent with the RI measurement on the wafer before and after bake, as shown in Fig. 2(a), as well as the literature report [6].

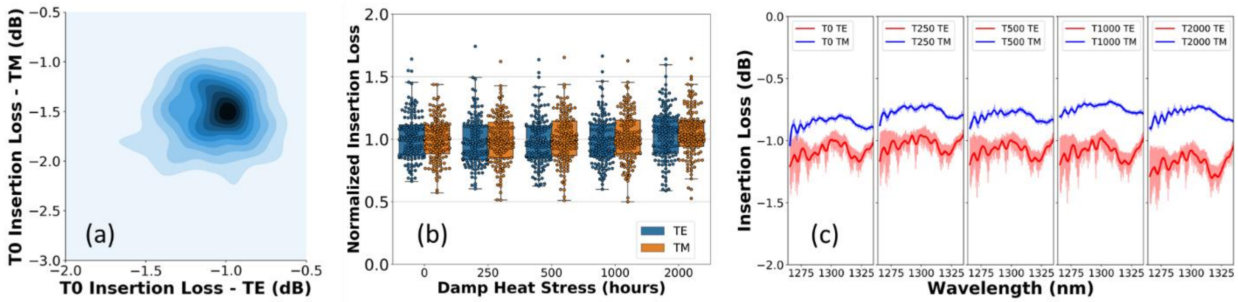

Fig.4. (a) T0 IL KDE joint plot for TE and TM. (b) Normalized IL during stress up to 2,000 hours. (c) O-band spectral profiles during stress.

To further ensure reliability of product PICs, similar stress and measurements were conducted on samples of 4 loopbacks from 12-V-groove block with targeted V-groove width. Standard cleaved fibers were used in self-aligned fiber attach assembly with optical adhesive fills. Fig. 4(a) shows the kernel density estimation (KDE) joint plot for TE and TM T0 IL, representing 864 ports out of 108 dies randomly selected from 8 wafers in 3 lots. This sample size is substantially larger than what we previously reported in the early reliability assessment (ERA) [3]. A better performance with median IL of 1.0 dB and 1.5 dB, peak performance of 0.6 dB and 0.7 dB, was also achieved for TE and TM, respectively. A subset of the hardware with 36 modules representing 288 ports were stressed up to 2,000 extended hours in damp heat. Fig. 4(b) plots the normalized IL at each stress readout, where both TE and TM polarizations show excellent stress performance without clear shift. The mean IL drift at each readout is less than 0.1 dB which is well within test variability. An example of O-band spectral performance is shown in Fig. 4(c), in which the spectral profiles maintained stability throughout the stress. Both results again demonstrate the effectiveness of MB in hermetically sealing the fiber couplers in product-like PICs.

3. Conclusion

In summary, we have qualified an optical I/O solution featuring V-grooves and meta-material SSCs. With self-aligned fiber attach on a PIC with a 12-V-groove block, median insertion loss of 1.0dB/1.5dB for TE/TM polarizations were achieved out of 864 ports. Moisture effect on the fiber coupler performance were extensively studied. It was found that, without moisture barrier protection, the coupling between fiber and PIC is significantly impacted by moisture induced refractive index increase of the oxide cladding. With moisture barrier protection, the fiber coupler showed excellent performance in excessive stress and test. Chip-level hermetic seal for the fiber coupler is achieved.

4. Acknowledgement

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5. References

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