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FABRICATION OF AVATREL PILLARS ON FUJITSU'S QUARTZ WAFERS

Final Report

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Summary

All phases of the project were completed. The samples were designed, test samples were fabricated, parts were fabricated, and materials were sent to Fujitsu for testing. Fujitsu performed the testing and evaluation. The work was performed in a collaborative manner with Fujitsu. The attached report is a summary of the fabrication, testing and conclusions and was written as a result of this project.

Flexible Pillars for Displacement Compensation in Optical Chip Assembly

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***Abstract*—In chip-to-chip optical interconnect systems with surface mounted light-sources and detectors thermal and mechanical effects can cause lateral displacements of the assembled devices. This displacement can result in optical signal losses that can critically deteriorate the bit-error-rate of the digital system. We demonstrate the use of flexible optical pillars with 150 µm height and 50 µm diameter. The lateral displacement tolerance doubles from about 15 to 30 µm for a given loss budget of 1 dB,. The pillars formed an air-free light path between the chip and the substrate and was fabricated from Avatrel polymer. The polymer pillars had excess losses less than 0.2 dB.**

***Index Terms*—Optical interconnects, optical assembly and packaging, waveguides, polymers**

I. Introduction

Optical technologies are of interest for interconnects in short-reach communication applications, such as board-to-board and chip-to-chip interconnects. A number of laboratory solutions have been proposed for high-speed chip-to-chip optical interconnects (OI) [1] and the technologies are maturing rapidly toward commercialization. The use of surface mount technology (SMT) can provide a robust and cost effective assembly for vertical-cavity surface-emitting lasers (VCSEL) and photo-diodes (PD) on OI substrates [2,3]. Chip assembly and displacement tolerances are among the critical issues as they make a strong impact on the cost of the OI modules and, thus, contribute directly to the competitiveness of the optical approach.

The bit-error-rate (BER) of a computing digital system is typically expected to be lower than 10^{-12} and, sometimes, even lower than 10^{-15}. Since the BER depends strongly on the detector sensitivity and the strength of the output optical signal, minimization of the total optical power loss of the OI module is of key importance for keeping the BER low. For example, an additional power loss of 1 dB can setoff the BER increase by several orders of magnitude (e.g., [4]). Thus, it is critical to have sufficient optical power at the detector, and to maintain the optical signal stability during the system operation.

In this work, test chips with flexible optical pillars were fabricated and the optical characteristics were measuremented. The results clearly demonstrate that the pillars significantly increase the displacement tolerances of the assembled chips with virtually no accumulated excess losses. The pillars significantly improve the stability of a chip-to-chip OI system operation.

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II. Results

The SMT chip assembly is schematically depicted in Fig. 1(a). The light couples directly through the air between the 45° reflector mirrors [5] of the substrate waveguides and the VCSEL/PD on the chip. Numerous thermal and mechanical effects, such as CTE mismatch, substrate bow, and chip bow, can cause lateral displacements of the chip relative to the substrate resulting in the optical power loss in the system and consequential deterioration of the BER. One way to improve the displacement tolerance is to mount microlenses or microlens arrays between the light sources and the substrate. [2,5] However, microlens fabrication, assembly, and alignment can add considerable cost to the OI module and also pose system design constrains such as the channel density, distances from the source to the waveguide mirrors, and underfill use.

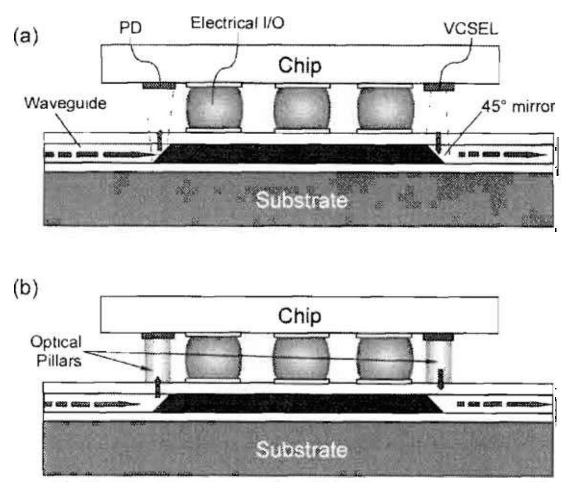

Figure 1 Schematics of optical chip assembly with the direct (a) and pillar assisted (b) light coupling between the VCSEL/PD and substrate waveguides.

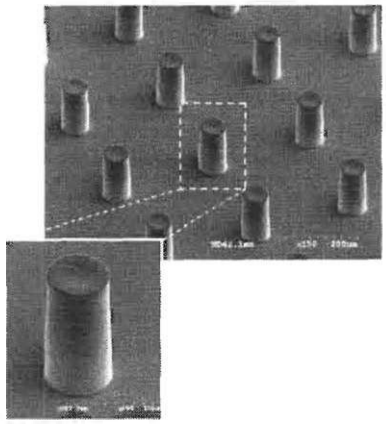

Figure 2 SEM images of Avatrel pillars with 150 μm heights and 50 μm diameters. The pitch is 250 μm.

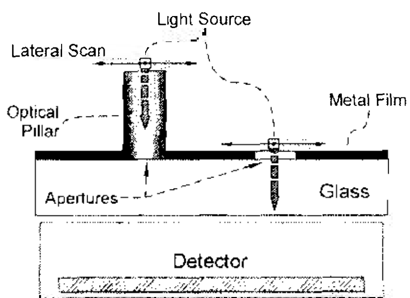

Figure 3 Testing structure for the pillar optical excess loss measurements.

Polymer pillars were recently introduced for the I/O interconnections in gigascale integration [6]. The pillar-assisted assembly of a chip is shown in Fig. 1(b). Although solid pillars have no advantages in terms of displacement compensation, flexible pillars can be used to accommodate lateral shifts in the components.

In this work, flexible optical pillars were fabricated from polynorbornene-based dielectric polymer Avatrel 2000P [7]. Various Avatrel has many attractive properties for dense photonic integration, such as photosensitivity, high transparency, good adhesion to a variety of materials, low stress, and low moisture uptake. Moreover, the low modulus (0.5 GPa) and high elastic flexibility make Avatrel a good candidate for highly flexible pillars. Pillars with aspect ratios at least up to 1:8 (height-to-diameter) were lithographically formed from Avatrel. The pillars had a diameter of 50 μm and height of 150 μm for the optical experiments reported below. The SEM images of some exemplary 50×150 μm Avatrel pillars are shown in Fig. 2.

The test chips were fabricated in the following process. 50 nm thick Ti/Au film was sputtered on a 500 μm thick glass substrate. An array of round apertures with a pitch of 250 μm were lithographically opened in the metal film. The Avatrel layer was coated on top of the metal film and the pillars were photopatterned matching the positions of the round openings in the metal layer. In this configuration, shown in Fig. 3, the light was launched into the pillar top perpendicular to the substrate. The light propagated through the pillar and the glass substrate and was captured by the detector mounted behind the test sample. Some of the metal apertures were left free of pillars so that the light transmission could be measured directly at the substrate surface, as illustrated at the right-hand side of Fig. 3. The light transmission through the pillar and substrate was compared to through the substrate only, to provide a measure of the pillar excess loss.

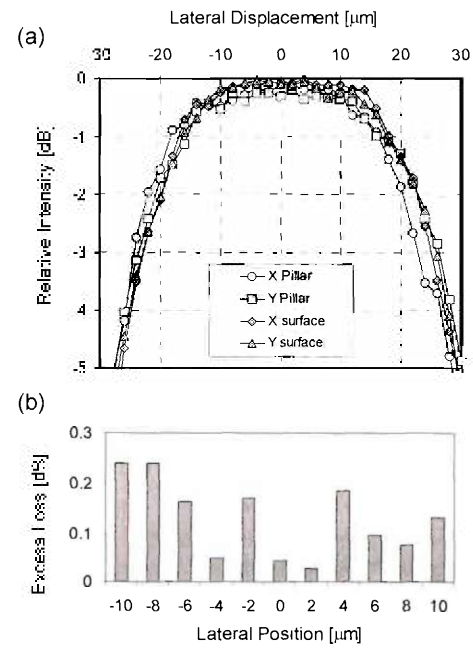

Figure 4 (a) Relative transmitted intensities as a function of the light source lateral displacement measured at the pillar top and directly at the substrate surface; (b) Pillar excess losses at different positions of the input light source.

The light source was a multimode VCSEL source at 850 nm wavelength. The pillar were irradiated with the 850 nm source via an optical fiber with a 50 μm diameter core . A mode scrambler in the light pass ensured a uniform light mode distribution at the pillar input. The position of the light source fiber output was scanned in lateral directions, X and Y directions. along the top surface of the test chip while the detector recorded the transmitted light intensity as a function of the lateral position of the source. The intensity as a function of lateral position along the top of the pillar and along the top of the aperture at the glass substrate surface is shown in Fig. 4(a). The transmitted intensities are normalized to the maximum transmission at the center of the open aperture without a pillar.

The pillar excess losses, shown in Fig. 4(b), were obtained by subtracting the relative intensities at different lateral positions in the X-direction for the pillar and no pillar cases from Fig. 4(a). The data presented in Fig. 4(b) shows that the pillar excess losses at ±10 μm lateral displacement does not exceed 0.2 dB. In fact, at the perfect alignment position (0 μm lateral displacement) has a loss of less than 0.1 dB. The uncertainty in the optical power loss measurements is approximately ±0.1 dB. Thus, for the 50×150 μm pillars, the excess losses are essentially negligible at the center of the pillar. At positions offset from the center of the pillar, the light intensity is less than 5% at ±10 μm lateral displacement.

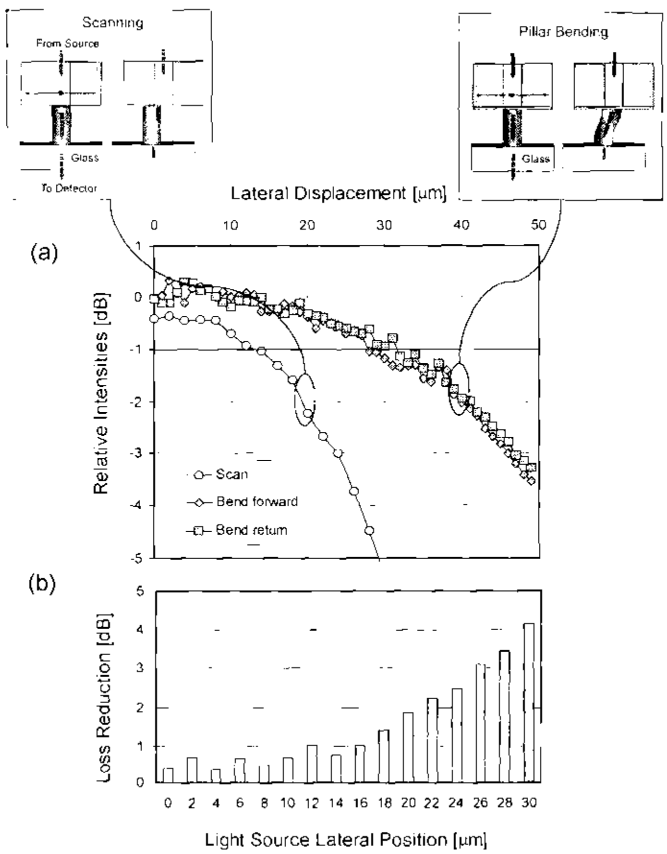

Figure 5 (a) Relative transmitted intensities for the lateral displacement of the light source in the cases of scanning and pillar bending which are visualized in the insets (b) Misalignment loss reduction by pillar bending.

The high flexibility of Avatrel allows the pillars to bend and stretch laterally which optically compensates for light source displacements with respect to the substrate. To quantify the pillar bending effect, two experimental configurations were uses, as shown in the insets to Fig. 5. In the first configuration, 'scanning', the light source was scanned laterally along the top of a straight pillar. In the second configuration, 'pillar bending', the light source was attached to the top of the pillar forming intimate contact between the optical fiber light source and the substrate. This configuration is equivalent to the pillar-assisted chip assembly shown in Fig. 1(b), where the pillar optically bridges the VCSEL and PD with the substrate waveguides. In the 'pillar bending' case, the lateral displacement of the light source causes sideway movement (bending) of the pillar. The pillar helps to keep the light confined in the pillar. and thus deliver a greater fraction of the incident light to the detector.

Fig. 5(a) shows the relative transmission intensity plotted versus the light source lateral displacement in the X-direction for the 'scanning' and 'pillar bending' configurations. Since the pillar and light source have radial symmetry the results in the Y-direction are identical to those in the X-direction. It is clear that the pillar bending range is limited by the elasticity of the pillar and its adhesion at the top and bottom surfaces. As shown in Fig. 5(a), the 50×150 µm pillar can bend 50 µm sideways. The optical transmission was measured during the pillar bending forward and also on its return to the original position showing no significant hysteresis. In device operation, the bending range will be less than tested here.

At zero lateral displacement, the 'bending' curve is about 0.2 to 0.3 dB higher due to the intimate contact of the optical fiber (air-free contact) minimizing the Fresnel back-reflection. Fig. 5(b) shows the loss reduction due to the use of pillar bending at different displacement of the light source. At displacements up to 15 µm, the loss reduction was less than 1 dB. The loss increases up to 4 dB at 30 µm displacement. As described in the introduction, the optical power loss can have a crucial effect on the BER of a digital system. Thus, a limited loss budget is allowed for system misalignment to maintain error-free operation. Fig. 5(a) clearly demonstrates that for a given loss budget, e.g. 1 dB, the 50×150 µm flexible pillars double the displacement tolerance from less than 15 to about 30 µm. The 4 dB pillar-assisted loss reduction at 30 µm displacement can easily decrease the BER by 10^4 or more.

III. Conclusion

Test chips with Avatrel pillars 150 µm in height and 50 µm in diameter were fabricated by direct photopatterning on glass substrates coated with metal-film, open apertures for light transmission experiments. The optical characteristics of the pillars show that the air-free connection to the pillars have an optical power loss less than 0.2 dB. The ability of the pillars to bend significantly improves the displacement tolerance of the assembled parts. The displacement tolerance was doubled from 15 to 30 µm in the case of the 50×150 µm pillars. Pillars with larger aspect ratios and smaller diameters can provide even higher displacement compensation in dense chip-to-chip OI modules.

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