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Reliability of adhesive bonded optical fiber array for photonic packaging

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In this paper, we investigated the environmental and mechanical reliability of adhesive based fiber array with reference to the Telcordia requirements. We found that the coefficient of thermal expansion (CTE) mismatch and surface contamination on the bonded surface were two critical causes for degradation in reliability of such components. Two types of adhesive with different CTE were used for assembling of fiber arrays to demonstrate the significant of these effects. By applying plasma cleaning technique to remove the surface contamination, we showed that the adhesion strength and consequently the reliability of fiber arrays were significantly improved.

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Keywords: Fiber array, Reliability, Delamination, core pitch deviation, Coefficient of thermal expansion (CTE) mismatch, Surface contamination and adhesion strength

1. Introduction

Planner lightwave circuit (PLC) technology based optical communication offers the advantages of low cost, ease in handling, highly reliable, multi-functionalities, low loss characteristics and high production through-put. A popular type of PLC is the arrayed waveguide grating (AWG) [1]. Many techniques can be used to create such optical devices on silicon wafer [2]. To complete the manufacturing of such devices that can be interconnected with others in a telecommunication network, individual PLCs must be cut from the wafer and fibers must be attached to the input-output (IO) ports. However, the approach needs to align each individual fiber to its corresponding IO port of the chip. This approach is desirable especially when the port count is very large. Moreover, its major drawback is the coupling problem between IO ports of the chip with fibers [3]. The simplest way to attach fibers to a multi-channel PLC is to first build a fiber array. Without fiber array it is difficult to align each individual fiber to its corresponding IO port of the chip. Thus the fiber array is a key component in next generation optical communication networks, enabling higher dense wavelength division multiplex (DWDM) channel counts than ever before [4].

An optical fiber array comprising a holding member which consists of a substrate forming a sectional V shaped groove for housing an optical fiber on a top face. The optical fiber having a fiber tip end bare portion need to house in the said holding member. It can be fabricated by placing individual fiber in the high precision V-groove with another flat slide on top of it for anchoring optical fiber(s) on precision engineered structure. Figure 1 is the schematic cross-section of such a fiber array, where 16 fibers (typically a number of 8, 16, 32 & 48 etc) are fixed on a V-groove fiber block for sub-micron positioning accuracy. Thus a fiber array functions as an effective coupling media to launch optical signals in and out the ports of a PLC chip.

There are three typical methods in fixing fibers to optical chip. They are soldering, laser welding and adhesive bonding. Among all those approaches, adhesive bonding tend to be popularly employed in mass production, because they offer the advantages of lower production cost, lower influence on PLC performance, the ability to bond different materials, light weight and flexible curing methods for different applications [5]. The adhesive used in our study is for anchoring the bare fiber, cover plate and substrate. As a result, the whole fiber package becomes a composite structure, the glass/silica core and the plastic buffer/adhesive may each respond differently to a variety of environmental factors and thereby adversely affect. For example, the above described fiber array when being placed under outdoor severe condition such as dry environment like a desert or humid high temperature situation. In this case, the fiber array will be subjected to a high temperature of about 100°C to a low temperature of about -40°C for a long time. So there is a chance to occur a phenomenon that the substrate & the cover plate fixing the optical fibers may displace due to the variation in adhesive properties resulting in unreliable fiber packages [6]. Therefore, the optical fiber array process capable to withstand such severe environment must be developed in order to maintain constant and proper characteristics for a long time. They must have to be rigid and dimensionally stable over a range of operating temperatures. However, such study on adhesive based low cost packaging seems to receive much less attention from the researcher before.

Nowadays, the continuous effort is paying to improve the characteristic of adhesive for packaging the fiber array. When packaged, the coefficient of thermal expansion (CTE) of the fiber, epoxy and V-groove have to be well matched. As there is a difference in CTE among the constituent materials, stress & strains in the packages are

bound to occur. And the stress concentration of the adhesive in the V-groove caused by these phenomena cannot sufficiently adopt by the thin adhesive layer. The stress caused by the adhesive increases particularly with larger CTE mismatch and higher young modulus of the adhesive [7]. Alternatively, increasing humidity causes expansion and relaxation of the adhesive [8]. Any misalignment among the optics will cause optical loss, resulting in out-of-specification. Any contamination on the bonded surface may weaken the adhesion force resulting in poor performance. It is not difficult to realize when such phenomenon occurs, an optical fiber may readily slip off from the substrate due to adhesion failure [6]. Therefore, developing suitable fiber array to minimize such deterioration, delamination, cracking or peeling out is very essential.

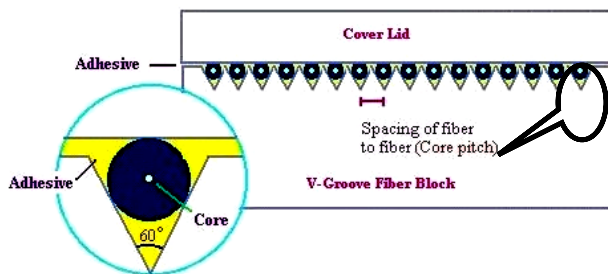


Fig. 1. Schematic cross-section of 16 Channel fiber array

Our previous studies find that the performance of such adhesive based fiber packages mainly depends on the optimum curing of adhesive, coefficient of thermal expansion and the adhesion properties of the constituent materials. The adhesive should be optimally cured to minimize the stress generation, induced delamination or adhesion failure. Moreover, the uneven curing induced delamination of fiber array was reported [9-10]. In this study, we found that even after optimum adhesive curing, delamination and degradation in performance were still observed due to the CTE mismatch and low adhesion force owing to the surface contamination. Therefore, the reliability issues due to the CTE mismatch and ways to improve the adhesion force by the plasma cleaning of the substrate are discussed in this paper. We believe our study will provide valuable information for manufacturers to optimize the materials and fabrication process to produce highly reliable optical fiber array for photonic packaging.

2. Experiments

The experiments mainly divided into two parts; fabrication & reliability test of fiber array and adhesion improvements of adhesive bonded silica slides. Fig. 2 shows the schematic of the whole experimental steps.

2.1 Fabrication of fiber array

2.1.1 Materials for fiber array

The fiber array packages are mainly made up of four different parts: the V-groove, fibers, adhesive and lid glass [10]. The V-grooved fiber blocks are prepared using the current state-of-art of micro-fabrication process by either anisotropic etching or precision machining [6]. Both the V-groove & lid glass can be made of quartz, offering an advantage that light can be exposed for adhesive curing from both top & bottom side of the V-groove. The size of the V-groove is appropriate for a fiber with a cladding diameter of 125 μm. The V-groove is symmetrical about a vertical plane and the pitch is 250 μm. The cladding and core material of fiber used is fused silica and 5wt% GeO_2 (Germanium oxide) – doped fused silica respectively. The refractive index of cladding and core material are 1.48 and 1.49 respectively. The adhesive used in this study is epoxy based polymer supplied in the form of reactive, cross-linkable monomer blends, which polymerize on exposure to radiation of an appropriate wavelength. Two types of UV curable adhesive with different CTE were selected for the reliability test of the fiber array assembly. Table 1 shows the typical properties of packaging materials in fiber array assembly.

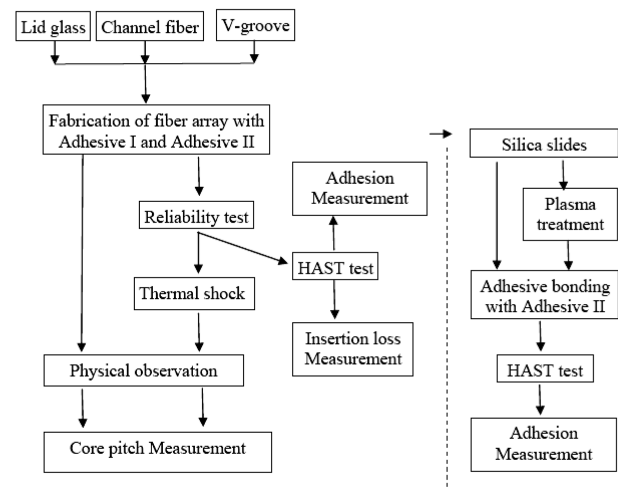


Fig. 2. Schematic of the whole experimental procedure

Table.1 Typical Physical properties of fiber packaging materials.

Parts	Material	CTE (ppm/°C)	T_g
Cover Lid	Quartz	0.55	-
V-groove	Quartz	0.55	-
Fiber	Silica	0.55	-
Adhesive I	Epoxy	55	145
Adhesive II	Epoxy	10.7	129

2.1.2 Fiber packaging

The procedure to assemble the fiber array for our study is described below. The acrylic coating of fiber was first stripped. Then 16- stripped fibers were inserted into the V-groove and the lid glass was placed on them, seating them firmly into the V-grooves. After the fibers were seated, low viscosity UV curable adhesive was applied to the leading-edge notch of the substrate. The adhesive wicks down the length of the V-grooves and underneath the fibers by capillary forces. Adhesive bonding occurs as a direct result of irradiation form an UV light source (EFOS N2001-A1 Novacure UV Spot Curing Light Source) for optimized curing condition. The UV curable adhesive was pre-cured by low intensity UV curing, then thermal post curing was applied for raising the adhesive glass transition temperature to increase the reliability. Upon curing, the fibers were permanently bonded into place. Fig. 3 shows the appearance of the bonded fiber array packages. The end faces of the fiber arrays are polished to remove the excess amount of adhesive from the fiber end [10].

Fig. 3. Appearance of the bonded fiber array packages.

2.2 Reliability study

2.2.1 Thermal shock

The fiber arrays assembled by Adhesive I and Adhesive II respectively were performed separately thermal shock based on Telcordia GR-1221-CORE requirement [11]. During the test, the specimens were alternately soaked in the cold (0°C) and hot (100°C) liquid bath for 15 cycles. And the exposure time for both temperature extremes was 5 min, with a transfer time less than 10 seconds.

2.2.1.1 Physical observation: Optical microscope was used to observe the defects such as the delamination problems within fiber arrays.

2.2.1.2 Core pitch Measurement: The core-pitch separation of fiber array is an important parameter to evaluate the quality and reliability for further application in PLC packaging. The core-pitch evaluation system (core-pitch Pro.ECOP-1) is used to precisely measure the linearity and pitch spacing of two fiber cores. A white light source is used to illuminate each fiber array for core-pitch measurement. The illuminated fiber cores are observed by the monitor. An optical profiler is used to detect the X-Y coordinates for each fiber cores by utilizing two CCD cameras. And two laser interferometers measure the number of fiber cores, its traveling position and distance in micron level accuracy. Then the core pitch separation of fiber array is precisely calculated by the pitch linearity of all the fiber cores [12].

2.2.2 Highly Accelerated Stress Test (HAST)

Highly Accelerated Stress Test (HAST) was performed to evaluate the temperature and humidity resistance of the optical adhesives used in fiber array. HAST is also called the Pressure Cooker Test (PCT). The major differences HAST from other general evaluation tests are that the temperature is set above 100°C with humid environment and the test is performed in an atmosphere with a high density of water vapor. The purpose of HAST is to accelerate moisture penetration into the internal parts of the devices by raising the water vapor pressure inside the test chamber to a level drastically higher than that inside the specimen in order to evaluate it's resistance to humidity [13]. In our case, the reliability of the bonded fiber array was tested at a HAST condition of 121°C/100%RH/2atm for 8 hrs.

Insertion Loss Measurement: The IL (Insertion loss) of all samples under HAST tests were measured by using an optical loss analyzer before and after the test. And the insertion loss was measured by fusion splicing optical fibers method in 1.55μm wavelength [14]. The measurement accuracy is less than ±0.05dB. In order to investigate the extent of delamination between cover lid and V-groove fiber block, a loading force was applied on the cover lid of the sample to observe any change in delta IL. The significant change between the two readings indicates a severe delamination between the cover lid & the V-groove block due to the CTE mismatch or surface contamination induced degradation.

2.3 Adhesion improvement

Plasma treatment process is one of the commonly used methods to remove surface contamination of substrate. In addition, this process may also be used to improve surface roughness for enhancing adhesive bonding as well as minimize the delamination [15]. To understand such surface cleaning effect, quartz silica slides were used instead of real fiber array products to save the experiment cost. The silica slides were cleaned with optical cleaning agent, distilled water and alcohol by ultrasonic cleaner. Then some slides were subjected to plasma treatment system using March AP-1000. In order to understand the surface improvement for optimized plasma treatment condition, AFM (Atomic Force Microscope) was used to measure the surface roughness. Two silica slides of same surface conditions were bonded

with adhesive. Paper tapes were used to control the adhesive thickness of 200 μm. In order to investigate the reliability, samples were also subjected to HAST with the same condition of fiber array mentioned in previous section; 121°C/100%RH/2atm for 8 hrs. Shear test was performed to evaluate the adhesive force by Instron Corporation Mini44 Universal Tensile Tester as shown in Fig. 4.

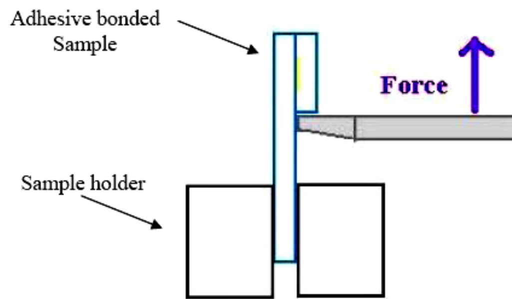


Fig. 4. Schematic instrumental arrangement for measuring the adhesion strength.

3. Results and discussion

A fiber array is mounted in a V-groove with a lid glass by an adhesive, and is formed in its complicated shape [16]. Thus, there exists a variety of stresses due to mismatch in the properties of constituents materials [17]. The coefficient of thermal expansion (CTE) mismatch is one of the examples and therefore investigated. Such stresses ultimately initiate the delamination during the temperature alteration and degrade in performance. The results obtained from the reliability test are as follows:

3.1 Effect of thermal shock

Thermal shock test was performed in order to observe the changes caused by the differing CTE of the materials composing in fiber arrays. These changes were observed by exposing specimens alternately to extremes high and low temperatures within a short period of time for number of cycles. Then the fiber array was characterized by the physical observation and core pitch measurement. The results are as follows:

3.1.1 Physical observation

After subjected to Telcordia tests, the pass criteria for the fiber array product should be no physical damage such as adhesive failure between cover lid & V-groove fiber block, fiber breakage, cracks, fiber pullout, cable jacket damage and delamination. Before the thermal shock, there is no such physical damage or delamination in the fiber packages. Fig. 5(a) and 5(b) shows optical microscopic figures of such delamination free fiber package by using Adhesive I and Adhesive II respectively. After thermal shock test, all samples under tests were also inspected visually to make sure about the physical damage. Fig. 6(a) and 6(b) shows such delamination between V-groove fiber block shoulder & cover lid for both Adhesives I and Adhesive II respectively. The extent of delamination seems much larger for Adhesive I than that of Adhesive II.

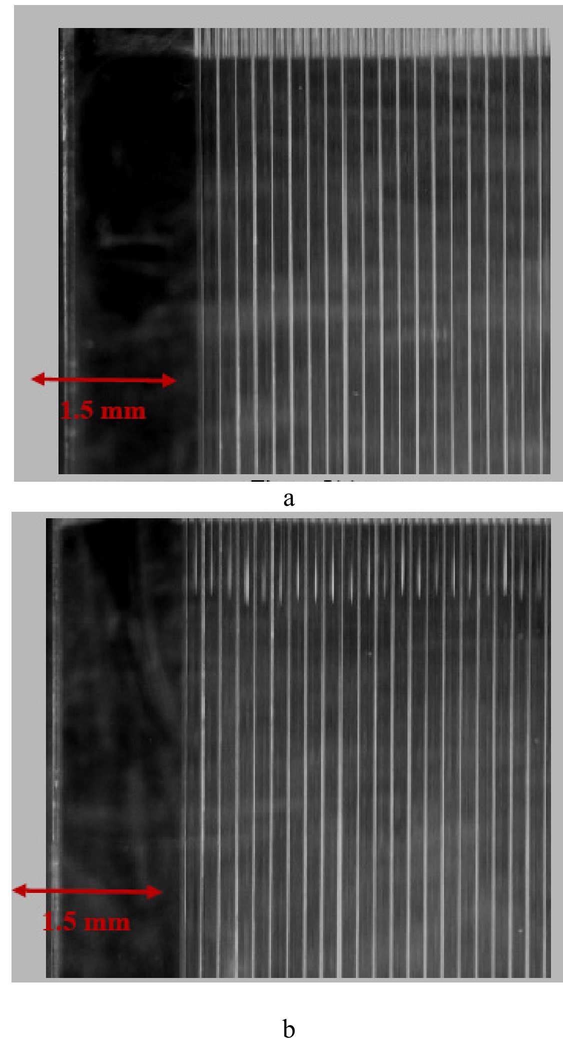
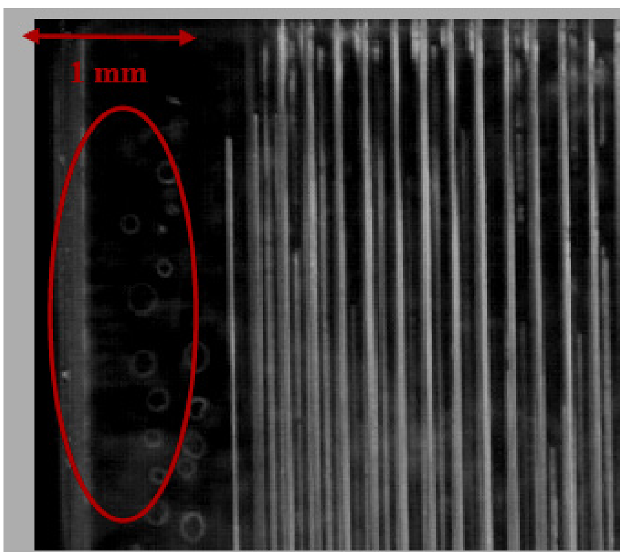


Fig. 5(a). Optical microscopic figures of delamination free fiber package by using Adhesive I, (b). Optical microscopic figures of delamination free fiber package by using Adhesive II

<u>Causes for delamination:</u> During thermal shock test, due to the temperature change the elongations or contractions are different for different materials. As a result, thermal stresses and strains are induced at the packages, which eventually cause interfacial delamination at the bonded interface [18]. Due to large CTE mismatch between the bonding adhesives and quartz, it induced thermal stress at the bonded adhesive interface. In worse cases, after a long term repeated temperature fluctuations, this interfacial delamination results in mechanical failure and severely degraded in optical performance. Since the CTE of Adhesive I is almost 100 times larger than that of quartz (substrate materials) and silica (fiber materials),

therefore it exhibits CTE contraction 100 times larger at low temperature. On the contrary, it also expands 100 times more at high temperature of 100°C. Since the CTE mismatch of Adhesive I with quartz is greater than that of Adhesive II, we can expect the delamination problem of Adhesive I should be much severe than Adhesive II. Therefore, CTE mismatch effect should minimize by selecting the appropriate materials in the packaging of fiber array.

a

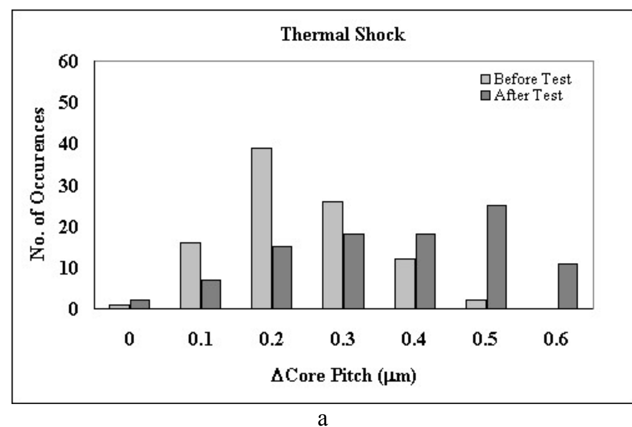


b

Fig. 6(a). Optical microscopic figures of delamination induced fiber package by using Adhesive I, (b) Optical microscopic figures of delamination induced fiber package by using Adhesive II.

3.1.2 Core pitch measurement

In addition to the physical inspection, it needs to measure the delta core pitch in order to investigate whether the core pitch of each channel is altered due to thermal shock. The sample size of each test is 11, which based on LTPD 20% requirement [19]. Before the thermal shock test, the delta core pitch was within the product specification of 0.5μm. However, after the thermal shock test, delta core pitch was increased up to 0.6μm. Figure 7(a) and 7(b) shows such delta core pitch measurement results for both adhesives I and adhesive II respectively. It can be observed that the number of fiber channel exceeding the 0.5μm limits of delta core pitch for fiber array using Adhesive I was much larger than that of using Adhesive II. This is because the CTE mismatch is larger that that of Adhesive II. In order to minimize the delta core pitch in fiber array assembly, we recommend selecting those bonding adhesive, which has a closer CTE with the bonding substrate.



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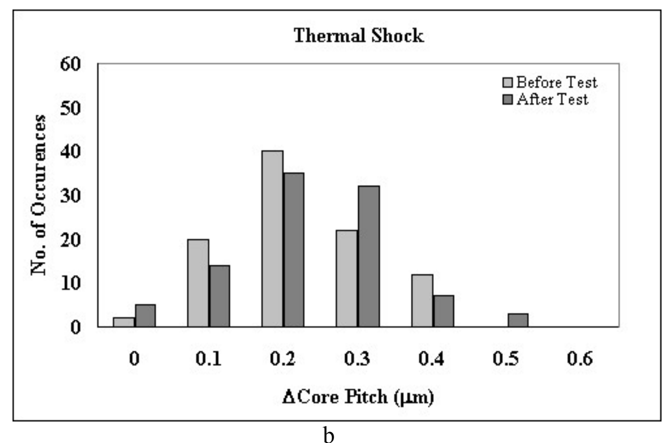


b

Fig. 7(a). Delta core pitch distribution of fiber package before and after thermal shock test by using Adhesive I, (b). Delta core pitch distribution of fiber package before and after thermal shock test by using Adhesive II.

3.2 Effect of Highly Accelerated Stress Test (HAST)

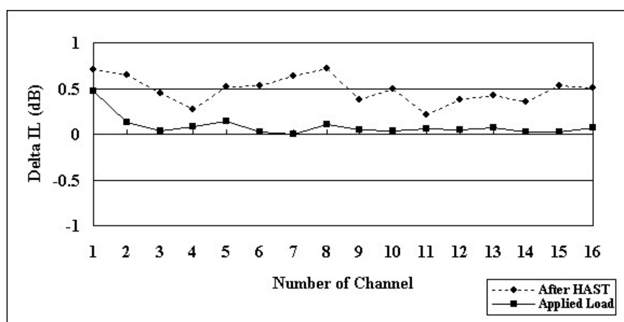
Highly accelerated stress test (HAST) was performed to evaluate the temperature and humidity resistance of the optical adhesive used in fiber array. The effect can easily be evaluated by measuring the insertion loss of the fiber array.

3.2.1 Delta insertion loss (IL) measurement

The insertion loss (IL) is the most important parameter to determine the optical performance of passive optical splitters. IL of passive components included the amount of light has been absorbed, scattered or reflected after device insertion. The IL in logarithmic terms is defined as the ratio of transmitted power to incident power [14]:

$$IL_{dB} = -10\log\left(\frac{P_{transmitted}}{P_{incident}}\right)$$

The delta IL is defined as the difference insertion loss (IL), before and after the reliability test. Fig. 8(a) and 8(b) shows the delta insertion loss distribution of fiber package with/without applied load by using for Adhesive I and Adhesive II respectively. The delta IL, when using Adhesive I as bonding adhesive, are larger than that of using Adhesive II. Again when a load was applied on top of the cover lid, there was a larger drop in the delta IL for sample using Adhesive I than Adhesive II. This suggested that severe delamination has occurred in fiber array when using Adhesive I for bonding.



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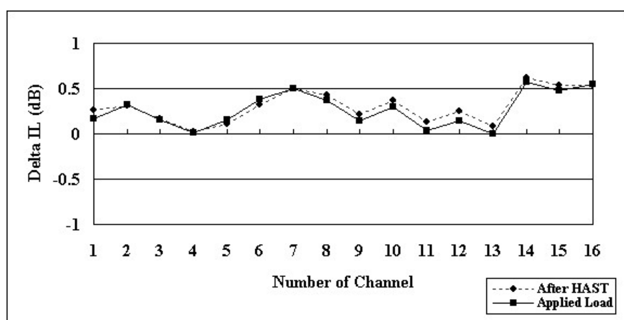

b

Fig. 8(a). Insertion loss distribution of fiber package after HAST with/without applied load by using Adhesive I, (b). Insertion loss distribution of fiber package after HAST with/without applied load by using Adhesive II

In HAST, the water molecules tend to diffuse through the package, however if there is a certain amount of contamination availability on the bonded surface, an osmotic pressure is built up at the region. The water molecules then tend to diffuse to the interface of cover lid and V-groove fiber block. The physical adhesion between cover lid and V-groove fiber block is also degrading when the distance between hydrogen atoms and oxygen atoms becomes larger. This distance is enlarged by stress (due to absorption of water by the bonding adhesive), by the higher temperature (molecule chains of the epoxy become more mobile) and by local osmotic pressure [15]. Increased water accumulation at the bonded interfaces results on greater degradation between the bonded interfaces, which eventually cause detachment. The significant change in the delta IL of sample using Adhesive I after added pressure on the cover lid also indicates that the adhesion strength of Adhesive I was greatly degraded. The temperature & moisture resistance of the sample of Adhesive II is found much better than Adhesive I. Therefore in the subsequent section, only Adhesive II was used for further investigation, which had a closer CTE with other constituent materials. In general, it is slightly difficult to find adhesive which has identical or nearly same CTE with FA parts. Thus, delamination due to CTE mismatch cannot be completely eliminated. One alternate solution is to increase the adhesion strength between the bonding interfaces through modification of bonding surface so as to counteract the stress induced by CTE mismatch problems.

3.3 Adhesion improvements by plasma cleaning of the substrate

Although the samples of Adhesive II passed in HAST, we found that delamination still occurred in thermal shock test. This is because the adhesion strength was decreased after HAST. The adhesion force measured before and after HAST in according to the section 2.3 were 14.28 N/mm^2 and 4.28 N/mm^2 respectively. There was a significant drop of adhesion strength by about 70% during the HAST. This is mainly due to surface contamination on the substrate. If there is a certain amount of contamination on the substrate surface, an osmotic pressure is built up at the region during HAST and initiate the delamination. The adhesion also depends strongly on hydrogen bonds between the oxygen atoms on the quartz layer and the hydrogen atoms of the bonding adhesive. In a contaminated surface less hydrogen bond may be formed between the cover lid and V-groove fiber block and causes to decrease the adhesion strength. Hence, the total adhesion depends strongly on the cleanliness of the quartz surface and the availability of oxygen atoms to form hydrogen bridges.

Contamination mainly caused by rough process control or environmental exposure, which present in the form of residues, mold release agents, anti-oxidants, carbon residues or other organic compounds on the bonding surface. The problem greatly caused degradation on the bonding surface in photonic packaging. In order to eliminate the delamination problem and enhance the adhesion for Adhesive II bonded fiber array, plasma

treatment based surface modification was used for surface cleaning and increasing surface roughness before bonding. Plasma's physical and chemical energy can be used to remove micron-level contamination. Roughening of the surface can increase the total contact area at interfaces, which significantly increase the adhesion between the adhesive and the substrate [20].

Shear test was performed to evaluate the adhesion force of plasma treated substrate after HAST test. In our study, quartz slides were used instead of real V-groove substrate. Table 2 summarizes the shear test results based on different plasma process gas and conditions. According to the shear test results, a combined physical-chemical process using Ar and O_2 gases can increase the adhesion force at the bonding interfaces. Physical reactions are generated with the use of noble gases such as Argon (Ar). Since the monatomic state of inert gases is a kinetic energy transfer reaction, the bombardment of positive ion caused ablation on the surface. This process can dislodge contamination from the surface, and can roughen the surface on an atomic scale. The chemical process is widely employed to remove a few microns layer of residual materials, such as organic films and oxides. The chemical process employs either reduction or oxidation chemistry via the gas-phase radicals. Oxygen plasma is commonly used for removing organic residues on the bonding surface, which causes a chemical reaction with surface contaminants resulting in their volatilization and removal from the plasma chamber. When exposed to the RF energy field, oxygen (O_2) is broken down into monatomic oxygen O, O+ and O-. O at pressures above 100mTr is the most reactive element in the plasma and will readily combine with any organic hydrocarbon. The resultant combination is water vapor, CO and CO_2, which is carried away in the vacuum stream [20].

Table 21 Shear test results of adhesive bonded silica slides after HAST for different surface treatment.

Gas	Pressure (mTr)	Power (W)	Time (mins)	Adhesion Force (N/mm^2)
Without any plasma treatment				1.8
Ar + O_2	200	200	30	3.6
		400	15	4.24
	300	300	15	4.77
	400	200	15	5.32
		400	30	5.82

Sufficient RF energy must be applied to produce a high plasma density because low power densities may decrease the removal rate and impede the removal process. The shear force of bonding adhesive increased with higher gas pressure and RF power in plasma treatment system. The optimized condition was applied 400mTr Ar gas with 400W RF power for 30mins. Moreover, the bonding surface of the sample with optimized plasma treatment condition was roughened 47.2Å according to AFM measurement. These provide a larger surface area for bonding, resulting in improved surface adhesion at interfaces. Thus, the optimized plasma treatment condition can be employed in fiber array assembly process, which can enhance the adhesion between adhesive-quartz interfaces and improve the long-term reliability of fiber array products.

4. Conclusions

The reliability of adhesive bonded optical fiber array is studied. The effect of coefficient of thermal expansion (CTE) of adhesive on the reliability is firstly investigated. Two adhesive of different CTE are used in the study. The samples were subjected to thermal shock and highly accelerated stress test (HAST) as the reliability study. Interfacial delamination, delta core pitch and insertion loss measurements are used to characterize the packages. The adhesive with less CTE mismatch with the constituent materials has showed better performance. In order to reduce such degradation in performance of fiber array assembly, we recommended to select those bonding adhesive, which has close CTE with the bonding substrate. Finally, adhesion strength was also measured before and after HAST. It was found very poor after HAST due to contaminated surface induced degradation. Therefore, to improve the adhesion, we suggest to clean the substrate surface by typical plasma treatment. In our studies, the adhesion strength was increased a lot after applying the proper parameters in the plasma surface treatment process. The study gives valuable dictation for the reliable assembly of adhesive based optical fiber array for photonic packaging.

Acknowledgement

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