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MATERIALS AND FABRICATION ISSUES OF OPTICAL FIBER ARRAY

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Abstract. Photonic devices are becoming widespread as an advanced information-communications network of the 21st century. With the increased use of photonic devices, there is a need for optical connecting path between photonic devices. The optical fiber array is such a smart approach for all optical functionality of the optical chip without any need of electrical wiring. However, it remains a challenge to develop the reliable fabrication know-how in manufacturing of fiber array. This paper will discuss the issues required in the reliable fabrication of optical fiber array, and integrating them to address the future needs of the information and communication technology sector. Issues affecting the quality of the optical fiber array mainly include the material selection, processing condition, and bonding technique. The advantages and disadvantages of each materials and fabrication method are discussed with the major failure issues. The findings can serve as a guide for optimizing the materials and process parameters in the reliable fabrication of optical fiber array in Photonic industry.

1. INTRODUCTION

Fiber optic communications have been developed since optical fibers were fabricated in 1970 and playing an important role in development of modern information technology. Planar 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. In order to implement such optical fiber communication system, many passive optical devices are used [1]. Now-a-days such passive devices are fabricated on silicon wafer [2]. To package such devices for commercialization, individual PLCs must be cut from the wafer and fibers must be attached to the input-output (IO) ports. In such an approach, it needs to align each fiber individually to the corresponding IO port of the optical chip. This is very desirable especially when the port counts is very large, causing a very high production. Therefore, the major draw back of the PLC devices is the coupling problem with fibers [3]. The simplest way to attach fibers to a multi-channel PLC is to first build a fiber array. In a fiber array, the optical fibers are arranged in one row and serve as input or output fibers for the chip. Without fiber array it is very difficult to align the individual fiber to the corresponding IO port of the chip. Thus the fiber array is becoming a key component in next generation optical communication networks, enabling higher dense wavelength division multiplex (DWDM) channel counts than ever before [4].

However, there is not enough information on the material issues and reliable fabrication of optical fiber array. In our previous research work, we studied the major failure issues of optical fiber array and found that the materials and related fabrication process mainly control the quality of the fiber array [5-7]. Therefore, the manufacturer needs detail information on the materials and fabrication

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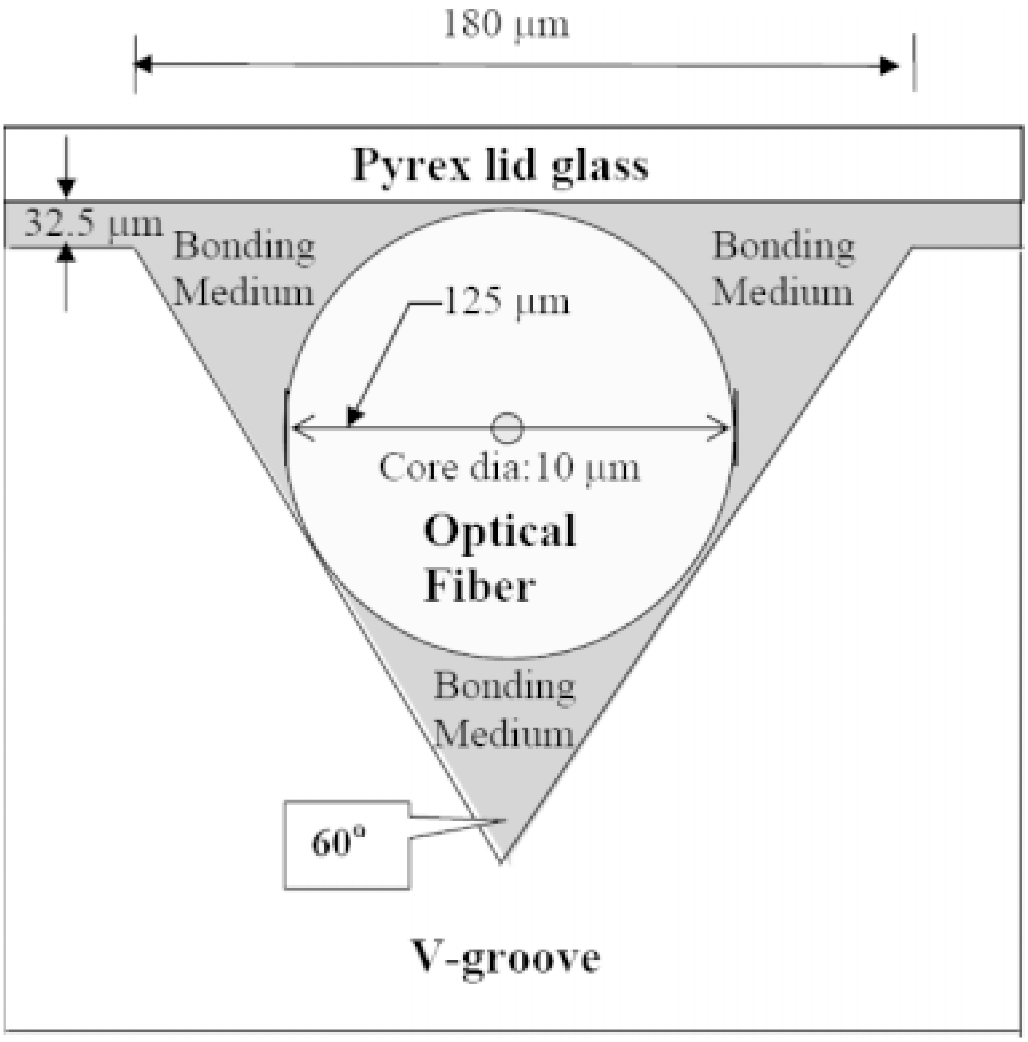

Fig. 1. Schematic of a typical cross-section of a single mode fiber in V-groove.

issues. Our purpose of this review is to have a better understanding of the material and fabrication issues of optical fiber array in manufacturing from laboratory to commercial package. Topics addressed include alternatives in terms of material, fabrication, packaging as well as major failure issues.

2. STRUCTURE OF FIBER ARRAY

Fig. 1 is the schematic cross-section of a single fiber on V-groove block for sub-micron positioning accuracy. However, a typical fiber array consists of 8, 16, 32, and 48 symmetrical single fiber in V-groove. The fiber array packages are mainly made up of four different parts: the V-groove, fibers, lid glass, and bonding materials [5]. The V-shaped sectional groove is the holding member that consists of a substrate for housing an optical fiber on a top face. The optical fiber having a fiber tip end bare portion need to house in said holding member. The lid glass is a flat slide on top for anchoring optical fiber(s) on precision engineered V-groove structure [6]. The sealing material is used to bond the fiber in V-groove with lid glass. Typical used sealing techniques are adhesive bonding, soldering and laser welding [7].

2.1. Materials and fabrication of V-groove

The V-groove can be formed by mainly three techniques on different materials:

2.1.1. Wet etching of silicon wafer

In general, due to different orientations of [(100) and (110)] silicon wafer, it can be etched for fabrication V-groove. The first step in the proposed fabrication process is to grow a masking layer to be used for the anisotropic etch of the V-groove. Thermally grown SiO_2 on same silicon as mask is suitable for this purpose, whereas other types of mask also can be used. A combination of wet and dry oxidation method can be used to grow 1.5 μm of silica oxide [8]. This oxide layer is then patterned using hydrofluoric acid (HF) to form the mask for the anisotropic etch. Anisotropic etchants of silicon include potassium hydroxide (KOH), tetramethyl ammonium hydroxide (TMAH), and ethylene diamine pyrocatechol (EDP) [9]. If the mask opening is accurately aligned with the primary orientation flat, i.e., the [110] direction, after prolonged etching the {111} family of planes is exposed down to their common intersection and the (110) plane disappears creating a V-groove with <111> oriented sidewalls at 54.74^o to the (100) surface [9-10]. Although this traditional Silicon wet etching technique is easier and less expensive, however has some limitations. The main limitation is that the UV light for adhesive curing can't be applied from the bottom side of the V-groove. Another important limitation is the larger CTE mismatch of silicon with other fiber array material [5].

2.1.2. Machining with V-shaped diamond wheel

It is a typical transferring process in which material is removed by the abrasive grains of two edge surfaces of the machining wheel to form the desired V-grooves. The machined V-groove can be obtained on both brittle and ductile materials keeping the precision of submicron level. The typical materials in making machined V-groove are pyrex, silica glass, zirconia, and quartz. In general, cutting effects during the V-grooves machining process result from interaction between the actual cutting points on the abrasive grains at the wheel surface and work piece materials. The machining wheel topography, macroscopic wheel shape, especially the edge sharpness of the wheel, significantly influences the profile accuracy of machined V-grooves [11]. Therefore, proper diamond machining wheel need to be carefully used to achieve optimal machining performance with satisfactory surface quality and profile accuracy. It is important to choose the fitting rake angle according to the materials when the depth of cut is small. The machining quality can be improved by modifying a tool surface that is perpendicular to the cutting direction. The machining induced V-groove surface roughness sometimes limits the usage of the technique.

2.1.3. Precision plastic molding

Polymer molding is highly suitable for the mass fabrication of high precision micro and nanostructures [12]. It requires thermoplastic polymers with good molding properties at moderate process temperatures. Injection molding is one of the most widely used techniques in the manufacturing of complex-shaped and thin-walled polymeric optical products. V-Groove block, manufactured by such precision plastic molding technology is a typical example. For this technique, mold must be prepared first and then the main process is polymer filling and curing. The melt filling of V-grooves can be affected by the pitch, direction of groove layout, melt viscosity, direction of melt flow and cavity pressure during melt-filling stage. During injection molding, the polymer experiences rapid deformation and extreme thermal history that affect the final mechanical and optical properties as well as the dimensional specification of the products. Typical materials can be used for manufacturing of V-groove substrates are optical grade polycarbonates (PC) and polymethyl methacrylates (PMMA) [13]. However, the major challenges in molding technique are molding master fabrication, anti-sticking layer formation, suitable polymer material, polymer flow pattern, polymer hardening and mold removing. The optical and mechanical performances of the final products are mostly determined by shrinkage during molding, surface structure and accuracy of the product. Polymer material is also sensitive to environmental changes such as temperature and humidity.

2.2. Types of fiber used

Optical fibers are classifies as Single Mode, Multimode and Polarization Maintaining (PM) fibers. Again on the material point of view, it can be in two class; glass optical fiber (GOF) and polymer optical fiber (POF) [14]. The typical diameter of the single mode & multimode fibers are 125 μm and 250 μm. The V-Groove array assemblies can be made with all types of fibers and precise passive alignment of individual fibers. The V-grooves are designed according to the fiber dimension.

2.3. Bonding medium

Until now, soldering, laser welding and adhesive bonding methods have been employed for assembly of optical fiber array. Soldering process need for metallization and high heat loads that may affects the reliability. Laser welding is regarded as having long-term stability, but it also requires metallization, high power lasers, and careful control of a variety of parameters. Adhesive are inexpensive, but long-term reliability and stability has been a perennial concern.

2.4. Top lid glass

The lid glass is a simple glass sheet of thickness about 1.0-1.5 mm to cover the fiber on V-groove. It should be low optical loss for UV transmission, when UV curable adhesive is applied for bonding. For soldering and laser welding purpose, it should have good adhesion with the deposited metal on it.

3. MANUFACTURING/PACKAGING OF FIBER ARRAY

Packaging, and in particular pigtailing, is becoming an increasingly important issue as optical networks move from the wide area network (WAN) domain to the local area network (LAN) domain with a resultant pressure to increase the production and reduce cost. The selection of appropriate bonding materials and method of attachment will determine the stability and reliability of the packaged device. As previously mentioned, the methods for fiber attachment such as laser welding [15], soldering [16], and adhesive bonding [17] are discussed in the subsequent sections.

3.1. Adhesive bonding

Adhesives bonding offer advantages in terms of mass-productivity and low-cost [17-18]. Adhesive can be cured by both thermal and UV curing system. UV Curable adhesive not only perform the function of bonding, but also have the high degree of light transmittance and other properties required to form a bond most suitable from the optics point of view. They can also be cured rapidly without affecting the fiber alignment. Light curing also provides a number of economic advantages over the operations usually used: rapid through-cure, low energy requirements, room temperature treatment, non-polluting, and solvent free formulations. In this way other heat sensitive materials in the assembly are not damage by the heat.

3.1.1. Typical bonding process

Fig. 2 shows the schematic of the bonding process for 8 channel fiber array using UV curable adhesive. To prepare fiber for placement into the V- grooves, it is stripped of its acrylic coating. The 8-stripped fibers were inserted into the V-groove and the lid glass is lowered onto them, seating them firmly into the V-grooves. After the fibers are seated, low viscosity UV curable adhesive is 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. The distance from the light guide output end to the target surface was 10 mm. The light guide position was such that it exposed perpendicularly at the center of the fiber array. Upon curing, bonds the fibers permanently into place. The end faces of the fiber arrays are polished to remove the excess amount of adhesive from the fiber end [7]. Fig. 3 shows the appearance of the bonded fiber packages on both the silicon and pyrex V-groove.

3.1.2. Adhesive selection criteria

The adhesive must satisfy the following requirements:

1) Suitable viscosity for dispensing to the surface or bonded structure;
2) Adhesive bond should be transparent and have a suitable refractive index;
3) Enough bond strength and line thickness;
4) Higher glass transition temperature, T_g.
5) Environmentally protective from exposures during final end use;
6) Minimum curing shrinkage to avoid the misalignment issues;
7) Matching in thermal expansion coefficient between the adhesive and adherend.

3.1.3. Limitations

The disadvantage of adhesive bonding is poor reliability in positioning the fibers for long-term stability. The specific failure issues are described in Section 4.

3.2. Soldering

Soldering is a process by which two metal surfaces are bonded together by means of an intermediary alloy. Because of its metallic strength, the solder will offer a much better thermal stability against creep than adhesive near room temperature. The

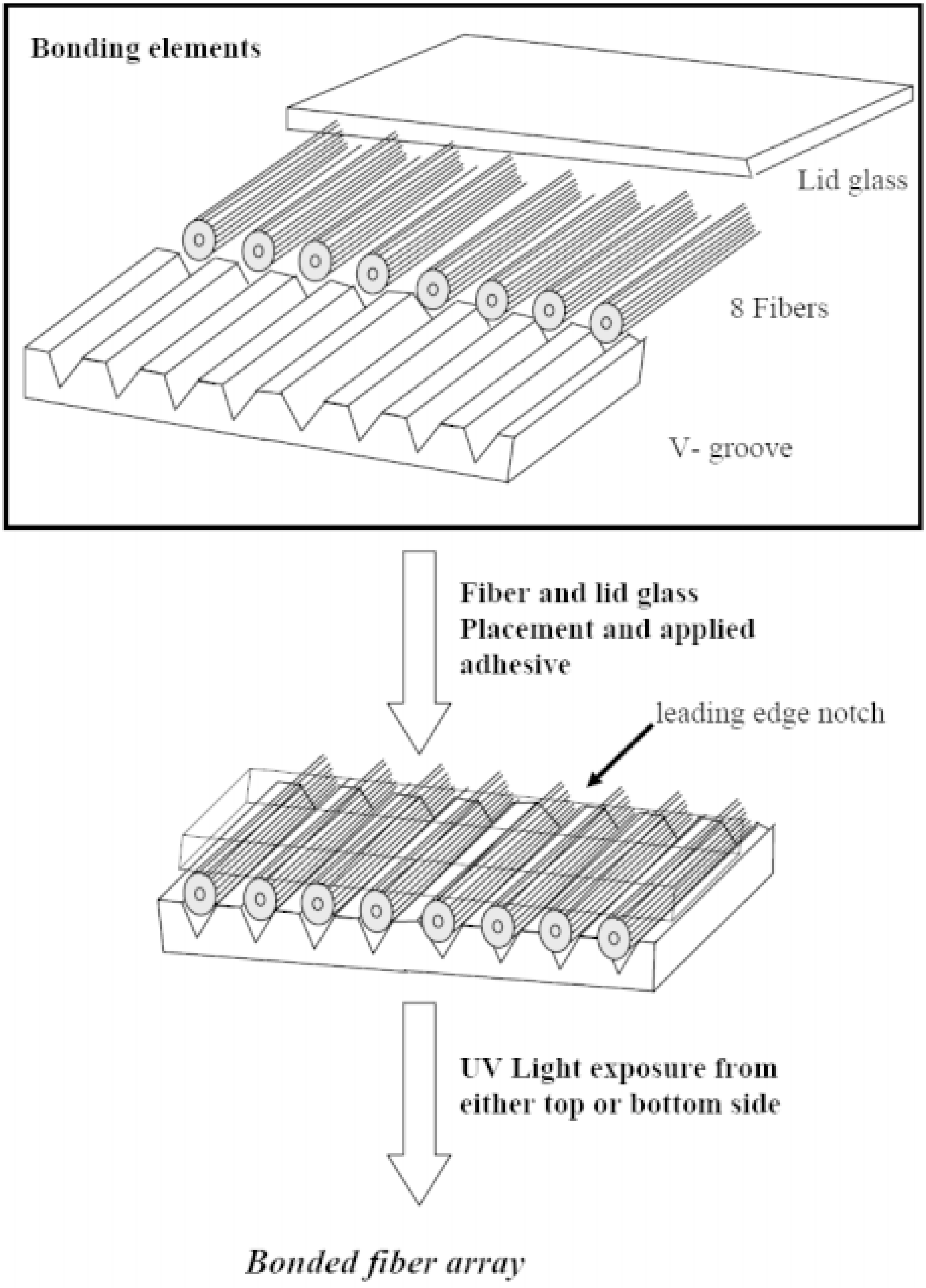

Fig. 2. Schematic of the bonding process for fiber array.

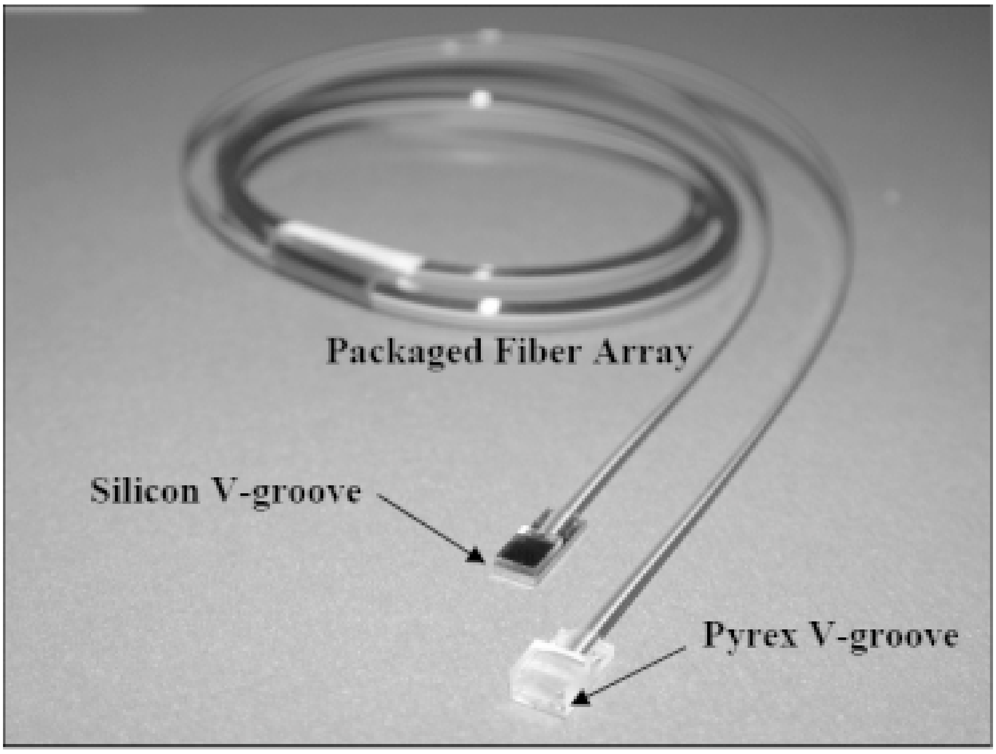

Fig. 3. Appearance of the bonded fiber packages.

solder also has a higher stability for thermal cycling, mechanical impacting, ambient aging, and moisture exposing. In addition, the metallic solder bonding can be hermetic and it can isolate the optical device from ambient environment [19].

3.2.1. Soldering process

It is well-known that solder does not wet the surfaces of fiber array materials (V-groove, fiber and lid glass). Therefore, need to deposit a coating of metal films on the V-groove surface, the surface of the optical fibers and lid glass. The metallization process can be done using sputtering or evaporation techniques [20]. The metallic films must adhere strongly to the surfaces and the molten solder should wet the thin films to achieve bonding. The adhesion of metallized layer is critical during the life of the components. The metallic film coating on the fiber with good adhesion can also protect the fiber from infrared noise interference. There are commercially available systems that provide some degree of automation for this process. During soldering, the solder flow can be achieved by electrical resistance heating, contact heating or laser assisted reflow. Since this joint is typically within close proximity to optics, the joint must also be made via a fluxless process.

3.2.2. Solder selection criteria

The solder must satisfy the following requirements:

1) As the alignment is a critical factor in production yields, extremely low creep solders must be used;
2) The solder should be lead-free to meet the environment concern of lead-poisoning;
3) It must have a low melting point due to the low glass transition temperature of the polymeric skin of the fiber/ribbon, so the melting point of the solder is limited to below 150 °C. For these reasons, the choice of the Pb-free solder is limited to SnBi and SnIn alloys;
4) Indium solder is not selected due to its high oxidation tendency [21];
5) The perceived advantages of using eutectic AuSn solder for this include good thermal conductivity and very little creep, as well as a lower melting point than other hard solders.

3.2.3. Limitations

Though soldering is a well established process of bonding of optical component, it is not well understood for optical alignment applications. Because shrinkage magnitude, direction of solder flow and long term stability are difficult to predict and control. In fact, soldering is normally required to be flux less to prevent contamination and degradation of the facets. The creep resistance is of concern because thermal expansion mismatches, almost invariably lead to some degree of warpage which cannot be allowed to vary with time in service.

3.3. Laser welding

Laser welding is a process that joins different parts by employing the heat generated by a laser beam directed onto the weld joint. The ability of laser welding with repeatable submicron precision distinguishes it from other forms of bonding technologies. Laser welding provides joint strength comparable to that of the substrate materials, low residual stress, and minimum distortion. As a non-contact process, laser welding can be integrated easily into computer controlled production systems. Since a non-contact technique, it does not introduce distortion by physical contact or process variability due to tooling degradation. Laser welding imposes less restriction on joint design, because welding electrode contact is not a design consideration. Most importantly, laser weld interaction time is very short resulting in minimum heat affected zones, thereby reducing distortion due to thermal and residual stresses [19].

3.3.1. Welding process

The bondable surfaces also need metallization. When a high energy density laser pulse is absorbed by the substrate materials, melting, mixing, and resolidification occur to form a fusion bond. A typical welding system consists of a pulsed Nd:YAG laser (1.06 pm wavelength), beam energy multiplexing units, and optical fiber beam delivery components. The beam delivery system is designed to deliver multiple simultaneous beams of nearly identical spatial profile. Simultaneous, multiple beams welding minimizes the effects of thermal distortion, solidification stresses, and stress relaxation inherent in the welding process. The joining process is completed with a sequence of multiple welds spaced in time to reduce average heat input. The use of multiple welds enhances joint strength and assures alignment stability [22].

3.3.2. Material selection criteria

The choice of material for the support for laser welding is normally between: Kovar, Invar, Stainless Steel, and Nickel. The presence of microcracks in the laser welds, which can then propagate during the life of the component, must be avoided. In stainless steel certain free machining types contain elements, for example Se which can cause the formation of such cracks. The presence of phosphorous must be avoided and electrolytic plating is therefore preferred for metallization. The thickness of the gold layer also must be tightly controlled during the metallization. To avoid plating problems the support can however be selectively plated to provide plating free zones where the component will be laser welded but this will increase cost [23].

3.3.3. Limitations

Laser welding needs the metal housing or metallization of fiber and requires the laser beams that have direct access to the weld joints, which limits the package design flexibility. They need for high weld energies and for precise control of energy delivered.

4. PERFORMANCE ANALYSIS

The core-pitch separation and insertion loss of fiber array are the important parameters to evaluate the quality and reliability for further application in PLC packaging. The core-pitch evaluation system (core pitch Pro.ECOP-1) can be 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 [5].

The insertion loss (*IL*) is another important parameter to determine the optical performance of passive optical fiber array. *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 [24]:

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

The delta *IL* is defined as the difference insertion loss *(IL)*, before and after the reliability test.

5. MAJOR FAILURE ISSUES

Failure normally identified by adhesion failure and increase in delta core pitch and insertion loss. The major failure issues are discussed below.

5.1. Surface contamination

As the integrated optical components are getting smaller with the use of advanced materials, contaminant free active surfaces are crucial to obtain high yield reliable products. Therefore an important part of the product reliability achievement is the control of contamination and ensure the good bondability between various mating surfaces [25]. Contaminants may introduce in the packages during the fabrication of the V-groove and lid glass and also from the environments. Contamination mainly caused by rough process control and present in the form of residues, mold release agents, anti-oxidants, carbon residues or other organic compounds on the bonding surface. The contaminant may cause serous defects, such as-

1. Greatly degrade the bonding surface of fiber packaging.
2. Weaken the adhesion force resulting in poor performance. When such phenomenon occurs an optical fiber may readily slip off from the substrate due to adhesion failure.
3. In a contaminant surface, an osmotic pressure is also built up at the region and initiates the delamination.
4. 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 & 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 [5].

Therefore, developing the suitable fiber array with minimized deterioration, delamination, cracking or peeling out is very essential. Therefore the impurities must be thoroughly removed before the bonding process. In order to eliminate the delamination problem and enhance the adhesion of fiber array, plasma treatment based surface modification can be 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 [26].

5.2. Entrapped air bubble

Air bubble entrapped in the adhesive is also a concern for reliable adhesion. Air bubbles may entrap during adhesive flow process. Trapped air bubbles are best avoided because they can cause adhesive delamination when the array is exposed to temperature cycling. Such defect also provides propagation path for stress and crack. The voids may nucleate at the interface and may propagate through the interconnection resulting in the loss of adhesion and may failure under low force [6,7,27].

5.3. Fiber misalignment

The position of the optical fiber in passive alignment is defined by the geometry of the V-grooves. If the fiber makes contact with the V-groove side walls, the centre of the fiber can be located as the radius is known. Therefore, the surface feature of the V-groove side wall is another significant factor affecting the fiber alignment. If the center of the fiber has an offset less than 2 μm to the theoretical center position, the fiber is declared as an aligned fiber. The buoyancy of adhesive under the fiber can cause the optical fiber to float upwards. Usually the cover plate is used to press the fiber against the side-wall of the V-groove. However, the optical property is affected if the pressing process is not well-controlled. The stress applied by the pressing cover may deform and even damage the optical fiber. Moreover, the pressing process may introduce voids and bubbles in the adhesive and this leads to reliability problems [28].

5.4. Uneven curing of adhesive

Uniform adhesive curing and bondline are very essential for minimizing the stress within the fiber package as well as the failure. The uneven curing of adhesive in the package can generate high interfacial stresses upon heating or cooling of the structure during fabrication, assembly, or in field use. The propagation of the resulting delamination along an interface can degrade or destroy the functionality of the system. Therefore, the interfacial delamination, due to the uneven curing of adhesive, is one of the primary concerns in photonic package designs. Alignment and shrinkage of the fiber array also depends on the effective UV ray penetration during the adhesive curing process. Due to the complexity of interconnects, it is also interesting to consider and study how UV light propagates through the uneven interfaces. High light reflectance from any interface of the assembly reduces the light intensity for the next layers and induces the uneven curing of adhesive. Shadowing due to light bending or optical element shape can also cause the incomplete or uneven curing [6].

The uneven curing induced delamination effect is extensively studied [7]. Shaded area and delamination were much larger when light exposed from bottom side of the V-groove. This is due to the geometrical shape of bonding element. Minimum shaded area and also the delamination was found at the middle fiber when light exposed from topside. These were larger when light exposed from bottom side and maximum at the outermost fiber. These effects are very severe for large value of, Dn, the refractive index difference between the adhesive and cladding materials. The study concluded that the delamination problem can be minimized by using the UV curable adhesive having the same or slightly higher reflective index than that of the cladding material. It is also recommended to light expose from topside and prefers the lower pitch V-groove for fiber packaging. This type of fiber array may result in more reliable assembly and also increase the productivity of the fiber-optic industry.

5.5. Coefficient of thermal expansion (CTE) mismatch

When packaged, the coefficient of thermal expansion (CTE) of the V-groove, fiber and bonding materials have to be well matched. If there is a difference in CTE among the constituent materials, stress, and strains in the packages are bound to occur. And the stress concentration of the bonding materials in the V-groove caused by these phenomena cannot sufficiently adopt by the thin bonding layer. The stress caused by the bond increases particularly with larger CTE mismatch and higher young modulus of the adhesive [29]. Alternatively, increasing humidity causes expansion and relaxation of the adhesive [30]. Any misalignment among the optics will cause optical loss, resulting in out-of-specification.

The effect of coefficient of thermal expansion (CTE) of adhesive on the reliability is firstly investigated [5]. 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, it is recommended to select those bonding adhesive, which has close CTE with the bonding substrate.

6. CONCLUSIONS

Optical fiber array have gained much attention, and significant progress has been made recently in order to meet the requirement of high-speed and large-capacity transmission of information at low cost. This review is aimed at obtaining a better understanding of the materials and process optimization in manufacturing optical fiber array. Within each area, major critical issues and recommendations are given. Insights gained from this study are very useful for manufacturers to package better fiber array with favorable performance for this application. It is believed that only after the materials and the processes have been broadly learned, incorporated and the manufacturing infrastructure is built, would fiber array be widely used and eventually replaces other conventional techniques.

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