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A Laser Assisted Bonding Method Using a Liquid Crystal Polymer (LCP) Film for MEMS and Sensor Packaging

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***Abstract*—In this paper, we present the development of a laser based bonding method using a liquid crystal polymer (LCP) film for cavity based packaging of sensors and MEMS devices. Liquid crystal polymer films possess the best properties among polymeric materials in terms of moisture resistance and temperature stability. We show that high quality bonding of silicon and glass substrates as well as encapsulation of molded LCP packages can be obtained using a laser assisted bonding method. Shear and leak tests were carried out to demonstrate good quality of the laser bonded microcavities and packages. *In situ* temperature monitoring was obtained by embedding a small temperature sensor just below the bonding interface of an LCP package. The average shear strength ranges from 20.8 MPa to 26.1 MPa depending on the design configurations and bonding conditions. The results of color liquid, gross and fine leak based tests show pin-hole free bonding and good hermeticity. The results of the temperature monitoring work show the potential of the laser based approach for low cost packaging of temperature sensitive devices in molded LCP packages.**

***Index Terms*— laser joining, packaging, MEMS, sensors, LCP film.**

I. INTRODUCTION

Cavity based packaging methods are widely used in manufacturing of microelectronic, MEMS and sensor devices. A critical process in the cavity based packaging method is bonding a cap or lid to an open cavity to produce a sealed environment for protection and reliable operation of the device in the package.

Several bonding methods have been developed for packaging of MEMS devices, including anodic bonding [1]-[4], eutectic bonding [6]-[9], glass frit bonding and solder bonding [8],[10],[11]. Although these approaches can achieve a strong bond, there are some drawbacks associated with these methods, for example a large voltage is required for anodic bonding [12-14], high temperature and an extremely flat surface are necessary in the fusion based bonding approach. In terms of heating methods for bonding, localized heating approaches have been investigated including microwave bonding [15], ultrasonic bonding [16], and laser bonding [17]-[19]. Localized heating methods can reduce thermal load on the devices to be packaged and thus, are suitable for temperature sensitive devices. These methods can be fast and energy efficient since the heated area for bonding is small. In this paper, we present the development of a laser assisted bonding method using an LCP thin film as the bonding medium.

Laser as an important heating source has been studied for MEMS packaging applications in direct bonding of silicon to glass and glass to glass substrates [17]-[19]. The direct bonding technique requires extremely clean and polished surfaces and also requires a high bonding temperature. Alternatively, the intermediate layer based approach has been investigated due to the advantages of low or moderate bonding temperature (< 300°C) and better tolerance to surface non-uniformity (unevenness). A number of intermediate layer materials have been studied for substrate bonding, including Au, Al [20], Au/Sn solder [9], Indium [21], Zn based wire [22], glass frit [23], [24], and benzocyclobutene (BCB) polymer [25], [26].

Liquid crystal polymer as a thermoplastic polymer material has been used in packaging of electronic devices because of its distinctive polymeric structure and the associated excellent moisture and oxygen barrier properties. In 2002, Wang *et al.* [27] described a technique for lamination based bonding of LCP to various materials such as glass, copper, gold and silicon surface. In order to achieve strong bonding, a reactive ion etching (RIE) process using oxygen plasma was used to surface treat the LCP material before lamination. Kottapalli *et al.* [28] studied two methods for bonding of an LCP film to a silicon substrate. The first method was an indirect bonding approach in which bonding was achieved at the interface of two SU-8 layers coated on the LCP and silicon surfaces prior to bonding. The second method is based on direct bonding by heating the LCP film about its glass transition temperature. Although a strong bond could be produced, the high interfacial stress after bonding caused wafer cracking in the dicing process. LCP as a near-hermetic material has also been studied for packaging RF-MEMS devices due to its excellent electrical properties such as low dielectric constant and loss [29], [30]. A hot water tube was used to bond a molded LCP lid to an LCP board both with a higher melting temperature using an LCP film with a lower melting temperature. The

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bonding temperature and time were 280°C and one hour respectively. Good bonding strength and hermeticity were demonstrated. The previous studies have shown good potential of LCP materials in electronic packaging applications.

In this paper, we present a laser-assisted bonding technique using an LCP film for cavity based packaging applications. Laser based LCP bonding of both planar silicon and glass substrates and also a molded LCP package has been investigated. For glass-glass bonding, a thin film titanium absorber in a spot pattern was used to facilitate absorption of laser beam in the bonding region for melting the LCP sealing ring to achieve substrate bonding. An embedded temperature sensor was used to monitor the temperature change at the bonding interface in bonding of a silicon cap to a molded LCP package. Shear and leak tests were performed to assess bonding strength and hermeticity of the laser bonded samples.

II. EXPERIMENTAL SECTION

A. *Liquid Crystal Polymer Material*

Liquid crystal polymer is a thermoplastic material with unique properties resulting from the rigid and flexible monomers linked to each other [31]. The rigid sections will align to each other when the polymer is in the liquid crystal state. Even when LCP is cooled below the melting point, the direction and structure of rigid segments are still maintained. Because of the distinct structure, LCP is not only used as a high-performance material for high density printed circuit board fabrication, but it has also been used for construction of molded packages for manufacturing of microelectronic and sensor devices [31]. LCP has the best moisture resistance capability among all of polymeric materials [31]. In terms of out-gassing, LCP has passed the tests for many applications and even satisfied the requirement for spacecraft applications [32]. As discussed in section I, LCP has good adhesion to other materials and thus, does not require of an additional adhesive layer for bonding to a substrate surface. The direct bonding capability eliminates the dielectric loss that would otherwise result from the intermediate bonding adhesive during the lamination process [29]. In mechanical properties, the coefficient of thermal expansion (CTE) of LCP is very low and is highly anisotropic, being the lowest in the direction of molecular alignment so that the CTE can be controlled to a predictable extent during the fabrication process [31].

There is a variety of LCP materials with different properties. The thickness range of commercial LCP materials is from 25 μm to 3 mm. Copper clad materials are also available for fabrication of laminated circuits. In our work, we used ULTRALAM® 3908 Bondply films supplied by Rogers Corporation as the bonding material. The thickness of the 3908 LCP film is 50 μm. Some typical properties of the LCP material are shown in Table I [33].

B. *Design Configurations*

The substrate and package configurations for laser based LCP bonding are shown in Fig. 1. Glass to glass bonding in Fig. 1 (a) is based on a square LCP ring with a thin film titanium spot pattern. The titanium film pattern absorbs laser radiation to produce the required temperature above the melting point of the LCP film in order to produce a bond between the substrate surfaces after cooling. The titanium film spots were produced by vacuum deposition. The diameter and the thickness of the spots were 0.6 mm and 500 nm respectively. The separation between the adjacent spots was 0.7 mm. The inner dimensions of the LCP ring were 4 mm x 4 mm and the width was 1.5 mm. For silicon-glass and silicon-silicon bonding as shown in Fig. 1 (b) and (c), the silicon substrate absorbs the laser radiation for bonding. The inner diameter and width of the LCP ring were 4 mm and 1 mm. Fig. 1(d) shows the configuration of bonding a silicon cap to a molded LCP cavity package. In all cases, the dimensions of the silicon and glass substrates were 10 mm x 10 mm. The thickness of the silicon substrate was 0.6 mm and it was 0.5 mm for the glass substrate.

C. *Fabrication of LCP Bonding Rings*

The LCP bonding rings were fabricated from a film sheet using a CO_2 laser machining system (Epilog Mini 18). After laser cutting, the residues of carbon ash around the cut edges were removed using Isopropyl Alcohol. The thin titanium film spot pattern for glass to glass bonding was produced on the LCP film by vacuum deposition using a PMMA based shadow mask which was fabricated using the same laser machining system. The thickness of the PMMA mask was 0.5 mm. As stated before the thickness of the titanium was about 500 nm.

D. *Laser Bonding Setup*

In this work, we used a high-power diode laser system with a fiber-coupled output at 970 nm. The laser output from the beam delivery fiber was transformed into a square beam with top-hat intensity distribution. The beam profile was produced using a custom-designed beam forming optical element [34]. The size of beam is 6 mm x 6 mm. A schematic of the experimental setup is shown in Fig. 2. The beam transmission module consists of collimation optics followed by a focusing lens with a focal length of 20 cm. The samples were placed on an X-Y translation stage. A ceramic plate with a thickness of 0.9 mm was placed under the substrate assembly in order to reduce thermal loss into the stainless steel platform [26]. In the bonding process, the substrates and the LCP bonding ring were aligned before the assembly was aligned to the laser beam. A glass plate was placed on the sample assembly for supporting a metal ring based mechanical load. This is to ensure good surface contact between surfaces of the substrates and the LCP film.

E. *Laser-assisted LCP bonding*

1) *Glass to Glass Bonding*

Glass-glass bonding was carried out using the design configuration as shown in Fig. 1(a). The titanium film spots on the LCP bonding ring absorb the incident laser beam resulting in melting of the LCP film and subsequent bonding of the two glass substrates. The bonding temperature was monitored using a K-type thermocouple (RS Components) which was placed underneath the bottom glass substrate. Several samples were produced under different laser bonding conditions in order to study the dependence of bond quality on bonding parameters. The laser power was in the range of 45 W and 50 W and the bonding time was between 50 s and 90 s. It was found that the laser power of 45 W was insufficient to generate the minimum temperature of 280°C (melting temperature of the LCP material) to realize joining of the two glass substrates while over-melting of the LCP film was observed at the laser power of 50 W with a bonding time of 50 s. Based on the results of optical inspection, the optimum laser power and bonding time for producing defect free bonding were determined to be 48 W and 75 s. The effect of bonding force as applied using customer designed copper loads was also investigated. It was determined that a bonding force of 4 N was sufficient in this work.

2) *Silicon to Glass/Silicon Bonding*

In silicon to glass/silicon bonding, no additional intermediate absorber layer was necessary since the upper silicon substrate can act as an effective absorber at the wavelength of the laser. As shown in our previous work [26], all laser radiation apart from reflection (~30%) can be absorbed by a silicon substrate with the same thickness as in our previous work (0.6 mm). The same arrangement for temperature monitoring as in the glass-glass bonding work was used. Since all of the laser beam energy was absorbed by the silicon substrate, hence the thermal efficiency was greater than in the configuration for glass-glass bonding. After conducting a similar parametric study of dependence of bond quality on bonding conditions, the optimum bonding parameters for silicon to glass bonding were found to be 23 W for laser power and 40 s for bonding time. For silicon to silicon bonding, the best results were obtained for the laser power of 35 W and bonding time of 40 s. In the latter case, the heat dissipation was faster through the bottom substrate (silicon) with a higher thermal conductivity than the glass substrate [26] and hence a higher laser power was necessary.

3) *Bonding of a Silicon Cap to a Molded LCP Package*

Molded LCP cavity packages are widely used for microelectronic devices and sensors in commercial applications. The current bonding method for capping is based on thermal curing of epoxy adhesives [35]. While this method is easy to use and a low cost solution, the performance of the resulting packages is limited by the thermal and moisture resistance of the epoxy adhesive materials. For example, the moisture resistance is two orders of magnitude poorer than that of the LCP material. Fig. 3 shows a schematic drawing of the molded LCP package. The outer dimensions of the LCP package were 8.9 mm × 8.9 mm and the corresponding inner dimensions were 7.3 mm × 7.3 mm. The depth of the cavity was 1.35 mm. The package material is a 35% glass reinforced LCP polymer (Vectra S135, Ticona) with a deflection temperature of 335°C. The package opening has a recess around its inner perimeter which was designed for epoxy bonding of a molded LCP lid. In order to bond a planar silicon substrate to the package, the LCP package was polished to obtain a flat surface (Fig. 3) for the laser based LCP bonding work. For temperature monitoring, two K-type temperature sensors were embedded in the LCP package: one just below the bonding surface and the second one at the base of the LCP package. After a study of the bonding conditions on bond quality, the suitable laser power, bonding (processing) time and bonding force were found to be about 20 W, 120 s and 4 N respectively. It should be noted that in bonding of the silicon cap to the LCP package, a quarter of the interface was bonded separately at each step since the laser beam size (6 mm x 6 mm) is smaller than the size of the LCP package (8.9 mm x 8.9 mm).

III. RESULTS AND DISCUSSION

A. Temperature Monitoring

Temperature monitoring provides important information about the temporal profile of the localized laser heating effect [26]. The actual bonding process will only start after the laser induced temperature has reached the melting temperature of the bonding medium, in this case, an LCP film with a melting temperature of 280°C. Fig. 4 shows the results of temperature monitoring for the three substrate configurations shown in Fig. 1 (a)-(c). The temperature was measured by placing the thermocouple under the bottom substrate and aligned to the center of the LCP bonding ring. The monitored temperature was expected to be lower than the interface temperature for bonding due to the temperature gradient across the bottom substrate. Although we have demonstrated a more accurate method for temperature monitoring in our previous work using an embedded thin film sensor array [26], the method used in this work is much simpler to implement and the monitored temperature for bonding is not much lower than the expected temperature at the interface of the substrates. The behaviors of temperature increase in silicon-glass and silicon-silicon bonding are similar although a high laser power is necessary in silicon-silicon bonding. Heat dissipation when the bottom substrate is silicon is much faster than for glass since the thermal conductivity of silicon is about 10 times higher than glass [26]. For glass-glass bonding, the temperature rise is slower than in the other two substrate configurations. The top substrate is glass and the laser beam is absorbed selectively by the pattern of the titanium thin film spots. The rate of heat transfer is lower resulting in a longer rise time in the temperature profile. Since the absorption of the laser beam is less efficient, a higher laser power is required to reach the bonding temperature.

The results of temperature monitoring for bonding the silicon cap to the LCP package are shown in Fig. 5(b). The laser power was 20 W. The maximum temperature when the laser beam was switched off was ~270°C. This temperature is lower than the melting temperature (280°C) of the LCP film, however the successful bonding indicates that the temperature at the bonding interface must have reached 280°C. This is because the main body of the temperature sensor is below the bonding interface and the laser induced temperature deceases below the surface of the LCP package. This is demonstrated in the output from the second sensor embedded at the center of the package base where the maximum measured temperature was only about 150°C. The significance of the temperature monitoring work is that it illustrates one of the key advantages of the laser based bonding method, i.e. it is ideally suited to packaging temperature sensitive devices. In this case, a temperature difference of ~ 130°C is obtained without using any active cooling as it was the case in [36] where a water-cooled copper block was used. The reason is that the thermal conductivity of LCP material is much lower than that of the ceramic package in [36] thus, providing a poor heat pathway from the bonding region to the package base.

B. Bonding Quality

1) Shear Test

Shear testing was carried out to evaluate the bond strength of the LCP bonded samples. The work was conducted on a commercial mechanical strength tester (Instron, model 2715-015). The samples were mounted in a vertical configuration so shear test could be conducted. Twenty-one samples were used to obtain the results shown in Table II, including 18 samples (6 each for glass-glass, silicon-glass and silicon-silicon bonding configurations) and 3 samples for silicon-LCP package bonding. Each shear strength value in Table II is the average of the number of samples tested. The corresponding bonding parameters are also shown in Table II. All samples were sheared at a displacement rate of 0.5mm/min. The measured results show that the shear strength of the samples is between 20.8 MPa and 26.1 MPa. This indicates that the LCP film has good adhesion to all of the substrate surfaces used in this work. After the shear test, fracture mode analysis under an optical microscope shows that in silicon to glass bonding most of the LCP material was left on the surface of the silicon substrate indicating a stronger bonding interface between the LCP film and silicon. For the other samples, the LCP bonding ring was left on both surfaces of the substrate or LCP package after shear test indicating that the interfacial adhesion exceeds the bulk strength of the LCP.

2) Cross-sectional Study

Cross-sectional study was conducted to evaluate the quality of the bonding interfaces formed between the two planar substrates and also the silicon cap and the LCP package. The samples were prepared by dicing followed by polishing using a liquid containing suspended diamond particles. Figure 6 shows a comparison of two glass-glass assemblies bonded under different conditions. The thicknesses of the LCP layers are 50 μm in Fig. 6(a) and 20 μm in Fig. 6(b), respectively. The results show that there is negligible change in LCP film thickness before and after bonding for the laser power and bonding time of 48 W and 75 s. However, the LCP film thickness was reduced significantly for the laser power of 50 W and bonding time of 75 s. The latter is a result of significant melting of the LCP film during the bonding process when a higher laser power was used. As can be seen in Fig. 6, there are no voids and other defects at each bonding interface indicating good bond quality. Fig. 7 shows the cross-sectional views of some samples based on the other bonding configurations. Although the bonding interfaces in Fig. 7 (a) and (b) are not as clear as that in Fig. 6, the reduction in LCP film thickness is not significant. The bonding conditions were 23 W and 40 s in Fig. 7 (a) and were 35 W and 40 s in Fig. 7 (b). The SEM picture in Fig. 7(c) shows that good interfacial bonding is obtained using an LCP film. The LCP film thickness is approximately 30 μm corresponding to the laser power of 20 W and bonding time of 120 s.

C. Leak Test

1) Color Liquid Based Test

The color liquid (usually colored ink diluted in water) based approach can be used to make a quick assessment of the sealing quality of the bonding interface of the microcavities for MEMS and sensor packaging [6], [11]. In this method, a bonded microcavity is immersed in a colored liquid for a few hours and then observing if there is any indication of water going into the cavity as indicated by the color of the liquid. In total, we used 6 samples in the colored liquid based leak test. The results show that all of the samples passed the test using water based liquid with green ink. Fig. 8 shows optical pictures of two samples after the color liquid test with no indication of the colored water penetrating into each microcavity produced by the laser based LCP bonding method.

2) Gross Leak Test

The gross leak test was carried out based on the MIL-STD-883E standard for testing hermeticity of microelectronic packages. In our work, twenty samples produced under different bonding conditions were tested. Two fluorinert liquids were used, FC-84 and FC-40 respectively, with corresponding boiling temperatures of 80°C and 155°C. The samples were immersed into the FC-84 for 24 hours at room temperature, and then transferred to a beaker containing the FC-40 liquid which was placed on the hotplate at 110°C. Bubbles would emerge from the cavity if there were any defects in the bonding track causing a significant leak. Among the 21 samples we tested, 20 of them passed the gross leak test. The one which failed the gross leak test was a sample of silicon bonded to the LCP package. Subsequent destructive inspection revealed that the leak was caused by package distortion due to the overheating effect resulting from misalignment of the laser beam.

3) Fine Leak Test

Since the cavity volume of the bonded samples was small, a through-hole based leak test method was used for fine leak test [37]. In this method, a sample was placed onto a helium leak detector (Inficon, UL 200) using an intermediate O-ring. A tight seal was obtained at the interfaces under a vacuum environment in the chamber of the detector. The leak rate was then measured by spraying helium at the bonding interface for each sample. Among the 18 samples tested, 17 of them showed leak rate below $1\text{x}10^{-8}$ mbar l s^{-1}. The best result for each substrate combination is shown in Table II. To our knowledge this is the first study of fine test in LCP bonded microcavities. The results of fine leak test are comparable to that of the glass frit bonded packages [23].

IV. CONCLUSIONS

In this paper, we investigated a laser based method using an LCP film for packaging of MEMS, sensors and other microelectronic devices. LCP is the best polymer material for high performance packaging applications due to its superior temperature stability and moisture resistance over the other commonly used polymers such as epoxy materials in manufacturing of sensors, microelectronic devices and circuits. We have shown that it is possible to use a laser based method with an LCP polymer for high quality substrate bonding applications. For glass-glass bonding, we have shown that thin film titanium material can be used as an effective optical absorber in the laser based LCP bonding technique. Glass-glass based cavities allow optical transmission and have potential applications for optical sensors and other photonic devices. Suitable bonding processes have been developed for reliable bonding in all of the cavity combinations based on glass and silicon substrates. Laser bonding of a silicon cap to a molded LCP package has been demonstrated successfully. The results of temperature monitoring using embedded sensors show that the temperature at the base of the LCP package (~130°C) is substantially lower than the bonding temperature (> 280°C). This demonstrates the unique advantage of the laser based approach in encapsulation of molded LCP cavity packages for packaging of temperature sensitive devices. Both shear and leak test have been carried out to show good reliability and hermeticity of the laser bonded microcavities.

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