

Understanding the Behavior of Liquid Crystal Polymer (LCP) in Direct Laser Assisted Bonding (DLAB) for Wafer-level Packaging of MEMS and Related Microsystems

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Abstract

Substrate-to-substrate bonding, device cavity and through wafer via interconnections are critical needs for wafer-level packaging (WLP) of MEMS and related microsystems. In particular, liquid crystal polymer (LCP) presents a unique choice for WLP of RFMEMS devices due to good RF performance, low absorption of moisture and cost effectiveness. LCP cap wafer to device carrier wafer (such as pyrex glass and LCP) bonding is an integral step in WLP for RFMEMS devices. Various substrate-to-substrate bonding techniques are of choice, and laser presents a unique opportunity due to region selectivity, controlled energy deposition, and fast manufacturing speed in a scaled up manufacturing process. It is important to study modification(s) to LCP, particularly mechanical strength and hermeticity as a result of DLAB processing. This paper will present findings of infrared (IR) laser processing of LCP for bonding through a set of analytical FTIR and acoustic imaging. Success of this process will present opportunities in low cost RFMEMS packaging for large scale production for wireless and related communication applications.

Keywords: Direct laser assisted bonding; wafer-level packaging; liquid crystal polymer; RFMEMS.

Introduction

Microelectromechanical systems (MEMS) as the name suggests are micron sized moving parts/assemblies that are developed for sensing and actuation purposes. MEMS find applications in diverse areas such as radio frequency (RF) switches and antennas, biomedical fluidic drug delivery system and implants, optical displays and switches, chemical reactors and fuel cells, etc. MEMS devices contain fragile and moving parts, so packaging of these devices is vital to their mechanical and electrical performance.

MEMS devices are application specific, so applying microelectronic packaging schemes to MEMS devices adds several packaging challenges including an increase in cost by 50% – 70% [1]. Hermeticity, outgassing and structural integrity are example of major concerns of the MEMS packaging industry. The processes of packaging MEMS devices determine the cost, electrical/mechanical performance, foot print and reliability.

New packaging initiatives for MEMS/RFMEMS have to reduce packaging cost by providing the suitable materials, designs, and methods of sealing. MEMS devices are typically packaged in ceramic lead frames [2]. In these packages individual dies are placed within a ceramic box, and wire bonds are used to provide interconnections from the device die to the package. A cap, either metal or dielectric, is brazed or attached to seal the box. Another approach is to use a polymer package such as what is used by Analog Device, Inc.'s (ADI) iMEMS[®] accelerometers. Metal packages are also used in addition to ceramic and polymer packages.

Liquid Crystal Polymer (LCP) as a Substrate

Polymer packaging have gained importance as they can be easily molded/extruded into many shapes and sizes, relatively less manufacturing and processing cost. Thermoplastic, liquid crystal polymer (LCP), noted for high temperature and excellent gas barrier properties has

been considered as a candidate material for designing a package for MEMS/RFMEMS devices in this research work. LCP had been previously used in the electronic industry for molded components. Chemically LCP is 2-naphthalenecarboxylic acid, 6-(Acetyloxy)-polymer with 4-(Acetyloxy) benzoic acid. LCP has been previously used in the electronic industry for molded components.

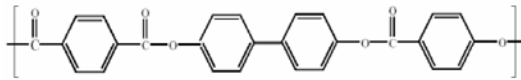


Figure 1: Chemical Structure of LCP.

LCP has high modulus and high melting temperature because of fibrous nature of liquid crystal morphology (rigid-rod like structure) [3]. LCP has anisotropic mechanical and thermal properties [4]. LCP is virtually resistant to almost all the chemicals used in the microelectronics fabrication industry.

Gas barrier properties:

LCP has very low moisture absorption about $\sim 0.02\%$ and equally low permeability comparable to glass. Gases such as oxygen, carbon-dioxide, nitrogen, argon, hydrogen and helium have average permeability through LCP [5].

Electrical and Radio Frequency (RF) properties:

Dielectric constant and the loss tangent of LCP remain constant over a frequency range 1 GHz to 35 GHz [6]. Laminated LCP-Si package simulations showed miniscule electrical degradation to the overall circuit performance [7]. Multilayer LCP packages achieved a return loss of -15 dB at 30 GHz and an insertion loss of less than 1 dB in the Ka-band [6, 7]. In summary, LCP is a promising material for RFMEMS packaging.

Direct laser assisted bonding (DLAB)

In this research work, LCP encapsulation [8] was used to reduce the packaging cost. The LCP encapsulation and pyrex glass carrier substrate have been chosen for the present study. Fabrication of RFMEMS packages includes wafer bonding/sealing, which provides a unique opportunity for construction of three dimensional structures. Bonding polymer to silicon is an emerging field and Table 1 gives a brief summary of the existing methods in the microelectronics industry. Heating sources such as dielectric heating and baking, heats the entire package, and so sets a

higher limit on the temperatures seen by the MEMS device. Using laser as a heat source concentrates the sealing/bonding to a confinement, and sets the operating temperature as the maximum temperature seen by the entire package. In this work, an IR CO₂ laser ($\lambda = 10.6 \mu\text{m}$) has been used to directly bond (without an extra bonding material) LCP substrate to pyrex glass substrate.

This paper discusses the findings of the sealed LCP packages. The sealed packages were tested for mechanical strength and for hermeticity. To understand the mechanism of bonding, analytical techniques such as scanning acoustic microscopy (SAM) and Fourier transform infrared spectroscopy (FTIR) have been used.

Experimental Setup

Laser system:

A CO₂ laser system (Preeco Model 3080, $\lambda=10.6 \mu\text{m}$) was used for DLAB process. Figure 2 shows the experimental setup of the DLAB process. Samples were placed on the XY translation stage, which is controlled by a stepper motor, the translation of the stage can be programmed using a software application provided by Velmex[®] NF-90 controller. The CO₂ laser energy distribution was obtained using 4-Sigma method which is shown in Figure 3. Figure 3 shows the Gaussian distribution of the unfocussed laser beam with a beam diameter of $\sim 7\text{mm}$ and the focused diameter of the laser beam at 17.5 cm working distance is $\sim 0.5 \text{ mm}$. The laser path of the DLAB process is shown in Figure 4 which is programmed at a specific speed (0.3, 0.5, 1.0, 1.5 mm/s) using Velmex[®] Controller. The laser parameters for DLAB process are given in Table 2 and the highlighted experimental conditions resulted in good mechanical strength.

Sample preparation:

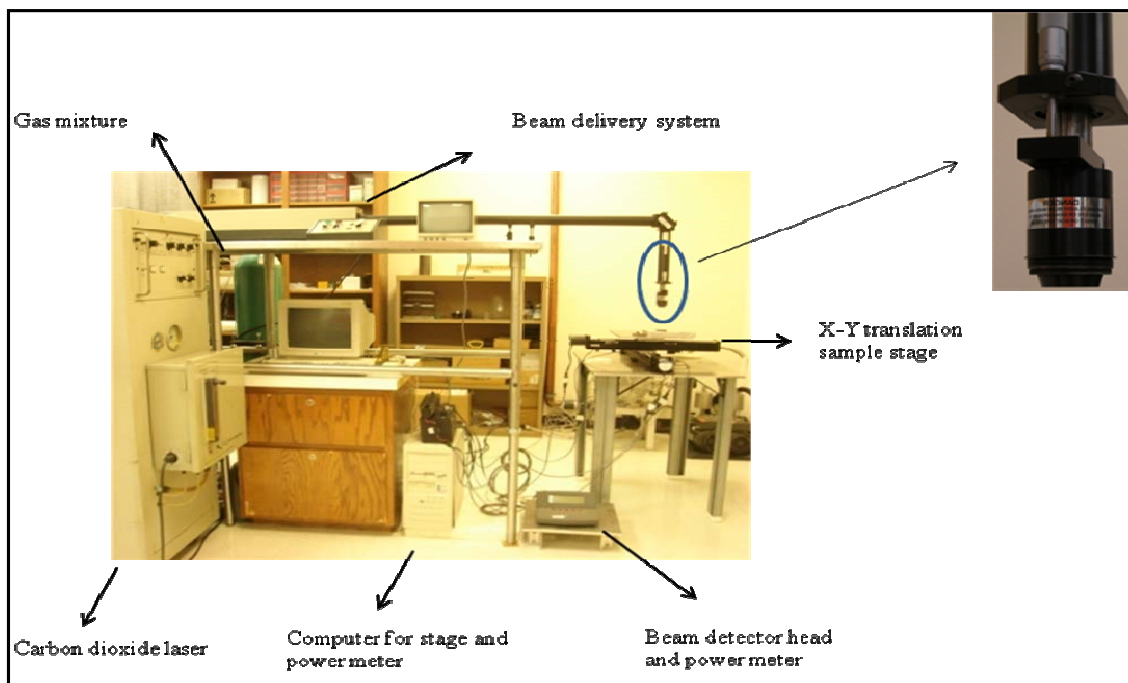
Direct laser assisted bonding (DLAB) requires clean surfaces, and so 1cm^2 pyrex glass samples were cleaned in freshly prepared Piranha (3 parts of H₂SO₄ and 1 part of H₂O₂) and LCP samples were cleaned using PM-925 (45% KOH solution). LCP sample and a pyrex glass sample were stacked face-to-face during DLAB process as shown in Figure 5.

Table 1: Comparison of Bond Strength Values Existing in the Literature.

Laser type	Mode of operation of laser	Substrates	External pressure/force (MPa)	Bond strength (MPa)
Nd: YAG (355nm) Nanosecond laser ⁹	CW	Top : glass Bottom: silicon	10	5-10
Diode laser (808 nm) ¹⁰	CW	Top: PMMA Bottom: PMAA	0.5 – 10	
Femtosecond laser ¹¹	Pulsed	Top: Glass Bottom: PMAA	No specific number given	
Diode laser (808 – 980 nm) ¹²	Pulsed	Plastics	No specific number given	
Nd: YAG (355nm) ¹³	CW	Top : glass Bottom: silicon	1	9.2
Nd: YAG (355nm) ^{14,15,16}	Pulsed	Top : glass Bottom: silicon	0.5 -2	11
CO ₂ laser (10.6μm)	CW	Top : glass Bottom: LCP	No	0.57-0.58

Table 2: Experimental Parameter Matrix.

Material system	Laser power (W)	Laser scanning speed (mm/s)
LCP-Pyrex glass	4, 4.5, 5, 5.5	0.3, 0.5, 1.0, 1.5

**Figure 2: Experimental Setup Showing the Laser Head.**

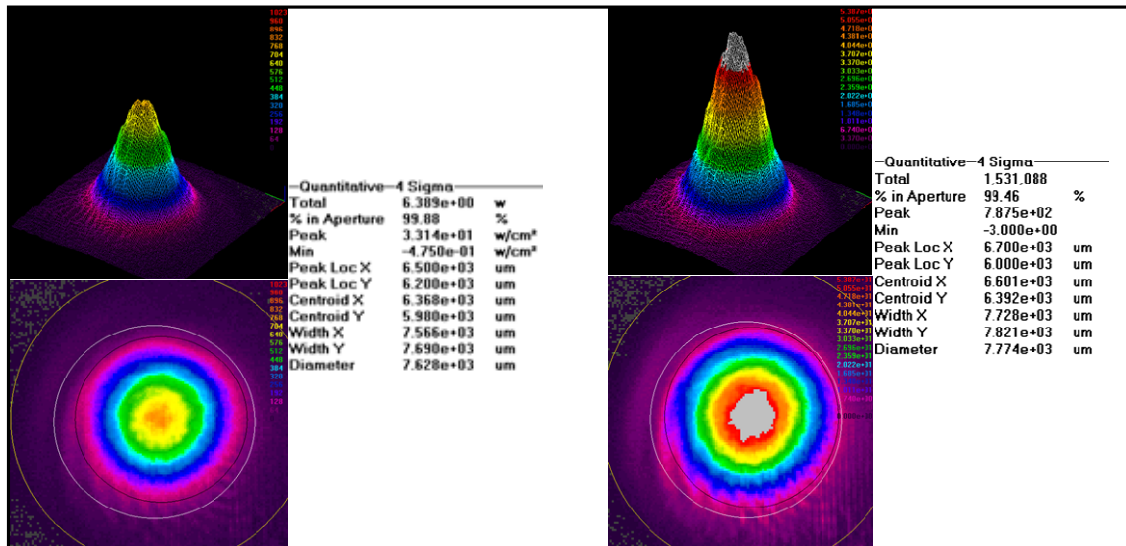


Figure 3: Laser Energy Distribution Obtained Using 4-sigma Method.

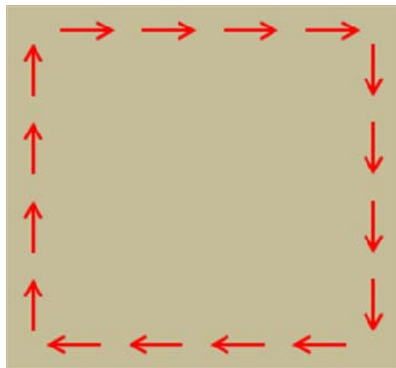


Figure 4: Lasing Path on Pyrex Glass Samples.

LAB processing parameters:

- Laser: CO₂ laser ($\lambda = 10.6 \mu\text{m}$)
- Lens used: Spherical Lens
- Focal length: 10"
- Working distance: 5"
- Laser beam size at 5": 500 μm
- Processing environment: Air

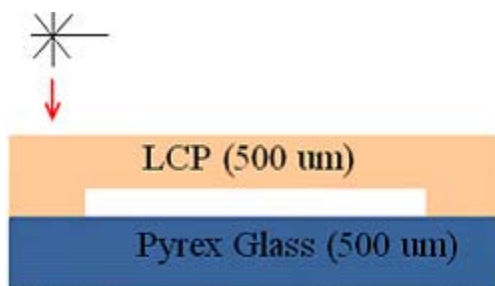


Figure 5: Schematic of DLAB Configuration.

Results and Discussion

125 mm diameter pyrex glass wafers were patterned and diced into 1cm² samples, LCP is available in sheets with copper cladding on both sides and so 125mm wafers had been cut out, patterned and etched. 50 μm deep cavity was etched (using oxygen plasma) with copper as the masking material before dicing into 1cm² samples.

Laser irradiation of material initially causes absorption of radiation energy by free electrons and subsequent heating of the material lattice through electron-lattice interactions. So for DLAB process, the initial experimental parameters were obtained by analytically modeling a Fourier 1D heat transfer between LCP-pyrex glass substrates. The model assumed heat input to be constant heat flux. It considered heating of the metal lattice through electron-lattice interactions and neglected the absorption of laser radiation. So laser input power has been modeled as increase in the temperature of the surface due to specific heat capacity plus heat transfer due to heat conduction minus heat transfer due to convection and radiation.

The laser input power values thus obtained were used to measure the surface temperature of the pyrex glass substrates. The surface temperature is important as these values determine the LCP-pyrex glass interface temperature. The glass transition temperature of LCP sets the lower limit for the interface (LCP-pyrex glass) temperature.

The LCP- pyrex glass packages were sealed according to the laser parameters shown in Table 3 and using the experimental setup shown in Figure 2. The pyrex glass samples were analyzed using FTIR before and after laser processing (not included due to formatting issues). It is believed that because of laser heating, a chemical bond is formed between LCP and pyrex glass. Bond formation could be because of the following reasons, firstly, FTIR peaks at 1500 and 1600 cm^{-1} indicate the presence of aromatic homocyclic rings on pyrex glass sample implies formation of a chemical bond between glass and the aromatic rings. Secondly, peaks at 1383 and 1341 cm^{-1} indicate C-O bonds connected to the naphthalene ring and the C-O bonds between the naphthalene ring and the phenolic oxygen, another indication of a chemical bond between naphthalene ring and the glass. [Peaks at 1605 and 1340 cm^{-1} indicate the presence of naphthalene units.]

Table 3: Experimental Parameters for DLAB.

Material system	Laser power (W)	Laser scanning speed (mm/s)	Remarks
LCP-pyrex glass	4.5	1.0	Very good bond

Mechanical Pull Test:

The Quad Group Inc., model SEBASTIAN FIVE-A pull tester was used to estimate the mechanical strength of the laser bonded seal. The laser sealed packages were tested based on MIL STD 883 E Method 1014.9 using helium leak detector ALCATEL Inc., Model ASM 110 TCL portable leak station. To check for the presence of voids in the lasing path scanning acoustic microscopy was performed on the laser sealed packages using SONIX – UHR 2000 series. The following sections describe the results obtained from each of the employed analytical techniques.

The laser sealed packages were attached to an Aluminum plate using JB weld and allowed to cure for 24 hours. The LCP-pyrex glass samples under mechanical pull test failed at the interface. The average test results for 4 samples are shown in Table 4. From the results it can be concluded that the LCP bonds very well to the pyrex glass.

Table 4: Mechanical Pull Test Results.

Laser Power (W)	Scanning Speed (mm/s)	Bond Strength (MPa)
4.5	0.5	0.57 - 0.58

Hermeticity Test:

Cavity volume of the packaged samples were $>0.05 \text{ cm}^3$ and $<0.5 \text{ cm}^3$ and so the helium leak detector was used to measure fine leak rate. The gross and the fine leak tests were conducted on 4 samples as described by Yi Tao [17, 18]. The results for the fine and the gross leak tests are tabulated in Table 5. The results show that the laser sealed LCP-pyrex glass samples passed the bubble test and the fine leak rate is well below the rejection limit ($5 \times 10^{-8} \text{ atm/cc}$).

Table 5: Fine and Gross Leak Test Results.

Laser power (W)	Scanning speed (mm/s)	Bubble test	Helium leak rate (atm/cc)
4.5	0.5	passed	2×10^{-9}

Scanning Acoustic Microscopy (SAM):

Figure 6 shows the SAM image of the LCP-pyrex glass laser sealed package. The SAM was operated at 110 Hz, with a gain of 15db and a working distance of 10 microseconds. The dark region in Figure 6 represents the bonded region due to heat input. Voids are typically visible as white patches in the SAM images and Figure 6 shows minor voids, which imply the lasing path to be continuous (approximately) allowing uniform bonding. It can be concluded that the laser sealing was good without voids in the lasing path.

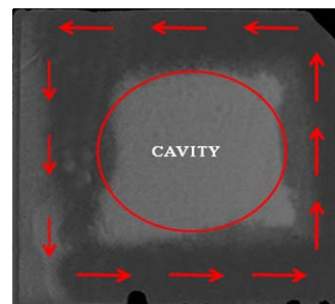


Figure 6: SAM Image of the Sealed Package.

Conclusions

The LCP-pyrex glass samples were fabricated and the successful DLAB process was discussed. The laser sealed LCP-glass packages were tested for mechanical strength and hermeticity. The results indicated good mechanical strength and a hermetic seal. The SAM results showed that the lasing path was continuous with minor voids. This research needs further analysis and electrical testing. This technology can be scaled up for manufacturing in wireless and telecommunication systems.

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