Carbon Fiber Encapsulation for Packaging Biomedical Lab-on-Chip Components

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Abstract *This paper describes a deflection of encapsulation material on Lab-on-Chip (LOC) Biomedical device. The packaging technologies as described in this paper represent important steps in developing a user-friendly, practically usable encapsulation LOC device from a bare biochip. This development aims at a prototype device that can be applied for the evaluation of the biochip's analytical properties and the implementation of suitable assays in the field of medical diagnostic testing. The study involve in determine the best material for outer encapsulation which is required to protect the sensitive element on LOC during high-pressure transfer molded packaging process. The encapsulant material has to have maximum top surface deflection of 100 um under 100 atm vertical loading. The modeling was simulated using CoventoreWare ver.2008 software. The material selected for these encapsulation LOC were polyphenylene sulfide (PPS) high modulus carbon fiber 55% and liquid crystal polymer (LCP) carbon fiber. From the result it conclude that the PPS high modulus carbon fiber 55% is suitable for encapsulates LOC compared to LCP carbon fiber due to its strength, capable to endure deflection less than 100 um under uniform pressure applied on the top of encapsulation.*

Keywords—Lab-on-Chip(LOC) Biochip, Encapsulation, Polyphenylene sulfide (PPS) high modulus carbon fiber 55%, Liquid crystal polymer (LCP) carbon fiber.

I. Introduction

A lab-on-a-chip (LOC) is a device that integrates one or several laboratory functions on a single chip of only millimeters to a few square centimeters in size. LOCs deal with the handling of extremely small fluid volumes down to less than pico liters. Lab-on-a-chip devices are a subset of MEMS devices and often indicated by "Micro Total Analysis Systems" (µTAS) as well. A most major challenge in LOC is to develop standardize packaging while maintaining reliability and functionality of the device [1]. Here, a report on the plastic packaging concept for a silicon biochip fabricated by MEMS (micro electro mechanical system) technology. Instead of plastic packaging, MEMS packaging varies with device function, thus affect the high cost of packaging. Therefore in order to develop the low cost of packaging, device capping followed by glob encapsulation technique in order to reduce the rigorous testing and screening required for low volume parts. [2]

A Biochip MEMS is typical of micro-electromechanical system (MEMS) where biological matter is manipulated to analysis and measurement its activity under any class of engineering and scientific study [3]. The most important applications based in Bio-MEMS are: biological and biomedical analysis and measurements, micro total analysis systems (uTAS). Most of the devices not require interaction with outside ambient devices. Normally, for the electrical connection of silicon dies in MEMS device fabrication, wire bonding and flip-chip technology was used. But there are problem of these technologies where the device potentially have to undergo mechanical, chemical or biological interaction with the environment [3]. This difficulty in finding suitable interconnection and encapsulation solutions is one of the main reasons, why the majority of biochip prototypes, which have been developed in scientific laboratories. During the last decade the encapsulation technology was discover so that it can be applied for the evaluation of the biochip's properties and implementation of suitable assays in field of biomedical LOC [3]. This paper develops a modeling of predicting deflection of encapsulation material of dome shape under uniform loading. Parameter considers due to the modeling simulation is mechanical properties which Young's modulus and Poison's ratio of the material. Therefore the material PPS carbon fiber and LCP carbon fiber are selected to be encapsulation material due to high strength characteristic. The deflections for each material are compared to select the best encapsulation material under given pressure loading and package thickness constraints.

Commonly MEMS device a build up with sensor or actuator element fabricated on silicon substrate. The sensor element usually movable and very sensitive to any contamination, therefore it require a protector in order to prevent it from being damage from the environment, while somewhat in contradiction, enabling interaction with that environment in order to measure or affect the desired physical or chemical parameters [1]. As a result, encapsulation method is applied to the device. Figure 1 show MEMS Biochip to be encapsulated. For the fabrication process due to encapsulation method, generally metal such aluminum or silicon used to be cap material, deposited on the top of sensor element. The standard deposition technique usually used are CVD or sputtering [4]. Then the silicon oxide is pre-deposited on the movable part to create gap between sensor element and cap. Silicon oxide is removed to create 100 um gap. For extra strength on the cap, encapsulation is needed during transfer molding process. Therefore, encapsulation material such as polymer is deposited on the top of MEMS device structure.

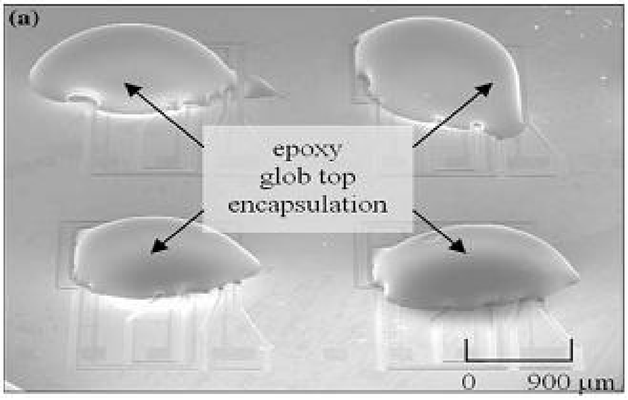

Figure 1 a) Epoxy encapsulation LOC device [1].

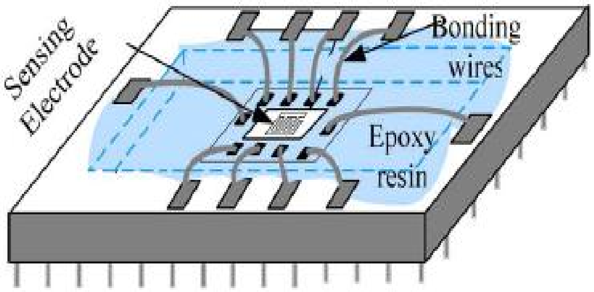

Figure 2 MEMS Microfluidic Biochip [2]

Figure 2 shows a MEMS biochip which is used to be encapsulated. The encapsulation applied to avoid direct contact between electrode sensors with fluid in the channel. Normally, for the electrical connection of MEMS devices fabrication used the sensor, wire bonding and flip-chip technology. However, these technologies potentially undergo mechanical, chemical and biological interaction with environment. Therefore the encapsulation used to reliably separate electrode sensor from fluidic interface [3].

II. Methodology

a) Analytical approach

For the encapsulation process, the general process flow is shown in Fig.3 below. Initially, the encapsulation design and dimension are determined. In this case, the glob encapsulation has to have spherical dome shape with thickness of 250 um. The thickness is sufficient to protect the sensitive element for the LOC before undergoing SMT packaging.

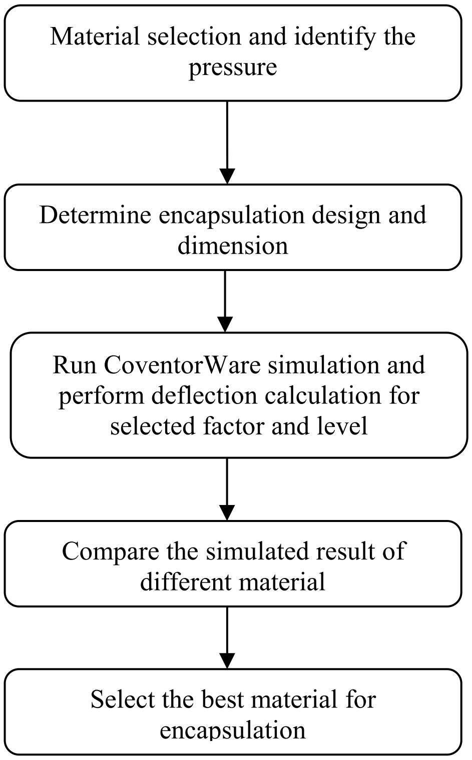

Figure.3 Flow chart of encapsulation process due to different material

The modeling of encapsulation is determined where the dome designs semi spherical shape because of capability the dimension to endure high external pressure applied on each side. In this case, the pressure was applied on the top of encapsulation due to maximum transfer molding process. The stress applied on the top originally distributed in meridional direction which denoted by w and υ as shown in Figure 4 [2]. The material for encapsulations is choosing so that it capable to hold for 100 atm external pressure applied on the top of encapsulation for deflection analysis. The gap between the sensor and the cap is 100 um. In MEMS Biochip device, the maximum allowable deflection due to its sensor is 100 um. Therefore, material selected in the simulation must be acceptable in the range of 100 um deflection.

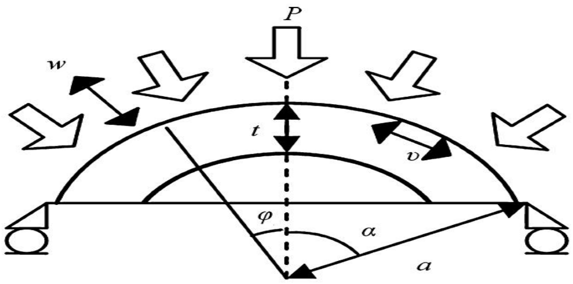

Figure 4 Schematic diagram showing the cross section and the parameter involve in encapsulation structure [1].

The parameter involve in the deflection of top encapsulation are lateral length defined as 2b which approximate to 5286.464 um. The radius of encapsulation defined as 'a' and vertical to base angle define as α. For mathematical simultaneous equation of the encapsulation, the value of '*a'* and *α* is 10156 um and 15.09°. The calculation for the parameter involve is shown below. The shell radius was calculated using Theorem Pythagoras.

$$a^2 = b^2 + (a - (100\ \text{um} + 250\ \text{um}))^2$$
$$2(350\text{um})\ a = 7.109\ \text{um}$$
$$a = 10156\ \text{um}$$

$$\sin \alpha = \frac{2643.232}{10156}$$
$$\alpha = 15.09°$$

To determine the vertical deflection due to pressure applied on the top of encapsulation, it must satisfy the shell bending theory. From the parameter above, the ratio t over curvature *a* is approximately 0.02 which is too small. The resultant of the ratio follow that the radial deflection *w* of the encapsulation could be approximate when loaded with uniform pressure using shell bending theory. The shell bending theory used to approximate deflection of thin semi-spherical structure where the deflection radial much smaller than the shell thickness. From shell bending theory, it state that for radial deflection of a thin shell structure under uniform pressure P, as shown in Figure 4, mathematical deflection equation can be derived as shown below [1].

$$w = \upsilon \cot \varphi - \frac{a^2 P}{Et}\left(\frac{1+v}{1+\cos\varphi} - \cos\varphi\right) \tag{1}$$

where;
w = Deflection
E = Young's Modulus
υ = Meridional Deflection
v = Poison's ratio
t = Shell thickness
φ = angle from vertical at which deflection considered

$$\upsilon = \frac{a^2 P(1+v)}{Et}\left(\frac{1}{1+\cos\alpha} - \frac{1}{1+\cos\varphi} + \ln\left(\frac{1+\cos\varphi}{1+\cos\alpha}\right)\right)\sin\varphi \tag{2}$$

Material selected for this encapsulation study was RTP 1390 HM Polyphenylene sulfide (PPS) high modulus carbon fiber 55% (RTP Company, Winona, MN USA) and RTP 3499-3 X 93110 liquid crystal polymer (LCP) carbon fiber encapsulation grade (RTP Company, Winona, MN USA). The mechanical properties of this material were taken as outstanding parameter for the deflection phenomena. The mechanical properties for both materials were summarized in Table 1 below.

Table 1 Young's modulus and Poison's ratio values for encapsulation material.

Material	**Young's modulus (GPa)**	**Poison's ratio**
PPS high modulus carbon fiber 55%	62.1	0.4
LCP carbon fiber	16.548	0.4

The CoventorWare ver.2008 was used for simulates the deflection on encapsulation. The designed encapsulation was approximately as shelled dome shown in Figure 4. By using the simulator, the encapsulation model have been shown in Figure 5 below, consists of silicon substrate and encapsulation shell.

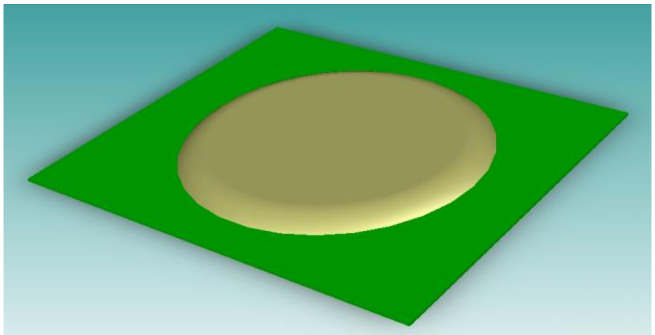

Figure 5 CoventorWare encapsulation model used in deflection simulation

III. Result and Discussion

The properties of encapsulation material have been proven by showing the differential deflection between two types of material. The simulation on deflection of the structure was applied on the top of encapsulation structure by using 100 atm pressures at the centre to ensure the maximum implementation case of encapsulation. The

Figure 6 shows the modeled encapsulation with deflection phenomena under 100 atm uniform pressures. The red color at the centre of encapsulation model indicates the maximum deflection. From the simulation, the deflection performed with encapsulation material, at 100 atm pressure and thickness of 250 um are tabulated in Table 2. It can be observe that the differential two types of material affect the deflection on the encapsulation. For 250 um thick PPS high modulus carbon fiber 55%, resultant deflection of 14.239 um while LCP carbon fiber deflect at 53.744 um. The different of Young's modulus parameter and thickness are corresponding to the deflection of encapsulant. The deflection value must not exceed 100 um to avoid any contact or squishing element by the encapsulated material itself.

Due to the deflection characteristic, both item are acceptable for LOC encapsulation for biomedical application since the deflection region under range of 100 um, comprises a central membrane having a micro-channel diameter of 100 μm. The packaged biochip provides a fluidic interface to the fluidic cartridge as well as electrical interfaces to the sensor electronics located in a readout instrument. As a result, encapsulation packaging method provides the strict separation between the wet sensing area and the electrical contacts.

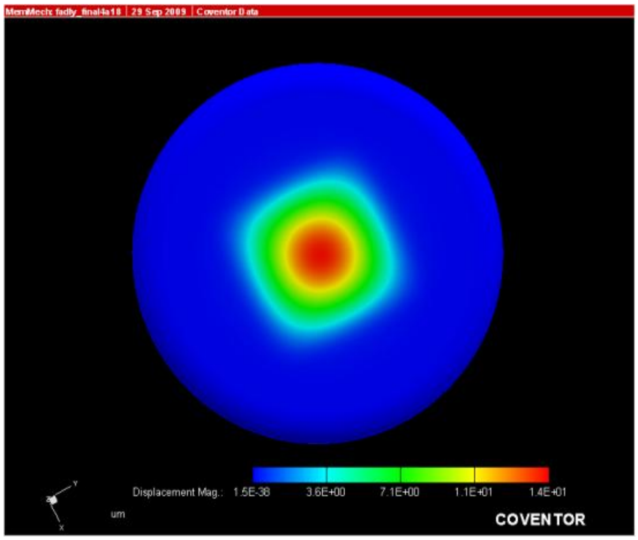

Figure 6 A simulation using CoventorWare showing 250 um thick PPS high modulus carbon fiber 55% deflection of 14.239 um under 100 atm pressure

Next, both material are re-simulate for encapsulation thickness of 200 um and 150 um to study the effect of thickness variation. These results of encapsulation were summarized in Table 3. The deflection of encapsulation was determined on z-plane since the loading pressure applied on the top of encapsulation to the bottom. From the result it is observe that the minimum thickness required for PPS carbon fiber and LCP carbon fiber are 150 um and 200 um respectively, to withstand 100 atm loading without excessive deflection. The simulated result was compared with the calculation result using the shell bending equation. According to Figure 6 it has shown that the major deflection concentrated at the center of encapsulation. The value of φ is set to approximately zero (φ ≈ 0) so that the implementation imitates maximum deflection of the encapsulation structure. The simple calculation on deflection was shown below using PPS carbon fiber with thickness of 250 um. Since the φ ≈ 0, therefore meridional deflection, υ = 0. Therefore, the resultant from calculated deflection is 20.195 um.

$$w = -\frac{a^2P}{Et}\left(\frac{1 + \nu}{1 + \cos\varphi} - \cos\varphi\right) \qquad (3)$$

$$w = \frac{10156\ \text{um}\,(10.1325\text{MPa})\,(0.30)}{(62.1\text{GPa})(250\ \text{um})} \qquad (4)$$

$$= 20.195\ \text{um}$$

The encapsulation deflection values obtained from simulation performed with PPS carbon fiber and LCP carbon fiber and thickness variation are close even there is huge error occur especially at thickness of 250 um and 150 um. But at 200 um thickness, the simulated result are very close, where the error less than 3%. Therefore, the calculated results provide a good basis for analysis verification. Based on the result, it could be conclude that the simulated values are approximate to the actual values at condition stated above. It also observed that Young's modulus is the most important factor on the encapsulation model. The small change in Young's modulus value would result greatly affect the deflection. For that reason, it is important to select material has correct Young's modulus value in order to obtain the desired deflection result.

Table 2 a) Deflection result on encapsulation for PPS high modulus carbon fiber 55% and b) LCP carbon fiber at 250 um thickness.

	Maximum (um)	**Minimum (um)**
Node Displacement	14.239	1.471e-38
Node x displacement	1.7909	- 1.789
Node y displacement	1.7914	- 1.7919
Node z displacement	0.02694	- 14.239

	Maximum (um)	**Minimum (um)**
Node Displacement	53.744	1.8859-37
Node x displacement	6.76274	- 6.758
Node y displacement	6.7661	- 6.7623
Node z displacement	0.08408	- 53.744

Table 3 a) Deflection result on encapsulation for PPS high modulus carbon fiber 55% and LCP carbon fiber at constant pressure 100 atm with different thickness.

Exp	Material	Thickness (um)	W_s (um)	W_c (um)	Error W_s/W_c (%)
1	PPS carbon fiber	250	14.239	20.195	- 29.49
2	LCP carbon fiber	250	75.769	53.744	40.98
3	PPS carbon fiber	200	25.796	25.244	2.19
4	LCP carbon fiber	200	92.715	94.73	-2.13
5	PPS carbon fiber	150	54.875	33.66	63.03
6	LCP carbon fiber	150	153.076	126.31	21.19

The tabulated result on deflection was plot into graph to compare the differentiation of material PPS carbon fiber and LCP carbon fiber shown in Figure 7. From the graph, the PPS carbon fiber has the lowest deflection compared to LCP carbon fiber. The thickness of encapsulation material is inversely proportional to deflection, since decreasing the thickness resultant increasing in deflection of encapsulation.

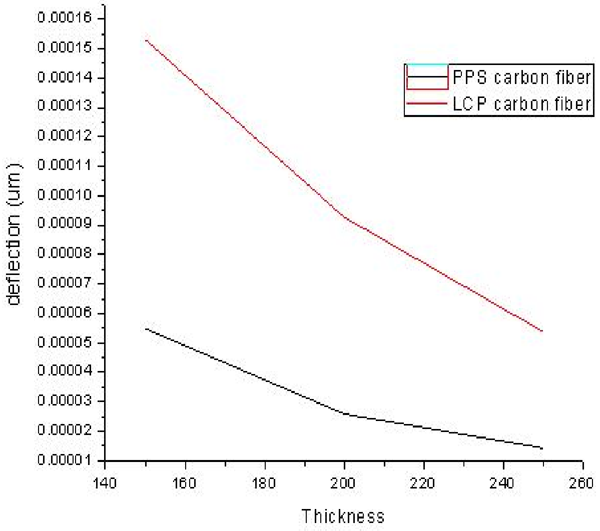

Figure.7 Graph deflection vs. thickness on material PPS carbon fiber and LCP carbon fiber

IV. Conclusion and Future Development

A final encapsulation modeling was successfully developed using CoventorWare software for deflection analysis on MEMS Biochip application. The uniform dome shaped encapsulation was simulated using CoventorWare ver.2008 with two types of materials. Both materials PPS high modulus carbon fiber 55% and LCP carbon fiber are acceptable for encapsulates MEMS Biochip due to deflection less than 100 um under 100 atm pressure applied on the top of encapsulation. Therefore, the encapsulation method can be implementing on Biochip chip component since the deflection less than maximum requirement for the devices. Finally, it can conclude that PPS carbon fiber is the best material used for encapsulation layer Bio-medical LOC with the thickness of 150 um under 100 atm due to its high strength. The application of the encapsulation can be used in the future technology based on MEMS and LOC device packaging. The development also will be on the ability of the material to be implement inside human body since the technology involve in many bio-medical devices.

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References

[1] Azrul Azlan Hamzah, Yusnira Husaini, Burhanuddin Yeop Majlis, Ibrahim Ahmad, Selection of high strength encapsulant for MEMS devices undergoing high-pressure packaging

[2] Study and characterization of plastic encapsulated packages for MEMS, Anjali W. Deshpande, Worcester Polytechnic Institute

[3] Experimental and Theoretical Approaches Ugural AC (1981) Stress in plates and shells. McGraw-Hill, New York

[4] Lebouitz KS, Mazaheri A, Howe RT, Pisano AP (1999) Vacuum Encapsulation of resonant devices using permeable polysilicon. In: Proceedings IEEE twelfth international conference on microelectro mechanical systems (MEMS'99), Orlando, Florida, pp470–475

[5] Chemical and Biological Applications of Digital-Microfluidic Devices Richard B. Fair, Andrey Khlystov, Tina D. Tailor, Vladislav Ivanov, and Randall D. Evans Duke University Vijay Srinivasan, Vamsee K. Pamula, and Michael G. Pollack, Advanced Liquid, Logic Peter B. Griffin Stanford University Jack Zhou Drexel University

[6] A Microfluidic Packaging Technique for Lab-on-Chip Applications Ebrahim Ghafar-Zadeh, Mohamad Sawan, Fellow, IEEE, and Daniel Therriault

[7] Microfluidics: Fluid physics at the nanoliter scale, Todd M. Squires* Departments of Physics and Applied & Computational Mathematics, California Institute of Technology, Pasadena, California 91125, USA

[8] Paul V. Dressendorfer, David A. Peterson, Cathy A. Reber Sandia, National Laboratories MEMS Packaging-Current Issues and Approaches.

[9] Coupled Package-Device Modeling for MEMS Stephen F. Bart, Susan Zhang, Vladimir L. Rabinovich, and Shawn Cunningham* Microcosm Technologies, Inc., 215 First Street, Suite 219, Cambridge, MA 02142 USA

[10] Sputtered Encapsulation as Wafer Level Packaging for Isolatable MEMS Devices: A Technique Demonstrated on a Capacitive Accelerometer, Azrul Azlan Hamzah, Jumril Yunas, Burhanuddin Yeop Majlis 1 and Ibrahim Ahmad

[11] Choon Ki Ahn, Jung Hun Park, and Wook Hyun Kwon 2D & 3D Finite Element Method Packages of CEM Tool for Engineering PDE Problems

[12] Concept for Packaging of Silicon based Biochip T. Veltena, M. Biehla, T. Knolla, W. Haberera a Fraunhofer Institute for Biomedical Engineering, Ensheimer Strasse 48, 66386 Sankt Ingbert, Germany

[13] Dolbow J, Gosz M (1996) Effect of out-of-plane properties of a polyimide film on the stress fields in microelectronic structures. Mech Mater 23(4):311–321

[14] Y. C. Lee, Member, IEEE, Babak Amir Parviz, Member, IEEE, J. Albert Chiou, and Shaochen Chen, Packaging for Microelectromechanical and Nanoelectromechanical Systems