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Fiber Bragg Grating Sensors For Failure Detection Of Fip Chip BGA In Four-Point Bending Test

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FIBER BRAGG GRATING SENSORS FOR FAILURE DETECTION OF FLIP CHIP BGA IN FOUR-POINT BENDING TEST

by

Rasha Hussain

B. Eng., Concordia University, Canada, 2006

A thesis

presented to Ryerson University

in partial fulfillment of the

requirement for the degree of

Master of Applied Science

in the Program of

Electrical and Computer Engineering

Toronto, Ontario, Canada, 2008

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Abstract

Fiber Bragg Grating Sensors for Failure Detection of Flip Chip BGA in Four-point Bending Test

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Master of Applied Science

Electrical and Computer Engineering

Ryerson University

Maintaining structural integrity is an important issue for advanced flip chip ball grid array (FC-BGA) packages especially due to the use of Pb-free solder replacing the Pb-contained solders and the large package size induced mechanical vulnerability. For such packages, the mechanical bending causes fracture in the interconnecting plastic PWB. To determine the critical load becomes a challenge to assembly manufacturers since the conventional testing methods based on monitoring electric continuity of the daisy chained solder joints fail to detect the PWB de-bonding near the interconnect. This thesis researches a new method that uses the Fiber Bragg Grating sensor to detect the interconnect fracture failure of 55 mm lead-free FC-BGA under four-point bend test. Experimental setups and procedures are studied, a proper test configuration is determined and a series of testing performed. The validity of the new method in monitoring the solder joint de-bonding is proved through analyzing the test results, which shows that the FBG sensors are sensitive to capture the onset of the fracture in different cases.

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List of Symbols

Greek Symbols	Description
λ_{Bragg}	Grating wavelength
Δn	Change in the core refractive index
Λ	Fiber Bragg grating period
Λ_{pm}	Phase mask corrugation period
n_{eff}	Effective refractive index
$\hbar$	Reduced Planck constant
k_i, k_f, K	Incident, scattered, grating wavevectors
Ω	Coupling coefficient between the forward-and backward propagation modes
β	Propagation constant of the fundamental LP_{01} mode
$\Delta\beta$	Detuning wave parameter
σ_B	Bragg wave number
$\eta(V)$	Modal overlap factor
ω_o	Angular frequency of the input optical carrier
ω_1, ω_2	Angular frequency of the subcarriers
ε	Engineering strain
δ	Crosshead travel distance
$\dot{\delta}$	Crosshead speed
ε	Global PWB strain
$\dot{\varepsilon}$	Global PWB strain rate
ρ	Specific resistance constant for each material
σ	Engineering stress

English Symbols	Description
B	Bandwidth
n_{core}	Non-modified core refractive index
n_{cladd}	Non-modified cladding refractive index
V	Normalized frequency of the fiber
L	Length of conductor
A	Cross sectional area of conductor
R	Resistance
K	Strain Gauge factor
L_s	Support span
L_L	Load span (centered within support span)
t	PWB thickness
E	Young's modulus

Acronym	Definition
PWB	Printed wiring board
PCB	Printed circuit board
BGA	Ball grid Array
HDI	High density interconnect
FC-BGA	Flip chip- Ball Grid Array
SMT	Surface mounted Technology
FBG	Fiber Bragg grating
IPC	Interconnecting and packaging Electronic Circuits
JEDEC	Joint Electronic Devices Engineering Council
IC	Integrate Circuit
EMI	Electromagnetic interference
UV	Ultraviolet laser

OSP	Organic solderability preservative
A/D	Analog to digital
DAS	Data acquisition system
I/O	Input / Output
DC	Direct current
AC	Alternating Current
CTE	Coefficient of Thermal Expansion
IMC	Intermetallic compound
ICT	In-Circuit test
SEM	Scanning electron microscope
WDM	Wave division multiplexing
OSA	Optical spectrum analyzer
SMD	Solder mask defined
ENIG	Electroless-Nickel and Immersion Gold
SOP	Small outline packaging
CSP	Chip scale size package
PGA	Pin grid array
FR-4	Fire retardant Glass Laminate
UBM	Under bump metallurgy
LVDT	Linear variable differential transformer
SMF	Single mode fiber
APC	Amphenol Precision connector

Chapter 1

Introduction

Electronic devices have long been part of our everyday life. The advances made in the packaging technology have brought optimized performance into the hands of the end users. As per the future of technology, new methods are made to increase the package density of the microprocessors; these are done in the form of ball grid array (BGA) package. Such technology has lead to an increasing number of interconnect density and a decrease in the pitch between solder balls. The packages are assembled on a printed wiring board (PWB also called as printed circuit board with PCB as its acronym) using a solder material. The PWB has high density interconnects (HDI) that carry signals throughout the board. The main purpose of the solder reflow is to establish a connection between the board and the packages. The circuit board assembly process is done by placing the BGA package on the board and passing it through the reflow oven as many times as required. The reflow oven melts the solder at a particular rate depending on the solder joints; to solidify the joints, the PWB is then passed through a cooling system. Once the solder joint connections are achieved, the electrical path between the BGA and the PWA are created.

The mechanical reliability of the component after the surface mounted process becomes very important. As the size of the flip chip ball grid array (FC-BGA) packaging increases, the interconnect densities also increases that may lead to fragile connections. As a consequence, there is a potential increase for flexure-induced damage. The assembly process which utilizes a solder reflow thermal process, the package substrate and the printed circuit board (PCB) co-planarity variation during the processes will cause interconnect and interfacial stresses which weaken the joints strength. All these are criteria that make the mechanical integrity become an important issue to electronic assembly manufacturers [1-4]. Figure 1.1 and 1.2 show the necessity of the strain gauge measurement at the steps of assembly process; this may provide crucial information regarding the stages which may subject the board to severe bending [4]. Another concern

regarding this technology is reliability evaluation of the material used for the solder bump. The conventional solder bump in a flip chip was eutectic Sn/Pb which was proven to be highly adequate for solder joint interconnect. Environmental studies conducted in the recent years have lead to the awakening about the severe outcome from even the slightest emission of Pb. The discarded PCBs end up buried in landfills resulting in the solubility of its oxide from the solder; through time, this oxide leaches into the groundwater and causes contamination. The above events have lead to the development of lead-free solder. The lead-free solder has a higher melting point (217-221°C) compared to a melting point of 183 °C for the eutectic Sn/Pb; as a consequence, a higher reflow temperature may cause higher thermo-mechanical stresses, leading to the reliability issues such as PCB warpage, delamination of interfaces, factures and more [5].

Figure1.1: Board assembly strain measurement [4].

Figure1.2: System assembly strain measurement [4].

The damages inflicted on the board may not only come from production processes, it may also happen during shipping, installation as well as end usage. The mishandling of the board will induce PCB flexure that can damage solder ball interconnects. Therefore, it is important to establish the relationship between the flexure induced strain on the PCB board or BGA substrate and the fracture of solder ball interconnects in order to provide assurance to customers that packages can withstand a reasonable amount of stress once assembled. Among many test methods, such as drop/shock tests, thermal cycling, and vibration etc., four-point bending test using strain gauges becomes a common method to obtain mechanical integrity information for BGA package [1].

The different experiments conducted to date regarding PCB reliability used strain gauge along with continuous monitoring of the daisy chain resistance. These tests were based on the Interconnecting and Packaging Electronic Circuits (IPC) and Joint Electronic Devices Engineering Council (JEDEC) standards. The drawback from the current technique is that the strain gauge cannot be laid close to the corners of the BGA where most of the pad lift, crack and interconnect fracture modes occur because of its physical dimensions. The

nearest position where the strain gauge can be attached is to a corner of the substrate; but, prior to this step, a corner of the lid has to be removed. This process results in an alteration of the stress distribution on the BGA package. Another problem in the use of the resistor to detect the electrical failure; is that mechanical damage can occur to a BGA substrate and/or a PCB during bending test prior to the detection of any electrical failure. Defects, such as pad lifts and delamination between flip-chip BGA and the PCB may not display electrical failure traces. As a result of this generalization, some failures induced in the interconnection between the BGA and PCB may not be detected by the resistor, leaving to a false assumption that the PCB did not fail. A new strain sensor or test method that could address these problems would be in great demand; that would allow the electronic assembly manufacturers to better define the flexure performance specification and enhance both the PCB productivity and reliability.

Experimental as well as theoretical studies have proven that FBG has several advantages over the mechanical strain gauge [6, 7]. Some of them are enumerated below:

- The data recorded is wavelength encoded making them independent of the light levels, connectors, fiber losses and other FBG wavelengths, self calibration.
- The length of the FBG sensor is determined by the laser beam size, which can be adjusted using the appropriate amplitude mask to control the length of the FBG sensor. The shortest length accounted for the FBG sensor can be made to be ~ 0.2 mm using polyamide fiber with a diameter of $160\text{ }\mu\text{m}$ which is much smaller than the size of the strain gauge. Their small diameter allows them to be used for internal body temperature profiling. The small size and the compatibility with composite materials allow them to be relatively non-perturbing to the matrix when embedded for in situ monitoring of strain.
- FBG is immune to electromagnetic interference (EMI), which makes it favourable to be used in strong electromagnetic field.
- FBG is a composite that is much resistant to harsh environmental conditions when compared to conventional copper wires (strain gauge).
- The capability of multiplexing; multiple sensors can be written on a single fiber with minimal loss. By utilizing this feature, the strain can be measured at many locations on the substrate.

- The use of a FBG sensor array allows information to be transmitted optically to the data acquisition system unlike the strain gauge where multiple wired connections are required to achieve the same result.

1.1 Literature Survey of Reliability Testing Methods of FC-BGA using Fiber Bragg Grating Sensor

Several researchers with a background in electronics have performed experiments on FC-BGA packages as it constitutes an essential part of the product development. Each experiment performed focuses on various aspects that may lead to the failure of the product. Some of such variations are the solder joint material, the geometry of the solder bump and the external bending conditions (assembly, shipping, testing, end usage, etc.). The previous researches used strain gauge as a tool to measure the strain of the board flexure and the simultaneously record the daisy chain resistance. The scanning electron microscope (SEM) and Dye and Pry are also used in failure analysis. Several studies have been conducted on the applications of the FBG sensors;[6,17,22] however, as the following literature review reveals, FBG sensors have rarely been used in experimental procedure as a sensor in the reliability test of the FC-BGA. Nonetheless, some recent published papers tend to indicate conclusive observations regarding the behaviours of the side lobe of the FBG sensor's under four point testing [12].

George Hsieh et al [8] has reported the use of two strain gauges to study bend mode effects. One of the strain gauge was attached to the corner of the FC-BGA substrate while the other was attached to the back side of the PCB. This study has revealed the possibility of associating substrate strain relaxation to the progress of landside cracking leading to a failure. Bragg. et al [1] recently reported the bend and drop test results for 45mm FC-BGA using three strain gauges installed on the PCB board. In-situ monitoring of daisy chain was used to record the resistance change. They determined pad lifts as the main failure mode in the four-point bending test.

Geng et al [9] conducted high strain rate 4-point bend tests to analyze the behaviour of Sn-Pb and SnAgCu solder joints with 0.8 FC-BGA assembled to a PCB and to evaluate

the solder joint strength under PCB flexure due to the size of the solder resists openings, the solder ball diameters and the metal defined pads. Their results were as follows; (1) the strength of the SnAgCu solder is lower than that of the SnPb solder; the failure observed for Pb free was of type 2 (package side failure) while type 3 (solder /Cu pad IMC failure) failure was found on solder mask defined pads and type 4 (PCB Pad cratering) failure was apparent on metal defined pads; (2) when the loading speed is high, the bend test demonstrates that the SnAgCu solder joints resulted in more brittle failure. (3) The diameter of the solder ball has a direct effect on the strain values measured at joint failure; (4) The eutectic solder joints have stronger joints as opposed to lead free solder joints when the PCB is put under flexural bending load;(5) The ball diameter effect has a lower implication when compared to solder alloy effect; (6) That smaller the solder resist, weaker is the solder joint.

Geng et al [10] also monitored the BGA solder joint failure under different strain rate using four point bending test and finite element modeling. The BGA was positioned at 45° with respect to the PCB resulting in the solder joint failure at the corner joints as well as to facilitate the finite element modeling. The study revealed the following: (1) the solder joint failure is highly dependant on the strain rate; (2) A high strain rate causes a solder joint failure at the lower PCB deflection. Both the strain and the strain rate have been referenced on the PCB for this work.

Harada et al [11] studied the solder joint failure where an Electroless-Nickel and Immersion Gold (ENIG) interfacial fracture occurred. The ENIG can cause electrical open failure when a mechanical stress is exerted at the In-Circuit Test (ICT) package mounted on a PCB. The reliability of the solder joint was tested using a four point bending test and was simulated using finite elements analysis. The experimental conditions for the four point bending test have been optimized such that the phenomena of electrical open failure match the description of the failure mode. The effect of the hold time after package mounting up to the strain value to failure is also studied. Their observations showed that: (1) the strain value to failure depends on the strain rate; furthermore, there was no occurrence of failure at lower strain rates; (2) The packages

tested shortly after being surface mounted has a lower strain value to failure (lesser brittle fracture) when compared with that from the boards few weeks after the mounting; (3) The simulation results were concurrent to the four point bending test. The results indicate that maximum stress of a solder ball is concentrated at the interfacing between a solder ball and a package substrate land which coincides with the location of the solder joint fracture.

The studies from Takashi et al [12] studied on the effect of three and four point bending on the level of the side lobes of the reflection spectrum in an FBG. As part of this study, the FBG was subjected to three-point loading as well as four-point loading with various loads; the spectrum was observed using the OSA to compare the effect of the three point loading on the spectrum of the FBG, and the effect of four point loading on the FBG. The study demonstrated that: (1) there is a linear correlation between the wavelength shift and the applied force; (2) during three points bending, a second side lobe was detected as the applied load reached 72N since the applied load was not uniform on the FBG sensor; (3) The above behaviour (second side-lobe) was not detected on a four points bending test with even a load of 242N because the applied load was uniform; (4) The strain distribution along the grating increases the bandwidth of the FBG reflection peak and the side lobes.

1.2 Review of In-Fiber Grating Sensors

The diversity of the fiber Bragg grating's applications has attracted extensive attention in sensing community. Studies have proven that it can be used to record static and dynamic measurements such as strain, pressure, and temperature etc. Such observations have led to the use of FBG in various disciplines such as in mechanics, aerospace, chemistry and electronics. This technology is also used to monitor composite material curing and fatigue life, civil structures (highway, buildings, bridges, etc.), remote sensing of oil wells, power systems and pipelines. The in-fiber grating sensors are classified into different types according to their specific applications [7, 13, 14].

(1) Uniform Bragg Reflector: This is the simplest yet widely used grating; it is characterized by a constant pitch. The length and reflectivity vary at production according to the FBG's application. This type of grating is suitable to be used in strain and temperature sensing devices since the measurements are wavelength encoded, eliminating amplitude and intensity fluctuations which occur in various other types of intensity-based fiber sensors.

(2) Blazed (tilt) Bragg Grating: This grating has a phase front tilt with respect to the fiber axis such that the angle between the grating planes and the fiber axis is less than 90 degrees. This type of grating is used to flatten the gain of a spectrum of erbium-doped fiber amplifier; mode converter. The tilted grating can also be used to couple a forward propagating core mode to a backward propagating cladding mode.

(3) Chirped Bragg Grating: This type of grating has a monotonically varying the period. This type of grating has a broader reflection spectrum with each wavelength reflecting at a different position resulting in a time delay difference for each wavelength. The monotonic period variation has led to its favouritism in certain applications in the domain of telecommunication and fiber sensor; one of its applications is the distributed strain sensing over a length of 100 mm.

(4) Long period grating (LPG): This is defined by a periodic modulation of the refractive index in the core of the optical fiber. Its period varies in the order of hundreds of μm with a length of approximately 20 to 50 mm. The advantages that best describes this type of grating are its nature which is comparable to the grating mode converters, its use in coupling light from the guided fundamental mode of a fiber to the forward propagating cladding modes. It is used in telecommunication for band rejection filters, polarization mode converter as well as rocking filters. LPGs are very sensitive to external factors. Its period could vary according to its external disturbances, the order of the cladding mode with coupling and the composition. This makes it favourable to be used for temperature, strain and refractive index sensors.

1.3 Major Contribution of the Thesis

This thesis emphasizes on the experimental study of the Fiber Bragg Grating (FBG) sensors to detect interconnect failures of lead-free 55 mm 2809 I/O FC-BGA package using four-point bending tests. FBGs can be surface mounted very close to the BGA as a result of its small size (5mm in length with a diameter of 160 μ m) which enhances the strain detection sensitivity; hence, the mechanical properties of the FC-BGA package are not altered since the metal lid doesn't need to be removed.

In this study, four FBG sensors were surface mounted on each corner of the substrate along with strain gauges on the PCB in order to monitor the onset of cracking, the behaviour of solder joint fracture and the global strain value and the strain rate on the PCB. Series of experiments were performed to: i) calibrate strain gauge factor for a single FBG, ii) compare performance of the FBG and strain gauge, iii) determine the onset, critical load of different board to test the reliability of the FC-BGA, iv) investigate the type of mechanical failure mode (interconnect failure mode) through the failure maps of PCB and BGA, and v) correlate the FBG strain variation to interconnect failure modes.

1.4 Outline of the Thesis

Chapter 2: Theoretical background. This chapter explains the photosensitivity of the optical fiber, inscribing of the Bragg grating, properties of Bragg gratings, the strain sensitivity of the Bragg gratings and the FBG interrogation system. This chapter will also elaborate on the assembly of the FC-BGA, reliability testing of the FC-BGA, mechanical failure modes. The chapter is concluded with the mechanical failure test methodologies.

Chapter 3: Experimental work. The fabrication process of the FBG used in the experiment is discussed in this chapter. The different steps such as test vehicle description, installation of the FBGs on the substrate of the PCB were also elaborated in this chapter. A detailed description of the experimental work was carried out to determine the strain gauge factor along with the two different experiments, beam bending and tensile test that were preformed in order to compare the performance of the strain gauge with the FBG sensors is also included. Four point bending as well as dye and pry experimental set up are also discussed in this chapter.

Chapter 4: Experimental Results and discussions. This chapter presents experimental results and discusses the details of the analysis and the observations from the experiments conducted on different boards types.

Chapter 5: Conclusion and Future Work. The closure discusses the final remarks in regards to the experimental works as well as the improvements for future studies.

Chapter 2

Theoretical Background

2.1 Photosensitivity of Optical Fiber

A short introduction to photosensitivity is required to understand the fabrication of the Fiber Bragg grating. Photosensitivity is defined as the effect that results in an irreversible change in the refractive index which is photo induced in the core of the optical fiber when exposed to UV radiation. In an optical fiber, the increase of the fiber's photosensitivity facilitates the writing of the grating. This phenomenon was first observed in germania-doped silica fiber in 1978 at the Communication Research Council of Canada. The research center was studying the non-linear effects in specially designed optical fiber by launching a laser light (488 nm) into the core of the fiber. The observations made indicated that the intensity of the reflected light increases with the time of exposure [15].

Although the findings related to photosensitivity date 30 years back, its mechanism is still a mystery at large. Several models were nevertheless introduced to explain the observations. Some of such are listed below: color center, dipole model, compaction model, etc. Although the review of these models may fall outside the scope of this thesis; those models share some common grounds of interest. All these models explain that the photo-induced index change is correlated to the germanium oxygen vacancy defects Ge-Si or Ge-Ge bond. These faulty bonds are generated by chemical-vapour depositions at high temperatures; during this process, Ge_2O dissociates to form GeO. When the molecules get in contact with glass, they result in the wrong bonds [14,15].

The change in the refractive index may be triggered by various factors such as the glassy composition of the fiber core, and UV conditions such as wavelength, intensity, total dosage of irradiating light [15].

2.1.1 Photosensitisation Techniques

Several techniques were developed to enhance photosensitivity of germanosilica fibers to ease the grating fabrication process since optical fibers made for telecommunication are known to have weak photosensitive properties by nature in the range of 10^{-5} to 10^{-4} . Some of such enhancement methods are the hydrogen loading, the flame brush and the boron co-doping [14-16].

The simplest and most common technique used to enhance the photosensitivity of the optical fiber is hydrogen loading. Hydrogen molecules are diffused into the fiber core prior to UV exposure as it is inserted in tube filled with hydrogen gas at a high pressure of 1100 psi. The process may last 14 days at room temperature for hydrogen to reach the fiber core. The exposure of the UV irradiation is absorbed by the fiber core and has no effect on the cladding. As the core absorbs the radiation, the Ge-O-Si bonds are dissociated to form OH bonds; this is a thermally driven reaction. The abundance of OH molecules increases the germanium oxygen vacancy which permanently alters the refractive index of the fiber core. The mechanism used in this technique is more complex than a regular thermal reaction. The maximum refractive index change that may be obtained using this method is 10^{-2} [15].

Some of advantages related to this method are listed below: (1) this procedure allows any optical fiber to be inscribed with Bragg gratings since it has the capability to write strong grating in both germanosilica as well as low germanium concentration fiber that has low intrinsic photosensitivity. (2) The change in the refractive index is only limited to the region of the fiber exposed to UV. (3) The diffusion of the hydrogen in the portion of the fiber unexposed to UV causes a negligible loss in the optical communication window. Like every other method this technique has its limitations; since the procedure is time consuming, multiple fibers are loaded at the same time depending on the size of the tube. The loaded fiber needs to be kept in an environment with an ambient temperature of -40°C to ensure that the hydrogen molecules don't diffuse out of the fiber.

The flame brushing and the hydrogen loading are comparable techniques; both techniques utilize hydrogen diffusion into the fiber core resulting into ionic bonding and a germanium-oxygen deficiency center. The latter creates a strong absorption band at 240nm in the Germanium core which makes it highly sensitive. The flame brushing technique diffuses hydrogen into the desired portion of the core by exposing it repeatedly to a flame brush fuelled with hydrogen and limited amount of oxygen at a temperature of $\sim 1700^{\circ}\text{C}$. The complete duration of the process is estimated to last about 20 minutes. The formation of Bragg grating involves both thermal and photolytic intervention. The thermal reaction is observed during the diffusion of the hydrogen molecules into the fiber's core. As the fiber is exposed to UV radiation, the refractive index is changed due to the bleaching of the germanium-oxygen deficiency center band. This technique permanently alters the photosensitivity of the fiber as opposed to hydrogen loading which loses its property as the hydrogen diffuses out. The drawback from this technique is a more fragile end product; the high temperature of the flame weakens the fiber making more susceptible to breaks [7].

The boron co-doping alters the photosensitivity as a result of photo-induced stress relaxation. The co-doping of boron and silica produces a glass compound with a lower refractive index through photo-induced stress relaxation. This procedure is initialized by the breaking of chemical bonds using UV light [7,14].

2.2 Fiber Bragg Grating Fabrication Techniques

The first fabrication technique used to write a Bragg grating into an optical fiber consisted of internally sending a 488nm laser light into a high germanium doped optical fiber, the light reflected from the fiber's end interferes with the diffused light creating a standing wave with a periodic intensity distribution of the light towards the fiber's end; this produces a refractive index pattern within the fiber core. The drawback to this technique is that the gratings' wavelength should concur with the inscribing light's wavelength during fabrication. As a result, all gratings have the same wavelength. The

length of grating is also limited within the coherent length of the writing light. To facilitate the fabrication of the Bragg grating, fabrications using external methods were proposed as a new idea [15].

Till date, there are only a few fabrication techniques used to externally write gratings into a photosensitive optical fiber. The interferometer, point by point and the phase mask are commonly used techniques. The gratings are side written into the core of photosensitive fiber by exposing it to a UV light source which increases the refractive index of the fiber; the refractive index is directly proportional to the reflectivity of the fiber which may reach a maximum value of $\sim 99.9\%$.

The sections below will elaborate on the phase mask method used in the fabrication of the FBG sensors for this thesis. The advantages of using this technique are as follows: (1) the simplicity of a stable structure to reproduce the FBG, (2) ease of alignment, and (3) this method can be used to fabricate a multiple variance of gratings (chirped, titled, polarized grating, etc).

The phase mask is a diffractive optical element which can be fabricated using two different techniques. The holographic technique generates simple patterns of phase mask without stitch errors, while the electron beam technique infers complex patterns such as quadratic chips, Moire patterns, which may indulge in stitch error. The end result is a one-dimensional periodic surface relief structure with a periodicity of (Λ_{pm}) modelled using a high quality fused silica flat which is transparent to the UV laser beam. The profile of the periodic surface is chosen such that it follows the condition below: when the UV beam is incident on the phase mask, the zero order phases is suppressed to less than 5% of the transmitted power while a maximization of above 35% is observed on the diffracted order, +1 and -1 respectively [7,14]. A near field fringe pattern can also be observed from the interference of the plus and minus first order diffracted beam as shown in figure 2.1. This interference pattern photo-imprints a refractive index in the core of the photosensitive fiber placed behind parallel to the mask. The procedure of writing the FBG sensors will be described in detail as a part of chapter 3.

The inscription of the grating and the measurement of the different parameters should be followed by a 15 hours of annealing at a temperature of 150 °C to stabilize the photo-induced refractive index increase. The grating decays very little at 600 °C, and it decays as low as 30% within 30 minutes from temperature rising to 700 °C. As the temperature reaches 800 °C, the grating is only visible for 10 minutes and disappears afterwards [17].

Figure 2.1: (a) Schematic of phase mask technique, (b) Refractive index of uniform FBG.

2.3 Apodization of the Spectral Response of Fiber Bragg Grating

During the fabrication process of the FBG with a uniform refractive index full lengthwise, the reflection spectrum is characterized by a main peak accompanied by symmetric side lobes on both sides. Along the same process, unwanted attenuation can be observed at shorter wavelength with respect to the main transmission attenuation peak mainly due to cladding losses. The apodization process tapers the strength on both ends such that the refractive index decreases gradually.

For many applications, it is necessary to decrease the intensity of the side lobes in order to improve the isolation. In telecommunication, while utilizing the FBG in wave division multiplexing (WDM), the suppression of the side lobes is required as it may cause the cross-talk from the adjacent channels. The cladding mode should also be kept low as to not attenuate other channels. Some other applications that require the presence of the lower side lobes are the gratings used in the Erbium doped fiber amplifier and pump laser; these low side lobes are used to reduce the unwanted lasing peaks as well as the system noise. In sensing applications, the side lobes should also be kept low as it may be detected as another grating and hence corrupt the sensing information.

There are various methods developed used to apodize the grating. Some of the methods are described below. (1) Selectively erasing refractive index by heating and irradiating using CO₂ laser. (2) The use of phase mask with non-uniform diffraction efficiency to transmit a uniform UV beam that radiates over the fiber. (3) Subjecting the optical fiber to interference patterns created using two non-uniform UV light beams. In regards to the phase mask technique, the apodization is performed by a varying the exposure time along the full length of the grating; this is achieved by double exposure, the scanning a small writing beam or placing an amplitude mask with a specially designed profile on the propagating path of a UV laser beam between the laser and a cylindrical focusing lens [18-20].

The FBG is created by inducing an AC modulation in its core refractive index that, however, also induces a DC offset. The offset value is equivalent to half of the amplitude of the AC modulation. The UV radiation is found to have a direct correlation with the spatial average of the index; this phenomenon is explained by the fact that UV light used in the fabrication of the grating is always positive. The value of the DC offset increases from a value n to a maximal value of $n + \Delta n$ as it reaches the centre of the grating then drops to the value of n as indicated by the blue line shown in figure 2.2a. The apodization process is achieved through the variation of coupling coefficient's amplitude along the grating full lengthwise. This results in a modulated refractive index on the full length of apodized grating generating shapes such as Gaussian, Cosine, Hamming, Blackman, etc.

Figure 2.2: (a) Index modulation of unapodized FBG, (b) Apodized FBG.

The modulation index used to eliminate the side lobes on either sides of the reflective spectrum is of the form $X + f(z)\cos(\)$, where the DC offset is indicated as X . A second exposure through the use of amplitude mask makes the “DC” index constant as shown in figure 2.2 b. The amplitude mask is known to have two UV exposing windows which are denoted as the apodized mask and the complementary mask. The first one is used for the FBG AC index modulation while the second one flattens the DC index to minimize the side lobes. The second exposure, which uses a single UV beam instead of two interfering beams, alters only the average of the DC index while leaving the AC component unchanged. The reflection spectrum of an unapodized FBG and an apodized FBG; both were fabricated in our lab is shown in figure 2.3.

Figure2.3: Reflection spectrum of (a) Unpodized FBG, (b) Apodized FBG.

2.4 Operation of Fiber Bragg Grating

Fiber Bragg grating in its simplest form is an intrinsic sensing element which consists of periodic modulation of the refractive index in the core of a single mode fiber. The basic operation of the optical fiber is to guide the light along the core of the fiber when a light

beam impinges on the fiber, since the core has a higher refractive index than the cladding. When a broadband source with a wavelength that is approximately similar to the Bragg wavelength is launched into the grating coupled fiber, a portion of the signal is reflected at the Bragg grating wavelength. In the transmitted signal, the spectral will be missing as shown in fig 2.4. The amount of light reflected is dependent on the total grating length, as each grating line serve to reflect a portion of the broadband signal, and the index change (Δn) [21].

Figure 2.4: Operation principle of FBG sensor.

The broadband light source guided along the core of the fiber is reflected by each grating plane. If both the light and the grating's wavelength do not concur, the reflected light at each plane becomes progressively out of phase resulting into the cancellation of the signal. If both wavelengths are identical, the reflected light of the various grating planes add up constructively in the opposite direction to form a back-reflected peak center at the grating wavelength [14]. The Bragg wavelength is given by the following expression:

$$\lambda_B = 2n_{eff} \Lambda \quad (2.1)$$

where Λ denotes the pitch of the grating, n_{eff} is the effective refractive index.

The requirements needed to satisfy the Bragg condition are the energy and momentum conservation. The energy conservation is depicted by an equivalent frequency for the incident radiation as well as the reflected radiation which is generally denoted by the equation below [14]:

$$\hbar \omega_f = \hbar \omega_i \quad (2.2)$$

The momentum conservation indicates that the wave vector sum of the incident k_i and the grating K should be equivalent to the scattered wave vector k_f .

$$\vec{k}_i + \vec{K} = \vec{k}_f \quad (2.3)$$

The diffracted and the incident wave vectors are equal in magnitude, but in opposite direction. The grating wave vector has a direction normal to the grating plane with a magnitude of $\frac{2\pi}{\Lambda}$ where Λ is defined as grating spacing. These characteristics allow the equation 2.3 to be rewritten in the following format.

$$\frac{2\pi}{\lambda_{med}} + \frac{2\pi}{\Lambda} = -\frac{2\pi}{\lambda_{med}} \quad (2.4)$$

The equation can be further simplified using the equivalence $\lambda_{med} = \frac{\lambda_B}{n_{eff}}$

$$2\left(\frac{2\pi n_{eff}}{\lambda_B}\right) = \frac{2\pi}{\Lambda} \quad (2.5)$$

This equation further simplifies into the following:

$$\lambda_B = 2n_{eff} \Lambda \quad (2.6)$$

2.5 Strain Sensitivity of FBG Sensors

The effective refractive index (n_{eff}) and the grating pitch (Λ) are important factors in determining the wavelength of the FBG. Both factors are very sensitive to ambient changes; therefore, the central wavelength is left tuneable in terms of strain, temperature, pressure, voltage, chemical effect, vibration acoustics, magnetic field, etc. The strain sensitivity is caused by the physical elongation of the FBG pitch and photo-elastic effects.

The stretching or the compression of the fiber changes the grating pitch, and the refractive index and therefore changes the central wavelength of an FBG by an increase or a decrease of its value. This is phenomenon can be illustrated in the fig. 2.5.

Figure 2.5: Central wavelength of FBG sensor under compression and tension.

In cases where the FBG is subjected to disturbance such as strain, the change in the central wavelength can be found by a partial differentiation of the central wavelength with respect to the length taken that the effect of temperature is discarded. The resulting equation is as follows [7]:

$$\Delta \lambda_B = 2 \left(\lambda \frac{\partial n_{eff}}{\partial l} + n_{eff} \frac{\partial \lambda}{\partial l} \right) \Delta l \quad (2.7)$$

Δl is the change in the length of the FBG sensor, ε_z is the longitudinal strain which is calculated as $\varepsilon_z = \frac{\Delta l}{l}$.

The above strain effect term expressed in equation (2.7) may be expressed as

$$\Delta \lambda_B = \lambda_B (1 - p_e) \varepsilon_z \quad (2.8)$$

where p_e is an effective strain-optic constant defined as:

$$p_e = \frac{n_{eff}^2}{2} [p_{12} - \nu(p_{11} + p_{12})] \quad (2.9)$$

where p_{11} , p_{12} are the components of the strain-optic tensor and ν is Poisson's ratio. The typical germanosilicate optical fiber is found to have the following values: $p_{11}=0.113$, $p_{12}=0.252$, $\nu=0.16$, and $n_{eff}=1.482$. Substituting the above mentioned values in equation 2.8 & 2.9, the anticipated strain sensitivity for an approximate wavelength of 1550nm is 1.2pm for every $1 \mu\epsilon$ applied. Similar results were obtained during the experimental work validating the observations.

2.6 Characteristics of In-Fiber Bragg Gratings

The elements that characterize an FBG sensor are its length, its chip rate, its modulation depth determined by the change in the refractive index, its period, and its apodization. These parameters help in determining the following: the shape of the spectral, the central wavelength, the bandwidth, and the reflectance peak. The reflectance is the measurement of proportionality of the reflected incident light at the central wavelength. The reflectivity of a grating with a constant amplitude modulation and period is [14,23]:

$$R(l, \lambda) = \frac{\Omega^2 \sinh^2(sl)}{\Delta\beta^2 \sinh^2(sl) + s^2 \cosh^2(sl)} \quad (2.10)$$

where l is the length of the grating, $\Delta\beta = \beta - \frac{\pi}{\lambda}$ is the detuning wave vector, $\beta = \frac{2\pi n_0}{\lambda}$ is the propagation constant, and $s^2 = \Omega^2 - \Delta\beta^2$ with Ω as the coupling coefficient for a sinusoidal variation of perturbation index along the fiber,

$$\Omega = \frac{\pi \Delta n}{\lambda} \eta(V)$$

$$\eta(V) \approx 1 - \frac{1}{V^2}$$

where V is the normalized frequency of the fiber and η is a function of fiber parameter V that represents the fraction of the integrated fundamental-mode intensity (fraction of optical power) contained in the fiber core.

There is no wave-vector detuning at the center of the grating which translates in a zero value for $\Delta\beta$. The reflectivity coefficient can hence be written as:

$$R(l, \lambda) = \tanh^2(\Omega l) \quad (2.11)$$

An increase in the grating's length or in the refractive index modulation leads to the increase of the grating's reflectivity. The max reflectivity $R_{\max}$ occurs at the FBG's central wavelength.

The bandwidth of the grating is described as the reflection or transmission band's width; it specifies the range of the reflected wavelength. The measurement is recorded as -3 dB bandwidth of the transmitted or reflected light. An approximation for full-width at half maximum (FWHM) is illustrated by [23]:

$$\Delta\lambda_{FWHM} = \lambda_{\text{Bragg}} s \sqrt{\left(\frac{\Delta n}{2n_{\text{core}}}\right)^2 + \left(\frac{\Lambda}{l}\right)^2} \quad (2.12)$$

where s is 0.5 for a weak grating and 1 for a strong grating and l denotes the length of the grating.

2.7 Electronic Packaging

Electronic packages are a collection of interfacing IC (integrated circuit) chips, modules, storage devices, circuit boards, etc. As the circuits get smaller in size, ICs are replacing most passive components found in old conventional circuits. The complexity of circuit is nowadays determined by the number of inputs and outputs that a circuit possesses. The increasing complexity of the circuits has led to the replacement of old through hole single-sided or double-sided designs to surface mount technology (SMT). This technology has introduced notions such as BGA (ball grid array), SOP (small outline packaging), and CSP (chip scale size package). The surface mount technology offers a high degree of automation, increased production, a higher quality at a lower labour cost, etc. BGA has created great interest as it allows maximizing the number of ports while keeping the area occupied as constant.

2.7.1 Printed Circuit Board (PCB)

A plastic/ organic PCB is a substrate made of epoxy-glass composite laminate and copper layers on which conductive traces can be etched to form a circuit [25]. Printed circuit boards are highly reliable and of very inexpensive cost when mass produced. They do require some pre-production effort and cost when compared to other low cost prototyping

techniques such as wire-wrapping or point-to-point constructed circuits. When a PCB is multi-layered, an insulating material is used to separate the various conducting layers. The layers are interconnected between one another through drilled and plated holes called vias; the electrical connection is achieved through electroplating or by the insertion of small rivets. The wholes do not generally interconnect all the layers of the board at once; instead they interconnected specific layers together. For simplicity of design and manufacturing, the wholes are drilled completely through the board. There exists high density boards that may differ to this generalisation; such boards may contain *blind vias* (which are visible only on one surface), or *buried vias* which are embedded and invisible.

The substrate material used for PCB depends on its application; the most commonly used substrate for the manufacturing of PCB is the Fire retardant Glass Laminate (FR-4); this material can also be used for certain type of BGAs. The FR-4 is a composite material made from epoxy-resin and glass fiber. The advantages of using this material are as follows: resistivity to high temperature, ductility and strength provided by the base material. If both the PCB and the BGA substrate are made of FR-4, there will be less CTE mismatch between the PCB and the components [25, 26].

The PCB serves as pathway to interconnect the different components using the traces etched on copper sheets laminated on a non-conductive substrate; it also serves as a base for mechanical mounting which provides support and secures the passive and active components on the board. To ensure proper assembly of the surface mount components, cleanliness, planarity, solderability of contact pads as well as proper solder mask are required.

2.7.2 Ball Grid Array (BGA)

Soldering components with ball grid array solder joints to PCB is a process that attracted the attention of many industries in the 90s. BGA is known as one of many techniques used to surface mount electronic packages; it consists of a square or rectangular shaped body which may vary from 4mm to 50mm in size depending on its application [26].

During the mounting, the BGA is put faced down such that the solder joints are in contact with the PCB to ensure a proper solder reflow to the electronic packaging.

BGAs are preferred over gull wing leads for the various advantages listed below: (1) the physical robustness; (2) smaller signal paths of the BGA offers a better conductivity for high speed applications; (3) allows a higher density of ports to be compacted in a single component; (4) provides low thermal resistance ensuring the long lasting circuit; (5) eliminates the necessity of producing small packages required for Pin grid arrays (PGA) and dual-in-line surface mount packages [26].

The mounting of an IC into a BGA can be accomplished in many ways; the methods vary according to the medium used to transmit the signal from the die to the solder ball array. The three commonly known medium are wire, ribbon-lead, and Flip Chip [26].

2.7.2.1 Flip Chip Ball Grid Array (FC-BGA)

In the early 1960s, IBM introduced the flip chip interconnection to be used for mainframe computers; until this very day, the technology is in use. Furthermore, studies are also conducted to improve the reliability of the FC-BGA. The flip chip allows the interconnections between an electronic component and the PCB's contact pads using solder bumps (solder joints), functional side face down. The method is also known as direct chip attach implying the absence of neither wires nor die attachments. Many of the newly manufactured packages use the flip chip technology since they provide high performance, better reliability, occupies less space, and cost effective [27]. In addition, the flip chip can be fabricated using a variety of materials. This method has some drawbacks as well; the package interconnections cannot be accessed once soldered because, the solder joints are hidden beneath the package. There are custom designed microscopes which may be used to inspect interconnects; they are very expensive equipments.

A flip chip BGA package is comprised of a substrate which contains die, an epoxy underfill found between the die and the substrate, and an array of solder ball joints placed

on the substrate. The manufacturing process of the flip chip consists of the following steps: the bumping of the die or wafer; attaching the bumped die to a board or substrate; filling the remaining space under the die using isolating material. The following under fill is used to counteract the stress induced by the coefficient of thermal expansion (CTE) mismatch between the die and the organic substrate, resist moisture absorption and provide physical body for the attachment of a heat spreader which ensures a better heat dissipation and improves the thermal warpage behaviour. The assembly of the solder bump structure on a flip chip interconnect will be discussed as the next topic.

2.8 Assembly of Flip chip Ball Grid Array

The process begins with the deposition of Under Bump Metallurgy (UBM) on the bonding of the wafers. The use of UBM favours the adhesion between the solder pads and the solder bump; it also generates a solder wettable layer. Moreover, it serves as a diffusion barrier as well as an oxidation barrier. The solder bumps are formed after the formation of the UBM; the chips are then diced and placed on the substrate. The solder bumps are then reflowed to create the bond between the bonding pads of the chips and the substrate metallization. The solder bump structure of the FC-BGA which consists of under bump metallurgy and solder bumps will be discussed in the section below.

2.8.1 Under Bump Metallurgy (UBM)

The under bump metallurgy and the solder bump compose the solder structure of a flip chip. As it is impossible to bond the solder bumps to the aluminium pad, the multilayered UBM is used to achieve the contact.

The UBM requires the following: (1) A good ohmic contact to the bonding pad metallization to achieve a good ohmic contact; back sputtering or chemical etching is used before the UBM deposition to prevent aluminium oxidization of the bonding pad surface. (2) A proper adhesion of the UBM to both the bonding pad metallization and wafer passivation layer; materials suitable for passivation are nitride, oxide, and polyimide. It is important that no pin holes are found on the passivation layer as it may

damage the IC circuit during UBM. (3) A solder diffusion barrier between the solder and the bonding pad metallization. (4) A wettable layer is required as the final layer which bonds to the solder bump. (5) A good solderability should be assured by an oxidation barrier; the oxidation of the UBM should be prevented during the solder bump formation process. (6) The stress exerted by the UBM layer on the silicon layer should be limited since an excessive amount of stress may fracture the silicon causing a permanent defect [28].

The UBM structure is composed of the following: an adhesion layer, an oxidation barrier layer and a solder wettable layer as shown in Figure 2.6. Each layer has a specific function and is made of a specific material with a predefined thickness. The adhesion layer uses materials such as nickel, palladium, titanium, chromium, and titanium/tungsten and may have a thickness which varies between $0.15\text{-}0.2\ \mu\text{m}$. This layer ensures a strong bond between the metallization pad and the IC layer. The oxidation barrier layer is made of gold with a thickness varying between $0.05\text{-}0.1\ \mu\text{m}$ and has the purpose of preventing the structure from oxidation. The final layer is the solder wettable layer; it is made of copper, palladium or nickel with a thickness of $1\text{ to }5\ \mu\text{m}$. The functionality of this layer is to provide a good adhesion surface for the solder bump. The UBM structure is a deterministic factor in the evaluation of the reliability of the connection between the UBM and the bonding, the UBM layers, as well as the UBM and solder bumps. Henceforth, compatibility between the UBM and the solder alloys used for the solder bump is required [29,30].

Figure 2.6: Solder bump with the different layers of the UBM [31].

2.8.2 Solder Bump Techniques

The tin/lead solder is widely used for solder bumps since it allows to be reflowed. These solder bumps have the capability to self-align and collapse during reflow. The accuracy required for placing the bare chips on the substrate is reduced by the self-alignment feature and cancelling the need for additional specialized equipments.

Some of the methods used for solder bumping are electroplating, evaporation, ball placement, solder transfer, ball bumping and printing. The printing technique was used for the conducted experiments in order to achieve the first level bumping. This method is cost effective; it uses either stencil or screen to print the solder paste onto the UBM. The use of stencil for printing is preferred as it complies with the industrial surface mount standards.

Once the UBM is deposited, the solder paste is printed on the UBM using either screen or stencil; the solder is then reflowed to form a spherical bump. Figure 2.7 illustrates the steps involved in solder printing. The reliability of the solder bump is dependent on the type of alloy used for the solder bump, the printing parameters, the stencil, the size of the bump, etc.

Figure2.7: The solder bump process [32].

2.9 Mounting to the Substrate

During this process, the bumped chip connected face down to the substrate. A reliable connection is ensured by removing the oxidation layer from the substrates. The flux is therefore dispensed on the pads of the substrates. Once completed, the die is flipped and positioned accurately on the flux layered on the connection pads of the PCB. The structure is then placed in a tray and heated in an oven to melts the solder which results in

metallurgical bonds with the bond pads on the substrate. The mounting process of the substrate is illustrated in figure 2.8.

Figure2.8: The FC-BGA mounting to the substrate [32].

2.10 Underfill Process and Heat Spreader

Underfilling is a process of filling the empty space that surrounds the chip and substrate with a non-conductive material. This is an important step in the assembly process as it improves the solder joint reliability by evenly distributing the stress in the solder joint hence reducing the effect of the global thermal expansion between the silicon IC and the substrate as well as the inelastic deformation of the solder joints. This process mutually deforms the chip, the underfill and the substrate as a single unit reducing the shear deformation between the chip and the substrates. The underfill also protects the chip from moisture, ionic contamination and hostile operating environments.

As the integrated circuits becomes compact in size yet providing higher performance, the heat dissipation of devices have also increased due to a high density of transistors operating at very high speeds on the silicon wafer. The use of heat spreader is necessary to absorb the heat produced by the device and hence assure maximum performance. All

the conducted experiments made use of heat spreaders attached to the back of the die providing it with environmental protection.

2.11 Solder Ball Mounting

The assembly process described so far complete the first two levels of interconnections denoted as zero and one. The level zero constitutes the gate to gate connections of the IC. The mounting of the Flip chip to the substrate through the solder bump is defined as level one. The level two is an important level of the solder joint consisting of the connection of the substrate to the PCB using solder balls allowing the traces to give room for off-the-board interconnections. The patterns of the PCB pads are made such that it matches the pattern of the solder balls. The soldering temperature has to be chosen according to the material used to prevent complete meltdown of the solder balls. The assembly is heated in a reflow oven at the preset temperature; the surface tension forces the liquefied solder to attach the substrate to the PCB. Figure 2.9 illustrates the multi-level interconnection of FC-BGA.

Figure2.9: The description of FC-BGA.

2.12 Inspection

Inspection of the assembly is performed as it is taken out of the reflow oven. The purpose of this inspection is to sort out and eliminate faulty assemblies. The techniques used during the following procedure are visual inspection to identify any human error which occurred during assembly, electrical inspection to account for functional defects and x-ray to determine voids and other structural defects. The boards used to perform the experiments were subjected to x-ray and electrical inspections.

2.13 Reliability Testing

Although semiconductors are available in various sizes and configurations depending on their application, they all use similar test methods to evaluate the reliability of the product and ensure its quality. The testing determines the life and reliability performance of each individual assembly and can be performed at various levels such as package level, board level and assembly level. The commonly used test methods to measure the reliability of the assembly are: temperature shock, thermal cycling, power cycling, vibration test, drop test, and bending test. These tests simulate failure modes that the product may undergo in an everyday life and under working environment.

The thermal cycle test examines the functionality of the product at harsh temperatures.

A possible observation which may be made during this test is the failure of the solder joints indicating a global mismatch between the component and the test board or a local mismatch between the solder and the component. The drop test is a test performed to evaluate the rapid vibrations which may be caused by a mechanical drop and shock. The bending test is used to test the integrated circuits used in portable devices such as cellular phones, PDAs, pagers, etc. The bending induced failures in real life can be seen in the devices with a keyboard; when a key is pressed, the PCB is deflected due to bending. Other phenomena which may result in bending failure are: localized bending of a board which could occur during housing or the device being inadvertently dropped resulting vibrations of the PCB that cause stress in the solder joints. With time, the stress caused minor defects may lead to the failure of the device. In real life, multiple factors may

affect a product reliability simultaneously resulting in various modes of failures; to study them, it is necessary to isolate the cause of each failure.

For this thesis, the reliability of the test board was performed using four-point-bend test where the board is subjected to a load curvature. Various studies have proven that four point-bending testing offers a uniform bending moment in the assembly and it can be used to test large packages. Table 2.1 shows the classification of the packages and how they vary with the thickness and the number of layers of the PCB.

Table 2.1: Test board thickness and layer count according to Celestica standard [2].

Package size (X)	Package dimension (mm)	PWB thickness (mm)	Copper layers, min
Small	$X \leq 15$	1.00	4
Medium	$15 < X \leq 40$	1.55	6
Large	$X \geq 40$	2.35	8

The four-point-bending can be achieved in two different ways; the first being a static monotonic bending test where the board undergoes a single stroke until the package or the solder joints on both the BGA and PWB are broken, and the second being the cyclic bending test during which, the board undergoes multiple cycles of bending.

2.14 Failure Analysis

The failure analysis verifies the ability of an electronic device to produce the desired and calculated output. An electronic failure of a device is described by its inability to perform its intended function. In real life situations, electronic failures are time-dependent and can be described by a bath tub curve consisting of three different stages of failure processes (infant mortality, useful life, and wear out) as shown in figure 2.10. The component's failures are categorized as follows: catastrophic failure which indicates a dead component, degradation failure which is explained by a fluctuation in the desired output signifying that the component is defective.

The failure mode along with the associated failure mechanism for any electronic components may differ according to the materials used, their configurations, the interconnection methods as well as other parameters relevant from the manufacturing or assembly process. To better examine the reliability of a product, it is necessary to understand the failure mechanisms as well as the stress generated by the coupling of dissimilar materials. The failure mode of an electronic component is represented by a change in its status such as open, short or a variation in the resistance. The failures detected (crack, void, or any other form of damage) originate and expand as a function of stresses related to thermal, mechanical, electromagnetic, or chemical loadings. The failures may also be a result of faulty assembly.

Figure2.10: Bathtub curve.

2.14.1 Mechanical Bending Induced Failure Modes in Solder Interconnects

BGA assembly package fracture failure due to mechanical bending have several modes as shown in figure 2.11 include the package body cracking and cracking between the various lead, Intermetallic compound (IMC), solder and printed writing board (PWB) metal pad interface. The four main failure modes that can be encountered during a four point bending test: the board- pad delamination, the board trace fracture failure, the solder fracture failure around the test pad and finally the solder fracture failure near the component interface. As a board pad de-laminated from the laminate core, it can move freely up and down. During this process, the test board continues to bend (PWB pad

lift/crater) and the length of the fracture interface increases until a final rupture is resulted into a failure. Such failure is only observed when the deflection is at its greatest.

For board trace failure; the trace and cracks occur near the solder mask opening. These cracks are not perceptible through visual inspection such as the dye-and-pry technique. The solder joint failure around a board pad is characterized by cracks emerging from the outer edge of the pad along the trace. The crack then propagates towards the bulk solder. It is possible to observe its failure on the test board pad interface, although this depends greatly on the board's materials. A solder fracture around the component interface is defined by a fracture which occurs along the package's IMC/solder and metal/IMC interfaces [3].

Figure 9.1 Interconnect Fracture Modes (Solder Ball Array Devices)

NOTE: SEM/EDX is required to distinguish between Failure Modes 2 & 3 as well as between Modes 7 & 8.

Figure2.11: Interconnect fracture modes [2].

Chapter 3

FBG Fabrication and Experimental Work

3.1 Fabrication of FBG Sensors

The SMF fibers used to fabricate the gratings were all hydrogen loaded for two weeks at 1500 psi at room temperature. The hydrogen-loaded fibers can be kept in a freezer at a temperature of -20°C to slow-down the diffusion of the hydrogen molecules out of fiber.

The phase mask technique was used to inscribe the FBGs. The collimated KrF excimer laser (Lumonics, Model PM 844) emitting a beam of 248nm with an energy from 150 to 350 mJ at a repetition rate of 30pps, was used. The amplitude mask was used to apodize FBG of 5mm in length. This apodization mask consists of a sinc function and a complementary sinc function. All grating used for the experiments were apodized to reduce unwanted side lobes that could increase during the bending test which the interrogator system may mistake them as FBGs.

The location of FBG on fiber was determined by a red mark as the reference that was aligned with the edge of the phase mask during fabrication process. The laser beam position was determined by irradiating a photosensitive paper that is aligned again the phase mask. The center of the FBG is thus 15 ± 0.5 mm from the red mark.

Once the preparation work was completed, the section of optical fiber was stripped off using a paint remover and was horizontally positioned behind the phase mask. The distance between the phase mask and the stripped fiber is important; as the distance increases, it requires a longer time to write the FBGs. When the distance between the fiber and phase mask is greater than the spatial coherence of the UV light; the absence of the interference pattern will make the grating not inscribable. During the writing process, the spectrum of the FBG was monitored with the optical spectrum analyzer (Ando, model AQ-6310 B). In all experiments, the FBG sensors used were characterized as follows:

polyimide coated with an apodized index profile of 5 mm in length, -3 dB bandwidths of ~ 0.320 nm, peak reflectivity greater than 80%, and isolation of ~ 27 dB.

After writing the grating, its spectrum was recorded. The stripped fiber is recoated using polyamide coating at positioning of the FBG using the Automated Polyimide Recoated with linear Proof Tester (PTR-200-PRL) while the remainder is recoated with polyacrylate using the Filament Fusion Splicing FFS 2000. Polyamide coating was chosen for this application because of its strong adhesion to the fiber.

The gratings were all spliced to a fiber cable with an APC connector using a fusion splicer (Ericson, Model: FSU 975), protecting the spliced area using a heat-shrink tube.

3.2 Basic Measurement

The measurement of the grating after the annealing is an important process as the values are known to change as a result of the polyimide coating and the annealing process. The fundamental system for testing the Bragg grating parameters is depicted in Figure 3.1.

The wavelength of the FBGs at rest was recorded using OSA. As the FBG was surface mounted to the substrate, its initial wavelength was re-measured. This was performed because the cure of the epoxy used to attach the FBG onto the substrate will cause strain within the FBG which shifts the central wavelength of the FBG downwards. During the four-point bending test, the initial wavelengths of the FBGs sensors were recorded from Si425. While the test is being performed, the changes in wavelengths were monitored with Si425. This procedure gives us the strain level of the board under test.

Figure3.1: Basic measurement system.

3.3 Calibration of FBG Strain Gauge Factor

The strain gauge factor of the FBG was determined using an experimental set up shown in figure 3.2 to measure the central wavelength shift of the FBG as a function of strain. Since the strain gauge factor may differ from the fiber type, it was important to obtain the strain gauge factor of the FBGs used in the experiment. The measurement system consists of a fiber clapper, a weight holder to apply different amount of strain onto the FBG, an optical spectrum analyzer (OSA), a circulator, and a broadband source. During this experiment, the initial wavelength was recorded when the FBG was hanged without any weight; by adding different weights, the central wavelength of the FBG was recorded from the reflection spectra from the OSA. Once that was done, the weight was converted to strain using Hook's Law.

$$F = M g = \varepsilon E A \quad (3.1)$$

where, E is modulus of elasticity of glass and A is the cross section area of the fiber which are 72.5 GPa and 0.0123 mm^2 respectively. Figure 3.3 shows the standard deviation of the fractional change in the Bragg wavelength as a function of strain. Using the linear fit function on the recorded data, the strain gauge factor was determined to be $1.2 \text{ pm}/\mu\epsilon$. This value is similar to the ones expressed by other researchers.

Figure3.2: Set up to measure strain gauge factor for a FBG.

Figure3.3: The shift of central wavelength of the FBG sensor as a function of induced strain by hanging weights.

3.4 Correlation of the FBG and Strain Gauge Measurements

Prior to the use of FBG's in the four point bending test, two experiments were conducted to compare the strain readings of the FBG to that of the strain gauge, bending beam test and tensile test.

3.4.1 Beam Bending Experiment

The first experiment that was conducted was beam bending test; the specification of the A1 6061-T6 beam, the FBG and the strain gauge are summarized in table 3.1. For this experiment, a polyamide coated FBG sensor was surface mounted using 353ND-T epoxy to one side of the AL-Bar while the strain gauge was attached to other side using M-bound 200 epoxy. One end of the fiber was spliced to the APC cable using the Vytran splicing machine and was then coated with an acrylate coating in order to prevent the spliced area from getting damaged. The other end of the fiber was cleaved at 45 degree angle to prevent back reflection. The Al-bar was oriented horizontally with one end fastened while the other end was left free. During the first experiment, the FBG was placed in compression and the strain gauge was placed under tension. Before starting the experiment, the initial values of both the strain gauge and the FBG were recorded from the strain gauge indicator and the Si425, respectively. The initial readings were $21\mu\epsilon$ and 1531.997 nm, respectively. After that, the free end of a cantilever beam was subjected to a point load (P), the beam will then be deflect into a curve. The load was applied gradually with a displacement of 0.05 inch per step to a maximum displacement of 0.6 inch. For each displacement, the wavelength shift of the FBG from the Si425 and the strain gauge reading were recorded, respectively. The initial value was subtracted from the recorded values at each displacement when calculating the strain from both sensors. The experiment was repeated 8 times to determine the accuracy of the results. The plots obtained from the recorded data demonstrated that both FBG and strain gauge sensors have an excellent linear correlation as shown in figure 3.4. The slope between the two sets of the strain readings was 1 which enhances the compatibility of the results. The resulting overall error in the measurements was determined to be less than 0.5%. This could be explained by the tolerance in the positioning of the strain gauge and the FBG.

Table 3.1: Parameters used in experimental set up of Beam Bending

Specification of the Beam	
Type of the Beam	Al 6061-T6
Length of the Beam	10 (inch)
Width of the Beam	0.998 (inch)
Thickness of the Beam	0.248 (inch)
Specification of the FBG	
Length of the FBG	5 mm
Wavelength	1539.997(nm)
Bandwidth	0.320 (nm)
Isolation	~ 27 dB (+ /- 0.5nm)
Reflectivity	> 80 %
Estimate splice loss	0.008
Specification of the Strain Gauge	
Length of the strain gauge	10 mm
Gauge factor	2.1 (+/- 0.5)
Transverse sensitivity	+0.4 (+/- 0.2) %

Figure 3.4: Correlation of FBG sensor and strain gauge measurements in a beam bending test.

3.4.2 Tensile Test

The tensile experiment is the latter experiment conducted to compare the performance between the FBG sensor and the strain gauge. The experimental set up is shown in figure 3.5. All specifications regarding the test are summarized in table 3.2. The tensile experiment has been performed using the servo hydraulic machine (model, MTS 322

with the controller being Test Star IIM) with a maximum load set to 1500 lb to prevent the yielding of the Al-bar dog bon's shape. The load was set on a ramp in increments of 100 lb from 0 up to 1500 lb, and then dwelled for 3 sec which was followed by a subtraction of the load in decrement of 100 lb to 0 lb. The optical sensing interrogator si425 was the data acquisition system used to monitor the strain observed on the FBG sensor. The software (MTS model 793.00, the module of that software is used for multiple purpose tests) was used to record the strain gauge data.

The experiment was repeated 6 times to verify the validity of the results. The plots obtained from the recorded data demonstrated that both FBG and strain gauge sensors show the same trend as indicated in figure 3.6a. The resulting overall error was calculated to be inferior to 0.5 %. The strain gauge returned a slightly higher strain value as compared to the FBG; this was explained by the fact that the FBG and the strain gauge were positioned at the opposite ends with their respective tolerance. The plotting of the experimental data from the strain gauge and the load cell indicated a linear correlation. As the load cell increased, the strain increased linearly from both sensors as shown in figure 3.6 b. The two experiments carried out to compare the performance of the strain gauge and the FBG indicated an error level of about 0.5 %.

Table 3.2: Facilities used in experimental set up of Beam Bending

Specification of the Beam	
Type of the Al-bar dog bon	Al 6061-T6
Dimension of the Al bar is	½ * 1/8 (inch)
Specification of the FBG	
Length of the FBG	5 mm
Wavelength	1533.274(nm)
Bandwidth	0.300 (nm)
Isolation	~ 27 dB (+/- 0.5nm)
Reflectivity	> 80 %
Estimate splice loss is	0.008
Specification of the Strain Gauge	
Length of the strain gauge	10 mm
Gauge factor	2.1 (+/- 0.5)
Transverse sensitivity	(+ 0.4 (+/-) 0.2) %

Figure 3.5: Experimental set up of tensile test.

Figure 3.6: (a) Strain from strain gauge versus strain from FBG sensor, (b) Load versus strain gauge.

3.5 Test Vehicle Description

The assembly test vehicles used in this experiment were made with two types of PCB boards of the in-plane size of 187.325 x 187.325 mm; one with 2.36 mm and 8 copper layers, and another of a thickness of 3.18 mm with 16 copper layers. A flip chip BGA (FC-BGA) package of 55 x 55 mm with 2809 I/O in a full array with 1 mm pitch was mounted in the center of the board. The module had three variations differing by the lid

thickness, flattening processes, and the target co-planarity as shown in table 3.3 .The Component size and solder ball distribution is shown in figure 3.7. The material of the PCB boards was of Polyclad 370 HR laminates with organic solder preservative (OSP) surface finish and solder mask defined; and designed based on the IPC/JEDEC-9702 requirements. The BGA pads were 19.5 mil (0.5 mm) in diameter. All internal layers were ½ oz. copper, outer layers were ½ copper plated up to approximately 1 oz. copper. The FC-BGA has tin/lead first level bumps, and lead free second level balls made from SAC305 with SMD pads. The two rows of peripheral solder balls of the FC-BGA were a daisy chained. After the assembly of the FC-BGA on the PCB, a complete net daisy-chain links should result in 100% coverage of the outer package interconnects parallel to the anvils. The daisy-chain connection was made in order to realize in-situ monitoring of the device board–level interconnects failure during the test.

In the four point bending test, the solder connections in the corners of the FC-BGA components usually failed prior to the interconnections in the interior area; this suggested that separate daisy chain nets for the package corners were preferable for such circuits. Once the boards were properly assembled and mounted using daisy-chain connections, they were inspected using transmission x-ray to detect any failure in the boards prior to the four point bending test. This was an important step if there was a pre-existed flaw in the PCB traces, the daisy chain resistance change can be result of the PCB failure prior to the bending test [33].

Table 3.3: Details of PCB and component variations studied.

Label of Sample	A	B	C	D
PCB thickness (mm)	2.36	3.18	2.36	
Lid thickness (mm)	2.0	1.0	0.5	1.0
Flattening	No		Yes	No
Target Co-planarity (mils)	5.5	8.5	5	12

Figure 3.7: Component size and solder ball distribution.

3.6 Installation of strain gauge and FBGs on Substrate of the PCB

For the test configuration defined in IPC/ JEDEC standard, finite element modeling indicated that the print wiring board (PWB) principal strain direction coincided with the longitudinal board axis at all board locations. Therefore, the sensing direction of the uniaxial strain gauge and the FBG sensors must be aligned with the longitudinal board direction. The uniaxial strain gauge of 3.2 x 3.2 mm in size (Vishay Micro-Measurements, CA-06-125-350) and 350 ohm was used in this experiment and was surface mounted using M-bond 200 adhesive on the same side of the component between the package edge and anvil centerline.

The location of FBG on fiber was determined by a red mark as the reference. The center of the FBG was thus 15 ± 0.5 mm from the red mark. The 5 mm long FBG sensors were mounted on the substrate at 1.5 mm inside the edge. The FBG sensors, due to their small size, were mounted at about 1 mm from the solder balls that would allow more sensitive strain measurement under board flexure. Fig. 3.8 shows the emplacement of the FBG on the substrate. All the tested boards had the gratings sensors positioned in the same way as shown in fig 3.8 a; except one experiment was conducted such that the FBG sensors were oriented in parallel to the load anvils as shown in fig 3.8 b.

Figure 3.8: Location of the FBG sensors and strain gauge (component side view).

Figure 3.9 shows an example of the surface mounting of an FBG on the substrate. The four corners of the board were clamped down in order to ensure that the board sits flat on an optic breadboard. The red mark was used as reference; the beginning point for the epoxy covers 1.5mm longer than the grating length. The red reference mark determined the beginning of the FBG, a marker was used to indicate 1.5 mm before the starting point of the FBG on the fiber; this was also used to align with the edge of the substrate. Two pieces of blue tape were used to temporary fix the FBG on the substrate. A thin layer of 353ND-T epoxy was then applied to cover the FBG on the substrate. The four clamps were removed once the epoxy was laid over the FBG; the board was then put on a hot plate for epoxy to cure. After that, the blue tapes were removed.

Figure 3.9: The steps to glue the grating to the substrate.

3.7 FBG Interrogation System

As the FBGs were subjected to the four-point bending test, it was important to have an accurate reading of the central wavelength shift to measure the strain level of the FBG sensor. The optical sensor used for this experiment was the Si425 and sm130 interrogation system from Micron Optics. These systems are assembled with a laser capable of a maximum scanning rate of 250Hz, 2000 Hz with a resolution of less than 0.2pm and a repeatability of 5 pm, respectively.

A fiber swept laser-based system offers the required optical output power for high channel and high sensor count without compromising on the data acquisition speed or a high measurement dynamic range. The procedure of the Si425 and Sm130 to detect the central wavelength of the sensor is described below. The laser emits light with a wavelength that increases with time. The emitted light is split into two branches using a 1x2 splitter coupler with a ratio of 90/10; one branch is used for the reference while the other is used for the sensor. A portion of the 10% of splitted light is directed through an optical reference photodiode; the remainder is sent to the sensor, gets reflected and is absorbed by the sensor photodiode. The simultaneous acquisition along the two

photodiodes results in a set of data approximation as illustrated in figure 3.10 and 3.11. The parameters relevant to the calculation of the sensor wavelength are as follows: (1) $t_{\lambda a}$, the time at which the reference peak a is detected, (2) λ_a , the wavelength of the reference peak a, (3) $t_{\lambda b}$, the time at which the reference peak b is detected, (4) λ_b , the wavelength of reference peak b, (5) t_{sensor} the time at which the sensor peak is detected, (6) distance between the sensor and the interrogator sensor [34, 35].

The instrument provides four pre-programmed operational modes used to monitor optical sensors: power level view (displays power levels for each sensor), sensor wavelength view (displays wavelength measurement with respect to time), and wavelength measurements (displays the number of sensors per channel along with the central wavelength), and power spectrum measurements (displays sensors' FFT view). Throughout the experiment, the Si425 was connected to a computer via a crossover Ethernet cable such that they can communicate to one another using the TCP-IP protocol. The "LabView" software was used to replicate the Si425's/ Sm130's user interface on computer. The operational modes used during the experiment were the power level view and the wavelength view. The power level view was used to monitor the power level on each sensor prior to test to ensure that none of the power level of the grating has been chirped. The wavelength view was used to record the data of FBG sensors versus time. All recorded data were saved as .txt files and were eventually transferred to an excel datasheet to be converted to the strain level as a function of time. Each channel can be equipped with as many as 128 sensors; but, for this experiment, only one sensor per channel was used.

Figure 3.10: Approximate optical schematic [34,35].

Figure 3.11: Illustration of reference/ sensor timing for calibration [34,35].

3.8 Four Point Bending Test

Low strain rate, quasi-static tests are conducted during which the test vehicles underwent different loading conditions. Before running the tests, various test parameters that affect the solder-joint failure of the packages were set, including the support span, the load span, the crosshead travel speed and distance. For the test data recording, the data acquisition frequency was pre-determined for strain gauge measured strain, displacement, load and daisy chain resistance/voltage as well the frequency for FBG measured strain.

The crosshead travel distance (δ) and the crosshead speed ($\dot{\delta}$) of the universal test machine were proportional to the PCB board assembly strain (ε) and strain rate ($\dot{\varepsilon}$) respectively. The crosshead displacement and the PCB global strain are related to one another as follows:

$$\delta = \frac{\varepsilon(L_s - L_L)(L_s + 2L_L)}{6t} \quad (3.2)$$

where, ε is the PWB strain, L_s is the support span, L_L is the load span, t is the PWB thickness. With the equation (3.3), the crosshead speed can be obtained from the equation:

$$\dot{\delta} = \frac{\dot{\varepsilon}(L_s - L_L)(L_s + 2L_L)}{6t} \quad (3.3)$$

The above equations (3.2) and (3.3) were used to give the initial estimate in the presetting the parameters of the crosshead travel distance and crosshead speed based on the IPC suggested global PWB strain and strain-rate. The actual parameters were determined in an iterative way from a set-up tests based on the actual interconnect failure of the test boards. The desired pattern of failed solder joints produced by such a bend test should limit the failed joints to the peripheral rows, which can only be reached after a few adjustments of the test parameters. A sample test board of the same type test vehicles was used to verify the load symmetry and the balance between the load span and support span. In this experiment, a bare PCB has been used to perform the verification test of the balance and test parameters. The balance of the load system was then adjusted using four jack screws, on the support anvil.

During this process the loading fixture was assumed to be a perfect fit. The loading fixture was moved down and stopped when the anvils touched the board. A visual inspection of the gap between the PCB and the fixture was conducted. Furthermore, the strain balance, between the two strain gauges symmetrically attached to the board, was checked. An estimate was reached as the result of the inspection for the needed tilt adjustment of the support fixture. The four jack screws were used to adjust the balance of

the PCB, as represented in figure 3.12. The adjustment took a few iterations of repetitive the steps until the two strain gauge readings were almost identical. Balancing the load anvils ensured a bi-directional balance which reduced the measurement error and ensured a symmetric failure pattern.

Figure 3.12: Support fixture with 4 screw jacks.

Once the alignment of the load was completed; the daisy chain resistor was soldered to the PCB and the daisy chain circuit was connected to the data acquisition system. The daisy chain was then connected to the power supply set to have a current of 0.2A. The load cell from the universal test machine was connected to the data acquisition system for load monitoring. Two Linear variable differential transformer (LVDT) displacement sensors were installed on the support fixture for recording the crosshead displacement monitoring the load symmetry.

The test system consisted of three pieces of equipment which were: the universal loading machine with a four-point bend fixture, a desktop computer provides the software to control the universal mechanical tester, and mechanical and optical data acquisition system. The universal loading machine (United Technologies, model SSTM5) is an electromechanical tester which realizes a displacement controlled loading of the capacity of 5000lbs (22.3 KN). The test data recording uses a data acquisition system (Daytronic, 'System 10' model 10KM851) with the data acquisition rate of 10 KHz. The data

acquisition system has a 16 bit analog to digital converter and 36 channel signal conditioning unit. The two optical sensing integrators used for recording the FBG strain were optical sensing integrator model si425 (maximum frequency 250 Hz), and another sm130 (maximum frequency 2000 Hz). During each test, the sample was connected to the two different (mechanical and optical) data acquisition systems at the same time. The strain gauges, the LVDT, the load cell, and the resistor were connected to the mechanical interrogator, while the FBG sensors to the optical interrogator. The mechanical and the optical interrogator systems were directly linked (hooked) to their respective individual desktop computer for data processing and recording. Then, the results from both sensors were monitored and saved using two different computers.

During this experiment, the BGA assembly being tested was placed in such a way that the BGA solder joints are subjected to tension rather than compression since the solder joint failure is mostly attributed to the tensile stress rather than the compression stresses. The two edges of the component were set to be in parallel to the load anvils. The anvils were adjusted to reach a load span of 115 mm, and a support span of 147 mm. These parameters were chosen based on observations made during the dye and pry test such that an interconnect failure will be induced into the solder joints from the first bending test. As a result, the crosshead speed was set to 8.4mm/sec generating the intended failure, while the crosshead travel distance was varied on each tested board to control the amount of the induced failure on the board. The observed PCB global strain was noticeably higher than the targeted value of $5000 \mu\epsilon/\text{sec}$ at the above mentioned speed. The final test parameters were determined to create and best capture of the initial solder-joint failure in the test. The different test conditions parameters that were used are tabulated in table 3.4.

The test procedure was as follows: a pre-load corresponding to 50-100 $\mu\epsilon$ of PCB global strain was set up to ensure that the load anvils were in contact with the PCB surface; this was used as a reference point from where the load anvils will go up 20mm from the surface of the board. Once the load anvil reached 20mm, the test was executed and 5 V trigger signal was sent to the solder joint resistance monitoring circuit to activate

the recording function. During the experiment, the boards were deformed to a preset value of displacement; the setup was dwelled for a few seconds before returning to its initial state. When the predetermined crosshead travel distance was reached, the monitoring systems are stopped and the crosshead was returned to the original position. While performing the experiment, the wavelength shifts of the FBG sensors, the strain from the strain gauge, the load cell, displacement, and the resistance were monitored and recorded. Figure 3.13 show the universal mechanical tester along with the two optical sensing interrogators.

Table 3.4 a: Test conditions for the component A

Label of Sample and Test	A1T1	A2T1	A3T1	A4T1
Load span (mm)	115			
Support span (mm)	147			
Crosshead speed (mm/s)	8.4			
Crosshead travel distance (mm)	2.0	4.0	10	4.0
Daisy chain voltage (1 ohm resistor) (V)	2.524	2.27	2.39	2.39
Resistance of daisy chain	12.8	11.8	11.7	12.2
Daisy chain constant current (A)	0.2			
Frequency of mechanical data acquisition system (Hz)	2000			
Frequency of si425 data acquisition system (Hz)	2000		250	2000

Table 3.4 b: Test conditions for the component B

Label of Sample and Test	B1T1	B2T1	B3T1	B4T1	B5T1
Load span (mm)	115				
Support span (mm)	147				
Crosshead speed (mm/s)	8.4			6.0	8.4
Crosshead travel distance (mm)	10	10	10	8.0	4.5
Daisy chain voltage (1 ohm resistor) (V)	2.16	2.308	2.29	2.17	2.18
Resistance of daisy chain	10.7	11.4	11.5	10.8	11.0
Daisy chain constant current (A)	0.2				
Frequency of mechanical data acquisition system (Hz)	2000				
Frequency of si425 data acquisition system (Hz)	250			2000	

Table 3.4 c: Test conditions for the component C

Label of Sample and Test	C1T2	C2T1	C3T1	C4T1	C5T1	C7T1	C8T1
Load span (mm)	110	115					
Support span (mm)	146	147					
Crosshead speed (mm/s)	8.4						
Crosshead travel distance (mm)	8.0	8.0	10.0	4.0	4.5	8.0	4.5
Daisy chain voltage (V)	2.344	2.244	2.24	2.34	2.255	2.13	2.389
Resistance of daisy chain	11.7	11.0	12.0	11.0	11.7	11.2	11.8
Daisy chain constant current (A)	0.2						
Frequency of mechanical data acquisition system (Hz)	2000						
Frequency of si425 data acquisition system (Hz)	250			2000			

Table 3.4 d: Test conditions for the component D

Label of Sample and Test	D2T1	D3T1	D4T1	D6T1
Load span (mm)	100		115	
Support span (mm)	146		117	
Crosshead speed (mm/s)	6	8.4	8.4	
Crosshead travel distance (mm)	4.5		4.0	4.5
Daisy chain voltage (1 ohm resistor) (V)	2.28	2.22	2.67	2.34
Resistance of daisy chain	11.6		13.1	11.5
Daisy chain constant current (A)	0.2			
Frequency of mechanical data acquisition system (Hz)	2000			
Frequency of si425 data acquisition system (Hz)	250		2000

Figure 3.13: Universal mechanical tester with (a) Si425, (b) Sm130.

3.9 Dye and Pry Test for Breakage Configuration

In the present study the occurrence of the solder interconnect failure was detected indirectly via monitoring the substrate stress relaxation due to the interconnect breakage. Yet the actual failure can only be verified through visual inspection of the sample after the test. Dye and pry test is a destructive flaw detection technique widely used in the failure analysis of microelectronics. As previously mentioned, an ideal test is the one that only produces the package's initial failure. The dye and pry test is an important process helping determine the test parameters that ensure the desired failure to happen, thus further determine the critical load of the assembly package under which the first fail takes places. The test was conducted on all test boards for failure analysis. The failure patterns obtained from the test yield the interpretation of the substrate strain behaviour obtained from the FBG sensors and the strain gauges. The dye and pry test indicates the locations where the solder joints are completely or partially broken.

This experiment consists of immersing the boards in low viscosity liquid dye kept in a vacuum chamber after completing the bending test. The liquid penetrates inside any cracks, delaminates on PCB, component and solder joints, and marks these areas. Once

the dye was applied, the component was removed by slightly bending the board in a repetitive way. The fractured joints were then visually inspected and the anomalies were photographed to record the areas by which the dye had penetrated. The dye and pry process is as follows; (1) The PCB was placed in the tray with the dye; the entirety was then moved into a vacuum chamber placed under an exhaust hood; (2) Once the vacuum process was completed, the pump was turned on for 2 minutes to reach 23 inch Hg. (3) Take the kit out and dry it using a tissue and the PCB along with its attached components were placed in a thermal chamber with exhausting hose and was placed for 20 minutes at 100 C;(4) Once the process completed, the PCB was clamped on a table vice and was pried manually one at a time until the package is taken off the PCB. (5) Using a double sided tape, the FC-BGA was attached to the PCB on the land area side for microscopic examination.

Chapter 4

Results and Discussion

4.0 Introduction

This chapter presents the experimental results obtained from the FBG sensor as well as the strain gauge results with the specific purpose of evaluating the reliability of a 55mm 2809 I/O lead-free FC-BGA. Four point bending test was performed with varying test conditions to observe the underlying behaviours. The data accumulated from the experiments are as follows: (1) FBG strain curve from each corner of the FC-BGA to determine the onset of the crack and to capture the local strain release, (2) strain gauge curve from the surface mounted strain gauge on the PCB to obtain the global PCB strain, (3) the load cell curve which determines the maximum load which the tested vehicle withstood, (4) resistance curve to determine the electrical failure, and (5) the failure map of each board to locate the failure and identify failure mode. Upon scrutinizing the results and observations, it was found that some characteristics were common to all boards while the others were unique to each type of board under specific testing conditions. Section 4.1 will discuss the features that were common to all boards while the subsequent sections concentrates on the unique attributes of each type of board tested.

4.1 Observation Common to All Boards

For each four point bending test, the time response from all four FBG sensors were plotted in addition to the strain gauge and load cell curves. The test parameters were selected such that a failure of the board was inevitable in the test process. The data recorded from both FBG sensors, and strain gauge concurrently provide the strain variation as a function of time along with the displacement values, and the daisy chain resistance as shown in Figure 4.9a. A linear response was observed from the substrate strain recorded by the four sensors surface mounted on the respective corners of the FC-BGA and strain gauge on a PCB at the beginning of the deflection. As the PCB strain displayed a linear response to the increase in deflection, the FBG substrate strain level

reached a peak value and then deviated from its linear trend; it then increased or decreased in a gradual or abrupt manner with an increase in the applied deflection depending on the type of PCB and lid thickness. In the 4-point bending test, an increase in the crosshead travel distance resulted in an increase of the load value, the global strain and the FBG strain. However, the FBG substrate strain value was dependent on the failure induced onto the board accounting also the failures around the FBG sensors. The increase of strain level on the substrate was not always follow by an electrical open of the solder joints. Nonetheless, the dye and pry test conducted on these boards showed the traces of pad lift/ crater from both the PCB and the FC-BGA.

During most of the conducted experiments, a resistance increase in a small amount was observed in the daisy chain, this increase was then recovered upon the unloading; nevertheless, the results from the dye and pry test indicated a pad lift/crater on the solder joint. The resistance change can be explained by the stretching of the wiring as the board was bent; this behaviour is denoted as elastic resistance since the resistance recovered to its original value as shown in Figure 4.1. The existence of an electrical open was only noticeable when the crosshead travel distance was set to be 10 mm; such displacement induced failure in almost all locations between the PCB and the FC-BGA. The electrical joint reached an infinite resistance only when the solder joint broke either between the trace leading up to the ball on the PCB or the trace leading to the same ball in the substrate of the FC-BGA, which is a catastrophic failure.

Figure4.1: Resistance change.

The above findings have led to the conclusions that the substrate strain obtained from the four corners of the FC-BGA by FBG sensors gave more insight in flexure testing of FC-BGA devices. This sensor detected the onset of pad cracking at the beginning of the damage progression whereas the strain gauge and the electrical daisy chain detected the failure only at the late stage of the bending test. The substrate strain can be used to clearly identify the onset for the failure modes. A component testing methodology that only relied on electrical opens can be misleading as there were various other modes of failures that the resistance could not detect. Using substrate strain level and resistance monitoring systems simultaneously may eliminate this risk as the electrical monitor still displayed a connection to the trace even when failures were found on the board and cracks on solder joint were present underneath the pad-laminate interface in the PCB.

Another observation was made from the load cell curve; a dip was present in the duration as shown in Figure 4.2, where the crosshead speed was kept constant, indicating a global unloading or stress relaxation due to the time dependant properties of the materials used for the packages. In contrast, the strain gauge mounted on the component side and centered between the package edge and the anvil was aligned with the corner most solder

joints; its global strain was then monitored. This global strain was dip free as demonstrated in Figure 4.2 indicating that the strain gauge was not sensitive enough to the response of the interconnect fracture of the FC-BGA unless most of the solder joints connecting the PCB and the FC-BGA were pad lifted. The above only occurred with the cross head travel distance of 8-10 mm which is found to be correlating with electrical resistor opening when most of the solder joints were full pad lift.

Figure 4.2: Load and global strain versus time.

The critical load is an important quantifier found by the four point bending test as it helped defining the flexure limit that the board can withstand during the assembly process. The critical load indicated the initiation of cracks but not necessarily an electrical open resistance; four critical load values were recorded from the four respective corners per sample and were determined based on the first spike for the board A as shown in figure 4.9a which referred to a brittle fracture or slope change for board C as indicated in figure 4.11a, which indicated a ductile fracture that indicated the appearance of a fracture in the solder joints. The strain release revealed smooth strain relaxation for board B as illustrated in figure 4.14a and the critical load was determined from the peak of the FBG as the failure onset point. The average load data recorded from the four FBG sensors indicated that an increase in the loads beyond the critical load value will result in a board failure. Figure 4.3 illustrates the critical load for the various samples.

Figure 4.3: Critical load for each board of all four types of the test vehicle.

The dye and pry test was conducted in order to identify the failure mode and failure distribution on the solder joints on all boards used in the four-point bending test. This analysis offered a three-dimensional view of the cracks in the solder joints though figure 4.4 shows the two dimensional view of the dye and pry test. The failure modes obtained by dye and pry process on the tested boards were identified according to the IPC/JEDC standards of the BGA joint schematic. Although, ten failure modes can be potentially found in the four-point bending experiment; the one which was repeated itself more frequently in this experiment was failure mode ten, pad lifts/ crater on board sides.

Figure 4.4: The dye and pry test revealed a big damaged area of mode 10 (pad crater on PCB), (a) PCB view, (b) component view.

The results obtained from the dye and pry test revealed that the majority of the failures (~96% of solder joints) were PCB pad lifts. Pad lift is the failure mode which leaves its trace on both side of the component and the PCB; it is denoted as failure mode 5 or 10 based on the IPC/JEDEC standards. Figure 4.5 illustrates the pad peel (package pad lift). The higher occurrence of the pad lift on the PCB side can be attributed to the fact that the interface and the load bearing capability of the pad crater mode between the copper pad and the PCB is left unchanged although the SnPb solder is replaced by a lead free solder for the solder joints. The leadless solder joints offered higher stiffness compared to the previously SnPb alloy. This higher stiffness of the lead free solder balls generated a higher force on the pad for the same applied deflection when compared to solder balls using SnPb solder which deformed to accommodate the physical change of the pad resulting in an excursion of a lower force on it. Although the material of the solder has been changed to lead free, the pad adhesion is unchanged. This has led the new solder (lead-free) balls to reach the force necessary to pull the pad out at a lower force; this behaviour is directly related to the ball property and not the pad's property.

Figure 4.5: Failure mode 5 (a) PCB side view, (b) component side view.

The stress transfer was defined by the mechanical properties of the materials used for the fabrication and its bonding characteristics at the interface as it was observed in the surface friction and the behaviour of the adhesive joints. The stress transformation at the adhesion interface is illustrated in figure 4.6a. The force applied on the adhesion interface created a compression and a shear joint on it. Since the stiffness of the material used for the solder joint and pad were different, the Von Mises stress distribution may show discontinuity across the interface as shown in figure 4.6b. The pad size and the PCB materials were used to determine the strength of the solder joints which attach the substrate to the PCB [39].

Figure 4.6: (a) stress transformation at the adhesive interface, (b) stress distribution at the interface of two different materials [39].

The above described were the observations made from the common data acquired from all boards. The individual board results will be discussed below starting with boards A

and C, followed by boards B and D. The boards A and C had the same PCB thickness but different lid thickness. The respective lid thicknesses were 2mm and 0.5mm. The data analysis performed on these two boards gave a better understanding on the effect of the lid thickness of the substrate. The boards B and D differed in PCB thickness (board B: 3.18 mm, board D: 2.36mm) while sharing a common lid thickness of 1mm. The results from these two boards show the effect of the board thickness. The variation of the above mentioned parameters ensured the reliability of different boards to meet customer requirements for its various applications.

4.2 Results of Board A

Two different behaviours were observed when experiments were conducted on board A are shown in figure 4.7 and 4.9 a. (1) an abrupt increase of the substrate strain which can be explained as follows: in the occurrence of brittle fractures in the solder joints uncovered by the FBG sensor, an unevenly load transfer was exerted on the solder joints covered by the FBG that caused sudden increase in strain; (2) a sharp strain drop caused by the brittle fractures on the solder joints covered by the FBG (load drop). While testing board A, as the solder joint started to suffer interfacial fracture from either the PCB or the component side, a spike was observed on the strain curve indicating a PCB pad lift. As the crack expanded in size, the slope started to decrease. Each vertical drop observed on the curve corresponded to an expansion of the crack. The various sections on the curve are indicated as follows: (a) initial pressing – elastic loading (near linear dependence), (b) load accumulation prior to de-lamination, (c) interface fracture – sharp drop in a strain level with a constant time indicating a rapid fracture in the solder joint, and (d) strain relaxation region which relates to the strain curve for board A3 as shown in figure 4.10.

Figure 4.7: Various data regions of FBG 4 for board A2.

The various factors that may affect the apparent brittle fractures are: (1) the presence of high strain rate during four point bending test specially in the occurrence of a version A board with a thick lid of 2mm; the strain relief in the solder bulk is impossible; (2) Micro-void at ball PWB interface; (3) remaining residues such as solder mask left on the pad, the interface can be weakened by contaminations even though the amount of the residue is very minimal as in the solder joint attachment to the PWB is still possible. The second and third reasons of the board A may also be reason of the failure on rest of the boards.

The analysis of the strain gauge and resistance results for boards A2, where the cross head travel distance of the boards was 4mm, did not display any spike or slope change even with the presence of failures in the board as mentioned earlier. This indicated that the strain gauge and the resistance cannot detect the partial fracture between the PCB and FC-BGA as indicated in figure 4.9a. However, the data observed from board A3, where the cross head travel distance was 10 mm indicated a spike in the strain gauge (Fig. 4.10a) and an open in the resistance because the majority of the solder joints had failed as showing in figure 4.8. The results accumulated for board A are tabulated in table 4.1.

Figure 4.8: Electrical resistance open for board A3.

Table 4.1-summarizes the test results for A boards.

Label of Sample and Test	A1T1	A2T1	A3T1	A4T1
Crosshead travel distance (mm)	2.0	4.0	10	4.0
Strain rate ($\mu\epsilon/s$)	14000	14000	18000	14000
Load (N)	989	4205	5957	4089
Resistance change (%)	0.07	0.542	Open	0.33
Global Strain ($\mu\epsilon$)	3204	6429	7915	6429
Max strain from FBG 1($\mu\epsilon$)	1723	2131.5	1642	2202
Max strain from FBG 2($\mu\epsilon$)	1282	Broken	2364	1623
Max strain from FBG 3($\mu\epsilon$)	1138	2393	1737	1763
Max strain from FBG 4($\mu\epsilon$)	1148	1959	1970	1709
Critical Load-FBG 1 (N)	817	506	4004	4089
Critical Load-FBG 2 (N)	604	Broken	4871	2930
Critical Load-FBG 3 (N)	873	549.35	3552	3943
Critical Load-FBG 4 (N)	983	540.98	1886	3766
Average of critical load	819	540	3578	3682
Overall average (N)	2155			

A better understanding of the FBG substrate strain was obtained when the FBG strain was correlated with the dye and pry. The failure modes indicated in the failure map were mode 10 defined by a pad lift/ crater. The red marks in the failure map indicated a full pad lift while the black marks indicated partial cracks. Another mode was mode 5 which is a full crack from the component side. From the failure map of A2 shown in figure 4.9b, it was observed that A2 recorded a lot less failures on the first corner, yet all failures observed on this corner were full pad lift from both sides (PCB and component). Two small spikes were recorded from FBG 1. The highest spike was recorded on FBG 4 while the lowest strain was also recorded on FBG 4 as well; by referring to the failure maps, it can be seen that there is a lot more full cracks on corner 4.

(a)

Figure 4.9: (a) FBG substrate strain level indicating spikes (brittle fracture) as a function of time in 4-point bending test, (b) Failure map for board A2.

From the failure map of A3 as shown in figure 4.10b, it was observed that almost all of the solder joints between the PCB and the FC-BGA were fully and partially pad lifted/ cracked. Thus the in situ resistance was able to detect the failure and a spike was observed from the strain gauge as indicated in earlier in this chapter. FBG 2 provided the highest strain value that corresponds to a lower number of failures were found when compared with the values from that of FBG sensors at the three other corners.

(a)

(b)

Figure 4.10: (a) FBG substrate strain level as a function of time in 4-point bending test, (b) Failure map of board A3.

4.3 Results of Board C

The strain response recorded from all four FBG sensors depicted an initial linear increase, as shown in Figure 4.11a, followed by a deviation from linearity at approximately half way through the displacement. The behaviour may indicate the beginning of plastic deformation of the solder joints. At approximately 75% of the full displacement, the changes of the strain slope was observed in all four FBG sensors that could be interpreted as a significant deformation of the solder joint as illustrated in figure 4.11a. The results obtained from board C displayed ductile fracture as shown in figure 4.11. Table 4.2 represents the results obtained from board C.

Table 4.2-summarizes the test results of board C.

Label of Sample and Test	C1T2	C2T1	C3T1	C4T1	C5T1	C7T1	C8T1
Crosshead travel distance	8	8	10	4.0	4.5	8.0	4.5
Strain rate ($\mu\epsilon/s$)	10230	7000	14000	14000	14000	**	**
Load (N)	5225	6738	6256	3674	4340	6263	4706
Resistance change (%)	0.294	0.354	Open	0.169	0.239	0.278	0.336
Global Strain ($\mu\epsilon$)	9208	9692	10391	6071	6920	9656	6920
Max strain from FBG 1($\mu\epsilon$)	3367	2450	1284	1249	1945	2672	1468
Max strain from FBG 2($\mu\epsilon$)	3746	3240	Broken	2354	1845	(a) 2482 (b) 2602	1554
Max strain from FBG 3($\mu\epsilon$)	3611	2955	1815	1968	2195	(a) 2869 (b) 3222	1691
Max strain from FBG 4($\mu\epsilon$)	3411	2444	494	2160	2280	2326	2210
Critical Load-FBG 1 (N)	4566	4272	2636	3333	3833	5817	3247
Critical Load-FBG 2 (N)	4517	4272	Broken	3674	4157	(a)3241 (b)3650	3540
Critical Load-FBG 3 (N)	4395	4272	2350	3375	4023	(a)4840 (b)5115	4309
Critical Load-FBG 4 (N)	4566	4272	*	3333	4236	3937	4608
Average of critical load	4511	4272	2493	3428	4062	4433	3926
Overall average (N)	3875						

*:FBG signal was weak.

**:No strain gauge.

The comparison of the boards A and C indicated that a decrease in the lid thickness may cause the solder joints to deform in order to accommodate the applied bending which in turn slowed down the failure process. The observations made on the ductile failure of the solder joints led to conclude that thinner substrates (less bending stiffness) could withstand larger global deformation. Furthermore, an inverse relationship can be found between the critical load and the lid thickness as shown in table 4.3. The critical load for board A was found to be smaller than the one for board C when the two boards were bent under the same test conditions; this indicated that a higher stiffness of the substrate lid resulted in a lower value of the critical load as shown in table 4.3.

Table 4.3: The critical load values recorded from each FBG sensor

Label of Sample and Test	A2T1	C4T1
Critical Load of FBG 1 (N)	506	3333
Critical Load of FBG 2 (N)	Broken	3375
Critical Load of FBG 3 (N)	549	3375
Critical Load of FBG 4 (N)	567	3333
Average of Critical Load	540	3354

C2-250 Hz

(a)

(b)

Figure 4.11: (a) FBG substrate strain level as a function of time in 4-point bending test, (b) Failure map of board C2.

The data collected from the four FBG strain curves as shown in figure 4.11a followed a similar trend but the four curves did not overlap on each other. This slight deviation is interpreted as follows: (1) a position tolerance variation from 0.5 mm-1.0 mm for the FBG sensors, (2) asymmetry in the edges of the substrate, (3) the warpage of the board, (4) the load asymmetry, (5) the difference in the interconnect strength. The FBG sensors were able to record a strain release when the pad lift/crater occurred; the strain magnitude of each FBG was associated with the failure and behaviour of the solder joints around the specific corner.

From the failure map of C2 as shown in figure 4.11b, more failures were found to be around corner 1 when compared with the failure location from the three other corners as a result the lowest strain was recorded on FBG 1. The results observed from FBG1 showed both slope change and initiation of strain relaxation prior to the end of the test. The results obtained from the FBG did correlate well with the ones from the dye and pry test. Figure 4.12 illustrates the failure map of board C under various crosshead travel distances; the same observation was made as the rest of the boards. It demonstrates that an increase of the interconnect fracture (failure induced between the PCB and the FC-BGA) was the result of a board flexure increase and solder joint fractures emerge from the corners inward.

Figure 4.12: (a) Failure map of C8 crosshead travel distance 4.5, (b) Failure map of C2 crosshead travel distance 8 mm, (c) Failure map of C3 crosshead travel distance 10 mm

4.3 Results of Board B

The collected FBG sensor data from the tests of board B showed a strain release instead of a sudden strain increase or decrease as observed from the results of board A, as illustrated in figure 4.14a. This behaviour indicated that the strain release increased gradually until it reached the board's complete fracture. The strain release was observed prior to the resistance opening. The substrate strain relaxation was caused by the variation in the component's stiffness; this change was a result of pad lifts causing crack openings. Such behaviour translated into a load drop that decreased the stress and consequently the strain. The test results from board B are represented in the Table 4.4.

Table 4.4-summarizes the test results of board B.

Label of Sample and Test	B1T1	B2T1	B3T1	B4T1	B5T1
Crosshead travel distance (mm)	10	10	10	8.0	4.5
Strain rate ($\mu\epsilon/s$)	15000	18000	18000	10000	16000
Load (N)	6122	6281	7410	6518	6396
Resistance change (%)	0.456	0.298	0.43	0.345	0.386
Global Strain gauge ($\mu\epsilon$)	8559	8354	10015	7608	8624
Max strain from FBG 1($\mu\epsilon$)	1424	1122	1885	1973	2262
Max strain from FBG 2($\mu\epsilon$)	1647	1145	1173	1456	1996
Max strain from FBG 3($\mu\epsilon$)	1208	1938	884	1505	1703
Max strain from FBG 4($\mu\epsilon$)	976	1005	2071	broken	2064
Critical Load-FBG 1 (N)	5524	3650	5848	4132	5915
Critical Load-FBG 2 (N)	5218	3650	3247	4712	5005
Critical Load-FBG 3 (N)	3174	6006	4889	6293	4840
Critical Load-FBG 4 (N)	2631	2777	6476	broken	5870
Average of critical load	4136	4020	5115	5045	5407
Overall average (N)	4745

(a)

(b)

Figure 4.13: (a) FBG substrate strain level, (b) Failure map of board B4.

From the failure map of board B4, it can be seen that corner 2 contained more failures when compared to the other corners. FBG 2's curve indicated a strain release. During analysis, the failure map indicated also solder joints failures around corner 3 and corner 1. FBG sensors one and three did detect a slope change.

Figure 4.14: (a) FBG substrate strain level, (b) Failure map of board B1

The failure map of board B1 indicated that a higher concentration of failures (full crack from PCB side) around corner 3 and 4; as a result, a higher level of strain release was observed from both FBG 3, and FBG 4. The above findings from the FBG tests concur with the data collected from the dye and pry experiment. The strain relaxation observed on the board B4 was much smaller in comparison to value noted from board B1; this could be a result of the difference within the crosshead travel distance of B4 and B1 observed to be 8mm and 10mm.

4.5 Results of Board D

The results obtained from board D is tabulated in table 4.5.

Table 4.5-summarizes the test results of board D.

Label of Sample and Test	D2T1	D3T1	D4T1	D6T2
Crosshead travel distance	4.5	4.5	4.0	8
Strain rate ($\mu\epsilon/s$)	7000	4000	*	**
Load (N)	1672	1605	1618	6378
Resistance change (%)	0.194	0.177	*	open
Global Strain ($\mu\epsilon$)	5372	5095	5109	**
Max strain from FBG 1($\mu\epsilon$)	1846	1911	1317	3450
Max strain from FBG 2($\mu\epsilon$)	1499	1163	1494	3065
Max strain from FBG 3($\mu\epsilon$)	1066	773	1828	2219
Max strain from FBG 4($\mu\epsilon$)	Broken	548	1715	1816
Critical Load-FBG 1 (N)	545	1605	1316	5847
Critical Load-FBG 2 (N)	1672	1587	1471	5273
Critical Load-FBG 3 (N)	1514	1099	410	5694
Critical Load-FBG 4 (N)	Broken	846	410	5389
Average of critical load	1243	1284	901	5550
Overall average (N)	2244			

*: lost the records of the readings during the test

** : No strain gauge was mounted on the board

(a)

(b)

Figure 4.15: (a) FBG substrate strain level, (b) Failure map of board D4.

The dye and pry test performed on board D4 indicated that the corners 1, 2, and 3 of the board were subjected to failure while the corner 4 did not display any failure as shown in figure 4.15. More failures were visible around corner 1, and 2 when compared to the other corners. A strain release was also observed from strain curve of FBG 1, and FBG 2. Failures observed during the tests conducted on board D6 were predominant around

corners 3 and 4, as shown in figure 4.16. The FBG4's curve indicated a brittle fracture. While a strain release was observed from FBG 3. Final analysis led to conclude that the data collected by the FBG sensors correspond to the information acquired from the dye and pry test.

Figure 4.16: (a) FBG substrate strain level, (b) Failure map of board D6.

The results from the dye and pry indicated that all failures were parallel to the load anvil. As a consequence, an experiment was conducted such that the orientations of the FBG sensors were parallel to the load anvil. The data collected from the FBG sensor, shown in

Fig. 4.17 gave the strain level for all four FBG sensors between 400 to 600 $\mu\epsilon$, which is expected because of passion ratio since the board was not bent in that direction. The four FBG strain curves had shown different set of properties; the non-linearity of the strain behaviour as the onset of the crack. The increase in the deflection led the FBG strain to show emerging signs of a crack propagation in the solder joint.

Figure 4.17: FBG substrate strain for board D8 as a function of time in 4-point bending test

Chapter 5

Conclusion and Future work

5.1 Conclusion and Final Remarks

The intention of this thesis was to use FBG sensors to detect de-bonding between the FC-BGA and the PCB and compare the results obtained with the data accumulated from strain gauge, in situ resistance as well as dye and pry experiments. The small size and light weight allow the FBG to be mounted in ways that strain gauge cannot be attached to the substrate. The process used by the strain gauge alters the stress distribution on the FC-BGA as the lid part needs to be removed; however using the FBG sensors, there is no need to remove the lid part of the substrate hence no alteration would occur in the stress distribution.

The experiments conducted helped to prove that the FBG sensors can detect the onset of the interconnect failure due to its high sensitivity; The use of fibre sensor provides more detailed information about the bending-induced failure as compared with that of strain gauge installed at one corner on the lid or on PCB board. The daisy chain and the global strain detect the failure only at the end of the damage progression. The first spike from the strain release data identified the critical load also known as the maximum load that the board can withstand before failure. Within the different versions of the boards tested, lower interconnect strength was found from the boards which had a high lid thickness. The data acquired from the FBG demonstrated three characteristics: brittle fracture, ductile fracture and strain release. The observed failures were dependant on the material used for the solder joints, the structure of the components as well as the PCB (thickness of the PCB and the substrate), and the input test parameters (strain rate, displacement, etc.) Finally the dye and pry test conducted on the tested boards revealed that more than 90% of the failure were pad lift from the PCB end. The results obtained from the FBG

did correlate with the ones from the dye and pry test. The results obtained from FBG sensors do comply with the results obtained from the dye and pry test.

5.2 Future work

Although there were conclusive results showing the advantages of using the FBG sensors over the conventional methods used to test the reliability of the boards, it still has to undergo some improvements to better analyze this method. The sampling rate of the data acquisition equipment provides low detail data due to its low sampling rate (250 Hz). As the methodology has not reached maturity, proper synchronization between the optical and the mechanical interrogator systems needs to be made. The inaccuracy of load cell readings also raises concerns. The asymmetry failure pattern on the board thus the load balances is also an issue that needs attention.

Some recommendations to further the studies are listed below:

1. The use of higher speed interrogator systems (more than 250 Hz) will provide higher sampling rate which will allow the collection of more data hence obtain a better interpretation of the results.
2. Conduct four point bending experiments using the FBG sensors mounted in parallel to the load anvil to determine if the low strain in that alignment is more sensitive to detect the onset and propagation of the solder joint crack.
3. Embedded FBG inside the substrate to better locate the onset of the cracks as well as to monitor their propagation.
4. Conduct finite element analysis to enhance the understanding of failure mechanism of the tested vehicle and to provide the theoretical insight in the experiment interpretation.
5. Utilize the Scanning Electron Microscope to study the fractured surface of the solder joints can offer more detailed interpretation on the nature of the crack in the solder joints and its propagation.

6. Determine the interfacial fracture through the record of energy release rate required for a crack delaminating of solder joint between the FC-BGA and PCB during the four point bending test in order to obtain the interfacial fracture energy.

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Appendix

Figure 1: daisy chain pattern for bend test vehicle [33].

Conventional Strain Gauge

The first metal foil strain gauge was fabricated by Saunders and Roe (England) in 1952 [24]. The strain gauge is a grid of metal wire or foil used to increase the length of the conductor which increases the sensitivity while limiting the gauge length. The metal foil grid is the product of a photo etching process. The versatility of this process allows the production of gauges with varying shapes and sizes. Nonetheless, the etched metal film grids are very fragile and can easily get distorted or torn. For better resistance, the metal film is bonded to a thin plastic sheet; this also serves as an insulator between the gauge and the component once the gauge is mounted. The insulating material is chosen depending on the application of the strain gauge; the different materials used for this purpose are listed below: thin sheet of polyimide (a flexible yet resistant plastic), epoxy (used for transducer applications yet not fit for general purpose strain gauges as it is brittle), glass fiber reinforced epoxy (used for high level cyclic strains, fatigue life and moderate temperature applications that reaches up to 400 °C) [24].

The resistance of a uniform conductor is given by:

$$R = \frac{L}{A} \rho \quad (2.18)$$

where ρ is specific resistance constant for each material, L is the length of the conductor, A is the cross sectional area. The standard gauge resistance is either 120 Ω or 350 Ω . The strain gauge reflects a variation in electric resistance as tension or compression applied on the gauge. As a result, when a gauge is surface mounted, the metal wire is moulded to the shape of the object altering its resistance. This change of resistance of the strain gauge value is explained by a variation of the geometrical dimensions and the resistivity. The change in resistivity is a direct result from the change in the number of free electrons as well as their freedom of mobility within the applied strain. Since variation of the resistivity is minimal, it is neglected and considered to be constant; therefore, the resistance is proportional to its physical changes. The change of the resistance may then be used to evaluate the strain using the following equation:

$$\frac{\Delta R}{R} = K\varepsilon \quad (2.19)$$

where K is a gauge factor which varies between 2 and 2.2 for most metals.

A widely used method in determining the resistance of the strain gauge is the Wheatstone bridge. The set up consists of four arms, each arm is coupled with a resistance; the resistance of three arms is known while the resistance of the fourth arm denoted as R_4 is variable. The resistance at R_4 is varied until a voltage of 0 is read by a voltmeter. When a strain is applied to the resistors, the bridge becomes out of balance displaying a change in voltage on the voltmeter. This observed change is proportional to the change in resistance.

Figure 2: (a) Strain gauge, (b) Wheatstone bridge.