A SELECTIVE ENCAPSULATION SOLUTION FOR PACKAGING AN OPTICAL MICROELECTROMECHANICAL SYSTEM

by

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ABSTRACT

This work developed a process to provide physical, electrical, and environmental protection to the electrical lead system of an optical switch device. A literature review was conducted to find materials and processes suitable to the stress-sensitive, high voltage characteristics of many optical switch devices. An automatic dispensing dam and fill process, and three candidate materials (two epoxy and one silicone) were selected for investigation. Experimental and analytical techniques were used to evaluate the materials. Methods applied included interferometric die warpage measurements, electrochemical migration resistance tests (ECMT), thermal cycling, and finite element analysis.

The silicone dam and fill system was selected based upon the results of die warpage and electrochemical migration resistance tests. A modified, selective dam and fill process was developed and preliminary reliability testing was performed. The paper provides detailed instructions for successful encapsulation of the optical switch's lead system.

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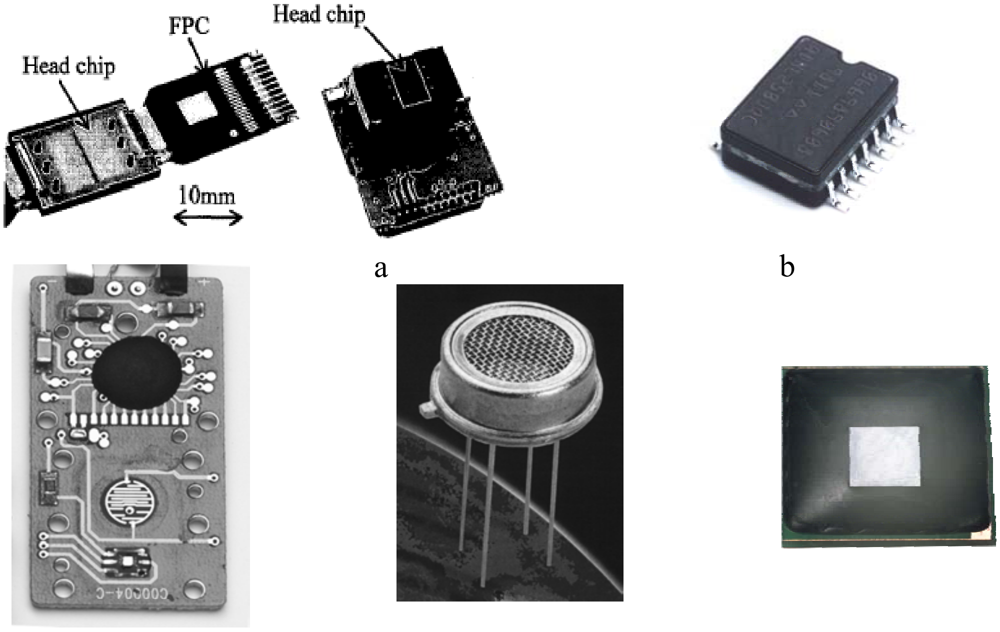
1. INTRODUCTION

Microelectromechanical Systems (MEMS) are tiny electrically activated, mechanical devices, ranging in size from microns to millimeters [1]. MEMS are typically fabricated on silicon or glass wafers using adapted semiconductor processing techniques. The mechanical components on MEMS devices are used in many common applications such as: pumping within ink jet printer heads (Fig. 1.1 a), accelerometers to activate automobile airbags (Fig. 1.1 b), pressure sensors (Fig. 1.1 c), and a variety of sensors (chemical (Fig. 1.1 d), optical (Fig. 1.1 e), electrical, or mechanical).



a b

c d e

Figure 1.1 Examples of MEMS devices – a) SeaJet ink jet printer chip attached with FPC and printer head unit [2]; b) Analog Devices accelerometer; c) Accutire pressure sensor; d) Motorola gas sensor; and e) 100-pixel IR sensor array [3]

1.1 Semiconductor Packaging

The technology used to manufacture and package MEMS devices is derived from the processes developed for the semiconductor industry. By transferring these well characterized and readily available materials and process technologies, the MEMS industry reduces the time and cost of development [4]. Moreover, using the batch processing approach of the semiconductor industry allows for low-cost, high volume manufacturing of MEMS devices.

A packaging hierarchy was established in the early days of mainframe computers to describe the concept of different packaging levels [5]. Figure 1.2 shows the hierarchy of electronic packaging from chip level to motherboard. Before packaging begins, the IC is diced from the semiconductor wafer. Chip level interconnection refers to connecting the chip to the first level package (e.g. solder bumps, or wires). A first level package refers to the IC, encapsulated to provide mechanical/environmental protection, and its electrical contacts. First level interconnection occurs when the first level package is connected to the second level package. A populated printed circuit board (PCB) is an example of a second level package. PCBs are ceramic or resin composite boards that interconnect active and passive components onto a single board. Second level interconnection occurs when the second level package is connected onto the third level package (e.g. the mother board). Higher levels of packaging exist at the system level.

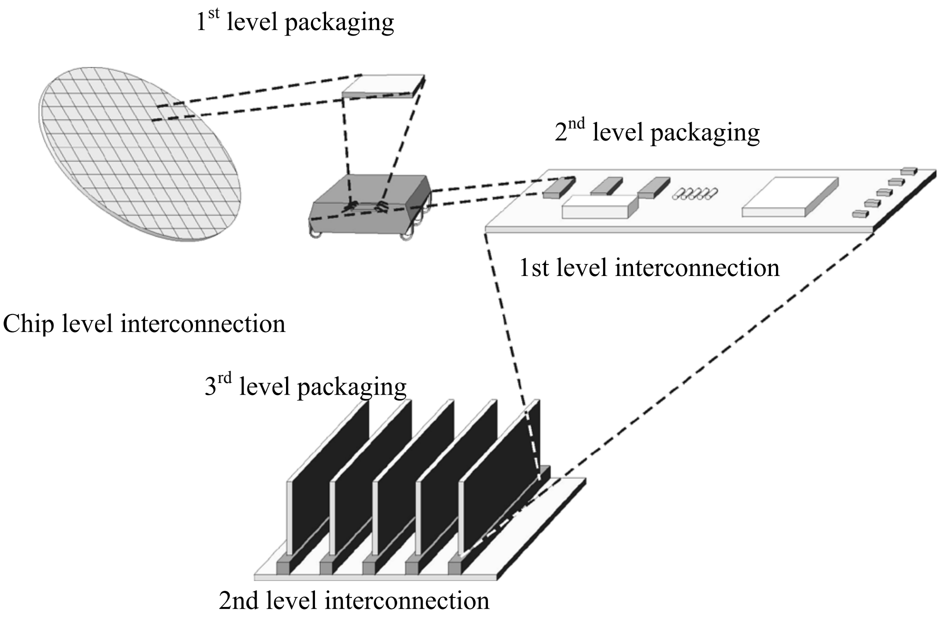


Figure 1.2 First three levels of the traditional packaging hierarchy [3]

Over the years, packaging hierarchy has evolved to fit the needs of new applications such as MEMS. Many modern packages no longer fit directly into the traditional hierarchy, although its structure is useful in the understanding of general package functionality. In some cases, the chip can be integrated directly into the system. The solution proposed for the MEMS application in this work is a chip level package to be integrated directly into the system.

In order to choose a packaging solution, one must consider the required functions of the package, and the limitations of the chip and its application. Chip characteristics that will affect the packaging solution include: clock speed, wafer thickness, dimensions, environmental sensitivity, physical vulnerability, heat generation, and heat sensitivity. The four basic functions performed by a package are to provide [6]:

1. Lead system (transfer/ connections),
2. Physical protection,
3. Environmental protection, and
4. Heat dissipation.

Examples of common lead systems are shown in Figure 1.3. The lead system is necessary to allow electrical interconnection to the chip. It provides a pathway for electrical power and read/write/signal data. For lead system design, it is important to keep in mind that signal lines are more sensitive to electrical disruption (e.g. noise, cross-talk, leakage) than power or ground lines. In fact, power and ground lines can be used to electrically shield signal lines [7].

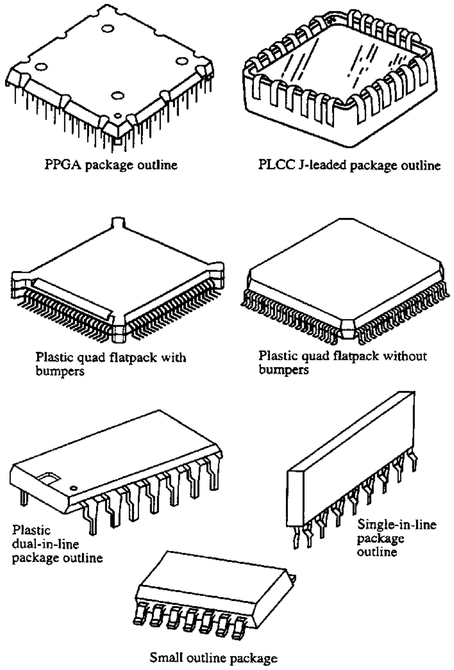


Figure 1.3 Plastic package configurations, featuring examples of common lead systems [8]

The completed package must provide physical protection to the semiconductor die as well as the electrical connections. It should protect the brittle semiconductor die from harm such as vibration or impact, and prevent breakage or crossing of the leads. In the case of the optical switch, it must also protect the fragile mirror components on the surface of the device.

Environmental protection is necessary to keep the device free from harm by its surroundings. The environmental protection requirements will vary depending upon the operating environment and the needs of the device being packaged. For example, the optical switch is sensitive to dust and particles, ionic contaminants, and moisture. A suitable packaging solution will protect the device from any environmental factors that will cause the device to fail, or reduce the lifetime of the device.

Heat dissipation is often required to remove the heat generated by powering the device. Increasing the temperature of a device typically changes the electrical parameters, and may eventually lead to permanent degradation and even failure of the device [7]. Temperature changes also affect the physical construction of the device, due to CTE mismatch between different materials. Figure 1.4 shows a heat fin and a heat spreader, two common methods used to dissipate heat from electronic packages.

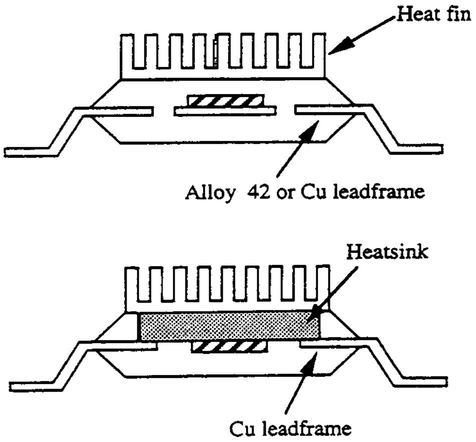


Figure 1.4 Heat fins and heat sinks - used in electronic packages to dissipate heat away from temperature sensitive components [9]

An enclosure is used to provide physical and environmental protection to the chip and the chip level interconnects. The choice of enclosure depends upon requirements of the application and reliability concerns. Common concerns include heat generation and dissipation, chemical contaminants, mechanical stress, and electrical integrity [6]. Examples of enclosures that address these concerns are polymeric encapsulation and polymer, metal, ceramic, or glass sealed packages.

1.2 MEMS Packaging Challenges

The following quote from the National Research Council's "*Microelectromechanical Systems: Advanced Materials and Fabrication Methods*" summarizes the importance of packaging to the MEMS industry:

> "Packaging, which has traditionally attracted little interest compared to device and process development, represents a critical stumbling block to the development and manufacture of commercial and military MEMS. The imbalance between the ease with which batch-fabricated MEMS can be produced and the difficulty and cost of packaging them limits the speed with which new MEMS can be introduced to market. Expanding the small knowledge base in the packaging field and disseminating advances aggressively to workers in MEMS could have a profound influence on the rapid growth of MEMS."

In most cases, semiconductor packaging technology cannot be directly transferred to MEMS. The unique challenges of packaging MEMS are characteristic of the differences between MEMS and typical semiconductor applications. Unlike ICs, MEMS often process non-electrical signals (e.g. mechanical, optical, chemical). The package design must accommodate the transmission of required electrical and non-electrical signals, while protecting the MEMS from external influences that may be harmful to the device or disruptive to the required signals. The micro components may be more adversely affected by stress (e.g. pressure sensors or accelerometers), or subjected to more harsh environments than ICs (e.g. chemical sensors). This deviance from typical processes and design rules tends to reveal the limitations of current packaging technology, and may require the development of new materials and processes [4]. A schematic representation of MEMS packaging development is shown in Figure 1.5.

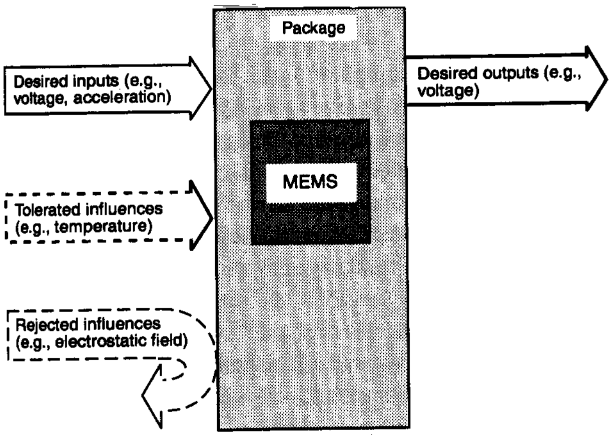


Figure 1.5 Block diagram of generic MEMS packaging requirements showing basic considerations of the package design [4]

The package design must accommodate the MEMS application, with respect to functionality and operating environment. Interaction between the MEMS and their environment is often required. Accordingly, the package needs to provide a protective enclosure with a "window to the outside world" [10].

1.3 Polymeric Encapsulation

Polymeric encapsulation is a standard semiconductor process used to provide physical, chemical, and electrical protection. Typically, the encapsulation process covers the entire semiconductor surface. This thesis will focus on adapting a polymeric encapsulation process to provide a "window to the outside world" to an optical MEMS (MOEMS) device.

There are three common types of polymeric encapsulation:

1. Transfer Molding (see Figure 1.6)
2. Potting

3. Glob Top Encapsulating

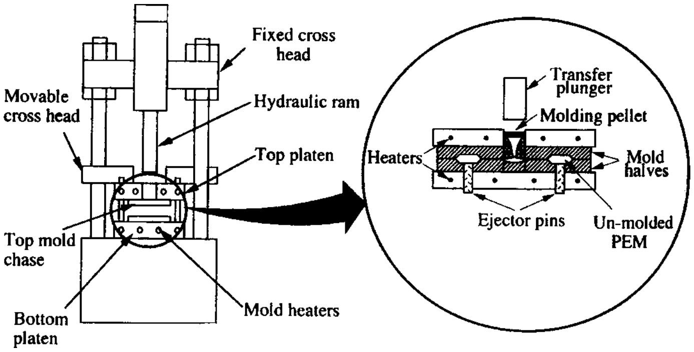


Figure 1.6 Schematic diagram of a transfer molding press [7]

1.3.1 Transfer Molding

Transfer molding is the most common IC encapsulation method for plastic packages [11]. It was developed as a repeatable, high speed, high throughput process. In the transfer molding process, a leadframe[1] is loaded into the bottom half of a mold; a plunger forces molding material from an auxiliary pot, through mold runners and gates, into a heated mold cavity; pressure is held to be sure that the cavity is filled; the polymer resin is cured; the mold is opened and the part ejected. An example of a selectively encapsulated, transfer-molded package is shown in Figure 1.7. Table 1.1 highlights the advantages and disadvantages of transfer molding.

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[1] A leadframe is a sheet metal connector framework used to connect the IC to the second level package.

Table 1.1 Advantages and Disadvantages of Transfer Molding

Advantages	Disadvantages
Low melt viscosity and “ram” pressure allow rapid encapsulation of many components simultaneously [12].	Parts must be able to withstand the elevated temperature and pressure of the transfer molding process. (This is a key problem for the MOEMS application.)
Encapsulated components have precise dimensions [12].	Filled resins used in transfer molding are highly viscous, threatening wire sweep, and necessitating high temperature and pressure [11].
Cycle times are fast [12].	The process tends to waste material, because material within the runners and pot are polymerized in the process, and cannot be re-used [11].
There is a uniform density of molded pieces [12].	The MEMS application requires a window to the outside world, which requires alteration of the standard transfer molding process and specialized equipment. High volume products, e.g. SensoNor’s pressure sensor have accomplished a signal window, but not an optically transparent window [13], [14]. See Fig. 1.7.
Process is very repeatable.	High capital cost of mold and press [12].

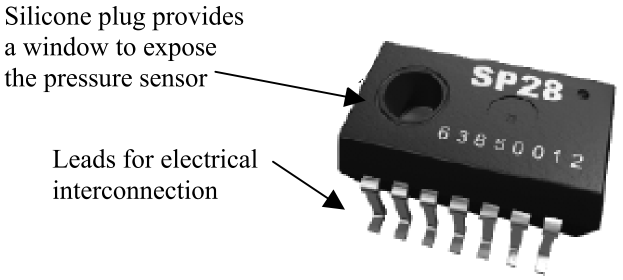


Figure 1.7 SensoNor SP28 tire pressure sensor - a transfer molded package with a silicone-filled window to expose the MEMS device [15]

1.3.2 Potting

Potting is the most simple encapsulation process [7]. The process involves placing the electronic component into a container, pouring a liquid resin over the component to fill the container, and curing the resin. The resin is a typically a thermoset polymer such as epoxy, silicone, or polyurethane. The containers are made out of rugged materials, such as metal, ceramic, or polymers. Potting results in rugged samples that are very conducive to automated pick-and-place processes [7]. An example of a potted MEMS device is shown in Figure 1.8.

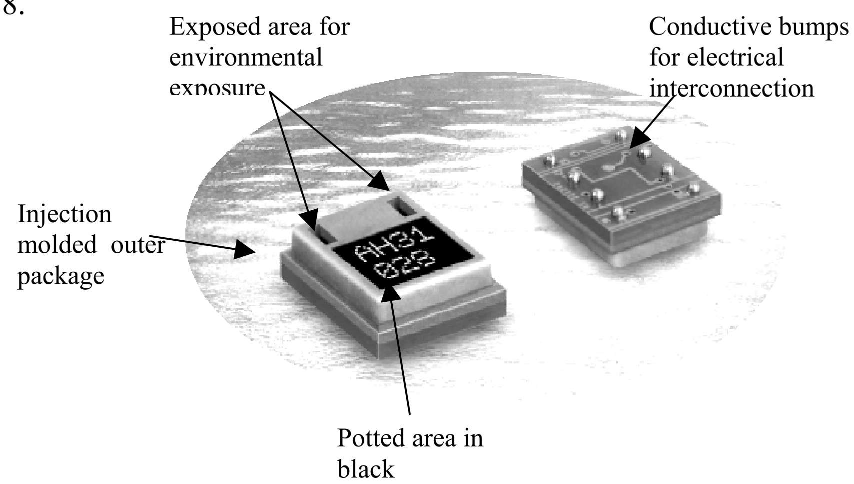


Figure 1.8 Sensiron AH31 humidity sensor is a potted package, with an opening to expose the sensor to the environment [16].

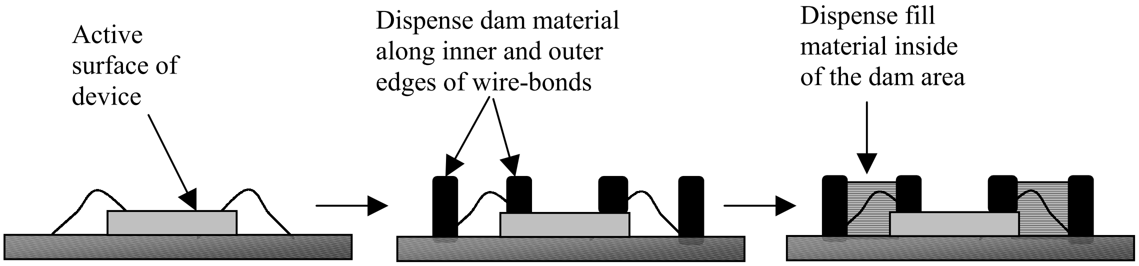
1.3.3 Glob Top Encapsulation

Glob top encapsulation using epoxy resin is one of the most common IC packaging processes used for chip on board (COB) applications. It is an inexpensive, easily automated process. The glob top provides physical and environmental protection, and helps to maintain the integrity of the wires (see Figure 1.9 a). The process is well known and the materials are readily available and well documented [7], [9], [11], [12].

There are single resin glob top processes and two-resin, “dam and fill” processes. In the single resin process, the thixotropic glob top material is dispensed over the device and wirebonds and cured (Figure 1.9 a). In the two-resin glob top process, a highly thixotropic "dam" material is dispensed around the area to be encapsulated. Next, the "dam" is filled with a lower viscosity material that covers the device and wirebonds (Figure 1.9 b).

Figure 1.9 Two styles of glob top on ICs (a) single-resin process; (b) two-resin process

Like many packaging technologies, the transfer of the technology from ICs to MEMS sometimes requires alteration of the process. For example, the glob top process can be modified to accommodate applications requiring an exposed device surface [3], [17], [18], [19], [20], [21]. In order to allow a window for exposure, the glob top must be applied to the wire bond area only, leaving the top surface of the MEMS exposed to the environment. Figure 1.10 highlights a "selective encapsulation" process that transfers the two-resin globtop process (Fig. 1.9 b) to allow environmental exposure of MEMS devices.



Bare wire-bonded device

Highly thixotropic dam material is deposited to protect the active area on device surface from the less viscous fill material.

High flow fill material is dispensed within the dam area, and allowed to flow around the delicate wire-bonds before curing.

Figure 1.10 Selective Glob Top Encapsulation Solution for MEMS Device

2. PROBLEM DEFINITION

The scope of this work is to investigate a particular MEMS packaging application. Specifically, the thesis will provide an encapsulation solution for a MEMS-based, optical switch device. The encapsulation process developed will provide electrical, physical, and chemical protection to the delicate wirebonds and bond pads, while allowing a "window to the outside world" for the optical switch. Figure 2.1 shows a flow chart summarizing the steps that will be followed to develop the encapsulation solution.

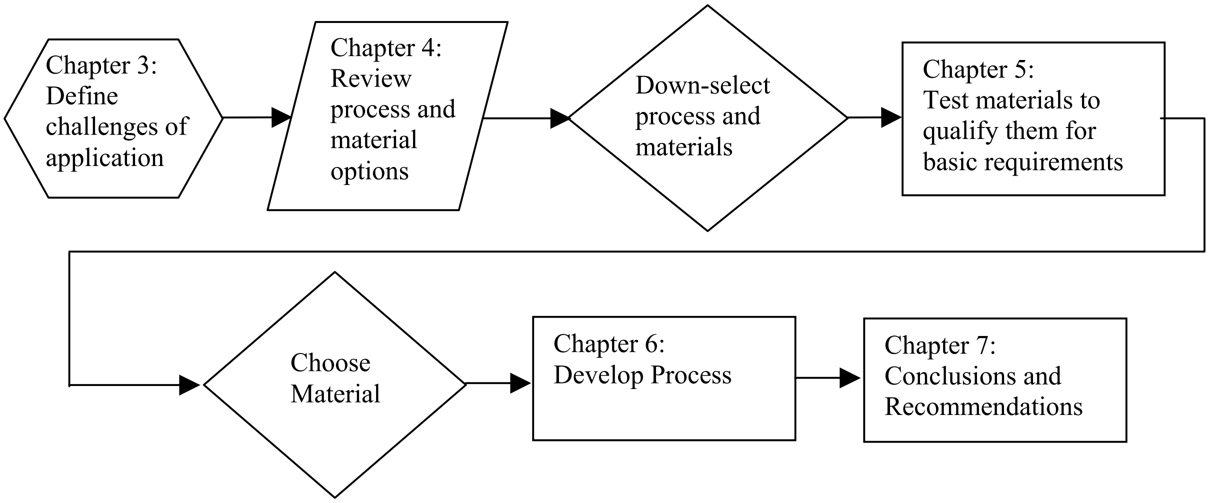


Figure 2.1 Thesis flow chart showing the process that will be used to develop an encapsulation solution

2.1 MEMS Device and Package

The MEMS device is used to optically switch between fiber optic telecommunication channels. It consists of a 16 x 16 array of gold plated silicon mirror switches. Each ~ 800 μm mirror is supported by two sets of gimbals (fabricated via a silicon etch process) that allow the mirror to rotate along two axes. Electrodes beneath each mirror are used to actuate an electrostatic charge, which deflects the mirror (see Figure 2.2).

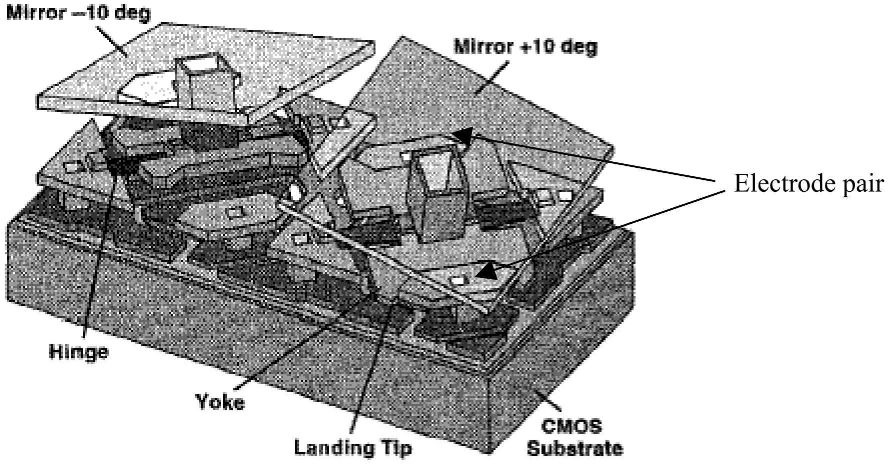


Figure 2.2 Two pixel, mirror switch in the Texas Instruments mirror array. The mirrors are shown as transparent. This array is used for an addressable electronic display, but it functions on the same concept as the telecommunications optical switch. [22]

The MEMS based optical switch device is a large, wirebond interconnected, semiconductor die, housing electromechanical components. Parameters specific to this device that will affect the encapsulation solution are a large die size (1 in.^{2} to 6.25 in.^{2}), sensitivity to stress (electromechanical device), high voltage (250 V), and high I/O density (>1000 wirebonds). The mirrors on the device surface require optical exposure to the environment (particularly within the wavelength range used for optical telecommunications). Due to these limitations, it is critical that the encapsulant be kept from the surface of the device, does not impart significant stress to the device, has a high dielectric strength, and isolates the wirebonds, without causing wire sweep or breakage (see Figure 2.3).

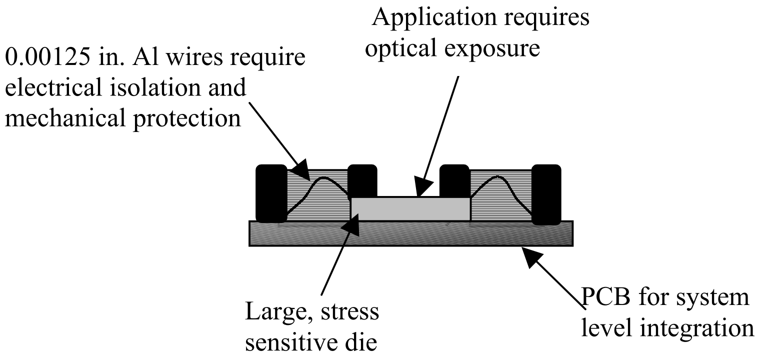


Figure 2.3 Overview of MEMS encapsulation concerns – The optical switch will require a low stress encapsulant that will meet the electrical requirements of the high voltage (~250 V), high wiring density (~1000 wirebonds over a 6.25 in.^{2} die) application.

After encapsulation, a cover plate and window will be sealed over the device, to protect the exposed, active device surface (see Figure 2.4). The window will serve as mechanical protection for the device. However, the encapsulant must protect the lead system, withstand thermomechanical stress and high voltage, and provide corrosion and electrochemical migration resistance to the wires and wirebond pads.

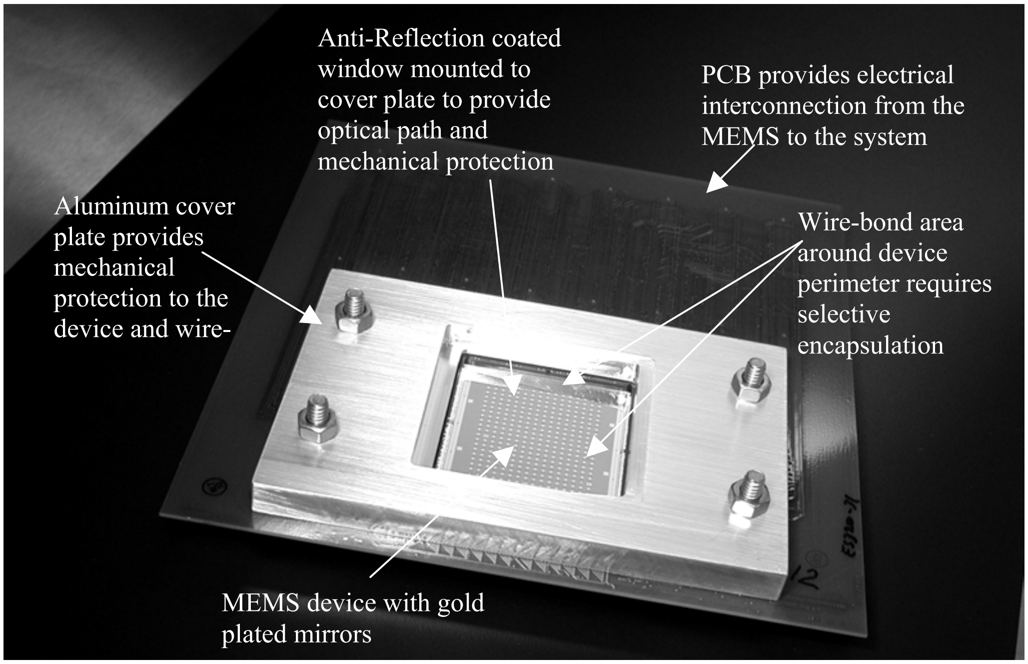


Figure 2.4 IntelliSense Corporation's packaged MEMS optical switch device (Source: IntelliSense March 2001)

2.2 Selective Encapsulation Packaging Concept

Packaging the MEMS-based, optical switch device involves mounting the device onto a thermally conductive (for heat dissipation), CTE-matched substrate, and wirebonding between the device and a printed circuit board (PCB) to provide electrical interconnection. The wire used for bonding is 0.00125-inch diameter wire, and is very susceptible to physical damage. The selective encapsulation concept illustrated in Chapter 1, Figure 1.10 is used to protect (physically and electrically) the electrical interconnections.

In the selective encapsulation process, a dam is deposited over the footpads (both on the device surface and on the PCB surface) of the wires. The method of deposition is typically an automatic adhesive dispenser such as the one shown in Figure 2.5. The dam is dispensed to be about the same height as the wirebond loops. The fill material is deposited inside of the dam, also using the automatic adhesive dispenser. The dam and fill are cured, to provide protection to the wirebond interconnects.

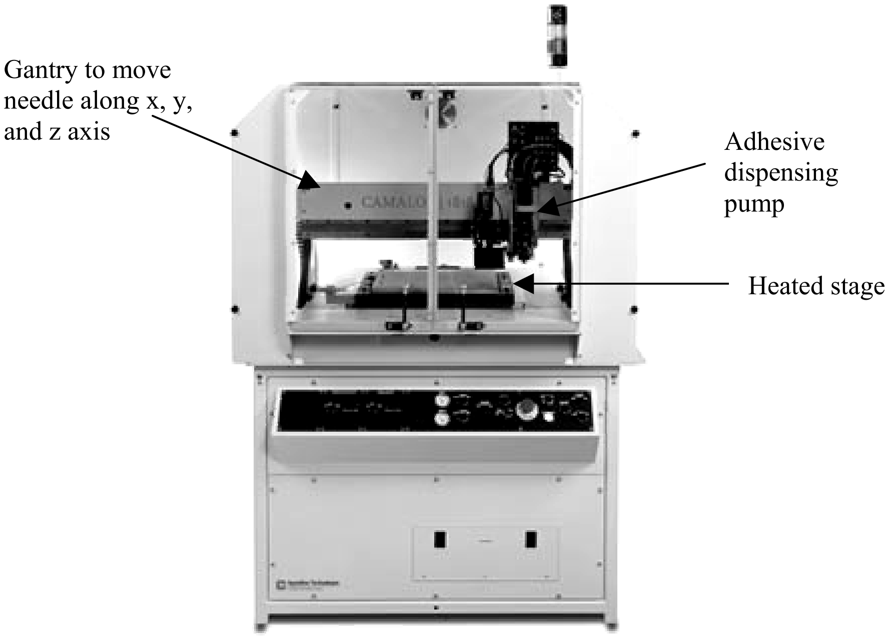


Figure 2.5 Automatic adhesive dispenser - Camalot

2.3 Specifications and Requirements

The selective encapsulation process is necessary to allow the package to fulfill the specifications and requirements of the optical MEMS-based device. As discussed in Chapter 1, there are a few primary requirements of electronics packaging. The package must provide a lead system for electrically interconnecting the device to the system, physical and environmental protection, and heat dissipation.

The encapsulation is used to protect the lead system physically, electrically and environmentally. First, and foremost, the encapsulant prevents mechanical damage of the wires. The small wires necessary to accommodate the fine pitch of the MEMS device are highly susceptible to mechanical damage such as wire sweep or breakage. The encapsulant may also provide stress relief to the wirebond contacts. It holds the wires in place, and provides electrical insulation and shielding. Encapsulation effectively prevents electrostatic attraction between wires. One significant specification for an encapsulant is that it must prevent corrosion and electrochemical migration between bond pads. Accordingly, the appropriate material will seal the interconnects from moisture and have low ionic content and/or mobility.

3. SELECTIVE MEMS ENCAPSULATION

Requirements for plastic (polymeric) encapsulation of MEMS' interconnects parallel those of the IC packaging industry. The encapsulant will serve as mechanical and environmental protection to interconnects, increasing the reliability of the device. Specific concerns include mechanical and thermomechanical stress, package warpage, affect on electrical and mechanical performance, process time, process repeatability, pot life, encapsulation area and thickness, voids in the encapsulation, finished encapsulation surface, and reliability [23]. Figure 3.1 shows possible failure modes associated with plastic encapsulated packages.

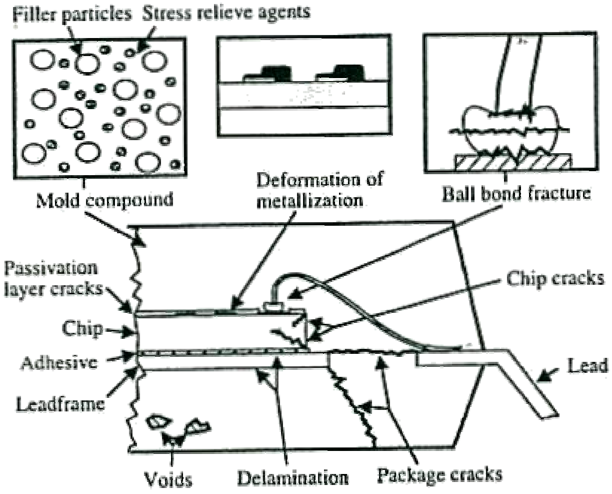


Figure 3.1 Typical failure mechanisms, sites, and modes in plastic-encapsulated devices [24]

Table 3.1 shows particular material property considerations that affect the concerns described above. The table offers "controlling factors", or material properties and processes that address each of the encapsulation requirements listed. The sections to follow will give further insight into controlling the properties of encapsulated packages.

Table 3.1 Material Property and Processes vs. Encapsulation Requirement

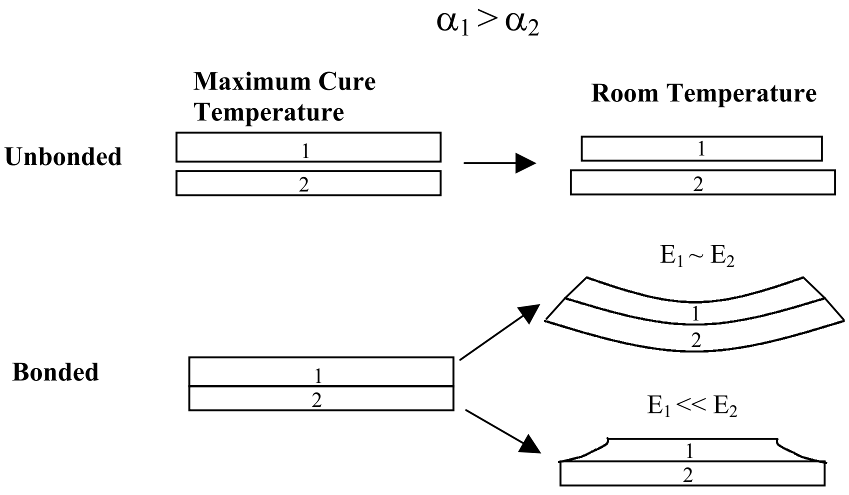
Encapsulation Requirement	Controlling Factors (Properties and Processes)	Comments
Minimize Mechanical and Thermo-Mechanical Stress	Coefficient of thermal expansion (CTE), shrinkage, glass transition temperature (Tg), modulus	Stress on the device may affect electrical and/or mechanical properties (e.g. piezoresistance, die bow, resonant frequency, etc.). Cure time and temperature have a significant affect on stress and Tg.
Optimize Electrical Performance	Dielectric constant, dielectric strength, ionic purity	A high dielectric constant is important for high-density applications, to prevent parasitic capacitances.
Process Results and Repeatability	Method of application, shelf life, pot life, moisture absorption, viscosity, wet ability, homogeneity, thixotropy	Changes in the material properties will affect processing.
Reliability	CTE, modulus, shrinkage, moisture absorption, chemical resistance, adhesion to surfaces	Among other properties these significantly affect reliability.

3.1 Mechanical and Thermomechanical Stress

The encapsulant material must not exert high stress on the device. Stress leads to warpage, which may be detrimental to the active components on MEMS devices. The dependability of the device relies heavily on characterizing and accounting for possible modes of warpage, and how that warpage affects the device [4].

For the optical switch application, warpage of the die makes it more difficult to align the mirrors with optical fibers, and alters the mirror rotation angle necessary for switching. If warpage exceeds the strength of the device passivation layer or of the die, it could crack the passivation or the device itself. Other possible affects of warpage are lifting, sweeping, or breaking of the wire bonds, and change in electrical and mechanical properties, e.g. piezoresistance and resonant frequency [25]. The choice of encapsulant material is a key decision that will significantly affect the amount of package warpage [26].

A major contributor to the overall stress in many devices is thermo-mechanical stress. Differences in the coefficient of thermal expansion (CTE) between substrate, silicon die and encapsulant are a major reason for thermally induced stress [25]. The likeliness of package warpage due to stress imposed by CTE mismatch increases dramatically with die size. Thermal mismatch causes the materials to expand at different rates when exposed to processing temperatures, inducing stress that causes the die to bend. The stress may cause delamination of the encapsulant, or as the stress exceeds the ultimate tensile strength (UTS) of the die, it will crack [27]. A low modulus of elasticity and good adhesion to the die and substrate surfaces will enhance the encapsulant's ability to dissipate stress caused by thermal mismatch and reduce the risk of delamination, respectively. The thermomechanical effects of cooling the encapsulant from its peak cure temperature are demonstrated in Figure 3.2.



α = Coeficient of thermal expansion
E = Young’s modulus

Figure 3.2 Warpage caused by cooling two bonded materials with different CTE values

Large die, such as the one in this application, are more affected by thermal mismatch than small die because of higher displacement values. This makes CTE matching between the encapsulant, MOEMS die, and packaging components particularly important. Matching the CTE will reduce thermomechanical stress induced during curing, reflow, and other thermal processes. Other sources of stress on encapsulated MEMS devices are cure shrinkage, thermal gradients and moisture ingression [28].

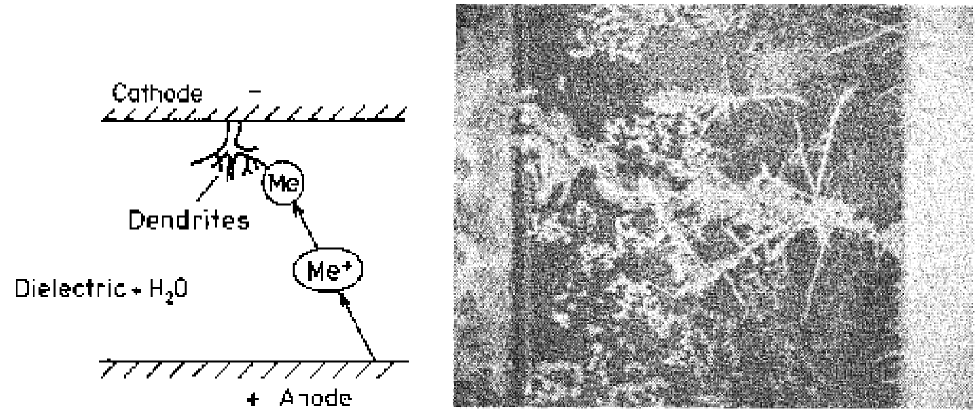
3.2 Electrical Performance

Specific electrical properties of interest are:

- Type and concentration of ionic contaminants,
- Volume resistivity, and
- Dielectric strength [29].

The significance of electrical concerns (e.g. wire sweep, noise contamination, electrical cross-talk, dendritic growth, and corrosion) increases with the density of the device's electrical contacts [11]. Fine wire pitch and high voltage bias increase the susceptibility of the wire bonds and pads to electrostatic forces and electrochemical migration.

Electrochemical migration (dendritic growth as shown in Figure 3.3) can occur under voltage bias, ionic contamination and humidity [5]. It leads to reliability failure when the tiny dendrites grow to the next line, causing a short. The short pulls current very quickly, and burns itself out. Electrochemical migration and galvanic corrosion is avoided by keeping the package free of moisture and/or ionic contaminants.



a b

Figure 3.3 Electrochemical Migration – (a) a schematic representation of the electrochemical migration processes –[30]; (b) SEM image of dendrites formed during electrochemical migration [31]

An encapsulant material should be chosen that is low in ionic content, and prevents moisture ingression. Moisture may lead to corrosion of the device, particularly if there are ionic contaminants remaining from processing or introduced by the glob top material (e.g. chlorine or bromine) [32]. Corrosion due to ionic contamination is a key reliability issue with encapsulated electronic devices [33]. Most glob top manufacturers list type and concentration of ionic contaminants (typically about 1 – 10 ppm) on the data sheets, often highlighting “low ionic content” as a key feature of their products. In addition to corrosion prevention, low ionic content helps to prevent leakage current, dendritic growth, and electrical cross talk.

The encapsulant must provide electrical insulation to the wires, pads, and leads. It is important to keep in mind that the optical switch will have a high voltage bias, ~250V. The dielectric breakdown strength of the encapsulant is very important for high voltage, high-density applications. High dielectric breakdown strength is important to prevent leakage, arcing, and cross-talk between signal lines due to dielectric breakdown [11]. A low dielectric constant would be important for high frequency devices with sensitive signal lines, however, it does not apply to the MOEMS application.

3.3 Processing Considerations

The process refers to how the encapsulant is deposited onto the device and cured. An initial set of process parameters must be defined to follow a few key objectives:

- Avoid wire damage (physical contact or wire sweep),
- Protect the device from electrostatic discharge (ESD),
- Avoid physical contact with the mirrors on the optical switch,
- Avoid contamination of the encapsulant or device,
- Ensure void free dispensing,

- Complete the dispensing within the time defined by the encapsulant’s pot life, and
- Do not exceed temperature limits of the device or package components.

After the initial set of process parameters is defined to fulfill the above objectives, the process can be optimized.

Process repeatability is a key issue, particularly in the manufacturing world. The process repeatability may be affected by the method of application, shelf life, pot life, moisture absorption, and any change in material properties of the encapsulant. Automated application methods make it much easier to apply the adhesive in a controlled and repeatable manner. Automatic dispensing equipment (see Figure 3.4) controls processing parameters such as temperature of the needle tip and substrate, dispensing pressure, height of the needle above the substrate, velocity of needle movement, position, and volume of material dispensed.

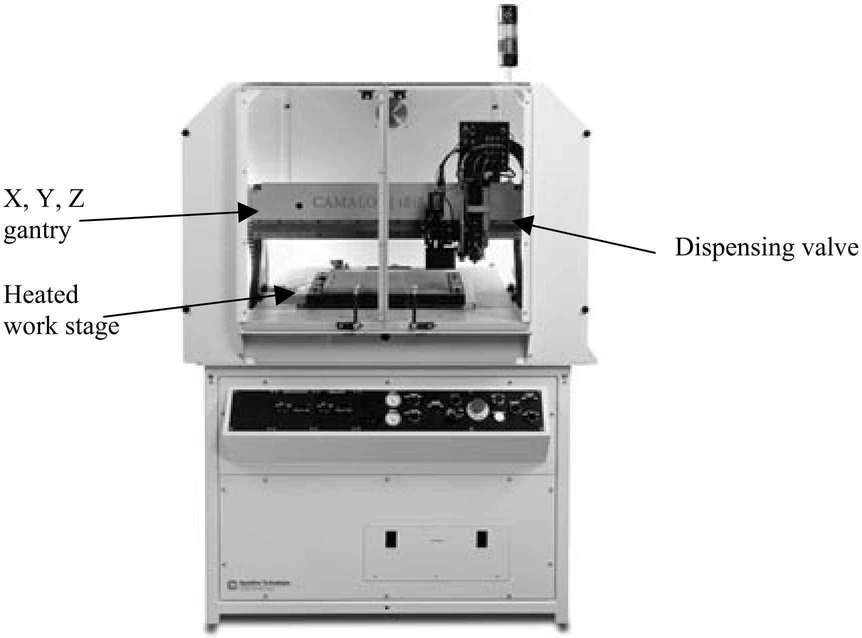


Figure 3.4 Camalot 1818™ dispensing system

Encapsulation area and thickness are of particular importance to the optical MEMS encapsulation solution. It is critical that the glob top be dispensed over the wirebonds without contacting the delicate mirror devices on the surface of the die. Material properties that will affect the area and thickness include thixotropy, wettability, and homogeneity. The amount and type of filler material will also affect the encapsulation area and thickness.

Voids in the encapsulation are an important electrical and reliability concern. Gas enclosures may develop during the mixing of adhesive components; voids may form during the cure cycle when the epoxy outgases; gas may be entrapped during dispensing, e.g. in dead corners of the device; or wetting issues may contribute to void formation. Voids are a source for moisture uptake, which may lead to a series of problems, e.g.

corrosion, delamination, electrochemical migration, or electrical cross talk [34]. A study of the causes of voids in globtop found that materials cured at higher than recommended temperatures have an increased tendency to form voids at the globtop-substrate interface [35].

Another important processing consideration is the quality of the finished, encapsulated surface. Properties and processes that affect the finished surface include viscosity, out-gassing, fillers used, method of application, and cure schedule. Surface flatness is important for components that are placed with vacuum pick-and-place equipment. It also contributes to the physical appearance of the finished part, and to the ability to mask the serial number, part number, and fiducials for automated pattern recognition systems or automated optical inspection systems.

3.4 Reliability

"Reliability is the characteristic of an object that provides a required function whenever such a function is sought. Failure to provide the function is a lack of reliability" [11]. Reliability can be estimated statistically as the probability that a component is still functioning after operating for a specific amount of time. Key encapsulant parameters affecting reliability are CTE, modulus, shrinkage, moisture absorption, chemical resistance, and adhesion to surfaces [36].

Reliability tests are used to assess packaging components/systems. The tests involve exposing the device to environmental stress according to a series of standards. Examples of reliability tests include temperature cycling, highly accelerated stress test (HAST), humidity bias life test and thermal shock (refer to Table 3.2). Test evaluations include visual inspection, electrical, and mechanical testing [37].

Table 3.2 Typical Reliability Tests Used to Assess Glob-Top Assemblies

Test	Conditions	Remarks	Purpose
Temperature Cycling (JEDEC Standard JESD22-A104-A)	-55/+125°C Transfer time < 1min. ≥ 10 min. dwell	Conditions vary per application; At least 10 cycles	To accelerate thermal stress induced failures (dry test)
Thermal Shock (MIL-STD-883E Method 1011.9 Cond. A)	0/+100°C Transfer time <10 sec ≥ 2 min. dwell	15 cycles	To accelerate thermal stress induced failures (wet test)
Highly Accelerated Stress Test (HAST) (JEDEC Standard JESD22-A110-B)	130°C/ 85% R.H./ 2.3 atm/ 96 hrs.	-5V, 0V, +5V bias	To accelerate corrosion mechanisms and failures for early identification
Steady State Temperature Humidity Bias Life Test (JEDEC Standard JESD22-A101-B)	85°C/ 85% R.H. 1000 hr.	250 hr. test intervals -5V, 0V, +5V bias	To accelerate corrosion mechanisms and failures for early identification
Resistance to Electrochemical Migration (IPC-TM-650 2.6.14.1)	Heat and humidity conditions vary 10 VDC bias 500 hr.	Conditions vary per application; Requires test specific board	To evaluate susceptibility to electrochemical migration

4. PROCESS AND MATERIAL SELECTION

There are many options to consider when choosing an encapsulant process and material to fulfill a particular packaging requirement. Processing requirements/ limitations are an integral part of the material selection process. Figure 4.1 is a flow chart, showing the critical steps involved in choosing an encapsulant, and defining the encapsulation process. The numbers in Figure 4.1 indicate the chapter and sections that will cover each step of the material selection and process optimization.

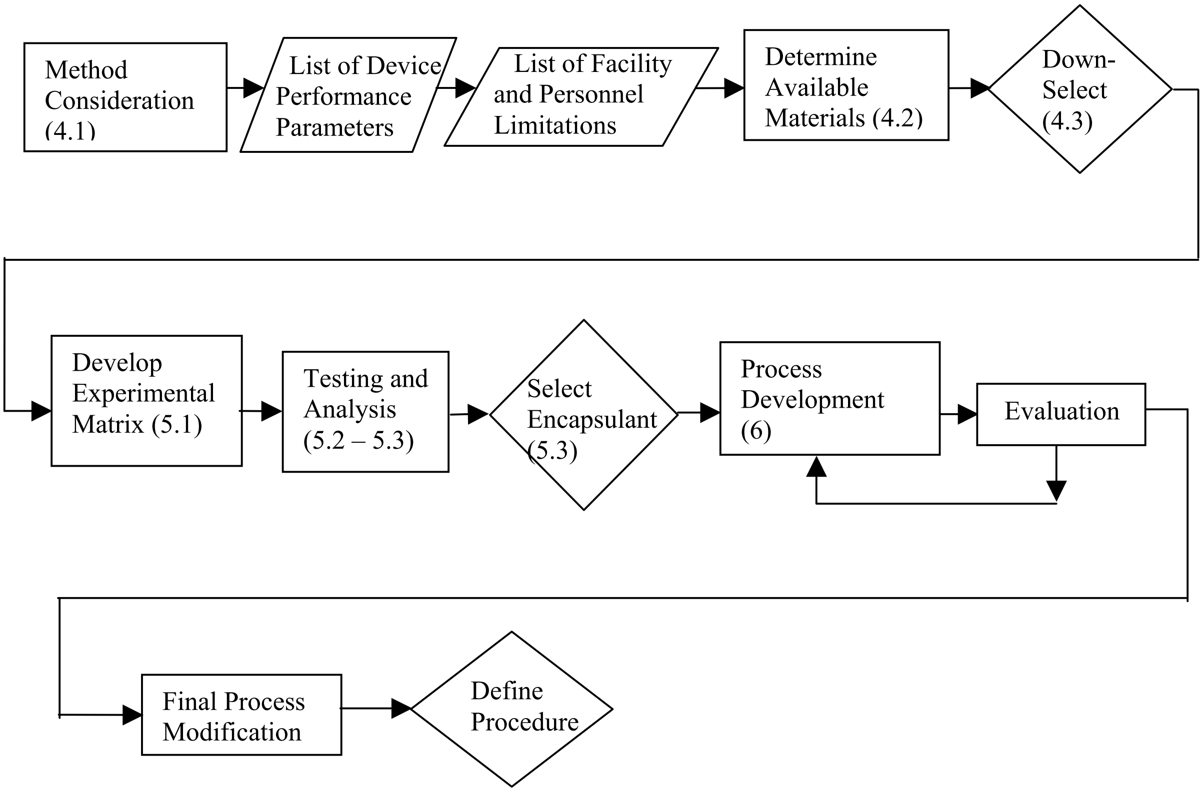


Figure 4.1 Encapsulation process flow chart showing the critical steps toward choosing an encapsulant and defining an encapsulation process.

4.1 Method Consideration

Method consideration refers to the selection of an encapsulation process that is suitable to the device. The method options will be narrowed by the device requirements, projected cost of the device, the number to be manufactured, and the facility and personnel limitations. The selection of a particular method will narrow the material options to those appropriate to the process.

There are several common encapsulation methods as defined below [12]:

Encapsulate or "glob top": Commonly used two ways: (1) the protection of an electrical or electronic device with a plastic material; and (2) the forming of a thick protective envelope (from 0.01 – 0.20 in. thick) around a device or component, applied by dipping, spreading, or dispensing.

Pot: The placing of a device or component in a container (the "pot"), usually referred to as a "can" if metal, or a "shell" if plastic. The container is then filled with the potting material. The container thus becomes the exterior wear surface of the component or device.

Cast: Same as pot except that the container is a temporary mold that is subsequently removed and is usually reused. The insulation (potting material) thus becomes the exterior wear surface of the component or device. The only difference between a cast and a pot is removal of the container.

Conformal Coat: Application of a thin coating, usually 0.010 inches or less, most often over a completed printed circuit (PC) board. Provides some environmental protection and fixturing of the components on the board. Conformal coatings are applied by spray, brush, or dip.

Mold: Placing a component or device in a metal mold, and forcing hot, molten plastic into the mold. When cured, the mold is opened and the molded component or device is ejected. The cycling times for molds are much faster than those for casts.

In order to select the appropriate encapsulation method, the device, facility, budget, and personnel requirements and limitations need to be considered. The lists in Table 4.2 show the requirements and limitations of each.

The most suitable encapsulation method for the optical MEMS based device will address the majority of the requirements and limitations listed in Table 4.1. Table 4.2 references the compatibility of each encapsulation method to the relevant requirements and limitations of the device, facility, budget and personnel.

Table 4.1 Requirements and Limitations Lists

Device Requirements and Limitations	Must have optical exposure to the environment within the wavelengths used for fiber optic based telecommunication Minimal die warpage (for optical alignment) Minimal stress (device has stress sensitive components) No contact should be made to the active area of the device Encapsulant must provide mechanical support, electrical insulation and moisture barrier to 0.00125 inch diameter aluminum wire bonds 250 VDC voltage supply 20 years of functional reliability for qualified device
Facility/ Personnel/ Budget Restrictions	Available equipment: Asymtec C-720M automatic dispenser with a pinch pump and an auger valve Manual EFD dispenser
	Budget: No specific funding has been set aside for the encapsulation solution - standard prototype level budget restraints apply
	Personnel/Safety: Minimize health and safety risk to personnel and the environment

Table 4.2 Process Requirements vs. Encapsulation Methods

	Encapsulate (“Glob Top”)	Pot	Cast	Conformal Coat	Mold
Optical Exposure	Yes, with simple modification	Yes, with modification	Yes, with modification	Yes, if masked	Very difficult to achieve
Warpage/ Bow	Material dependant	Requires excellent CTE match	Requires excellent CTE match	Minimal	Requires excellent CTE match
Minimal Stress	Yes, with attention to CTE and modulus	Requires excellent CTE match	Requires excellent CTE match	Yes	Difficult to achieve
Wire Protection	Yes	Yes	Yes	No	Yes
Compatible with Available Equipment	Yes	Requires a custom shell to allow optical exposure	Requires a custom mold to allow optical exposure	Yes – prototype only	No
Cost Expenditure	Minimal	Minimal	Minimal	Minimal (prototype) High (mass production)	High

Table 4.2 compares the process requirements with each of the encapsulation systems. The chart indicates that molding and conformal coating do not meet the basic requirements for the MOEMS application. It would be very difficult to achieve optical exposure with molding equipment. Although there are molding processes established to allow mechanical exposure for small pressure sensors [14], they do not allow optical exposure. The pressure sensor processes typically utilize a plug of silicone gel that allows the transfer of mechanical signals, but would not be optically transparent [13], [14], [15]. Conformal coating is a characteristically thin layer of material that would not offer sufficient mechanical protection to the wire bonds. In addition, molding equipment and production quality conformal coating equipment is not currently available at the IntelliSense facility. Both molding and conformal coating equipment require a high capital investment.

Potting and casting would require the design and fabrication of a custom shell or mold to allow optical exposure. The mold would need to mask off the mirror array area from the liquid, without physically contacting the delicate mirror area. Potting and casting typically encapsulate the entire device, and are more suitable to small devices that are not as susceptible to mechanical stress caused by CTE mismatch or shrinkage. Accordingly, although a potting or casting process may be possible for the MOEMS device, both would require substantial process modifications and extremely well matched thermomechanical properties.

Through the process of elimination, glob top encapsulation has been selected as the best match for the requirements and limitations of the MOEMS encapsulation process. Glob top offers the most flexible and adaptable encapsulation method to allow optical exposure and minimal stress, while protecting the delicate wire-bonds. Automatic dispensing equipment can be used to define a glob top pattern that coats the wirebonds while avoiding contact with the mirror area of the device. In addition, it is one of two methods found to be compatible with available equipment.

A typical glob top is shown in Figure 4.2a. In the standard process, glob top is dispensed over the top of the IC and wire bonds and cured to provide mechanical protection, and to maintain the integrity of the wires. The process is well known and the materials are readily available and well documented. Like many packaging technologies, the transfer of the technology from ICs to MEMS often requires alteration of the process.

For the optical MEMS based application, the glob top process will be modified to allow an optical opening for the device (see Figure 4.2b). The approach entails using a dam to prevent the flow of encapsulant onto the active surface of the MEMS device, while allowing protection of the metal areas (e.g. wires and bond pads). Potential areas of concern for the glob top process modification include: wire sweep, increased mechanical, thermal and thermomechanical stress, and process control (high precision is necessary, to avoid covering device surface).

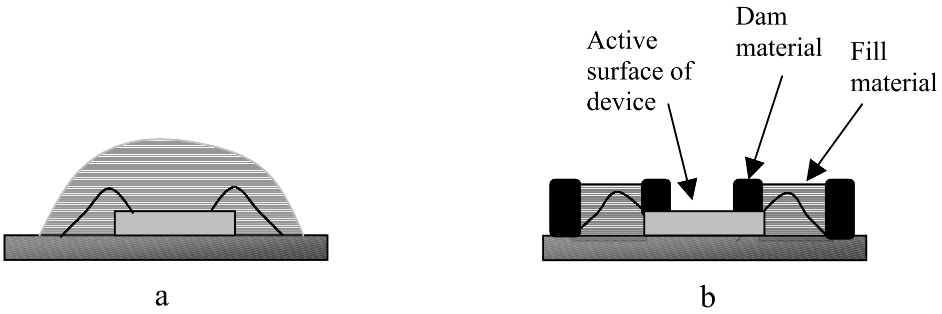


Figure 4.2 Comparison between (a) standard glob top used on ICs and (b) selective glob top encapsulation solution for MEMS device

4.2 Determine Available Materials

For the optical MEMS device, the choice of encapsulant is based upon its ability to perform required functions. The optimal encapsulant will be able to provide mechanical, electrical, thermal and chemical protection to wirebond interconnects. It must provide such protection with minimal impact on the device parameters over an extended period of time, and should be easily processed [29].

The most common encapsulant materials are epoxy-based [38]. Alternatives include silicones, polyurethanes, phenolics and polyimides, among others [10]. In order to choose an encapsulant, a literature review was performed to find the characteristic properties of glob top options. Some of the key properties of the three most common glob top materials are outlined in Table 4.3.

Table 4.3 Comparison of Encapsulant Properties*

	Epoxy	*Silicone*	*Polyurethane*
Adhesion	Excellent	Poor, often requires primer	Excellent
Mechanical protection	Excellent Hardness ~ Shore D 80	Fair Hardness ~ Shore A 47	Excellent Hardness ~ Shore D 70
Thermal stability	Good ~ 200 ^{o}C	Excellent ~ 315 ^{o}C	Poor ~ 100 ^{o}C
Ionic Contaminants	Moderate Cl- = <10 ppm Na+ = <10 ppm K+ = <10 ppm	Very Low	High
CTE[10]	Low (10 - 70 ppm/ ^{o}C)	High (150 - 1000 ppm/ ^{o}C)	High (100 – 250 ppm/ ^{o}C)
Modulus [10]	High (3 – 10 GPa)	Low (0.3 - 2 MPa)	Low – Medium (2 – 16 MPa)
Electrical properties	Moderate Resistivity~5x10^{16} ohm-cm Dielectric Strength ~ 16 KV/mm	Excellent Resistivity = 1x10^{15} ohm-cm Dielectric Strength ~ 19.5 KV/mm	Good (poor at high temp.) Resistivity ~ 4.2x10^{14} ohm-cm Dielectric Strength ~ 15.1 KV/mm
Moisture Resistance	Good - Excellent (0.0034% water absorption)	Excellent (0.1% water absorption – refer to section 4.2.2 for explanation of silicone's superior moisture resistance)	Poor (2.1% water absorption)

*Quantitative values for CTE, electrical properties, moisture resistance, and hardness taken from MatWeb.com "The online materials information resource", Copyright 1997-2001 by Automation Creations, Inc. MatWeb. The data have been taken from proprietary materials in the MatWeb database. Each property value reported is the average of appropriate MatWeb entries.

4.2.1 Epoxy

Epoxy was commercially introduced in 1947 [36]. It has a long history and has been widely used, leading to a large database of information. Epoxies have been the most common encapsulant material, and many formulations are available for glob top applications through vendors such as Epoxy Technology, Dexter-Hysol, and Emerson and Cuming [38].

Cure promoters or fillers may introduce ionic contaminants such as chloride to epoxy materials during synthesis [29], [39]. The glob top specific epoxies have been carefully formulated to contain very few ionic contaminants, have low dielectric constants and high dielectric breakdown voltages.

Epoxies have excellent wetting characteristics, low permeability to water, and adhesion to a wide variety of substrates under many environmental conditions [11], [10]. They have high strength and are chemically resistant, providing good mechanical and chemical protection [10], [11]. Epoxies are easy to process, suitable for all thermosetting processing methods, and reproducible. They tend to have high dielectric breakdown strength and volume resistivity.

Epoxy materials have a high modulus of elasticity [10]. They are known for high stress, moisture sensitivity, and a short shelf life (can be extended if stored at low temperatures, or as two separate components) [11]. The high modulus, high strength nature of epoxies may cause warpage of the large MOEMS die. Warpage of the die will make the die more difficult to optically align, and will alter the mechanical response of the active components on the surface of the device. Epoxies tend to absorb moisture, which may lead to reliability problems such as electrochemical migration, corrosion and popcorning [40]. Electrochemical migration is a key concern for this high-density application, so ionic contamination and moisture absorption would be particularly detrimental.

4.2.2 Silicone

Silicone is a low modulus alternative to epoxies. This low stress encapsulant has excellent electrical properties, good chemical resistance, low water absorption, good ultraviolet (UV) resistance, and high thermal stability (up to 315^{o}C) [11]. The combination of high thermal stability and a low modulus makes silicone superior to epoxy in reliability tests such as thermal cycling and highly accelerated stress tests (HAST) [39].

Superior silicone bonding to hydroxyl groups blocks adsorption of moisture films and prevents conductive electrolyte paths between traces and modules [11]. This is a key feature of silicones, and explains why they have performed very well under the highly accelerated stress test (HAST) when used to protect silicon dies. The hydroxyl group bond is the source of silicone's moisture resistance. It is critical that contamination be minimized for optimal hydroxyl group adhesion.

The disadvantages of silicones are the mechanical properties (e.g. lower adhesion and strength than epoxies) and high CTE [33]. They are also less resistant to ion-contaminated water than epoxies. Processability is also a key issue for silicones - they tend to have batch-to-batch variations (not very reproducible); are very sensitive to surface cleanliness; and can be poisoned by contaminants, inhibiting the cure process.

4.2.3 Polyurethane

Polyurethane glob tops are a second alternative to epoxies, and are less commonly used for glob top applications. Like epoxies, polyurethanes require mixing a resin and a hardener. However, their mix ratios are much more critical than epoxies, significantly affecting material properties when ratios don't follow specification [41].

Polyurethanes have good mechanical properties. Adhesion in lap shear and peel strength are very strong. The hardness ranges from flexible to semi-rigid. This resiliency enables them to accommodate differences in thermal expansion between materials and to absorb mechanical shock [41]. Polyurethanes remain flexible at low temperatures, however their physical and electrical properties are impaired at higher temperatures [12]. Use of polyurethane should generally be limited to the -50 to 100° C range [10]. Within the appropriate temperature range, polyurethanes have good electrical properties such as low dielectric constant and dissipation factor and high dielectric strength and insulation resistance [12].

One major difference between polyurethanes and silicones or epoxies is their moisture sensitivity of the resin [9]. The urethane reacts preferentially with water, causing reduced reactivity toward the curing agent, and sometime frothing (due to the evaluation of CO_2) [12], [41]. Other disadvantages of polyurethane include toxicity of the hardener component, ionic contaminants, short pot life, and high CTE [12], [10], [41].

4.2.4 Filler Materials

Filler materials are often used to complement the properties of the encapsulant itself. The choice of filler material depends on the requirements of the application. Advantages of using fillers include: increased thixotropy, increased viscosity, reduced shrinkage, improved toughness, improved abrasion resistance, reduced water absorption, increased heat-deflection temperature, increased thermal and/ or electrical conductivity, and reduced thermal expansion coefficient. Disadvantages of using fillers include increased weight, increased dielectric constant, and added abrasiveness (may damage dispensing equipment) [42]. Table 4.4 shows a comparison of some of the most common filler materials.

Table 4.4 Common Fillers and Properties [42]

Alumina	Abrasion resistance, electrical resistivity, dimensional stability, toughness, thermal conductivity
Aluminum trioxide	Flame retardation
Beryllium oxide	Thermal conductivity
Calcium silicate	Tensile and flexural strength
Copper	Electrical conductivity, thermal conductivity, tensile strength
Silica	Abrasion resistance, electrical properties, dimensional stability, thermal conductivity, moisture resistance
Silver	Electrical conductivity, thermal conductivity

For this project, a filler material will be beneficial to increase the thixotropy of the dam material. The filler will also be helpful to improve dimensional stability of the dam, for maintaining the height of the dam, and keeping the dam from flowing onto the active area of the device. Moisture resistance will also be a key property, as the high voltage needed to drive the device makes it susceptible to electrochemical migration. As can be concluded from Table 4.4, silica is the best filler candidate for the application because it meets the requirements of the MOEMS application.

4.3 Down Select

The goal of the literature review on available materials was to select several primary candidates for the MOEMS encapsulation solution. Table 4.5 shows a general comparison between the process requirements/ limitations and the available types of glob top materials.

Table 4.5 Process Requirements/Limitations vs. Glob Top Materials

	Epoxy	Silicone	Polyurethane
Minimal Warpage/ Bow		x	x
Minimal Stress		x	x
Wire Protection	x	x	
Electrical Insulation	x	x	
Moisture Barrier	x	x	
Low Ionic Content	x	x	
Temperature Stability	x	x	
Compatible with available equipment	x	x	x

Silicone and epoxy are most likely to satisfy the bulk of the process requirements. Polyurethane has a higher reliability risk, due to poor temperature stability and high ionic content.

There are many companies that supply epoxy (e.g., Emerson Cummings, Epoxy Technology, Hysol Division of Dexter Corporation, 3M Co.) and silicone (e.g., Dow Corning Corp., General Electric Co., Castall, Inc., S.W.S. Silicone Corp.) materials [12]. Most suppliers have a substantial list of available encapsulant formulations, each formulated for specific needs. The suppliers typically provide lookup tables to aid in material selection. The tables are organized into groups by key functions of the encapsulant (e.g., thermally conductive, electrically insulating, low stress). Suppliers also list material property values that aid customers in choosing their most suitable candidates within a particular group.

“Encapsulation of Electronic Devices and Components” by Edward Salmon gives an excellent summary of how to approach the selection process for encapsulant materials. The process begins with a review of the requirements and limitations of the device and facility (refer to Table 4.2). In his book, Salmon makes the point that the best material for the job may not be available or practical. The selection process is a balance between device performance, facility and personnel capabilities, supply availability, and cost.

4.3.1 Epoxy Selection

Supplier tables, supplier's applications engineers, and electronics industry literature were consulted to select epoxy encapsulant materials to be evaluated in this work. The candidates selected were chosen based upon their availability, cost and likeliness to fulfill the specifications described in Table 4.2. Epoxy selection was narrowed down to two dam and fill systems (see Table 4.6). It is important to have compatible materials for the dam and fill, so that cure cycles, CTE, and shrinkage properties are compatible, thus reducing thermally induced stress.

Table 4.6 Material Properties of Selected Epoxy Encapsulants

	CTE (ppm/°C)	Hardness (Shore D)	Ionic Content (ppm)	Volume Resistivity (ohm-cm)	Water Absorption (wt. %)
Epoxy 1 - Dam and Fill (Silica used as a filler to increase thixotropy of the dam)	40	89	N/A	5×10^{15}	0.1
Epoxy 2 - Dam	20	90	$Cl^- <10$ $Na^+ <10$ $K^+ <10$ $NH_4^+ <10$	3.3×10^{14}	≤ 0.4
Epoxy 2 - Fill	20	90	$Cl^- <10$ $Na^+ <10$ $K^+ <10$ $NH_4^+ <10$	N/A	N/A

Epoxy 1, is pertinent because it had been used to selectively encapsulate an IR micro system device (see Figure 4.3). In that system, the epoxy had been selected for superior electrical properties, including resistance to electrochemical migration [3]. Epoxy 1 is an easily accessible, general purpose, two-part epoxy, with good adhesion. It has a low viscosity, and is compatible with machine dispensing. The material's low viscosity is characteristic of a fill material. However, amorphous silica filler can be used to increase thixotropy and dimensional stability, so that it can also be used as a dam.

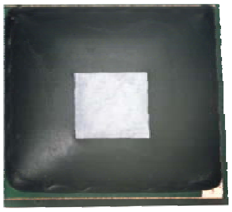


Figure 4.3 An IR micro system device that has been selectively encapsulated with Epoxy 1

Both Epoxy 2 materials were designed for use as a system, having compatible material properties. The Epoxy 2 dam and fill are single component epoxies, minimizing lot-to-lot variation and voiding caused by air introduced during the mixing process. This system features low stress (low CTE), high purity, and low ionics. The fill is intended for situations where the number and density of the wire bonds require an especially easy flowing glob top. Low stress and low ionics are key features that will minimize die warpage and electrochemical migration between the dense wires and bond pads on the device.

4.3.2 Silicone Selection

As in the epoxy selection process, supplier tables, supplier's applications engineers, and electronics industry literature were consulted to select silicone encapsulant materials to be evaluated. Again, candidates selected were chosen based upon their likeliness to fulfill the specifications described in Table 4.2, availability, and cost. Two silicone candidate systems were selected for the study. Silicones are much more compliant than epoxies, so thermal mechanical issues are less of a concern. Silicones are available individually, rather than in dam and fill systems. A comparison of their properties is shown in Table 4.7. Ionic content and water absorption values were not available for the silicones.

Table 4.7 Material Properties of Selected Silicone Encapsulants

	CTE ($ppm/^o C$)	Hardness (Shore A)	Volume Resistivity (ohm-cm)
Silicone 1- Dam (1-part)	N/A	39	7.7×10^{14}
Silicone 1- Fill (2-part)	300	45	1.0×10^{14}
Silicone 2 – Dam and Fill (2-part)	200	75	$> 10^{14}$

Silicone 1 dam is a readily available, one-component, non-slumping silicone material formulated for use with corrosion-sensitive electrical equipment. It is a general-purpose sealant and adhesive, easily dispensed with automatic equipment. It has the consistency of a paste, which renders useful as a dam material.

Silicone 1 dam reacts with moisture in the air to cure. As described in Section 4.2.2, the key to silicone’s moisture resistance is the bonding of hydroxyl groups that block adsorption of moisture films, preventing conductive electrolyte paths between traces and modules [11]. Device cleanliness is more critical for silicone encapsulants than the absorption of water. Contaminants may block the hydroxyl group bond between the silicone and surface of the device, metallization, and wirebonds.

The Silicone 1 fill data sheet claims that it has excellent adhesion. Unlike most silicone encapsulants that are available, it requires no primer. It has long shelf and pot lives (24 months and > 3 days, respectively), and a low viscosity (1500 cP), making it useful for the high wire density of the MOEMS application.

Silicone 2 has very low shrinkage (0.002 cm/cm), is non-corrosive, and claims high reliability of its encapsulated assemblies. However, the material requires a primer for adhesion. The primer adds an additional step in the encapsulation process, which would decrease the ease/ speed of manufacturability. Accordingly, it was not pursued further.

5. QUALIFICATION AND RELIABILITY TESTING

Considerations for qualification of a material include cost, availability of materials, reproducibility of the process, and reliability of the finished product [7]. The goal of qualification testing is to identify the capability of the encapsulants to function according to the requirements of the device [9]. Qualification tests include accelerated tests to indicate the reliability of different materials. Figure 5.1 is a flow chart, showing the steps involved in qualifying an encapsulant material for the MOEMS application.

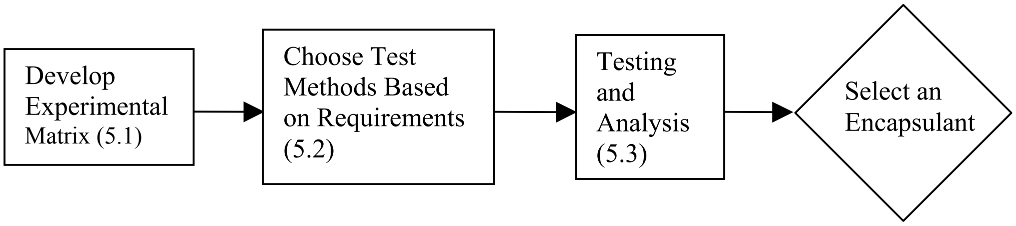


Figure 5.1 Process flow for qualifying and selecting an encapsulant material

5.1 Develop Experimental Matrix

The objective of this study's experimental matrix, is to select a set of experiments that will aid in the down-selection of a material for MOEMS development. This study does not address testing extensively to qualify the materials at a manufacturing level. In selecting a material, data is taken from many sources, such as test data from material suppliers, qualification data for similar products, and accelerated test data from subassemblies and materials [12]. [9] summarizes a plastic encapsulation qualification process that will cost-effectively assure that the item will meet requirements:

> "The qualification process includes the following steps:

> - Determine the aim of the specific qualification process in terms of required nominal reliability.
> - Determine the environmental and operational stresses at the upper and lower design limits. Typical qualification stresses include time and special dependent electrostatic discharge, current, and voltage.
> - Identify the likely failure mechanisms and modes (during manufacture, system assembly, transportation, storage, and service), and determine the relevant acceleration models and factors.
> - Conduct tests and collect the necessary failure data to assess reliability and durability of the product. Typically this involves accelerated testing. A sample size is chosen to achieve the qualification goals; complete electrical measurements may be required before and after each qualification test to uncover any failures.
> - Interpret data, and report results and conclusions with feedback for continuous improvement."

According to the qualification process plan outlined in [9], there are a few specific questions that will help direct the qualification process to a suitable set of tests and acceleration models. Table 5.1 answers the first three bullets in the qualification process guideline, setting the stage to determine the most relevant set of tests. For more detailed specifications and requirements, please refer to Chapters 2 and 3.

Table 5.1 Planning Qualification of MOEMS Encapsulant Material

	Electrical	Mechanical/ Thermomechanical	Processing
Goal of qualification process (nominal reliability)	- Minimize electrochemical migration - Volume resistivity $\geq 1 \times 10^{14}$ ohm-cm - Dielectric breakdown strength $\geq$ 300 V/mil	- Minimize warpage and stress	- Encapsulant needs to be kept away from mirror area - Fill material has to infiltrate the dense wirebonds without wire sweep or breakage
Environmental and operational stress	- 250 V operating bias - Humidity - Ionic contaminants	- Operating temperature range of -40^{o}C – 85^{o} C for telecommunication devices [9] - Handling and exposures during the assembly process and test	- Viscosity and flow pressure of uncured fill material - Cure temperature
Likely failure mechanisms and modes	- Electrochemical migration and/or corrosion (voltage bias, ionic contaminants and humidity) - Dielectric breakdown	- Warpage or cracking of MOEMS due to thermomechanical stress or shrinkage - Impact due to mis-handling	- Wire sweep/ breakage (accidental contact with dispensing needle; fluid pressure) - Material spreading onto optical surface of MEMS - Voids in dam or fill

The data in Table 5.1 provides the information necessary for choosing appropriate qualification tests. Specific material properties, such as volume resistivity and dielectric breakdown strength are typically available from the manufacturer. The qualification tests have to provide information on whether the encapsulant materials are able to withstand 250V operating bias, temperature fluctuations within the range of -40^{o}C to 85^{o}C, and humidity fluctuations. Testing will also address concerns such as warpage, adhesion, moisture ingression, and voiding. Table 5.2 is a test matrix showing relevant tests and qualification information attainable from each test.

Table 5.2 Qualification Tests vs. MOEMS Encapsulant Requirement

	Summary of Test	Warpage	Tolerance of 250 V	Resistance to Electro-Chemical Migration	Voids/ Cracks	Reliability
Optical inspection	Microscope or SEM				x	
Acoustic Microscopy for Non-hermetic Encapsulated Electronic Components (IPC/JEDEC J-STD-035)	Acoustic Microscopy				x	
Interferometer measurements	Use interferometry to measure surface profile	x				
Resistance to Electrochemical Migration (IPC-TM-650 2.6.14)	Voltage bias (10V) under heat and humidity		x indication	x		x
Steady State Temperature Humidity Bias Life Test (JEDEC JESD22-A-101-B)	85^o C, 85% RH, 5V bias, 1000 hour		x indication			x
Highly Accelerated Temperature and Humidity Stress Test (JEDEC JESD22-A110-B)	130^o C, 85% RH, 2.3 atm, 96 hours with or without DC bias – results simulate 85/85 test above		x indication			x
Dielectric Breakdown Strength	Increasing voltage until arc over occurs		x			
Temperature cycling (JEDEC JESD22-A104-A Cond. A)	-40 – 125 ^{o}C, 10 min. dwell, 10+ cycles in air					x
Thermal shock (MIL-STD-883E Method 1011.9 Cond. A)	0 – 100 ^{o}C, 2 min. dwell, 15 cycles in water					x

5.2 Test Selection

Chapter 3 detailed the specific requirements of the encapsulant materials. The primary concern is that the encapsulant provides more protection than harm to the device. The adhesive materials are bound to induce some degree of stress (primarily thermo-mechanical stress), introduce ionic contaminants, and absorb moisture. The key lies in finding a material and process that balances the specifications of the device with cost, facility, and time limitations. [12]

5.2.1 Experimental Plan

Table 5.2 compares device requirements to standard tests of the packaging industry. The table indicates which tests can be used to screen for each of the device requirements. Tests were selected to demonstrate the compatibility of encapsulation materials with critical device specifications (i.e. minimal warpage, resistance to electrochemical migration, and thermomechanical reliability).

Optical inspection was performed before and after each encapsulation process, to look for cracks on the device, contamination in the mirror area of the device, and voids in the encapsulant. Acoustic microscopy was not used at this time, due to cost and equipment availability constraints.

Warpage measurements were made using a Zygo interferometer, capable of profiling the die surface with better than 5 μm accuracy. Measurements taken on bare die were compared to measurements taken after the dam and fill materials were applied and cured. The extent of die bow was compared between the three material systems.

Table 5.2 indicates three tests that may be used to evaluate voltage tolerance and overall reliability. Electrochemical Migration Resistance Test (ECMT) was selected over the Steady State Temperature Humidity Bias Life Test and the Highly Accelerated Temperature and Humidity Stress Test. ECMT is the only test that specifically evaluates resistance to electrochemical migration. Electrochemical migration resistance is a critical requirement for an encapsulant used to protect the lead system of the optical switch device. The high voltage and narrow line spacing of the device make it particularly susceptible to dendritic growth, and subsequent shorting between signal lines. ECMT was performed based upon IPC-TM-650 2.6.14 Rev. C, but adjusted to account for the high voltage application (refer to section 5.2.3).

Both thermal cycling and thermal shock tests may be performed to evaluate reliability under thermomechanical stress. Thermal cycling is a dry test, and thermal shock requires immersion of the device into fluids. The devices are not water tight, so thermal shock testing does not make sense. Thermal cycling tests are best performed on the entire assembly to evaluate thermomechanical interactions in the system as a whole. There was a limited number of assemblies available for testing, so thermal cycling was performed only on the final down-selected material, after processing experiments.

The experimental plan is shown in Figure 5.2. The results of the warpage measurements, ECMT, and optical inspection will be used to down-select to a single encapsulation system. The selected system will be used to develop a process for encapsulating the wirebonds, and thermal cycling reliability tests will be performed on that system.

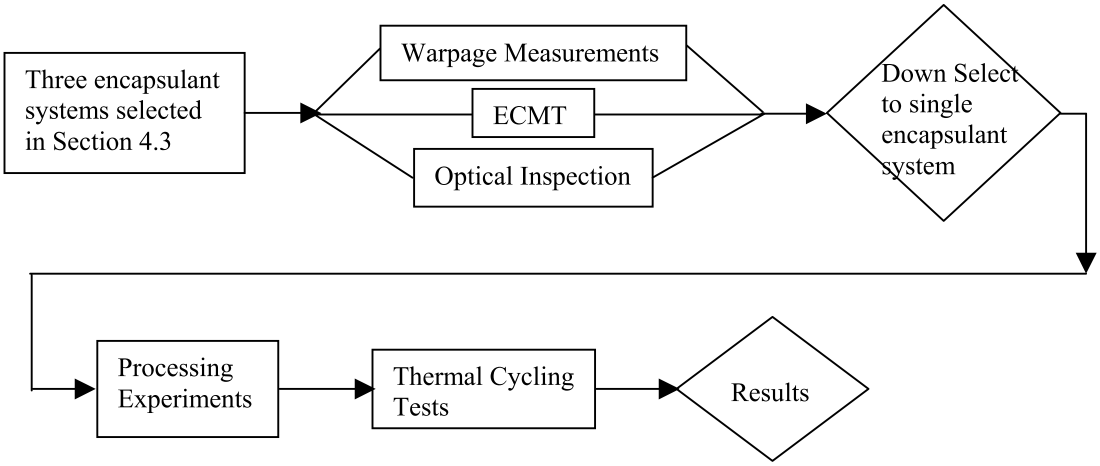


Figure 5.2 Experimental Plan

5.2.2 Surface Profiling

A primary concern for this application is warpage. The MOEMS device is a large silicon chip (up to 2.5 x 2.5 in^2). Adhesive manufacturers have developed encapsulant materials for ICs, typically smaller than 0.2 x 0.2 in^2. Larger die sizes inherently experience greater thermomechanical stress due to increased strain. This is an optical application, requiring precision alignment, so die warpage must be minimized. The large die size, and strict flatness requirement make warpage a primary concern for the MOEMS application.

Interferometry provides a precise way to measure the surface profile. A Zygo interferometer will be used to evaluate die warpage induced by the encapsulant materials. Figure 5.3 shows the equipment and a schematic of interferometry. The interferometer contains a light source and a beam splitter. The light from the source is split between an internal reference source and the device under test. After reflection, the beams recombine in the interferometer, producing light and dark fringes through the interference pattern [43]. The Zygo has better than 5 μm accuracy, allowing the measure of minute die curvature.

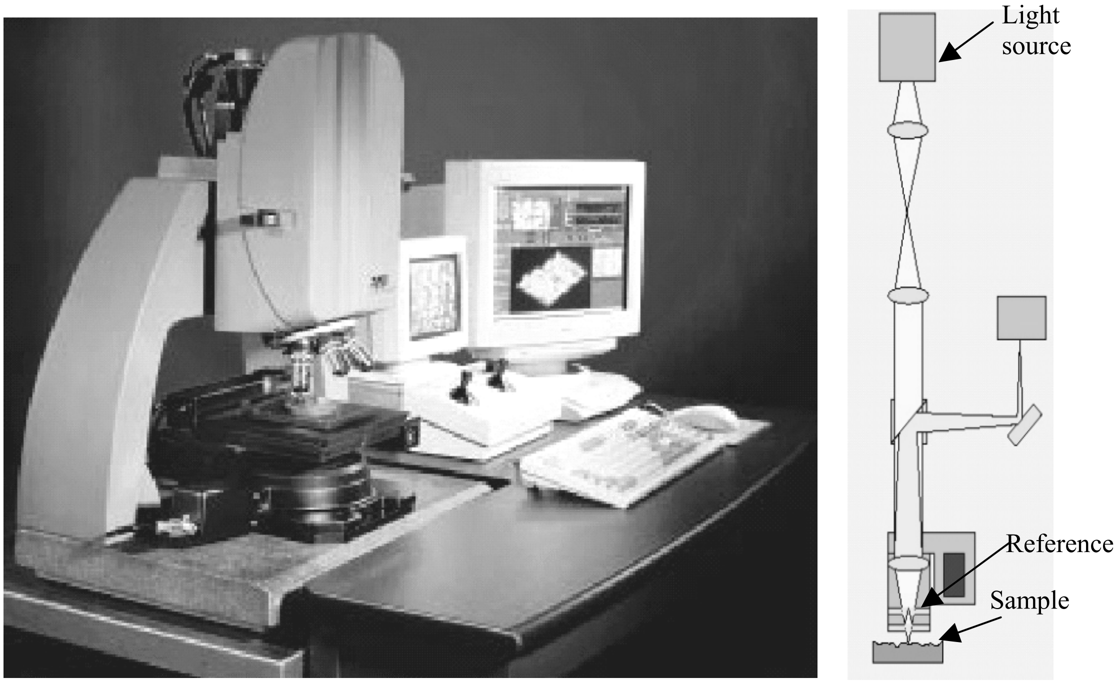


Figure 5.3 Zygo System Advanced Metrology Systems – NewView 5000™ 3D Surface Profiler [43]

5.2.3 Resistance to Electrochemical Migration

Electrochemical migration (refer to Figure 3.2) can occur under voltage bias, ionic contamination, and humidity [5]. The result of electrochemical migration between conductor lines is deposition of metal ions at the cathode metallization stripe, leading to the formation of metallic dendrites [30]. It leads to reliability failure when the tiny dendrites grow to the next line (over time), causing a short. The MOEMS device has a fine pitch (0.008 in., center-to-center), and the application has a high voltage bias (250V). A high electrical field makes this device particularly susceptible to electrochemical migration. Accordingly, a primary goal of the encapsulant material is to protect the wire bond pads from ionic contamination and humidity (i.e. from the formation of an electrolyte), thereby preventing electrochemical migration.

The resistance to electrochemical migration test (IPC-TM-650 2.6.14) exposes test samples to a voltage bias in a humid atmosphere for an extended duration of time. The test mimics a pitch between the printed circuit board's conductor lines, by holding the voltage bias between comb structures (see Figure 5.4). The test evaluation is a comparison of electrical resistance measurements before, during, and after the test duration. Failure criteria are defined as a minimum resistance value or maximum drop in resistance over the duration of the test.

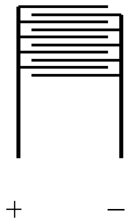


Figure 5.4 An example of a comb structure used to mimic the voltage bias across signal lines during the Resistance to Electrochemical Migration test (IPC-TM-650 2.6.14)

5.2.4 Thermal Reliability Tests

Temperature cycling and thermal shock are widely used tests to determine package reliability, especially for plastic encapsulated devices. Both tests are instrumental in determining thermal and thermo-mechanical stress related failures. Thermal reliability tests will be performed on fully packaged test devices, to most accurately model the thermomechanical behavior of the entire system. Evaluation of thermal reliability tests typically involves electrical testing and inspection for mechanical failure. Thermal shock requires that the device be fully immersed in a liquid material. As the prototype MOEMS devices used in this study will not be sealed, thermal shock testing will not be performed.

Temperature cycling (JEDEC JESD22-A104) is a dry test that consists of exposing the device to a temperature variation of a specific amplitude about a mean value. The device is held at each temperature for a set dwell time, and cycled between the two extremes. The temperature cycles expose the device to stress due to CTE mismatch; stress due to temperature gradients; and fatigue due to stress cycles. In a plastic-encapsulated microelectronic device, test results are affected by encapsulant thickness, die size, die passivation integrity, wirebond integrity, die cracks, and adhesion at the interfaces [9]. The large die size of the MOEMS device makes the device particularly susceptible to thermal reliability failure.

5.3 Testing and Results

Three dam and fill systems, selected in Chapter 4, were evaluated through die warpage and electrochemical migration tests. Key material properties for the three dam and fill systems are shown in Table 5.3. As described in Chapters 2 and 3, die warpage and electrochemical migration are the primary failure concerns of the MOEMS device. Accordingly, these two tests were the primary qualification tests. Due to the limited availability of fully packaged modules to be used as samples, process development, and thermal cycling were reserved for the best performing system. The leading material from the warpage and electrochemical migration resistance testing has been selected for process development and thermal cycling.

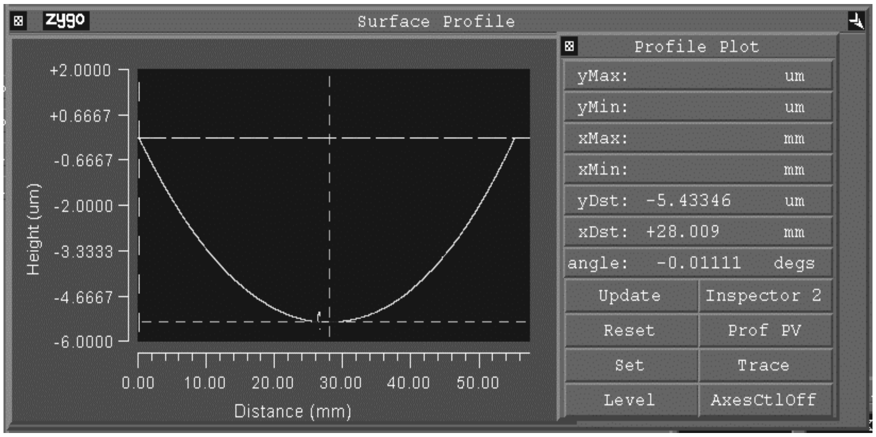
Table 5.3 Key Material Properties for Dam and Fill Systems

	Chemistry	CTE (10^{-6}/°C)	Young's Modulus (MPa)	Hardness	Cure Schedule	Viscosity (centipoise)	Dielectric Breakdown Strength (V/mil) [kV/mm]	Volume Resistivity (ohm-cm)
Dam 1	Epoxy	40	7000 - 9000	89 Shore D	1.5 hr. at 125°C	N/A	N/A	5×10^{15}
Fill 1	Epoxy	40	7000 - 9000	89 Shore D	1.5 hr. at 125°C	N/A	N/A	5×10^{15}
Dam 2	Epoxy	18	8200	94 Shore D	1 hr. at 100°C + 1 hr. at 150°C	5500 - 7500	N/A	3.2×10^{14}
Fill 2	Epoxy	20	8200	90 Shore D	1 hr. at 100°C + 1 hr. at 150°C	2500 – 4500	N/A	N/A
Dam 3	Silicone	200 - 300	3 - 5	39 Shore A	12 hr. at ambient	N/A	N/A	$7 \times 7.\ 10^{14}$
Fill 3	Silicone	300	4	45 Shore A	3 hr. at 85°C	1500	520 [20.5]	1.0×10^{14}

5.3.1 Surface Profile Test and Results

The procedure used for surface profile tests is highlighted below:

- Die were cut from Pyrex 7740 (CTE matched to silicon) to the device dimensions of 2.50 in. x 2.13 in.
- The initial die bow was measured by a Zygo interferometer. A typical Zygo profile result is shown in Figure 5.5. Bare die had concave curvatures with average peak-to-valley measurements of 6.13 +/- 3.14 µm across the die.



yMax: um
yMin: um
xMax: mm
xMin: mm
yDst: -5.43346 um
xDst: +28.009 mm
angle: -0.01111 degs

Figure 5.5 Typical Zygo interferometer surface profile results

- Dam material was deposited onto Pyrex die following the pattern shown in Figure 5.6, and cured according to the manufacturer's suggested cure schedule. The volume of each dam was kept uniform between encapsulant systems by measuring the dispense rate of the dam material in grams per second, and plugging the value into equation 5.1:

$$V = R/(\rho \cdot v) \tag{5.1}$$

Where:

V = Volume dispensed [cm^3/in]

R = Dispense rate of material for specific needle, pressure, and auger valve rotation speed [g/s]

ρ = Density of encapsulant material [$\mathrm{g/cm}^3$]

v = Velocity of dispense needle for specific needle, pressure, and auger valve rotation speed [in/s]

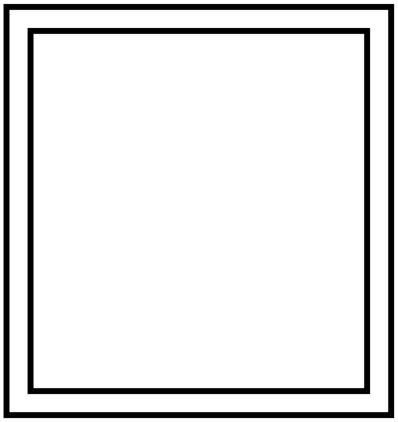


Figure 5.6 The pattern used to dispense dam material onto Pyrex die mimics the selective encapsulation pattern that will be used to protect the wirebonds on the MOEMS device.

- A Zygo interferometer was used to evaluate the change in die bow caused by the dam materials.
- Fill material was deposited onto the Pyrex die inside of the dam material as shown in Figure 5.7, and cured according to the schedule assigned by the manufacturer of the material. Equation 5.1 was used again, to keep the volume of material dispensed uniform between samples.

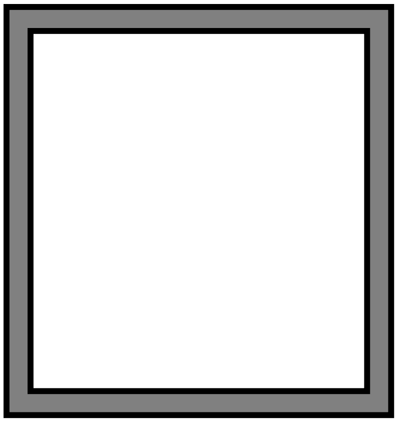


Figure 5.7 The pattern used to dispense fill material onto Pyrex die mimics the selective encapsulation pattern intended to be used to protect the wirebonds on the MOEMS device.

- A stereoscope was used for optical inspection. Post-cure inspection revealed that the epoxy dams spread out more than the silicone dam, resulting in larger contact areas the silicone system.
- A Zygo interferometer was used to measure the change in die bow caused by the fill materials.
- The encapsulant systems were compared to show which material caused the most die warpage. The graph in Figure 5.8 summarizes the results of the measurements.

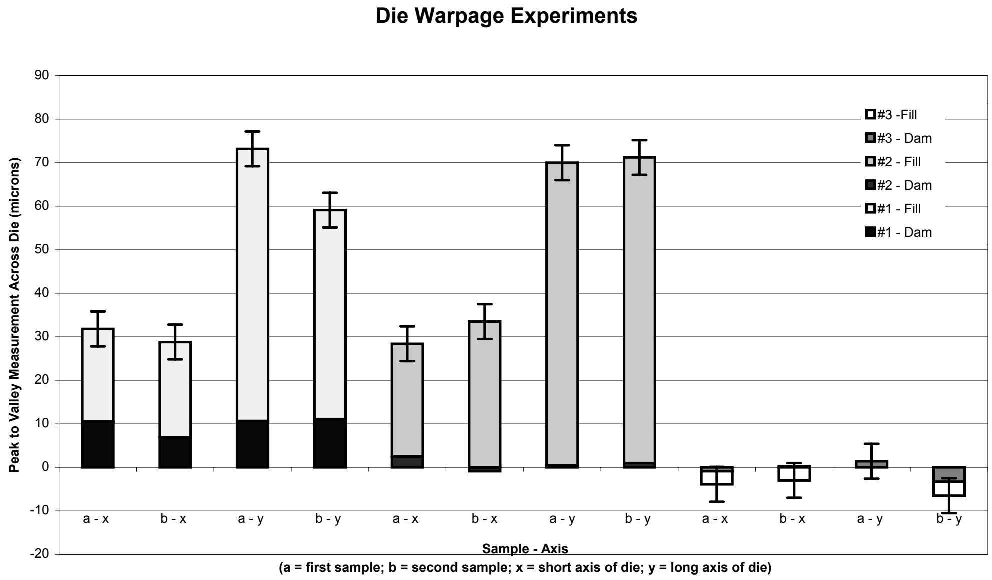


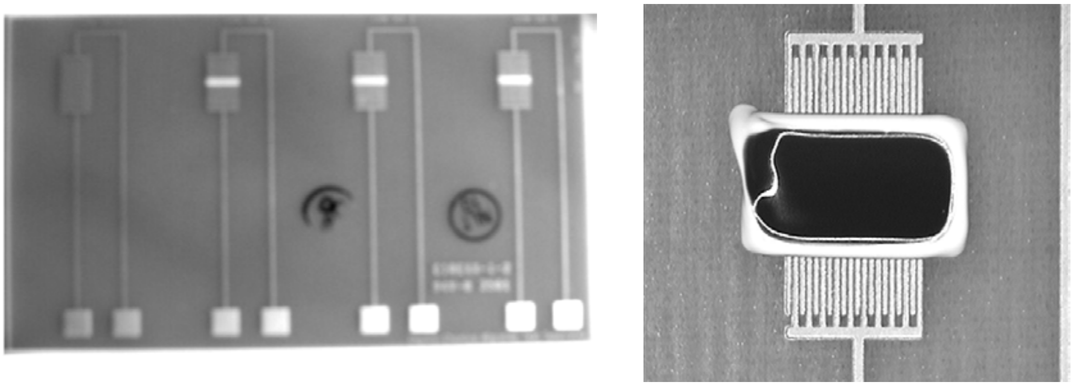
Figure 5.8 Zygo interferometer surface profile results, showing the change in die bow after encapsulant materials were cured onto Pyrex die

In Figure 5.8, a positive peak reflects a concave die bow, with the encapsulant side facing the top. The results show that System 3, having the highest CTE and lowest modulus, had the least amount of warpage. Although the same volume was used for each dam and fill system, each took a different shape. The shape was dependant upon the thixotropy and viscosity of each of the materials. The silicone dam in System 3 was the most thixotropic, yielding to a tall, narrow dam topography. The System 2 dam was the least thixotropic, and spread out, resulting in a higher contact area between the dam and glass test die.

5.3.2 Electrochemical Migration Resistance Test and Result

The procedure used to evaluate electrochemical migration resistance was based upon *IPC-TM-650 2.6.14.1 Electrochemical Migration Resistance Test.* In summary, *IPC-TM-650 2.6.14.1* specifies the use of a test board with a comb pattern of conductor lines (Figure 5.4), having line widths and spaces of 0.0125 in. [0.318 mm]. The test method specifies that the conductor lines be left as untreated, bare copper, unless another surface finish is part of the evaluation. The method gives several temperature and humidity options. Testing is performed under a 10 VDC voltage bias, after a 96-hour stabilization period of temperature and humidity exposure.

The standard procedure was adapted to better represent the electrical field of the MOEMS application. Changes made to the standard test simulated the fine pitch and high voltage of the MOEMS application. The adapted comb pattern had a series of 0.004 in. [0.102 mm] copper conductor lines and spaces. Four comb patterns were used per test coupon (see Figure 5.9a). The lines of the first comb pattern were covered with solder mask, to be used as a reference. The remaining three had openings left in the solder mask to simulate the Cu/Ni/Au wirebond pads that will be encapsulated (see Figure 5.9b). The voltage bias was increased from 10VDC to 100VDC, to simulate the high voltage used for this application. This amounts to a three-fold increase in line density and 10-fold increase in bias. The lowest temperature/humidity combination of 40^o C and 93% relative humidity was used to prolong the test long enough to have a measurable comparison between systems.



a b

Figure 5.9 (a) Electrochemical migration test coupon used to test the encapsulant systems' ability to prevent dendritic growth under a voltage bias, at elevated temperature and humidity (b) encapsulant pattern used to cover the exposed area on the ECMT coupons

The electrochemical migration testing was performed at Robisan Laboratory, Inc. They have the capability of simultaneously testing 64 comb patterns on a surface insulation resistance (SIR) meter set-up to run the test in an environmental chamber. Robisan typically uses the IPC test to evaluate solder mask materials, which provide a dielectric coating over conductor lines on printed circuit boards. IntelliSense does not currently have a SIR meter, or a chamber capable of controlling temperature and humidity. Although, it is possible to maintain a humid environment using salt solutions, they introduce ionic contaminants to the system, potentially accelerating electrochemical migration.

Figure 5.10 shows the electrochemical migration test (ECMT) sample coupons hooked up to the power source, in the test chamber. The coupons are hard-wired to the power source using PTFE-insulated solid conductor wire, as specified in the test standard. They are hanging from a rack that maintains spacing between the specimens, so that airflow is parallel to the direction of the specimens in the chamber, per *IPC-TM-650 2.6.14.1.*

Figure 5.10 Electrochemical migration resistance test set-up, showing test coupons inside of the environmental chamber, connected to a 100 VDC power supply [45]

Susan Mansilla, Technical Director of Robisan Laboratory described the typical criteria necessary for a solder mask to pass *IPC-TM-650 2.6.14.1.* Typically, the resistance measurement between conductor lines should be a minimum of $5x10^8$ ohms, with no dendritic growth between lines, or the resistance drop between 0 and 500 hr. should not exceed one decade. It is also very important that there is no delamination of the insulating material after the ECMT is complete. Figure 5.11 compares the resistance measurements taken before and after the 500-hour bias period in the environmental chamber.

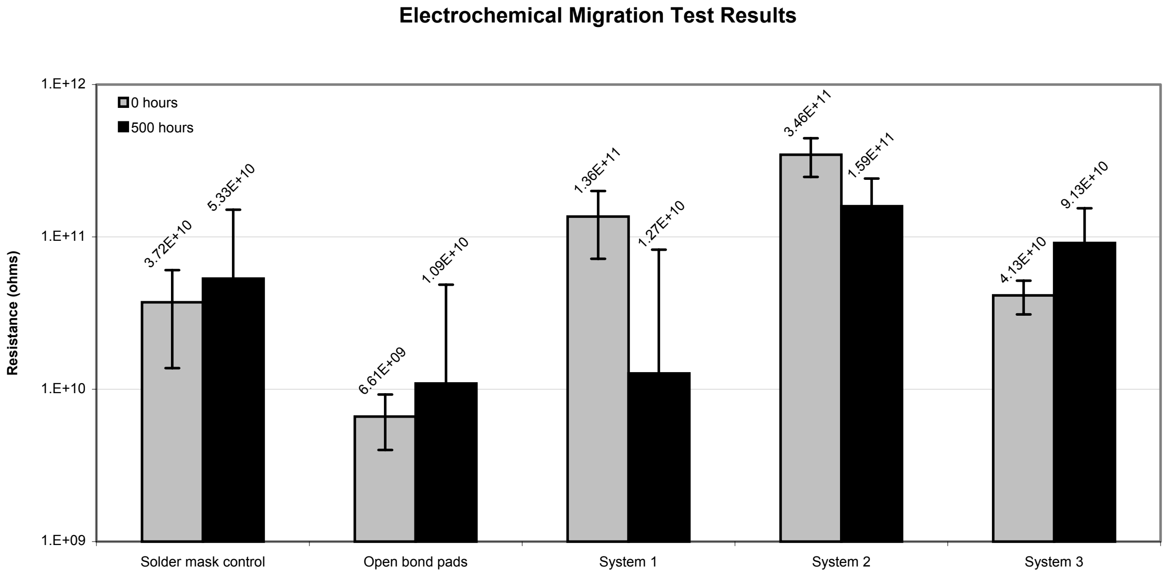


Figure 5.11 Comparison of the average insulation resistance (IR_{avg}) of samples before and after the 500-hour voltage bias/ environmental exposure

The test results reflect the change in the average resistance of 64 sets of comb structures after 500 hours of exposure to 100VDC bias, 40°C and 93% relative humidity. The resistance values for the solder mask control, open bond pads, and System 3 increased after the 500 hours of exposure. This is a common result for electrochemical migration testing, and may be an affect of having surface volatiles burn off during the environmental exposure [45]. All samples, including the open bond pads, performed well under the adapted *IPC-TM-650 2.6.14.1* test, indicating that the original printed circuit boards were clean and had very little ionic contamination. System 1 showed the worst performance, as the resistance dropped by slightly more than one decade, indicating failure.

Visual inspection after the ECMT was limited to the uncoated area outside of the encapsulation. Upon examination of the 64 line sets, two burns were found on control channels, and three areas were found with dendritic growth between lines, outside of the coated area. Figure 5.12 shows burn and dendritic growth examples. The dendritic growth (Figure 5.12a) causes electrical shorts, which burn out under the applied voltage, causing burns like the one in Figure 5.12b.

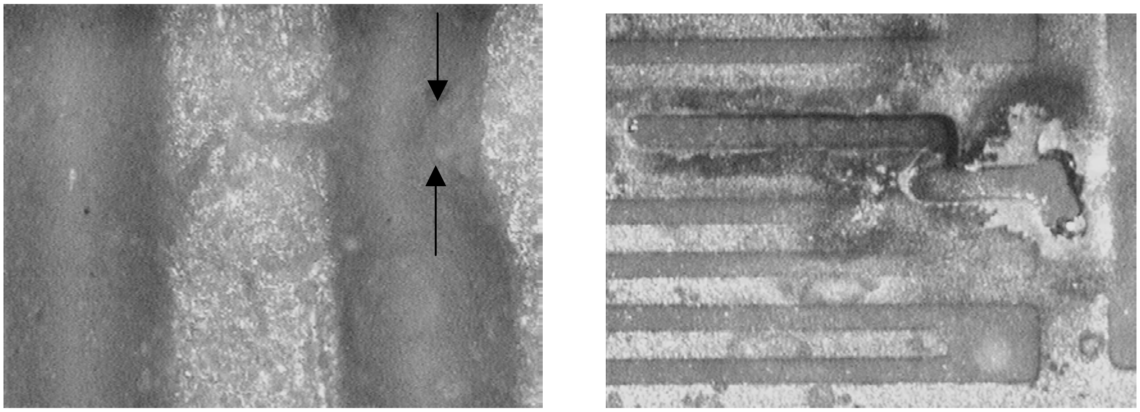


Figure 5.12 Optical examination of the 64 line sets after 500 hours exposure to 100 VDC bias, 40^{o}C and 93% relative humidity revealed a few examples of (a) dendritic growth between metallized lines and (b) burns on the control lines

5.3.3 Optical Inspection

A stereoscope was used to inspect both die warpage and electrochemical migration test samples after the encapsulant materials were cured. Optical inspection at 60X magnification revealed voids in the two-component Fill 1 and Fill 3 materials (see Figure 5.13). No voids were found in the single-component Fill 2 material. Fills 1 and 3 were hand mixed, two-component materials. The voids would most likely be avoidable through improved mixing and outgasing techniques.

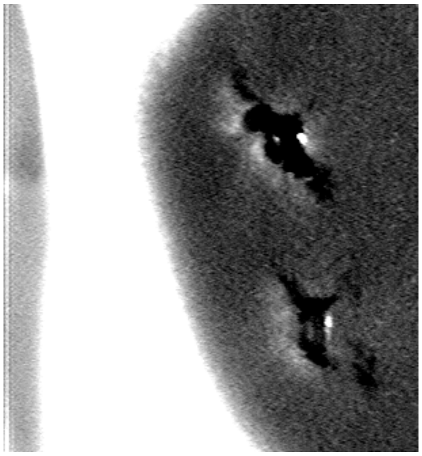


Figure 5.13 Photomicrograph of voids found in the silicone Fill 3 – may be avoidable through improved mixing and outgasing techniques

5.4 Finite Element Analysis

Finite element analysis (FEA) is a mathematic modeling technique that may be used to complement laboratory experimentation to optimize a process. FEA requires updating with laboratory results, so that the mathematical model is based on actual system behavior. FEA may be used to select materials or optimize processes. A 3-D, quarter, FEA was built to simulate the dam and fill encapsulation around the MOEMS device [44]. The assumptions included: no heat convection in the thermal symmetric boundary;

a $30^{o}C$ reference temperature; and the bottom of the substrate was fixed in the z direction. The dam and fill materials were assumed to be soft elastic (Poisson's ratio<0.5) to simplify time-dependant and temperature-dependant visco-elastic behavior. The load cycle was assumed to be stress free at the maximum cure temperature. The meshed model is shown in Figure 5.14.

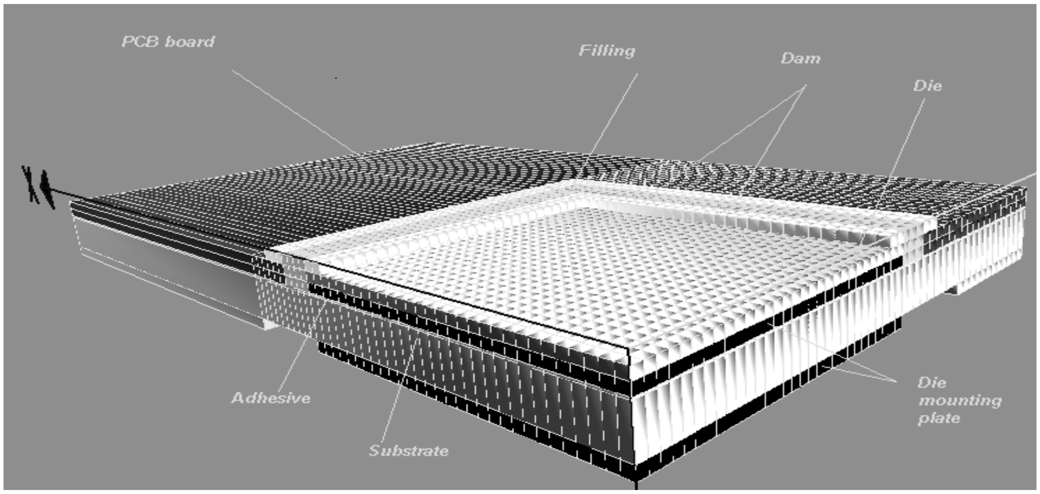


Figure 5.14 Finite element model used for analyzing the thermomechanical behavior of dam and fill materials [44]

The model showed that the dam and fill materials add stress to the assembly and cause warpage, as shown in Figure 5.15.

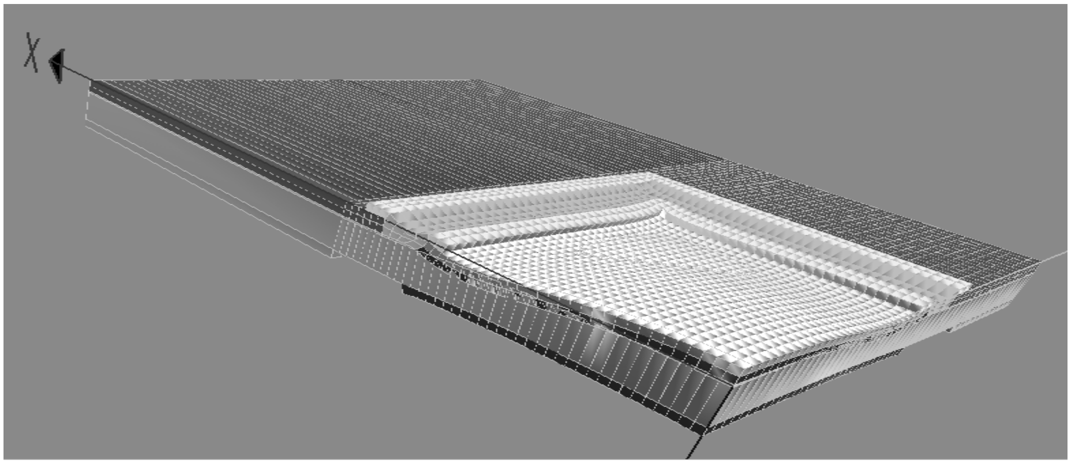


Figure 5.15 Finite element model showing magnified deformation characteristic of the MOEMS die after the dam and fill process [44]

The model was used to compare the three dam and fill systems with regard to die warpage. Dam and fill System 3 showed the least amount of die warpage. Although the warpage values differ, the trend correlates with the results of profilometry experiments discussed in section 5.3.1.

Different encapsulant geometries were input to the finite element model, to see the effect of dam and fill shape on die warpage. The study showed that shape formed by the dam and fill materials (refer to section 5.3.1) had a significant impact on the warpage. Die bow can be reduced by minimizing the surface area covered by the encapsulant. Accordingly, the more thixotropic dam materials (e.g. the silicone dam used in System 3) have a geometric advantage, because they maintain a narrow profile. In addition, the study showed that warpage could be further reduced by leaving the corners of the die, the area of highest stress, free of encapsulant material. The open cornered pattern showed a significant reduction in the finite element model's warpage. Figure 5.16 shows the results.

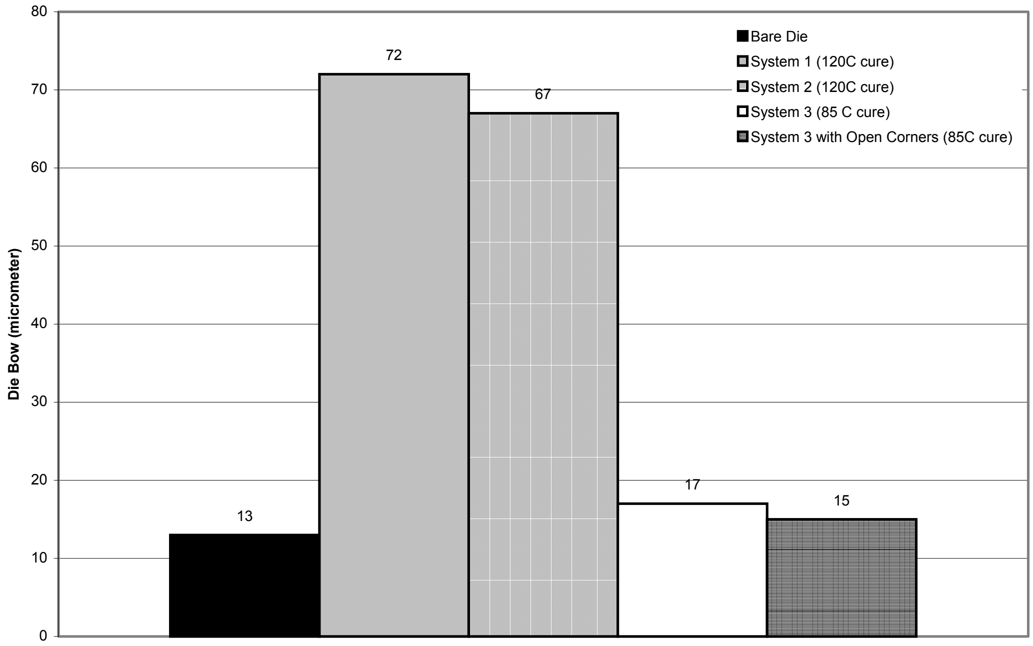


Figure 5.16 Performance Comparison Between Dam and Fill Systems [44]

5.5 Select an Encapsulant

Table 5.4 shows the matrix used to down-select an encapsulant. The table demonstrates each encapsulant system's ability to meet requirements evaluated through experimental testing. Each encapsulant system is rated with a value from 1 (poor) to 5 (excellent) for the specifications that were evaluated in testing, and the system with the highest score was selected for processing experiments and thermal cycling.

Table 5.4 Encapsulant Selection Matrix

	Minimal Warpage	Electrochemical Migration Resistance	Resistance to Voids and Cracking	Total Value
System 1 (Epoxy)	1	3	3	7
System 2 (Epoxy)	1	4	3	8
System 3 (Silicone)	5	5	4	14

All of the dam and fill encapsulation systems performed reasonably well for the electrochemical migration testing. The test results for System 1 were just below the typical criteria for *IPC-TM-650 2.6.14.1,* which is still fairly impressive when considering that the voltage bias was ten-fold higher than in the standard test. The ECMT results were favorable for dam and fill encapsulation systems 2 and 3.

The interferometry/surface profile results showed that System 3 is a considerably better candidate than either System 1 or 2. The change in surface profile after curing System 3 was an order of magnitude lower than either of the other systems, so low that it was within the 5 μm accuracy of the Zygo interferometer. Systems 1 and 2 caused significant warpage of the die after cure. These results can be attributed to three characteristics that gave System 3 a thermomechanical advantage over the other systems:

1. Low Young's modulus of elasticity (3 – 5 MPa for System 3 versus 7000 – 9000 MPa for Systems 1 and 2),
2. Low cure temperature (85^{o} C for System 3 versus 125 - 150^{o} C for Systems 1 and 2), and

3. Geometry of dam and fill after cure (high thixotropy of System 3 minimized contact area between encapsulant and die).

System 3 showed a significant superiority over the other two dam and fill systems in thermomechanical interaction with the Pyrex test die. Thermomechanical FEA results also suggested that system 3 would minimize encapsulant-induced die warpage, particularly with the open-corner pattern. Accordingly, system 3 was the only one chosen for processing experiments.

6. PROCESS DEVELOPMENT

The encapsulation process refers to how material is selectively deposited onto the device and cured. There are several key requirements that make the process a success. Referring back to Chapter 5, Table 5.1, the nominal requirements include infiltrating the dense wirebonds without wire sweep or breakage, and avoiding physical contact with the mirror area. Other important objectives are:

- Protect the device from electrostatic discharge (ESD) – High wiring density and the design of the MOEMS make the device vulnerable to ESD.
- Avoid contamination of the encapsulant or device – Particle contamination could cause mechanical and optical failure of the MOEMS. The MOEMS and encapsulation could electrically fail from ionic contamination, whereas organic or inorganic contamination could decrease the adhesion or inhibit the curing of the silicone material.
- Ensure void free dispensing – Voids entrapped in the encapsulation could cause reliability issues for the device.
- Complete the dispensing within the time defined by the encapsulant's pot life - If the pot life has been exceeded, the properties of the material start to change, impacting, e.g., the flow characteristics, curing, and adhesion of the encapsulant.

- Keep within temperature limits of the device or package components - Exceeding the temperature limits can introduce stress, degrade materials, and cause damage to the device.

6.1 Processing Experiments

An automatic dispenser was used for the processing experiments. The parameters that need to be defined for the process are e.g., geometry, valve type, needle gage, back pressure, needle speed, and height of needle. The process can also be enhanced by setting delays at the beginnings of the dispensed lines to allow the material time to flow, and sweeping back along the line to remove strings of material. Table 6.1 highlights specific actions considered in the process development to satisfy the above requirements.

Table 6.1 Solutions to Key Processing Requirements

Requirement	Action
Infiltrating the dense wirebonds without wire sweep or breakage	Avoid needle contact with the wires by choosing a small needle size and maintaining sufficient height above bond pads and distance from wires) Choose a low viscosity fill material Heat may be applied to the needle and/or chuck to lower the viscosity of some materials
Avoid physical contact with the mirror area	Avoid needle contact with mirror area Choose a thixotropic dam material Ensure that the dam prevents the fill material from entering the mirror area
Protect the device from electrostatic discharge (ESD)	Maintain a common ground between device and handler Use static dissipative laboratory supplies Ionize non-conductive materials that are in the area of the device, to avoid charge build-up
Avoid contamination of the encapsulant or device	Perform work in a cleanroom environment Keep the device covered and sealed in an ESD bag when not in use Wipe the dispenser tip clean before dispensing
Ensure void free dispensing	Be careful not to entrap air while mixing two-part adhesive systems Apply a vacuum to de-gas materials before using Purge the needle before dispensing
Complete the dispensing within the time defined by the encapsulant's pot life	Be aware of the pot life, and work within the limits (count-down clocks can be used for the timing) If the encapsulant's consistency begins to vary, replace it with fresh material
Keep within temperature limits of the device or package components	Choose appropriate materials with low cure temperatures To cure, use the lowest temperature recommended by the manufacturer

6.1.1 Defining the Selective Encapsulation Pattern

The initial set of processing experiments served to define the pattern of the selectively encapsulated area. The first experiment defined an inner dam area on the device, halfway between the wirebond pads and the edge of the mirror array (Figure 6.1a). The outer dam was just outside of the bond pads on the printed circuit board. The advantage of this arrangement was to keep the dam at a maximum distance from both the mirror array and the wire bonds, to help avoid physical contact. The dam process was successful, however, the fill material infiltrated to the mirror area along the channels for conductor lines connecting the mirrors to the wirebonds. In order to prevent the capillary forces from drawing the fill material into the mirror area, the dam was re-positioned to the wirebond trench area (Figure 6.1b). The re-positioned dam seals the channels and fills part of the trench, as shown in Figure 6.2. It has been found to cause no problems if the dam covers the stitch area of the wirebonds. However, the dam must not cover the wire loop. The dam material's thixotropy would inhibit the impregnation of the wires and cause voiding. Finally, the repositioned dam minimizes the area of MOEMS covered by the encapsulant, thus, lowering the stress introduced by the encapsulation materials.

After experimentally specifying an encapsulation area, the pattern was further refined through finite element analysis. The finite element simulation predicted a reduction in die stress by reducing the amount of material, particularly at the corners of the die (refer to Figure 5.10) [44].

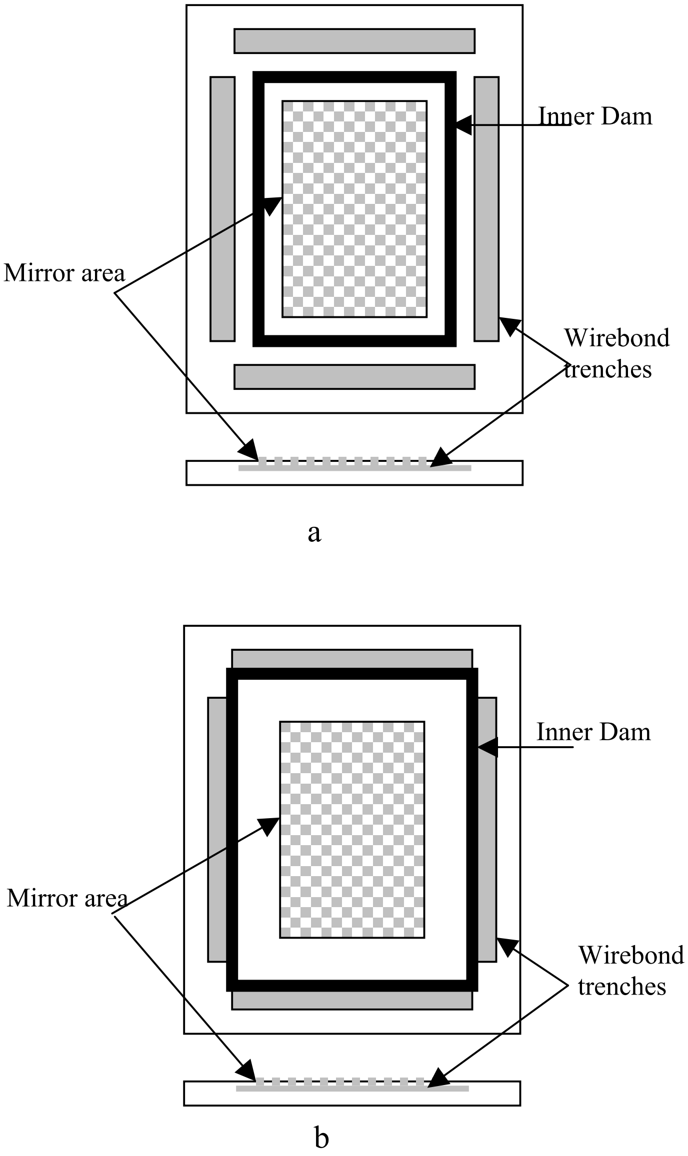


Figure 6.1 Two positions for inner dam (a) midway between wire bond trenches and mirror array does not keep fill material from entering mirror area along interconnect lines; (b) dam moved to inner edge of wire bond trenches to block fill material from conductor lines, while avoiding contact between the dispensing needle and delicate wirebonds

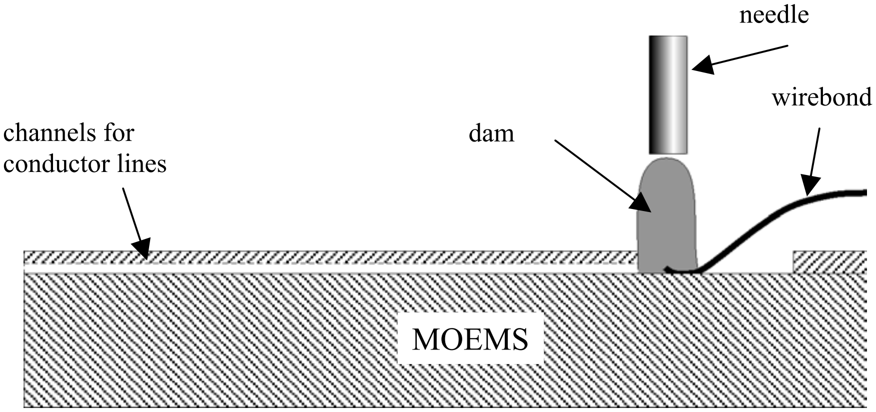


Figure 6.2: Schematic cross section of the dam position – The position was optimized to seal off the channels for the conductor lines, and prevent fill material from flowing into the mirror area.

6.1.2 Refining the Process

Selecting the pattern for the encapsulation is only the beginning of the process development. The dispenser parameters, e.g. valve type, needle gage, needle height, needle speed, have to be adjusted to accommodate the material properties and pattern shape. The height of the dam material is dependant upon the material's thixotropy, and height, gage and speed of the needle.

An auger valve was selected to dispense the thixotropic dam material. Auger valves combine back-pressure with a rotating auger to dispense the materials in a well controlled, repeatable manner. In order to avoid contact between the needle or dam material and the wires, the dam material should be deposited with the finest needle capable of dispensing the viscous material. Pneumatic valve pressure and auger speed have to be adjusted to allow the dam to flow consistently from the needle. Line width can be controlled by the needle speed and height.

A pinch pump was selected for use with the fill material. The pinch pump features a mechanical stop, which holds the dispensing tube shut until sufficient back-pressure is applied. The pinched tube is advantageous to use with low viscosity fill materials, to keep them from dripping at the needle tip. The auger valve is unnecessary for fill materials, because they do not require fine volume control.

Further refinements include adjusting the dispenser parameters to avoid, e.g., inconsistency, widened lines, and line gaps. Examples of typical processing challenges are illustrated below.

Wavy, inconsistent lines occur when the material is not flowing from the needle consistently. This effect, shown in Figure 6.3, is often seen when material flowing from the needle tip does not make immediate contact with the substrate. Possible solutions include:

- Lowering needle height to allow the material to make contact with the substrate;
- Slowing needle speed to dispense more material along the line;
- Increasing auger speed or back-pressure to dispense more material along the line.

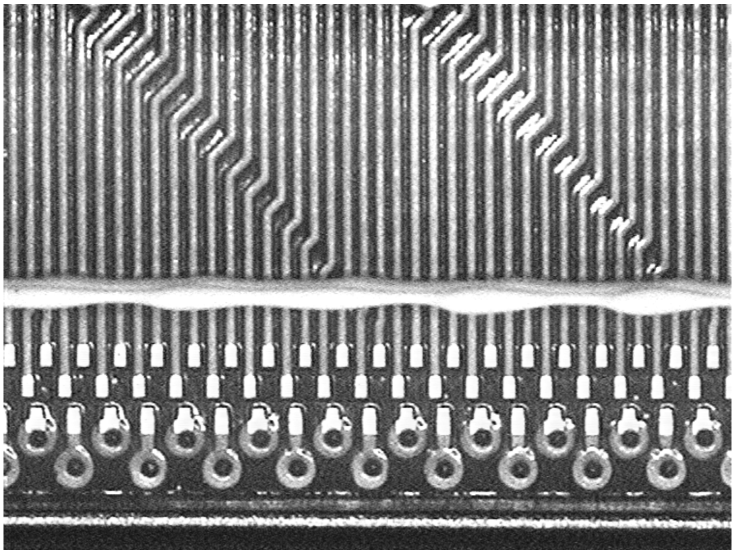


Figure 6.3 Wavy, inconsistent lines often occur when the needle is too high for the volume of material being dispensed.

Flat, widened lines are an indication that the distance between the needle and substrate is too narrow for the volume of material being dispensed. Possible solutions include:

- Increasing needle height;
- Increasing needle speed so less material is dispensed over the line;
- Decreasing auger speed or back pressure.

Strings, as shown in Figure 6.4, indicate that the material is sticking to the needle after the line has been dispensed. Possible solutions include:

- Programming the dispenser to have the needle backtrack over the lines, sweeping the material from the needle. Backtrack parameters include distance, height, and speed.
- If the backtracking does not work, the needle can be programmed to touch down onto the substrate in a non-critical spot to break-off the string.

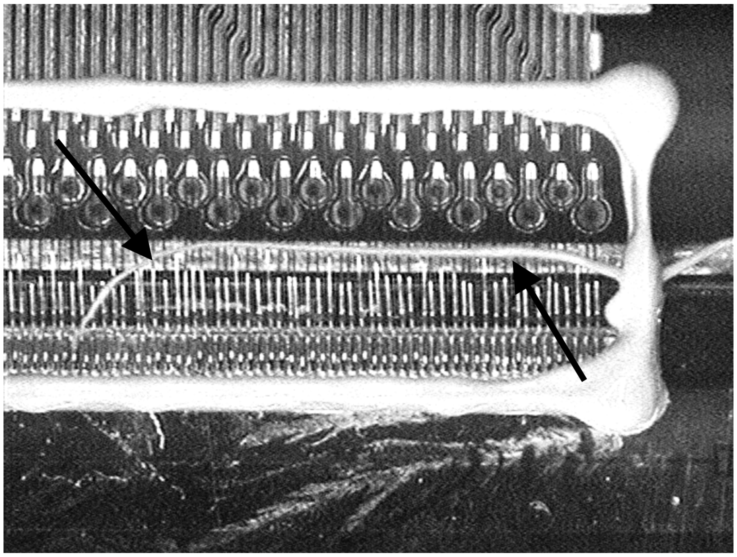


Figure 6.4 Strings occur when excess material sticks to the needle after the line has been dispensed.

Figure 6.5 shows an open line. Opens in the line indicate that the material is not flowing from the needle, or that enough material has not been dispensed to make effective contact. If they occur at the beginning of the line, it is likely that the material is still working its way down the needle. If they occur in the middle of a line, it is likely that there are voids in the syringe. Possible solutions include:

- Set the program to delay movement at the beginning of the line, to allow time for the material to exit the needle tip and contact the substrate before motion begins.
- If the opens occur in the middle of the lines, the material in the syringe may contain voids, and should be de-gassed.

- If it is apparent that the material is flowing, but not sufficiently to make effective contact, the needle speed should be slowed or the needle height should be lowered.
- Check the valve and needle tip for clogged material. The valve should be kept clean at all times. If the needle tip is clogging, switching to a conical tip or using a larger needle may suffice to avoid material back-up.

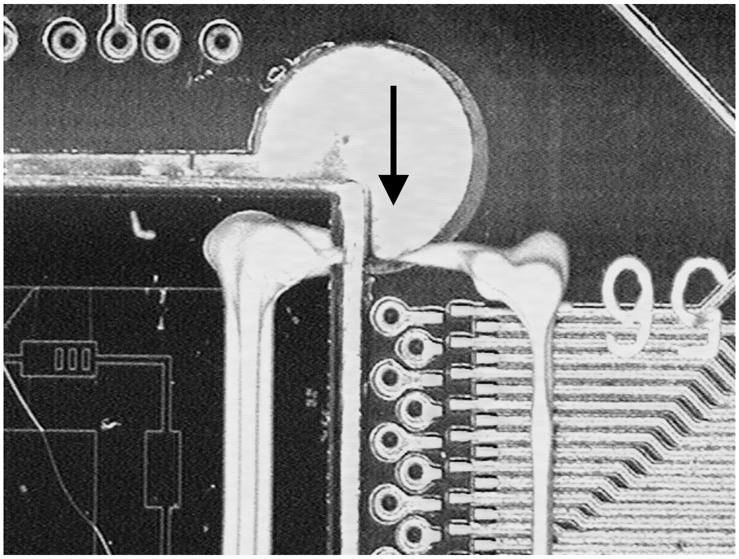


Figure 6.5 Opens in the lines often occur when the material is not flowing adequately from the needle tip.

After adjusting the process, and making the refinements described above, the dispenser is programmed to make a smooth consistent dam line, like the one shown in Figure 6.6.

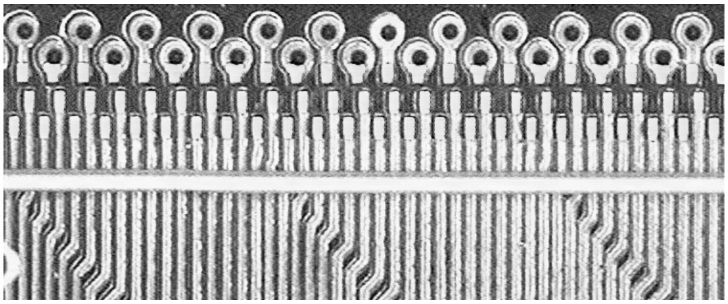


Figure 6.6 Properly dispensed dam lines feature a smooth, rounded surface, no gaps, and no strings

The fill material is not required to hold tight geometric tolerances. After meeting the electrical, mechanical, and thermo-mechanical specifications, the fill needs only to remain void free, cover the wirebonds, and infiltrate between wires and within the entire dammed space without overflowing the dam.

Upon completion of experiments to meet the specifications for both dam and fill, dispensing programs were finalized. The dam program makes three passes over the pattern. Each pass is at a consecutively higher needle position in order to match wirebond height, maintain a narrow wall within the wirebond trench, and avoid contact with the wire loops. The program parameters are shown in Table 6.2. Dispensed dam and fill were cured according to manufacturer's recommendations i.e., 24 hours at room temperature for the dam material, and 3 hours at 85°C for the fill material.

Table 6.2 Program Parameters for Selective Encapsulation Process

	Pump Type	Needle Size (gage)	Needle Height (in.)	Delay (s)	Needle Speed (in/s)	Backtrack			Valve Settings	
						Height (in.)	Speed (in/s)	Length (in.)	Pressure (psi)	Auger Speed (rpm)
Dam Layer 1	Auger	25	0.018	0.5	0.37	0.018	0.2	0.4	10	3
Dam Layer 2	Auger	25	0.023	0.5	0.40	0.023	0.2	0.4	10	3
Dam Layer 3	Auger	25	0.031	0.5	0.41	0.031	0.2	0.4	10	3
Fill	Pinch	18	0.040	0.1	0.16	0.043	2.0	0.1	16	N/A

6.2 Temperature Cycling Test

The process described in Table 6.2 was implemented for the selective encapsulation of test devices. The availability of test devices was limited by the high cost of the MOEMS devices and packaging materials. The devices available for experimentation were five rejected parts, which failed inspection due to cracks, high die curvature, electrical failure, or low device yield. Selective dam and fill encapsulation was performed according to the parameters described in Section 6.1.

Temperature cycling tests were performed on the best three out of five low yield devices. Prior to encapsulation, the devices were optically inspected for cracks. Devices 1 and 2 had no cracks, Device 3 had a small crack at one edge as shown in Figure 6.7.

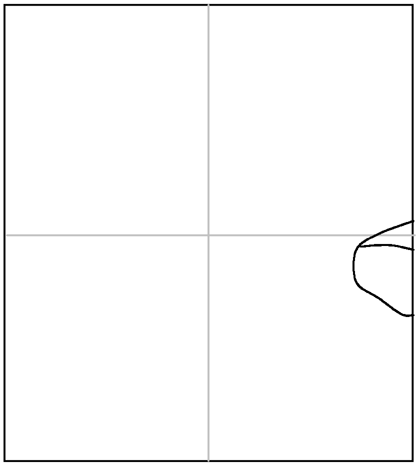


Figure 6.7 One of the three thermal cycling test devices had a small crack (as shown) prior to encapsulation.

Temperature cycling tests were performed in accordance with the JEDEC test standard JESD22-A104. The temperature was performed between two chambers held at -40^{o}C and 125^{o}C, respectively. The samples were subjected to 10 cycles with 10 minutes soak time and 1 minute transfer time between chambers.

After testing, the devices were optically inspected at 50X magnification. Electrical testing was not performed, because the devices were low yield, rejects. Device 1 had no visible cracks. Devices 2 and 3 had cracks as shown in Figure 6.8.

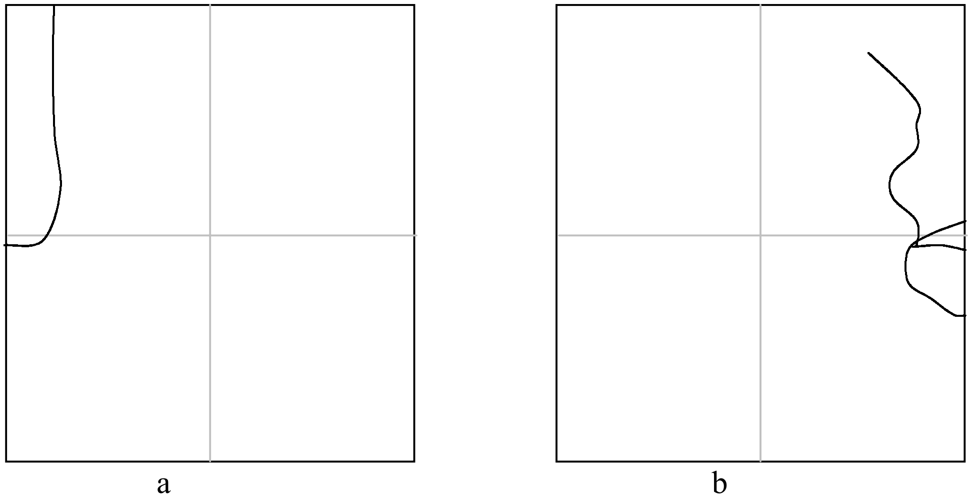


Figure 6.8 Cracks found in Devices after thermal cycling (a) Device 2 and (b) Device 3

The results of temperature cycling tests were inconclusive. Device 1 survived thermal cycling without cracking. The crack found in Device 3 grew from another crack that had been found prior to temperature cycling. This indicates that the crack was due to a stress concentration within the device, not necessarily related to the encapsulation. The crack found in Device 2 was indicative of temperature cycling failure, however, not necessarily caused by the encapsulation materials. Several packaged, non-encapsulated MOEMS prototype devices have had cracking problems. Typically, cracks occur in devices from the same lot, and are likely an indication of inferior material quality or processing parameters. The devices used in testing were, by definition, substandard.

7. CONCLUSIONS AND RECOMMENDATIONS

Although optical switches ultimately require hermetic packaging for long-term reliability, selective encapsulation offers several benefits to MOEMS applications. The non-hermetic solution offers a simplified, low-cost, quick-turn alternative, ideally suited to the research, development, and prototyping of MOEMS devices. A non-hermetic prototype package results in cost and time-savings by allowing parallel development of the MOEMS device and its final, hermetic package. In addition, selective encapsulation techniques may improve cost and manufacturability of MOEMS packaging solutions. By hermetically sealing a window directly to the active area of the device, selective encapsulation may be used to protect interconnects in the final MOEMS package.

7.1 Results and Conclusions

A literature review was performed to select candidate processes and materials for selective encapsulation. Process techniques and material properties were evaluated to compare their ability to meet the MOEMS device's primary requirements:

- Optical exposure to the mirror array of the device;
- Minimal thermomechanical, thermal, and mechanical stress on the device;
- Mechanical protection of the 0.00125 inch wirebond interconnects;
- Prevention of electrochemical migration and corrosion between wirebond pads; and
- Prevention of dielectric breakdown.

Automatic dispensing of a selective dam and fill encapsulation pattern provides a process suitable to protect MOEMS wirebonds, minimize stress, and provide optical exposure to the mirror array of the device (refer to Table 4.3 for a comparison of processes). The dam and fill process was chosen based upon literature review, device requirements, cost, and equipment availability. Three candidate sets of dam and fill, two epoxies and one silicone, were selected for analytical and experimental evaluation. Methods applied included interferometric die warpage measurements, electrochemical migration tests, and finite element analysis. Processing experiments were performed after material selection. Thermal cycling and visual inspection were used to evaluate processing results.

7.1.1 Material Selection

The literature review revealed that epoxy and silicone materials were the best candidates for the selective encapsulation process. Epoxy was selected because it is the most common glob top material, offering many formulations. Properties that made epoxy an attractive candidate include:

- Low CTE (compatible with silicon die),
- Excellent wetting and adhesion,
- Low water permeability,
- Low ionic contaminants (through specific formulations), and
- Ease of processing.

Silicone is a popular alternative to epoxy-based encapsulants, offering different properties that make it suitable to the MOEMS application, including:

- Low elastic modulus,
- High dielectric strength,
- Low ionic contaminants, and
- Low cure temperature.

Two epoxy dam and fill systems and one silicone system were selected for further evaluation, based upon device specifications, facility requirements, availability and cost.

7.1.2 Analytical and Experimental Evaluation

An experimental matrix was developed to choose relevant tests to evaluate dam and fill materials. Packaging industry standards were included in the matrix, shown in Figure 5.2. Tests were selected from the matrix based upon their ability to provide information on whether the encapsulants were able to withstand 250 V operating bias, and humidity and temperature fluctuations. Selected tests included:

1. Optical inspection to evaluate voiding;
2. Interferometer profilometry to measure warpage;
3. Resistance to electrochemical migration to evaluate reliability under a voltage bias and exposure to humidity (per a modification of IPC-TM-650-2.6.14); and
4. Temperature cycling to accelerate thermal stress induced failure after processing (per JEDEC JESD22-A104).

A finite element analysis was performed to complement the experimental work, and to aid material selection and process development.

Experimental and analytical results showed that die bow is minimized by choosing materials with low modulus of elasticity, low cure temperatures, and by optimizing the geometry of the encapsulation area. Specifically, the encapsulation area should be limited to the wirebond area, avoiding areas most susceptible to stress concentration such as the device corners. Figure 7.1 shows a schematic of the final dam and fill encapsulation pattern.

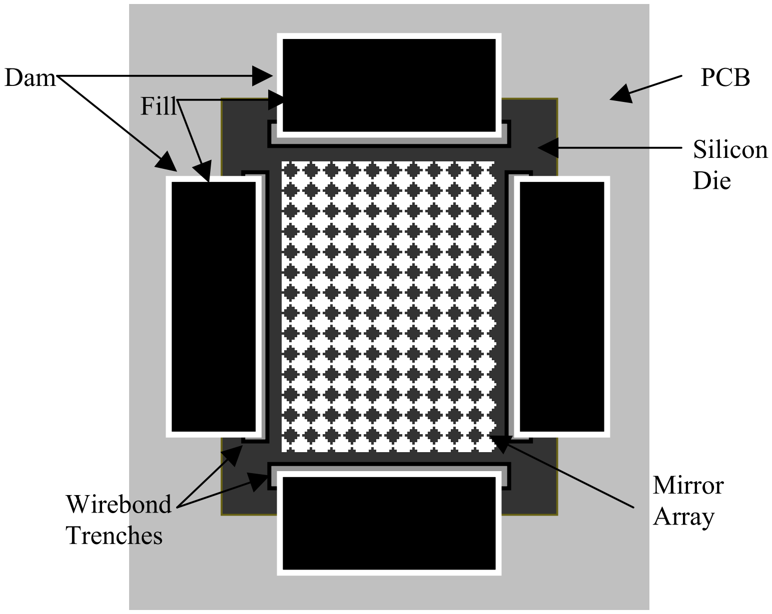


Figure 7.1 Final dam and fill encapsulation pattern

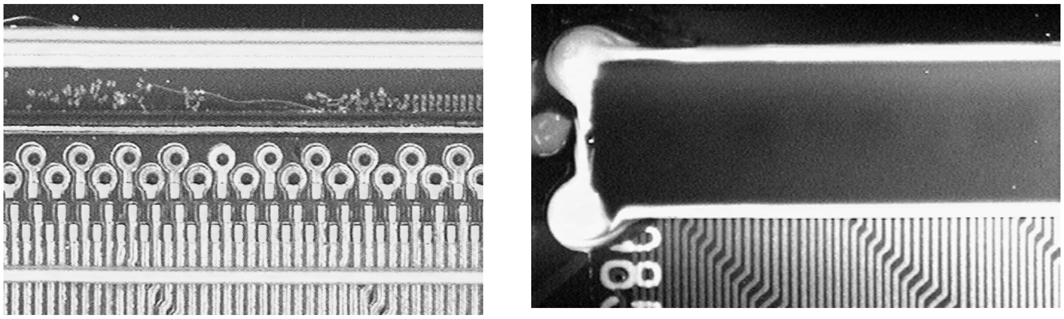
A modification of the electrochemical migration resistance standard was used to evaluate the encapsulant materials under a high electrostatic field, reflecting the operating voltage and device line spacing. Results showed that one of the two epoxy systems failed, by having a resistance drop greater than one order of magnitude.

Of the three candidate systems, the silicone was the only one to pass both warpage and electrochemical migration resistance experiments. The low modulus of elasticity and low cure temperature of the silicone system resulted in minimal die warpage, an order of magnitude lower than either epoxy system. Accordingly, it was the only encapsulant selected for processing experiments.

7.1.3 Processing Experiments and Evaluation

Protection of the mirror area of the MOEMS device can be achieved through careful positioning of the dam material. The dam material needs to be sufficiently thixotropic to hold its shape after dispensing through a fine needle. Several fine strips of dam material may be deposited on top of one another, to obtain a narrow dam with sufficient height to protect the wirebond area. The dam should be dispensed inside of the wirebond trench, because it is less susceptible to the capillary forces than the fill material. In so doing, the watery fill material is prevented from flowing along electrical lines to the mirror array.

An auger valve and fine needle combination allow accurate and repeatable dam dispensing results. The geometry of the fill material does not require as much precision control, so a pinch pump and large needle is sufficient. The fill material may be deposited in a single pass. The final dispenser program parameters are defined in Table 6.2. This recipe can be used to successfully encapsulate the lead system of the MEMS-based optical switch device. Figure 7.2 shows the results of the final process.



a b

Figure 7.2 Final Dam (a) and Fill (b) results

Optical inspection revealed several voids at the surface of the fill material, after the encapsulants were cured. This suggests that there may be more voids in the wirebond area. Optical inspection also revealed cracks in two of the three thermal cycled devices. The fact that one of the three devices survived temperature cycling without visible cracking is a positive indication for the silicone encapsulant material.

7.2 Recommendations

The post-processing voids found during optical inspection require further investigation. Acoustic microscopy (*Acoustic Microscopy for Non-Hermetic Encapsulated Electronic Components IPC/JEDEC J-STD-035*) is commonly used for packaging applications, to reveal whether there are voids under the surface of the plastic encapsulated area, and at the device/encapsulant interface. In addition, optical examination of polished cross sections may be helpful to reveal voids, but require critical analysis, as voids may be present outside of the cross-sectioned areas.

There are several options available to help prevent voids from occurring:

1. After mixing components, add steps to the de-gassing process, to include vacuum and back-pressure cycles, rather than a single vacuum step; or
2. Use pre-packaged, single component materials to avoid trapping air during the mixing process;
3. Leave room at the edges when dispensing the fill within the dam area, so that trapped air may escape; and
4. Pull vacuum on device after fill is applied, prior to cure (again, a vacuum/back-pressure cycle may enhance the removal of trapped gas).

In addition to addressing the void problem, the selective encapsulation process requires further reliability characterization. The testing performed in this work is suitable to a prototype/ development scale package. In order to qualify the encapsulant materials for inclusion to a production/ manufacturing level package, extensive tests would be required. In particular, thermal cycling and long term reliability tests need to be performed on more encapsulated devices, preferably devices that have satisfied inspection requirements and can be electrically characterized.

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