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Overcoming Some of the Challenges in 3D Micro-Assembly Techniques to Package MEMS Devices

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Abstract

This article compiles the most important packaging techniques for micro electromechanical systems (MEMS). In addition, the main electrical interconnection techniques are investigated: wire-bonding, tape automated bonding (TAB), adhesive-based bonding, and flip-chipping. For each specific technique, some examples are demonstrated which were developed or adapted in our lab. A low cost micro-dispensing technique has been developed to run precise dispensing using manual dispensers. An improvised approach of using flexible printed circuit boards (PCBs) as well as conventional solid PCBs is depicted to electrically bond MEMS prototypes and prepare for tests. This article demonstrates adapting 3D printing for packaging of overhanging MEMS structures. This packaging technique is known for its low cost and quick manufacturing capacity and it is also capable of building structures with bio-compatible materials. Additionally, a small vacuum chamber has been designed and manufactured to examine the mechanical response of MEMS devices under vacuum before fully package them. Although this paper provides a platform to deal with some of the main 3D packaging challenges, the same techniques could be expanded for numerous applications and for mass production of MEMS devices.

Keywords: Packaging; Micro-assembly; Wire-bonding; TAB; Flip-chipping; Adhesives

Introduction

The packaging is a vital bridge between semiconductors and printed circuit boards (PCBs) [1]. Packaging in general terms is categorized in various subsections such as biological micro-electromechanical systems (bio MEMS) packaging [2,3], packaging of optoelectronics [4] and radio frequency (RF) devices package [5]. However, the package must satisfy multiple functions including: protection (from the surrounding environment); connectivity (electrical, material transport, radiant energy, external force); compatibility (chip-to-package, package to PCB); routing (electrical, materials); mechanical stress control; thermal management; assembly simplification; testability; and rework ability [1]. Although the packaging, testing and calibration importance and cost (70% of the manufacturing cost [6]) are more than even fabrication, it has gained less consideration in literature. It is known that the packaging belongs to industrial and commercial fields [7]. However in this article, the focus is on low cost techniques to provide some ideas for MEMS and microelectronics researchers to consider when dealing with their packaging and testing experiences. The article starts with a brief overview of packaging possibilities. Die separation which is the first step of most packaging processes comes next. Then, three possible ways of providing electrical connections are presented followed by two other sections discussing the package for wafer level tests and package for the individual dies.

Available Packaging Techniques for MEMS1

Packaging of micro-sensors and micro-actuators is different than general microelectronic devices [7]. In the case of microelectronics, a particular package type can be used for various chips. The size and number of wire-bonds might change but the shape could be the same. However for MEMS devices, the package design crucially depends on the function of the device [7]. Therefore, the MEMS device and its package must be considered simultaneously to take into account each design's limitations for designing the other.

Individual MEMS devices must be diced and then mounted on a package and attached to a metallic, ceramic or plastic platform. A number of dicing and die-attach [8] techniques have been reported. Wiring and electrical interconnections are usually the next process in packaging. Various packaging techniques have been developed based on the specific device's requirements. Micro fluidic interconnections are needed for micro fluidic devices such as micro pumps and micro valves. Ceramic packaging, which is one of the main techniques of electrical packaging, has been extended to the MEMS packaging. Many commercial micro machined sensors use ceramic packaging. This packaging is expensive comparing to other techniques [9]. However, the high reliability, interesting material properties such as electrical insulation and hermetic sealing and easy shaping keeps ceramic packaging one of the main techniques in electronic packaging. Metal packaging, molded plastic packaging, and multichip modules are some other MEMS packaging methods [10]. Integrated MEMS devices merge microstructures and microelectronics on a single substrate to reduce overall size, electrical noise, and system power requirements. However, there are some challenges in terms of materials, process incompatibilities, and high cost [11-13]. As an alternative, hybrid packaging with separate MEMS device and electronic processes could be exploited [14].

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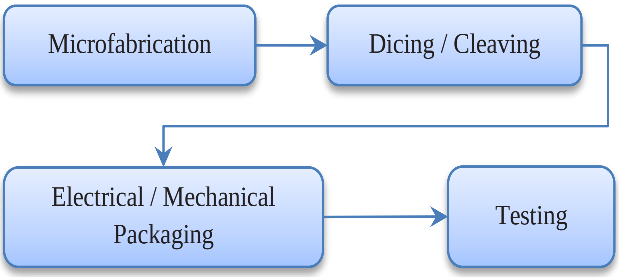

Figure 1: Manufacturing process steps for MEMS devices.

Table 1 – Available packaging techniques.

Packaging	Configuration	Method
Electrical	Cavity up (Face up)	- Wire-bonding - Die attach (TSVs)
	Cavity down (Face down)	- Wire-bonding - Flip-chipping - Die attach (Conductive Adhesives)
Mechanical	Covers & caps	- Metal packaging - Ceramic packaging
	Plastic Encapsulation	- Transfer molding - Injection molding - Reactive injection molding (RIM)

Figure 1 demonstrates the path should be taken in MEMS manufacturing. Table 1 provides a summary of the most important available packaging techniques. Most of the information in Table 1 is taken from [15]. The focus of this article is to investigate electrical interconnections used for MEMS packaging and to review various mechanical packaging techniques developed for individual MEMS devices.

Dicing & Cleaving

Other than the devices to be tested on a wafer level, in most cases the MEMS die has to be separated from the wafer right after fabrication is complete. Dicing is commonly known as a die separation technique. High technology dicing machines provide very thin cutting lines and the blade could be aligned microscopically to cut through the fabricated devices in a short time. A tape is usually used to hold all the separated dies together and prevent them from separating prematurely. Usually a layer of photo resist is spun on the main side of the wafer to protect it from scratches or potential damage due to handling issues. However, in the case of fragile or overhanging (fully released) devices, processing the wafer under dicing machines could easily damage the fabricated devices [2,16]. There has been some research done on improving the reliability of dicing, however, dicing free techniques seemed to be required [17,18]. Laser-based dicing [19] and a diamond scriber [20-22] have also been used to separate dies. In most of the dicing-free attempts, deep reactive ion etching (DRIE) process has widely been used to cleave the silicon substrate [23-29]. Figure 2 demonstrates front and back side of a silicon wafer with numbers of overhanging cantilever designs. The cleaving trenches made by deep backside silicon etching helps to keep the wafer in one piece during handling and at the same time, it provides the capability to easily separate each die from the substrate. This is done by using a modified DRIE process to make two different etch depths on the back side of the silicon wafer [30]. A scanning electron microscope (SEM) picture of two cantilevers after cleaving is shown in Figure 3.

Electrical Interconnection Techniques

Once the devices are diced or cleaved they have to be electrically connected to a printed circuit board (PCB) or other means to apply voltage to the device (in the case of actuators) or receive voltage from the device (in the case of sensors). The standard packaging technologies are: wire bonding, tape automated bonding, dispensing adhesives, flip-chip assembly, soldering, substrate technology, and housing technology [4]. Among numbers of techniques to make electrical connections between tiny MEMS devices and a PCB, in this article, three major categories are considered: wire-bonding, tape automated bonding, and flip-chipping. In addition, dispensing adhesives is also presented individually; however, it is usually coupled with flip-chip bonding. Each of these methods has various sub-groups which are briefly introduced in the following sections. The advantages and disadvantages of above techniques are presented in Table 2. Most information for this table is taken from [7,15,31-33].

Wire-bonding

Wire-bonding for MEMS is a fairly standard packaging technique. It is known as the most widely used interconnection technique to

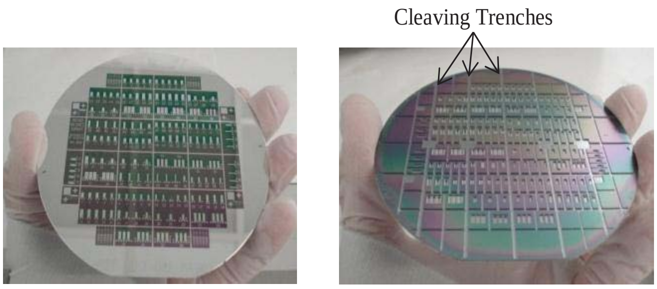

Figure 2: Front side (left) and back side (right) of the wafer with cleaving trenches between devices.

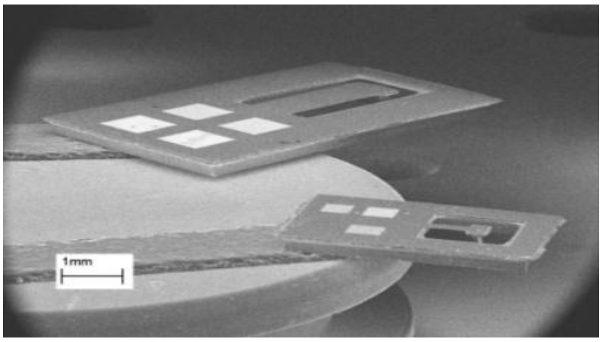

Figure 3: SEM image of individual devices after cleaving [30].

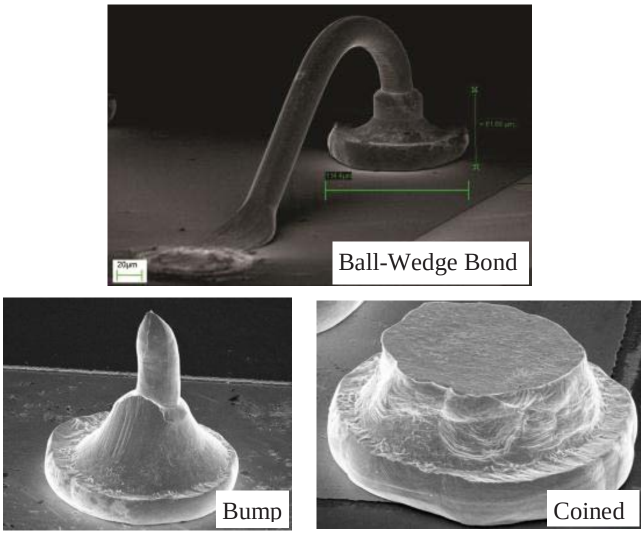

Figure 4: Three different wire-bonds [34,35].

electrically connect a MEMS die to the package. Typically, gold and aluminum wires are used in wire-bonding but silver and copper wires are also reported [15]. Bonding of gold wires seems to be easier than bonding aluminum wires. However, it is difficult to find gold wires above 50μm diameter, whereas, aluminum wires are available up to 560μm in diameter which makes them the only solution for high current applications [10]. In addition, wire-bonding seems to be problematic for RF applications. The resistance of thin wires and bonds could result in significant losses and, depending on wires' lengths, some parasitic inductance might be added to the system [33]. Soft platforms for the die are a source of challenge for wire-bonding and typically needs coupling of ultrasonic energy into the bonding region [7].

Reliable wire-bonds are essential for proper electrically functionality of the package. In operational point of view, achieving to a proper bond is challenging. Purity and contamination-free wire, optimizing capillary feed, clean operation, and optimized process parameters such as temperature, pressure, and ultrasonic energy must be considered to achieve a reliable bond [15].

In addition to creating wire connections, a wire-bonder may be used for bonding a single ball to a metal pad. Figure 4 demonstrates three different bonds made by West Bond Inc. wire-bonder. A ball-wedge bond is used to connect pads of a chip to pads on a PCB. The single ball, known as a stud bump, is created using a stud bumping tool. The stud bumping process is usually performed in combination with a secondary process, known as coining, which uses a tool with no capillary and a flat tip to compress one or several bumps down to the same height [34]. Coined bumps are used as interconnects in flip chip processes.

Tape automated bonding

One another integrated circuit die packaging is tape automated bonding (TAB). This fine-pitch packaging technique uses fine-line conductor patterns on a flexible printed circuit or on bare copper [31]. A process called Bumping is used to make raised surfaces at the die bonding region. The bump could be made on the wafer or the tape carrier [31]. TAB is highly costly and some semiconductor manufacturers refuse investing for this technology while they have access to wire-bonding or flip-chipping. However, TAB has some advantages that allow this technology grow over time (Table 2).

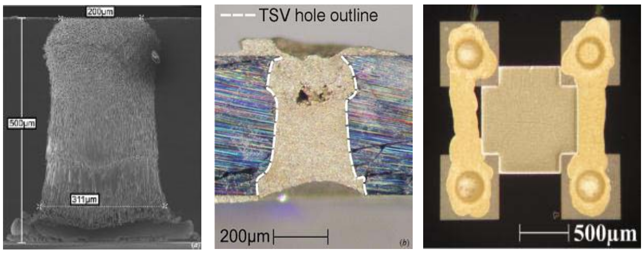

Figure 5: Dispensing technique used to fill TSVs [48,49].

Dispensing Adhesives

Adhesives could be used for various purposes such as thermal conduction, electrical conduction, reduce parasitic capacitance between traces and leads, under fill process for flip-chip, and gluing and encapsulating chip on board [32]. In this section, the focus is on dispensing electrically conductive adhesives. Through silicon via (TSV) is a vertical interconnection through the thickness of a silicon substrate enabling electrical conductivity between components on top and bottom of the substrate. A variety of TSV designs has been reported [36-40]. All designs consist of a through hole in the substrate, an insulating layer which prevents current leakage to bulk silicon, metal layers on both sides for the traces or pads, and conductive materials filled in the void. A number of materials have been investigated as conductive fillings such as electroplated copper [41], poly silicon [42,43], conductive adhesive [44,45], tungsten [46], and even wire-bonds to lower the capacitance of the coupling [47]. One another approach was presented using TSVs and flip-chip bonding to package MEMS devices [48]. In this method, conductive epoxy is dispensed into the TSV. Figure 5 demonstrates a 200μm TSV made by cryogenic DRIE in a 500μm thick silicon wafer. Also, cross

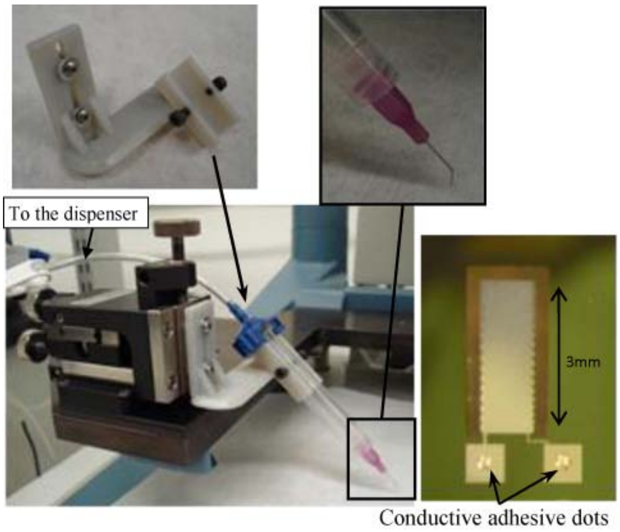

Figure 6–A precise dispensing technique developed to replace manual dispensing.

Table 2 – Advantages and disadvantages of electrical interconnection techniques.

Methods		Advantages	Disadvantages
Wire-bonding	Thermocompression ball bonding	· Omnidirectional (2nd bond can be moved in any direction from the 1st bond) · No unique fixture is needed during bonding · Easiest process to develop & control	- High working temperature - Need large bonding land and wire-bond clearance for high yield/rate production - The most sensitive process to surface contamination[1] - Challenging with soft platforms - Relatively slow bond time - Aluminum wire is not usable
	Ultrasonic wire bonding	· A room-temperature process · Least sensitive to surface contamination[1] · Workable with smaller[2] lands · Good for high current applications with Al wires	- Unidirectional - Package-wall proximity must allow bonding-tool clearance (larger overall package) - Difficult to characterize/control due to acoustical energy measurement problems
	Thermosonic wire bonding	· Moderate bonding temperature · Omnidirectional · Less sensitive to surface contamination[2]	- Need min. land size $(0.1\times0.1\text{mm}^2)$ - Need to control the acoustical energy - Require special fixture - Limitation in wire-looping
Tape Automated Bond (TAB)	Bumping (to provide a raised surface at the die-bonding sites)	· Higher[3] density (twice bigger than wire-bonding) · Less propagation delay and smaller signal loss (due to shorter lead length & lower impedance) · Better reliability (due to sealing with thin film metallization to protect from moisture & chemicals) · Higher assembly throughput (due to using mass bonding) · Automation · Lower packaging profile (≤0.08mm) · Testing & burn-in of TAB devices before existing the die for next-level assembly · Better thermal management due to use of copper TAB leads and ground planes	- Much higher investment is needed to set up TAB facility - Manufacturers are unwilling to invest - Require tight planarity to distribute bonding force evenly - Difficulties in handling blank etched TAB tape - Hard to satisfy cost-efficiency
Flip-Chipping	Under bump metallurgy (UBM) and Solder ball	· Best[4] circuit performance (due to having shortest interconnection, good for RF applications) · Highest packaging density · Better reliability (due to simple path between chip & substrate) · Efficient for hybrid packaging · Good for capped devices	- Need for highly specialized assembly process - Unable to visually inspect all assembled chips - Limited availability of specially designed I/O chips (e.g. stepped areas) - Difficult flux removal - Thermal management complications - Unable to pretest/burn in the chip prior to assembly

[1] Among all wire-bonding processes

[2] Comparing to thermocompression ball bonding

[3] All TAB properties are compared to wire-bonding properties

[4] All flip-chipping properties are compared to wire-bonding and TAB

section and top views of a fully filled TSV are shown. It is challenging to fill high aspect ratio TSVs. Therefore, epoxy is dispensed from both sides of the substrate. This process was performed using a fluid dispensing system with a syringe tip which had an internal diameter of 50µm [48].

There are a variety of automatic dispensing tools. For instance, Fine tech GmbH & Co. provides submicron die positioning and also offers dispensing of various materials such as optical, thermal, isotropic, and anisotropic conductive adhesives. They also provide rework services for preassembled dies by removing and re-dispensing solder paste. However, automatic dispensing equipment is costly and possibly not available for all researchers to use. Alternatively, manual dispensers are used. The main challenge with manual dispensers is accuracy in positioning due to shaking of the hand. In a new approach, an adapter was designed to hold a dispensing syringe and be installable on a micropositioned which is capable of positioning in three axes within one micrometer accuracy. A micropositioner from Quarter Research and Development (Model XYZ 500 TIS) and a dispensing system from Nordson EFD (Ultimo's II) were used in this case. Figure 6 demonstrates the designed adaptor and the orientation of the needle and also presents precisely placed adhesive dots in the middle of tiny pads. The tip of the syringe needs to be oriented in the same orientation as the hole to enhance the filling of a TSV. But, using a straight needle as syringe's tip blocks the microscope view. Therefore, instead of straight needles, angled ones (45^{O}) were used and the 3D printed adaptor was designed such that the syringe was oriented 45° to the surface. Consequently, the tip of the needle is perpendicular to the surface and neither syringe nor the adaptor blocks the user's view.

Flip-chip bonding

Flip-chip or direct chip attach (DCA) is a low volume, 3D vertical integration scheme that allows for direct connection between PCB and the die (top-face-down). Capped devices could easily be made by a flip-chipper. DCA provides a number of joining systems from conventional metallic solders to low-temperature conductive polymers. DCA has four subdivisions: device bumps, joining material, and under-fill [1]. There is usually a relatively small gap (50–200µm) between the die and the packaging substrate [10]. Therefore, the parasitic inductance and capacitance for each interconnection is minimized due to minimum transmission line length which makes the flip-chipping a better packaging technique than wire-bonding for RF applications [33]. In addition, unlike wire-bonding which requires bond pads away from die to prevent wires from crossing, flip-chip involves placing bond pads on top of the die resulting in a significant increase in input/output connection density [10]. Flip-chip is attractive for MEMS industry due to providing the capability of packaging a number of dies in a single package substrate with multi-level electrical traces (hybrid packaging). Wire-bonding could also be used to build a similar system, however, not only its area usage will not be as efficient, but also its reliability will be doubtful due to too many wires in the package. One of the disadvantages of flip-chipping is that it is not compatible with released microstructures. For instance, a MEMS device with a thin diaphragm could be damaged during the flip-chip process [10].

Apart from exploiting a flip-chipper to precisely place dies, it can also be used to create electrical and mechanical bonds. Compression-based, thermal-based, ultrasonic-based, or any combination of these methods could be performed to achieve a bond with conductive epoxy, non-conductive epoxy, anisotropic and isotropic films and stud/solder bumps [34]. Figure 7 demonstrates packaging resonators to PCBs with the flip-chip technique. Conductive adhesive dots are placed on the device's pads (using the technique shown in Figure 6) and then the flexible or conventional PCB's pads are flip-chipped on them. Flexible PCBs (FPCBs) are soft and could be cut by scissors. Pads and traces could be designed very close (3µm width, 5µm gap). However, the process is expensive for prototyping. In comparison although solid PCBs are much cheaper, they need a tool to be diced and do not have as high resolution as FPCBs.

If the pads on the sensing chip are too close and overflowing is unavoidable, anisotropic conductive adhesive (ACA) could be used to prevent short circuiting of one pad to the ones next to it and also allow vertical electrical connection to the PCB pad on top of it. Figure 8 shows a cross section of a packaged sensing chip on a PCB. In this case, there are many pads and they located close to one another and using ACA seemed to be unavoidable.

Figure 9.a demonstrates a top view of a membrane sensor. The design of the sensor requires the face-down packaging configuration. In this case, dispensing adhesive on the pads will overflow on the membrane and affect its performance. Therefore, tall SU-8 layers are deposited to avoid overflowing of the ACA on the membrane. The pads of both sensing chip and the PCB have gold stud bumps and ACA is dispensed on the chip pads and then flip-chipped on the PCB pads (Figure 9.b).

Packaging for Wafer-Level Tests

Wafer level packaging is usually done for devices made by surface micromachining. This packaging avoids the challenges of separating individual dies and therefore enhances the reliability and yield of the packaging/testing stage. Wafer level packaging is generally done by bonding a lid wafer to the device wafer or by making a cavity through etching a sacrificial layer. Anodic bonding, metal bonding, plasma-activated bonding, and bonding with an intermediate melting material are some of the interfacial bonding techniques used for wafer level packaging [51].

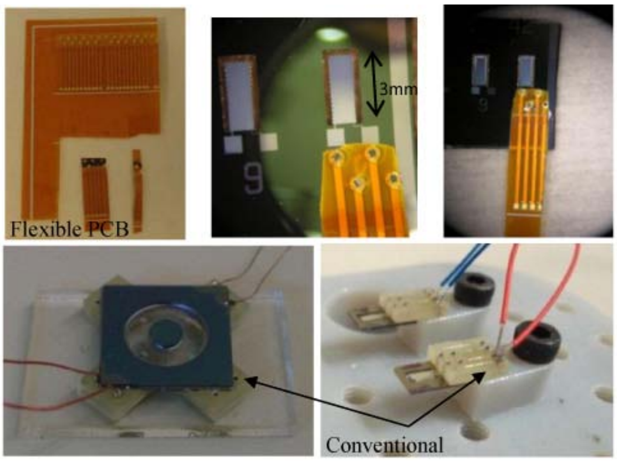

Figure 7–Flip-chipping is used to package resonators to flexible and conventional PCBs.

On the other hand, some of the MEMS devices could be tested on the wafer without separating individual dies. A probing station could be exploited to land the probes on the devices' pads. Then, electrical signals could be sent or received from those devices. For instance, in a surface acoustic wave sensor (Figure 10), the input signal is applied through a ground-signal-ground (GSG) probe to the input interdigitated transducer (IDT) and the sensor's response is received by the output IDT. Therefore, the size and location of the pads are the only considerations that need to be taken into account for the packaging during the fabrication masks design.

Package for Individual Devices

As opposed to wafer level testing, sometimes individual MEMS devices have to be separated from the substrate due to testing setup requirements. For instance, to run a bending test on a stress sensor it has to be diced and placed on a bending structure (Figure 11.a). Also, to run a vibration test on a resonator, it must be separated from the substrate and raised from the ground to provide some space for the proof mass to oscillate (Figure 11.b).

Therefore, a MEMS device could be directly mounted on a PCB and electrically connected to it using one of above techniques or a mechanical structure is required to optimally mount both device and PCB on it and then electrically connect them. Both methods are

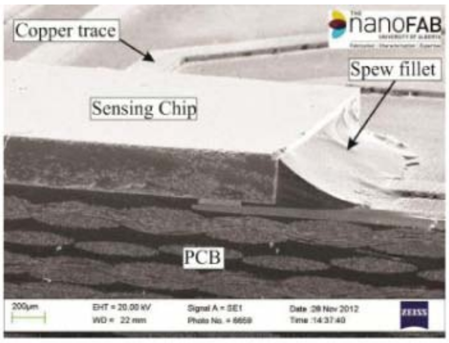

Figure 8–Anisotropic conductive adhesive is used to connect a sensing chip to a PCB [50].

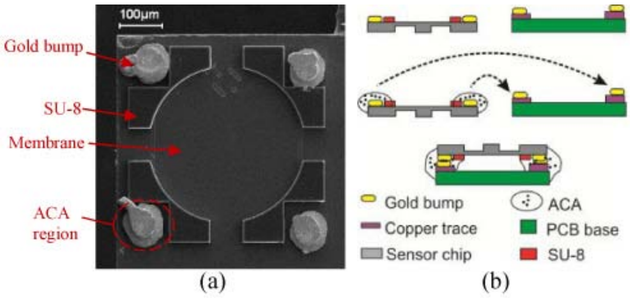

Figure 9–(a) top view of the membrane with stud bumps, (b) schematic of the dispensing and flip-chip processes.

demonstrated with examples in the following.

Packaging MEMS devices on PCB

A fabricated micro sensor could be mounted on a PCB [54-58] with various RF connectors to secure it in terms of handling and allow the possibility of using various connectors and testing equipment. Figure 12 demonstrates the same SAW sensor shown in Figure 10 but, it is mounted and wire-bonded to a PCB and using two cables connected to a network analyzer.

FPCBs have also been used for MEMS packaging [59-61]. The flexibility of flexible PCBs is beneficial in terms of reducing the size and weight of the final device because the PCB can bend or take the shape of the final structure. However, the cost of its prototyping is much higher than the conventional PCBs. Figure 13 demonstrates MEMS sensors along with electrical modules packaged on a FPCB to be mounted on a structure.

Usually bonding MEMS device on PCB is used for sensors which do not need base excitation to function. However, due to very small deflections (≤1mm) of MEMS resonators, conventional solid PCBs with ~1.5mm thickness can be used for primary testing purposes. Figure 14 demonstrates a PCB designed with a hole in the middle to provide space for the oscillation of the proof mass of an energy harvester. Wire-bonding and soldering are used to make electrical connections.

Packaging with a mechanical support

In some cases especially for resonators, the MEMS device(s) and PCBs have to be as a structure [62-66]. The structure could be as simple as Figure 15 where two polymer sheets are cut and glued such that there is enough space for the cantilever's proof mass to vibrate. However due to mass production and reliability issues, a more robust method must be chosen. In this section, 3D printing is proposed as an alternative.

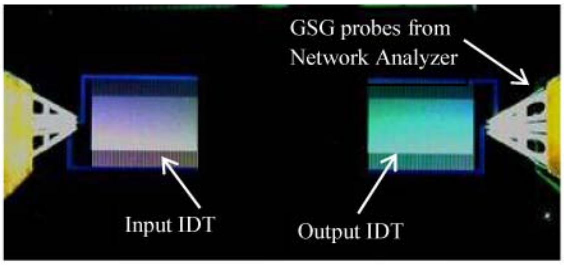

Figure 10–A SAW sensor under wafer level testing.

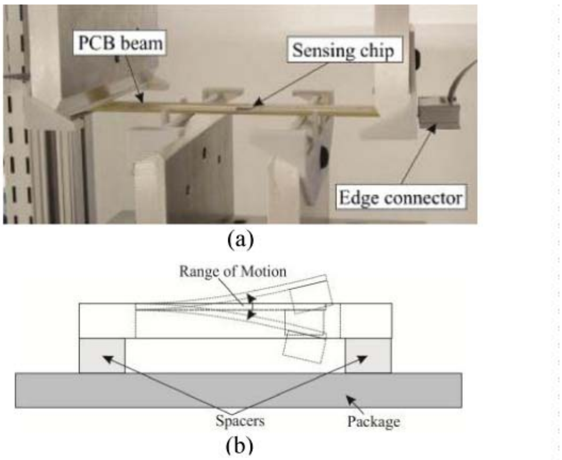

Figure 11–(a) a stress sensor under bending test [52], (b) a resonator under vibration test [53].

Lately, MEMS inertial sensors are in transition from fully hermetic ceramic to plastic packaging that helps meet their price margins [1]. 3D printing is a cheap and quick manufacturing technique to build such tiny structures and customize them for special shapes and designs. In addition, researchers have recently developed, and are still working on developing, biocompatible materials to be used for 3D printing machineries [67-71]. These materials could also be exploited to make packaging structures for covering energy harvesters from its environment for use with biological systems. 3D printing could also be used for the prototyping stage to keep the costs down. Figure 16 demonstrates customizing a structure design to mechanically support both a MEMS device and a tiny PCB. Wire-bonding and soldering was used to make electrical connections. The 3D printed part was designed such that it could be clamped to the shaker table (Figure 17). To make the 3D printing parts, an Eden 350V from Object was used with high resolution layers of 16μm in Z axis, accuracy of 0.1–0.3 mm and with glossy quality.

3D printing could also be considered for sealed box packages to completely protect the device from its environment (Figure 18). Various dispensing adhesives or laser sealing which are used to seal plastic packages [1] could be exploited to seal the lid to the bottom of a 3D printed structure. MEMS ink-jet chip packaging, capping

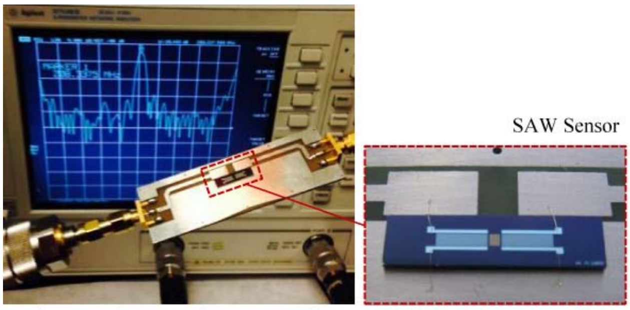

Figure 12–A surface acoustic wave (SAW) sensor wire-bonded to a PCB under test.

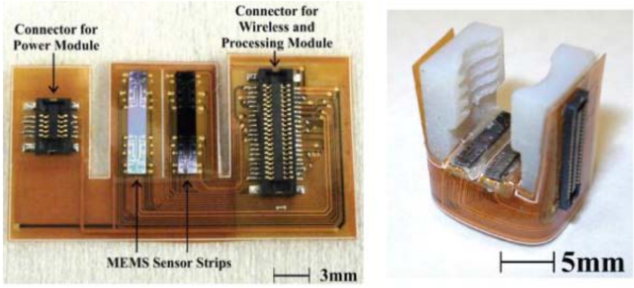

Figure 13–Packaging MEMS devices on a Flexible PCB [48, 49].

process and thermoplastic injection molding are some of the other methods to build a structure to protect the chip from its environment. However, none of them is as fast, cheap and customizable as the 3D printing process.

Package for Under Vacuum Pretest

Testing under vacuum would decrease the air damping effect and consequently increase the quality factor of a resonator. In the case of an energy harvester, a device under vacuum would have higher vibration amplitude which in turn causes higher output energy for the same excitation amplitude. Researchers would always prefer to package their devices under vacuum to improve the output results [72-75]. Various techniques have been developed for chip-level and wafer-level vacuum packaging of MEMS devices [76-82]. However, before pursuing a vacuum packaging process, one would like to test and characterize the fabricated MEMS device under vacuum.

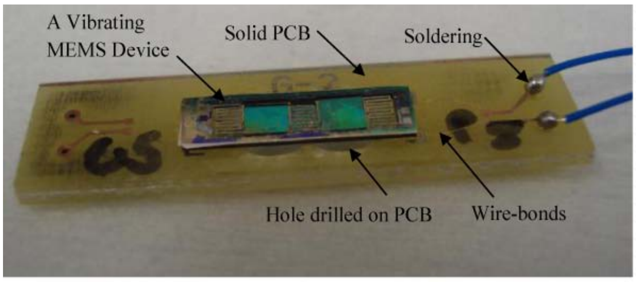

Figure 14–Conventional solid PCB is used to package a MEMS vibrating device [35].

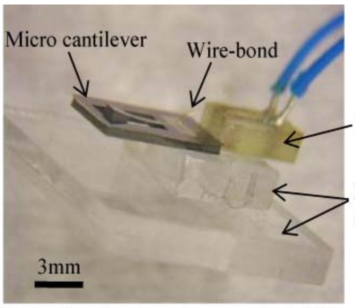

Figure 15–A simple structure to hold the device and PCB and provide some space for cantilever's oscillation.

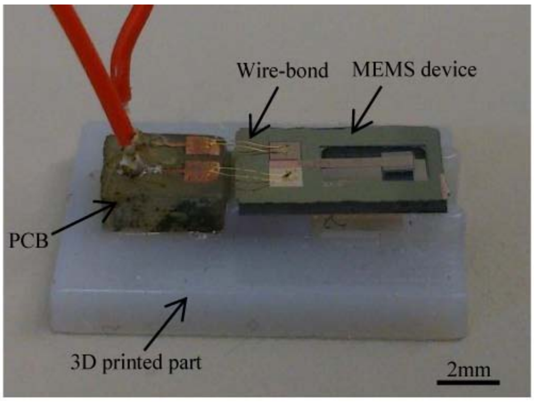

Figure 16–3D printed part is customized as a mechanical support for a resonator.

Considering the low yield of any packaging technique in general, it would be beneficial to test a device under vacuum before it is fully packaged.

A small chamber has been designed and built to ease the primarily testing and characterization steps. This low cost chamber is shown in Figure 19. The main body is made by 3D printing. The cap is a glass slide to allow a laser to shine on the MEMS device and make vertical displacement measurements. Two thin wires are vacuum sealed and provide electrical connections across the chamber. A connector to the vacuum pump and a spring clamp to hold the MEMS devices inside the chamber are the other components of this design. Using this chamber, any MEMS devices could be tested under vacuum to ensure its functionality before any further processing.

Conclusion

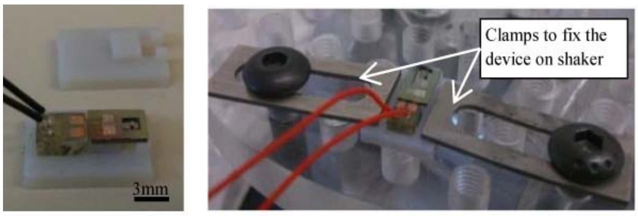

Figure 17–A sample of 3D printed part. All packaging structures allow them to be clamped to a shaker table.

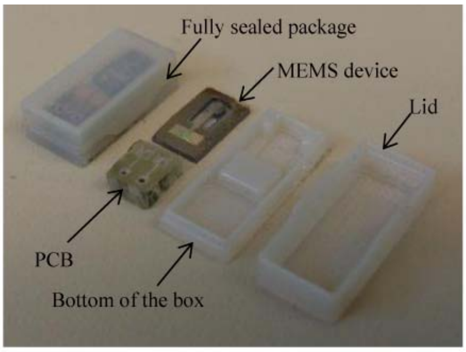

Figure 18–A sealed box was manufactured by 3D printing.

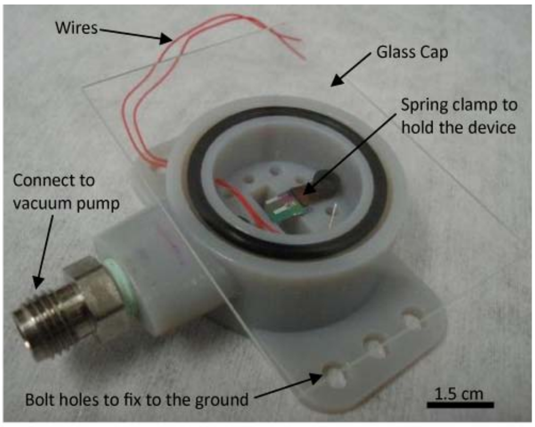

Figure 19–A small vacuum chamber designed for testing resonators under vacuum.

A number of 3D micro-assembly techniques have been demonstrated in this article to electrically and mechanically package MEMS devices. In terms of electrical interconnections, wire-bonding, tape automated bonding, adhesive-based bonding and flip-chipping were examined and a number of sample prototypes were presented for each case which were developed or adapted in our lab. Additionally, an improvised application of flexible and conventional solid PCBs was demonstrated to bond to MEMS devices and allow electrical characterization. In addition, a low cost technique was developed to use a manual dispenser and precisely dispense adhesive dots for MEMS packaging applications. Besides, 3D printing was exploited to build customizable mechanical packages for MEMS devices. This technique is expandable for bio MEMS applications as well due to the capability of 3D printing technology to build structures with bio-compatible materials. Finally, a small vacuum chamber was designed to examine mechanical responses of micro-resonators under vacuum before finalizing their electrical and mechanical packaging. The packaging methods in this article were practically shown on prototype MEMS devices to provide a platform to deal with some of the main 3D packaging challenges; however by slightly tweaking them, many can be used for mass production purposes as well.

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