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Electro-Microfluidic Packaging

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Electro-Microfluidic Packaging

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Abstract

Electro-microfluidics is experiencing explosive growth in new product developments. There are many commercial applications for electro-microfluidic devices such as chemical sensors, biological sensors, and drop ejectors for both printing and chemical analysis. The number of silicon surface micromachined electro-microfluidic products is likely to increase. Manufacturing efficiency and integration of microfluidics with electronics will become important. Surface micromachined microfluidic devices are manufactured with the same tools as IC's (integrated circuits) and their fabrication can be incorporated into the IC fabrication process. In order to realize applications for surface micromachined electro-microfluidic devices, a practical method for getting fluid into these devices must be developed. An Electro-Microfluidic Dual In-line Package (EMDIP™) was developed to be a standard solution that allows for both the electrical and the fluidic connections needed to operate a great variety of electro-microfluidic devices. The EMDIP™ includes a fan-out manifold that, on one side, mates directly with the 200 micron diameter Bosch etched holes found on the device, and, on the other side, mates to larger 1 mm diameter holes. To minimize cost the EMDIP™ can be injection molded in a great variety of thermoplastics which also serve to optimize fluid compatibility. The EMDIP™ plugs directly into a fluidic printed wiring board using a standard dual in-line package pattern for the electrical connections and having a grid of multiple 1 mm diameter fluidic connections to mate to the underside of the EMDIP™.

Acknowledgment

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Murat Okandan was helpful in defining the packaging needs for electro-microfluidic devices. Dawn Bennett provided technical assistance for assembling and testing of packaged electro-microfluidic devices. David Martinez gave us guidance in the design of the Fluidic Printed Wiring Board. Clint Atwood did the detailed design work for the EMDIP™ and the mold used to fabricate EMDIP™ . Rachel Giunta worked with 3M to identify a suitable adhesive tape used for die attach and the bonding of the various layers in the EMDIP™ . Matt Donnelly provided mold design guidance. Rex Jaramillo poured and disassembled the mold. Ken Peterson and Steve Garret reworked ceramic DIP modules to function as an EMDIP™. Robert Stokes gold plated the lead frame. Peter Krulevitch and William Benett provided microfluidic connector information. Jay Jakubczak, Alan Parker, Kathryn Hanselmann, and Rene Gonzales provided support for promoting and marketing EMDIP™ as a product.

This report serves to summarize the results and satisfies the requirements for the Laboratory Directed Research and Development (LDRD) project "Electro-Microfluidic Packaging", project number 10794. This LDRD project was funded by the Advanced Manufacturing Investment Area.

Contents

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1.0 Introduction

There are many examples of electro-microfluidic products that require cost effective packaging solutions. Industry has responded to a demand for products such as drop ejectors, chemical sensors, and biological sensors. Drop ejectors have consumer applications such as ink jet printing and scientific applications such as patterning self-assembled monolayers or ejecting picoliters of expensive analytes/reagents for chemical analysis. Drop ejectors can be used to perform chemical analysis, combinatorial chemistry, drug manufacture, drug discovery, drug delivery, and DNA sequencing. Chemical and biological micro-sensors can sniff the ambient environment for traces of dangerous materials such as explosives, toxins, or pathogens. Other biological sensors can be used to improve world health by providing timely diagnostics and applying corrective measures to the human body. Electro-microfluidic packaging can easily represent over fifty percent of the product cost and, as with Integrated Circuits (IC), the industry should evolve to standard packaging solutions. Standard packaging schemes will minimize cost and bring products to market sooner.

A two level packaging scheme has been developed for electro-microfluidic devices fabricated in silicon. Although our electro-microfluidic devices were fabricated at Sandia in polysilicon on a silicon wafer using surface micromachining technology (i.e. silicon based MEMS technology), this packaging scheme would still be beneficial to devices fabricated in other materials using other fabrication technologies. The first level is the die or device level package and is designed to be small, modular, and easy to handle, yet provide for the critical micron size electrical and fluidic connections. The second level is the board level package that connects and interfaces to multiple first level packages. There is a third level, system package, that is not discussed in this report. The system level package may contain multiple board level packages and resembles the finished product. This two level packaging scheme is distinguished by a layered architecture and is not limited to a particular material. Thermoplastics, thermosets, glass, ceramics, and stainless steel are all potential packaging materials. The thermoplastics range from a high performance material like PEEK to inexpensive materials like ABS, polyethylene, polypropylene, acrylic, or polycarbonate.

The first level package should provide many useful functions. It needs to be adaptable to accommodate the great variety of electro-microfluidic devices, including inexpensive consumer products and critical chemical sensors. The package should take advantage of economies of scale for large volume production. Each product will require a specific set of electrical and fluidic interconnects. The interconnects need to be simple and designed for manufacturability. Although the fluidic interconnects will require the precision alignment of holes on the order of 200 microns, the alignment and mating of interconnects must be suitable for automation. The fluidic interconnects and subsequent channels must be compatible with a great variety of fluids both liquid and gas. The package needs to provide both front side and back side access for either environment sampling or optical interfaces. The package needs to be hermetic when necessary and free of outgassing byproducts. If the electro-microfluidic device is fabricated in polysilicon on a die then the package must secure the die (i.e. die attach) and structurally protect the delicate electrical interconnects (e.g. wire bond). Overall the package must protect the device in its operational environment (e.g. vibration, shock, temperature, humidity). Heat producing devices can be thermally managed by dedicating fluidic channels for cooling and by the selection of heat conducting materials. The thermal coefficient of expansion of the die relative to the packaging material must be considered. Poor packaging is a source of failure for many silicon based MEMS devices. The package should be easy to handle, easy to ship, and easy to assemble into the second level package. Finally, the first level package should allow for the device to be tested at the component level prior to shipping or assembly into the second level. These are the attributes of the EMDIP™ first level package described in the next section of this report.

The second level package is basically what the first level package plugs into. The second level package must connect to all of the electrical and fluidic interfaces found on the first level package. Most fluidic applications will require a leak-tight seal at this interface. There must be a method of attachment for securing the first level package to the second level package. The attachment method should not require precision alignment. Some applications will necessitate the attachment of multiple first level packages to a single second level package. A useful feature is for the first level package to be removable. This feature will facilitate maintenance and troubleshooting of the electro-microfluidic system. Consumable products and biomedical products that may become contaminated will also benefit by being replaceable. The materials used in the second level package must not compromise the fluid compatibility advantages provided by the first level package. In order to minimize the number of different materials that the fluid contacts, it may be desirable to fabricate the first level and second level package from the same material. Also, identical materials for both the first level and second level package will negate any concerns regarding a mismatch of the thermal coefficient of expansion. The second level package should have the option of cable connectors that are both electrical and fluidic. These cable connectors, whether electrical or fluidic, should be capable of making multiple independent connections through a single receptacle. Finally, the second level package should be inexpensive to manufacture and compatible with printed wiring board manufacturing processes like wave soldering. Simply stated, the second level package should resemble a thick printed wiring board.

The packaging scheme needs to satisfy seemingly contradictory requirements. It must protect the delicate electro-microfluidic device from the environment yet allow access for environmental sampling. It needs to have the look and feel of a standard package yet be flexible to accommodate a great variety of electro-microfluidic applications from ink jet printing to chemical sensing. The challenge is to develop an electro-microfluidic packaging scheme that satisfies a great many requirements yet is inexpensive. The strategy is to develop a packaging scheme analogous to the Integrated Circuit industry. Packaging cost can be minimized by adopting standard packaging methodologies and by leveraging economies of scale. Mass production can be accomplished by distributing the manufacturing needs of a product to suppliers of electro-microfluidic components that are common to many different products. These suppliers basically produce a module by pre-packaging their electro-microfluidic component as a first level package. These modules can be shipped to multiple original equipment manufactures (OEM). The OEMs would perform the final assembly of the finished product. The two level packaging scheme described in this report is a modular approach that enables distributed manufacturing and is different than the highly integrated approach. Figure 1.1 is a flow diagram that illustrates how a distributed manufacturing network promotes mass production of individually packaged electro-microfluidic components.

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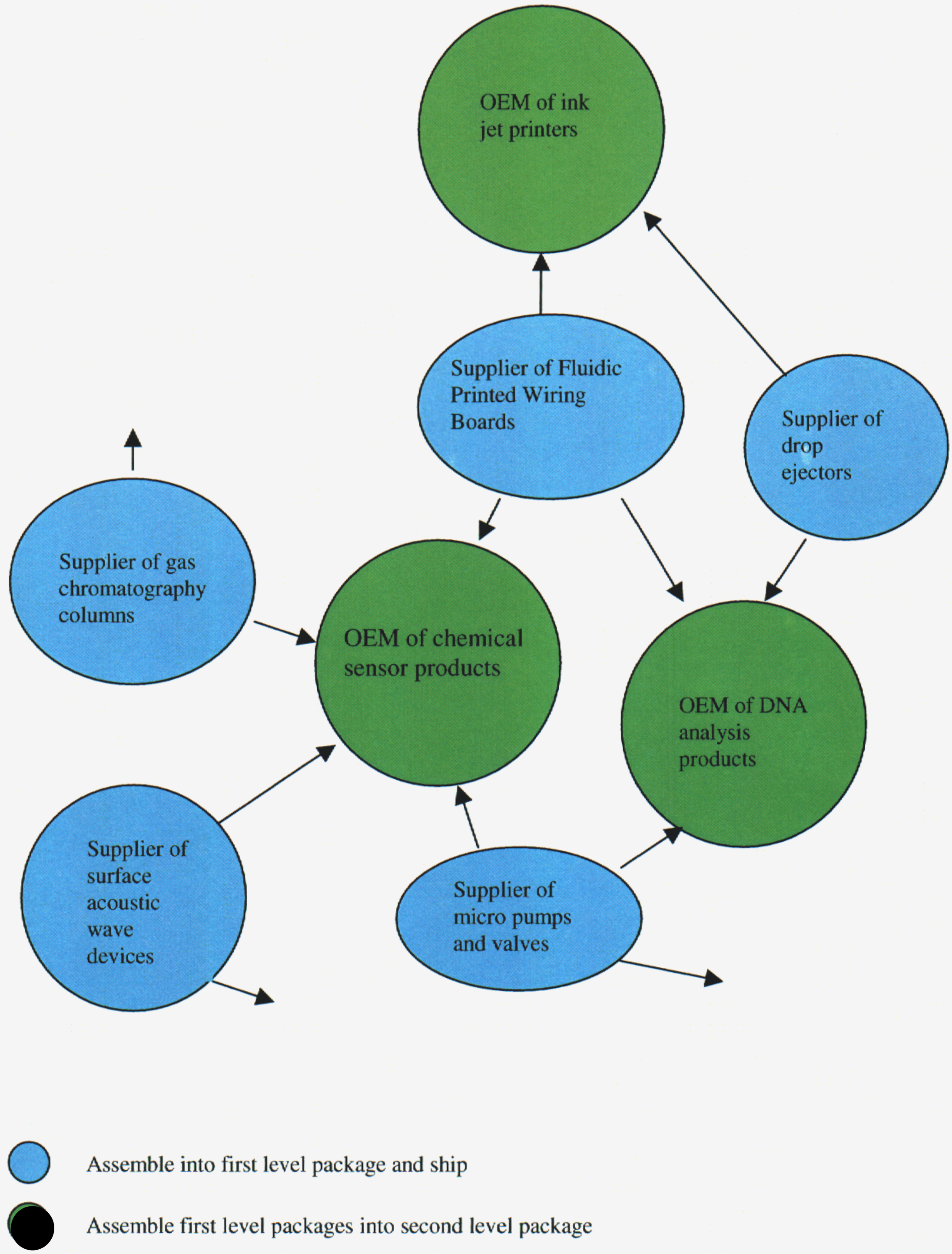

Figure 1.1: Example of the distributed manufacturing of electro-microfluidic products.

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2.0 Design of the Electro-Microfluidic Dual In-line Package (EMDIP™)

The EMDIP™ (patent pending) was developed as a first level package for electro-microfluidic devices fabricated in silicon. This packaging methodology is analogous to the Dual In-line Package often used to package Integrated Circuits (ICs). EMDIP is an acronym for Electro-Microfluidic Dual In-line Package. Figure 2.1 is an exploded view of the 24-pin, 8-channel EMDIP™. This particular configuration allows for connecting the electro-microfluidic device to a maximum of 24 independent electrical connections and 8 independent fluidic connections. If the number of electrical or fluidic connections required for a particular device are less than the maximum then the balance can remain unused and nonfunctional.

The EMDIP™ is constructed in layers. The base looks like a modified DIP (Dual In-line Package). The spacing for the electrical leads are standard and will plug into a standard DIP socket. The base has eight 1mm diameter through holes that become the fluidic interfaces to the second level package.

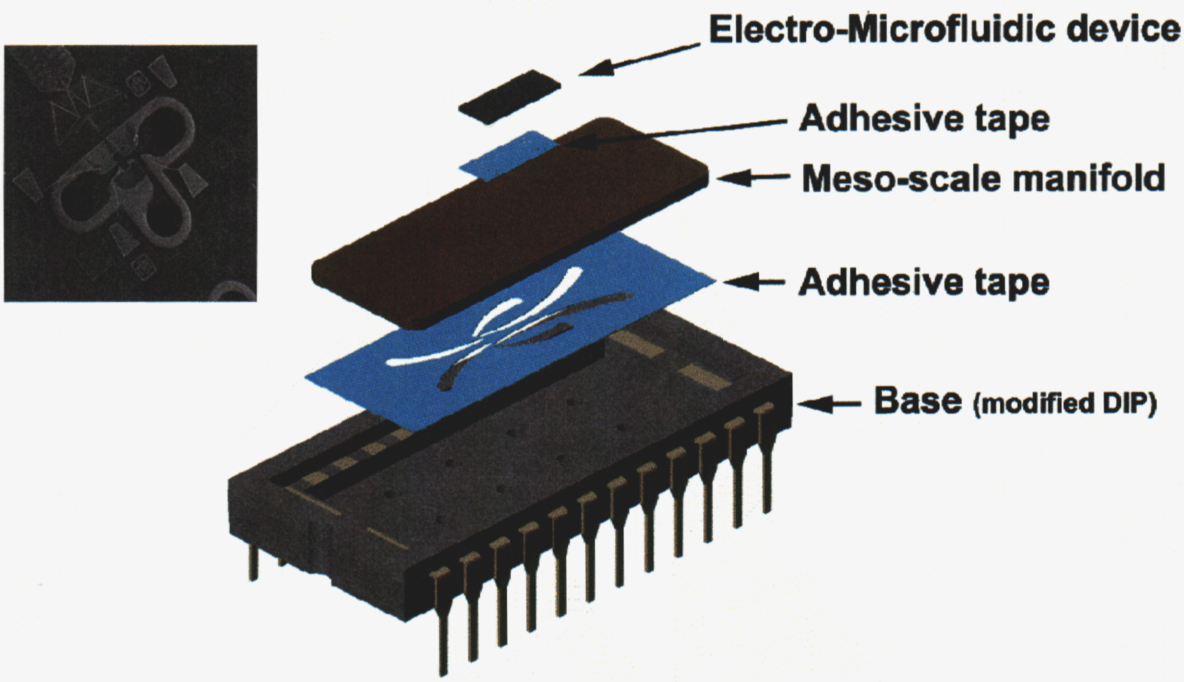

Figure 2.1: Exploded view of the 24-pin, 8-channel EMDIP™. The insert is an SEM image of a cell microtransfection device on a section of the die (Courtesy of Murat Okandan, Sandia National Laboratories). Note the three bosch etched holes matching the same pattern shown in figure 2.2a

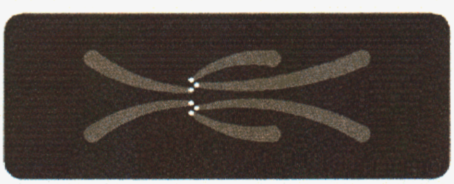

Figure 2.2a: Manifold, bottom view.

Figure 2.2b: Manifold, tilted bottom view

Along the periphery of the cavity in the base are the bond pads that are available for wire bonding to the bond pads found on the top surface of the electro-microfluidic device. This particular manifold, also shown in figure 2.2, utilizes only six of the possible eight fluidic connections. The top side of the manifold is visible in figure 2.1 and the bottom side is visible in figure 2.2. The six tapered fluidic channels are illustrated in figure 2.2. These channels provide a gradual transition from the 1 mm diameter holes found on the base to the 200 micron bosch etched holes found on the silicon device. Figure 2.2a clearly shows six 200 micron diameter through holes that connect the top side of the manifold to the narrow portion of the tapered channel. Figure 2.2b clearly shows the sidewalls of the tapered channel and the depth of the channel into the thickness of the material. In this example, the channel depth was .020 inches into .030 inch thick material.* Therefore, the 200 micron through hole only needed to pass through the remaining .010 inch of material. The tapered channel design eliminates sharp corners in the channel and reduces locations that stagnant fluid can collect. Also, the tapered channel facilitates the priming of liquid into the electro-microfluidic device. The manifold is attached to the base with an adhesive tape. The adhesive tape can be patterned to have the footprint of the tapered channels prior to application. Compared to liquid adhesives, adhesive tape has the advantage of not flowing into the small fluidic channels and inadvertently blocking fluid flow. The electro-microfluidic device is positioned to precisely overlay the 200 micron diameter bosch etched holes onto the matching 200 micron diameter through holes on the manifold. The device (die) is sealed and secured with adhesive tape. This assembly can be completed in a number of ways depending upon the application. The cavity can be encapsulated to protect and seal the device from the environment. A lid can be fastened to the top surface of the base to seal and protect the device. A custom lid can be fitted in place to provide access for environmental sampling, or the lid can be made of transparent materials for optical access. This layered assembly is amenable to methods other than adhesive tape for fastening one layer to the other. If the layers are constructed from thermoplastics then it is possible to plastic weld one layer onto the other without the use of an intermediate material.

The only application specific part in this packaging assembly is the manifold. The base is generic. The reason that the manifold is application specific is because the manifold must interface to custom placed bosch etched holes on the silicon device. The number of different manifold designs can be made finite, however, if the electro-microfluidic designing community can be convinced to place their bosch etched holes on a standard grid. The maximum number of different manifold designs can be calculated as a combination of “n” items taken 8 at a time. Where “n” is the total possible locations on the largest die for a given grid size, “d”. Obviously, the grid size, “d”, must be greater than the diameter of the bosch etched holes. The number of combinations, “C”, can be precisely calculated by the following equations assuming that r = 8 and that the active dimensions of the die are, “x” and “y”. The active dimensions are the dimension on the die that would reasonably contain bosch etched holes. The order of the 8 items is assumed to be unimportant because the designer probably does not need to dictate which particular 1 mm hole is routed to a particular 200 micron bosch etched hole. Certainly a callout would be provided that defines what goes to what.

$$n = (x/d + 1)(y/d + 1) \qquad \textbf{Equation 2.1}$$

$$d > 200 \text{ microns}$$

$$C(n,r) = n!/[r!(n - r)!] \qquad \textbf{Equation 2.2}$$

* The authors apologize for mixing metric units with English units. Metric units are commonly used in silicon based MEMS design while English units are commonly used for purchasing plastic sheet material and for DIP package interconnects.

For example, let's assume that "d" equals 1 mm and the active dimensions of the die are 2 mm by 4 mm.

$$n = 15, \textit{ (3 by 5 grid for bosch etched holes)}$$

$$C(15,8) = 6{,}435$$

There are 6,435 different manifold design options given these assumptions. Much too many for stocking parts or tooling, however, the number of combinations for a smaller package are more practical. The calculation for the smaller package is shown at the end of this section.

Figure 2.3 is a drawing of the base to the 24-pin, 8-channel EMDIP™. The EMDIP™ was fabricated to this drawing. For reasons that are not obvious to anyone, the eight 1 mm (.039 inch) through holes were spaced .203 inches (5.16 mm) within a row and the rows were spaced .169 inches (4.3 mm) apart. Future EMDIP™ designs will likely be spaced on a square grid of 5 mm by 5 mm.

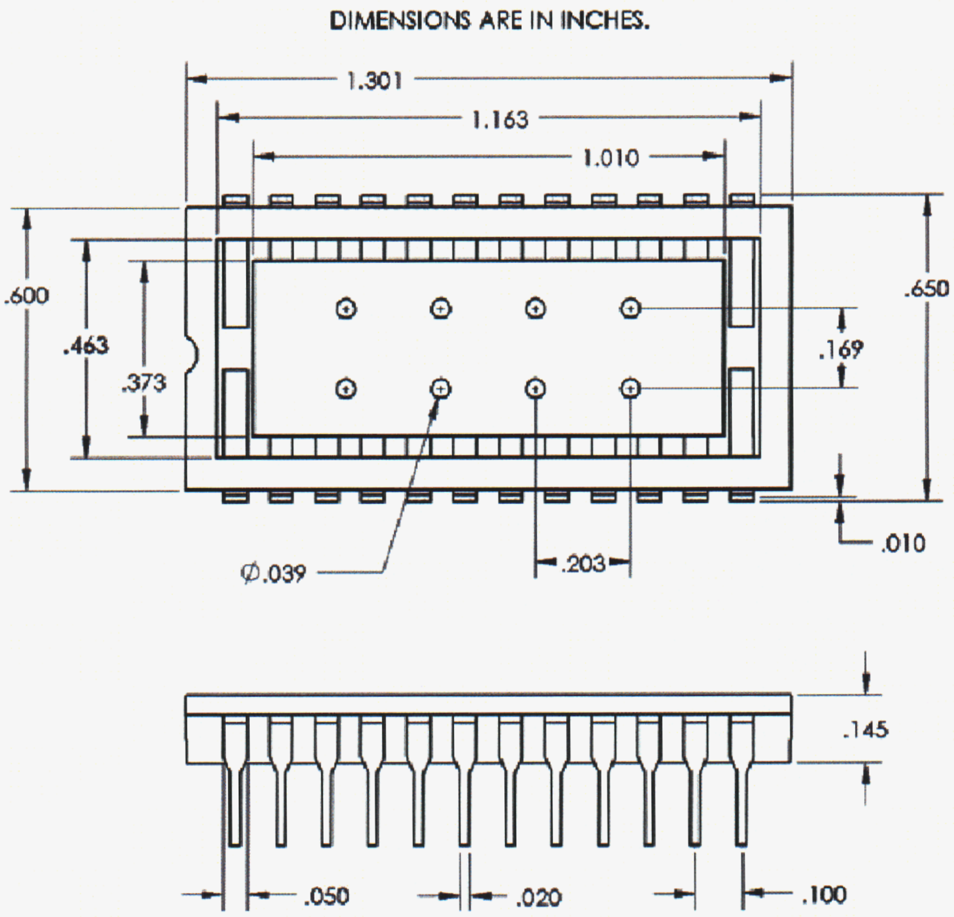

Figure 2.3: 24-pin, 8-channel EMDIP™ base.

Figure 2.4 is an exploded view of the newer, compact EMDIP™ design. This particular configuration allows for connecting the electro-microfluidic device to a maximum of 12 independent electrical connections and 4 independent fluidic connections. Unlike the 24-pin, 8-channel, this compact design has not been fabricated at this point in time.

As was done for the 24-pin, 8-channel design, it is interesting to calculate the number of different manifold designs for the 12-pin, 4-channel EMDIP™ . Let's assume that the grid spacing, "d", for the bosch etched hole locations on the die is equal to 1 mm and that the effective die area is confined to 2 mm by 2 mm. From equation 2.1,

$$n = 9, \textit{ (3 by 3 grid for bosch etched holes)}$$

The number of combinations of 9 items taken 4 at a time is calculated from equation 2.2.

$$C(9,4) = 126$$

There are 126 different manifold design options given these assumption. This is a much more manageable quantity. It is possible to stock manifold parts or have tooling available for all 126 designs to serve a multitude of potential customers.

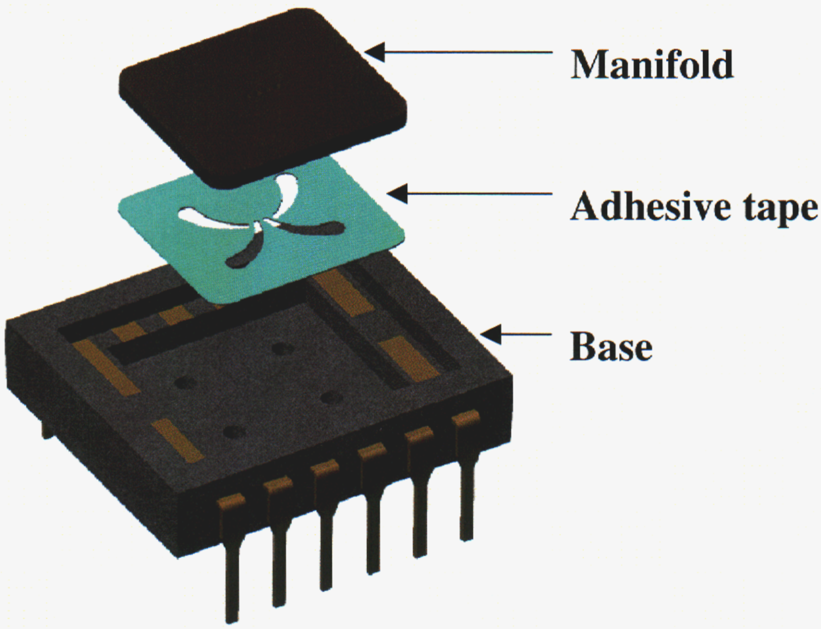

Figure 2.4: Compact 12-pin, 4-channel EMDIP™ . This model shows the base, the adhesive tape, and the manifold.

3.0 Design of the Fluidic Printed Wiring Board (FPWB)

The Fluidic Printed Wiring Board (FPWB) is the second level package and is designed to interface to multiple EMDIP™ modules as well as standard electronic components. Figure 3.1 is an exploded view of the FPWB, electrical connector, and fluidic connector. The materials used to construct the FPWB would not likely be standard circuit board materials (e.g. FR4 or Thermount) but rather high temperature thermoplastics or glass. It is possible to use an identical material for both the FPWB and the EMDIP™ which is desirable for applications that require a minimum number of different materials that contact the fluid. The FPWB consists of two parts, the channel board and the cover board. Similar to the EMDIP™ , the channel board and cover board can be injection molded. The channel board would typically be thicker than the cover board to accommodate the channel depth and bores along the edge for the fluidic connector. For example the channels shown in figure 3.1 are 1 mm wide by 1 mm deep and is sized for the 1 mm though holes shown on the cover board. The bores along the edge are .135 inches (3.4 mm) in diameter. Currently the cover board is designed to be 1 mm thick and the channel board is designed to be 5 mm thick. The channel features in the channel board and the 1 mm through hole features in the cover board would be formed during the injection molding process. The FPWB is assembled by attaching these two boards together.

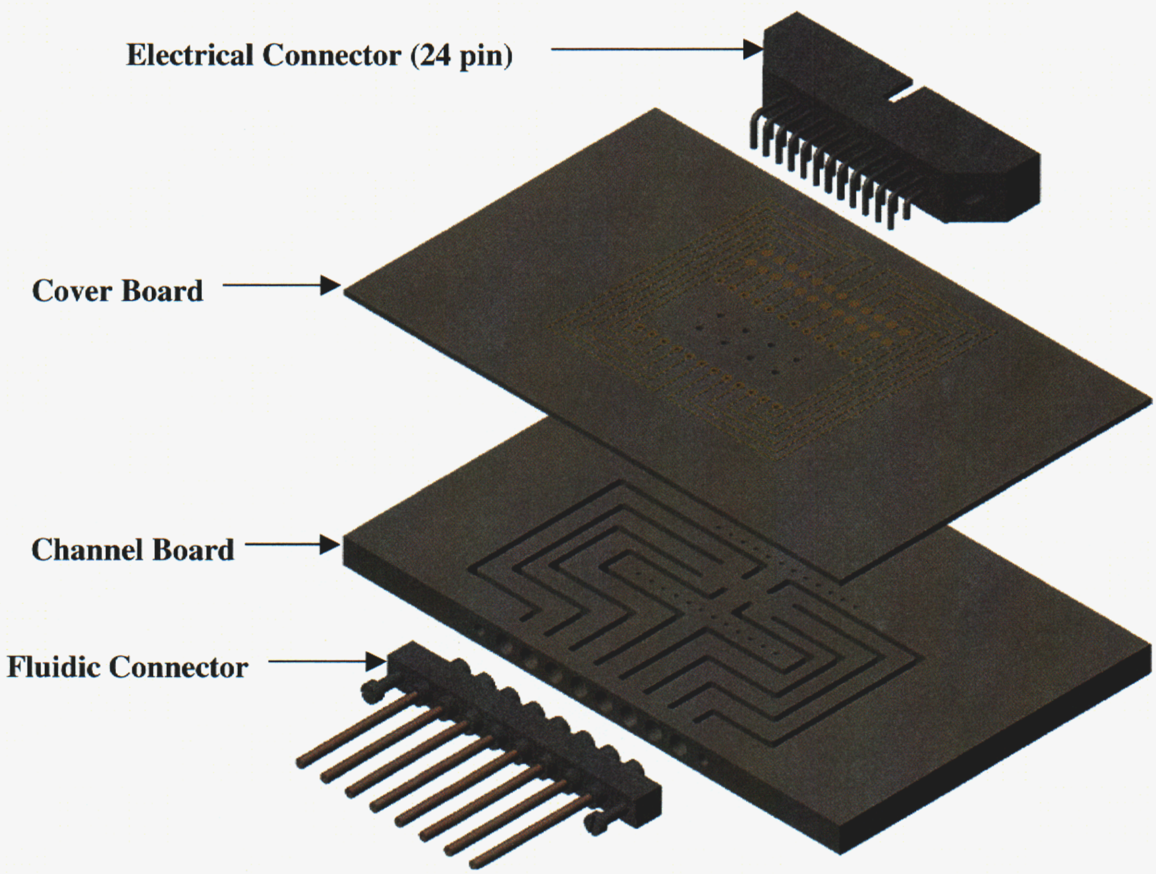

Figure 3.1: Exploded view of the Fluidic Printed Wiring Board with a standard 24 conductor electrical connector and an 8 channel fluidic connector. The fluidic connector was developed and patented by Lawrence Livermore National Laboratories (Courtesy of Peter Krulevitch and William Benett)

Attaching the cover board to the channel board presents challenges similar to attaching the manifold to the base for the EMDIP™ . If liquid adhesives are used then care needs to be taken to prevent the adhesive from inadvertently flowing into and obstructing the channels. A proper adhesive needs to be compatible with the fluid that flows through the channels. Otherwise, the fluid could act as a solvent and de-bond the cover board from the channel board or the adhesive could release chemicals into the fluid that adversely affect the operation of the electro-microfluidic device. Adhesive tape is one option for bonding the cover board to the channel board. The adhesive tape can be patterned (e.g. punched) to have the same channel pattern as the channel board. The patterned adhesive tape avoids the problem of adhesive flowing into the channels and minimizes contact between the adhesive and the fluid. Another option is to bond the cover board onto the channel board without the use of adhesives and instead to take advantage of the properties of thermoplastics. Some thermoplastics respond well to solvents that dissolve a thin layer of plastic material long enough to form a paste that will adhere to the adjoining layer. Still another option is to quickly heat the faces of the cover board and the channel board long enough to melt a thin layer that will form a plastic weld when joined to the mating surface.

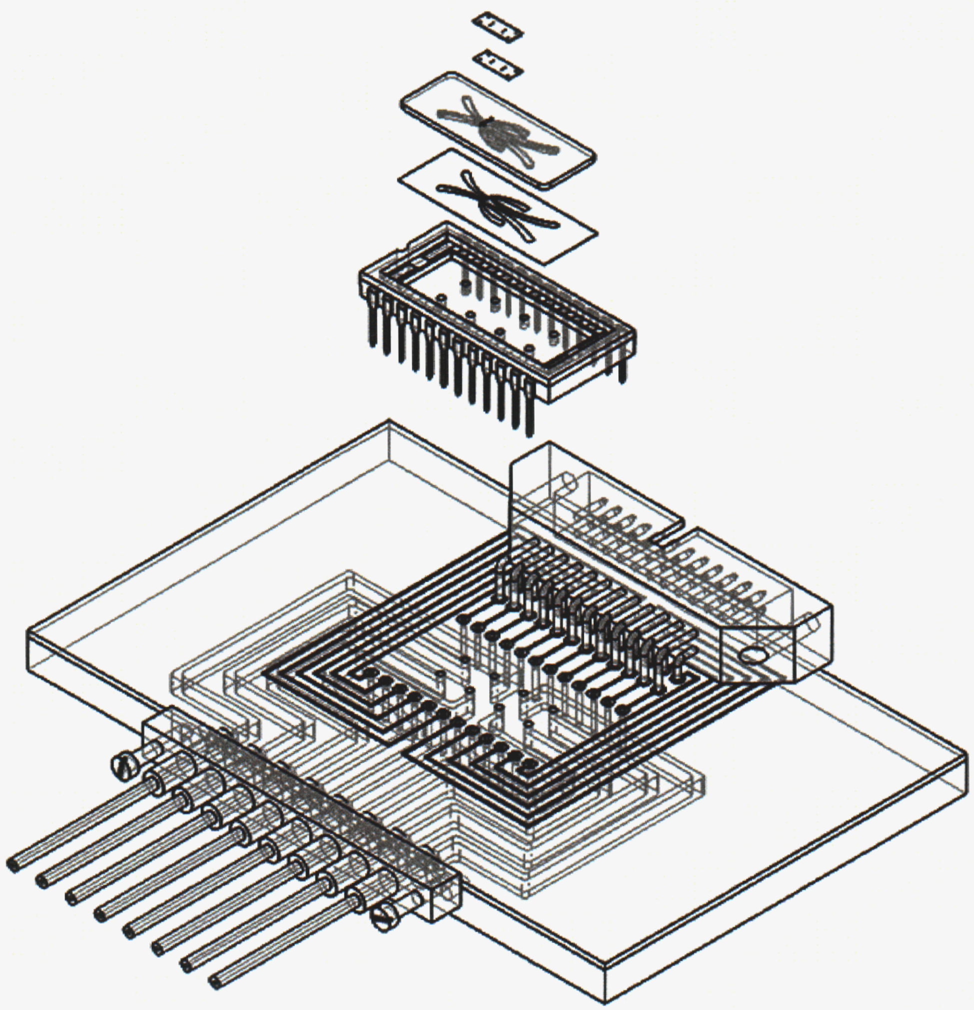

Figure 3.2: Orientation of the EMDIP™ piece parts as assembled to the FPWB.

In many ways the cover board can be processed like a standard circuit board. The cover board can have photo defined copper traces that not only electrically connect the EMDIP™ to an external electrical connector but also provides electrical connections necessary for discrete devices and other pre-packaged Integrated Circuits. A high temperature thermoplastic, like PEEK, would be capable of surviving soldering temperatures and render the cover board as compatible with wave soldering processes.

Attaching the EMDIP™ to the FPWB is not trivial. This interface makes both electrical and fluidic connections. This interface joins the array of 1 mm diameter holes on the EMDIP™ to the matching 1 mm diameter holes on the FPWB. The fluidic connections must also be secure, leak tight, and compatible with the fluids, however, the connection at this interface should be detachable for some applications. Applications requiring system maintenance will benefit from the ability to replace one EMDIP™ module with another. As designed, the bottom face of the EMDIP™ can come into intimate contact with the FPWB unimpeded by the electrical leads. The electrical leads pass freely through the mating holes on the cover board and into relief holes in the channel board. The leads do not control the height of EMDIP™ as it is situated on the FPWB. On the other hand, gull wing surface mount packages present a difficulty because the electrical connections control the space between the package and the printed wiring board. Ball grid array surface mount packages present a different challenge in that the bottom surface of the package can get a little cramped having both the electrical and fluidic connections. These problems with surface mount technology can be overcome. Gull wing designs can have mechanical compliance to provide the margin necessary to make intimate contact around the 1 mm holes. Solder seal rings can be placed concentric to all of the 1 mm holes to simultaneously seal the interface with solder when making the ball grid array electrical connections. The sealing and securing of the EMDIP™ can be accomplished in a variety of ways. As mentioned above, solder seal rings is also an option for EMDIP™ but makes removal difficult. Adhesives both liquid and tape will seal and secure the EMDIP™ but again removal is difficult. Plastic welding of the EMDIP™ to the FPWB makes removal almost impossible. Compression seals such as gaskets or O-rings at this interface can provide an adequate seal but compression seals do not inherently secure the EMDIP™ module. If the base of the EMDIP™ module is made of an elastomer material then the base becomes the gasket. The compression seal approach facilitates the removal of the EMDIP™ module, however, it also necessitates a mechanical compressive force. The mechanical force can be provided by a either a spring clip or a connector known as a "Zero Insertion Force" (ZIF connector). The compression seal approach makes soldering the electrical connections impractical. The electrical connections are instead made by mechanical contacts.

The fluidic connector shown in figures 3.1 and 3.2 is capable of making eight independent fluidic connections through one connector. Each one of the eight individual tubes on this connector can be independently coupled to a different bosch etched hole on the die. The fluidic connector is compact enough to fit along the edge of the board. This fluidic connector was developed and patented by Lawrence Livermore National Laboratories. Each tube is sealed in its mating bore in the FPWB by an elastomer compression seal. The tubing and compression seal piece parts are similar to the parts shown in figure 3.3.

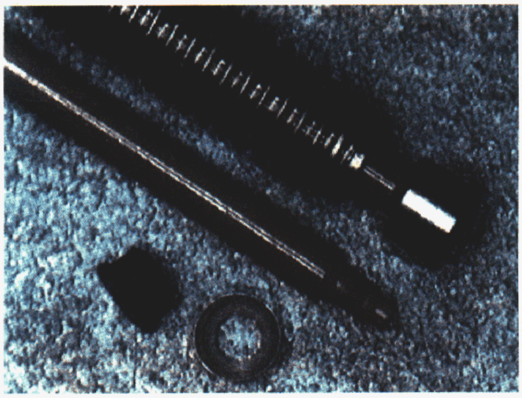

Figure 3.3: Individual fluidic connector developed by LLNL (Courtesy of Peter Krulevitch and William Benett).

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4.0 Fabrication of EMDIP™

A common dilemma in the development of a new product is how does someone design the product so that it is both mass producible and yet can be fabricated as a prototype in small quantities. Prototypes are typically expensive but necessary to demonstrate functionality, but the product must eventually become cost effective in a large volume production environment. Often times the final product design is a variation of the prototype design. The EMDIP™ may be an exception in that the prototype design is identical to the large volume design (*this statement is speculative given that the EMDIP™ has not been mass produced at this time*). The design may be the same, however, the fabrication processes and costs are vastly different. The EMDIP™ manifold and base (see figure 2.1) was designed to be injections molded in a suitable thermoplastic material. The recurring cost for either injection molded bases or manifolds is estimated to be tens of cents, however, the nonrecurring (upfront) costs are high. Therefore, the prototypes were cast into a casting mold using one of two different thermoset plastics, Slygard 184 silicone elastomer and Epon 828 epoxy resin.

The electrical lead frame is positioned in place prior to assembling the three part mold shown in figure 4.1. Twenty lead frames were fabricated in parallel by Electro Discharge Machining (EDM) a stack of twenty .010 inch thick copper sheets. In a large volume production scenario, these lead frames would likely be fabricated via stamping or chemical etching and not fabricated by EDM. The lead frames were nickel plated, to promote adhesion, followed by a gold plating. The casting mold was fabricated out of 6061 aluminum and fitted with steel pins. Eight 1 mm diameter steel dowels were pressed into the upper part of the mold to form the 1 mm through holes in the base of the EMDIP™. Two larger diameter steel pins were pressed into the lower part of the mold for alignment. The eight 1 mm dowels partially engage into 1 mm diameter holes on the lower part of the mold when assembled. Two socket head cap screws tightly secure all the parts together prior to the pouring operation.

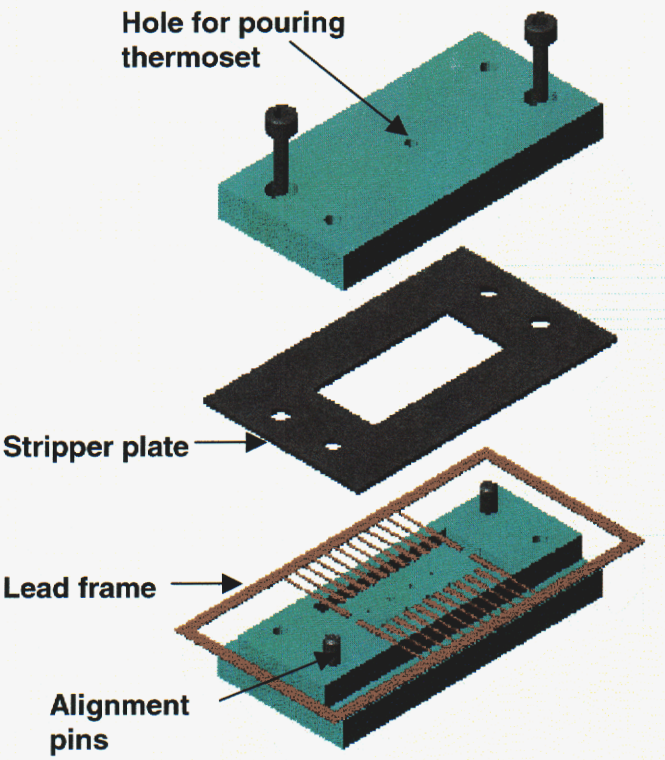


Figure 4.1: Casting mold for EMDIP™ base

The thermoset is allowed to cure for 24 hours before the mold is disassembled and the EMDIP™ base is released. The EMDIP™ base was designed with draft angles to facilitate mold release.

Prototype quantities of the EMDIP™ manifold were fabricated out of a .030 inch thick sheet of PEEK material. First a rectangular section is machined to precisely fit within the 1.010 inch by .373 inch void on the EMDIP™ base (see figure 2.3). The open tapered channels shown in figure 2.2 are machined with an .008 inch diameter end mill. The channel is machined to a depth of .020 inches.

Prior to machining the .008 inch through holes on the manifold, adhesive tape is applied to the top side of the manifold. The protective paper is left on the adhesive tape and not removed until later (for die attachment). The .008 inch through hole is simultaneously drilled through the remaining .010 inches of PEEK, through the adhesive tape, and through the protective paper. In this way the .008 inch through holes on the adhesive tape are precisely aligned with the .008 inch through holes on the manifold. The adhesive tape is .002 inch thick VHB™ made by 3M™ corporation. Although the .008 inch (200 microns) features on the manifold are meso-scale and have feature to feature tolerances better than 20 microns, the manifold can still be injection molded for large volume production.

The most critical assembly is the die attach. Up to eight different .008 inch diameter bosch etched holes must be aligned to the mating .008 inch through holes on the manifold. This critical alignment and die attaching operation is performed with a flip chip bonder. The flip chip bonder is capable of optically aligning and joining the die to the manifold to within 1 micron. The objective is to keep the bosch etched hole to the manifold hole misalignment to within 10% of the diameter (or 20 microns). The flip chip bonder mates the surfaces to be joined and applies a predefined pressure and temperature for a given duration. The flip chip bonding operation can be automated for large volume production.

Once the die is attached to the manifold, the manifold is placed into the void in the base and joined with the VHB™ adhesive tape. The adhesive tape at this interface both seals and secures the manifold. As mentioned previously, methods other than adhesive tape are being investigated for this interface. The rectangular void in the base provides the mechanical alignment necessary to align the 1 mm diameter though holes in the base to the large end of the taper on the manifold. Figure 4.2 is a photograph of the manifold assembled into the base without the die. Figure 4.3 is a photograph of the die packaged in EMDIP™ . The electrical connections are made by wire bonding the pads on the die to the pads along the periphery of the EMDIP™ base.

At this point all the parts shown in figure 2.1 are assembled. Finishing operations can still be performed depending upon the application. Encapsulant can be applied to cover the die and manifold for environmental protection. A lid can be attached to the rim of the base to hermetically seal the device. An optical cover can be attached to the rim of the base. A lid with a port can be attached to provide access for environmental sampling. The frame is sheared away from the leads and the leads are bent 90 degrees downward. The EMDIP™ is now ready for second level packaging.

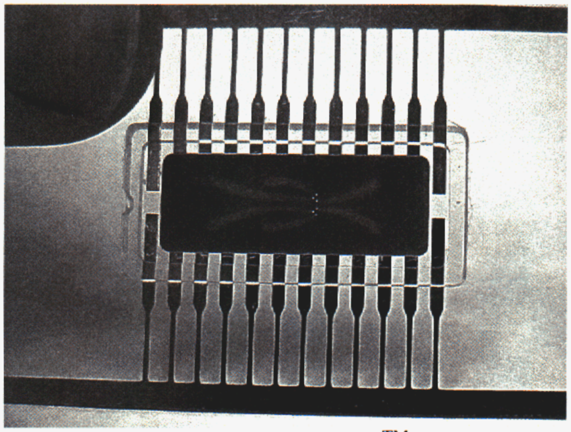


Figure 4.2: Top view of EMDIP™ manifold assembled to base. Note the six .008 inch diameter through holes

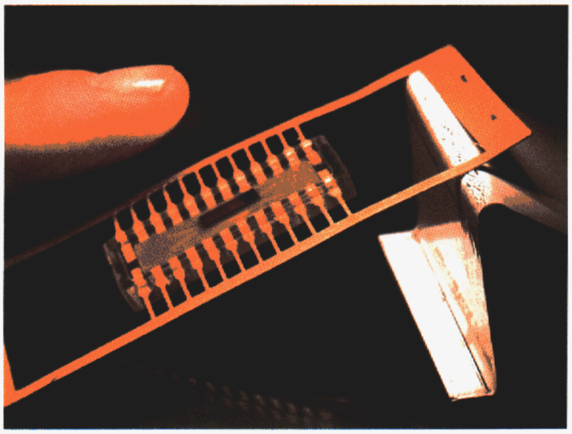


Figure 4.3: Electro-microfluidic die assembled into EMDIP™ .

5.0 Testing of EMDIP™

Three sets of characterization tests were performed on aspects of the packaging configuration – a liquid leak pressurization test of the EMDIP™ configuration with a blank silicon wafer, a helium gas leak test of the tape attachment using a silicon tab, and a test of a sealed surface micromachine silicon device attached to the EMDIP™ manifold using the adhesive tape. The liquid leak test was performed using dyed water to fill the acrylic flow manifold (similar to that of Fig. 4.1a). A syringe pump (Harvard Apparatus, Cambridge MA) was used to fill the acrylic manifold and PEEK part channels. The PEEK part was attached to the acrylic using either 0.005" (125 micron) double-sided adhesive tape or silicon rubber gaskets of similar thickness. The gasket was clamped using a screw-down cover with a hole cut in it to allow optical and electrical access to the front of the chip. A silicon chip without any microfluidic devices was attached to the PEEK using the tape as described above. This effectively blocks off the end of the PEEK channel. Using the syringe pump the liquid was forced into the PEEK channels compressing the air trapped therein. An in-line pressure transducer was used to record the gauge pressure achieved. A pressure of 14 Bar was measured without any liquid leakage. Also, this pressure was maintained for several hours without any drop in pressure by stopping the syringe, indicating no air leakage over that time period. The flow channels are small enough and the compression rate low enough for the compression process to be considered isothermal. The test was stopped when the pressure reached 14 bar to avoid damaging the pressure transducer (Entran, Fairfield NJ) which was rated to 14 bar. Since the surface micromachined devices on the front of the silicon chip fail at approximately 3-5 bar the >14 bar of pressure demonstrated is more than adequate for our purposes.

The second set of tests consisted of helium gas leak tests performed on the tape joint holding a tab of silicon to an aluminum manifold around a single hole. These leak tests were similar to blister and bulge tests such as those used to test the strength of adhesive bonds or to characterize the mechanical properties of thin films. The setup for the helium leak and pressurization tests of the tape/silicon bond was performed using pressurized helium and a 400 psi pressure regulator. Stainless steel tubing (1/16" diameter) and Swagelok fittings (Swagelok, Solon OH) were used to connect the pressurized helium line to an aluminum manifold. The pressurized helium was routed to a hole in the test manifold that was either 1 mm, 500 microns, or 200 microns in diameter. Covering the holes were 0.002" (50 micron) or 0.006" (150 micron) thick silicon membranes. The membranes were attached to the aluminum manifold using the double-sided adhesive tape in the manner previously described. A 1 or 3 mm hole was cut in the tape to insure that the pressure impacted the silicon, not the tape. This setup ensured that the joint that failed was the silicon/tape joint – the joint we were interested in.

The pressure was gradually increased and the entire setup was checked for helium leaks using a helium leak tester with a sniffer attachment (Varium, Lexington MA). The leak rate was below the background detectable helium concentration ($<2.5 \times 10^{-8}$ cc/sec-atm) until either the silicon membrane or the tape/silicon joint failed. The bulge tests were performed on an interferometer (λ=532 nm) so that we could measure the deflection of the silicon membrane by counting fringes. This provided verification that the pressure was applied to the right location and a way to independently check that the pressure levels set by the regulator were correct. An interferometric image of a 0.002" thick silicon membrane under pressure is shown in Fig. 4.2 and the deflection of the membrane as a function of applied pressure is shown in Fig. 4.3. The maximum pressure achieved with the 0.002" thick membrane was >3 atm. At this pressure the membrane broke – the tape/silicon joint did not fail. We repeated this test with the 0.006" thick membrane and achieved a pressure of approximately 350 psi (23 atm) at which point the membrane fractured. Some delamination of the silicon membrane from the tape was observed after failure. These tests indicate that there is at least a 2X and possibly as high as 5X margin for the packaging configuration described over the 5 atm pressure at which the surface micromachined microfluidic devices on the front of the wafer will fail.

The third set of tests checked the sealing of the assembled EMDIP™ in a test manifold (Fig. 4.1a,b). The test manifold allows pumping of pressurized helium into silicon channels through standard SwageLok fittings. The helium leak checker was again used to identify leaks. By submerging the test manifold in water we were able to locate leaks. We determined that the only leaks were through the etch release holes in the silicon channel (Fig. 4.4), indicating that the entire packaging flow path was leak tight to <10-7 cc/sec (background level of helium). To determine the maximum pressure of the taped joint we replaced the flow channel chip with a blank piece of silicon blocking all manifold exits. The manifold was then pressurized until a helium leak was measured. The tape joint failed at approximately 10 Atm. of pressure between two adjacent flow channels in the PEEK (Fig. 4.5). Since in most applications the microfluidic channels would operate at pressures less than 10 Atm the VHB™ tape provided an effective seal.

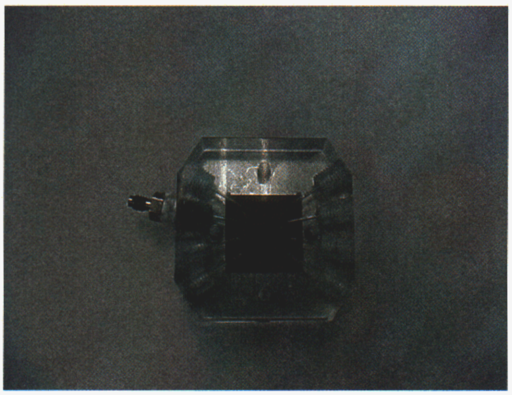
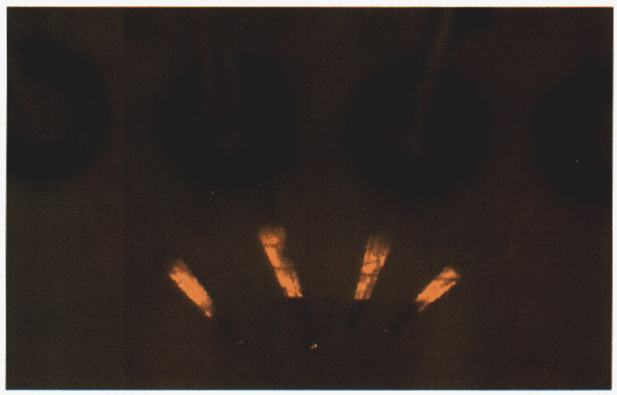


Figure 4.1 (a) EMDIP™ flow manifold.



(b) Backside of EMDIP™ manifold with close-up of flow passages

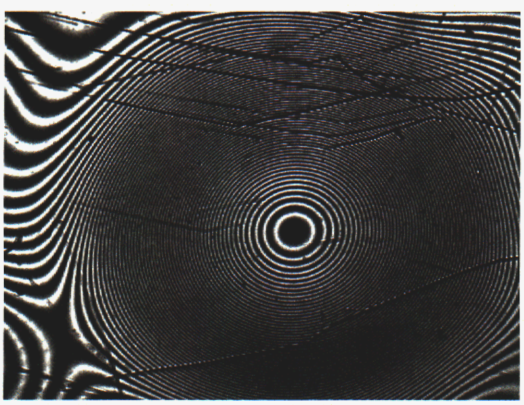


Figure 4.2 Interferrometric Image of 0.002” thick silicon membrane deflecting

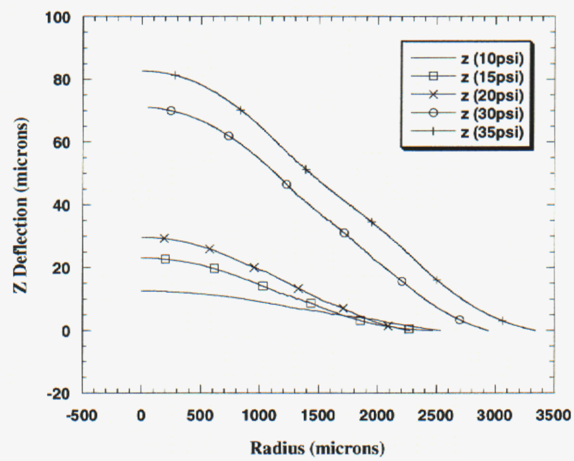


Figure 4.3 Deflection of 0.002” thick silicon membrane as a function of applied pressure.

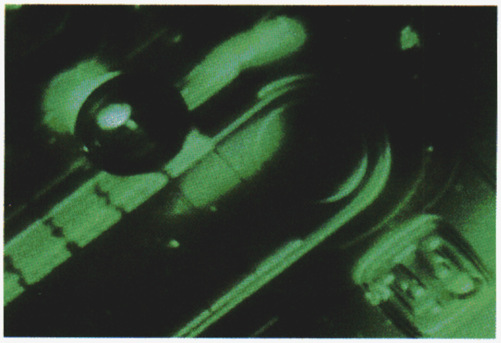


Figure 4.4 Underwater Trapped Helium Bubble Exiting Microfluidic Channel.

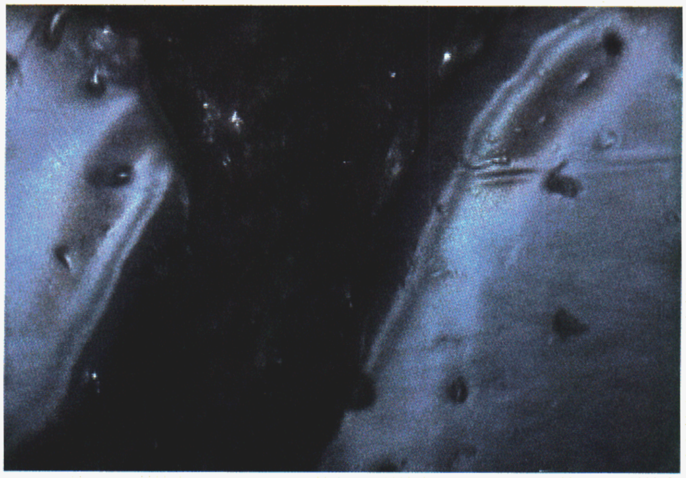


Figure 4.5a Tape barrier between two EMDIP^{TM} flow channels.

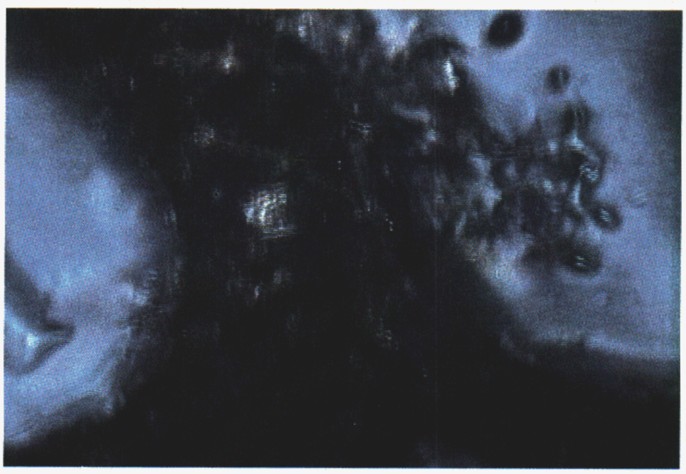


Figure 4.5b Tape barrier between EMDIP^{TM} flow channels after failure at 10 Atm pressure.

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6.0 Summary

The Electro-Microfluidic Dual In-line Package (EMDIP™) and the Fluidic Printed Wiring Board (FPWB) comprise a two level packaging scheme that satisfies the packaging requirements for many electro-microfluidic applications. Although the EMDIP™ was originally designed to package electro-microfluidic devices fabricated via silicon surface micromachining technology, this packaging scheme could be adapted to devices fabricated by other means. The attributes of this packaging scheme are listed below.

- Adaptable to great variety of electro-microfluidic devices, from drop ejectors to chemical sensors.
- Mass producible and inexpensive in large quantities
- Layered assembly
- Selection of a great variety of materials (e.g. thermoplastics, thermosets, and glass)
- Optimal fluid compatibility with materials
- Protects delicate device and wire bonds from the environment.
- Hermetic seals
- Compatible with optical devices
- Accommodates environmental sampling
- Accommodates cooling channels
- Easy to test at the component level
- Modular, easy to handle, and easy to ship
- Serviceable (EMDIP™ modules can be detached and replaced)
- Accommodates fluidic connector having multiple independent fluidic connections
- Encourages distributed manufacturing for economies of scales

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