Fresenius J Anal Chem (2001) 371 : 270–275
DOI 10.1007/s002160101002

SPECIAL ISSUE PAPER

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Silicon couplers for microfluidic applications

Received: 7 March 2001 / Revised: 8 June 2001 / Accepted: 19 June 2001 / Published online: 31 July 2001

Abstract Several types of silicon fluidic coupler have been designed, fabricated, and tested to facilitate external connections to MEMS (microelectromechanical systems) fluidic devices. By using both bulk micromachining and DRIE (deep reactive ion-etching) techniques, couplers of different geometry have been produced for use with any standard MEMS fluidic port. In addition, couplers are easily modified to accommodate any arbitrary fluidic port geometry. For ease of use, these couplers interface with PEEK (polyetheretherketone) and fused-silica capillary tubing, both of which are commonly used in HPLC (high-performance liquid chromatography) systems and are supported by a wide range of plumbing products. Coupler performance was evaluated and an operating range of at least 0–8963 kPa (0–1300 psig) is attainable.

Introduction

Micromachined fluidic devices have great potential to make an impact in the field of chemistry. The main advantages are small volume fluid flow, integrated subsystems, minimal power consumption, and small footprint. One major problem that has hampered the development and utilization of these MEMS (microelectromechanical systems) devices is the lack of a reliable and efficient means of accessing input/output ports to MEMS fluidic devices. In the macro world, connections are easily made, because of the wealth of commercially available plumbing. Standard prefabricated tubing and fittings are easily configured to achieve the desired result. On the MEMS scale, which is of the order of millimeters or smaller, however, such a varied selection of suitable connections is not currently available. Much research has been devoted to solving this problem, yet an adequate solution has not yet been found [1, 2, 3, 4]. The most common method to achieve fluidic connections is to manually align and glue tubing to ports. Numerous disadvantages plague this method including low yield, complex assembly, misalignment, large footprint, and difficulty of salvaging used components. In an effort to develop standardized MEMS connections, device-independent prefabricated fluidic couplers have been conceived [5].

Design

Directly attaching tubing to fluidic ports has proven to be an extremely difficult and unreliable way to achieve a fluidic connection. By introducing an intermediate piece that accurately mates the tubing and port, this problem can be avoided. Micromachined fluidic couplers serve as a convenient intermediary between external fluidic plumbing and the inlet/outlet ports of a fluidic device. They are discrete silicon structures consisting of alignment structures and sleeves that enable geometrically matched fits to fluidic ports and tubing. A single fluidic connection to an array of fluidic ports using such a coupler is shown in Fig. 1,

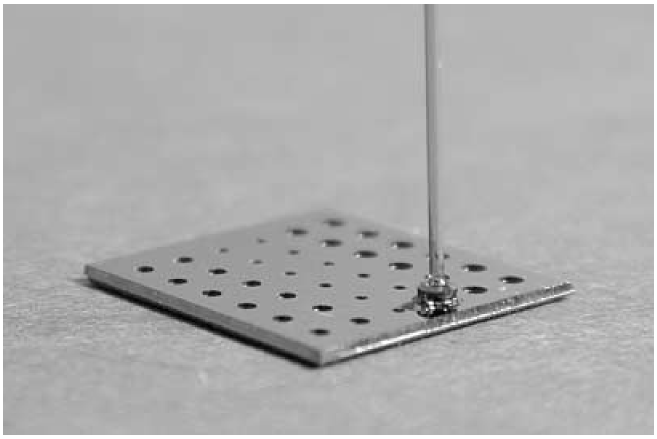

Fig. 1 Post coupler attached to a fluidic port

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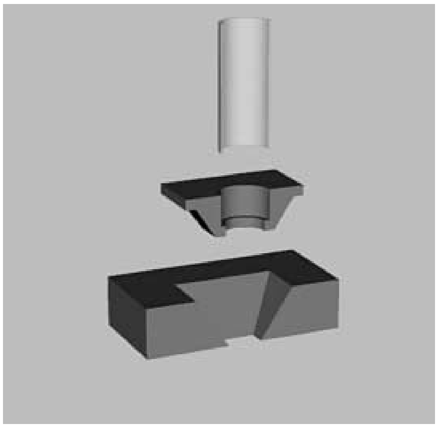

Fig. 2 3D Exploded cross-sectional view of a bulk coupler assembly

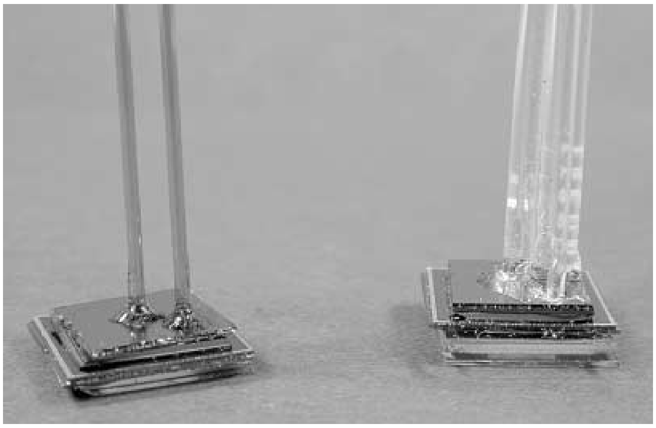

Fig. 3 Comparison of a conventional fluidic interconnection and our method

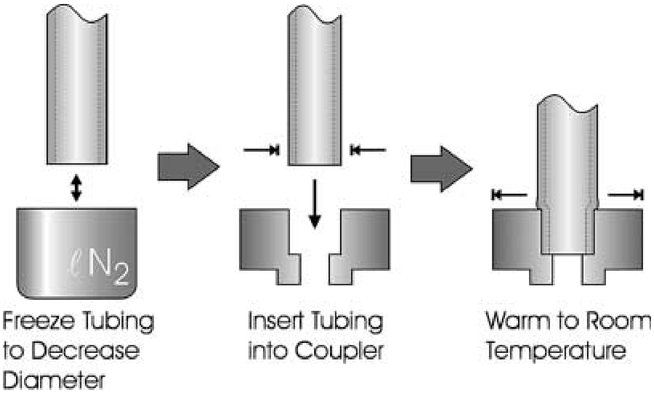

Fig. 4 Process flow for the cryogenic insertion technique

and the interlocking nature of the couplers is depicted in Fig. 2. The spatial advantages gained by using couplers, compared with traditional manual coupling techniques, is demonstrated on thermopneumatic valves from Ref. [6] in Fig. 3. In addition to alignment structures, stepped sleeves that serve as a tubing insertion depth guide can also be included in the couplers.

Both fused-silica capillary and PEEK (polyetheretherketone) tubing can be used with couplers. These were chosen for their ease of use and wide range of commercially available plumbing accessories. Adhesive can be used to connect couplers to tubing, however, when the dimensions of the mating receptacle are appropriately calibrated, cryogenic insertion is also an option (Fig. 4). By means of this technique the tubing size can be reduced by cooling it in liquid nitrogen or other similar agent for ease of insertion into a coupler. Previously, couplers were individually attached to fluidic ports by means of adhesive [7]. This approach is time-consuming, inconsistent, and extremely inconvenient. To mitigate these issues, a batch process was developed (Fig. 5). By using Crystalbond, a thermoplastic adhesive, wafer level spray coating to thousands of couplers at once is achieved. The thermoplastic nature of Crystalbond enables easy attachment and removal of parts by thermal cycling. Alternatively, couplers can also be molded with a thermoplastic material and subsequently re-flowed to form a connection. It is also possible to use other adhesive joining methods, and solder and eutectic bonding at the coupler-to-I/O port interface. Modified couplers with fitting structures at both ends of the capillary can also be used to concatenate microfluidic devices.

Fluidic ports are typically created by anisotropic etching, drilling, or DRIE (deep reactive ion-etching). The geometries associated with these fabrication methods dictate coupler design. Various coupler designs stem from two common geometries encountered in MEMS fluidic devices (Fig. 6). The first incorporates the truncated pyramidal geometry associated with anisotropic etching. Although it is possible to glue tubing directly to pyramidal pits, leakage paths because of mismatch (non-interlocking halves) result in clogging when less viscous adhesives are used. In addition, each of these structures can be designed with a shoulder to constrain the usable height of the coupler. The second scheme can be used with fluidic ports of circular cross-section that are formed by drilling or DRIE. Furthermore, by using DRIE, virtually any cross-sectional port or tubing geometry can be matched. Each of these designs incorporates alignment structures and has a low dead volume, and only a minimum amount of adhesive is exposed to fluid flow.

Fabrication

Three types of coupler using different sizes of capillary and PEEK tubing have been fabricated. Process flows for fabricating the various types of couplers are shown in Figs 7, 8, 9.

Bulk coupler

Bulk couplers are formed by taking advantage of the structures formed when anisotropically etching silicon. The name “bulk couplers” arises from the use of bulk mi-

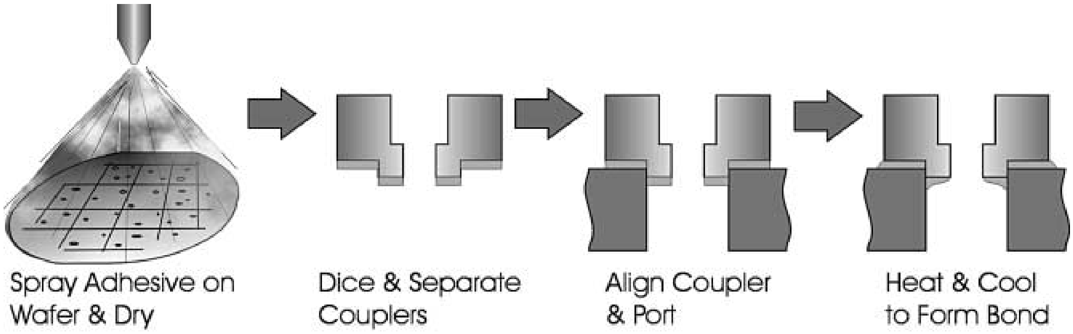

Fig. 5 Process flow for the thermoplastic spray-coating technique

Fig. 6 (**a**) Bulk, (**b**) molded, and (**c**) post couplers with capillary tubing

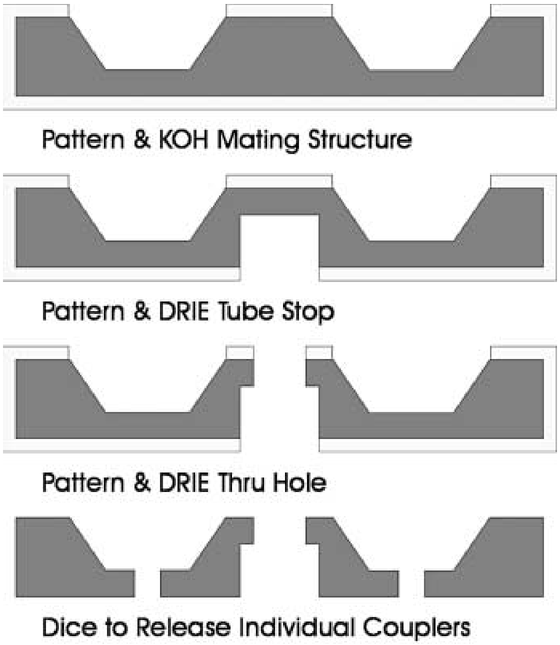

Fig. 7 Bulk coupler process flow

cromachining techniques to fabricate these structures (fabricating structures by etching into the substrate material). First, oxidized silicon wafers (~1.5 μm) are patterned and etched in KOH (potassium hydroxide) until islands approximately 270 μm high are formed. These islands form the basic bulk coupler structure. Press-fit pits for tubing are then etched into the center of these islands by DRIE. Depending on the application, a stepped pit can be formed by leaving approximately 50 μm silicon then etching a smaller diameter hole through the remaining silicon. This additional shoulder forms a tubing stop and is shown in Figs 10 and 11.

As is evident from the desired geometry, corner compensation is required to fabricate bulk couplers. Two schemes were investigated and etching results are shown in Fig. 12. The merits of each method are described in Refs [8] and [9], respectively. Additional features in Fig. 12a, b are artifacts attributed to the DRIE of masking gaps, because of poor photoresist step coverage. Although a certain amount of undercut is observed for both convex corners, slight modifications to the etch mask and careful attention to etching progress should eliminate these features.

Molded bulk coupler

Molded bulk couplers are a variation on the standard bulk coupler and are fabricated from two bonded wafers (Figs. 8 and 13). One is an oxidized wafer etched with KOH to create through-holes; the other wafer is DRIEd to form an array of circular pegs. These pegs form alignment structures for tubing. By bonding these two structures together

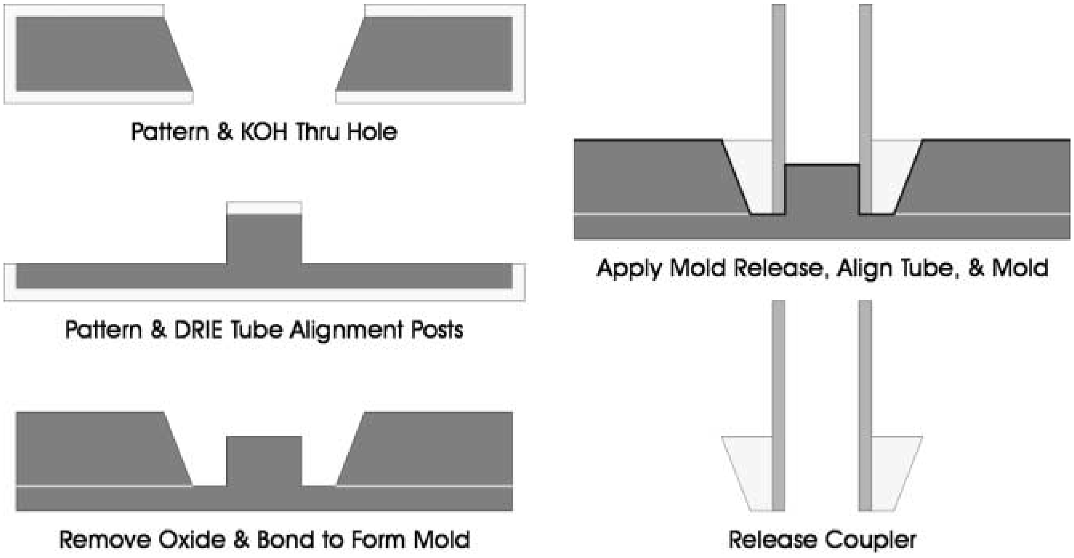

Fig. 8 Molded coupler process flow

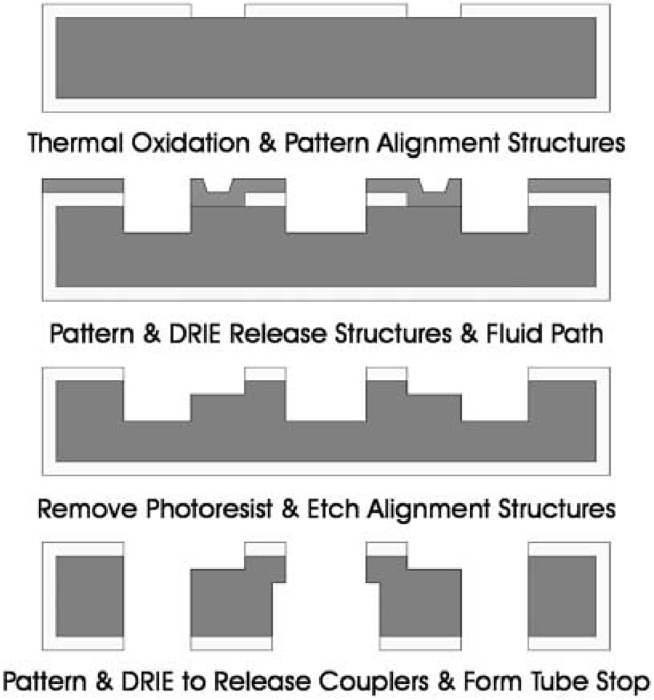

Fig. 9 Post coupler process flow

and coating with a PTFE (polytetrafluoroethylene)-based release layer, a mold is formed. The release layer facilitates removal of the molded coupler from the mold structure and prevents adhesion of the molded coupler to the mold. It is also possible to substitute other types of mold-release layers. Plasma-deposited Teflon and Parylene C are also being investigated as candidates for mold-release layers. Moldings are realized by melting raw material such as a hot-melt polyolefin around fused silica tubing fitted on mold posts. When the polyolefin material has cooled, couplers can be release simply by pulling them

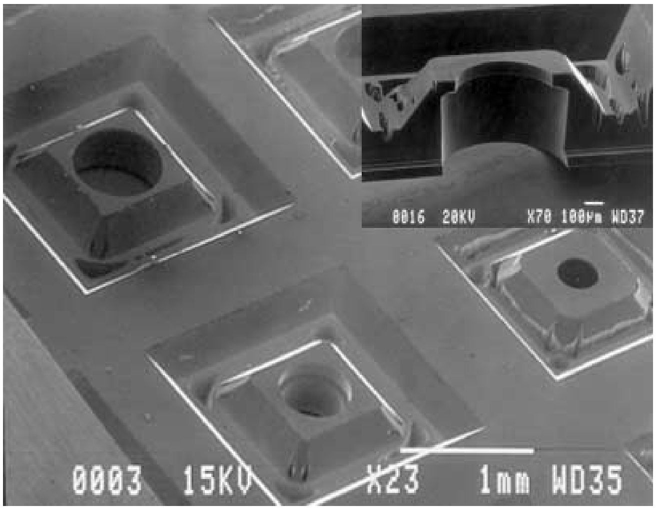

Fig. 10 SEMs of bulk couplers

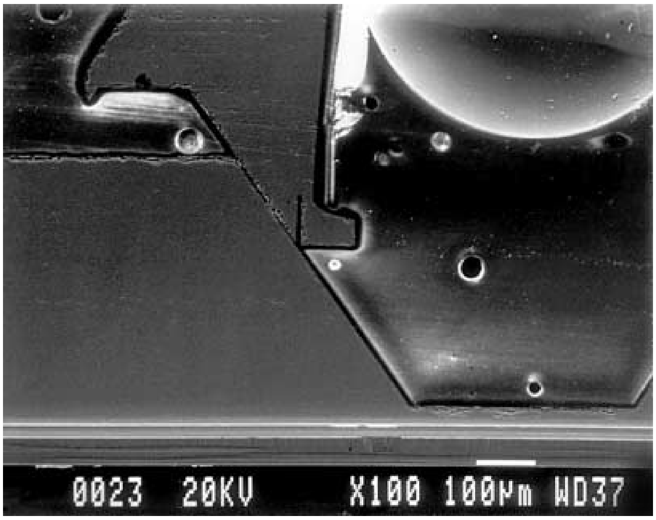

Fig. 11 Cross-sectional SEM view of an assembled bulk coupler

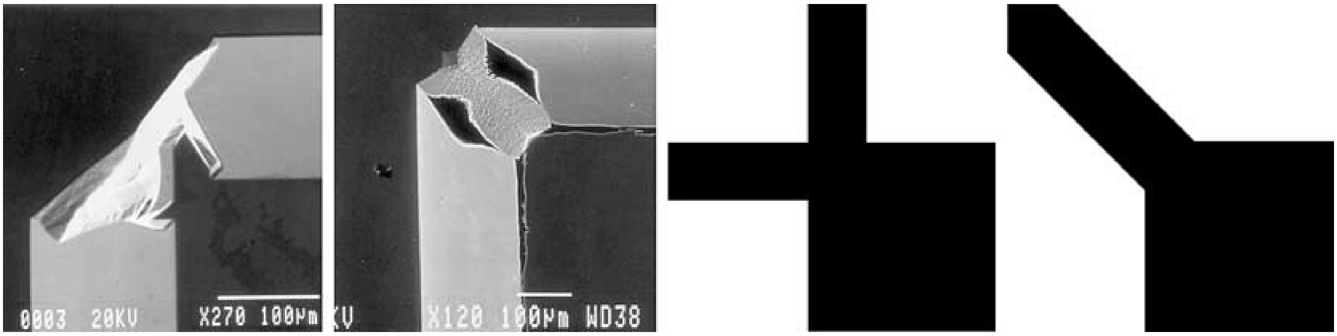

Fig. 12 (**a**) and (**b**) Corner compensation structures with respective mask layouts (**c**) and (**d**)

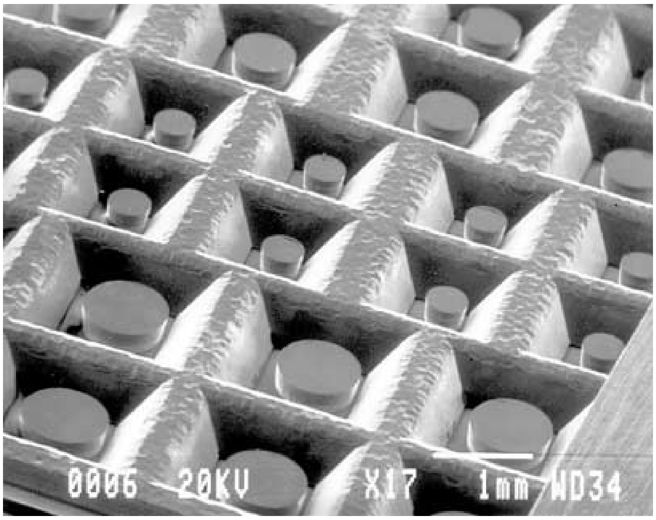

Fig. 13 SEMs of coupler molds

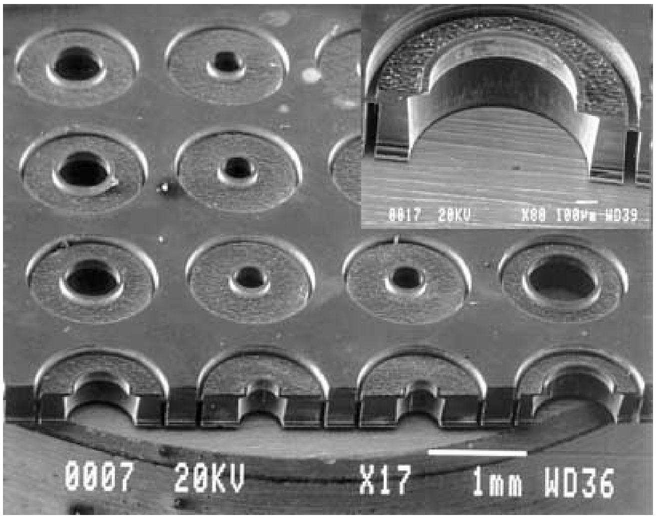

Fig. 14 SEMs of post couplers

away from the mold. Released structures are then attached to fluidic ports simply by re-heating the polyolefin, enabling it to reflow and adhere to the silicon port. In applications where heating is unacceptable, adhesive joining can be used. An advantage of using these couplers is the reduction in fabrication costs afforded by a reusable mold and polymer structural material.

Post coupler

The nature of DRIE processing enables flexibility in creating two-dimensional geometries across a wafer surface. A two -dimensional feature corresponding to the desired coupler geometry can be defined and etched in silicon. Thus, post couplers (Figs 9 and 14) can be used with virtually any fluidic port and tubing. Here, a generic process flow is described and the process flow for a cylindrical coupler is depicted.

First, an opening is defined in an oxidized wafer to form a tubing insertion depth guide. Then alignment structures and tube receptacles are etched. Tubes are then press-fitted into the receptacles and joined to a fluidic port.

Testing

To determine the failure point and the operating range, blocked couplers were pressurized using filtered (0.1 μm) nitrogen gas from a cylinder (Fig. 15). The testing equipment was constructed from stainless-steel Swagelok plumbing to withstand high pressures of the order of 1000 psig. PEEK and Valco stainless-steel high-performance liquid chromatography (HPLC) fittings were used to connect the small-diameter PEEK and fused-silica capillary tubing

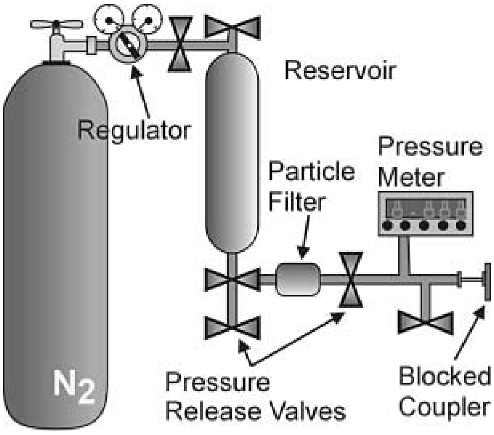

Fig. 15 Schematic diagram of testing equipment

Table 1 Comparison of different methods of fluidic coupling

Description of Coupler	Operation Range	Refs
Silicon finger microjoint with silicone gasket and Tygon tubing	>30 psig (210 kPa)	[1]
Silicon/plastic coupler with silicone gasket and capillarytubing	~60 psig (415 kPa)	[2]
Silicone gasket sealed silicon coupler with capillary tubing	~80 psig (550 kPa)	[4]
Silicon sleeve coupler with capillary tubing	~500 psig (3550 kPa)	[2]
Polymer coupler with fused capillary tubing	~900 psig (6200 kPa)	[5]
Silicon coupler with cryogenically inserted PEEK tubing	>1300 psig (8960 kPa)	This work
Silicon coupler with fused capillary or PEEK tubing	>1300 psig (8960 kPa)	This work and [5]

from the coupler to the rest of the pressure-testing equipment. Pressure was measured by use of an Omega PX120–2KGV pressure transducer in conjunction with an Omega DP25-S strain gage panel meter.

Bulk and post couplers with capillary tubing were able to withstand at least 8963 kPa (1300 psig). This corresponds to the maximum measurable pressure of the experimental apparatus. Post couplers with cryogenically inserted PEEK tubing were also tested and are identical in performance with couplers with glued tubing. Molded couplers, however, failed at approximately 6200 kPa (900 psig) because of poor bonding between the molding material and the capillary. These results are summarized and compared with other work in Table 1.

Discussion

Determination of the failure load of the adhesive joint between the coupler and the fluidic port is a difficult problem because of complex joint geometry and the inability to ascertain the exact failure mechanism(s). General observations concerning the design and resulting mechanical behavior of the joints can be made, however. To maximize strain capability and toughness of adhesives, joints are ideally designed such that compression and shear are more dominant than tension, cleavage, or peel stresses. Thus, post couplers are expected to have better performance, because compression and shear have the largest stress contributions under loading. In addition, the surface roughness accrued during the DRIE process promotes mechanical interlocking and increases the surface area available for bonding. Bulk couplers, however, experience a combination of tension and shear stresses. By using liquid adhesives, the excess adhesive squeezed from the joint, or spew fillet, can provide the added benefit of reducing the stress concentration at the edges of joints, further increasing overall strength [10].

Conclusion

To create standardized microfluidic connections to MEMS fluidic devices/systems, micromachined fluidic couplers have been designed, fabricated, and tested. These couplers are compatible with PEEK and fused silica capillary tubing and are capable of withstanding pressures up to 8963 kPa (1300 psig). These couplers can also be used with typical fluidic ports and can, if necessary, be customized for use with special geometries.

Acknowledgements The authors would like to thank Mr Tuan Hoang for help with proofreading and Mr Trevor Roper and Mr Hung Bui for assistance with fabrication.

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