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METAL TRANSFER MICROMOLDING (MTM) PROCESS FOR HIGH-ASPECT-RATIO 3-D STRUCTURES WITH FUNCTIONAL METAL SURFACES

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ABSTRACT
A three-dimensional (3-D) metal transfer micromolding (MTM) fabrication process for low-cost, manufacturable, high-aspect-ratio MEMS structures with a patterned metal layer for electrical and biological functionalities is presented in this paper. The mechanism of MTM lies in the differences in adhesion strengths between mold-metal and replica-metal interfaces. This is an extension of a non-covalent 2-D nanotransfer printing (nTP) process and enables a simultaneous replication of high-aspect-ratio 3-D structures from a mold in a single polymer molding process. The conductive layer is patterned at this same step, enabling the resulting structure to have a patterned electrically/biologically functional 3-D metallic layer defined on the high-aspect-ratio polymer structure. This metallic layer on the polymer device has been utilized as a bio-compatible site for cell culturing, an electrode for spontaneous recording from cells and for RF MEMS functionalities. Thus combining the virtues of a conventional micromolding process such as the large-area, high-throughput, and low-cost with simultaneous transfer of patterned metal layer, the MTM process can be applied to a wide range of applications in the chemical, high-frequency, and biomedical areas.

INTRODUCTION
Electrically and biologically functional 3-D microstructures have a wide range of potential applications in biomedical, chemical, physical, and electronic areas. One way to implement these microstructures is to use non-conducting materials such as polymer or ceramic for structural fabrication, and use electrically conducting materials such as metal, conductive polymer, conductive oxide etc. for layer deposition and patterning, which will allow the device to have electrical functionality. Alternatively the MTM process utilizes surface properties of materials involved and in essence combines the two above-mentioned processes resulting in intricate, high-aspect-ratio structures that can be cost-effectively implemented with relative ease as compared to traditional micromachining approaches. Micromolding has developed as one of the most promising fabrication technologies for developing complex 3-D structures. Unlike traditional LIGA processes or even the cheaper SU-8 based LIGA process micromolding-based approaches are less expensive (no need for X-Ray sources or specialized masks) and offer flexibility in choice of materials involved. This can be based on the desirable dielectric, mechanical and thermal properties, required in the device of interest. However, selective metal patterning for electrical/biological functionality on the high-aspect-ratio 3-D structures which are fabricated using conventional micromolding, LIGA and/or photolithography approaches is a challenge.

In this paper, a MTM process is introduced for patterning a metal layer in the implementation of electrically/biologically functional 3-D structures. The MTM process takes advantage of the large-area, high-throughput, and low-cost nature of micromolding. The simultaneous fabrication of high-aspect ratio structures with electrical/biological functionalities is implemented using an *in-situ* metal transfer step during the micromolding process. This enables the process to be versatile for various applications. Several applications using proposed MTM process: high-aspect-ratio polymer pillars coated with metal for solid fuel combustion, a polymeric microstructure with metallized surface for tissue engineering, electrically/biologically functional 3-D structures for biomedical applications and metal-patterned and air-lifted radio-frequency (RF) components are introduced in this paper.

METAL TRANSFER MICROMOLDING (MTM)

The ideal fabrication technique for the functional 3-D microstructures should have the following requirements: extremely low cost and high precision, flexibility in the choice of materials (eg. bio-compatible polymers for biomedical applications), and ease of metal patterning in micro-scale structures.

A conventional micromolding process, which is considered to meet most of these requirements, is composed of master fabrication, mold preparation, and casting to form the final device. In the MTM process, an additional step is introduced: a metal is pre-patterned in the mold, and then is simultaneously transferred to the final device during the casting step. Similar to nTP [1], the proposed MTM process is also based on the different strengths of nonspecific adhesion between the polydimethylsiloxane (PDMS)-metal and polymer-metal interfaces, extending the non-covalent 2-D metal transfers to 3-D. This is accomplished primarily due to the extremely low surface energy (19.8 mJ/m^2) of the PDMS. The adhesion strength of the metal-PDMS interface is weaker than most other metal-material interfaces. The MTM process is schematically illustrated in Fig.1 and described in the next section.

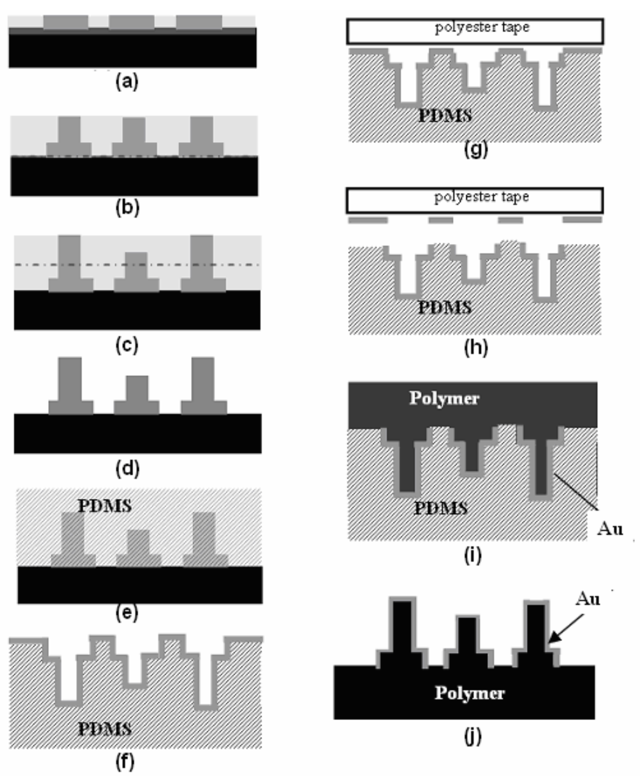


Figure 1: MTM process flow

Mold Master Fabrication

A master structure is initially fabricated and can be repeatedly used to generate multiple batches of molds and devices. There are many approaches for master structure realization, including conventional photolithography on either thick or thin resists, inclined UV lithography [2], and stereolithography. Photolithography of the negative-tone epoxy SU-8 to make high aspect ratio 3-D structures is a popular technique in the MEMS community. Curvature in different planes can be introduced in 3-D shapes by changing mask patterns in 2-D and utilizing inclined UV lithography offering another advantage to this process as opposed to traditional lithographic techniques. A typical multilayer fabrication process is shown in Fig. 1(a)-(d). A first layer of SU-8 is patterned to define a planar structure (Fig. 1(a)). Then several layers of SU-8 are sequentially patterned to define the 3-D structures with differing height as shown in Fig. 1(b), (c). After multi-exposures and subsequent baking steps, the 3-D structure is realized in one developing and curing step (Fig. 1(d)).

Mold Preparation

After the master is fabricated, a negative mold is created by casting and curing a suitable molding material, such as PDMS, around the master, as shown in Fig. 1(e). The mold is then separated from the master structure.

Mold Metalization

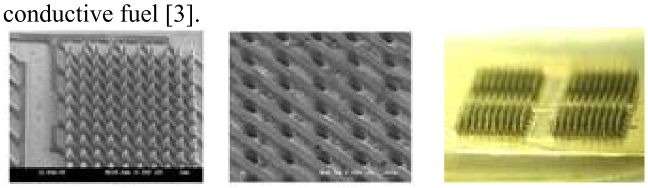
The PDMS mold is then coated with a thin metal film (usually 300nm–500nm Au or Ti/Au/Ti multilayer) by e-beam or sputter deposition (Fig. 1(f)). The patterning of the deposited metal is performed by removing the metal film on the raised regions of the PDMS mold by bringing it into contact with a flat, smooth substrate that has a higher surface-energy (Fig. 1(g)) than PDMS. The higher surface-energy substrate leads to "wetting" and eventual adhesion of the metal to the substrate and is then gently peeled off, resulting in the transfer of metal in the raised region while metal in the recessed regions of the original PDMS mold remains, as shown in Fig. 1(h). The 3-D regions are isolated in this step. No subsequent patterning on 3-D surfaces is required.

Metal Transfer Micromolding

Finally, a polymer in the liquid state is cast into the PDMS mold (Fig. 1(i)). Although standard injection molding approaches can be used in this step, a vacuum and heat treatment approach is used in order to ensure the full wetting and filling of the polymer into the PDMS mold. Further, the patterned metal layer on the recessed regions of the mold modifies the surfaces to hydrophilic, which helps the wetting process. After the cast polymer is solidified, the PDMS mold is peeled off and the metal film, which was originally on the recessed region of the mold, is completely transferred to the molded part (Fig. 1(j)). The 3-D patterned and transferred metal is then optionally thickened using either electrodeposition or electroless deposition of appropriate metals.

Several polymers that are widely used in replica molding have been utilized for the demonstration of the 3-D MTM process: polymethyl methacrylate (PMMA) and polyurethane (PU); biodegradable polymers such as poly(L-lactic acid) (PLLA); photo-curable epoxy resin such as stereolithography (SLA) resin; and epoxy based negative photo resists such as SU-8. The metal films can be completely transferred from PDMS to the above-mentioned cast polymers. The transferred metal film on the cast polymers shows similar adhesion strength to the metal film directly deposited on the polymers based on scotch™ tape adhesion tests.

Figure 2 shows SEM and optical microscopic images of a molded array of micro pillars coated with a metal film using the MTM process. In this example, the micro pillars were created for a solid-fuel micro-combustor. Here, gold was used as the choice of material for the metal film. The pillars were electrically interconnected in a diagonal pattern and the feasibility of the device was demonstrated as a metal-coated polymer combustor for the ignition and reaction of the solid conductive fuel [3].



(a) (b) (c)

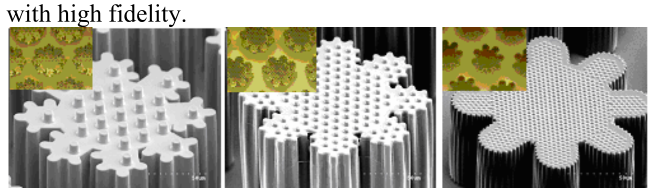
Figure 2: An array of electrodes (100 μm diameters) molded by photocurable epoxy resin. (a) Master structure by SU-8 (b) PDMS mold (c) molded epoxy resin structure with transferred gold on the surface

APPLICATION I: UNITARY POLYMERIC MICROSTRUCTURES WITH METALLIZED SURFACES FOR TISSUE ENGINEERING SCAFFOLDS

The developed MTM process is very useful in biological applications where complex 3-D, mostly polymeric structures, which require microtexturing and use of tissue-friendly materials for the electrical/chemical functionalities [4]. In biological applications, PDMS is particularly used widely as the choice of material for molding based on its high fidelity, chemical inertness, biocompatibility and ease of processing. However, the high surface hydrophobicity of PDMS often prevents a cast polymer from wetting the mold conformally and results in the failure of attainment of high-aspect-ratio microstructures through micromolding. As a solution, many approaches have focused on the modifying the hydrophobic PDMS surface to a hydrophilic surface by treating the surface with oxygen plasma [5], corona discharges [6] and ozone assisted UV irradiation [7]. However, these approaches often increase the difficulty of the demolding process due to the strong adhesion between the PDMS mold and the cast replica.

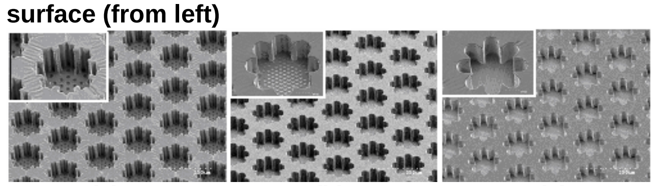
In order to increase the ease of the demolding process while maintaining some level of adhesion between the mold and the replica, thin metal layer deposition on the mold can be an attractive alternative to the above-mentioned surface treatments of the PDMS mold. In the proposed MTM process to fabricate 3-D structures for biomedical applications, a thin bio-compatible metal layer such as gold is conformally deposited on the surface of the complex, high-aspect-ratio PDMS mold before casting the replica material into the mold. Upon the demolding process, the gold layer is completely transferred to the replica polymer due to the superior adhesion of metal-replica polymer as opposed to metal-PDMS. This step acts as a substitute for the above-mentioned surface treatment processes in addition to providing biocompatibility, and enhancement of the chemical inertness of the molded replica [8].

A typical two-step SU-8 photolithography process is used for mold-master fabrication. As shown in Fig. 3, three SU-8/Si mold-masters with 10, 5, 2 μm protrusion features on top of 150 μm-tall columns (with small salient features of 10, 5, and 2 μm along the column sidewall) were successfully fabricated. PDMS is cast against this mold master and then cured to form the mold that can be used repeatedly. A 100 nm thick gold layer is deposited on the PDMS mold as shown in Fig. 4. Then, PU is cast into the mold and cured. During the demolding of PU from the PDMS mold, the thin gold layer is completely transferred to the PU replica as shown in Fig. 5. The replicated PU structures bearing 10, 5, and 2 μm features on 150 μm "snow-flake structures" were successfully demolded from the PDMS mold with high fidelity.



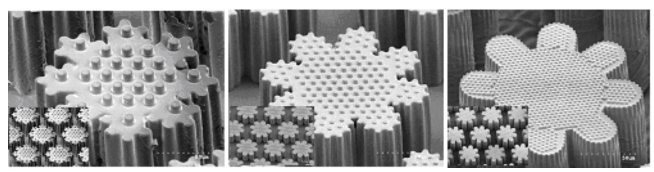
(a) (b) (c)

Figure 3: SU-8 master structure on silicon substrate: 150 μm tall columns with 10, 5, and 2 μm salient features on sidewall and protrusions on the top surface (from left)



(a) (b) (c)

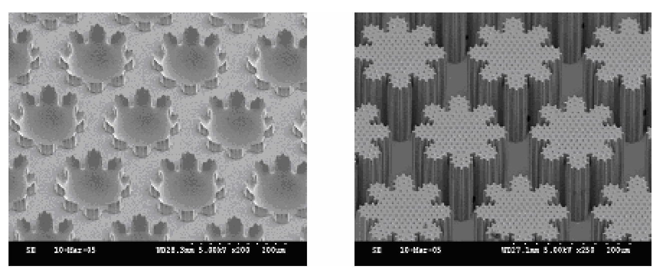
Figure 4: Elastomeric PDMS mold coated with Au: column wells with 10, 5, and 2μm salient features on sidewall and dimples on the bottom (from left)



(a) (b) (c)

Figure 5: PU structure from Au coated PDMS mold with metal transfer with 10, 5, and 2μm salient features on sidewall and protrusions on the top surface (from left)

Figure 6 (a) shows partial wetting of PDMS mold by the replica material (without gold), resulting in only partial replication of the mold shape.



(a) (b)

Figure 6: (a) PU cast from Au coated PDMS mold with metal transfer and (b) from a PDMS mold without metal coating

However, when a gold layer is introduced as an intermediate metallization layer on the mold, it greatly increases the hydrophilicity of the PDMS surface, resulting significant enhancement of the wettability of the replica material (PU). Figure 6(b) shows the gold-coated PU structures replicated from the PDMS mold using the proposed MTM process.

APPLICATION II: 3-D MICROELECTRODE ARRAYS FOR BIOMEDICAL APPLICATIONS

Microelectrode arrays (MEAs) are vital tools for the analysis of electrically active cells and cellular networks. Several two-dimensional (2-D) MEAs have been reported for stimulation and recording [9] from brain slices using conventional substrates such as silicon and glass. However there is a recent shift away from silicon and toward using polymeric substrates such as PDMS [10] and parylene [11] for microfabrication of 2-D MEAs. Traditional MEAs are planar or two-dimensional (2-D) and are limited in their ability to stimulate cells and record biological signals from 3-D *in-vitro* cultures that are closer to the morphological organization of the brain. It has been reported that three-dimensional (3-D) MEAs show improved performance and increased data capture of electrical activities of *in-vitro* neuronal cultures compared to their 2-D counterparts [12]. Brain slices tend to have substantial 3-D structure making it imperative that they be studied with 3-D MEAs. Although success in 3-D MEA fabrication has been reported using assembly approaches [13-14], integrated microfabrication remains as a major challenge. The main limitation is in performing lithography on 3-D surfaces that are 500µm-1mm above the planar surface. MTM technology was evaluated to solve this problem as it can simultaneously form 3-D high aspect ratio structures with patterned metal on these structures. The MTM process can be a useful tool for fabricating 3-D MEAs with varying electrode heights in an integrated fashion, which makes it possible to record from several points along the z-axis in a slice culture/3-D co-culture. A schematic representation of a 3-D MEA is shown in Fig. 7. It depicts a 5x5 array of metallized towers in the center of the chip and electrodes at the bottom of each tower (2-D counterparts). The height of the proposed electrodes is 300-500µm which is far greater than what has been reported by integrated fabrication approaches [12, 15].

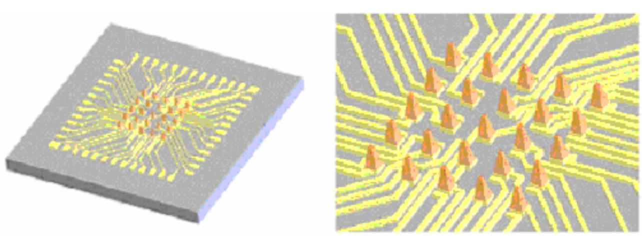
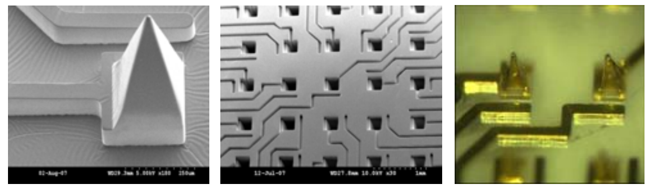


Figure 7: Schematic of the proposed 3-D MEA

Microfabrication of the MEA is described in detail elsewhere [16]. Briefly, a 2-layer SU-8 mold is fabricated using inclined UV lithography and planar lithography respectively. This is copied twice using micromolding to form the same shape in PDMS. A SEM of the final mold is shown in Fig. 8 (b). This mold is metallized and patterned using a high surface energy plate (similar to the description in Application I). A target polymer (PU, PMMA or SU-8) is then cast and processed. During this process, the metal is transferred from PDMS onto the target polymer, and the 3-D MEA is demolded from the PDMS structure. SEM and optical images of the 3-D MEA are shown in Fig. 8 (a) and (c). Electrodes are embedded in both the base layer and at the tips of the pyramids, offering two levels of electrodes in the z-plane. The MEA is further packaged and insulated using a 10µm thick layer of parylene. Recording sites are defined using a combination of excimer laser micromachining and RIE etching. Platinum is electrodeposited on the recording sites.



(a) (b) (c)

Figure 8: (a) SEM image of a 3-D and 2-D electrode; (b) SEM image of the SU-8 mold; (c) Optical image of a PU 3-D MEA

The packaged 3-D MEA is electrically evaluated using impedance spectroscopy. Figure 9 shows impedance results before and after platinum plating. The results show a clear drop in impedance (as expected) due to the plating process. The details of these processes are described elsewhere [17].

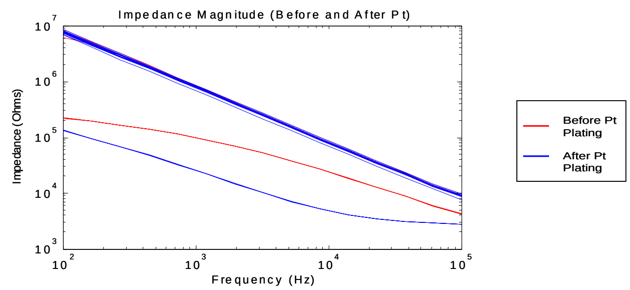


Figure 9: Electrical impedance spectroscopy results of the 3-D MEA before and after platinum plating.

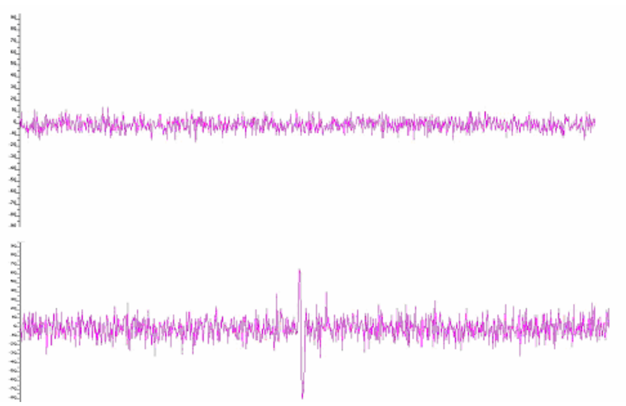
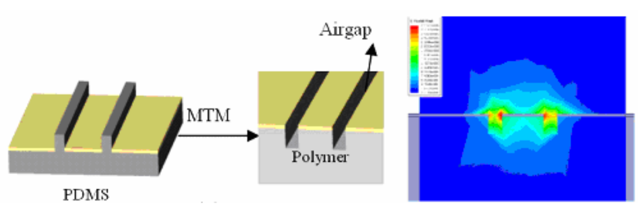


Figure 10: Baseline noise of the system (above) and spontaneous spike recordings from hippocampal slices of 10 day post-natal rat pups (below).

Electrophysiological spike recordings from 10 day post natal rat pups are demonstrated, as shown in Fig. 10. The tissue slices for these experiments are derived from the hippocampal region (of the brain) of decapitated rat pups. The slices are arranged on the 3-D MEA with a buffer and spontaneous extracellular measurements are performed by interfacing the packaged device (with slices) with commercial Multichannel Systems (MCS) recording pre-amplifier and software. Spike recordings greater than ±50μV are clearly distinguished above the baseline noise of the system as shown in Fig 10.

APPLICATION III: METAL PATTERNED AND AIR-LIFTED RF DEVICES

An implementation of micro RF components can be a good application for the developed MTM process since it requires 3-D structures with conductive metal layer for electrical functionality. Planar millimeter-wave components such as microstrip antennas or resonators are widely used because of their ease of manufacturing, low cost, simple fabrication, and relative ease of integration with monolithic systems. However, those printed-circuit passive components suffer from substrate dielectric loss, mutual coupling with the substrate, and surface wave perturbation issues [18]-[20]. Air-lifting of the RF components is considered to be an alternative method that can resolve all of these problems [21]-[23]. Also, the integration of air-lifted RF components and CPW transmission lines can greatly help the shrinkage of the RF front-end system. Thus, the applications of the MTM process for the fabrication of low-cost organic millimeter-wave components have been explored.



(a) (b)

Figure 11: (a) MTM process of coplanar waveguide (CPW) with air gap (b) simulated E-field in the air-gap CPW

Transmission lines are the basic interconnect units in RF systems. Particularly, coplanar waveguide (CPW) geometry is widely used as electrical feeding lines in many RF modules, primarily because of its simple processing requirements with no via holes, as well as its capability for integration with active devices. Using the proposed MTM process, a CPW transmission line with air gap can be directly formed on organic substrates without any subsequent processes. A schematic view of the fabrication process for CPW structures using MTM is shown in Fig. 11(a). As mentioned earlier, the metal film on the bottom of the mold transfers to the target polymer during the micromolding process. Metal on the raised region of the PDMS mold is removed by using a high surface-energy substrate, such as polyester tape. This process uniquely forms electrically isolated air gaps that reduce the substrate coupling and the subsequent loss. The simulated electric field distribution of the MTM-fabricated CPW is given in Fig. 11(b), which shows that the electric field is mainly confined between the edges of the metal lines. Due to the air gaps between metal lines, most of the substrate coupling occurs in the regions with dense electric field, thus reducing coupling and subsequent loss [24, 25].

Filters are also key components in many RF applications. A CPW band-stop filter is first designed and fabricated using the proposed MTM process. This filter is designed based on the triple-folded CPW short stub resonator to minimize the size of the filter [26]. The stub length is λ/12 at 30 GHz with the width of each stub finger at 50μm. The schematic design of the filter is shown in Fig. 12 (a). The optical microscopic photographs of the fabricated structures are presented in subsequent figures (Fig. 12(b)-(e)). The fabrication process for the filter is similar to the CPW component. The molded structure and the final filter array after electroplating on a flexible epoxy substrate are shown in Fig. 12(d), and 12(e), respectively. The characteristics of the MTM molded filters with 35μm air gaps are measured and plotted in Fig. 12(f). From the experiment, the insertion loss (S21) is observed to be less than 2.5 dB in pass-band. The insertion loss in stop-band is approximately 20dB which is very close to the HFSS simulation. The loss in pass-band is primarily due to the high loss tangent of epoxy materials. Results from the band-pass-filter (BPF) demonstrate that planar components such as CPW transmission lines and stub filters can be successfully fabricated using the MTM process.

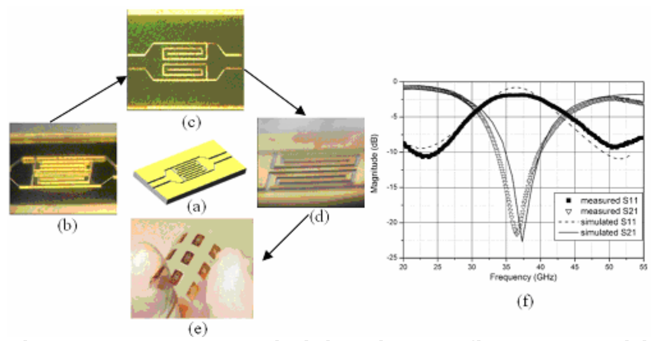
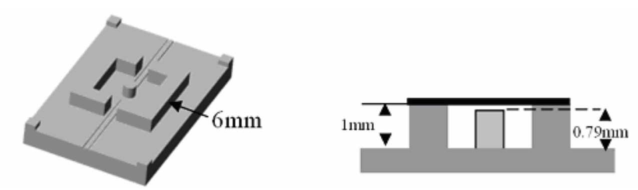


Figure 12: MTM molded band stop filter array: (a) schematic design (b)-(e) fabrication flow of devices (f) measured and simulated S11 and S21

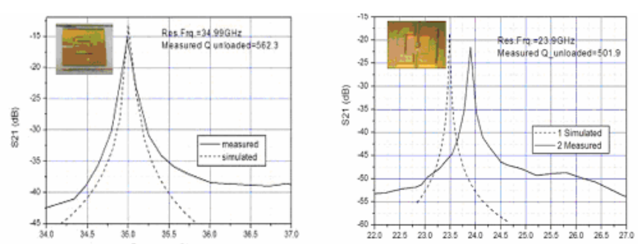
The integration of a CPW transmission line and an air cavity resonator is further demonstrated. One of the major millimeter-wave components is the high Q resonator. Such resonators are required in many applications such as local-area-networks (LANs), point-to-point communications, automotive radar, and RF sensors. Although there have been recent efforts to develop cavity resonators with high Q performance, conventional microwave high Q resonators (mostly made by metallic rectangular or cylindrical waveguides), are heavy, large, and expensive to manufacture. Furthermore, they are not easy to implement with monolithic integrated circuits. With the advent of micromachining techniques, it is now possible to make miniature micromachined waveguides or cavities [27, 28] as building blocks for the development of high-Q resonators or filters. The quality factor that can be achieved with this technique is much higher than the quality factor of traditional microstrip resonators either printed on a dielectric material or suspended in air with the help of a dielectric membrane. Although the most widely used fabrication technique for a cavity resonator is silicon micromachining, the cavity dimension is limited due to the thickness of silicon wafers and the time-consuming etching process. The proposed MTM technique which includes the fabrication of complicated high-aspect-ratio polymer component with *in-situ* patterned metal is very attractive to this application since it achieves small size and cost-effective manufacturing.

Figure 13 shows the schematic view of a CPW fed evanescent-mode cavity resonator. The cavity with a capacitive post as well as CPW fed lines is designed to be 6mm wide and 1mm high and is fabricated utilizing the MTM process. Compared with the usual half-wavelength cavity-based resonators, evanescent-mode resonators have advantages such as a smaller size and an improved spurious-free region [29]. By loading a resonant cavity with a capacitive post, the resonant frequency of the cavity can be reduced, while still maintaining a reasonably high unloaded Q factor [30]. The fabricated devices and characterization are shown in Figure 14. Due to the small fabrication tolerances of molding process, the dimension deviation of the molded structures is less than 2% from the mold master structures. In the design, the resonant frequency is significantly reduced from 35GHz to 24GHz due to the evanescent mode excited by the small gap (210μm) between the top of the capacitive post and the top of the cavity. For a given frequency of operation, a 45.8% size reduction has been achieved. The measured resonance shows good agreement with the HFSS simulation. High unloaded Q of more than 500 for both cavity resonators have been achieved (562.3 for half-wavelength cavity and 501.9 for evanescent mode cavity).



(a) (b)

Figure 13: Schematic of the CPW fed cavity resonator design (a) lateral view (b) side view



(a) (b)

Figure 14: Characteristics of MTM fabricated cavity resonators (a) conventional cavity resonator (b) evanescent-mode cavity resonator

CONCLUSIONS

We have demonstrated a three-dimensional (3-D) metal transfer micromolding (MTM) fabrication process for high-aspect-ratio structures with an *in-situ* metal transfer process that is achieved during the micromolding step. This process enables simultaneous fabrication of metallic functional sites with the micromolded polymer structures and is useful for the implementation of electrical and biological functionalities 3-D structures. Since the MTM process adopts the advantages of conventional micromolding process such as the large-area, high-throughput, and low-cost with simultaneous patterned-metallization process, it can be applicable to a wide variety of applications in the chemical, high-frequency, and biomedical arenas.

We have demonstrated that the MTM technique is very promising in the fabrication of biomedical micro instrumentation for scaffolds (to support cell growth) and 3-D MEA (to record from hippocampal tissue slices). Further we have demonstrated organic air-lifted RF component for the applications in the RF wireless communication modules or wireless passive sensors. In conclusions MTM process is a unique MEMS fabrication approach that addresses the device needs of many MEMS communities as it is a high-throughput, low cost mass-manufacturing approach.

ACKNOWLEDGMENTS

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