FABRICATION OF SUSPENDED POLYMER MICROSTRUCTURES USING SACRIFICIAL LAYER MICROMOLDING AND PATTERNED SUBSTRATE MICROMOLDING

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ABSTRACT

Two soft lithography based fabrication techniques were employed for fabricating mechanically independent, freely suspended polymer microstructure from poly(n-propyl methacrylate) (PPMA) and poly(methyl methacrylate) (PMMA). Both methods involve a micromolding process followed by thermal bonding to the substrate. The first method, sacrificial layer micromolding, uses a water-soluble sacrificial layer, allowing functional structures to be released by immersion in water. The second method, patterned substrate micromolding, uses a permanent substrate patterned via photolithography. Functional regions of the polymer structures are suspended over the voids in the photoresist pattern. The processes have been applied to the fabrication of polymer microstructures with a variety of geometries for specific applications. Devices have included microcantilevers, beams, and other more complicated microstructures. The thermal molding process is conceivably applicable to the fabrication of microstructures from a wide variety of thermoplastic polymers, allowing material selection to be tailored based on application.

INTRODUCTION

MEMS technology has traditionally been focused strongly on silicon based fabrication techniques. In order to broaden the potential applications of MEMS devices, novel materials must be considered for some applications. Polymers are of particular interest due to their unique and diverse material properties and low cost relative to silicon. Polymer MEMS (P-MEMS) also hold great potential for biological application due to the inherent biocompatibility of many polymer materials. While silicon based fabrication techniques are well established and understood, new processing techniques need to be developed for polymer materials. This work introduces two methods for fabrication freely suspended three dimensional polymer microstructures for bioMEMS applications: sacrificial layer micromolding (SLaM) and patterned substrate micromolding (PSM).

Photolithography has been the standard in fabricating polymer microstructures due to its prevalence in microelectronics processing. Recently, several processes have been developed for microfabrication of polymeric microstructures and devices from materials other than standard photosensitive materials. Hot embossing [1] and injection molding [2] have been scaled down from their use in macroscale polymer processing to accommodate microscale fabrication. A class of soft lithography based fabrication methods, including replica molding [3], solvent assisted micromolding (SAMIM) [3], microtransfer molding (µTM) [4], and micromolding in capillaries (MIMIC) [5], and have also been developed for fabrication of polymer microstructures. While these processing methods have found utility in a number of biomedical applications such as microfluidic diagnostic and analytical devices [6-7], tissue engineering [8-9], and drug delivery [10], there has been little work in development of suspended polymer microstructures such as cantilevers for bioMEMS applications.
Both SLaM and PSM are capable of producing suspended polymer microstructure analogous to silicon devices fabricated using standard MEMS processing techniques. Both SLaM and PSM involve a multi-step modified microtransfer molding process followed by alignment and bonding to a micropatterned substrate. The processes are capable of yielding polymer microstructures from thermoplastic polymers with resolution comparable to the resolution of the photolithography process. In the present work, PPMA and PMMA were used as model polymers. However, the same basic process could be extended to a variety of thermoplastic polymer materials. The processes provide a simple and cost effective method for fabrication of polymer devices for integrating into MEMS based sensor and actuator systems.

FABRICATION METHODS

PDMS Mold Fabrication

The device geometries were initially fabricated from photoresist using standard photolithography. A layer of either SU8-5 negative tone photoresist (MicroChem Corp.) or 1813 positive tone photoresist (Shipley) was spin coated on a (100) p-type silicon wafer (WaferNet). The photoresist and spin speed used in the initial process were selected based on the desired final structure geometry and thickness. After coating, the wafers were processed according to the manufacturer’s suggestion processing parameters.

The photoresist features were transferred into a poly(dimethylsiloxane) (PDMS) elastomer for use in fabricating the final polymer structural features. The process of PDMS molding from a photoresist master is described in detail elsewhere [6]. Briefly, a 10:1 ratio of T-2 transparent base and curing agent (Dow Corning) were mixed and stirred thoroughly. The mixture was then poured over the patterned silicon wafer and placed in a vacuum dessicator to remove bubbles incorporated during mixing. The sample was removed from the vacuum periodically, and a razor blade was used to remove surface bubbles. After the bubbles were completely removed, the PDMS mold was allowed to cure at room temperature for 48 hours before removing the mold from the wafer. The wafer could be used multiple times for making PDMS molds. When using 1813 as the pattern material, a layer of hexamethyldisilazane (HMDS) was vapor deposited on the wafer at 150° C prior to pouring the PDMS to prevent the mold from sticking to the wafer. This process was not necessary when using the SU8 photoresist.

Sacrificial Layer Micromolding

Figure 1 shows the fabrication process used in the sacrificial layer molding process. Poly(vinyl alcohol) (PVA) (Sigma-Aldrich) was chosen as a sacrificial layer due to its solubility in water and insolubility in organic solvents. A 10:1 ratio of deionized water and PVA were mixed and heated to 70° C to promote dissolution. After the polymer had completely dissolved, the solution was filtered through high flow rate filter paper to remove impurities. The PVA/water solution was spin coated on silicon wafers for 60 seconds at a spin speed of 1000 rpm. After coating, the wafers were baked at 95° C for five minutes to remove any residual water. The resulting sacrificial layer thickness was ~750 nm. Characterization of sacrificial layer thickness was performed using tapping mode atomic force microscopy (AFM) (Digital Instruments). A thin layer (~400 nm) of poly(methyl methacrylate) (PMMA) (MicroChem Corp.) was then spin coated on the PVA layer and baked at 115° C for two minutes. The PMMA layer acted to protect the PVA from being dissolved during development in the upcoming photolithography process. A layer of SPR 220 positive tone photoresist (Shipley) was spin coated on the PMMA layer at 4500 rpm resulting in a photoresist thickness of ~4.5 µm. The photoresist was processed according to the manufacturer’s processing parameters to expose the anchor regions of the underlying PMMA and PVA layers.
The PMMA and PVA layers were then etched with an oxygen plasma in a benchtop reactive ion etcher (Technics, Micro-RIE 800). The patterned SPR 220 layer acted as an etch mask. An oxygen flow rate of 15 sccm, power of 200W, and 163 mTorr pressure were used during the etch process. After the exposed PMMA and PVA were selectively removed and the substrate anchor points were exposed, the wafer was immersed in acetone for two minutes to remove the PMMA and photoresist layers, leaving only the patterned PVA. After removal from the acetone bath, samples were washed with a gentle stream of nitrogen.

The structural portion of the devices was fabricated via a modified micro-transfer molding process [11-12]. Poly(n-propyl methacrylate) (PPMA) (Advances Polymer Products) and PMMA were chosen as the structural material. Polymers were dissolved in anisole (Sigma-Aldrich) at concentrations ranging from 1 -10% (wt/wt). The polymer solution was spin coated onto the patterned PDMS mold at spin speeds from 1000-6000 rpm for 60 seconds. Resultant device thickness was a function of the PDMS mold depth, polymer concentration, and spin speed. Devices ranged from ~ 200 nm to >5 µm based on the above parameters. To remove the surface material not in the recessed features, the mold was brought into contact with a glass slide heated to 175° C. The same temperature was used for both polymer materials. The mold was held on the slide for ten seconds under the pressure of its own weight. The mold was immediately removed with the glass slide still in contact with the heat source. The process was repeated if necessary to completely remove the surface PPMA or PMMA, leaving the polymer only in the recessed portions of the PDMS mold.

The selectively patterned PDMS mold was then aligned with the sacrificial layer under an optical microscope. The substrate was heated to 95° C for PPMA and 175° C for PMMA and a

Figure 1. Schematic of the sacrificial layer micromolding method. (1) Sacrificial layer patterning process. (1a) Substrate is coated with PVA, PMMA, and photoresist, respectively, and the photoresist is patterned via photolithography. (1b) Surface is exposed to O₂ plasma to etch the PMMA and PVA layers. (1c) Photoresist and PMMA are removed with acetone. (2) Micromolding. (2a) Patterned PDMS mold is uniformly coated with the structural polymer. (2b) Coated mold is brought into contact with a heated glass plate to remove surface material. (2c) Glass plate is removed leaving polymer only in the recessed portions of the mold. (3) Alignment and Bonding. (3a) Sacrificial layer and patterned mold are aligned. (3b) Sacrificial layer and structural layer are brought into contact and bonded under heat and pressure. (3c) Mold is removed. (3d) Sacrificial layer is removed by immersion in water.
pressure of 30 lb/in² was applied to the backside of the mold and held for 10 seconds. The pressure brought the structural material into contact with the substrate material and the heating process promoted adhesion between the sacrificial and structural layers. The molds were removed, resulting in the final unreleased structures. Devices were characterized using a mechanical stylus profilometer (Veeco Dektak, Series 3), atomic force microscopy (Veeco, Nanoman Dimension 3100), and scanning electron microscopy (Hitachi, 3800).

The devices were released by immersion in deionized water, dissolving the sacrificial PVA layer. Stiction due to the drying process prevented post-release SEM characterization. Our studies have shown that the released devices remain separated from the substrate so long as they are maintained in an aqueous environment. For biological applications, the primary operating mode is in an aqueous environment, so the stiction during drying is not a significant limitation for P-MEMS.

**Patterned Substrate Micromolding**

The patterned substrate method is similar to the sacrificial layer method in that the same microtransfer molding process is used for fabrication of the structure portion of the devices. The method differs in choice of the substrate material. For the sacrificial layer method, silicon or glass acted as the substrate material and anchor region for the devices, and a sacrificial material is removed to release the device. For the patterned substrate method, a layer of patterned photoresist acts as the substrate materials, and voids in the photoresist layer act as the suspended portions of the devices.

Figure 2 shows a schematic of the patterned substrate fabrication method. A layer of SU8 25 negative tone photoresist was patterned via standard photolithography processing. The photoresist was coated as 2000 rpm, yielding a film thickness of approximately 25 μm. The model substrate geometry for this work consisted of 20-30 μm channels with 500 μm spacing between the channels.

![Figure 2. Schematic of the patterned substrate micromolding process. (a) Micromolding process described previously is used to select the PDMS mold. (b) The mold is aligned with a photolithographically patterned substrate. (c) The structural polymer and patterned photoresist are bonded under heat and pressure. (d) Mold is removed.](image-url)
Following the photolithography process, the microtransfer molding process described early was preformed with a PMDS mold of the desired device geometry. In this case, 5 µm channels with 45 µm spacing was used as the mold geometry, yield a final structure consisting of 5 µm wide beams suspended over the 20-30 µm channels in the photoresist.

RESULTS AND DISCUSSION

Scanning electron micrographs of device resulting from the SLaM process are shown in Figure 3. The images show that multiple and complex geometries are achievable and that the integrity of the feature geometry can be maintained throughout the PDMS molding and micromolding processes. The features in Figure 3a are nominally 750 nm, indicating that the resolution of the features in comparable to that of the photolithography process. The devices are shown prior to release of the sacrificial layer. Resulting devices from the patterned substrate micromolding process are shown in Figure 4. The images show that the devices remain suspended over the channels with no observable sagging. The ability to fabricate flat structures over the channels is constrained by the width of the channel (i.e. the portion over which the device is suspended). For the work described here, 30 µm was the maximum channel width used for fabrication of 5 µm wide structural features. Further work is needed to determine the maximum attainable functional region for this or other feature geometries. The non-uniformity of the channels in the substrate is a result of the use of a printed transparency mask [13] as opposed to a standard chrome/glass mask. Resolution of the substrate channels could be considerably improved by use of a chrome/glass mask, but a significant increase in cost would also be incurred.

The proper choice of a polymer MEMS fabrication method is dependant on the given application. Both fabrication methods are limited by practical fabrication constrains. The most significant constraint for the sacrificial layer micromolding process at present is the inability to operate device in dry condition due to sticiton issues. Work is current being done to develop a drying process to minimize this affect, allowing the devices to remain suspended in air. The geometrical constrains of the SLaM technique are minimal, as
suspended regions in the 100’s of microns can be achieve and remain suspended in aqueous environment. In contrast, the PSM allows devices that can be operated in dry condition, but the length of the suspended regions of the device are limited to those that maintain their structural integrity.

CONCLUSION

Successful fabrication of suspended polymer microstructures was achieved using two different fabrication methods. Both processes are soft lithography based and rely on a two-step micromolding process. The choice of substrate material (i.e. sacrificial layer or patterned substrate) is application dependant as each method is capable of producing device for of different geometries and for specific operating condition. The processes are relatively simple and low cost as compared to silicon fabrication techniques, and the transition from silicon to polymer materials could potentially broadens both the functionality and applicability of the devices in a biological setting.

REFERENCES