Production of Structures for Microfluidics using Polymer Imprint Techniques

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Abstract

We present a technology for the fabrication of three dimensional microfluidic channels in optically transparent substrates consisting of polymers with different properties. The microstructures are fabricated using polymer replication techniques with a view to the production of microfluidic devices with characteristics suitable for biomedical applications. The replication processes can be used to fabricate large numbers of highly precise, complex microchannels via replication from a single similarly precise master, containing microstructures fabricated from silicon-based materials using lithographic micromachining techniques. Silicon oxide and silicon nitride-based masters have been used, due to their anti-adhesion properties, to produce microchannels, in the transparent polymers, that are suitable for channel profiling measurements and optical studies of fluid flow.

Keywords: Hot Embossing, Nanoimprint lithography, Micromolding, Micromechanisation, Polymers.

1. Introduction

The miniaturisation of chemical, mechanical and fluidic devices for micro electromechanical systems (MEMS) has gained a great deal of attention in industry over recent years [1]. The microfluidic channels of such microdevices were mostly based on silicon, glass, or quartz and were typically fabricated by photolithographic, wet chemical etching, and cover bonding procedures [2]. However, the use of these materials and techniques for developing microfluidic devices has not only resulted in high cost, but also many limitations in fabrication, packaging and testing. For many applications, particularly in the biochemistry and biomedical field, polymeric materials are better choice of fabrication material because of their lower cost and biocompatibility. Recently, several alternative technologies have been presented, using organic polymers such as SU-8 [3], polycarbonate (PC) [4], poly(dimethylsiloxane) (PDMS) [5], and poly(methylmethacrylate) (PMMA) [6], to fabricate micro-fluidic devices. The microfabrication methods for the polymer substrates varied, ranging from micromoulding techniques [7], to UV laser machining [4] and to X-ray lithography [8].

Here, we describe techniques for the production of silicon-based masters for hot embossing and nanoimprint lithography with inherent anti-adhesion properties. We describe the methods for production of the masters, including the production of focused ion beam modified structures, and suggests some advantages of using these materials, as masters for polymer replication techniques, compared to using purely silicon-based masters. Structures designed in the master surface have then been used to imprint channels, for eventual use in microfluidic devices, in polymers with a variety of properties useful for biomedical applications.

2. Experimental

2.1. Silicon master fabrication

A battery of masters was fabricated within the cleanroom at the IBM-CSIC using a design that included several types of device structures, with widths ranging from 2.5 μm to 40 μm , and heights ranging from 5 μm to 350 nm. The microstructures were defined in the master surface to give masters with positive superficial structures (where the features are higher than the surface) which, when imprinted, will produce the channels in the polymer surface. The masters contained four microfluidic channel designs in a 1 cm^2 area, and included reservoirs, 300 μm wide, for later interface to fluidic connectors. A number of these masters could therefore be fabricated from a single silicon wafer, with silicon dicing used to define the individual masters. The masters were fabricated from substrate materials, including crystalline silicon (Si), silicon oxide (SiO_2) and silicon nitride (Si_3N_4), to examine the anti-adhesion properties of each of the master types in the later polymer replication techniques.

The fabrication method used for the production of the master depended on the required physical make-up of the master. For masters fabricated solely from crystalline silicon, deep reactive ion etching (DRIE) was used to etch a silicon substrate, to a depth of 5 μm , after photoresist patterning using established photolithography techniques. As the DRIE apparatus (601 DRIE, Alcatel, France) has been developed, in principle, to machine whole silicon wafers, the process etching conditions were optimised to minimise parameters such as scalloping, footing, etc.

Production of masters in SiO_2 and Si_3N_4 was completed using two different fabrication methods, giving masters with different feature heights. The first method involved the growth of layers of oxide and nitride on the surface of a silicon wafer

capable of being patterned using the method described previously. For SiO₂ masters, a 50 – 100 nm thick thermal oxide was grown on the surface of the underlying patterned silicon. For the Si₃N₄ masters, a 50 nm thick SiO₂ layer was thermally grown on the patterned silicon surface before a 50 nm thick Si₃N₄ layer was added on top of the SiO₂ layer. In this case, the SiO₂ layer is necessary due to compensate for the intrinsic stress in the thermally evaporated layers: a silicon nitride will not adhere directly to the surface of the silicon wafer, but requires the SiO₂ layer as an intermediary.

The second method for fabrication of the SiO₂ and Si₃N₄ masters involved thermally growing oxide or nitride layers on a pristine silicon wafer, before photolithographic patterning and DRIE of the modified silicon to the required depth, using a similar method to that described above. In the case of the SiO₂ masters, 800 nm of the oxide was grown on the silicon before DRIE to a depth of 700 nm was performed. For the Si₃N₄ masters, 50 nm of oxide was again added to the silicon surface before deposition of 400 nm of the nitride, and subsequent DRIE to 300 nm depth.

DRIE was preferred over other techniques, such as reactive ion etching (RIE) or inductively coupled plasma (ICP) etc., because the DRIE method was already well optimised for etching these multilayer systems and gave good definition of the side walls to depths of hundreds of nanometres.

In addition to these fabrication conditions, each master was produced in two further configurations; one using the original 500 nm thick silicon wafer, modified as described above, and one where the 500 nm thick silicon wafer is anodically bonded to a 1 mm thick pyrex wafer, prior to modification, to increase the strength, and hence the lifetime, of the master. For this second configuration, it was necessary to use silicon wafers polished on both sides in order to allow for the bonding step.

Further modification of all these masters was possible, with the introduction of extra micro or nanostructures, by using focussed ion beam (FIB) milling. The FIB (Strata DB235; FEI Co., Netherlands) apparatus was used to mill structures into the raised features on the original master which, when imprinted, would replicate the structures within the channels in the polymer.

The $\text{SiO}_2/\text{Si}_3\text{N}_4$ layers on the master surface were used to prevent adherence problems between the master and the polymer; however, after modification of the master using the FIB a monolayer of fluoroalkylsilane (trichloro(tridecafluorooctyl)silane; United Chemical Technologies, USA), was sometimes required to eliminate any sticking problems. Figure 1a depicts the molecular structure of the fluoroalkylsilane, which was deposited from the liquid phase using a method described previously [9].

2.2. Polymer imprinting

Poly(ethylene naphthalate) (PEN) and PMMA sheets (125 μm thick) were used as supplied from Goodfellow Ltd. (UK). Poly(lactic acid) (PLA: PURASORB PLDL 95%-L/5%-DL copolymer; PURAC, Netherlands), with an inherent viscosity of 6.15 dL/g, was formed into freestanding thin films by a solvent casting technique. A 5% w/v PLA solution was prepared by dissolving the polymer in chloroform (CHCl_3 ; Panreac, Spain) for 48 hours. Once fully dissolved, the polymer solution was cast into a Teflon mould and the solvent evaporated at room temperature over another 48 hours. This technique provided PLA thin films of ~ 200 μm thickness. For each imprinting experiment, the polymer was cut to the approximate size of the master to be used for the imprint. The polymer was rinsed with isopropanol (IPA, Aldrich Chemical Co., UK), to

remove any dust particles, and dried using a stream of nitrogen gas.

Polymer imprinting was achieved via two methods, hot embossing lithography and nanoimprint lithography (HEL and NIL respectively). HEL was performed using a Jenoptik HEX 01 hot embossing system (Jenoptik Mikrotechnik GmbH, Germany). The polymer was placed onto a piece of borosilicate glass, positioned on the base of the hot embosser, which stopped the polymer from adhering to the base plate of the apparatus. The master was then placed on top of the polymer with the surface to be embossed in contact with the polymer and the hot embossing proceeded in typical fashion [10, 11].

NIL was carried out in a similar fashion to HEL and was performed using an Obducat nanoimprinter (Obducat AB, Sweden). The polymer was placed onto an unstructured piece of the material used to produce the master stamp, positioned on the base of the nanoimprinter. The master was placed on top of the polymer, again with the surface to be embossed in contact with the polymer and the imprinting proceeds in a fashion similar to that used for hot embossing [12]. A schematic diagram of the hot embossing/nanoimprinting process is given in figure 1b, and typical replication conditions for each polymer are given in table I.

By cooling the imprinted polymer films to below that of the polymer glass transition temperature, prior to removal of the applied pressure, the polymer was forced to adopt the shape given by the sandwich of the master and the second piece of master material and ensured that the polymer remained flat. Characterisation of the surfaces of the masters and the patterned polymers was achieved using white light interferometry (Wyko NT110; Veeco Metrology, USA) and scanning electron microscopy (SEM; Strata DB235; FEI Co., USA).

3. Discussion

Figure 2a gives an example of a master for production of microstructures in the polymers. The raised features on the master surface are used to replicate serpentine microchannels and their complimentary reservoirs in the polymer surface via polymer replication. Preliminary trials, where the polymer replicas were produced using purely silicon-based masters, revealed an adherence problem between the polymer and the master surface. This meant that the polymer tended to be damaged when it was separated from the master, with polymer remaining on the master surface, being “pulled” into spiked features and, in extreme cases, tearing. The addition of the oxide and nitride layers reduced this problem significantly, possibly because the DRIE etching produced a much flatter surface on the Si_3N_4 than on the native Si and hence, as the Si_3N_4 presents a lower surface area, it is less likely to adhere to the surface of the polymer. Further, when necessary, modification of the master surface using the silane monolayer practically eliminated any sticking.

Consequently, the SiO_2 and Si_3N_4 based masters were used to produce replicas in each of the polymers tested here, using conditions relevant to each of the polymer systems (Table 1). As an example, figure 2b shows a section of the serpentine microfluidic channel system hot embossed in PMMA. The channels in the PMMA surface are seen to replicate the corresponding features in the master. The same master has been used to imprint channels in PEN using NIL (Figure 2d), although in this case, there is some evidence of spikes forming at the edges of the channels due to some local adhesion. Optimisation of the replication conditions and the use of a suitable anti-adhesion layer on the master should help to overcome this problem.

Figure 3a gives an example of a crucifix shaped master that has been modified using the FIB. Arrays of holes are milled in the upper surface of the master feature, which do not extend below the antisticking nitride or oxide layers, for replication within the microfluidic channel after imprinting. In this case, it was normally necessary to silanise the surface of the master to avoid adhesion of the master and the polymer in the modified area. It is thought that the increase in the adhesion in the modified area is due to Gallium ion implantation in the master surface, which causes the surface hydrophobicity to change, and hence make the modified areas more prone to sticking. Addition of the fluorosilane monolayer overcomes this problem by coating the area in a hydrophobic layer, eliminating interactions between the surface and the polymer.

NIL has been used in an attempt to replicate the FIB-modified masters; the higher resolution of the NIL technique allowing the nanostructures patterned within the microchannels to be replicated. Figure 3b gives an example of these in-channel structures replicated in PLA. The 40 μm wide channel structure has been replicated in the polymer surface, as have the posts within the channel. Their slightly rounded shape is thought to be due to the shape produced by the FIB milling. A fluidic structure like this could conceivably be used as a filter system for size exclusion of biological material in a flowing stream of liquid. The large size of the posts, $\sim 2\text{ }\mu\text{m}$ in diameter, makes it easier to replicate both the posts and the channel simultaneously. The different channel sizes produced, suitable for the passage of biological material such as cells, show that the method of production of these devices using this method is relatively versatile.

A major advantage of using a freestanding piece of polymer as the substrate for these structures, as opposed to using an opaque substrate, means that the imprinted

surface can be used in applications where the inherent transparency of these polymers is necessary. With transparencies that rival that of glass [13, 14], thin films of the polymers used here are ideal for utilisation in biomedical applications where optical microscopy is required. The diverse physical properties of each of the polymers also makes them attractive for other biomedical and chemical applications; PMMA has excellent structural properties [14]; PEN forms an efficient UV barrier and is resistant to strong thermal and chemical conditions [15, 16]; PLA is biocompatible and biodegradable [17].

As we have shown, SiO_2 and Si_3N_4 based masters can be used for polymer replication techniques to reduce the amount of sticking occurring between the polymer and the master, as compared to the purely silicon based masters. The methods described for the production of the SiO_2 and Si_3N_4 masters involve only a single photolithography step for pattern definition and do not require anodic bonding steps (with the exception of the addition of pyrex to the back surface of the master for strengthening purposes). Further, the conditions required for the DRIE etching of the oxide and nitride surfaces are less severe than those required for etching silicon. The use of polymer replication techniques, where a single master can be used to produce a number of replicas, further reduces the cost of device production, and hence allows the final devices to be disposable if required. Ongoing experiments are in place to test the structured polymer surfaces with respect to sealing, to produce fluidic devices, and with respect to further testing the biocompatibility of the polymers.

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Figure captions

- Figure 1 Chemical structure (a) of the fluoroalkylsilane antistick coating for the masters, trichloro(tridecafluoro-octyl)silane. (b) Schematic diagram of the imprinting technique. (1) The polymer (i) is sandwiched between the master (ii) and a second piece of the master material (iii), which, (2) after imprinting, leaves a freestanding polymer film containing the superficial structures.
- Figure 2 Optical images (100x magnifications) of portions of (a) a silicon oxide master containing the structure for imprinting serpentine microfluidic channels and (b) the channels hot embossed in PMMA. (c) A sectional analysis of a white light interferometric image of the PMMA channel with inset a 3-D rendering of the image. (d) A SEM image of a channel in PEN, nanoimprinted using the same master [bar = 10 μm].
- Figure 3 (a) SEM images of a master modified using FIB milling, and (b) complimentary image of the modified master imprinted in PLA using NIL [bars = 20 μm]. The channel is 40 μm wide and 500 nm deep, and the circular features added via the FIB modification are 2 μm in diameter and 500 nm tall.

Table captions

- Table I Typical polymer imprinting conditions using the silicon-based masters.

Table 1 *Mills*

Polymer	Imprint conditions			
	$T_{\text{(heating)}} / ^\circ\text{C}$	t / s	P / MPa	$T_{\text{(release)}} / ^\circ\text{C}$
PMMA	130	300	3	80
PEN	200	600	3	90
PLA	60	300	3	40

Figure 1.

Figure 2

Figure 3.