FABRICATION OF MULTIPLE HEIGHT MICROPROBES USING UV LITHOGRAPHY ON TIMED-DEVELOPMENT-AND-THERMAL-REFLOWED PHOTORESIST

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ABSTRACT

A three dimensional (3-D) microprobe array with multiple heights has been fabricated using the timed-development-and-thermal-reflow (TDTR) process and an additional UV lithography process. After the TDTR process, the reflowed polymer profiles between the substrate and a micro wall are differing as a function of the development time and the surface properties of the side wall such as hydrophobicity and the contact angle between the wall and the reflowed polymer, resulting in a convex, linear, and concave shape. A polymeric micro slab array with continuously varying heights and a micropillar array with multiple heights, where the overall surface profile follows the reflowed surface after the TDTR step are successfully demonstrated. As an application, a 2 x 5 microprobe array with linearly changing multiple heights and metallic signal traces has been fabricated for 3-D neural probing and stimulation. Three different microprobe sets with a pillar diameter of 40 μ m and a different probe height range of 381 μ m to 482 μ m, 97 μ m to 164 μ m, and 21 μ m to 60 μ m, have been also demonstrated. DC resistance property of a probe has been tested.

INTRODUCTION

3-D microprobes with multiple heights are highly demanded in many advanced biomedical applications such as neural mapping or signaling [1] in multilayered cells or tissues. Many conventional methods for cell or tissue investigation use a printed type flat electrode array or an extruded micro electrode array with a uniform height. While many diagnoses on the cells or the tissues are conducted by measuring voltages, currents, and therefore their impedance using such micro electrodes, the measurements with the conventional probes with a uniform height would provide very limited information available only from a single layer, which does not fully reveal cell and tissue activities and communications occurring between cells and tissues from different layers and functional groups. For example, retina tissues are composed of several layers such as a ganglionic layer, a plexiform layer, and a nuclear layer. These layers are connected and reacted as one functional tissue [2]. To understand and study such inter/intra layer activities, appropriately spaced 3-D probes with multiple heights are highly desired.

Recently, a multiple height micro needle array using advanced micro/nano fabrication processes has been reported including the doped silicon array made by the vapor-liquid-solid growth method [1] and an inclined UV lithography and micromolding process [3]. However, the Si process requires several alignments, the needle growth process is complicated, and the fabrication time is relatively long. The inclined UV lithography approach requires a different foot print for a micro needle with a different height, therefore requiring a relatively large area for a multiple height probe array. Very recently, a timed-development-and-thermal-reflow (TDTR) process has been reported as a simple fabrication method for 3-D microstructures with various shape and heights such as a micro lens, rounded microfluidic channels, and pillar arrays with multiple heights by the authors [4, 5].

Figure 1. Fabrication process: (a) Softbake and primary exposure, (b) Timed development, (c) Thermal reflow, (d) Backside exposure for multiple height pillars

In this work, a 3-D microprobe array with multiple heights using the TDTR process has been fabricated in a controllable manner by applying an additional or multiple UV lithography step(s) on the profile controlled photoresist, and a metallization step. The TDTR process can produce a convex, linear and concave profile by controlling the amount of the remaining polymer after timed development and using the surface phobicity of the substrate surface and a wall during the thermal reflow step. To show the process feasibility and utility, a 3-D microprobe array with discrete multiple heights integrated with the electrode trace is demonstrated.

MULTIPLE HEIGHT MICROPROBES

Multiple height micro pillar array

To fabricate the multiple height pillar array, the timed-development-and-thermal-reflow (TDTR) fabrication process is utilized. The TDTR process is divided into two steps: the timed development step which controls the amount of remaining uncrosslinked polymer and the thermal reflow step which forms a smooth surface profile in a convex, linear, or concave shape. Figure 1 describes a general TDTR fabrication process for a multiple height pillar array. With a prepatterned glass photomask which is also served as a substrate, both topside exposure and backside exposure have been applied for polymer block and pillar definition, respectively. First, SU-8 (2025, Microchem, Inc.), negative tone photopatternable epoxy, is coated on a chromium patterned glass substrate, followed by softbake at 95°C, UV exposure from topside, and post exposure bake steps (1a). The topside UV exposure defines a reference position where the curve of the 3-D microstructure starts. Uncrosslinked polymer on the sample is partially developed using propylene glycol monomethyl ether acetate (PGMEA) in a time controlled manner (1b). The partial developing process is conducted without stirring in room temperature. The sample is baked at 95°C for an hour.

Figure 2. Contact angle as a function of developing time

The solid state uncrosslinked polymer is turned into a liquid state when it is heated above its glass transition temperature forming smooth surface curvature, which is called as the thermal reflow process, to form a concave curvature on the surface (1c) and cooled down to room temperature. The remaining amount of the uncrosslinked SU-8 is varied by the SU-8 developing time. The curvature profile is controllable by adjusting the developing time and surface property. Additional backside UV exposure is applied on the concave structure to form a multiple height pillar array (1d) after the complete developing process in the PGMEA solution. The lateral distance from the reference block determines the pillar height. The farther distance from the reference, the shorter pillar height will be.

To examine the variation of the curvature profile, 1 mm thick SU-8 photoresist is coated on a glass substrate. The sample is baked at 95°C for 40 hours and cooled down to room temperature. The reference block is patterned by topside UV exposure. After one hour post exposure bake at 95°C on a hot plate, the sample is timed-developed and observed in different developing time. As development proceeds in the uncrosslinked area, the resultant contact angle also varies as shown in Figure 2, transitioning from the semi convex shape at the earlier stage of development to the semi concave shape at the later stage of development. The contact

Figure 3. 3-D structures with tapered profiles: (a) Semi concave slab, (b) Linearly tapered slab, (c) Linearly decreased pillar array, (d) Pillar array with a wavy profile

angle is defined as the angle between the reference side wall and the surface of the uncrosslinked polymer. A linear tapered shape is formed when the half amount of the uncrosslinked polymer is developed. Finally further development forms a concave shape after thermal reflow. The contact angle decreases for the sample with longer development time. It reaches to a critical angle of 2.8° for the sample with 30 minute or longer development. An additional UV lithography step after the TDTR process forms a pillar array with various heights or other 3-D microstructures. The profile of the top portion of each pillar follows that of the surface profile formed by the TDTR process. Figure 3 shows various microstructures with continuously or discretely varying heights. The semi concave slab (3a) and the linearly tapered slab (3b) result from the different developing time. By applying additional UV exposure through the prepatterned hole array on the Cr coated glass substrate, a linearly decreasing pillar array (3c) is formed. The micro pillar array with more arbitrarily varying multiple heights (3d) shows that the position and the shape of the reference block can be utilized to form a complex surface profile and an ultimate pillar array with the profile.

The heights of the multiple pillars are calculated from an equation for a curvature profile derived from the Young-Laplace equation [6].

$$\eta(\chi) = \ell_c \cot(\theta) e^{(-\chi/\ell_c)} \quad (1)$$

where $\eta(\chi)$, ℓ_c , θ , and χ are the curvature profile, the capillary length, the contact angle and the distance from the reference block. The function $\eta(\chi)$ shows the height of the pillar located in the distance χ in millimeter (mm), between the reference block and the pillar. The capillary length, ℓ_c , is experimentally measured between the glass substrate and the SU-8 interface as 1.3mm.

Figure 4. SEM images of the electrode trace design: (a) Overview of the addressing electrodes, (b) The center electrodes, (c) The pad dimension

TRACE ELECTRODE DESIGN

For a multiple height microprobe array, each microprobe is electrically connected to the external circuit through an electrode trace. The electrode traces for a 2×5 pillar array with different heights are designed as shown in Figure 4, where an overall view (4a), a trace electrode view (4b), and a pad (4c) are highlighted. The electrode trace is designed in a glass substrate with an area of 1 inch by 1 inch. The width and the gap of the center electrode are $30 \mu\text{m}$ and $40 \mu\text{m}$, respectively. The size of the electrode pad is designed to be 2 mm by 2 mm for easy connection. Each electrode line is evenly spread out and symmetrically aligned to reduce the signal noise and the crosstalk between probes and traces. The electrode is made of $10 \mu\text{m}$ thick copper.

FABRICATION PROCESS OF A MICROPROBE ARRAY

The multiple height pillar array is integrated to the electrode traces. Figure 5 shows the fabrication process of the multiple height microprobe array. After cleaning a glass substrate (5a), a titanium adhesion layer and a copper seed layer of 30nm and 300nm, respectively, are deposited. A 2×5 hole array for pillar definition is patterned using UV lithography and metal etching (5b). The electrode traces are defined on the metal layer by UV lithography with a photoresist, NR9-8000 (FUTURREX, Inc.) (5c) followed by electroplating with $10 \mu\text{m}$ copper (5d). After removing the photoresist (5e), the negative photoresist, SU-8, is applied for the TDTR process (5f) as described earlier. Additional UV lithography with the backside exposure scheme produces a multiple height pillar

Figure 5. Fabrication process of the multiple height microprobe array

Figure 6. Curvature profile with contact angles of 11° , 16° , 30°

array (5g). The titanium and copper seed layer are timed-etched in a diluted hydrofluoric acid (HF) and sulfuric acid with hydrogen peroxide, respectively. (5h). Negative tone photoresist, AZ5214, is coated and exposed from the back side of the sample, using the pre-patterned metal layer as a self aligned photomask (5i). An additional copper layer with a thickness of 100nm is coated on the sample using sputtering (5j). In this step, titanium instead of copper can be coated on the sample requiring biocompatible metallization. The standard lift-off process isolates each electrode (5k) and additional electroplating is optionally conducted for thicker metallization on the multiple height pillars (5l).

RESULT

The heights of the multiple pillar array are controllable by the TDTR process. The developing time and the lateral distance from the reference block are two parameters to determine the height of the pillar. Three samples for the multiple height microprobes are prepared with a different period of development such as 20, 25, and 27 minutes. The distance between the reference block and the first pillar is set as 0.75mm. The different developing time results in a different contact angle such as 30° , 16° , and 11° , respectively. The multiple height pillar array profiles are calculated using Eq. (1) and plotted in Figure 6. The heights vary from $380 \mu\text{m}$ to $480 \mu\text{m}$ with a contact angle of 30° in the red line, from $95 \mu\text{m}$ to $165 \mu\text{m}$ with 16° in the black line, and from $20 \mu\text{m}$ to $60 \mu\text{m}$ with 11° in the blue line. Figure 7 shows the fabricated three different microprobe sets with multiple heights showing good agreement with the calculated pillar profile as summarized in Table 1. The photomask of the 2×5 micro hole array has each hole diameter of $40 \mu\text{m}$. And the tip of each pillar is not flat but slanted and the measured heights are the average values. Each electrode trace has a line width of $30 \mu\text{m}$ at the end, on which a micro pillar is located. The other end of the electrode trace is connected to outside circuitry.

The fabricated microprobe has been tested for the DC I-V curve as shown in Figure 8. A $480 \mu\text{m}$ tall probe has been chosen for the characterization. One test probe is connected to the top of the pillar and the other is at the end of the electrode pad. The voltage from -1.5V to 1.5V has been measured while the current from -0.8A to + 0.8A has been applied.

Figure 7. Multiple height microprobe array: (a) 380.51 μm , 407.18 μm , 433.86 μm , 458.86 μm , and 482.05 μm in the increasing order, (b) 96.86 μm , 110.40 μm , 128.40 μm , 145.86 μm , and 164.44 μm in the increasing order, (c) 20.92 μm , 30.83 μm , 39.08 μm , 49.76 μm , and 59.61 μm in the increasing order

Table 1: Summary of the dimension of the fabricated probes

	Contact angle	Pillar height [μm]*				
		1	2	3	4	5
Device 1 (Fig 7a)	30°	<u>380.5</u> (380)	<u>407.1</u> (405)	<u>433.9</u> (430)	<u>458.5</u> (455)	<u>482.0</u> (480)
Device 2 (Fig 7b)	16°	<u>96.86</u> (95)	<u>110.40</u> (112.5)	<u>128.40</u> (130)	<u>145.86</u> (147.5)	<u>164.44</u> (165)
Device 3 (Fig 7c)	11°	<u>20.92</u> (20)	<u>30.83</u> (30)	<u>39.08</u> (40)	<u>49.76</u> (50)	<u>59.61</u> (60)

*Pillar height in a center point of each pillar: measured, and (calculated)

CONCLUSION

Multiple height microprobes have been implemented using the TDTR method, additional UV lithography, and metallization. The TDTR process has been extended to the fabrication of convex, linear, and concave microstructures without an additional micromolding step, and the fabrication of pillar arrays with multiple heights using an additional UV lithography process. By controlling the development time and therefore changing the amount of the remaining uncrosslinked polymer, or adopting a different geometry of the reference blocks, various surface profiles could be produced. Using an additional backside exposure scheme, discrete micro pillar arrays with multiple heights have been successfully demonstrated.

Figure 8. I-V curve measurement of a single microprobe

The TDTR process has shown many advantages such as its simplicity in microfabrication for complex 3-D structures with continuous or discrete height change, and process compatibility with conventional micromachining processes. The development time in the TDTR process and the lateral distance from the reference block determine the profile curvature ultimately affecting the height of the pillars. The Young-Laplace equation is utilized to design the multiple height pillars array. The surface profiles of the fabricated three different sets of a 2 by 5 micro probe array with different heights shows good agreement with those of the calculated ones. A fabricated multiple height microprobe has been tested for a DC I-V curve. Potentially, the multiple height microprobe can be used for stimulating or sensing neurosignals of the different layers of tissues in retina or brain.

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