ULTRA-HIGH ASPECT-RATIO PDMS MICROPILLARS WITH SELF-ALIGNED MICROSPHERES FOR AIR-FLOW SENSING

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ABSTRACT

We developed a new technique that enables routine fabrications of high aspect-ratio PDMS micropillars. The key enabling factor is the adoption of the direct drawing technique incorporated with the *in situ* heating for simultaneous hardening and solidification of the PDMS micropillars. In addition, our technique allows self-aligned installation of highly reflective microspheres at the tips of the micropillars. Using the transparent PDMS micropillar as a flexible waveguide and the microsphere as a self-aligned reflector, we transformed the microsphere-tipped PDMS micropillars into all optically interrogated air-flow sensors and successfully demonstrated the air-flow sensing capability.

INTRODUCTION

Micropillars made of PDMS have seen rapid expansion in their application scope, from bio-mimetic dry adhesion [1] and surface wetting control [2] to cell mechanics studies [3]. The newest addition to their application list is mass flow transduction where PDMS micropillars with higher aspect ratios are preferred for their greater deformability, enabling highly sensitive transduction in a small form factor. Realizing high aspect ratio PDMS micropillars, however, is a difficult challenge, especially with the use of conventional, replica-molding-based fabrication techniques [4]. The main obstacle is the need to de-mold the PDMS micropillars after curing. Despite the efforts to improve the yield of the process [5], the failure rate increases inevitably with the aspect-ratio. Another source of difficulty is the inherently low Young's modulus, E_Y of PDMS (typically ~ 1 MPa) [6], which frequently leads to the collapse of the micropillar and then irreversible bonding to the substrate [7].

In this report, we present a new technique that enables routine fabrications of PDMS micropillars with aspect ratios higher than 40 [8]. The key enabling factor is the adoption of the direct drawing technique incorporated with the *in situ* thermal hardening for the realization of the high aspect-ratio PDMS micropillars, eliminating the de-molding process. To date, the direct drawing technique has been applied to polystyrene [9], PMMA [10], PTT [11], nylon [12], sucrose [13], polyurethane [14], SU-8 [15], and adhesives [16]. Its application to PDMS, however, has not been reported due mainly to the material's softness and slow solidification rate. We address the issues by incorporating *in situ* heating into the drawing process so that the micropillar gets simultaneously hardened and solidified during its formation. In addition, our technique allows self-aligned installation of highly reflective microspheres at the tips of the micropillars, leading to the realization of microsphere-tipped micropillars. Using the transparent PDMS micropillar as a flexible waveguide and the microsphere as a self-aligned reflector, we transformed the microsphere-tipped PDMS micropillars into all optically interrogated air-flow sensors and successfully demonstrated the air-flow sensing capability.

FABICATION OF PDMS MICROPILLARS

The PDMS MSMPs (microsphere-tipped micropillars) fabrication steps are depicted in Figure 1. We started out with the preparation of the drawing probe array. The microspheres were first assembled on a photo-lithographically patterned Su-8 grid and then

transferred onto a piece of double-stick tape attached to a glass substrate shown in Figure 1a. We used two types of microspheres as the drawing probes: ~ 50 μm -diameter PMMA microspheres and ~ 58 μm -diameter Ag-coated hollow glass microspheres. The latter was more effective for increasing the levels of reflection and tip-visibility. We then flipped the microsphere array and attached it to a micro-manipulator. Also, a 25 μm PDMS layer was prepared and then pre-baked at 100°C on a hot plate. During the pre-bake, we lowered the microsphere array towards the PDMS thin film until they got separated by 50 μm . Upon completion of the pre-bake, we further lowered the microsphere array so that it can physically contact the PDMS thin film, as shown in Figure 1c. After 40 sec, we lifted the micro-manipulator, drawing PDMS micropillars as shown in Figure 1d. The temperature was maintained at 100°C throughout these steps for simultaneous solidification and hardening of the PDMS micropillars. Completed PDMS micropillars were then post-baked at 100°C for 2 hours and at room-temperature for 24 hours. After the post-bake, we further lifted the micro-manipulator so that the micropillars got elongated by 100%. The resulting tension induces gradual detachment of the microspheres from the double stick tape, leading to the realization of PDMS MSMPs as shown in Figure 1e.

Figure 1. Fabrication flow (a) Microsphere assembly (b) PDMS thin film (c) After pre-baking of the PDMS thin film, the microsphere array physically contacted the PDMS thin film followed by an additional baking. (d) Directly drawing by lifting the microsphere array and the completed micropillars were then post-baked. (e) The double-stick tape was manually detached from the microspheres, completing the realization of the MSMPs

At this step, the main cause of failure is insufficient curing of the PDMS micropillar which detaches the microsphere from the micropillar, rather than from the tape.

PHYSICAL CHARACTERISTICS OF PDMS MICROPILLARS

The direct drawing technique enabled routine fabrications of mm-scale PDMS micropillars with aspect-ratios > 40 . Here, we defined the aspect-ratio as the ratio between h , the height and d_{ave} , the average of the top, middle and base diameters of the PDMS micropillar. The micropillar in Figure 2a was drawn with a 50 μm -diameter PMMA microsphere. With its h and d_{ave} at 1134 and 13.5 μm , respectively, the micropillar exhibits an aspect-ratio of 84. Such a high aspect-ratio was attainable for arrayed micropillars as well. The micropillars in the 4×4 array shown in Figure 2b were drawn with a matching array of 58 μm -diameter Ag-coated hollow glass microspheres. In average, they were 877.2 μm high and tapered with their diameter changing from 14.4 μm right underneath the microsphere to 29.8 μm at the base. With 20.8 μm in d_{ave} , their average aspect-ratio was 42. As pointed out above, capping the tip with a metallic microsphere greatly enhanced the micropillar's tip-visibility. Figure 2c shows the highest micropillar obtained so far. With its h and d_{ave} at 2400 and 21.3 μm , respectively, the aspect-ratio reached 112. To the best of our knowledge, this is the highest aspect-ratio reported for a vertical PDMS micropillar. Figure 2d shows the relation between h and d_{ave} of micropillars. Initially, the aspect-ratio increases with h . However, beyond $h \sim 1.1\text{mm}$, the increase in h induces a matching increase in the base diameter, saturating the aspect-ratio in the range of 70 $\sim$ 110.

From the observations that the directly drawn PDMS micropillars can stand upright and support the weight of microspheres despite their thinness and high aspect-ratio, we conjectured that the *in situ* thermal hardening has indeed hardened PDMS. To quantify the impact of the *in situ* heating on PDMS hardening, we measured the PDMS micropillar's Young's modulus, E_Y based on the reference cantilever method [17] as shown in the inset of Figure 2e, in which a reference cantilever with known spring constant K_r is used to deflect the test cantilever and its spring constant K_t is estimated from the relation $K_t \cdot \delta_t = K_r \cdot \delta_r$, where δ_t and δ_r represent the deflection lengths of the test and reference cantilevers, respectively. For conically tapered beams, K and E_Y are related by $K = 3\pi \cdot E_Y \cdot d^4 \cdot T / (64 \cdot h^3)$ where T is the taper constant defined as d_{min} / d_{max} [18]. We chose a section of commercial PMMA fiber ($E_Y \sim 3.0\text{ GPa}$) as the reference cantilever and the two MSMPs in Table 1 were targeted for this characterization. From the results shown in Figure 2e, E_Y of MSMP-A and MSMP-B was calculated as 2.45 MPa and 2.31 MPa, respectively, which are higher than most E_Y values for bulk PDMS ($\sim 1\text{ MPa}$). Therefore, we attribute the $\sim 1\text{ MPa}$ increase in E_Y to the *in situ* thermal hardening incorporated into the direct drawing process so that the directly drawn microsphere-tipped PDMS micropillars can stand upright despite of their thinness and high aspect-ratio.

Table 1: Characteristics of the PDMS micropillars under test

	h [μm]	d_{ave} [μm]	Aspect Ratio
MSMP-A	800	19.8	40.4
MSMP-B	1600	22	72.7

Figure 2. Optical micrographs of (a) a 1134 μm -high PDMS micropillar integrated with a 50 μm PMMA microsphere. Its aspect-ratio is 84. (Scale bar: 100 μm), (b) a 4×4 array comprising 877.2 μm -high micropillars integrated with 58 μm Ag-coated hollow glass microspheres. (Scale bar: 700 μm), and (c) the micropillar with the highest aspect-ratio of 112 ($d_{top} = 9\text{ }\mu\text{m}$, $d_{mid} = 14\text{ }\mu\text{m}$, $d_{base} = 41\text{ }\mu\text{m}$, and $h = 2.4\text{ mm}$, scale bar: 100 μm). (d) The average diameter d_{ave} of the micropillar plotted as a function of h . The dotted lines mark the aspect-ratios. (e) The results of the reference-cantilever method-based measurements. The inset outlines the setup. The dotted lines represent the results of linear fit with zero or non-zero x -intersection assumed.

BIO-INSPIRED ACOUSTIC SENSING

To demonstrate acoustic sensing capabilities of the PDMS MSMPs, we turned MSMP-A in Table 1 into an airflow sensor by adding the optical read-out setup as shown in Figure 3a. There, the PDMS micropillar functions as a flexible waveguide which deforms under airflows. The probe light enters the micropillar from the base and then gets reflected at the top facet back into the photodetector. The flow-induced bending of the micropillar reduces the reflection power through spoiled waveguiding and beam deflection. Critical to the success of the scheme is guaranteeing high-level reflection at the micropillar's top facet. We accomplish it by capping the micropillar with a Ag-coated microsphere and used its surface as the reflector. Figure 3b, c shows the MSMP-A's deformation in the absence and

presence of airflow, respectively. In the absence of an air-flow, the MSMP stays straight, producing maximal reflection. Upon contact with a constant airflow, it bends due to the fluidic drag force, which decreases the reflection.

Figure 3. (a) A schematic diagram of an air-flow transducer configuration based on the MSMP (b) and (c) MSMP-A's deformation in response to the absence and presence of an air-flow, respectively. (d) The change in the reflectance as functions of the flow-rate. The deflection length was also plotted for convenience.

The change in the reflection levels is plotted in Figure 3d for MSMP-A as a function of the airflow rate. It exhibits a quasi-linear regime sandwiched between two slowly varying curved regimes. The onset of the first curved regime can be defined as the threshold velocity of the MSMP-based air-flow sensors. Figure 3d indicates that it was 0.07 m/sec for MSMP A. The curve also indicates that the decrease in the reflection saturates beyond a certain velocity, forming a flat pedestal at 29 % level. It is due mainly to the residual reflection at the air-glass interface, which is not affected by the airflow, and can be reduced with anti-reflection coating. In the

quasi-linear regime, the optically retrieved reflection level can function as a good measure of the air-flow velocity. The data represent 10-measurement averages.

CONCLUSION

In conclusion, we demonstrated an optically interrogated air-flow sensor based on the PDMS micropillars with high aspect ratios ranging from 40 and 112. Due to the high aspect-ratio and the excellent flexibility of PDMS, the PDMS micropillars deform substantially under airflows, bringing in high sensitivity to small form-factors. The high aspect-ratio PDMS micropillars were fabricated by a new soft-lithography technique based on the combined utility of the *in situ* thermal hardening and the direct-drawing technique. Our scheme also allows self-aligned capping of the micropillar with microspheres. For this work, we exploited the feature as a way to realize highly reflecting top facets, so that we can interrogate the micropillars' deformation all-optically.

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