PRESSURE MAPPING OF MICROFLUIDIC FLOWS WITH COLORIMETRIC PRESSURE SENSING PARTICLES

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ABSTRACT

In this paper we present calorimetric pressure sensitive microparticles for flow field pressure measurements. Direct measurement of the absolute internal chip pressures has been achieved with these particles distributed throughout the chip implementing a particle imaging manometry (PIM) system. As a functional demonstration, the pressure distribution of a binary dilution network chip has been measured using this method.

KEYWORDS: Pressure sensing, Microfluidics, Microfabrication

INTRODUCTION

Flow visualization is the process of making the physics of fluid flows (gases, liquids) visible. Flow field mapping is essential in understanding of flows in many engineering fields in the biomedical, chemical, oil and aerospace industries. Any flow is characterized by its velocity and pressure field. The velocity field within a microfluidic chip can be readily mapped via particle image velocimetry (PIV). Unlike PIV there is no equivalent technique for the complementary pressure field mapping. Previously pressure fields have been indirectly inferred via observations of channel deformation [1] and fluorescence of O_2-sensitive pressure sensitive paints [2-4]. In this paper, we will present a new method which enables direct pressure mapping in complex microfluidic chips using calorimetric particles.

THEORY

Each pressure-sensing slab-type microparticle consists of a semi-transparent elastic shell enclosing a reference vacuum cavity as shown in Figure 1. The vacuum cavity has a characteristic optical resonance. The thickness of the shell is designed such that the cavity gap is dependent on the external absolute pressure. The optical resonance frequency, and the corresponding pressure, can hence be interrogated optically. In essence each microparticle behaves as a Fabry-Perot pressure sensor [5, 6] embedded in the flow setup. In a simple Fabry-Perot resonator, at normal incidence the optical reflectance as a function of wavelength λ is

$$R(\lambda) = \frac{1}{1+\frac{T_d^2}{4R_d}\cdot csc^2(\frac{2\pi g}{\lambda})} \tag{1}$$

where T_d and R_d are the diaphragm transmission and reflection coefficients, and $g(\Delta P)$ is the pressure dependent gap. Figure 3 shows a plot of the calculated reflected light spectrum under normal incidence for two different gaps with $T_d = 0.7$ and $R_d = (1 - T_d) = 0.3$. Note that the spectral curve shift is proportional to the gap and that the reflectance is zero when the argument of the $csc()$ is 2π hence $\lambda_{min} = g(\Delta P)$. The minimum reflectance wavelength shift is hence related to the external pressure.

If the particle has cylindrical symmetry with diaphragm radius a and t thickness, the particle gap change under pressure is

$$g(\Delta\lambda) \approx g_0 - 2 \cdot d(\Delta P) \tag{2}$$

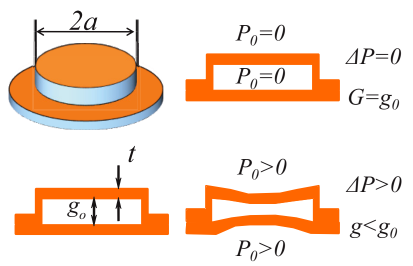

Figure 1. (a) Schematic of slab-type colorimetric pressure sensing particle. The particle diaphragms deflect under a pressure differential thus changing the cavity gap.

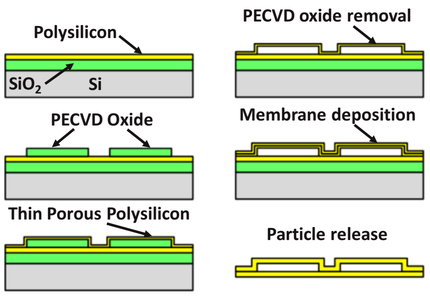

Figure 2. Simplified pressure-sensing microparticle process flow. The particles can be released and stored in a methanol suspension.

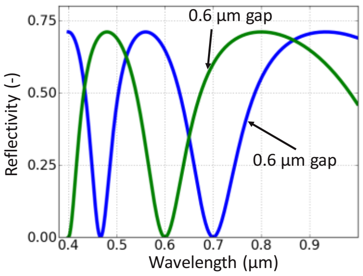

Figure 3. Normal reflectivity of Fabry-Perot pressure sensing particle versus wavelength.

Where $d(\Delta P)$ is the deflection of each diaphragm. If the particle has cylindrical symmetry with diaphragm of radius a, thickness t, Young's modulus E and Poisson's ratio v, the deflection is roughly [7]

$$\frac{\Delta P\cdot a^4}{Et^4} = \frac{16}{3(1-\nu^2)}\left(\frac{d}{t}\right) + \frac{(7-\nu)}{3(1-\nu)}\left(\frac{d^3}{t^3}\right) \qquad (3)$$

Therefore the thickness and radius of the diaphragm can be adjusted to tune the specific pressure range of the interest. The particle gap is adjusted to determine the spectral region of the detection instrumentation. In the optical visible range, gaps in the 0.4-0.8 µm should be used for the particle.

PARTICLE FABRICATION

The colorimetric microparticles are batch microfabricated on silicon wafers using the porous polysilicon [8] process shown in Figure 2. In this approach the top diaphragm is made very thin such that pores or holes are present in the diaphragm. This permits the removal of the sacrificial spacer without patterning additional access holes. After the spacer is removed the pores can be sealed by depositing the rest of the diaphragm thickness. Submicron pores are known to exist in LPCVD polycrystalline silicon (E=160GPa) under certain conditions when the polysilicon thickness is below 0.1 µm [8]. The pores are completely sealed once the thickness exceeds about 0.15 µm. Based on the constraints and method discussed above we selected a polysilicon diaphragm thickness target of 0.25 µm and a default gap of 0.8 µm. The particle cavity is thus formed and sealed using the porous polysilicon method which does not require extra lithographic steps hence producing a minimal-size particle. A typical 150 mm diameter wafer produces a total of ~50 million batch fabricated particles. After release the particles can be kept in suspension in methanol.

EXPERIMENTAL METHODS AND RESULTS

Figure 3 shows an optical photograph of released 0.7 µm-gap, 14 µm-diameter slab microparticles on a glass substrate and the corresponding optical reflectance at atmospheric pressure measured using an Ocean Optics spectrometer (USB 4000) attached to a Mitutoyo FS70 microscope. The particle reflectance shows characteristic dips at 0.6 and 0.7 µm.

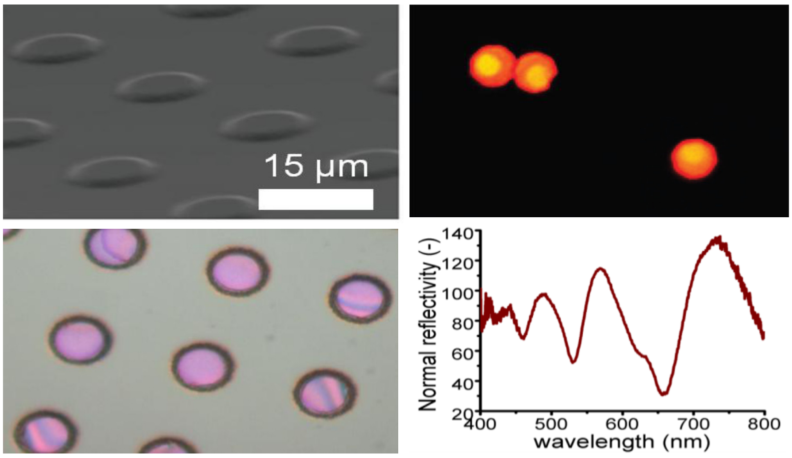

Figure 3. (a) SEM and Optical photograph of released 14 µm-diameter colorimetric slab-type particles in a water suspension. (b) Experimental measurement of slab microparticle reflectivity at normal incidence in air.

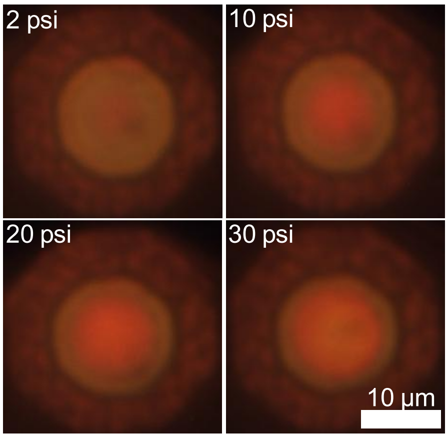

Figure 4. Color change of released particle vs. external pressure (0-30psi).

Figure 4 shows the observed particle color changes versus external pressure for a single particle. In order to use the microparticles within microfluidic chips we embed the particles within a thin layer of PDMS as shown in the process of Figure 5. This layer is attached to a glass slide substrate followed by conventional processing of one or two-layer PDMS chip construction. Figure 6 shows the pressure dependence of a microparticle embedded on a thin PDMS film on glass. The spectral dip change can be correlated to the pressure-dependent compression of the optical cavity. To demonstrate the functionality of the pressure sensing particles, a binary dilution network PDMS chip with embedded particles has been fabricated and tested. Figure 7a shows the schematic of the binary network chip and the locations of the particles

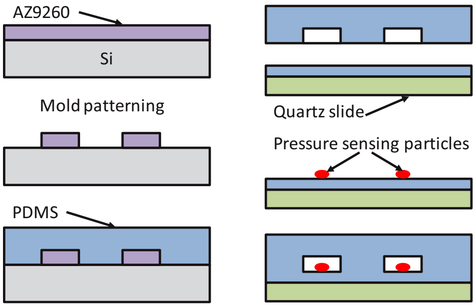

Figure 5. Process flow used for embedding microparticles inside the microchannel walls.

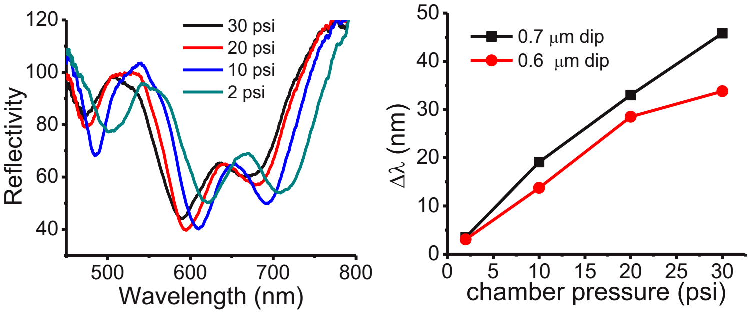

Figure 6. (a) Measured particle reflectivity vs pressure inside the PDMS device. Note the shift in the resonance consistent with the corresponding reduction of the cavity gap. (b) Wavelength shift vs. chamber pressure around two different spectrum dips.

which have been tested. Figure 7b shows a picture of the actual chip. The channel dimensions are 25×16 μm^2. Figure 7c shows a photograph of the PMDS chip with embedded particles inside the lower channel wall at random locations along the channel. Prior to the measurement, the flow is stopped and the spectrum reflectance of each of the particles is calibrated for a given uniform pressure. Next the flow is re-established and the particle reflectance is measured at each point. Table 1 and Figure 8 compares the theoretical pressure values with those measured with the pressure sensing particles as marked in Figure 7(a).

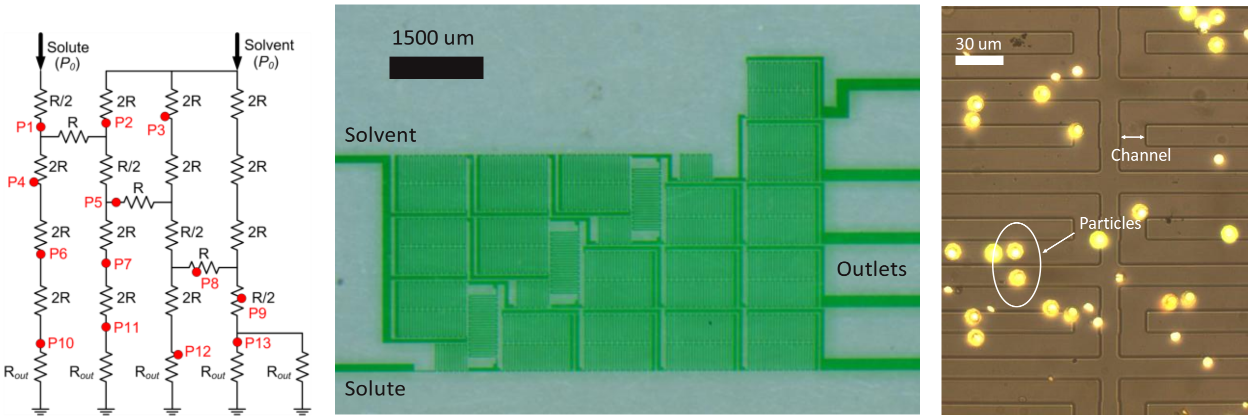

Figure 7. (a) Schematic of the binary network device and the locations of the measured sensing particles. (b) Photograph of the device. (c) Photograph showing the particles inside the channel.

Table 1. Comparison between Simulated and Measured Results

Particle Number	Simulated Results (PSI)	Measured Values (PSI)	Difference (percentage)
1	17.5	17	2.94
2	15.5	15.1	2.65
3	16.4	16	2.50
4	13.9	13.6	2.21
5	12.7	13	2.31
6	7.5	7.6	-1.32
7	7.6	8.1	-6.17
8	6.4	6.1	4.92
9	3.8	4.2	-9.52
10	2.7	3.3	-18.18
11	2.6	3.04	-14.47
12	2.5	2.46	1.63
13	2.5	2.4	4.17

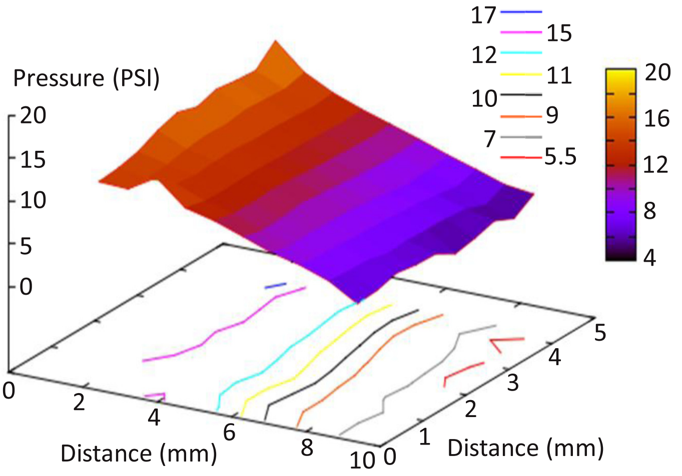

Figure 8. Pressure distribution inside the binary network microfluidc chip.

CONCLUSION

We present a method to measure pressure inside microfluidic chips using colorimetric pressure sensing particles. Each particle consists of a deformable vacuum sealed cavity with its dimension and corresponding optical resonant spectra dependent on the external pressure. By embedding these pressure sensing particles within the PDMS device, we demonstrated the experimental mapping of internal pressures for a binary network microfluidic chip.

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