Sensors and Actuators A 245 (2016) 63–67

Contents lists available at ScienceDirect

Sensors and Actuators A: Physical

journal homepage: www.elsevier.com/locate/sna

An image contrast-based pressure sensor

A.R. Chaudhury [a], A.K. Pantazis [b], N. Chronis [a,b,*]

[a] Department of Biomedical Engineering, University of Michigan, Ann Arbor, MI 48109, USA
[b] Department of Mechanical Engineering, University of Michigan, Ann Arbor, MI 48109, USA

ARTICLE INFO

Article history:
Received 4 April 2016
Accepted 24 April 2016
Available online 29 April 2016

Keywords:
Pressure
Sensor
Image
Contrast
Powerless
Electronics-free

ABSTRACT

We present the design of an image contrast based fluid pressure sensing scheme that employs a powerless, low-cost, pressure sensor. The sensor consists of a sealed pressure microchamber whose top surface consists of a deformable, semi-transparent, polydimethylsiloxane (PDMS) membrane and its bottom surface consists of a rigid glass substrate. When the microchamber is pressurized, the membrane is deflected but the position of the glass substrate remains fixed and therefore the distance between them changes with applied pressure. Using a precision z-scanning module, the distance between the top and bottom surfaces is measured using a custom-made image contrast algorithm and the applied pressure is extracted. The image contrast is enhanced by adding food color during the fabrication of the membrane and by patterning the glass substrate with photoresist. The sensor operates over a pressure range of 0–100 mbar, with a ~2 mbar resolution in the 0–20 mbar pressure range and ~10 mbar resolution in the 20–100 mbar pressure range. The maximum error was measured to be less than 7% throughout its dynamic range. The novel pressure monitoring concept presented here can be used in various biomedical applications as well as in the consumer electronics industry.

1. Introduction

Pressure microsensors are widely used in various industrial sectors, including automotive, aerospace, gas/oil, biomedical and consumer electronics. They have been optimized to operate in various environments with excellent accuracy, sensitivity and precision.

In piezoresistive pressure microsensors, strain gauges detect pressure induced mechanical strain on a thin deformable membrane [1–3]. Capacitive pressure microsensors, typically, have a parallel plate architecture where one flexible plate deflects when exposed to pressure [4,5]. Both piezoresistive and capacitive sensors require the use of electronic components that need to be interfaced with the sensor, making integration and packaging a challenging and expensive task. Optical pressure microsensors have similar performance when compared to piezoresistive and capacitive sensors with the additional advantage that their operation is not affected by electromagnetic radiation [6]. One of the most popular optical pressure sensors is the Fabry-Perot (FP) interferometric fiber sensor [7] where a FP cavity is integrated at the tip of an optical fiber. However, such microsensors require accurate optical alignment between the sensor and the various optical elements, and sophisticated optoelectronic integration [8–11].

In recent years, the combination of microfluidics and micro-optics has resulted in a variety of easy-to-fabricate, low-cost pressure microsensors. Song et al. [12] demonstrated the use of a polydimethylsiloxane (PDMS) microfluidic device that measures fluid pressure by taking an image of the interference pattern formed by two collapsing membranes. The interference pattern is converted into a pressure value using a custom-made pattern recognition algorithm. Chung et al. [13] developed a microfluidic-based pressure measurement system that uses the displacement of a suspension of fluorescent particles to detect membrane deflection. An image analysis method was used to measure the diameter of the particle-free area of the membrane in order to evaluate applied pressure. Measuring fluorescence intensity has been a popular approach for pressure sensing: Hardy et al. [14] visualized the deformation of pressurized PDMS microfluidic channels by filling them up with a fluorescent dye. Similarly, Grevias et al. [15] used fluorescein-conjugated serum albumin solution and a confocal microscope to extract the pressure applied on shallow PDMS microfluidic channel walls. Ozsun et al. [16] estimated the pressure distribution in a deformable micro channel using a fluorescent dye and optical interferometry. All those methods require a sophis-

* Corresponding author at: Department of Biomedical Engineering, University of Michigan, Ann Arbor, Michigan 48109, USA.
E-mail address: chronis@umich.edu (N. Chronis).

http://dx.doi.org/10.1016/j.sna.2016.04.057
0924-4247/

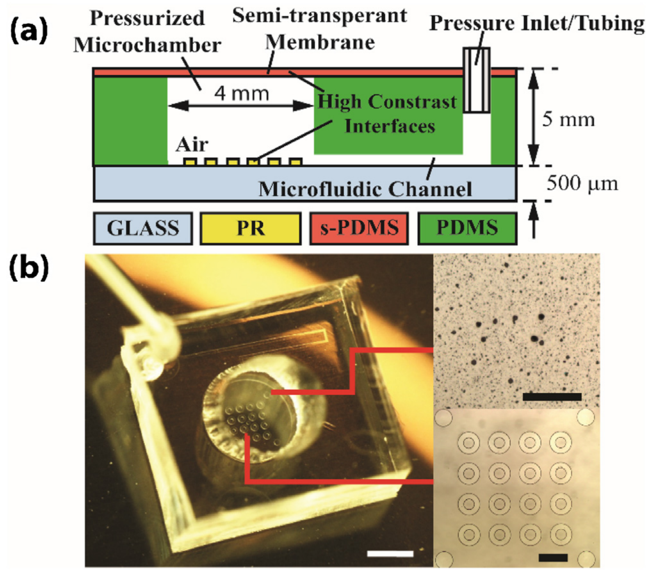

Fig. 1. (a) Cross–sectional schematic of the PDMS pressure sensor. 'PR' and 's-PDMS' stand for 'PhotoResist' and 'Semi-transparent PDMS' respectively. (b) Stereoscopic image of the fabricated sensor (scale bar, 2 mm) along with bright field micrographs of the PDMS membrane with food color aggregates (top right) as well as the photoresist patterns on the glass substrate (bottom right) (scale bars, 400 μm).

ticated readout setup (e.g., interferometry, confocal fluorescence microscopy), while fluorescent dyes photobleach and their emission properties are temperature-dependent.

In this paper, we present an electronic-free, image contrast based pressure sensor (Fig. 1). The pressure value is extracted by imaging the sensor using an objective lens, a CCD camera, a white light source and z-scanning module. The simplicity of the sensor design eliminates the need for expensive and sophisticated readout approaches such as fluorescent particle imaging [14–16] and interferometry [16]. Key design element of the sensor is the incorporation of a deformable, 10 μm thick, semi-transparent PDMS membrane (indicated as 's-PDMS' in Fig. 1(a)) that is exposed to pressure. The membrane is attached to a thick PDMS slab that contains a circular microchamber, a microfluidic channel and one inlet that is used to pressurize the membrane. A rigid thick patterned glass substrate seals the entire sensor.

2. Design and fabrication of the pressure sensor

The pressure sensor functions as a 'displacement sensor' (Fig. 2(a)): pressure deflects the thin, PDMS membrane and the distance between the membrane and the top surface of the glass substrate is measured using a precision, z-scanning module. This module consists of a microscope objective lens (5×) and a computer controlled, high speed (10 ms/step) piezoelectric stage (Fig. 2(b)). The z-scanning module focuses first at the inner (top) glass surface of the microchamber, and then at the inner (bottom) surface of the semi-transparent PDMS membrane using a custom-made image contrast analysis algorithm. The z-scanning module is able to focus on those two surfaces because the refractive index changes significantly from glass to air and from air to PDMS and therefore those interfaces (PDMS/air and glass/air interfaces) have higher image sharpness or in other words greater image contrast while in focus compared to air.

An inexpensive fabrication process is employed using a combination of low cost materials and standard soft lithography techniques to manufacture the sensor which consists of 3 layers: (a) a 5 mm thick, PDMS slab. The slab is replicated from an SU-8 mold and contains the microfluidic channel which is 10 mm long, 200 μm wide and 100 μm thick. After the slab is peeled off from the SU-8 mold, two through holes – corresponding to the microchamber and pressure inlet- are made using a hole puncher, (b) a 10 μm thick, semi-transparent PDMS layer. This layer contains the pressurized membrane and is fabricated by spin casting and curing on a bare silicon wafer a mixture of 30% by weight of food color (Nourriture Coloration, FD&C Red #3, 0.5% in Aqueous Solution) and PDMS elastomer (10:1 wt ratio), and (c) a 500 μm thick borosilicate glass substrate that mechanically supports and seals the sensor. A 20 μm thick photoresist film (KMPR® 1000, MicroChem) is photolithographically patterned on the top surface of the glass substrate. The photoresist patterns are used to increase image contrast (see Fig. 1(b)). The glass substrate is then aligned and irreversibly bonded to the bottom surface of the slab after treating the surfaces with air plasma (700 mTorr chamber pressure, 50 W, 60 s exposure time) [17]. The slab is finally bonded to the 10 μm thick, semi-transparent layer. The portion of the membrane covering the pressure inlet hole is pierced to create the inlet and to allow the insertion of a metallic needle in order to pressurize the microchamber.

Food color was added while fabricating the 10 μm thick membrane to make it semi-transparent and, thereby, to increase its

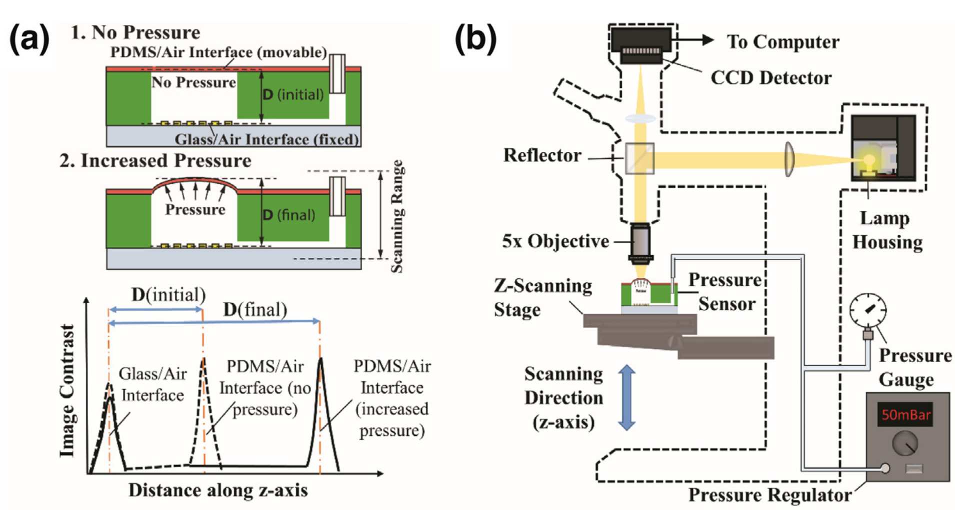

Fig. 2. (a) Operating principle of the contrast image based pressure sensor. (b) The z-scanning setup for measuring the distance between the 2 interfaces. The same setup was used to characterize the sensor. The image is not to scale.