# A PDMS-Membrane Optical Pressure Sensor with Threshold Logic and Its Fabrication Method

**Kamal Kishor Upadhyay[1*], Upendra Kumar[2]**

**[1]Postdoctoral Fellow, Lincoln Global University Malasia**
**[1]Department of ECE, Manipal University Jaipur, Jaipur, Rajasthan, India**
**[2]Department of Computer science, IET Lucknow, Uttar Pradesh, India**
Kamal.upadhyay@jaipur.manipal.edu, Upendra.ietlko@gmail.com

**Abstract:** Microfluidic pressure sensing is commonly proven on the conceptual or system level, but a practical prototype also relies on a reproducible fabrication and assembly sequence. This work reports a fabrication process of a PDMS-membrane optical pressure sensor coupled to hysteretic threshold logic. The proposed sequence consists of a photolithographic master, molded PDMS flow and cavity-spacer layers, a spin-coated PDMS membrane, oxygen plasma bonding, a glass cover and laser-photodiode readout followed by analogue-to-digital conversion and microcontroller-based categorization. The present work examines process compatibility, small-deflection geometry scaling and deterministic logic behavior, rather than experimental sensor performance as fabricated-device data were unavailable. with example, the plate model predicts that the peak deflection will rise 46.4% with a 10% increase in membrane radius, and decrease 24.9% for a 10% increase in thickness. Four stage logic sequence ensures that the system correctly switches state from OK to ALERT and vise versa for normalized thresholds of 0.50 and 0.60. The report consequently provides a defined course for subsequent prototyping and calibration but does not present analytical conclusions as measured performance.

**Keywords:** optical pressure sensor, threshold logic, microfluidics, PDMS membrane, soft lithography

## Introduction

Microfluidic platforms are frequently employed to manipulate small amounts of liquids in biomedical researches and lab-on-chip systems [1], [5]. In these devices the pressure in the channel is a local quantity, a pressure set on an upstream pump is not always representative of the situation at the sensing point. Even if the pump setting has not been altered, a partial obstruction, trapped bubble or leak can affect local pressure. The objective here is to perceive the pressure inside the region of interest rather than depending on the drive conditions outside the region of interest [6], [7]. Poly(dimethylsiloxane) (PDMS) is a good candidate for this kind of sensor due to its optically transparent, elastomeric qualities and the possibility of being made by soft-lithography techniques [2], [3]. The PDMS membrane can be used to sense the change in separation of two optical cavities which can be detected by optical sensors [6]. It is easier to use a laser diode and photodiode than to take photographs of the fringe patterns that form between the two optical cavities [6]. However, the PDMS membrane should be consistently manufactured and connected to a substrate with the optical components suitably positioned to provide accurate measurements of the separation change between the two optical cavities. The design of a PDMS-membrane sensor and the necessity for logic-level outputs from the sensor were described in a conference article, although without the detail of the manufacture of such a sensor [8]. In this study we discuss the processes for fabricating a PDMS-membrane sensor with logic-level outputs.

As the study did not offer calibration data for the sensor, the discussion will focus upon the feasibility of constructing the sensor according to the specified process, the analytical scaling of the sensor's dimensions and the verification of the logic circuits within the sensor.

## RELATED WORK

Soft lithography allows the fabrication of PDMS structures with great resolution and accuracy [2, 3]. Optofluidics integrates fluidic and optical functions in a single device [4]. Song and Psaltis fabricated a two-layer PDMS membrane interferometer on a glass substrate. To change the optical characteristics of the interferometer, pressure was applied to the air-gap between the two layers. The change in optical properties was recorded using a microscope and a camera [6]. Another group, Hoera et al., used an optical pressure sensor embedded in a glass microfluidic chip with a cavity with a luminous sensor layer [7].

The two devices previously built are not shown in this publication. However, the construction of these devices was a forerunner for the fabrication of the prototype device reported below. A comparison of the two devices is given in Table 1. The proposed device is composed of a PDMS flow layer, a separately produced membrane and cavity spacer, a glass cover and a permanently connected laser-photodiode readout. Not images. The firmware reads the laser signal.

**Table 1: Representative instances of fabrication and readout.**

| Methodology | Basis of manufacture | Readout | Significance |
|---|---|---|---|
| [6] Interferometer with PDMS membrane | Two structured PDMS layers on glass substrate | Microscope + camera | Shows membrane/air gap transduction |
| [7] Optical sensor incorporated inside a chip | Sensor layer luminescent | Shows on-chip optical pressure sensing | air gap transduction |
| Proposed Sensors | PDMS flow layer + spun membrane + spacer + glass | Laser + photo-diode | Sequence of fabrication + logical conclusion |

### Major Contribution

The main contribution of the paper is the description of the fabrication process of the proposed layer stack. The manufacturing process steps are outlined in depth including the order in which each step is to be completed. Further, the paper gives three kind of evidence separately: compatibility of known process with literature, scaling of analytical geometry and deterministic verification of threshold rule. Each of these sort of evidence are crucial in the setting of the study as they relate to the measurement of the sensors to be manufactured according to the proposed layer stack.

### Fabrication Procedure and Methodology

The suggested stack is a molded PDMS flow layer, a spin-coated PDMS membrane, and a patterned PDMS spacer to produce an air cavity, and a glass cover. The liquid channel is separated from the cavity by the membrane. In the baseline configuration, a laser diode interrogates the cavity at normal incidence, and a photodiode measures the resulting intensity. Photocurrent is converted to voltage by

a transimpedance amplifier, the signal is sampled by an analog to digital converter and baseline correction, filtering, calibration lookup and hysteretic state classification is performed by the microcontroller. We assume no camera or image processing pipeline. The optical fixture should allow for separate adjustment of the laser and detector such that alignment does not load the bonded chip. The photodiode baseline is verified against the maximum useable range of the amplifier and converter before any pressure is applied. If the signal is close to saturation or below the acceptable range, alignment or gain is modified first. This check minimizes confusion between membrane response and readout-range problems.

**Workflow Fabrication**

The procedure begins with the creation of discrete flow-channel and cavity-spacer patterns in CAD and the transfer of these patterns via photolithography to photoresist masters on rigid substrates. Following development, feature continuity and crucial dimensions are measured before the casting of PDMS. The PDMS is mixed, degassed, cured on the master and then peeled and trimmed to produce the flow and spacer layers. Inlet and outlet ports are punched post visual verification of molded features only. No laboratory process sheet was supplied therefore values are not placed here. The final mixing ratio, cure schedule and dimensions should be recorded using the chosen PDMS system and local process. A second thin film of PDMS is then spin coated on a clean, release-treated carrier. Spin speed and cure conditions are chosen from thickness trials and the membrane thickness is measured, not inferred from the spin setting alone. Rejected for tears, pinholes, wrinkles, particulates, inadequate coverage. The flow layer and the membrane are activated with oxygen plasma, aligned under a stereomicroscope and brought into conformal contact. The carrier is withdrawn only after the bond has grown sufficiently to support manipulation.

Next, the PDMS spacer is aligned on top of the membrane to define the air cavity and plasma bonded in place. The cavity is closed by a clean glass cover. The tubing is attached without providing mechanical load on the membrane area. The completed chip is next filled with deionized water under low pressure and checked for leakage, delamination, blocked ports and trapped air. Devices that pass these checks progress to optical alignment and calibration. The recorded controls and go/no-go criteria are shown in Table 2.

**Table2. Production procedures, recording controls, acceptance checks**

| **Step** | **Operation.** | **Control captured** | **Acceptance test** |
|---|---|---|---|
| **1.** | Design and review master | Typical dimensions | Features are complete and clean |
| **2.** | Flow of cast and spacer layers | MIXING AND CURE LOG | No voids or torn features |
| **3.** | Punch inlet and outlet ports | Port location and size | Clean layer; open ports |
| **4.** | Spin coating membrane | thickness; spin/cure record | Film continuous without granules |
| **5.** | Membrane Bond flow layer | Plasma and alignment data | Complete perimeter contact |

| | | | |
|---|---|---|---|
| **6.** | Release. Spacer for bonding and glass | Alignment of cavity | Clean, closed cavity |
| **7.** | Connect and fill low pressure | Applied, fluid and pressure | Leak free and no delaminating |
| **8.** | Align optical readouts | Dark voltage and baseline voltage | ADC range signal/ |

**Analytical Design Model:** For geometric scaling the membrane is modelled as a clamped circular plate of radius and thickness h under a uniform pressure p. The maximum displacement in the bending-dominated small-deflection regime is [9]. The membrane motion can change the cavity length from L0 to L0 - w0 for the present geometry. A low-finesse version of a sinusoidal approximation to the cavity interference for planning a calibration can be stated as $I_b$ is the background term, A is a scaling factor, V is fringe visibility, n is the refractive index, $\lambda$ is the laser wavelength and $\varphi_0$ is the static phase. Due to the periodicity of the optical response the calibration must find a monotone interval around the operating point. The plate equation is only used to compare geometry in the small-deflection regime; after a device is constructed, the observed pressure-intensity curve must be utilized to replace this assumption for calibration.

**Logic Calibration and Testing**

Once the integrity check of the chip is passed, the dark signal of the photodiode and zero-pressure baseline are recorded. Then a traceable pressure source is employed to make ascending and falling steps over a cautious range determined by preliminary leak and integrity testing. Initially, bubble free deionized water is utilized and then water-glycerol mixes are introduced to study the effect of viscosity. Repeated cycling is necessary to determine the location of a monotonic optical interval and assess the repeatability and hysteresis. Sensitivity, error, response time, drift, and false-alarm performance should be given only when these measures are available. The hysteresis band is between 0.50 and 0.60. This keeps the system from oscillating back and forth between ALERT and OK while the signal is hovering around a particular threshold.

**Results and Discussion**

The suggested sequence uses techniques normally available in a microfabrication laboratory: photolithography, PDMS casting, spin coating, oxygen plasma bonding and discrete optoelectronic reading. These acceptance checks target common fabrication hazards such as change of membrane-thickness, release damage, particles in the cavity, layer misalignment and incomplete bonding. By inspecting each layer before further assembly you limit the probability that a known flaw is conveyed into the completed chip. This validates the viability of the process sequence; it does not prove that the sensor has been produced before.

The theoretical calculation addresses scaling of geometry, not actual sensitivity. Since $w_o$ is proportional to $a^4$, the expected peak deflection is multiplied by $1.1^4 = 1.4641$ or 46.4% when the membrane radius is increased by 10%. Increasing thickness by 10% increases the projected peak deflection by $1/1.1^3 = 0.7513$, a decrease of 24.9%, since $w_o$ is proportional to $h^{-3}$. Hence the radius and thickness must be measured during manufacture. A larger or thinner membrane leads to a larger anticipated deflection, but it also shifts the design into a regime of significant deflection behaviour and smaller mechanical margin. Table 3 Four ordered input sequences used to the state rule the output is

initially OK and only switches when the signal exceeds the higher threshold in the upwards sequence. When ALERT is triggered, values in the band 0.50-0.60 remain in that condition and only after crossing the lower threshold the sequence recovers to OK. The outcome verifies a physical false alarm rate or pressure threshold, not the state logic itself.

**Table 3. Deterministic verification of normalized threshold logic with hysteresis.**

| Case of verification | INPUT STRING | Initial condition | Result of logic |
|---|---|---|---|
| Stable base line | 0.35 | O.K. | OK.Below $T_L$ |
| signalling rising | 0.48–0.63 | OK | WARNING if $S_f$>= 0.60 |
| in-band modification | 0.51 to 0.59 | WARNING | ALERT was held |
| Healing | 0.56 through 0.47 | CAUTION | OK for $S_f$ <= 0.50 |

PDMS creep, temperature, laser-intensity drift, cavity pollution, fluid refractive index change, and trapped bubbles may also impact a fabricated prototype. These effects have to be measured on real devices. Therefore, the numerical sensitivity, detection limit, reaction time and long-term drift, device-to-device variance and suitability for blood-mimicking flow are not addressed in the findings given here.

**Conclusion**

**Method:** The suggested method involves photolithography, PDMS casting and spin coating, oxygen plasma bonding, glass-cavity assembly, low-pressure integrity checks, laser-photodiode readout, and hysteretic microcontroller logic.

**Key findings:** the plate model predicts an increase in the peak deflection of 46.4% for an increase of the radius of 10% and a decrease of 24.9% for an increase of the thickness of 10%. The four logic sequences yield the expected state transitions for the normalized test thresholds.

**Limitation and next step**: These checks are analytical and deterministic. The performance of the sensor may be claimed only after calibration of the sensor, repeatability, drift, response-time and fluid-dependent tests.

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