Design Framework for a Low-Cost Optical PDMS-Membrane Microfluidic Pressure Sensor for Blood-Flow Micro-pressure

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Abstract

Pressure measurement within the channels used in microfluidic devices is important for vascular-on-a-chip studies as well as accurate microfluidic measurements at the point of care. Most of the pressure sensors found in microfluidic devices use an expensive imaging system, have complex multi-step fabrication processes, or produce analogue output signals. This article highlights some of the fundamental components in PDMS-based microfluidics, optofluidic pressure sensors, polymer-based photonic membranes, and microfluidic logic circuits. From the review of these concepts, a gap in the literature emerges; there is a lack of simple optical pressure sensors that produce logic level signals with adjustable thresholds. Based on this knowledge, the proposal in this manuscript presents an optical pressure sensor consisting of a PDMS membrane based optical cavity and laser diode/photodiode, followed by threshold logic using a microcontroller. The manuscript discusses the proposed methods and hypotheses.

Keywords
Microfluidics; PDMS membrane; optofluidics; optical pressure sensor; microfluidic logic; point-of-care

Introduction

Mechanical phenomena, including pressure and shear, impact both fluid dynamics and cellular activity in microfluidic blood models. Pressure fluctuations in vascular-on-chip platforms can alter the pattern of shear distribution, thus affecting endothelial cells' reaction, platelet aggregation, and the general reliability of the assay. If the pressure in a system is solely determined by external pump settings, possible failures such as partial obstruction, leakage, or formation of gas bubbles will likely remain unnoticed. Such issues will negatively affect experimental precision and might damage fragile biological samples. As microfluidic devices continue to evolve beyond scientific research into routine biomedical and diagnostic application, the development of compact measuring instruments, along with intuitive decision-making output, becomes ever more relevant [1], [6]. Direct integration of sensing components on the microfluidic platform increases security, accuracy, and control, without relying upon bulky imaging equipment or extra measurement tools. While microfluidic devices offer unprecedented flexibility when controlling the shape of channels and other characteristics of fluid flow, this advantage relies on maintaining a high level of consistency in measurements.

Poly (dimethylsiloxane), or PDMS, is commonly used in microfluidics because of its transparency, flexibility, and biocompatibility as well as compatibility with soft lithography manufacturing techniques [2]. The elastic nature of PDMS enables the creation of a membrane capable of mechanical deformation through the application of pressure, making it suitable for creating an integrated sensor. In biomedical applications, the presence of a local pressure sensor will prevent accidental over-pressurization of the device and increase experiment's repeatability. Additionally, this type of component can facilitate continuous monitoring of the pressure during assays, including the study of blood flow and cell-based experiments [5], [6]. The current paper does not contain any new experimental results. Instead, it discusses existing concepts, limitations, and opportunities, while identifying research goals and hypotheses

System Design Justification and Review

This literature review is selective, focusing on practical issues related to the design of microsystems, including the materials used, sensing techniques, and integration mechanisms. The literature has been reviewed based on keywords such as "microfluidic pressure sensor," "PDMS membrane," "optofluidic interferometer," "photonic membrane pressure," and "microfluidic logic," with preference to highly cited implementation-related works. PDMS is suitable for mold replication and multilayer bonding techniques, and hence, membranes can be easily incorporated in microfluidic devices [2]. Mechanical deformation of the membranes in response to pressure is a predictable phenomenon. Multilayer soft lithography is known to fabricate stable membrane valves and pumps, which confirms stable mechanics of membranes within microfluidic channels [3]. Optofluidic systems integrate optical and fluidic systems to develop miniaturized sensor systems [4]. Song and Psaltis developed a PDMS optofluidic membrane interferometer to measure pressure based on optical cavity changes arising from membrane deflection [7]. Other chip-based optical pressure sensors highlighted the need for effective packaging and alignment of structures for stable measurement of signals [10]. Photonic membranes made of polymers have good optical properties even in a state of mechanical deformations; for example, the use of polymer elastomers to produce pressure-dependent colour changes [8]. On the other hand, there is research on microfluidic logic which involves the development of different physical states within microfluidic channels that perform logic functions, as seen in bubble logic circuits [9]. A vital point for sensing applications is the conversion of the mechanical variable to a binary output signal. Therefore, membrane-based optical pressure sensors combined with logic systems present a promising system for measuring pressure.

Research gaps and problem statement

Prior work provides strong proof-of-concept devices, but several practical gaps remain when the target is a compact sensor that can operate in blood-mimicking flows and deliver actionable outputs.

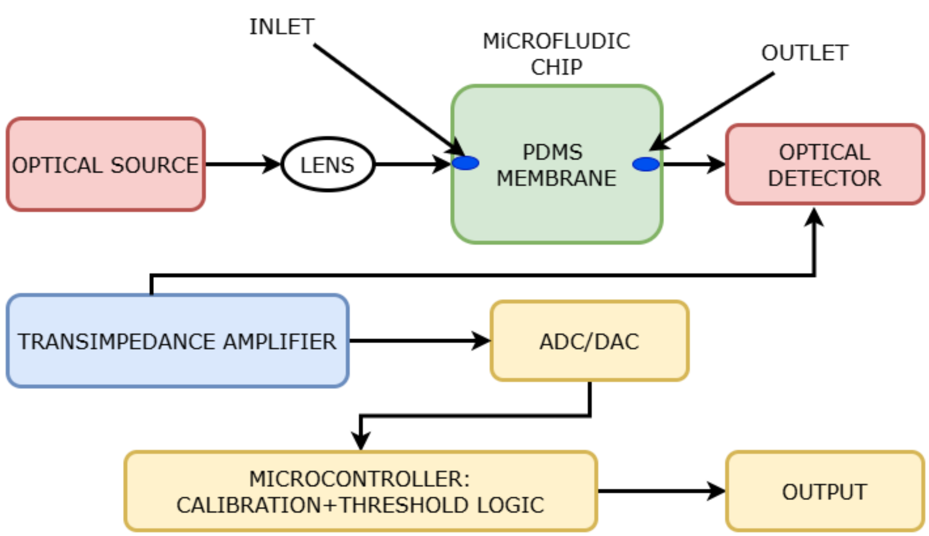

Fig. 1. *Proposed chip-scale concept: PDMS membrane and optical cavity interrogated by a laser diode and photodiode, with threshold logic for a digital output.*

The majority of optical pressure sensors described previously utilize microscopy-based imaging systems as means of signal detection, thus increasing complexity of their construction, price and difficulty of use. One of the major issues with currently developed solutions is the lack of small form-factor readout chain, made using relatively inexpensive optical elements like a laser diode and photodiode but offering accurate calibration and error calculation in practical conditions [7], [10]. The use of these sensors in biofluids causes additional problems – differences in fluid properties such as viscosity, presence of various particles or possibility of fouling, as well as appearance of bubbles and partial blockage of channels can impact the operation of membrane and its optical response. Moreover, real-life applications involve pressure spikes caused by sudden changes in pressure level inside microfluidic structures. Thus, another critical issue is the fact that existing systems produce analogue readings, which require extra interpretation. It is desirable to have self-contained devices with adjustable pressure threshold setting and logic-level output signal with hysteresis [8], [9]. Reliability is also one of the concerns related to long-term operation – polydimethylsiloxane can suffer from mechanical creep, and low-cost optical sources might experience intensity drift, affecting the performance of optical pressure sensors [2], [10]. Taking into account the discussed aspects, the summarized problem statement is development and testing of a PDMS-based microfluidic pressure sensor using small form-factor optics with ability to set a tunable threshold and logic-level output in blood-mimicking environment.The proposed architecture enables compact, low-cost, and integrated pressure measurement with direct logic-level output, reducing external instrumentation and signal interpretation effort.

Research questions and testable hypotheses

The above-listed gaps are formulated into research questions and hypotheses that can be experimentally validated according to the proposed experimental scheme.

1. Research questions

RQ1. Is it possible to achieve a monotonic and repeatable pressure to an optoelectronic signal conversion based on a PDMS optical cavity?

RQ2. Can optical tuning of the membrane or cavity allow changing the calibration curve, thus moving the threshold value without any re-fabrication of the device?

RQ3. Can a hysteretic logic mapping improve accuracy in detecting the bubble by preventing false triggers caused by transient phenomena?

2. Hypotheses

H1. The optical feature chosen is monotonic and repeatable over a certain pressure range.

H2. The optical tuning is capable of predictable shifting of the calibration curve, thus allowing setting the required threshold value in real-time.

H3. Logic-level processing near the optical sensor improves the accuracy of detection.

Proposed sensor concept and working principle

The principle incorporates membrane mechanics, optical cavity detection, and intuitive logic implementation. The design is intended for manufacture through conventional soft lithography and inexpensive optoelectronic components.

1. Device architecture and transduction

A microchannel is physically isolated from an optical cavity by means of a PDMS membrane. Deformation of the membrane due to pressure variations controls the effective optical length of the cavity or optical path. This builds on the principles established in optofluidic membrane interferometers [7]. Tunability can be provided by incorporating a photosensitive material into the membrane, which allows the light input to affect optical contrast and decision threshold [8].

2. Signal processing and logical implementation

The optical circuit consists of a laser diode, simple optics, and a single or dual photodiode sensor. Instead of imaging the entire field, the device focuses only on a few calibration-friendly parameters, including the ratio or difference in intensity values. The microcontroller processes the information using a filtering algorithm and threshold logic with hysteresis to deliver binary output (OK or Alert). AND logic can be implemented using two criteria through firmware programming, motivated by microfluidic logic without implementing complex gates [9].

Table 1. Design-oriented comparison of representative approaches.

Approach	Key benefit	Main practical risk	Representative source
Membrane interferometer sensing	High sensitivity in PDMS	Imaging dependence and drift	[7]
Photonic or colour-shift membrane	High optical contrast, tunability	Nanostructure fabrication and fouling	[8]
Chip-integrated optical pressure sensor	Compact readout, broad range	Cavity packaging and alignment	[10]
Proposed tunable cavity + threshold logic	Low-cost module and decision output	Needs validation in blood analogues	This work

Planned methods and evaluation metrics

The upcoming article will discuss methods and initial results. This section describes the minimum setup that can be used to test hypotheses H1-H3.

1. Device Production and Assembly

Produce channels and membranes using soft lithography. Control the thickness of the membrane by casting or spin coating and attach to glass or PDMS through plasma bonding [2], [3]. Assemble the cavity area and incorporate the tuning layer if needed.

2. Calibration and Interference Tests

Calibrate using a known pressure source with step and ramp functions. Test the device's performance in water-glycerol solutions and particle-containing fluids. Create air bubbles and occlusions to determine false alarm rates and recovery from these disturbances [5], [6].

3. Performance Metrics

Report performance metrics for sensitivity, detection limit, hysteresis, response time, cycle repeatability, and drift over several hours. For decision-making processes, report the probability of correct alarms and false alarms.

Conclusion

These seminal findings have synthesized knowledge of PDMS membrane mechanics, optofluidic sensing, and threshold detection to create an efficient design for microfluidic channel pressure sensors. The identified areas needing work, questions raised, and hypotheses proposed help to chart out a concrete path towards the development of methods/results-based papers.

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