Definition

A substance that, following a reaction, becomes an intrinsic part of a chemical product. The material must be stable at room temperatures. During the CVD process, the precursor material is vaporized. The precursor gas is transported to the surface where it undergoes a chemical reaction to produce the desired thin film.

Cross-References

▶ Chemical Vapor Deposition for Film Deposition

Pressure

Synonyms

Absolute pressure; Differential pressure; Gage pressure

Definition

The absolute pressure is referenced against a perfect vacuum (no gas molecule present in a defined volume). The gage pressure is the difference between absolute pressure and atmospheric pressure. The differential pressure is the difference between a measured pressure and a reference pressure. Pressures are measured in Pascal (N/m^2) according to the International System of Units (SI). Further commonly used units include bar, Torr (millimeters of mercury column), pounds per square inch, and others.

Cross-References

▶ Glass-Polymer Bonding
▶ Wall Shear Stress

Pressure Injection

Definition

Pressure injection is another important technique for transferring samples to microfluidic chips.

Cross-References

▶ Transferring Samples to Chips, Techniques

Pressure Measurements, Methods

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Synonyms

Methods for pressure measurements; Pressure sensors

Definition

Experimentation and novel measurement techniques are crucial for the further development of microfluidic devices. Pressure is one basic parameter involved in microfluidic experiments. However, it is not realistic to apply the conventional pressure measurement techniques to microsystems, since the characteristic dimension of these measurement instruments is already comparable with the size of the microdevices. Therefore, novel pressure measurement methods are needed for pressure measurement at the microscale.

Overview

By the use of the conventional sensors, it is not practical to measure the pressure inside the

micro- and nanochannels, since it is very difficult or impossible to implement these relatively bulky (compared to the microsystem dimensions) sensors to microsystems without disturbing the flow field. Therefore, some novel methods are demanded for pressure measurement at the microscale.

The common practice to measure the pressure drop along a microchannel is to use pressure transducers at the inlet and exit reservoirs, which gives overall information about the pressure rather than the pressure distribution along the channel. This approach is used in many studies related with the fluid flow in microchannels [1–4].

More recently, many researchers proposed designs to measure pressure within a microfluidic channel [5–14] or even within a nanochannel [9, 10]. In these studies, the pressure within the micro-/nanochannel is measured by sensing:

- The capacitance change of a gap [5]
- The electric transition of armchair single-walled carbon nanotubes [6]
- The resonance frequency shift [7, 8]
- The deflections of a thin plate over a channel surface by the topographic imaging of the thin plate using AFM [9]
- The interaction of atoms or molecules with photons [10, 11]
- The movement of liquid-air interface [12]
- The interference patterns generated by the flexible air gap which is optically illuminated by monochromatic light [13]
- The focal spot of pneumatically tunable microlenses [14]
- The voltage output of a conventional pressure transducer [15]

Basic Methodology

In pressure measurement techniques, the most common way is the detection of strain on a membrane or diaphragm. The main source of displacement of a membrane is pressure of the fluid. The strain measured by the generation of electrical signal is commonly converted to pressure with some manipulations. The applied technique to measure the strain determines the type of the pressure sensors. For instance, an optical pressure sensor uses light to measure the change in displacement, and this change is processed to obtain the pressure. Common pressure sensors that are using the detection of strain are based on a capacitive, optical, piezoresistive strain gauge, piezoelectric, or potentiometric principle. There are other types of pressure sensors which are not using strain. The most common ones are based on PSP (pressure-sensitive paint) by using image processing, resonant structures by measuring the change in the resonant frequency, and thermal principles by measuring the change in the thermal conductivity.

Key Research Findings

Sekimori et al. [5] developed a pressure sensor which has an embedded miniaturized structure, high chemical resistance, and no interference to the flow during the measurement for use in lab-on-a-chip (LOC) devices. Their pressure sensor element has a volume of 1 mm^3 and was fabricated by using MEMS technology. They installed the pressure sensor element on a LOC by gluing it into a hole without any dead volume and disturbance to the flow in the microchannel and were able to measure the pressure within the microchannel (see Fig. 1).

Single-walled carbon nanotubes (SWNT) were proposed as nanoscale electromechanical pressure sensors [6]. It was demonstrated by computation that a pressure induced a reversible shape transition in armchair SWNTs, which in turn induced a reversible electrical transition from metal to semiconductor. The potential long lifetime nature of this pressure sensor due to the excellent mechanical durability of the carbon nanotubes was pointed out as a superior aspect. SWNTs can also be used, besides as pressure sensors, as mass, strain, and temperature sensors by sensing the resonant frequency shift of a carbon nanotube resonator when it is subjected to changes in attached mass, external loading, or temperature [7, 8]. The feasibility of such a sensor was illustrated by means of computer
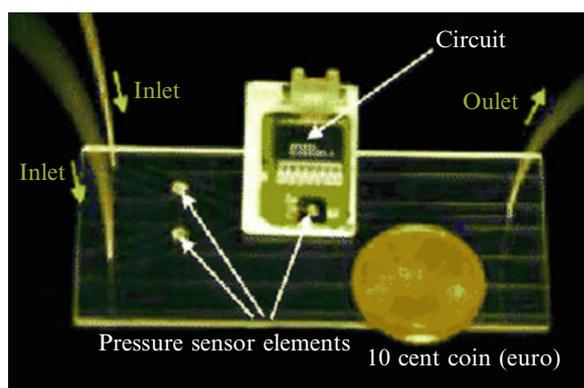
Pressure Measurements, Methods, Fig. 1 Installation of the pressure sensor to a microchip (Reprinted from [5] with permission from Dr. Kitamori)

simulation using atomistic modeling together with molecular structural mechanics. Computer simulations revealed that the sensing capability of this nanoscale sensor was superior to that of current microsensors, and sensitivity of such a sensor could be further enhanced by using smaller-size carbon nanotubes.

The use of atomic force microscopy (AFM) for measuring the pressure profile in micro-/nanochannels has been suggested [9]. The method is based on the measurement of the deflections of the thin plate over the channel surface by the topographic imaging of the thin plate using AFM. This measurement technique was numerically verified with artificially generated topographic data. Since the topological imaging takes quite a long time, this technique is only applicable to steady-state processes. Moreover, special attention should be considered for providing a vibration-free surrounding, since the transmitted vibrations via the fluid can cause noise in the data, which would lead to loss of accuracy.

Matsuda et al. [10] have pioneered the use of the pressure-sensitive pain (PSP) technique, which is based on the interaction of atoms or molecules with photons, to measure the pressure inside the micro-/nanochannels. The luminescent molecules are illuminated at particular wavelengths. Emitted light from the molecules is collected with a photodetector and processed with image processing equipments. Huang et al. [11] measured the pressure distribution inside the microchannel and entrance of the channel for gaseous flow using PSP. The pressures between 0.001 and 30 psi can be obtained with this method. Nonlinear pressure distribution is observed within the microchannel due to the compressibility effect. They were able to capture 5 μm resolution pressure maps at the inlet of channel with this method with the help of a CCD camera. This technique is limited to the gaseous flow and has drawbacks for high-pressure and low-speed applications. Moreover, the surface where the pressure is to be measured must be visible by the detector. The temperature sensitivity of the PSP should also be considered for the calibration.

Srivastava and Burns [12] developed a method for measuring pressure of liquids and air at any point inside a microchannel by using a microfabricated sealed chamber. The chamber contains one inlet where pressure is to be measured and no exit, as shown in Fig. 2. The pressure of the trapped air (P_g) inside the sealed chamber can be calculated by applying the ideal gas law, where the volume changes are calculated with the help of the movement of the liquid-air interface. The method can be applied for laminar and turbulent flow in LOC devices. The fabrication process of the sensor is simple due to the primary use of the microfluidic sealed chamber which is fabricated together with the microchannel by soft lithography. By using two chambers, the pressure difference between the points can be calculated and this pressure difference can also be used for the determination of the volumetric flow rate of the flowing liquid within the microchannel. The method is not suitable for permeable substrates such as PDMS because of the evaporation of the trapped liquid plug, which would cause reading errors.

Song and Psaltis [13] offered integrated optofluidic membrane interferometers (OMIs) to measure pressure and flow rate by processing the captured images. The OMI consists of two layers of PDMS and flexible air gap between them
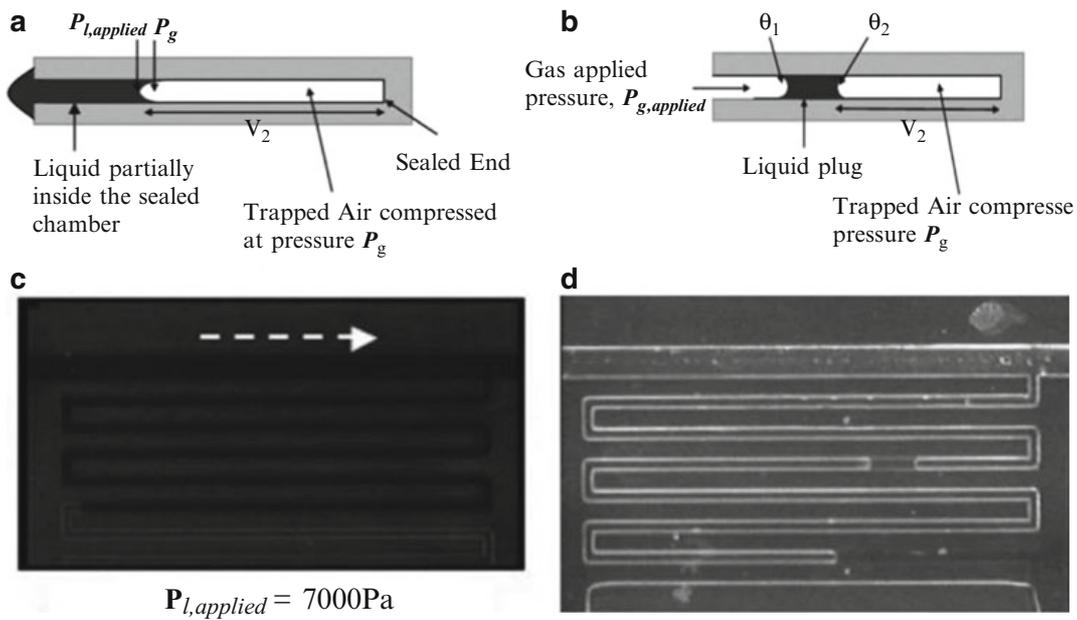
Pressure Measurements, Methods, Fig. 2 (**a**) Schematics of liquid pressure measurement. (**b**) Schematics of air pressure measurement. (**c**) Snapshot of liquid pressure measurement in microchannel ($P = 7,000$ Pa). (**d**) Snapshot of air pressure measurement in microchannel ($P = 78,559$ Pa) (Reprinted from [12], with permission from The Royal Society of Chemistry)
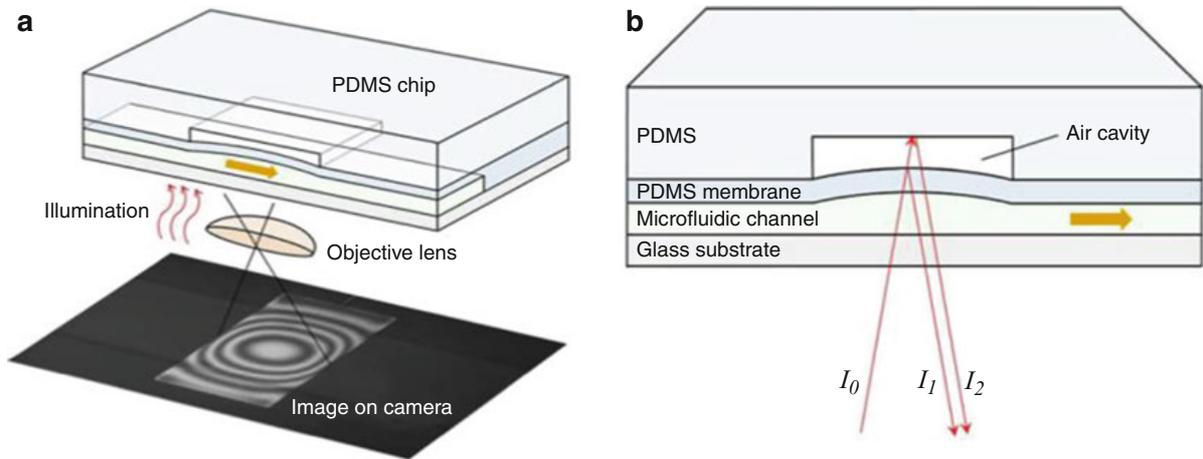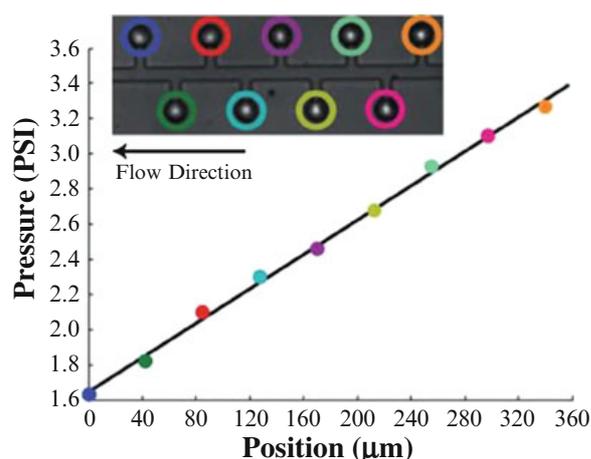

Pressure Measurements, Methods, Fig. 3 (**a**) Schematic of the measurement system. (**b**) Structure of the OMI (Reprinted from [13] with permission from Dr. Psaltis and American Institute of Physics)

(schematic of the OMI is shown in Fig. 3). The monochromatic light sent on the flexible air gap creates interference patterns, which are captured by the microscope and are processed with a suitable pattern recognition algorithm in the computer to determine pressure. The flow rate can be obtained using the pressure difference between two OMIs in the channel. Simple fabrication, low cost, large dynamic range, and high sensitivity are the benefits of this pressure sensing method.

Orth et al. [14] suggested the use of pneumatically tunable microlenses (circle structures) as seen in Fig. 4. The pressure is measured with a transmission microscope by processing the
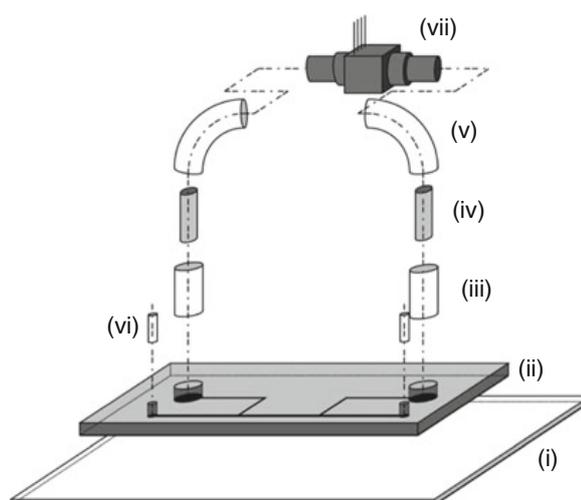
Pressure Measurements, Methods, Fig. 4 The pressure versus distance along the microchannel and micrograph of the microchannel together with the measurement points (Reprinted from [14] with permission from The Royal Society of Chemistry)

Pressure Measurements, Methods, Fig. 5 The schematic of the microchannel and external pressure transducer. Details: (*i*) glass slide, (*ii*) PDMS layer, (*iii*) transducer port, (*iv*) linking tube, (*v*) transducer tubing, (*vi*) main channel port, (*vii*) pressure transducer (Reprinted from [15] with permission from Dr. Shen and American Institute of Physics)

image of the focal points of the microfluidic device with respect to a calibration curve. The fabrication of the pressure sensor is simple and low cost via the soft lithography technique. Moreover, the stability, low noise, and multiplicity are the advantages of the sensors. The pressure range of measurement was indicated as 2–15 psi. Some pressure values are also represented in Fig. 4.

Cheung et al. [15] demonstrated a simple way to determine pressure drop using a commercial external pressure transducer. The technique helps to avoid modifying the existing channel and applying additional fabrication processes. The integration of the sensor to the system is through openings for connecting the tubing that forms the access channels to the pressure transducer (see Fig. 5 for details). A better fit of the measured data was obtained by modifying the rigid channel theory by a deformability parameter.

Among the pressure measurement techniques discussed in this entry, the ones which are applied and tested are summarized in Table 1. Some important characteristics of these techniques are also included in the table to guide for the researchers in the microfluidics field.

Measurement techniques are crucial for the further development of the microfluidics

technology and for the fundamental understanding of the fluid flow at microscale. Although several techniques are suggested by many researchers, the measurement techniques for microscale are still going to be challenging and open-ended topics in the near future.

Future Research Directions

Although the mentioned pressure measurement techniques have some clear advantages, there still exist difficulties associated with these techniques which need to be solved in the future. These issues can be summarized as follows:

- Channel sizes in microfluidic application are in the range of 10–1,000 μm. Therefore, pressure measurement methods or devices should be compatible with microchannels with different channel size. Flexible pressure measurement methods which can cover this size range are still a challenge.
- Some methods require modification in the shape of the channel geometry that brings extra cost and effort in the measurement

Pressure Measurements, Methods, Table 1 Summary of the characteristics of the measurement techniques

	Measurement method	Size	Pressure range	Fabrication	Comments
[5]	Measurement of change in capacitance at the gap due to distortion of diaphragm	~100 μm channel width 1 mm^3 sensor size	0–100 kPa	Wet etching for the channel. Sensor element: bulk micromachining	Applicable for highly corrosive fluid flow in microchannel
[11]	Capturing the response of pressure-sensitive point (PSP) to light with a CCD camera	~μm PSP layer thickness	0.001–30 psi with accuracy of 0.001 psi	Langmuir-Blodgett (LB) technique for PSP fabrication	Applicable for high Knudsen number flows; Not suitable for high-pressure, low-speed flows; Applicable for microchannels; Useful to obtain pressure distribution inside the channel; Applicable for gas flows
[12]	Monitoring the liquid-air interface movement with a color CCD camera	400 μm main channel width 150 μm indicator channel width	Air: 700 Pa–100 KPa (700 Pa resolution); Liquid: 70 Pa–10 kPa (100 Pa resolution)	Photolithography and wet etching	Applicable to several lab-on-a-chip devices; Not applicable for PDMS; Bubbles should not be trapped; Applicable for both gas and liquid pressure measurement
[13]	Optical measurement with a mono-color CCD camera and image processing	200 × 480 μm^2 sensing area	0–10 psi and ±2 % accuracy	Multilayer soft lithography (MSL)	Applicable to PDMS and suitable for pressure drop measurements; Not suitable for negative pressures
[14]	Optical measurement by pneumatically tunable lenses with a CCD camera and image processing	~40 μm diameter sensing hole	2–15 psi 0.5 % resolution	Soft lithography	Can be used for highly localized pressure measurements; Can be used for dynamic measurements
[15]	External pressure transducers for pressure drop measurement	200–1,000 μm main channel width 200 × 68 μm^2, 200 × 97 μm^2 sensing area	0–34 kPa	Soft lithography	Good for pressure drop measurement in a PDMS channel; Good for dynamic measurements; Very simple integration

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process. Pressure measurement methods which require little or no modifications to the channel geometry may introduce more flexibility for the microfluidics applications.

- The calibration and validation of pressure measurement techniques for microfluidic applications requires relatively complicated procedures. A measurement technique with ease of calibration and validation would be very convenient for microfluidics.
- Although the proposed pressure sensors can measure the pressure on a local area, inclusion of multiple sensors to obtain a pressure distribution (except [11, 14]) is still problematic.
- In today's microfluidic technology, not many applications require dynamic pressure measurement. A pressure measurement technique with a good dynamic would extend the boundaries of microfluidics technology.

Several issues have been discussed. Although some of the current methods could address some of those issues, a pressure measurement technique, which would address all of the aforementioned issues, would be crucial for the further development of the microfluidics technology and for the fundamental understanding of the fluid flow at microscale. Therefore, pressure measurement techniques at the microscale will continue to be a challenging and open-ended research topic for the near future.

Cross-References

- ▶ Control of Micro-Fluidics
- ▶ Nanofluidics in Carbon Nanotubes
- ▶ Mechanical Nanosensors
- ▶ Velocity Sensors

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Pressure-Driven Flow

Definition

Flow driving principle used to create fluid flows through microfluidic channels. By applying pressure at the inlet the fluid is pumped through the channel. The fluid velocity near the walls approaches zero, and a parabolic velocity profile is produced within the channel.