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Silicon microfabrication based particulate matter sensor

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ABSTRACT

With the increasing public awareness of the impact of particulate matter (PM) on human health, real-time monitoring of PM exposure level has attracted more interest than ever before. While a great deal of effort has been put into the miniaturization of PM sensors, a wider range of applications is still hindered by big form factor and high cost. In this paper a novel design of PM sensor based on silicon microfabrication is presented. Silicon microfabrication and assembly process enables relatively small form factor and low cost. The operation principle of the sensor is light scattering method, an indirect way of measuring PM concentration. Silicon-based microfluidics serve as air flow channel and provide sealed sensing chamber for collecting scattered light by aerosol particles. The main chip components are integrated in the form of bare dies, reducing the size of the whole system. The main body of the sensor possesses small size of $15 \times 10 \times 1\ \text{mm}^3$, enabling easy integration into portable and wearable electronics. The light source in the sensor consumes less than 5 mW of power and the total power consumption is still low enough to make it suitable for battery-powered devices. In-lab and field testing and calibration results have shown that the sensor can achieve an accuracy of less than 10 μg/m^3 and prompt response (within s) to particle concentration changes. Detailed design, fabrication as well as testing results will be explained in this paper.

1. Introduction

Airborne particulate matter (PM) monitoring has aroused numerous attention in the past decades due to the negative impact of particles on human health [1,2]. With the increasing public health awareness, standards and rules for exposure limits of PM have been formulated by different governments and organizations. In most of current standards, the quality of the air is documented by the particle mass concentration in size fractions up to 2.5 μm ($PM_{2.5}$) or 10 μm (PM_{10}), e.g. in the EU the 24-h limit value of PM_{10} is 50 μg/m^3 and in US the 24-h limit value of PM_{10} and $PM_{2.5}$ is 150 μg/m^3 and 35 μg/m^3, respectively [3–5].

While high demand has been posed on continuous personal monitoring of PM exposure levels, the currently available PM monitors lack the portability due to big form factor. PM concentration can be measured by directly collecting PM or be estimated based on an indirect measurement. Traditional PM monitors collect particles by gravimetry on a filter within a certain period of time and the mass of particles can be measured by weighing the filter [6] or calculated by β-ray attenuation method (BAM) [7,8]. The particles can also be collected on a sensing element, such as tapered element oscillating microbalance (TEOM) [9], quartz crystal microbalance (QCM) [10], surface acoustic wave (SAW) [11], and film bulk acoustic resonators (FBAR) [12]. Besides the gravimetric collecting mechanism, recently new methods have been proposed to enhance the sensing sensitivity. Electrostatic precipitation method uses micro-fabricated discharger to charge the particles and measures the current carried by them [13]. Thermal precipitation method has been used to collect particles onto a FBAR device [12]. Among all the indirect methods of estimating particle mass, light scattering method has been most widely implemented into portable PM monitors [14–16]. Compared with direct measurement methods, light scattering method enables continuous real-time monitoring of particle concentration. Moreover, light scattering method provides the possibility of making simple and compact sensors enabling a wider range of applications.

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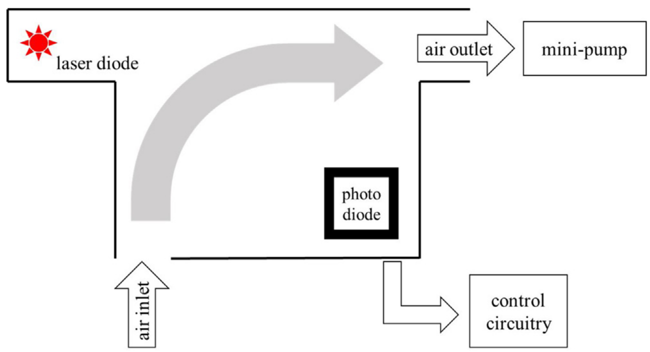

Fig. 1. Schematic of the sensor components. The main part is the sensing unit, hosting a light source and a photodiode inside the sensing chamber, connected with the control circuitry and a mini-pump.

In this paper, we present the design and fabrication of a miniaturized PM sensor, and demonstrate the performance of the sensor by laboratory testing. The proposed sensor uses light scattering method to sense the particle mass concentration. Compared with currently available commercialized PM sensors, our sensor has relatively small form factor (15 mm × 10 mm × 1 mm) and low power consumption, enabling easy integration into a portable or even wearable device, such as cell phones or smart watches. The presented sensor is an upgraded version of the prototype previously developed by our group and shows enhanced performance [17].

The rest of the paper is structured as follows: Section 2 describes the principles of operation of our sensor and the design of the sensor. The microfabrication and assembly process of the PM sensor is described in detail in Section 3. Section 4 describes the experimental testing and presents the experimental results. Finally, Section 5 summarizes the features of the sensor and possible improvement aspects and discusses future work.

2. System design

The operation principle of the proposed sensor is light scattering method. Fig. 1 illustrates a schematic of the sensor with the functions of each component. The sensor consists of a sensing unit and control circuitry. In this section, the design of each component will be explained in details.

2.1. The sensing unit

The sensing unit is formed by two stacked silicon submounts, with the size of 15 mm × 10 mm × 1 mm, the fabrication of which will be discussed in Section 3. The bottom silicon submount hosts the chip elements as well as the interconnections. A red light laser diode with a wavelength of 650 nm is used as a light source in this work. A photodiode (T1670P, Vishay Inc.), used as light receiver, is placed into a cavity. On each submount, two pairs of light source and receiver are assembled for design redundancy as well as easing the sensor testing. Laser diodes with different wavelengths can be mounted on each side of the sensor to accommodate wider range of particle size and composition. On the edge of the bottom submount, metal pads are placed for connecting all the chips with external control circuitry. The top submount contains air flow channels with inlet and outlet. When the two submounts are stacked, a sealed sensing chamber is formed with light source and receiver in between, as illustrated in Fig. 2. No physical or virtual filter is designed in this sensor so no particle size selection will be applied. The readings of this sensor will represent the total airborne particle mass concentration.

Different from most commercialized particle monitors [14], in our miniaturized sensor the light source and receiver are placed in the same chamber without using optics except for a short channel collimating the diverted light from the laser diode. The short collimating channel is added to reduce direct incident light from the laser diode onto the photodiode which was found unfavorable from our previous design [17]. Direct incident light leads to higher output of the photodiode which makes difficult for the scattered light of the PMs to be detected. With the collimating channel, the direct incident light is effectively suppressed, whereas light can still be reflected onto the photodiode inevitably by the inner surface of the chamber. The aerosol particles will scatter the light when they pass through the chamber with the air flow. Due to the light scattering effect, the photodiode is expected to receive more light. Fig. 3 illustrates the light scattering effect of aerosol particles.

To find out the correlation between the particle presence and the intensity of the light received by the photodiode, the simulation

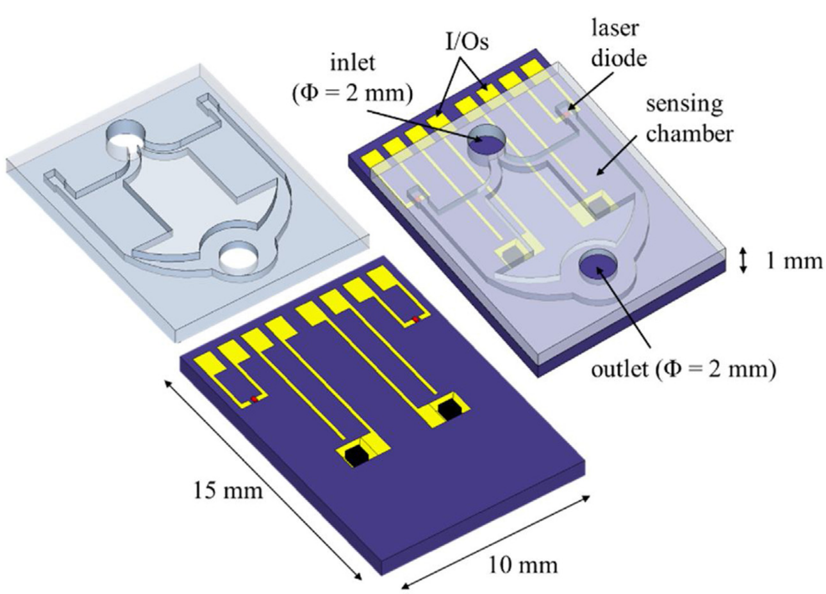

Fig. 2. Layout of the sensing unit. Bottom submount accommodates chips and electrical connections while top submount forms air channel and sensing chamber by stacking onto the bottom half.