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Microfabricated air-microfluidic sensor for personal monitoring of airborne particulate matter: Design, fabrication, and experimental results☆

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ABSTRACT

We present the design and fabrication of a micro electro mechanical systems (MEMS) air-microfluidic particulate matter (PM) sensor, and show experimental results obtained from exposing the sensor to concentrations of tobacco smoke and diesel exhaust, two commonly occurring PM sources. Our sensor measures only 25 mm × 21 mm × 2 mm in size and is two orders of magnitude smaller than commercially available direct mass PM sensors. The small shape allows our sensor to be used for continuous recording of personal PM exposure levels. The sensor contains an air-microfluidic circuit that separates the particles by size (virtual impactor) and then transports and deposits the selected particles using thermophoretic precipitation onto the surface of a microfabricated mass-sensitive film bulk acoustic resonator (FBAR). The mass-loading of the FBAR causes a change in its resonant frequency, and the rate of the frequency change corresponds to the particle concentration in the sampled air volume. We present experimental results that demonstrate the performance of our sensor for measuring PM mass emitted from diesel exhaust and tobacco smoke, and show that it exhibits sensitivity approaching 2 μg/m^3 with up to 10 min integration time.

1. Introduction

Atmospheric particulate matter (PM) is a category of airborne pollutants that includes dust, tobacco smoke, diesel exhaust, and other primary sources and secondary particles formed from gas phase precursors. Fine particles that have a diameter of 2.5 μm or smaller ($PM_{2.5}$) are especially damaging to human health because of their ability to penetrate deep into our respiratory system [1]. Exposure to $PM_{2.5}$ has been linked to reduced lung functionality, bronchitis, and heart attacks [2–4]. The negative health impacts of $PM_{2.5}$ have, for example, recently prompted the U.S. Environmental Protection Agency (EPA) to formulate new rules for the safe exposure limits of $PM_{2.5}$ [5] and influenced the Beijing Municipal Environmental Protection Bureau to start publishing $PM_{2.5}$ levels in response to high public demand. While the increasing awareness of the negative health impacts of PM shows the need for higher spatial density monitoring, the currently available direct reading PM mass sensors lack the form factor that will allow seamless integration into a device that can perform continuous personal monitoring of $PM_{2.5}$ exposure levels. Although light-scattering based PM sensors such as [6,7] have been made portable, such sensors collect particle count data and have to infer the particle concentration based on assumptions about particle density and size distribution, reducing their accuracy and applicability.

In this work we present the design and fabrication of a MEMS air-microfluidic PM sensor, and show experimental results obtained by exposing the sensor to concentrations of tobacco smoke and diesel exhaust, two commonly occurring PM sources. Our sensor is two orders of magnitude smaller than commercially available PM mass sensors, and is an order of magnitude smaller than the prototype previously developed in our lab [8]. Its small size (25 mm × 21 mm × 2 mm) enables easy integration into a portable platform for personal $PM_{2.5}$ monitoring. The sensor consists of a microfabricated air-microfluidic circuit that provides both filtration for the target particle size (by virtual impactation) and direct measurement of the particle mass concentration using a mass-sensing microelectromechanical film bulk acoustic resonator (FBAR). In this paper we describe the design of the sensor, provide a detailed description of its microfabrication process, and present the experimental results obtained from exposing two fabricated sensor prototypes to tobacco smoke and diesel exhaust. The results show that our sensor has low-end sensitivity on the order of 2 μg/m^3, which is adequate for personal pollution monitoring applications.

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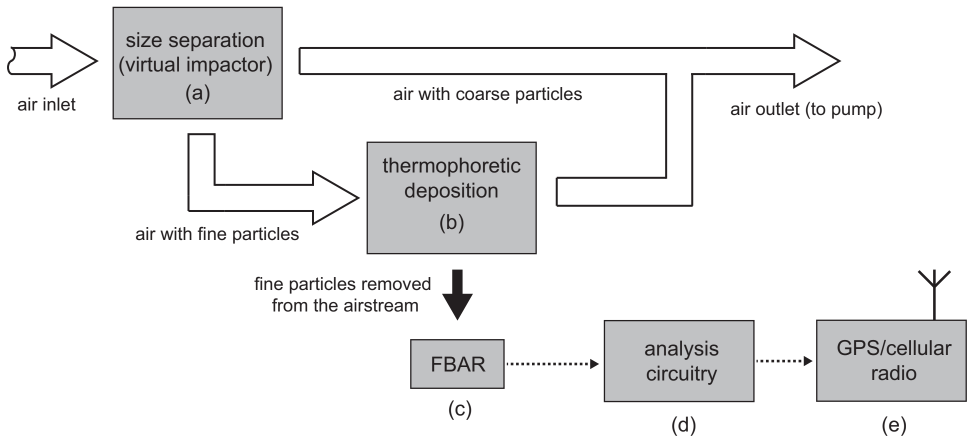

Fig. 1. Schematic drawing illustrating the components and functions of the air-microfluidic MEMS PM sensor.

An abbreviated version of this work was previously presented in [9].

The remainder of the paper is structured as follows: In Section 2 we briefly describe related work regarding small-sized PM sensors. A description of the principles of operation of our sensor and the design of the air-microfluidic circuit is presented in Section 3. The microfabrication process of the three-wafer stack constituting the PM sensor is described in detail in Section 4. Section 5 describes the experimental setup, while Section 6 presents the experimental results, detailing the exposure of our sensor to both tobacco smoke and diesel exhaust. Finally, Section 7 concludes with a discussion of the applications of the technology to personal monitoring of PM exposure levels and discusses future work.

2. Related work

PM concentration is determined either by measuring PM mass in a given size range by gravimetry or estimating it from an indirect measurement such as light scattering [10,11]. Direct gravimetric methods are either time-integrated, that is, particles are collected on a filter and weighed in a laboratory after collection [12] or continuously (1-h average or less), where particles are collected on a sensing element, such as a tapered element oscillating microbalance (TEOM) [13] or a quartz–crystal microbalance (QCM) [13]. Mass is measured in the latter two based on the change in frequency of the oscillating element or piezoelectric resonator, respectively. The most common indirect method for estimating PM mass over the size range of 0.3–10 μm in diameter is based on light scattering [11,13]. In this case, particles are illuminated by single or multiple wavelengths of light and the scattered light (forward and or backscattered) is measured and can provide an estimate of the mass of particles in the given volume of air. A number of assumptions are made in this indirect measurement of PM mass [11].

Particles within a given size range are most often selected based on particle inertia. Widely used approaches include impactors, cyclones, and virtual impactors (VIs) [14]. In all three cases particles are accelerated through a jet (e.g., nozzle or slit) to obtain a certain inertia. Particles smaller than the desired cutpoint remain in the major air flow, while those greater than the cutpoint are removed either by a real surface (plate or wall, the latter in the case of a cyclone) or pass through a minor flow collection jet (nozzle) in the case of the virtual impactor. Recently, miniature VIs, cyclones, and real impactors have been developed to separate particles at very low flow rates, in the range of 0.005–0.5 L/min [15–17].

Personal PM monitoring relies on portable mini-samplers that can be carried unobtrusively by individuals to record their PM exposure as they go about their daily activities [18]. Currently, these devices operate at flow rates of few L/min, weigh up to a kg, and are more than 10 cm in height [19–21]. In contrast, the device presented in this work measures 25 mm × 21 mm × 2 mm, weighs only a few grams, and operates at a flow-rate of approximately 6 mL/min. This low flow-rate enables low-power consumption which is advantageous for use in a portable personal PM monitor. A good comparison of this and other small-scale sensors is presented in [22].

3. System design

Fig. 1 shows a schematic drawing illustrating the functions of our air-microfluidic micro electro mechanical systems (MEMS) PM sensor. Air enters the microfluidic circuit through the inlet and immediately flows into an inertial size separator, commonly known as a VI [14] (a). The VI separates particles by size into a fine particle

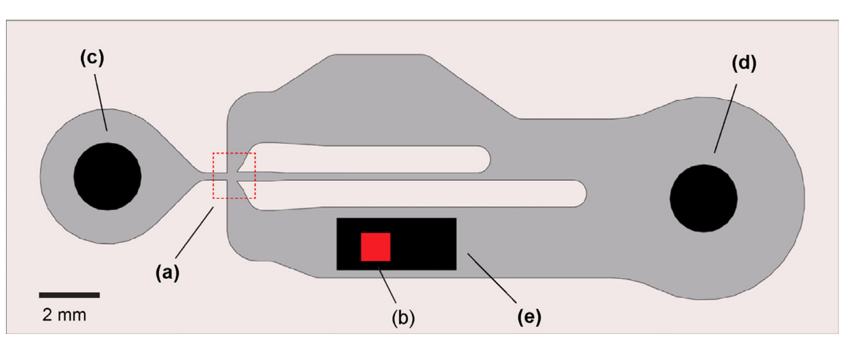

Fig. 2. Layout design of the microfluidic circuit. The VI and the thermophoretic deposition region are annotated (a) and (b), respectively. The dark gray areas indicate the flow channels of the microfluidic circuit, while the black regions indicate the through-holes for the inlet (c), outlet (d), and the FBAR insertion opening (e).