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Capacitive detection of micrometric airborne particulate matter for solid-state personal air quality monitors

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ABSTRACT

A novel microsensor for capacitive detection of particulate matter (PM) directly in air is presented. The feasibility of detecting single PM_{10} particles (calibrated 10 μm polystyrene beads) by means of ad-hoc designed coplanar microelectrodes (4 μm gap), a PDMS air deposition system, and a low-noise (~2 aF capacitive resolution) readout electronics is experimentally demonstrated. Finite element numerical simulations have been performed to optimize the design of the microelectrodes, investigate the detection limit and validate the experimental results. The real-time deposition on the sensor surface of sequences of single industrial talc particles (average diameter of ~8 μm, corresponding to a signal of ~12 aF) has been successfully tracked with 10 ms temporal resolution and, subsequently, validated by microscope inspection. This CMOS- and MEMS-compatible capacitance detection technique enables radical miniaturization of next generation air quality monitors, paving the ways to their embedment in personal portable devices for pervasive mapping of air pollution.

1. Introduction

It has been widely demonstrated that there is a correlation between high concentrations of particulate matter (PM) in the atmosphere, mostly in urban environments, and the increase of some pathologies, in particular of pulmonary diseases [1–4]. Although the exposure to fine and ultrafine dust, among other air polluting agents, has been identified as a threat for human health (as well as for the environment and for cultural properties), several toxicological effects of inhaled micro and nanoparticles still need to be elucidated [5]. At the same time, the policies implemented to reduce PM emission, such as vehicular traffic restrictions, often have been shown to be ineffective [6]. This impasse is due to the complex and poorly understood dynamics that governs the generation and transport of PM. This process can be subdivided in three phases: (i) PM generation (in localized industrial plants such as mines, power generation plants and waste incinerators, as well as due to distributed sources among thousands of internal combustion vehicles and building heating systems) and release in the atmosphere, (ii) PM long range transport in the atmosphere, deposition and chemical contamination of the ground surfaces in relation to atmospheric activity, (iii) PM human exposure through inhalation (penetration in the lungs at different depths, according to the particle diameter [1]), and its toxic effects on the human body at various scales (molecular, cellular and tissutal). Although accurate models of these mechanisms are under investigation, advances are significantly hampered by the currently available monitoring instrumentation that lacks portability and appropriate spatio-temporal resolution [7–9]. Two are the main limitations of the current airborne dust analyzers [10]. On the one hand, several dust analyzers (such as the gravimetric ones [11] or real-time microbalances, based on mass-sensitive MEMS cantilevers, for micro [12] and nano-particles [13]) provide only the total mass of PM in a given volume of sampled air (for instance, max. 50 $\mu g/m^3$ of PM_{10}, as currently required by European regulations). They cannot measure the granulometry of PM (i.e. the distribution of particles sizes usually divided into PM_{10}, $PM_{2.5}$ and PM_1 size classes) which is extremely relevant from a toxicological point of view. On the other hand, other systems based on laser scattering [14] or cascade of impactors with electrometers [15], while providing real-time detection and fast single particle analysis and granulometry, are too bulky (weight >1 kg) and expensive (>1000 $) to be capillary disseminated in a city. Therefore, the spatial resolution achievable

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with these devices is that allowed by only a few fixed (background stations) or movable sampling stations continuously operating in a metropolitan area.

Thus, motivated by the need to overcome such limitations, we devised a novel detection method based on a highly sensitive capacitive microsensor. In this article we demonstrate the feasibility of direct dielectric detection of single PM_{10} particles in air with the intent of paving the way to the development of highly miniaturized single particle (granulometric) detection devices. We believe that this impedance-based technique will eventually enable the embedment of solid-state air quality monitors in personal and networked mobile devices, such as smartphones, allowing radically new air monitoring strategies [5] based on real-time indoor and outdoor pervasive monitoring, personal dosimetry and participative pollution mapping.

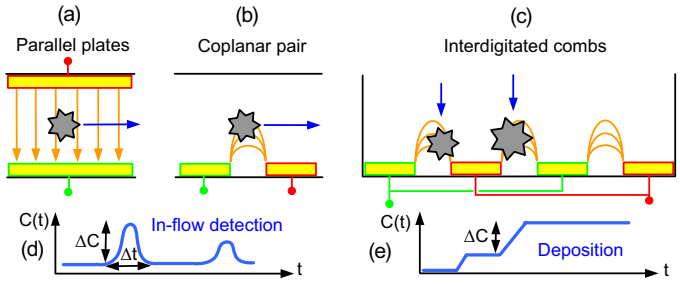

Fig. 1. Possible configurations of the proposed solid-state direct capacitive sensor of PM in air: (a) parallel-plate microelectrodes for in-flow detection of PM, (b) single coplanar pair of electrodes and (c) multiple interdigitated electrodes, an extension of (b), to cover a larger deposition area. The latter are suitable for both stream flow (d) and deposition (e) detection.

2. Theory

2.1. Principle of detection

Our detection technique relies on the impedance variations measured by a pair of microelectrodes placed in the proximity of a stream of PM. The presence of a particle (replacing the equivalent fraction of air dielectric with its volume) interacts with the electric field lines and increases the capacitance between the electrodes because the relative permittivity of a particle is larger than that of air. A similar approach has been already validated for label-free counting and characterization of single biological cells (5–10 μm) and implemented on microfluidic platforms for impedance flow cytometry [16] or for detection of metallic debris in lubricant oils [17]. In this article we present a similar, but more challenging, approach for the detection of PM in air. Note that humidity, in the form of micro water droplets ($\varepsilon_r = 80$), could generate miscounting as it happens in other in-air PM detection techniques (laser scattering and microbalance). This problem, however, can be easily solved by adding a pre-heating microchamber to the air sampling duct to force the evaporation of the airborne water droplets before they can reach the sensor.

Two in-liquid techniques for the detection of airborne particles have been proposed in literature, but they cannot be implemented in our case. The first technique has been developed only for particles of a given size (pollen ~330 nm) that were dispersed in a conductive liquid and transported through a size-tailored nano-channel (500 nm) with transversal microelectrodes, allowing contemporary ionic blockade and transversal current sensing [18]. The second technique leverages the condensation of water vapor on nanoparticles to increase their detectable diameter. In this way it is easier to count the particles, but it is more difficult to determine their size and, therefore, characterize the granulometry distribution [19].

Since our goal is to detect PM present in air, we decided to design a device able to characterize the distribution of microparticles directly in air. There are two main challenges. The particle transport is hard to implement because the density of air is much smaller than the density of the particles. The detection of particles is difficult because the dielectric contrast is small. It could be tempting to use a liquid buffer to overcome these difficulties. However, the price to be paid is high because dissolving the particles dispersed in air in a liquid is far from being trivial and the buffer liquid has to be highly purified and contained in a specifically designed water-tight reservoir. Therefore, this choice would make the design more complicated and harder to integrate in a portable device.

In the case of a highly conductive buffer liquid the conductivity contrast is high and, thus, the insulating particles can be detected measuring a large conductance decrease (current signal $\Delta I \sim -10\,\mu A$). In air, instead, the dielectric contrast is small and, thus, the capacity signal ΔC produced by a 10 μm particle is of the order of 10 aF, corresponding (at 1 MHz) to a signal $\Delta I \sim +60$ pA, i.e. about five orders of magnitude smaller than the corresponding measurement obtained using a buffer fluid. In order to resolve the tiny capacitance variations induced by nanoparticles in air, a specific design of the sensing electrodes is needed and will be presented in the next section.

2.2. Parallel versus coplanar electrode configuration

The architecture of the electrodes is crucial for optimizing the performance and operability of the sensor. Fig. 1 shows the two main configurations (parallel and coplanar) conceivable for a solid-state sensor system. In the parallel-plate geometry (see Fig. 1a) a stream of PM is forced to flow between the electrodes. The presence of a particle generates a capacitive jump (ΔC) whose amplitude is related to the diameter D and dielectric constant ε_r of the particle. However, due to the homogeneity of the electric field, the jump is independent of the vertical distance H of the particle from the electrodes. Note that the concurrent variability of D and ε_r might make ambiguous the determination of the particle size using a single ΔC measurement. However, this ambiguity can be substantially reduced by recalling that $\Delta C \sim D^3$ and $\Delta C \sim \varepsilon_r$, and combining in cascade or in parallel multiple sensors of different geometries. The same kind of ambiguity affects the instruments based on laser scattering detection, where the intensity of the scattered light depends on the particle diameter (as D^6 or D^2 depending on the diameter/wavelength ratio) and on its refraction index (whose distribution is ignored and an average value is assumed) [20]. The main limitation of the parallel-plate geometry is that it cannot be used for detecting particles having a wide range of sizes. In fact, the diameter of the largest particles determines the distance between the plates (with appropriate margins and input filters to prevent clogging), thus reducing the magnitude of the sensor capacitance and its modulation ΔC, which are crucial for detecting the smallest particles.

The coplanar geometry (Fig. 1b) has several advantages over the parallel-plate geometry. First, the coplanar electrodes are easier to fabricate. Second, it permits detecting particles over a wide range of sizes with minimal risk of clogging. Third, this geometry permits operating the sensor in two different conditions: when the PM flows over the electrodes or when the PM sediments, by natural settling or forced deposition, over the electrodes. Note that the coplanar configuration allows us to take advantage of the non-negligible effect of gravity on the particles enabling significant relaxation of the detection speed requirements.

The motion of the particles with respect to the coplanar electrodes has, obviously, an impact on the shape of the signal to be