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Capacitive single-particle microdetector for real-time pervasive PM_{10} monitoring

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Abstract

In order to address a widespread demand for capillary, distributed and participatory mapping of micrometric airborne dust concentration in smart cities, we present a novel single-particle detection technique suitable for counting and sizing micrometric particulate matter based on capacitance sensing. The realized compact instrument, suitable for both in-door and out-door operation, provides a resolution of a few aF with 10 ms response time, suitable for real-time tracking of single particle of 8-10 μm diameter depositing on ad-hoc designed planar microelectrodes (experimentally demonstrated with polystyrene beads, industrial talc and printer toner particles). These results pave the way to the miniaturization and consequently large-scale diffusion of personal PM_{10} monitors.

Keywords: Particulate matter; capacitance sensor; attoFarad reoslution; smart city.

1. Introduction

Nowadays the awareness of the risks for health due to the lifelong exposure to particulate matter (PM), especially in urban areas, is growing in the society. Thus, citizens are beginning to require from local and national environment protection agencies capillary and real-time information about air quality (Lonati et al., 2011). In order to address such a widespread demand for distributed and personal mapping of PM, we present a novel detection approach based on high-resolution dielectric sensing of single dust particles in air. As illustrated in Fig. 1, this technique relies on the direct measurement of the dielectric contrast between the air stream (properly focused by a microfluidic channel) and the single

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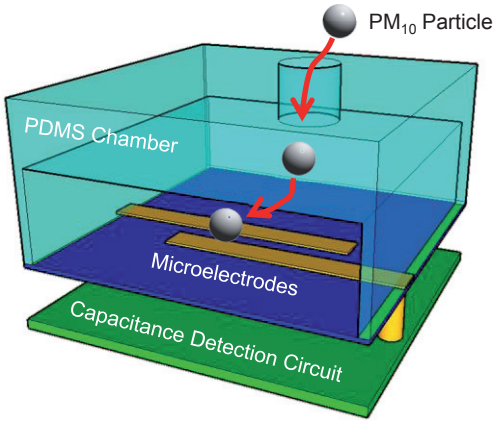

Fig. 1. Single PM particle detection and granulometry by means of high resolution coplanar capacitance sensing.

airborne particle, flowing inside a microscale capacitor. This solution combines the compactness and low cost of nephelometers (Budde et al., 2013) with the capability of single particle analysis and granulometry, typically provided by bulky and expensive instruments based on laser scattering (Carminati et al., 2011a). Applications made possible by this technique include the capillary diffusion of wireless networks of hundreds of compact PM detection nodes in urban environments (*smart cities*) or in specific high-exposure areas such as mines or construction sites. Furthermore, personal and participatory monitoring is enabled thanks to the envisioned embedment of such sensors in portable devices such as smart phones. Clearly, the impact of these revolutionary distributed sensing scenarios directly affects citizens and workers healthcare, as well as the development of better atmospheric, environmental and toxicological models.

This novel electric approach profits from the consolidated techniques for single particle analysis in liquids. In fact, high-throughput microscale single particle detection and sizing in a highly-conductive ionic solution has been widely demonstrated for instance of biological cells in the context of microfluidic impedance flow cytometry (Carminati et al., 2010) and recently also for magnetic particles of 1 μm diameter (Carminati et al., 2014). In this case, the presence of a micrometric particle altering the electric field of the air microcapacitor produces a tiny capacitance increase (in the atto- or sub-attoFarad range) whose detection represents a challenge for the readout electronics.

2. Instrument design

The instrument is composed of three major parts, strongly interacting and co-designed: the microelectrodes, the capacitance detection electronics and the fluidic for air sampling and dust convoy. Despite a highly non-uniform electric field, the coplanar geometry has been chosen for the electrodes, since it avoids the risk of clogging, which affects parallel-plate configuration across a narrow fluidic channel.

The optimization of the electrode geometry has been performed by means of finite-element numerical simulations. As illustrated in Fig. 2, thanks to the symmetry of the problem, only a quarter of the domain has been simulated. Simulations confirm that the capacitance increase ΔC due a single particle, present in the sensitive volume above the gap between the microelectrodes, scales with the particle volume (and linearly with the relative

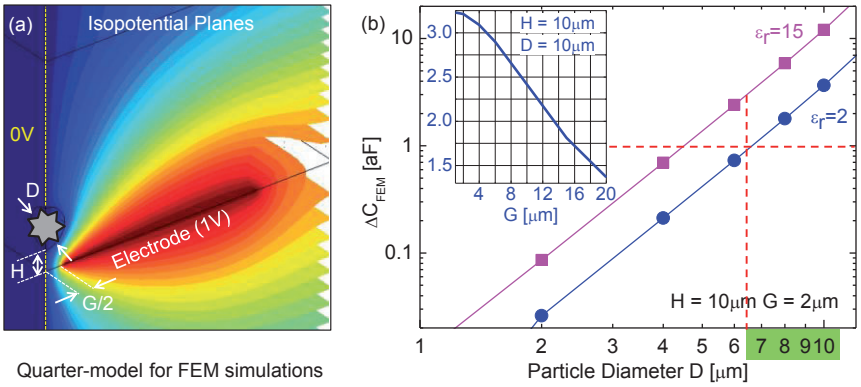

Fig. 2. FEM simulations (a) employed for the analysis of the capacitance signal due to a sphere of diameter D (b).

dielectric constant of the particle ε_r). Taking ~1 aF as the best resolution achievable with discrete-component electronics, this preliminary analysis indicates that the minimum detectable diameter is ~7 μm, thus suitable for PM_{10}. Since with ultra-low noise integrated circuits (Carminati et al., 2011b) it is possible to achieve zeptoFarad capacitive resolution, smaller PM fractions are addressable in perspective. Simulations also show (Fig. 2b inset) that if the particle is close to the electrodes, the signal ΔC is maximized by reducing the inter-electrode gap. Consequently, pairs of parallel coplanar microelectrodes separated by the minimum gap achievable with reliability in the available standard lift-off process (4 μm) and 3 mm long have been fabricated on a glass substrate, in order to avoid the detrimental effects of a silicon substrate (Carminati et al., 2012).

Capacitance is measured by applying a sinusoidal signal to one electrode and sensing the current induced at the second electrode with a low-noise transimpedance amplifier realized with an integrator (feedback capacitor = 1 pF matched with the total electrode stray capacitance) to avoid the thermal noise of the feedback resistor, providing a frequency-independent voltage signal to a lock-in phase-sensitive demodulator.

The instrument prototype is visible in Fig. 3a. The glass chips with the microelectrodes are bonded to the fluidic chamber fabricated in PDMS and attached on a small PCB with dual-in-line connectors for interchangeable connection to the sensing motherboard. The main PCB contains all the low-noise analog circuits (integrator front-end and inverting buffer for differential sensing) and power-supply filters and is connected to an external digital 50 MHz lock-in detector (HF2LI by Zurich Instruments).

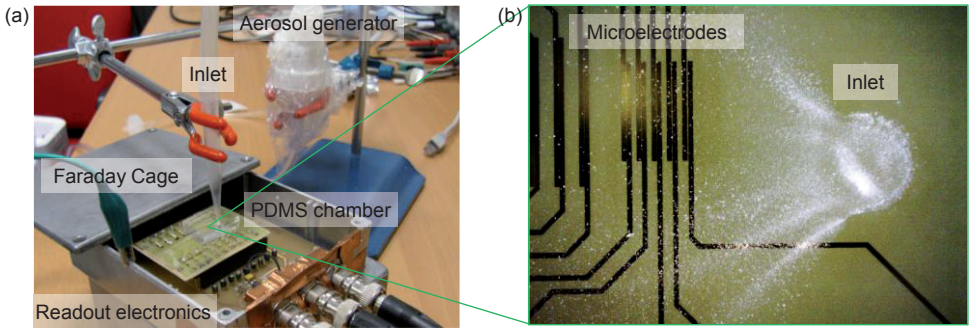

Fig. 3. (a) Measurement setup (b) high concentration dust deposition experiment on the electrodes chip.

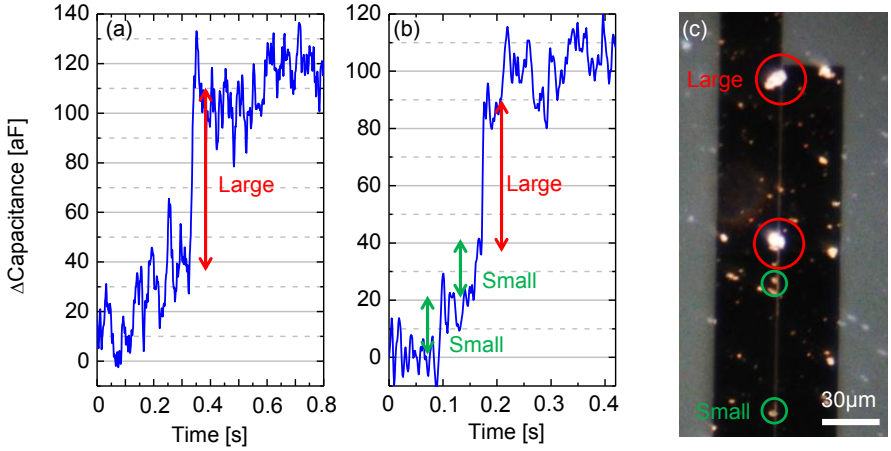

Fig. 4. (a-b) Real-time detection (7.5 aF rms noise with 1 V applied at 1 MHz, 100 Hz detection bandwidth) of single talc particles depositing between the electrodes (4 μm gap), imaged with the microscope in dark field (c).

Fig. 3b shows a dust deposition experiment. The height of the 1 cm-wide PDMS chamber (200 μm) has been sized in ordered to force the deposition of the particles. The highest concentration of deposited particles is directly below the inlet, while, by adjusting the distance between the electrodes and the inlet, it is possible to simply tune the desired surface density of deposited particles.

3. Experimental results

3.1 Dynamic detection of talc

The instrument has been preliminary validated in static conditions with calibrated polystyrene beads (10 μm and 20 μm diameter) manually placed and removed from the electrodes. The feasibility of single PM_{10} detection has been thus demonstrated. A differential sensing approach is adopted to reduce the impact of the lock-in amplifier noise (dominating the front-end noise): the instrument provides a resolution of 1.16 aF with 1 s response time, 3.3 aF with 10 ms response time (increasing to 7.5 aF in the case of reduced matching between the electrodes, due a larger distance between the sensing chamber and the dummy chamber imposed by the microfluidics).

Industrial talc has been used to simulate ambient PM_{10}, thanks to its abundance, non-toxicity and lognormal size distribution with an average diameter of 8 μm. Its dielectric constant has been experimentally measured with a parallel plate capacitor (2 cm diameter, 2mm thickness) filled with talc, obtaining $\varepsilon_r = 2.4$ which is in agreement with the literature. The talc powder is loaded in the aerosol generation chamber, where a pulsating pump with HEPA filters creates the air suspension.

The deposition of single talc particles is tracked in real-time, with 10 ms temporal resolution as shown in two examples in Fig. 4. Two main classes of events are recorded: small capacitance steps of ~15-20 aF consistent with the average size of talc particles (simulations indicate $\Delta C = 25$ aF for a 10 μm sphere with $\varepsilon_r = 2.6$) and larger capacitance steps of ~60 aF. Microscope inspection of the electrodes (performed after each deposition

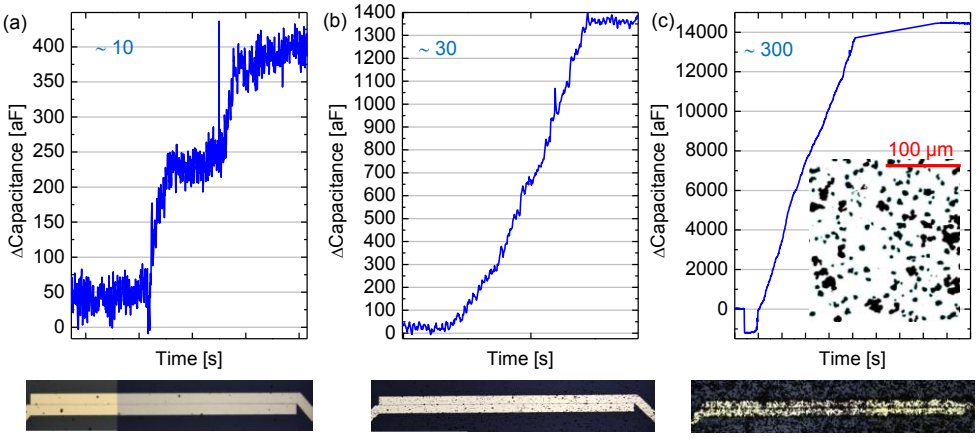

Fig. 5. Detection of toner particles for increasing concentrations (10, 30 and 300 particles deposited on the sensing area 4 x 3000 μm^2). The microscope photographs are performed at the end of each experiment.

experiment) confirm the presence of both "small" and "large" particles (see dark field image in Fig. 4.c).

3.2 Toner detection

After the successful validation of the system with talc micropowder, we tested the instrument also with particles of a laser printer toner. The use of toner particles, beyond having a similar mean diameter (8-10 μm) and similar dielectric constant of talc (measured 2.5) but a sharper size distribution, is motivated by its relevance for in-door air quality monitoring, particularly in workplaces (Destaillat et al., 2008). In fact, in public and private offices printers and copy machines are usually placed in small rooms with inadequate aeration and their emission of PM is hazardously ignored. Consequently, we envision another innovative application of this compact capacitive dust detector in printer/copier rooms or directly embedded in printers.

As reported in Fig. 5, black toner (consisting of a polymer resin matrix mixed with a carbon pigment) has been loaded in the shaking chamber and tests with different concentrations have been performed. In the first case, shown in Fig. 5a (about 10 particles deposited in a 4 x 3000 μm^2 sensitive area), the granularity due to the deposition of single particles can be appreciated. Despite similar volume, toner particles produce a larger capacitance increase (~80 $zF/\mu m^3$) with respect to the values (~10-40 $zF/\mu m^3$ depending on the shape) obtained for talc and polystyrene ones, which were been confirmed by finite-element simulations. The origin of this larger signal could be due to the particle charge, engineered expressly for printing purposes (Daly et al., 1986), or to the tendency to create clusters, visible in the microscope photograph shown in the inset of Fig. 5c.

When increasing the concentration by a factor 3 and 30, Fig. 5b and Fig. 5c respectively, the total capacitance increase scales linearly with the particle concentration, confirming the capability of the instrument to quantify PM volumetric concentration.

4. Conclusions

An original capacitive detector for real-time PM_{10} counting and granulometry has been proposed and validated with polystyrene, talc and toner particles. Thanks to high-resolution electronics and microfabricated electrodes, aF resolution has been achieved, thus allowing robust solid-state dielectric detection of airborne particles.

Several aspects of the instrument need to be further engineered, including an efficient and compact fluidic system for sampling of large air volumes, a pre-heating system for forcing evaporation of water droplets in humid environments and an integrated module for periodic cleaning of sensor surface by means of ultrasounds, surface waves or air jets.

Being intrinsically CMOS-compatible, this approach enables in perspective the realization of microelectronic microsystems for PM detection, featuring sub-micrometric electrodes combined with ultra-low-noise capacitance detectors with sub-aF resolution (Carminati et al., 2011b) that would make possible $PM_{2.5}$ and PM_1 detection. Such a miniaturized single-chip PM detection MEMS platform could be embedded into personal portable consumer devices for participatory and pervasive air quality mapping.

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