Emerging Miniaturized Technologies for Airborne Particulate Matter Pervasive Monitoring

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***Abstract*—In order to address the increasing demand for real-time and capillary monitoring of air quality and, in particular, of particulate matter (PM), novel solid-state sensor technologies and compact instrumentation for PM detection have been recently proposed. Within the context of smart cities and dense wireless sensor networks, we review miniaturized optical, mass-sensitive and capacitive approaches for detection of micrometric airborne dust, along with the new participatory and ubiquitous monitoring strategies enabled by the integration of these sensors with personal mobile devices such smartphones.**

***Index Terms*—air quality; dust; participatory sensing, high-resolution capacitance detection.**

I. INTRODUCTION

Nowadays, in the societies of both developed and developing countries, the concern for the risks for health related to continuous exposure of citizens to particulate matter (PM) is rapidly growing [1]. At the same time, and at the same pace, is also growing the awareness of the inadequacy of current air quality monitoring approaches [2], that present severe limitations in terms of spatio-temporal resolution and often lack granulometric data (i.e. the size distribution of the particles, extremely relevant from the toxicological point of view, since the penetration in organism depends on the particle aerodynamic diameter). As illustrated in Fig. 1a, traditional PM monitoring approaches are based on a very limited number (<10) of monitoring stations, either fixed or mobile. Fixed stations are usually installed in specific plants (1), such as waste incinerators, whose emissions must be continuously monitored by law or in a few cabins or shelters (2) used to monitor air quality. Mobile laboratories (3) are also employed by local environment protection agencies to perform periodical measurement campaigns along reconfigurable spatial patterns or in specific "hot-spots", for instance during emergency events. The main limitation of this architecture is the poor spatial resolution (only a few sampling points across the city). Depending on the technology adopted for PM detection and analysis, the temporal resolution can also be too poor to provide real-time information, suitable for modeling and prediction purposes [2].

A new monitoring paradigm based on dense networks (Fig. 2b) is emerging, in particular within the context of smart cities [3]. The feasibility of this alternative approach is supported by the fast development and convergence of smartphone-based geo-localized services, wireless sensors networks (WSN) as well as of the *Internet-of-the-Things* (IoT) i.e. of dynamic infrastructures constituted by thousands of wireless interconnected nodes, often endowed with low-cost and compact sensors measuring physical quantities of direct interest to the population. Thus, it can be envisioned that, due to its relevance for air quality assessment, PM sensors can be embedded inside such sensing nodes along with other sensors (such as, for instance, gas sensors and microphones for noise pollution) [4], [5].

Of course, the full potential of these highly dense sensors networks is achieved when they are combined with Cloud-based, very powerful and efficient "big data" collection and analysis algorithms, as for instance planned in the Green Horizon project, a recently started 10-year joint initiative between IBM and the Chinese government, committed to improve air quality, in particular starting from the most critical situations such as in Beijing municipal area.

In this chapter we briefly review current advances in miniaturized technologies, oriented to portable and, thus, personal and pervasive PM monitoring. Sec. II reports an introductory analysis on the possible deployment and integration scenarios enabled by these technologies. In Sec. III the most recent solutions targeting micron-sized particles are presented, while Sec. IV focuses on nanoparticles detection. Finally, in Sec. V some concluding considerations are discussed.

II. NETWORKING SCENARIOS

The best deployment strategy and the specific type of WSN in which such PM sensors can be inserted depend on their degree of integrability, i.e. mainly on their size, cost and power consumption. As pictured in Fig. 2, the sensor bulkiness determines the network type (fixed vs. dynamic, proprietary vs. participatory). Three possible scenarios can be envisioned. In the first case, when the size, cost, volume and power consumption of the detector do not allow personal transportation - but still hundreds of units can be installed in fixed positions in the city - a dense network operated by municipal agencies can be installed. Such nodes can be powered, for instance, by means of photovoltaic panels (Fig. 2a) and wirelessly interconnected by means of dedicated radio

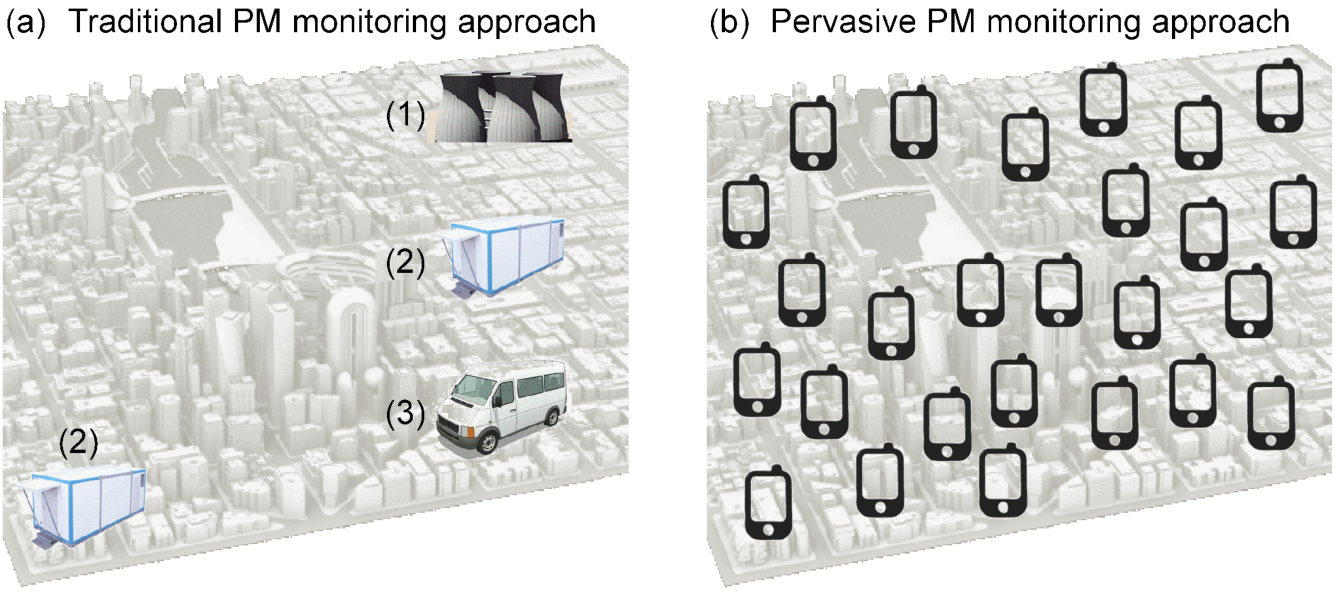

Fig. 1. Envisioned evolution from current sparse (a) to future ubiquitous and very dense networks (b) of PM monitoring nodes based on the combination of microfabricated sensors, high-sensitivity integrated detection electronics, WSNs and smartphones.

networks. A preliminary example of such an approach has been tested for capillary monitoring of ground-level PM in the area of the London Heathrow airport (within the SNAQ project [6]) by means of up to 50 units incorporating, among other polluting gas sensors (CO_2, O_3, SO_2 and VOCs), low-cost optical particle counters allowing size speciation of PM (in 16 size classes from 0.38 to 17.4 μm) [7]. A simple miniaturized fan (used for PC CPU cooling) allows an aspiration flow rate of 1.5 l/min [8].

If the sensor is compact enough to be handheld (Fig. 2b), it can be carried around by motivated people in order to provide real-time capillary mapping of PM levels. Such a pocket-sized sensor would be extremely valuable as personal dosimeter, tracking individual exposure to PM during the day (both indoor and outdoor) and, in particular, in high-risk workplaces such as mines and construction sites. The device can immediately trigger an alarm in case safety concentration thresholds are exceeded. It can be used in combination with a smartphone serving as user interface (mainly for data visualization and logging) and as the wireless gateway to the network. An example of this approach is represented by the TECO Envboard including low-cost optical off-the-shelf dust sensors [9] connected via Bluetooth to the phone.

Finally, if the detection technology enables a significant miniaturization of the sensor (such as the capacitive technique described in Sec. III.D) down to a few mm2, it can be directly embedded inside consumer handheld devices, such as smartphones and tablets. Clearly, several engineering issues should be tackled, in particular for the aspiration and convey of the air sample inside the device, whose operating conditions might be extremely variable. This scenario would be definitively revolutionary since, being totally transparent to the users, such sensors could be mounted inside every phone, leading to networks composed by millions of sensing nodes.

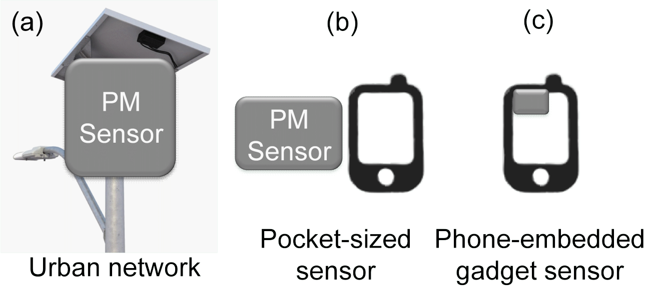

Fig. 2. Possible future network integration scenarios depending on the PM detector size and power consumption: (a) fixed nodes, (b) portable nodes and (c) miniaturized sensors integrated inside handheld consumer devices.

The relevance to the user and the community depends also on the features offered by the sensor, in particular on the detectable particle size range, concentration range, measurement accuracy, response time and on the capability to sort PM into dimensional classes (granulometry). According to the final use of the acquired data (from personal gadget to relevant urban monitoring infrastructure) different trade-offs between sensor cost/size vs. data density/resolution can be identified and accepted, the bottom line being that the poor quality of the single sensor can be compensated, to a certain extent, by dynamically combining together several homogeneous or heterogeneous sensors.

III. MICROPARTICLES DETECTION TECHNIQUES

A. *Smartphone-Based Optical Detection*

The use of the mobile phones within the specific context of PM detection has been recently proposed [10]. The idea is to physically combine low-cost optical nephelometers with mobile phones. As in the prototype picture of Fig. 3, the flash lamp of the phone is used as light source (the light pulse being guided in a short external optical fiber to the modified Sharp GP2Y1010 sensor), while the phone camera is employed as photodetector. Average particle density is measured and good qualitative correlation with state-of-the-art instruments have been demonstrated in the field. However, the sensitivity is limited to the mg/m^3 range, mainly to the unsufficient source light power and non-optimized optical path.

B. *Digital Cameras for Dust Deposition Imaging*

Another interesting approach, also based on consumer-grade CMOS image sensors, has been recently proposed [11]. The detection principle is extremely simple: since the pixels of a high-resolution commercial CCD or CMOS image sensor have an area comparable to the size of the largest PM particles (6 μm x 6 μm in MT9V032 sensor chosen in [11]), it is possible to let them deposit directly on the imager surface (provided that lenses are removed) and periodically take a picture and compare the increase of covered pixels. A uniform light source is necessary to provide a homogenous background. Furthermore, image processing algorithms are used for noise reduction (contrast enhancement), segmentation and shape recognition (filiform vs. globular shapes) leading to a pixel-based dust size distribution. Relying on unforced particle deposition on a small area (8 mm diagonal), the deposition rate is quite low, thus demanding for a long image acquisition interval of 30 min. However, for long term employment, cleaning the sensor surface represents one of the main challenges, still to be faced (the sensor was operated with 45° degree tilt, in order to favor temporal dust permanence). This kind of static approach appears particularly promising for fixed operation in indoor and well controlled environments, such as cleanrooms and museums. In fact, the system operation has been successfully validated in the prestigious context of the Vatican Museums in Rome [11].

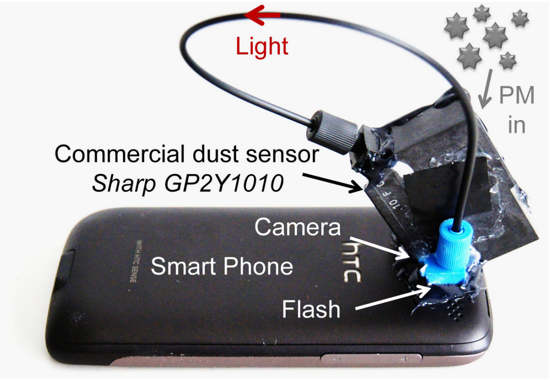

Fig. 3. Optical nephelometer deploying the flash light source and camera detector of a mobile phone (*image courtesy of M. Budde* [10]).

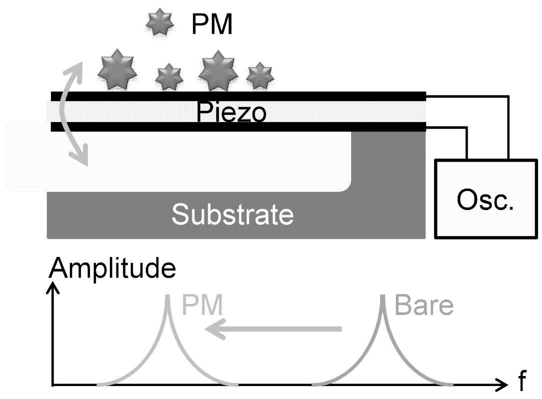

Fig. 4. Solid-state gravimetric PM detection based on a MEMS resonating cantilever measuring the mass increase as a shift of its resonance frequency.

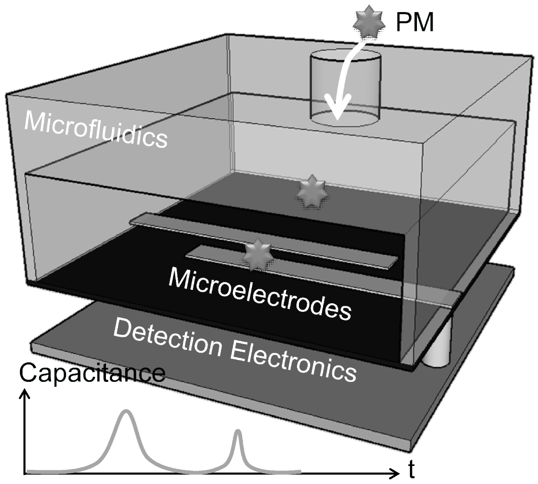

Fig. 5. Single PM counting and sizing based on capacitive sensing across a pair of microelectrodes whose spacing is in the micrometer range.

C. *Mass-Sensitive Microfluidic Detection*

Micromechanical resonators are employed in mass-sensitive devices. As illustrated in Fig. 4, a resonating micromachined structure, such as a cantilever, is used as a microscopic weighing scale. The change in the mass deposited on the resonator produces a variation of the resonance frequency that is monitored in real-time. The sensitivity of these sensors is thus expressed in terms of Hz/μg and the capability to detect the mass of single particles depends on the detector resolution. Several MEMS technologies can be used to realize the resonator and detection circuit. In particular, a film bulk acoustic resonator (FBAR) for PM detection has been recently proposed [12]. This very compact device, targeting PM$_{2.5}$, combines (i) a microfluidic system for the manipulation of the air sample and for aerodynamic separation of particles (dynamic filtering according to their size) with (ii) a thermophoretic actuator forcing the deposition of PM on the FBAR sensor.

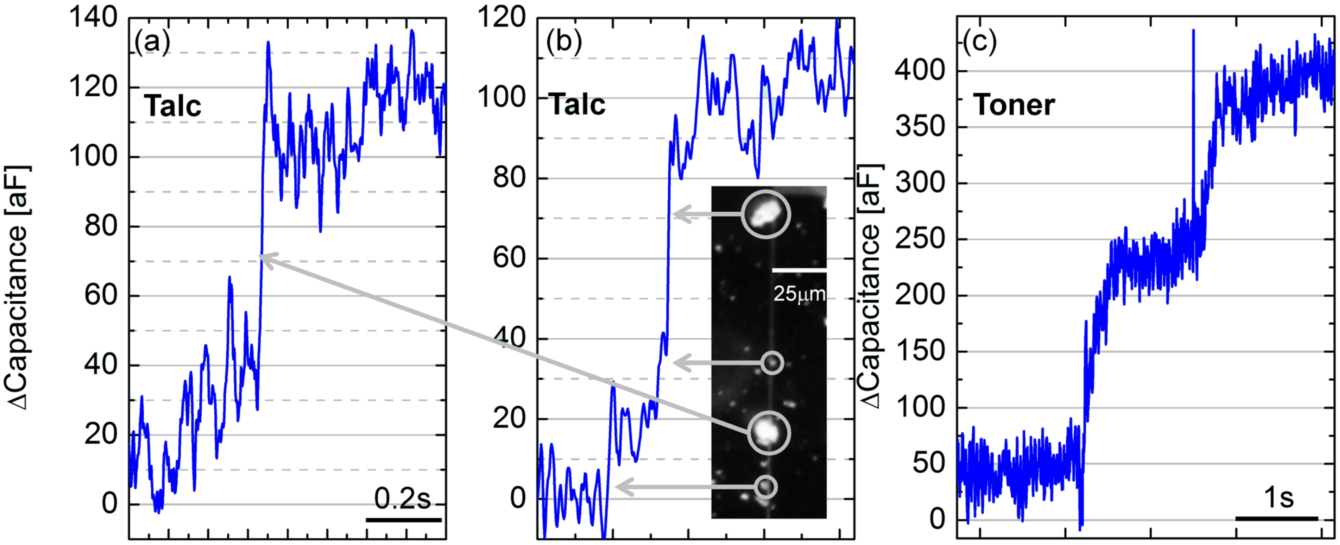

Fig. 6. Examples of real-time capacitive detection of the deposition of single PM particles of talc (a-b) and laser printer toner (c). In these conditions (applying a 1 V signal at 1 MHz to a triad of differential electrodes) the capacitive resolution is ∼7 aF rms with 10 ms measurement time. Particles deposition is forced in 200 μm thick microfluidic PDMS chamber connected to pulsed powder shaking pump [13].

The complete instrument was validated against a commercial aerosol monitor with high concentration bursts of tobacco smoke and exhaust fumes of diesel engines, demonstrating a resolution of 2 μg/m^3 for an integration time of 10 min.

D. High-Resolution Capacitive Detection

We have recently proposed a detection technique that is alternative to mass and optical sensing, leveraging the measurement of the dielectric properties of PM. As illustrated in Fig. 5, the detector consists of a pair of electrodes close enough to be sensitive to the capacitance increase due to the presence of a single microparticle. This sensor is extremely simple and robust, having no moving parts and requiring no contact between the particles and the electrodes. Most importantly, this approach is quantitative and from the amplitude of the capacitance increase is it possible to estimate the particle diameter. For this purpose it is necessary to estimate the average dielectric constant (similarly to the estimate of the average refraction index performed in instruments based on laser scattering). Thanks to the combination of properly designed microfabricated planar band electrodes (4 μm separation) and low-noise electronics (with attoFarad capacitive resolution) it has been possible to demonstrate the detection of single PM_{10} particles depositing on the inter-electrode gap, of polystyrene (20 μm and 10 μm diameter), industrial talc (8 μm average diameter) [13] and printer toner (∼10 μm) [14], as reported in Fig. 6. This technique appears very promising for deployment in smartphone-based pervasive networks of personal dosimeters for the following reasons: (i) both the microelectrodes and the capacitance measuring circuit are inherently CMOS-compatible and can be implemented. (ii) Although simple and dramatically miniaturizable, this low-cost technology allows single-particle analysis and the extraction of granulometric spectrum. (iii) Although demonstrated only for PM_{10}, a clear margin of improvement is apparent since zeptoFarad resolution has been demonstrated [15], i.e. about three orders of magnitude better than what shown in Fig. 6, thus suggesting that single PM_1 is achievable.

IV. NANOPARTICLES DETECTION

Although this review is focused on microparticles (mainly in the PM_1-PM_{10} range), the challenges related to the detection of nanoparticles must be also mentioned, due to their toxicological relevance, as well as growing technological and scientific interest and employment. The minimum detectable particle diameter in light scattering instruments is set by the laser wavelength (around 0.3 μm). Thus, traditional nanoparticles detection approaches are based on the condensation of alcohol droplets (of micrometric diameter) around single nanoparticles, followed by standard optical counting. In order to retrieve the size distribution, electrostatic separation according to the size-dependent electric mobility is performed upstream with differential mobility analyzers, resulting in high-voltage and bulky instruments [2].

In this particle range, the most interesting emerging solid-state technology is again based on highly scaled silicon resonant microstructures. In particular, oscillating silicon nanopillars with high aspect ratio and sub-micrometric diameter have been demonstrated to achieve ∼7 Hz/fg sensitivity, allowing the discrimination of single airborne TiO_2 nanoparticles (of ∼150 nm diameter), sticking directly on the pillar and thus altering its resonance frequency [16]. Although sensitive, quantitative and real-time, this approach still lacks a reliable, simple and automatable cleaning procedure for embedment in portable devices.

V. CONCLUSIONS

The convergence of microfabrication technologies with ubiquitous wireless networks is enabling a new paradigm in PM monitoring based on pervasive and participatory sensing. Among different miniaturized and low-cost technologies based on optical or mass-sensitive detection, low-noise capacitance sensing based on attoFarad resolution appears as the most promising candidate for counting and sizing of single particles of micrometric diameter. Power dissipation and air conveying engineering issues need to be addressed in order to achieve integration inside consumer devices that would trigger mass diffusion, bringing such a personal safety gadget into the mainstream.

VI. ACKNOWLEDGMENT

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REFERENCES

[1] G. Sancini, F. Farina, C. Battaglia, I. Cifola, E. Mangano, et al. *Health risk assessment for air pollutants: alterations in lung and cardiac gene expression in mice exposed to Milano winter fine particulate matter (PM2.5),* PLoS ONE, vol. 9, pp. e109685/1-13, 2014.

[2] M. Carminati, M. Sampietro, G. Carminati, *Analysis of instrumentation performance for distributed real-time air Quality monitoring*, Proc. IEEE EESMS, pp. 28-33, 2011,

[3] E. G. Snyder, T. H. Watkins, P. A. Solomon, E. D. Thoma, R. W. Williams, G. S. W. Hagler, D. Shelow, D. A. Hindin, V. J. Kilaru, and P. W. Preuss, *The changing paradigm of air pollution monitoring,* Environ. Sci. Tech., vol. 47, pp. 11369-11377, 2013.

[4] A. de Nazelle, E. Seto, D. Donaire-Gonzalez, M. Mendez, J. Matamala, M. J. Nieuwenhuijsen, M. Jerrett, *Improving estimates of air pollution exposure through ubiquitous sensing technologies,* Environ. Pollut., vol. 176, pp. 92-99, 2013.

[5] M. I. Mead et al., *The use of electrochemical sensors for monitoring urban air quality in low-cost, high-density networks,* Atm. Environ., vol. 70, pp. 186-203, 2013.

[6] http://www.snaq.org [Sensor Networks for Air Quality at Heathrow Airport].

[7] R. L. Jones, O.A.M. Popoola, M. I. Mead, V. B. Bright, I. Heimann, R. North, G. B. Stewart,, P. H. Kaye, C. Hueglin,, M. Mueller, D. Carruthers, J. Saffell, *High density air quality network at Cambridge and London Heathrow airport: first results and interpretations,* Proc. Air Quality Monitoring New Technologies, New Possibilities, 2013.

[8] P. H. Kaye, W. R. Stanley, E. Hirst, J. Saffell, Z. Ulanowski, *A low-cost optical particle counter for networked deployment,* Proc. 1st International Conference Atmospheric Dust, 2014.

[9] M. Budde, R. El Masri, T. Riedel, M.Beigl (2013) *Enabling low-cost particulate matter measurement for participatory sensing scenarios,* Proc. 12th International Conference on Mobile and Ubiquitous Multimedia, 2013.

[10] M. Budde, P. Barbera, R. El Masri, T. Riedel, M. Beigl *Retrofitting smartphones to be uUsed as particulate matter dosimeters,* Proc. 17th International Symposium on Wearable Computers, p. 139-140, 2013.

[11] A. Proietti, F. Leccese, M. Caciotta, F. Morresi, U. Santamaria, C. Malomo, *A new dusts sensor for cultural heritage applications based on image processing,* Sensors, vol. 14, pp. 9813-9832, 2014.

[12] I. Paprotny, F. Doering, P. A. Solomon, R.M. White, L. A. Gundel, *Microfabricated air-microfluidic sensor for personal monitoring of airborne particulate matter: design, fabrication, and experimental results,* Sens. Actuators A, vol. 201, pp. 506-516, 2013.

[13] M. Carminati, L. Pedalà, E. Bianchi, F. Nason, G. Dubini, L. Cortelezzi, G. Ferrari, M. Sampietro, *Capacitive detection of micrometric airborne particulate matter for solid-state personal air quality monitors,* Sens. Actuators A, vol. 219, no. 1, pp. 80-87, 2014.

[14] M. Carminati, L. Pedalà, F. Nason, E. Bianchi, G. Dubini, L. Cortelezzi, G. Ferrari, M. Sampietro, *Capacitive single-particle microdetector for real-time pervasive PM10 monitoring* Proc. 1st International Conference Atmospheric Dust, 2014.

[15] M. Carminati, G. Ferrari, F. Guagliardo, M. Sampietro, *ZeptoFarad capacitance detection with a miniaturized CMOS current front-end for nanoscale sensors,* Sens. Actuators A, vol. 172, pp. 117-123, 2011.

[16] H. S. Wasisto, S. Merzsch, A. Stranz, A. Waag, E. Uhde, T. Salthammer, E. Peiner, *Silicon resonant nanopillar sensors for airborne titanium dioxide engineered nanoparticle mass detection,* Sens. Actuators B, vol. 189, pp. 146-156, 2013.