Proceedings

Characterization of a Capacitive Sensor for Particulate Matter †

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Abstract: We characterize a novel micro-sensor with pairs of interdigitated combs of microelectrodes designed to detect particles in air. We evaluate the sensor's response to 1 µm Polystyrene Latex (PSL) particles experimentally and crosscheck the results with simulations. Experiment and simulation show good consistency. Based on the promising results we propose a redesign of the capacitive particle sensor with respect to PM2.5.

Keywords: particle sensor; capacitive sensing; particle deposition

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1. Introduction

Small and very small particles in the ambient air, such as PM2.5—commonly known as fine dust -and PM1 represent a serious threat to life and limb [1]. Increasing awareness among the population and stricter regulations on the part of the legislation also lead to greater demands on the measurement and monitoring of air quality with respect to particle concentration. A close-meshed and wide-area monitoring has up to now failed due to the size, complexity and cost of the currently available systems. The aim of this work is to explore the possibility to use a novel capacitive sensor as a PM2.5 sensor. Since the sensor is already processed using a standard CMOS technology, a major advantage is the cost efficiency and relatively easy scalability which both are premises for a dense sensor network. The detection principle relies on interdigitated pairs of electrodes which are arranged on a surface [2,3]. Particles induce a sudden change in capacitance when deposited on this surface, see Figure 1. Width, height and spacing of the electrodes is 1 µm which allows 1 µm particles to be deposited both onto the electrodes as well as in between them. The capacitive change depends on size, shape, dielectric constant, and the exact position of the particles. Since the dispersed particles are uniform within an experiment, the only influence left is the position of the particles relative to the surface structure of the sensor.

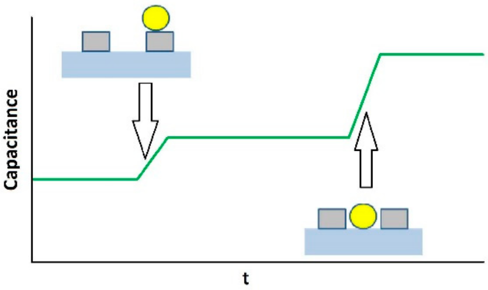


Figure 1. Detection principle of the capacitive sensor. The grey rectangles indicate micro-electrodes on top of the blue SiO_2. Yellow spheres indicate particles deposited on top of the electrodes, which then cause the capacitance to change abruptly.

2. Materials and Methods

We have built a setup for selective deposition of well-defined spherical particles in order to evaluate the performance of the capacitive microsensor, see Figure 2. The deposition setup consists of an atomizer (Topas ATM221) in combination with a diffusion dryer (Topas DDU 570), which disperses PSL particles in air. Said particles are then neutralized (TSI Aerosol Neutralizer 3077) in order to minimize charge effects. A nozzle is used to accelerate the particles towards the sensor in order to use impaction as a means of depositing. The sensor is placed underneath the nozzle in a distance of a few millimeters where the particles are then deposited. A needle valve in parallel to the nozzle allows for steady control of the flow rate through the nozzle. We are able to assign detected events of the sensor to deposited particles with a digital microscope (Keyence VHX and VHZ-250R), see Figure 1. Deposited particles are detected both optically using a digital microscope, see Figure 3, and utilizing the described sensor effect. The experiment is further simulated using Comsol, results see Figure 5.

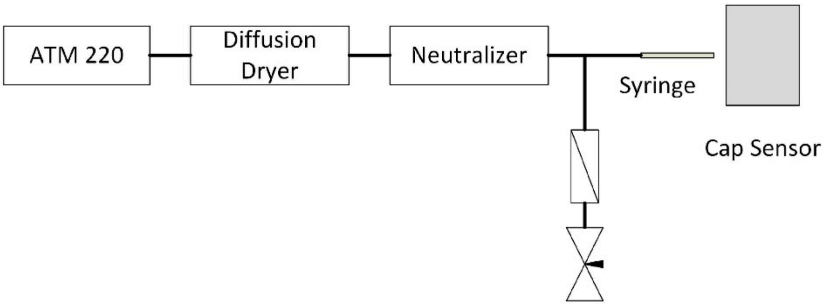


Figure 2. Setup for deposition of 1 µm PSL spheres onto the surface of the investigated capacitive sensor.

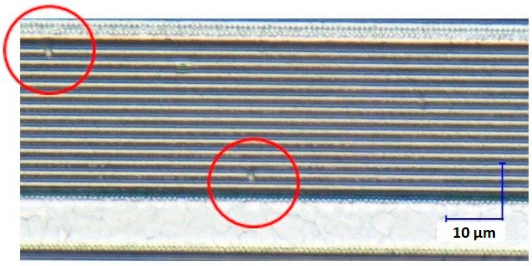
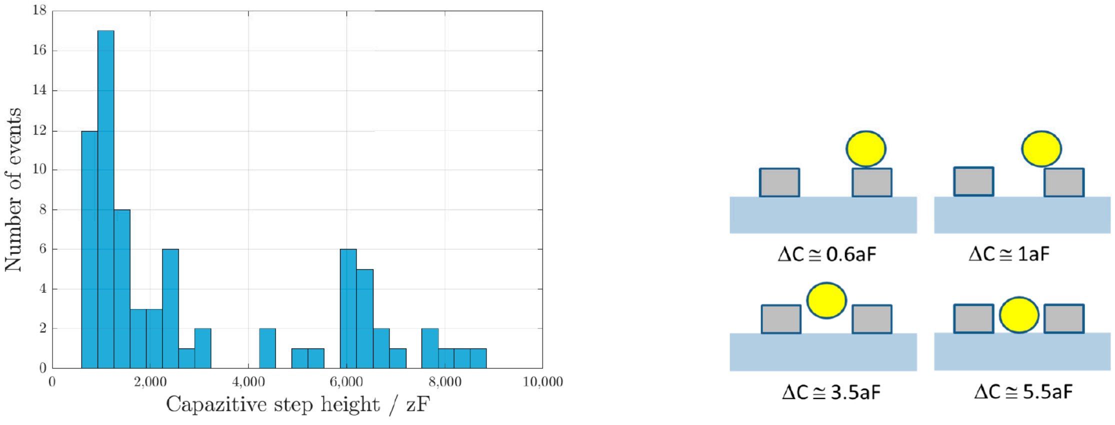


Figure 3. Image of deposited 1 µm spheres on top of the sensor's surface. Spheres are in the middle of the red circles. The horizontal lines are the microelectrodes, which form the sensor.

3. Results

We are able to show that the sensor is able to correctly count deposited particles on the surface, which is confirmed using the microscope to count deposited particles optically. The number of detected capacitive steps matches the number of deposited particles.

The response of the sensor to a particle is an abrupt change of the capacitance with step heights of roughly 0.5 aF up to 10 aF for the investigated particles, results see Figure 4. The relatively broad distribution of capacitive steps caused by monodisperse 1 µm particles stems from the distribution of positions of the particles relative to the microelectrodes. A particle on top of the electrodes will lead to a weaker signal compared to a particle in between the combs, results see Figure 4. Since the electrodes protrude above the SiO_2, particles are more likely to be deposited onto the electrodes rather than in between them leading to a weaker signal. Experimentally a small number of larger capacitance steps than predicted by simulation are observed, which is most likely due to inhomogeneities of the sensor's surface. Overall, the experimental results match the simulation reasonably well.



(a) **(b)**

Figure 4. (**a**) Histogram of the observed capacitive changes caused by monodisperse 1 µm PSL particles. (**b**) Simulation of the sensor's response to the monodisperse 1 µm PSL particles. The position of the particles relative to the electrodes has a significant impact on the signal.

As particles of larger diameters than the distance between two electrodes cannot fall between the electrodes, the sensor can operate in two regimes: large particles are detected on top of the electrodes, smaller ones which would induce a low capacitance change on top of the electrodes are detected in between them. This finding can be utilized to redesign the capacitive microsensor with a focus on the detection of PM2.5.

4. Conclusions and Outlook

The setup for the dispersion and deposition of 1 µm PSL particles works and allows a systematic investigation of various sensors where particle deposition is necessary.

We have shown that the investigated sensor is able to count monodisperse PSL particles with a diameter of 1 µm correctly. Simulation and experimental results regarding the response of the sensor agree reasonably well for the investigated particles. We have shown that the sensor can work in two regimes. Particles larger than the pitch are detected on top of the electrodes whereas smaller ones can be detected in between them. This effect is to be used for a redesign of the sensor with respect to PM2.5 by reducing the pitch to roughly 0.5 µm in order to push the lower limit of detectable particles to lower diameters. Recent findings from a Focused Ion Beam (FIB) and Scanning Electron Microscope (SEM) investigation are to be taken into account for the simulations, see Figure 5. This regards the trapezoidal shape of the electrodes as well as the depth of the gaps between the electrodes. The electrodes are underetched due to a time-dependent etching step in the fabrication process of the sensor. In a redesign of the sensor, the introduction of a defined etch-stop-layer to prevent unwanted underetching would be beneficial.

Further research is necessary to determine the exact limit of detectable particles in terms of size and concentration and to explore the possibility to discriminate different particle sizes by the signal. In conclusion the capacitive sensor is a promising candidate for a cost-efficient and integrated sensor.

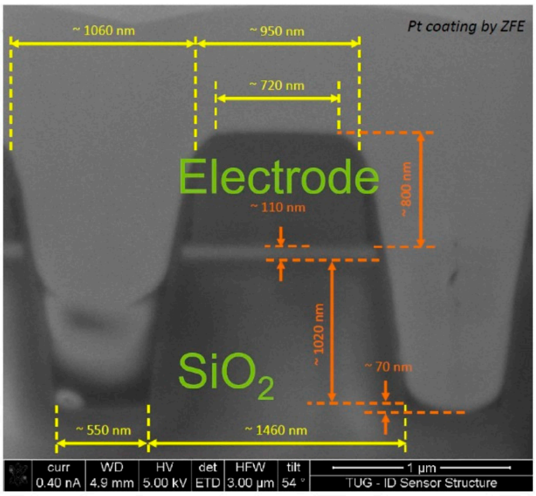


Figure 5. FIB cross-section of the sensor done at FELMI-ZFE. The shape of the electrodes is trapezoidal rather than rectangular. Also electrodes are slightly underetched due to a time-dependent etching step in the fabrication process.

Author Contributions: Conceptualization, G.R., M.S. and A.B.; Methodology, P.M., M.C., G.F., G.R., M.S. and A.B.; Software, P.M., M.C.; Validation, P.M., M.C., G.F., G.R., M.S. and A.B.; Formal Analysis, P.M.; Investigation, P.M.; Resources, M.S. and A.B.; Writing—Original Draft Preparation, P.M.; Writing—Review & Editing, M.C., G.F., G.R., M.S. and A.B.; Visualization, P.M.; Project Administration, M.S. and A.B.; Funding Acquisition, G.R., M.S. and A.B.

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References

1. Kioumourtzoglou, M.A.; Schwartz, J.D.; Weisskopf, M.G.; Melly, S.J.; Wang, Y.; Dominici, F.; Zanobetti, A. Long-term PM(2.5) Exposure and Neurological Hospital Admissions in the Northeastern United States. *Environ. Health Perspect.* **2016**, *124*, 23–29, doi:10.1289/ehp.1408973.
2. Ciccarella, P.; Carminati, M.; Sampietro, M.; Ferrari, G. Multichannel 65 zF rms Resolution CMOS Monolithic Capacitive Sensor for Counting Single Micrometer-Sized Airborne Particles on Chip. *IEEE J. Solid-State Circ.* **2016**, *51*, 2545–2553, doi:10.1109/jssc.2016.2607338.
3. Carminati, M.; Pedalà, L.; Bianchi, E.; Nason, F.; Dubini, G.; Cortelezzi, L.; Ferrari, G.; Sampietro, M. Capacitive detection of micrometric airborne particulate matter for solid-state personal air quality monitors. *Sens. Actuators A Phys.* **2014**, *219*, 80–87, doi:10.1016/j.sna.2014.09.003.