CHARGED PARTICLE DETECTION USING A MICROMECHANICAL ELECTROMETER

G. Jaramillo^{1*}, M. Li¹, C. Buffa², F.J. Brechtel³ and D.A. Horsley¹

¹University of California-Davis, Davis, California, USA

²Politecnico di Milano, Milano, Italy

³Brechtel Manufacturing, Inc., Hayward, California, USA

ABSTRACT

We have developed a MEMS-based electrometer for the detection of small currents from ionized particles in an aerosol particle detection system. We utilize a porous sensing-electrode coupled to a MEMS resonating electrometer. Our electrometer achieved a noise floor below 1 fA rms produced by 10 nm diameter particles within an airflow of 1.0 L/min. At this flow rate, the minimum detectable current (1 fA) corresponds to a minimum measurable particle density of 400 cm⁻³. We compared and calibrated the MEMS electrometer with two commercial units: a Faraday cup electrometer and a MCPC (Mixing Condensation Particle Counter). The MEMS electrometer achieved an experimental sensitivity of 19.68 $\mu\text{V}_{\text{rms}}/\text{fA}$ and charge-detection efficiency of $5.476 \times 10^7 \text{ V/C}$.

INTRODUCTION

Environmental air quality monitoring is important in assessing the health risks posed by particulate matter (PM). Particles in the ultrafine range, defined as smaller than 100 nm diameter, have become increasingly important in understanding pollutant health effects. Studies of ultrafine particles have begun to show the hazards associated with indoor and occupational aerosol exposure as well as outdoor exposures in urban areas [1]. These studies can benefit from instruments capable of quantitative measurement of particulate concentration as a function of size. One method of particle detection and classification consists of exploiting the size-dependent electrical mobility of nano-particles. Electrical mobility is a parameter that determines the velocity of a charged nanoparticle moving in an electric field. A differential mobility analyzer (DMA) separates nano-particles as a function of electrical mobility and can be employed for size-sorting over large particle ranges [2]. The size-sorted charged particle stream from the DMA output can then be fed to electrical or optical detectors for counting. One typical electrical detector consists of a Faraday cup electrometer.

Electrometry is a technique for measuring small electrical currents. Electrometer instruments are commonly used in tunneling microscopy, mass spectrometry, surface charge analysis and many other scientific fields. Many types of electrometers exist, including single-electron transistors, nano-mechanical resonators at cryogenic temperatures [3], graphene resonators [4], and units based on the vibrating reed devices. The time-varying capacitance electrometer or vibrating reed can be implemented using MEMS parallel plate sensors and actuators. MEMS sensors allow for the reduction of cost, size, weight, and power while potentially increasing the sensitivity and signal-to-noise ratio.

We present the design and characterization of a MEMS based electrometer for the counting of nanometer-sized aerosol particulate. This device aims to reduce the cost, size, weight and power of current commercial electrometers used in the aerosol scientific field. The MEMS electrometer is based on parallel plate and comb drive capacitive actuators to generate a time varying capacitance, thereby modulating a slowly-varying input charge signal to a frequency $> 1 \text{ kHz}$ at which the measurement noise is greatly reduced.

Figure 1: Illustration of the MEMS electrometer. Center shuttle oscillates at f_n generating a detection signal at $2f_n$ proportional to input charge Q_C .

DEVICE DESIGN AND CHARACTERIZATION

Sensor Design

The MEMS electrometer approach was first proposed by Riehl [5]. Sub-10 electron resolution has since been demonstrated for similar MEMS designs at room temperature [6]. In comparison to these earlier demonstrations in which test charges were transferred from a local capacitor, the real-time aerosol-based measurements described here pose the additional challenge of a relatively large porous sampling electrode, introducing additional input capacitance and possible electromagnetic interference. Similar to earlier micromechanical charge sensors, our electrometer measures the induced voltage when an unknown amount of charge Q_C is transferred onto the variable capacitor $C(t) = (C_V + C_P)$,

$$v_i(t) = \frac{Q_C}{C(t)} \quad (1)$$

Figure 1 shows a schematic of the MEMS device; the 1 mm x 1.2 mm moving shuttle is supported by four flexures. The MEMS devices were fabricated in 15 μm thick epitaxial polysilicon using ST Microelectronics ThELMA (Thick Epitaxial Layer for Micro-actuators and Accelerometers) process and vacuum sealed at the chip level. The device's electromechanical characteristics were presented in [7] and are summarized in Table 1.

Comb drive actuators for push-pull driving are placed at both ends of the shuttle while the parallel plate electrodes that form the measurement capacitor C_V are located in the middle. To maximize the capacitance variation at a given excitation voltage, forcing occurs at the structure's first in-plane natural frequency, which is ideally above the $1/f$ corner frequency of the detection circuitry. Operating the device as a resonant sensor ensures that the electrostatic force is amplified by the mechanical quality factor Q and allows for the possibility of operating the device as a closed-

loop resonator. Each moving parallel-plate electrode faces two fixed electrically-connected electrodes, generating a term at the second harmonic when (1) is expanded. This design modulates the sense signal to $2f_n$ and has the benefit of separating the charge signal from the capacitive feedthrough signal at f_n . The charge-to-voltage conversion gain can be defined by [5]

$$\frac{dv_i}{dQ_C} = x_0^2 \frac{C_0}{2\sqrt{2}(C_0 + C_P)^2} \quad (2)$$

where C_P is the parasitic capacitance, C_0 is the rest capacitance of the parallel plates, and $x_0 = \hat{x}/g$ is the displacement normalized by the capacitive air gap g . Achieving a large conversion gain depends on minimizing C_P and maximizing the normalized displacement x_0 .

Electromechanical Characterization

Preliminary electrical characterization of the MEMS device was conducted to measure the voltage-displacement characteristic and to identify the air gap of the parallel-plate capacitors. Measurements were collected by electrostatically exciting the frame into motion using the comb drives on the sides of the frame. The resulting motion was sensed by applying an AC carrier signal to the moving shuttle and using the parallel-plate measurement electrodes as a capacitive pick-off. The sense current from the pick-offs was amplified by a trans-resistance amplifier and a lock-in amplifier (Zurich Instruments HF2LI) was used to both generate drive signal and demodulate the sense signal. Figure 2(A) shows the displacement amplitude at resonance with respect to amplitude of the driving voltage on the comb drive actuators. The device starts showing nonlinear behavior at $x_0 = 0.12$, which is a result of Duffing behavior from spring stiffening in the flexure suspension. The air gap drawn on the mask was $3.0 \mu\text{m}$ but changes due to reduction of line width during device fabrication. The fabricated gap was extracted by measuring the dependence of the natural frequency on the amplitude of the carrier signal applied to moving shuttle, which creates an electrostatic softening spring [8]. Based on this measurement, Figure 2(B), the fabricated air gap was identified as $3.6 \mu\text{m}$.

Table 1: Specifications for the MEMS electrometer and charge calibration parameters. Measured and calculated values correspond to the AC and DC voltage operating point in table.

Parameter	Value	Units
Spring-beam Length	428	μm
Spring-beam Width	2.4	μm
Structural Layer Thickness	15	μm
Spring Constant	1.59	N/m
Shuttle Mass	6.58	μg
Resonance f_n	2.3	kHz
Comb Drive Gap	2.6	μm
No. Combs	96	
dC/dx for Comb Drive	8.58	nF/m
Sense Plate Gap	3.6	μm
Sense Plate Length	426	μm
No. Sense Plates	66	
Sense capacitance C_P	2.1	pF
Normalized Displacement x_0	0.17	$\mu\text{m}/\mu\text{m}$
Quality Factor Q	180	
Parasitic Capacitance C_P	20	pF
DC Drive voltage	2	V
AC Drive Voltage	200	mV _{rms}

Figure 2: (A) Normalized displacement x_0 at f_n with respect to drive voltage amplitude showing nonlinear response at displacements above 120 nm. (B) Measured dependence of natural frequency on bias voltage amplitude

Figure 3: Frequency response around $2f$ while driving the MEMS electrometer around f_n . The measured quality factor is $Q = 180$.

The electrometer's frequency response was also measured by applying a constant charge of 300 pC applied to $C(t)$ and monitoring the $2f$ component of the output voltage from (1) using a lock-in amplifier. The resulting measurement, in Figure 3, shows that the peak output signal occurs at $2f_n = 4.68 \text{ kHz}$, in good agreement with the natural frequency $f_n = 2.3 \text{ kHz}$ predicted using FEM. This measurement was recorded using the circuit labelled G_V in Figure 4 as a high-impedance buffer between the MEMS device and the lock-in amplifier.

the Ioner electrometer having a slightly better rms noise resolution of ~ 0.5 fA. The MEMS electrometer sensitivity was measured as 49 nV/cm^3 .

Figure 6: MEMS electrometer output with respect to input charge Q_C . (A) First experiment showing MEMS output with respect to input charge Q_C ($I_{\text{test}} \approx 134 \text{ fA}$); measured sensitivity of $5.48 \cdot 10^7 \text{ V/C}$. (B) Second experiment showing the output rising with time as the test current is increased; inset shows the step change in output due to the step change in test current, ΔI_{test} .

Figure 7: MEMS Electrometer output voltage versus input charge Q_C . Charge is computed for different test currents at $t = 500 \text{ sec}$.

Figure 8: Current and voltage output for the two electrometers with respect to particle concentration. MCPC was used to measure concentrations. MEMS electrometer has a linear sensitivity of $49 \text{ nV}_{\text{rms}}/\text{cm}^3$ and Ioner electrometer $0.004 \text{ fA}/\text{cm}^3$.

CONCLUSIONS

We demonstrated a MEMS based charge sensor capable of detecting aerosol particles in the nanometer size range at particle concentrations near 400 cm^{-3} . The resolution of the electrometer can be further reduced by improving the noise and parasitic at the interface and readout electronics. The smaller footprint and lower cost of this particle detector could increase the accessibility to better measurement tools by aerosol and environmental scientists.

REFERENCES

- [1] A. Ibaldu-Mulli, H. E. Wichmann, W. Kreyling, and A. Peters, "Epidemiological evidence on health effects of ultrafine particles," *J Aerosol Med*, vol. 15, pp. 189-201, Summer 2002.
- [2] E. O. Knutson and K. T. Whitby, "Aerosol classification by electric mobility: Apparatus, theory, and applications," *J. Aerosol Science*, vol. 6, pp. 443-451, 1975.
- [3] A. N. Cleland and M. L. Roukes, "A nanometre-scale mechanical electrometer," *Nature*, vol. 392, pp. 160-162, 1998.
- [4] J. S. Bunch, A. M. van der Zande, S. S. Verbridge, I. W. Frank, D. M. Tanenbaum, J. M. Parpia, H. G. Craighead, and P. L. McEuen, "Electromechanical resonators from graphene sheets," *Science*, vol. 315, pp. 490-493, 2007.
- [5] P. S. Riehl, K. L. Scott, R. S. Muller, R. T. Howe, and J. A. Yasaitis, "Electrostatic charge and field sensors based on micromechanical resonators," *J. Microelectromech. Syst.*, vol. 12, pp. 577-589, 2003.
- [6] J. Lee, Y. Zhu, and A. Seshia, "Room temperature electrometry with sub-10 electron charge resolution," *J. Micromech. and Microeng.*, vol. 18, Feb 2008.
- [7] G. Langfelder, A. Tocchio, M. J. Thompson, G. Jaramillo, and D. A. Horsley, "Assessing micromechanical sensor characteristics via optical and electrical metrology," in *Sensors, 2010 IEEE*, 2010, pp. 1765-1769.
- [8] M. Li, V. T. Rouf, M. J. Thompson, D. A. Horsley, "Three-axis Lorentz-force magnetic sensor for electronic compass applications," *J. Microelectromech. Syst.*, accepted.

CONTACT

*G. Jaramillo, tel: +1-530-752-5180; geomartinez@ucdavis.edu