Implementation and Characterization of a femto-Farad Capacitive Sensor for pico-Liter Liquid Monitoring

J. Wei\textsuperscript{a}\textsuperscript{*}, C. Yue\textsuperscript{b}, Z. L. Chen\textsuperscript{b}, Z. W. Liu\textsuperscript{b}, K. A. A. Makinwa\textsuperscript{a}, P. M. Sarro\textsuperscript{a}

\textsuperscript{a}Dimes, Delft University of Technology, Delft, Netherlands
\textsuperscript{b}IMETU, Tsinghua University, Beijing, China

Abstract

An fF-level capacitive sensor, intended for pL liquid measurements, has been fabricated with MEMS technology and successfully characterized. The sensor measures liquid level variations in a microfluidic channel. The sensor’s capacitance varies from 1.5 fF (channel empty) to 12.8 fF (channel filled with 63 pL of water). To reliably detect such small capacitance changes, a low noise measurement system, based on a lock-in amplifier, was implemented. The measured sensitivity of the system is 14.1 mV/fF, and the capacitance detection limit is 0.057 aF/Hz\textsuperscript{1/2}, which corresponds to a volumetric resolution of about 0.22 fL/Hz\textsuperscript{1/2}.

Keywords: Capacitive sensing, charge amplifier, lock-in amplifier, MEMS, inkjet

1. Introduction

Liquid monitoring is an important issue in modern fluidic applications, such as chemical analysis [1], biotechnology [2] and high precision microfluidic dispenser systems [3]. Capacitive sensors are often used to detect the capacitance variations associated with changes in liquid level. As the dimensions of fluidic systems shrink, the liquid volumes need to be monitored decrease to the 10-100 pL level. Consequently, the nominal capacitances of capacitive sensors are only in the order of a few fF. This results in high sensor impedances and small signal levels, which are easily corrupted by electrical noise and disturbed by the presence of parasitic capacitances. These factors limit sensor resolution, and make the design of the sensor and the signal detection strategy quite challenging.

This paper presents a prototype sensor designed to monitor the motion of liquids in an inkjet nozzle (Fig.1). In order to detect missing droplets caused by air bubbles or clogging as well as the size of droplets, a capacitive volume sensor is integrated to track the motion of the ink meniscus inside the nozzle. Using an IC-compatible process, silicon electrodes, isolated by oxide, are embedded in the sidewall of the nozzle. A dedicated measurement setup is used to reduce the influence of parasitic capacitances and minimize electrical noise. The measurement strategy of the sensor is introduced in the next section, followed by a section about its fabrication. The measurement results are shown and discussed in the final section.

* Corresponding author. Tel.: +31-15-2781237; fax: +31-15-2622163.
E-mail address: j.wei@tudelft.nl.
2. Measurement Strategy

The typical capacitance variation in the proposed sensor is in the order of 10fF. To measure such a small capacitance variation, two main challenges need to be overcome:

- The high impedance of the sensor leads to a low signal level, and, therefore, a low noise level is required in order to reach an acceptable resolution.
- The parasitic capacitance of the sensor is at the pF level, which is 1000 times larger than the capacitance of the sensor itself. These parasitics reduce the signal level and generate offset, therefore the influence of the parasitic capacitors must be reduced as well.

To circumvent these challenges, a dedicated readout system, based on a lock-in amplifier [4], was used. Fig. 2a shows a schematic diagram of the system. The sensor is driven by an AC voltage $V_{in}$, which converts its capacitance variations into current variations. These current variations are modulated to a higher frequency where the noise floor is low. A charge amplifier converts the modulated current into a corresponding voltage, which is then fed into a lock-in amplifier for demodulation. In this way, the amplifier’s flicker noise is separated and removed from the sensor signal, and the noise of the output is determined by the thermal noise floor and the demodulation bandwidth. Fig. 2b shows the signal and noise at each node of the system in the frequency domain.

The chosen readout system is also insensitive to parasitic capacitance. In Fig. 2a, the input of the sensor is connected directly to the signal generator, so that the parasitic capacitance at the input node ($C_{p1}$) can be ignored. The sensor output node is connected to the inverting input node of a charge amplifier, which is a virtual ground. Provided that the loop gain of the charge amplifier is sufficiently large, the parasitic capacitor here ($C_{p2}$) can be ignored as well. $C_r$ is a reference capacitor, driven by $-V_{in}$ which generates a compensating current that cancels the input current due to the nominal value of the capacitive sensor.
3. Fabrication

The sensor was fabricated with an IC-compatible process (Fig.3) [5], where silicon electrodes are embedded in the sidewall of a nozzle. A thick oxide isolation layer is used to reduce the influence of parasitic components (Fig.3.b). Fig. 4 shows the SEM photo of the fabricated sensor. The nozzle is 40 µm in diameter and 50 µm deep, corresponding to a total liquid volume of 63 pL. Each electrode is 30 µm wide, and located in the top 35 µm of the nozzle. The corresponding measurable liquid volume is 44 pL. The surfaces of the electrodes are covered with a 0.5 µm thick oxide layer to isolate the electrodes from the liquid in the nozzle.

![Fig. 3. Schematic view of the fabrication process.](image1)

![Fig. 4. SEM photos of the fabricated sensor.](image2)

4. Results & Discussions

The impedance of the sensor as a function of frequency is measured with an impedance analyzer. For an empty nozzle, the capacitance of the sensor was found to be 1.5 fF (Fig. 5).

![Fig. 5. The impedance measurement of the empty sensor.](image3)

The low noise measurement system, shown in Fig. 2, was implemented as shown in Fig. 6 to investigate the response of the sensor to variations in the level of the liquid in the nozzle. The measurement was done with a probe-station, and a microscope was used to inspect the sensor’s condition. A plastic pipe with a syringe was attached to the backside of the device, allowing liquid to be injected into the nozzle. Conductive water was used in this experiment. The oxide layer coated inside the liquid channel provides a hydrophilic surface, thus capillary action automatically sucks water into the channel. The level of water in the channel can be determined by observing the reflection of light on the water surface at the channel opening.

In order to reduce parasitic capacitances, the sensor was directly wire-bonded to the PCB board carrying the charge amplifier. At the beginning of the measurement, the sensor’s liquid channel was completely filled with water.
Then, the channel was emptied by pulling water back with the syringe, while the sensor’s output was simultaneously recorded with an oscilloscope. A 100 kHz, 20 Vpp sinusoidal driving signal was applied to the sensor input. The change in the output signal of the charge amplifier was about 160 mV. Fig. 7 shows the measurement result.

![Fig. 6. The measurement setup of the capacitive sensor.](image)

![Fig. 7. The output signal change of the charge amplifier.](image)

Since the value of the feedback capacitor \(C_F\) in the charge amplifier is 0.5 pF, the effective capacitance change of the sensor \(C_s\) can be extracted from the measurement result. The extracted value is 11.3 fF, corresponding to an estimated sensitivity of 14.1 mV/fF. Assuming that the capacitive change is linearly related to the liquid level inside the channel, the corresponding volumetric sensitivity is 275 pL/V. At 100 kHz, the noise level at the output of the charge amplifier is 0.8 µV/Hz\(^{1/2}\) and the corresponding resolution of the capacitance measurement is 0.057 aF/Hz\(^{1/2}\). This in turn corresponds to a volumetric resolution of 0.22 fL/Hz\(^{1/2}\).

5. Conclusion

A femto-Farad-level MEMS capacitive sensor for pico-liter liquid monitoring and a high performance measurement setup have been successfully demonstrated. Silicon electrodes are integrated inside the microfluidic channel of a nozzle with an IC-compatible process. Depending on the liquid level, the capacitance of the sensor varies from 1.5 fF (channel empty) to 12.8 fF (channel filled with 63 pL of water). A measurement system, based on a lock-in amplifier, successfully suppresses the influence of parasitic capacitances and noise. The system has a capacitive-sensing resolution is 0.057 aF/Hz\(^{1/2}\), which corresponds to a volumetric resolution of 0.22 fL/Hz\(^{1/2}\).

Acknowledgements

The authors would like to thank Dr X. Li from Electronic Instrumentation of TUDelft/DIMES for many useful discussions, and the DIMES IC-process group for technical support.

References

1. K. T. Hjelt, R. van den Doel, et al., High-Resolution Liquid Volume Detection in Sub-nanoliter Reactors, Sensors and Actuators, 2000, Vol.83, p. 61-66
2. X. Cai, N. Klaude, et al., Ultra-Low-Volume, Real-Time Measurements of Lactate from the Single Heart Cell Using Microsystems Technology, Analytical Chemistry, 2002, Vol.74 pp. 908-914
3. Velden, M. van der; Wei, J. Spronck, J.W., Munng Schmidt, R.H., Sarro, P.M., Characterization of a nozzle-integrated capacitive sensor for microfluidic jet systems, Proceedings of the IEEE 2007, 2007, pp. 1241-1244
4. M. Tavakoli and R. Sarpehshkar, An offset-cancelling low-noise lock-in architecture for capacitive sensing, IEEE J. Solid-State Circuits, 2003, vol. 38, pp.244-253
5. J. Wei, M. van der Velden, and P.M. Sarro, Fabrication of vertical electrodes on channel sidewall for picoliter liquid measurement, Proc. of Transducers07 & Eurosensors XXI, Lyon, 2007, p. 1613-1616