Paper-Based Capacitive Mass Sensor

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***Abstract*—Paper-based MEMS is a new area in the field of micro-electro mechanical systems. We have developed a paper-based MEMS sensing device that is capable of measuring masses as small as 2mg (~20µN) with a sensitivity of 0.5fF/mg. Using this device, we monitored changes in capacitance values, which can be related to mass changes. This capacitive-based mass sensor, which uses a cantilever beam design, promotes and advances the use of paper in the design of micro systems. The work presented in this paper on building a capacitive sensor is advantageous because the overall costs are considerably reduced and the methods used can serve as a building block to conduct initial tests and analyses for future MEMS sensors.**

I. Introduction

Paper-based MEMS is a new development in microsystems engineering targeting applications where low-cost, rapid implementation is required eliminating the need for sophisticated cleanroom facilities. A piezo-resistive force sensor and a microfluidic chip have already been implemented using this technology at Harvard University [1]. This paper introduces the first paper-based mass sensor utilizing a capacitive measurement system schematically shown in Fig. 1. It consists of a cantilever and a gap-varying capacitor. Upon deflection of the cantilever with an external mass, the capacitance between the patterned electrode on the beam and the stationary electrode changes with respect to the weight of the applied mass.

This project was in fact accomplished as a team-based term project for the course, ECE 5210: MEMS from Fabrication to Application, offered at Virginia Tech. The idea was to create a paper-based mass sensor and its associated measurement system that could be emulated using low-cost consumer products. A standard MEMS process requires an in-depth knowledge of both material properties and microfabrication techniques along with expensive machinery to create high quality microsensors. This project shows the promise of paper-based MEMS technology for educating undergraduate and graduate students about the field of MEMS and microsensors and improving their interdisciplinary teamwork skills through such low-cost hands-on experiments. Moreover, this paper clearly demonstrated the ability to use household items to mass produce sensors with acceptable resolutions where financial, human, and manufacturing facilities resources are extremely limited, example of which are remote sites in certain countries as well as areas affected by severe natural disasters. Such a low-cost, on-site-implemented, disposable, yet accurate mass sensor can be used to weigh small quantities of objects.

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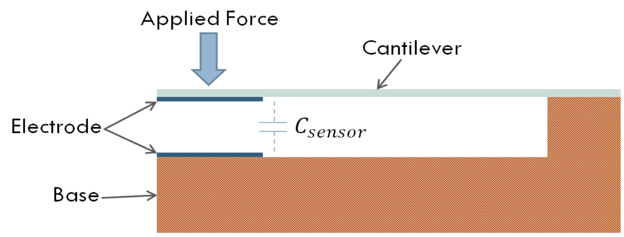

Figure 1. Schematic of the mass sensor comprising a cantilever and a varying-gap capacitor. One electrode is positioned on the base (stationary) and the other is located on the backside of the cantilever (movable).

II. Materials and Methods

Multiple capacitive sensors were built in order to determine their sensitivity (high capacitance change for slight mass increase). The first generation (Gen-1) of capacitors was made simply using paper, aluminum foil, and conductive epoxy as shown in Fig. 2. Different paper types were used to implement these sensors.

Figure 2. Initial capacitor design made using paper and aluminum foil/ conductive epoxy.

The choice of the dielectric material is an important factor in designing a capacitive-based sensor not only because it affects the electrical properties of the device but also because it contributes to the sensitivity of mass variation. Ideally, a material that does not impede the modulation of distance between the parallel plates should be used. In this case, a small change in force applied to one or both plates will cause a distinct change in the capacitance. For the second generation (Gen-2), other device designs, shown in Fig. 3, were implemented using sound dampening foam, nitrile rubber, and packaging foam as the dielectric and aluminum foil as the

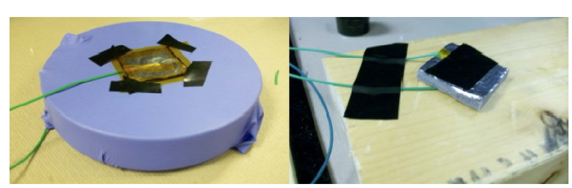

Figure 3. Initial capacitor designs made using foam tape and air as the dielectric material.

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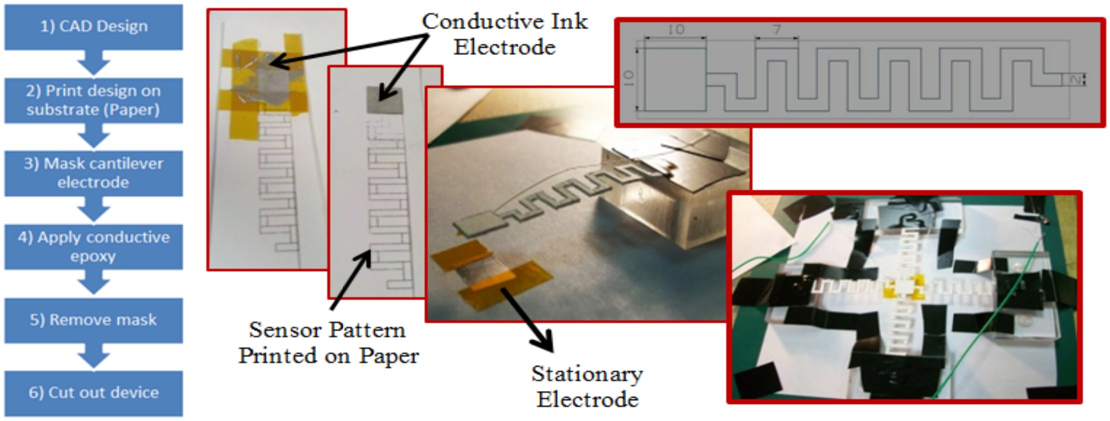

Figure 4. Process flow for the fabrication of the capacitive mass sensor using Bristol paper and conductive ink. Sensing configurations with one of or more meander-shaped cantilevers can be implemented using this technique.

electrodes. As discussed later, none of these simple configurations were able to yield enough sensitivity, and hence, more complicated geometries were investigated.

To achieve a greater capacitance change for a small mass increase, a cantilever design needed to be implemented where the sensitivity depended on the stiffness of the paper and the geometrical dimensions of the cantilever. The fabrication method used for the creation of these paper-based MEMS devices (Gen-3) is summarized in Fig. 4. The process starts by first transferring any pattern designs on a chosen paper, depositing an electrode, and then cutting the devices out manually. Multiple capacitive sensors were built and tested in order to determine their sensitivity. Different paper types including water color, rough Bristol paper, and soft Bristol paper were used; their Young's modulus was determined experimentally to be 0.9GPa, 2GPa, and 1.6GPa, respectively, using a simple beam and the force vs. deflection models. The Young's Modulus was also used in a Finite Element Analysis to determine if a simple cantilever beam or meandered beam would provide better sensing results

III. Measurement Setup

One goal of this project was to create an inexpensive capacitance measurement tool capable of sensing changes in capacitance on the order of 1fF. It was found that the $\Delta - \Sigma$ based AD7746 Capacitance-to-Digital converter coupled with a PIC Microcontroller provided a capacitance sensing interface capable of sensing capacitance changes in this realm. The popularity of the AD7746 for capacitive touch sensing and the existence of a breakout board allowed rapid prototyping. The PIC18F13K50 Microcontroller was used to communicate with the AD7746, format the data, and stream it serially into a host computer. A LabVIEW program was created to read the data, calculate the instantaneous capacitance value and plot the data in real-time. The prototyped circuit is shown in Fig. 5.

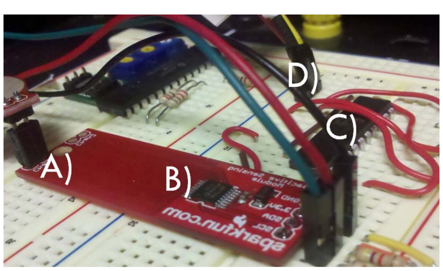

Figure 5. The capacitive measurement system showing A) the capacitive sensor connection, B) the AD7746, C) the PIC18F13K50 microcontroller and D) the serial connection to the host PC. Alternatively, a multimeter with capacitor readout can be used.

IV. Results

Gen-1 sensors made of paper and aluminum foil/conductive epoxy showed minute changes in capacitance even when a mass as large as 500mg was introduced. Gen-2 devices fabricated from nitrile rubber and foam demonstrated an improvement in sensitivity with values around 5.6 fF/g for the foam-based devices and 10.5 fF/g for the nitrile rubber-based devices. Capacitance versus mass plot was generated for both designs as depicted in Fig. 6.

These results led us to develop our Gen-3 devices with enough stiffness to keep the electrodes from touching but flexible enough to yield a considerable capacitance reading change for a small mass deposited at its tip. The mechanics of a simple cantilever beam are well known; the tip displacement can easily be related to the force or pressure that provokes the displacement. The equation that relates the force to the displacement is given by: $F = kx$, where F is the force exerted at the tip of the beam, k is the stiffness of the beam, and x the tip displacement value.

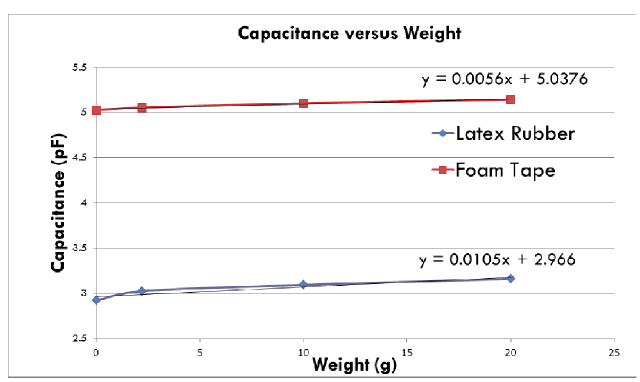

Figure 5. Capacitance versus mass plot for Gen-2 sensors.

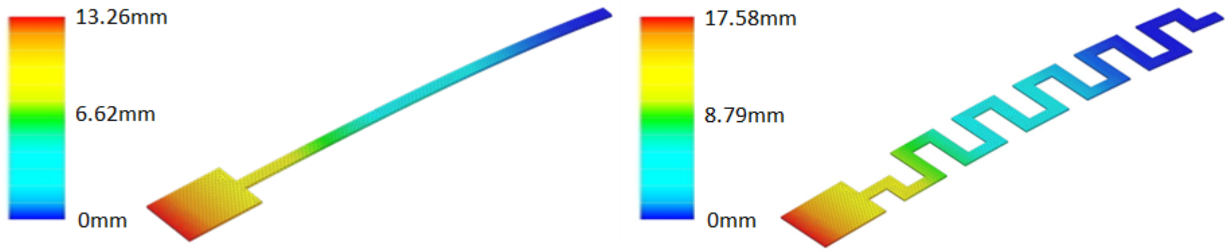

Figure 6. Finite Element Analysis of a simple cantilever beam and meandered cantilever beam showing the deflection due to a 1N force placed on the tip. The magnitude of deflection is higher in the meandered cantilever model which is in agreement with the results shown in Fig. 7.

For Gen-3, we evaluated three different papers as mentioned earlier: water color, rough Bristol, and smooth Bristol. The stiffness for each beam was approximately determined using different loads applied at the tip of the implemented cantilevers and measuring the amount of deflection. The stiffness values were then used to characterize and determine the Young's modulus, E. The Young's modulus can be determined knowing the geometrical parameters of the beam as well as its stiffness in bending. The Young's Modulus for a cantilever is found using the following equation:

$$E = \frac{4kL^3}{bt^3}$$

where L is the length of the beam; b is the width of the beam and t is the thickness. Rough Bristol paper was determined to have the highest Young's modulus value, which translates to quick relaxation time for this type of material. A small relaxation time is ideal because this will allow consecutive measurements to be executed without waiting long for the cantilever to return to its original state.

Following paper selection using simple beams, we explored the use of simple cantilever beams as well as meandered cantilever beam designs for our final MEMS sensor. Both designs were analyzed using Unigraphics, a CAD software, under same boundary conditions and parameters (same beam width, length and thickness). A dummy force of value of 1 N was applied at the tip of each cantilever; the displacement for each beam was then derived. As displayed in Fig. 6, the meandered design gave the highest tip displacement when compared to the simple cantilever beam design. In the case of the meandered sensor, a single arm (fixed-free) design gives the best capacitance to mass slope (highest). The addition of arms would make the system more robust but at the cost of reduced sensitivity.

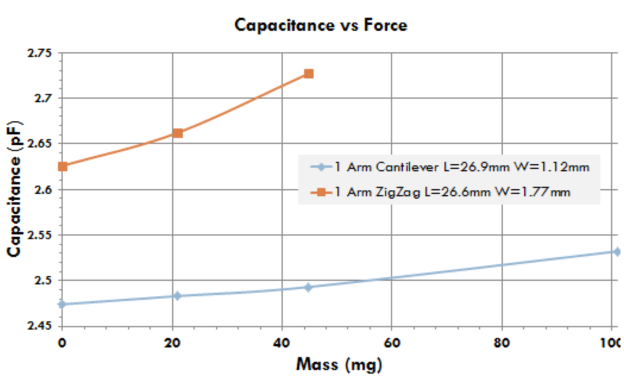

Figure 7. Capacitance vs. mass measurement for two cantilever designs: (red) our zigzag (meander) configuration and (blue) a simple cantilever. The linearly slopes depict the resolution of weight measurement with respect to capacitance.

Fig. 7 depicts the measured capacitance change with respect to mass for two of our designs, the simple beam and the meander-shaped cantilever. The latter with dimensions shown in Fig. 2 yielded a lower stiffness coefficient and was able to resolve 2mg, achieving a sensitivity of 0.5fF/mg. It is noteworthy that the simulation results correlate relatively well with experimental results we have determined. Under the same boundary conditions, for a mass of 20.9g located at the tip of the one-arm meandered beam, the simulation was accurate to 21% with the tip displacement obtained experimentally. This discrepancy comes from measurement errors in determining the Young's modulus of the paper and the fact that the paper was not perfectly cut.

V. CONCLUSIONS

This work presents one of the first few MEMS devices made using household items. The sensor uses Bristol paper for the structural material and conductive epoxy for the capacitor electrodes. The meander-shaped configuration was able to sense weights as low as 2mg. This report which is the result of a team-work project in the course "ECE5210: MEMS from Fabrication to Application" at Virginia Tech, is a proof-of-concept that paper-based MEMS can be a great low-cost, rapid-prototyping technology to teach the essential of MEMS and system integration at both graduate and undergraduate levels. To implement such devices, students do not need to have access and get trained to use sophisticated cleanroom facilities.

REFERENCES

1. X.Y. Liu, M.O.B., M. Mwangi, X.J. Li, and G.M. Whitesides. "Paper-Based Piezoresistive MEMS Force Sensors", Proceeding IEEE MEMS 2011, Cancun, Mexico, pp. 133-6.