# Micromachined Nickel Floating Element Shear Stress Sensor Array

Z. Zhao[a], J. Gallman[b], R. White[a],
[a] Department of Mechanical Engineering, Tufts University, Medford, MA 02155, USA
[b] Spirit Aerosystems, Wichita, KS 67278, USA

This paper describes the design, fabrication, characterization and packaging of a 256 element MEMS floating element shear stress sensor array-on-a-chip. This device is targeted at measuring time resolved fine spatial scale shear stress beneath the turbulent boundary layer (TBL) for aerospace applications. The differential measurement shows a sensitivity of 0.08 mV/Pa at 0.27 mV/$\sqrt{Hz}$. The linear ranges are observed up to 3.6 Pa and 6 Pa respectively for 3μm and 10 μm-thick structure.

## Introduction

The understanding of shear stress is a major part in any aerodynamic or hydrodynamic design. Fluctuating shear stress can act as a source of structural vibrations. However, shear stress is not easily measured using one sensor for all kinds of different fluid situation.

Conventional techniques for skin fraction and shear stress measurement have been described as early as 1954 (1-4), however, they are inadequate due to their poor spatial and temporal resolution. In the last two decades, MEMS-based floating element shear sensors have been developed by various groups (5-8). All previous examples of MEMS-based sensors to appear in the literature were produced as individual floating elements. In this paper, we describe a design for arraying the individual sensing elements into a group, and combining several groups in parallel into a chip to create an array-in-an-array sensor topology. One chip consists of 4 by 4 groups, each of which has 4 by 4 elements as one signal output. The spatial resolution of the array-on-a-chip is on the order of a millimeter. The local shear stress or average shear of a single chip is capable of being detected simultaneously. Additionally, one dead element during fabrication or operation will not kill the whole sensor.

## Design

One floating element, as shown in left image of figure 1, has one center shuttle, which is free standing on the top of substrate, and supported by eight fold-beams on left and right hand sides. Two sets of comb fingers on the top and bottom sides are used to drive and sense the motion of the center plate. The signal can be read on three pads connected to the fingers and ground (not shown in the figure).

Comb fingers consist of a series of parallel plates. Since one side is fixed, and the other is free to move, drag force generated by the flow will move one side of finger up and down in y direction and change the overlap area between two fingers in terms of the displacement Δx, as shown in the right drawing of figure 1. If the effect of fringing electrical field is neglected, the change of capacitance ΔC is proportional to the Δx, we have

$$\Delta C = K \cdot \Delta X \qquad [1]$$

where the constant K is determined by the three dimension geometry of the sensor. In the elastic deformation, relationship between shear stress and displacement is given by

$$\tau = \frac{K_y}{A_m} \cdot \Delta X \qquad [2]$$

where $K_y$ is the stiffness of the y-axis direction and $A_m$ is the surface area of the floating element. Combing Eq. [1] and [2], the sensitivity is obtained by

$$\frac{\tau}{\Delta C} = \frac{K_y}{K \cdot A_m} \qquad [3]$$

It is worth nothing that such a relationship is established on the assumption that there is no out-of-plane motion. We will discuss this more in the sections on calibration and results.

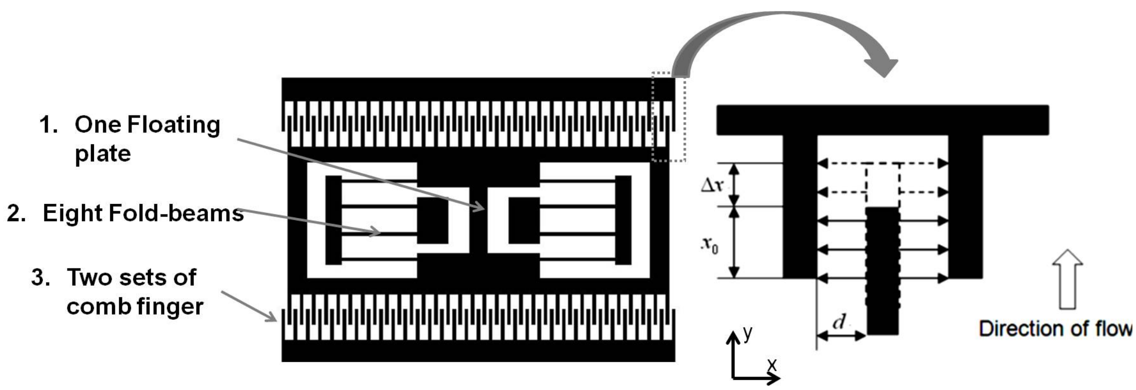
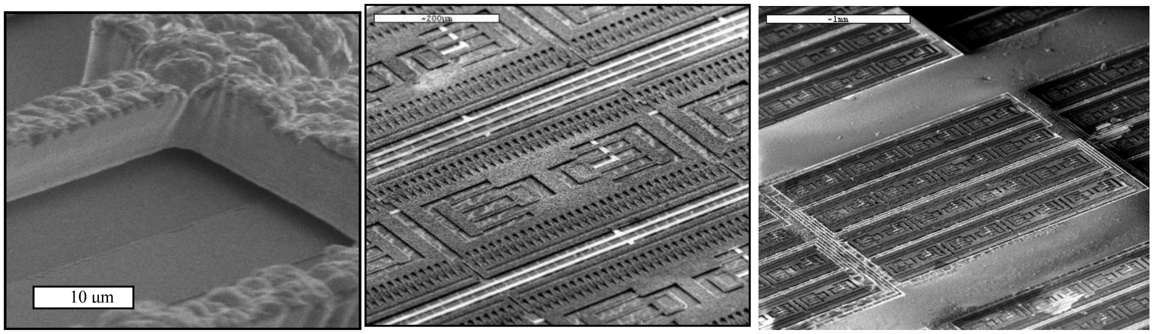



Figure 1. One element of floating sensor (left) and one finger as well as its movement in the flow (right)

## Fabrication

The sensors are fabricated using surface micromachining and electroplating. First, Cr/Au interconnects are sputtered onto the glass substrate and patterned by liftoff. A 2 µm thick electroplated Cu sacrificial layer is deposited using a copper sulfate plating solution (Technic Copper FB) and patterned lithographically. A Nickel structural layer with varied thickness is deposited from a nickel sulfamate plating solution (Technic Nickel Sulfamate SemiBright) and patterned lithographically. Both 3 µm and 10 µm thick Nickel structure layers have been electroplated on the top of copper layer. The structure is released in 1:1:18 Acetic Acid:Hydrogen Peroxide:Water. The resulting structure can be seen in Figure 2. After array fabrication, a customized ceramic PGA package is used to house the die. The package is wirebonded and potted in epoxy with special care taken to keep the devices planar to the surface.




(a) (b) (c)

Figure 2. SEM figure of floating element (a) 10-μm thickness and 2-μm air gap underneath. (b) One floating element. (c) One group out of 16.

**TABLE I.** The critical dimensions of fabricated floating element

| Dimensions | G1 Sensor_$V_1$ | G1 Sensor_$V_2$ |
|---|---|---|
| Thickness t(μm) | 10 | 3 |
| Finger Gap d (μm) | 1 | 3.3 |
| Beam Width w (μm) | 4 | 4 |
| Aspect-Ratio of t/w | 2.5 | 0.75 |
| Separation Gap (μm) | 2 | 2 |

## Calibration

### Flowcell

The flow channel with the high aspect ratio (~ 70) rectangular cross section has been designed and formed by the shim plate as shown in the figure 3. The distance between the sensor and the inlet hole is longer than flow entrance length to ensure the flow passing the sensor is fully developed. The actual shear stress $\tau$ is calibrated by the pressure drop measurement *dp/dx* in four pressure taps in the fully developed region,

$$\tau_{yx} = -\frac{1}{2} h \left( \frac{dp(x)}{dx} \right) \quad [4]$$

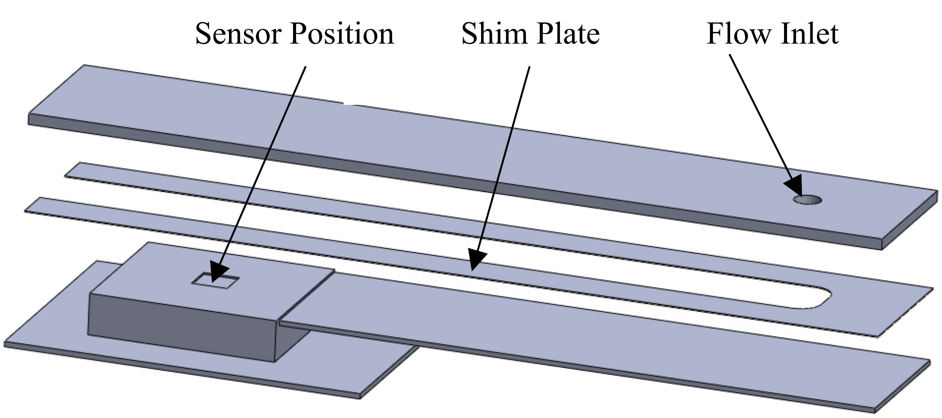
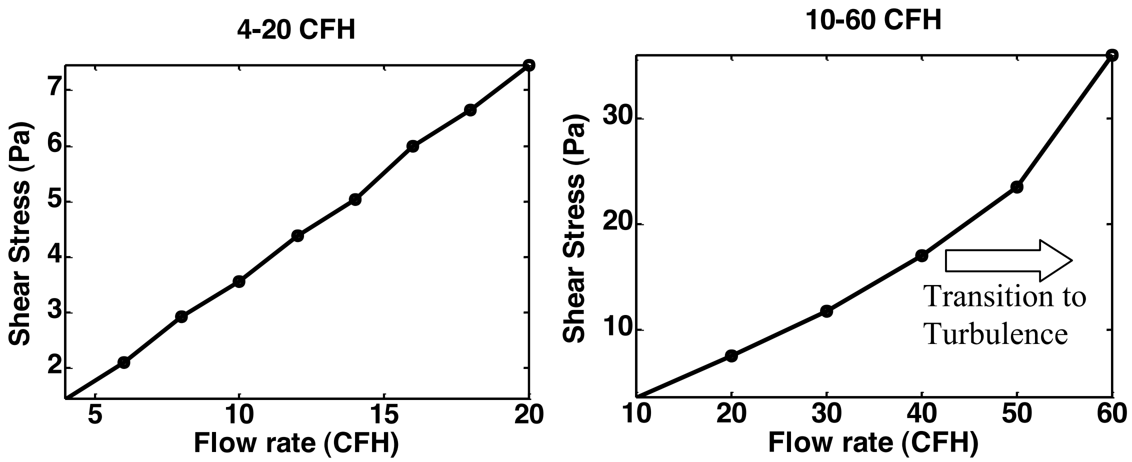



Figure 3. A schematic of multi-components of the flowcell.

Figure 4 shows the shear stress is linear increasing with the volume flow rate at low Reynolds number, and more rapidly increasing following a higher order curve when the Reynolds number goes above 2300 at a rate of 50 CFH. At this flow rate, the flow is reaching the transition range to turbulence.




(a) (b)

Figure 4. (a) Flow rate from 4 CFH to 20 CFH, (b) flow rate from 10 CFH to 60 CFH.

Single Measurement

Single side measurements (either top electrode or bottom electrode) are applied on the sensor with 10 µm structure. Figure 5 shows the sensitivities of 0.24 fF/Pa and 0.36 fF/Pa for one group (16 elements) and two groups (32 elements), respectively, within the range of 6 Pa shear stress. Repeatability of single measurement strongly depends on how large is DC drift and how the temperature of the testing environment changes. Also, note that the sensor responds linearly only up to 6 Pa. At higher stress levels, the sensitivity is reduced by nonlinear structural effects.

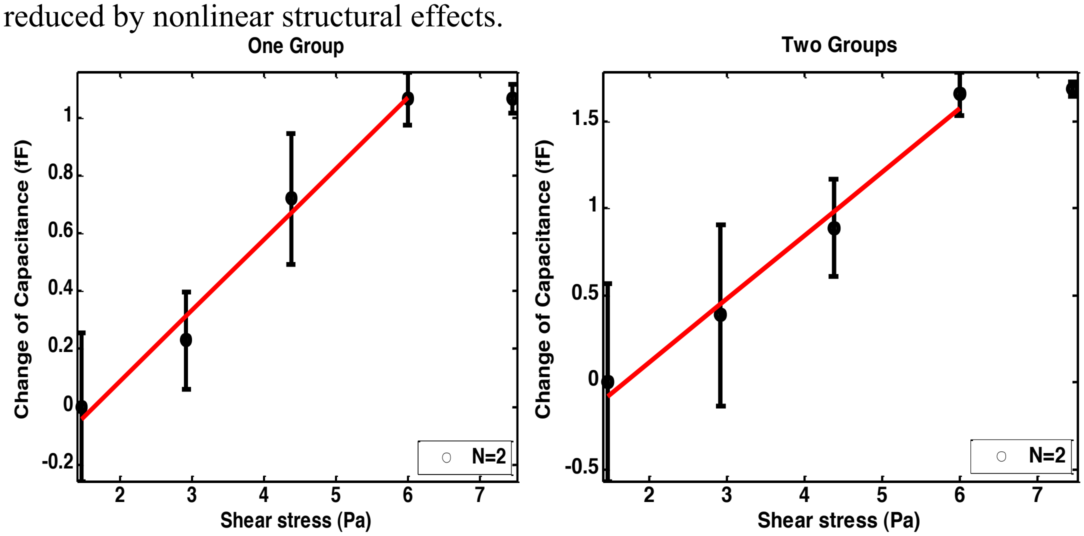


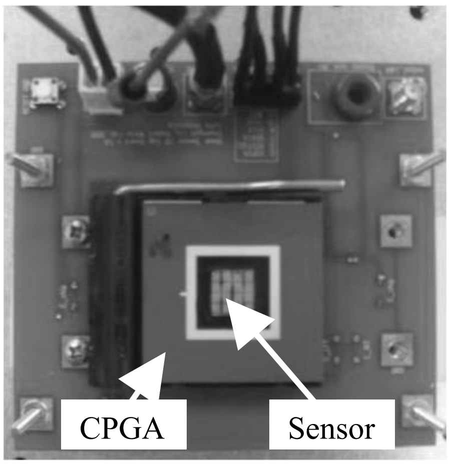

Figure 5. Capacitance measurement as a function of shear stress on the single electrode of G1 Sensor_$V_1$, (a) one group; (b) two groups.

Electronics

The figure 6 shows the front side of PCB board with a sensor package, and back side mounted a MS3110 capacitance readout chip. This chip is a capacitance to voltage converter, and includes a low pass filter, and is capable of balancing the capacitance of the two input channels $C_{Bottom}$ and $C_{Top}$ (Figure 7 and Eq. [5]). The transfer function is given by the datasheet [9]:

$$V_0 = A \cdot \frac{(C_{Bottom}+CS2)-(C_{Top}+CS1)}{C_f} + B \quad [5]$$

where the parameters $A$ and $B$ can be altered in the settling program of MS3110, $CS1$ is a balance capacitor array, $CS2$ is a trim capacitor array, and $C_f$ is a feedback capacitor array.



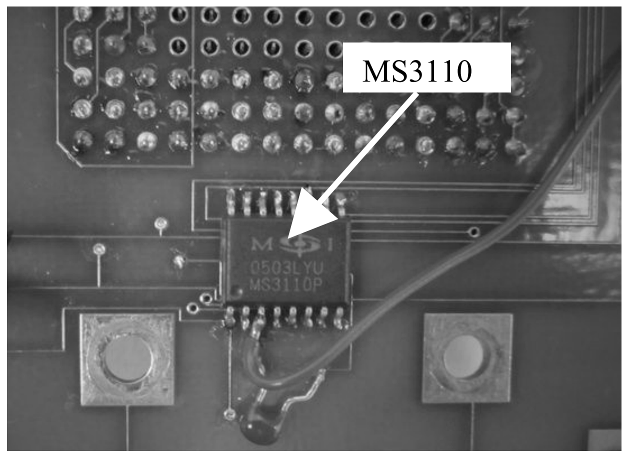




Figure 6. The electronics mounted with a sensor package on the front side (Left) and MS3110 chip on the backside (Right).

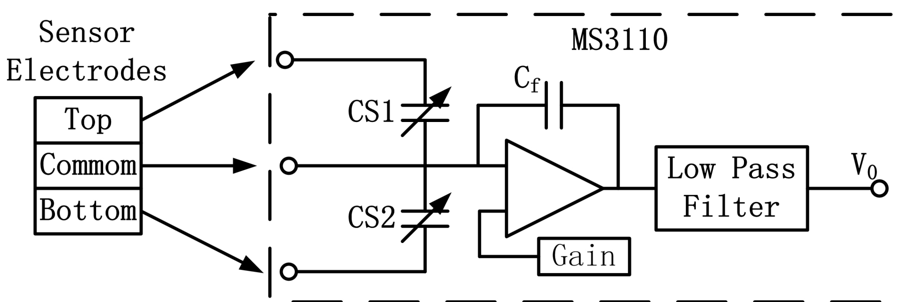



Figure 7. A schematic of MS3110 capacitance readout chip.

Differential Measurement

The sensitivity of a 3μm thick sensor was calibrated with differential measurement using the electronics described above. The shear stress corresponding to the flow rate is varied from 1.5 Pa to 4 Pa. A linear range of the 3 μm structure is observed up to 3.6 Pa, which is smaller than the 10 μm structure due to the different aspect ratios of t/w in Table 1. The sensitivity plot of two groups is shown in Figure 8, and it is approximate 0.08 mV/Pa in MS3110 setting of 8 kHz low pass filter and 5 pF $C_f$ feedback capacitor

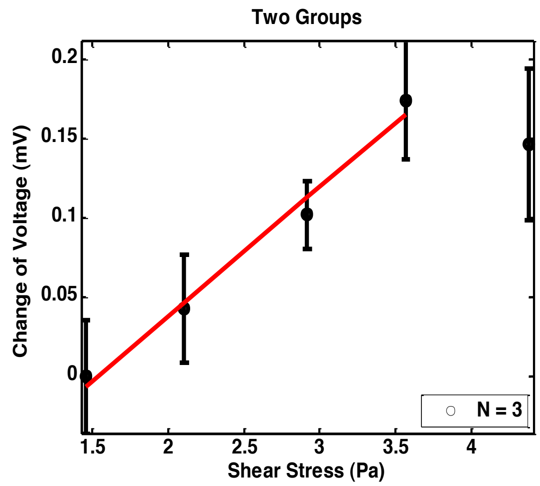


Figure 8. Voltage output as a function of shear stress on the differential measurement.

## Conclusion and Future Work

The unique topology of array-based shear stress sensor of floating element was developed with the goal of achieving both small and large spatial resolution simultaneously. The 10.1 mm square sensor chips with two different thickness of structure corresponding to the different linear ranges of sensitivity have been fabricated and packaged. It is observed that the differential measurement of two groups using a MS3110 capacitance readout chip demonstrates a sensitivity of 0.08 mV/Pa. Also, the linear range of sensitivity is limited. Higher aspect ratios increase out-of-plane stiffness and thereby increase the dynamic range.

Demonstration of a second generation sensor with higher sensitivity and a larger dynamic range is the first priority for future work. The fabrication procedure, packaging technology, as well as calibration experimental setup, will be improved in order to reduce the defects due to fabrication, optimize the yield ratio in the packaging process and understand the repeatability of sensor performance.

## Acknowledgments

Thanks to Spirit Aerosystems for supplying funding for this research project.

## References

1. J. H. Preston, "*The determination of turbulent skin friction bymeans of Pitot tubes*" Journal of the Royal Aeronautical Society,vol. 58, pp. 109–121, (1954).
2. M. R. Head and I. Rechenberg, "*The Preston tube as a means of measuring skin friction*" (1962).
3. M. R. Head and V. V. Ram, "*Simplified presentation of Prestontube calibration(Preston skin friction measuring tube calibration,presenting Patel analytic method simplification*" AeronauticalQuarterly, vol. 22, pp. 295-300, (1971)

4. K. G. Winter, "*An outline of the techniques available for the measurement of skin friction in turbulent boundary layers*" Progress in aerospace sciences, vol. 18, pp. 1-57, (1979).
5. M. A. Schmidt, R. T. Howe, S. D. Senturia, J. H. Haritonidis, and C. Mit, "*Design and calibration of a microfabricated floating-elementshear-stress sensor*" IEEE Transactions on Electron Devices, vol. 35, (1988).
6. A. Padmanabhan, H. Goldberg, K. D. Breuer, and M. A. Schmidt, "*A wafer-bonded floating-element shear stress microsensor withoptical position sensing by photodiodes*" Journal of Microelectromechanical Systems, vol. 5, (1996).
7. T. Pan, D. Hyman, M. Mehregany, E. Reshotko, and S. Garverick, "*Microfabricated shear stress sensors, part 1: design and fabrication*" AIAA Journal, vol. 37, (1999).
8. Chandrasekharan, V., Sells, J., Meloy, J., Arnold, D.P., Sheplak, M., “*A metal-on-silicon differential capacitive shear stress sensor*”, in Solid-State Sensors, Actuators and Microsystems Conference, TRANSDUCERS , (2009).
9. MS3310 Universal Capacitive Readout$^{TM}$ IC, Irvine Sensors, datasheet.