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**Metallic Micro Displacement Capacitive Sensor
Fabricated by Laser Micromachining Technology**

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ABSTRACT

This paper presents design, fabrication and performance testing results of the micro displacement capacitive microsensor fabricated by femtosecond laser machining technology. The microsensor having overall dimensions of 1275 (W) x 1153 (L) μm consisted of 20 pairs of comb fingers of 24 (W) x 300 (L) μm with a gap between the fingers of 6 μm , suspension springs, inertial mass and support anchors. The sensor structure was fabricated from a 25 μm thick tungsten foil. The fabricated microsensor was able to deliver 230 fF capacitance variations for measured displacements up to 25 μm . The results on the performance testing and geometry evaluation under pins the laser micromachining technology as an effective tool to fabricate miniature functional components and mechanisms. The developed microsensor can be used for micro/nano scale displacement measurements in MEMS applications.

1. INTRODUCTION

Micro-electro-mechanical system (MEMS) is an integrated system normally composed of micro mechanical components, micro sensors, micro actuators and associated electronics. The conventional semiconductor technologies used to fabricate MEMS are lithography-based integrated circuit (IC) processes that are common in microelectronics industry. Therefore, the materials adopted for MEMS fabrication are primarily silicon based. In recent years, more and more MEMS applications emerged in other fields, e.g., biomedical industry desires biocompatible MEMS sensors, actuators, operational tools, etc. This increased demand calls for a broad range of materials [1] for MEMS fabrication, e.g., instead of silicon a MEMS neurosurgery catheter may be made of electroactive polymer to accommodate the requirement of biocompatibility. Other materials include polymers, metals, as well as functional materials, such as, shape memory alloy, piezoelectric, etc. Unfortunately, initially adopted IC fabrication processes are not suitable in shaping or machining the aforementioned materials. On the other hand, IC fabrication processes are suitable for mass production. Also, the prototyping costs for a MEMS design using IC processes are high. Therefore, for

research and development purposes, technologies with ability to process a large variety of materials are desired to develop the prototype devices.

Based on laser ablation, laser direct-write processing using precise CNC motion system provides a quick and efficient prototyping means. This material removal process can be applied to almost all the materials without using expensive masks which are required for IC processes, thus offering a simple, low cost, and flexible micromachining technique [2, 3] as an alternative, that enables fabrication of small features that are difficult to obtain with conventional machining methods. The feature size for typical MEMS devices generally varies from nano/micro scale to meso scale ($0.1\ \mu\text{m}$ - $100\ \mu\text{m}$) [4]. The smallest feature size that laser micromachining process can fabricate is typically of the order of a few microns. Therefore, within a range of micro to meso dimensions, laser micromachining can play an important role in the fabrication of some of the MEMS devices.

This paper demonstrates suitability of the laser micromachining technology for the development of prototype MEMS devices through the design, fabrication and performance testing of a tungsten-based capacitive micro displacement sensor. The microsensor was fabricated with accuracy and precision within $\pm 1\ \mu\text{m}$, with superior wall quality using a femtosecond laser micromachining system. Measurements on input/output micro displacements and corresponding changes in capacitance values were used to evaluate the performance characteristics and the sensitivity of the fabricated microsensor.

2. DESIGN AND MODELLING

A. Mechanical Design of the Sensor

The sensor has four general components as shown in Figure 1: sensing element as a set of capacitive sensing comb fingers, suspension springs, mass, and anchors which support the entire sensor. The sensing element in which, two groups of comb fingers arranged across each other, forms a capacitor with movable lower group of comb fingers that are attached to the two springs. The mass/shuttle block has a centrally hollowed rectangular space, which potentially allows addition and tuning of the

mass and consequently enables the change in the resonant frequency of the sensor. During testing of the displacement sensor, the shuttle is the component that engages itself with the driving probe and delivers the motion to the comb fingers.

['Insert Figure 1 about here']

B. Dynamic Modeling of the Suspension Spring

Figure 2 shows a dynamic model of the suspension spring. Based on our experience with similar microdevices [5-7], it was assumed that the mass of the sensor has no effect on in-plane performance of the sensor, i.e., the weight of the moving part of the sensor will not deform the springs in out-of-plane direction, and the two springs are identical in geometry and equally share the force applied on the mass, m . If a force $2F$ applies on the mass m , the force applied to each spring (see Figure 1) is F . By design, each suspension spring has nine segments labeled by a number within parenthesis in Figure 2a. All segments have the same cross sectional area and are made of the same material. Consequently, the Young's Modulus, E , and moment of inertia, I , of all segments are the same. Free body diagrams for each segment under the force F are illustrated in Figure 2b.

['Insert Figure 2 about here']

The moments M_i , $i = 1, \dots, 3$ are:

$$M_1 = F \cdot L_1 \quad (1)$$

$$M_2 = F \cdot (L_1 + L_3) \quad (2)$$

$$M_3 = F \cdot (L_1 + L_3 + L_5) \quad (3)$$

The compression and extension strains of the vertical segment 2 and 4 are insignificant and can be overlooked compared to the deflection of the rest of the segments. Due to the short length of the vertical segments, their rotations have

negligible effect on the deflection of the segment 1 when external force F was applied. Based on the above assumption, the deflection of the unsupported end of the spring can be approximately calculated as:

$$\delta = F \cdot \frac{(L_1 + L_3 + L_5)^3}{3EI} \quad (4)$$

The stiffness of the system is:

$$k = \frac{6EI}{(L_1 + L_3 + L_5)^3} \quad (5)$$

The proposed microsensor can be used as a displacement/force sensor as well as an accelerometer. As a displacement/force sensor, the mass block structure is used as a sensor probe, which transfers the displacement of the device under test (DUT) to the sensor. The geometry parameters, L_1 , L_3 , and L_5 , of the tungsten-based sensor reported here are $420 \mu\text{m}$, $350 \mu\text{m}$, and $420 \mu\text{m}$ respectively, and Young's modulus is 410 GPa , the width and the thickness of the spring is $30 \mu\text{m}$ and $25 \mu\text{m}$, the stiffness of the system calculated from Eq. (5) is 104 N/m , i.e., to displace the fingers by $1 \mu\text{m}$, the force delivered to the shuttle is approximately $100 \mu\text{N}$. Consequently, the force that deforms the springs is generated in the DUT and is calculated using the stiffness of the system using Eq. (5). When microsensor is used as an accelerometer, the force that deflects the springs is treated as an inertia force of the mass block itself because of acceleration which can be calculated using the classical Newton's second law with the mass of the mass block and the acceleration of the DUT. In this regard, it is obvious that at certain acceleration, the inertia force is proportional to the mass and eventually influences the accelerometer's sensitivity.

C. Capacitance Modeling of the Sensing Element

The sensing element of the proposed microsensor is a set of comb fingers interlacing together and forming a group of parallel variable capacitors. Figure 3 shows

a capacitance model of the sensing elements: comb fingers 1, 2 and 3, where total capacitance of the sensor is a linear combination of capacitances formed by all comb fingers. However, capacitance between each individual finger and its neighbors is a complex combination of three separate capacitors, namely, top, side and bottom capacitors that change their capacitance in different ways with respect to the applied displacements.

['Insert Figure 3 about here']

The capacitors formed by the top surface of the finger 1 and the bottom surface of finger 2 are denoted by C_t and C_b respectively. The capacitors formed by the side wall of finger 2 with the side walls of fingers 1 and 3 are represented by C_L and C_R respectively. The sensing element has twenty originally fabricated identical fingers on both top and bottom combs with identical gap between fingers. Therefore, C_t and C_b are equivalent. However, during testing, the gaps between two sensing fingers side walls could be unequal because of transverse motion of the shuttle. The total capacitance formed by all fingers can be simply calculated as follows:

$$C_{total} = n(C_t + C_b) + nC_L + (n-1)C_R, \text{ where } n = 20 \quad (6)$$

Figure 4 shows overlay dimensions of two overlaid fingers for calculation of the total capacitance, where W is the width of all fingers, L_g is the gaps between the side walls of two adjacent coupling fingers, L_{gL} and L_{gR} are used for the calculation of C_L and C_R respectively. The symbol L_c is the overlaid length of the two fingers, and L_o is the length of comb fingers. In this case, $C_{L,R}$, C_t and C_b are calculated as:

$$C_{L,R} = \frac{\epsilon A_{L,R}}{d_{L,R}} = \frac{t \epsilon L_c}{L_{g(L,R)}} \quad (7)$$

$$C_t = C_b = \frac{\varepsilon A_b}{d_b} = \frac{t\varepsilon W}{L_o - L_c} \quad (8)$$

where ε is dielectric coefficient of air, t is the thickness of the fingers. The total capacitance of the sensor comes to C_{total} :

$$C_{total} = n \frac{t\varepsilon L_c}{L_{gL}} + (n-1) \frac{t\varepsilon L_c}{L_{gR}} + 2n \frac{t\varepsilon W}{L_o - L_c} \quad (9)$$

the sensitivity of the sensor can be calculated from Eq. (9):

$$K_c = \frac{\Delta C}{\Delta L_c} = n \frac{t\varepsilon}{L_{gL}} + (n-1) \frac{t\varepsilon}{L_{gR}} + 2n \frac{t\varepsilon W}{(L_o - L_c)^2} \quad (10)$$

['Insert Figure 4 about here']

The calculated initial capacitance with the parameters presented in Table 1 was ~ 145 fF with a sensitivity of 1.43 fF/ μ m. In general, the initial capacitance value is not an important characteristic of the fabricated sensor, since this sensor measures a relative displacement with respect to the initial position, and therefore, the sensitivity becomes a critical parameter for the functional sensor. During testing, the shuttle was observed to shift approximately 4 μ m to the left resulting L_{gL} and L_{gR} to 2 and 10 μ m respectively when the shuttle travels less than 7 μ m, and within 7 to 20 μ m driving range, the shuttle transversely moved to the left to ~ 5.8 μ m and resulting L_{gL} and L_{gR} of 0.2 μ m and 11.8 μ m values respectively. Consequently, from Eq. (10) the corresponding sensitivities were calculated as 2.6 and 22 fF/ μ m. When the driving range exceeded 20 μ m, observable out-of-plane rotation occurred and the Eq. (9) is not suitable to predict the sensor's sensitivity any more.

[Insert Table 1 about here]

3. LASER MICROMACHINING

A. Laser Micromachining Setup

Figure 5 shows the schematics of the laser micromachining system. Tungsten foil with a thickness of $25\text{ }\mu\text{m}$ was used in this study for machining the sensor prototype. A vacuum fixture equipped with a fine control valve was used to hold the foil flat and precisely at the focal point of the laser beam. The fixture was placed on a multi-axis positioning system: X and Y translation stages together with an in-plane rotation θ stage. The Z translation stage carrying an objective lens was used for focusing of the laser beam. All stages were mounted on a NewportTM anti-vibration table. The translation stages of the motion system had a positioning accuracy of $0.5\text{ }\mu\text{m}$. The laser system used was a Clark-MXR CPA 2010 femtosecond laser. An in-house designed laser beam delivery system with a combination of a beam expander and a “MicroSpot” focusing objective was used to focus the laser beam on the workpiece. Both the laser and the motion system were controlled using in-house developed software, which allowed the operator to set up the process parameters and required tool path. All the pulse energy measurements were carried out using a calibrated laser power meter (model: TMP-300 from Gentec Inc). More detailed information on laser micromachining system and process parameters optimization can be found in [7,8].

[Insert Figure 5 about here]

B. Laser Micromachining Experiments

Laser ablation is an increasingly recognized method for prototyping MEMS device development. However, it is a complex material removal process in which, the geometric quality of fabricated parts and components significantly depends on optimized process parameters related to laser, optics, workpart material, and the motion system [8-11]. Figure 6 shows line cutting on a $25\text{ }\mu\text{m}$ thick nickel foil with passes varying from 1 to 19 at focus point. At 8 mW, with a travel speed of 20 mm/min, it requires 11 passes

to fully cut through. Also, it was observed that as the number of passes increased, the width of the cuts also increased. Figure 7 shows effect of the number of laser passes on the cut width. Using this "line test" procedure it was found that the optimum number of laser passes for nickel foil was 12 passes with a cut width of approximately 6 μm , and for tungsten foil 15 passes required to cut through with vertical walls due to its physical-mechanical properties, e.g., strength, hardness, and stiffness.

It is also well known that laser pulse duration significantly affects the quality of the cut surface [7, 12]. Laser micromachining with wider laser pulse widths generates significant heat affected zone and rough cutting edges as shown in Figure 8. In comparison, femtosecond laser machining provides significantly better cut quality with smoother cutting edges and sharp corners, and minimal heat effects as shown on Figure 9.

['Insert Figure 6 about here']

['Insert Figure 7 about here']

['Insert Figure 8 about here']

['Insert Figure 9 about here']

C. Fabricated Prototype

Figure 10 shows a fabricated prototype of the sensor made out of a tungsten foil with a 25 μm thickness having overall dimensions of 1275 (W) x 1135 (L) μm . Table 2 summarizes the results of the geometry evaluation of the fabricated prototype in terms of desired/machined dimensions and absolute/relative accuracy. The average absolute accuracy is 1.81 μm . However, it was very difficult to achieve high accuracy for smaller features such as the width of comb fingers where dynamic errors of motion were comparable with the feature size itself. Note that some dimensions of the fabricated prototypes were within sub-micron accuracy, for example, the width and length of the suspension spring had accuracy of 0.8 μm and 0.5 μm respectively due to high

positional accuracy of the motion system and proper synchronization of the laser on/off events, motions and desired geometry.

[‘Insert Figure 10 about here’]

[‘Insert Table 2 about here’]

The fabricated sensor was attached to a plastic substrate using nonconductive glue. Two platinum wires $\sim 60 \mu\text{m}$ in diameter were welded to the anchor pads of the sensor and to the socket in the package box. A typical laser micro welded wire to a metal pad is demonstrated in Figure 11.

[‘Insert Figure 11 about here’]

4. PERFORMANCE TESTING

A. Experimental setup and procedure

Figure 12 shows an experimental setup for performance testing, where the packaged sensor was mounted on YZ-stage. A mechanical actuation probe made of a stainless steel, 0.5 mm diameter wire was attached to a linear motor with $0.5 \mu\text{m}$ resolution of motions and was used to drive the sensor. The motor was able to move along X axis that is controlled by a programmable motion controller. Fingers’ motion was captured by a CMOS camera with a video speed of 100 frames per second. An AgilentTM capacitance meter (model 4288A) was used to measure on-line relative capacitance values of the sensor under actuation.

[‘Insert Figure 12 about here’]

Initially, the actuation probe was engaged with the sensor shuttle. Afterwards, the sensor was actuated by the linear motor programmed to move of 16 continuous steps with $50 \mu\text{m}$ per step, and the video images of the sensor geometry and relative

capacitance values were recorded simultaneously. The actual motion of the sensor fingers was measured using the captured video images and Vision Builder software by National InstrumentsTM. Note that actual displacements of the sensor were not identical to the applied motor motions due to the flexibility of the actuation probe.

Alignment of the actuation probe and the shuttle was the most critical element during the performance testing. This was because the contact surface between the probe and the shuttle directly affected the direction of the applied force and therefore the orientation of motions of comb fingers affecting reliability of measured data. When the force direction was not parallel to the desired actuation direction, the comb fingers rotated in-plane or out-of-plane resulting in two types of basic failures in sensing. The first failure was that direct contact of the two groups of sensing fingers resulted from the in-plane misalignment between the actual and desired actuation direction. The second failure was the out-of-plane rotation resulted from the vertical misalignment between the actual and desired driving direction.

B. Performance Testing Results and Analysis

Figure 13 shows the performance of the prototype sensor as a function between the applied displacement and the generated relative capacitance which can be linearly approximated by:

$$\Delta C = K_c \delta \quad (11)$$

where ΔC is the relative capacitance, fF, and δ is the applied displacement, μm . From the previous section, the sensitivity, K_c , varies when the comb fingers reconfigured.

The experimental results (Fig. 13) show that the sensor has a variable sensitivity within a motion range of $24 \mu\text{m}$. However, two diapasos of the linear performance with different slopes corresponded to the sensitivity, K_c , can be observed within a range of applied displacements $< 20 \mu\text{m}$. When the shuttle moves $< 7 \mu\text{m}$, K_c is $2.9 \text{ fF}/\mu\text{m}$, and between 7 to $20 \mu\text{m}$, K_c is $17.2 \text{ fF}/\mu\text{m}$. These values are within reasonable agreement with the calculated sensitivity from the Eq. (10), which is $2.6 \text{ fF}/\mu\text{m}$ and $22.0 \text{ fF}/\mu\text{m}$

correspondingly. It was also observed that the measured capacitance had smaller variations within measurements when the applied displacements were $<15\ \mu\text{m}$. The difference between simulation and experiments could result from the measurement of the transverse travel distance of the shuttle and the effect of the applied contact force and the stiffness of the actuation probe. The performance above $20\ \mu\text{m}$ (see Fig. 13), where larger force was generated in the shuttle-probe contact area, was inconsistent and can not be recommended for practical application. This increased force deformed both the shuttle and the actuation probe, and increased the misalignment between the actual and desired directions of the sensor displacements. When the shuttle moved over $20\ \mu\text{m}$, out-of-plane and in-plane rotations of the movable comb fingers were observed due to the deformations and twisting of the actuation probe.

['Insert Figure 13 about here']

5. CONCLUSION

In this paper, a metal-based micro displacement capacitive sensor was designed and fabricated using laser micromachining technology with accuracy and precision within $\pm 2\ \mu\text{m}$ for most of the components. The highest capacitance sensitivity of $17.2\ \text{fF}/\mu\text{m}$ was achieved for displacements between 7 to $20\ \mu\text{m}$. Operation of the fabricated functional prototype was successfully demonstrated and characterized for displacement/force measurement applications. A part of the study also demonstrated the suitability and effectiveness of the laser micromachining technology for prototyping microsensors to be used in MEMS applications.

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Table 1. Constants and parameters.

Table 2. Geometry evaluation.

Table 1. Constants and parameters.

geometric parameters		
t	thickness of the fingers (μm)	25
L_o	length of each finger (μm)	300
W	width of the each finger (μm)	24
L_{gL}	Initial gap forming C_L (μm)	6
L_{gR}	Initial gap forming C_R (μm)	6
L_c	length of initial overlaid coupling fingers (μm)	100
electrical parameters		
ε	dielectric coefficient of the air ($\mu\text{F}/\mu\text{m}$)	8.85×10^{-12}

Table 2. Geometry evaluation.

<i>desired dimension, μm</i>	<i>machined dimension, μm</i>	<i>absolute accuracy, μm</i>	<i>relative accuracy, %</i>
420.0	419.5	0.5	0.12
420.0	418.2	1.8	0.43
350.0	354.8	4.8	1.37
100.0	100.4	0.4	0.40
300.0	303.2	3.2	1.07
425.0	423.1	1.9	0.45
1185.0	1184.6	0.4	0.03
1275.0	1273.5	1.5	0.12
260.0	261.2	1.2	0.46
30.0	30.8	0.8	2.67
26.0	26.7	0.7	2.69

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Figure 1. Mechanical design of the sensor.

a) geometrical design

b) free-body diagram

Figure 2. Dynamic model of the suspension spring.

(a) comb fingers and formed capacitors

(b) total capacitance

Figure 3. Capacitance model of the sensing element and its' components.

Figure 4. Overlay dimensions of two coupling comb fingers.

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