Displacement Sensor for Detecting Sub-micrometer Motion

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***Abstract* --- This paper describes a design of a displacement sensor that detects motion of a platform by measuring change in capacitance due to the fringing electric field. Several variations of the sensor's design were simulated to establish performance sensitivity and the simulation results are presented. Proof of concept testing was performed and encouraging outcomes were recorded. The sensor was able to detect motion of a platform with resolution of 100 nm or better at the distance of several micrometers**.

***Index Terms* --- Capacitance measurement, displacement measurement , nano-size positioners, nanotechnology, sensitivity.**

I. INTRODUCTION

Development of reliable sensors to measure sub-micrometer displacement of moving platforms is required by ever-shrinking nano-scale devices. The most restricting limitations include small area for placement of the sensor and its electrical connections, and even smaller active sensing area. Since the moving platform is very thin and cannot be loaded by attaching sensor electrodes, nor can it be connected to the potential to aid the measuring method, sensor design is reduced to a very simple and small footprint.

Extremely small displacements can be measured using light interferometry or capacitance changes due to motion of a conducting platform in a well-defined electromagnetic field. This paper discusses the capacitance approach for simplicity while achieving acceptable sensitivity. Measuring displacement of a moving platform at the sub-micrometer level was explored in [1]. The objective of the experiment given in [1] is to develop a capacitance-based displacement sensor with sensitivity of 10-nm while measuring motion of a 25 μm thick platform in the range of 5 μm to 15 μm away from the sensor.

A prototype of a displacement sensor for a Micro Electro Mechanical System (MEMS) nanopostioning application was developed and tested [1]. The experience gained was invaluable and presents the basis for further development. The sensor had a comb pattern and was fabricated using silicon on insulator wafer. A sensitivity of 0.001 pF/μm was achieved while measuring the peak-to-peak motion with a range of several micrometers above the active sensitive area of 0.3 mm^2. Tested prototype sensitivity deviated from the simulations given in [1] due to a number of practical features used to build the sensor. The most significant limitation to achieving better resolution in the experiment given in [1] was high dissipation factor of the planar silicon wafer-based capacitor and the lack of coaxial connections from the sensor to the capacitance meter.

This paper describes the design of a displacement sensor that detects the presence of a moving platform by using a fringing electric field as shown in Figure 1. Its electrodes are commercially prefabricated Teflon-insulated wires. This solution provides for excellent insulation between the sensor electrodes. Consequently, it allows us to use high voltage to drive a capacitance bridge and achieve better resolution in measuring the sensor capacitance. The size of the wires explored in the paper follows standard American wire gauge AWG. The smallest diameter of a bare conductor is of the order of 25 μm, permitting us to solder the coaxial cable connectors from the capacitance bridge to the sensor electrodes. This approach achieves good connectivity and reduces the noise level.

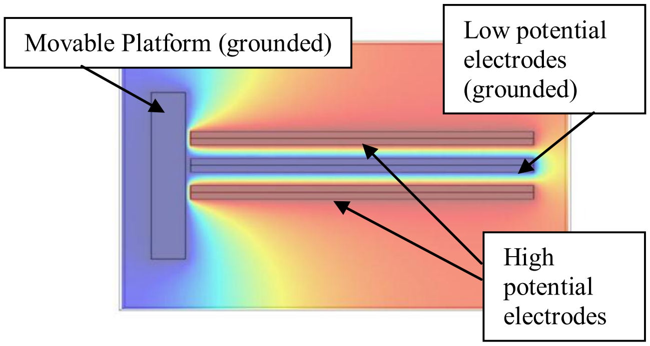

Figure 1. Displacement sensor. Simulation results of electric potential for sensor with three electrodes. The electrodes create a fringing field in which the platform moves. Capacitance changes are measured between the electrodes. Electrode spacing is fixed due to Teflon insulation, with thickness equal to the conductor radius.

II. SENSOR DESIGN

A number of electrodes in our sensor configurations, as well as the conductor sizes and the MEMS nanopositioner moving platform widths, were explored with the goal of measuring the platform displacement at the nano- meter level. A sensor example given in Figure 1 consists of two outer conductors connected to the high potential and the inner conductor connected to the low potential of the driving AC voltage signal from a commercial capacitance meter. The moving platform does not come closer to the supporting frame than several micrometers. The platform is made from doped silicon and it was grounded in the simulations. It may be possible to ground the platform in real experiments.

Table 1 summarizes the simulation results for a set of different electrode radius values for two cases of platform widths. As can be seen from these results, enlarging the active sensing area (electrode radius) improves the sensor sensitivity. In one case, the platform width was kept constant at 25 μm (to reflect actual experiment) and in the other case the platform was made 60 % wider than the electrode diameter. Even though the second platform case is not practical in our experiment, the exercise confirmed the expectations of better sensitivity, but it improved sensitivity only from 7 % to 47 % depending on the conductor radius. Increasing the platform width is not effective when thin wires are used for sensing. Sensor conductor area and platform width overlap is necessary for higher sensitivity. The electrode radius sizes were selected from the set of AWG wire gages {44 48 49 50}. These sizes represent limitations in general manufacturing (AWG 50) and in sensor area available (AWG 44).

AWG	R_b [μm]	P_W [μm]	S_V [pF/μm]	S_{25} [pF/μm]	$(S_V - S_{25})/S_{25}$ [%]
50	25.4	85	0.0010589	0.0007223	46.6
49	16.2	55	0.0004965	0.0004305	15.3
48	13.97	46	0.0003871	0.0003447	12.3
44	12.7	42	0.0003284	0.0003068	7

Table 1. Sensitivity of a sensor with five electrodes. Sensor sensitivity is measured in capacitance per distance between platform and sensor in the range of 5 μm to 15 μm. R_b radius of electrode bare conductor. P_w platform width, $P_w= 10\ R_b /3$ (the platform is 60 % wider than the sensor electrode diameter). S_V sensitivity for variable width platform, $S_V = 0.00006R_b - 0.0004$ (linear fit, $R^2 = 0.9979$). S_{25} sensitivity for 25 μm wide platform, $S_{25} =0.00003R_b - 0.0001$ (linear fit, $R^2 = 0.9992$).

The sensitivity given in Table 1 represents average value. Figure 2 shows the sensitivity calculated for each 0.5 μm segment in the range from 5 μm to 15 μm, in the case of 25 μm wide platform and five-electrode sensor with wire radius 12.7 μm. This example reflects a practical solution to be tested in the next step of displacement sensor development. The instrument used to measure the capacitance has a resolution of 0.1 aF, so the graph of Figure 2 suggests that in the presence of low noise it will be possible to detect platform motion of the order of 10 nm to 100 nm, depending on the proximity of the platform to the sensor.

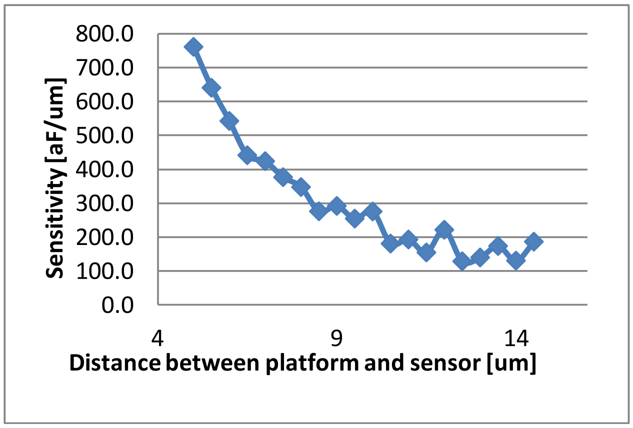

Figure 2. Simulated sensor sensitivity. Five-electrode sensor. P_w=25 μm. R_b=12.7 μm.

III. PRELIMINARY TESTS

To verify the presented simulation results, a sensor prototype was constructed and tested based on the given specifications. A sensor was made using five Teflon insulated wires with the bare conductor radius of 25.4 μm. The moving grounded object had a radius of 394 μm with a motion period of 30 s. The active sensor area is about 0.0081 mm^2. This is significant improvement over the previous design where the active sensor area was 0.3 mm^2. Sensor wires were connected to the capacitance bridge coaxial cable within several cm from the sensing area. The capacitance bridge used in measuring the sensor capacitance has 0.1 aF resolution. Figures 3a and 3b show the results for two object distances. In the case when the object is closer to the sensor (Fig. 3a), the average sensor sensitivity is 650 aF/μm, high enough to allow motion detection of several tens of nanometers. When the sensor is further away (Fig 3b.), it has an average sensitivity of 80 aF/μm and can detect motion of several hundreds of nanometers.

During testing, it was observed that the sensor wires must be cut at a precise angle (guillotined) in order to have maximum effectiveness of the sensing area. Laying sensor wires in tight parallel formation as shown in Fig. 1 was not achieved in the preliminary testing and needs to be addressed in a future design.

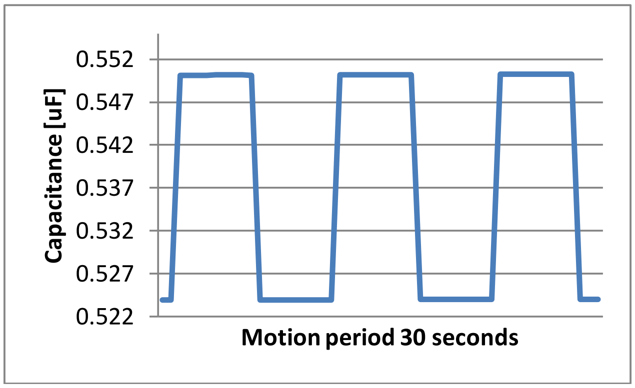

Figure 3a. Sensor response to a moving object positioned at an average distance of 2.5 μm from the sensor and moving with a peak-to-peak amplitude of 4 μm. The average sensor sensitivity is 650 aF/μm .

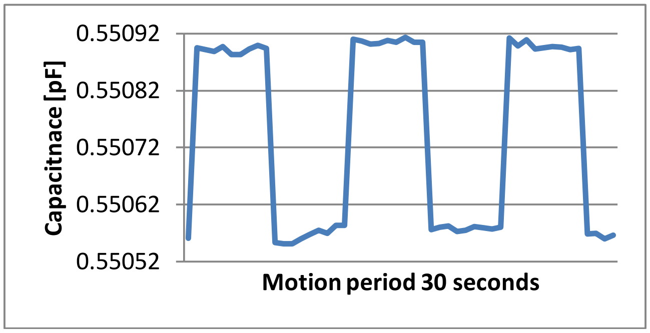

Figure 3b. Sensor response to a moving object positioned at an average distance of 4 μm from the sensor and moving with a peak-to-peak amplitude of 4 μm. The average sensor sensitivity is 80 aF/μm .

IV. REFERENCE

1. Avramov-Zamurovic, S.; Dagalakis, N.G.; Rae Duk Lee; Jae Myung Yoo; Yong Sik Kim; Seung Ho Yang; " Embedded Capacitive Displacement Sensor for Nanopositioning Applications", IEEE Transactions on Instrumentation and measurements, Volume: 60, Issue: 7 , Page(s): 2730 – 2737.