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Capacitive displacement sensor for detecting planar submicrometer motion

Svetlana Avramov-Zamurovic,[1] Jae Myung Yoo,[2] and Nicholas G. Dagalakis[3]
[1]*Weapons and System Department United States Naval Academy, 105 Maryland Avenue, Annapolis, Maryland 21402, USA*
[2]*Applied Materials, Santa Clara, California 95054, USA*
[3]*Intelligent System Division, Engineering Laboratory, National Institute of Standards and Technology, 100 Bureau Dr., Gaithersburg, Maryland 20899, USA*

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This paper describes the design of a very simple displacement sensor that measures the change in the position of an object by sensing the change in capacitance due to the movement of this object in the sensor fringing electric field. Two sensor geometries with small footprints were considered and several sensor variations were built and tested. At distances of approximately 0.5 μm and 30 μm, test results demonstrated that the sensors' resolution was in the order of tens of nanometers. [http://dx.doi.org/10.1063/1.4952585]

I. INTRODUCTION

Development of new reliable sensors to measure submicrometer displacement of moving objects is required by the continuous size reduction of state-of-the-art nano-scale devices. The most challenging sensor design requirements are nano applications dependent on shape, size of the area for sensor placement, and electrical connections. The active sensing area has to be created only by the sensor itself and cannot incorporate the moving object. Common nano applications involve objects that cannot tolerate additional weight from electrical connections and/or are made from materials that cannot be electrically charged.[1,2] These limitations lead to the design of a very simple sensor that has a small footprint.

There are several displacement measuring methods.[7,8] The classical method measures the change in capacitance due to an object moving in the fringing electrical field created by sensor electrodes.[9–12] Recent applications of nano scale capacitive sensors demonstrate great variety of designs and performances.[4,13–17] Authors in Ref. 14 built a comb actuator with a motion range of 2 μm with capacitance resolution of approximately 5 fF. Authors in Ref. 15 built a sensor with a periodic structure (period of 18 μm) and gap of 1 μm with maximum sensitivity of 4 fF/μm. Authors in Ref. 16 reported building a nanopositioner (size 500 μm) with a sensor connection glued to the moving structure. They achieved a capacitance resolution of 30 aF/Hz$^{-1/2}$ that corresponds to an input displacement resolution of 1.3 nm in a 10 Hz bandwidth. Authors in Ref. 17 reported achieving sensitivity of approximately 0.30 pF/μm with a 40 mm diameter moving membrane sensor at a separation of approximately 30 μm. These results show very good sensitivity but these sensors are not noncontact devices. Extremely small displacements can also be measured using light sensors with resolutions of approximately 15 nm over the range of 11 mm,[18] but the measurement system is complex and the resolution is limited by the wavelength of the light used for the measurements. The abovementioned techniques were considered and the decision was made to proceed with the design of a planar noncontact sensor.

This paper discusses measuring displacement using the capacitance approach. This method is selected due to its relatively simple design and implementation while achieving acceptable sensitivity. The contribution of our work is in the presentation of the complete sensor prototype development from concept design through fabrication. Finally, an experimental evaluation of the designed sensors, applied to a practical nanopositioning device, is presented.

The motivation for our design is a displacement sensor for a nanorheometer.[3] A rheometer measures the dynamic properties of the flow of matter, in the liquid state and also "soft solids" for a desired range of frequencies. Oscillatory strain is produced in a sample sandwiched between a planar one degree of freedom (1-D) nanopositioner moving stage and a glass plate. The resulting stress–strain relationships are obtained by the measurement and analysis of the actuation input command signal and the moving stage motion displacement. Characterizing the dynamic micro/nano rheology properties of an array of novel materials is critical in many science and engineering fields, including biorheology, microfluidics, construction materials, and polymer thin films.

Measuring the displacement of a moving micro platform was explored in Refs. 5 and 6 and the prototype of a displacement sensor using a comb pattern for a Micro Electro Mechanical System (MEMS) nanopositioning application was developed and tested. A sensitivity of 0.001 pF/μm was achieved while measuring the peak-to-peak motion with a distance between the sensor and the nanopositioner of several micrometers. The active sensitive area of the MEMS sensor was 0.3 mm^2 demonstrating a small footprint. The experience gained from the comb design was used to improve upon the present design. Most notably: the high dissipation factor of the planar silicon wafer-based capacitor and the lack of coaxial connections from the sensor to the capacitance meter reduced the capacitance measurement resolution significantly. Because of these disadvantages of MEMS based sensors, we explored a simple discrete component sensor that can directly be used with a commercially available capacitance meter, without a complex interface in order to read measured displacement.

II. SENSOR DESIGN

A capacitive planar sensor in our design created a fringing electrical field which was modified in the presence of the nanopostioning platform, shown in Fig. 1. A small sensor footprint is critical when used in the applications that sense the motion of the micrometer size nanopositioners. The capacitive planar sensor's range and resolution are determined by the shape of the sensor electrodes and by the strength of the generated electric field. This statement assumes that there are no deviations in the practical realization from the perfect geometry, in terms of the electrode spacing, misalignment between the moving object and the sensor, etc.

A. In-line design

This paper describes the design of a displacement sensor formed by the tips of closely spaced wires, conceptually shown in Fig. 2. The electrodes' charge was alternating and the spacing between the wires was fixed due to Teflon insulation. The moving object was a conductive rectangular prism, simulating a nanopositioning platform, set to low potential (shown on the left in Fig. 2). The simulation in Fig. 2 provides only a qualitative representation of the fringing electrical field created by the sensor. The actual experiments were run with the sensor electrodes set to high, low potential from the AC bridge, and the moving object was grounded.

The given electrode configuration was considered because tightly spaced conductors with opposite charge produce strong and relatively even fringing electrical field at the wire tips (shown on the right in Fig. 2).

Close electrodes spacing and their wider diameters force a higher field to extend deeper and sense the object placed further away from the sensor, as desired. Very thin wires do not create strong enough fields for the proposed application and their manipulation poses significant challenges during sensor fabrication. The field distribution influences the alignment of the sensor and the object, requiring a parallel position for the best results. We experimented with different sensor wire diameters using an in-line configuration for sensing objects that are thin and a pillar configuration for sensing broader objects. The smallest commercially available Teflon-insulated wire diameter is about 25 μm, and opens up the possibility to design effective displacement sensors for a variety of MEMS applications.

The length of the sensor's wires does not significantly influence sensor sensitivity, but allows us to make sensors with nominal capacitance in the order of 1 pF. This capacitance level is desirable for most commercially available capacitance bridge instruments to operate at their optimal accuracy and resolution.

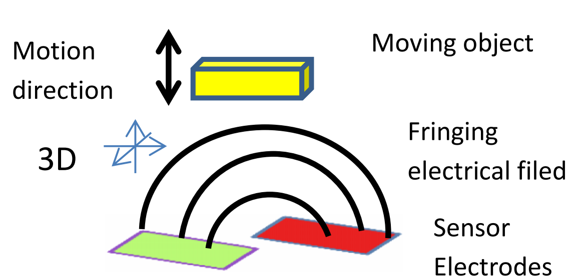

FIG. 1. Planar displacement sensor principle of operation. Moving object is simulating nanopositioning platform.

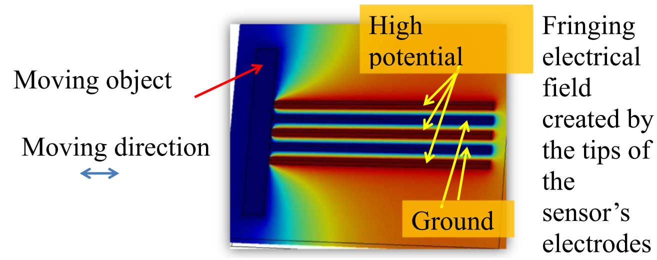

FIG. 2. Simulation results of the electric potential for a displacement sensor with five in-line electrodes. Blue color depicts ground and red color represents the applied high potential. The shades in between provide the information on the field distribution intensity.

We used commercially available Teflon-insulated wires following standard American Wire Gauge (AWG) specifications as the prefabricated sensor electrodes. This solution provided an excellent insulation between the electrodes and permitted soldering to the coaxial cable connectors of a capacitance bridge. This approach reduced the noise level and dissipation, allowing us to use high voltage to drive the bridge and therefore achieve very good resolution in measuring the sensor's change in capacitance.

B. Pillar design

The sensor shown in Fig. 2 is best suited for thin moving objects. To explore the sensing of a wider area target, as applicable in the case of the rheometer, a pillar design was suggested (see Fig. 3).

To evaluate the performance of the pillar design, the geometry given in Fig. 3(a) was analyzed. The critical features for the satisfactory sensor performance are (1) the number of electrodes facing the moving object, as well as their size, (2) an even distance between the sensor electrodes, (3) an even distance between the sensor electrodes and the moving object, and (4) the conducting surface of all electrodes facing the moving object must be in a plane orthogonal to the object motion.

To create the "pillar" sensor geometry, the wires were tightly sandwiched in a sensor holder to establish mechanical stability that leads to repeatable capacitance measurements (Fig. 3(c)). The wire tips facing the moving object were guillotined after the assembly. The sensor image (Fig. 3(b)) shows practical realization imperfections in terms of the extent of the electrodes' shape deformations, slight variations in the distance between the electrodes, and minor roughness of the tips facing the moving object.

III. EXPERIMENTAL SET UP

The displacement sensors were built and tested using the experimental setup shown in Fig. 4. A commercial moving platform (B) was used to move a target object in front of the stationary sensor, (C). The connections between the sensor and the capacitance bridge are detailed in Figs. 5 and 6.

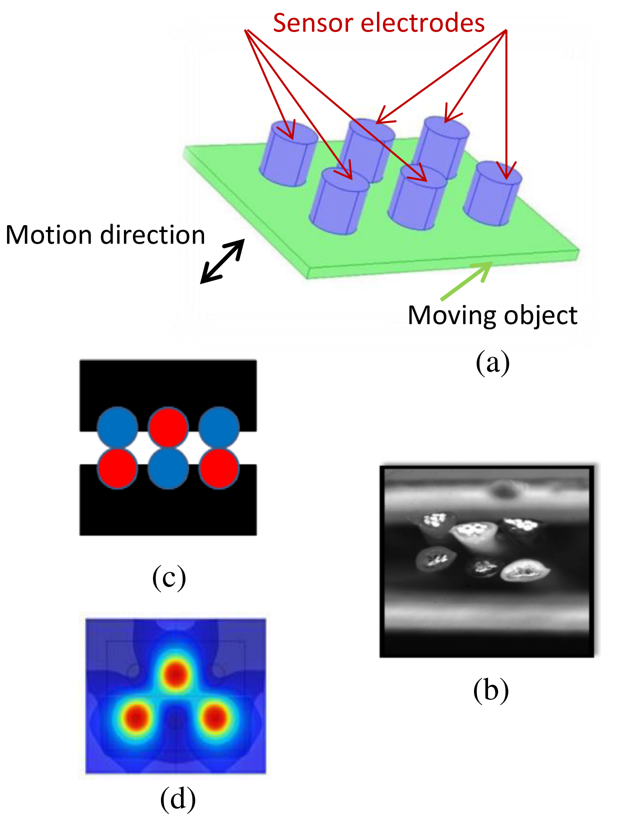

FIG. 3. Pillar sensor design. (a) Sensor with two rows of three electrodes. An object is moving in the orthogonal direction to the sensor tips. (b) Image of a pillar displacement sensor (wire diameter 152 μm). (c) Electrode polarization: High electrical potential is labeled red and low is blue. (c) Simulation of the electric potential under the moving object plane. Blue color depicts ground and red color represents the applied high potential. The shades in between provide the information on the field distribution intensity.

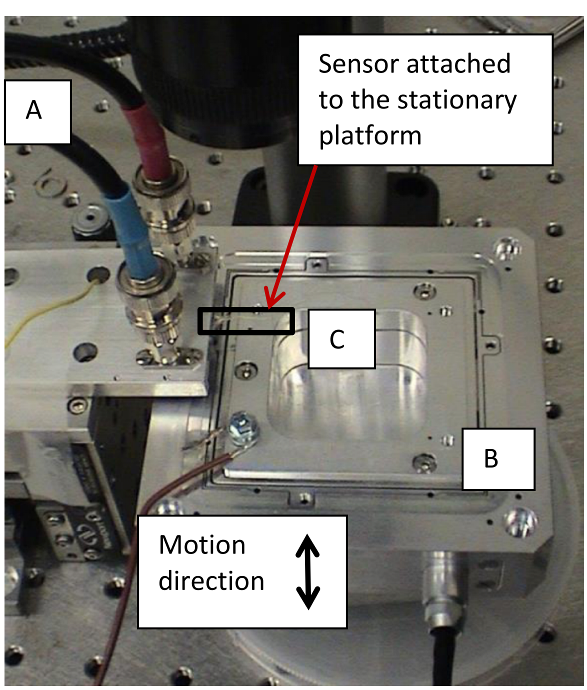

FIG. 4. Experimental setup for the displacement sensor testing. (A) Capacitance bridge coaxial connection. (B) Commercially available moving platform. (C) Sensor placed on the stationary surface.

Fig. 5 shows simplified schematics of how an in-line sensor with three electrodes was attached to the pads that connect to the high and low ports of the capacitance bridge. The capacitance bridge is a three-port instrument ((A) from Fig. 4). Red color labels high potential, blue color depicts low potential, and gray color shows ground or guard potential. It measures the capacitance between the two ports, high and low coaxial inner conductors, with the outer conductor, third port, connected to the guard. The sensor electrodes were color-coded and labeled $H1_s$ and $H2_s$ for the high potential connections and L_s for the low potential connection. The sensor was attached to a holder with three pads. The high potential pad was connected to the sensor wires $H1_s$ and $H2_s$ and to the high potential coaxial capacitance bridge connector. The low potential pad was connected to the middle sensor wire, L_s, and the low potential coaxial capacitance bridge connector. The Teflon isolated sensor wires were sandwiched between the copper tape and the holder, which were both connected to the guard pad. The guard pad was connected to the guard connector of the capacitance bridge. Fig. 6 is an image of the actual sensor connections to the bridge and the labeling follows the schematic introduced in Fig. 5.

The capacitance bridge used in this project was the commercially available Andeen-Hagerling[19] instrument. It was configured to measure capacitance and dissipation at 1 kHz with a voltage drive magnitude of 15 V.

Capacitance data were collected at the rate of five data points per second. For each data point shown in Figs. 7–9, sixteen samples were averaged resulting in 40 capacitance measurements over 2 min. The slow rate allowed for a significant reduction in random noise, but limited the speed of platform motion. The capacitance bridge has a resolution of 0.1 aF when measuring a change in capacitance of approximately 1 pF with accuracy of the order of 1 aF. The measured dissipation in our experiments was approximately 2 μrad. The commercially available moving platform allowed testing versatility and controllability for displacement sensor prototypes. Its resolution was 0.2 μm with a range of 80 μm. This

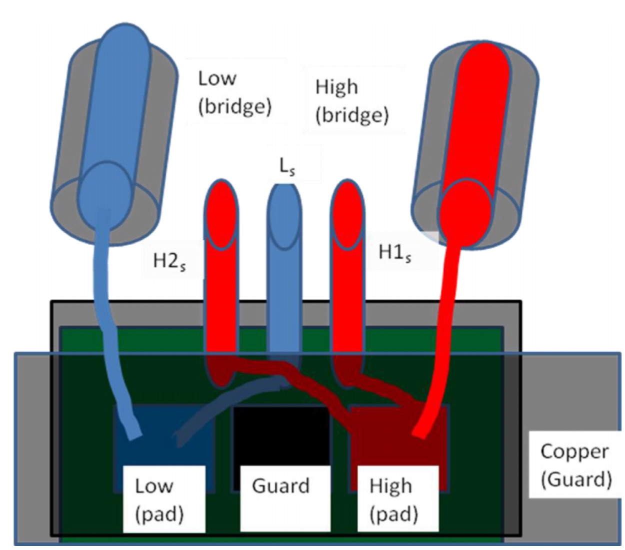

FIG. 5. Simplified representation of the sensor connections to the capacitance bridge, (three-electrode in-line design).

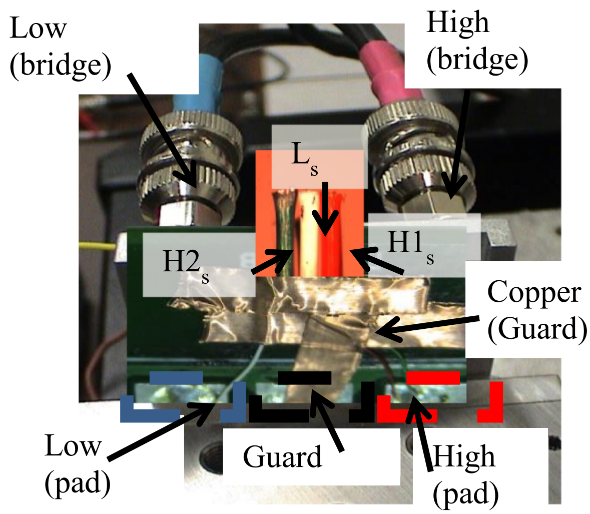

FIG. 6. Photograph of the actual sensor connections, as described in Fig. 5. This figure consists of three pictures superimposed to represent in detail the sensor connections to the capacitance bridge. Note that the copper tape is lifted in order to expose the connection for clarity.

capability was limited by the noise of the power amplifier providing the command voltage to move the platform. Also, the motion resolution was restricted by the resolution of the strain gauge position sensor. This sensor provided feedback to the controller used to control the movement.

All of the testing was conducted in a temperature controlled laboratory space with less than 1 °C variation in order to minimize temperature induced measurement drifts. We observed a drift of approximately 2 aF/min. The drift was included in the sensor resolution calculation.

IV. TEST RESULTS

A. In-line sensor

1. Sensor with five electrodes

The sensor with five electrodes was fabricated using wire with a diameter of 254 μm (AWG 30) as shown in Fig. 7(a). The sensor was protruding from the holder approximately 2 mm, minimizing wire flexing and providing good mechanical stability. The active sensitive area at the wire tips was 4 mm^2. This was a large sensor and its performance was studied as a proof of concept. Fig. 7(b) summarizes all of the measurements taken over the testing range and provides the measure of the sensor's resolution at each tested distance. The mean value for each data set was subtracted to emphasize the change in capacitance at the given distance. Peak to peak motion range was 4 μm. The results showed the resolution over the range of 54 μm to be between approximately 80 aF/μm and 30 aF/μm. Random noise from Fig. 7(b) has a standard deviation less than 10 aF (except for one outlier). This result demonstrated the displacement measurement sensitivity from approximately 125 nm for motion closer to the sensor, and 330 nm for the motion further away.

Figure 7(c) shows the measured average capacitance. The fitted second order curve shows the nonlinearity of the sensor response of 2 aF/(μm)^2. The second order fit was chosen as a simple relationship between the measured capacitance and the gap between the sensor and the moving object. Theoretical predictions suggest reduced capacitance when the object is closer to the sensor and non-linear response over the wide range of displacements.[4]

Further tests focused on the sensitivity at closer and further distances. Sensitivity of approximately 8 aF/μm was achieved at the distance of 30 μm with a motion peak-to-peak amplitude of 1 μm. In the case of a moving object at an average distance of 0.5 μm from the sensor and motion amplitude of 0.2 μm, the achieved sensitivity was approximately 600 aF/μm. This experiment translated to an achieved sensitivity of approximately 1 μm at the distance of 30 μm and approximately 60 nm at 0.5 μm. Improved sensitivity in close proximity is theoretically corroborated.[4] Inferior sensitivity of 1 μm at the distance 30 μm, compared to the full range of testing, is contributed to the fact that even a slight sensor

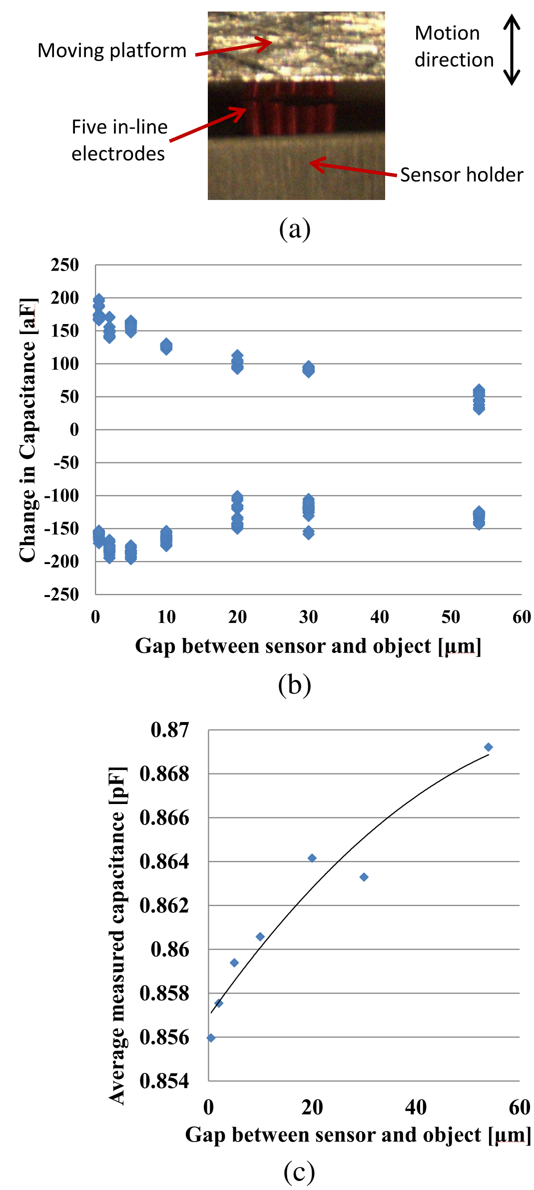

FIG. 7. (a) Five electrode in-line displacement sensor. (b) Measured sensitivity. Lower capacitance value indicates the sensor closer to the object. (c) Measured average capacitance.

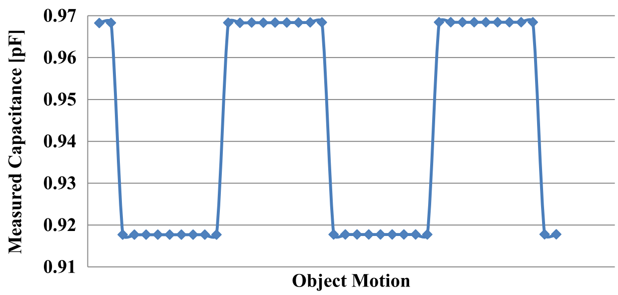

FIG. 8. Pillar sensor displacement sensitivity.

misalignment results in loss of performance at the greater distances.

The smallest sensor we built consisted of five in-line electrodes with a wire diameter of 51 μm (AWG 44) and achieved a sensitivity of approximately 80 aF/μm. The moving object was a 24k gold round plate with a diameter of 1 mm and motion range of 4 μm at a distance of 4 μm. The mechanical support for the slimmer sensor has to be extraordinarily delicate in order to achieve good alignment and thus satisfactory performance.

2. Sensor with three electrodes

A sensor with three in-line electrodes was constructed with a wire diameter of 645 μm (AWG 22). The active sensitive area at the wire tips was 15.6 mm^2. The achieved sensitivity at a distance between the sensor and the moving object of 54 μm was approximately 23 aF/μm for the peak-to-peak motion amplitude of 1 μm. The standard deviation of the noise was less than 5 aF demonstrating the sensor sensitivity of 220 nm at 54 μm. The fitted second order curve to the measured average capacitance over the range of 54 μm showed the nonlinearity of the sensor response of 0.5 aF/(μm)^2.

Besides the difference in the active sensitive area, the major distinctions between the three-electrode in-line sensor and the five-electrodes were reduced standard deviation of noise, better linearity, and higher sensitivity at the further range. Finer conducting mesh, as formed with five wires with smaller radius, created a field that is more sensitive to a small displacement at close range. Larger conducting pads with wider spacing between them created a strong field at further distance. This feature contributed to the linearity of the responses in a given range and less sensitivity to the noise. The drawback of the tested three-electrode sensor was its large footprint that could limit its applicability to some MEMS systems.

Based on the experimental investigation, it was confirmed that the proposed in-line capacitive sensors have suitable sensitivity for nanopositioning. They are simple to construct and have excellent electric characteristics in terms of electrical connections and electrode insulation. Even though smaller sensors demonstrated appreciable performance and a wide application range, they are fragile to handle and susceptible to poor alignments. Test results from the in-line electrodes sensor demonstrated a capacitance measurement resolution on the order of 5 aF to 10 aF. This is the significant improvement as compared to the comb sensor developed on the silicon substrate given in Ref. 6 that has a resolution on the order of 300 aF.

B. Pillar sensor

The six-electrode pillar sensor shown in Fig. 3(d) was constructed with a wire diameter of 127 μm (AWG 36). The active sensitive area at the wire tips is 1.2 mm^2. This footprint size is adequate for the nanorheometer applications. Through experimentation it was observed that sensor alignment in relationship to the moving object is crucial to its sensitivity. In the case of the most favorable alignment, the results presented in Fig. 8 were achieved. The moving object's minimal distance from the sensor was 30 μm and the motion range was 4 μm. In this case the sensitivity was approximately 1250 aF/μm.

Fig. 9 shows measured capacitance over the range of 20 μm–80 μm. The motion peak-to-peak amplitude is 4 μm. The sensitivity of this data set was approximately 100 aF/μm. The fitted second order curve shows the nonlinearity of the sensor response of 0.1 aF/(μm)^2.

Table I summarizes the measurement analysis at a distance between the sensor and the object of 0.5 μm and 30 μm. This set of measurements shows the possibility of sensing motion at the order of nanometers and it represents the experimentally proven performance limit of the proposed sensor prototype.

The results shown in Table I required extraordinary care with sensor alignment. Theoretically, the field created by six wire tips with a small diameter has a checker board pattern with limited distance where the fringing field extends (Fig. 5(d)). Any tilt of the target loses the field lines over an area and this situation leads to reduction in measured changes in capacitance when the target is in motion. The same effect is created when the wire tips were not guillotined perfectly orthogonal to the target plane. Practically, the sensor's sensitivity dropped one hundred fold with a slight misalignment.

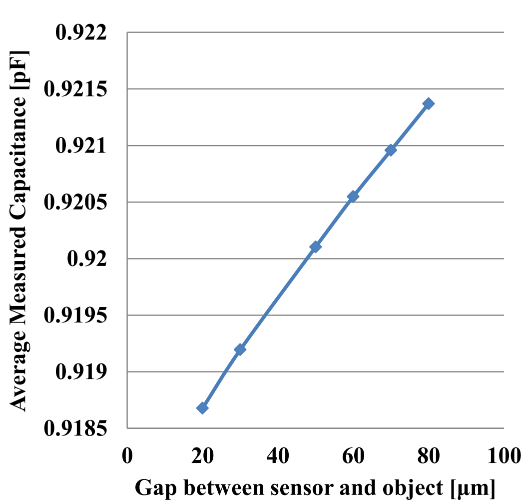

FIG. 9. Measured average capacitance for the pillar sensor.

V. DISCUSSION

The presented sensor research demonstrated the possibility to construct very simple proximity displacement

TABLE I. Pillar sensor performance.

Distance between the sensor and the object μm	Averaged measured capacitance pF	Standard deviation of measurement aF	Cap. sens. aF/μm	Dist. sens. nm
0.5	0.917 713 7	27	12 667	~10
0.5+4	0.968 382 7	66		
30	0.929 715 2	23	11 627	~10
30+4	0.976 223 6	15		

sensors with adequate sensitivity embedded in nanopositioning devices. In our first iteration of designing a planar displacement sensor on a silicon wafer,[6] we discussed several areas of improvement: simulation benefits, high dissipation factor and noise, and measurement stability.

The new experimental prototype presented in this paper had approximately a 100-fold improvement in sensitivity, with an adequately lower noise level due to the reduction of the dissipation factor. The measurement uncertainty of the mechanical components of the experimental setup (Fig. 4), when measuring displacement, is significantly less than the measurement uncertainty of the electrical components. The noise in measuring the capacitance is the most significant contribution to the measurement uncertainty and the new sensor design's reduction in noise standard deviation. It is also a major benefit over the prior sensor design.

Even though the simulations provided valuable qualitative guidelines, more research is necessary to drive the simulation results to match the measurements. Specifically, needed areas of research include further study of wire tips surface imperfections and of sensor plane tilt in relationship to the target position. These tasks will be included in the next sensor research project.

The sensor prototype's measured stability was 2 aF/min in the case where the sensor was far away from the object. This level of drift is the major issue to be addressed in the future. In a practical application where the displacement sensor is actually embedded, a solution to reducing the effect of the drift may include compensation via a "dummy" sensor incorporated through adaptive calibration.

The most significant issue to be considered in the next iteration is sensor alignment in relationship to the object motion. Once implemented, the sensor will be permanently placed and mechanically secured within the nano structure. This customization is one of the advantages of the proposed sensor design and it will allow for fine initial adjustments in the calibration measurement step.

VI. CONCLUSIONS

Several prototypes of capacitance based sensors using fringing electrical field were designed and their performance was experimentally evaluated. The sensors have simple Teflon insulated electrodes and could be easily customized for various nanopositioning applications, including rheometers. The inline sensor configuration is better suited for determining the displacement of narrow thickness XY nanopositoners and the pillar configuration could be used under wider areas such as for rheometers. Comprehensive testing provided confirmation of sub-micrometer displacement detection for a wide range of distances. In the case of careful pillar sensor alignment with the moving object, nanometer resolution at tens of micrometers distance was achieved.

ACKNOWLEDGMENTS

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[19]Certain commercial equipment is identified in this paper to adequately describe the experimental procedure. Such identification does not imply recommendation or endorsement by the National Institute of Standards and Technology nor does it imply that the equipment identified is necessarily the best available for the purpose.