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Robotic Tactile Sensor Array Fabricated From a Piezoelectric Polyvinylidene Fluoride Film

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ABSTRACT

A robotic tactile sensor comprised of 25 discrete sensor electrodes arranged in a 5x5 grid was designed and fabricated from a piezoelectric polyvinylidene fluoride (PVDF) film coupled to an integrated circuit (IC). Each of the 25 sensing electrodes in the IC grid were connected to metal-oxide-semiconductor field effect transistor (MOSFET) amplifiers which provided sufficient gain to generate usable response signal levels.

Sensors fabricated from varying thicknesses of PVDF film were evaluated. The sensor based on the 25 μm thick PVDF film was considered to be the optimal sensor configuration based on its bias-time performance and its linear response over the loading range tested (0.8 to 76 grams). There was no detectable coupling between the nearest-neighbor sensing elements in any of the sensor configurations. As a final demonstration, the optimal sensor configuration was used to recognize a toroidal-shaped load.

INTRODUCTION

Historically, there have been several approaches in implementing tactile sensing (optical, piezoelectric, piezoresistive, and capacitive) [1]. The advantages of the poled piezoelectric polyvinylidene fluoride (PVDF) polymer (durability, high conformality, and sub-millimeter spatial resolution of applied loads) prompted the investigation of a tactile sensor based on this material [2,3]. The major disadvantage of this material is the limited number of charge carriers produced for applied loads. In order to overcome this disadvantage, the PVDF film was coupled to an IC containing MOSFET amplifiers to boost the sensor's signal level.

This research was concerned with realizing a tactile sensor array that possessed the following features: an overall size approximating that of the adult fingertip, a tactile spatial resolution four times greater than the human fingertip, and an enhanced force sensitivity compared to previous experimental PVDF film tactile sensors. These goals were accomplished by electrically coupling the PVDF film with the gate-electrode contacts of metal-oxide-semiconductor field effect transistor (MOSFET) amplifiers configured in a two-dimensional array.

The MOSFET electrode arrays were designed using in-house computer-aided design (CAD) tools and fabricated by the Metal-Oxide-Semiconductor Implementation Service (MOSIS) [4]. The fabricated circuits were then coupled to a homogeneous sample of the piezoelectric PVDF film. This research was limited to an investigation of the force (pressure) sensitivity and coupling effects (mechanical and electrical) of several sensor configurations. The critical variables were the PVDF film thickness and electrode spacing.

TACTILE SENSOR DESIGN

The size of the sensor element electrodes was influenced by two important factors: the tactile spatial resolution of the human fingertip (the minimum distance between two points before they become indistinguishable) and the amount of space available on a MOSIS fabricated integrated circuit (IC). Since the largest feasible IC size was limited to a 7900 μm x 9200 μm rectangle, and a portion of this area had to be reserved for the amplification circuitry, the actual area available for the electrodes was limited to a 6000 μm x 6000 μm square centered on the IC.

In order to minimize the degree of electrical and mechanical coupling between discrete sensor elements, a 5x5 sensor array was utilized. Individual electrodes were separated from their nearest neighbors by a distance equal to the edge length of a square electrode array element. Twenty-five electrodes (600 μm x 600 μm each) in a 6000 μm x 6000 μm square corresponds to a spatial resolution that is approximately four times greater than that of the human fingertip (2-3 mm) [5].

The choice of the electrode size affects the voltage generated by the PVDF film in response to an applied force. That is, the generated voltage (V) is related to the sensor's electrode area by $V = (qt)/(\varepsilon A)$, where q is the charge generated in the PVDF film, t is the thickness of the PVDF film, $(\varepsilon = \varepsilon_0 \varepsilon_r)$ is the permittivity of the PVDF film ($\varepsilon_r = 11$), and A is the area of a sensor's electrode [6,7]. The limiting case would be the voltage generated by the thinnest film (25 μm thick) with an applied load of 1 g (an applied force of 0.01 N). Consequently, when this force is distributed over an area of 600 μm x 600 μm a voltage of approximately 0.1 V should be generated. A maximum voltage would be generated by the thickest film (110 μm thick) with an applied load of 100 g (an applied force of 1 N). This configuration should produce a voltage at the sensor electrode of approximately 50 V (this assumes that there is no charge saturation effect). However, because there is a limited number of charge carriers available in the PVDF film, the actual minimum and maximum voltages will likely be less than the calculations indicate. Therefore, to ensure that these voltages

could be accurately measured, in situ, high-input impedance MOSFET amplifiers were incorporated in the sensor's design.

In order to achieve the desired level of gain from the amplifiers, two cascaded inverting amplifiers were used. The schematic of the MOSFET amplifier circuit is shown in Figure 1a, and its CAD layout is shown in Figure 1b.

The amplifier was modelled with the Spice software using the three-micron feature size MOSIS models to determine the appropriate resistor values. Since the fabrication process parameters could vary between the default Spice model and those of the actual fabricated amplifier, it was designed such that its linear region would be centered on 5 volts (for a 10 V V_{dd}). Since the minimum voltage response generated by the PVDF film was calculated to be 0.1 V, the amplifier's output voltage, with a gain of 5 in the linear region (see Figure 2), would be 0.5 V. The resulting linear amplification region was approximately 2 V wide (Figure 2).

To minimize the gate electrode's parasitic line resistance and capacitance, the amplifier should be located as close to the sensor's electrode as possible. However, since the gate electrodes must be located beneath the PVDF film, a compromise was attained, and the amplifiers were placed on the periphery of the integrated circuit.

The complete layout of the sensor's integrated circuit is shown in Figure 3. The two vertical amplifier strips on either side of the circuit are electrically isolated, so the second strip can be used if one strip becomes damaged. Located at each of the four corners are large external bias pads which were connected to the surface electrode of the PVDF film. The entire electrode array is surrounded by alignment marks to facilitate locating particular elements after the array is covered with the PVDF film. The pads on the extreme left (16 pads) and right (17 pads) are the bonding pads. Finally, the two edges without bonding pads were used to attach the PVDF film.

Loading Test Probe Design. The minimum and maximum test probe loading forces were derived from the human tactile force thresholds; that is, a minimum force of 10^{-2} N applied over an area of 10^{-6} m^2, and a maximum force of 10 N applied over the same area [5]. These thresholds correspond to a minimum weight of 3.7 g applied uniformly to an electrode area of 600 μm x 600 μm, and a maximum weight of 3.7 Kg applied to the same area. Since the maximum weight was unrealistic for this sensor design (equivalent to administering a 3 Kg weight via a pencil point to the human fingertip), it was reduced to a more practical level of 76 g. Similarly, the minimum weight was reduced to 0.8 g.

Since it was necessary to determine, within the width of one electrode (600 μm), where the loading probe would make contact, a means of aligning the probe with respect to the tactile sensor's surface was devised. To this end, a micromanipulator loading probe sub-assembly, which was compatible with an existing micromanipulator arm, was designed and used with an IC microprobe station (see Figure 4).

With no additional weights, the probe presented a load of 0.8 g to a balance located in the same plane as that of the tactile sensor. With all three supplemental weights, the probe presented 76 g to the balance. This probe was used to compare the force sensitivity of the tactile sensors (0.8 g to 76 g of weight distributed over the 0.36 mm^2 surface area of each electrode). This situation correlates with pressures spanning 0.28 N/cm^2 to 28 N/cm^2.

Tactile Sensor Fabrication. The procedure for fabricating the tactile sensors was developed and refined after attempting several experimental procedures. Unanticipated problems with charge storage effects on both the MOSFET amplifiers' floating gates and the PVDF film squares damaged several of the integrated circuits. To minimize this failure

mechanism, the charges were neutralized using a water-soluble conductive solution. The sensors were then fabricated by coupling the PVDF film squares to the surface of the IC using photoresist (Shipley Microposit 1400-17) as an adhesive.

TACTILE SENSOR TEST AND EVALUATION

In the first phase of evaluation, the PVDF film was tested to ensure that it generated an adequate voltage response to an applied load and to determine the polarity of the bulk film samples. The second phase focused on the performance of the tactile sensors to an applied load (individual elements, coupling effects between elements, and the array response).

The PVDF film performance evaluation was accomplished using four different PVDF film thicknesses (25, 40, 52, and 110 μm). Shown in Figure 5 is the average of six test trials (three with a positive orientation and three with a negative orientation) associated with the 40 μm thick film (Solef, Brussels, Belgium) when subjected to a saturating load of 500 g. For the first three test trials, the PVDF film was biased such that the amplifier produced a 4 V output signal in the no-load state. The PVDF film was oriented such that an applied load produced a positive change in the amplifier's output. Since the onset of amplifier saturation occurs with an input voltage of approximately 6 V (Figure 2), there is only a 2 V linear region in the increasing positive voltage sense; hence, the amplifier obviously saturated for the load used in this evaluation. Nevertheless, this evaluation was useful for verifying the piezoelectric properties of the PVDF film.

An additional key piece of information revealed by this evaluation was the polarity of the film. The last three test trials shown in Figure 5 depict the result when the same sample of PVDF film was turned over (oriented in a negative direction), and the test was repeated. Reversing the orientation of the film reversed the direction of the voltage change when a load was applied. Using this simple test, the polarity of each of the bulk PVDF film sheets was determined. Consequently, the correct metallized film surface, which was subsequently etched, was properly selected to be the surface which made electrical contact with the gate electrode array. This orientation produced a positive change in the output voltage when a load was applied.

The tactile sensor performance evaluations were composed of the individual sensor element response test, the nearest neighbor response test, the bias voltage response test, and the array's (multiple sensor elements) response test. The individual sensor response test was accomplished to determine the optimal sensor configuration for the array response test.

Individual Sensor Element Response. The individual sensor element response test was performed using film thicknesses of 25, 40, 52, and 110 μm. The 110 μm thick film was chosen as the upper bound since it was too rigid to uniformly conform to the surface features of the IC. The 25 μm thick film was chosen as the lower bound because the 9 μm thick film tended to buckle and wrinkle.

A typical example of the discrete test results associated with the application of a 21 g load to a sensor fabricated from the 25 μm thick PVDF film is shown in Figure 6. A summary of the average measurements associated with each of the four tactile sensor configurations is shown in Figure 7. Since the 110 μm thick film was operating close to the saturation point of the amplifiers when biased with 2 V, this test was repeated with a no-load 1.5 V amplifier bias.

For the conditions of this test, the film thickness which performed optimally was the 25 μm thick film. It exhibited a nearly linear response for loads spanning 0.8 g to 76 g. The

other film thicknesses could also be biased to exhibit a linear response as long as the bias voltage was appropriately decreased, as demonstrated with the 110 μm thick film and the 1.5 V no-load bias.

Nearest Neighbor Response. The nearest neighbor loading response revealed that there was essentially no detectable response (consistently 10 millivolts or less) for any combination of load (0.8 g through 76 g) or film thickness. This characteristic implies that the sensor elements can be placed much closer together than they were in this IC design.

Bias Voltage Response. Although the various sensor configurations performed equally well in the tests discussed above (assuming appropriate biasing conditions), the time required to attain an initial equilibrium bias state for each film thickness varied considerably (Figure 8). The 25 μm thick film attained equilibrium bias conditions the fastest. This was expected for two reasons. First, as the film thickness decreases, the amount of material that must be reoriented (through the dipole moment interaction) is reduced. Second, the thinner the film, the larger the magnitude of the electric field for a fixed applied voltage. Consequently, the 25 μm thick film represented the optimum thickness because it possessed a linear response in the load test, and it attained an equilibrium bias state the fastest.

Array Response. The final test utilized the optimal sensor configuration (the 25 μm thick film) and a toroidal-shaped load to determine the response of the sensor to a load which was larger than a single sensing element. The major difficulty encountered in performing this test was obtaining a consistent no-load output voltage across the entire electrode array. That is, even if all of the electrodes had an identical charge state at the beginning of the test (that is, immediately after tactile sensor fabrication), the first time a load was placed on the sensor, each of the sensor electrodes was driven to a different charge state. This problem was solved by scanning the array twice, calculating the difference between discrete sensor element responses and then normalizing the resulting data set. The initial scan was accomplished immediately prior to loading the sensor, and the second scan was completed immediately after loading the sensor.

A topographical slice through the normalized data set at the 60 percent threshold level (chosen after the data was collected) reveals a recognizable representation of the toroidal-shaped load (Figure 9). Since the distance between the centers of neighboring sensor elements is 1.2 mm, Figure 9 depicts an inner diameter of two elements (or 2.4 mm), and a toroidal-shaped thickness of one element (or 1.2 mm). The actual inner diameter of the applied load was 2.5 mm, and the outer diameter was 5 mm.

CONCLUSIONS

The goal of this research was to design, fabricate, and evaluate the performance of a tactile sensor that electrically coupled a piezoelectric PVDF film to an array of gate electrodes in an integrated circuit that contained a corresponding set of high input impedance amplifiers. In order to accomplish this objective, specialized test hardware and a performance evaluation methodology were devised. The hardware consisted of an integrated circuit (25 discrete sensor electrodes arranged in a 5x5 array with 25 corresponding MOSFET amplifiers) and a loading test probe (capable of applying loads between 0.8 g and 76 g). The test methodology was developed to characterize the performance of discrete sensor elements, coupling effects between sensor elements, and the sensor's array response.

The response of the optimal sensor configuration (fabricated from 25 μm thick PVDF film) was linear throughout the load range investigated (0.8 g to 76 g). There was no detectable electrical or mechanical coupling between nearest neighbor sensor elements. The sensor's array response test demonstrated the potential of using this tactile sensor in future robotics applications to recognize fundamental shapes.

Several performance improvements have been motivated by this research. The following recommendations are made to facilitate the practical transfer of this technology.

Gate-Electrode Switch. In order to initialize the charge state on each of the sensor electrodes to the same value, an additional MOSFET for each electrode should be introduced as a gate-electrode switch. The drain of this new MOSFET should be connected to the interconnect between the sensor electrode and the amplifier shown in Figure 1a. The source of all of the gate-electrode switches should be connected together to an external pad, and their gates should be connected and routed to another common external pad. By applying a high voltage to the gates of these switches, the charges on all of the sensor electrodes would be forced to attain the bias value provided by the external pad, and thus, the entire electrode array would be driven to a constant bias state. A sensor reading could then be accomplished, and the problems with inhomogeneous charge distributions could be eliminated.

PVDF Film Adhesive. Although the photoresist adhesive was adequate to accomplish the short-term performance tests, and it proved useful for recycling ICs for multiple tests (the photoresist was easily removed with acetone), the photoresist bond failed with continuous use. Since the fundamental design has been validated, subsequent research should focus on fabricating sensors for long-term use. Therefore, a more robust adhesive will be required. The conformal coatings used for printed circuit boards are possible candidates. They are available (Miller Stephenson, Danbury, Connecticut) in a variety of formulations (silicone, urethane, and acrylic), their viscosity is suitable for uniform thin film depositions across the surface of an IC, and they possess the desirable electrical insulating properties.

Increased Electrode Density. Since it was determined that there was no detectable coupling between nearest neighbor elements, the density of the sensor array could be quadrupled by placing additional sensor elements between the existing gate electrodes. The resulting spatial resolution will be approximately sixteen times greater than that of a human fingertip. Also, since the response of the optimal sensor configuration (25 μm thick film) to a load of 0.8 g was a voltage change in excess of 1 V, the size of the individual sensor elements could be reduced, further increasing the spatial resolution of the sensor.

Resident Analog Multiplexer. Finally, a resident analog multiplexer would permit scanning the entire electrode array without having to reposition the data collection probe. This analog multiplexer could be implemented with either an internal clock or an external interrogation signal to select the discrete sensor elements.

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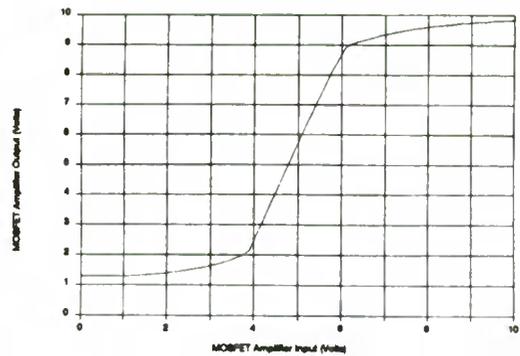
Figure 2. Spice plot of the MOSFET amplifier characteristics.
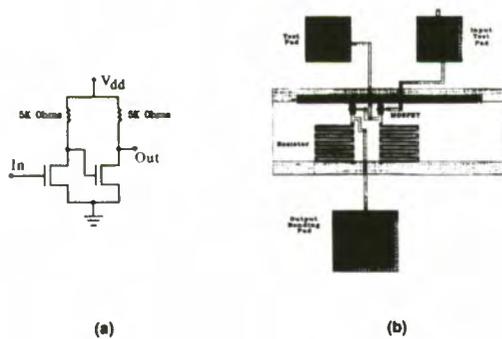
Figure 1. (a) Schematic of the discrete sensor element amplifier. (b) Caltech Intermediate Form (CIF) plot of the tactile sensor's amplifier.
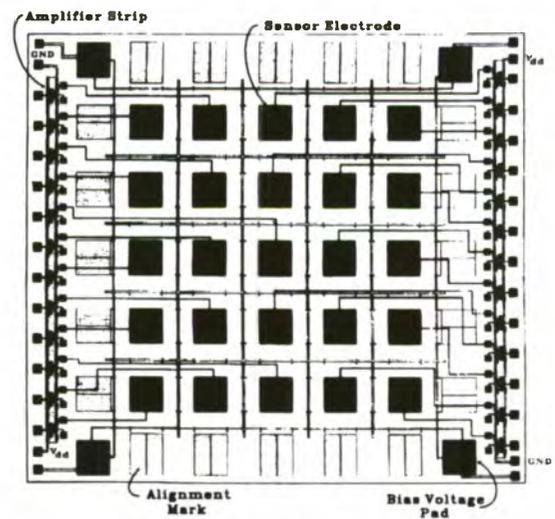
Figure 3. Caltech Intermediate Form (CIF) plot of the complete integrated circuit.
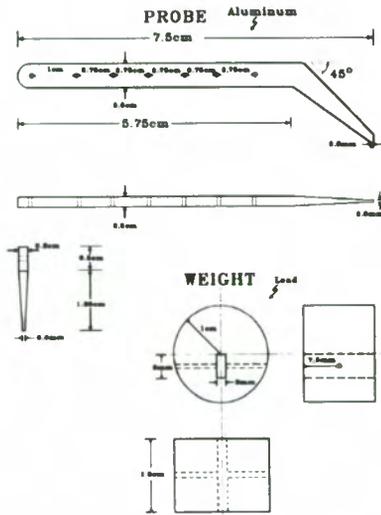
Figure 4. Microprobe sub-assembly used to apply loads to the sensor spanning 0.8 to 76 grams.
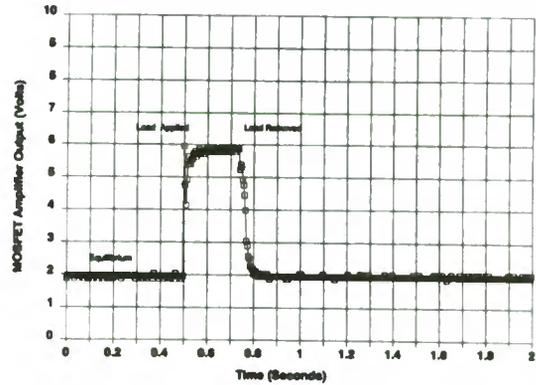

Figure 6. Individual sensor response to a 21 g load placed on a tactile sensor fabricated from the Solef 40 μm thick PVDF film.
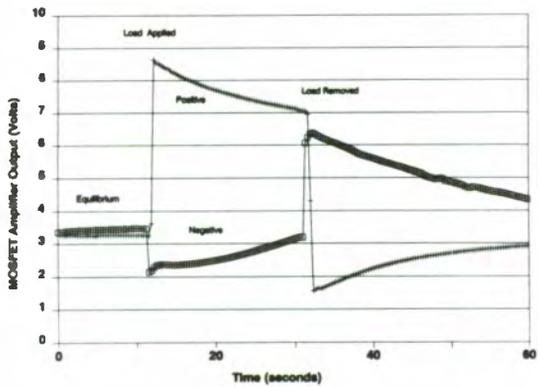

Figure 5. Response of the Solef 40 μm thick PVDF film oriented in the positive and negative directions with an applied 500 g load.
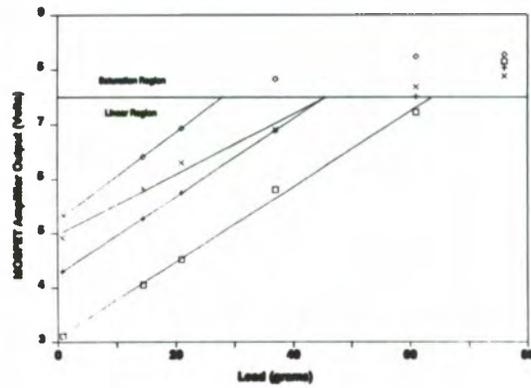

Figure 7. Amplifier output and linear least-squares fit for each of the tactile sensor configurations. The least squares analysis utilized only those data points in the non-saturated region of the amplifier (that is, output signals greater than 7.5 V were not included). Legend: (x) 110 μm thick film with a 1.5 V bias, (◇) 52 μm thick film with a 2 V bias, (+) 40 μm thick film with a 2 V bias, and (□) 25 μm thick film with a 2 V bias.
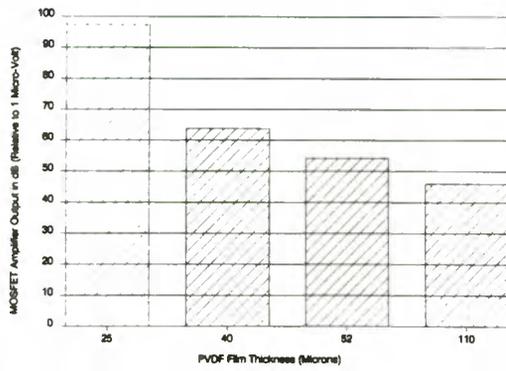
Figure 8. Amplifier output after 10 minutes with a 10 V applied bias for the various sensor configurations.
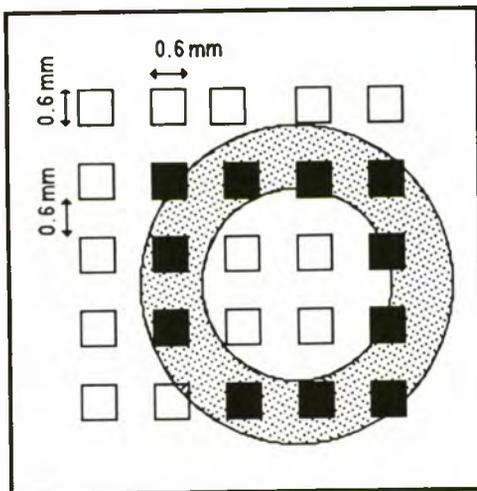

Figure 9. Tactile sensor array response to a 300 g toroidal-shaped load (threshold level is 60% of the normalized difference between the loaded and pre-loaded states).