Tactile Sensing Arrays for Humanoid Robots

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Abstract—**Development of robots capable of operating in unstructured environments or intended to substitute for man in hazardous or inaccessible environments, demands the implementation of sophisticated sensory capabilities, far beyond those available today. In this regard, the development of tactile sensors is one of the key technical challenges in advanced robotics and minimal access surgery. In this work we present arrays of 'taxels' (tactile elements) which will be placed on the distal phalange of the humanoid robot in our lab. We present two different designs and implementations. In the first one, microelectrode arrays (MEAs) of 32 elements, with 1mm center to center distance, have been designed. The taxel is implemented by epoxy-adhering the sensing material (piezoelectric polymer film of PVDF-TrFE) on a microelectrode. Each taxel is intended to be used as an extended gate of an FET (external to the chip); the taxel collects the charge/voltage generated, as consequence of the applied stress, on the deposited piezoelectric polymer film (i.e. the extended gate itself). The second design and implementation integrates both the taxels array and the FET devices, on the same silicon die.**

I. Introduction

An important issue for the humanoid robots is the way they interact with the environment. Real-world objects exhibit rich physical interaction behaviors on touch. These behaviors depend on how heavy and hard the object is when hold, how its surface feels when touched, how it deforms on contact and how it moves when pushed etc. The information about real world objects e.g. differences in shapes can be obtained by moving robots in all directions around the object and collecting data by using vision sensor. But, it is not always possible to move the robot around the object whereas same can be done with touch sensing easily and also faster.

Whereas, touch sensing is the process of detection and measurement of a contact force at a defined point, tactile sensing is the process of detection and measurement of the spatial distribution of forces perpendicular to a predetermined sensory area and the subsequent interpretation of the spatial information. Cue from human tactile sensing system can be helpful in bringing the level of tactile sensitivity and acuity that humans possess, to the manipulators and to other human/machine interfaces. A general purpose robotic tactile system, in addition to being cost effective, should possess the following characteristics [1]-[3]:

1) A limited number of taxels to minimize tactile image processing time; typical estimated range is between 25 and 256 elements.

2) Human like spatial sensitivity i.e. 1mm center to center distance between taxels.

3) Sensitivity to forces, spanning from 1gmf (0.01N) to 1000gmf (10N) with incremental force resolution of 1 g.

4) Discrete taxel response bandwidth of 1000 Hz.

A reasonable response linearity and negligible hysteresis are also desired. Although high quality cameras (used for visual sensing in robots) are readily available in market, it is difficult to find something similar for tactile sensing. Touch sensors using different transduction mechanisms realized in past are mainly discrete touch sensor elements and provide only limited information like touch or no touch. Relative merits, limitations, performance and reviews of earlier technologies for the tactile sensing have been reported in [3, 4]. For object recognition and to have human like touch sensitivity, a large number of taxels are required. Use of a large number of discrete touch sensor elements would increase the number of interconnections and also the electrical interference. Besides these problems, a limited space on the robot finger makes this approach impractical. These issues can be addressed by way of miniaturization.

In this paper, we present an approach for the development of robotic tactile sensing system by integrating "smart materials" like piezoelectric polymers with the Integrated Circuits (ICs). Fig 1 shows the proposed tactile sensing system. The integration of sensing elements with electronics on silicon will reduce electrical interference thereby improving the signal to noise ratio. This will also help in solving wiring complexity, a key problem in robotics. We report the progress toward realizing an array of tactile sensors by direct coupling of piezoelectric polymers thin films to MEAs realized on silicon die. This is further followed by the second design, which is based on the development of MEAs operated as extended gates of FETs integrated on the same chip.

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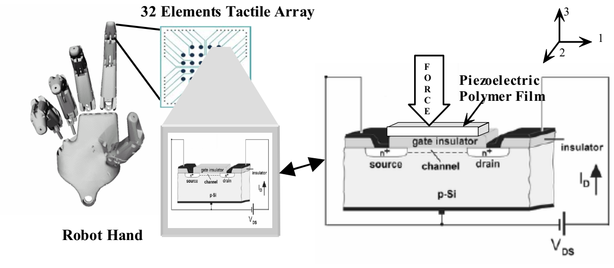

Figure 1. Proposed tactile sensing system.

In the following sections, we present the principle of operation, modeling and analysis of the sensing element, design and fabrication of devices and the future direction.

II. Principle Of Operation

A piezoelectric film working in the generating mode, gives a charge/voltage output when a mechanical input is applied. The generated charge/voltage is proportional to the applied stress. Thus, if the polysilicon gate of a MOSFET is replaced by a piezoelectric polymer film, the charge (and hence the voltage) generated due to the stress applied on the piezoelectric polymer film controls the charge in the MOSFET channel. In other words, the charge in the channel is modulated by the applied mechanical stress. The signal is amplified by the MOSFET and is then further processed by electronic circuitry.

A similar approach to develop ultrasonic sensors was reported by Swartz et al. [5]. They used PVDF polymer as sensing material in their acoustic sensor. In addition of having better electromechanical properties, PVDF-TrFE used in our tactile sensor is easy to deposit on the silicon. General parameters of PVDF and PVDF-TrFE are given in Table 1.

Due to economic reasons, changing the oxide layer thickness, and other dimensions of the devices, by modifying a standard fabrication process is not always possible. The ease with which PVDF-TrFE can be spin coated on the silicon die, provides us with an alternative method to control the capacitance of the polymer film with respect to the oxide and other capacitances of backing material (silicon in our case) and hence to optimize the sensitivity of the transducer.

III. Modelling And Analysis

A piezoelectric film produces charge/voltage due to the applied stress. The electromechanical behavior of piezoelectric materials can be represented by following mathematical relations [7]:

$$T_3 = c_{33}^{D} S_3 - h_{33} D_3 \quad (1)$$

$$E_3 = -h_{33} S_3 + \beta_{33}^{S} D_3 = -h_{33} S_3 + \frac{D_3}{\varepsilon} \quad (2)$$

Where T_3, S_3, D_3, E_3, c_{33}^{D}, h_{33} and ε are the stress, strain, electric displacement, electric field, elastic constant, piezoelectric constant and permittivity respectively. The subscripts give the direction of polarization and the direction of applied force. For simple analysis, the direction of polarization and applied force are considered same i.e. 3 direction. Since piezoelectric polymers are anisotropic, the piezoelectric constant is different in different direction. This fact may be advantageous for studying the shear forces as well. The performance of the piezoelectric polymer under various conditions of polymer thicknesses, type and thickness of the substrate etc. can be analyzed by using its equivalent circuit. This will also help in optimizing the design of tactile sensing systems. A modified version of the original Mason's model for piezoelectric ceramics was presented by Redwood [8] using the transmission line theory. SPICE implementation of the equivalent circuit for lossless piezoelectric materials operating in transmitting/actuating mode has been reported earlier [9]. We have implemented the equivalent circuit shown in Fig. 2, in the receiving/sensing mode using PSpice.

Various stages from mechanical input to electrical output have been clearly defined in Fig. 2. The transmission line represents the mechanical equivalent of acoustic transmission. The impedance of the transmission line, $Z_0=\rho v A$, is obtained by physical parameters of polymer viz: the density ρ, sound velocity in the polymer medium v and electroded area A. Length of transmission line is equal to the thickness of polymer film. The mechanical to electrical conversion is represented by a transformer having a transformation ratio dependent on the piezoelectric constant, h_{33}. This transformation from mechanical domain to electrical was implemented in SPICE by using controlled voltage and current sources. The electrical part is represented by the electrical load which is large resistance R_{out}. If the electrodes at the two sides of polymer are thick then due to change in acoustic impedance, they can have significantly alter the response of polymer. In our case, the thickness of the Al/Cr metal layer was 800 A^0, and its effect was found to be negligible. The effect of electrodes can be observed by using transmission line as shown in Fig. 2. The equivalent circuit of a tactile sensing element on the array can be obtained by replacing the resistance R_{out} at the electrical output, with SPICE model of MOSFET.

TABLE I. PROPERTIES OF PIEZOELECTRIC POLYMERS

Parameter	PVDF[a]	PVDF-TrFE[a]
Density, ρ (Kg/m^3)	1780	1880
Longitudinal Velocity, v (m/s)	2200	2400
Acoustic Impedance, Z (MRayl)	3.92	4.32
Clamped Dielectric Constant, ε_{33}^{S}	5.0	4.0
Dielectric Loss Tangent, $tan\delta_e$	0.25	0.12
Mechanical quality factor, Q_m	13	25
Thickness coupling factor, k_t	0.15	0.30

[a]From [6]

The implementation of polymer model in SPICE is advantageous as will help is optimizing the tactile sensing system right from the input stage by integrating the polymer model with SPICE model of associated electronic circuitry.

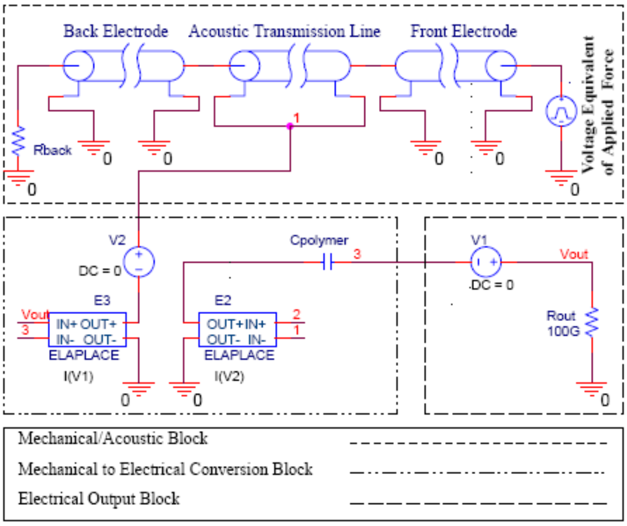

Figure 2. SPICE model of piezoelectric polymer in the sensing mode. R_{out} is a very large resistance, connected for the purpose of getting a open circuit output from the polymer.

Using the supplier's data, (1), (2) and the mathematical relations given in [7], open circuit voltage generated ($V=d_{33}*F/C_{polymer}$) by a 50 µm thick polymer should be nearly one volt when a 0.01N (one gram) force is applied on one taxel (area 0.196 mm^2) of MEA. The simulated electrical open circuit response (obtained by assuming very high resistance at electrical output terminal) when a fast rising voltage equivalent of step force of 0.01N is applied at the force input terminal is shown in Fig. 3. The voltage equivalent of the force is applied at one end of the transmission line and the other end of the line is terminated with the equivalent of acoustic impedance of silicon.

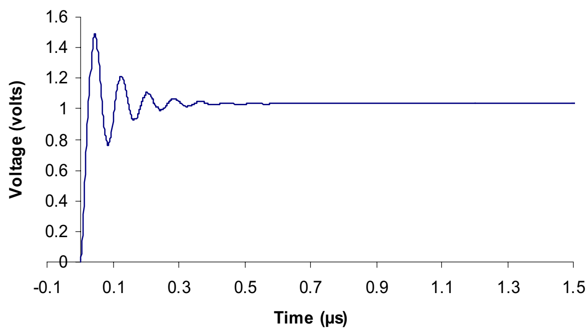

Figure 3. Transient response of the polymer when a voltage equivalent to a force of 0.01N was applied. The

At low frequencies the polymer can be approximately represented by a voltage source in series with the capacitance *Cpolymer*. In order to have maximum voltage at the gate terminal of the FET device, the substrate capacitance of extended gate and the FET device capacitances should be comparable or less than the *Cpolymer*.

IV. Design And Fabrication

The integration of the taxels array and the active devices demands for a fabrication process both technologically reliable and economically suitable to be integrated with different technologies, such as Al-microelectrode fabrication and piezoelectric polymeric layer deposition.

As a first step towards implementation of the touch sensor we have designed and developed test structure based on 32 elements microelectrode arrays at FBK-IRST. One such test structure devoted to characterize the polymeric material and to perform the electrical/mechanical tests to refine the read out electronics is shown in Fig. 4(a). To study the electrical response of different taxels PVDF-TrFE polymer (supplied by Piezotech) with 25, 50 and 100 µm have been deposited using the steps mentioned in table II. The front and backside of the MEA after depositing polymer is shown in Fig. 4(b). The fabrication of MEA is implemented on a fuse silica quartz substrate a Al:Si 1% /Ti/TiN, respectively of 410/30/140 nm thick, low resistance multilayer for both microelectrodes and electrical connections. The TiN top-layer has been introduced to guarantee a low contact resistance to the final Au/Cr (5/150 nm) seed-layer. The metal wires passivation has been guaranteed by a SiO_2/Si_3N_4 (20/210 nm) layer deposited by PECVD. These thicknesses have been chosen to keep the substrate capacitance low and hence to get the maximum of the voltage produced by polymer at the gate terminal. Here, quartz wafer has been used instead of silicon to minimize the cross talk. Future arrays will be implemented on silicon wafers.

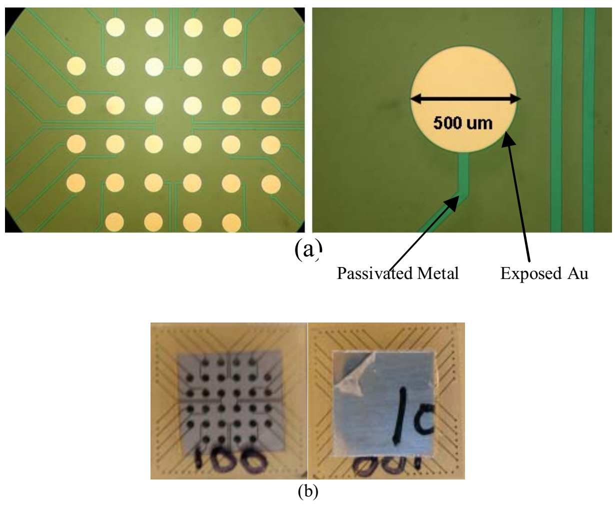

Figure 4. a) MEA for the extended gate-FET approach. Chip dimension is 1cm x 1cm. and diameter of the taxels is 500µm (b) Back and front sides of MEA with 100 µm polymer covering all the electrodes. A general purpose protecting tape can also be seen.

In the second implementation, as shown in Fig. 5, the taxels array and the MOSFETs are integrated on the same silicon die. The developed chip consists of an array of 25 n-MOS elements (with W/L = 300) where the exposed dielectric gate and metal ring have been connected in a diode configuration in order to optimize the device versus read-out connections. The reference fabrication process for this second design is the n-MOS technological module of a non standard 4-µm Al gate p-well ISFET/CMOS technology [10]. The main features are a Si_3N_4/SiO_2 double layer as a gate dielectric and a second metal for implementing microelectrodes and metal-rings. In order to achieve a “Piezoelectric polymer - MOSFET” working mode, piezoelectric polymeric layer (PVDF-TrFE) will be spun onto the whole wafer surface.

TABLE II. DEPOSITION OF PVDF-TRFE FILM

a	PVDF-TrFE films of 7X7 mm^2 area and 25, 50 and 100µm thicknesses, metallised from both sides (supplied by Piezotech) were deposited on a glass slide using epoxy adhesive. Another glass slide was kept on top of the polymer and this arrangement was kept in vacuum for one hour. Then the arrangement was heated at 65 degree for 30 minutes. Then the polymer film was peeled off from the glass slide to remove the metal layer from one side of the polymer.
b	The film was deposited using epoxy adhesive on the MEA, covering all all 32 taxels. The film was covered with glass slide and the arrangement was again kept under vacuum to remove air between polymer and MEZ and to ensure uniform thickness of the adhesive. For better adhesion the arrangement was kept at 65 degrees for thirty minutes.

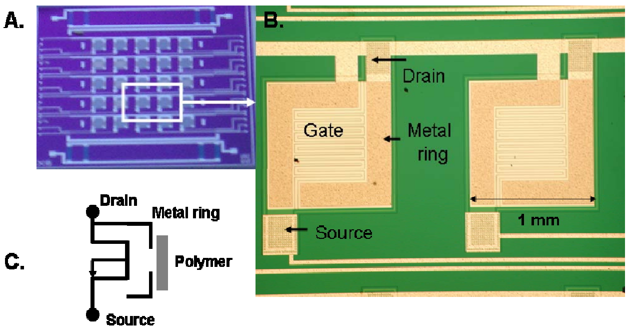

Figure 5. A) Chip prototype (1 cm × 1 cm die size) B) Enlarged photograph of the n-MOS sensor cell; C) Scheme of the electrical configuration.

V. CONCLUSION AND FUTURE WORK

An approach for development of new tactile sensor system for humanoid robots is presented along with the preliminary designs for testing the piezoelectric polymers separately and with FET. The SPICE model of piezoelectric polymer in sensing mode is presented for a lossless case. Simulated output is found to be in agreement with the theoretical results. As reported earlier [6], the piezoelectric polymers have more losses than piezoceramics. The SPICE model presented in this work can be improved by introducing the complex values of piezoelectric constant, dielectric constant and the elastic constant. By using a combined SPICE model of piezoelectric polymer and FET device, effect of various parameters on the overall sensitivity of sensor can be analyzed. The SPICE model of polymer would be used in future to optimize the layout of devices and design of sensor system. Future work will involve the study of electrical output of a single taxel as well as that of the array, by applying forces with different magnitudes and frequencies. For this purpose, a dynamic test bench, charge and voltage amplifiers are being developed.

Piezoelectric polymers in general, respond to both mechanical and temperature changes. Since the humanoid robots are expected to work at different environmental conditions, it is necessary to ensure that the sensor responds only when touched or when the robot touches something. The same argument applied to other potential applications like biomedical applications. Thus, the pyroelectric effect of the polymer needs to be compensated. This compensation can be done either by observing the response of piezoelectric polymer due to changes in temperatures only and then mathematically compensating it in the overall response of the sensor or by using some other material that is more responsive to mechanical changes than temperature changes. The effect of temperature variations can also be compensated by introducing a temperature sensing device on the chip itself and hence keeping the temperature of polymer constant. In the second design of the chip this technique would be implemented. Also, in the next stage of the fabrication process, a process for array of n-MOS devices without metal gate will be realized and the complex circuits including both sensors and read-out will be accommodated in the chip.

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