Bio inspired Tactile Sensing Arrays

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ABSTRACT

This work presents the development of tactile sensing arrays, inspired by cutaneous sensing in humans, for the fingertips of a humanoid robot. The tactile sensing arrays have been developed in two phases. Microelectrode arrays (MEA), having 32 sensing elements - each epoxy adhered with 25µm thick piezoelectric polymer (PVDF-TrFE) film, were fabricated in the first phase. When connected to the gate of FET devices (external to the chip), each element on MEA acts like an extended gate; thereby facilitating modulation of charge in the induced channel by the charge generated in PVDF-TrFE film - as a result of applied force. Thus, each sensing element converts force into voltage. The tactile sensing arrays developed in second phase work on the same principle but are free from any extended gate. These arrays (having 25 sensing elements) use POSFET (Piezoelectric Oxide Semiconductor Field Effect Transistors) touch sensing elements – in which, piezoelectric polymer film is directly spin coated on the gate area of the FET devices. Thus, a POSFET touch sensing element 'senses and partially processes at same site' – as is done by receptors in human skin. The spatial-temporal performance of these chips is similar to that of skin in the human fingertips.

Keywords: Tactile Sensing, Touch Sensor, POSFET, MEA, Robotics, PVDF-TrFE, Piezoelectric polymer, Human Touch

1. INTRODUCTION

Tactile Sensing – defined as the detection and measurement of contact parameters in a selected area [2] - is an essential component of robotics, haptics, rehabilitation and many other applications. Among others, tactile sensing is needed for exploration and precise manipulation of real world objects. Movement of robots from the structured environment of manufacturing plants to the daily life has also added new tasks like safe interaction in a human-populated environment. The way robots interact with the environment is an important issue as real-world objects exhibit rich physical interaction behaviors which 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. Such interaction behaviors can be better understood by touching or physically interacting with them – as humans do.

In last two decades or so, the pursuit of improving tactile sense capability, of various robotic devices, has resulted in many touch sensors, exploring nearly all modes of transduction [2, 3] viz: resistive, quantum tunneling, capacitive, piezoelectric, magnetic etc. Production of touch sensors with innovative designs still continues, but, despite all this development, they largely remain unsatisfactory for robotics either because they are single big sized touch elements and are too big to be used without sacrificing the dexterity of robot, or because they are slow, or fragile, or due to lack of elasticity, flexibility and mechanical robustness and also in some cases due to their digital nature i.e. all or none. Despite being an important active research area of robotics, for roughly as long as vision sensing, tactile sensing could not make much headway vis-a-vis other sense modalities - thereby strongly limiting the real world interaction and the cognitive capabilities of robots. In addition to the absence of satisfactory tactile sensors or 'taxels' that can be incorporated into the system, this could also be attributed to the complex and distributed nature of tactile sensing and partly also to the absence of a system approach while designing touch sensors or the tactile sensing arrays [4]. Absence of something like CMOS (Complementary Metal Oxide Semiconductor) optical array, for tactile sensing, is also considered as one of the reasons why effective usage of tactile sensing lags behinds other sense modalities [2, 5]. Some other reasons for the neglect of tactile sensing in a general mechatronic system are discussed in [3].

Design of a meaningful robotic tactile sensing system must be guided by a broad but integrated knowledge of how tactile information is encoded and transmitted at various stages of interaction. In this context, various studies on human 'sense of touch' can provide a good starting point. Scientific studies on humans, like neurophysiology of sense of touch, role of skin biomechanics, movements for optimum exploration of material properties, object recognition, active and passive perception, selective attention, sensory guided motor control etc., have addressed many issues that are challenging to roboticists as well. In absence of any rigorous robotic tactile sensing theory, such studies may be helpful in specifying important parameters like sensor density, resolution, location, bandwidth etc. Such parameters vary across various body parts in humans. As an example, the mechanoreceptors – the receptors embedded in human skin, converting the mechanical stimulus in to action potentials - are distributed all over the body with variable density. The number of mechanoreceptors in the fingertips is higher than the palm of adult humans. They have different receptive fields – the extent of body area to which a receptor responds - and also different rates of adaptation [6-8]. The spatial acuity varies across the body - being highest at fingertips, face and toes and lowest at thigh, shoulders and belly. The spatial resolution in the palm is about seven times smaller than that of the fingertips [9]. One can resolve two points as close as 3 mm on the fingertips, and up to 30 mm on the belly [10]. More sensitive psychophysical methods show that the spatial resolution on the fingertips is about 1 mm [11, 12]. These results place the tactile acuity somewhere between vision and audition - being worse than vision, but better than audition [10]. Key features of cutaneous sense of touch at human fingertips are given in Table 1.

Like sense of touch in humans, it is desirable to have tactile arrays, or a coordinated group of distributed tactile sensors, with density and spatial distribution of taxels (tactile elements) depending on the body site where the sensors are installed. For the sites like fingertips, that are involved in tasks like exploration and fine manipulation, a large number of quick responding (of the order of few milliseconds) taxels are needed in a small space (~ 1 mm spatial resolution). Considering the limited available space on the robot finger (~ 1 cm x 1 cm), miniaturization seems to be the solution for accommodating a large number of sensors and hence same is adopted in this work. In past, miniaturization of tactile sensors has been achieved with two main approaches: MEMS based approach [13-15] and polymers based sensors realised on organic/inorganic substrate [16-19]. MEMS based tactile sensing devices, generally use capacitive or piezoresistive mode of transduction. While piezoresistive devices offer higher linearity, the capacitive devices are an order of magnitude more sensitive. With the MEMS based approach, it is possible to get higher spatial resolution. A MEMS based approach has also been used for detecting the shear components of contact force, with a piezoresistive bridge arrangement on the sensing array [13]. But, MEMS based tactile sensing devices cannot withstand large forces/pressure due to their inherent fragile nature. Also, it is difficult to realize flexible tactile sensing arrays by the MEMS approach. Polymers based touch sensors, realized on organic substrates, generally use pressure conductive rubber as transducer and are flexible. Due to higher spatial resolution (~ 2 – 4 mm) and slower response, they are better suited to large area skin applications. As an example, in the 32 x 32 flexible tactile sensing array developed by Someya et al. [16] with organic FET approach, each taxel has a pitch of 2.54 mm and the response time of 30 ms (only of organic FETs). Overall response time is even higher because pressure sensitive rubber, used as transducer, has a response time of the order of hundreds of milli-seconds. These figures are quite high with respect to the one that can be obtained by standard silicon based IC (Integrated Circuit) technology. Thus, if such an array is placed on the fingertips then the requirements like high pitch and the fast response, would limit the number of taxels on the array.

This work presents two phases of the development of tactile sensing arrays for the fingertips of humanoid robot. The concept and working principle of a touch sensor on tactile sensing arrays, developed in two phases, is given in section II. In first phase, presented in section III, the MEA based tactile sensing chips have been realized for the fingertips. The tactile sensing chips use "smart materials" viz: piezoelectric polymer PVDF-TrFE (Polyvinylidene Fluoride - Trifluoroethylene), as transducer. The tactile sensing chip consists of a 2-D array of 32 microelectrodes epoxy adhered with thin piezoelectric polymer film [1, 20]. Each microelectrode when connected to the gate terminal of the FET devices (external to chip), acts as extended gate of the FET devices (external to the chip). The extended gate approach brings the sensor and conditioning electronics closer and hence the overall response is better than that of conventional approach - where the sensor and conditioning electronics are placed at a distance. However, as discussed in following

Table 1 Some Features For Cutaneous/Tactile Sense at Fingertips of Humans

Feature	Value
Mechanoreceptor Density	100 in 1.0 x1.5 cm^2 area.
Range of Forces involved during normal manipulative tasks	0.1-0.9 N
Detectable Frequency range of vibration	DC-700 Hz
Spatial Resolution	1 mm
Receptor level processing of contact data	Yes

sections, this approach suffers from large oxide capacitance introduced by the extended gate. Therefore, in the second phase, presented in section IV, the tactile sensing arrays using POSFET devices have been developed. POSFET devices are free from any extended gate as piezoelectric polymer film is directly spin coated on the gate area of the FET devices. The design of POSFET device and the tactile sensing arrays are inspired by sense of touch at human fingertips. While use of piezoelectric polymer film as a transducer, in both approaches, improves the speed of response; the marriage of transducer and electronics will improve force resolution, spatial resolution, signal to noise ratio. With absence of any wired connection between transducer and transistor, POSEFT based approach will help reducing the wiring complexity – a key robotics problem.

2. WORKING CONCEPT OF A TOUCH SENSOR ON THE ARRAYS

A piezoelectric film working in the sensing mode generates a charge/voltage when mechanical force/stress is applied. This charge/voltage is proportional to the applied force/stress [21, 22] and they are related as:

$$Q_t = d_{33} \times F \qquad (1)$$

Where, Q_t is the charge developed on a taxel due to applied force F and d_{33} is the piezoelectric constant. By connecting the piezoelectric polymer to the gate terminal of FET devices – as in MEA based tactile sensing arrays, or by depositing the piezoelectric polymer directly on the gate area of FET devices – as in POSFET Based tactile sensing arrays, such a charge/voltage of the piezoelectric polymer can be used to modulate the charge in the induced channel of FET, which is then amplified by the FET and further processed by an electronic circuitry. Thus, each sensing element converts force into voltage and each also touch sensing element 'senses and partially processes at same site' – as is done by receptors in human skin [23]. In this context, a comparison of POSFET touch sensing device, with the receptors embedded in the skin, is shown in Figure 1. Schematics of, both, MEA based touch sensors and POSFET based touch sensors are shown

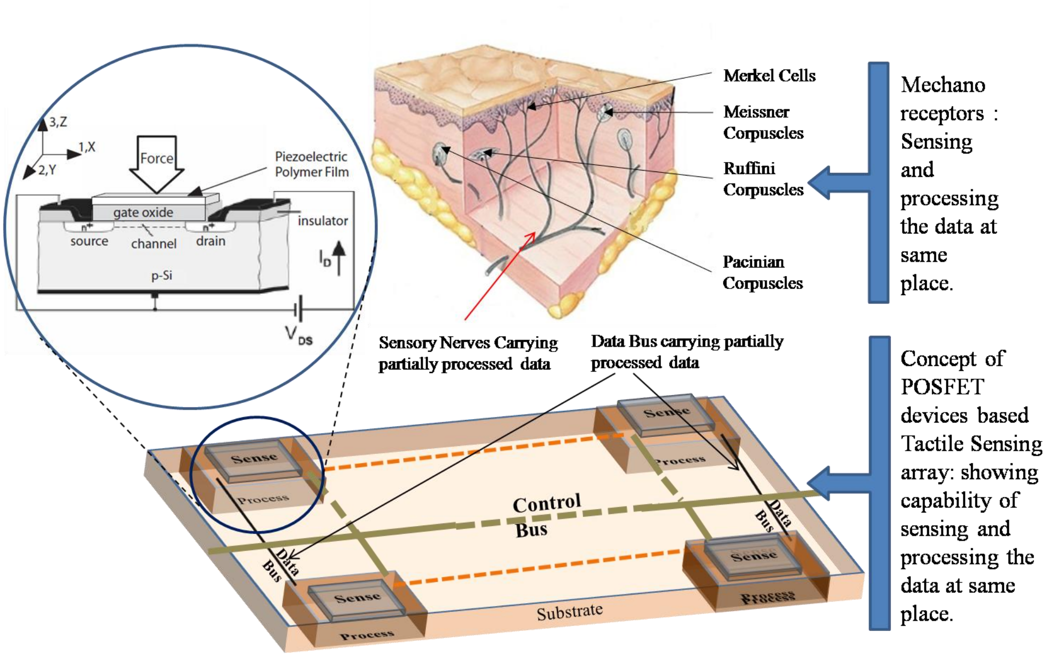

Fig. 1. A functional comparison of touch sensors and the receptors in the skin.

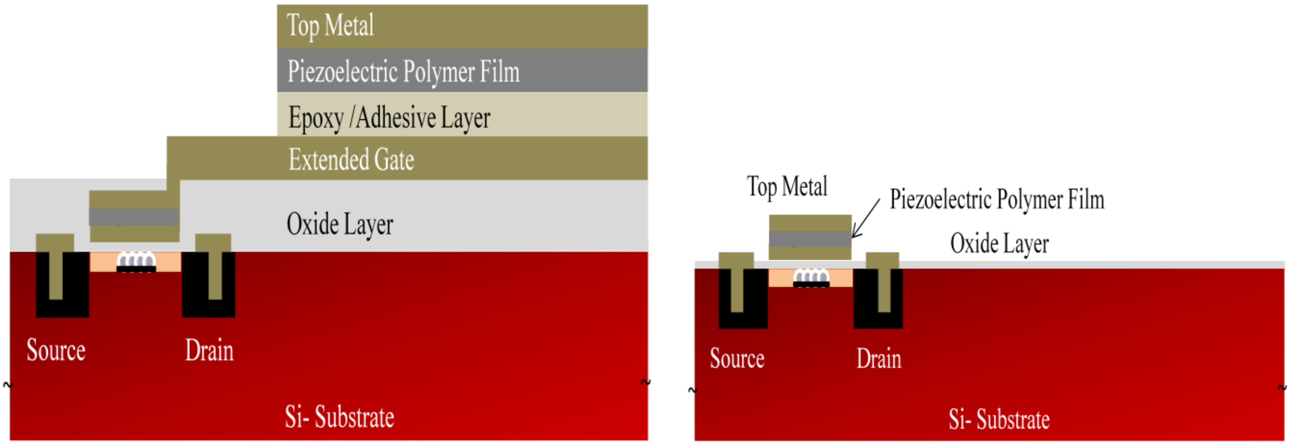

Fig. 2. *(left)* Scheme of a touch sensing element on MEA based tactile sensing arrays, developed in first phase. *(right)* Scheme of a POSFET touch sensing element used on the tactile sensing arrays developed in second phase.

in Figure 2. Somewhat similar approach was used by Swartz et al. [24] for the development of ultrasonic sensors and by Kolesar et al. [19] for the touch sensors. In both cases, the extended gate FET devices epoxy-adhered with PVDF film were used. In present work, the PVDF-TrFE polymer films are used, as unlike PVDF, they do not need mechanical stretching [25] - a standard step while making PVDF polymer films. This is a significant advantage of PVDF-TrFE as it allows the spin coating of polymer directly on to silicon wafer. In addition, PVDF-TrFE has nearly same piezoelectric constant as that of PVDF, has lesser losses and generates approximately the same charge/voltage output for the same force input.

3. MEA BASED TACTILE SENSING ARRAYS

As a first step towards realizing tactile sensing system, two dimensional, 32 taxels, MEAs based test chips are designed and fabricated on quartz wafer. Detailed design and fabrication process are explained elsewhere [20]; however, the key points are briefly given here. The overall size of MEA chip is 1 cm x 1 cm and each taxel on the chip has a diameter of 500 µm. To get a spatial resolution comparable to that of human tactile sensing (~ 1 mm), the center to center distance between the taxels is kept as 1 mm. Here, quartz wafer is used instead of silicon to minimize the noise. The fabricated MEA test chip and enlarged view of one of the taxels are shown in Fig. 3(a). Each sensing element on the MEA test chip can be used as extended gate of the FET devices, which are external to the chip.

The MEA test chips were epoxy-adhered with one side metalized piezoelectric polymer (70:30, PVDF-TrFE) thin films of 25 µm, 50 µm and 100 µm. Polymer films with different thickness are used to study the effect of thickness on the response of a taxel. The front and backsides of a MEA test chip with a 50 µm polymer film and the chip on package are shown in Fig 3(b). On the package, only 28 terminals (out of 32) are gold bonded to the pads of MEA as all corners are gold bonded to the upper metal layer of the piezoelectric polymer film. Thus, corners of the package, all together, serve as one of the terminals of charge/voltage source (generated by the applied force).

The performance of MEA based test chips is evaluated in variable force - constant frequency, under ambient conditions. In the variable force - constant frequency mode, a normal sinusoidal 15 Hz force, in the range 0.02 N - 4 N (~ 2 gmf - 400 gmf), is applied on the taxels. In these experiments the taxels are pre stressed by a 2 N force. The resulting plots between average taxel output and the force input are shown in Fig. 4. These plots relate average maximum values of the sinusoidal output of three taxels - located at the centre of chips, with corresponding maximum values of the applied

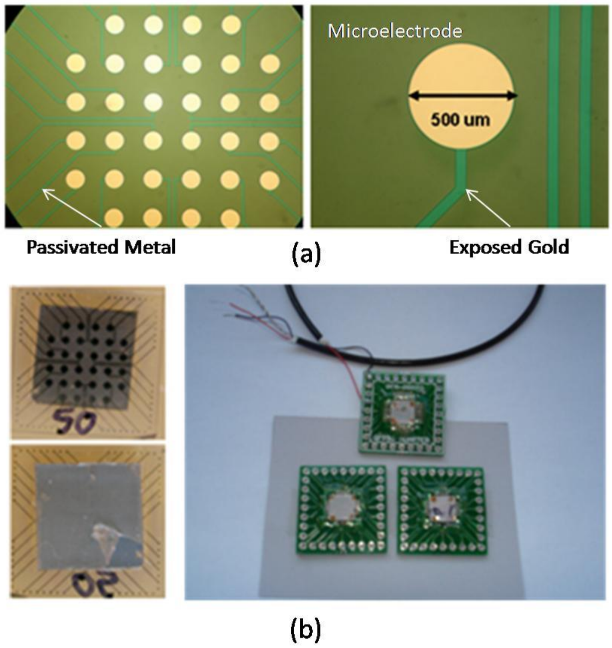

Fig. 3 (a) 32 taxel MEA test chip (left) with enlarged view of a taxel (right); (b) Front and backsides of MEA test chip epoxy-adhered with 50 µm PVDF-TrFE film *(left)*; Packaged MEA chips *(right)* [1].

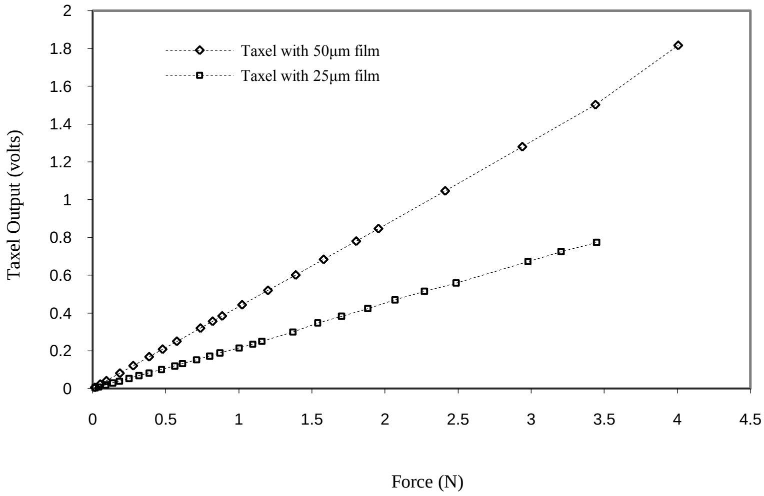

Fig. 4 Average maximum of sinusoidal taxel output versus maximum value of sinusoidal input force.

sinusoidal forces. The response of each of the three taxels tested in this case was within approximately 6% of the average output shown in Fig. 4. Such a variation among outputs of different taxel could be due to the non-uniform thickness of polymer or due to slight misalignment of probe and taxel. Besides others, the uniform deposition of a thin polymer film is a challenging task for the tactile sensing arrays presented in this work. The response of taxels was further investigated for “cross-talk” as spatial resolution also depends on it. The higher the cross talk, the lower will be the spatial resolution. The crosstalk of MEA based tactile sensing arrays was found to be approximately 20% [1]. Higher crosstalk can be attributed to the fact that while taxels are independent entities under the polymer film (MEA side of the film); they are all connected by a uniform thin metal film on the top. In other words, taxels are still mechanically connected, which is the primary reason for the presence of the cross talk in both the chips. The parasitic capacitance between adjacent elements also contributes to cross-talk.

4. POSFET BASED TACTILE SENSING ARRAY

4.1 Advantages over MEA approach

The extended gate approach, discussed in previous section, significantly improves the performance over the conventional approaches - where transducer and processing circuitry are separate entities. Still, issues like presence of epoxy, large substrate capacitance and cross-talk etc. restricts the original advantages offered by this approach. With no extended gates, the POSFET touch sensing devices, shown in Fig. 1, are free from such bottlenecks. It can be noticed from Fig. 1 that both epoxy, used as adhesive to deposit the polymer film on extended gate [1, 19, 20, 24], and oxide under the extended gate introduce additional capacitances. Keeping in view the presence of these additional capacitances, the ratio of voltage available at gate terminal (for a worst case scenario, the transistor in assumed to be connected in a common source configuration) and the stimulus generated voltage at polymer, can be written as [26]:

$$\frac{V_g}{V_{polymer}} = \frac{C_{polymer}}{C_{polymer} + \left(\frac{C_{polymer}}{C_{adhesive}}+1\right)[C_{sub}+C_{gs}+C_{gd}(1+A_v)]} \tag{2}$$

Where, A_v is the voltage amplification of the transistor, C_{gs} is gate to source capacitance and C_{gd} is gate to drain capacitance of transistor. It is evident from (2) that a large substrate capacitance, C_{sub}, together with the capacitance of epoxy, $C_{adhesive}$, attenuates the voltage at the gate terminal. Since, $C_{polymer}/C_{adhesive} > 0$, the net effect of $C_{adhesive}$ is to increase the contribution C_{sub} - in reducing the voltage available at gate terminal. The effect is significant, if the substrate capacitance is much larger than that of polymer capacitance, $C_{polymer}$. On other hand, the POSFET device, shown in Fig 1, is more or less free from substrate capacitance and the capacitance due to adhesive. The transistor is again assumed to be connected in a common source configuration. The ratio of voltage available at gate terminal and the stimulus generated voltage at polymer, in this case, can be written as:

$$\frac{V_g}{V_{polymer}} = \frac{C_{polymer}}{C_{polymer} + [C_{gs}+C_{gd}(1+A_v)]} \tag{3}$$

Thus, overall sensitivity of the POSFET based tactile sensing devices is expected to be higher than that of tactile sensors obtained with extended gate approach. Further, the presence of polymer only on the gate area, as in POSFET devices, makes the net polymer area lesser than that on the extended gate devices. This means, for same thickness of the polymer, the effective capacitance is lesser and so is the *RC* time constant. The interconnects needed for connecting extended gate to the gate terminal of FET devices are also absent in case of POSFET, which further reduces the *RC* time constant as resistance of such interconnects is not present. Direct fallout of the reduction of *RC* constant is the faster response and improvement in range of frequencies, over which POSFET devices can be used. The use of POSFET devices in an array also leads to higher spatial resolution and low cross-talk among closely placed sensors on an array. The spatial resolution of 1 mm is obtained with POSFET based tactile sensing arrays and this can be further improved by reducing the spacing between POSFET devices and also by reducing the size of the devices. Besides performance improvement, removal of extended gates by using POSFET tactile sensing devices helps in saving some of the real estate on the silicon wafer.

4.2 Design, Fabrication and Evaluation

POSFET based tactile sensing arrays with 25 n-MOS elements, shown in 5, have been developed following the fabrication steps explained elsewhere [27]. Each tactile sensing element on the array has a dimension of 1mm x 1mm and the center to center distance between adjacent POSFET elements is 1 mm. The overall dimension of a POSFET based tactile sensing test chip is 1.5 cm x 1.5 cm. The reference fabrication process, for FET devices in POSFET touch sensors, is the n-MOS technological module of a non standard 4µm Al gate p-well ISFET/CMOS technology [28]. In order to have large transconductance and a large transistor, the n-MOS devices were designed to have W= 7500 µm and L=12µm. A Si_3N_4/SiO_2 double layer is used as a gate dielectric in this case. A 2.5 µm thick PVDF-TrFE piezoelectric polymer film is then spin coated from solution. A number of experiments, performed on dummy silicon wafers (i.e. without any MOS device) [25], yielded that a 10% solution spin coated with 3000 rpm for 30 seconds results in ~2.5 µm thick polymer film and hence same is used in present work. Further steps for *in situ* processing of polymer film include

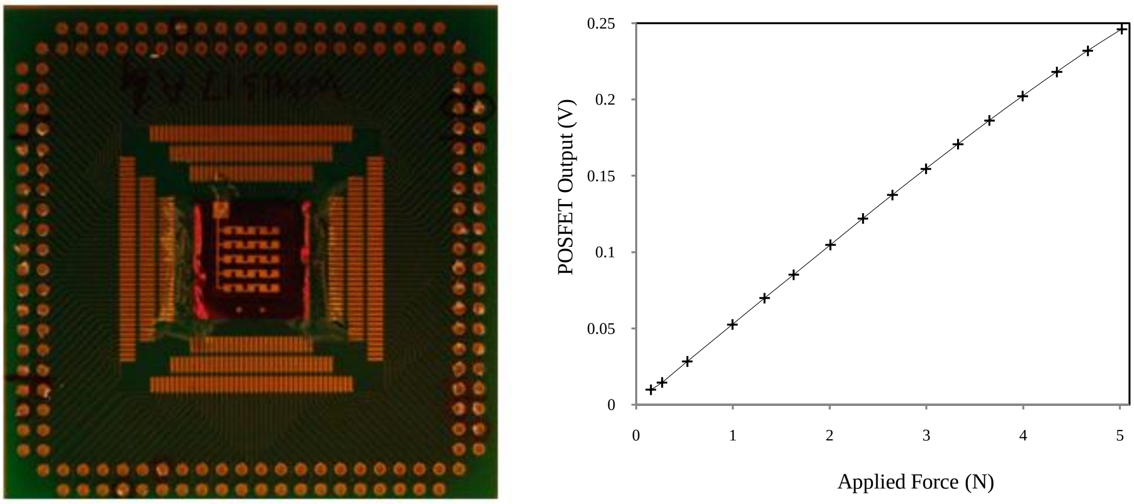

Fig. 5: *(left)* POSFET based tactile Sensing Array. *(right)* Output of POSFET device versus 20 Hz force applied in normal direction.

annealing at 120°C for three hours; vacuum deposition of 200 nm metal (Au/Cr) on top of the polymer film; dry etching the polymer film and thereafter poling of the polymer film. The *in situ* poling is quite challenging due to the fact that a voltage of 250 volts is needed to polarize the 2.5 µm thick polymer film. The transistors or the tactile sensing elements are designed to be large in size; in order have the spatial resolution comparable to that obtained with sense of touch in humans. In fact, the transistor size can be reduced to obtain even better spatial resolution.

The response of POSFET touch sensing device, to dynamic normal forces, is recorded by connecting it in a source-follower circuit arrangement with floating gate. Source-follower configuration results in less than unity gain, and hence POSFET devices can be tested for wide range of forces. Alternately, common source configuration can be used to have better force resolution. As shown in Fig 5, the response of POSFET touch sensing device is linear over tested range of dynamic normal forces (0.15-5N, sinusoidal, 20 Hz). The output of POSFET device is linear, over the tested range, with a slope 49 mV/N. This range of forces very well covers the range of forces, given in Table I, experienced by humans in normal manipulative tasks.

5. CONCLUSION

The human sense of touch inspired, tactile sensing arrays, presented in this work, are able to match various features of human sense of touch at fingertips. They show a linear response over range of forces (0.15-5N) which is much wider than the forces experienced by humans in normal manipulative tasks. In addition to sensing and processing at same site and the improved performance, the POSFET devices as an integral "sensotronic" unit offer practical advantages like reduction in number of wires - which is a key issue in robotics. The performance, utility and local processing capability of POSFET touch sensors can be further improved by including complex circuitry and following a System on Chip/ System in Package approach. Though primarily designed for robotic applications, due to the fact that impedance of PVDF-TrFE matches well with human tissues, these devices can also be suitable for various medical applications.

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