POSFET Devices Based Tactile Sensing Arrays

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Abstract**—This work presents and experimentally evaluates novel POSFET (Piezoelectric Oxide Semiconductor Field Effect Transistor) devices based tactile sensing arrays. The arrays, primarily developed for the robotic applications, consist of 5 x 5 POSFET touch sensing devices or taxels. The POSFET touch sensing devices are developed by spin coating piezoelectric polymer P(VDF-TrFE) film on the gate area of MOS devices and polarizing the film *in situ*. To detect contact events, the taxels utilize the contact forces induced change in the polarization level (and hence change in the induced channel current) of piezoelectric polymer. Both, individual taxels and the array are designed to match spatio-temporal performance of the human fingertips. Experimental results demonstrate that the POSFET tactile sensing arrays presented here are able to detect complex dynamic contact events such as rolling of an object.**

I. INTRODUCTION

Tactile sensing plays an important role in various applications such as robotics, electrotextiles and medical prosthesis. In robotics, the tactile information is needed during tasks like manipulation and exploration. The movement of robots from the structured environments to our daily life has added new tasks such as safe robotic interaction – where tactile sensing is important. The way robots interact with real world objects is an important issue - as such interactions depend on how heavy and hard the objects are, how their surface feels when touched, how they deform on contact etc. Such interaction behaviors can be better understood by touching or physically interacting with the objects – as humans do.

Over the years, tactile sensing technology has improved and many force/pressure sensors and sensing arrays, using different materials and transduction methods, have been developed [3]. Most of these sensors are big in size and respond slow enough to detect static and quasi-static contact events. However, real world contact events are generally dynamic in nature. The bigger size too makes many sensors unsuitable for body sites like robot's fingertips – which are involved in majority of daily tasks. For fingertips large numbers (high density) of fast responding touch sensors are needed. For these reasons, miniaturized touch sensors using MEMS approach have also been developed [4]. However, the usage of MEMS based touch sensor has been limited to the contact forces that are at best equal to the lowest forces experienced by humans in a normal manipulative tasks (see Table I). Mechanically flexible sensors using organic FETs have also been developed for large area skin applications [5]. However, best organics are known to have a mobility of about 1cm^2/Vs versus more than 100 cm^2/Vs for silicon based MOS devices [6], which limits their usage to recording of slow varying contact forces only. Moreover, the organic FET based touch sensors are too big to achieve the spatial acuity similar to that of humans' fingertips (see Table I). Nevertheless they are good enough to match spatial acuity of less sensitive parts (e.g. palm, belly etc.) of the human body.

This work presents and evaluates the novel POSFET devices based tactile sensing arrays that are primarily developed for fingertips of the humanoid robot 'iCub' [7]. The work presented here extends the previous work [8], on POSFET touch sensing devices, to an array level. Earlier the POSFET touch sensing devices were found to have linear response over wide range of dynamic forces (0.1-5 N at 20 Hz). This work presents the results from POSFET devices, when forces with variable frequency (2 Hz – 2.13 kHz, constant amplitude) are applied on them. The stable gain-phase plots, thus obtained, demonstrate the utility of POSFET devices over entire range of the forces experienced by humans in normal manipulative tasks (see Table I). With taxels separated by 0.5 mm, the tactile arrays have human fingertip like spatial resolution. Further, the taxel size of 1mm x 1mm ensures human like spatial acuity. The tactile sensing arrays can be used to measure dynamic contact events that are distributed, both, in space and time. This has been demonstrated by rolling of a ring shaped probe on the surface of the array.

This paper is organized as follows: The working of a POSFET touch sensing devices is explained in section II. The design and fabrication steps of the tactile sensing arrays are presented in section III. The experimental evaluation of the tactile sensing array is presented in Section IV and the results are summarized in the section V.

TABLE I. FEATURES OF TACTILE SENSE IN HUMAN FINGERTIPS [1, 2]

Feature	Value
Receptor Density	100 in 1.0 x1.5 cm^2 area.
Forces range in normal manipulative tasks	0.15-0.9 N
Detectable Frequency range of vibration	DC-700 Hz
Spatial Acuity	< 1 mm
Receptor level processing of contact data	Yes

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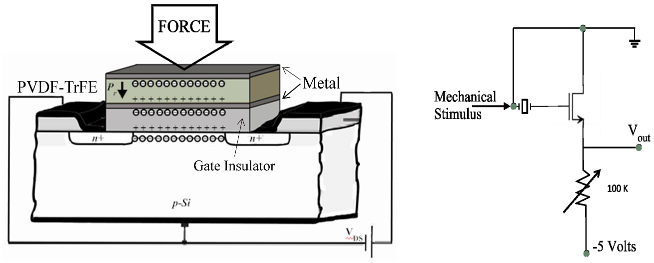

Figure 1. (*left*) The Structure and working of a POSFET taxel. (*right*) The source-follower (floating gate) connection scheme of each taxel on the array.

II. WORKING OF POSFET TOUCH ELEMENTS

The structure of POSFET taxels, shown in Fig. 1, is similar to a metal-ferroelectric-metal-insulator-semiconductor FeRAM (Ferroelectric Random Access Memory). The fixed charges ± Q, shown in Fig. 1, appear due to the remanent polarization (P_r) of the piezoelectric polymer film and the charge neutrality condition. The charge carriers thus accumulate at the surface of the semiconductor according to the polarization direction. For piezoelectric polymers working in thickness mode, as in this work, the mechanical stress T_3, electric field E_3 and electric displacement D_3 are related as [9]:

$$D_3 = d_{33} T_3 + \varepsilon_{33} E_3 \qquad (1)$$

Where, d_{33} and ε_{33} are the piezoelectric and dielectric constants of piezoelectric polymer respectively. Following (1), the electric displacement and hence the polarization can be controlled by the electric field E_3 and the applied force F or stress T_3. While former is used in FeRAM to switch the polarization state, the latter is used in the POSFET taxels to modulate the charge in induced channel of underlying MOS device [8]. Thus, the force variation is directly reflected into channel current of POSFET devices - which can be further processed by an electronic circuitry that may be present on the same chip. Thus, each taxel is an integral “sensotronic” unit comprising of transducer and the transistor and is capable of ‘sensing and partially processing at same site’. In this sense, a POSFET taxel can be compared with the mechanoreceptors in human skin - that not only sense the contact parameters, but also partially process the tactile data at same site [2]. Such a marriage of sensing material and the electronics helps in improving signal to noise ratio and the force sensitivity.

A similar approach, but with extended gates, has been reported in past for ultrasonic [10] and force sensing [11]. The extended gate approach brings the sensor and conditioning electronics closer and hence the overall response is better than the conventional approach - where the sensor and conditioning electronics are placed apart. However, extended gates introduce a large substrate capacitance, which in turn, significantly attenuates the voltage available at gate terminals of MOS transistors. Thus, benefits of closely located sensor and electronics are not fully exploited. Further, the extended gates occupy a large area which otherwise can be used for on-chip electronics. The reliable interconnects between extended gate and MOS transistor is also an issue – more so in case of flexible touch sensing devices. The POSFET taxels used in this work are relatively free from such problems.

III. TACTILE SENSING ARRAY – DESIGN & FABRICATION

For body sites like fingertips the tactile sensing arrays should have high spatio-temporal response – which requires many miniaturized sensors in a limited space. The 5 x 5 element tactile sensing arrays, shown in Fig. 2, are designed to have spatial resolution and acuity similar to that of human fingertips. The overall dimension of the tactile sensing arrays is 1.5 cm x 1.5 cm. Each POSFET taxel on the array is designed to be 1 mm x 1 mm in size, thus ensuring human like spatial acuity. The center-center distance of 1.5 mm between two adjacent taxels ensures human like spatial resolution. The MOS part of the POSFET taxel is obtained by using the n-MOS technological module of a non standard CMOS technology, based on 4μm p-well ion sensitive FET (ISFET)/CMOS process. The MOS devices are designed with interdigitated structure, for high aspect ratio (W=7500μm; L=12μm) and hence large transconductance.

The fabrication step for developing tactile sensing arrays are same as those used to develop a POSFET touch sensing device [12]. However, the fabrication of tactile sensing arrays involves additional challenges such as uniform deposition of polymer film over the array and polarizing the polymer films (a step needed to orient the dipoles in the thickness direction and thus to obtain remanent polarization Pr) on all the taxels simultaneously. A number of experiments were performed on dummy silicon wafers (without any MOS device) to obtain uniform and controlled thickness of polymer films over large areas [13]. The concentration of solution, spinner’s speed and spinning time were used as variables in these experiments. A 10% P(VDF-TrFE) solution spin coated with 3000 rpm for 30 seconds resulted in a uniform (< 1% variation across a 4 inch Si wafer) 2.5 μm thick polymer film and hence same is used in this work. The thickness of polymer film on various POSFET taxels in the array, measured with profilometer (Zygo NewView 6000), was found to be uniform. The *in situ* poling is another challenge due to the fact that a voltage of 200-250 volts is needed to polarize the 2.5 μm thick polymer film. Such high voltages might alter the MOS device characteristics and hence measures such as (a) short circuiting the substrate and the metal layers under polymer and grounding them, and (b) increasing the voltage in four cumulative steps of 50 volts, were adopted to avoid damaging the POSFET devices.

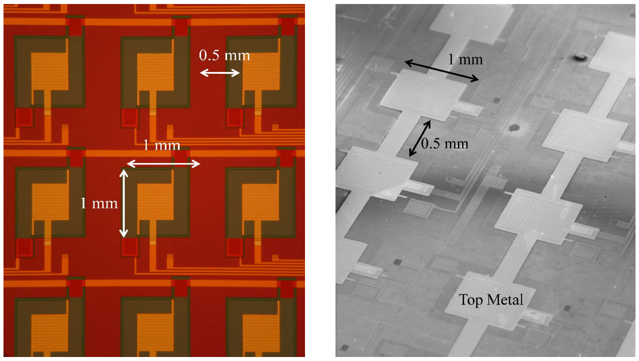

Figure 2. (*left*) A portion of the POSFET tactile sensing array before P(VDF-TrFE) deposition. (*right*) SEM image of POSFET array after polymer film deposition.

IV. RESULTS

The experimental arrangement, to obtain gain-phase response plots of the taxels, is similar to the one used earlier and explained elsewhere [8]. The POSFETs are connected in a source-follower (with floating gate) arrangement, as shown in Fig. 1. The gain-phase plots, shown in Fig. 3, are obtained by applying 1N sinusoidal force in the frequency range 2 Hz-2.13 kHz. The gain (converted in db from (V/N)) is stable over whole tested range and the phase is almost zero. The response of taxels matches well with previous results (-26 db = 50mV/N) [8]. The POSFETs could not be tested below 2 Hz, as this is the rated lower limit of the vibration generator used as stimuli. Similarly, the devices were tested only up to 2.13 kHz, as this frequency is already higher than that perceived by human fingertip. Even if POSFET touch sensors are tested up to 2.13 kHz, they will have much higher bandwidth due to the higher bandwidth of silicon based MOS devices and the high pass characteristics of piezoelectric polymers. The peaks at around 2 kHz are due to mechanical resonance of the experiment set up and thus can be ignored.

A real world stimulus may vary both in time and space. Hence collective performance of the array was evaluated by manually rolling a probe (a 3 mm wide ring bearing) over its diagonal taxels (i.e. POSFETs). The simultaneous excitation of many sensing elements on the chip also gives an idea of the spatial resolution and its object imaging capability. The representative arrangement of the experiment is shown in Fig. 4. Since the probe was rolled manually, a controlled force could not be applied in this experiment – even if it was maintained more or less constant. In this context the results from this experiment are qualitative rather than quantitative. The width of probe is good enough to fully cover and press the diagonal taxels and partially the adjacent taxels (immediately next to diagonal taxels). The, response of various taxels is shown in Fig. 5. The diagonal taxels have higher response then off-diagonal elements. The maximum response of the diagonal taxels is around 0.15 volts and that of adjacent taxels is less than half of this value. The minor variations, among the outputs of diagonal taxels and the taxels adjacent to them, is also be due to the fact the controlled force was not applied. The contact sequence, reproduced from the taxels' responses and shown in Fig. 5, clearly demonstrates the capability of tactile sensing arrays to detect dynamic contact events that are distributed, both, in space and time. The time period of 0.41 sec for one rolling cycle (to and fro rolling of diagonal taxels e.g. t1- t17, t2 - t18 etc.) obtained from Fig. 5 is in good agreement with the actual travel time of 0.416 sec. A total of six rolling cycles were completed in period of 2.5 seconds. Thus, the tactile sensing arrays presented here are capable of detecting the complex dynamic contact events like rolling.

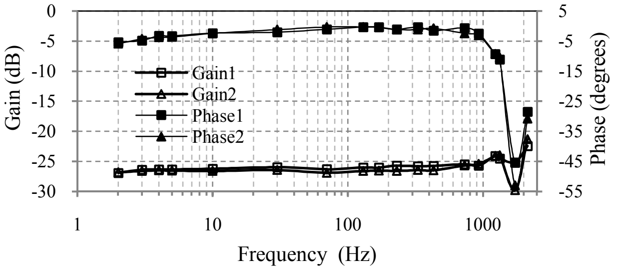

Figure 3: Gain and phase plots of two taxels on the tactile sensing chip.

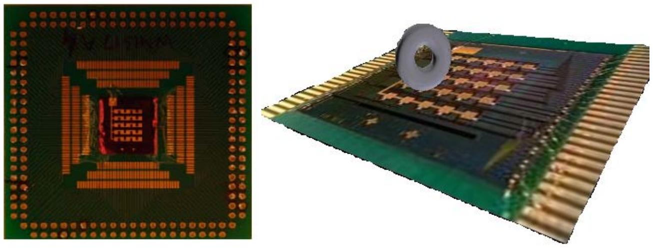

Figure 4. (*left*)Test array on package. (*right*) The representative arrangement of the experiment. A thin ring bearing (~3 mm wide) was used as probe.

V. CONCLUSIONS

Tactile sensing arrays presented in this work have spatio-temporal features similar to that of receptors in the human fingertip. They are able to detect dynamic contact events that vary both in space and time. This has been demonstrated by way of rolling a probe on the surface of array. The arrays presented here can be used to detect contact events such as slippage. However, more experiments are needed to demonstrate it. By realizing touch sensing devices on silicon, one can take advantage of the standard integrated circuit technology and also develop complex electronic circuitry on the same chip. In other words, with POSFET like touch sensing devices, it is possible to develop a full system on chip (SOC) or in a package (SIP). This will not only improve the real time capability of the tactile sensing arrays but also make way for local processing of the tactile data – as done in humans. Realization of the arrays on flexible substrates will further improve their utility in robotics and other areas.

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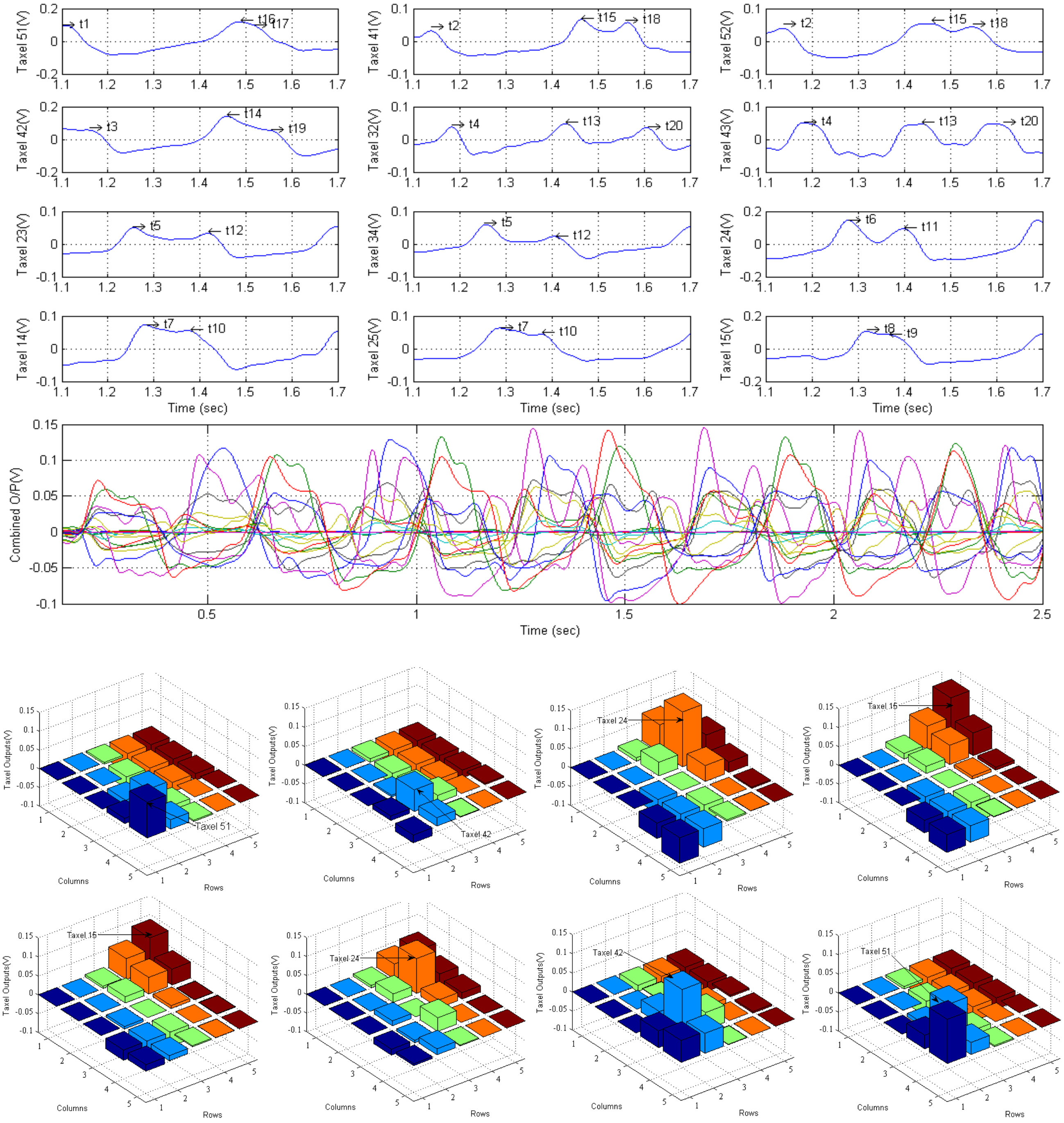

Fig. 5. (*top*) The responses of various taxels, when the probe is rolled over the diagonal sensing elements. Only responses of diagonal and those adjacent to diagonal taxels are shown here. The instants showing the maximum response of the taxels are marked. The time from t1 to t8 (left-right arrow) show the response of taxels when probe is rolled from taxel (5, 1) towards taxel (1, 5). Similarly t9 to t17 (right-left arrow) depict the movement in opposite direction. (*middle*) Response of all taxels over 2.5 seconds measurement period. (*bottom*) 3D plot snap-shots obtained from the individual responses of various taxels when probe is rolled over from taxel (5, 1) towards taxel (1, 5) (time instants: t1→t3→t6→t8) and back (time instants: t9→t11→t14→t16). The direction of rolling is evident from the spatio-temporal response of the taxels on the array. Taxel (1,2) and (3,3) on the tested array were not working.