

CMOS Implementation of POSFET Tactile Sensing Arrays with On Chip Readout

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Abstract—This work presents a new design of the novel POSFET (Piezoelectric Oxide Semiconductor Field Effect Transistor) devices based tactile sensing chips - currently under fabrication. The tactile sensing chip, primarily developed for the robotic applications, consists of 4×4 POSFET touch sensing devices or taxels. In addition to the touch sensing devices, the new chip includes electronic circuitry comprising of multiplexors, current mirrors and buffers. The POSFET touch sensing devices are obtained by spin coating piezoelectric polymer P(VDF-TrFE), poly(vinylidene fluoride - trifluoroethylene), film on the gate area of MOS (Metal Oxide Semiconductor) 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.

Keywords-POSFET; Read Out; Tactile Sensing; Robotics

I. INTRODUCTION

Tactile sensing plays an important role in many applications such as robotics, electrotexiles and medical prosthesis. In robotics, the tactile information is needed during tasks like manipulation and exploration. The movement of robots from 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. The involvement of hands in majority of the exploratory, manipulation and interaction tasks calls for equipping robotic hands with tactile sensors. And desire to obtain human like touch sensing capability calls for placing a large number of tactile sensors in the limited space on body parts such as fingertips of a robot's hand.

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 [1]. Most of these sensors are big in size and 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 un-

suitable 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 (Micro-Electro-Mechanical-System) approach have also been developed [2]. 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. Mechanically flexible sensors using organic FETs (Field Effect Transistors) have also been developed for large area skin applications [3]. However, best organics are known to have a mobility of about $1 \text{ cm}^2/Vs$ versus more than $100 \text{ cm}^2/Vs$ for silicon based MOS devices [4] - limiting their usage to recording 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. 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 an improved design of novel POSFET devices based tactile sensing arrays - primarily developed for the fingertips of humanoid robot 'iCub' [5]. The work presented here extends the previous works on POSFET touch sensing devices [6] and tactile sensing chips [7]. The key features of the new POSFET tactile sensing chips, presented here, are: the implementation in CMOS (Complementary Metal Oxide Semiconductor) technology, on chip electronic circuitry (multiplexers, buffers and current mirrors) and 4×4 POSFET devices. Keeping in view the final size of chip (equal to the space available on the fingertip of 'iCub'), the number of touch sensing elements have been reduced to 4×4 (against 5×5 , reported in previous works). The reduction in the number of sensing elements also frees up space for on chip read out circuitry and the choice of 4×4 elements helps in optimum usage of read out circuitry. With center to center distance of 1 mm between adjacent taxels, the tactile arrays have human fingertip like spatial resolution. Further, the taxel size of $0.9 \text{ mm} \times 0.9 \text{ mm}$ ensures human like spatial acuity.

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

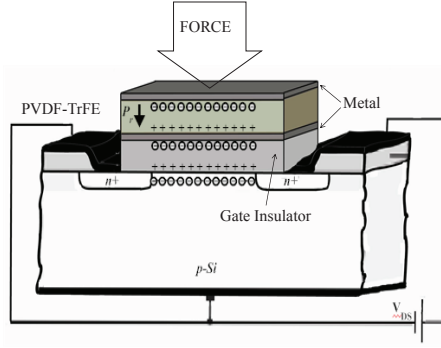


Figure 1. The Structure and working of a POSFET taxel.

II. POSFET TOUCH DEVICE - WORKING PRINCIPLE

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 $\pm Q$, 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 [8]:

$$D_3 = d_{33} \times T_3 + \epsilon_{33} \times E_3 \quad (1)$$

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 [6]. 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 [9]. 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 touch sensing devices used in this work are relatively free from such problems. They have linear response over wide range of contact forces (0.1-5 N at 20 Hz) and have already been tested for wide dynamic range (forces with constant amplitude and variable frequency) of 2 Hz - 2.13 kHz - much wider than previously reported works [6], [7].

III. TACTILE SENSING ARRAY - DESIGN AND IMPLEMENTATION

The layout of new POSFET devices based tactile sensing chip is shown in Fig.2. The key features of the new POSFET tactile sensing chip are: 4×4 POSFET touch sensing devices and on chip electronic circuitry comprising of multiplexers, buffers and current mirrors. In order to obtain a compact and small size chip, the biasing and POSFET array interface circuits are integrated on the same chip. The POSFET devices have been designed to be compatible with the CMOS (Complementary Metal Oxide Semiconductor) technology. They MOS part of the POSFET touch sensing devices will be implemented using the n-MOS technological module of 4 μm p-well CMOS process. The implementation technology has only one metal layer for wiring - resulting into an increased wiring area and hence the chip size. However, the final size of chip is decided by the space available on the fingertips of target robot, ‘iCub’. Keeping these factors in view, the number of

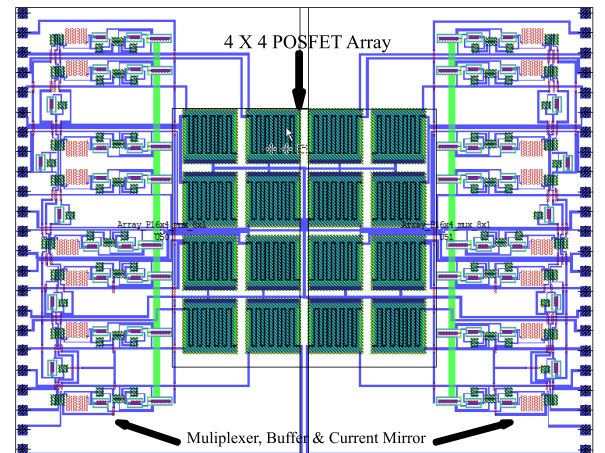


Figure 2. The layout of the improved version of POSFET devices based tactile sensing array.

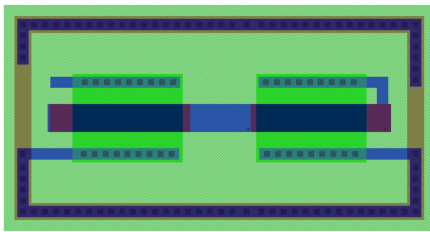
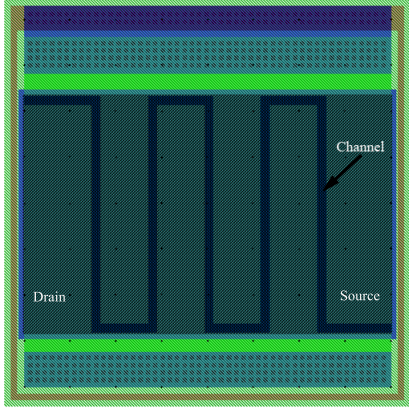


Figure 3. (top) The layout of a POSFET touch sensing device. (bottom) The layout of a current mirror

touch sensing elements have been reduced to 4×4 (against 5×5 , reported in previous works [7]). The reduction in the number of sensing elements also frees up space for on chip read out circuitry and the choice of 4×4 elements helps in optimum usage of read out circuitry.

For body sites like fingertips, the tactile sensing arrays with many miniaturized sensors are needed - especially if a spatial resolution and acuity similar to that of human fingertips is desired. The 4×4 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 chip is $0.8 \text{ cm} \times 1.0 \text{ cm}$ - smaller than the space available on the fingertips of target robot. With center to center distance of 1 mm between adjacent taxels, the tactile arrays have human fingertip like spatial resolution. Further, the taxel size of $0.9 \text{ mm} \times 0.9 \text{ mm}$, as shown in Fig. 3, ensures human like spatial acuity. The MOS part of each POSFET touch sensing device has an interdigitated structure, for high aspect ratio ($W=3096 \mu\text{m}$; $L=18 \mu\text{m}$) and large transconductance.

The scheme of the new POSFET tactile sensing chip (layout shown in Fig. 2) is given in Fig. 4. To obtain a compact and small size chip, the biasing and POSFET array interface circuits are integrated on the same chip. The layout of POSFET chip shown in Fig. 2 and corresponding scheme given in Fig. 4, have a 4×4 POSFET array,

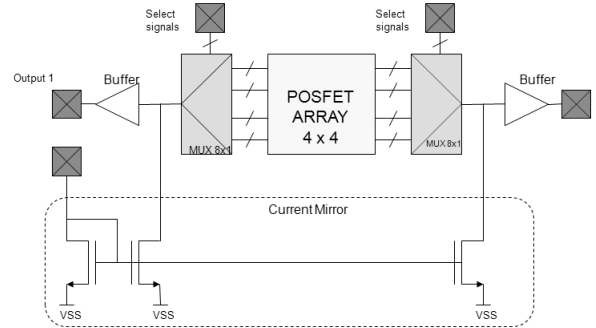


Figure 4. The schematic of the improved version of POSFET tactile sensing chip.

two multiplexers, two current mirrors and output buffers. To save the silicon area, only two current mirrors have been implemented. These current mirrors bias a given POSFET, only when it is addressed for reading, i.e. when a POSFET is addressed it is biased as well (through the output of current mirror). The layout of a current mirror is shown in Fig. 3. The alternative implementation (each POSFET device biased with a current source) would have involved sixteen current sources (and related current mirrors) and hence large silicon area. To speed up the array scanning, two independent reading channels, for even and odd POSFET devices, have been implemented. When a particular POSFET taxel is addressed and being read (e.g. an even numbered POSFET) the next (odd numbered POSFET) is biased at the same time. In this way, the transients related to biasing of the next (i.e. odd numbered) POSFET device does not increase the acquisition time. The output buffers too have been implemented on the chip for impedance adaptation. Many other test structures and chip architectures, not shown here, have also been designed and will be fabricated on the same wafer. Once fabricated, the tactile sensing chips will be integrated with more electronics circuitry and tested on a PCB (Printed Circuit Board). After required optimization steps, the PCB will be placed and tested on the fingertips and palm of the target robot.

The fabrication steps for developing tactile sensing arrays will be same as those used earlier [12]. However, fabricating current version of tactile sensing arrays will involve additional challenges such as simultaneous polarizing the polymer films (a step needed to orient the dipoles in the thickness direction and thus to obtain remanent polarization P_r) on all the taxels. A voltage of $80\text{-}100 \text{ V}/\mu\text{m}$ is needed to polarize the polymer film in

a desired direction and hence there is risk of damaging the MOS devices during *in situ* polarization step. Though this step was successfully carried out in past, presence of additional electronic circuitry in the new version will attract more attention.

IV. CONCLUSION

The POSFET devices based tactile sensing chips, presented in this work, have been designed to have spatio-temporal features similar to that of receptors in the human fingertips. 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. Keeping this in view, this work extends the research on POSFET devices based tactile sensing array and the new design also includes on chip electronic components such as multiplexers, current mirrors and buffer.

Future work will involve testing of the chips and further extending the research to develop a full tactile sensing system on chip (SOC) or in a package (SIP). Keeping this in view, attempts will be made to realize on chip circuitry for local data processing. 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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