Chapter 8
POSFET II—The Tactile Sensing Chip

Abstract This chapter extends the research on POSFET devices, presented in previous chapter, toward the tactile sensing system on chip. The tactile sensing chip presented in this chapter comprises of 5 × 5 array of POSFET devices and two integrated temperature sensors. The size of each POSFET device on the chip is 1 mm^2 and the center–center between two adjacent POSFETs is 1.5 mm. With these features, the tactile sensing chips have human fingertip like spatial resolution and spatial acuity. With a 2-D array of POSFETs and the integrated temperature sensors, the tactile sensing chips are capable of measuring dynamic contact forces and the contact temperature. The chips have been extensively tested over wide range of dynamic contact forces and temperatures and the test results are presented. The experiments presented in this chapter have been performed with the aim to examine the collective performance of a set of POSFETs. The reader interested in the electromechanical evaluation of an individual POSFET device may refer to the results presented in the previous chapter. In fact, this chapter is fundamentally linked to previous chapter hence the reader may first go through previous chapter. Since the time the POSFET tactile sensing chips were reported first, they have been redesigned and the new version have POSFETs with integrated readout electronics on the chip. A discussion is also presented in context with the redesigned tactile sensing chip and the future trend in this area. Finally, new application areas of POSFET like devices are discussed.

Keywords High resolution tactile sensing · POSFET · Tactile sensing chip · System on chip · Artificial skin · Sensor integration · Multifunctional · Wiring complexity · Integrated systems · FET · CMOS · PVDF · PVDF-TrFE · Piezoelectric polymers · Microfabrication · Flexible electronics

8.1 POSFET Tactile Sensing Chip—Design and Fabrication

The design of a distributed tactile sensing structure is greatly influenced by the target application. Referring to a humanoid robot as an example, the distribution of sensors in an area depends on the part of robot's body where sensing structure is to be placed [1, 2]. For fingers, involved in precise manipulative tasks, the sensors must be close enough to yield a good spatial resolution. This is also important for getting a better tactile image of the contacted object and for the medical applications. However, if

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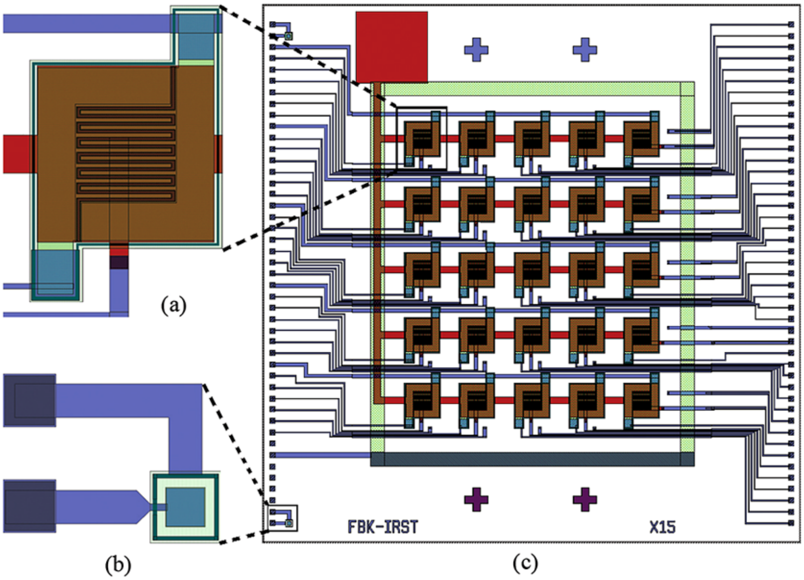


Fig. 8.1 (**a**) The layout of a POSFET device on the chip; (**b**) The layout of temperature diodes on the chip; (**c**) The layout of tactile sensing chip with 5 × 5 POSFET devices array and two temperature diodes

the sensors are to be distributed over body area such as belly or back of a humanoid then one can probably settle with lesser number of sparsely distributed sensors. If cues are taken from the human body then the sensitivity and pressure thresholds should also vary across the body.

The layout of the tactile sensing chip is shown in Fig. 8.1(c). The tactile sensing chip consists of an array of 5 × 5 POSFET touch sensing devices and two integrated temperature sensors. The layouts of a POSFET device in the tactile sensing arrays is given in Fig. 8.1. The overall dimension of the tactile sensing chip is 1.5 cm × 1.5 cm. The size of each POSFET device on the array is 1 mm × 1 mm and the center–center distance between two adjacent POSFETs is 1.5 mm. The size and spacing between POSFETs ensure human like spatial acuity and spatial resolution. With integrated sensing structures such as POSFETs it is easy to scale up/down the size and spacing between sensing elements and hence the spatial resolution. The tactile sensing chips presented here are designed for human fingertip like spatio-temporal characteristics.

The tactile sensing chip shown in Fig. 8.1(c) have integrated temperature sensors for measuring the contact temperatures. These integrated temperature sensors are basically the diodes whose output is known to vary with temperature. The lay out of a temperature diode on chip is given in Fig. 8.1(b). These integrated temperature diodes have been designed to work at 100 μA forward bias current and they have linear response up to temperature value of 70°C. A human like tactile sensing system should be able to measure multiple contact parameters such as force, temperature, hardness etc. The integration of temperature sensors on the chip, therefore, extend the capability of tactile sensing chips toward measurement of multiple dynamic contact events—the contact temperature and dynamic contact forces in present case.

The fabrication steps for the tactile sensing chips are essentially same as those followed to realize the single POSFET devices [3, 4]—presented in previous chapter. The fabrication of tactile sensing chip, however, involves some additional challenges related to—(a) deposition of the piezoelectric polymer layer with uniform thickness over all POSFETs in the array; (b) fabrication of the chip with minimum spread in the characteristics of n-MOS devices; and (c) simultaneous and uniform polarization of the piezoelectric polymer layer over all POSFETs in the array.

A number of experiments, performed on dummy silicon wafers (i.e. without any n-MOS device), to investigate the steps for obtaining uniform and controlled thickness of polymer films over large areas are reported in [5]. The concentration of solution, spinner's speed and spinning time are used as variables in these experiments. The outcome of these experiments is also described in previous chapter. The particular outcome from these experiments is spin coating a 10% P(VDF-TrFE) solution, at spin rate of 3000 rpm over for a time period of 30 sec. This combination of solution concentration, spinner's speed and spinning time results in a uniform 2.5 μm thick piezoelectric polymer layer having $<1\%$ variation across a 4 inch Si wafer. The same recipe is used in the POSFETs of the tactile sensing chips presented here. On measuring the thickness of the polymer film on various POSFETs with a profilometer (Zygo NewView 6000), the above mentioned recipe is found to yield uniform polymer film thickness.

The spread among the devices on a wafer is a common problem and a large number of factors are responsible for it. The reader interested in investigating these reasons may refer to standard literature on the device fabrication [6, 7]. The 'spread' among devices means that no two devices on a wafer have the same characteristics—they only have similar characteristics. The degree of dissimilarity is often represented as 'spread'. By carefully following the fabrication steps the spread among devices can be brought down to the permissible limits. The spread among the n-MOS devices on the tactile sensing chip can be obtained from their input characteristics. The threshold voltages (V_{TH}) and transconductance (g_m) values, obtained from the input characteristics of various n-MOS devices, are shown in Fig. 8.2. It can be noticed from figure that V_{TH} and g_m of various POSFETs are fairly uniform. The spread among POSFETs is quite low, if not negligible, and there is need to bring it down further.

The in situ polarizing of the piezoelectric polymer film is another challenge due to the fact that a voltage of 200–250 V is needed to polarize the 2.5 μm thick polymer film. Such high voltages can alter the MOS device characteristics. In addition to this, the uniform polarization of polymer, over all POSFETs, is also desired. These challenges related to polarization were met by adopting the measures highlighted in previous chapter. These measure include: (a) electrical grounding of the substrate and the metal layers under the piezoelectric polymer film of all the POSFETs on the chip; (b) putting the top metal of polymer in all POSFETs at same higher potential; and (c) increasing the potential across piezoelectric polymer in four cumulative steps

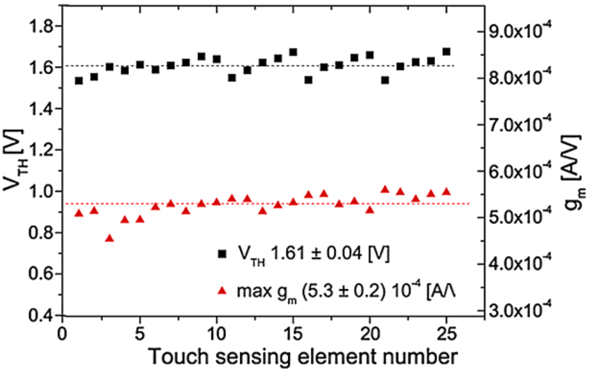
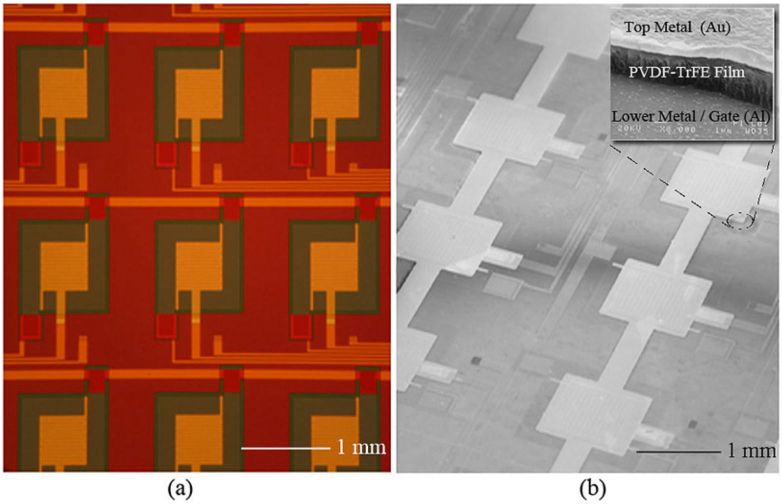


Fig. 8.2 The threshold voltages (V_{TH}) and transconductance (g_m) (at $V_{DS} = 0.5$ V and $V_{GS} = 2.5$ V) of all POSFET elements on the chip

of 50 V each. In this way, uniform polarization can be obtained in all POSFETs—without altering their characteristics. The SEM images of resulting POSFETs array before and after processing the piezoelectric layer are shown in Fig. 8.3.

8.2 Experimental Evaluation

The quantitative and qualitative evaluation of the tactile sensing chips has been carried out by applying dynamic normal forces on single or a group of POSFETs. The experimental arrangement and the source-follower (floating gate) connection scheme of POSFETs in these experiments are same as those used in previous chapter. However, they are again shown here in Fig. 8.4(a)–(b). The POSFET tactile



(a) (b)

Fig. 8.3 (**a**) A part of the 5 × 5 POSFET tactile sensing array before polymer deposition; (**b**) The SEM image of the POSFET tactile sensing array after polymer film deposition [8]

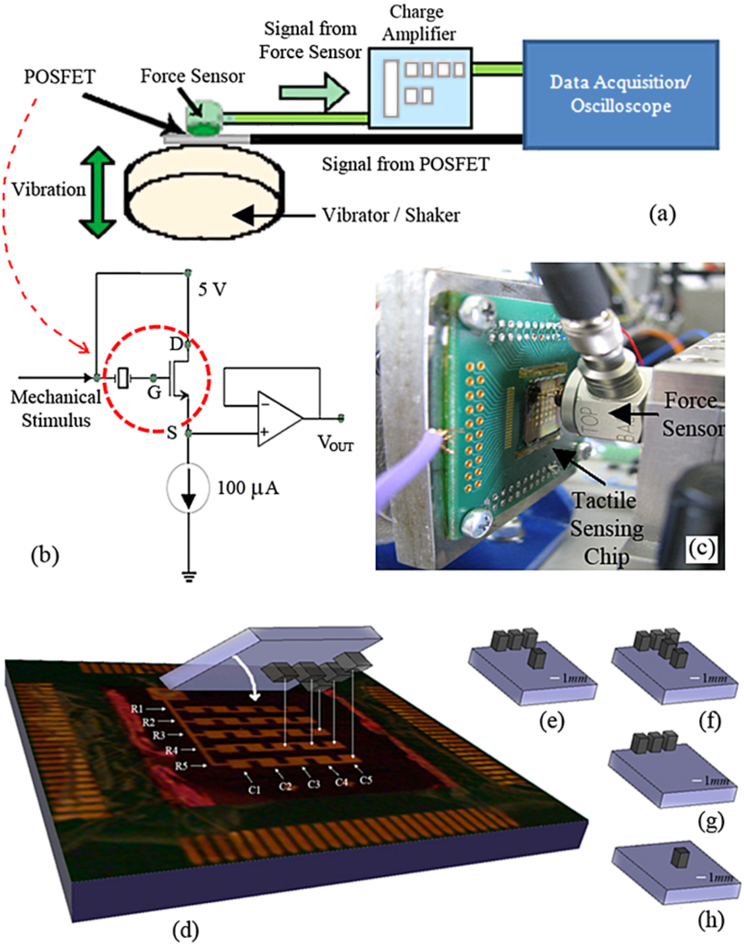
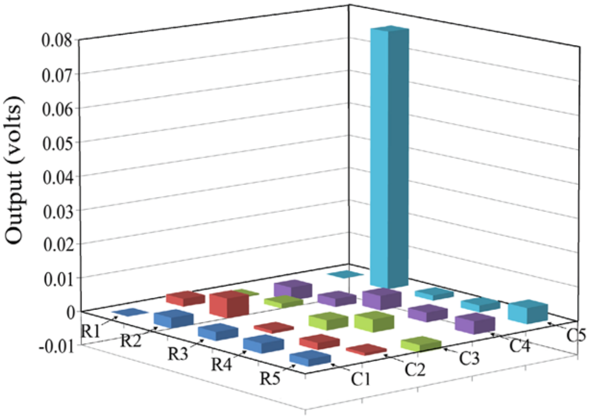


Fig. 8.4 The experimental arrangement. (**a**) The scheme of the experiment set up; (**b**) The connection scheme of POSFETs; (**c**) The image of the experiment set up; (**d**) The placing of the probes on the chip; (**e**)–(**h**) The probes employed for applying the force on single/multiple POSFETs

sensing chip is firmly placed on the TIRA shaker/vibrator, as shown in Fig. 8.4(c). The shaker is driven by a waveform generator. The dynamic force applied to the sensor is measured by an uniaxial PCB—Piezotronics force sensor. The force sensor is anchored to a manual 3D micrometer positioning device, which facilitates placing the probe right on the desired POSFETs. The 1 mm^2 sized probes are attached to the force sensor and they are employed to apply the dynamic forces on single/multiple POSFETs—as shown in Fig. 8.4(d). Various probes used for evaluating the performance of tactile sensing chips are given in Fig. 8.4(e)–(h). These probes are obtained with Eden250 3D printing system that provides high quality rapid prototyping with typical tolerance of 100 µm. During the experiments, the

Fig. 8.5 The snap-shot of the outputs of all the POSFETs on the array at the moment when output of POSFET (2,5) is maximum. A 20 Hz sinusoidal force is applied only on the POSFET (2,5)

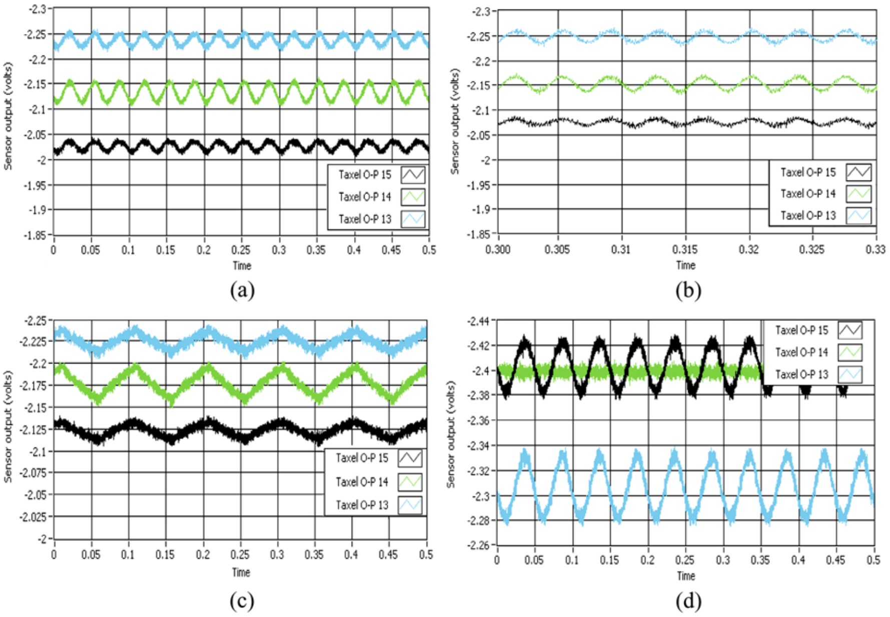


chip is covered with a 200 μm PDMS protective film. A pre-load is also used in some of the experiments to avoid loss of contact between the POSFETs and the probe. The outputs of the POSFETs and the force sensor are acquired with NI Data Acquisition board NI6259 that can synchronously acquire up to 32 analog inputs and 4 analog outputs with 16 bits of resolution and single-channel sampling rate of 1.25 MS/s.

8.2.1 *Experiments with Single POSFET Device*

Before putting the tactile sensing chips to use, it is useful to quantify the response of tactile sensing elements in terms of gain/sensitivity and range of stimuli etc. For this purpose, individual POSFETs (one at a time) on the chip were evaluated. The experimental conditions for these experiments were similar to that reported in previous chapter. Likewise, the experimental results too were found to be agreement with those reported in previous chapter. For this reason, the results related to single POSFETs are not presented here and reader may refer to previous chapter for more details.

An additional experiment related to single POSFET is to investigate the cross-talk among the sensing devices on the array. For this purpose, a dynamic force can be applied on a particular POSFET and the outputs of all the POSFETs on the array is recorded at the same time. Applying a 20 Hz sinusoidal force on the POSFET labeled (2,5), using a probe similar to the one shown in Fig. 8.4(h), results in the array of outputs shown in Fig. 8.5. The outputs shown in this figure, refer to the moment when response of POSFET (2,5) is maximum. The X and Y, in a label (X, Y), refer to the row and the column of the array respectively. From Fig. 8.5 it is clear that the outputs of POSFETs other than the one labeled (2,5) are negligible and so is the cross-talk. In a sense this also means that the tactile sensing chip can provide accurate location of the contact and good spatial resolution. The negligible cross-talk and good spatial resolution are desired for better shape/object recognition.



(a) (b)

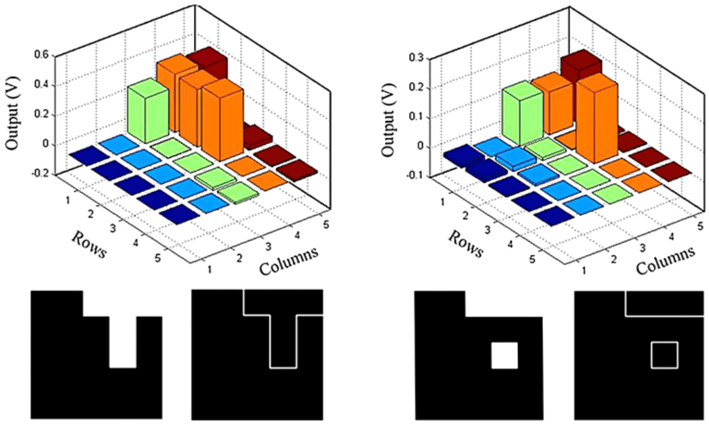
(c) (d)

Fig. 8.6 (**a**) The outputs of POSFETs (1,3), (1,4) and (1,5) for a 30 Hz sinusoidal applied force; (**b**) The outputs of the same POSFETs for a 270 Hz sinusoidal applied force; (**c**) The outputs of the same POSFETs for a 10 Hz triangular force; (**d**) The outputs of the same POSFETs for a 20 Hz sinusoidal applied force. In this case force is applied only on POSFETs (1,3) and (1,5)

8.2.2 Experiments Involving Multiple POSFETs

The previous section presents a snap-shot of the outputs of the POSFETs on the chip when force is applied only on one of them. That experiment is repeated here, but with force applied simultaneously on multiple POSFETs. Measuring the response of all POSFETs while force is applied on the selected few, one may investigate the degree of cross-talk and the variation among outputs of POSFETs. Some of the measurements made by applying dynamic normal force on multiple POSFETs are shown in Fig. 8.6.

The plots shown in Fig. 8.6(a)–(b) have been obtained by applying sinusoidal forces in normal direction on the top of POSFETs (1,3), (1,4) and (1,5)—which form a small line. The frequency of applied force in these experiment varied between 10 and 270 Hz. Using a snap-shot of these outputs, at a particular moment, one may conveniently say that response is because of a line contact. This observation is true even at higher frequencies of applied force—as evident from Fig. 8.6(b). The observations also hold if the applied force is triangular instead of sinusoidal—as evident from Fig. 8.6(c), which shows the output of POSFETs when applied force varies in triangular form. The outputs of POSFETs (1,3), (1,4) and (1,5), when a 20 Hz sinusoidal force is applied only on POSFETs (1,3) and (1,5), are shown in Fig. 8.6(d). As the spacing between two adjacent POSFETs is just 0.5 mm, one might



(a) (b)

Fig. 8.7 The response of POSFETs when force is applied using (**a**) 'T' probe of Fig. 8.4(e); (**b**) partial 'T' probe of Fig. 8.4(f)

expect some output from POSFET (1,4) due to undesired feature such as cross-talk etc. However, such spurious output is absent in the plots shown in Fig. 8.6(d). These results indicate that the tactile sensing chips have low or negligible cross-talk and the high spatial resolution (< 1 mm).

The response of various POSFETs to a 670 Hz sinusoidal force, applied on the POSFETs (1,3), (1,4), (1,5), (2,4), and (3,4), is shown in Fig. 8.7(a). The POSFETs (1,3), (1,4), (1,5), (2,4), and (3,4) all-together make a 'T' shape. The 'T' shaped probe of Fig. 8.4(e) is employed in this case for applying the force. In Fig. 8.7(a), the POSFETs pressed by the probe can clearly be differentiated from others. The variation among the responses of the POSFETs that were pressed is low (maximum of 18.1 mV is recorded for POSFET (3,4) and minimum 16.4 mV from POSFET (1,3)) and as expected they are in phase. A snap-shot of the bar and binary images, obtained from the normalized response of various POSFETs is also shown in Fig. 8.7(a). Similar outputs is observed with 20, 120, 370 Hz sinusoidal forces. The same experiment when repeated with the probe of Fig. 8.4(f) results in the response given in Fig. 8.7(b). The negligible output of POSFET (2,4), in Fig. 8.7(b), is in tune with the results presented in Fig. 8.6(d). These result validate the high spatial resolution (< 1 mm)—for which, the chip is designed. The data obtained from these experiments is also used to detect the edges of the contact. The edge detection results, carried out using gradient operators, are also shown in Fig. 8.7.

The experimental results presented above extensively evaluate the performance of tactile sensing chips. These experimental studies involve the application of dynamic normal force on selected POSFETs or the selected points in space, whereas a real world stimulus generally varies both in time and space. Therefore, it is also important to see if and how much effective are the tactile sensing chip when they are subjected to such a stimuli. As an example, would it be possible to detect or reproduce the motion of an object if it rolls over the chip—as in Fig. 8.8. In case

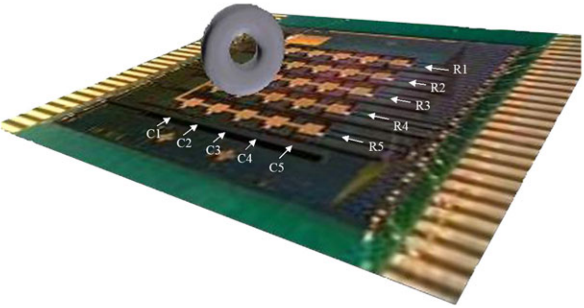


Fig. 8.8 A *ring* bearing rolling over the diagonal POSFET devices on the chip

of rolling the contact point moves over one POSFET to next and therefore involves both spatial and temporal variations. With this in mind, the performance of the chip is evaluated by rolling a probe manually over the diagonal POSFETs on the array. The probe used in this experiment is a ring bearing that is 3 mm wide and has outer diameter of 1.5 cm. The width of probe is good enough to fully cover and press the diagonal POSFETs and partially the adjacent ones (immediately next to diagonal POSFETs). The representative arrangement of the experiment is shown in Fig. 8.8. Since the probe is rolled manually, the force applied in this experiment is not controlled as it is hard keep it constant. In this context, the results from this experiment are qualitative in nature. The response of various POSFETs is shown in Fig. 8.9(a)–(b). The response of diagonal POSFETs is higher than that of the off-diagonal elements as they were fully covered by the probe. The maximum response of the diagonal POSFETs is around 0.15 V. The response of adjacent POSFETs is less than half of this value. The minor variations among the outputs of diagonal POSFETs is mainly because the controlled force is not applied. The contact sequence reproduced from the POSFETs' responses is shown in Fig. 8.9(c)–(j). It clearly demonstrates the capability of tactile sensing chip to detect dynamic contact events that are distributed, both, in space and time. The time period (from t1 to t17; from t2 to t18 etc.) of 0.41 sec for one rolling cycle (i.e. back and forth rolling of diagonal elements) obtained from Fig. 8.9 is found to be in good agreement with the actual travel time of 0.416 sec. A total of six rolling cycles are completed in period of 2.5 seconds shown in Fig. 8.9(a). Thus, the tactile sensing chips presented here are also capable of detecting the complex dynamic contact events like rolling of an object.

8.2.3 Temperature Measurement

In addition to the array of POSFET devices, each tactile sensing chips contains two temperature diodes that can be used to measure the ambient as well as contact temperatures. The performance of temperature diodes can be evaluated from the diode characteristics at various temperatures. The characteristic plots of the temperature diodes at various temperatures, in the range 25°C–75°C, are given in Fig. 8.10(a).

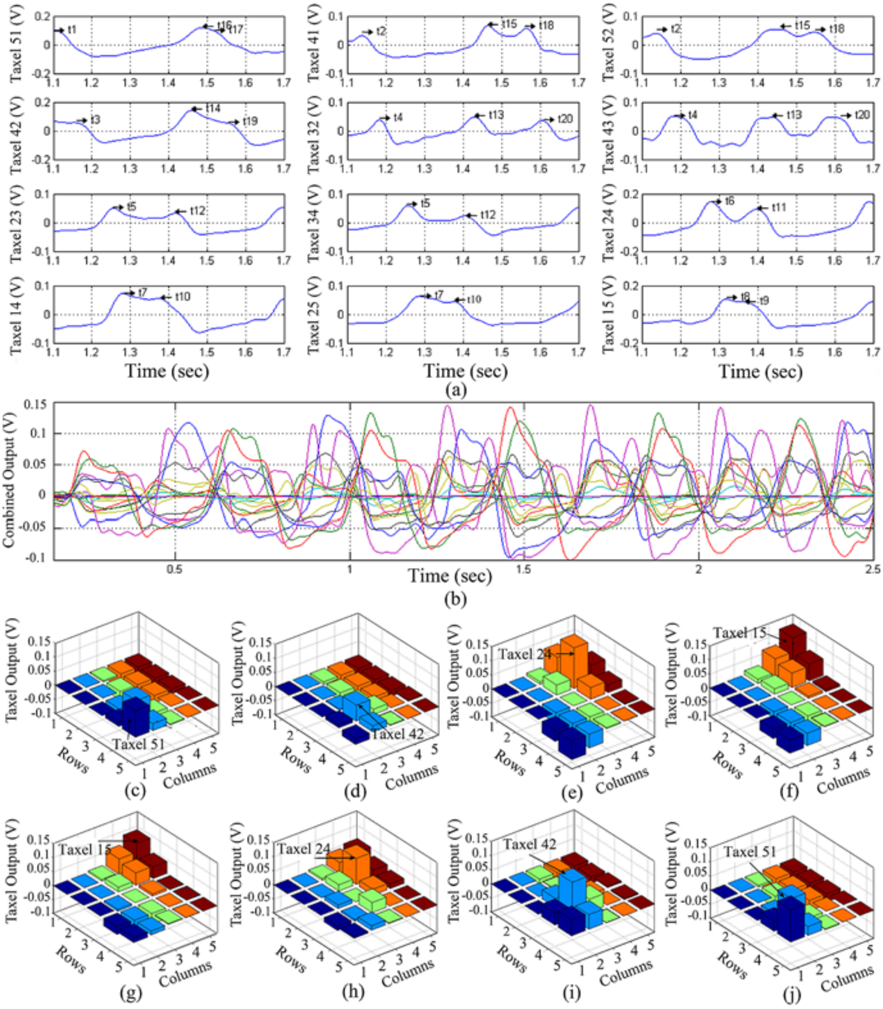
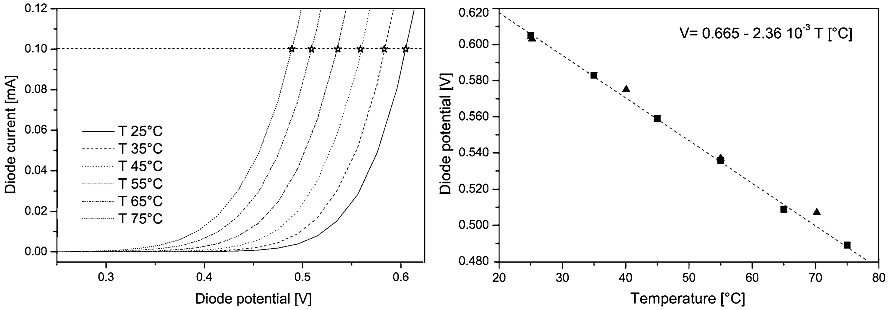


Fig. 8.9 (**a**) The outputs of all POSFETs (or taxels) on the chip when probe is rolled over the diagonal elements. The time t1–t8 refer to the instants of maximum outputs when probe rolls over the POSFETs from (5,1) toward (1,5). Similarly, t9–t17 refer to instants when probe rolls in the opposite direction; (**b**) The outputs of diagonal and adjacent POSFETs during the period between t1=1.1 sec and t21=1.7 sec; (**c**)–(**j**) The snap-shots of the outputs at instants: t1 → t3 → t6 → t8 and t9 → t11 → t14 → t16. The POSFET (3,3) on the chip is not working

Using these plots one can obtain the diode potentials at a fixed diode current, but at different temperatures. In this manner, the diode potential is related to the contact temperature and changes in diode potentials is used to obtain the changes in temperature. In case of tactile sensing chip presented here, the temperature diodes are designed for forward bias current of 100 μA and hence the same is used to obtain the relation between diode potential and temperature. The variation of diode output



(a) (b)

Fig. 8.10 (**a**) The characteristics plots of a temperature diode at various temperatures; (**b**) The output of the diode at various temperatures. The diode current value is 100 μA

(i.e. diode potential) with the temperature is shown in Fig. 8.10(b). It is clear from the figure that the temperature diode output is linear with sensitivity of 2.36 mV/°C.

It should be noted that even if the temperature diodes have primarily been integrated on the chip to measure the contact temperatures, they can also be used to detect variations in the ambient temperature. The latter gains significance in the light of the fact that P(VDF-TrFE) polymer also exhibits pyroelectric behavior i.e. the variations in the ambient temperature also results in the generation of charge [9, 10]. This means that while measuring contact forces any variation in the contact or ambient temperature could introduce error in the POSFET's output. Such errors can be mathematically compensated by using the value of temperature variation recorded by the diode and relating the same with the database carrying the response of P(VDF-TrFE) at various temperatures. In this regard, the presence of temperature diodes is especially useful when the chip is put to use in a real world environment.

8.3 Future Dimensions

The experimental result presented in this chapter, as well as in previous chapter, tell a great deal about the utility of POSFETs based tactile sensing chips. However, it is worthwhile to note that the chips are yet to employed in a real world environment. There are many challenges to be overcome before that happens. As an example, it is desirable to have digital and reduced amount of data coming out of the chip. Digitizing the signal on the chip certainly helps in reducing the number of wires needed to transfer the data to other levels of processing. Reduced number of wires are highly desirable in applications like robotic hands where large number of wires can counter the dexterity of the hand. Similarly, it is desirable to reduce the data coming out of the chip—not only to efficiently utilize the communication channel but also for optimum usage of the limit computational throughput. The data coming out of the chip can either be reduced by rejecting any redundant data on the chip itself or by locally processing the raw data on the chip. Similarly, it is also desired

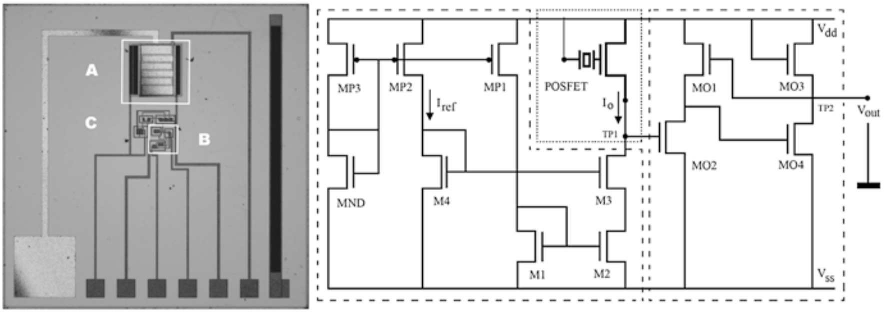


Fig. 8.11 (*left*) The image of the chip with a POSFET tactile sensing chip (*A*) and the integrated electronics (*B*) and the high compliance current sink (*C*). (*right*) The circuitry scheme of the chip. POSFET is used in source-follower (floating gate) configuration, connected to a current sink (on the *left side*) and an output buffer (on the *right side*), highlighted with *dashed contours*

to have touch or tactile sensing structure that can bend, stretch and conform to any surface. All these desired requirements become important especially when touch sensors or tactile sensing arrays are to be spread over large areas. The reader may refer to Chap. 4 *(on system issues)*, where some related issues are discussed. The work in this section is related to some of the recent advances on POSFETs and related research.

8.3.1 Toward Tactile Sensing System On-Chip

8.3.1.1 POSFET Device with On-Chip Signal Conditioning Module

One of the recent additions to the advances on POSFET research, is the design of new POSFET tactile sensing devices with on-chip electronics and its implementation using CMOS technology [11]. The chip shown in Fig. 8.11 consists of POSFET device and the integrated bias and signal conditioning circuitry to obtain a compact miniaturized system, keeping in view the system level extension planned for the future. In particular, a high compliance current sink and an output buffer have been integrated. The high compliance current sink provides the current I_{DS} (= 90 μA) for the POSFET device and the output buffer help in impedance matching and decoupling the sensing device from the chip output. Furthermore, for large transconductance the n-MOS device in POSFET has also been redesigned with an aspect ratio (W/L) of 273. The POSFET device has been designed to have an active area of 0.9 mm × 0.6 mm so as to obtain spatial acuity comparable to that of human fingertips (∼1 mm). The large value of channel width (W) is obtained by designing a serpentine like or interdigitated gate structure, similar to the one shown in the layout in Fig. 8.1(a). The length of source and drain diffusions has been reduced in the new design to reduce the source and drain parasitic resistance by a factor 5, which reflects a significant improvement of the actual transconductance over

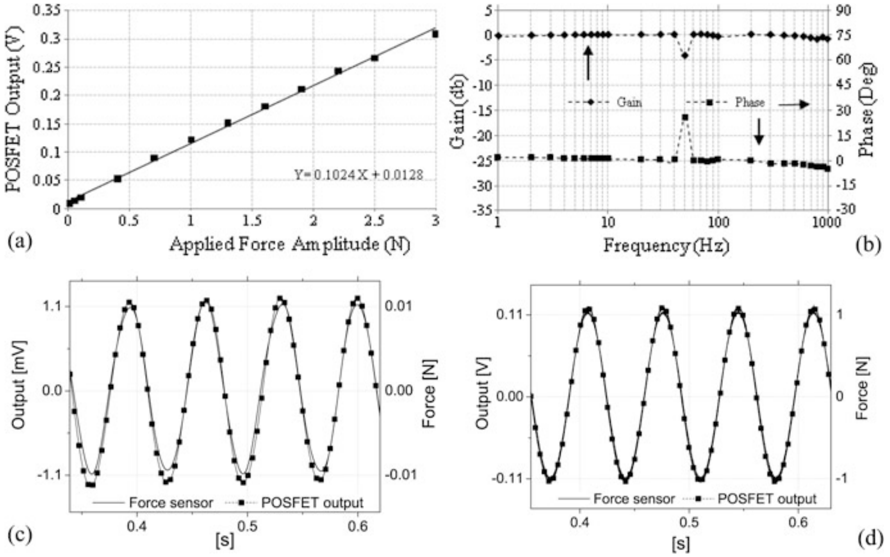


Fig. 8.12 (**a**) The response of POSFET tactile sensing device to normal dynamic forces in the range 0.01–3 N; (**b**) The gain-phase plots. The peaks at 50 Hz are due to the 50 Hz electrical noise; (**c**) The output of POSFET when 0.01 N, 15 Hz sinusoidal force is applied; (**d**) The output of POSFET when 1 N, 15 Hz sinusoidal force is applied

the previous version of POSFET. In the chosen circuitry implementation, shown in Fig. 8.11, the POSFET is connected in source follower configuration. In operative conditions the FET gate i.e. the lower electrode of the P(VDF-TrFE) piezoelectric film is floating and the top contact is short-circuited to drain. The chosen source-follower configuration does not provide amplification like a common source configuration. Nonetheless, this configuration provides higher output robustness to gain mismatches between different devices, which is useful when an arrays of sensors is used.

The response of POSFET devices to normal dynamic forces in the range 0.01–3 N is given in Fig. 8.12. The new POSFET devices are capable of detecting contact forces as low as 0.01 N (∼1 gmf), with negligible delay between input force and output of POSFET. It should be noted that the POSFET outputs in the results presented here are unamplified. The response plot is linear in the tested range and the sensitivity of POSFET devices is 102.4 mV/N—which is more than twice the value for previous version of POSFET device. Therefore, the on chip electronic module and redesigned POSFET have resulted in an improved sensitivity. The gain-phase plots are flat in the tested frequency range of 1–1000 Hz.

8.3.1.2 POSFET Array with On-Chip Electronics

Another extension of the POSFET research is toward the tactile sensing chips consisting of tactile sensing arrays and on-chip electronics. The scheme of the new

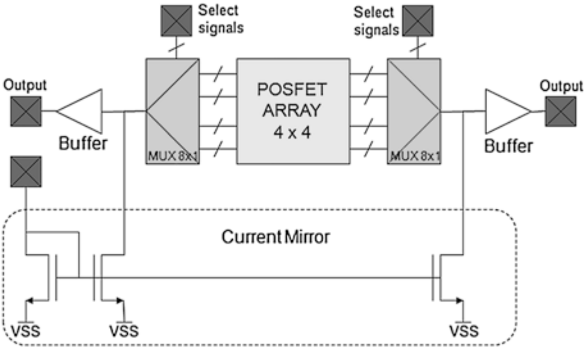


Fig. 8.13 The scheme of the POSFET tactile sensing chip with biasing and array interface circuits

POSFET tactile sensing chip is given in Fig. 8.13. In addition to the POSFETs array, the new scheme also includes the biasing and interface circuitry. The new scheme has a reduced number of sensing elements (4 × 4) in the POSFETs array. The choice of 4 × 4 array is better than 5 × 5 as it results in an optimum usage of the read out circuitry. The scheme of new tactile sensing chip, given in Fig. 8.13, has a POSFET array, two multiplexors, two current mirrors and output buffers. Going by the earlier POSFET connection scheme, shown in Fig. 8.4(b), sixteen current sources would be required on the chip. If followed, this would mean a large area on the chip would be consumed by the current sources. Therefore, to save the silicon area, only two current mirrors are used in the new scheme. 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) [12]. The new scheme has two independent reading channels, for reading even and odd POSFET devices. The independent reading channels are employed to speed up the array scanning. When a particular POSFET 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 in the new scheme provided impedance adaptation.

The layout of new tactile sensing chip, following the scheme presented in Fig. 8.13, is given in Fig. 8.14 [13]. As mentioned earlier, the chip consists of a 4 × 4 POSFET array, two multiplexors, two current mirrors and output buffers. The size of POSFET array has been reduced to 4 × 4—which has made available more space for on chip read out circuitry. The POSFET devices have been designed to be compatible with the CMOS (Complementary Metal Oxide Semiconductor) technology. The overall dimension of this tactile sensing chip is 0.8 cm × 1.0 cm, size of each POSFET is 0.9 mm × 0.9 mm, and the aspect ratio is high (Channel width, $W = 3096\ \mu\text{m}$; Channel length, $L = 18\ \mu\text{m}$). With center to center distance of 1 mm between adjacent POSFETs, the tactile arrays will have human fingertip like spatial resolution. The biasing and interface circuits are integrated with the array on the chip. To save the silicon area, only two current mirrors have been implemented. The output buffers too have been implemented on the chip for impedance adaptation. Many other test structures and chip architectures, not shown in Fig. 8.14, have also

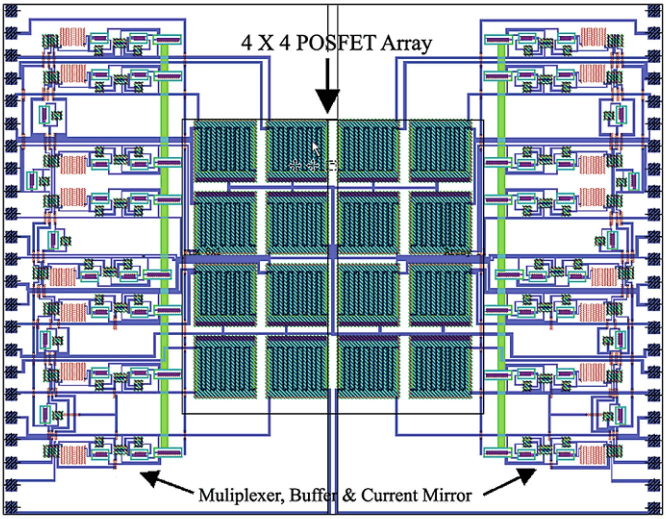


Fig. 8.14 The layout of the tactile sensing chip with integrated electronics and POSFET array

been designed and will fabricated on the same wafer. After fabrication and required optimization steps, the tactile sensing chips can be used at places like fingertips of a robot. With these advances, the POSFET devices based tactile sensing system on chip can potentially provide the much required tactile analogous of the CMOS optical array.

8.3.2 *Toward Bendable Tactile Sensing Chip*

The aforementioned POSFET devices based tactile sensing chips are fabricated on planar silicon. However, in Chap. 4 it is argued that any tactile sensing structure with sensors distributed in an area should be mechanically flexible so as to conform to the body parts of a robot or any 3D surface. Therefore, obtaining the mechanically flexible tactile sensing chips is an important future direction of the POSFET research. To this end, the potential alternatives include the fabrication of tactile sensing chips following the ‘chip-on-flex’ concept. With this approach, the bendable version of POSFET chip is obtained by first fabricating the devices on the SOI (Silicon on Insulator) wafers and then etching the oxide under the thin top silicon layer. Following this step the chip is finally transferred to flexible receiver substrates. Another interesting approach is to follow the nanostructures based route for flexible electronics. The nanostructures based route for flexible electronic systems is particularly interesting as it allows printing of electronics and sensors over unconventional substrates (e.g paper, plastic etc.) and over areas that could be larger than the wafer size. Furthermore, nanostructures can be tailored to sense different type of parameters. In

Fig. 8.15 The envisioned picture of light-weight, ultra-flexible, high-performance and cost-effective electronic skin. The devices in the picture are similar to the POSFET devices presented in this chapter

this approach, the nano-/micro structures are fabricated or synthesized (using top–down or bottom–up approach) of substrates like glass, silicon etc. These structures are then selectively transferred to large and flexible receiver substrates using elastomeric transfer stamps. Once on the receiver substrates, the arrays of nano-/micro structures can be processed to obtain the electronic devices such as TFTs (Thin Film Transistors) [14, 15]. Repeating the procedure, the integrated electronic circuits can be obtained over large areas. The POSFET like devices can also be developed after fabricating the transistors on the flexible substrates. The approach is promising for robotic tactile sensing as it will enable high-performance and cost-effective electronic skin or textile solutions, as envisioned in Fig. 8.15. Furthermore, the skin will be light-weight and ultra-flexible solutions. As an example, if an array of 100 silicon wires (assuming dimensions of each wire to be 2.5 μm × 10 μm × 1000 μm and 10 μm spacing between the wires) is used to develop an electronic or sensing component over a 50 μm thick flexible polyimide (e.g. Kapton) substrate, then the total weight of the structure will be around 7.4 mg/cm^2 (considering the densities of silicon and polyimide to be 2.33 g/cm^3 and 1.42 g/cm^3 respectively. This value is approximately 100 mg/cm^2, if the substrate thickness is considered same as that of average human skin thickness i.e. 0.7 mm. These values are much lower than the per cm^2 weight of human skin (223 mg/cm^2) presented in Chap. 3.

8.4 Summary

The design, fabrication and experimental results from the novel POSFET based tactile sensing arrays have been presented in this chapter. At first glance, the POSFET based tactile sensing arrays—in the present state, do not appear fit to be termed as ‘tactile’ (strictly following the definition of tactile sensing, presented in Chap. 2) as there is no local processing circuitry. However, a closer look shows that POSFET sensing elements—integral devices comprising of transducer and the electronic unit i.e. transistor, have some inherent processing (although very basic) and hence they are truly ‘tactile’. The presence of temperature sensing devices, makes them multi-functional. The integral sensor unit or the POSFET device conforms very well with the ‘Sense and Process at the same place’ concept, presented in Chap. 4. POSFET based tactile sensing arrays are expected to be more sensitive than those obtained with similar approaches like the extended gate approach. An argument has also been presented in this regard. The processing of polymer film on the POSFET devices has been successfully achieved, as is evident from various figures and results presented in this chapter. The relatively low melting point ($T_m \approx 150°\text{C}$) of P(VDF-TrFE) and the fact that melting point may destroy the device, places the tightest constraints on chip packaging, post-processing and assembly conditions. Certain fabrication steps like in situ polarization of the polymer film are challenging and should be performed carefully in order to ensure higher yield. It is observed that the tactile sensing array presented here have good spatial resolution ($\sim$1 mm) and a linear dynamic response over wide range of forces. The POSFET devices, in a source-follower configuration, has been tested for a wide range of input forces (0.2–5 N) and wide range of frequencies (2 Hz–2.13 kHz). It is observed that the average response of a POSFET based taxel is 49 mV/N—which can be higher if the same POSFET device is used in common-source configuration. The new version of POSFETs, with on-chip electronics, has an improved sensitivity of 102 mV/N, which is more than twice the previous value. Better spatial resolution allows the detection of contact point and contact image, more accurately, which has been demonstrated with a number of plots. The results presented here are promising and to fully exploit the advantages and capabilities of POSFET based tactile sensing arrays, more experiments—like detecting complex object shape and the ability to detect shear forces etc., are needed to be performed. The POSFET based tactile sensing chips, presented in simplest form, can be easily extended to accommodate read-out circuitry and some local processing circuitry. To this end, POSFETs with on-chip electronics have already been fabricated. The POSFET based approach provides a strong basis for having a SIP/SOC, which can potentially solve the wiring complexity also.

The POSFET tactile sensing chips are primarily meant to be used for robotic body sites such as fingertips. However, with some changes in the design and distribution of POSFETs, they can also be employed other applications such as biomedical instrumentation and wearable textiles. For instance, due to presence of piezoelectric polymers, parameters like pulse rate, heart beat and body temperature etc. can be detected with POSFETs, after some modifications. Humidity, which is known to affect the output of piezoelectric polymers, could be another parameter. Among others, the requirement of mechanical flexibility is the most important feature needed for making POSFETs suitable for these applications.

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