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POSFET tactile sensing arrays using CMOS technology

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ABSTRACT

This work presents new tactile sensing chips consisting of 4 × 4 array of POSFET touch sensing devices (or taxels) and 4 diodes to measure contact temperature. In the new version presented here, the tactile sensing chips have been fabricated using CMOS technology. Both, the individual taxels and the array are designed to match spatio-temporal performance of the human fingertips. To detect contact parameters such as contact force, the taxels utilize the contact induced change in the polarization level of piezoelectric polymer (and hence the changes in the induced channel current of MOS). The performance of POSFET device has been evaluated in the dynamic contact forces range of 0.01–3 N. The response of POSFET is linear in the tested range, with the sensitivity (without amplification) of 102.4 mV/N – which is more than twice the response of POSFETs presented earlier.

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1. Introduction

Touch sensing plays an important role in various application domains such as robotics, electrotextiles and medical prosthesis. A large amount of efforts has been devoted on the development of tactile sensors and over the years many new touch sensors using different materials and transduction methods, viz.: resistive [1], piezoresistive [2], piezoelectric [3,4], capacitive [5], optical [6], magnetic [7], electron tunneling [8], etc. have been developed. Suitability of these sensors to any application depends on a number of constraints including sensor size, sensor response time, and physical features such as bendability or conformability of the sensor patch etc. [9,10]. For instance, many times the sensors are big in size. Considering also the electronic circuitry associated with sensors the big sized sensors are unsuitable for body sites like robot's fingertips, where large numbers of sensors with high density are needed. For this reason, MEMS based miniaturized touch sensors with on-chip electronics have been explored [2,11,12]. MEMS based sensors are quite sensitive. However, their usage is limited to applications where the strength of the contact forces (to be measured) is very small. For instance, the maximum contact forces (∼0.25 N) that MEMS based sensors can detect lie in the lower range of the contact forces experienced by humans in a normal manipulative tasks (∼0.15−0.9 N).

The mechanically flexible OFETs have been recently reported for measuring parameters like pressure [13,14]. Besides bendability, the OFETs have advantage of economical fabrication. However, organic semiconductor based devices typically have short life, are less robust, and much slower in comparison with the devices developed using silicon technology. Organics are known to have a low mobility (about 1 cm^2/Vs versus about 1000 cm^2/Vs for single crystal silicon) – which limits the usage of organic semiconductor based devices or sensors to the measurement of slow varying contact events. Through systematic studies and design of various organic molecules, organic semiconductor based devices with higher mobility (an order of magnitude higher than usual value) have been reported recently and further optimization may be achieved in the future [15,16]. However, when it comes to high-performance electronics the challenges are not just related to mobility. Other factors such as channel length, high quality dielectric, ohmic contacts, etc. are also important for high-performance of device. All together these factors pose significant challenge in realizing high performance systems with organic semiconductors. On the other hand, the precision down to sub-micron scale, and the high quality of materials used in silicon technology allows us to have high performing and miniaturized sensors with possibility of having high performance electronics on the chip (leading to a full tactile sensing system on chip) [4]. The touch sensing chips reported in this work are therefore developed using the silicon technology.

This work presents the design, fabrication and evaluation of a new version of POSFET devices based tactile sensing chip. The tactile sensing chip, with an array of 4 × 4 POSFET devices, has been implemented using CMOS technology. The CMOS implementation

Abbreviations: POSFET, Piezoelectric oxide semiconductor field effect transistor; OFET, organic field effect transistor; P(VDF–TrFE), poly(vinylidene fluoride–trifluoroethylene); MOS, metal oxide semiconductor; MEMS, microelectromechanical systems; CMOS, complementary metal oxide semiconductor; LTO, low temperature oxide; LPCVD, low pressure chemical vapor deposition; PDMS, polydimethylsiloxane.

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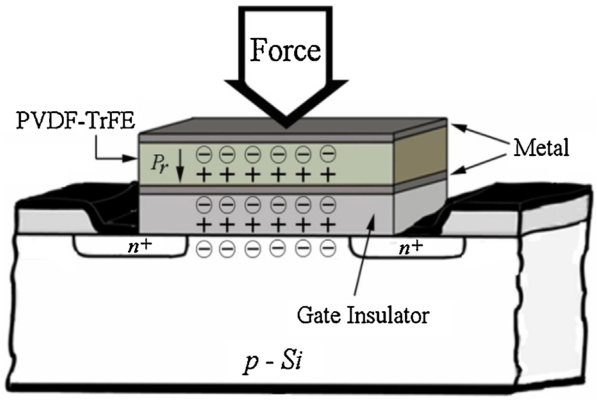


Fig. 1. The structure and working principle of a POSFET touch sensing device.

is useful as it will allow us to realize on-chip electronics and further extend the present work toward tactile sensing system on chip. This also extends our previous work on the POSFET tactile sensing devices, where POSFET sensing device and tactile sensing chip were realized using NMOS technology only [3,4,17]. The POSFET devices in the new chip have also been redesigned to have an aspect ratio (W/L) of 273. As shown later in Section 4, the redesigned POSFET results in improved sensitivity, which is more than two times that reported previously [3].

This paper is organized as follows: The concept and working principle of POSFET touch sensing device are presented in Section 2. Section 3 presents the design and fabrication of the POSFET tactile sensing arrays. The evaluation of new POSFET based tactile sensing chip is presented in Section 4. Finally, the results are summarized and discussed in concluding Section 5.

2. Working principle of a POSFET touch sensing device

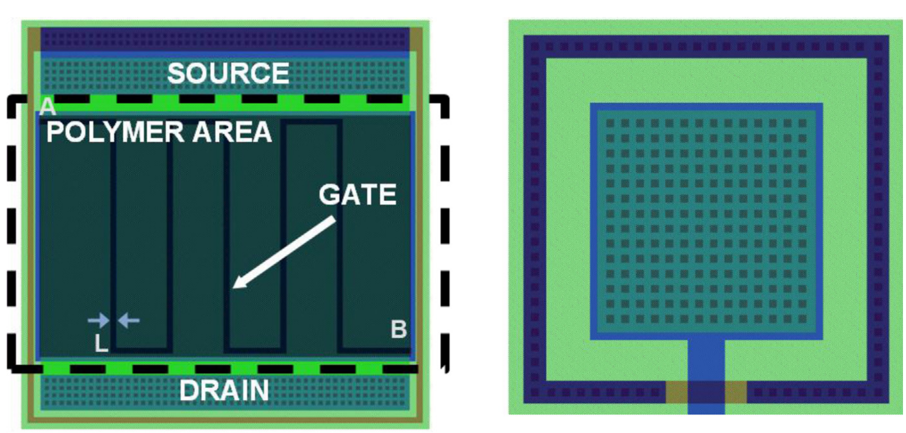
The structure of a POSFET touch sensing devices is shown in Fig. 1. The piezoelectric polymer film is present over the gate area of the MOS device. The transducer material is thus an integral part of the device. The remnant polarization (P_r) of the polarized polymer results in an intrinsic electrical dipole equivalent to fixed charges $\pm Q$, as shown in Fig. 1. In real devices, either through external connections or parasitic resistance of the capacitor, free charge is redistributed on capacitor terminal in order to compensate the electrical dipole. When external force is applied on the POSFET device, additional charges (proportional to the applied force) are generated in the piezoelectric polymer film. Because of charge neutrality requirements the additional charge (or the force variation) is reflected into the channel, thereby modulating the charges in the induced channel. In this way the (contact) force is directly reflected as the variation in channel current of the POSFET devices – which can be further processed by an electronic circuitry that may also be integrated on the same chip. Using semiconductor devices as sensor, as proposed here, enables true system integration, as the integration of sensor and electronics begins right from the transducer level.

Similar approaches, but using extended gates, have been reported in the past for ultrasonic [18], pressure sensing [19] and touch sensing [20,21]. In the extended gate approach, the gate terminal of a MOS device is connected to a large size electrode or to an extended gate that is located elsewhere on the chip. Like POSFETs, the extended gate approach too 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 (whose value depends on the substrate), which in turn, significantly attenuates the voltage available at the gate terminals of MOS transistors. Thus, benefits of closely located sensor and electronics are not fully exploited with extended gate approach. With piezoelectric polymer on the gate of the MOS itself, the POSFET touch sensing devices are relatively free from such issues. Further, unlike extended gate approach, the POSFETs occupy lesser area on the chip. The saved silicon area can be used to accommodate on-chip electronics and signal conditioning/processing circuitry.

3. Array design and fabrication

3.1. Design of POSFET devices

The POSFET touch sensing devices on the chip have been designed to have an active area of 0.9 mm × 0.6 mm, to obtain spatial acuity comparable to that of human fingertips (∼1 mm) [22]. The n-MOSFET devices in POSFETs have been designed to have an aspect ratio (W/L) of about 273 for large transconductance (g_m). In practice, the transconductance varies with the operating regions and biasing of the transistors. Nonetheless, it is proportional to the process parameter (k_n) in both linear and saturation regions of the transistors. The process parameter, which is defined as $k_n = \mu C_{ox} (W/L)$ (where μ and C_{ox} refer to mobility and gate oxide capacitance per unit area respectively) is directly proportional to the aspect ratio and therefore during the design phase the value of



(a) (b)

Fig. 2. (a) The POSFET touch sensing device design (W is the length between the ends marked as A and B. The channel length L is shown as distance between the two arrows). (b) The design of temperature diodes.

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