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A conceptual and simulation study on curved MOSFET based current mirror integrated pressure sensors (CM-CMIPS)

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A simulation study on curved MOSFET-based current mirror integrated pressure sensors (CM-CMIPS) has been presented in this paper. The pressure sensing structures studied in this work have contained circular and square curved MOSFETs embedded on circular and square silicon diaphragms. The proposed pressure sensors have utilized the piezoresistive effect in MOSFETs as transduction mechanism and have employed current mirror circuits as readout circuits for detecting the externally applied input pressure. This work has included a comparative study for the following six pressure sensing structures: two structures each utilizing a p-type and n-type circular curved channel MOSFET embedded on circular diaphragms, two structures each utilizing a p-type and n-type square curved channel MOSFET embedded on square diaphragms, one structure consisting of both p- and n-type circular curved channel MOSFETs each embedded on two separate circular diaphragms, and the last one consisting of both p- and n-type square curved channel MOSFETs each embedded on two separate square diaphragms. The proposed CM-CMIPS sensors have been designed using standard 5µm CMOS technology. The pressure sensitivities of square-shaped CM-CMIPS employing p-MOS, n-MOS, and CMOS (both p- and n-MOS) structures have been found to be approximately 515, 407, 2151 mV/MPa, respectively, and 505, 661, 2223 mV/MPa, respectively, for the circular-shaped sensors.

Keywords: CMOS, Current Mirror, MEMS, MOSFET, Piezoresistive effect, Pressure sensor

1 Introduction

Pressure is a physical quantity and an important parameter that has been linked to a range of results in diverse research domains and applications, including consumer electronics, automotive, industrial, bio-medical, aerospace, and defense applications[1-4]. A pressure sensor is a device consisting of mechanical, electrical, and electronic components that converts physical pressure signal into an electrical signal and can measure absolute, gauge, and differential pressure[5-6]. The present and future market demand for miniaturized pressure sensors is significantly high, and its market estimation is expected to be 18 billion USD in the year 2024 and approximately 28 billion USD by 2029[3]. Advancements in semiconductor microfabrication, micromachining, and packaging techniques have led to the evolution of miniaturized pressure sensors employed on Micro-Electro-Mechanical-System (MEMS) technology that acquired great demands due to their small-scale size, low price, outrageous performances, and ability to be integrated with microelectronics[7-8]. A basic MEMS pressure sensor mainly employs a thin flexible diaphragm which converts an externally applied input pressure into deflection (i.e., mechanical signal) and a transduction mechanism which converts the diaphragm deflection into an electrical output signal. Silicon diaphragms of square, rectangular, and circular shapes that are fabricated using micromachining techniques are used as pressure sensing mechanical elements in MEMS pressure sensors[5-6]. The most commonly and frequently used transduction mechanism in MEMS pressure sensors is piezoresistive sensing[9-14]. Piezoresistive pressure

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sensors employ one or more silicon piezoresistors whose changes in resistance results in the diaphragm deflection under the application of external pressure. The input applying pressure is proportional to an output voltage that can be achieved by connecting the piezoresistors in Wheatstone bridge configuration[5-6]. The piezoresistive pressure sensors have great advantages due to their simple construction, lower in price, robustness with good resistance, vibration, and dynamic pressure changes, and employing Wheatstone bridge-based readout circuits are very simple. However, these piezoresistive pressure sensors accrue major disadvantages of the requirement of temperature compensation circuits, as the silicon piezoresistors suffer from the temperature cross-sensitivity[13-14].

The recent advancements in technologies, circuit integration, and sensing principles, promoted the development of MOSFET-embedded sensing techniques and the use of CMOS readout circuits as an alternative to traditional piezoresistive sensing and Wheatstone bridge-based readout circuits for pressure sensor applications[15-18, 20]. The MOSFET-embedded sensing mechanism works on the piezo-MOS effect i.e. the piezoresistive effect in MOSFET and works on the theory that the drain current variation leads to the variation in mobility of electrons and holes of the transistor under applying input pressure[17]. The current mirror circuit is one of the extensively used CMOS circuits for biasing and active load[19], has been recently explored as a readout circuit for pressure sensors[20]. The MOSFET sensing technique and current mirror readout circuit are completely congruent with the standard CMOS technology and can be utilized for future development of higher-sensitivity CMOS-MEMS miniaturized pressure sensors. Our research group has been working and focusing on the development and design pattern of CMOS-MEMS mass and pressure sensors employing MOSFET-embedded sensing mechanisms with current mirror readout circuits in the recent past[20-26]. The work reported in this paper is an extension of our previous work on current mirror-integrated pressure sensors[25-26].

This paper carries out a study on the comparison of the designing and simulation of Curved MOSFET based Current Mirror Integrated Pressure Sensors (CM-CMIPS) employing square and circular curved channel MOSFETs embedded on circular and square silicon diaphragms. The paper has been organized as follows: The introduction and related literature survey are discussed in Section-1, the physical structure and working principle of the curved channel MOSFET-based CM-CMIPS structures are discussed in Section-2, the output results of simulation of proposed pressure sensors are presented in Section-3, and the conclusion of work carried out in this paper in Section-4.

2 Materials and Methods

2.1 Physical structure & working principle of curved MOSFET based current mirror integrated pressure sensors (CM-CMIPS)

The basic concept and working principle of proposed CM-CMIPS pressure sensors is based on the deformation of thin films under input pressure, piezoresistive effect in MOSFET for strain sensing, and the current mirror circuit to obtain the output voltage of the CM-CMIPS. The circuits for p-MOS, n-MOS, and CMOS (i.e. combined p-MOS and n-MOS) CM-CMIPS are shown in Fig. 1(a), (b), and (c), respectively.

The circuit diagram in Fig. 1(a) shows the p-channel resistive load MOSFET current mirror pressure sensing circuit. There are two p-channel MOSFETs (MP1 and MP2) of equivalent properties in this current mirror circuit where the transistor MP1

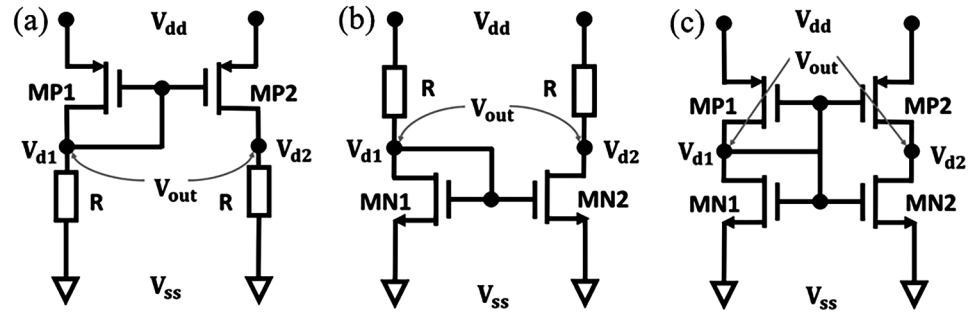

Fig. 1 — (a) p-MOS based CM-CMIPS, (b) n-MOS based CM-CMIPS, and (c) CMOS circuit based on combination of both p-MOS & n-MOS CM-CMIPS.

of the mirror operates as a transistor in reference and MP2 operates as the pressure-sensing transistor integrated on a pressure-sensing diaphragm. Fig. 2(a) and (b) represent the circular and square curved channel MOSFETs embedded on circular and square diaphragms, respectively. The cross-sectional image of the CM-CMIPS sensing structure with its reference MOSFETs and pressure sensing MOSFETs (either circular or square ring-shaped) integrated on the silicon substrate and pressure sensing diaphragm(s), respectively, is shown in Fig. 3.

From Fig. 2 and 3, it is clearly seen that the curved channel of the sensing MOSFET of pressure is placed around the periphery, i.e. near the diaphragm's fixed edge which senses the maximum tensile stresses developed under the input pressure to the diaphragm. The deflection in diaphragm under the input pressure will cause a change in carrier mobility due to the piezo-MOS effect and thus, there will be variation of drain current and drain voltage for sensing MOSFET MP2. The drain terminal of the sensing transistor and reference transistor (MP1& MP2) are where the output voltage is found when an external pressure is applied. Similarly, Fig. 1(b), 2, and 3(a) shows the schematic circuit and pressure sensing diagrams of n-channel resistive load MOSFET integrated current mirror circuit embedded on pressure sensor structure and its working is same as that of the p-MOS based sensor.

Fig. 1(c) is the schematic diagram of a CMOS pressure sensing circuit consisting of a combination of both n-type and p-type MOSFET integrated current mirror readout circuits. The cross-sectional image of the diaphragm embedded with either square or circular curved channel MOSFETs, respectively, is shown in Fig. 3(b). This circuit consists of two identical p-MOSFETs (MP1 and MP2) and two identical n-MOSFETs (MN1 and MN2). In this CMOS circuit, transistors MP1 & MN1 are the reference MOSFETs and MP2 & MN2 are the pressure sensing MOSFETs, each embedded on separate diaphragms. Under applied pressure, the diaphragm deflections will cause a change in carrier mobilities of both the pressure-sensing MOSFETs (MP2 & MN2) due to piezo-MOS effects and as a result, there is a variation in their drain current and drain voltage. Thus, obtaining an output voltage at the common drain terminals of the MOSFETs.

In this work, the study has been carried out comparatively for the following six pressure sensing structures: two structures each utilizing a p-type and n-type circular curved channel MOSFET embedded on circular silicon diaphragm, two structures each utilizing a p-type and n-type square curved channel MOSFET embedded on square silicon diaphragm, one structure consisting of a combination of both p- and n-type circular curved channel MOSFETs each embedded on two separate circular silicon diaphragms

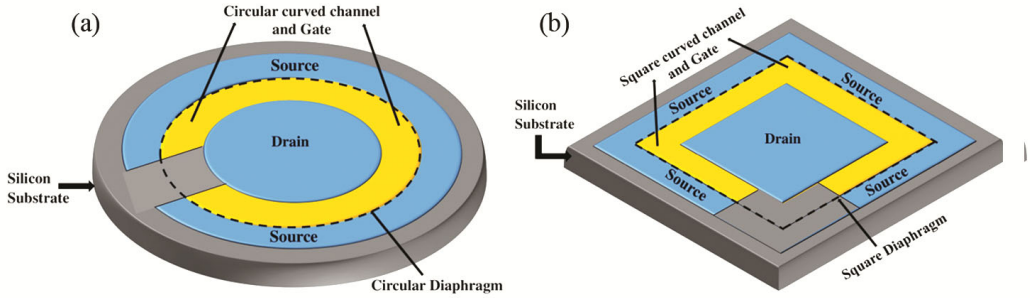

Fig. 2 — Pictorial representation: (a) circular curved MOSFET integrated on circular diaphragm, and (b) square curved MOSFET integrated on square diaphragm.

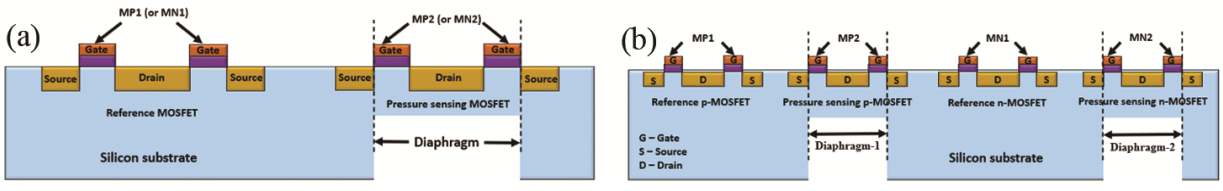

Fig. 3 — Physical structures of CM-CMIPS pressure sensors with reference and pressure sensing circular or square curved MOSFETs embedded on the circular or square diaphragm(s).

and the last one consisting of combination of both p- and n-type square curved channel MOSFETs each embedded on two separate square silicon diaphragms.

The mathematical model of working in CM-CMIPS pressure sensor structure(s) is given in the following sections:

2.2 Mechanical element(s): Circular and square silicon diaphragm

The CM-CMIPS pressure sensors have been designed for both circular and square silicon diaphragms. The maximum deflection (W) and stress (σ) in the circular and square diaphragms under the applied pressure (p) are well developed[6] and the mathematical expressions of equations are given below:

$$W_{(Circular)} = 0.19pa^4\frac{(1-\nu^2)}{Eh^3} \quad \ldots (1)$$

$$W_{(Square)} = 0.26pa^4\frac{(1-\nu^2)}{Eh^3} \quad \ldots (2)$$

$$\sigma_{(Circular)} = 0.75p\frac{a^2}{h^2} \quad \ldots (3)$$

$$\sigma_{(Square)} = 1.23p\frac{a^2}{h^2} \quad \ldots (4)$$

where a, h, E, and ν are the diaphragm's radius or side, thickness, Young's modulus of elasticity, and Poisson ratio, respectively.

2.3 Electrical transduction mechanism: MOSFET embedded sensing or Piezoresistivity in MOSFET

The CM-CMIPS pressure sensors employ the MOSFET embedded sensing for sensing the stress occurring in the diaphragm under pressure and converting it into an electrical signal. MOSFET-embedded sensing is based on the principle of variation in drain current due to changes in the carrier (electron or hole mobility) of the transistor under applied stress[17]. The expression for relative mobility changes under the applied stress is given by Eq. (5).

$$\frac{\Delta\mu}{\mu} \approx -\frac{\Delta R}{R} = -\pi\sigma \quad \ldots (5)$$

$$R_{ch} = r_0 = \frac{V_A}{I_D} \quad \ldots (6)$$

where μ, R_{ch}, r_0, π, σ, V_A, and I_D are the carrier (electron or hole mobility), channel resistance, output resistance, piezoresistive coefficient, applied stresses, Early voltage, and drain current of MOSFET, respectively. ΔR_{ch} and Δμ are the changes in channel resistance and changes in channel mobility of MOSFET.The drain current flowing through the MOSFET of the current mirror circuit under zero and applied pressure is defined in Eq. (7) and (8).

$$I_D = \frac{1}{2}\mu C_{ox}\frac{W}{L}(V_{GS}-V_t)^2 \quad \ldots (7)$$

$$I_{D(p)} = (\mu \pm \Delta\mu)C_{ox}\frac{W}{L}\frac{(V_{GS}-V_t)}{2} \quad \ldots (8)$$

From the above equations the terms, C_{OX}, W, L, V_{GS}, and V_T are the gate-oxide capacitance, channel width, channel length, gate-source voltage, and threshold voltage, respectively, of the MOSFET.

2.4 Readout circuit: Current mirror circuit

The CM-CMIPS pressure sensor employing the current mirror readout circuit(s) is represented in Fig.1. Here the placement of reference transistor(s) is on the substrate, due to which they do not respond to any applied pressure, and therefore their drain current(s) and drain voltage(s) remain constant. However, the pressure-sensing MOSFET(s) are placed on the diaphragm, certain stresses will establish on the diaphragm whenever the pressure is exerted on it, and therefore, the pressure-sensing MOSFET(s) will ascertain a change in the carrier (electron or hole mobility) resulting in the variations in drain voltage(s) and drain current(s) proportional to applied pressure. Therefore, in the given Eq. (9), it can be seen that around the drain reference transistor (V_{D1}) and pressure sensing drain transistor (V_{D2}), an output voltage (V_{OUT}) is attained due to the exerted pressure.

$$V_{out} = (V_{D1} - V_{D2}) \quad \ldots (9)$$

3 Results and Discussion

The current mirror and curved MOSFET integrated pressure sensors (CM-CMIPS) were designed utilizing the standard 5 μm CMOS device parameters. COMSOL Multiphysics software was utilized for the simulating the piezoresistive response of pressure sensing MOSFET(s) and TSPICE for obtaining the electrical behavior of the CM-CMIPS pressure sensing device. The parameters used for circular and square curved MOSFET-based CM-CMIPS sensor(s) are given in Tables 2 and 3, and the device parameters of 5 μm CMOS technology are given in Table 1.

3.1 Simulation of circular & silicon diaphragms

As discussed in Sections 2.1 and 2.2, the CM-CMIPS pressure sensors employ circular and square silicon diaphragms as pressure sensing mechanical elements. The side length, radius and thickness of square and circular diaphragms were 100 μm, 50 μm

and 2.5 µm, respectively. Fig. 4 and 5 show the deflection and stress profiles of circular and square shaped silicon diaphragms, respectively, for an input pressure of 1000 kPa. It is observed that the utmost highest deflection takes place at the mid of the circular and square diaphragms of approx. 0.41 µm and 0.52 µm. It is also found that the maximum stress of approx. 360.7 MPa and 477.14 MPa is occured near the periphery of the circular and square diaphragms for both circular and square silicon diaphragms. The plot of deflection and stress profiles of the circular and square diaphragms for the given pressures is shown in Fig. 6 (a) and (b). From the simulations results, it is also observed that the stresses developed in circular diaphragm vary along the radius from center to fixed edge of the diaphragm and are uniform across the circumference of the diaphragm in comparison to the square diaphragm. In square diaphragm, the stresses are more concentrated in the middle of the fixed edges of narrow regions and not throughout its periphery as that of circular diaphragm.

Table 1 — Standard 5 µm CMOS parameters[19].

Parameter	Unit	PMOS	NMOS
Channel length (L_{MIN})	µm	5	5
Gate oxide thickness (t_{OX})	nm	85	85
Gate oxide capacitance (C_{OX})	fF/µm^2	0.406	0.406
Electron & hole mobility (µ)	cm^2/Vs	250	750
Threshold voltage (V_T)	µA/V^2	-1	1
Supply voltage (V_{DD})	V	10	10
Early effect voltage (V'_A)	V/µm	6.67	20

3.2 Simulation of MOSFET equivalent piezoresistor

As seen in Section 2.3, MOSFET embedded sensing is the piezoresistive effect in MOSFET and

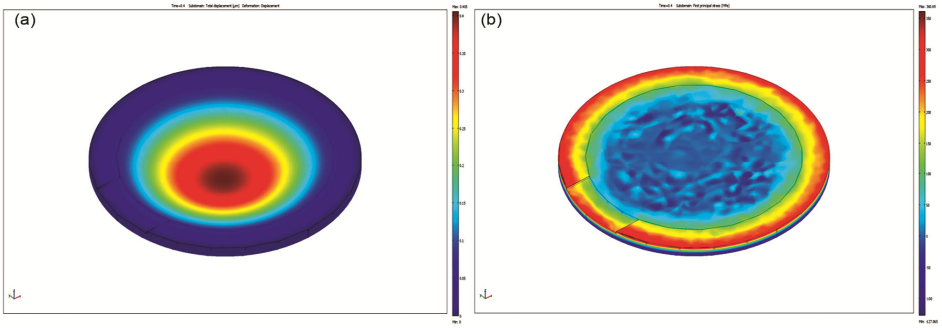

Fig. 4 — (a) Displacement profile, and (b) Stress profile of circular silicon diaphragm for 1MPa of input pressure.

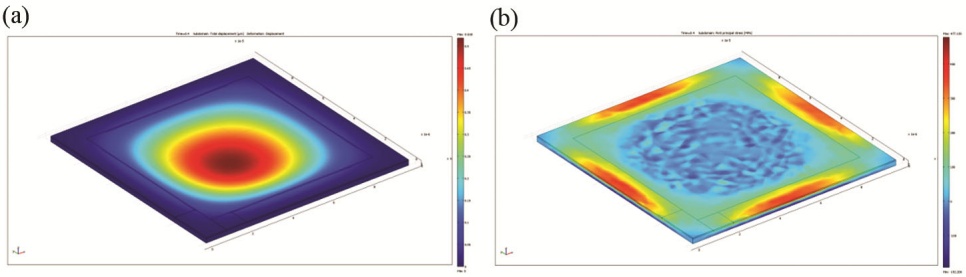

Fig. 5 — (a) Displacement profile, and (b) Stress profile of square silicon diaphragm for 1MPa of input pressure.

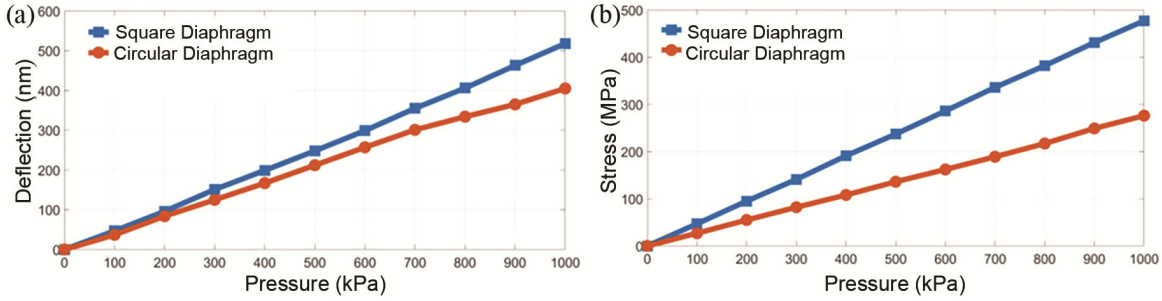

Fig. 6 — Graphs of (a) Deflection versus Pressure, and (b) Stress versus Pressure for both square & circular silicon diaphragms.

Eq. (5) defines the change in electron and hole mobilities is proportional to the change in MOSFETs channel resistance with opposite sign. Therefore, to realize the behavior of MOSFET embedded sensing the pressure sensing p- and n-channel MOSFETs have been considered as MOSFET equivalent piezo resistors as shown in Fig. 7 with each having initial resistances of R_{ch} ($=V_A/I_D$) and piezoresistive coefficients mentioned in Table 2[23]. A common channel length of 10 µm and average channel widths of 330 and 263 µm were considered for the square and circular curved channel MOSFETs and equivalent piezoresistors. A thickness of 0.5 µm was considered for both circular and square curved piezoresistors[20]. A constant voltage that is similar to the Early voltage of MOSFET (i.e. 66.7 V for p-MOS and 200 V for n-MOS as per CMOS 5 µm technology) is applied across the equivalent piezoresistors. Pressure is then applied within the range of 0 to 1MPa in steps of 100 kPa on the pressure sensing diaphragm(s) for

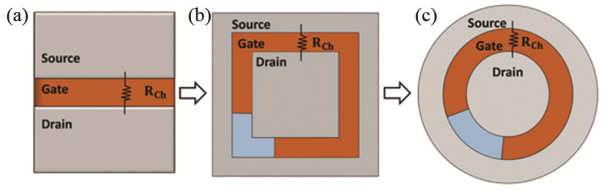

Fig. 7 — MOSFET equivalent piezoresistor for (a) conventional MOSFET, (b) square, and (c) circular curved channel MOSFET.

Table 2 — Parameters used for circular shaped CM-CMIPS.

	PMOS	NMOS[26]	CMOS circuit	
			NMOS	PMOS
A. Parameters used in T Spice for circuit simulation				
Channel dimensions (µm)	Channel length = 10, Channel width = 263			
Reference current (µA)	1000.18	1000.51	4768.65	4768.65
Drain resistor (Ω)	6640 Ω	7600Ω	--	--
Gate-to-source voltage (V)	3.36	2.4	4.02	5.98
B. Parameters used in COMSOL Multiphysics for structural simulation				
Circular diaphragm	Diameter = 100 µm, Thickness = 2.5 µm, Material = Silicon			
MOSFET piezoresistor (KΩ)	66.7	200	41.92	13.98
Voltage applied across piezoresistor (V)	66.7	200	200	66.7
Piezoresistive coefficients ($\times 10^{-11}$ Pa^{-1})	N-MOSFET: π_{11} = 102, π_{12} = −53.4, π_{44} = 13.6 P-MOSFET: π_{11} = -6.6, π_{12} = 1.1, π_{44} = -138			
Pressure range	0 to 1 MPa in steps of 100 KPa			

p-MOS, n-MOS, and CMOS based CM-CMIPS sensors, and corresponding change in channel resistance proportional to the exerted pressure was obtained. As shown in Fig. 8 this is evident from the change in the values of maximum current densities of the circular and square curved piezoresistors from 11.53 & 13.43 µA/µm^2, respectively, under zero applied pressure to 11.34 & 11.6 µA/µm^2, respectively, for the 1 MPa of input pressure.

3.3 Simulation of p-MOS & n-MOS CM-CMIPS

The representation of circuit for resistive load p-MOS current mirror and curved MOSFET integrated pressure sensors, as shown in Fig. 1(a), was designed for output currents of approx. 1000 µA (or 1 mA) for both square and circular curved channel MOSFET based CM-CMIPS. These sensors were simulated as per the procedure mentioned in section 3.2 with parameters mentioned in Tables 1, 2, and 3. In Fig. 9(a) and (b) it can be seen from the outcomes of the simulation that the channel resistance decreases, and carrier mobility increases with increasing pressure for both square and circular shaped CM-CMIPS. Fig.10 (a) and (b) represents that the drain current (I_D) of MOSFET increases and drain voltage decreases with increasing applied input pressure. This is due to the increase in carrier mobility and the current-voltage characteristics of MOSFET.

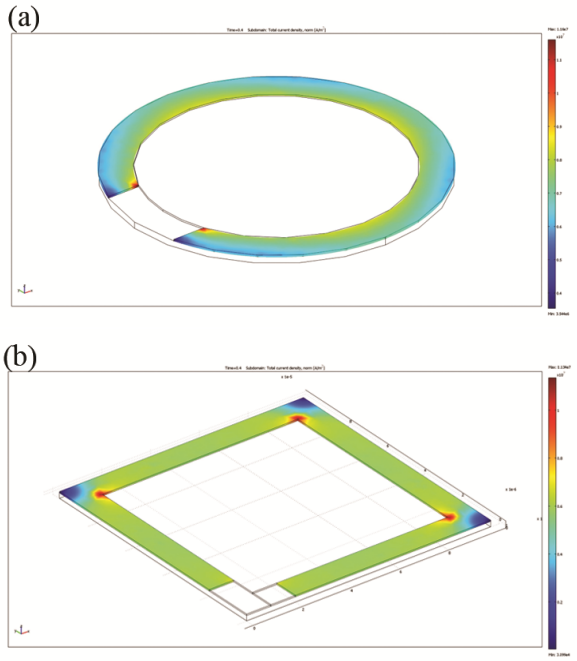

Fig. 8 — Current density profile of (a) Circular and (b) Square curved piezoresistor for zero and 1 MPa of input pressure.

Table 3 — Parameters used for square shaped CM-CMIPS.

	PMOS	NMOS[25]	CMOS circuit	
			NMOS	PMOS
A. Parameters used in T Spice for circuit simulation				
Channel dimensions (μm)	Channel length = 10, Channel width = 330			
Reference current (μA)	1000.1	1000.82	5560.62	5560.62
Drain resistor (Ω)	6810	7700	--	--
Gate-to-source voltage (V)	3.19	2.29	4.02	5.98
B. Parameters used in COMSOL Multiphysics for structural simulation				
Square diaphragm	Side = 100 μm, Thickness = 2.5 μm, Material = Silicon			
MOSFET piezoresistor (KΩ)	66.7	200	35.97	12
Voltage applied across piezoresistor (V)	66.7	200	200	66.7
Piezoresistive coefficients ($\times 10^{-11}$ Pa^{-1})	N-MOSFET: π_{11} = 102, π_{12} = −53.4, π_{44} = 13.6 P-MOSFET:π_{11} = -6.6, π_{12} = 1.1, π_{44} = -138			
Pressure range	0 to 1 MPa in steps of 100 KPa			

An output voltage that is found at the drain terminal of MOSFETs (i.e. $V_{out} = V_{d1} - V_{d2}$) decreases with increasing applied pressure as shown in Fig. 10(c). The sensitivities of the circular and square curved channel MOSFET based CM-CMIPS were approx. 505 and 515 mV/MPa, respectively. Table 4 gives the values of various parameters under zero and

Table 4 — Results of PMOS based CM-CMIPS.

Structure →	Square P-MOS based CM-CMIPS		Circular P-MOS based CM-CMIPS	
Parameter ↓	0 Pa	1 MPa	0 Pa	1 MPa
Channel resistance $R_{ch(MP2)}$ (KΩ)	66.7	60.62	66.7	63.13
Hole mobility, $\mu_{(MP2)}$ (cm^2/Vs)	250	272.77	250	263.39
Drain current, $I_{D(MP2)}$ (μA)	1000.1	1075.79	1000.18	1076.26
Drain voltage, $V_{D(MP2)}$ (mV)	3189.33	2673.89	3358.79	2853.66
Output voltage, $\lvert V_{OUT} \rvert$ (mV)	515.44		505.13	
Sensitivity (mV/MPa)	515.3		505	

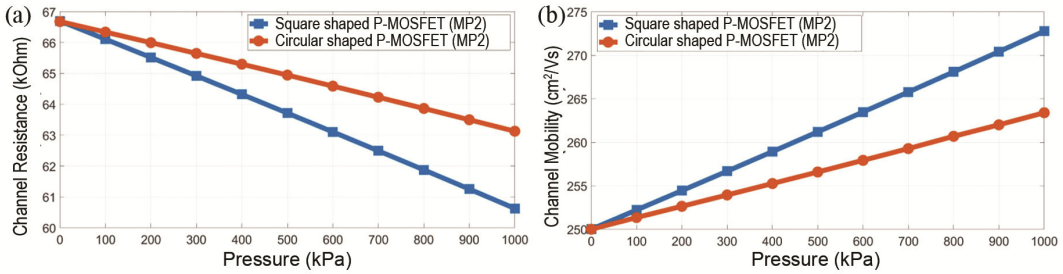

Fig. 9 — Graphs of (a) Channel resistance versus Pressure and (b) Hole mobility versus Pressure for square and circular curved p-MOS based CM-CMIPS.

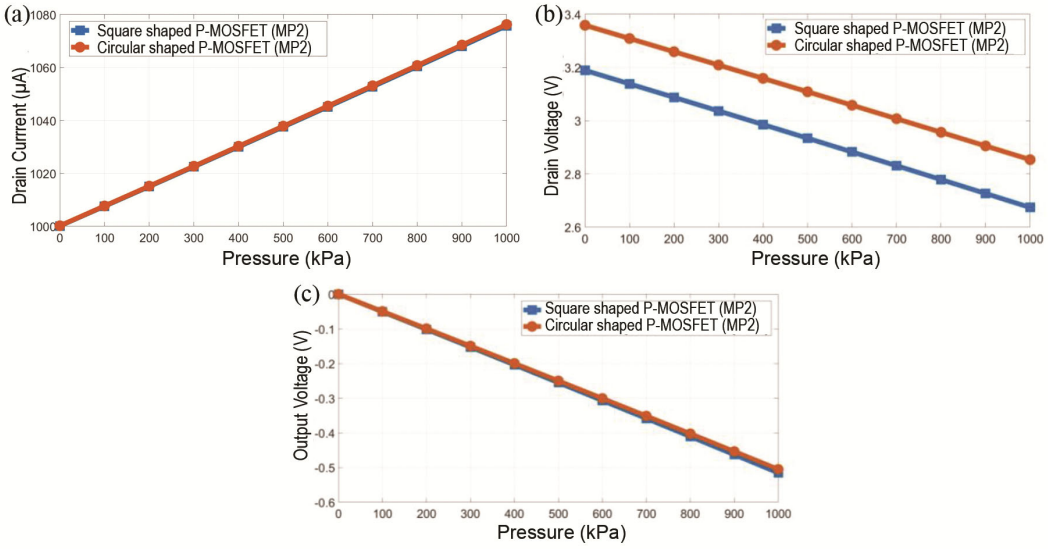

Fig. 10 — Graphs of (a) Drain current versus Pressure and (b) Drain voltage versus Pressure, and (c) Output voltage versus Pressure for both square &circular p-MOS CM-CMIPS.

1 MPa of applied pressure for both circular and square shaped p-MOS CM-CMIPS.

The n-MOS based CM-CMIPS for both circular and square curved structure pressure sensors were designed and simulated and the results were reported in our previous work[25-26]. Table 5 gives the values of various parameters under zero and 1 MPa of applied pressure for circular and square n-MOS based pressure sensors. The sensitivities of the square and circular CM-CMIPS were found to be approx. 406.88 and 657.91 mV/MPa, respectively.

Table 5 — Results of NMOS based CM-CMIPS.

Structure →	Square N-MOS based CMIPS[25]		Circular N-MOS based CMIPS[26]	
Parameter ↓	0 Pa	1 MPa	0 Pa	1 MPa
Channel resistance $R_{ch(MN2)}$ (KΩ)	200	211.94	200	220.45
Hole Mobility, $\mu_{(MN2)}$ (cm^2/Vs)	750	707.5862	750	680.29
Drain current, $I_{D(MN2)}$ (μA)	1000.82	947.98	1000.52	913.3978
Drain voltage, $V_{D(MN2)}$ (mV)	2293.7	2700.6	2396.08	3058.18
Output voltage, $\lvert V_{OUT} \rvert$ (mV)	406.88		662.1	
Sensitivity (mV/MPa)	406.8		661.5	

3.4 Simulation of CMOS (p- & n-MOS) based CM-CMIPS

In this section, CMOS based CM-CMIPS pressure sensors consisting of both p- and n-type ring-shaped channel MOSFETs, each embedded on separate diaphragms as shown in Fig. 1(c) and 3(b). CMOS based CM-CMIPS have been designed and simulated for both circular and square curved pressure sensor structures with parameters given in Tables 1, 2 &3.

Figures 11(a & b) show that with the increase in input pressure, the channel resistance decreases, and the mobility increases for p-channel pressure sensing MOSFET for both square and circular curved structures. However, the channel resistance increases, and mobility decreases with increasing input pressure for n-channel pressure sensing MOSFET for both square and circular curved structures.

From Fig. 12, it is observed that for both the square and circular curved structures, the pressure

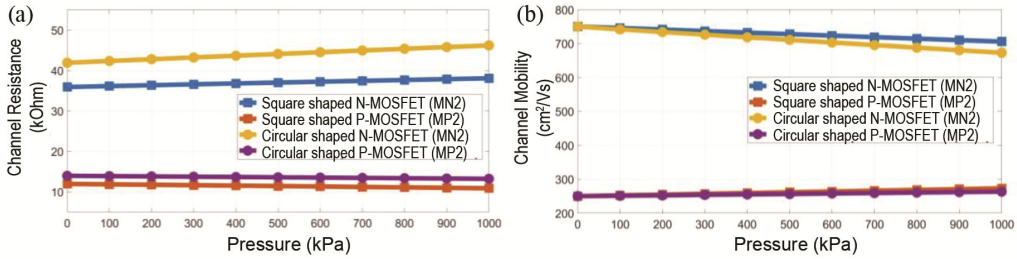

Fig. 11 — Graphs of (a) Channel resistance versus Pressure and (b) Hole mobility versus Pressure for square and circular curved CMOS based CM-CMIPS.

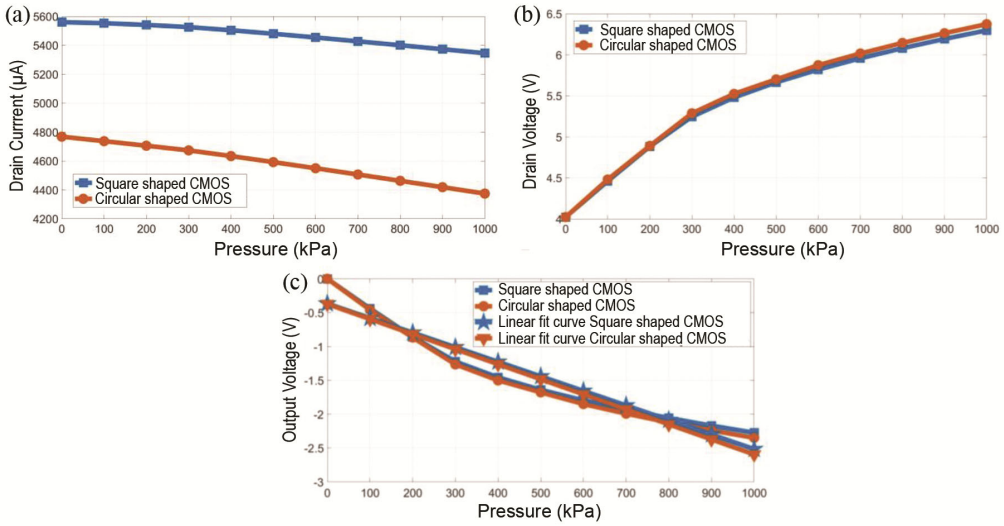

Fig 12 — Graph of (a) Drain current versus Pressure, (b) Drain voltage versus Pressure, and (c) Output voltage versus Pressure for both square & circular CMOS based CM-CMIPS.

Table 6 — Results of CMOS based CM-CMIPS.

Structure →	Square CMOS based CM-CMIPS		Circular CMOS based CM-CMIPS	
Parameter ↓	0 Pa	1 MPa	0 Pa	1 MPa
Channel resistance $R_{ch(P2)}$ (KΩ)	35.95	38.09	41.94	46.23
Channel resistance $R_{ch(N2)}$ (KΩ)	11.98	10.89	13.98	13.23
Hole mobility,μ_{P2} (cm^2/Vs)	750	705.592	750	672.87
Electron mobility,μ_{N2} (cm^2/Vs)	250	273.035	250	263.33
Drain current, I_{D2} (μA)	5560.62	5345.79	4768.65	4374.95
Drain voltage, V_{D2} (mV)	4023.95	6299.07	4023.95	6374.31
Output voltage, $\lvert V_{OUT} \rvert$ (mV)	2275.12		2350.36	
Sensitivity (mV/MPa)	2151		2223	

Table 7 — Comparison of MOSFET-based pressure sensors reported in literature.

Ref.	Pressure sensor structure & elements	Sensitivity (mV/MPa)
Gardner*et al.*[16]	n-MOSFET in full bridge Wheatstone form.	2400
Wolde& Gupta[27]	Two n-MOSFET circuits in the configuration of a Voltage divider.	30
Zhao *et al.*[28]	Four p-MOSFET Nc-Si/c-Si hetero-junction in Wheatstone bridge configuration.	2153
Zhang *et al.*[15]	The readout circuit consists of two MOSFETs and two piezoresistors.	300
Rathore*et al.*[25]; Rathore&Panwar[26]	n-channel ring-shaped based resistive load MOSFET current mirror integrated pressure sensor	407, 658
This work	p-MOS curved MOSFET based current mirror integrated pressure sensor (CM-CMIPS) structures	515, 505
	CMOS (combined p- & n-MOSFET) curved MOSFET based current mirror integrated pressure sensor (CM-CMIPS) structures	2151, 2223

sensing MOSFETs the drain current (I_{D2}) decreases and drain voltage (V_{D2}) increases with increasing applied input pressure. An output voltage that is found at the drain terminal of reference MOSFETs MP1 & MN1, and pressure sensing MOSFETs MP2 & MN2 (i.e. $V_{out} = V_{d1} - V_{d2}$) decreases with increasing applied input pressure as shown in Fig. 12(c).

The sensitivities of the square and circular curved CMOS based CM-CMIPS pressure sensors are approx. 2151 and 2223 mV/MPa, respectively. Table 6 gives the values of various parameters under zero and 1 MPa of input pressure for both circular and square curved CMOS based CM-CMIPS. Table 7 shows that the pressure sensitivities of our curved channel MOSFET based CM-CMIPS pressure sensors are comparable with the other works reported in the literature.

4 Conclusion

This paper conducted a simulation study on curved MOSFET based current mirror integrated pressure sensor (CM-CMIPS) structures. The pressure sensing structures contained circular and square curved MOSFETs embedded on circular and square silicon diaphragms. The simulation results of the six CM-CMIPS structures have been compared for their sensitivities. The pressure sensitivities of square-shaped CM-CMIPS sensors employing p-MOS, n-MOS, and CMOS (both p- and n-MOS) structures were found to be approximately 515, 407, & 2151 mV/MPa, respectively, and approximately 505, 658, & 2223 mV/MPa, respectively, for the circular shaped sensors. Thus, from the study reported in this paper, we found that all six CM-CMIPS sensors have good pressure sensitivity and the CMOS-based CM-CMIPS sensors have the highest sensitivity. These curved-shaped MOSFET-embedded CM-CMIPS sensors have the potential to compete with the existing pressure sensors in the market in the near future.

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Conflict of Interest

The authors have no conflict of interests relating to the contents of the study presented in this manuscript. The authors have no conflict of interests related to financial or non-financial interests. All authors have participated in the work carried out in this paper.

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