Electric Modulation on the Sensitivity and Sensing Range of CMOS-MEMS Tactile Sensor by Using the PDMS Elastomer Fill-In

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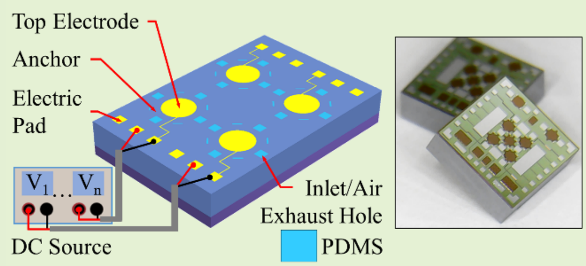
***Abstract*—This study presents the design and implementation of a MEMS capacitive tactile force sensor with polydimethylsiloxane (PDMS) filler for in-process and in-use modulation of the sensing range and sensitivity performance. The presented MEMS tactile force sensor consists of a loading unit with driving electrodes, PDMS filler, and a sensing unit. By varying input voltages on the driving electrodes (either in curing process or in-use), the stiffness of the PDMS filler as well as the loading unit can be modulated. Thus, the sensitivity and sensing range of the presented tactile force sensor was modulated accordingly. Since each sensor has its own driving electrodes and electrical routings, different input voltages can be applied to modulate the PDMS for each individual sensor. As a result, tactile sensors of different sensitivities and sensing ranges can be simultaneously fabricated and monolithically integrated on the same chip using the presented approach. The tactile sensors were implemented using TSMC 0.18 μm 1P6M standard CMOS process together with the in-house post-CMOS releasing and the polymer filling processes. Experiments demonstrate the capabilities of implementing various tactile sensors with different sensing ranges and sensitivities on a single chip by the in-process and in-use modulation techniques. Through the in-process and in-use modulation, the presented CMOS-MEMS tactile sensors show the sensing window: (1) for sensitivity modulation: 8.6 fF/N to 219.1 fF/N, and (2) for sensing range modulation: 30 mN to 270 mN.**

***Index Terms*—CMOS-MEMS, electric modulation, tactile force sensor.**



I. Introduction

TACTILE sensors are important human-machine interfaces and can find broad applications in various fields, such as consumer electronics (mobile phones, notebooks), robots, or medical instruments. Tactile load sensors provide contact information for different applications, such as grasping forces for robot manipulation, contact forces for medical surgery and precision assembly, and so on. The size and cost of tactile force sensors can be reduced through the MEMS (micro-electro-mechanical-systems) technologies, so as to enhance their performances in applications. To date, many MEMS tactile force sensors with different sensing mechanisms, such as piezoresistive, piezoelectric, inductive, and capacitance, have been reported [1]–[5]. Moreover, many micromachining process technologies have also been developed to fabricate the tactile force sensors. For example, the silicon-based and the polymer-based process technologies have been reported for different applications [6]–[8]. The Complementary Metal-Oxide-Semiconductor (CMOS) processes are mature fabrication technologies available in many commercial foundries. Since the CMOS processes offer many dielectric, metal, and poly-silicon layers, the design of multi-layer structures and the electrical routings for sensing units can be achieved. Thus, the CMOS processes have been exploited to fabricate various MEMS devices [9] including the tactile force sensors [10].

Based on the requirements of applications, tactile force sensors with different sensing ranges and sensitivities are required to meet specifications [11]. Many approaches have been presented to modify the sensitivity or sensing range of the tactile sensors, such as by varying the stiffness of MEMS structures as well as the dielectric constant of capacitive

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TABLE I
THE STRATEGIES OF MODULABLE CHARACTERISTICS OF TACTILE SENSORS

The Strategies of Modulable Tactile Sensors					
Modulation Strategies	Dielectric Property	Stiffness			
Reference	[15]	[13], [14]	[16]	[17]	This Study
Modulated Materials/ Mechanism	Modified the Shape of Dielectric Liquid between the Sensing Electrodes	Modified the Curing Agent Ratio of PDMS between the Sensing Electrodes	Modified Particles Distribution in ER-fluid between the Sensing Electrodes	Modified Particles Distribution in ER-elastomer between the Driving Electrodes	Modified Molecular Distribution in PDMS between the Driving Electrodes
Electrically Modulable	V	X	V	V	V
In-Process Modulation	X	X	X	V	V
In-use Modulation	V	X	V	V	V
Sensing Range Modulation	V	V	V	V	V

sensors. It is straightforward to change the design of MEMS structures to meet the specifications of tactile force sensors. However, the time and cost [12] required for the new design are concerns. Thus, many approaches have been investigated to modify the sensitivity and/or sensing ranges of the tactile force sensors without changing the mask designs. For example, as reported in [13], [14], the stiffness of tactile sensors is modulated by using different fill-in materials (e.g. PDMS with different curing ratios) after the fabrication of MEMS structures. Furthermore, the approach of in-use modulation (by applying voltage) of sensitivity and sensing range is revealed in [15] to be by tuning the dielectric constant of the capacitive sensing tactile sensors by varying the shape of dielectric liquid. Moreover, the suspended MEMS structures that are filled with smart materials such as Electrorheological (ER) fluid or ER-elastomer have been used to tune the stiffness as well as sensitivities and sensing ranges of tactile force sensors [16], [17]. The distribution of nanoparticles in fluid or polymer is changed by applying voltages so as to further modify the stiffness of the sensing structures. Thus, through the existing technologies, the sensitivities and sensing ranges of tactile force sensors can be modified either during the fabrication processes (in-process), or during operation (in-use). Table I lists common strategies of modulable tactile sensors.

This study extends the concept in [17] to present an approach for modulating the stiffness of the MEMS structures in-process and/or in-use to modify the sensitivity and sensing range of the capacitive type tactile sensors. As discussed in [17], the gap between two driving electrodes is filled with PDMS nanocomposite (PDMS mixed with dielectric nanoparticles). However, it is challenging to prepare the PDMS nanocomposites with good uniformity. In this regard, the MEMS devices are fabricated first and then filled with the PDMS elastomer with electric polarization characteristics. Thus, the stiffness of the PDMS filler as well as the sensitivity of the tactile sensor can be modulated using input voltages. To achieve the proposed design, many thin film layers are required to fabricate the MEMS structures, the sensing and driving electrodes, and the related electrical routings. Thus, this study leverages the standard CMOS process with its many available thin film layers to implement the proposed design. Moreover, the post-CMOS micromachining/polymer coating processes, and the voltage modulation during the polymer curing are also adopted to fabricate the MEMS tactile sensor. Experiments demonstrate the capabilities of in-process and in-use modulation approaches to implement various tactile sensors with different sensing ranges and sensitivities on a single chip.

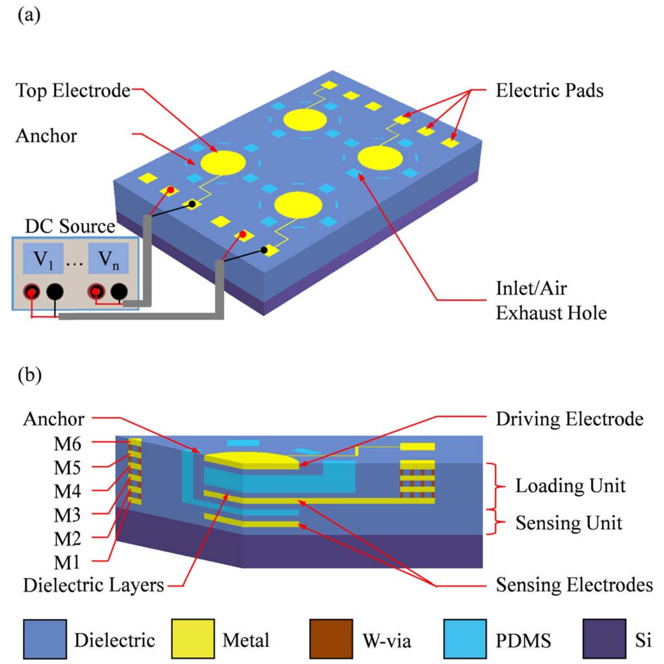


Fig. 1. (a) Schematic of the proposed CMOS-MEMS tactile sensor with polymer fill-in for in-use and in-process performance modulation, and (b) the cross section view of a single tactile sensor to show its loading unit and sensing unit, with the stacking of thin film layers and polymer fillers also displayed.

II. DESIGN CONCEPTS

Figure 1 illustrates the proposed capacitive tactile sensor design based on the TSMC (Taiwan Semiconductor Manufacturing Co.) 0.18 μm 1P6M CMOS standard process with in-house metal wet-etching releasing and PDMS fill-in techniques. Such a design enables the in-process as well as the in-use modulation of the sensitivity and sensing range of the proposed tactile sensor. Figure 1a depicts the surface of the capacitive tactile sensing chip showing the top electrode of loading unit, electric pads, inlet holes for the PDMS filler, and outlet holes for the exhaust air. Each tactile sensor has its own electric routings to input DC driving voltage independently (for instance, V_1 to V_n). Thus, different voltages can be applied to each sensor simultaneously. The cross section in Fig. 1b further reveals the detailed structure of the tactile sensor. As marked with the dashed lines, the loading unit consists of two suspended circular diaphragms formed by dielectric layers with the embedded M3 and M6 metal films (as the driving electrodes), and the PDMS filler. The boundary of circular diaphragm is anchored to the substrate. Note that

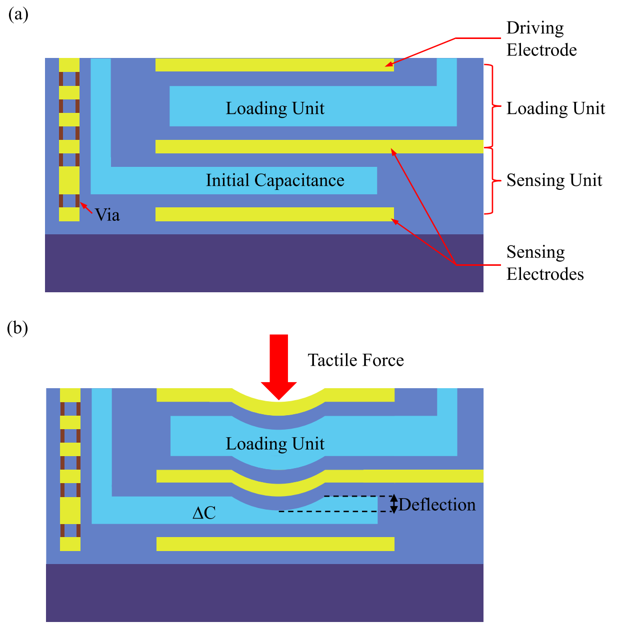


Fig. 2. The sensing schematic of the proposed CMOS-MEMS tactile sensor, (a) before applying a tactile load, and (b) after applying a tactile load to deform the loading unit, the deflection of the loading unit can be detected by the capacitance change of sensing unit. The stiffness of the PDMS filler as well as the loading unit can be modulated by the driving electrodes.

the space for the PDMS filler is defined by the sacrificial metal (M4 and M5) and dielectric layers. This study also employed the M1 and M3 metal layers to form the sensing unit. The M3 metal layer that is embedded in the suspended structure acts as the deformable sensing electrode, and the M1 metal layer that is anchored to the substrate acts as the reference sensing electrode. PDMS is also filled into the space defined by the sacrificial metal (M2) film as the buffer layer for the sensing electrodes. Moreover, the electrical routings for the sensing and driving electrodes can be achieved by using the metal layers of CMOS process. When the loading unit is deformed by a tactile force, the electrode (M3) will be bent to cause a gap variation between the sensing electrodes, as shown in Fig. 2. Thus, the tactile force can be detected by the capacitance change of the sensing electrodes. The gap variation induced by the tactile force is proportional to the net stiffness of the loading unit. Moreover, since the loading unit is stacked with the metal films, dielectric layers, and PDMS filler, the net stiffness of the loading unit is determined by the stiffness of metal films, dielectric layers, and PDMS filler.

In this study, the stiffness modulation of the PDMS filler (in the loading unit) by applying voltage on the driving electrodes is proposed as a method to modify the sensitivity and sensing range of the tactile sensor. Figure 3a displays the 1st approach to modulate the stiffness of the PDMS filler during the curing process (named the in-process modulation). After the uncured PDMS molecules (mixed with PDMS base and cure agent) are filled into the gaps of sensors, the PDMS molecules are distributed randomly. As shown in Fig. 3a, the PDMS molecules inside the gap of the loading unit will be aligned when applying a voltage (curing voltage, V_c) on the M3 and M6 driving electrodes during curing. The electric field E_c polarizes the

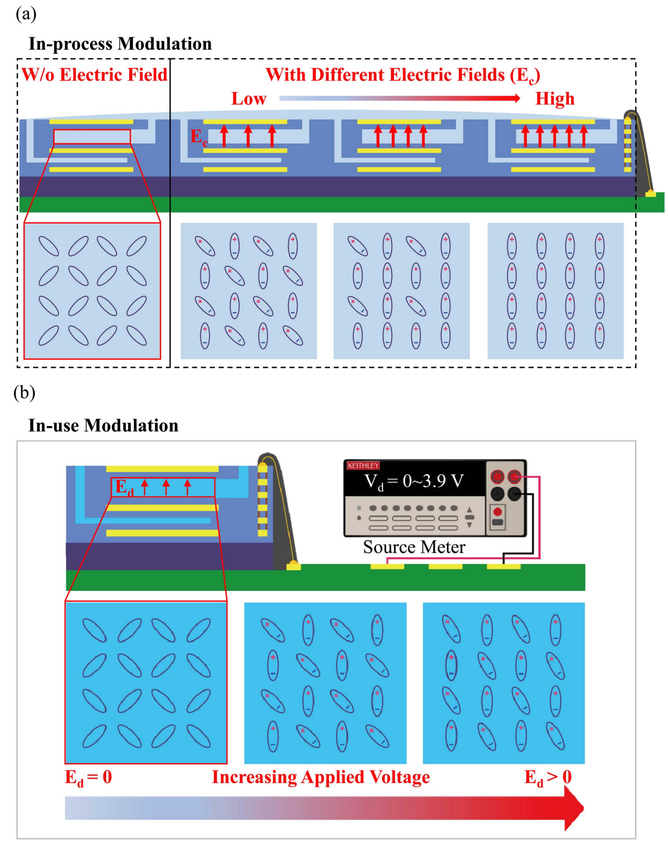


Fig. 3. The mechanism of electric stiffness modulation of the loading unit for performances modulation of the proposed tactile sensors, (a) in-process modulation, during the curing process, to change the distribution of PDMS molecules (in loading unit) by varying the intensity of electric field; after the curing process, the distribution of PDMS molecules after removing electric field; (b) in-use modulation, during use, to further change the distribution of molecules for cured PDMS (in loading unit) by applying voltage on driving electrodes.

dielectric materials (uncured PDMS molecules) into polarized dipoles [18]–[21]. The electric field E_c also provides an electrostatic force to the polarized dipoles to influence the distribution of the PDMS molecules [22]–[24]. As such, the alignment of the PDMS molecules can be enhanced with the increasing electric field. After curing and removing the applied voltage, the PDMS molecules were crosslinked with the curing agents and maintained their distribution as driven by the electric fields. The equivalent stiffness of the loading unit changes with the distribution of molecules in the cured PDMS. Therefore, the performance (such as sensing range and sensitivity) of the proposed tactile sensor can be modified by varying the voltage applied on driving electrodes during curing. Moreover, as shown in Fig. 1a, each sensor on the chip has its own electrical routings for driving and sensing electrodes, and hence different driving voltages (electric fields) can be applied to the selected tactile sensors. Thus, sensors with loading units of different stiffnesses can be monolithically and simultaneously realized on the same chip through the post-process voltage modulation. Figure 3b depicts the 2nd approach to modulate the characteristics of the proposed tactile sensor during use (named the in-use modulation). For the in-use modulation, a driving voltage (V_d) was applied on the cured PDMS to form an electric field E_d. When $E_d = 0$,

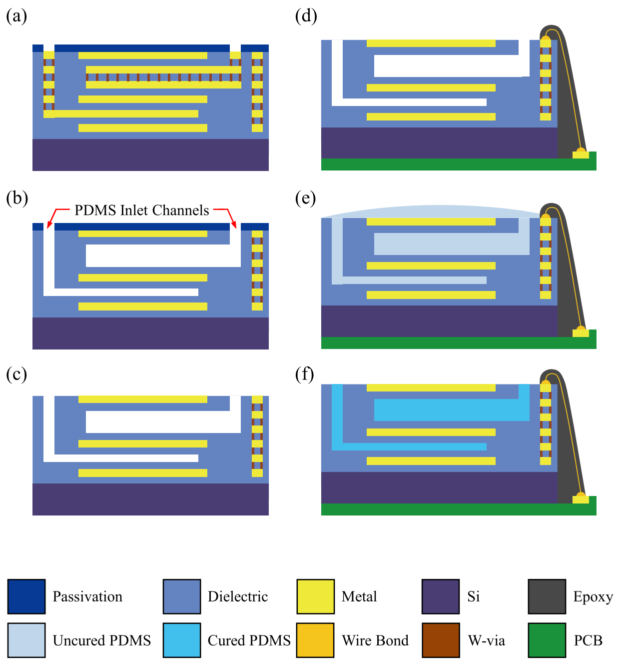


Fig. 4. Fabrication process steps, (a) chip prepared by TSMC 1P6M CMOS process, (b) the metal wet etching to define sensing gaps and fill in channels, (c) RIE to remove passivation for wire bonding, (d) wire bonding on PCB and wire protection using epoxy, (e) PDMS coating, and curing with different voltages V_c, and (f) remove residual PDMS on top of the chip.

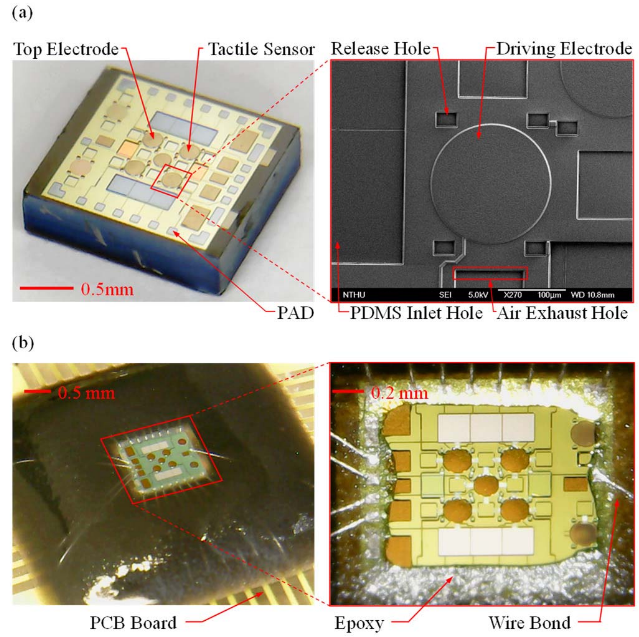


Fig. 5. Typical fabrication results, (a) the optical micrograph of CMOS chip after the in-house post-CMOS metal etching, and the zoom-in SEM micrograph to show more details (metal release, polymer inlet, and air exhaust holes) on the chip; and (b) the optical micrographs to display the fabricated chip after wire-bonding on PCB with epoxy protection of wires, and the right zoom-in micrograph to show the exposed sensing area with tactile sensors.

the distribution of the cured PDMS molecules is as depicted in Fig. 3a. While the electric field is applied, the dielectric molecules will be polarized. Therefore, the alignment of the dielectric molecules can be enhanced by increasing the electric field and electrostatic force. Despite the fact that PDMS molecules are crosslinked by the curing agents, the distribution of molecules can still be modified by varying the driving voltage V_d. Therefore, the equivalent stiffness of the loading unit can be modified through the in-use modulation to further change the performance of the tactile sensor.

III. Fabrication and Results

The proposed tactile sensors were implemented using the standard TSMC 0.18 μm 1P6M process together with the in-house post-CMOS micromachining process. Figure 4a shows the stacking and patterning of metal and dielectric layers on the CMOS chip prepared by the TSMC. As shown in Fig. 4b, the H_2SO_4 and H_2O_2 solutions were employed to etch the sacrificial metal layers (M2, M4, and M5) and the tungsten vias [25]. Thus in this step, the two suspended circular diaphragms formed by the dielectric layers with embedded M3 and M6 metal films were patterned, and the M1 metal film that is anchored to the substrate as the reference sensing electrode was also defined. Moreover, the gaps to accommodate the PDMS filler, and the inlet channels to fill in the PDMS were also fabricated. In this step, the metal layers that act as the driving/sensing electrodes as well as the electric routings were protected by dielectric films. As depicted in Fig. 4c, the reactive ion etching (RIE) was used to remove the passivation layer to expose the metal pads. Figure 4d indicates that the wires for electric connections between the chip and the PCB (printed circuit board) were bonded and then protected by epoxy. As shown in Fig. 4e, the PDMS (Sylgard 184, Dow Corning Corporation with 10:1 curing agent ratio) was coated on the chip and ready for curing process. During the curing process, multiple voltages V_c can be simultaneously applied on different tactile sensors, as displayed in Fig. 1a. Thus, sensors of different characteristics can be simultaneously and monolithically fabricated on the same chip. The in-process modulation was achieved during this step. Note that the curing process is completed under room temperature. Finally, as shown in Fig. 4f, the cured residual fill-in material on the chip surface was removed.

Micrographs in Fig. 5 display the typically fabricated devices. The optical micrograph in Fig. 5a shows the CMOS tactile sensor chip, and the chip has five tactile sensors. The brown color shows the metal layer of the top driving electrodes and bonding pads. Moreover, the left optical micrograph in Fig. 5a depicts the CMOS chip after the in-house metal releasing process (in Fig. 4b), with the inlet holes to fill in the PDMS filler and the air exhaust holes are fabricated. The top electrodes and bonding pads (in brown color) that is protected by the passivation layer survived after the metal release. The zoom-in scanning electron microscope (SEM) micrograph in Fig. 5a shows more details including the driving electrode, the etching release holes, and the air exhaust holes of the tactile sensor (at voltage: 0.5 kV, magnification: x270). The top micrograph in Fig. 5b displays a typically fabricated chip after wire-bonded onto the PCB. The chip and bonded wires are protected by the epoxy. The zoom-in micrograph shows that the tactile sensors are not covered by the epoxy in order to conduct the following loading tests.

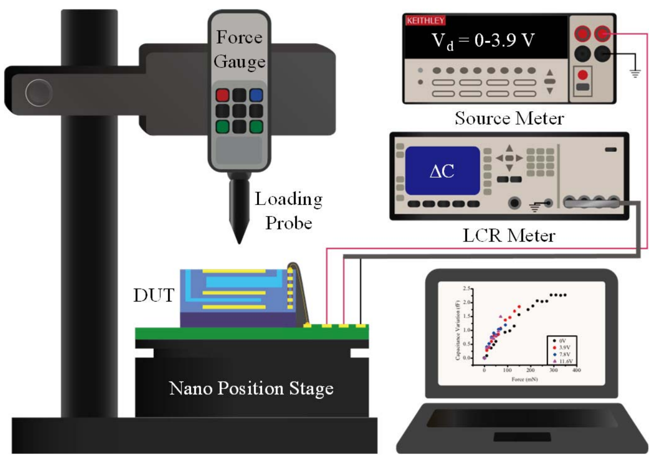


Fig. 6. The schematic of the measurement setup.

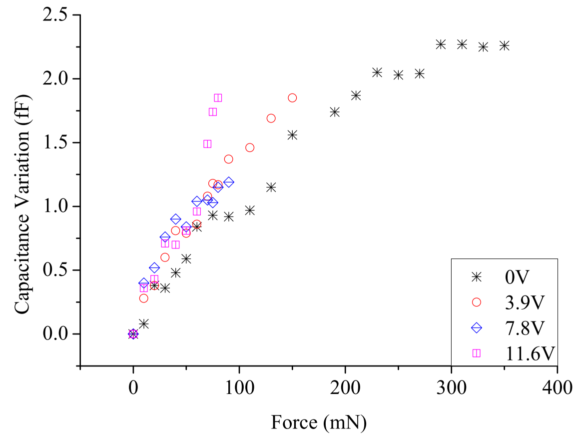


Fig. 7. Measurements of sensing capacitance variation under tactile loads for four different samples prepared with different driving voltages (0 V to 11.6 V) on the PDMS filler during curing (in-process electric modulation).

IV. Measurements and Discussions

The experimental setup shown in Fig. 6 was established to characterize the modulation performance of the tactile sensors. The precision PZT position stage (Physik Instrumente (PI) P-841.6 preloaded piezo actuators) was used to specify an upward displacement of the sample. The sample displacement was precisely controlled by a feedback controller (PI E-503/509 controller with E-518.I3 computer interface) with a resolution of 1.8 nm. After the rigid probe on the force gauge (Yotec FSH-5N with 1 mN input force resolution) contacted the sample at the center of the loading membrane, a tactile load was applied onto the sensing chip. Thus, the force gauge readings were recorded as the tactile load was applied on the sample. Meanwhile, an LCR meter (Keysight 4980A) was employed to measure the output signals from the sensing electrodes of the tactile sensor. Moreover, a source meter (Keithley 2410) was used to apply a modulation voltage V_d (or electric field E_d) on the driving electrodes of sensors. A computer was used to control the position of stage and also record the measurement results. By using this experiment setup, this study further performs the loading tests on the fabricated sensors prepared through both the in-process and in-use modulation of the PDMS filler.

Firstly, this study characterizes the performances of the proposed CMOS-MEMS tactile sensors (on the same chip) prepared under different in-process modulating curing voltages V_c of the loading unit PDMS filler. Thus, four different V_c (0 V, 3.9 V, 7.8 V, and 11.6 V; i.e. 0-3 kV/mm) are respectively applied onto the loading units of four tactile sensors on the CMOS-MEMS chip. After that, the sensing ranges and sensitivities of these four tactile sensors were characterized using the test setup in Fig. 6. Measurement results in Fig. 7 shows the variation of sensing capacitances under tactile loads for these four different sensors. Table II further summarizes the sensing ranges and sensitivities of these four in-process modulated sensors based on the results in Fig. 7. The results indicate that the sensitivity of tactile sensors is enhanced from 8.6 fF/N to 23.9 fF/N as the driving voltage V_c is increased from 0 V to 11.6 V. On the other hand, the sensing range of tactile sensors dropped from 270 mN to 30 mN as the driving voltage V_c is increased from 0 V to 11.6 V. In conclusion, the stiffness of the PDMS filler can be modulated by the driving voltage V_c during curing, so as to change the net stiffness of loading unit. Thus, the sensitivity and sensing range of the tactile sensor can be modulated by varying the driving voltage V_c. The results demonstrate the concept of in-process modulation depicted in Fig. 3a.

TABLE II
In-Process Electric Modulation of the Proposed Tactile Force Sensors

In-process Electric Modulation Results				
Curing Voltage V_c (V)	0	3.9	7.8	11.6
Sensitivity (fF/N)	8.6	14.2	23.8	23.9
Sensing Range (mN)	270	125	40	30

This study further characterizes the CMOS-MEMS tactile sensors during the in-use modulation of PDMS filler using voltage V_d. The in-use modulation voltage V_d was applied onto tactile sensors (on the same chip) respectively cured at four different voltages V_c (0V, 3.9V, 7.8V, and 11.6V; i.e. 0-3 kV/mm). As shown in Fig. 3b, the PDMS molecules can be re-distributed by the driving voltage V_d even after it is cured. Thus, the test setup in Fig. 7 was used to characterize the variation of sensing signals with tactile loads when applying driving voltages V_d onto the electrodes of the loading unit. Measurement results in Fig. 8 show the variation of sensing capacitances under tactile loads at various V_d (0 V, 1.9 V, and 3.9 V; i.e. 0-1 kV/mm) for the four test samples prepared with different curing volatages. Table III summarizes the sensing ranges and sensitivities of these four in-use modulated sensors based on the results in Fig. 8. As shown in Fig. 8a, the PDMS filler in the test device was cured under $V_c = 0$ V. Measurement results show that as V_d is increased from 0 V to 3.9 V, the sensitivity is enhanced from 8.6 fF/N to 205 fF/N and the sensing range is decreased from 270 mN to 40 mN. As shown in Fig. 8b, the PDMS filler in the test device was cured under $V_c = 3.9$ V. Measurement results show that the sensitivity is enhanced from 14.2 fF/N to 219.1 fF/N and the sensing range is decreased from 125 mN

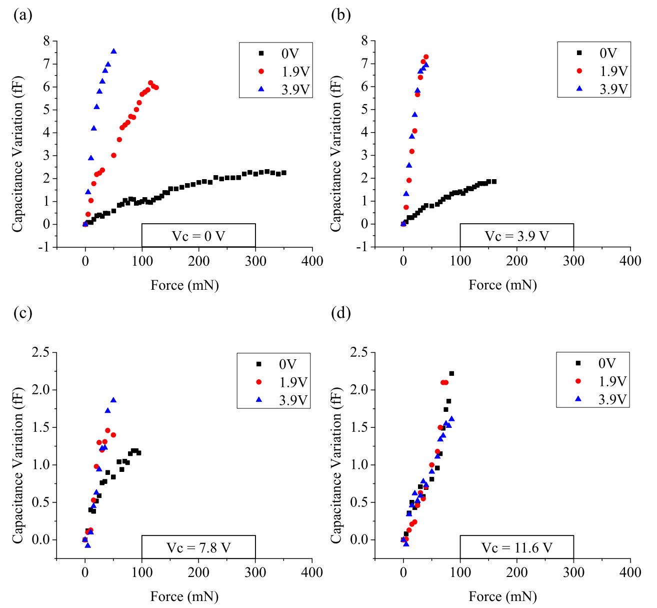


Fig. 8. Measurements of sensing capacitance variation under tactile loads while applying in-use modulation voltages (1.9 V and 3.9 V) on proposed sensors. The tests are performed on four different samples prepared at distinct curing voltages Vc on the PDMS filler (a) Vc = 0 V, (b) Vc = 3.9 V, (c) Vc = 7.8 V, and (d) Vc = 11.6 V.

to 35 mN when V_d is increased from 0 V to 3.9 V. It is worth noting that the sensitivity and sensing range of this sample will reach a limit (~219 fF/N, and 35 mN) as $V_d \geq 1.9$ V. Moreover, Fig. 8c shows the measurements on the test sample cured at $V_c = 7.8$ V. The initial sensing range and sensitivity are respectively 40 mN and 23.8 fF/N when $V_d = 0$ V. As the driving voltages V_d is increased to 3.9 V, the sensitivity is increased to 37.9 fF/N and the sensing range becomes 35 mN. In this case, the sensitivity and sensing range of this sample also reach a limit (~38 fF/N, and 35 mN) as $V_d \geq 1.9$ V. Finally, Fig. 8d reveals the modulation behavior under $V_c = 11.6$ V and $V_d = 0 - 3.9$ V. However, the sensitivities (~20 fF/N) and sensing ranges (~30 mN) of this sample do not vary with differing driving voltages V_d. In conclusion, the stiffness of the PDMS filler as well as the net stiffness of the loading unit can be further modulated by the driving voltage V_d while in use. Thus, the sensitivity and sensing range of the tactile sensors can be modulated by varying the driving voltage V_d to demonstrate the concept of in-use modulation as shown in Fig. 3b. Measurement results reveal that increasing V_d will reduce the stiffness of PDMS filler, thus causing an enhancement in sensitivity and reduction in sensing range. The applied curing voltage V_c also affects the characteristics of sensors during in-use modulation. Moreover, the modulation of sensitivity and sensing range for the presented tactile sensor may reach a limit as V_d exceeds a given voltage. In conclusion, measurement results indicate that the voltage applied on the driving electrodes of loading unit could reduce the stiffness of the PDMS filler while in-process or in-use.

Regarding the modulation mechanism of PDMS, it has been reported in [26]–[28] that the stiffness of the electrode-polymer-electrode structure can be modulated by applying voltages on the electrodes. In these cases, the electrostatic force (pressure) between two electrodes will cause the polymer

TABLE III
IN-USE ELECTRIC MODULATION OF THE PROPOSED TACTILE FORCE SENSORS

In-use Electric Modulation Results						
Curing Voltage V_c (V)	0			3.9		
Driving Voltage V_d (V)	0	1.9	3.9	0	1.9	3.9
Sensitivity (fF/N)	8.6	57.4	205	14.2	213.2	219.1
Sensing Range (mN)	270	115	40	125	35	35
Curing Voltage V_c (V)	7.8			11.6		
Driving Voltage V_d (V)	0	1.9	3.9	0	1.9	3.9
Sensitivity (fF/N)	23.8	38.1	37.9	23.9	19.9	22.2
Sensing Range (mN)	40	35	35	30	30	30

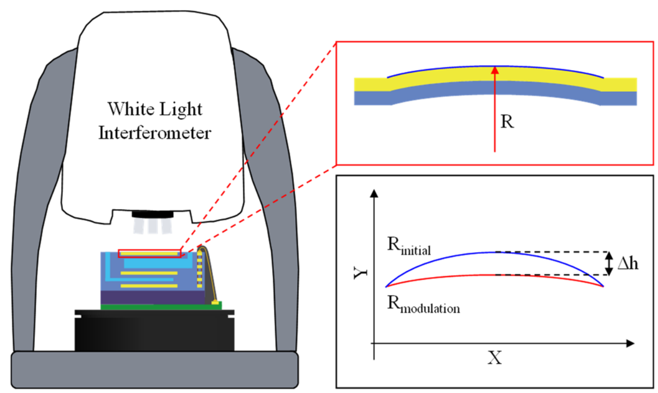
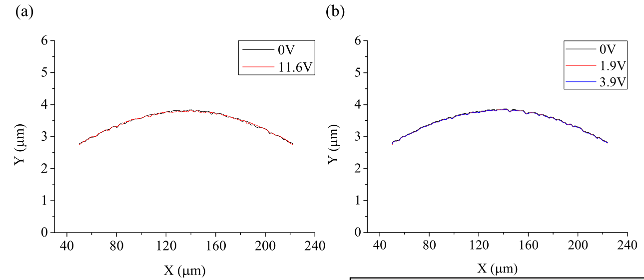


Fig. 9. Measurements of the radius of curvature of bent top electrode (by driving voltage) using the white light interferometer to determine the related thickness variation of PDMS filler.

to be squeezed in thickness and stretched in length and width, modulating its equivalent stiffness [29]. However, in this study, since the suspended structures (consisted of dielectric layers with embedded driving electrodes) are anchored to the substrate, the bending of the suspended structures caused by the electrostatic force between driving electrodes is very small. To better understand the nature of the stiffness modulation mechanism in this study, the radius of curvatures (R) of the top electrodes have been measured by a white light interferometer to determine the thickness variation (Δh) of PDMS filler caused by the electrostatic force, as shown in Fig. 9. Measurements in Fig. 10 summarize the percentage of thickness variation (Δh/h) during in-process curing and in-use modulation. Figurate 10a reveals a change in radius of curvature from $R_{initial} = 3641.6\ \mu m$ to $R_{modulation} = 3657.1\ \mu m$ after applying 11.6 V (the maximum curing voltage) during the curing process. The related percentage of thickness variation is 0.46 %. Moreover, for in-use modulation, the tactile sensor cured under 0 V was chosen as the testing device. Figure 10b shows a change in radius of curvature from $R_{initial} = 3657.6\ \mu m$ to $R_{modulation} = 3670.1\ \mu m$ and $3665.6\ \mu m$ after applying 1.9 V and 3.9 V during in-use modulation. Due to these radius of curvature measurements, the stiffness change of the loading unit caused by the thickness variation of PDMS filler can be ignored. Thus, as shown in



Thickness Variation of PDMS (In-process)		
V_c (V)	R (μm)	Thickness Variation (%)
0	3641.6	0.00
11.6	3657.1	0.46

Thickness Variation of PDMS (In-use)		
V_c (V)	R (μm)	Thickness Variation (%)
0	3657.6	0.0
1.9	3670.1	0.7
3.9	3665.6	0.4

Fig. 10. Measurement results of the top electrode radius of curvature variation and the loading unit PDMS thickness variation caused by the driving voltages during, (a) the in-process modulation, and (b) the in-use modulation.

Fig. 3, this study considers the modulation mechanism of the PDMS stiffness to be the alignment or distribution of polarized PDMS molecules by the driving voltages V_c and V_d. Further investigations are required to better understand the mechanism of PDMS stiffness modulation by applying voltages.

V. Conclusion

This study presents the CMOS-MEMS capacitive tactile force sensor consisting of a loading unit with driving electrodes, PDMS filler, and a sensing unit. The stiffness of the PDMS filler as well as the loading unit can be modulated by varying the input voltage on the driving electrodes. Thus, the sensitivity and sensing range of the presented tactile force sensor can be modulated either in curing process or in use. Since the CMOS process offers multiple metal and dielectric layers, each sensor has its own driving electrodes and electrical routings, and different input voltages for distinct sensors were applied to modulate the PDMS filler. By using the TSMC standard CMOS platform and in-house post-CMOS processes, tactile sensors of different sensitivities and sensing ranges can be simultaneously fabricated and monolithically integrated on the same chip through the presented approach. In-process modulation tests show that, as the driving voltage V_c is increased from 0 V to 11.6 V, the sensitivity of tactile sensors is enhanced by 2.8-fold (from 8.6 fF/N to 23.9 fF/N) and the sensing range of tactile sensors is dropped by near 10-fold (from 270 mN to 30 mN). Moreover, the sensitivity and sensing range can be further modulated by applying the voltage V_d while in-use. The presented CMOS-MEMS tactile sensors show that the tactile sensing window through the in-process and in-use modulation, the sensitivity modulation is from 8.6 fF/N to 219.1 fF/N, and the sensing range modulation is from 30 mN to 270 mN. In conclusion, the PDMS under electric field reveals a stiffness reduction; applying higher voltages during curing or driving results in higher sensitivity and lower sensing range.

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