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Multi-height micropyramids based pressure sensor with tunable sensing properties for robotics and step tracking applications

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Abstract

Precise sensing of pressure is essential for various mechanical and electrical systems. The recent emergence of flexible pressure sensors has enabled novel applications, such as human–machine interfaces, soft robotics, and wearable devices. Specifically, the piezoresistive sensing scheme is widely adapted for flexible pressure sensors as it is simple and exhibits outstanding measurement sensitivity and stability. The sensing properties of piezoresistive pressure sensors mainly depends on the materials and contact morphologies at the interface. This paper proposes a flexible pressure sensor based on multi-height microstructures in which the measurement sensitivity and detection range are tunable. Such tunability is due to the sequential contact of micropyramids with different heights. The multi-height micropyramid structured PDMS layer with stamp-coated multi-walled carbon nanotubes (MWCNTs) acts as a conductive active layer and a gold interdigitated electrode (IDE) patterned polyimide (PI) layer works as the bottom electrode. The fabricated sensor exhibits a sensitivity of 0.19 kPa^{-1}, a fast response speed of 20 ms, and a detection range of up to 100 kPa. The sensor is applied to a robotic gripper for object recognition and integrated into a shoe to track walking motions.

Keywords: Flexible pressure sensor, Piezoresistive, Multi-height, Carbon nanotubes, Robotic sensor

Introduction

The flexible and wearable pressure sensors have drawn much attention as they can detect various biomechanical motions, actuation of mechanical systems, and environmental factors [1–4]. Owing to their thin structure and soft body, flexible pressure sensors exhibit high measurement sensitivities, which is enough to detect human pulse and vocal cord vibrations [5]. Recently, the emergence of durable and high-sensing range pressure sensors has enabled the development of pressure sensor integrated robotic systems and wearable devices. Such pressure sensors mimic human sensory systems and can realize sophisticated human–robot interfaces and electronic skins.

Among various sensing mechanisms, piezoresistive sensors possess advantages such as high durability, a simple setup, and a wide range of materials selection [6–9]. In piezoresistive sensors, the pressure-dependent change in the contact area of conducting microstructures induces a shift in electrical resistance [10–13]. The material and morphology of microstructures decide the sensor properties, such as sensitivity and detection range. Various microstructures of porous structures, microdomes, micropyramids, and microfibers, have proved the measurement sensitivity of pressure sensors [12, 14–19]. Fabrication of microstructures using template molding allows a rapid and straightforward fabrication [17, 20,

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21]. Researchers have used sandpapers, lotus leaves, and etched silicon wafers as molds to create microstructures [17, 18, 20–25]. In most cases, the detection range is inversely proportional to the sensitivity, limiting the use of flexible pressure sensors to only a few kPa ranges [17, 21, 23, 25]. In addition, many studies adopt microstructures with identical designs and the effect of using multi-height microstructures are not well understood.

This study presents a multi-height micropyramid-based pressure sensor to adjust the sensitivity and detection range. For mold fabrication, potassium hydroxide (KOH) wet etching of silicon with different openings generates micropyramid cavities with different heights and base widths. The developed piezoresistive pressure sensors consist of microstructures of up to three different sizes or heights and analyzed their sensing properties. The sensors are applied to step tracking and integrated onto a robotic gripper system, showcasing a possible application area of the presented multi-height pressure sensor.

Materials and methods

Mold and pressure sensor fabrication

Figure 1a shows the fabrication process of KOH etched silicon mold with multi-height micropyramid structures. Initially, the 6-inch < 100 > silicon wafer with 200 nm of silicon nitride (Si_3N_4) is prepared by plasma-enhanced

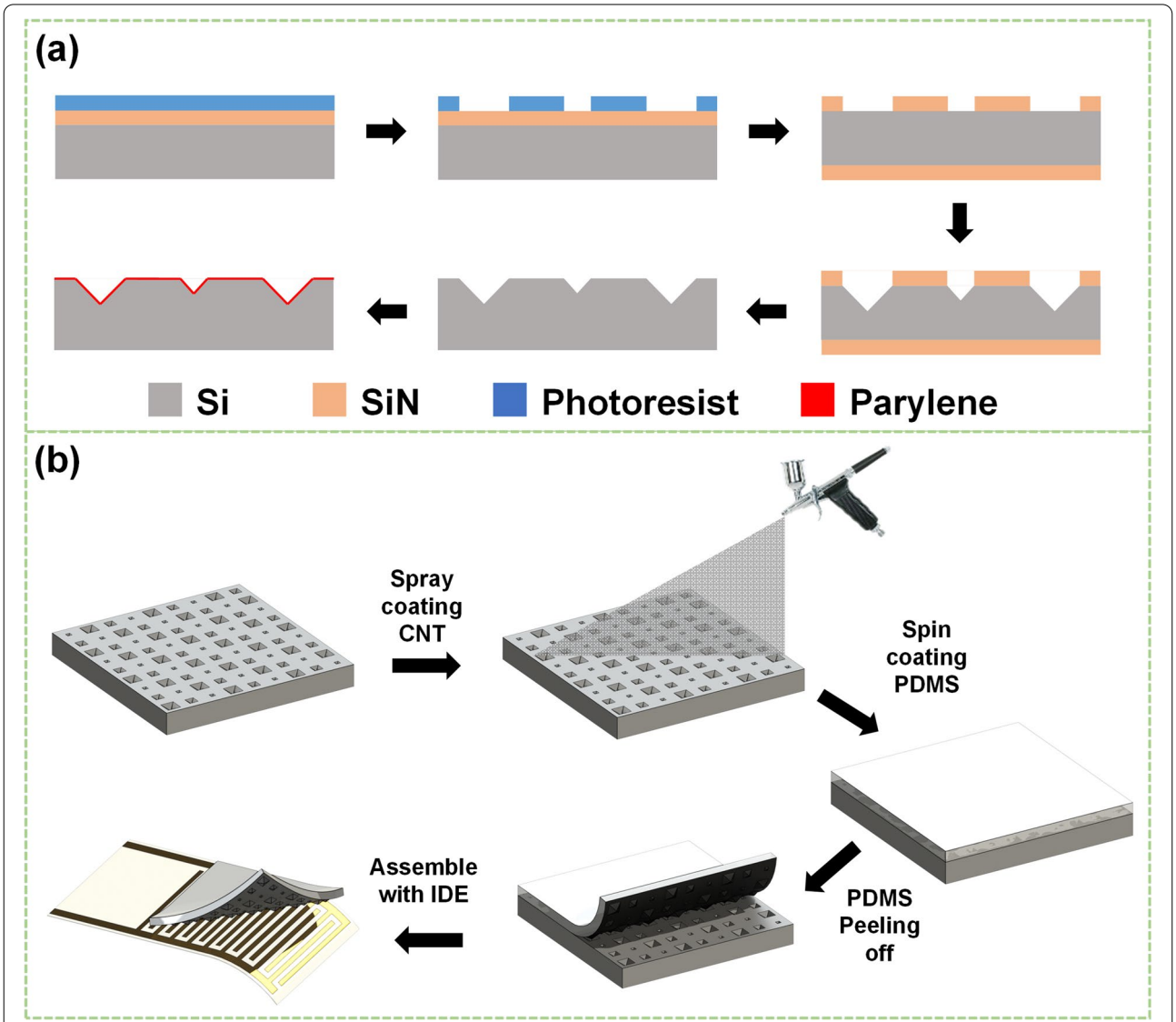

Fig. 1 **a** Fabrication process of KOH etched silicon mold with multi-height micropyramid structure. **b** Sensor manufacturing procedure of CNT coated PDMS active layer with bottom IDE

chemical vapor deposition (PECVD). The photolithography process is used to pattern the photoresist (AZ GXR 601), and then reactive ion etching (RIE) is performed to make a Si_3N_4 mask for KOH etching. After the PR removal using acetone, a-200 nm-thick Si_3N_4 is PECVD deposited on the backside of the wafer to protect the wafer from KOH wet etching. KOH anisotropic etching is processed for 36 min to make a maximum 42.4 μm height (*h*) of micropyramid structure (60 μm of bottom width, *w*) followed by a buffered oxide etch (BOE) to remove Si_3N_4. By controlling the size of the opening, the final height of micropyramids can be adjusted. Finally, the multi-height micropyramid structure patterned silicon wafer is coated with parylene-C to lower the adhesion of PDMS during the molding and peeling process.

Figure 1b shows the pressure sensor manufacturing process. CNT is spray-coated on the fabricated silicon mold for 100 s (0.5 wt.% MWCNT in IPA, Outer diameter: 5 ~ 15 nm, length: 50 μm) at a rate of 0.15 mL/sec. The distance of 30 cm between the spray nozzle and the sensor substrate ensures the formation of a highly uniform CNT layer. Then, a PDMS mixture solution (Sylgard 184, base: agent = 10: 1) is spin-coated at 300 rpm two times, followed by a 30 min vacuum treatment to enhance the adhesion between CNT and PDMS. After curing the PDMS at 150 ℃ for 10 min, the PDMS/CNT layer detached from a Si mold, forming a conducting active layer. Unlike the conventional spray-coating CNTs on the substrate, the proposed process spray-coats CNTs before PDMS casting and curing. We define such a method as stamp-coating. The bottom interdigitated electrode (IDE) was fabricated on a polyimide (PI, VTEC 1388) tape by the photolithography and liftoff process. The electrode consists of a 10 nm Cr adhesion layer and a 100 nm Au. The size of a sensor is 1×1 cm^2.

Device characterization and experiment

For materials and device characterization, a Raman spectrum (Nanobase XPER RF) study was performed and scanning electron microscopy (SEM, Hitachi S 4800) analyses. Au wires were soldered to the end of IDE contacts to form electrical connections to the sensor. The electrical resistance of the sensor is monitored using a digital multimeter (Agilent 34401A) connected to a PC with a LabView program. A universal testing machine (UTM) is used for loading and durability measurements. All measurements were taken under ambient conditions of atmospheric pressure and temperature of 25 °C.

Results and discussion

Figure 2a–e show the SEM micrographs of the fabricated micropyramids with different designs. The proposed molding method results in micropyramids of various sizes and a sharp tip. Figure 2a shows the pristine PDMS micropyramids of identical size and height. Figure 2b–d show the various dimensions of PDMS

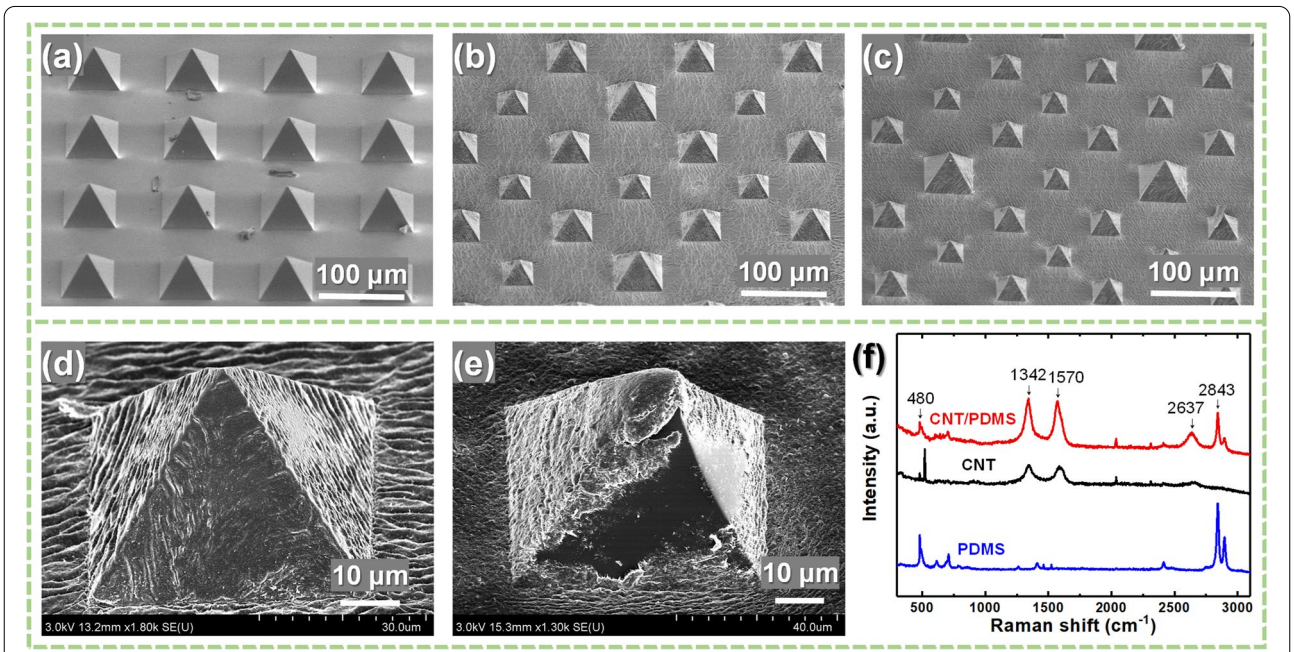

Fig. 2 SEM micrographs of the (**a**) bare PDMS micropyramid, CNT-coated PDMS micropyramids with (**b**) 2 different heights and (**c**) 3 different heights, micropyramids with a (**d**) stamp-coated CNT layer and (**e**) spray-coated CNT layer. **f** Raman spectrum of PDMS, pristine CNT, and CNT-coated PDMS

micropyramids with CNT coated using the proposed stamp-coating method. As the layer of CNT is coated on the mold before the PDMS curing, it is clear that CNT makes good and conformal adhesion to PDMS micropyramids. In addition, the tip of the micropyramid is fully covered with CNT using this method. In contrast, the conventional method of spray-coated CNTs on PDMS microstructures resulted in peeling and nonuniform surface coverage, as shown in Fig. 2e. Thus, the proposed stamp-coating method of CNT on PDMS is robust and adequate to form conducting layers on 3D microstructures. A Raman study is performed to validate that the presented fabrication method does not degrade the quality of CNTs. Figure 2f shows the acquired Raman spectra of PDMS, pristine CNT before coating, and CNT/PMDS composite film. The measured Raman peaks of PDMS and CNT follow the reported values. The CNT/PDMS composite also shows representative peaks of CNT (D-peak, G-peak, 2D-peak) and PDMS. The measured D-peak to G-peak intensities is 1.030 and 1.038 for the pristine CNT and CNT/PDMS composite.

Figure 3a shows the working principle of the multi-height micropyramid flexible pressure sensor. At the initial state, only the tip of the tallest micropyramids makes contact with the bottom electrode. When pressure is applied, the contact area of the taller micropyramid increases, resulting in a decrease in the sensor's electrical resistance. As the applied pressure increases, the smaller micropyramids contact the bottom electrode. Such a sequential contact mechanism allows a wide range of pressure sensing and improvement in measurement sensitivity. Table 1 shows the design parameters of fabricated multi-height micropyramids-based pressure sensors. In this work, up to 3 different sizes of micropyramids with based widths (w) of 18, 36, and 60 μm are studied. For the sensor with single-height micropyramids, the w of the micropyramid is 60 μm. The sensor with two and three

Table 1 Design of studied multi-height micropyramids based pressure sensor

No. of different micropyramid sizes	No. of Microstructures (per cm^2)			Initial resistance(Ω)
	$w = 60$ μm	$w = 36$ μm	$w = 18$ μm	
1	6161	–	–	591
2	5776	–	5776	1464
3	1369	5476	4107	2180

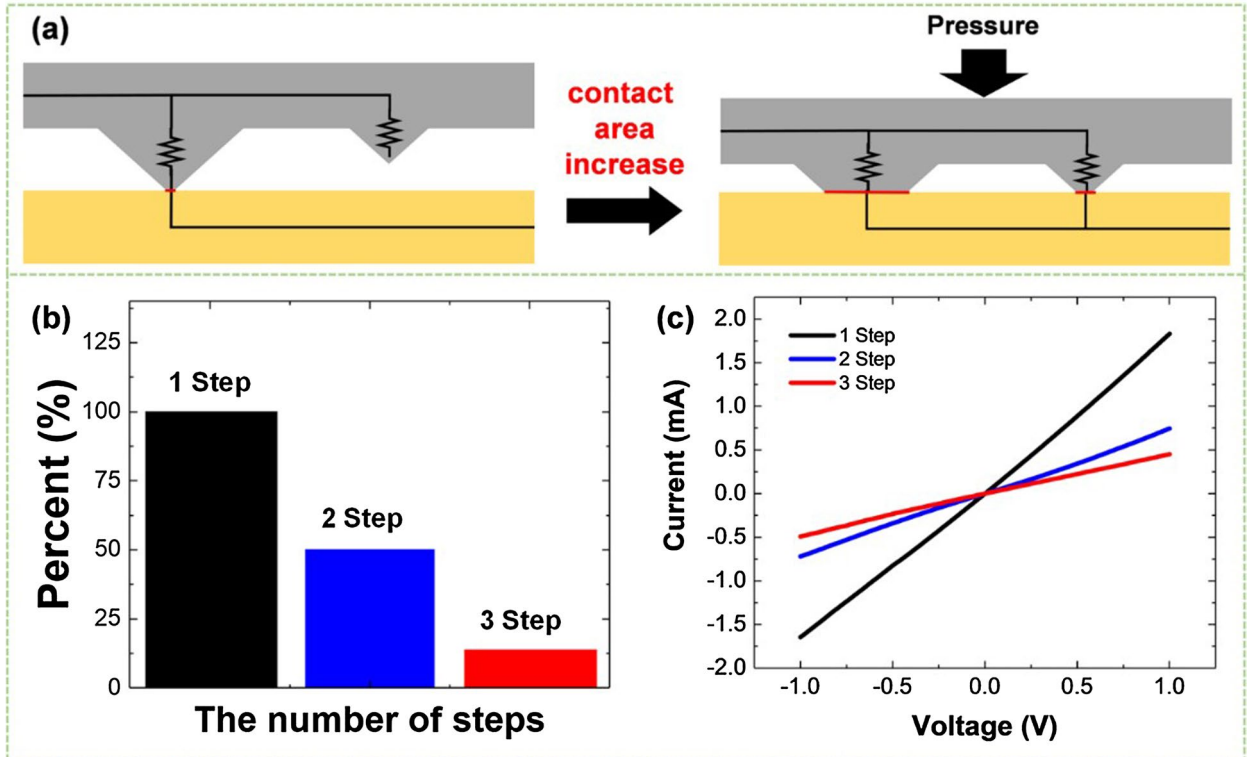

Fig. 3 **a** The schematic illustration of multi-height micropyramid structure. **b** The initial contact pyramid ratio according to the number of steps. **c** The I-V curve of the pressure sensor with different step numbers

different micropyramids heights is designed to have the micropyramids of w = 18, 60 μm, and w = 18, 36, and 60 μm, respectively.

Since the developed sensor consists of multi-height micropyramids, only the tallest micropyramids make contact when no pressure is applied, as shown in Fig. 3b. The sensor's electrical resistance without an applied pressure decreases as the number of the tallest micropyramids decreases. Figure 3c shows the I–V curve of the unloaded sensor and the measured resistance of 2180, 1464, and 591 Ω for 3-step, 2-step, and 1-step sensors, respectively. The linear I–V relation confirms a conformal and stable electrical contact between the CNT/PDMS active layer and bottom IDE.

The compression test is conducted over the pressure range from 0 to 100 kPa to analyze the piezoresistive response of the pressure sensor. Figure 4a shows the resistance change under varying pressure of each sensor. The measurement sensitivity, a %change in sensor resistance divided by applied pressure up to 66.7% of saturation value, is 0.0075 kPa^{-1}, 0.030 kPa^{-1}, 0.165 kPa^{-1}. The detection range defined as the point where sensor response reaches 90% of the saturation value is 23.8 kPa, 13.2 kPa, and 3.5 kPa for 1, 2, and 3-step sensors. From this, it can be concluded that both the measurement sensitivity and detection range can be tuned by adjusting the size and composition of multi-height micropyramids. Such unique characteristics allow building of a flexible pressure sensor with adjustable sensing properties for target sensing applications. Figure 4b shows the resistance response of the 3-step pyramid pressure sensor with different size compositions. The sensitivity is 0.084 kPa^{-1}, and the detection range is 7.6 kPa for the 60, 54, and 48 μm pyramid composition: the sensitivity increases but the detection range decreases as the size composition changes. Thus a fine-tuning of sensing performances of the multi-height sensor is possible by using different size compositions of micropyramids.

The sensor response is monitored at three different applied pressures, 2, 3.3, and 13 kPa, to verify the sensor performance under varying loads, as shown in Fig. 4c. The results show that the developed sensor can track changes in pressure and reach a stable output under a consistent loading. Response and recovery duration is also essential parameter for pressure sensors. Figure 4d shows a response of the sensor under pulsed loading by human touch. The response time if measured to be 20 ms, and the recovery time was 40 ms. The sampling time was limited to 10 ms due to the experiment conditions, but the developed sensor can track rapid changes in applied pressure. Figure 4e shows the result of the durability test of 2500 cycles of loading at 2 kPa at a rate of 1.25 cycles/sec. The cyclic test shows no drift in the sensor response, showing that the presented sensor is robust and suited

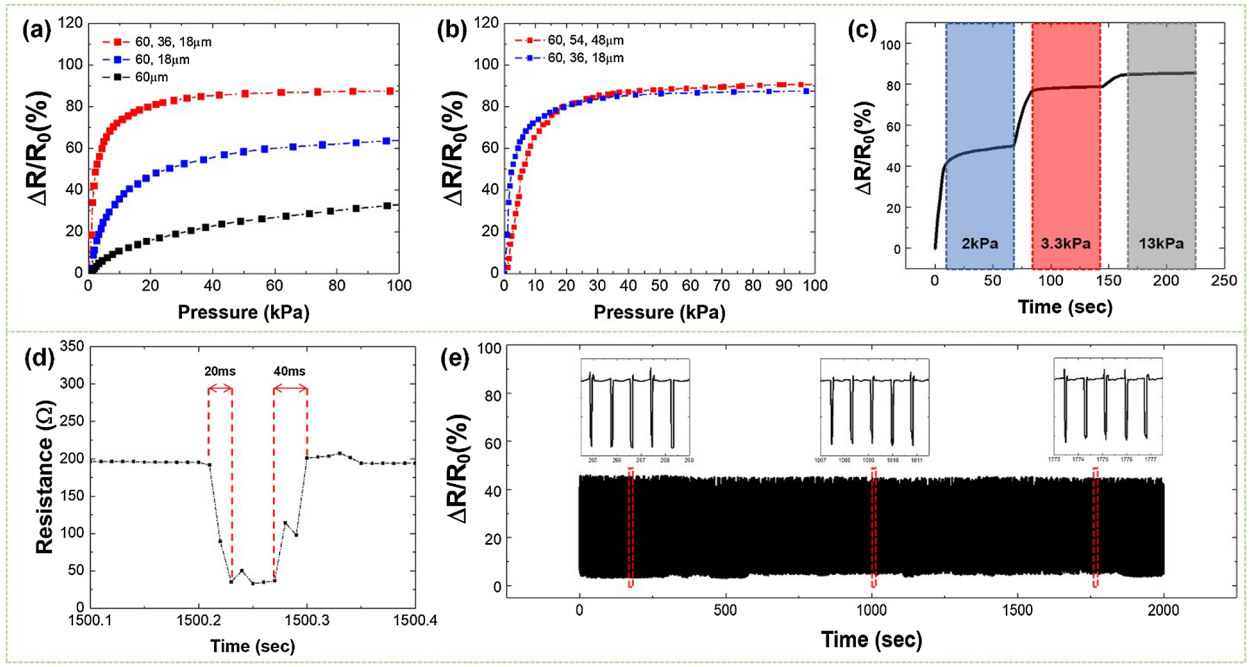

Fig. 4 **a** The resistance response of the sensor with a different number of steps. **b** The resistance response of 3 step pyramid pressure sensor with different height compositions. **c** Compression maintenance test at the applied pressures of 2, 3.3, and 13 kPa. **d** Response and recovery performance of the sensor. **e** Durability test under 2500 cyclic loading at 2 kPa

for prolonged operation in various circumstances. In addition, there was no visual damage to the sensor after such a lengthy operation.

The developed multi-height pressure sensor is used for various applications. Figure 5a–c shows the pressure sensor attached robotic gripper with two fingers. The angle between fingers can be precisely controlled to quantitatively analyze the grasping pressure as a function of the finger position. The sponge ball is used as an object, and it exerts different pressure values at different gripping positions, as shown in Fig. 5d. Flexible pressure sensors can be used for healthcare and human motion tracking. Here, the sensor is attached to the shoe insole and is used to count the number of steps, as shown in Fig. 5e. The sensor response is fast enough to track the user's rapid walking motion (~ 100 steps/min). As the last application, the 2×2 array of the sensor can acquire not only the pressure data but also the spatial information. Figure 5f shows the sensor array and placing of objects with different weights and shapes. Such array integration allows using the developed sensor for large area pressure monitoring with sub-cm spatial resolution.

Conclusion

This work presents the design, fabrication, characterization, and application of a multi-height pressure sensor consisting of a CNT/PDMS active layer and bottom IDE. The active layer implements PDMS micropyramids fabricated using a KOH wet etched silicon as the mold. In addition, the stamp-coating of CNT ensures a robust and conformal adhesion of the CNT layer on PDMS micropyramids. The sensors with varying sizes of micropyramids are fabricated and tested over a loading range up to 100 kPa. The results indicate that the integration of multi-height micropyramids affects measurement sensitivity and detection range. The developed sensor exhibits good durability and a response time of 20 ms. The sensor can measure grasping pressure when attached to a robotic gripper. In addition, the sensor successfully tracks the walking motion at different step rates. This study shows the optimized combination of multi-height microstructures for flexible pressure sensors to fine-tune the sensor properties without replacing the sensor materials or changing the sensing scheme.

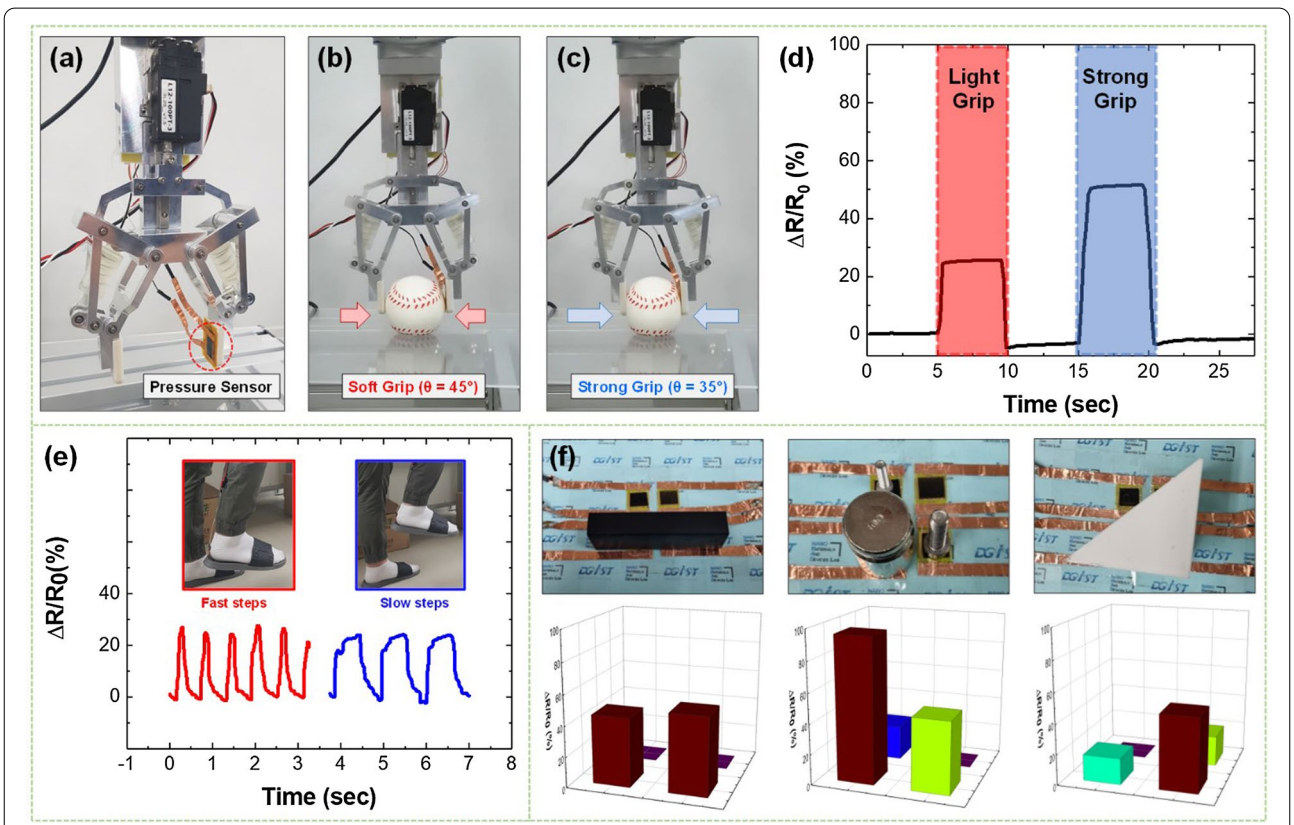

Fig. 5 **a**–**d** Gripper integration test with a light grip and strong grip. **e** Insole attaching test with fast step and slow step. **f** Array test with different weights and shapes of structures

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Author contributions
DOh: experiment, data curation, formal analysis, writing–original draft; JS: formal analysis, writing-original draft; HGK, CR: data curation, device fabrication; SB: experiment; SP: resources, writing-review and edit; HJK: supervision, funding acquisition, writing-review and edit. All authors read and approved the final manuscript.

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Availability of data and materials
All data generated or analyzed during this study are included in this published article.

Declarations

Ethics approval and consent to participate
Not applicable.

Consent for publication
Not applicable.

Competing interests
The authors declare that they have no competing interests.

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