

Enhanced Sensitivity Iontronic Pressure Sensor Gauge Using Laser-created Micro-pyramid Structures for Wide Linear Range

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Abstract

The achievement of high sensitivity, ultrahigh pressure resolution, and great linearity across a wide pressure range under huge pressure preloads remains a challenge despite the substantial development of flexible capacitive pressure sensors. Here we offer an ultrathin ionic layer-integrated microstructure creation process that is configurable. At 1700 kPa, the sensor's linear range sensitivity is 33.7 kPa-1; at 2000 kPa, the pressure resolution is 0.00725%, and the detection limit is 0.36 Pa. Extremely high-resolution smart weight scales and chairs, interactive robotic hands, and delicate pulse detection are just a few of the applications that can benefit from the sensor's fast response/recovery and outstanding repeatability. Other iontronic sensors may be simply created with the help of the suggested fabrication techniques and design toolkit, which is furthermore useful for rapidly altering the performance of sensor's performance for the pressure for a range of intended uses. This research shows an improved iontronic pressure sensor gauge that uses laser-cut micro-pyramid shapes to get a large linear range. This new micro-pyramid design greatly expands the touch area and pressure sensitivity, which makes

the sensor work better. Laser manufacturing makes sure that the nanoscale is formed precisely and consistently, which leads to results that can be relied on and repeated. Experiments show that the sensor is very sensitive, responds quickly, and has a large linear detecting range. This means it can be used in robots, healthcare, and wearable tech, among other things

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INTRODUCTION

Flexible pressure sensors quick development has created new applications for them in robotics, health monitoring, prosthetics, and machine-human interfaces. Capacitive pressure gauge are a promising type of flexible sensor because they are simple to manufacture, stable, and have low power consumption. However, one challenge in the development of capacitive pressure sensors is achieving linearity and high sensitivity over a broad range. One way to improve the linearity and sensitivity of capacitive pressure gauge is to use

micro-structures on the sensor surface. Microstructures can increase the gauge's sensitivity by increasing the surface area of the sensor and by providing a means for the sensor to deform in a controlled manner. However, the use of microstructures can also reduce the sensor's linearity [1].

One method to become better the linearity of a capacitive pressure gauge with microstructures is to use non-uniformly distributed microstructures. This can be done by using a gradient of microstructures, where the size or density of the microstructures increases with increasing pressure. This approach can improve the linearity of the sensor by spreading out the sensor's response over a wider range of pressures. Another method to become better the linearity of a capacitive pressure sensor with microstructures is to use materials with different dielectric constants at different locations on the sensor surface [2]. This can be done by using a composite material, where the different materials are arranged in a specific pattern. This approach makes the gauge linearity better by making the gauge's response more sensitive to changes in pressure. Research is now underway to produce flexible pressure sensors with excellent sensitivity, linearity, and a broad working range. The approaches discussed above are just a few of the many ways that researchers are working to enhance capacitive pressure sensors' functionality [3].

Researchers have been working to improve the sensitivity of capacitive pressure sensors by mixing high dielectric materials with nanomaterials, such as $\text{CaCuTi}_4\text{O}_{12}$, MXenes, carbon nanotubes, and Ag nanowires. However, these sensors still have limited linear sensing range. For the purpose of creating programmable microstructures for iontronic sensors, such as gradient pyramidal microstructures (GPM), a novel manufacturing technique utilising a CO_2 laser with a Gaussian beam profile has been devised [4]. Each pyramid in the gradient array has a height and profile that may be on a personal level altered & optimized to supply uniform distortion as pressure rises. An ultrathin ionic liquid (IL) layer combined with programmable microstructures yields an iontronic sensor with a very wide linear identification range of up to 1710 kPa, outstanding linearity (0.99), & high sensibility (33.7 kPa^{-1}). In addition to integrating using a control mechanism to enable intelligent communication between humans and machines, the sensor may be used to detect minute pressure differences under an ultrahigh pressure load and faint pulses from the fingertip. The new fabrication method is scalable and can be used to create sensors with different shapes and sizes. This enables the development and demonstration of smart interfaces for humans and machines, intelligent prosthesis interfaces, and the foreseeable future of health monitoring devices.

EXPERIMENTATION

Construction

Manufacturing the PMMA Mould

A CO_2 laser system (30W, $10.5 \mu\text{m}$ wavelength, VLS2.3Inc.) was used in ambient conditions for manufacturing the PMMA mould. Inkscape was used to generate the patterns. Raster mode was used to create the gradient structure, using 20% of the maximum speed, 0–31% of the highest power, 1050 PPI, & a picture density of 6.5. First, laser intensity was gradually reduced from dark black to dark red, and subsequently to dark purple, to generate the microstructures' gradient base (Supplementary Figure 1). Then, pyramidal structures were formed at the same site by using the lower laser power in the next laser processing phase [5].

Setting up the lower electrode

- *PDMS layer creation:* To create a consistent layer with a thickness of around 250 micrometres, The Sylgard 184 base and curing agent were spin-coated onto the PMMA mould at 400 rpm in a weight ratio of 10:1. After degassing, the coated layer was cured for an hour at 90 degrees Celsius in an oven. Next, the PMMA mould was carefully removed from the hardened PDMS layer.
- *Air plasma treatment:* The PDMS layer was treated with air plasma at 30 watts for 10 minutes. This treatment improved the adhesion of the PDMS layer to the Au bottom electrode.

- APTES treatment: The PDMS layer was dipped in a solution of APTES for 11 hours. This treatment further improved the adhesion of the PDMS layer to the Au bottom electrode.
- Au bottom electrode sputtering: A 50-nanometer-thick Au layer was sputtered onto the PDMS layer using a Quorum Q150R sputter coater. The Au layer served as the bottom electrode of the sensor.

Iontronic Layer and Top Electrode Preparation

PVDF-HFP & Acetone were combined in a mass-to-volume ratio of 20:3 to create the iontronic layer. Next, using a mass-to-volume ratio of 25%, 36%, or 55% of PVDF-HFP, IL [EMI][TFSI] was added. To dissolve all of the PVDF-HFP, the mixture was heated to 120 degrees Celsius and agitated at 1000 revolutions per minute. After that, the homogeneous solution was spin-coated for 30 seconds at 1000 revolutions per minute onto ITO/PET film, which had been trimmed to 1.2 cm by 1.2 cm. The iontronic layer was cured and the acetone completely evaporated by drying the solution in a fume hood over a hot plate at 80 degrees Celsius [6].

Assemblage of Pressure Sensors

The pressure sensor was put together using clear medical tape (3M Tegaderm film). To form a seal, the tape was positioned at the border between the bottom and bottom electrodes. After that, the tape was used to firmly secure the sensor on the finger. This made it possible to detect pulses at the fingertips. A chair has four pressure sensors positioned beneath its legs. The sensors were positioned in between two 1.5 cm by 1.5 cm by 0.1 cm PMMA boards. This made it possible to weigh objects and show off excellent pressure resolution. Unless otherwise noted, the pressure sensors were utilised for other purposes while still in their packaging [7].

Measurements and Characterization

With the use of Zeiss FESEM Gemini 500 field emission-scanning electron microscopy, the surface morphology of the bottom electrode was described. Unless otherwise noted, the pressure gauge capacitance (10.5 mm × 10.5 mm) was gauged at a frequency of 1.5 kHz using an LCR metre (Hioki IM3536). The pressure was applied and recorded using a gauge of force. Using an Arduino nano board, two capacitors' signals were observed for robotic hand application. An actuator for a straight rail guide slider was utilised to confirm repeatability. The ionic gel is positioned within two flat ITO / PET electrodes allowed for the measurement of areal capacitances [8].

Operation

The polyethylene terephthalate (PET) / indium tin oxide (ITO) top electrode, the lower structured electrode, & the iontronic insulator layer comprise the flexible iontronic pressure gauge. The sensor works by measuring the change in capacitance between the two electrodes as the iontronic dielectric layer is compressed. The sensor has a gradient pyramidal structure, which means that the height of the pyramids increases gradually from the bottom to the top. This design allows the sensor to have a broad linear range of sensing, 0 to 1700 KPa. Additionally, at a pressure of 2000 kPa, the gauge has a low 0.35 Pa identification limit & 0.00726% pressure resolution. The Iontronic the pressure Sensors overview is illustrated in Figure 1.

The sensor is made using a low-cost, multi-step process that involves laser-ablating polymethyl methacrylate (PMMA). The sensor can be assembled quickly and easily by detaching the PMMA mold's structural electrode and assembling it with the PET/ITO covered in iontronic gel. The flexible sensors of iontronic pressure has a number of advantages over other types of pressure sensors. It is flexible, which makes it suitable for wearable applications. It is also has a fast response/recovery time, which makes it suitable for applications where real-time feedback is required. Numerous possible uses for the flexible iontronic pressure sensor exist, such as smart weighing scales, human-robot interface, and health tracking [9].

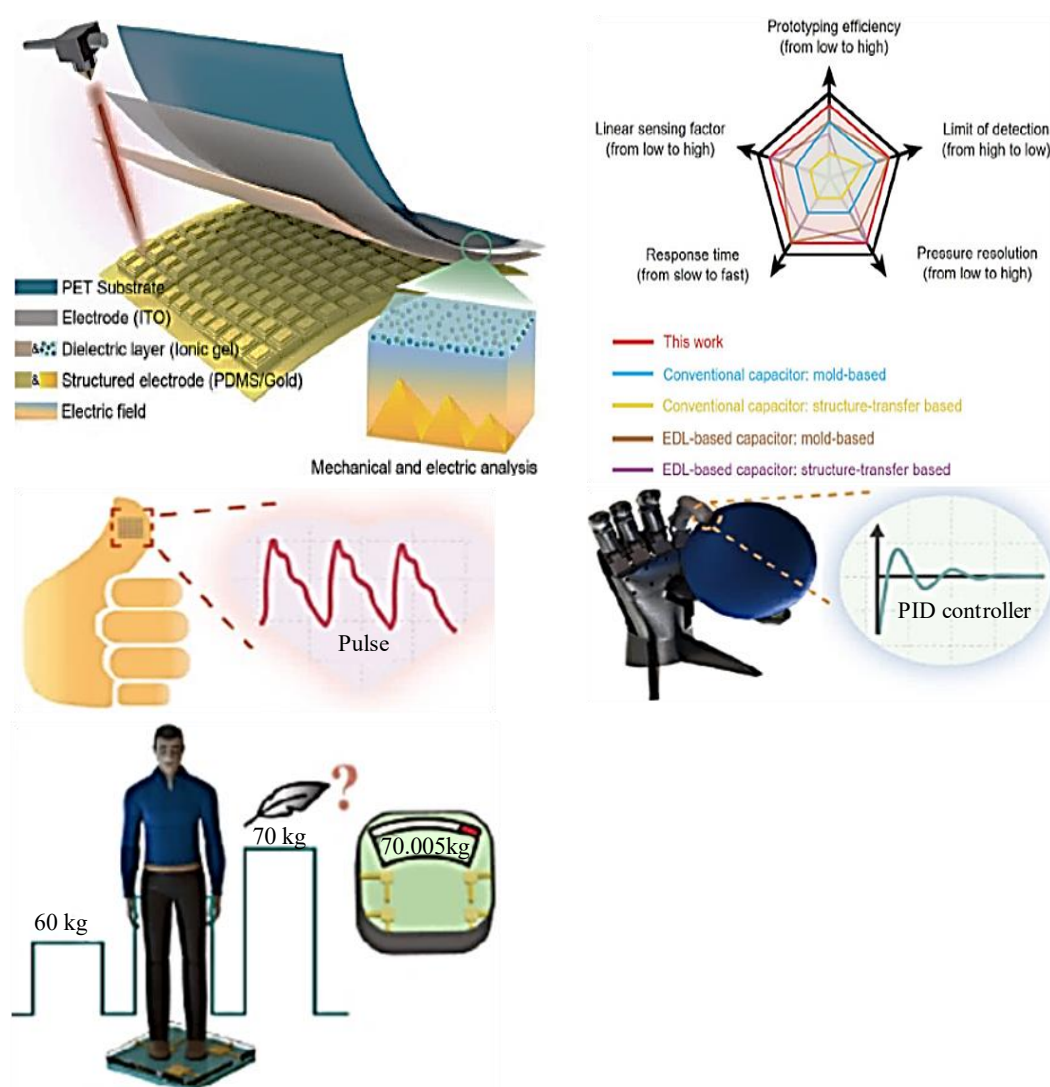


Figure 1. An Iontronic the pressure Sensors overview, Health monitoring, Interactive Robotic hand, Smart weight scale<>

Here are some of the specific improvements that were made to the sensor in this study:

- The use of a gradient pyramidal structure increased the sensor's linear gauging range, 200 kPa - 1700 KPa.
- The use of an ultrathin ion gel improved the gauge's sensibility from 12.43 KPa^{-1} - 33.7 KPa^{-1} .
- The use of a laser-ablation process reduced the cost of manufacturing the sensor.
- The findings of this study show that iontronic pressure gauges have a lot of potential uses.

OBSERVATIONS

Gradients Pyramidal Microstructures Produced From Moulds Ablated With a Laser

PMMA can be transformed from a solid to volatiles through a a single-step process of volatilization and thermal breakdown. This is caused by the response of C-O bond cleavage, $[\text{CH}_2\text{C}(\text{CH}_3)(\text{CO}_2\text{CH}_3)]_n \rightarrow \text{CO} + \text{CO}_2 + \text{H}_2\text{O} + \text{H}_2$. A Gaussian laser power distribution of intensity with a rectangular shape produces a Gaussian-looking profile in the laser-ablated holes. Conical, cone, and square frustums are only a few examples of the many microstructures that may be made using different programmed laser patterns. High consistency square frustum microstructures may be produced via square laser patterns [10].

The ability of gradient microstructures to provide good sensitivity over a broad sensing range makes them useful. In the whole sensing range, well-crafted gradients can also provide great linearity. Gradient microstructure manufacturing is, however, historically difficult, despite sophisticated photolithographic techniques. Using a gaussian dispersed laser beam for laser ablation of PMMA offers a straightforward and practical way to get around this problem. Changing the laser intensity is the most natural technique to adjust the structure height in order to create gradient microstructures. Microstructures get taller and thinner as the maximum laser power is increased. But when under duress, their high aspect ratio might cause them to bulk up. The linearity of the sensor's performance is compromised by this nonlinear deformation caused by buckling [11].

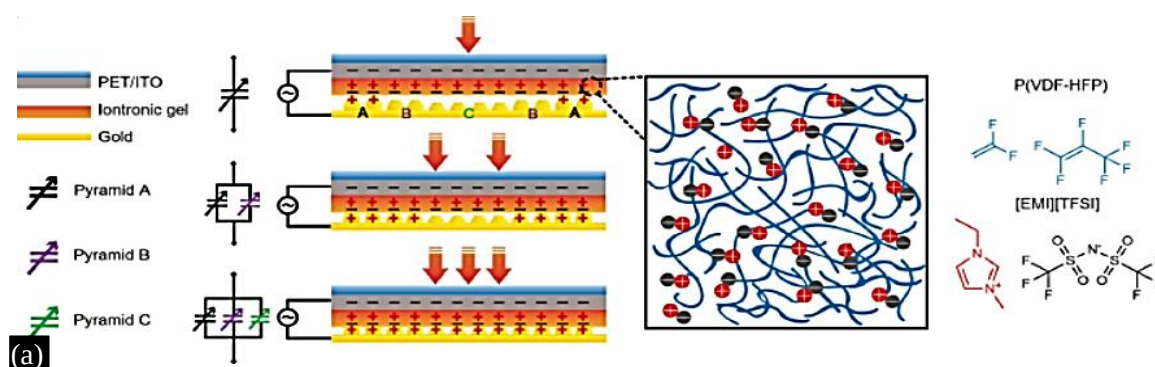
Multiple laser ablations have been used to produce multi-layered gradient pyramidal microstructures in order to overcome this problem. In comparison to the preceding ablation, the subsequent laser ablations show a broader spread but lesser intensity [12]. Under pressure loading, Similar cross-sectional dimensions in multiple-layered micro structures are prone to bulking. In order to solve this problem, each layer's square laser pattern is expanded while the laser strength is lowered. PMMA with three layers templates & matching PMDS pyramidal micro-structures with progressively smaller cross-sectional areas are produced as a result.

More laser ablation layers can result in a microstructure that resembles a pyramid and has more precise characteristics. Pyramidal microstructures of various sizes may be created by varying the laser pattern's sizes while keeping the three layers' ratio constant. Prior to laser ablation of the PMMA template's three layered structures, an extra layer made of variable powers can be added to produce varying elevations within the final pyramidal micro-structure. Different layers' microstructures may have traits that are hierarchically similar [13].

Monitoring Capabilities of Various Laser-Induced Structure

First, to study the two-dimensional deformation of various microstructures under the loading of pressure FEA used. Modifications to the contact region ($\Delta A/A_0$) at the dielectric interface / electrode are the primary cause of the changes in capacitance caused by pressure in EDL-based capacitor sensor. The sensor with pyramidal structures has the maximum sensitivity because of its lowest tip area, as evidenced by the shift from homogeneous microstructures with the same heights in comparative area of contact or capacitance as pressure increases [14].

As pressure increases, the gradient pyramidal microstructure (GPM), in contrast to the uniform microstructure (UPM), is compressed progressively from the tallest to the shortest structures. This causes the electrode/dielectric interface to have a steadily greater area of contact. When comparing the GPM to the UPM with the identical pressure being applied, GPM's initially smaller contact area leads to bigger modifications and increased sensitivity. Furthermore, contrasted to a GPM with a little disparity in height, the GPM greater disparity in height exhibits somewhat higher sensitivity.



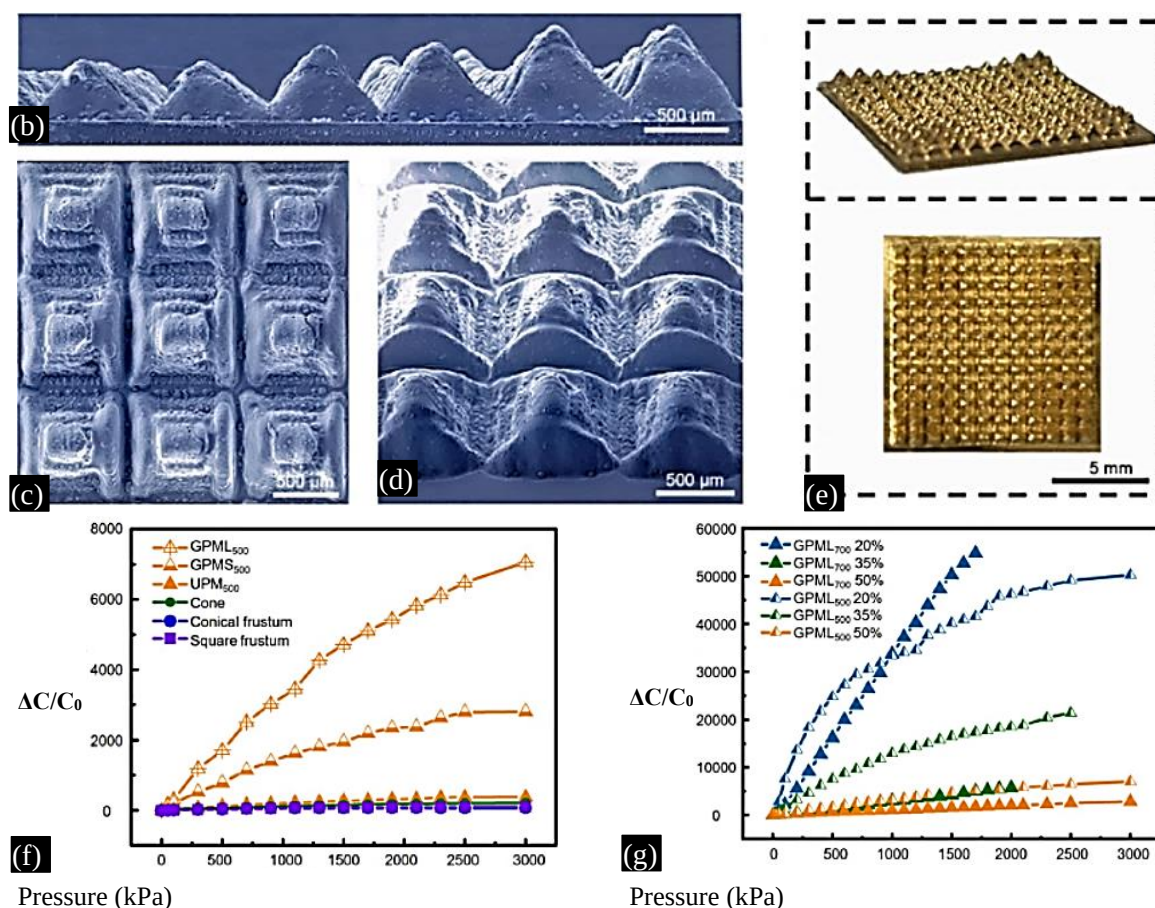


Figure 2. Iontronic pressure sensor design and characterization based on gradient pyramidal microstructures, (a) Diagram showing how the iontronic pressure gauge works Gradient electrode shown by the images captured using a scanning electron microscope (SEM) from (b) perspective, (c) top, & (d) side perspectives. The gradient electrode's optical pictures in tilt (top) and top (bottom) perspectives, (e) Evaluating the capacity of sensors to sense pressure when they have (f) varied microstructures (20 weight percent IL) & (g) different percentages of IL weight.

Outcomes of an experiment using microstructures made from PMMA ablated by laser moulds confirmed the design lessons & FEA forecasts. The pyramidal microstructure, which has a lower tip area than cone- and frustum-like microstructures, gives the detector the most variations in capacitance and relative contact area when pressure is applied [15]. In addition, the GPML shows more sensitivity than the GPMS and UPM. Consequently, inside a 3000 kPa ultrawide range ($R^2 = 0.97$), the extreme sensitivity of 2.491 kPa^{-1} may be attained in GPML. Figure 2 illustrates the Iontronic pressure sensor design and characterization based on gradient pyramidal microstructures.

The Augmented EDL Effect Modulates Sensing Performance

By adjusting the concentration of ionic liquid (IL) in the dielectric layer, the iontronic pressure sensor's detecting performance may be adjusted. This improves the primary working mechanism of the gauge, the electric double layer effect. An increase in capacitance (areal) 35.90 to $983.50 \text{ pF cm}^{-2}$ at 99.5 Hz is the consequence of growing the content of IL from 20.5 to $50.5 \text{ wt\%}$. However, as the IL content rises, the range of linear sensing decreases from 3005 to 700 kPa . A gradient pyramidal microstructure (GPM) may be designed with great care to optimise the ratio of linear sensing range to sensitivity [16]. An increase in the unit cell's base size from 550 to 750 μm , for example, produces a more powerful field of electric that more nonlinear fluctuations. In order to keep variations in linear capacitance, this helps offset the slower rise in capacitance during the latter compression stage (greater pressure loading).

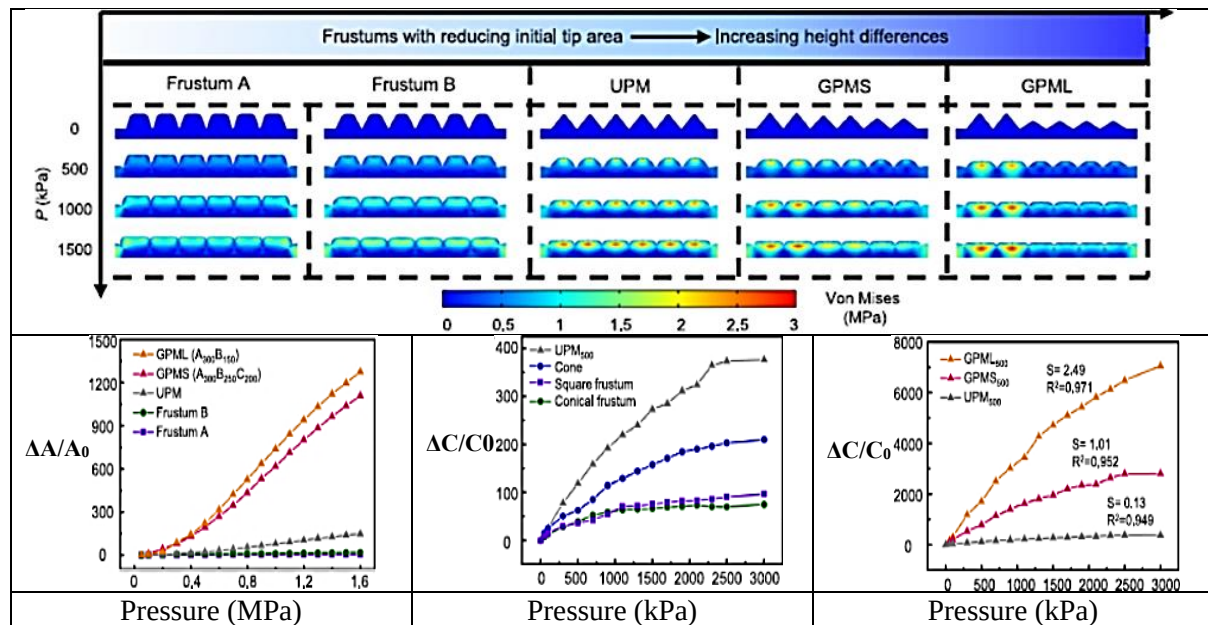
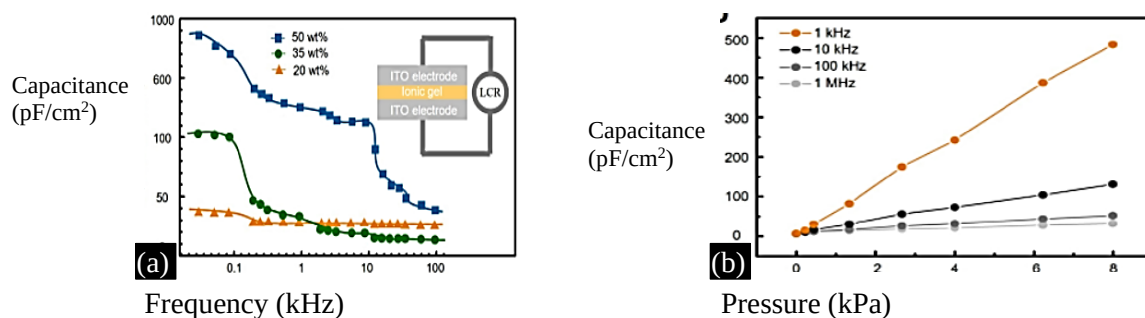


Figure 3. Investigations were conducted into the creation of an iontronic pressure gauge that has optimised microstructures. The spread of stress & the normalised change in the relative area of contact ($\Delta A/A_0$) at the ion-liquid (IL) interface / electrode during the loading of pressure on gauge with different microstructures were investigated using FEA. The outcomes showed that gauge with gradient microstructures had a more uniform stress distribution and a larger $\Delta A/A_0$ than the sensor with uniform microstructures. This suggests that the sensor with gradient microstructures has better performance concerning linearity and sensitivity.

Figure 3 illustrates the Investigations were conducted into the creation of an iontronic pressure gauge that has optimised microstructures. In comparison to earlier literature studies, the pressure gauge for iontronic capacitive exhibits exceptional sensibility over an ultrabroad linear range of sensing [17]. The sensor's flexibility makes it simple to affix to a curved surface. But under bending circumstances, the sensor's performance is greatly diminished, most likely as a result of the microstructures changing. When the iontronic pressure sensor is directly produced using a modified laser setup on 3D freeform surfaces, further improvement may be conceivable. After a pressure application of 5 kPa, the pressure gauge of iontronic with gradient microstructures demonstrates a quick reaction or recovery of 6/11 ms. This is quicker than biological skin and the reaction times of piezoresistive, capacitive, and piezoelectric pressure gauge. The sensor can identify a light weight paper because of its lower limit of identification of 0.37 Pa. Under high pressure, the gauge may also pick up on minute pressure variations. For instance, the sensor is still able to detect pressures of 99.80 Pa, 199.50 Pa, & 1.1 kPa when a high pressure of 200 kPa is applied. Over 4500 cycles, there is essentially no drift in the sensor response, which remains consistent and steady under cyclic loads. Utilizing the relative standard deviation (RSD) of 3.12%, the sensor response's batch-to-batch variance is similarly minimal. The extremely dependable manufacturing method is to blame for this. Figure 4 shows the electron double layer (EDL) effect can be modulated in order to enhance the effectiveness of pressure gauge [18].



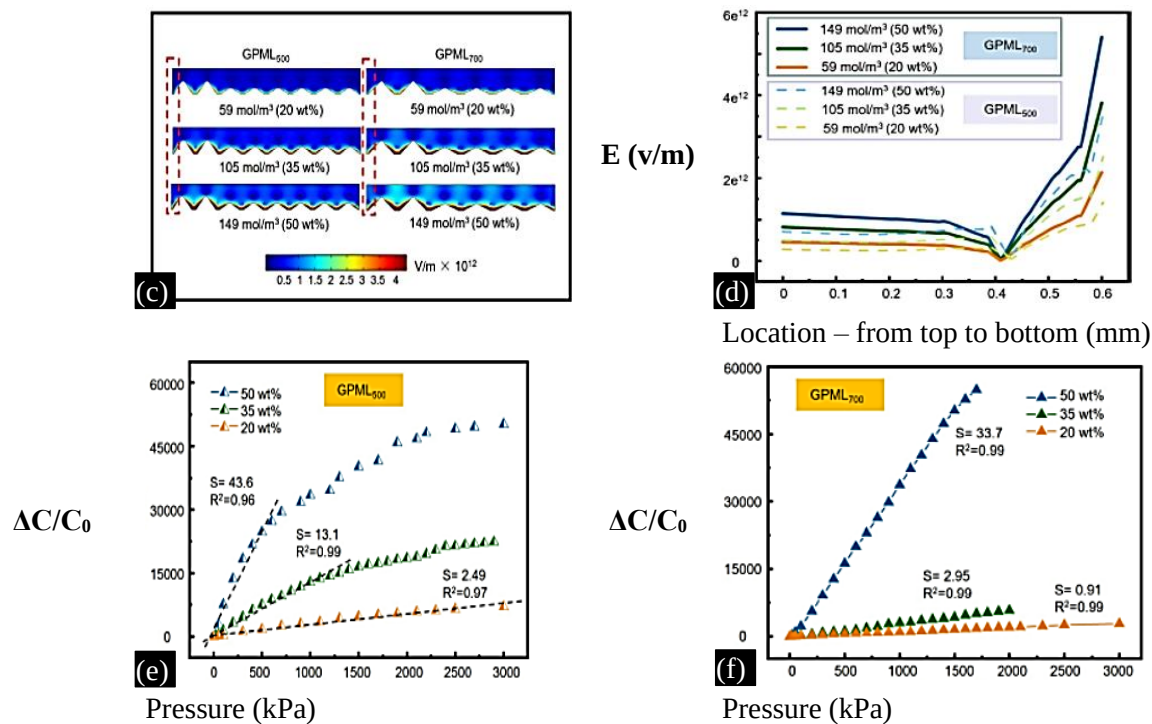
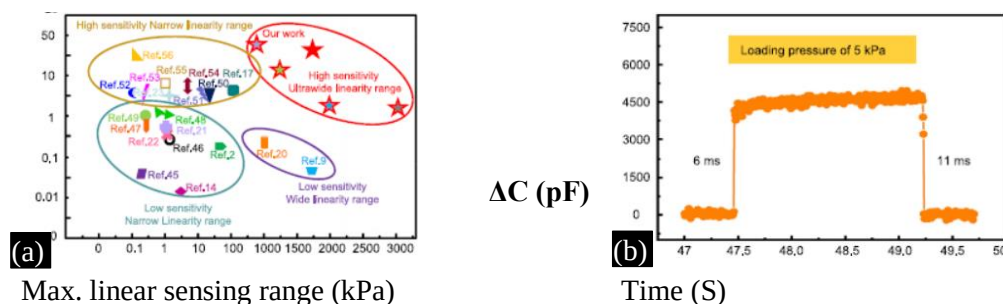


Figure 4. The electron double layer (EDL) effect can be modulated in order to enhance the effectiveness of pressure gauge. (a) The areal capacitance of the dielectric layer based on the measurement frequency and the IL concentration. The capacitance increases with increasing IL concentration and decreases with increasing measurement frequency. (b) The capacitance of the sensor increases with increasing pressure at all measurement frequencies up to 8 kPa. The capacitance increases more rapidly at lower measurement frequencies [19]. (c) The field of electric in GPML was simulated with varying IL concentrations. The results showed that the electric field strength increases with increasing IL concentration. (d) Within the upper and microstructured lower electrodes, there is a very nonlinear field of electric. The area in c where the red dashed box is located is where the field strength is strongest. The sensors built using GPML500 and (e) (f) GPML700 have different weight percentages of ILs. The sensor with a higher IL weight percentage has a larger linear range and increased sensitivity.

Detections of Minute Movements, Both Dynamic and Static

It was possible to create a flexible, iontronic capacitive pressure sensor that is sensitive to minute pressure changes and minute movements. It is possible to detect physiological signals from unusual places, such the fingertip, with this sensor. The sensor clearly identified the waves as T, D and P in the pulse signal obtained from the fingertip of a human subject in good health. When the participant went from resting to exercising, their heart rate went from 68 to 104 beats per minute. Additionally, hold-and-drag gestures and mouse clicks can be recognized by the gauge. This illustrates in Figure 5, the gauge's stability and dependability under both pressure conditions (dynamic and static) [20].



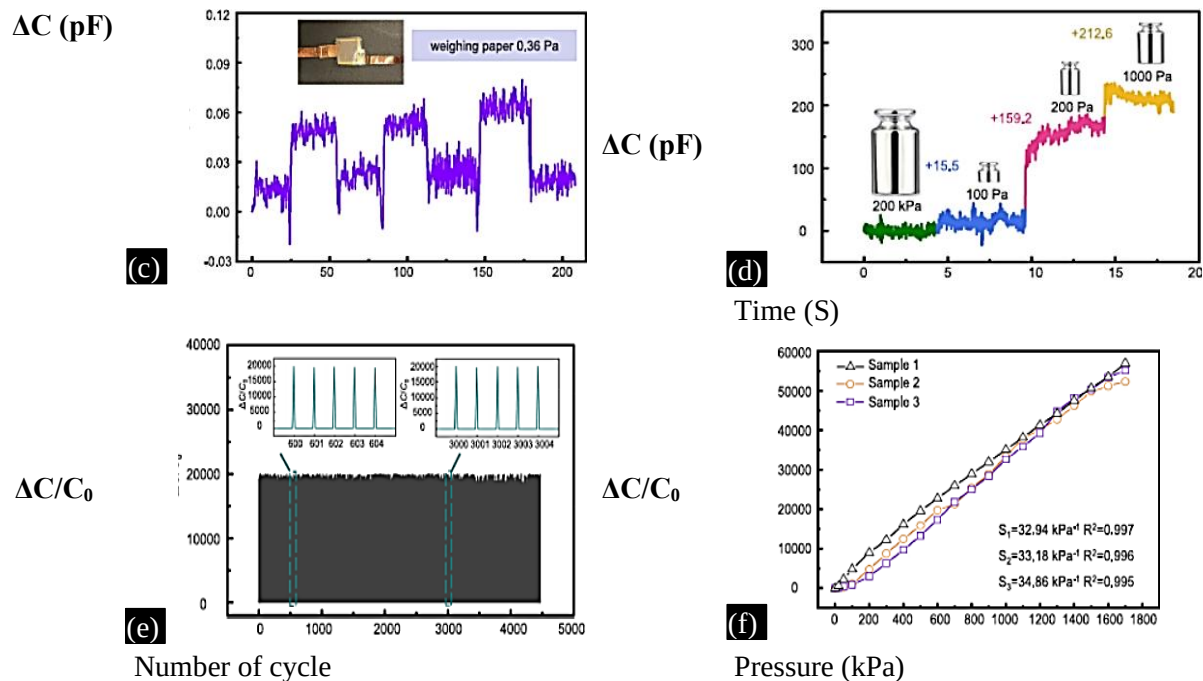
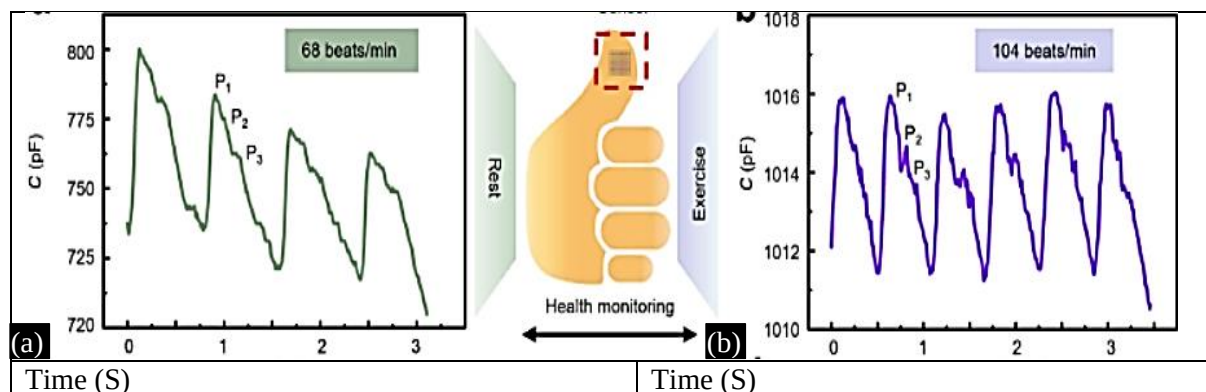


Figure 5. The iontronic pressure sensor with 50wt% IL was characterized for pressure sensing performance. (a) The adjustable iontronic pressure gauge's sensitivity and greatest linear sensing range developed in this study were compared to those of existing capacitive pressure gauges. (b) The response and recovery time were determined using the iontronic pressure sensor's response curve at 1 kHz. (c) Using a weighing paper little piece of loaded repeatedly on the gauge, the identifying the limit of 0.37 Pa was shown. (d) With a preload pressure of 2 kg already in place, find tiny extra pressures of 1.1 g, 2.1 g, or 10.1 g. (e) Test the repeatability of the sensor throughout 4500 cycles of pressure cycling at 800 kPa. (f) Readings are obtained from three distinct pressure sensors.

High Resolution of Pressure Even With High Pressure Preloads

Most microstructure pressure sensors are only useful in low pressure applications because their sensitivity is either significantly diminished or saturated over 100 kPa. Furthermore, minuscule detection of pressure is only achievable at virtually preload with disappearing pressure, & lower limit of identification often arrives at the expense of a restricted sensing range [21]. Our iontronic pressure sensor's GPM, which has small features on its pyramidal surface, enables it to detect minuscule pressure at high pressure or large loads in order to achieve ultrahigh pressure resolution. In order to showcase our sensor's capabilities, we positioned four sensors—encased in PMMA—beneath each leg of an intelligent chair. The chair and human subject may produce a maximal uploading pressure on every gauge of up to 2510 kPa on each sensor, each of which has an area of 1 cm².



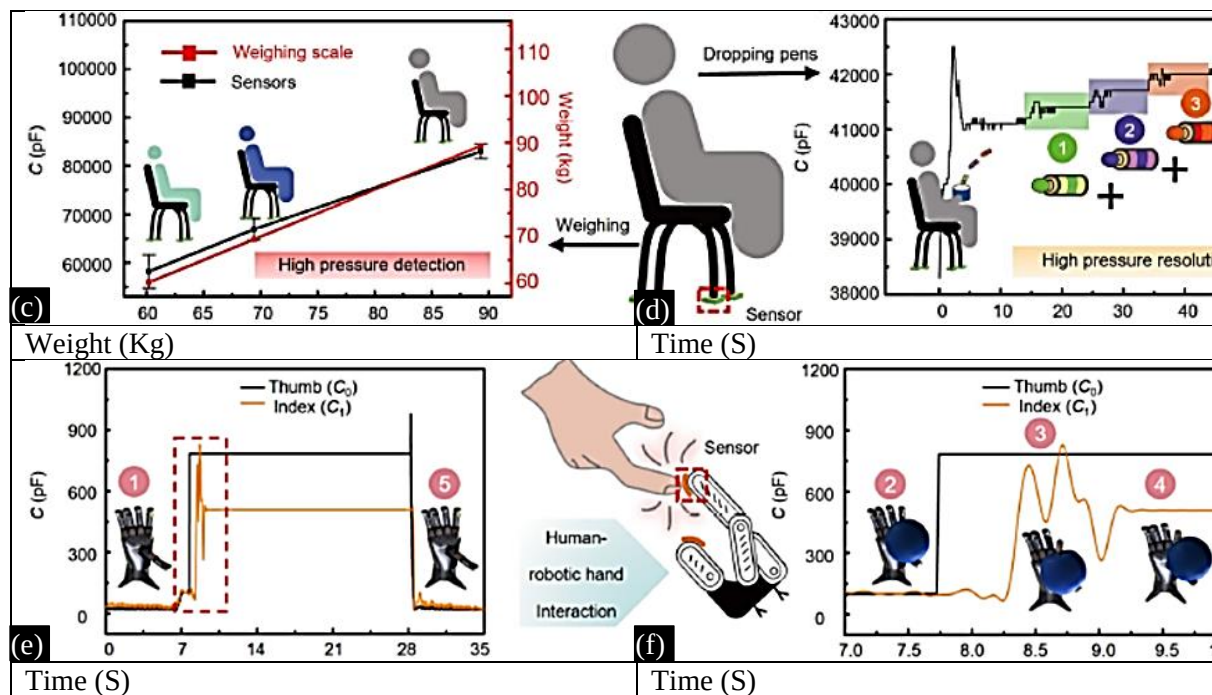


Figure 6. Human-robot interface, smart, high-precision weight scales, and fingertip pulse monitoring are just a few of the uses for iontronic pressure sensors. (a) Displays a healthy human subject's thumb pulse readings both at rest and during activity. (b) Compares the data from the commercial weight scale with the capacitive reaction of the gauge beneath the chair to volunteers of various weights. Standard deviation is shown by the error bar. (c) Provides evidence of high-pressure resolution by detecting an extra-small pressure of 145 Pa under a 2MPa huge preload. (d) Displays, with a zoomed-in view in the inset.

Additionally, the sensor demonstrated accuracy in detecting minute pressure under high preload. A 69.4 kg individual was able to pick falling pen (every weighing 5.81 g and with a pressure of around 145 Pa) while picking a pot of brush on a chair with a preload pressure of about 2000 KPa. Each falling event was distinct and recorded by the strong capacitive shifts. Under a preload of 2 MPa, our sensor's pressure resolution (0.00725%) is noticeably higher than that of previous microstructured pressure sensors, human skin, and commercial weight scales. Because of this, our sensor is a viable option for a number of uses, including robotics, industrial control, and health monitoring. Figure 6 shows as Human-robot interface, smart, high-precision weight scales, and fingertip pulse monitoring are just a few of the uses for iontronic pressure sensors [22].

Hand Controlled by a Robotic Interface in Closed-loop

Two iontronic pressure sensors (50wt%) were attached to the index fingers and thumb of the robotic hand to show the interactive robotic hand. The thumb's sensor identified the thing, and the index finger's sensor appropriately grasped it. A PID controller was used to enable the robotic hand to manipulate delicate things with dexterity. To stop the robotic hand from being accidentally activated, a threshold value (C_b) was specified. The capacitance (C_0) of the thumb sensor rose to around 800 pF as soon as the balloon was put on it, exceeding the predetermined C_b . This caused the controller (PID) to start moving the finger (index) at lower direction for grasping and alerted the system to recognize the object [23].

The objective operation, such as handling things, required the intended value of the capacitance of index finger gauge, which was measured or established as $C_{1\text{setpoint}}$. The PID controller computed the required rotation output ($\Delta\theta$) in the motor to move the index finger based on the discrepancy among the capacitance value that was actually measured, C_1 from the index finger sensor and $C_{1\text{setpoint}}$. The

observed variations in the C_1 values around the $C_{1\text{setpoint}}$ provided insight into the iterative process. Once the motion was finished according to the closed-loop feedback control, the balloon was carefully grasped with the appropriate force amid the index and thumb fingers. When a human hand squeezed the balloon vertically, lowering the gauge/balloon contact to a low gauge response (C_1 or C_0) than the predetermined threshold, the balloon was freed from the robotic hand [24].

CONCLUSION

In conclusion, this study describes a scalable manufacturing process founded on gradient pyramidal microstructures that may be programmed and may be used to create flexible iontronic pressure sensors. Electric double layers (EDLs) can develop at the electrode / ion gel interface thanks to the mixing of the nanoscale ultrathin ionic liquid and GPM electrode. This leads to an increased sensibility of 2.491 KPa^{-1} across a wide range in linear of sensing of 3010 KPa . The capacitive pressure sensing capability is further improved by varying the concentration of IL and the GPM unit cell's pyramidal profiles, leading to an ultrawide linear gauging range of 1700 KPa and an ultrahigh sensitivity of 33.7 KPa^{-1} . A useful design toolbox is offered by the flexible modification among these specifications throughout the gauge creation process, which may help overcome the restriction in the ratio of linear sensing range to sensitivity. Furthermore, the gauge can find the extremely pressure 0.361 Pascal not using preload & a minuscule pressure change of 145.5 Pascal utilizing a preloaded pressure in Mpa 2.1 in order to get an extremely high resolution of pressure of 0.00726% thanks to the fine features on the GPM surface that minimise the sensor's initial contact area. Future wearable health monitoring technologies, intelligent human-machine cooperation systems, and smart prosthetic skins are all made possible by the represented demos in this paper.

Even with the great sensibility throughout a large range of linear sensing, more performance gains are still achievable. For more substantial contact area modifications, bigger pyramids can be used to increase ILs concentration in order to expand the range of detection and boost sensibility. By adding a space for air amid the electrode and the dielectric layer, the detection limit may be further reduced. Because the microstructures control the variations in capacitance, they may also be used to increase the linear sensing range. In our upcoming efforts, we will continue to optimize the laser settings to generate different combinations of heights in microstructures and conduct theory analysis to forecast the other sensing parameters and account for bending.

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