Artificial Somatosensors: Feedback Receptors for Electronic Skins

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The human skin is the largest sensory organ, made up of complex sensors that detect noxious stimuli to rapidly send warning signals to the central nervous system to initiate a motor response. It is complex to mimic key skin features using existing tactile sensors, and there exists no somatosensor that responds to real stimuli of pressure, temperature, and touch. Herein, three critical skin receptors created by realizing integrated electronic systems that mimic the feedback response of somatosensors are experimentally demonstrated. Fully functional Pacinian corpuscles, thermoreceptors, and nociceptors are realized using a combination of stretchable pressure sensors, phase-change oxide thin films, and threshold-based resistive switching (memristor) memory elements. The ability to detect and respond to pressure, temperature, and pain stimuli above a threshold with real-life performance characteristics is demonstrated with explanation of underlying mechanisms. The ability to design and realize artificial skin receptors enables replacement of affected human skin regions, augment skin sensitivity for agile applications in defense and sports, and drive advancements in intelligent robotics.

1. Introduction

Skin is the largest human sensory organ covering the entire body. Every region of the skin is full of sensors (somatosensors), which detect external stimuli and actively measure the level of such stimuli.[1] Sensory skin feedback is indicative of health. For instance, pin pricks are used to study the response of a nervous system to evaluate degree of paralysis from nerve damage. Artificial skin receptors that demonstrate such feedback ability are integral to advancements in healthcare and intelligent robotics.[2] Such receptors can replace damaged receptors, augment sensation of specific stimuli, or serve as the feedback mechanism for human–machine or machine–machine interfaces.

The most prevalent and critical skin receptors relate to pressure, temperature, and pain[1]—the Pacinian corpuscle,[3] thermoreceptor,[4] and nociceptor,[5,6] respectively. All these receptors detect stimuli, measure levels of stimuli, and transmit signals to the brain triggering reactions. The working principle is like other common sensations, such as vision, hearing, somatic sensation, taste, and olfaction (smell).[7]

The characteristic features of the human sensory system are quite complex to be mimicked by existing tactile sensors (exteroceptive sensors)[8] and data processing based on traditional complementary metal oxide semiconductor (CMOS) devices in which downsizing is limited.[9] The report on an artificial spiking afferent nerve (ASAN) system that can convert the analog signal from artificial sensors into spikes in spiking neural networks appeals for development of a fully functional artificial sensory system.[10] Very recently, an artificial nociceptor has been reported based on a diffusive memristor, which can exhibit the normal state consisting of threshold and relaxation behaviors, and abnormal state with allodynia and hyperalgesia behaviors of nociceptor using the stimuli as voltage.[11–14] These findings are particularly important, because the switching mechanism of memristor depends on the conductive filaments, which are approximately sub-nanometer in diameter.[15] By exploiting the thermoelectric module[14] and the piezoelectric pressure module,[12] the threshold and relaxation behaviors among four basic functionalities of nociceptor are successfully demonstrated. The developed conceptual framework for different memristors was not entirely converted for allodynia and hyperalgesia using the thermoelectric module and the piezoelectric pressure module. Currently, fully functional optoelectronic nociceptor including all mentioned behaviors with a high potential for artificial eye is reported.[11] Still, the bottlenecks remain to demonstrate the fully functional nociceptor for skin with real-life

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stimuli, such as temperature, pressure, and pain. Though there are more and more nanoscale sensors being developed using 1D, 2D, and hierarchical 3D nanomaterials, the data processing of the existing sensory systems remains bulky. Moreover, to acquire all the four states of nociceptor (threshold, relaxation, allodynia, and hyperalgesia), multiple CMOS circuit units are required. Memristors, which mimic characteristics of human nervous system, can essentially resolve the bottleneck due to their exceptional switching performance in sub-nanometer scale. Therefore, it is of great scientific and technological importance to develop a somatosensory, which responds against real-life stimuli in the form of pressure, temperature, and pain, exploiting memristor as the fundamental unit. The replication of somatosensor can pave new pathways in the development of skin-like electronics and human-like robots. Here, we report artificial electronic receptors that mimic the Pacinian corpuscle, thermoreceptor, and nociceptor. This is achieved using a combination of multiple functional units: an oxygen-deficient strontium titanate SrTiO$_{3-x}$ (STO)-based decision-making memristor, a gold on stretchable elastomer (polydimethylsiloxane [PDMS])-based pressure sensor, and a phase-change oxide (vanadium oxide, VO$_2$)-based temperature trigger. Unlike the previously reported papers, we do not need separate and complex thermoelectric module, and a piezoelectric pressure sensor for the practical translation of conceptual somatosensors. The work, therefore, combines low-cost, readily available, manufacturing-compatible oxide thin films and wearable pressure sensors on biocompatible PDMS to create a device that self-sufficiently performs key skin operations of “sensing.”

STO has been selected as the representative memristive material, as it offers excellent memory performance with high ON/OFF ratios, repeatability, endurance, and retention. It is deposited at room temperature, which also provides opportunities to be developed on flexible and stretchable platforms. PDMS-based pressure sensor is chosen due to the exceptional stretchable properties, conformal nature, and very high sensitivity to pressure less than 3 kPa. VO$_2$ is selected due to its ability to undergo insulator-to-metal transition (IMT) with temperature.

When the skin temperature is raised above 30 °C, the thermoreceptor detects the warmth to start firing action potentials. The firing frequency increases with the stimulus temperature until it reaches a saturation value. On the other hand, thermal nociceptors, which detect pain signals, start to fire at temperatures around 45 °C. These are cells specialized at detecting noxious heat and burns. When a noxious stimulus is received by a thermal neuron located at the free nerve ending, an electrical response is sent to nociceptor to compare whether the amplitude crosses the threshold to generate an action potential and send to the central nervous system via nerve fibers (shown in red in Figure 1a).

To make the analogous artificial receptors, we used gold and PDMS-based pressure sensors, which switch between low resistance state (LRS) and high resistance state (HRS) and with applied pressure for mimicking Pacinian corpuscle (Figure 1b,c). To replicate the thermoreceptor and nociceptor behaviors, we utilized phase change VO$_2$, which can transition from HRS at room temperature to LRS above transition temperature of 68 °C. In addition, STO-based resistive switching memory is used to act as the decision-making element to evaluate threshold levels.

For the artificial Pacinian corpuscle, when there is no detectable pressure, the current through the decision-making memristor ($i_1$) is insufficient due to the bias voltage to initiate the motor response (Figure 1b). Upon applying a pressure on the sensor, the sensor transitions to HRS blocking $i_2$, which allows maximum current to pass through the memristor. Owing to the higher $i_1$, the STO-based memristor switches to LRS (few kΩ). Consequently, higher current flows through the corpuscle to initiate the motor response (Figure 1c).

For the thermoreceptor and nociceptor, VO$_2$ can demonstrate three to four orders change in resistance at transition temperature. Below transition temperature, it is an insulator. As such, negligible amount of current flows through the receptor, and the voltage that appears across the memristor is insufficient to turn it ON (Figure 1d). Once the transition temperature is reached, VO$_2$ switches to LRS, resulting in a higher potential to appear across the memristor, which causes it to switch to LRS. When both VO$_2$ and STO are in LRS, elevated current flows through the receptor (Figure 1e).

### 2. Results and Discussion

#### 2.1. Conceptual Framework for Creating Artificial Somatosensors

Toward the implementation of artificial skin receptors, a hypothetical framework to realize functional Pacinian corpuscle, thermoreceptor, and nociceptor was developed (Figure 1).
2.2. Mimicking the Pacinian Corpuscle

To build an artificial solid-state Pacinian corpuscle, we used an oxygen-deficient STO-based memristor with a stack structure of Pt (100 nm)/Ti (10 nm)/STO (55 nm)/Pt (25 nm)/Ti (7 nm) on a SiO₂ substrate. The STO memristor behaves similarly to that of our previous reports. [27] The bottom Ti is used as the adhesion layer of bottom Pt and top Ti is used as the oxygen reservoir as well as the adhesion layer of top Pt. Though the bottom Pt takes part in the switching process, top Pt works as an inert material to prevent the formation of TiO₂ due to the exposure to environmental oxygen. The representative behaviors of the STO-based memristor are represented in Figure S1, Supporting Information. The design of the pressure sensor is inspired by the biological Pacinian corpuscle, which exhibits a spiral shape with a track width and gap of 100 μm. The entire spiral shape is 7.8 mm in diameter. To build the sensor, we deposited Au (200 nm)/Cr (20 nm) on a 300 μm thick PDMS (see Section 4). The artificial equivalent of the corpuscle with the integration of memristor and pressure sensor is shown in Figure 2a. The pressure sensor network operates in such a way that it enables a receptor potential to activate the memristor, which works as a decision-making component. On reaching sufficient receptor potential such as biological system, the decision-making component can create an electrical impulse to activate the motor of the central nervous system. To fully mimic this functionality with specific threshold value, a degree of pressure variance is required from the pressure sensor. As this work focusses on proof-of-concept demonstration of somatosensory components, we just discuss about the working procedure of Pacinian corpuscle without pressure and with strong pressure. A fixed resistance of 100 kΩ is carefully selected to limit the current passing through pressure sensor network, which has a resistance of only 0.6 kΩ, to ensure that the system shows very low current when there is no pressure. Figure 2b shows the response and repeatability of the standalone pressure sensor. Upon applying the pressure from finger tips, the pressure sensor goes to very HRS with a resistance around 1 GΩ due to the deformation and cracks, which are very common occurrences for PDMS-based sensors. [36] Due to the deformations and cracks, the performance of pressure sensor can degrade after
extensive endurance cycles. But, there are well-known techniques to improve the stability of PDMS-based resistive pressure sensor. Moreover, and most significantly, the conceptual Pacinian corpuscle performance can be achieved using any flexible pressure sensing platform incorporated into our proposed arrangement (with electrical resistances of the components optimized). When the pressure is released, the gaps due to the cracks are closed again, creating the LRS, whereby the sensor returns to its initial state. This is similar to biological sensor that deforms, resulting in a shift of chemical ions when pressure is exerted. It should be noted that the decision-making component comprised of STO-based memristor element has to be initially electroformed by applying a bias at a very low compliance current of 1 μA to the top and bottom electrodes as in Figure S1a, Supporting Information. This electroforming step creates a localized channel for the formation of conductive filaments through STO. Though the formation is completed, a voltage sweep is required to switch the device between HRS and LRS states. When a bias is applied after electroforming across the entire corpuscle to switch the memristor, the voltage appears in parallel to the decision-making memristor and the sensing network, which is in series with the fixed resistance, whereas the current is divided into the two branches, as shown in Figure 1b.

So, without applied pressure, the current that streams through the memristor is insufficient to switch it. However, when the pressure is applied, the pressure sensor containing branch goes to HRS state, resulting in the maximum receptor potential across the memristor, as shown in Figure 1c. Upon reaching the receptor potential threshold, the decision-making memristor switches from HRS to LRS state, as shown in Figure 2c. In this state, the applied sequence 0 → +0.85 V → 0 → 1.12 V → 0 switches the device to LRS for the positive cycle and HRS state for the negative half cycle. The corresponding equivalent circuits are presented in Figure 2d,e for the elaboration of working principle from a circuit perspective. To turn the device into LRS, the positive half cycle is only considered. According to Figure 2d, when no pressure is applied, the pressure sensor network has an overall resistance of 100.6 kΩ, whereas the decision-making component (memristor) that is in parallel has a resistance of 70 kΩ. So, the equivalent resistance of the entire

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**Figure 2.** Artificial Pacinian corpuscle response characteristics. a) The connected diagram of the photograph and optical microscopy image of spiral pressure sensor with a diameter of 7.8 mm and memristor with an oxide layer of 60 × 60 μm², respectively. b) The individual response of the pressure sensor. c) Effective electrical response of the corpuscle without and with pressure. Equivalent circuit diagram d) without and e) with the application of pressure, noting the change in pressure sensor resistance changes current ratios causing memristor switching.

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Pacinian corpuscle is 41.2 kΩ. This equivalent resistance allows only 0.02 mA current through the entire circuit, which can be considered as the relaxed state. The application of pressure converts the pressure sensor network to an extremely high resistive state of ≈1 GΩ, whereas the memristor resistance is only about 2.5 kΩ, altering the equivalent resistive of the entire corpuscle around ≈2.5 kΩ. This low resistive state permits ≥0.35 mA current through the whole circuit. To avoid any confusion, the equivalent circuit is presented with and without the memristor in Figure S2, Supporting Information, which clearly illustrates the importance of incorporating the memristor in parallel with the pressure sensor branch. So, the pressure stimulus generates a response signal, which is almost 18× higher than the relaxed state, which can enable the central nervous system to initiate its motor response. Once the motor response is accomplished, to initialize the Pacinian corpuscle, a reverse polarity can be applied to memristor using the unused electrode pads. Though we have considered scenarios for no pressure and strong pressure for the demonstration of Pacinian corpuscle in this section, the temperature variance and, thereby, the operation of threshold response are described elaborately for the nociception in the later section. Further work needs to be undertaken to use pressure sensors to precisely control and modulate the Pacinian corpuscle response. The electronic equivalent of the switching mechanism of Pacinian corpuscle is presented in Video S1, Supporting Information.

2.3. Mimicking the Thermoreceptor

To build the thermoreceptor, we used the same metal–insulator–metal (MIM) stack for memristor as described for the Pacinian corpuscle. A portion of the top electrode is shared with the VO₂ surface, as shown in Figure 3a,b, to connect the thermal sensor in series. To bias the entire device, this electrode layer comprising of Pt (100 nm)/Ti (10 nm) is deposited on the VO₂ surface. A substantial separation of 100 μm is maintained between the source electrode and the top electrode of memristor. Figure 3c demonstrates the connection diagram of the thermoreceptor where the bias is applied through metal on thermal sensor, and the ground is connected to the bottom electrode of the decision-making memristor. The morphology and compositional

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![Figure 3](image_url)

**Figure 3.** Artificial thermoreceptor response characteristics. a) Photograph of the fabricated devices and b) enlarged microscopy image of the thermoreceptor showing VO₂ is connected in series to the memristor. The memristor oxide layer is of 60 × 60 μm² in size. c) Schematic diagram for the connection. d) Hysteresis loop for the heating and cooling cycles of VO₂. e) Switching behavior of standalone STO memristor under varying temperatures with no noticeable change in switching behavior. f) Thermoreceptor behavior under elevated temperature. Though there is a two order of magnitude change in resistance, the thermoreceptor is yet to switch at 0 to 0.8 V as a portion of the applied bias voltage is dropped across the VO₂.
analysis of VO₂ thin film using atomic force microscopy (AFM), X-ray photoelectron spectroscopy (XPS), and Raman spectroscopy are described in detail in the Supporting Information, and the corresponding spectra are shown in Figure S3–S5, Supporting Information. The characteristic resistivity versus temperature curve of insulator-to-metal transition (IMT) of VO₂ thin film using the four point probe technique is represented in Figure 3d. It is evident that there is four orders of magnitude in drop in resistivity upon reaching transition temperature. The resistance versus time is also shown in Figure S6, Supporting Information. An obvious thermal hysteresis is also observed through the heating and cooling cycles. To avoid any ambiguity, we measured the I–V characteristics curve and, thereby, the resistance versus voltage curve of our STO-based memristor at elevated temperature. There is no recognizable effect of temperature on the resistive switching, as shown in Figure 3e. The memristor can exhibit resistance change from ≈100 kΩ to as low as ≈2 kΩ during the switching process. But, for clarity, we consider the HRS state resistance as 93 kΩ and LRS state resistance as 9 kΩ at 80 mV of reading voltage (V_read), as the maximum switching ratio R_off/R_on is observed at that voltage. The switching voltage sequence of our standalone device is 0 → +0.65 V → 0 → 0.80 V → 0. When the same sequence is applied across the entire thermoreceptor, the resistance decreases, and consequently, the receptor current increases with the elevated temperature, as shown in Figure 3f. Though the resistance decreases of the entire receptor, allowing a higher voltage drop across the metal oxide, the memristor is yet to display the full switching curve with high ON/OFF ratio as a portion of the applied biased drops across the VO₂.

To allow the required switching voltage, we keep the receptor at 70 °C to ensure that VO₂ is in the LRS state. Then, the application of 0 to ±2 V biasing voltage completely SET and RESET device, as shown in Figure 4a. The thermoreceptor is dominated by the thermal response of the series VO₂. For the decision-making memristor, the original resistance 93 kΩ is much lower than the HRS of the thermal sensor, which is 11 MΩ; thus, the partial voltage that appears across the decision-making memristor cannot reach V_SET threshold to transform it from HRS to LRS (according to the voltage divider rule). So, both the thermal sensor and memristor are at HRS state, allowing a minimal current flow through the thermoreceptor, as shown in Figure 4b(i). When a critical temperature of 70 °C is applied, the resistance of the thermal sensor decreases by four orders of magnitude; thus, the partial voltage of the memristor increases to SET voltage gradually with increasing the receptor response, as shown in Figure 4b(ii). Once the V_SET is achieved to turn the memristor ON, it goes to LRS from HRS with a resistance of 9 kΩ, as shown in Figure 4b(iii). So, the maximum receptor response is generated at this stage. The LRS of the memory will be maintained for a long time even though the thermal stimulus is completely removed. To reprogram the memristor, a negative V_RESET voltage can erase it from LRS to HRS, as shown in Figure 4b(iv). To achieve this, the negative voltage can be applied from unused electrode pads, as shown in Figure 3c. This sequence shows the full functional sequence of a thermoreceptor, while noting that the temperature threshold can be tailored based on applications (for example, VO₂ transition can be decreased to ≈40 °C by including dopants, such as W or Mo).[31,32]

2.4. Mimicking the Nociceptor

Among all other receptors, nociceptor is a critical and distinguishable receptor that generates a pain signal to the central nervous system to initiate a motor response. Nociceptors are available all over the human body and found at the end of the sensory neuron’s axon. To avoid the impact of the noxious stimuli, the nociceptor responds in two particular ways: normal and abnormal conditions. Under the normal condition, when the skin-ending nerve receives a noxious stimulus, the response signal is sent to the nociceptor to compare whether the signal
is over a certain threshold value and decide whether an action potential is required to be generated to the central nervous system. Under this normal condition, the nociceptor is turned off slowly for a time period, known as the relaxation process. Using this threshold and relaxation process, the nociceptor insulates the body from any unwanted critical and continuous impact of stimuli. On the other hand, an abnormal condition occurs when the body confronts stimuli that is close to the damaging threshold of the nociceptor, and under this condition, the nociceptor works like a common receptor to avoid further damage. In case of an injury, the vulnerability of the effected tissue increases. The nociceptive system adapts to this enhanced vulnerability by locally lowering the nociceptive threshold and facilitating the nociceptive response, thereby ensuring adequate tissue protection.

The nociceptor exhibits two distinguished behaviors under abnormal conditions: allodynia and hyperalgesia. Allodynia produces response signal at underthreshold value, whereas hyperalgesia generates stronger response signal at the overthreshold value, indicating that, at the abnormal condition, there is no threshold for the nociceptor. We now demonstrate the functionalities of our device operating as a nociceptor under normal and abnormal conditions.

To observe the behaviors under normal condition in our artificial thermoreceptor, which works as nociceptor during noxious stimulus, we switch the device to the LRS and read the device at a \( V_{\text{READ}} \) of 80 mV. As the biological nociceptor’s triggering is extremely dependent on the stimulus intensity, a train of temperature pulse stimuli with different intensities ranging from 66 to 82 °C is applied on the artificial nociceptor, as shown in Figure 5a. Figure 5b demonstrates the response signal with respect to the applied thermal intensity. It should be noted that the nociceptor is not turned on until the temperature pulse reaches 68 °C, which is the transition temperature of our VO₂. So, when the VO₂ goes to the LRS due to the temperature-induced transition, higher current starts flowing through the whole circuit. This is akin to the threshold behavior of a biological nociceptor, which generates brain-triggering action potential above the critical stimulus value. Further increment of stimulus intensity above the threshold results in a larger current. This is consistent with a biological nociceptive neuron, which shows larger response intensity corresponding to the higher noxious

Figure 5. Artificial nociceptor response characteristics. a) Applied thermal stimulus pulses on the nociceptor and b) corresponding electrical response. The nociceptor shows response only from a temperature of 70 °C, the IMT threshold for VO₂. c) Enlarged views of the stimulus and corresponding response signal. d) The response signal reduces with time showing the relaxation behavior of nociceptor.
stimulus. Figure 5c shows the heating and cooling stimuli and corresponding response signal at 68 °C. Figure 5d represents the decaying of response signal over time after the noxious stimuli are withdrawn, which is termed the relaxation process. This process is completely determined by the VO2, as there is no influence of temperature on STO-based memristor, as discussed in Figure 3e, and it retains its LRS until the reprogramming pulse is applied. Due to the increasing trend of VO2 resistance as temperature decreases over time, the artificial nociceptor limits the current through the circuit, and hence, we observe the reducing magnitude of the response signals. The stronger response signal due to the higher stimuli takes a relatively longer time to entirely relax. For example, 68 °C response signal takes 100 s to reach the base current of 0.5 μA, whereas the corresponding 80 °C response signal is unable to completely relax by 100 s. Human experience can clarify the behavior, as stronger pain typically takes longer to subside.

To observe the behaviors under abnormal conditions, we applied a much stronger stimulus intensity to our artificial nociceptor compared with the normal condition. We heated the nociceptor to 90 °C at a ramp up rate of 20 °C/min and cooled down to 60 °C, which is lower than the threshold value of 68 °C at the normal condition for our device. We choose 60 °C, because the sensitization of nociceptive nerve ending leads to a shift in the stimulus–response function to lower stimulus intensities, which typically occurs in case of an injury. For example, in sunburnt skin, the amplified sensitization of the nerve ending results in a lower threshold. Following that, we heat the nociceptor again from 60 to 90 °C to see if the reduced threshold and amplified response, which are the basic properties of allodynia and hyperalgesia, are generated. The 60 → 90 → 60 → 90 °C is applied across the standalone VO2 and also the entire nociceptor containing VO2 and STO-based MIM stack to compare their responses. The response signals are shown in Figure 6a,b, correspondingly. It can be clearly seen that the response signal is much more linear across the VO2 (Figure 6a) compared with that of the whole nociceptor, as shown in Figure 6b. This is rational in the sense that at this higher stimulus, the VO2 is in almost metallic state with a relatively low resistance of ≈5 kΩ after transitioning. Moreover, the applied $V_{\text{READ}}$ (80 mV) bias voltage electrically tunes the VO2 to make it further metallic, which results in the linear response.[38]

![Figure 6](https://www.advancedsciencenews.com)

**Figure 6.** Critical allodynia and hyperalgesia behaviors of nociceptor. a) Over-threshold heating–cooling–heating sequence across the VO2 only shows linear behavior due to the metallic behavior of VO2. b) The same heating–cooling–heating sequence across the nociceptor shows nonlinear behavior. c) Typical response versus stimuli behavior in normal and damaged state (re-drawn based on the previous study[13]). d) The mimicking of allodynia and hyperalgesia such as real biological nociceptor. Temperature ramp rates used in all experiments presented here are 20 °C min⁻¹.
On the other hand, when the same $V_{\text{READ}}$ bias appears across the whole nociceptor, according to the voltage divider rule, the maximum voltage drop occurs across the memristor, which is in LRS state ($\approx 9\Omega$). At this stage, the voltage appears across the VO$_2$ is not sufficient to show the linear response. As a result, the behavior is nonlinear. Figure 6c shows a schematic representation of alldynia and hyperalgesia behaviors, which reveal that in a biological system, the response intensity is higher in the abnormal state for underthreshold (alldynia) and overthreshold (hyperalgesia) of the stimulus intensity. Figure 6d shows the response with respect to two heating cycles of the $60 \rightarrow 90 \rightarrow 60 \rightarrow 90$ °C sequence and reveals that the response for the second heating cycle is amplified and the threshold is reduced. The alldynia behavior under the threshold intensity and hyperalgesia behavior above the threshold intensity of 70 °C can be clearly observed from the response of our artificial nociceptor. The resultant behavior for the same sequence but at different ramp rates is also presented in Figure S7, Supporting Information. Hence, by reducing the threshold and amplifying the response intensity, the nociceptor enables and enforces protective behavioral responses, such as withdrawal or avoidance to acute painful stimuli.

3. Conclusion

In summary, we demonstrated solid-state artificial somatosensors with the representative critical and distinguishable functionalities such as Pacinian corpuscle, thermoreceptor, and nociceptor with respect to real-life stimuli. The effect of pressure, temperature, and pain on the receptors generates considerable response current. This serves as an accurate feedback mechanism to mimic real skin properties on artificial electronic skin to augment or compensate human skin or for the development of realistic humanoids. The critical and very complicated functionalities of the pain signal such as threshold, relaxation, alldynia, and hyperalgesia are mimicked owing to the outstanding combination of VO$_2$, which transitions due to thermal stimuli and STO-based memristor, which is not affected by thermal stimuli. Further experimentation to develop the receptors on soft/stretchable substrate will enable the realization of skin-like somatosensor. The endurance test of stretchable platforms will help to explore the longevity of sensors performance on the skin. This exceptional demonstration and mimicking of complex functionality of somatosensation will enable new paradigms in bioinspired sensing and neuromorphic engineering technologies.

4. Experimental Section

**Pressure Sensor Fabrication**: PDMS was prepared mixing the Sylgard 184A (base) and Sylgard 184B (curing agent) manufactured by Dow-Corning in a ratio of 10:1, removing the trapped air bubbles in a vacuum desiccator, and curing at room temperature for 24 h on a cleaned Si wafer. A liftoff photolithography process to define metal electrodes was performed with a mask-less aligner (MLA; Heidelberg Instruments) with AZ1512 photoresist. The structures were designed as a two-terminal spiral-shaped resistor with the gap and track widths of 100 μm. After developing the photoresist, Au (200 nm) with a Cr (20 nm) adhesion layer was deposited by electron beam evaporation (Kurt J. Lesker PVD75 Pro-line) at a pressure of $1.5 \times 10^{-7}$ Torr, a deposition rate of 0.3 Å s$^{-1}$, and at room temperature. Functional spiral structures were achieved with the liftoff process utilizing acetone. Then, the PDMS with the patterned metal structures was carefully peeled off from the Si wafer to create a free-standing pressure sensor.

**STO-Based Memristor**: STO-based memristors were fabricated by standard photolithography processes, oxide thin film deposition, top and bottom electrode deposition, and liftoff process for each step. α-STO of 55 nm thickness was deposited by radio frequency (RF) sputtering (Kurt J. Lesker PVD75 sputtering system) in 100% Ar atmosphere at a process pressure of $3.5 \times 10^{-7}$ Torr at room temperature from a commercial ceramic STO target (99.95%, Testbourne Ltd) using 200 W RF (13.54 MHz). The bottom Pt (25 nm) on Ti (7 nm) and top Pt (100 nm) on Ti (10 nm) were deposited at a rate of 0.3 Å s$^{-1}$ by electron beam evaporation.

**VO$_2$ Deposition**: Vanadium dioxide (VO$_2$) thin films were deposited onto patterned AZ1512 photoresist on plasma-cleaned SiO$_2$ wafer using pulsed direct current magnetron sputtering (Kurt J. Lesker PVD75 sputtering system) at a base pressure of $4.0 \times 10^{-7}$ Torr, a sputtering pressure of $2.8 \times 10^{-7}$ Torr, a power of 200 W, and with 30% oxygen partial pressure in an Ar environment. After performing liftoff to achieve patterned VO$_2$, the sample was annealed at a pressure of 250 mTorr and at a temperature of 550 °C for 90 min. The resultant VO$_2$ thickness from 30 min deposition was 50 nm.

**Receptor Device Fabrication**: To fabricate the functional thermoreceptor and nociceptor, the VO$_2$ and memristor were required to be connected in series. VO$_2$ was deposited and patterned as the first layer. For the power supply, electrode comprising Pt (100 nm) on Ti (10 nm) was deposited on VO$_2$ after photolithography. As the VO$_2$ thickness is 50 nm and the top electrode of memristor is 110 nm, the device was fabricated in such a way that the top electrode of memristor overlapped a portion of VO$_2$ thin film. A gap of 100 μm is maintained between the top electrode and the supply electrode.

**X-Ray Photoelectron Spectroscopy**: XPS analysis was carried out by a Thermo Scientific K-Alpha instrument equipped with an aluminum Kα radiation source with an energy of 1486.7 eV. The core-level elemental spectra were collected from a bare VO$_2$ thin film deposited directly on SiO$_2$ substrate. The surface of the VO$_2$ on SiO$_2$ was in situ cleaned by Ar under high vacuum ($<5 \times 10^{-7}$ Torr) before collecting data using X-ray beam 400 μm in diameter. It was ensured that Ar-assisted cleaning caused minimal oxygen removal using a short (<3 s) Ar milling step with low beam energy (<200 eV). The binding energies of all principal elements were referenced corresponding to the adventitious carbon binding energy (C 1s) of 285 eV. The standard Gaussian–Loewntzian function followed by the Shirley background correction was used to resolve all the spectra.

**AFM and Raman Spectroscopy**: The topography and surface roughness of VO$_2$ thin film was evaluated using a Digital Instruments D3100 atomic force microscope in tapping mode. The composition of VO$_2$ crystal was obtained using a LabRam HR Evolution Raman Spectrometer (laser excitation at 532 nm with a 50x objective). The acquisition time and accumulations for the measurements were 20 s and 10, respectively.

**Electrical Characterization**: A Jandel cylindrical four-point probe is utilized to measure the IMT. A Linkam stage is used for heating and cooling during the measurement. The I–V characteristics for all receptors were carried out in an ambient atmosphere using an Agilent B2912A source meter semiconductor characterization system for two-probe measurements.

Supporting Information

Supporting Information is available from the Wiley Online Library or from the author.

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Conflict of Interest

The authors declare no conflict of interest.

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