

## Research Article

# A Multifunctional Flexible Ferroelectric Transistor Sensor Based on Si/Fe-Doped Indium Oxide for Electronic Skin

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As the sensing basis and data source of the new generation of information technology, sensors play a vital role in today's information age. The purpose of this work is to construct a flexible ferroelectric field-effect transistor (FeFET) as a prototype for a multifunctional sensor for electronic skin. The FeFET device is fabricated from poly(vinylidene fluoride-dimethylsiloxane) (P(VDF-DMS)) and Si/Fe-doped indium oxide (SFIO). Furthermore, this device is capable of three-in-one sensing. Specifically, it can detect temperature changes from 0°C to 70°C and monitors external forces with a linear sensitivity of 4.6 nA·kPa<sup>-1</sup> across a pressure range of 50 kPa to 150 kPa. Additionally, electrostatic interaction enables the gadget to detect the approach of a charged item. Furthermore, this gadget was built to detect physiological signals produced by the human body, such as pulse, respiration, and finger movements. It is very bend-resistant and retains transmission properties after 1200 cycles of bending. Moreover, we will examine the device's sensitivity to temperature variations and charged particles when bent to a radius of 1.09 mm. This design will promote the next generation multifunctional E-skin.

## 1. Introduction

With the increasing improvement of material living conditions, people put forward higher requirements for electronic consumer goods [1]. Because flexible electronics have the advantages of flexibility, extensibility, and portability, flexible electronics has become a research hotspot in the electronic industry [2]. Flexible electronics is a new electronic technology that prepares electronic devices on flexible substrates that can be bent. At present, it has been preliminarily applied in sensors, solar cells, and memory. Besides, with the development of computer technology, network technology, flexible electronic technology, and other new technologies, robot technology is the focus. Robots can replace human beings to complete simple, repetitive, and dangerous production activities [3]. In particular, humanoid robots are gradually developing towards intelligence, human-computer interaction, and rigid flexible integration of bionic structure. Intelligent and fine operation of robots has become the main research direction. Robot intelligence means that the robot can generate corresponding working strategies according to the changes of the environment, which requires the robot to have a strong sense and per-

ception of the external environment [4]. One of its key technologies is multisensor information coupling technology, and the sensor is the medium for the robot to perceive the external environment. Thus, the accuracy of the sensor largely determines the intelligent level of the robot. Furthermore, electronic skin (E-skin) based on flexible sensor technology has great application prospects [5]. Multiple sensors are often dispersed over the same surface or layered on a conformal or flexible substrate to build electronic skins [6, 7]. Numerous efforts to produce multipurpose electronic skins have also garnered attention for pressing industrial demands [8]. In terms of the multipurpose electronic skin sensing unit, there are two approaches: employing various sensors or using one integrated multifunctional sensor for detecting a variety of physical or chemical inputs. These developments increase the E-attractiveness of skin as a new platform for applications in human-computer interface, health diagnostics, treatment, robotics, prostheses, and monitoring [9–12]. Field-effect transistors (FeFETs) have shown tremendous promise in advanced flexible electronics throughout the peak decades of flexible or wearable electronics [13]. To increase the capabilities of this FET gadget, it may be connected to any flexible

or uniquely formed surface [14, 15]. FeFETs have been developed in recent years as sensing devices for detecting and identifying substances such as NH<sub>3</sub> and O<sub>2</sub> gases, DNA, light, force, and charged objects [16–18]. Additionally, as an E-skin component, FeFET-based sensors provide a number of advantages, including improved mechanical and electrical properties, fewer cross-linking between pixels for exact signal distribution patterning, and interoperability with complementary metal-oxide-semiconductor technologies [19].

The development of bright electronic skins that can detect and react to a wide range of stimuli and conditions, as well as physical and chemical changes in the environment, will be a critical component of future potential [20, 21]. However, other changes, such as temperature or electrical charge, are difficult to detect due to the intrinsic sensing capabilities of electronic skin, which has been the topic of the most relevant research to far [22, 23]. An alternate approach has been shown by Dahiya et al., who have demonstrated an electrostatic proximity sensor that does not need any physical contact to determine its near to an object [24]. The use of a FeFET-based sensor on a stiff substrate has allowed for the implementation of proximity sensing in flexible electronic skin [25, 26]. Single-function sensors are incompatible with high-performance electronic skins that have several functions. As a result, it is important to have an integrated multipurpose sensor that can detect a number of different input signals. Polymers based on ferroelectric polymers have been extensively explored in nonvolatile memory and mechanical sensing applications, as well as energy harvesting [27]. To alter the conductivity of the semiconductor layer, ferroelectric polymers may be combined with ferroelectric field-effect transistors (FeFETs), which modify the threshold voltage of the FeFET device in response to changes in the polarization state of the ferroelectric layer [28–30]. Mechanical and thermal stimuli will affect the polarization state and threshold voltage of the FeFETs, which is predicted to be sensitive to both piezoelectric and thermoelectric capabilities. Other investigations have shown that a field-effect transistor can detect the presence of a charged item by detecting the electrostatic interaction of the charged object with its gate electrode [31]. Because of this, FeFET devices are likely to be utilized to create three-in-one sensors.

In this work, we proposed a novel FeFET-based flexible sensor as the electronic skin (E-skin). Poly(vinylidene fluoride-dimethylsiloxane) (P(VDF-DMS)) and Si/Fe-doped indium oxide (SFIO) form the channel layer and the insulating gate layer, respectively. Touch pressure and environmental temperature are all detected by the gadget. Besides, the gadget can measure pressures between 60 and 180 kPa, and thus, this device can detect physiological signals and human movements. It has a temperature range of 0 to 70°C while in temperature sensor mode. When in electrostatic induction sensing mode, it can detect the presence of electrically charged items within close proximity. The device has quite durable mechanically and reliability, and it can be bent about 100 times without any loss of electrical characteristics or mechanical durability. Based on the preceding, the future generation of E-skin is projected to use this technology.

## 2. Methods and Material

On the flexible Kapton substrate, a ferroelectric copolymer P(VDF-DMS) and an amorphous oxide semiconductor SFIO were combined to generate a top-contact top-gate ferroelectric crystal, as shown in Figure 1(a). Due to its superior electrical characteristics and low processing temperature, SFIO has been employed as a channel material. As the flexible substrate, the Kapton film can be well matched with other functional layers. The electrical properties of the SFIO films can be regulated by using sputtering deposition under high temperature. Figure 2(b) illustrates the scanning electron microscope (SEM) image of SFIO film surface. Due to their flexibility and thermal stability, amorphous oxide semiconductors are preferred. Furthermore, the size of the device is set as 18 mm × 18 mm, and the thickness of Kapton substrate is about 100 μm. The thickness of P(VDF-DMS) film is about 10 μm. Moreover, in this design, the aluminum layer serves as the source/drain electrodes. Figure 1(c) illustrates the output characteristic curve prior to the occurrence of ferroelectricity. Thus, even with a restricted range from 0 to 10 V of  $V_{GS}$ , the drain current ( $I_{DS}$ ) tends to saturate at relatively high drain voltages. The electromagnetism response of FeFET to external stimuli was statistically investigated with the use of a home-built mechanical vibration device, as illustrated in Figure 2(d).

## 3. Results and Discussion

The moving parts of the mechanical device is electrically connected to the excitation source. And the frequency response of the moving parts is determined by the signal generator. The FeFET is fixed on the metal plate surface, and a quartz force meter that is commercially available is pressed against the metal plate. A source meter is a device that monitors the electrical response of a transistor to an external mechanical stimulation. During the testing, the drain is biased at a constant voltage of 10 V while the gate is allowed to float freely. To more accurately describe the FeFET's electrical reaction to an external stimulus (pressure, temperature, and proximity), we define  $\Delta I_{DS} = I_{DS}(t) - I_{DS0}$ , where  $I_{DS0}$  and  $I_{DS}(t)$  denote the drain current before and after the external stimulus is applied, respectively. Besides,  $I_{DS}(t)$  is a time-dependent function. Figure 2(a) presents the influence of machinery frequency on the  $\Delta I_{DS}$  reaction applied by a sinusoidal pressure with a constant amplitude of 0.8 kPa and a frequency range of 0.3 Hz to 10 Hz. Moreover, the highest  $\Delta I_{DS}$  response is around 1.3 nA at all stimulation frequencies and is frequency-insensitive. Figures 2(b) and 2(c) show the  $\Delta I_{DS}$  signal of FeFET device under different pressures. Meanwhile, Figure 2(d) presents the linear relationship between  $\Delta I_{DS}$  values and pressures.

Noteworthy, the FeFETs sensor has potential application value in human health monitoring and motion posture analysis. Specifically, pulse diagnosis plays an important role in medical diagnosis. However, relying on manual diagnosis has brought some inconvenience to medical services. The

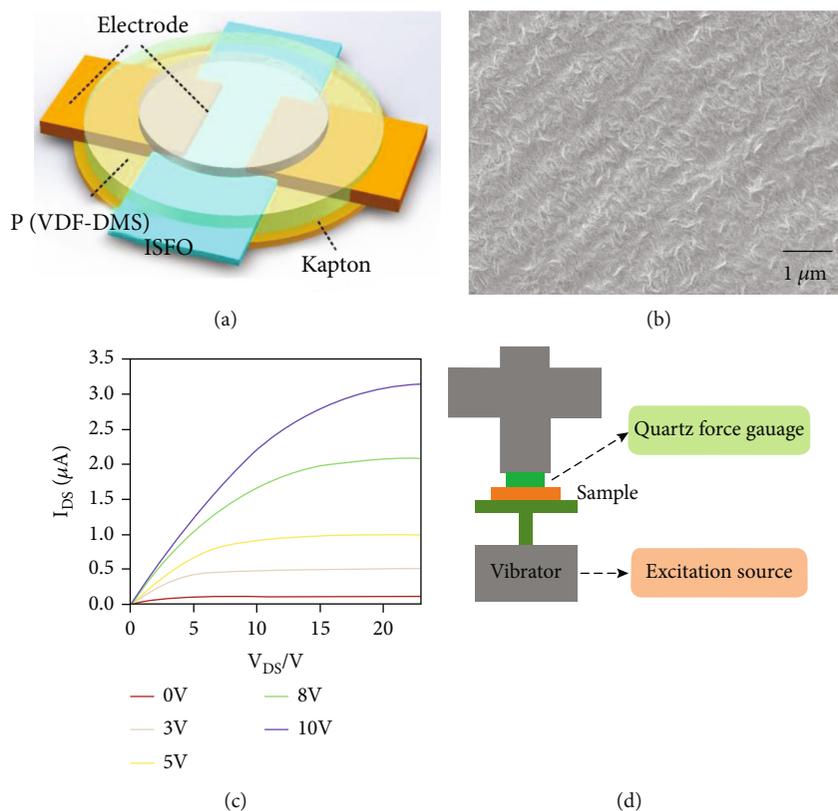


FIGURE 1: Electrical properties of ferroelectric transistor devices: (a) schematic diagram of the FeFET device. (b) The SEM image of SFIO film surface. (c) Electrical characteristics of FeFET devices before polarization. (d) Schematic diagram of the mechanical drive system.

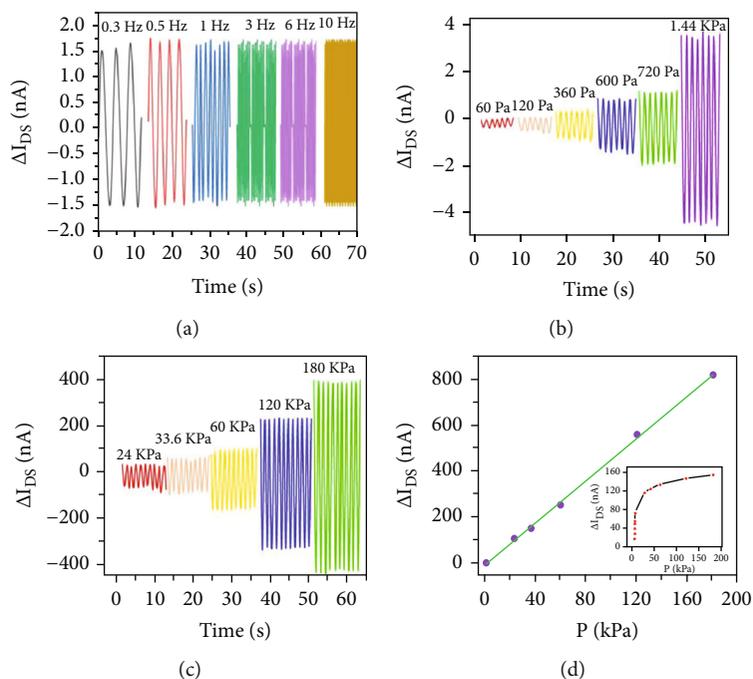


FIGURE 2: (a) The FeFETs sensor performance test. (b, c) The  $\Delta I_{DS}$  signal of FeFETs device under different pressures. (d) The relationship between  $\Delta I_{DS}$  values and pressures.

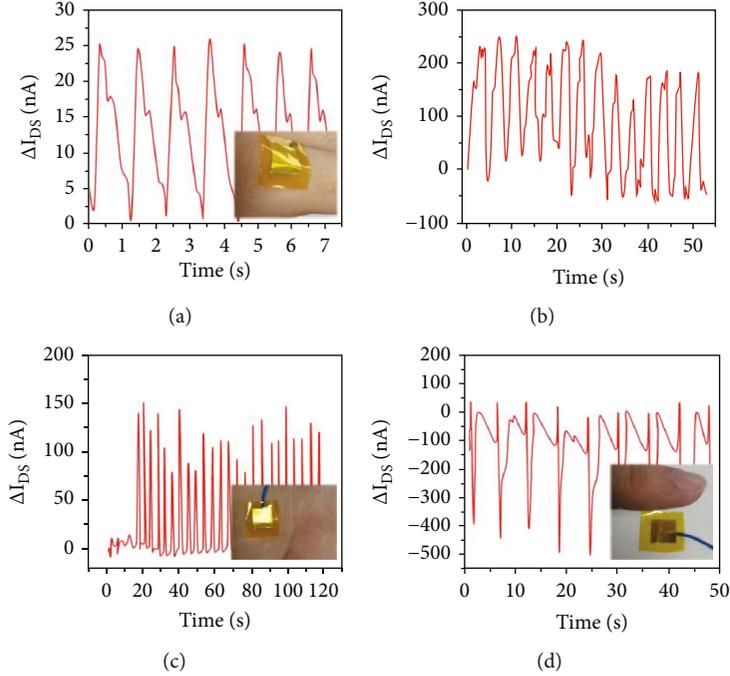


FIGURE 3: The sensor signal of FeFET device driven by (a) pulse and (b) respiratory movement. (c) The finger key sensing information of FeFET device. (d) Finger press signal generated by a FeFET sensor device.

FeFET sensor uses its ferroelectric capacitor to sense pulse beat. As shown in the inset of Figure 3(a), the FeFET's sensor was installed on the wrist artery of the volunteer's hand. Figure 3(a) represents the response signal of leakage current to human pulse beat. And the detailed pulse information can be obtained by further analyzing the output signal curve. Besides, the FeFET's sensor can detect human respiratory movement when it is installed in the neck. According to the results in Figure 3(b), the tested person breathed 19 times per minute. Furthermore, this FeFET sensor can monitor the key posture changes of the finger when he is installed on the finger, as presented in Figure 3(c). Meanwhile, the output signal of FeFET sensor can also record finger pressing information to serve as the touch sensor, as shown in Figure 3(d).

The ability of the human skin to detect temperature is another critical feature that may assist the body and its surroundings maintain a healthy biological balance and identify potentially dangerous conditions. In this work, we developed the application of FeFET device in temperature monitoring. Specifically, the source and drain electrode of a FeFET device were linked to two thin copper wires using silver paste. And the source meter was attached to the opposite end of both copper wires to measure drain current. A plastic tweezer moved the sensor between an Al plate at room temperature (RT) and a variable temperature stage at a pre-set temperature ( $T_{stage}$ ). Figure 4(a) illustrates the  $\Delta I_{DS}$  response of FeFET device installed at a 25°C Al plate and afterwards rapidly shifted to a heat or chilling stage at a specific  $T_{stage}$ . Figure 4(b) presents the relationship between  $\Delta I_{DS\_stable}$  and  $\Delta T$  ( $\Delta T = T_{stage} - 25^\circ\text{C}$ ). Obviously, when the  $\Delta T$  values grow, the  $\Delta I_{DS\_stable}$  values

of FeFET device increase accordingly. Besides, the data can be well fitted by following equation:

$$\Delta I_{DS\_stable} = 8 \times 10^{-5} T_{stage}^2 + 0.002 T_{stage} - 0.11. \quad (1)$$

When the temperature of the device increases, the electronic activity inside  $a$  increases, resulting in an increase in current, according to previous studies [32]. Numerous materials and biological products are electrically charged in daily life and industrial contexts. In the meantime, triboelectric phenomena can occur between any two materials. Thus, the FeFET sensors are capable of sensing their surrounding information. The reaction of its  $\Delta I_{DS}$  to the vicinity of certain typical items is present in Figure 4(c). Indeed, our earlier research has shown that the acquired materials retain a detectable surface potential. The distance between these things and the gadget is between 10 and 50 mm. Often, the Teflon, Kapton, and PDMS are all negatively charged; it is possible to see negative  $\Delta I_{DS}$  responses. In addition, the skin and nylon are positively charged, leading to a positive  $\Delta I_{DS}$  response. Therefore, surface potential has an effect on how far the  $\Delta I_{DS}$  response can change. The reaction of  $I_{DS}$  when a prejudiced metal rod with a surface potential of -500 V is approached on a periodic basis is shown in Figure 4(d). The motion of the item is controlled by a linear motor with a rated resolution of 5 m, and the distance between the object and the gadget may be adjusted between 5 and 35 mm. Due to the negative bias of the metal, its approach results in a reduction in drain current, i.e., an adverse  $I_{DS}$  reaction. Between approaching and departing activities, a 5-second holding period occurs during which the distance between the item and the device remains

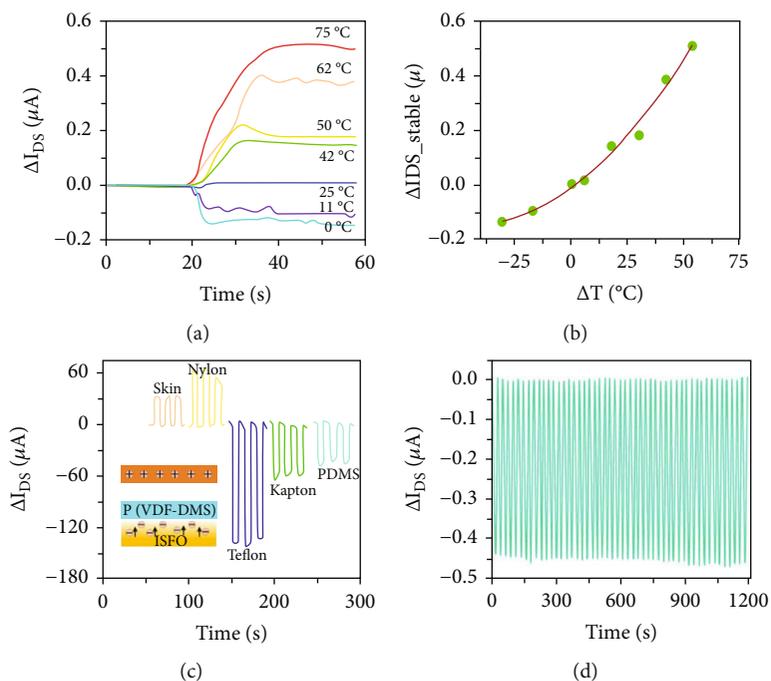


FIGURE 4: The sensor signal of FeFET device driven by (a) pulse and (b) respiratory movement. (c) The finger key sensing information of FeFET device. (d) Finger press signal generated by FeFET sensor device.

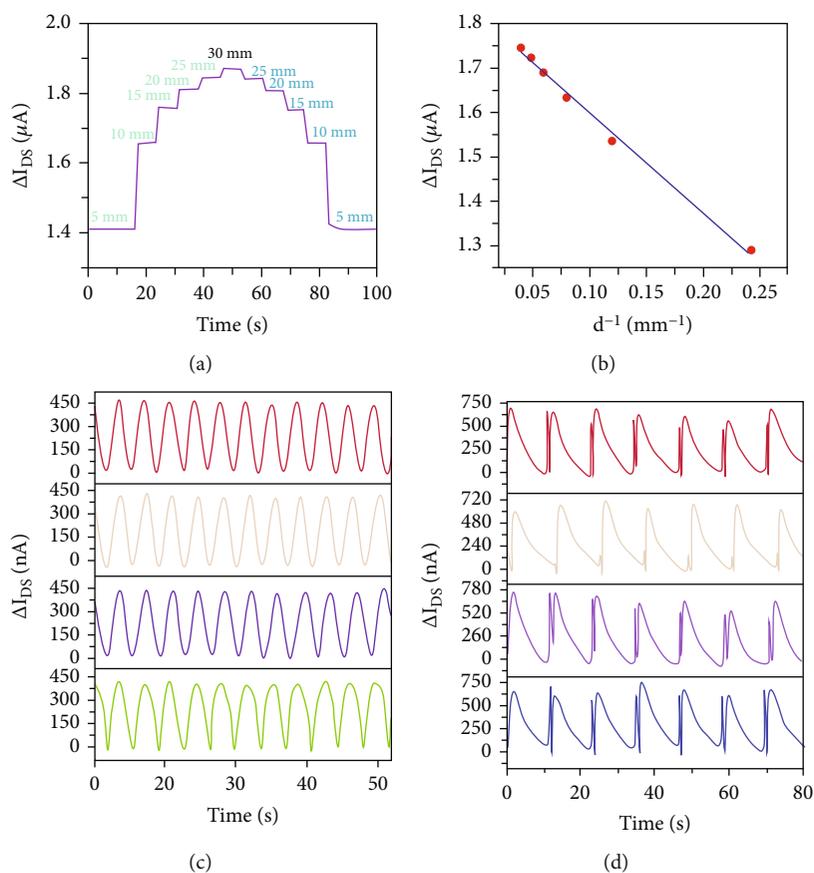


FIGURE 5: (a) The  $I_{DS}$  response signal of FeFET device about the approach and retraction of a  $-600$  V-biased metal rod. (b) The output  $I_{DS}$  signal under different reciprocal of  $d$ . (c, d) The  $I_{DS}$  signal response of FeFET device with different  $R$  values.

constant. Throughout this time span, the  $I_{DS}$  value has remained relatively persistent, indicating the FeFET device's stability in proximity sensing applications. The drain current ranges between 5 and 35 mA as the distance between the item, and the gadget varies between 5 and 35 mm.

Figure 5(a) shows the results of the approach and withdrawal processes, which are shown as upward and downward steps. Both procedures provide about the same  $\Delta I_{DS}$  number for the same object-to-device distance. Figure 5(b) illustrates  $\Delta I_{DS}$  dependency on the distance ( $d^{-1}$ ) reciprocal, demonstrating a solid linear connection between  $\Delta I_{DS}$  and  $d^{-1}$ . It is believed that the distance may be calculated from the obtained drain current using a linear fit. Take note that the charged object's surface potential has little influence on the ferroelectric monolayer in this case. The voltage drop caused by applying a charged item to the ferroelectric layer may be approximated crudely. Consider the air space between the ferroelectric coating, the sensor, and the object as two series capacitors. As a result, use a parallel plate capacitive as an approximation:

$$\frac{\epsilon_{\text{air}}}{d_{\text{air}}} V_{\text{air}} = \frac{\epsilon_f}{d_f} V_f, \quad (2)$$

where  $\epsilon_{\text{air}}$ ,  $d_{\text{air}}$ , and  $V_{\text{air}}$  are the allowability, air gap thickness, and voltage drop all related to the air gap, while  $\epsilon_f$ ,  $d_f$ , and  $V_f$  are the ferroelectric layer's permittivity, thickness, and breakdown voltage. It is verified that this low electric field does not affect ferroelectric polarization. While FeFET devices can detect pressure, temperature, and closeness, it is crucial to note that all of these illuminations currently generate a drain current response in FeFET sensors, which means that the device cannot identify the exciter. In other words, if many excitation sources are employed concurrently, the FeFET sensor will react appropriately, but it will have no idea which sort of excitation source generated the current response. Additional device design and construction and sensing technique development are necessary to provide this power identifying feature.

Therefore, the electrical response of flexible sensors to strain has gotten less attention than it should have received up to this point. We are continuing to investigate the effect of mechanical bending on sensor response, which is crucial in applications that make use of flexible electronic skin, such as medical devices. Due to the fact that the force-sensing qualities of bent FeFET devices are not yet known, we will only discuss their vicinity and temperature-sensing capabilities in this section. The proximity and heat responses are shown in Figure 5(c). The PTFE rod approaches and exits the bent FeFET device regularly during the proximity sensing measurements, traveling at a speed of 7 mm/sec throughout a distance range of 10–50 mm. In the unbent condition, the greatest  $I_{DS}$  response was 372 nA, followed by 369 nA at 3.8%, 361 nA at 5.4%, and 290 nA at 6.9%. This data suggests that tiny strains (e.g.,  $\epsilon < 5.4\%$  here) have minimal influence on proximity sensing performance, but big strains tend to reduce the drain current response. Thermal induction properties were determined by lighting the bent gadget with a

green laser pointer on a periodic basis. As shown in Figure 5(d), the maximum  $I_{DS}$  reaction for flat devices drops from 536 nA to 520 nA at 3.8%, 503 nA at 5.4%, and 494 nA at 6.9%. Additionally, this study validates the influence of bending degree on temperature-sensitive features. However, it should be said that once it has been set to a certain  $R$ -value (or strain), it can show how close and how hot the charged object is to it.

## 4. Conclusion

To summarize, we developed a flexible three-in-one FeFET sensor for flexible electronic skin. The FeFET sensor device can detect external mechanical stimuli and temperature changes by using the piezoelectric and thermoelectric capabilities of the ferroelectric P (VDF-DMS) layer. Additionally, because of the electrostatic effect, it detects the vicinity of charged items. Experiments demonstrate that the gadget can detect mechanical excitations ranging from 50 Pa to 150 kPa and temperature changes ranging from 0 to 70 degrees Celsius. The gadget was used to monitor the human finger's pulse, respiration, and movement. This FeFET has excellent bending resilience and retains its electrical characteristics after 103 twists. Even when bent to a radius of curvature of 1.09 mm, the FeFETs demonstrated excellent electrical responsiveness to temperature variations and proximity to electric charges.

## Data Availability

All data, models, and code generated or used during the study appear in the submitted article.

## Conflicts of Interest

The authors declare that they have no conflicts of interest.

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