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Bioinspired Passive Tactile Sensors Enabled by Reversible Polarization of Conjugated Polymers

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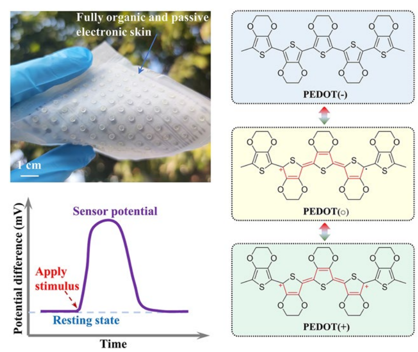
HIGHLIGHTS

- Fully organic and passive tactile sensors are developed via mimicking the sensing behavior of natural sensory cells.
- Controllable polarizability of conjugated polymers is adopted for the first time to construct passive tactile sensors.
- Machine learning-assisted surface texture detection, material property recognition, as well as shape/profile perception are realized with the tactile sensors.

ABSTRACT Tactile perception plays a vital role for the human body and is also highly desired for smart prosthesis and advanced robots. Compared to active sensing devices, passive piezoelectric and triboelectric tactile sensors consume less power, but lack the capability to resolve static stimuli. Here, we address this issue by utilizing the unique polarization chemistry of conjugated polymers for the first time and propose a new type of bioinspired, passive, and bio-friendly tactile sensors for resolving both static and dynamic stimuli. Specifically, to emulate the polarization process of natural sensory cells, conjugated polymers (including poly(3,4-ethylenedioxythiophene):poly(styrenesulfonate), polyaniline, or polypyrrole) are controllably polarized into two opposite states to create artificial potential differences. The controllable and reversible polarization process of the conjugated polymers is fully in situ characterized. Then, a micro-structured ionic electrolyte is employed to imitate the natural ion channels and to encode external touch stimulations into the variation in potential difference outputs. Compared with the currently existing tactile sensing devices, the developed tactile sensors feature distinct characteristics including fully organic composition, high sensitivity (up to 773 mV N^{-1}), ultralow power consumption (nW), as well as superior bio-friendliness. As demonstrations, both single point tactile perception (surface texture perception and material property perception) and two-dimensional tactile recognitions (shape or profile perception) with high accuracy are successfully realized using self-defined machine learning algorithms. This tactile sensing concept innovation based on the polarization chemistry of conjugated polymers opens up a new path to create robotic tactile sensors and prosthetic electronic skins.



KEYWORDS Passive tactile sensors; Reversible polarization of conjugated polymers; Tactile perception; Machine learning algorithm; Object recognition

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1 Introduction

Tactile sensation, a fundamental sense of the human body, enables us to acquire a wide spectrum of information that we leverage for object recognition and manipulation, including pressure, shear, strain, vibration, sliding, and so on [1, 2]. Tactile sensation is also a crucial medium for us to safely and efficiently navigate our surrounding environment. Imitating the tactile sensing functions in natural skin has attracted enormous attention in the emerging fields of advanced robots and prosthesis, biomedical equipment, and human-interactive systems [3–6].

In the past decades, artificial tactile sensors have witnessed remarkable progress, marked by advancements in high sensitivity [7, 8], low detection limit [9], multiple functionalities [10, 11], self-healing capability [12, 13], high pixel density [14], etc. [15]. Looking into these achievements, most of them are realized based on active sensing principles, including resistive sensing [16], capacitive sensing [17], transistor-based sensing [7], optical sensing [18], magnetic sensing [19], and so on [20]. These active sensing devices are operated by applying a source signal (e.g., current and voltage) to the devices first and then measuring specific electrical parameters (e.g., resistance, capacitance, and current) that are encoded with tactile information. Active tactile sensors are capable of detecting static and dynamic tactile stimulations, but they require a continuous power supply even in a standby state, resulting in high power consumption up to milli-watts per sensing unit. Such high power consumption limits their practical applications, especially for the isolated tactile sensing systems without external power supply.

In contrast, passive sensing devices (such as piezoelectric, triboelectric, and piezoionic devices) do not necessitate external energy supply and can generate signal outputs by themselves when subjected to tactile stimuli, featuring ultralow power consumption [21–24]. Nevertheless, these passive tactile sensors typically respond only to dynamic or transient mechanical stimulations, unable to resolving static and slowly varying tactile stimuli, restricting their application scenarios in comprehensive tactile analysis. Recently, a passive electrochemical sensing mechanism is proposed to resolve static touch stimulations [25–29]. However, these sensing devices necessitate sophisticated organic/inorganic hybrid material systems (e.g., Ag/AgCl-Fe^{2+}/Fe^{3+}, and VO_2/MnHCF/MoS_2-Zn/Zn^{2+}), which increases their manufacturing complexity and cost. Furthermore, these material systems could pose potential biotoxicity to the human body during usage and can also increase the environmental burden after usage. Hence, it still remains an unfilled research gap to achieve facile fabrication of fully passive and bio-friendly tactile sensing devices for detecting both static and dynamic stimulations.

Natural skin is an energy-efficient sensory organ that is capable of perceiving diverse stimulations, including light touch, pressure, vibration, and pain [30]. An essential reason behind the energy efficiency of natural skin lies in its nearly passive sensing style. As shown in Fig. 1a, b, different sensory receptors can be found in natural skin, including Merkel cells, Ruffini endings, Pacinian corpuscles, Meissner corpuscles, etc. [31, 32]. These sensory cells can be transformed from a non-polarized state to a polarized state (Fig. 1c) by pumping specific ions across the cell membrane, giving rise to an electrical potential difference (i.e., membrane potential). Upon external stimulations, the ion channels in the cell membrane will be opened with ions flowing across the membrane, leading to a remarkable variation in the membrane potential (i.e., action potential, Fig. 1d) [33]. The membrane potential variations encoded with specific tactile information are finally transmitted to the brain cortex for tactile interpretation. Such passive tactile sensing process based on stimulus-triggered potential difference variations provides a highly effective but energy-efficient way to sense and perceive a wide spectrum of tactile stimulations.

Here, to mimic the natural tactile sensations, a new type of fully passive and bio-friendly tactile sensing devices is presented based on the unique reversible polarization chemistry of conjugated polymers. To emulate the polarization process of the sensory cells, an arbitrary conjugated polymer (such as poly (3, 4-ethylenedioxythiophene):poly (styrenesulfonate) (PEDOT:PSS), polyaniline, or polypyrrole) is polarized into two opposite states (i.e., positively polarized state and negatively polarized state), thus to develop an artificial potential difference (Fig. 1e). Then, solid ionic electrolytes with surficial microstructures are employed to

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