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High-performance capacitive pressure sensors Fabricated by introducing dielectric filler and conductive filler into a porous dielectric layer through a Biomimic strategy

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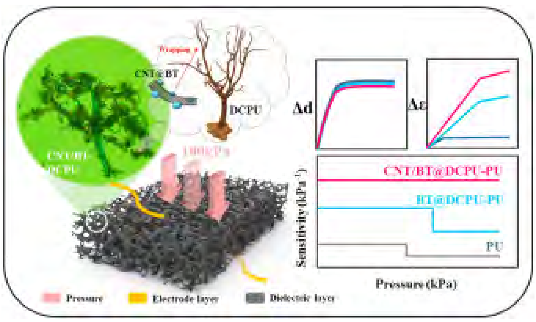
Abstract

Capacitive sensors have vast application prospects. Their dielectric layer is hardened under high pressure, the sensitivity is reduced and sensing behavior is nonlinear. To tackle this, a novel strategy is used to incorporate voids, dielectric filler and conductive filler into the dielectric layer. Firstly, "root" like dendritic colloid polyurethane (DCPU) is prepared to grasp different content of carbon nanotube (CNT) and barium titanate ($BaTiO_3$, BT), before such hybrid filler is coated onto the backbone of PU foam. For capacitive pressure sensors, it is observed that sensitivity increases with increasing filler content. More importantly, the addition of CNT into the inner layer of hybrid filler containing BT in the outer layer leads to linear pressure sensing behavior in a wide pressure range. Furthermore, the overall performance achieves a sensitivity of 2.51 kPa^{-1} under 0–100 kPa and ~~a~~ linearity of R^2=0.9989, and stable signals after 1000 cycles. Finally, it is successfully demonstrated that petals with a weight of 96 mg and the physiological signals of the human body such as heartbeat, swing arm amplitude, and joint bending can be detected. This work provides ~~a~~ new design inspiration for capacitive sensors with high sensitivity and high linearity in realizing medical health monitoring and motion detection.

Graphical abstract

Introducing conductive/dielectric fillers into porous dielectric layers to study their capacitance-sensitive behavior.



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Introduction

With the rapid development of 5G technology, many smart scenes in life are well foreseen [[1], [2], [3]]. It should be mentioned that flexible wearable electronic devices provide many possibilities for imagination, such as sensors that sense touch to achieve human-computer interaction and electronic skins that monitor physiological signals [[4], [5], [6], [7]]. According to the mechanism, flexible pressure sensors are mainly divided into resistive [8], capacitive [9] and piezoelectric [10]. From performance point of view, capacitive sensors have advantages of high sensitivity, low power consumption and fast response, and are widely used in a variety of scenes that monitor signal changes [[11], [12], [13]]. However, it often exhibits a high degree of non-linearity and sharp drop in sensitivity under wide range of pressure, which greatly limits its further development [14]. It is critical that the pressure sensor responds linearly in a wide working range and maintains high sensitivity. Having linear response characteristics can greatly simplify the tedious process of calibrating electrical signals and improve the reliability of the data [[15], [16], [17], [18]]. And when the system is integrated, many processing systems can be omitted, making it more portable and miniaturized. The reason for the observed nonlinear sensitivity of the capacitive sensor is mainly caused by a variety of influencing factors. According to the capacitance formula $C = \frac{\varepsilon_r \varepsilon_0 A}{d}$ [19], it is simultaneously influenced by three parameters including contact area (A), dielectric constant (ε) and the distance (d) between two electrodes [20,21]. When the neat polymer is used as the dielectric layer, the mechanism for change in capacitance for most capacitive sensors at low voltage originate from the change in the thickness of dielectric layer. The dielectric layer is hardened under high pressure with decreased d; thus, the sensitivity would also decrease.

The main strategies to modify pressure sensing behavior of capacitive sensors include altering the interfacial contact area between elastic electrode and dielectric layer, and introducing voids, dielectric or conductive fillers into dielectric layer [[22], [23], [24], [25], [26], [27]]. These two main strategies could also be combined to modify the pressure sensing performance. Besides, the modification ~~on~~ of the electrode layer could add additional functionality to the overall sensor [28]. Regarding the interfacial modification strategy, Bao and colleagues [29] proposed that the introduction of microstructure voids on the surface of dielectric layer can effectively reduce the elastic modulus of the active layer. This measure is conducive to the large deformation of capacitive sensor under pressure; thus, the sensitivity is improved. Meanwhile, Guo et al. designed an interface combining a micro-columnar electrode and an ion gel layer to achieve a high linear capacitance-pressure response under large range pressure [30]. Furthermore, a number of similar studies have also reported the construction of special interfacial morphology between electrode and dielectric layer. Such a strategy seems quite effective at modifying the pressure sensing behavior of these capacitive sensors.

Regarding another strategy for the modification of dielectric layer, the introduction of voids, dielectric or conductive fillers into dielectric layer have also been widely studied [24,[31], [32], [33]]. For instance, Li et al. added spike nickel into the dielectric layer below the percolation threshold [34]. The spike shape of nickel can locally enhance the electric field to amplify the capacitive signal. The design strategy is very simple, and the sensitivity is highly linear in the range of 1.7 MPa. Nevertheless, the sensitivity is only 0.0046 kPa^{-1}. Moreover, adding dielectric fillers into the porous dielectric layer is also an effective way to control the sensing behavior. For instance, Park et al. added dielectric filler calcium copper titanate ($CaCu_3Ti_4O_{12}$, CCTO) to PU sponge by dip coating, which can achieve a sensitivity of 0.73 kPa^{-1} at low pressure (<1.6 kPa) [35]. But the sensitivity drops sharply to 0.026 kPa^{-1} under 25–100 kPa. There is a number of studies on similar topic regarding introducing voids, dielectric or conductive filler into dielectric layer. Nevertheless, these studies often illustrate rather low sensitivity and multi-region linear sensing behavior as shown in Table S1. Moreover, the content and distribution of various fillers in the porous dielectric layer are uncontrolled, despite ~~of~~ the fact that such strategy has demonstrated an important influence on the capacitive sensing behavior. Therefore, there is still plenty of room to explore ~~on~~ introducing voids, dielectric filler or conductive filler into the dielectric layer.

Along this line of thought, we intend to introduce voids, dielectric filler and conductive filler into the dielectric layer with controlled content and distribution. To achieve this, a “root” like dendritic colloidal polyurethane (DCPU) was prepared to grab a large number of carbon nanotubes (CNT) and barium titanate ($BaTiO_3$, BT) forming hybrid filler. Such filler was coated onto the skeleton of PU foam to serve as the dielectric layer. This strategy provides an effective strategy for the fabrication of high-performance capacitive sensor with controlled content and distribution of voids, dielectric filler and conductive filler.

Section snippets

Materials

CNT (purity >90%) were purchased from Nanocyl S.A, Belgium. Barium titanate ($BaTiO_3$, BT) with a molecular weight of 233.21 was provided by Aladdin, its particle size <100 nm. Polyurethane prepolymer (PU, HD-3028) had a solid content of 30%, obtained from Huada Chemical Group Co., Ltd. All reagents including isopropanol (IPA), N, *N*-dimethylformamide (DMF) of analytical grade were purchased from Chengdu Kelong Chemical Co., Ltd. All reagents and materials were used as received without…

Fabrication and structural characterization of CNT/BT@DCPU-PU

Illustration of the fabrication process for CNT/BT@DCPU-PU foam based capacitive sensor is shown in Fig. 1a. In brief, the schematic diagram consists of four steps: First, adding the dissolved PU/DMF solution dropwise to a strong shear turbulent (18,000 rpm). Then mixing one-dimensional CNTs (Fig. 1b) with the above solution to prepare CNT@DCPU dendritic colloid. Subsequently, spherical BT shown in Fig. 1c was added to form composite fillers of CNT/BT@DCPU with BT covering CNT@DCPU. The…

Conclusions

To conclude, dendritic colloid PU is used to facilitate the preparation of hybrid fillers BT@DCPU and CNT/BT@DCPU. Then, these hybrid fillers were coated onto porous PU foam to obtain a high-performance capacitive sensor. Such biomimetic coating strategy could effectively control the content of void, dielectric filler and conductive filler in the dielectric layer. By comparing sensors based on BT@DCPU with CNT/BT@DCPU, it is noted that the presence of CNT in the hybrid filler leads to highly…

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.…

Acknowledgements

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