Skin-Conformable Displays and Sensors Using Soft and Stretchable Electronic Materials

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Abstract

We developed highly skin-conformable displays and sensors using stretchable conducting polymers. Wearable devices enable long-term monitoring of healthcare signals, but the form factor has been limited to be small and rigid, exemplified by watches or rings. Soft and stretchable electronic materials enable very high skin-conformability with high comfort of wear. In this report, we show the development of stretchable conducting polymers that enable highly skin-conformable displays and sensors. The conducting polymers show stretchability higher than 50% and high transparency. Our ultrathin and soft electronic devices show exceptional integratability with the skin.

Author Keywords

Stretchable electronics; Electrochromic display; Wearable electronics; Skin display; Stretchable display

1. Introduction

Wearable devices enable long-term healthcare monitoring of healthcare signals. Different from traditional diagnosis by doctors, the long-term monitoring of healthcare signals let us find the diseases in very early stage, or prevent their development. Current wearable devices are mostly watches or rings. To ensure the comfort of wearing, the form factor is limited to be small. Soft and stretchable electronic materials will realize the next-generation wearable devices (1). The devices can acquire skin-like softness, and achieve very high skin conformability to improve the comfort of wear, device size, healthcare signal integrity, and robustness against motion artifacts (Figure 1) (2). In addition, the soft devices show better intractability with skin (3). The usage in VR/AR can significantly enhance the immersiveness of the wearers.

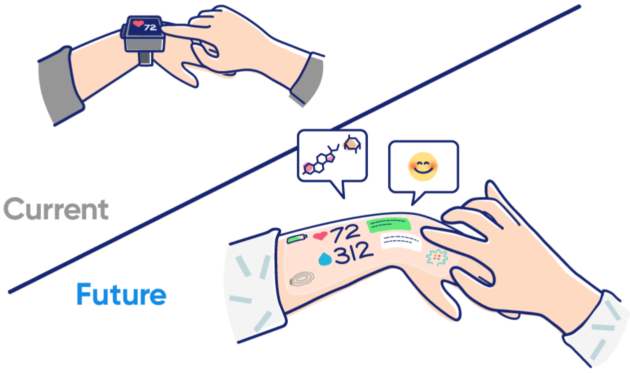

Figure 1. Future wearable devices by soft and stretchable electronic materials (2).

Designing Skin Conformability: The conformable contact of soft electronic devices on skin can be designed by reducing the flexural rigidity (*D*), which can be defined by Young's modulus (*E*), thickness (*t*), and Poisson's ratio (*v*) using the following Equation 1 (4,5). Very high skin conformability can be achieved once the flexural rigidity is very low (5), so that the reduction of both Young's modulus and thickness is important. Additionally, the materials with reduced Young's modulus tend to deform easily, and need to follow the deformation of the skin during the usage. Therefore, the stretchability needs to be higher than 30% or more to overcome the stretchability of the skin (6).

$$D = \frac{Eh^3}{12(1-\nu^2)} \tag{1}$$

Purpose of This Report: In this report, we show the design of a stretchable conducting polymer, which show low Young's modulus among stretchable conductors, and the application in highly skin-conformable displays and sensors. Our conducting polymer shows high stretchability over 100%, high transparency, and patternability in high resolution. The skin-conformable displays and sensors show very high integration with the skin, and high gas-permeability to ensure the long-term usage on the skin.

2. Stretchable conducting polymers

Materials: Our stretchable conducting polymer is based on Poly(2,3-dihydrothieno-1,4-dioxin)-poly(styrenesulfonate) (PEDOT:PSS). Although PEDOT:PSS shows high conductivity, the stretchability of the pristine materials are limited by the charge interaction between ionic PSS. The stretchability can be enhanced by ionic additives to screen the hydrogen bonding interaction (7). Figure 2 shows the materials used in this study. Lithium Bis(trifluoromethanesulfonyl)imide (LiTFSI) (7), Lithium Bis(pentafluoroethanesulfonyl)imide (LiBETI) (8), and 4-(3-ethyl-1-imidazolio)-1-butanesulfonate (IonE) (9) were added to PEDOT:PSS solution (Figure 2). The solutions were spin-coated onto two kinds of stretchable substrates which are thermoplastic polyurethane (TPU) and styrene-based thermoplastic elastomer (SEBS) to characterize the conductivity and stretchability.

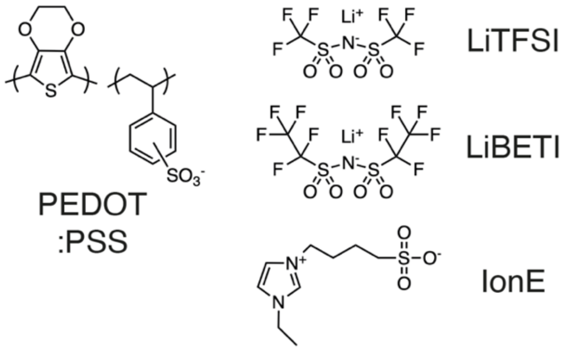

Figure 2. Materials for stretchable conducing polymers.

Electrical characteristics: Figure 3 shows the conductivity under non-stretching conditions of PEDOT:PSS with different additives in Figure 2. By choosing LiBETI as the additive, the conductivity was improved to 330 S/cm. This value is higher than the conductivity of 270 S/cm obtained with LiTFSI, which was

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used in previous studies (7). The mechanism of the conductivity improvement was the enhanced conductivity of PEDOT by LiBETI, which was confirmed by GIWAXS measurement.

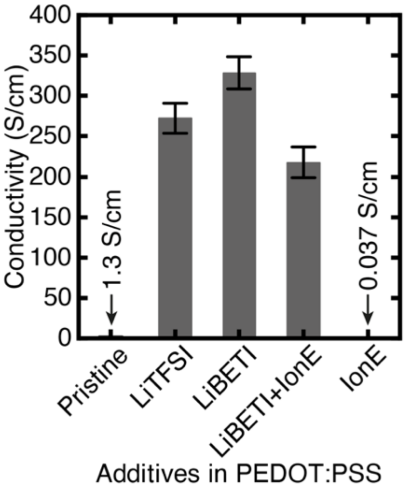

Figure 3. Conductivity of PEDOT:PSS with different additives.

Mechanical characteristics: Figure 4 compares the mechanical properties of PEDOT:PSS with different additives. All the additives effectively improved the crack-on-set strain, and reduced the hardness. The crack-on-set strain of pristine PEDOT:PSS on the SEBS substrate, which was around 10%, was improved to about 30% with the addition of LiBETI. Furthermore, TPU substrate significantly improved the crack-on-set strain to around 160% with the use of LiBETI as the additive. The mechanism behind the large stretchability of conducting polymers on TPU is likely the similar mechanical properties of the PEDOT:PSS with LiBETI and TPU. The Young's modulus of the PEDOT:PSS with LiTFSI added system is reported to be 55 MPa. The Young's modulus of the SEBS and TPU substrates used in this study are 5.5 MPa and 30.6 MPa, respectively. Additionally, the Poisson's ratios of PEDOT:PSS, SEBS, and TPU are 0.35, 0.49, and 0.45, respectively.

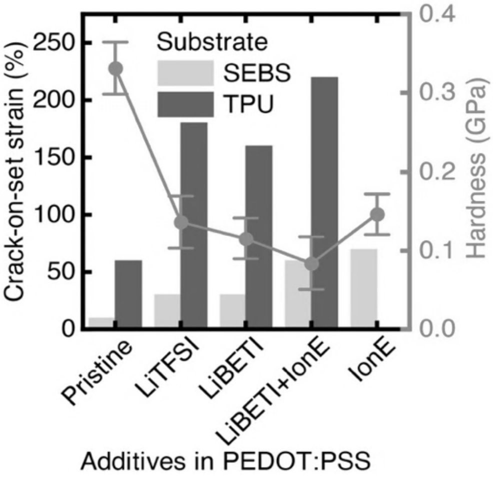

Figure 4. Mechanical properties of PEDOT:PSS with different additives.

Transparency: Figure 5 shows the transmittance of PEDOT:PSS with additives. The transmittance was improved in all systems with additives compared to those without additives. This is because the additives have almost no absorption spectrum in the visible light range. The transmittance at 550 nm, including the substrate, is around 85%, sufficient for applications such as displays and sensors. In addition, the conducting polymer was able to be patterned in high resolution (<10 μm) using UV laser ablation.

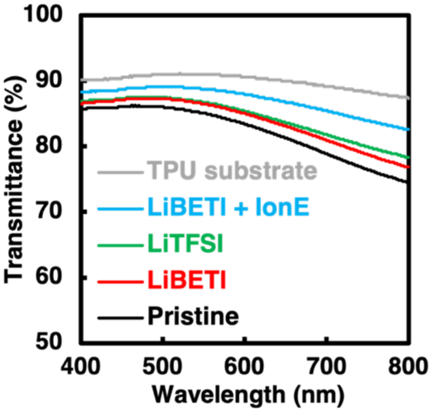

Figure 5. Transparency of PEDOT:PSS with different additives.

3. Skin-conformable electrochromic display

Structure: Using the stretchable conducting polymer, we developed skin-conformable and stretchable electrochromic display (ECD). The ECD consists of 6 layers: sacrificial supporting layer, substrate, conducting polymer, electrolyte, conducting polymer, and superstrate. The sacrificial supporting layer is 20-μm thick polyvinyl alcohol (PVA) and water-soluble. As the total thickness of the other stretchable layers is only 6 μm, the sacrificial supporting layer works as the temporary substrate until the device is attached to the skin using water. The substrate and superstrate are bilayers of SEBS and TPU. The conducting polymer layer is PEDOT:PSS:LiBETI. The electrolyte layer is TPU doped with ionic liquid 1-Ethyl-3-methylimidazolium Bis(trifluoromethanesulfonyl)imide (EMIMTFSI).

Skin conformability: Figure 6 shows our skin-conformable ECD. The lamination on the skin was completed by dissolving the sacrificial layer by water. When 2 V is applied between a top and bottom electrode, one conducting polymer layer is reduced to show a color. The total thickness of the ECD is only 6 μm, and the Young's modulus is less than 10 MPa, thus the flexural rigidity is only ~0.1 nN m. Therefore, our display showed high conformability even to the wrinkles of the skin.

Stretchability and electrical properties: The ECD showed a reasonable color contrast even under 50% strain. The ECD also showed high stability against cyclic strains (20% strain, 1000 cycles) and air stability over a week. Furthermore, displaying in multi-pixel was also confirmed by the patterning of the bottom conducting polymer layer to the array (Fig. 7). The color of the display can be changed by tuning the band gap of the conducting polymer. For example, a red expression on the cheek may enable novel electronic, cosmetic applications that can enhance communication between people.

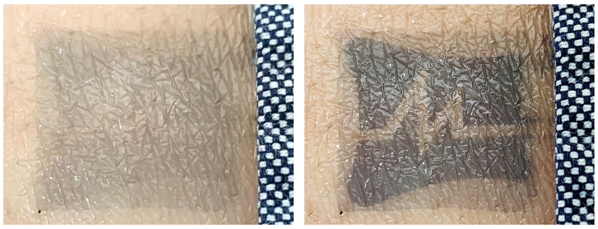

Figure 6. Skin-conformable electrochromic display. Left, no voltage is applied. Right, 2 V is applied.

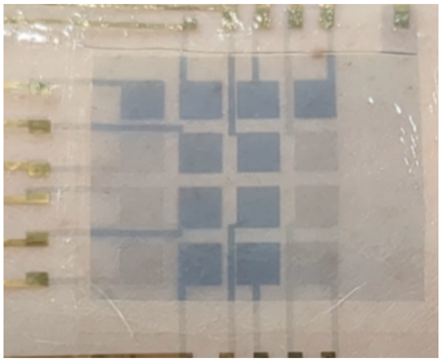

Figure 7. Multi-pixel skin-conformable ECD describing “T”.

Gas Permeability: Our ECD also showed high gas permeability to minimize damage to the skin by long-term wearing. Figure 8 compares the transepidermal water loss (TEWL) of bare skin, our 6-μm-thick devices, and 100-μm-thick SEBS substrates. The TEWL is as high as ~7 g/m^{2}h, while bare skin showed ~8 g/m^{2}h. High gas-permeability has been achieved mainly by making substrates porous, which can sacrifice the displaying area. On the other hand, our approach of using thin elastomer does not sacrifice the fill factor of the display at all.

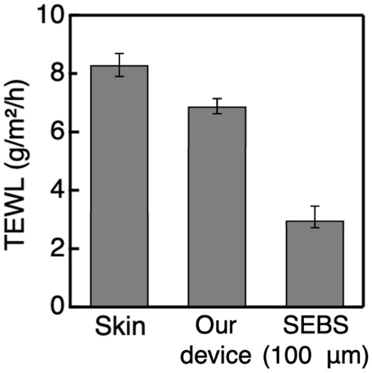

Figure 8. Transepidermal water loss of our ECD.

4. Skin-conformable sensors

Structure: Using the same structure as a highly skin-conformable ECD, we developed a highly skin-conformable piezoelectric sensor. The piezoelectric sensor consists of 6 layers: sacrificial supporting layer, substrate, conducting polymer, piezoelectric layer, conducting polymer, and superstrate. The piezoelectric layer is a composite of poly(vinylidene fluoride-co-trifluoroethylene) (PVDF-TrFe) and poly(vinylidene fluoride-co-hexafluoropropylene) (PVDF-HFP). The addition of PVDF-HFP modifies the elasticity of piezoelectric PVDF-TrFe. After the fabrication, the piezoelectric layer was poled with a DC voltage of 200 V. When the sacrificial layer was dissolved, the sensor showed exceptional skin conformability (Fig. 9)

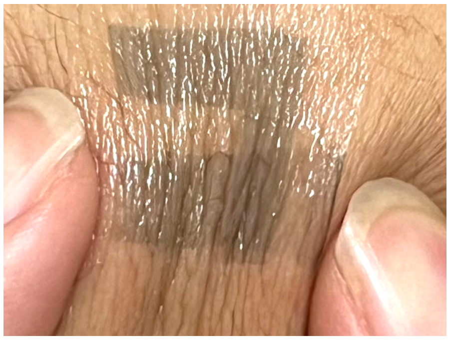

Figure 9. A highly skin-conformable piezoelectric sensor.

Piezoelectric sensing: Figure 10 shows the piezoelectric performances of our highly skin-conformable sensors. The sensor is very soft and doesn’t influence the motion of wearers. The sensor was laminated onto a wrist. When a wrist was bent with different angles, a clear output voltage corresponding the angle of the wrist was obtained.

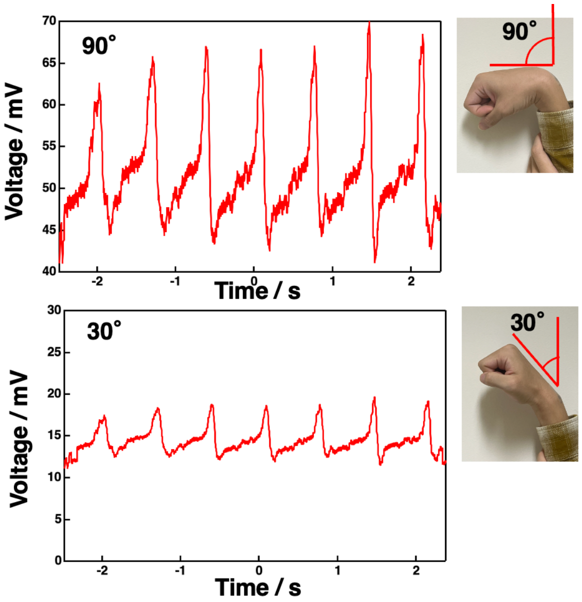

Figure 10. Motion sensing by a highly skin-conformable piezoelectric sensor.

5. Conclusion

In this communication, we have developed a stretchable conducting polymer, which shows low Young’s modulus, high stretchability, high conductivity, and high transparency. Furthermore, the conducting polymer enabled the fabrication of highly skin-conformable electrochromic displays and piezoelectric sensors. The devices are made of stretchable electronic materials, and the total thickness is only 6 μm. The devices also realized high gas permeability to minimize the damage to the skin by long-term wearing. The devices will be the components of future wearables with good comfort of wear.

Furthermore, the high-level integration with skin may enable the unprecedented application of electronics, including electronic cosmetics, to enhance emotional expressions.

6. Acknowledgements

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7. References

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