MECHANICS OF EPIDERMAL ELECTRONICS

Shuodao Wang[*], Jian Wu[**] Yonggang Huang[*a)] & John A. Rogers[***]
[*]*Department of Mechanical Engineering, Department of Civil & Environmental Engineering, Northwestern University, Evanston, IL 60208, USA*
[**]*Department of Engineering Mechanics, Tsinghua University, Beijing, 100084, China*
[***]*Department of Materials Science and Engineering, University of Illinois, Urbana, IL 61801, USA*

Summary We report classes of electronic systems that achieve thicknesses, effective elastic moduli, bending stiffnesses and areal mass densities matched to the epidermis. Unlike traditional wafer-based technologies, laminating such devices onto the skin leads to conformal contact, and adequate adhesion based on van der Waals interactions alone, in a manner that is mechanically invisible to the user. This concept could be used to build systems incorporating elecrophysiological, temperature and strain sensors, as well as transistors, light emitting diodes, photodetectors and radio frequency inductors, capacitors, oscillators and rectifying diodes, solar cells and wireless coils provide options for power supply, etc. Confocal micrographs of Epidermal Electronics system (EES) mounted on pig skin show remarkably conformal contact between the EES and the skin. These observations are consistent with analytical mechanics treatments that use macroscopic models of the EES and account for interfacial adhesion and microscopic structures on the skin.

1. INTRODUCTION

Physiological measurements that exploits interfaces to the skin have been studied for over 80 years[1], but these conventional, wafer-based approaches are still poorly suited for practical applications outside of research labs due to difficulties in achieving robust electrical contacts with the skin and in achieving portable integrated systems with small size, light weight, and bio-compatible shapes. Kim et al. recently proposed a different technology [2], in which the electronic circuits, sensors, wireless power units, and communication components are integrated into ultrathin, low modulus, lightweight, stretchable membranes (Fig. 1a-b) that could be mounted onto the skin by van der Waals interactions alone, in a manner that does not irritate the skin during prolong use. The epidermal electronic system (EES) is almost mechanically unnoticeable to the carrier, and could retain conformal contact with the skin under compression/tension (Fig. 1c-d). It will have many important medical applications such as to monitor brain or heart activities, or premature babies; to enhance the control of prosthetics; and to realize human-machine interface.
Physical coupling of electrodes to the surface of the skin is one of the most important features for many uses of EES, and is studied via a simple, analytical mechanic model in this paper. It accounts for the macroscopic properties in Section 2, and microscopic morphology of the skin in Section 3. Results are validated with finite element analysis, and agree very well with experimental observations on two types of EES designs: (1) the filamentary serpentine (FS) EES (Fig. 2a) where ultrathin active devices adopt FS layouts and continuously integrate with narrow FS interconnects, and (2) island-plus-serpentine (IPS) EES (Fig. 2c) where active device islands are integrated with similar FS interconnects.

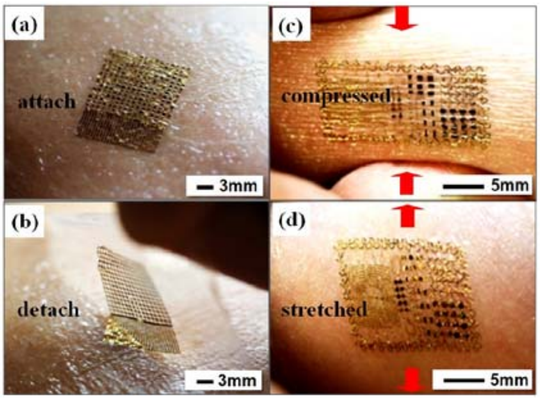

Figure 1 EES under deformations.

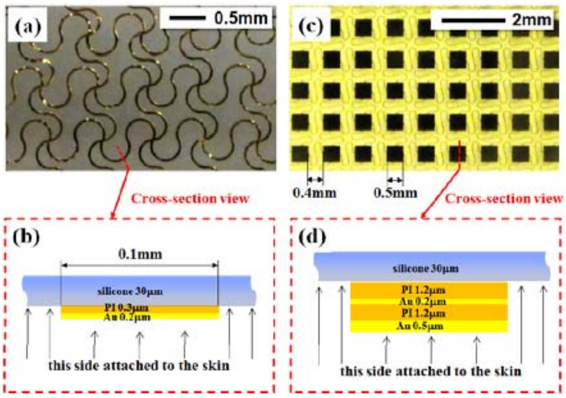

Figure 2 top-view and cross-section view of two types of EES.

2. MACROSCOPIC PROPERTIES OF THE EES

The FS-EES (Fig. 2a-b) consists of a backing layer of silicone, and narrow FS strips made of polyimide (PI) and gold; the IPS-EES (Fig. 2c-d) consists the same backing layer and electrode islands interconnected with FS bridges.
The adhesion between the EES and the skin is determined by both the work of adhesion and the contact area, and the effective work of adhesion is obtained as

[a)] Corresponding author. Email: y-huang@northwestern.edu.

$$\gamma \approx (1-\alpha)\gamma_{\text{silicone/skin}}, \tag{1}$$

where α is the area fraction of device and $\gamma_{\text{silicone/skin}}$ is the work of adhesion between silicone and the skin. For narrow FS strips distributed over the entire surface of FS-EES, the effective bending stiffness of EES is averaged similarly as

$$\overline{EI}_{\text{EES}} = \alpha \overline{EI}_{\text{device}} + (1-\alpha)\overline{EI}_{\text{silicone}}. \tag{2}$$

Where, $\overline{EI}_{\text{device}}$ and $\overline{EI}_{\text{silicone}}$ are the bending stiffness of device and silicone, respecitvely. For α~22.5% from Fig. 2a, Eq. (2) gives the effective bending stiffness 0.27×10^{-9} N-m, which agrees reasonably well with 0.30×10^{-9} N-m obtained by finite element analysis.

3. CONTACT BETWEEN EES AND SKIN

Microscopic morphology of the skin (Fig. 3) is accounted for in this section to study the contact between the EES and skin. For non-conformal contact (Fig. 3) between the EES and skin, the former remains flat and the contact area is almost zero, therefore $U_{\text{non-conformal}}=0$. For conformal contact (Fig. 3), both the EES and the skin deform to give their total displacement the same as the skin roughness. The total energy for conformal contact $U_{\text{conformal}}$ consists of bending energy of EES, elastic energy of the skin and the adhesive energy between EES and skin. Conformal contact requires $U_{\text{conformal}}<U_{\text{non-conformal}}$, which gives

$$\frac{\pi \overline{E}_{\text{skin}} h_{\text{rough}}^2}{\gamma \lambda_{\text{rough}}} < 16 + \frac{\overline{E}_{\text{skin}} \lambda_{\text{rough}}^3}{\pi^3 \overline{EI}_{\text{EES}}}. \tag{3}$$

The above scaling law involves two dimensionless combinations of EES and skin properties. It clearly shows that EES with low bending stiffness (thin, soft devices/backing layer), smooth and soft skin, and strong adhesion all promote conformal contact. The criterion above implies that EES loses conformal contact once the skin roughness amplitude exceeds 27 μm (Fig. 4, blue line), which is consistent with partial contact observed in the confocal microscopy image (Fig. 4 inset) where the range of skin roughness is 20~50 μm (marked by the blue bar in Fig. 4).

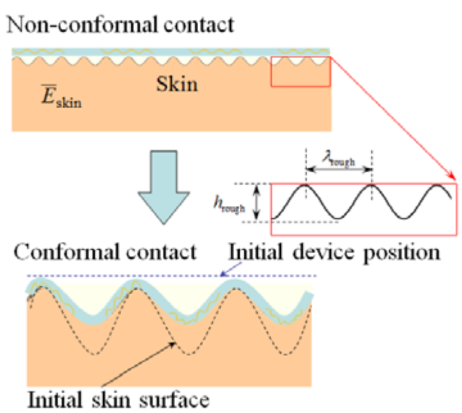

Figure 3 non-conformal and conformal contacts between EES and skin.

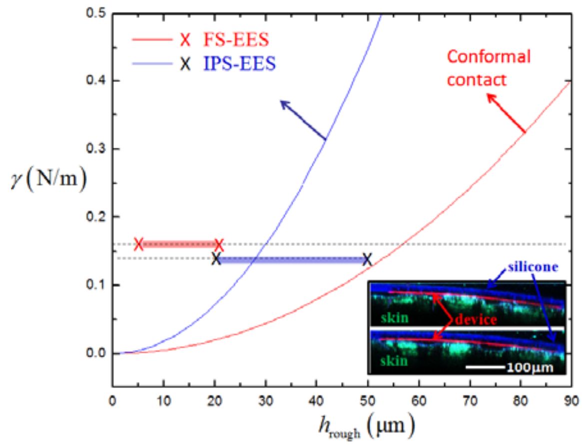

Figure 4 Deformation map governing the conformal contact.

For FS-EES, the effect of device thickness is studied by changing thicknesses of all layers proportionally. For FS-EES with device thickness of 0.5 μm in experiments, the maximum contact pressure is only 12.5 kPa, which is below the human skin sensitivity (~20kPa [3]) and therefore is mechanically unnoticeable and would not induce discomfort.

4. CONCLUSIONS

Simple, analytical mechanics concepts presented in this study lead to successful design of integrated high-performance, highly portable EES that offers robust, intimate contact with the surface of the skin. The scaling law governing the conformal contact between EES and the skin, the effects of device thickness, size and skin roughness, and the contact pressure on the surface of the skin are all studied in details. The results, validated by finite element analysis, agree well with experimental observations and are useful for future designs that exploit different functionality of EES.

References

[1] Berger, H., 1929, "Uber das electrenkephalogramm des menchen," *Arch Psychiatr Nervenkr*, **87**: 527-570, 1929.

[2] Kim, D.-H. *et al.*, "Epidermal Electronics," *Science*, **333**(6044): 838-843, 2011.

[3] Kaneko, A., Asai, N., and Kanda, T., *Journal of Hand Therapy*, **18**(4): 421-425.