Mechanics of Interfacial Delamination in Epidermal Electronics Systems

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In order to provide continuous diagnostic and therapeutic options that exploit electrophysiological signals from the epidermis, this study discusses epidermal electronics systems (EES) that conform to the skin surface via van der Waals force alone, which is otherwise susceptible to artifacts associated with motion-induced changes. This paper not only establishes a criterion of conformal contact between the EES and the skin for both initial contact and the case where the skin is subject to external loading but also investigates the criterion to prevent any partial delamination between electronics and the skin. These results improve the performance of EES by maximizing intimate contact between the EES and skin, revealing important underlying physical insights for device optimization and future design. [DOI: 10.1115/1.4025305]

Keywords: epidermal electronics, interfacial delamination, adhesion

1 Introduction

The monitoring of physiological signals is of critical importance for medical diagnosis and therapeutics [1,2]. Measurements of such signals are based on electrical coupling between biological tissues and electrodes. Exploiting this mechanism, a wide range of electronics systems can be explored to measure electrophysiological signals, such as electrocardiograms, electromyograms, and electrooculograms. Conventional flat, rigid electronics have the ability to capture these types of electrical signals and have their applications in some contexts, but they do not offer continuous, real-time, or portable operations. Fixed to the skin surface by caps, belts, conductive glues, or tapes [3], these conventional electronics usually yield inaccurate measurements. In addition, such devices/setup may irritate the skin [4] and modify the electrical coupling nature when the skin is mechanically loaded. In contrast, a recently developed concept of epidermal electronics [1,5,6] enables electronics to be intimately integrated onto the skin surface, such that the accuracy of measurements can be guaranteed. This noninvasive integration also blocks signal noises resulted from artifacts such as motion induced changes. Here we first introduce the model for initial contact of epidermal electronics to the skin and then discuss the criterion to prevent delamination when the system is subject to external loading. The latter discussion is essential for continuous, portable operations of epidermal electronics during normal human activities that deform the skin to as much as ∼30%.

2 Initial Contact of Epidermal Electronics to the Skin

Epidermal electronics systems exploit arrays of sensors for large area mapping. A representative system, shown in Fig. 1(*a*), places ultrathin metal electrodes/interconnects on one side of a silicone backing layer (Solaris in this study, inset of Fig. 1(*b*)) for improved mechanical robustness and intimate contact. The filamentary mesh design (Fig. 1(*a*)) minimizes the strain in both the sensors and the interconnects during deformation [1]. Flat epidermal electronics systems were laminated on a wavy skin surface, followed by pressing on the top surface of EES to initiate the contact [1]. The flexure rigidity of EES is fairly small for a thin EES, which enables it to slide along the morphology of skin to achieve conformal contact. For simplicity, the initial morphology of the skin is characterized by a sinusoidal function as $y(x) = h_{\text{rough}}\left[1+\cos\left(2\pi x/\lambda_{\text{rough}}\right)\right]/2$, where h_{rough} and λ_{rough} are the characteristic amplitude and wavelength of the skin, respectively. After EES conforms to the skin, the skin morphology becomes $w(x) = h\left[1+\cos\left(2\pi x/\lambda_{\text{rough}}\right)\right]/2$, where h is the deformed amplitude to be determined. The displacement of the skin surface is then given as the difference between the initial and deformed morphologies as $u_z(x) = y(x) - w(x)$. The total energy of the EES/skin system $\bar{U}_{\text{conformal}}$ consists of bending energy of EES $\bar{U}_{\text{bending}}$, elastic energy of skin $\bar{U}_{\text{skin}}$, and surface adhesion energy at EES/skin interface $\bar{U}_{\text{adhesion}}$, i.e., $\bar{U}_{\text{conformal}} = \bar{U}_{\text{bending}} + \bar{U}_{\text{skin}} + \bar{U}_{\text{adhesion}}$ [7]. The membrane energy of EES is not considered in the analysis because it is negligible compared to the bending energy due to the sliding between EES and skin (initially at the peak of the skin, material points A and C would slide along the skin surface to points A′ and C′, respectively, as shown in Fig. 1(*b*)). Taking L_0 as the initial length of EES, the bending energy of deformed EES is derived as

$$\bar{U}_{\text{bending}} = \frac{1}{2}\int_0^{L_0} \overline{EI}_{\text{EES}}(w'')^2 dx = \frac{\pi^4 \overline{EI}_{\text{EES}} h^2}{\lambda_{\text{rough}}^4} L_0 \tag{1}$$

where $\overline{EI}_{\text{EES}}$ is effective bending stiffness of EES. This effective bending stiffness is given as a weighted average of bending stiffness $\overline{EI}_{\text{device}}$ in the device region and bending stiffness $\overline{EI}_{\text{wo}}$ in the region without device, i.e., $\overline{EI}_{\text{EES}} = \alpha\overline{EI}_{\text{device}} + (1-\alpha)\overline{EI}_{\text{wo}}$, and the weight α is the area fraction of gold device over the entire area [7].

Gold device mesh is placed between Solaris backing layer and the skin. For a multilayer structure, the bending stiffness $\overline{EI}$ of the

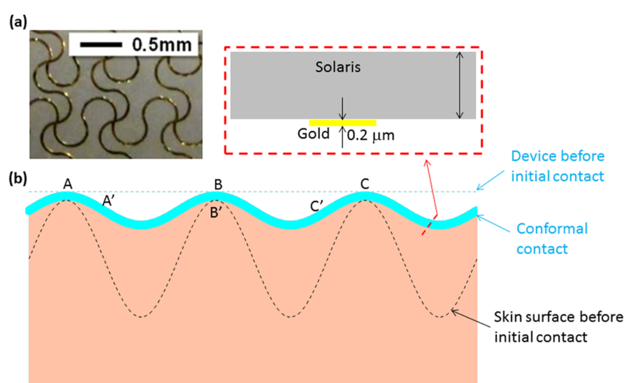

Fig. 1 (*a*) Top view of epidermal electronics system and (*b*) schematic illustration of initial contact (inset: cross-section layout of EES)

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Manuscript received August 7, 2013; final manuscript received August 20, 2013; accepted manuscript posted August 28, 2013; published online October 16, 2013. Editor: Yonggang Huang.

structure is related to the plane strain Young's modulus $\bar{E}_i$ and thickness h_i of each layer as

$$\overline{EI} = \sum_{i=1}^{N} \bar{E}_i h_i \left[\left(b - \sum_{j=1}^{i} h_j \right)^2 + \left(b - \sum_{j=1}^{i} h_j \right) h_i + \frac{1}{3} h_i^2 \right] \tag{2}$$

where N is the number of layers and $b = \sum_{i=1}^{N} \bar{E}_i h_i \left(\sum_{j=1}^{i} h_j - h_i/2 \right) / \sum_{i=1}^{N} \bar{E}_i h_j$ is the distance from the neutral axis to the bottom surface. For the structure in the current study as shown in the inset of Fig. 1(*b*), the bending stiffness $\overline{EI}_{\text{device}}$ in the device region can be obtained from Eq. (2) with $N=2$, $\bar{E}_1 = \bar{E}_{\text{Solaris}}$, $h_1 = h_{\text{Solaris}}$, $\bar{E}_2 = \bar{E}_{\text{Au}}$, and $h_2 = h_{\text{Au}}$, whereas $\overline{EI}_{\text{wo}}$ is simply $\overline{EI}_{\text{Solaris}} = \bar{E}_{\text{Solaris}} h_{\text{Solaris}}^3 / 12$. The use of beam theory for the substrate thickness in interest (up to $\sim 100\,\mu$m; EES with thicker cannot conform to the skin) is discussed and validated by Wang et al. [7].

The elastic energy of the skin is related to the skin surface displacement as [8]

$$\bar{U}_{\text{skin}} = \frac{\pi \bar{E}_{\text{skin}} \left(h_{\text{rough}} - h \right)^2}{16 \lambda_{\text{rough}}} L_0 \tag{3}$$

where $\bar{E}_{\text{skin}}$ is the plane strain Young's modulus of the skin. The interfacial adhesion energy is the multiplication of work of adhesion and the contact area, which is a constant $\bar{U}_{\text{adhesion}} = -\gamma L_0$. Minimization of the total energy $\bar{U}_{\text{conformal}} = \bar{U}_{\text{bending}} + \bar{U}_{\text{skin}} + \bar{U}_{\text{adhesion}}$ gives the deformed amplitude as

$$h = \frac{h_{\text{rough}}}{\dfrac{16\pi^3 \overline{EI}_{\text{EES}}}{\lambda_{\text{rough}}^3 \bar{E}_{\text{skin}}} + 1} \tag{4}$$

Conformal contact requires $\bar{U}_{\text{conformal}} < \bar{U}_{\text{nonconformal}} = 0$, which gives

$$\frac{\pi h_{\text{rough}}^2}{\gamma \lambda_{\text{rough}}} < \frac{16}{\bar{E}_{\text{skin}}} + \frac{\lambda_{\text{rough}}^3}{\overline{EI}_{\text{EES}} \pi^3} \tag{5}$$

The total energy (per unit length) $U_{\text{conformal}}/L_0$ of a typical EES/skin system ($\alpha = 0.25$, $\bar{E}_{\text{Au}} = 97$ GPa, $h_{\text{Au}} = 0.2\ \mu$m, $\bar{E}_{\text{Solaris}} = 0.129$ MPa, $\lambda_{\text{rough}} = 140\ \mu$m, and $h_{\text{rough}} = 55\ \mu$m) is shown in Fig. 2, and it is clearly seen that the total energy (per unit length) for conformal contact is lower than that of nonconformal contact (zero) for Solaris thickness smaller than $27.5\,\mu$m, which defines the critical thickness of Solaris.

When the stress $\sigma = \overline{EI}_{\text{EES}} d^4 w / dx^4$ at the EES/skin interface exceeds the EES/skin cohesive strength $\bar{\sigma}$, partial delamination between the EES and skin may occur. To ensure conformal contact after the initial lamination, the maximum interfacial stress $\sigma_{\max}$ needs to be smaller than $\bar{\sigma}$, i.e.,

$$\overline{EI}_{\text{EES}} \frac{h}{2} \left(\frac{2\pi}{\lambda_{\text{rough}}} \right)^4 < \bar{\sigma} \tag{6}$$

where h is given in Eq. (4). For a typical EES/skin cohesive strength $\bar{\sigma} = 40$ kPa that is based on van der Waals force alone [9], the thickness of Solaris is required to be smaller than $28.4\,\mu$m, which indicates the EES with a Solaris layer thinner than critical thickness ($27.5\,\mu$m) remains completely conformal contact to the skin.

Skin motion induces an applied strain of $\varepsilon_{\text{apply}}$ on the deformed EES/skin system, and this leads to a new morphology of skin $w' = h' \left[1 + \cos\left(2\pi x / \lambda_{\text{rough}} \right) \right] / 2$ [8], where the amplitude h' is to be determined. The analysis is similar to that of initial contact such that only the elastic energy of skin in Eq. (3) needs to be replaced by [8]

$$\bar{U}_{\text{skin}} = \frac{\pi \bar{E}_{\text{skin}} \left(h_{\text{rough}} - h' \right) \left(h_{\text{rough}} - h' + 2\varepsilon_{\text{apply}} h_{\text{rough}} \right)}{16 \lambda_{\text{rough}}} L_0 \left(1 + \varepsilon_{\text{apply}} \right) \tag{7}$$

Similarly for the bending energy, L_0 in Eq. (1) needs to be replaced by $L_0 \left(1 + \varepsilon_{\text{apply}} \right)$ to account for the length change due to external loading. Minimization of the total energy gives

$$h' = \frac{h_{\text{rough}} \left(1 + \varepsilon_{\text{apply}} \right)}{\dfrac{16\pi^3 \overline{EI}_{\text{EES}}}{\lambda_{\text{rough}}^3 \bar{E}_{\text{skin}}} + 1} = h \left(1 + \varepsilon_{\text{apply}} \right) \tag{8}$$

Equation (8) indicates h' is linearly proportional to h. The analysis of partial delamination upon loading also follows that of initial contact, where h is replaced with $h \left(1 + \varepsilon_{\text{apply}} \right)$. The critical Solaris

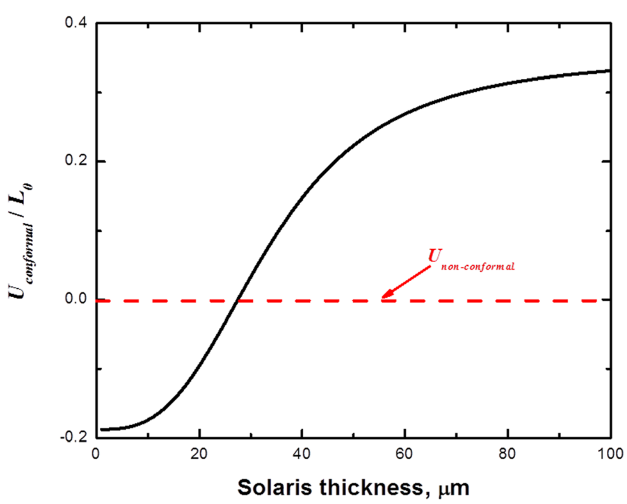

Fig. 2 Total energy (per unit length) of a typical EES/skin system $U_{\text{conformal}}/L_0$ versus Solaris thickness

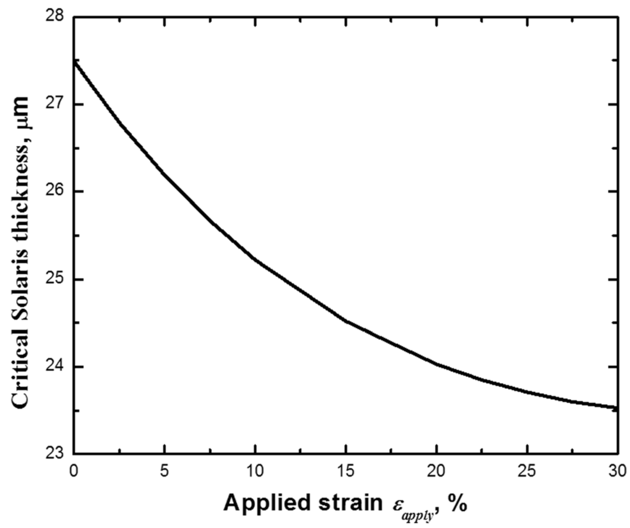

Fig. 3 Critical Solaris thickness decreases as the applied strain increases

thickness can then be determined by comparing the total energy $\bar{U}_{\text{conformal}}$ of EES/skin system to that of nonconformal contact $\bar{U}_{\text{nonconformal}} = 0$, and this critical thickness decreases as the applied strain increases (Fig. 3), indicating easier delamination upon higher applied strain.

3 Conclusion

Using the method of energy minimization, this paper developed a criterion to determine whether epidermal electronics system laminates smoothly onto the skin for both initial contact and the case upon stretching/compression of the skin. In the current study, the thickness of Solaris substrate can be designed (smaller than the critical thickness) to ensure conformal contact of EES to the skin. Upon increased deformation, the critical thickness of Solaris decreases. This provides design guidance of Solaris thickness once the maximum strain loading is given, depending on the location where EES is mounted, for different types of applications.

Acknowledgment

H.C. acknowledges the support from the NSF (DMR-1242240), Martin Outstanding Graduate Fellowship, and Engineering and Health Center Fellowship at Northwestern University.

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