Stretchable strain-tolerant soft printed circuit board: a systematic approach for the design rules of stretchable interconnects

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ABSTRACT
Reported herein is a stretchable strain-tolerant soft printed circuit board (SPCB) following optimized circuit design rules. Inkjet-printed interconnects with a wrinkled structure and rigid epoxy patterns allow the outstanding stretchability and strain distribution controllability of the SPCB, respectively. The prototype circuits show reliable operation under various mechanical deformations, even in the 180° folding state and the irregular deformed state with 25% tensile strain. This research paves a promising route for the realization of highly reliable soft printed circuits with a high degree of design freedom, which can thus be used for driver chip mounting or driver board interconnection for the stretchable display applications.

1. Introduction
The ultra-thin electronic skin (e-skin) has expanded the potential of electronics by mediating the interaction between human and autonomous artificial features. Non-invasive epidermal health-monitoring systems enabling the users to collect their body motion signals [1–3] and vital signs [4,5] with high fidelity have attracted much attention of late as representative applications of e-skin. Moreover, as the demand for customized (i.e. personalized) electronics has significantly increased, the next-generation e-skin circuits will be developed to be conformable to the arbitrary shapes of the human body or soft robots [6]. To achieve these requirements, it is necessary to introduce mechanically compliant soft platforms and associated fabrication strategies with a high-degree-of-freedom design [7–12]. In this regard, additive inkjet printing is one of the most attractive candidates due to its easy customization through its direct writing, scalability, and low-temperature processing abilities [13].

In this paper, a strain-tolerant soft printed circuit board (SPCB) realized through inkjet printing is presented, with focusing on the realization of highly reliable inkjet-printed stretchable interconnects and efficiently strain-distributed contacts based on theoretical and experimental analyses. The optimized interconnect showed great reliability and well maintained the initial conductivity during 10 k-cycling tests under 25% tensile strain, whereas unexpected rupture during the long-term operation was exhibited in the interconnect without structural engineering. In addition, by employing strain-mediated structures, the concentrated tensile strain near the interfaces between the rigid components and the soft platforms due to the large difference in Young’s modulus was successfully distributed, resulting in better device reliability under tensile stress. These experimental results are further supported by finite element method (FEM) analysis. These optimizations enable the realization of highly reliable SPCBs under various mechanical deformations, even in the completely folding condition and the irregularly deformed state with 25% tensile strain.

2. Experiment methods

Soft board: The prepared PDMS mixture (Sylgard 184, Dow Corning, and a curing agent with a 20:1 weight
ratio) was spun at 400 rpm for 60 s onto a carrier glass where a thin polyvinyl alcohol (PVA) (Sigma Aldrich, avg. Mw 31000-50000, 87–89% hydrolyzed) layer was deposited as a sacrificial layer. The prepared PDMS films were 300 μm thick. After curing the PDMS layer at 100°C on a hot plate for 2 h, it was detached from the carrier glass and pre-stretched (25%) using the researchers’ home-made machine.

**Stretchable interconnect:** Before the formation of a metal interconnect using inkjet printing, ultraviolet-ozone (UVO3) treatment was conducted on the soft board for 30 min to increase the surface energy (i.e. hydrophilic) for achieving a better ink wetting property. Silver nanoparticles ink (AgNP ink; DGP 40LT-15C, ANP Co.) was printed by an inkjet printer (DMP-2831, Dimatix Co.) on the pre-stretched PDMS substrate, and was then annealed at 125°C for 1 h. Note that the nozzle clogging issues did not occur during the whole printing process due to the optimized jetting conditions (Supplementary Figure S1). To connect integrated chips (ICs) with the printed interconnect, highly conductive Ag epoxy layers were introduced for an adhesive layer using a dispenser (SHOTmini 200Sx, Musashi Eng.).

**Strain distributor:** Using a customized biaxially controllable printing equipment, dielectric adhesive epoxy was printed near the printed contact pads on the PDMS where the ICs would be placed by a pick-and-place equipment (TM220), which is commonly used for implementing the printed circuit board (PCB) to prevent strain concentration near the contact pads, and was then annealed at 170°C for 1 h in a convection oven. As the UVO3 surface treatment had already been conducted for 30 min, the printed epoxy showed good wettability and adhesion to the PDMS surface (Supplementary Figure S2) [14]. The SPCB with stretchable wrinkled interconnects was realized after the soft board was released to the initial state. The fabrication process is shown in Supplementary Figure S3.

### 3. Results and discussion

#### 3.1. Strain-tolerant soft printed circuit board

Figure 1 shows a highly reliable strain-tolerant SPCB under mechanical deformations. By employing an ultra-thin PDMS substrate, the SPCB showed outstanding conformability to arbitrary shapes, allowing it to be utilized on the human skin (Figure 1a). The presented soft systems consisted of spatially efficient stretchable wrinkled-interconnect, strain-mediated structures, and ICs onto the stretchable substrate. To ensure the reliable ICs’ operation under various deformations, such as stretching, twisting, folding, and crumpling (Figure 1b-e, respectively), spatially efficient stretchable wrinkled-interconnect and strain-mediated structures were introduced. The optimal thickness of the inkjet-printed films enabled the realization of a highly ordered wrinkled interconnect that prevents permanent electrical/mechanical failures under tensile stress. Moreover, it is well known that the degree of strain concentration can

![Image](https://example.com/figure1.png)

**Figure 1.** (a) An optical image of the SPCB attached to the human body. (b-e) Operation of SPCBs under various mechanical deformations, stretching, twisting, folding, and crumpling, respectively.
be modulated by introducing additional structures with different Young’s moduli with the soft substrate [8,9]. In this work, a further advanced design of the strain modulator and their computational simulation results are suggested.

3.2. Inkjet-printed stretchable interconnects

The representative strategy for realizing stretchable interconnects is the introduction of wrinkled-structured thin metal films [13,15–19]. By printing metal electrodes onto the pre-stretched PDMS that has a sufficiently large elastic potential, the wrinkled structure can be introduced on the printed metal electrodes after the release. The stretchability is dominantly determined by the regularity of the wrinkles. If the printed film was too thick, it would be irregularly wrinkled while regular wrinkles were formed on the thin counterpart (Figure 2a) because a large external force is required to compress the thick film. The thickness of a printed film is primarily determined by the distance between the printed drops, called ‘drop spacing (DS)’; thus, if the printing process is performed with a smaller DS, the relatively thicker film will be printed (Supplementary Figure S4). The profiles of printed interconnects with different DSs are shown in (Figure 2b). Note that DS 35, 25, and 15 indicate 35, 25, and 15 μm distances between the drops, respectively. For the thick electrodes (DS 15; $t_{\text{avg}} = 2.97 \mu m$), the mechanical strain was more concentrated on the specific thick-edge areas produced by the coffee ring effect [20,21], showing distinct cracks only after 4 k-cycles stretching, dissimilar to the results of the thin electrodes (DS 35; $t_{\text{avg}} = 0.92 \mu m$) (Figure 2c). To investigate the reliability of the inkjet-printed wrinkled interconnects with different thicknesses, the 10 k-cycling test was also conducted under 25% tensile strain (Figure 2d). The initial sheet resistances of the electrodes (DS 35, 25, and 15) were 0.99, 0.74, and 0.52 $\Omega$/sq. Almost the same patterns of interconnects and similar results for the electrical resistance changes could be repeatedly obtained due to the fixed printing conditions, such as the printing temperature, inkjetting frequency, input pulse for inkjetting, and nozzle height.

3.3. Strain distribution analysis

To verify the optimized design of epoxy strain distributors (ESDs), an effective mechanical strain distribution was analyzed via FEM. The purpose of ESDs is to lower the concentrated strain near the contact pads compared
Figure 3. (a-b) Example of the proposed model for the analysis of the strain distribution near the ICs on the soft substrate. (c) Simulation model without and with an ESD. (d) Simulation results showing the strain distribution on the top surface of the substrate (left) and in the substrate (right), respectively. (e) Strain profiles of the substrate depending on the design of the strain distributors analyzed via FEM.

Figure 4. (a) Design of the ESDs and (b) calculated strain profiles according to the package of ICs (4-SMD, 8-UFQFN, 0603, and 0402).
to the target strain (pre-stretched strain). The simulation model was set up with four directional strain values applied to a compressed board, where the initial length of the board was \((1 + \varepsilon) L_0 (\varepsilon; \text{target strain})\) and the deformed length after the strain is applied is \(L_0\) (Figure 3a). The computational simulation was performed based on the measured dimensional and material parameters of the soft board (PDMS), an IC, contact pads with Ag epoxy, and ESDs (Figure 3b). Strain analysis was conducted for both cases, without and with ESDs (Figure 3c). The simulation results showed the strain distribution on the top surface of the substrate (Figure 3d, left) and in the substrate (Figure 3d, right), respectively. Although the top surface could be fixed by the rigid components, the 300-μm-thick PDMS substrate could be shrunk, especially at the bottom side (Figure 3d, right). The simulation results clearly showed that the strain was effectively distributed along the ESDs, resulting in a less concentrated strain near the contact pads (Figure 3e). As the length of the ESD \((L_E)\) increased, the maximum concentrated strain near the contact pads decreased. Thus, \(L_E\) should be as short as possible to enhance the conformability of the SPCB onto arbitrary-shaped surfaces.

The strain-concentrated area (SCA) where other printed interconnects should not pass near the ESDs was defined. The utilization of printing to integrate the ESDs allows a design with a high degree of freedom depending on the ICs, corresponding to the facile customization. Furthermore, the design of the ESDs was optimized to introduce a maximum strain lower than the target strain (Figure 4a). If the width of the contact pad was larger than 200 μm, the ESD would be designed to surround the contact pad to effectively dissipate the strain. The maximum strain concentration was also modulated to provide an attractive pathway for determining the effectively applied strain between the soft board and the rigid components (Figure 4b).

Based on the aforementioned results, a prototype of the SPCB was successfully implemented using printing techniques. The layout of the circuit consisting of an oscillator, frequency dividers, shift resistors, and LEDs is shown in Figure 5a and Supplementary Figure S5. Pulse wave signals with a 32 Hz frequency were changed to those with a 2 Hz frequency by the frequency dividers connected in series, and then the signal was inserted to the series of shift resistors. After the 3 k-cycling test at a...
25% biaxial strain, even when stretched (target $\varepsilon = 25\%$, after 1 s), the SPCB showed reliable operation; when the clocks were accurately divided by the frequency dividers, the regularly shifted operation was synchronized to 2 Hz clock, and turned on the LEDs (Figure 5b-e). These behaviors can be shown only when all the components, including the interconnect, ICs, and epoxy layers, are strain-tolerant, without disconnection, fatigue, or delamination issues, under 25% tensile strain.

4. Conclusion

Proposed herein are two key strategies for realizing a strain-tolerant soft printed circuit board (SPCB) using printing technologies: the introduction of wrinkled metal interconnects and strain distributors near the junction between a soft board and rigid integrated chips (ICs). This allows the reliable operation of the prototype SPCB under various deformations. In addition, the strain distribution analyzed via the finite element method (FEM) supported the effects of epoxy strain distributors (ESDs). The results of this study can open a promising route for the realization of highly reliable customized circuits under mechanical deformation, even stretching conditions.

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