

Shrinkage-transfer-assisted printing of microcircuits on fibers

Corresponding Author: Professor Yingying Zhang

This file contains all reviewer reports in order by version, followed by all author rebuttals in order by version.

Version 0:

Reviewer comments:

Reviewer #1

(Remarks to the Author)

This is a highly innovative manuscript, with advances in both the printing of microcircuits and the fabrication of fiber devices. The authors utilize a two-dimensional stretchable silicone platform as the substrate for screen printing, thereby overcoming the resolution limit of conventional screen printing techniques and achieving flexible EGaln microcircuits. The proposed method also provides valuable guidance for other planar circuit fabrication techniques beyond screen printing. As an application demonstration, the authors transfer the miniaturized circuits onto fiber surfaces. This surface-based circuit construction approach makes the fabrication of fiber devices versatile, and the transfer strategy appears to be extendable to other small and complex curved surfaces. In addition, the manuscript is logically organized and clearly written. I would recommend acceptance after minor revision, provided that the authors address the following points:

- 1) In page 3, the authors chose silk sericin as the stabilizer. It is suggested that the authors include comparative SEM images to show the influence of adding silk sericin on the morphology of EGaln microparticles, in order to further demonstrate the necessity of using the stabilizer.
- 2) The authors are encouraged to include a discussion on the choice of fiber substrate material. Specifically, why was aramid fiber selected as the transfer base for EGaln microcircuits?
- 3) According to Fig. 3b and Supplementary Video 2, patterned plasma treatment on the silicone substrate enhances the wettability and adhesion of the water-based EGaln/sericin ink, ensuring accurate pattern deposition. Why is patterned plasma treatment necessary instead of treating the entire surface uniformly? The authors should elaborate on the processing steps and rationale for using patterned plasma treatment.
- 4) Page 6, line 174: "This transfer-induced sintering arises from competitive interfacial adhesion...". While this mechanism is clearly illustrated in Supplementary Fig. 9, the authors are advised to provide supporting data to further substantiate this claim of competitive interfacial adhesion.
- 5) Page 2, line 62: The authors employ a polyvinyl alcohol (PVA) film as the transfer medium for EGaln microcircuits, primarily due to its water solubility and affinity toward EGaln microparticles. It is suggested that the authors further justify the advantages of choosing PVA, for instance by explaining its chemical structure or interfacial interactions in more detail.
- 6) Page 7: It is suggested that the authors add a brief discussion on the potential applications of the fiber device described in Fig. 4. For example, what practical scenarios this fiber device could be applied to.

Reviewer #2

(Remarks to the Author)

This manuscript presents a highly original approach to addressing the persistent challenge of integrating microscale circuits onto curved fiber surfaces. The proposed shrinkage-transfer-assisted printing (STAP) method elegantly bridges the gap between 2D circuit fabrication and 1D fiber device realization, achieving impressive miniaturization (up to 80% shrinkage) and 360° conformal coverage. The concept is novel, technically sound, and well supported by systematic experiments. The

combination of stress-engineered silicone substrates, EGaIn/sericin ink chemistry, and capillary-driven transfer represents a meaningful advance in fiber-based electronics.

The manuscript is generally well written, visually clear, and methodologically detailed. It convincingly demonstrates functionality through the electroluminescent fiber device. The work is clearly distinct from previously published studies—including our earlier Nature Communications paper on integrated microfibre electronics—by offering a different dimensional transformation and processing strategy.

That said, a few aspects need clarification and strengthening before acceptance. These concern (1) the universality and scalability of the claimed “universal fabrication strategy,” (2) quantitative treatment of the scaling-down limit for metallic patterns, and (3) mechanical durability and interfacial reliability under extended cyclic deformation.

Overall, this is an excellent and innovative contribution that will attract broad attention in the field of fiber electronics and soft-matter circuit integration. The concept of geometric transformation from 2D to 1D is elegant, and the results are compelling. Addressing the issues above, particularly regarding the scaling limit and mechanical reliability, will further strengthen the manuscript’s impact and technical completeness.

Major Comments

- The Introduction concludes that STAP is a “universal fabrication strategy,” yet experimental demonstrations are limited to EGaIn and PVA-based transfer. To substantiate this claim, the authors should briefly discuss whether the STAP process is compatible with other inks (e.g., silver nanoparticle, conductive polymer) or elastomeric substrates.
- A comparative comment on scalability with respect to textile-level or roll-to-roll fabrication methods would provide valuable context for its practical universality.
- What is possible resolution and Scaling-Down Limitations?
- While the manuscript demonstrates a 60 μm feature size and 35 μm electrode gaps, it remains unclear what factors fundamentally limit further miniaturization, whether by the screen mesh resolution, ink rheology, or mechanical shrinkage threshold of the substrate. Please provide in detail.
- Providing a scaling analysis or discussing the potential challenges in pushing resolution below 50 μm would be insightful. For instance, could oxide shell rupture or uneven compressive stress during shrinkage impose a lower limit?
- The manuscript claims retention of 98.6 % conductivity after 16,000 bending cycles, which is impressive. However, the detailed stress conditions (bending radius, strain amplitude, test frequency) should be more explicitly stated in Methods or figure captions to allow fair comparison with prior works.
- Since the circuit–fiber interface is critical, it would be helpful to discuss or test failure modes such as delamination or crack initiation, particularly under humidity or temperature variation. Supplementary Fig. 14 shows morphological stability but does not provide long-term cycling data.
- If available, resistance evolution over more extreme bending radii (≤ 4 mm) or torsional deformation would enhance confidence in durability claims.
- The Methods should specify environmental parameters (temperature, humidity) during shrinkage and transfer, as these can influence EGaIn’s viscosity, oxidation, and adhesion.
- Clarify how uniform stretching was maintained—manual stretching may lead to edge effects. Was a biaxial stretcher or measured tension used? Including a schematic or photo of the setup (possibly in Supplementary Fig. 1) would improve reproducibility.

Minor Comments and Editorial Suggestions

1. Figure 1c: Add explicit “before” and “after shrinkage” labels and indicate quantitative shrinkage ratios on the figure or in the caption.

Supplementary Figures:

1. Fig. 1: Add direct annotations (e.g., “Ecoflex cast film,” “peeled film,” “stretched film on frame”) instead of relying solely on the caption.
2. Fig. 2–3: Clarify whether EGaIn–PVA interfaces exhibit cracking or delamination during shrinkage.
3. Fig. 3c: Mark the region of the high-magnification image within the main panel.
4. Terminology: Replace “universal fabrication strategy” with “versatile fabrication strategy” unless broader material compatibility can be experimentally verified.
5. Supplementary Video 3: A brief quantitative comparison of luminance stability under bending would add scientific value beyond qualitative demonstration.

Reviewer #3

(Remarks to the Author)

The manuscript is generally well written and clearly presented. However, there are several issues that limit the overall scope and relevance of the work.

Material specificity:

The materials used in the study are very specialized and are not easily replaced or adapted to other functional materials (substrate, ink, GaIn)

Scalability and reproducibility:

Key steps in the process—such as pre-stretching, tension release, transferring onto a PVA sheet, water-assisted transfer, and the shrinkage of the printed circuits—introduce a lot of variability and are not easily scalable. As a result, achieving consistent reproducibility is challenging. In addition, the conductivity variations that come from shrinkage sintering and transfer sintering need to be supported with more detailed statistical data.

Multilayer printing limitations:

The approach does not seem capable of true multilayer printing. In the demonstrated device, the conductive layer is printed and transferred onto the thread, while the luminescent layer is applied by coating rather than printing. This highlights an inherent limitation of the technique.

Limited use on small-diameter substrates:

The method is demonstrated only on threads a few millimeters in diameter. Its potential for use on finer fibers or true one-dimensional substrates is not addressed, which restricts the broader relevance of the work.

Version 1:

Reviewer comments:

Reviewer #1

(Remarks to the Author)

The authors have addressed all of the issues with this manuscript, which is suitable for publication in Nature Communications. I believe this work will have a significant impact on the future preparation of functional fibers/fabrics.

Reviewer #2

(Remarks to the Author)

The authors have addressed all of my questions carefully. The revised manuscript is now acceptable without further revision.

Reviewer #3

(Remarks to the Author)

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Response to Reviewers' comments

We thank the reviewers for the constructive comments and suggestions on our manuscript. Accordingly, we have carried out additional experiments and revised the manuscript carefully. The changes are marked in **BLUE** in the revised manuscript and are marked in **RED** here. The following is a point-to-point response to each of the comments.

Reviewer #1:

Summary Comment:

This is a highly innovative manuscript, with advances in both the printing of microcircuits and the fabrication of fiber devices. The authors utilize a two-dimensional stretchable silicone platform as the substrate for screen printing, thereby overcoming the resolution limit of conventional screen printing techniques and achieving flexible EGaIn microcircuits. The proposed method also provides valuable guidance for other planar circuit fabrication techniques beyond screen printing. As an application demonstration, the authors transfer the miniaturized circuits onto fiber surfaces. This surface-based circuit construction approach makes the fabrication of fiber devices versatile, and the transfer strategy appears to be extendable to other small and complex curved surfaces. In addition, the manuscript is logically organized and clearly written.

Reply:

Thank you very much for your careful review and high evaluation of this work. Your constructive comments and suggestions have helped us to further improve our manuscript. Our point-by-point responses to your comments are listed below.

Comment #1:

In page 3, the authors chose silk sericin as the stabilizer. It is suggested that the authors include comparative SEM images to show the influence of adding silk sericin on the morphology of EGaIn microparticles, in order to further demonstrate the necessity of using the stabilizer.

Reply:

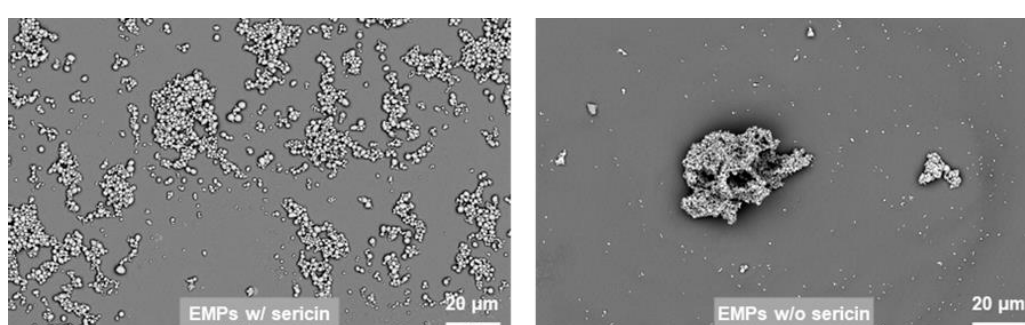
Thank you for your constructive suggestion. Sericin in the ink serves to isolate the EGaIn microparticles (EMPs), preventing their aggregation through physical separation and Coulombic repulsion. In addition, the attachment of sericin onto the EMP surface helps slow down overall oxidation. In order to provide experimental evidence, we carried out further experiments. Inks with and without sericin were exposed to a harsh atmospheric environment at 60 °C for 30 min, followed by SEM characterization of the resulting EMP morphologies. The results showed that the sericin-free inks exhibited agglomeration, whereas the sericin-containing inks did not.

Accordingly, we added discussion in the main text and Supplementary Fig. 6 in the supplementary information. The related contents are copied in the following for your convenience:

In the main text:

(Page 3, Line 99) Furthermore, sericin is negative charged in neutral aqueous solution (isoelectric point = 4)²⁸, inducing electrostatic repulsion among sericin-coated EMPs due to Coulombic forces (Fig. 2b). The combined steric and electrostatic stabilization effects allow the EMPs to remain well-dispersed in water for more than one week without agglomeration (Fig. 2c, Supplementary Fig. 5).

In the supplementary information:



Supplementary Fig. 5. SEM images comparing morphologies of EMPs in inks with and without sericin, after being placed in an atmospheric environment at 60 °C for 30 min.

Comment #2:

The authors are encouraged to include a discussion on the choice of fiber substrate material. Specifically, why was aramid fiber selected as the transfer base for EGaIn microcircuits?

Reply:

Thank you for raising this point. We selected aramid fiber as the circuit substrate due to its hydrophilic nature and relatively high dielectric constant, which facilitate water-assisted transfer and support the high electric field required for electroluminescence.

Accordingly, we added related information in the main text. The related contents are copied in the following for your convenience:

In the main text:

(Page 7, Line 221) The capillary-driven transfer process enables precise conformal wrapping of EGaIn microcircuit onto fiber substrates. Aramid fiber is chosen as the substrate due to its intrinsic hydrophilicity and relatively high dielectric constant.

(Page 8, Line 265) Although the aramid fiber substrate has high tolerance to strong electric fields ³⁶, the breakdown of emissive functional layer remains affecting luminescence efficiency. Thus, an intermediate gap width is required to achieve optimal luminescence...

Comment #3:

According to Fig. 3b and Supplementary Video 2, patterned plasma treatment on the silicone substrate enhances the wettability and adhesion of the water-based EGaIn/sericin ink, ensuring accurate pattern deposition. Why is patterned plasma treatment necessary instead of treating the entire surface uniformly? The authors should elaborate on the processing steps and rationale for using patterned plasma treatment.

Reply:

Thank you for raising this insightful point. Yes, plasma treatment of the silicone substrate (Ecoflex film) is crucial, because silicone is inherently hydrophobic, exhibiting a water contact angle as high as 104.5° (Fig. 3a). As a result, the water-based EGaIn/sericin ink cannot properly wet or adhere to its surface. The use of patterned plasma treatment serves two purposes. First, it enables the ink to remain confined within the patterned regions without spreading. Second, it facilitates the subsequent peeling of the PVA layer. If the entire silicone surface were plasma-treated uniformly, the wet PVA would also contact the activated silicone, and after drying, strong hydrogen-bond interactions would form, making the PVA layer impossible to peel off.

Accordingly, we added related discussion in the main text and Supplementary Fig. 8 in the supplementary information. The related contents are copied in the following for your convenience:

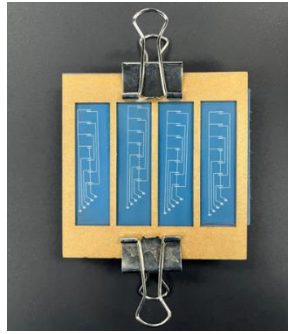
In the main text:

(Page 6, Line 157) Prior to screen printing, pre-stretched silicone substrate is partially treated with air plasma (Fig. 3a, Supplementary Fig. 7-8) to enhance ink adhesion.

(Page 10, Line 334) Fabrication of Shrunk microcircuits

First, a 200 µm-thick Ecoflex film was omnidirectionally stretched and mounted onto a clean acrylic frame under tension. Next, a patterned screen was placed on the surface of the Ecoflex film as a mask and the sample was exposed to air plasma for 3 minutes. Then, EGaIn/sericin ink was screen-printed onto the film.

In the supplementary information:



Supplementary Fig. 8. Photograph showing the mask placed on the pre-stretched Ecoflex substrate for plasma treatment and the screen printing.

Comment #4:

Page 6, line 174: “This transfer-induced sintering arises from competitive interfacial adhesion...”. While this mechanism is clearly illustrated in Supplementary Fig. 9, the authors are advised to provide supporting data to further substantiate this claim of competitive interfacial adhesion.

Reply:

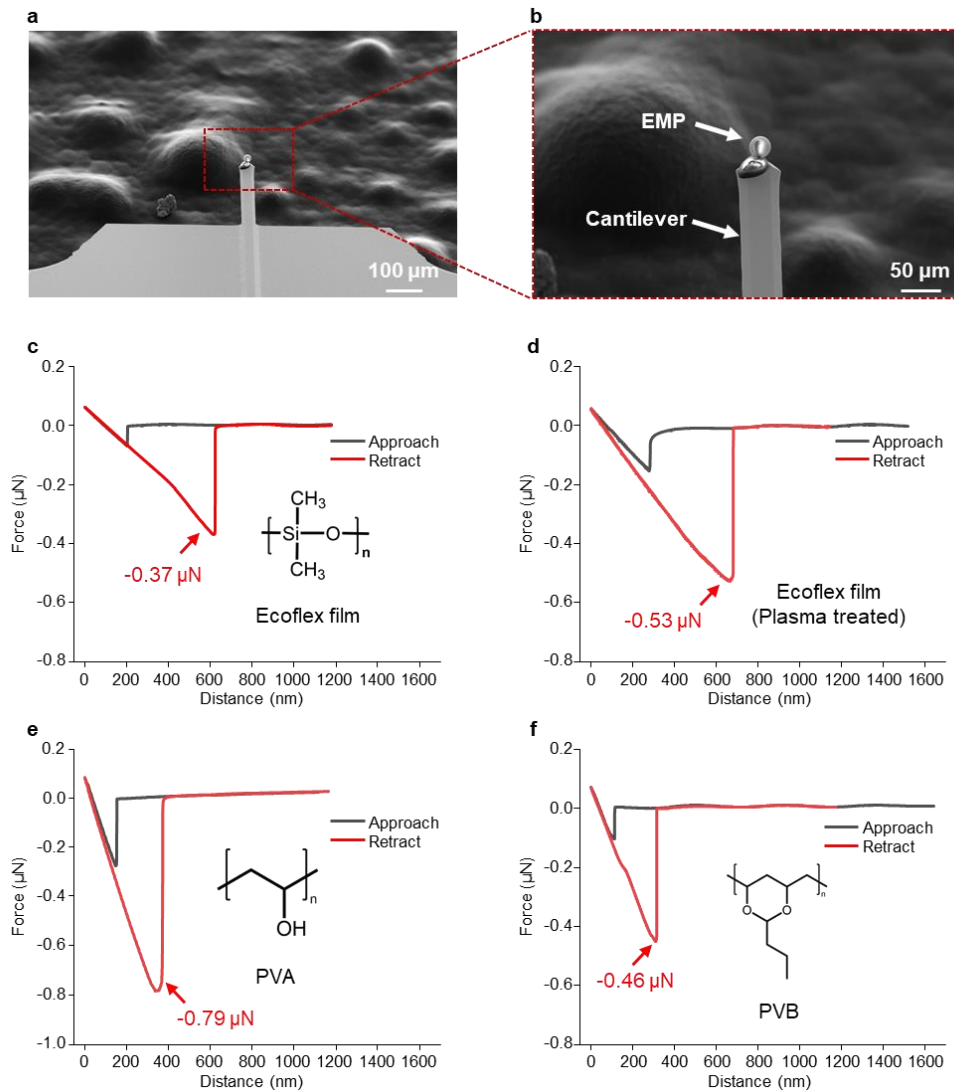
Thank you for your constructive suggestion. To address this point, we carried out further experiments to provide more evidence for the mechanism. We investigated the interactions between EMP and different substrates using atomic force microscopy (AFM). The results indicate the EMP exhibit strong affinity toward the substrates, which facilitates the rupture of their oxide shells during separation and thereby enables sintering. PVA with stronger adhesion to the EMPs tend to retain more EGaIn on its surfaces, which explains the observed transfer behavior.

Accordingly, we added related discussion in the main text, and Supplementary Fig. 12 in the supplementary information. The related contents are copied in the following for your convenience:

In the main text:

(Page 6, Line 174) This transfer-induced sintering arises from competitive interfacial adhesion: the plasma-activated silicone and the PVA film both exhibit strong affinity to the EMPs, showing adhesion forces of 0.53 μN and 0.79 μN , respectively (Supplementary Fig. 11-12). Consequently, the separation process ruptures the oxide shells, triggering instantaneous liquid metal coalescence.

In the supplementary information:



Supplementary Fig. 12. Force measurements between the EMP and different substrates. (a) SEM image of an EMP attached to an AFM probe. (b) Magnified view of the probe shown in (a). (c-f) Approach-retract force curves acquired between the EMP and a pristine Ecoflex film (c), an Ecoflex film treatment with 3 min plasma (d), a PVA film (e), and a polyvinyl butyral (PVB) film (f).

Comment #5:

Page 2, line 62: The authors employ a polyvinyl alcohol (PVA) film as the transfer medium for EGaln microcircuits, primarily due to its water solubility and affinity toward EGaln microparticles. It is suggested that the authors further justify the advantages of choosing PVA, for instance by explaining its chemical structure or interfacial interactions in more detail.

Reply:

Thank you for the insightful suggestion. In this work, the hydroxyl groups on the PVA chains form hydrogen bonds with the oxide shell of the EMPs, contributing to the strong

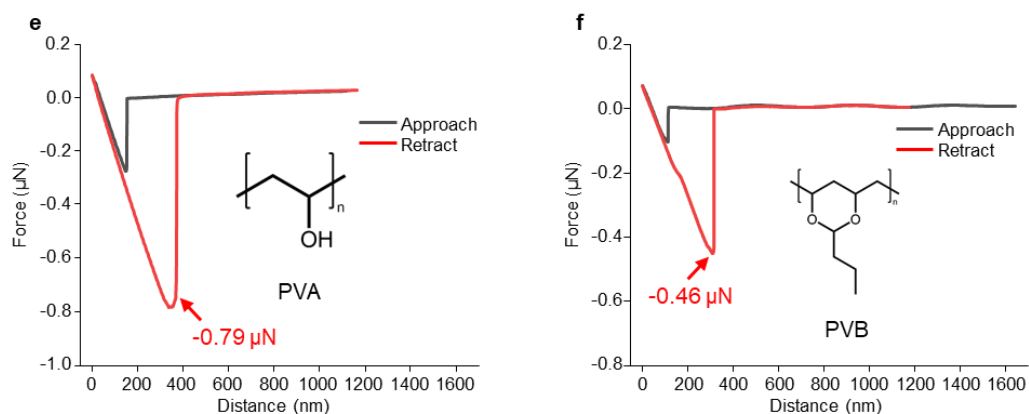
interfacial affinity. To validate the role of hydroxyl groups, we carried out further experiments to compare PVA with polyvinyl butyral (PVB), a structurally similar polymer in which a portion of the hydroxyl groups is blocked through acetal formation. Mechanical measurements on PVB films show an adhesion force of $0.46\ \mu\text{N}$ toward the EMPs, substantially lower than that of PVA ($0.79\ \mu\text{N}$), confirming the critical contribution of hydroxyl groups to the affinity.

Accordingly, we added related discussion in the main text and Supplementary Fig. 12e-f in the supplementary information. The related contents are copied in the following for your convenience:

In the main text:

(Page 6, Line 177) The stronger affinity between PVA and EMPs results in preferential transfer of the EGaIn circuits to the PVA surface. The affinity of PVA is primarily attributed to hydrogen bonds between the hydroxyl groups of PVA and the EMPs. To verify the role of hydroxyl groups, comparative adhesion tests were conducted using polyvinyl butyral (PVB), a polymer structurally analogous to PVA but with a portion of its hydroxyl groups blocked by acetal formation. Mechanical measurements reveal that the adhesion force of PVB films toward EMPs is $0.46\ \mu\text{N}$, significantly lower than that of PVA ($0.79\ \mu\text{N}$) (Supplementary Fig. 12e-f).

In the supplementary information:



Supplementary Fig. 12 Approach-retract force curves acquired between the EMP and a PVA film (e), and a polyvinyl butyral (PVB) film (f).

Comment #6:

Page 7: It is suggested that the authors add a brief discussion on the potential applications of the fiber device described in Fig. 4. For example, what practical scenarios this fiber device could be applied to.

Reply:

Thank you for the valuable suggestion. Accordingly, we have added a brief discussion on the potential applications of the single-fiber displays in the main text. The related contents are copied in the following for your convenience:

In the main text:

(Page 9, Line 280) Single-fiber displays, featuring pixel-level addressability, can be seamlessly woven into protective garments for dynamic visual communication. In critical scenarios such as firefighting, rescue operations, and outdoor exploration, they can provide real-time navigation, hazard alerts, or team status. They also enable monitoring of vital signs for medical assistance and facilitate communication by displaying information for individuals with speech or language barriers.

Reviewer #2:**Summary Comment:**

This manuscript presents a highly original approach to addressing the persistent challenge of integrating microscale circuits onto curved fiber surfaces. The proposed shrinkage-transfer-assisted printing (STAP) method elegantly bridges the gap between 2D circuit fabrication and 1D fiber device realization, achieving impressive miniaturization (up to 80% shrinkage) and 360° conformal coverage. The concept is novel, technically sound, and well supported by systematic experiments. The combination of stress-engineered silicone substrates, EGaIn/sericin ink chemistry, and capillary-driven transfer represents a meaningful advance in fiber-based electronics.

The manuscript is generally well written, visually clear, and methodologically detailed. It convincingly demonstrates functionality through the electroluminescent fiber device. The work is clearly distinct from previously published studies—including our earlier Nature Communications paper on integrated microfibre electronics—by offering a different dimensional transformation and processing strategy.

That said, a few aspects need clarification and strengthening before acceptance. These concern (1) the universality and scalability of the claimed “universal fabrication strategy,” (2) quantitative treatment of the scaling-down limit for metallic patterns, and (3) mechanical durability and interfacial reliability under extended cyclic deformation.

Overall, this is an excellent and innovative contribution that will attract broad attention in the field of fiber electronics and soft-matter circuit integration. The concept of geometric transformation from 2D to 1D is elegant, and the results are compelling. Addressing the issues above, particularly regarding the scaling limit and mechanical reliability, will further strengthen the manuscript’s impact and technical completeness.

Reply:

We sincerely thank you for your careful review of our manuscript and greatly appreciate your constructive suggestions. Accordingly, we have carried out further experiment and carefully revised the manuscript. Below are point-by-point responses to each of your comments.

Comment #1:

The Introduction concludes that STAP is a “universal fabrication strategy,” yet experimental demonstrations are limited to EGaIn and PVA-based transfer. To substantiate this claim, the authors should briefly discuss whether the STAP process is compatible with other inks (e.g., silver nanoparticle, conductive polymer) or elastomeric substrates.

Reply:

Thank you very much for raising this point. In order to address this point, we carried out further experiments. Beside the EGaIn/sericin ink, three commercially available and

widely used inks, including Ag/AgCl ink and carbon ink, which are commonly employed in printed electrochemical sensors, and PEDOT:PSS ink, which is one of the most broadly used conductive polymers, were studied. We found that all the three inks can be successfully applied in our process, demonstrating the versatility of the STAP process. We propose the following are the requirements for the inks used in this process: (i) The ink should remain flowable during the interval between printing and substrate shrinkage, which allows the shrinkage-induced stress to propagate upward from the bottom of the pattern and to drive spatial reorganization of the ink material. (ii) The ink should possess adequate viscosity, since low-viscosity inks would easily overflow the intended pattern boundaries during substrate motion and cause feature distortion. (iii) The ink should have affinity toward the targeted film, which in this work is PVA. For example, EMPs with hydrophilic surfaces exhibit strong affinity to PVA, which is essential for successful transfer.

As for the selection of elastomeric substrates, the STAP process requires substrates with high stretchability, recoverability and hydrophobicity. The silicone elastomer we used fits these requirements perfectly. Other common elastomers such as styrene-ethylene-butylene-styrene copolymer (SEBS) and thermoplastic polyurethane (TPU) could in principle work with STAP, but their stretchability is usually lower than that of silicone unless molecular modification is applied. Therefore, in this work, we selected commercial Ecoflex and did not study other elastomeric substrates.

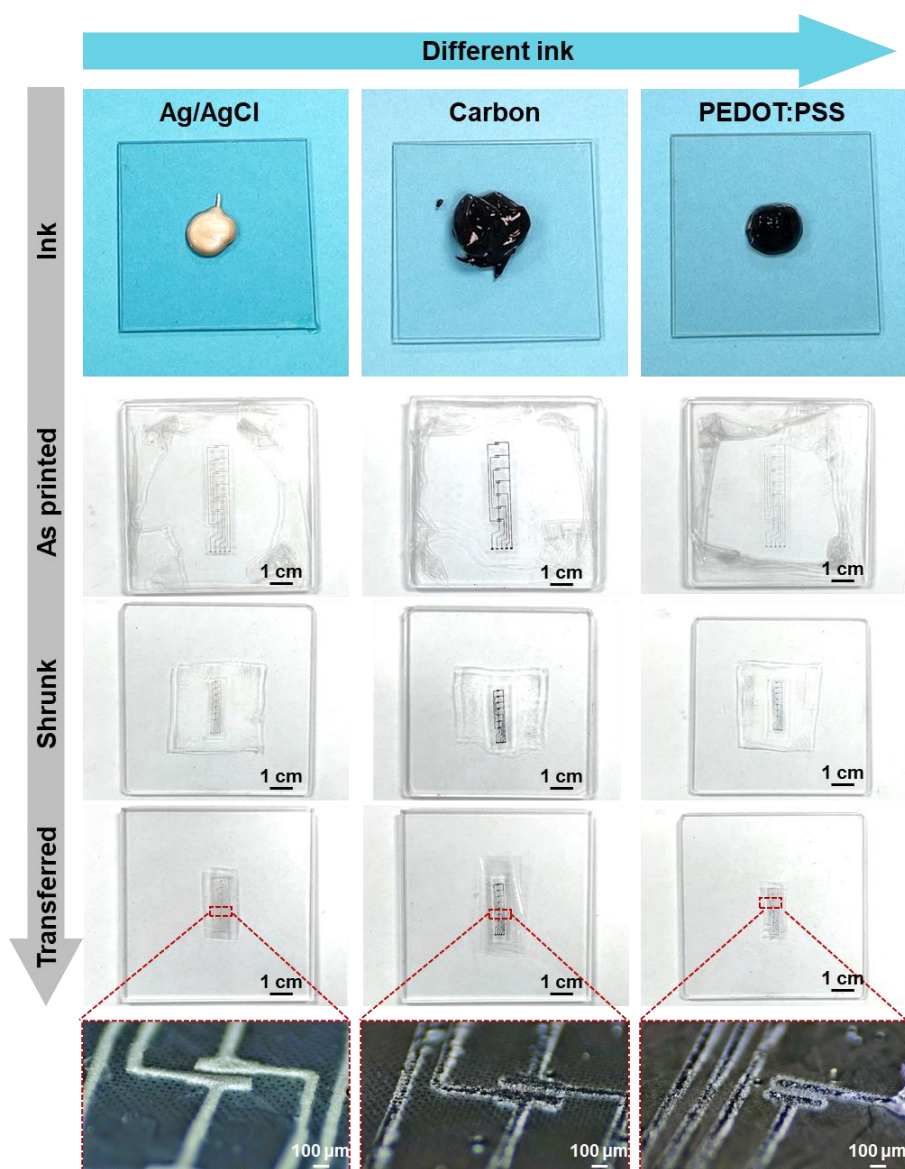
Accordingly, we have added related discussion in the main text, and Supplementary Fig. 24 in the supplementary information. Besides, we have replaced the term “universality” with “versatility” in the main text to be more rigor. The related contents are copied in the following for your convenience:

In the main text:

(Page 9, Line 285) It is noted that the STAP process is also compatible with other typical commercially available inks besides the EGaIn/sericin ink (Supplementary Fig. 24).

(Page 9, Line 310) Looking forward, several key challenges must be addressed to advance the practical deployment of STAP... Finally, standardizing process parameters and characterization protocols across different material systems will be essential for ensuring reproducibility and facilitating broader adoption in flexible and textile electronics. By addressing these challenges, STAP can evolve from a laboratory-scale technique into a practical manufacturing process for producing high-performance, seamlessly integrated fiber-based devices.

In the supplementary information:



Supplementary Fig. 24. Applying STAP process using three typical commercial electronic inks. The inks include Ag/AgCl ink (purchased from Prtronic), carbon ink (purchased from Loctite), and PEDOT:PSS ink (purchased from Prtronic), showing consistent printing, ~80% shrinkage, and successful transfer, confirming the compatibility of the STAP process with other inks.

Comment #2:

A comparative comment on scalability with respect to textile-level or roll-to-roll fabrication methods would provide valuable context for its practical universality.

Reply:

Thank you for this valuable suggestion. Frankly, we think that the textile-level and roll-to-roll fabrication methods currently offer advantages in scalability over our present laboratory-scale preparation. Nonetheless, we believe STAP possesses potential for

large-scale implementation, though several challenges remain at this stage. The stress-engineered 2D silicone platform could be scaled up by using larger substrates. However, continuous large-scale manufacturing would require an automated stretching system capable of applying uniform tension along the entire film. On the other hand, the transfer step is in principle compatible with roll-to-roll processing. After shrinkage, the silicone film carrying the microcircuits could be brought into contact with a continuous PVA roll, following by wetting, drying, transfer and collection along a production line. This approach appears feasible and would mainly require engineering design to automate wetting and rapid drying.

Overall, your comment provides a forward-looking perspective on the practical deployment of STAP. Accordingly, we have added related discussion in the main text. The related contents are copied in the following for your convenience:

In the main text:

(Page 9, Line 288) Further efforts on developing automated stretching and continuous transfer systems could improve the scalability of STAP and facilitate its adoption in practical manufacturing settings.

(Page 9, Line 310) Looking forward, several key challenges must be addressed to advance the practical deployment of STAP ...Second, scaling the technology for industrial production will require the development of automated stretching systems capable of applying uniform omnidirectional strain to large-area elastic substrates, thereby improving reproducibility.

Comment #3-5:

(Comment 3) What is possible resolution and Scaling-Down Limitations?

(Comment 4) While the manuscript demonstrates a 60 μm feature size and 35 μm electrode gaps, it remains unclear what factors fundamentally limit further miniaturization, whether by the screen mesh resolution, ink rheology, or mechanical shrinkage threshold of the substrate. Please provide in detail.

(Comment 5) Providing a scaling analysis or discussing the potential challenges in pushing resolution below 50 μm would be insightful. For instance, could oxide shell rupture or uneven compressive stress during shrinkage impose a lower limit?

Reply:

We appreciate the insightful questions regarding resolution and scaling-down limitations. Since Comments #3-5 are closely related, we address them collectively below. We have supplemented the discussion with schematic illustrations, SEM characterizations and additional data. The fundamental limits on resolution and miniaturization arise from two main aspects:

(i) Printing resolution on the pre-stretched silicone substrate. The initial patterning fidelity is governed by the screen-printing process. The resolution here refers to the clarity and continuity of the printed EGaIn/sericin pattern after the ink passes through the screen mesh. This printed pattern must be optically distinguishable and electrically continuous after shrinkage. Screen mesh resolution and ink rheology are key factors. Screens with larger mesh openings reduce pattern resolution but allow more ink to pass through, which benefits conductivity, but at the cost of feature definition. Conversely, finer meshes improve printed resolution but reduce ink deposition, lowering conductivity, a trade-off illustrated in Fig. 3j. Ink viscosity also plays a critical role. higher viscosity helps suppress post-printing spreading and improves pattern fidelity (Hong et al., *J. Mater. Sci. Technol.*, 67, 145-155 (2021)), yet it also limits ink passage and conductivity. Optimizing print resolution thus requires balancing these competing parameters.

(ii) Ink overflow under extreme shrinkage. When the silicone substrate is shrunk severely, the resulting compressive stress can cause EMP ink to overflow beyond the intended pattern boundaries, distorting the printed features. In this study, the Ecoflex film can sustain large uniaxial strains up to 700%, as shown in Supplementary Fig. 10. Under omnidirectional stretching, a 200- μm -thick film can reach approximately 300% strain, corresponding to an area expansion of $\sim 16\times$, as demonstrated in the newly added Supplementary Video 1. Theoretically, this allows up to $\sim 94\%$ areal shrinkage, but in practice we observe reliable shrinking only up to $\sim 80\%$. Beyond this point, EMPs overflow becomes pronounced, leading to line broadening, loss of resolution, and in capacitor structures (e.g., interdigitated electrodes), catastrophic short-circuiting. This overflow persists even with a finer 300-mesh screen. However, when using a finer 420-mesh screen, the ink can no longer pass through to form continuous conductive pathways, presenting a key barrier to achieving features below 50 μm .

Accordingly, we have included the data from our initial orthogonal experiments in Table S1 to show how different screen parameters affect the printing resolution before and after shrinkage. A schematic illustration is provided in Supplementary Fig. 14, and SEM images of EMP overflow under shrinkage are presented in Supplementary Fig. 15, in the supplementary information. The related contents are copied in the following for your convenience:

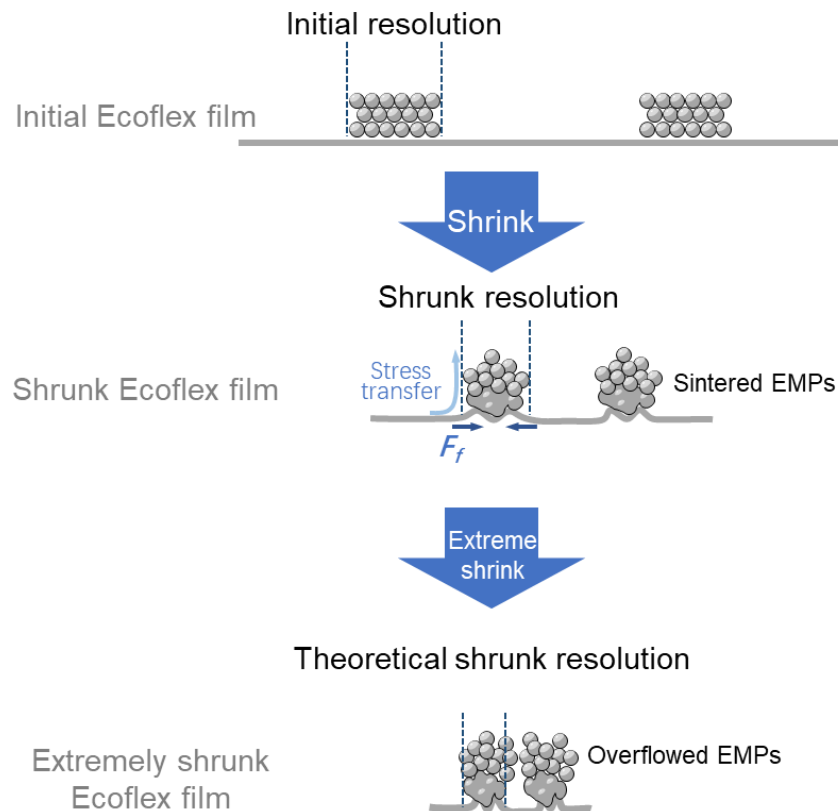
In the main text:

(Page 6, Line 190) The ultimate resolution achievable by STAP is governed by the initial screen-printing precision and the shrinkage behavior of the EMPs on the silicone platform. The intrinsic resolution defined by the screen-printing process determines the fineness of the microcircuit patterns. Screens with higher mesh counts provide finer patterning but reduce ink passage, lowering the amount of deposited EGaIn and creating a fundamental compromise between resolution and conductivity. In this work, 300-mesh represents a practical upper limit. Finer meshes fail to transfer sufficient ink to form continuous pathways even after shrinkage...

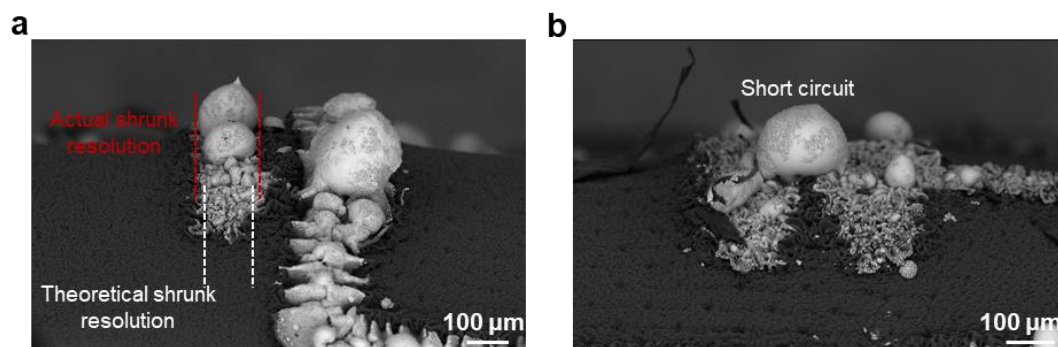
(Page 6, Line 201) ...The resolution and lateral deviation of microcircuits fabricated with different screen meshes were systematically examined under an extreme area shrinkage of 80% (Table S1).

(Page 6, Line 204) ...During shrinking, the compressive stress originating from the recovery of the silicone (F_f) is transmitted upward through the microcircuit (Supplementary Fig. 14). Under extreme shrinkage, this stress can induce overflow of EMPs beyond the designed pattern boundaries. Since further improvement in the as-printed resolution is hindered by insufficient ink transfer through higher-mesh screens, these two factors together limit the final attainable result resolution (Supplementary Fig. 15).

In the supplementary information:



Supplementary Fig. 14. Schematic illustration showing the shrinkage-induced resolution limit in the shrinkage process. Excessive shrinkage causes overflow of EMP ink beyond the pattern boundaries, thereby limiting the minimum achievable resolution.



Supplementary Fig. 15. Side-view SEM images of microcircuits shrunk by 94% in area. (a) The actual line width becomes larger than the designed width due to EMP overflow. (b) Short-circuit behavior observed in the capacitor.

(Page S19) **Table S1.** Parameters of screens with different mesh counts, the resolution of as-printed EGaIn/sericin ink, and the resolution after shrinkage (shrunk by 80% in area).

Mesh count (/inch)	EMPs coverage ratio (%)	Resolution (μm)	Resolution-after-extreme shrink (μm)
420	12	Discontinuous	Discontinuous
300	16	136	63
250	21	160	74
200	26	202	95
180	29	245	122
150	34	272	128
120	41	285	138
100	47	300	148
80	54	325	180
60	63	420	221

Comment #6:

The manuscript claims retention of 98.6 % conductivity after 16,000 bending cycles, which is impressive. However, the detailed stress conditions (bending radius, strain amplitude, test frequency) should be more explicitly stated in Methods or figure captions to allow fair comparison with prior works.

Reply:

According, we have added the related information into Figure caption. Besides, the key information is also presented in the main text. The related contents are copied in the following for your convenience:

In the main text:

(Page 7, Line 210) **Fig. 4. Construction and performance of electroluminescent fiber devices. ...f, Relative change in resistance of the fiber under cyclic bending deformation with bending radius of 16 mm at 1 Hz (upper) and different bending radii (lower). Temperature, 20 °C; Relative humidity, 50%.**

(Page 8, Line 249) The resulting fiber devices exhibit exceptional mechanical compliance, enduring 16,000 bending cycles at a curvature radius of 1.6 cm with only a 1.4% increase in resistance... (Fig. 4f)

Comment #7:

Since the circuit–fiber interface is critical, it would be helpful to discuss or test failure modes such as delamination or crack initiation, particularly under humidity or temperature variation. Supplementary Fig. 14 shows morphological stability but does not provide long-term cycling data.

Reply:

Thank you for your constructive suggestion. According, we carried out further experiments to investigate the failure modes and the performance of the fiber circuits under different temperature and humidity.

We found that the failure modes at the circuit-fiber interface are primarily governed by the fracture of the PVA adhesive layer. When examining the SEM image of the fiber-circuit tip bent at a curvature radius of 1.8 mm under 20 °C and 50% relative humidity (RH), we observed speckled EGaIn residues on the PVA surface as well as exposed fiber substrate underneath. This indicates that plastic deformation of the PVA layer exceeded the flow limit of EGaIn, leading to electrical failure.

To study the influence of temperature, we investigated interfacial failure at -20 °C, which is below the melting point of EGaIn. In this condition, the critical curvature radius (defined as the bending radius at which $\Delta R/R_0$ begins to exceed 200%) increased from 2.3 mm at 20 °C to 20 mm at -20 °C. SEM examination revealed microfibrils generated by the fracture of PVA. The results indicate failure still originates from the PVA layer, whose increased brittleness at low temperature leads to a larger critical curvature radius. In contrast, elevated temperatures (30-60 °C) do not significantly affect the critical curvature radius. Besides, while oxidation of EGaIn at high temperature could be a concern, we did experimental study and the results show that the resistance increased by only 2.6% after continuous heating at 100 °C for 12 h, indicating that thermal oxidation is negligible under these conditions.

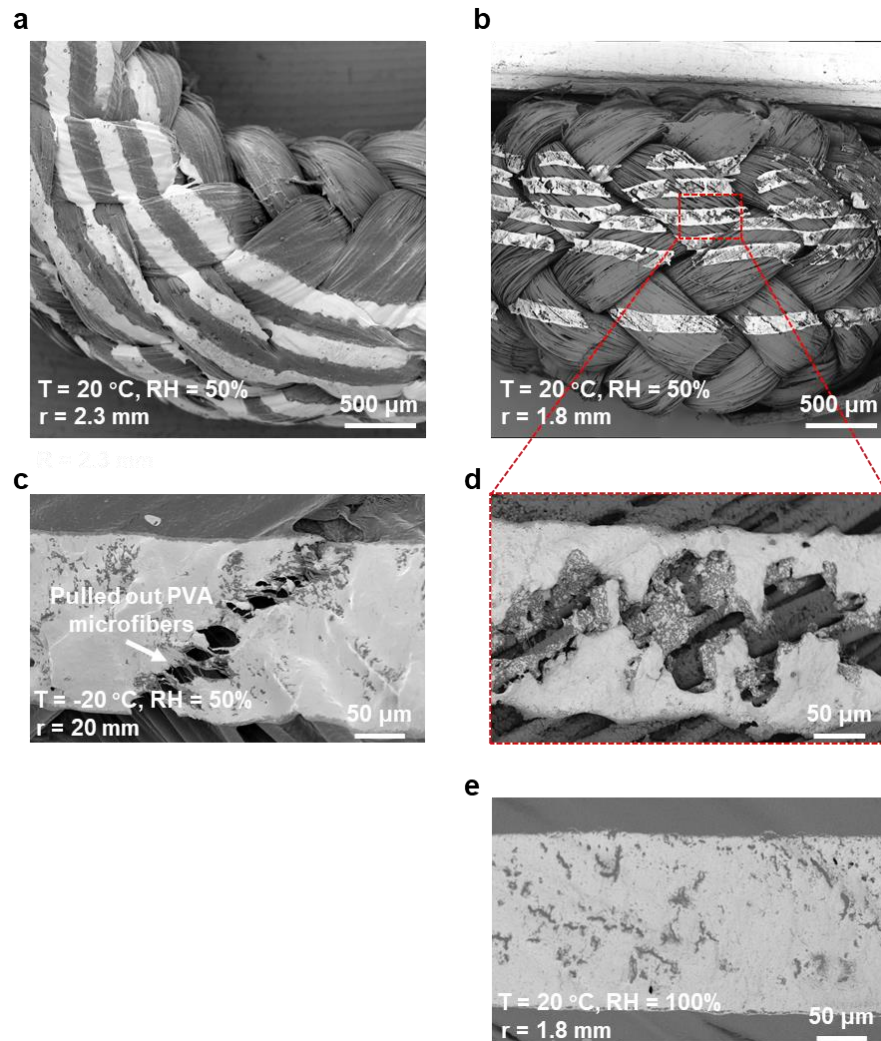
The influence of RH on the PVA adhesive layer mainly through its effect on flexibility. Higher humidity induces solvent-mediated plasticization, which increases the elongation at break of PVA. Correspondingly, the critical curvature radius of the EGaIn microcircuit decreases progressively with increasing RH, consistent with expectations.

Accordingly, we have added related discussion in the main text and Supplementary Fig. 21 and Supplementary Fig. 22 in the supplementary information. The related contents are copied in the following for your convenience:

In the main text:

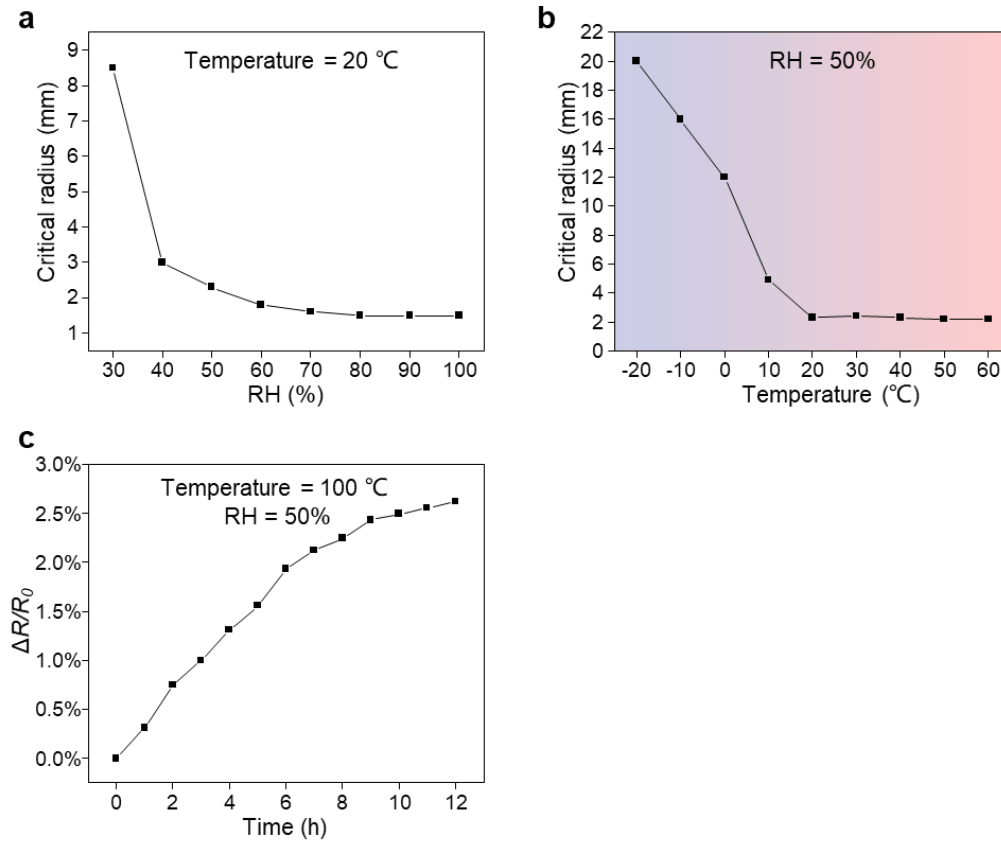
(Page 8, Line 252) This performance originates from the intrinsic fluidity and strain-insensitive conductivity of EGaIn, as confirmed by microscopy observations of continuous EGaIn pathways during bending (Supplementary Fig. 21). The bending limit of the fiber microcircuit is governed by the PVA adhesive layer, whose flexibility increases with temperature and humidity, leading to different critical radii across different environmental conditions (Supplementary Fig. 22).

In the supplementary information:



Supplementary Fig. 21. SEM images of the circuit-fiber interface at different temperature and humidity. (a) Interfacial morphology at 20 °C and 50% relative humidity (RH). Bending radius: 2.3 mm. (b) Morphology of the interface after bending-induced failure under the same environment conditions as in (a). Bending

radius:1.8 mm. (c) Image of the fracture at -20 °C and 50% RH, showing PVA microfibrils at the failure cross-section, indicating PVA-dominated interfacial failure. (d) Magnified view of (b), revealing abundant EGaIn speckles at the fractured region, indicating plastic deformation of the PVA. (e) Intact interface at bending radius of 1.8 mm under 20 °C and 100% RH, in contrast to the fractured interface in (d).



Supplementary Fig. 22. Influence of humidity and temperature on the mechanical stability of EGaIn microcircuits on fibers. (a) Influence of RH on the critical radius at 20 °C. Critical radius is defined as the bending radius at which $\Delta R/R_0$ begins to exceed 200%. (b) Influence of temperature on the critical radius at 50% RH. (c) Resistance variation of the microcircuit during prolonged thermal exposure at 100 °C and RH of 50%. All samples were stored under the corresponding environmental conditions for 3 h to ensure equilibrium.

Comment #8:

If available, resistance evolution over more extreme bending radii (≤ 4 mm) or torsional deformation would enhance confidence in durability claims.

Reply:

Following your suggestion, we studied the resistance evolution under more extreme bending radii (≤ 4 mm) and characterized the failure morphology using SEM (as shown in Reply to your Comment #7). To facilitate discussion, we defined critical radius as the bending radius at which $\Delta R/R_0$ begins to exceed 200%. We confirmed that the critical radius is 2.3 mm at temperature of 20 °C and RH of 50%.

Accordingly, we have added the resistance evolution at smaller bending radii (≤ 4 mm) in Fig. 4f. The related contents are copied in the following for your convenience:

In the main text:

(Page 8, Line 249) The resulting fiber devices exhibit exceptional mechanical compliance, enduring 16,000 bending cycles at a curvature radius of 1.6 cm with only a 1.4% increase in resistance. The fiber microcircuit can be bent to a critical radius (r_c , defined as the bending radius at which $\Delta R/R_0$ begins to exceed 200%) of 2.3 mm (Fig. 4f), demonstrating good robustness for wearable applications.

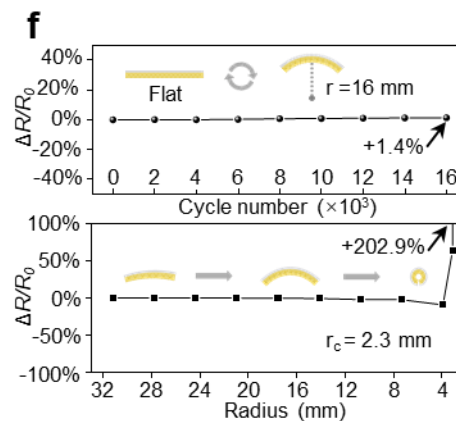


Fig. 4f. Relative change in resistance of the fiber under cyclic bending deformation with bending radius of 16 mm at 1 Hz (upper) and different bending radii (lower). Temperature, 20 °C; Relative humidity, 50%.

Comment #9:

The Methods should specify environmental parameters (temperature, humidity) during shrinkage and transfer, as these can influence EGaIn's viscosity, oxidation, and adhesion.

Reply:

Accordingly, we added these information into the Methods in the main text:

In the main text:

(Page 10, Line 334) **Fabrication of Shrunk microcircuits**

... All the processes, including the fabrication of shrunk microcircuits and its transfer, were performed at 20 °C and 50% relative humidity, unless otherwise specified.

Comment #10:

Clarify how uniform stretching was maintained—manual stretching may lead to edge effects. Was a biaxial stretcher or measured tension used? Including a schematic or photo of the setup (possibly in Supplementary Fig. 1) would improve reproducibility.

Reply:

Thank you for raising this question regarding the uniformity of stretching. The stress-engineered 2D silicone platform requires precise strain regulation, where the strain along each point of the perimeter should be carefully adjusted to ensure that every element remains distortion-free after stretching. Conventional biaxial stretching fixtures often fail to maintain uniform strain near the four corner regions. To overcome this limitation, we employed a frame-based stretching approach that allows manual adjustment of the silicone film's deformation, enabling the elimination of localized strain non-uniformity during the process. While the current manual adjustment method has certain limitations, it effectively ensures uniform omnidirectional stretching under controlled conditions. We acknowledge that further automation and standardization of the stretching process would be beneficial for improving reproducibility and scalability.

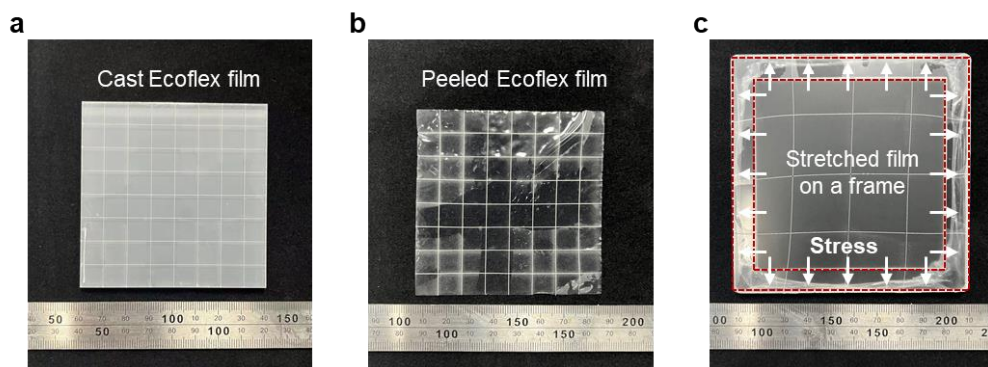
Accordingly, we have revised Supplementary Fig. 1 and added a new video S1 in the supplementary information to more clearly illustrate the stretching process. The related contents are copied in the following for your convenience:

In the main text:

(Page 2, Line 57) ...First, a silicone substrate (Ecoflex film) is **omnidirectional** pre-stretched to a defined ratio and secured on an acrylic frame to maintain tension (Supplementary Fig. 1, Video 1)....

In the supplementary information:

(Page S2) **Supplementary Video 1. (Separate file) | Fabrication of stress-engineered 2D silicone platform**



Supplementary Fig. 1. Ecoflex film platform used for shrinking EGaIn circuits. (a) Ecoflex was cast onto an acrylic plate to prepare a stretchable platform (the $1\text{ cm} \times 1\text{ cm}$ grid here is to help to illustrate the uniformity of the stretchable platform, which will not present during actual shrink process). (b) Ecoflex film peeled off from the acrylic plate. (c) Uniformly stretched Ecoflex film fixed onto an acrylic frame, ready for circuit construction on its surface.

Comment #11:

Minor Comments and Editorial Suggestions

Figure 1c: Add explicit “before” and “after shrinkage” labels and indicate quantitative shrinkage ratios on the figure or in the caption.

Reply:

Accordingly, we revised the Figure 1c and updated the corresponding caption. The updated ones are provided below:

In the main text:

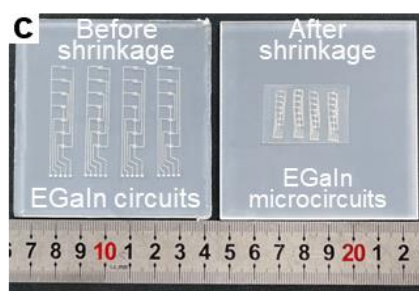


Fig. 1c, Optical images of EGaIn circuits on an Ecoflex film before and after shrinkage (shrunk by 80% in area) ...

Comment #12:

Supplementary Figures:

Fig. 1: Add direct annotations (e.g., “Ecoflex cast film,” “peeled film,” “stretched film on frame”) instead of relying solely on the caption.

Reply:

Thank you very much for your careful review and kindly suggestions. Accordingly, we added direct annotations in Supplementary Fig. 1 and checked the manuscript for similar issues.

Comment #13-14:

Fig. 2–3: Clarify whether EGaIn–PVA interfaces exhibit cracking or delamination during shrinkage.

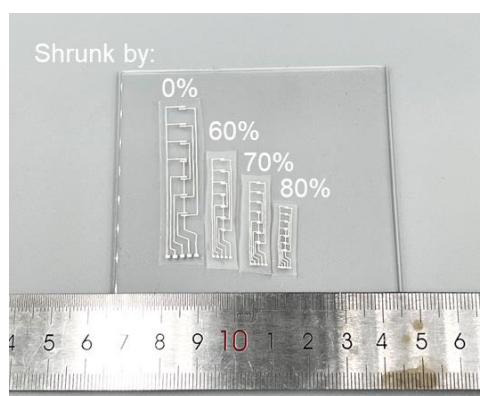
Fig. 3c: Mark the region of the high-magnification image within the main panel.

Reply:

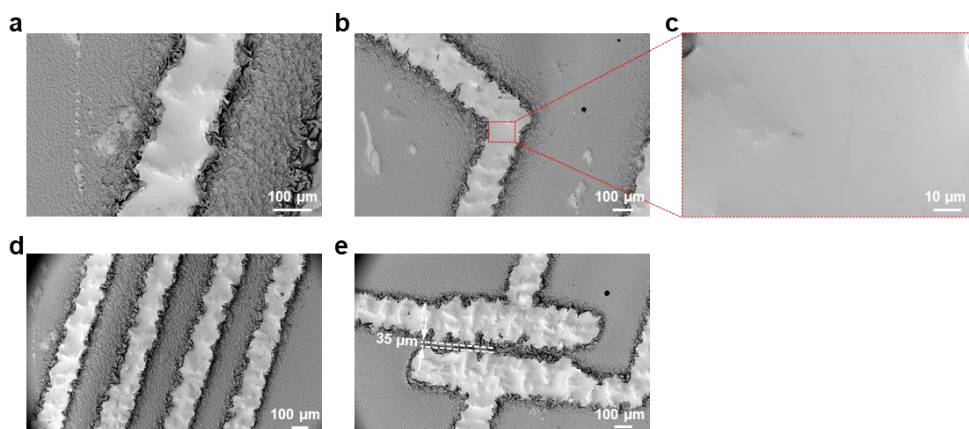
Thank you for raising this point. We agree that the interfacial interactions between different components are very important for the successful STAP process. Supplementary Fig. 2 and 3 respectively show the Ecoflex-EMP interface after shrinkage and the EGaIn-PVA interface after transfer. The PVA film is attached to the EGaIn microcircuits only after the shrinkage process. Thus, during the shrinkage process, no EGaIn-PVA interface is present. We guess the misunderstanding may have arisen from the original caption for Supplementary Fig. 2 and 3. As for the Ecoflex-EMP interface, during the shrinkage process, it remains stable and does not show cracking or delamination. The interfacial area simply decreases uniformly as the Ecoflex shrinks. However, new interfaces will generate when EMP overflow occurs under extreme shrinkage, as discussed in Reply to your Comments #3-5.

Accordingly, we revised the corresponding caption of Supplementary Fig. 2-3 to avoid such confusion and updated the Supplementary Figure 3. The related contents are copied below for your convenience:

In the supplementary information:



Supplementary Fig. 2. Images of EGaIn microcircuits on Ecoflex films with different shrinkage ratios. From left to right, shrunk by 0%, 60%, 70%, 80% in area.



Supplementary Fig. 3. Transferred EGaIn microcircuits on PVA. (a) A single line. (b) Sharp corner of the circuit. (c) Enlarged view of the circuit surface. (d) Multiple lines. (e) Small gaps (35 μm).

Comment #15:

Terminology: Replace “universal fabrication strategy” with “versatile fabrication strategy” unless broader material compatibility can be experimentally verified.

Reply:

Thank you for your insightful comment. As discussed in details in Reply to your Comment #1, we have experimentally verified the compatibility of this strategy with other inks, supplied new data and discussion in the revised films. Besides, we have also replaced “universal fabrication strategy” with “versatile fabrication strategy” to be more rigor.

Comment #16:

Supplementary Video 3: A brief quantitative comparison of luminance stability under bending would add scientific value beyond qualitative demonstration.

Reply:

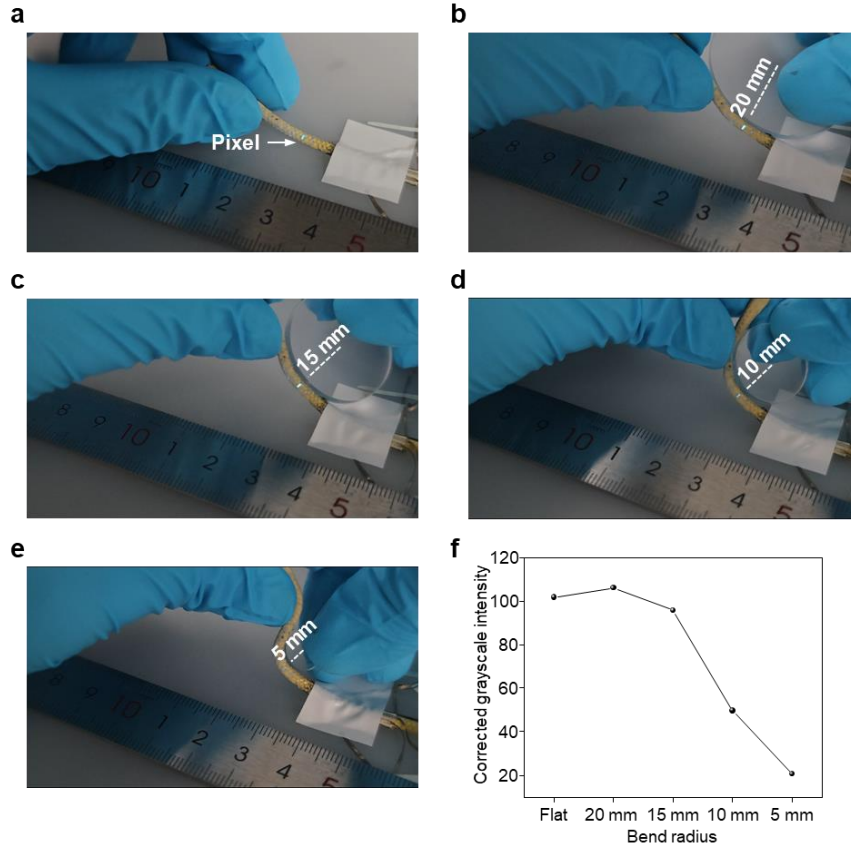
Thank you for your professional suggestion. We have carried out experiments to quantitatively compare the luminance stability of the EL pixel under different bending radii. We collected digital photographs of the same sample under the same environmental conditions at different bending radii, then used software (ImageJ) to measure the average grayscale intensity of the emitting pixel after subtracting the corresponding background brightness. The results show that the luminance stability remains 94% when bent to a radius of 15 mm, but then decreases sharply as the curvature increases.

Accordingly, we have added related discussion in the main text and corresponding luminance stability data (Supplementary Fig. 23) in the supplementary information. The related contents are copied below for your convenience:

In the main text:

(Page 9, Line 277) Selective pixel activation can be achieved by electrical addressing through designated contacts (Fig. 4l, Supplementary Video 4), enabling the multiplexed display on a single fiber. **Luminance stability remains 94% when bent to a radius of 15 mm, but then decreases rapidly as the curvature increases further (Supplementary Fig. 23).**

In the supplementary information:



Supplementary Fig. 23. Evolution of brightness of luminance pixel with decrease of bending radius. (a-e) Optical images of a single EL pixel on the fiber device bent to different curvature radius ((a) flat, (b) 20 mm, (c) 15 mm, (d) 10 mm, (e) 5 mm). (f) Corrected grayscale intensity extracted from a fixed region of interest (ROI) for each pixel. Pixel brightness was quantified using ImageJ by measuring the mean grayscale value and subtracting a nearby background region to remove illumination variations.

Reviewer #3:**Summary Comment:**

The manuscript is generally well written and clearly presented. However, there are several issues that limit the overall scope and relevance of the work.

Reply:

Thank you very much for your careful review and insightful comments/suggestions on our manuscript. Accordingly, we carried out further experiments and revised the manuscript to address each of the points you raised. These revisions should be helpful for refining the boundaries of this work and strengthening its scientific relevance. We sincerely appreciate your constructive guidance. The following is a point-by-point response.

Comment #1:

Material specificity:

The materials used in the study are very specialized and are not easily replaced or adapted to other functional materials (substrate, ink, GaIn)

Reply:

Thank you very much for raising this point. In order to address this point, we carried out further experiments.

Beside the EGaIn/sericin ink, three typical commercial conductive inks, including Ag/AgCl ink and carbon ink, which are commonly employed in printed electrochemical sensors, and PEDOT:PSS ink, which is one of the most broadly used conductive polymers, were studied with the STAP process. All the three inks can be successfully applied in the STAP process, demonstrating the versatility of the process. We propose the following are the requirements for the inks used in this process: (i) The ink should remain flowable during the interval between printing and substrate shrinkage, which allows the shrinkage-induced stress to propagate upward from the bottom of the pattern and to drive spatial reorganization of the ink material. (ii) The ink should possess adequate viscosity, since low-viscosity inks would easily overflow the intended pattern boundaries during substrate motion and cause feature distortion. (iii) The ink should have affinity toward the targeted film, which in this work is PVA. For example, EMPs with hydrophilic surfaces exhibit strong affinity to PVA, which is essential for successful transfer.

As for the selection of elastomeric substrates, the STAP process requires substrates with high stretchability, recoverability and hydrophobicity. The silicone elastomer we used fits these requirements perfectly. Other common elastomers such as styrene-ethylene-butylene-styrene copolymer (SEBS) and thermoplastic polyurethane (TPU) could in principle work with STAP, but their stretchability is usually lower than that of silicone

unless molecular modification is applied. Therefore, in this work, we selected commercial Ecoflex and did not study other elastomeric substrates.

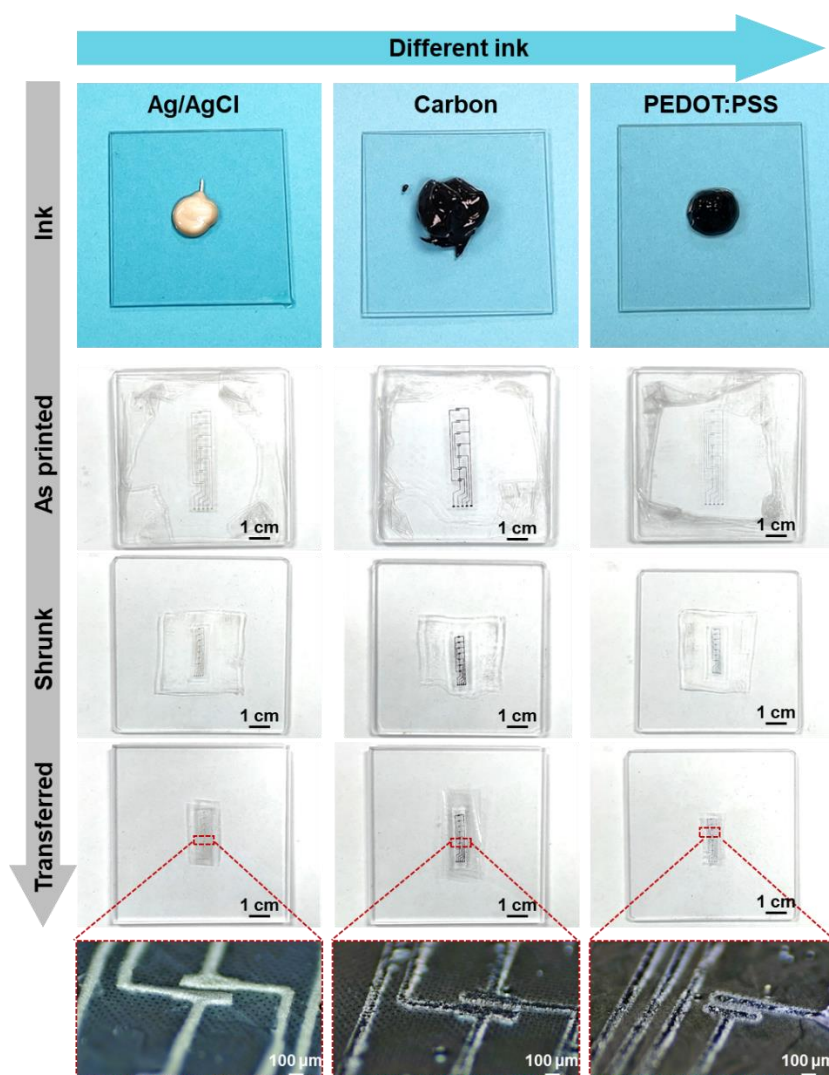
Accordingly, we have added related discussion in the main text, and Supplementary Fig. 24 in the supplementary information. Besides, we have replaced the term “universality” with “versatility” in the main text to be more rigor. The related contents are copied in the following for your convenience:

In the main text:

(Page 9, Line 285) It is noted that the STAP process is also compatible with other typical commercially available inks besides the EGaIn/sericin ink (Supplementary Fig. 24).

(Page 9, Line 317) Finally, standardizing process parameters and characterization protocols across different material systems will be essential for ensuring reproducibility and facilitating broader adoption in flexible and textile electronics.

In the supplementary information:



Supplementary Fig. 24. Applying STAP process using three typical commercial electronic inks. The inks include Ag/AgCl ink (purchased from Prtronic), carbon ink (purchased from Loctite), and PEDOT:PSS ink (purchased from Prtronic), showing consistent printing, ~80% shrinkage, and successful transfer, confirming the compatibility of the STAP process with other inks.

Comment #2:

Scalability and reproducibility:

Key steps in the process—such as pre-stretching, tension release, transferring onto a PVA sheet, water-assisted transfer, and the shrinkage of the printed circuits—introduce a lot of variability and are not easily scalable. As a result, achieving consistent reproducibility is challenging. In addition, the conductivity variations that come from shrinkage sintering and transfer sintering need to be supported with more detailed statistical data.

Reply:

Thank you for your insightful comment. We agree that the STAP workflow involves multiple steps, imposing challenges for scalability and reproducibility.

Regarding reproducibility, all the key steps, including pre-stretching, tension regulation, circuit shrinkage, hydration of the PVA film, and the final transfer, can be governed by controllable experimental parameters. The pre-stretching process is performed on a stress-engineered silicone platform with adjustable pre-strain, and the deformation state can be monitored using an orthogonal finite-element grid (Supplementary Video 1). We also investigated the effects of shrinkage and transfer parameters on the restoration of EMP conductivity. The PVA-assisted transfer reliably recovers the conductivity of EMP networks to the same order of magnitude as bulk EGaIn, and experimental results show that the transfer and reconstruction process proceeds with a very high success rate (nearly 100% for across 20 times trials). Besides, the screen printing in the STAP process is an industrial-scale patterning method widely used in textile manufacturing.

Regarding scalability, we acknowledge that our current laboratory-scale preparation has limitations. Despite of this, we think it has potential for large-scale applications as the mechanism itself does not impose fundamental barriers to scaling. The stress-engineered 2D silicone platform could be scaled up by using larger substrates. However, continuous large-scale manufacturing would require an automated stretching system capable of applying uniform tension along the entire film. After shrinkage, the silicone film carrying the microcircuits could be brought into contact with a continuous PVA roll, following by wetting, drying, transfer and collection along a production line. This approach appears feasible and would mainly require engineering design for automate wetting and rapid drying. Your comment provides a forward-looking perspective on the practical deployment of STAP.

Accordingly, we have added a discussion in the main text. And the detailed conductivity data associated with shrinkage sintering and transfer sintering have been included in the supplementary Table S2. The related contents are copied below for your convenience:

In the main text:

(Page 6, Line 199) ...Moving along this boundary toward higher F_f enables smaller feature sizes while preserving electrical continuity (see Table S2 for electrical conductivity for each point)

(Page 9, Line 286) ...This STAP strategy overcomes the long-standing challenge of integrating high-precision microcircuits onto curved fiber substrates, paving the way for multifunctional and high-density wearable electronics. Further efforts on developing automated stretching and continuous transfer systems could improve the scalability of STAP and facilitate its adoption in practical manufacturing settings.

(Page 9, Line 312) Second, scaling the technology for industrial production will require the development of automated stretching systems capable of applying uniform omnidirectional strain to large-area elastic substrates, thereby improving reproducibility.

In the supplementary information:

(Page S19) **Table S2.** Conductivity of EGaIn microcircuits prepared with different pre-stretch ratio and EMPs coverage ratio.

EMPs coverage ratio (%)	Pre-stretch ratio							
	0%	75%	150%	225%	300%	375%	450%	525%
63.2	0	0.25	0.36	0.39	0.42	0.46	0.47	0.48
53.7	0	0.13	0.18	0.20	0.24	0.29	0.32	0.33
47.4	0	0.06	0.10	0.13	0.18	0.21	0.21	0.24
41.1	0	0/28.8	0.05	0.09	0.15	0.20	0.21	0.21
33.8	0	0/28.3	0/28.5	0.02	0.08	0.17	0.19	0.21
29.2	0	0/27.6	0/28.5	0.01	0.05	0.11	0.16	0.17
26.3	0	0/27.2	0/28.2	0/28.4	0.02	0.02	0.03	0.04
20.6	0	0	0/27.9	0/28.2	0/28.2	0/28.4	0/28.4	0/28.5
16.4	0	0	0	0/27.3	0/27.3	0/27.5	0/27.5	0/27.5
12.4	0	0	0	0	0	0	0	0

Note: Corresponding to the measured electrical conductivity ($\times 10^5 \text{ S m}^{-1}$) after shrinkage. A single non-zero value indicates conductivity obtained by shrinkage alone. Entries in the form “0/x” denote circuits that remained non-conductive after shrinkage but became conductive ($x \times 10^5 \text{ S m}^{-1}$) after transfer.

Comment #3:

Multilayer printing limitations:

The approach does not seem capable of true multilayer printing. In the demonstrated device, the conductive layer is printed and transferred onto the thread, while the luminescent layer is applied by coating rather than printing. This highlights an inherent limitation of the technique.

Reply:

Thank you for your insightful comment. Accordingly, we carried out further experiment to explore the possibility for construction multilayer circuits with the STAP strategy. We found that multilayer circuits can be constructed on separate PVA films using different screen-printing masks. These films can then be sequentially transferred to the aligned position of the fiber surface. We also considered that possibility for the printing of the luminescent layer. However, as for the STAP process involves the wetting and drying of the PVA film, constructing a non-permeable luminescent layer on the film would influence the wetting behavior, and thus introduce non-uniform stress.

Accordingly, we have added related discussion in the main text and an image of a fiber with multilayer-circuits (Supplementary Fig. 20). The related contents are copied below for your convenience:

In the main text:

(Page 8, Line 247) Notably, this transfer step can also be applied to fibers of different materials and diameters (Supplementary Fig. 19), and can be repeated on one fiber to construct multilayer circuit (Supplementary Fig. 20).

In the supplementary information:



Supplementary Fig. 20. Optical image of a fiber (diameter, 1.5 mm) with two layers of EGaIn microcircuits.

Comment #4:

Limited use on small-diameter substrates:

The method is demonstrated only on threads a few millimeters in diameter. Its potential for use on finer fibers or true one-dimensional substrates is not addressed, which restricts the broader relevance of the work

Reply:

Thank you for your raising this critical comment the use of smaller-diameter fibers. We agree that extending the method to finer one-dimensional substrates is an important direction for broader applicability.

In the present work, the fiber devices were designed primarily to demonstrate single-pixel electroluminescence. As fiber diameter decreases, pixel crosstalk between densely packed microcircuits becomes significantly more pronounced. To ensure clear functionality and avoid signal interference, we therefore used relatively thicker fibers in the main demonstrations.

In this work, the minimum diameter of fibers we used is 1.5 mm. We think the minimum usable fiber diameter in our approach is constrained mainly by two factors: (1) the achievable printing resolution, and (2) the shrinkage limit of the substrate. Together, these define the smallest reliable circuit feature size, which in turn determines how thin a fiber can be reliably patterned. Moving to significantly thinner fibers will require further downscaling of the circuit dimensions, which is one of the goals of our future work.

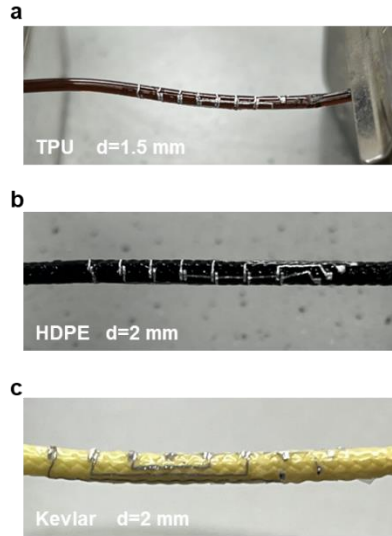
Accordingly, we have added discussion on the key challenges in the main text, and images of fiber devices fabricated on 2.0 mm and 1.5 mm fibers made of different materials (Supplementary Fig. 19) and multilayer circuits fabricated on 1.5 mm fibers (Supplementary Fig. 20) in the supplementary information. The related contents are copied below for your convenience:

In the main text:

(Page 8, Line 247) Notably, this transfer step can also be applied to fibers of different materials and diameters (Supplementary Fig. 19) ...

(Page 9, Line 310) Looking forward, several key challenges must be addressed to advance the practical deployment of STAP. First, extending the method to finer fiber diameters will necessitate advances in ink formulation and substrate engineering to prevent pixel crosstalk and ensure reliable patterning at the microscale. Second... Third... Finally, standardizing process parameters and characterization protocols across different material systems will be essential for ensuring reproducibility and facilitating broader adoption in flexible and textile electronics. By addressing these challenges, STAP can evolve from a laboratory-scale technique into a practical manufacturing process for producing high-performance, seamlessly integrated fiber-based devices.

In the supplementary information:



Supplementary Fig. 19. Optical images of EGaIn microcircuits on fibers with different materials and diameters. (a) Thermoplastic polyurethane (TPU), smooth surface, diameter 1.5 mm. (b) High-density polyethylene (HDPE), rough surface, diameter 2 mm. (c) Kevlar, rough surface, diameter 2 mm.



Supplementary Fig. 20. Optical image of a fiber (diameter, 1.5 mm) with two layers of EGaIn microcircuits.

Finally, we would like to thank all the three reviewers for the insightful comments and constructive suggestions, which have helped us in further improving this work.

Response to Reviewers' comments

We thank the reviewers for their careful evaluation of our manuscript. In this round of review, both Reviewer #1 and Reviewer #2 indicated that all of their previous comments had been fully addressed and that the revised manuscript is acceptable for publication without further revision.