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# Intrinsically stretchable solid-liquid thin metal films

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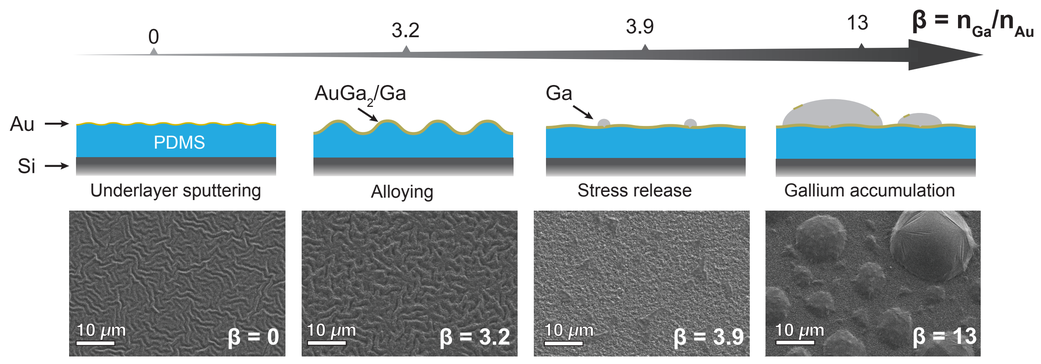
## Context

- Stretchable conductors are the foundation of soft electronic circuits [1].
- Gallium-based liquid metals offer metallic conductivity and high stretchability [2] .
- There is no patterning technique available that combines high resolution and batch processing over large area [3].
- We introduce physical vapor deposition and micro-patterning of solid-liquid thin metal films with high electromechanical performance [4].

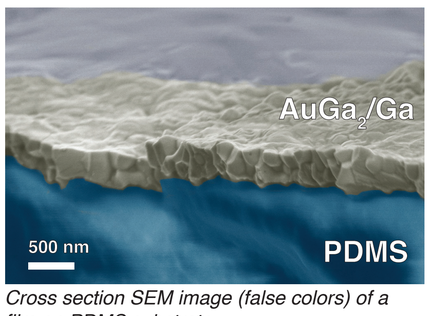
## Film formation

- An elastomer (PDMS) substrate is coated with 60 nm of sputtered gold (Au). Gallium (Ga) is then thermally evaporated. It spreads by diffusing and alloying with gold and accumulates in microscopic bulges.

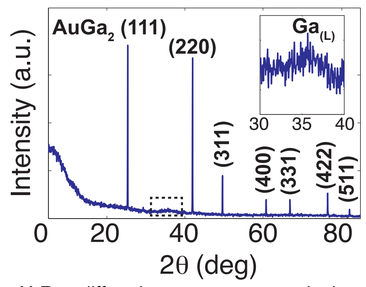



*Scanning electron microscope (SEM) of the film's surface at different stages of growth. β is the Ga/Au atomic ratio.*

- Ga ($T_{fusion}$=29.8 °C) supercools and remains liquid at room temperature.



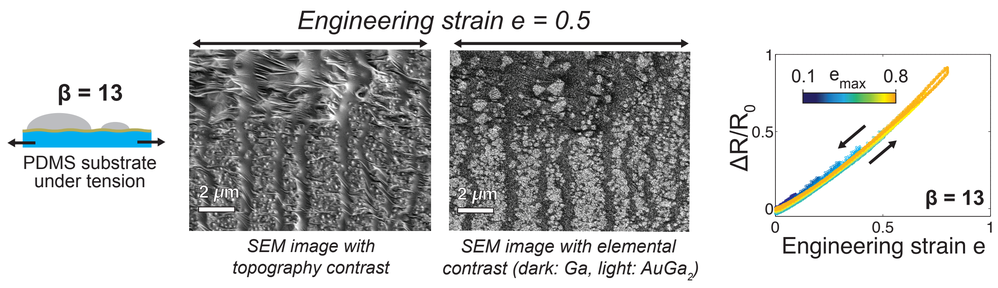

*Cross section SEM image (false colors) of a film on PDMS substrate.*




*X-Ray diffraction spectrum reveals the presence of solid $AuGa_2$ and liquid Ga.*

## Electromechanical behavior

- The films have a sheet resistance of 0.5 Ω/sq (as prepared).
- The solid-liquid conductor deforms and maintains continuity and high electrical conductivity when the films are stretched up to 1 million times [4].

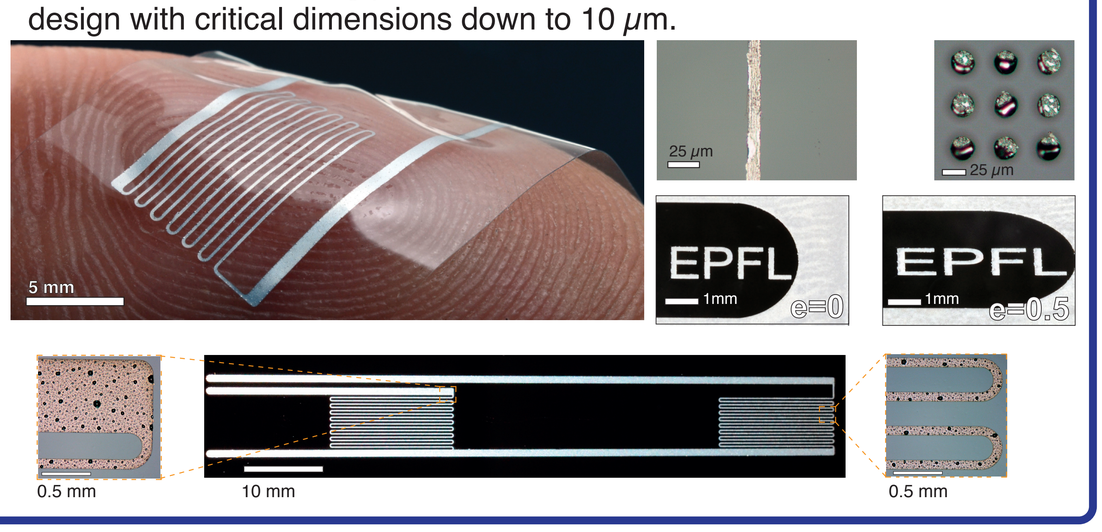



*SEM image with topography contrast*

*SEM image with elemental contrast (dark: Ga, light: $AuGa_2$)*

## Patterning

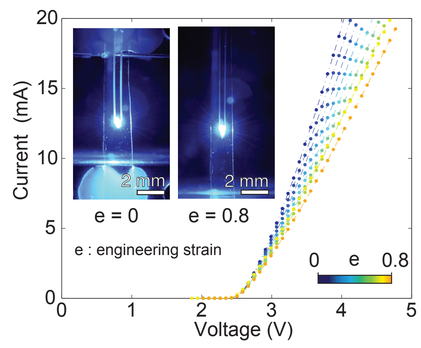
- Lift-off micro-structuring process on PDMS substrate offers freedom of design with critical dimensions down to 10 μm.

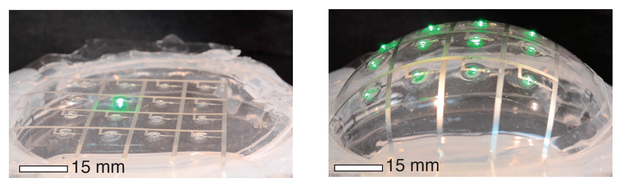



## Applications

- **Stretchable multilayer optoelectronic circuits**

  Large uniaxial and multiaxial strains minimally impact the function of soft circuits integrating LEDs interconnected with the solid-liquid films.

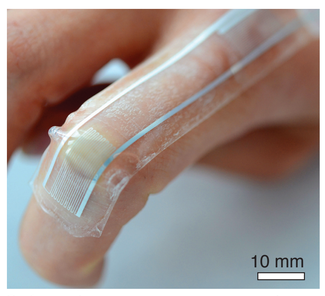


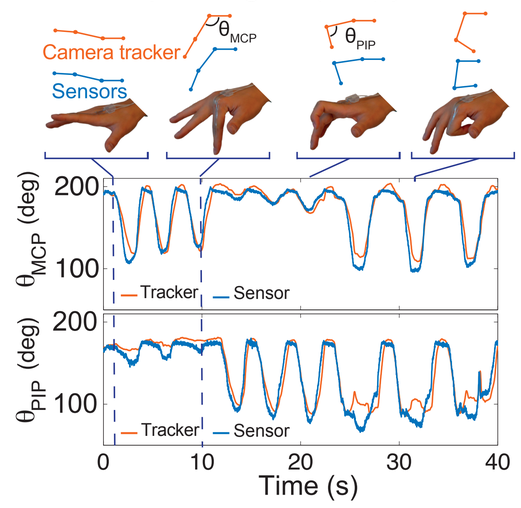

*Surface-mount LEDs are integrated in a thin (0.3 mm) PDMS membrane. The matrix maintains functionallity when inflated.*

- **Skin-like motion sensors**

  Thin (150 μm) and soft resistive strain gauges encode the flexion of the metacarpophalangeal (MCP) and proximal-interphalangeal (PIP) joints of the index.

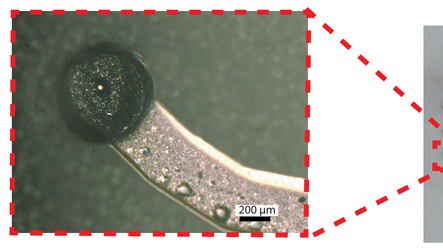



*Soft strain gauges are mounted on the index using skin adhesive.*

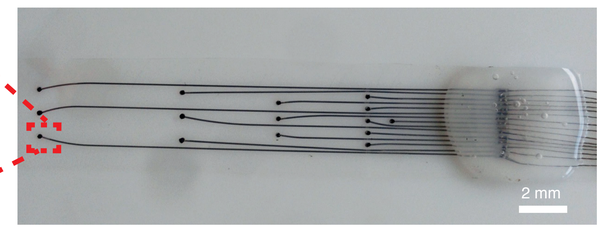



- **Soft electrodes**

  Patterning capabilities enable dense arrays of soft electrode with low impedances



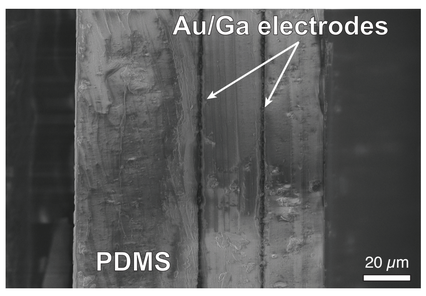

*Magnified view of a 300 μm Pt composite stimulating electrode interconnected by solid-liquid gold gallium thim film.*



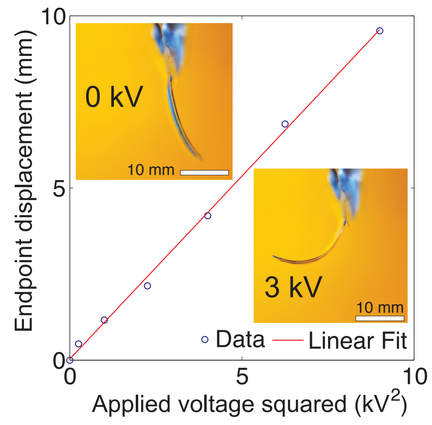

*Fifteen electrodes array for stimulation of the spinal cord.*

- **Soft dieletric actuators**

  Highly compliant, conductive and thin electrodes are desired for soft actuators [5].




*Cross section of a dielectric elastomer actuator cantilever prepared with PDMS and solid-liquid gold-gallium thin films electrodes.*




## Conclusion

- We use high throughput micro-fabrication techniques to deposit and pattern thin, solid-liquid metal films.
- The films maintain high electrical conductivity under large strains.
- We demonstrated their application in a range of soft transducers: optoelectronic circuits, skin-like sensors, micro-heaters and actuators.
- Future implementations include bioelectronic interfaces and sensors for rehabilitation and soft robotics.

**References:**

- [1] M. L. Hammock, A. Chortos, B. C.-K. Tee, J. B.-H. Tok, and Z. Bao, *Adv. Mater.*, vol. 25, no. 42, pp. 5997– 6038, 2013.
- [2] M. D. Dickey *et al.*, *Adv. Funct. Mater.*, vol. 18, pp. 1097–1104, 2008.
- [3] I. D. Joshipura, H. R. Ayers, C. Majidi, M. D. Dickey, *J. Mater. Chem. C* , vol. 3, pp. 3834-3841, 2015.
- [4] A.Hirsch, H.O. Michaud, A.P. Gerratt, S. de Mulatier and S.P. Lacour, *Advanced materials (2016).*
- [5] L. J. Romasanta, M. A. Lopez-Manchado, and R. Verdejo, *Prog. Polym. Sci.*, vol. 51, pp. 188-211, 2015.

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