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Highly stretchable and transparent nanomesh electrodes made by grain boundary lithography

Chuan Fei Guo[1], Tianyi Sun[1], Qihan Liu[2], Zhigang Suo[2] & Zhifeng Ren[1]

[1]Department of Physics and TcSUH, University of Houston, Houston, Texas 77204, USA. [2]School of Engineering and Applied Sciences, Kavli Institute for Bionano Science and Technology, Harvard University, Cambridge, Massachusetts 02138, USA. Correspondence and requests for materials should be addressed to Z.R. (email: zren@uh.edu).

Anirban Som
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Introduction

- Few electronic conductors are both stretchable and transparent.
- The existing stretchable and transparent electrodes, such as graphene sheets, carbon nanotube films and metal nanowire networks, suffer from either high sheet resistance or low stretchability.
- The latest understanding is that fully interconnected metal nanowire networks can have good electrical conductance since they do not have the problem of high wire-to-wire junction resistance.
- Although metal interconnects are more conductive than the random metal nanowire-networks, it is still a challenge for a metal interconnect to work under ultralarge strains.
- Moreover, few reports have offered physical insight for the flexibility of transparent metal interconnects. Therefore, clarifying the underlying physics of the ultrahigh stretchability is of great both scientific and practical importance.

In this paper….

- Here a method called grain boundary lithography, for making metal nanomesh electrodes is presented. The nanomesh is a network of fully interconnected metal wires of gold.

- It avoids the problem of high junction resistance and has good electrical conductivity as well as transparency.

- The Au nanomesh exhibits ultrahigh stretchability: it has a modest increase in electrical resistance even if it is stretched to a strain as large as 160% or after 1,000 cycles at a strain of 50%.

- The good stretchability results from two facts: the stretched nanomesh adherent on an elastomeric structure undergoes distributed rupture of nanowires and the serpentine nanowires deflect out of the plane.

- Besides, the Au nanomeshes do not have oxidation problem like Ag and Cu, causing a remarkable decrease of electrical conductivity for Ag and Cu nanowirenetworks under a mild temperature of 200 °C or even at room temperature.

Fabrication of metal nanomeshes

(1) Deposition of a 65 nm thick SiO_x sacrificial layer on Si wafer (resistivity: 5–7O ohm cm, thickness: 0.5 mm), followed by depositing a 100 nm thick In film.

(2) Etching in 20 wt.% HNO_3 for gap formation.

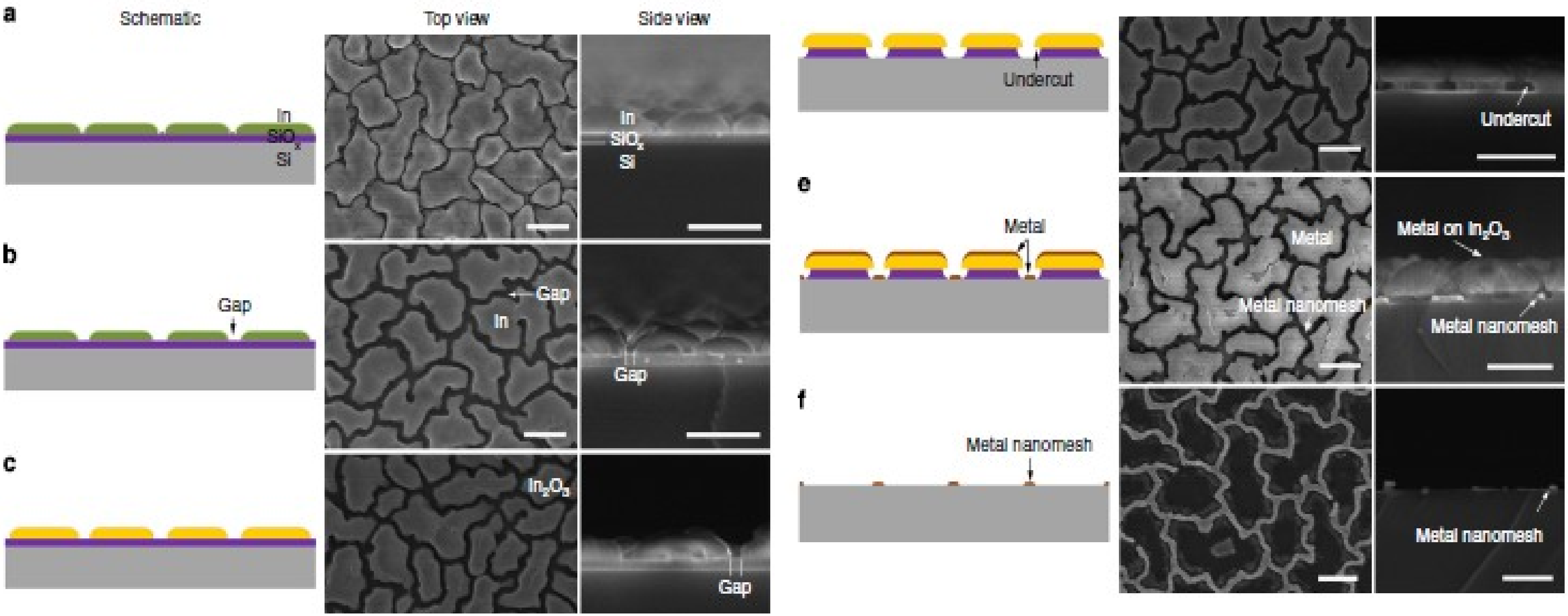
(3) Thermal oxidation at 400 °C for 2 h to form In_2O_3 islands.

(4) Rinsing in 5 wt.% HF for 12 s, leading to the formation of undercuts.

(5) Deposition of metal film of Au on top of the In_2O_3 film, so that a metal nanomesh is formed in the gaps.

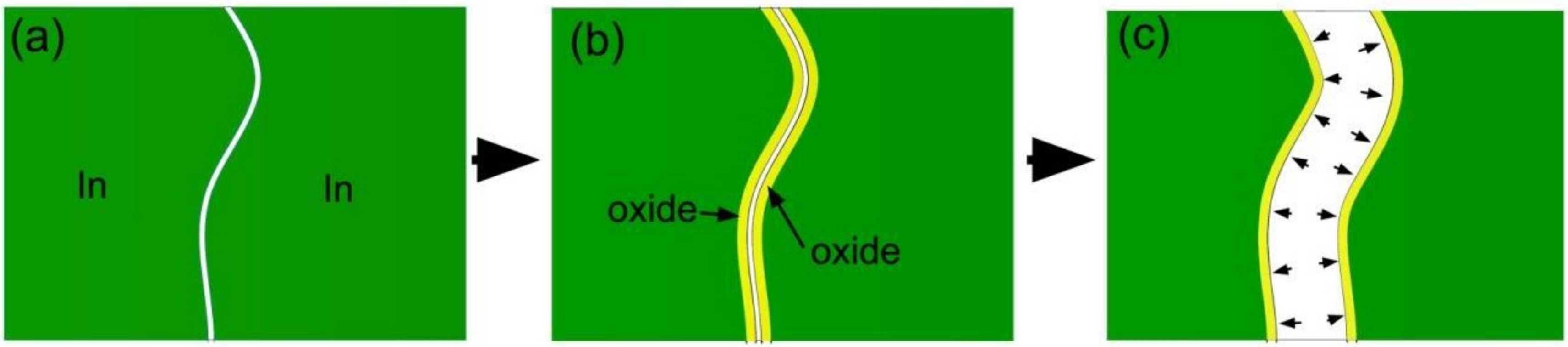
(6) Lift-off process to dissolve the SiO_x and removal of In_2O_3 islands in 5% HF solution to form a metal nanomesh on the substrate.

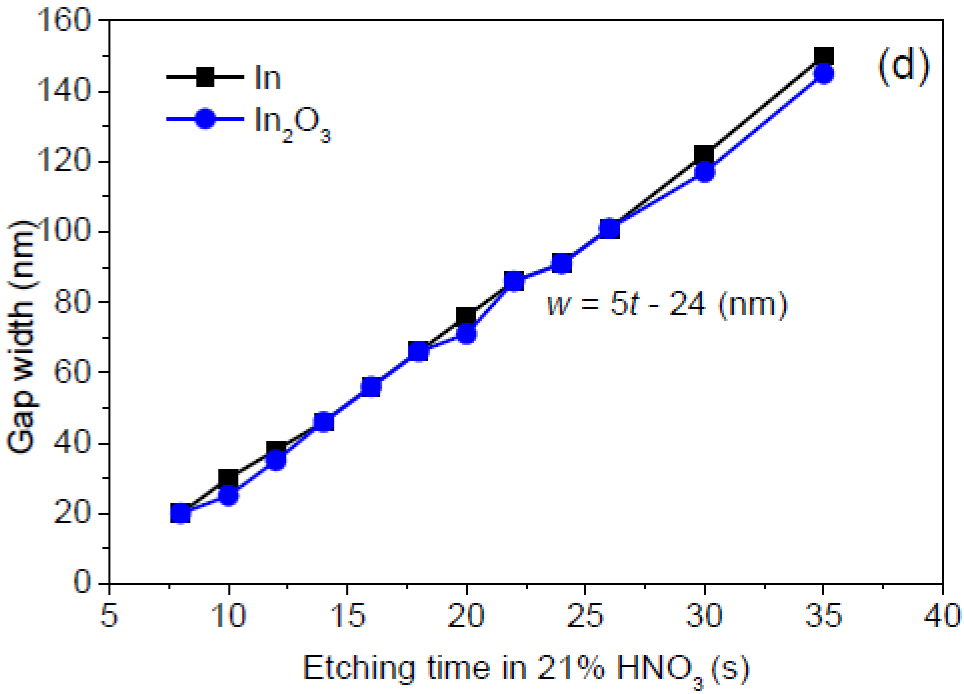
Fabrication of metal nanomeshes



(a) Deposition of In/SiOx bilayer on a Si wafer. (b) Gap formation by etching in diluted HNO3. (c) Conversion of In islands into In2O3 islands by thermal oxidation. (d) Undercut formation by rinsing in diluted HF. (e) Deposition of metal film leading to the formation of metal nanomesh in the grooves. (f) Lift-off process to remove In2O3 and SiOx. Scale bar, 500 nm.

Formation mechanism and controllability of gaps by HNO3 etching

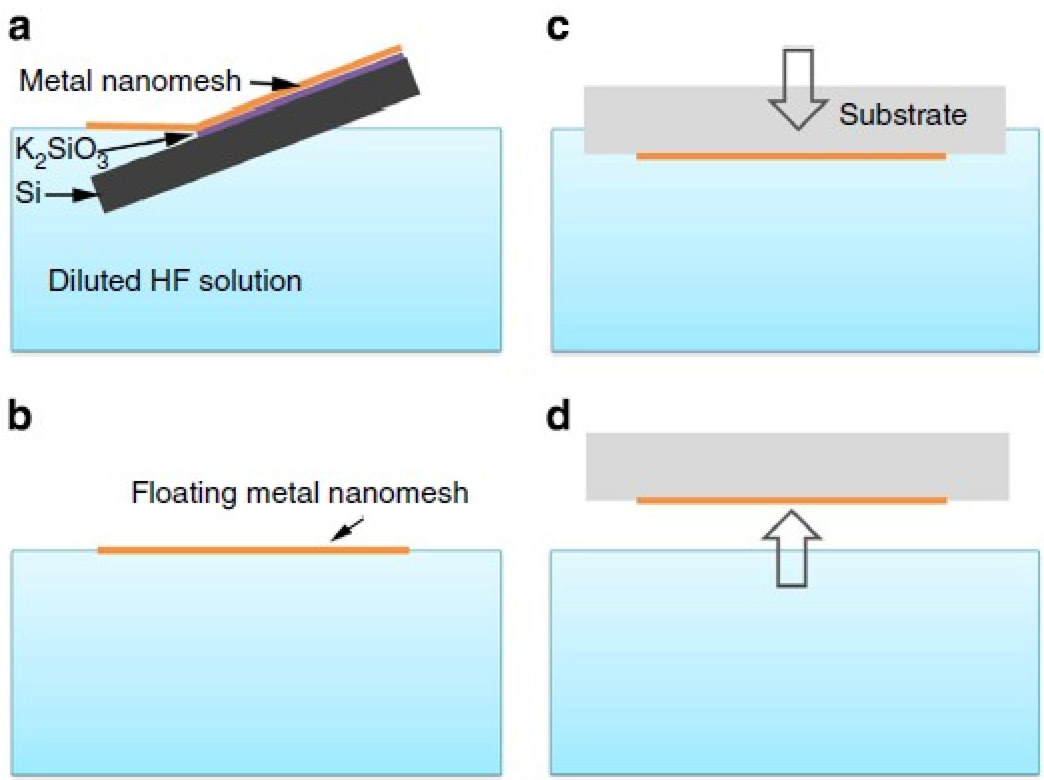




$$2In + 2HNO_3 \rightarrow In_2O_3 + 2NO \uparrow + H_2O$$

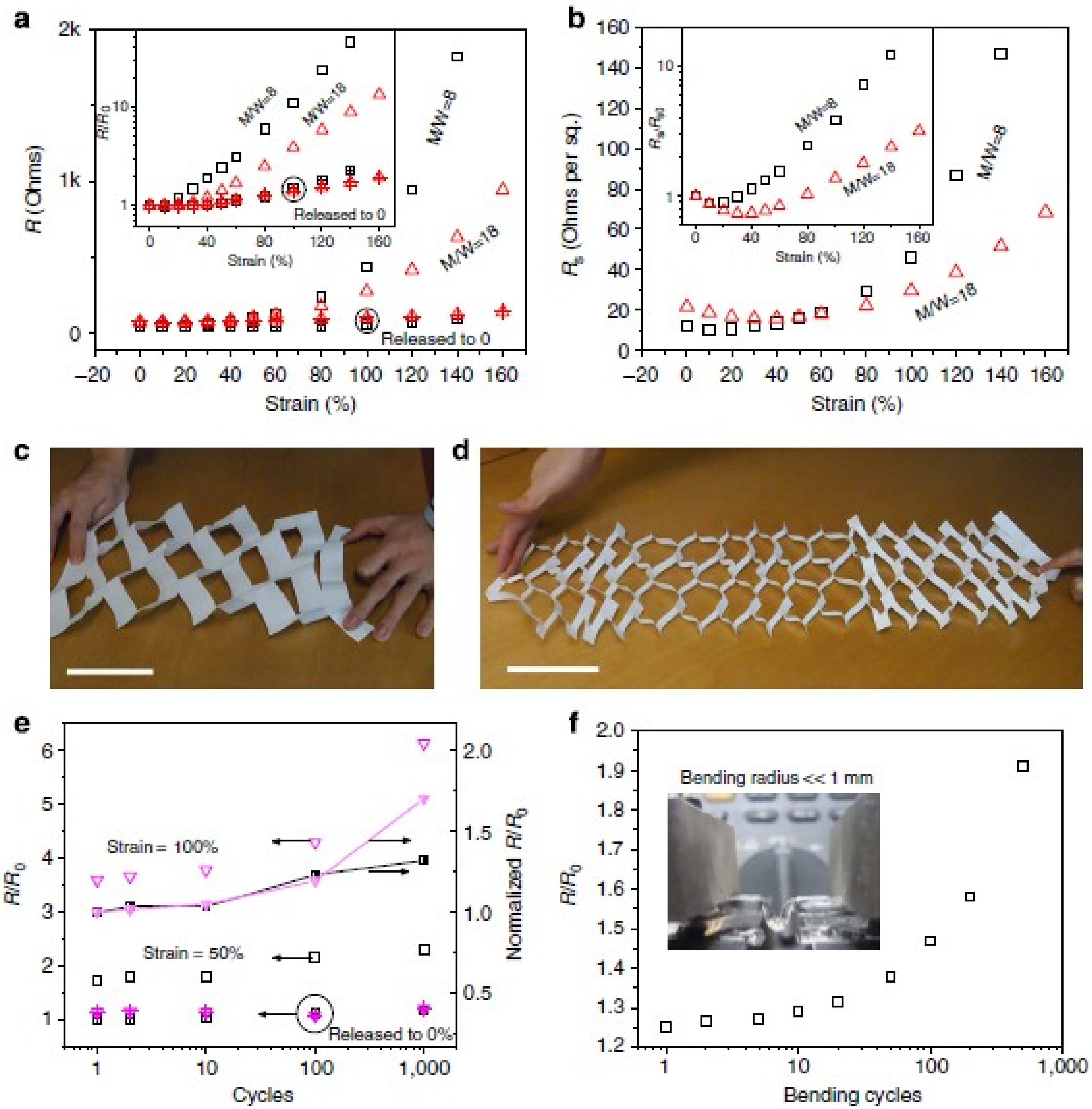
$$In_2O_3 + 6H^+ \rightarrow 3H_2O + 2In^{3+}$$

Transfer of the metal nanomesh

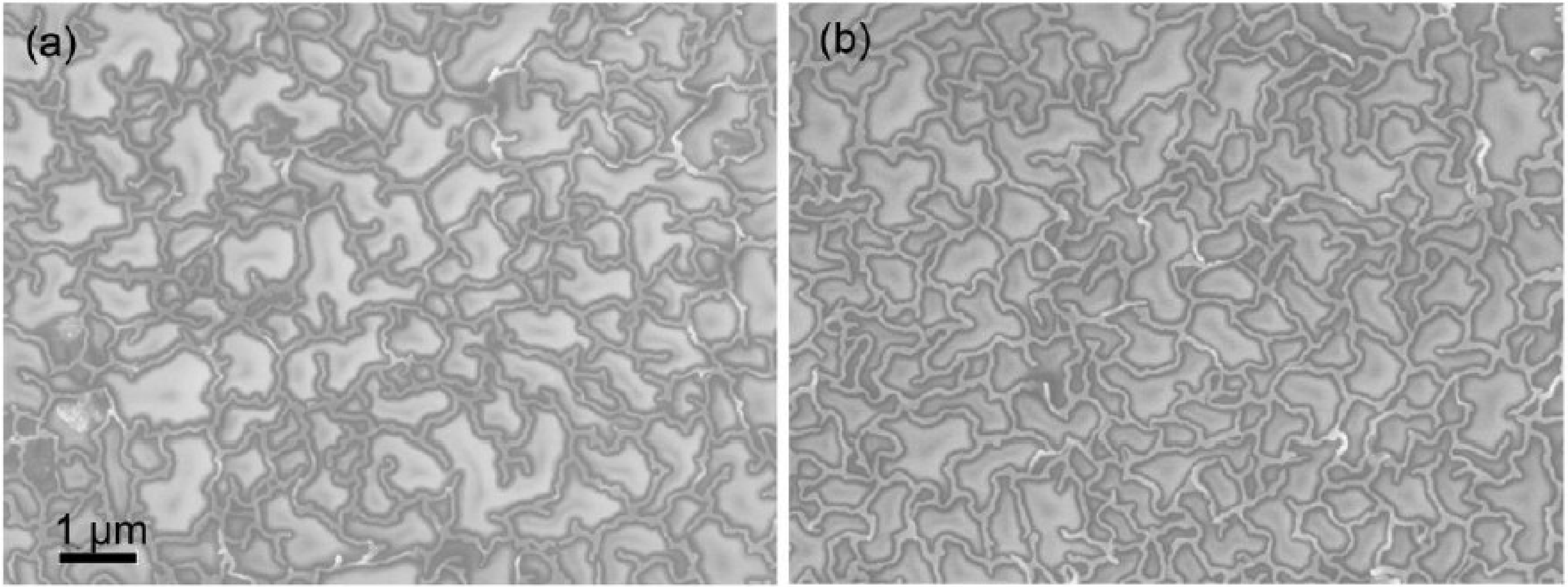


(a) Wedging transfer of metal nanomesh. (b) Floating metal nanomesh. (c) Pressing a target substrate on the metal nanomesh. (d) Lifting the nanomesh.

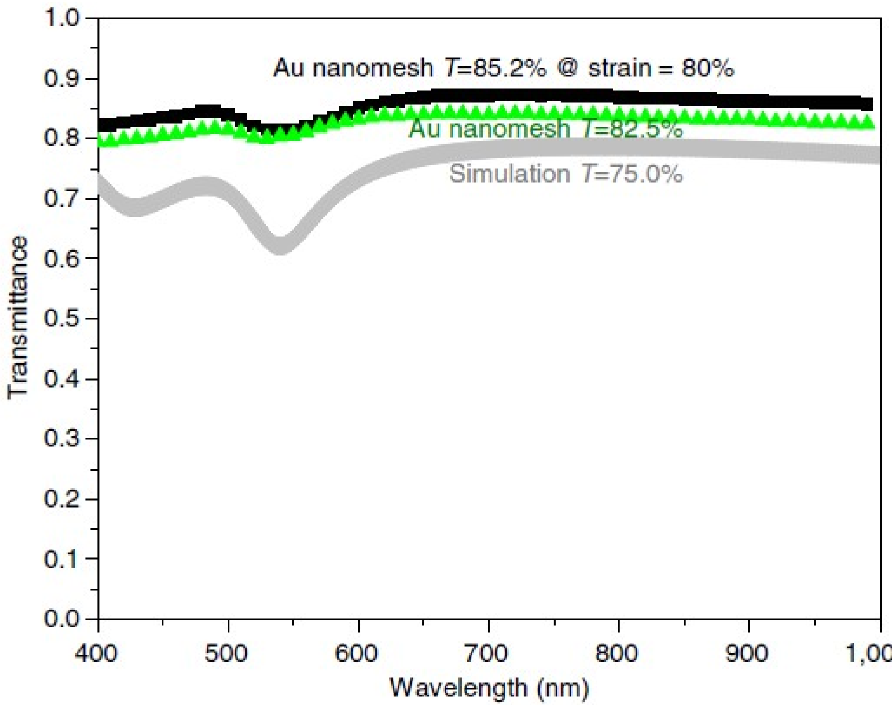
Flexibility and resistance of nanomeshes

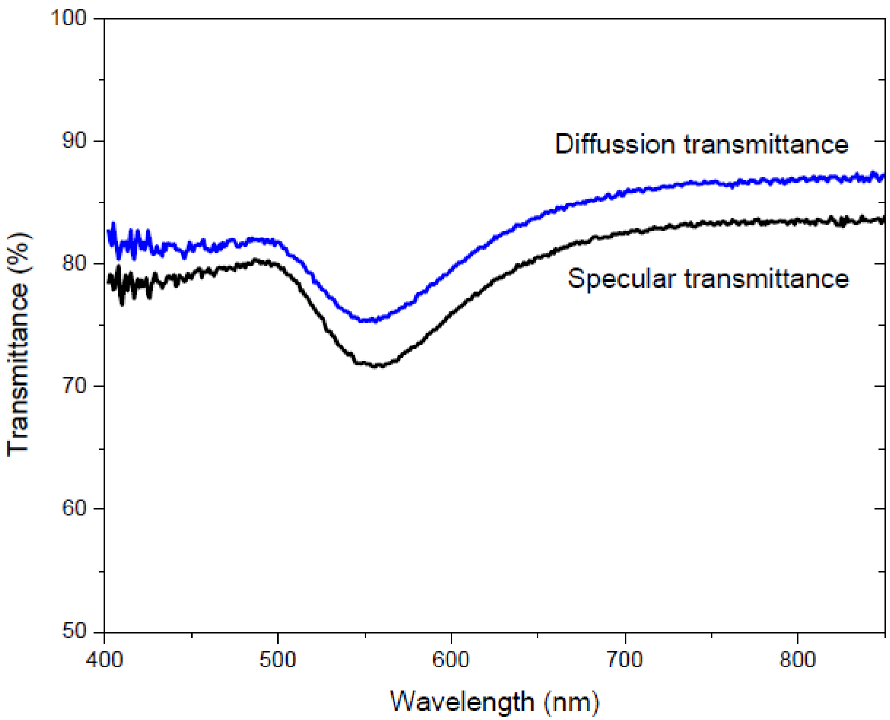


Morphology of Au nanomeshes on PDMS



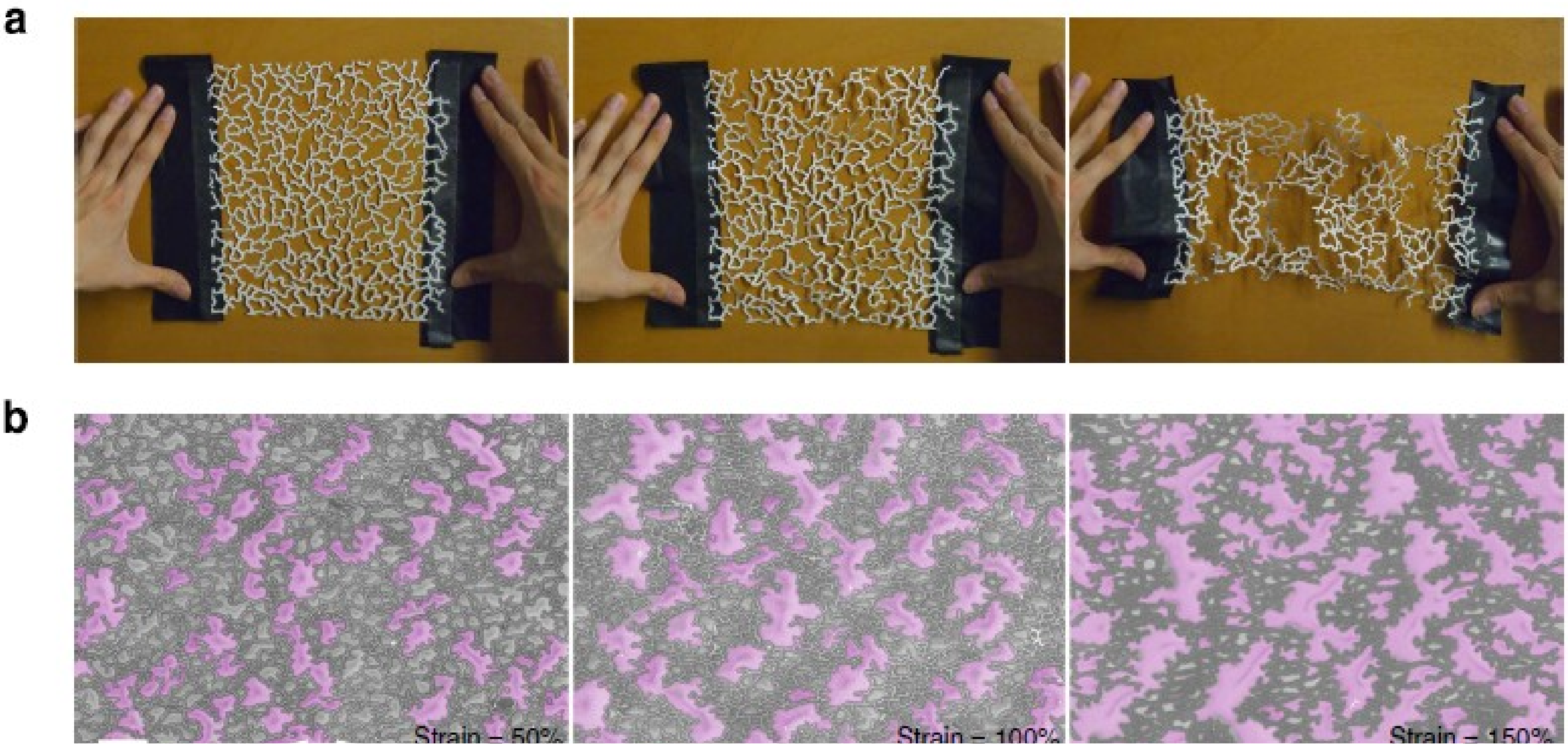
Transmittance spectra



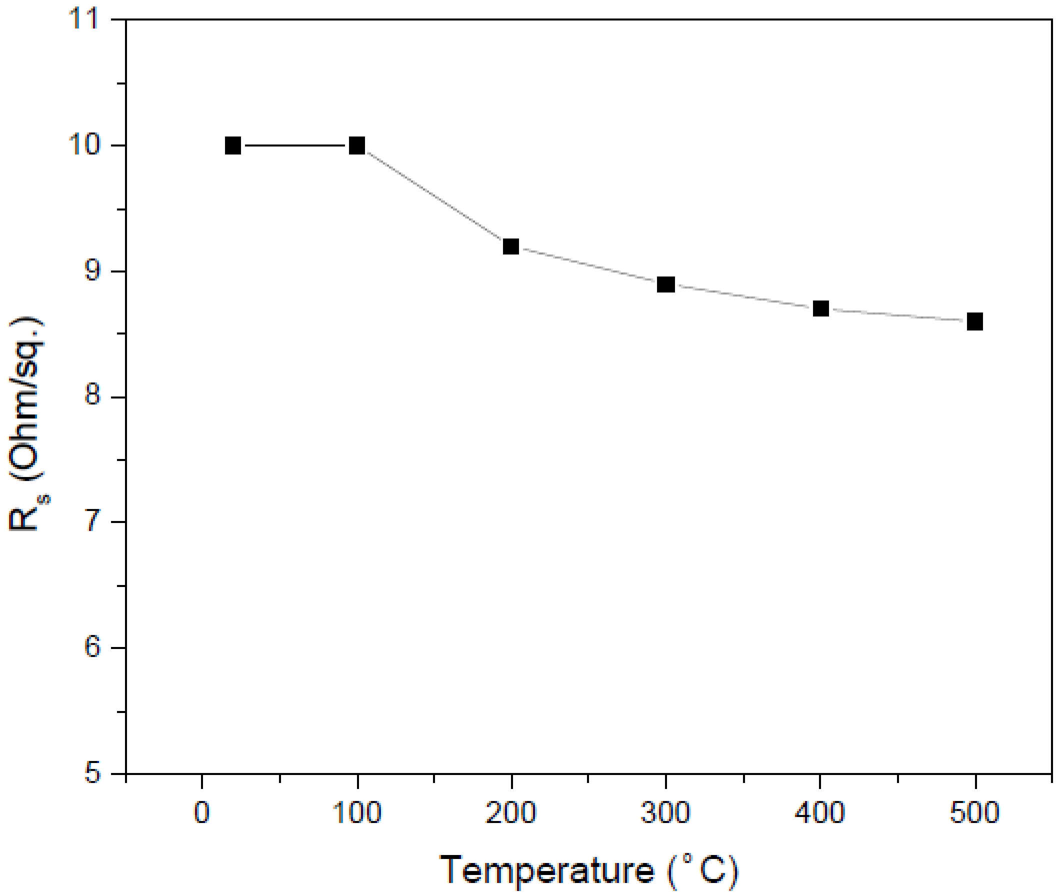


In the wavelength range of 400–1,000 nm, the Au nanomesh presents a transmittance of 82.5% (green triangles), close to the simulated result (B75.0%) (grey line). The transmittance of the Au nanomesh becomes larger after stretching (it changes from 82.5 to 85.0% (dark line) with strain changes from 0 to 80%). Comparison between specular (black line) and diffusion (blue line) transmittances of a Au nanomesh, showing that the difference is only ~3%.

Distributed rupture and formation of nested self-similar mesh



Thermal stability



Sheet resistance of Au nanomesh as a function of annealing temperature with 1 h heating. The sheet resistance even drops with increasing temperature, probably as a result of smoother surfaces of annealed Au nanowires

Conclusion

- Grain boundary lithography was introduced to fabricate Au nanomesh electrodes with excellent mechanical stretchability, electrical conductivity and optical transparency.

- The vast difference in the elastic moduli of Au and PDMS allows the stretched Au mesh to deflect out of the plane, while the substrate stabilizes distributed rupture of Au ligaments.

- A nested self-similar mesh is formed at quite large strains and this allows the electrode behaving like the case at small strains, and therefore it can be further stretched to larger strains.

- This work shows that the Au nanomesh electrodes are promising for applications in foldable photoelectronics and muscle-like transducers.

Thank You