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Self-healing electronic skins for aquatic environments

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Abstract

Gelatinous underwater invertebrates such as jellyfish have organs that are transparent, stretchable, touch-sensitive and self-healing, which allow the creatures to navigate, camouflage themselves and, indeed, survive in aquatic environments. Artificial skins that emulate such functionality could be used to develop applications such as aquatic soft robots and water-resistant human–machine interfaces. Here we report a bio-inspired skin-like material that is transparent, electrically conductive and can autonomously self-heal in both dry and wet conditions. The material, which is composed of a fluorocarbon elastomer and a fluorine-rich ionic liquid, has an ionic conductivity that can be tuned to as high as 10^{-3} S cm^{-1} and can withstand strains as high as 2,000%. Owing to ion–dipole interactions, it offers fast and repeatable electro-mechanical self-healing in wet, acidic and alkali environments. To illustrate the potential applications of the approach, we used our electronic skins to create touch, pressure and strain sensors. We also show that the material can be printed into soft and pliable ionic circuit boards.

Fig. 1: Design of a gel-like, aquatic, stretchable and self-healing electronic skin (GLASSES).

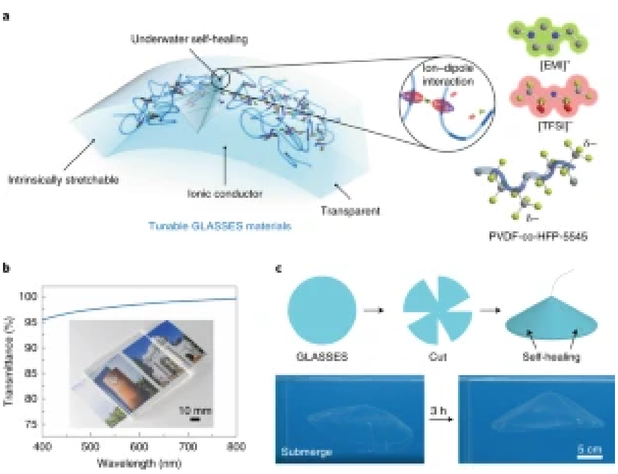


Fig. 2: Tunable electrical and mechanical properties of the GLASSES material.

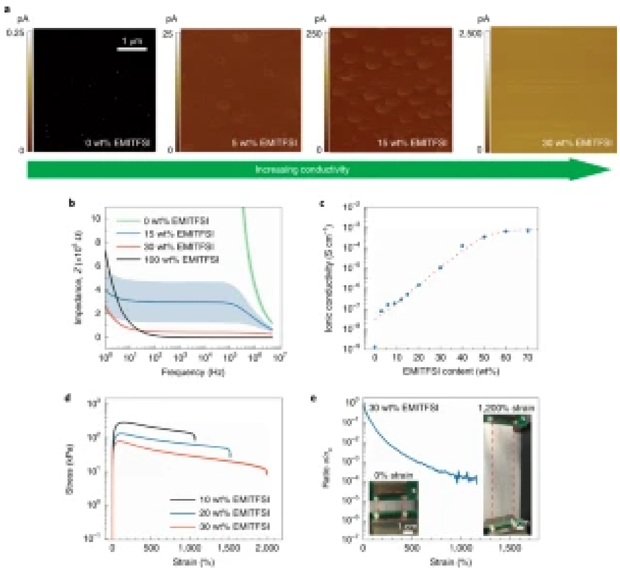


Fig. 3: Electro-mechanical self-healing abilities.

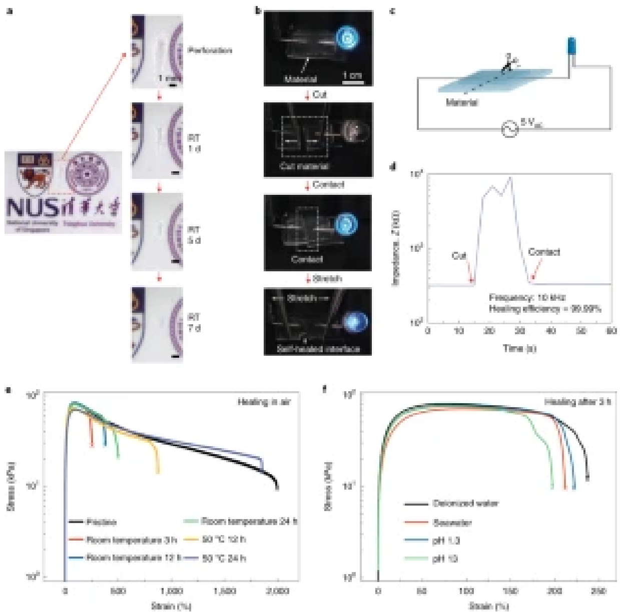


Fig. 4: Touch, pressure and strain sensors fabricated from GLASSES.

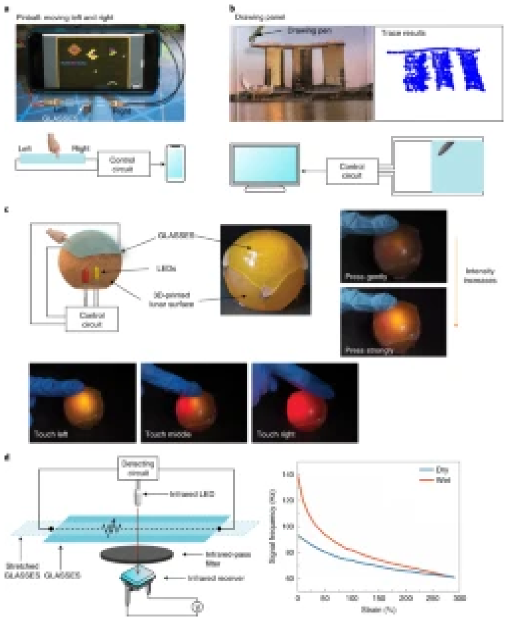
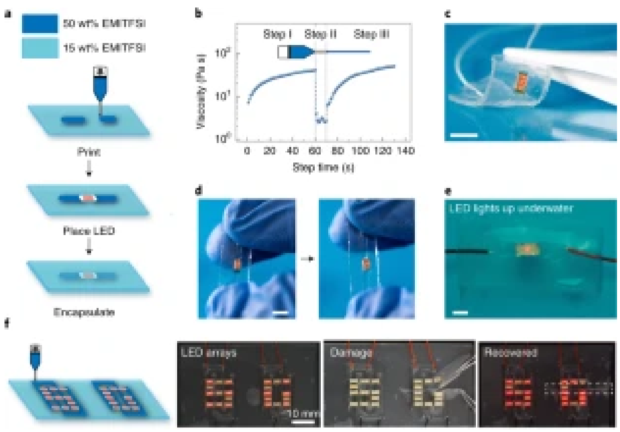


Fig. 5: Soft, stretchable, transparent, self-healing PCB.



Data availability

The data that support the plots within this paper and other findings of this study are available from the corresponding author upon reasonable request.

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Contributions

B.C.-K.T., C.W., Y.C., and Y.J.T. conceived and designed the experiments; Y.C., Y.J.T., S.L. and W.W.L. carried out experiments and collected the overall data; Y.C., Y.J.T. and H.C.G. contributed to materials fabrication and characterization. S.L., W.W.L. and Y.J.T. performed electrical properties characterization and worked on sensors demonstration. S.L. and Y.J.T. worked on transparent and self-healable soft PCB. Y.Q.C. contributed the DFT calculations. Y.J.T., B.C.-K.T., Y.C., S.L. and C.W. analysed all the data and co-wrote the paper. All authors discussed the results and commented on the manuscript.

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Ethics declarations

Competing interests

The authors declare no competing interests.

Additional information

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Supplementary information

Supplementary Information

Supplementary Notes 1–4, Supplementary Tables 1–4 and Supplementary Figures 1–22

Supplementary Video 1

Autonomous self-healing of GLASSES. The video starts with a time-lapse capture with the transparent material laid on a picture, then a puncture is made through the material. The material is observed under a microscope for three days. It self-heals without any external stimuli such as pressure, temperature or organic solvents. After that, a new piece of material is bifurcated, and self-healed. The material can be stretched again after healing in ambient conditions for 24 hours.

Supplementary Video 2

Playing a snake game on the GLASSES touch panel. The position of touch and swipe actions of a finger can be sensed by the material for human–machine interactions.

Supplementary Video 3

The position of touch can be sensed by the transparent material by utilizing its surface capacitance system and external amplifying circuits, which is used to make a drawing panel.

Supplementary Video 4

Conformable pressure sensor linked to LEDs for visualization of changes in pressure and touch locations. When the fingertip touches the material, a surface capacitance is introduced. When the fingertip presses down on the material, the contact area increases as the material is deformable, resulting in an increase in surface capacitance.

Supplementary Video 5

GLASSES material used as a strain sensor with optically encoded signal output. The frequency signal is changing with strain.

Supplementary Video 6

GLASSES is made into a strain sensor, and is transparent and able to send out optical communication information of its strain state. This video is a demonstration of an infrared communication system in air and water, and the signal–strain plot showing that the transmitted signal carrying information (frequency) is dependent on the strain. The display on the phone shows the balloon status. The infrared signal is directed through GLASSES only. As demonstrated in the beginning of the video, the signal is interrupted when the balloon is being tilted as the infrared LED is not aligned with the receiver. The status shows ‘Expanding’ when the balloon starts to expand, corresponding to a decrease in frequency output. We also show that the demonstration works when the GLASSES are submerged in water. After touching the water surface, the display changes to ‘In water’, correlating to a sudden increase of frequency output. When the frequency signal decrease again, the status changes to ‘Expanding in water’.

Supplementary Video 7

Self-healed GLASSES (with LED) submerged in water as an unobtrusive soft ‘robot’ among small underwater creatures. The transparent materials allow light to transmit through them. The multiple self-healed regions remain intact underwater. The LED-embedded GLASSES mimics the bioluminescence of jellyfish underwater, sending messages to the shrimps that they react to by escaping from the bright ‘jellyfish’. The same setup is repeated by using LEDs embedded in an opaque material, where the shrimps did not visibly react when the LEDs are turned on because the light cannot transmit through the material. The shrimps reacted only after the opaque material is ‘toppled’, when the light intensity suddenly increases.

Supplementary Video 8

GLASSES material can be printed into soft, stretchable, transparent PCB. The PCB can be mechanically twisted and stretched.

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