Paper presentation

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Ultra-conformal drawn-on-skin electronics for multifunctional motion artifact-free sensing and point-of-care treatment

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Srikrishnarka

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A cellulose/β-cyclodextrin nanofiber patch as a wearable epidermal glucose sensor

Kyu Oh Kim, [a] Geon Jin Kim[a] and Ji Hye Kim*[b]

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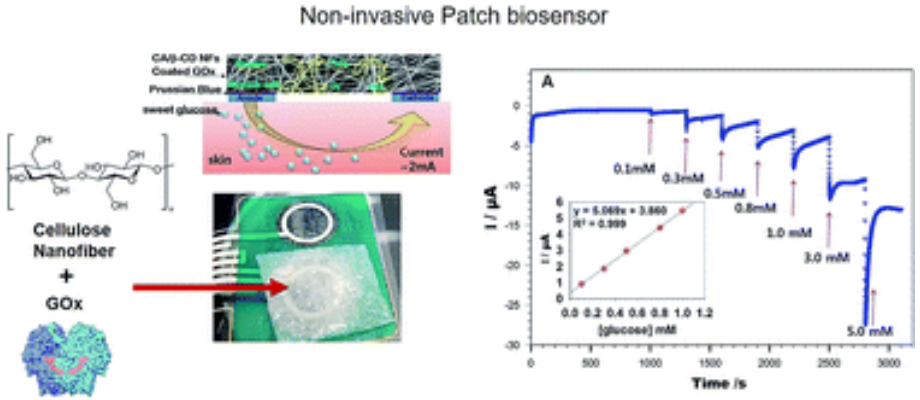
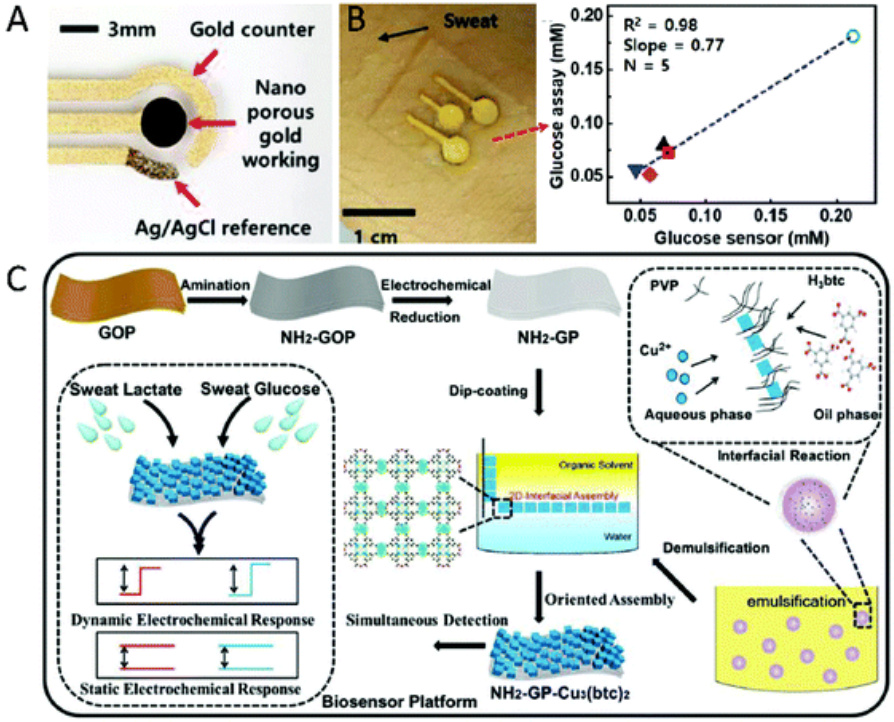
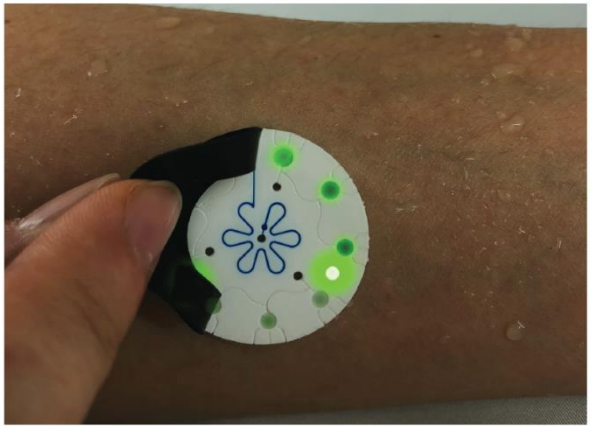
Wearable biochemical sensors for human health monitoring: sensing materials and manufacturing technologies

Guanglei Li and Dan Wen*





Cite this: *Lab Chip*, 2018, **18**, 2178



A fluorometric skin-interfaced microfluidic device and smartphone imaging module for *in situ* quantitative analysis of sweat chemistry†

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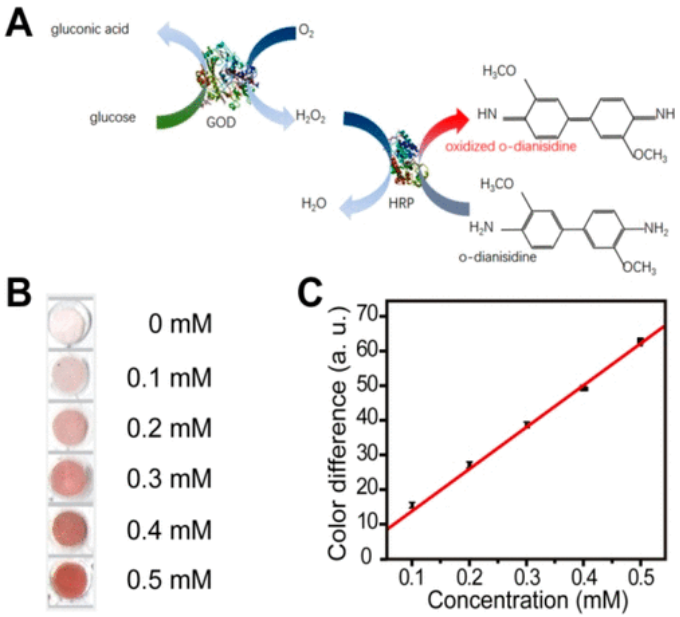
Microfluidic Chip-Based Wearable Colorimetric Sensor for Simple and Facile Detection of Sweat Glucose

Jingyu Xiao,[‡] Yang Liu,[‡] Lei Su,*[,‡,§] Dan Zhao,[§] Liang Zhao,*[,‡] and Xueji Zhang*[,‡]



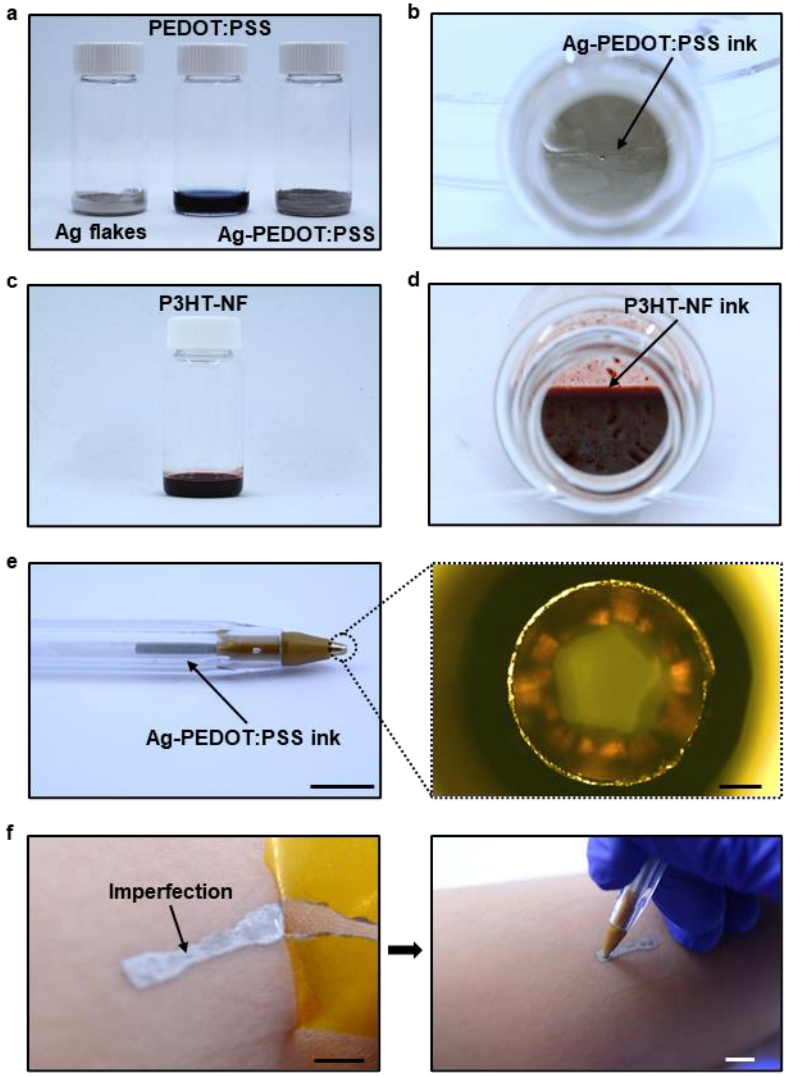
Motivation…

- Frugal engineering
- Ease of fabrication
- Real-time monitoring of sensor data
- Multifunctionality…unlimited possibilities, localized heating, skin hydration sensor, transistors, ECG, EMG, Electrophysiological sensor (EP) faster healing capability.

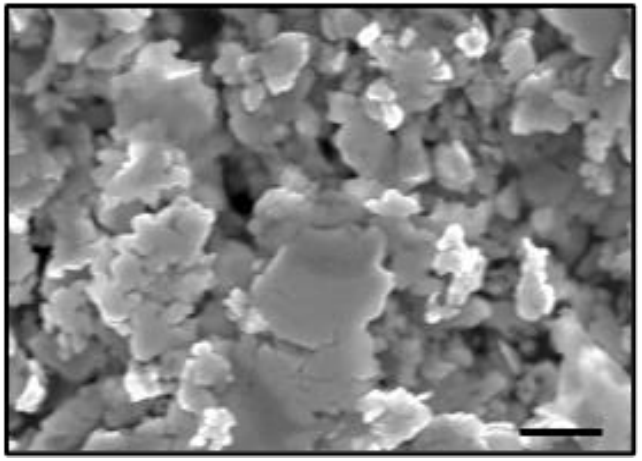
Materials used:

1. Ag flakes/poly(3,4-ethylenedioxythiophene)- poly(styrenesulfonate) (Ag-PEDOT:PSS)
2. poly(3-hexylthiophene-2,5-diyl) nanofibrils (P3HT-NF)
3. polydimethylsiloxane (PDMS)
4. Porcine
5. poly(vinylidene fluoride-co-hexafluoropropylene) (PVDF-HFP) + 1-ethyl-3 methylimidazolium bis(trifluoromethylsulfonyl)imide ([EMIM] [TFSI]

Fabrication of conducting ink and stencils for electrode fabrication



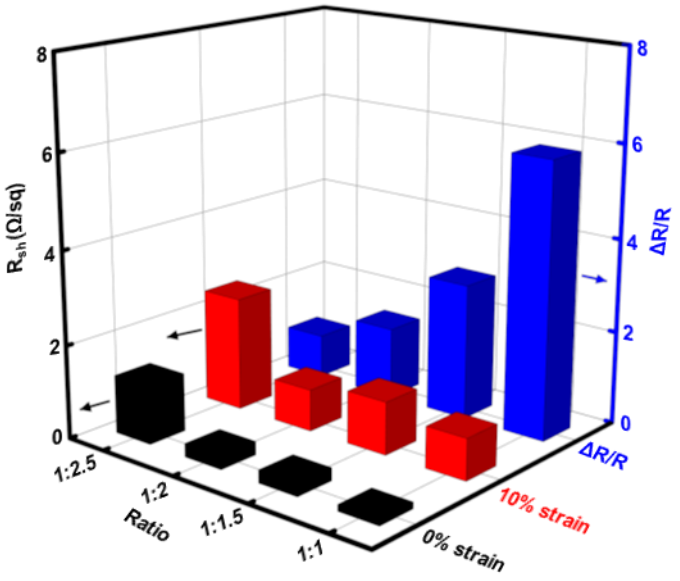
Optical images of the conducting ink and ball-point pen to draw the ink on skin



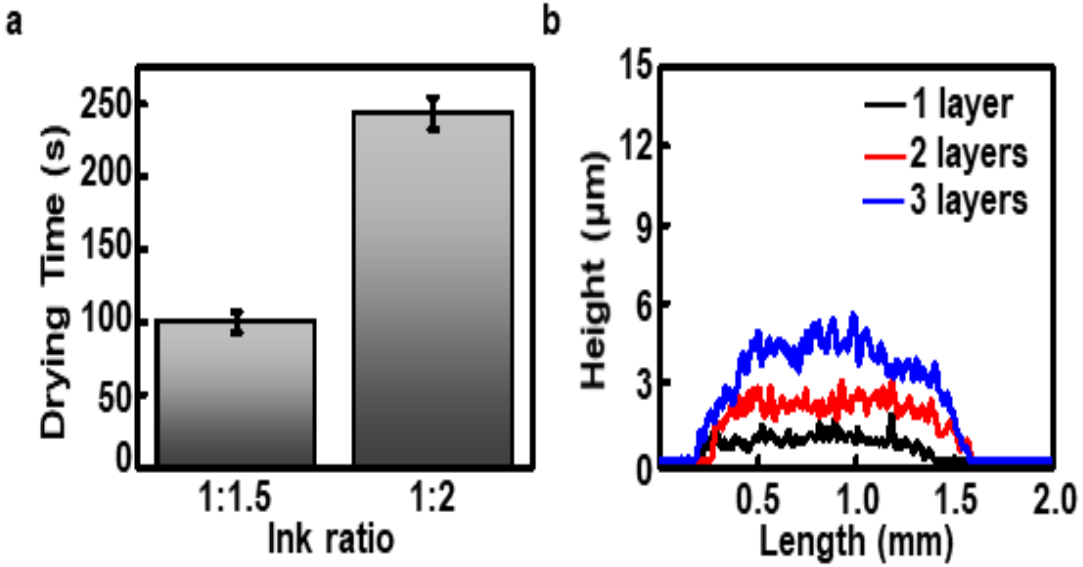
SEM image showing the nano/micro-flake structures of the Ag-PEDOT:PSS ink (scale bar 2 µm)

The Ag-PEDOT:PSS ink is drawn into the transistor stencil (left). The P3HT-NF ink is drawn into the semiconductor stencil (middle). The ion gel ink is drawn into the dielectric stencil (right). The stencils are removed after the corresponding ink layer is dried (scale bars 5 mm).

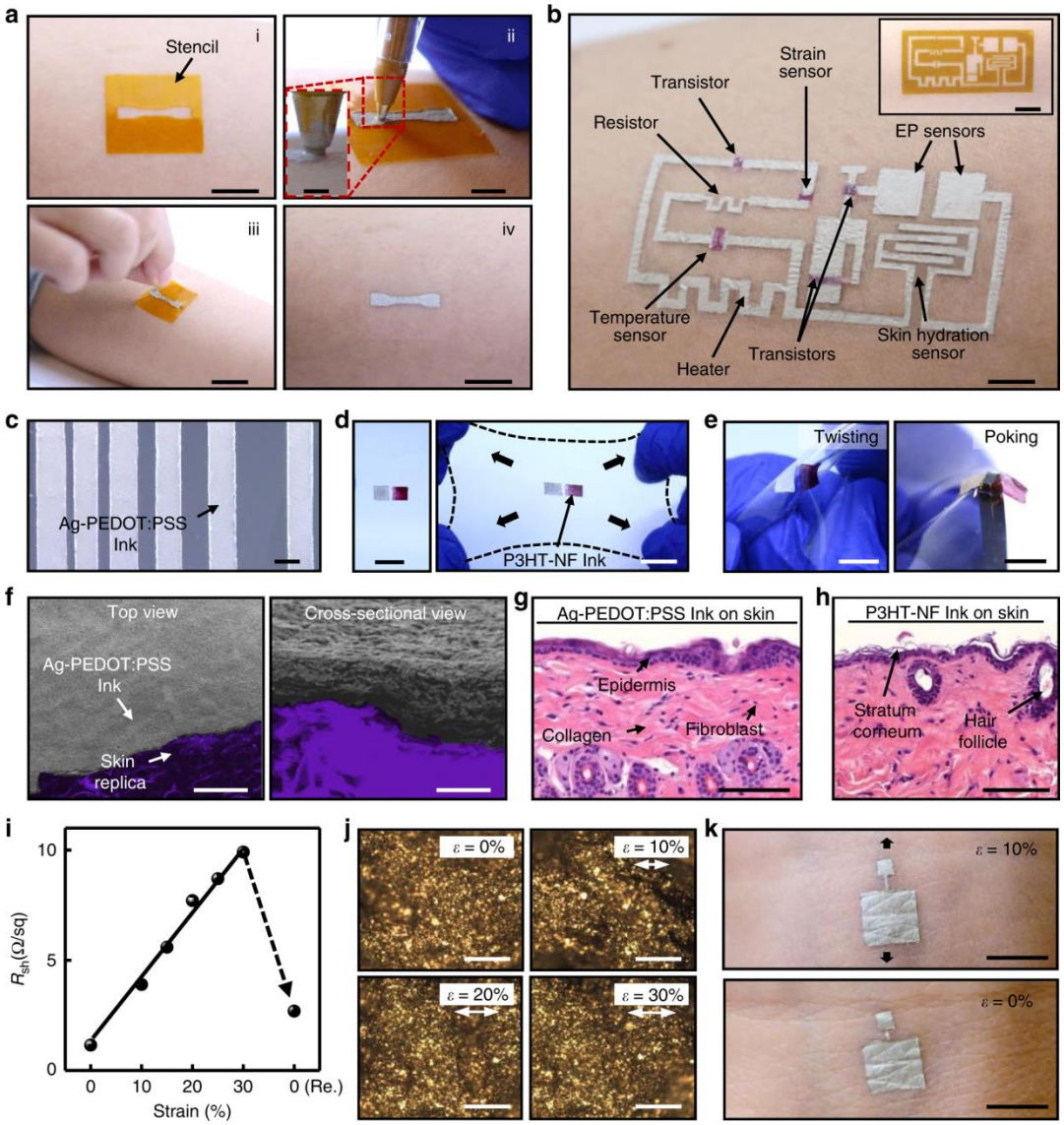
Characterization of the conducting ink



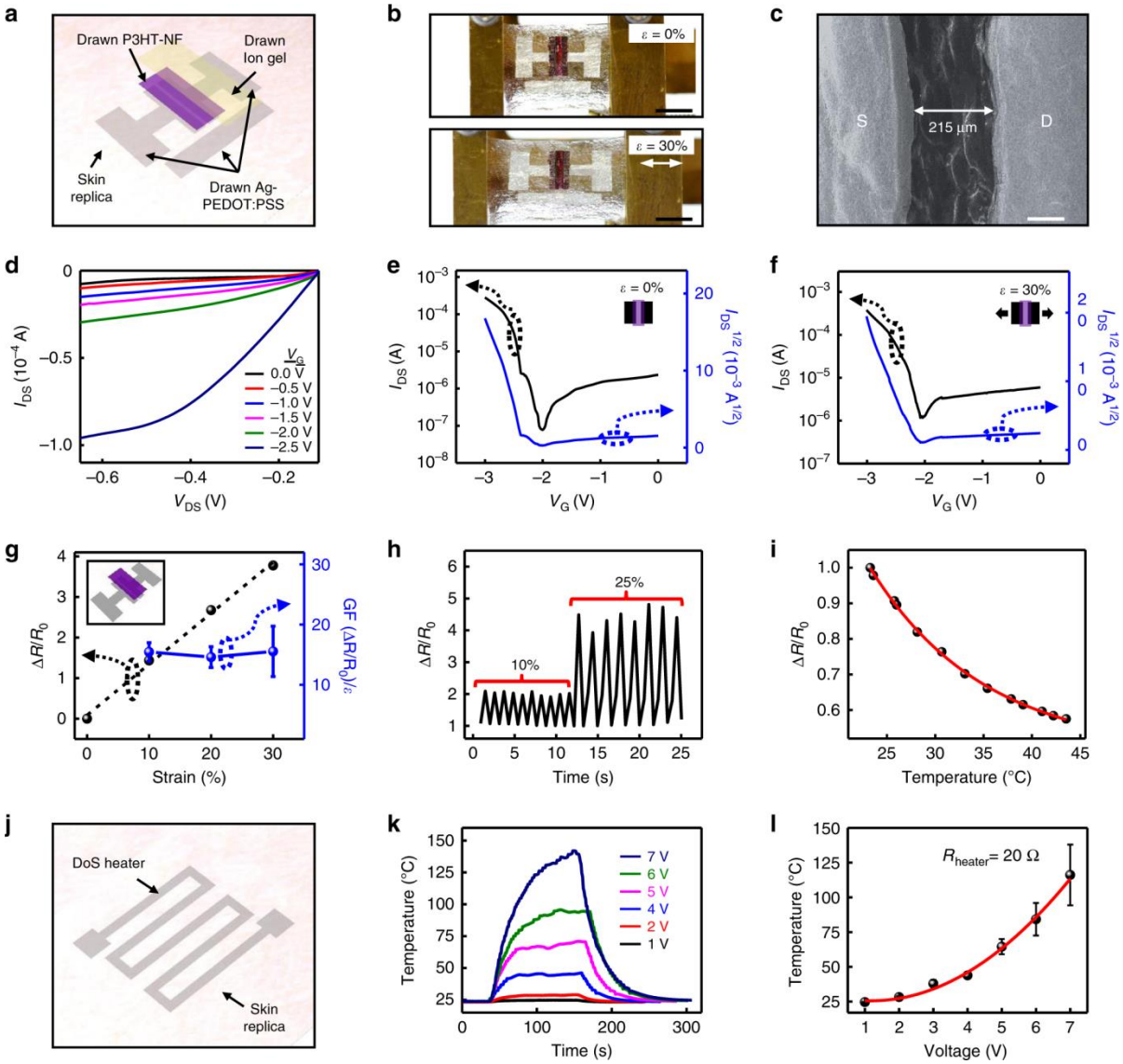
Comparison between the sheet resistances, stretchability, and change in resistance of different Ag flakes : PEDOT:PSS ink ratios.



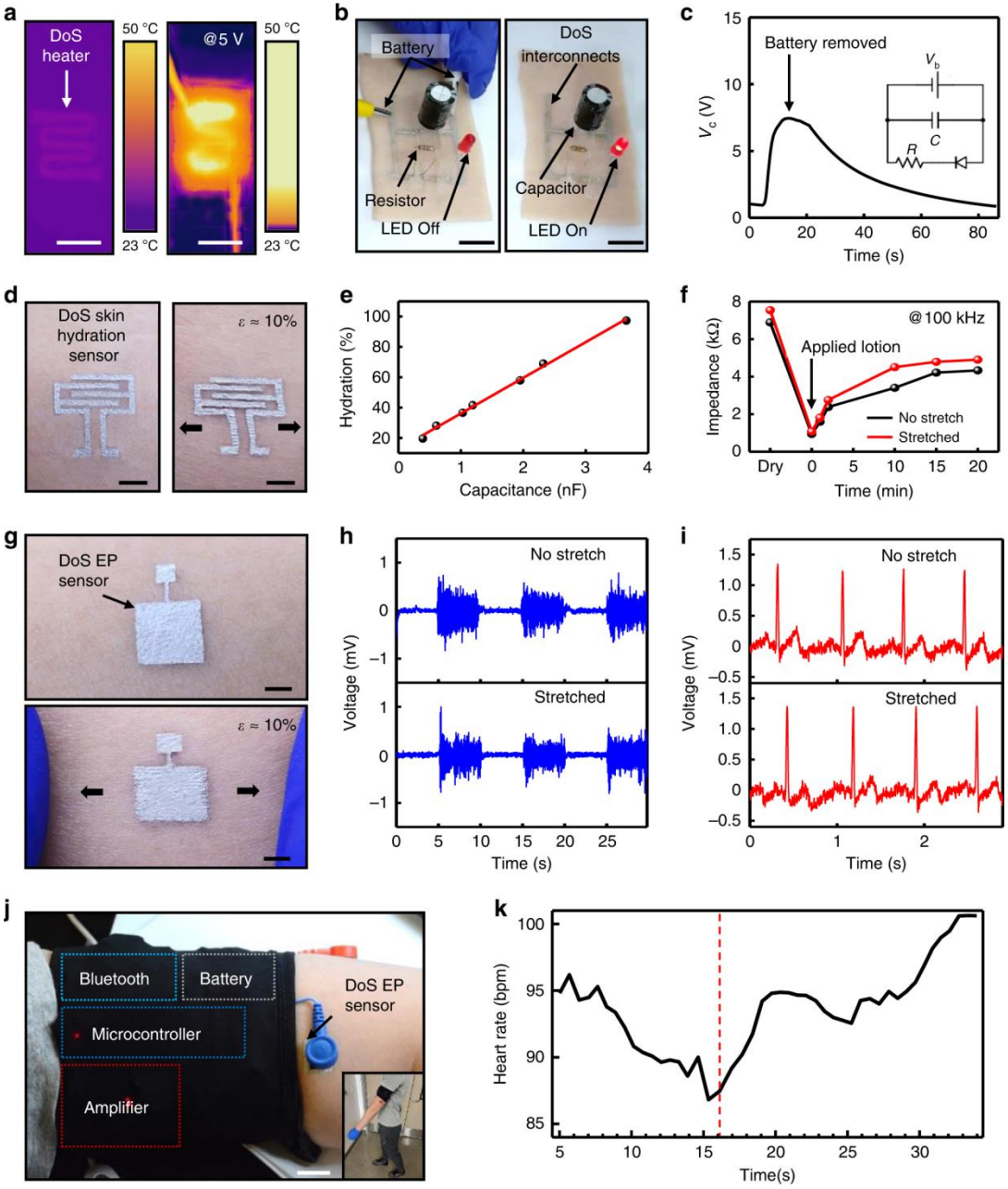
a, Time required for two different Ag-PEDOT:PSS ink ratios to visibly dry. **b,** Thickness obtained with a profilometer of the Ag-PEDOT:PSS ink based on drawing multiple ink layers.



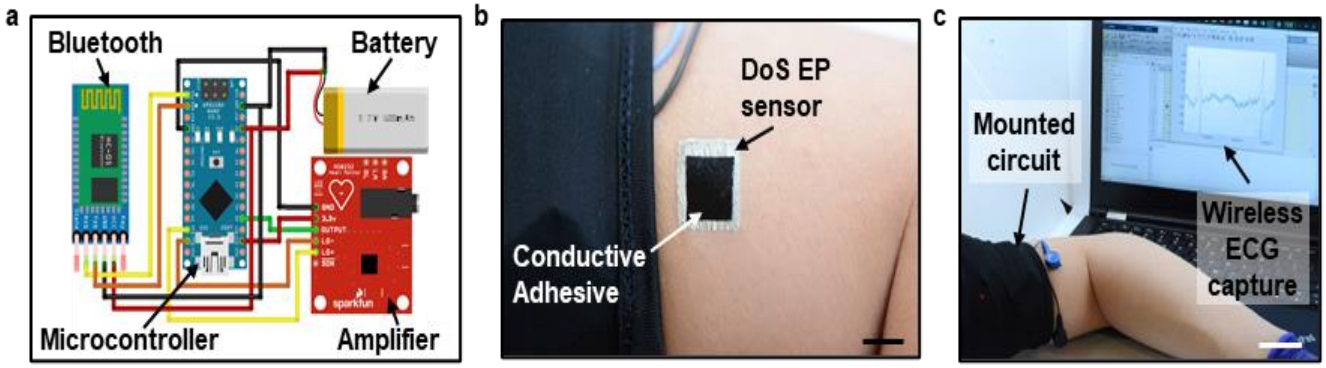
a DoS electronics drawing process.
b An example DoS integrated system including a resistor, transistors, heater, EP (electrophysiological) sensors, temperature sensor, strain sensor, and skin hydration sensor drawn on human skin (scale bar 5 mm). The corresponding stencil for the conductor is shown in the inset (scale bar 1 cm).
c Achievable line spacing using stencils and the conductive Ag-PEDOT:PSS ink (scale bar 1 mm).
d Non-stretched (left, scale bar 1 mm) and biaxially stretched (right, scale bar 1 cm) states of the drawn structure consisting of Ag-PEDOT:PSS conductive (left square) and P3HT-NF semiconducting (right square) inks on PDMS.
e Twisting (left) and poking (right, scale bars 1 cm) deformations of the drawn structure with conductive and semiconducting inks.
f SEM images of the Ag-PEDOT:PSS ink showing ultraconformal contact with the grooves and bumps (left, scale bar 250 μm) on top of skin replica and cross-section showing Ag-PEDOT:PSS microstructure (right, scale bar 20 μm). The purple color indicates the skin replica.
g Histology image of the Ag-PEDOT:PSS ink on skin of mice after 48 h (scale bar 100 μm).
h Histology image of the P3HT-NF ink on skin of mice after 48 h (scale bar 100 μm).
i Sheet resistance vs. strain while stretching the Ag-PEDOT:PSS ink up to 30% and releasing. The error bars represent the s.d.
j Optical microscope images of the Ag-PEDOT:PSS ink on skin replica stretched up to 30% (scale bars 100 μm).
k DoS EP sensor on the wrist of subject in stretched (top) and non-stretched (bottom) states (scale bars 5 mm).



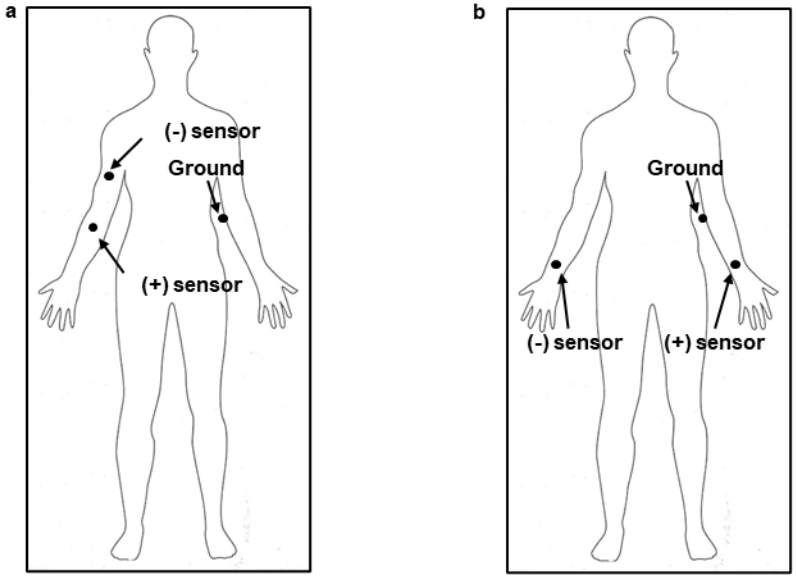
a Schematic of the DoS transistor based on the Ag-PEDOT:PSS ink as the conductor, P3HT-NF ink as the semiconductor, and ionic gel ink as the dielectric.
b DoS transistor on skin replica under no strain (top) and 30% strain (bottom, scale bars 5 mm).
c SEM image of the drawn source (S) and drain (D) electrodes and the channel (scale bar 100 µm).
d I-V curve of DoS transistor without applied strain.
e, **f** Transfer curves of DoS transistor without and 30% strain along the transistor channel length direction.
g Electrical resistance of the DoS strain sensor under applied mechanical strain up to 30% and the corresponding gauge factors. Inset shows a schematic of the DoS strain sensor. The error bars represent the s.d.
h Relative resistance change of the DoS strain sensor under cyclic stretching and releasing at 10% and 25% strain.
i Relative resistance change of the DoS temperature sensor under different temperature conditions.
j Schematic of the DoS heater based on the conductive ink.
k Temperature profiles under different applied voltage on the DoS heater.
l Calibration curve of the DoS heater. The error bars represent the s.d.



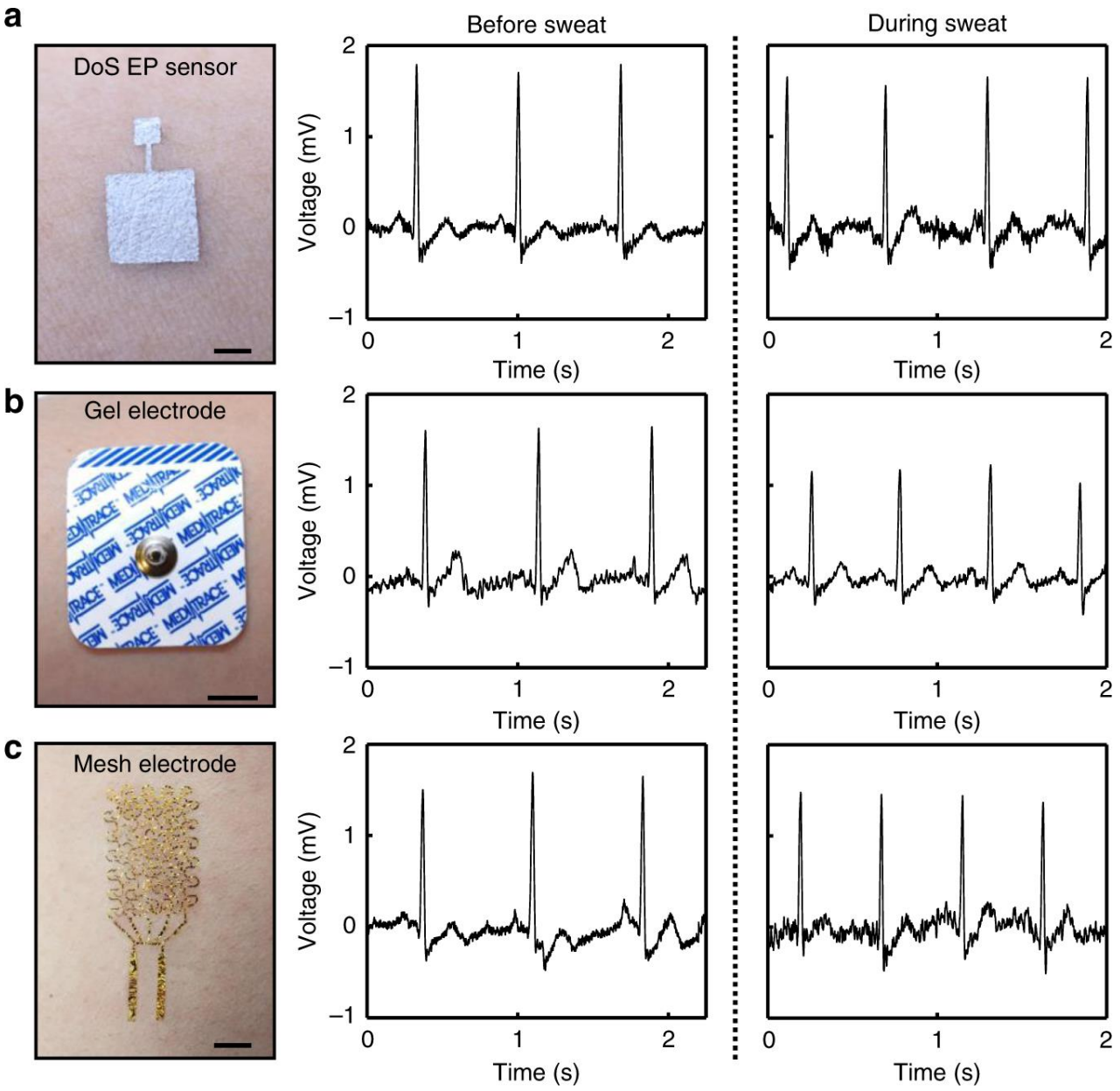
a IR camera images of the DoS heater on skin without applied voltage (left) and with an applied voltage of 5 V (right, scale bars 1 cm).
b Ag-PEDOT:PSS ink serving as the interconnection during charging of a capacitor (left) and discharging through the resistor and LED (right, scale bars 2 cm).
c Voltage of the capacitor showing charging until the battery is removed and then discharging afterwards. Inset is the circuit diagram showing a battery connected to a capacitor, which is connected to a resistor and LED that are connected in series.
d DoS skin hydration sensor on skin without (left) and with applied strain (right, scale bars 2 mm).
e Calibration of the DoS skin hydration sensor using a commercial hydration meter.
f Impedance of the DoS skin hydration sensor without and with mechanical stretch. The arrow indicates the time at which lotion was applied to the dry skin.
g DoS EP sensors without (top) and with applied strain (bottom, scale bars 2 mm).
h Recorded EMG signals without (top) and with applied strain (bottom). **i** Recorded ECG signals without (top) and with mechanical stretch (bottom).
j Schematic of the wireless transmission circuit components mounted on the arm and interface with the DoS EP sensors (scale bar 2 cm).
k Average beats/min over all trials derived from the ECG signals attained with the DoS EP sensors. In the time prior to the red dashed line, the subject was standing still. After the red dashed line, the subject began walking.



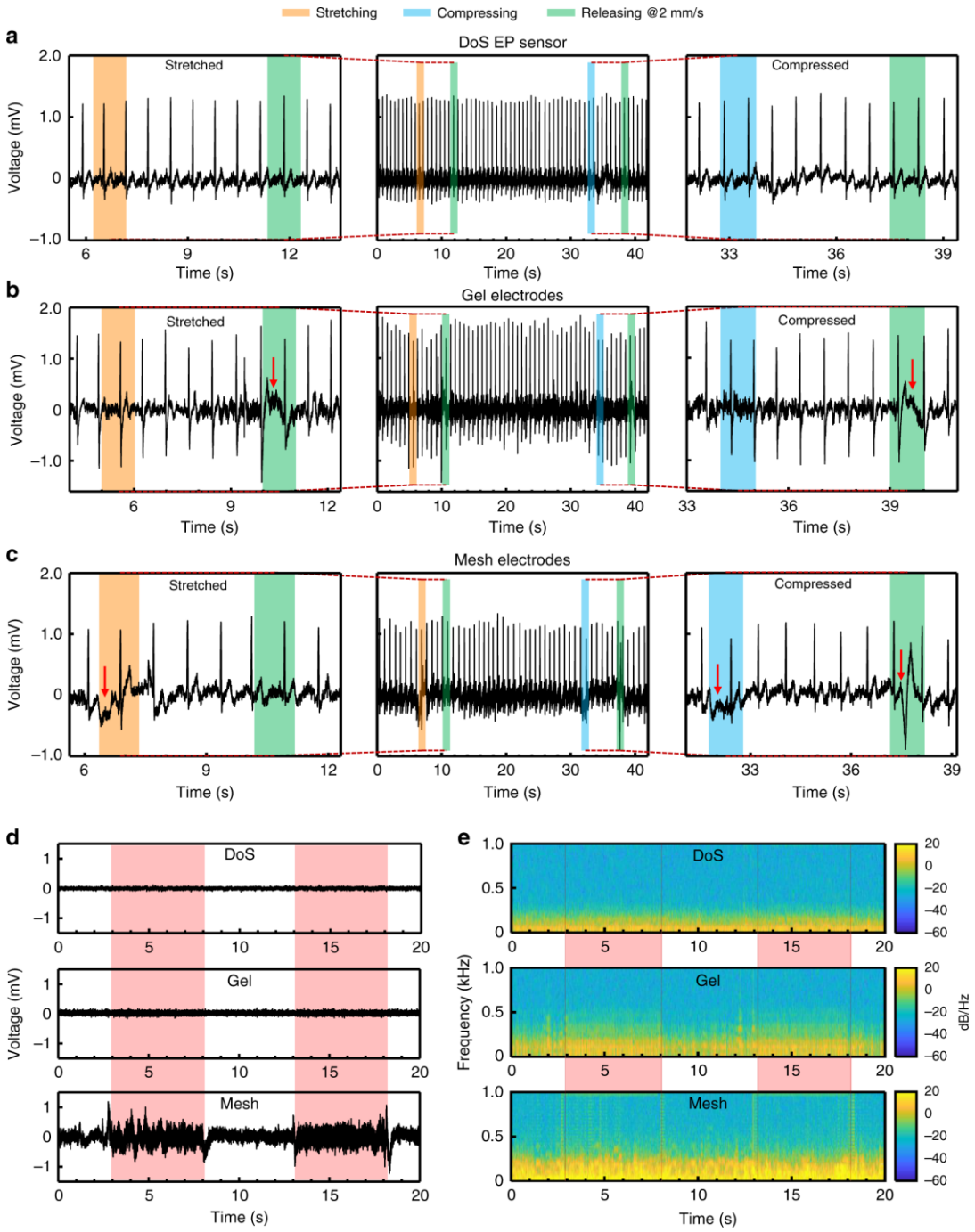
a, Diagram of the circuit created using Fritzing software. **b,** Photo of the interface without the snap electrical lead (scale bar 1 cm). **c,** Image of the mounted circuit on the arm and ECG signal acquisition via Bluetooth (scale bar 5 cm).



a, Schematic of EMG sensor placement on the right forearm and upper arm.
b, Schematic of ECG sensor placement on the wrists.



a DoS EP sensor (left, scale bar 2 mm) with ECG signals recorded before sweating (middle) and while sweating (right).
b Gel electrode (left, scale bar 1 cm) with ECG signals recorded before sweating (middle) and while sweating (right).
c Mesh electrode (left, scale bar 5 mm) with ECG signals recorded before sweating (middle) and while sweating (right).



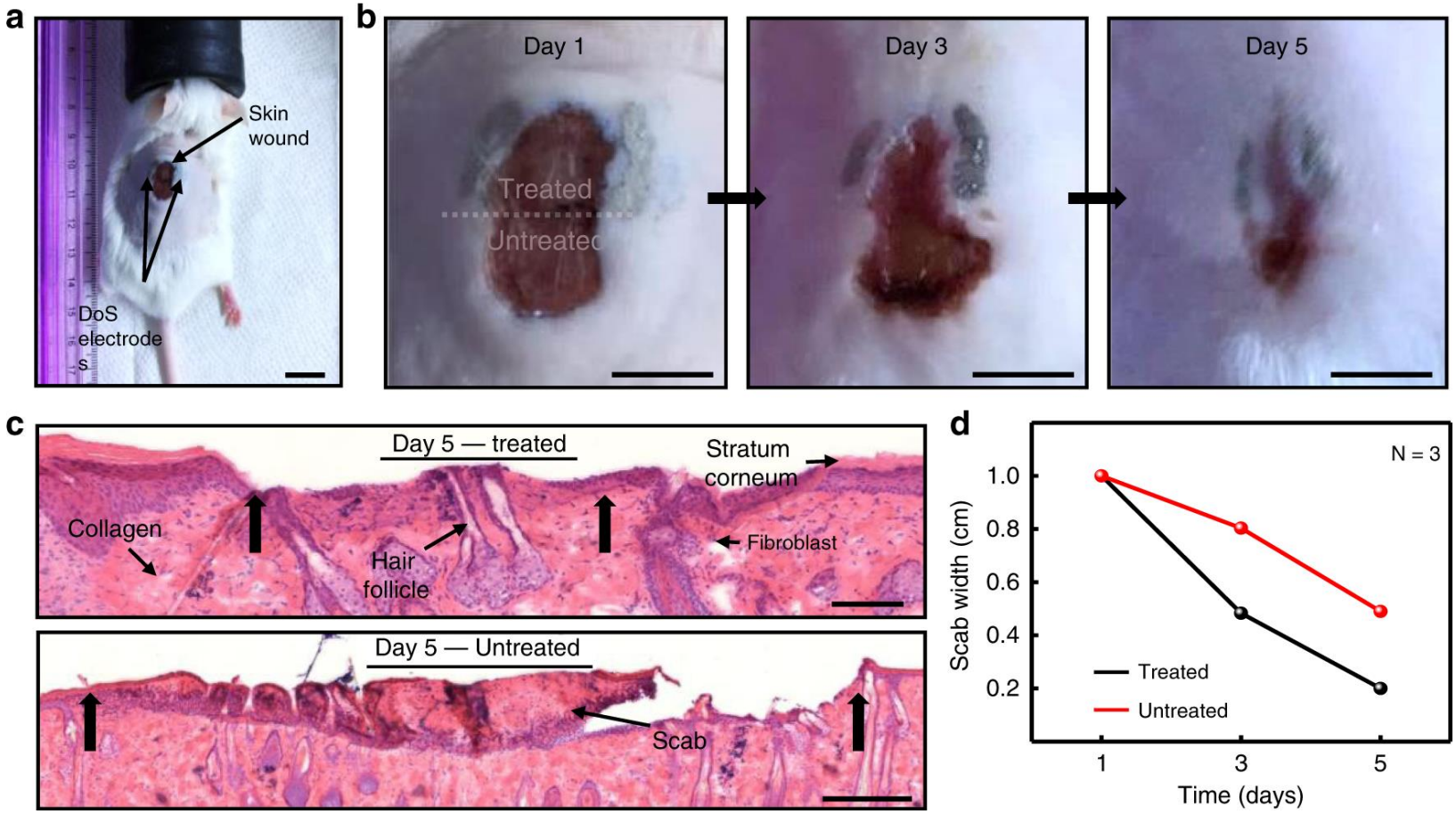
a Recorded ECG signals (middle) from the DoS EP sensors during local stretching/releasing cycle (left) and compressing/releasing cycle (right). The orange bars indicate the duration of the stretching motion, the blue bars indicate the duration of the compressing motion, and the green bars indicate the duration of the releasing motion.

b Recorded ECG signals (middle) from the gel electrodes during local stretching/releasing cycle (left) and compressing/releasing cycle (right). The red arrows indicate artifacts.

c Recorded ECG signals (middle) from the mesh electrodes during local stretching/releasing cycle (left) and compressing/releasing cycle (right). The red arrows indicate artifacts.

d Resting EMG signals recorded with vibration-induced motion of the arm. The pink bars indicate the duration of time in which the VM was turned on for the DoS EP sensors (top), gel electrodes (middle), and mesh (bottom) electrodes.

e TF maps of the resting EMG signals with the vibration-induced motion for the DoS EP sensors (top), gel electrodes (middle), and mesh (bottom) electrodes. The pink bars and red lines indicate the duration of the vibrations.



a Experimental setup showing DoS electrodes around a skin wound on the back of mice (*N* = 3). The DoS electrodes served as conductive paths for electrical stimulation (scale bar 2 cm).
b Photos of the wound healing on day 1 (left), day 3 (middle) and day 5 (right). Top half of the wound was treated with electrical stimulation while the bottom half was left untreated and healed naturally (scale bar 1 cm).
c Histology images of the treated (top, scale bar 100 µm) and untreated (bottom, scale bar 250 µm) halves of the wound on day 5. The black arrows indicate the width of the wound.
d Scab width over time for the treated (black) and untreated (red) halves of the wound.

Conclusion…

The inclusion of semiconductor and dielectric inks that are drawable on skin enables the development of active electronics, directly on skin

Immunity to motion artifacts is a substantial advancement for bioelectronics and suggests the daily usability of DoS electronics, especially in low-resource areas

DoS electronics can be implemented as a new, simple, and easily accessible yet promising personalized bioelectronics and healthcare tool