Supplementary Information (SI) for Materials Horizons.
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Supplementary Information

Highly transparent, intrinsically stretchable, photo-patternable, and vacuum-deposited electrodes for wearable sensors and displays

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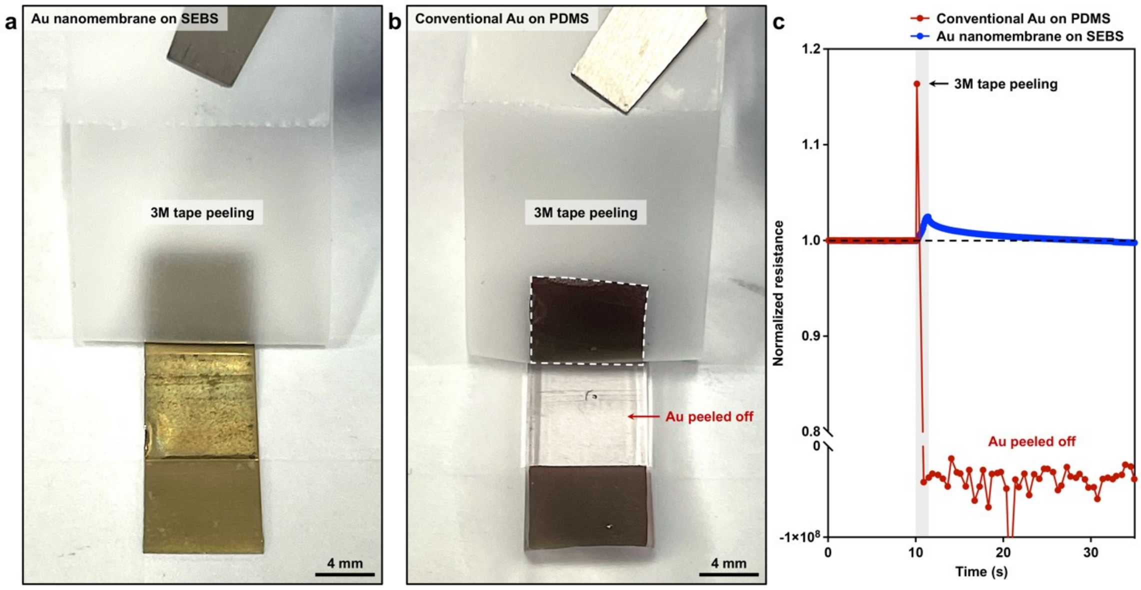
Legend for Supplementary Video 1

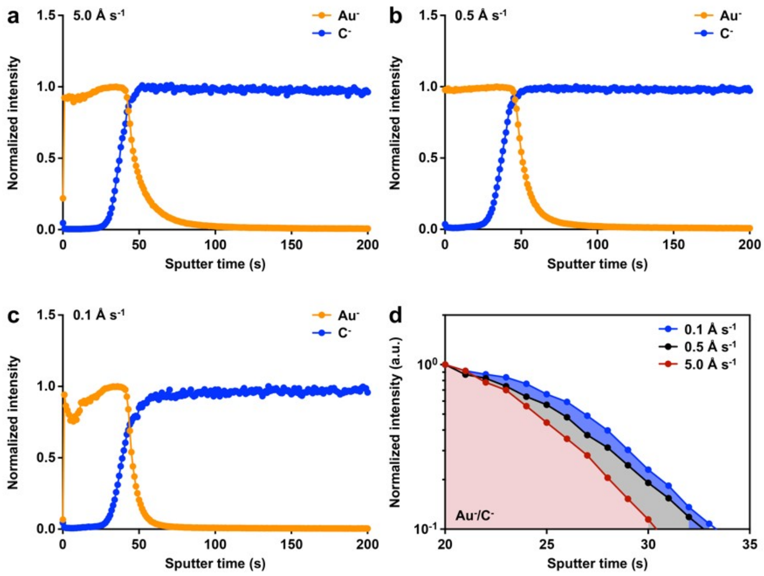
Other Supplementary Materials for this manuscript include the following:

Supplementary Video 1

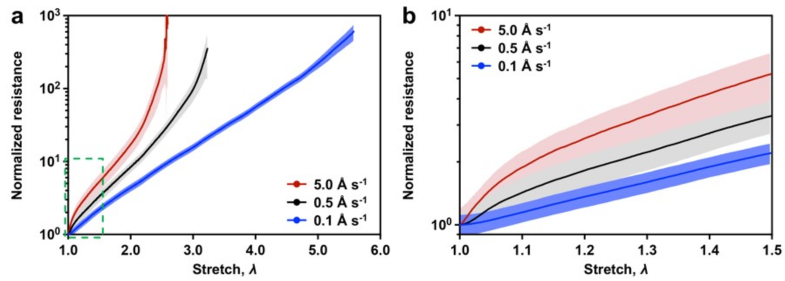
Supplementary Figures



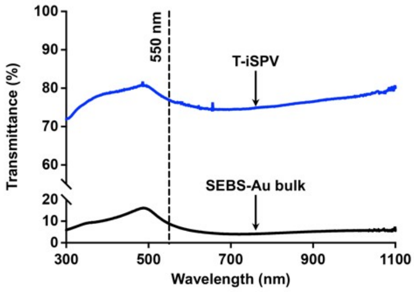
Supplementary Fig. 1 | Tape peeling test showing the robustness of Au nanomembrane on SEBS against mechanical abrasion. a, The Au nanomembrane on SEBS shows high resistance against tape peeling, while the surface remains nearly unbroken after tape peeling, due to its interpenetrating structure. **b,** The conventional Au on PDMS has weak bonding between AuNPs and substrate, thus the Au was easily peeled off by tape, leaving transparent substrate. **c,** Relative resistance changes of the Au nanomembrane on SEBS under tape peeling compared to the conventional Au on PDMS, which demonstrate the mechanical and electrical robustness of the Au nanomembrane on SEBS.



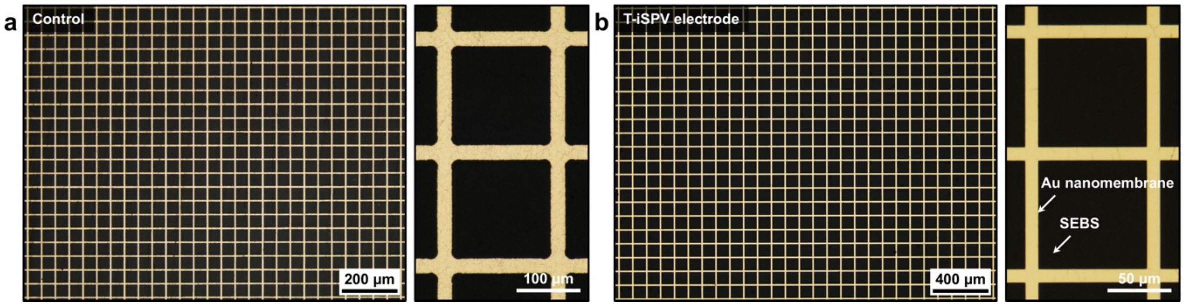
Supplementary Fig. 2 | TOF-SIMS analysis of AuNPs diffused within the SEBS elastomer matrix at different deposition rates. a–c, Au dispersion profiles at deposition rate of 5.0 Å s^{-1} (a), 0.5 Å s^{-1} (b), and 0.1 Å s^{-1} (c). **d,** The Au^--to-C^- peak ratio. Au^- (yellow) and C^- (blue) were selected as the characteristic group during sputtering to evaluate the nano-dispersion of the AuNPs to SEBS elastomer matrix along the film thickness direction.



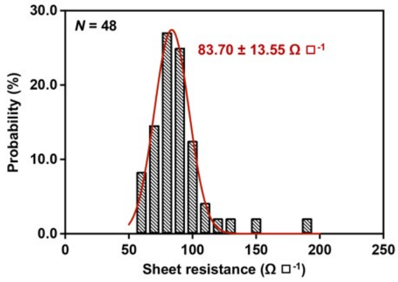
Supplementary Fig. 3 | Normalized resistance changes of Au nanomembrane electrodes under strain, displayed on a logarithmic scale. a,b, Measurements across strain ranges of 1.0–6.0 (a) and 1.0–1.5 (b). The sample has a width of 1 cm and a length of 3 mm.



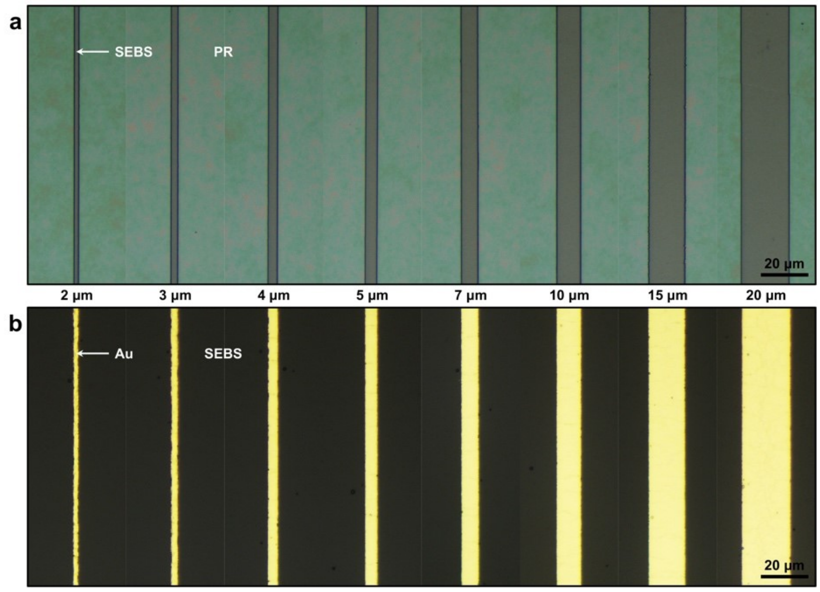
Supplementary Fig. 4 | Transmittance of the T-iSPV electrode compared to that of the SEBS-Au bulk electrode.



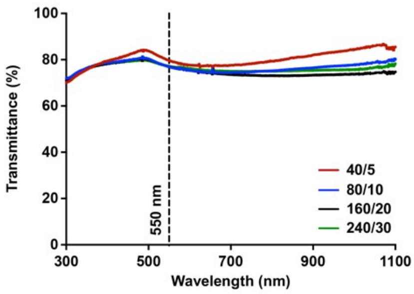
Supplementary Fig. 5 | OM images show the as-fabricated mesh electrodes after the wet etching process (a) and the lift-off process (b).



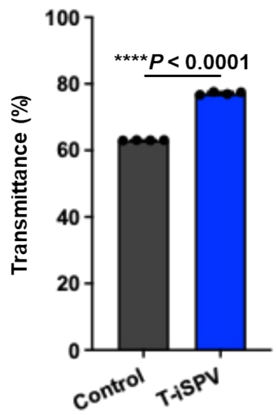
Supplementary Fig. 6 | The sheet resistance distributions of the T-iSPV. Histograms showing the sheet resistance for 48 individual electrodes.



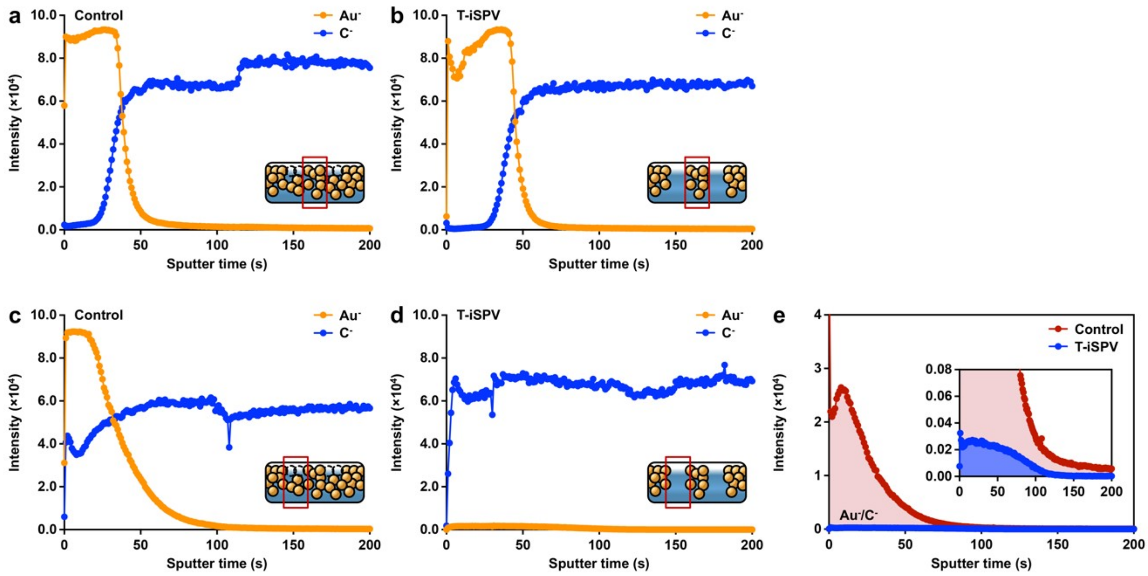
Supplementary Fig. 7 | OM images of patterned PR (a) and Au nanomembrane (b) on SEBS.



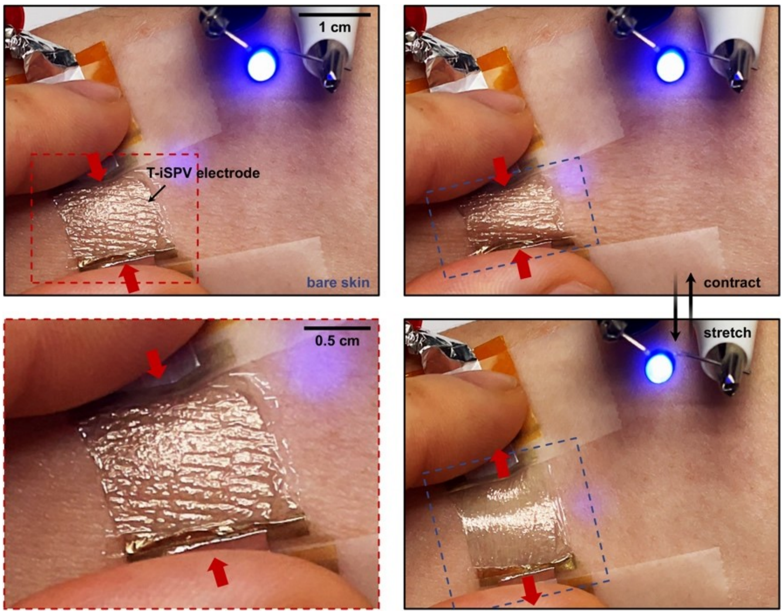
Supplementary Fig. 8 | Transmittance of the T-iSPV electrode as determined by the ratio of pitch to line width.



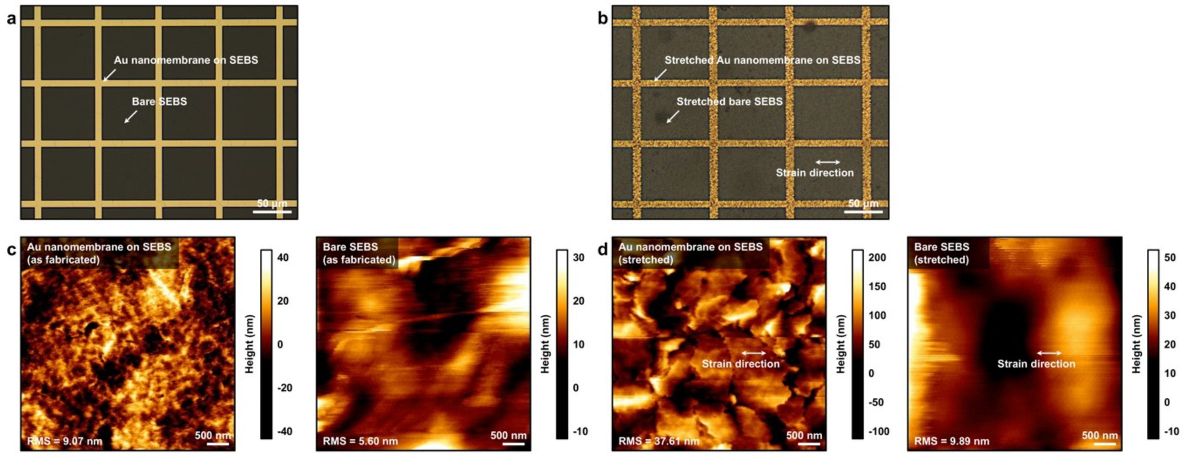
Supplementary Fig. 9 | Photographs and transmittance of the wet-etched control electrode and the T-iSPV electrode.



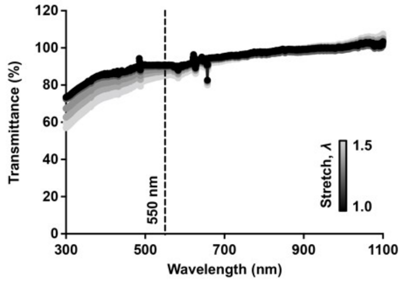
Supplementary Fig. 10 | TOF-SIMS analysis of AuNPs diffused within the SEBS elastomer matrix. a–d, Au dispersion profiles in the control line mesh region (a) and its adjacent blank region with residual AuNPs (c), compared to the T-iSPV line mesh region (b) and its blank region without AuNP accumulation at the surface (d). **e,** The Au^--to-C^- peak ratio. Au^- (yellow) and C^- (blue) were selected as the characteristic group during sputtering to evaluate the nano-dispersion of the AuNPs to SEBS elastomer matrix along the film thickness direction.



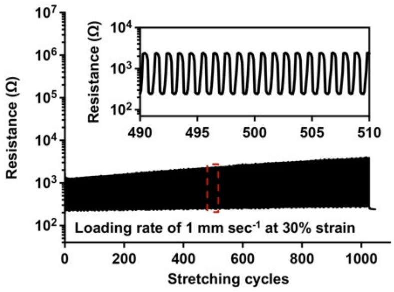
Supplementary Fig. 11 | Photographs of T-iSPV on the forearm skin. The blue dashed boxes on the right highlight the outer boundary of the electrode, while the red arrows indicate the directions of compressive and tensile strains. The red dashed box at the top left corresponds to the field of view shown in the bottom left. After undergoing compressive and tensile strains, the T-iSPV remained conductive.



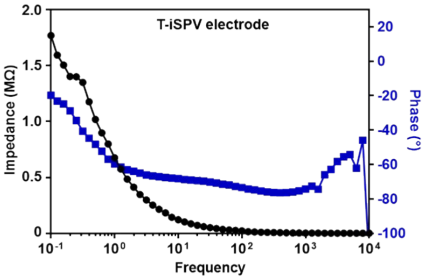
Supplementary Fig. 12 | OM and AFM images of the T-iSPV line mesh region and its adjacent blank region, before and after stretching. RMS, root mean square roughness.



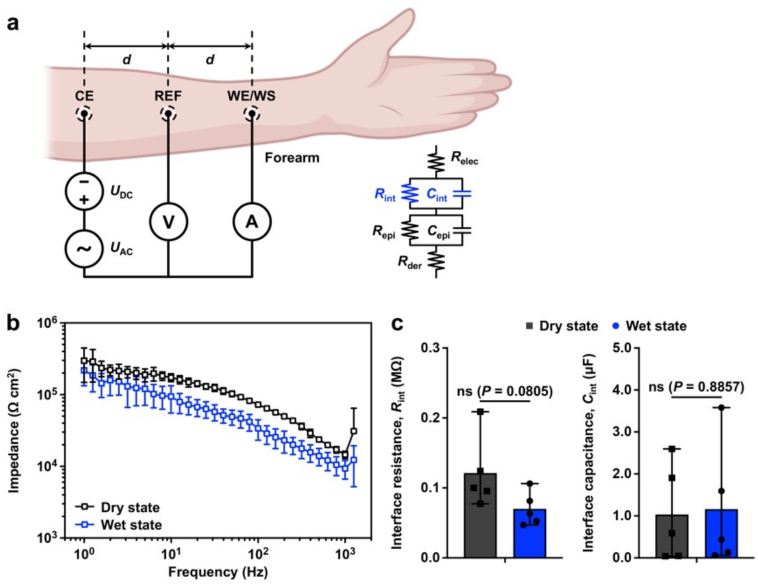
Supplementary Fig. 13 | Transmittance changes in T-iSPV electrodes under strain.



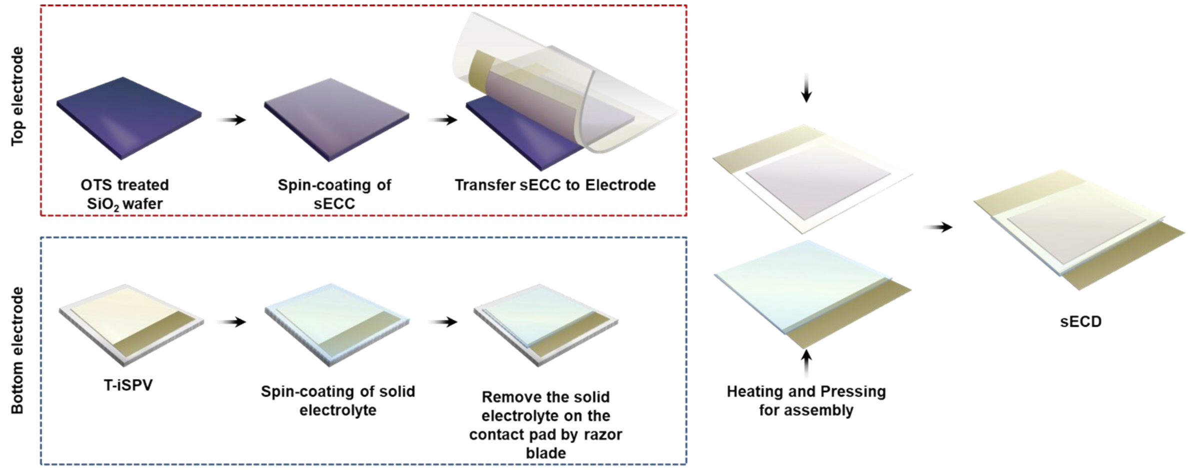
Supplementary Fig. 14 | Resistance changes in the T-iSPV electrodes during stretching cycles at 30% strain. The inset shows magnified resistance changes over 20 stretching cycles.



Supplementary Fig. 15 | Impedance of T-iSPV.

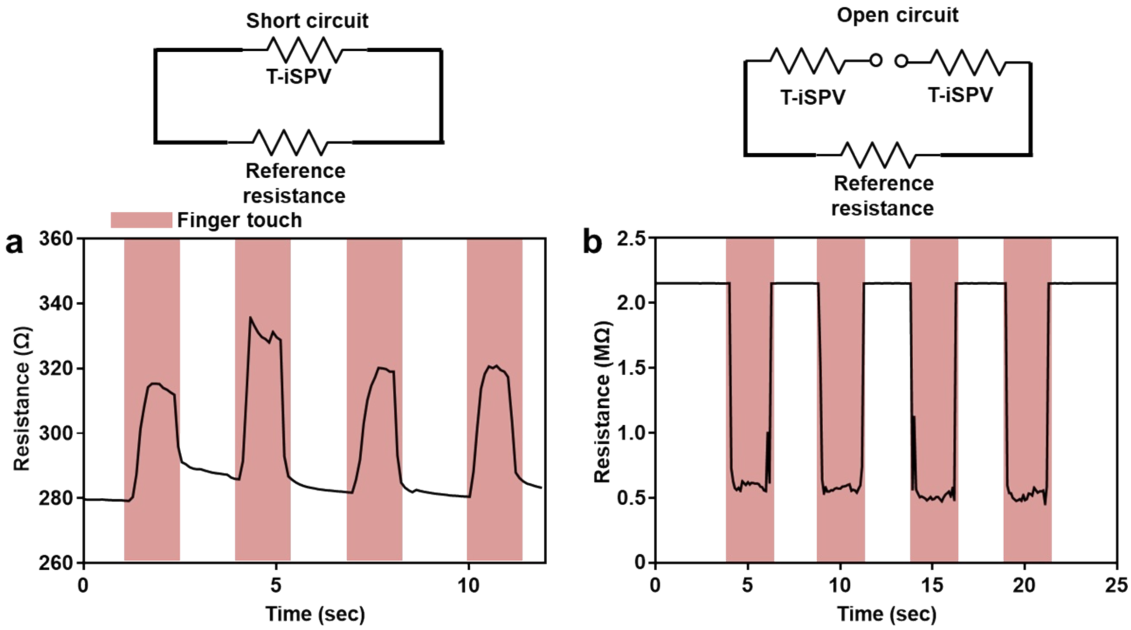


Supplementary Fig. 16 | EIS impedance measurement between the T-iSPV and the skin surface. a, Schematic illustration of the EIS measurement setup. REF, reference electrode; CE, counter electrode; WE, working electrode; WS, working sense electrode. **b,** Impedance measured on the forearm in contact with the T-iSPV in dry state for normal skin condition (black) and wet state for skin surface moistened with 1X PBS to mimic sweat exposure (blue). **c,** EIS fitting parameters, from the equivalent circuit diagram of the contact impedance, including the T-iSPV-skin interface resistance (left) and the T-iSPV-skin interface capacitance (right). Data are expressed as the mean ± s.d. (n = 5 for independent samples). Statistical significance and P values were determined by two-sided unpaired t-tests; ns, not significant. [Illustration in (a) was created with BioRender.com]



Supplementary Fig. 17 | Schematic illustration of fabrication process of sECD.

This revision more precisely describes the vertical stacking and bonding process used to assemble the sECD. We hope this explanation and the added visual aid address the reviewer's concerns thoroughly.



Supplementary Fig. 18 | Resistance changes measured from tactile sensors upon finger touch. a, Sensor configuration based on a short-circuit design, exhibiting negligible resistance variation due to a direct conductive path. **b**, Open-circuit sensor configuration with a parallel resistor, showing a distinct resistance change upon touch, enabling reliable tactile signal detection.

```matlab
%% Connect to LabChart and Initial Settings
clc;
clear all;

% Global variables (related to LabChart)
global gLCApp;
global gLCDoc;
global gChans;      % Channel number containing BPM data (e.g., 1)
global gChansData;  % Data retrieved from LabChart

% Check LabChart connection
try
    gLCApp = actxGetRunningServer('ADIChart.Application');
catch err
    error('Please start LabChart first.');
end
if isempty(gLCApp.ActiveDocument)
    error('Please open a document in LabChart.');
end

gLCDoc = gLCApp.ActiveDocument;
gChans = 1;   % Channel with BPM data (modify if necessary)
RegisterLCEvents(gLCDoc);  % Register LabChart event handler

%% Arduino Serial Communication Settings
serialPort = "COM8";  % Arduino connection port (modify as needed)
baudRate = 115200;
arduinoObj = serialport(serialPort, baudRate);

%% Plot Setup and CloseRequestFcn for the Figure
stopLoop = false;  % Loop termination flag
figureHandle = figure(1);
% Execute closeFigure callback when figure is closed
%set(figureHandle, 'CloseRequestFcn', @closeFigure);

time = []; % Array to store time data

subplot(4,1,1);
h7 = plot(nan, nan, 'b-'); % Tactile sensor data plot
xlabel('Time (s)');
ylabel('Tactile sensor');
sensor1 = []; % Array to store sensor data

subplot(4,1,2);
h2 = plot(nan, nan, 'g-'); % ECD ch1 data plot
xlabel('Time (s)');
ylabel('ECD1 state');
ECD1 = []; % ECD ch1 monitor

% BPM data plot (value from LabChart)
subplot(4,1,3);
hBPM = plot(nan, nan, 'b-');
xlabel('Time (s)');
ylabel('BPM (LabChart)');
bpmData = [];   % Array to store BPM data

subplot(4,1,4);
h3 = plot(nan, nan, 'g-'); % ECD ch2 data plot
xlabel('Time (s)');
ylabel('ECD2 state');
ECD2 = []; % ECD ch2 monitor

% Set fixed y-axis and hide ticks for all plots
subplot(4,1,1);
h7 = plot(nan, nan, 'b-');
ylabel('Tactile sensor');
ylim([-1000, 1000]);
set(gca, 'XTick', [], 'XTickLabel', [], 'YTick', [], 'YTickLabel', [])

subplot(4,1,2);
h2 = plot(nan, nan, 'g-');
ylabel('ECD1 state');
ylim([-1, 2]);
set(gca, 'XTick', [], 'XTickLabel', [], 'YTick', [], 'YTickLabel', [])

subplot(4,1,3);
hBPM = plot(nan, nan, 'b-');
ylabel('BPM (LabChart)');
ylim([40, 100]);
set(gca, 'XTick', [], 'XTickLabel', [], 'YTick', [], 'YTickLabel', [])

subplot(4,1,4);
h3 = plot(nan, nan, 'g-');
ylabel('ECD2 state');
ylim([-1, 2]);
set(gca, 'XTick', [], 'XTickLabel', [], 'YTick', [], 'YTickLabel', [])

startTime = tic; % Record start time

%% Main Loop: Run while figure is open
while ~stopLoop
    currentTime = toc(startTime);

    % BPM data from LabChart
    if ~isempty(gChansData) && ~isempty(gChansData{1})
        bpmValue = gChansData{1}(end);
    else
        bpmValue = 0;
    end

    % Store time and data
    time(end + 1) = currentTime;
    bpmData(end + 1) = bpmValue;

    % Process data received from Arduino
    receivedData = readline(arduinoObj);
    values = split(receivedData, ',');

    if numel(values) >= 4
        value1 = str2double(values(2));
        value2 = str2double(values(3));
        value3 = str2double(values(4));

        sensor1(end + 1) = value1;
        ECD1(end + 1) = value2;
        ECD2(end + 1) = value3;
    end

    % Index for data within the last 10 seconds
    recentWindow = 10; % seconds
    recentIdx = time >= (currentTime - recentWindow);

    % Update plots (last 10 seconds of data)
    if isvalid(hBPM)
        set(h7, 'XData', time(recentIdx), 'YData', sensor1(recentIdx));
        set(h2, 'XData', time(recentIdx), 'YData', ECD1(recentIdx));
        set(h3, 'XData', time(recentIdx), 'YData', ECD2(recentIdx));
        set(hBPM, 'XData', time(recentIdx), 'YData', bpmData(recentIdx));
        drawnow;
    else
        break;
    end

    % Send control value to Arduino
    if bpmValue <= 70
        sendValue = 2;
    else
        sendValue = 1;
    end
    writeline(arduinoObj, num2str(sendValue));

    % pause(0.005); % Uncomment if needed
end

% Clean up serial port after loop ends
clear arduinoObj;

%% Callback Function: CloseRequestFcn for Figure
function closeFigure(src, ~)
    global stopLoop;
    stopLoop = true;
    delete(src);
end
```

Supplementary Fig. 19 | Matlab code applied for TIBS.

```cpp
const int analogPin1 = A5;
int tactile = 0;
int tactileValue = 0;
int previousTactileValue = 0;

// PWM pins
const int ecdPin1_High = 3;
const int ecdPin1_Low  = 5;
const int ecdPin4_High = 7;
const int ecdPin4_Low  = 9;

bool power = true;
bool lastPower = true;

String Rx = "";
String lastRx = "";

int pwm1_H = 0, pwm1_L = 0;
int pwm4_H = 0, pwm4_L = 0;
int state1 = 0, state4 = 0;

// Timing variables
unsigned long powerChangeTime = 0;
unsigned long rxChangeTime = 0;
bool powerChanged = false;
bool rxChanged = false;

void setup() {
  Serial.begin(115200);
  Serial.setTimeout(50);

  pinMode(ecdPin1_High, OUTPUT);
  pinMode(ecdPin1_Low, OUTPUT);
  pinMode(ecdPin4_High, OUTPUT);
  pinMode(ecdPin4_Low, OUTPUT);
}

void loop() {
  // Read sensor and calculate value
  tactile = analogRead(analogPin1);
  tactileValue = (tactile - 400) * 5 + 1600;

  // Toggle power state
  if (previousTactileValue > 0 && tactileValue <= 0) {
    power = !power;
    powerChanged = true;
    powerChangeTime = millis();
  }
  previousTactileValue = tactileValue;

  // Receive command
  String receivedData = Serial.readString();
  if (receivedData.length() > 0) {
    String newRx = receivedData.substring(0, 1);
    if (newRx != Rx) {
      Rx = newRx;
      rxChanged = true;
      rxChangeTime = millis();
    }
```

```cpp
  // Reset PWM values
  pwm1_H = 0; pwm1_L = 0;
  pwm4_H = 0; pwm4_L = 0;

  // Power on: pwm1_H = 300 for 1 second
  if (powerChanged && power && (millis() - powerChangeTime < 1000)) {
    pwm1_H = 250;
    state1 = 1;
  }
  // Power off: pwm1_L = 300 for 1 second
  else if (powerChanged && !power && (millis() - powerChangeTime < 1000)) {
    pwm1_L = 250;
    state1 = 0;
  }
  else {
    // Maintain state after 1 second
    powerChanged = false;
    if (power) {
      state1 = 1;
    } else {
      state1 = 0;
    }
  }

  // Handle Rx command when power is ON
  if (power) {
    if (rxChanged && (millis() - rxChangeTime < 1000)) {
      if (Rx == "1") {
        pwm4_L = 150;
        state4 = 0;
      } else if (Rx == "2") {
        pwm4_H = 150;
        state4 = 1;
      }
    } else if (rxChanged && (millis() - rxChangeTime >= 1000)) {
      rxChanged = false;
      // Maintain state4 based on Rx, but reset PWM
      if (Rx == "1") state4 = 0;
      else if (Rx == "2") state4 = 1;
    }
  } else {
    state4 = 0;  // Force OFF if power is off, regardless of Rx
  }

  // PWM output
  analogWrite(ecdPin1_High, pwm1_H);
  analogWrite(ecdPin1_Low, pwm1_L);
  analogWrite(ecdPin4_High, pwm4_H);
  analogWrite(ecdPin4_Low, pwm4_L);

  // Serial output
  Serial.print("Data,");
  Serial.print(tactileValue);
  Serial.print(",");
  Serial.print(state1);
  Serial.print(",");
  Serial.println(state4);

  lastPower = power;
  lastRx = Rx;

  delay(5);
}
```

Supplementary Fig. 20 | Arduino code applied for TIBS.

Supplementary Tables

	T-iSPV	ITO[1,2,4]	Cu metal mesh[3]	Graphene[4,5,6]	AgNW[7,8]	CNT[9,10,11,12]
Intrinsic stretchability	**50%**	≈3%	X	≈6%	100%	80%
Sheet resistance (Ω □$^{-1}$)	**83.7**	250, 30	0.22	350-1200, 125	13, 11.01	59-110, ~560
Optical transmittance (@ 550nm)	**77.17**	≈ 90%	83%	~ 97.4%	85%, 90.6%	71-80%, 75%
Microfabrication compatibility	**O**	O	O	O	X	X
Substrate thickness (Skin conformity)	**≈ 5 µm**	200 µm	-	25 µm, 188 µm	150 µm	230 µm
Uniformity	**O**	O	O	X	X	X
Biocompatibility	**O**	X	X	X	X	X

Supplementary Table 1 | Comparison of T-iSPV with transparent conductive electrodes

Year	Material strategy	Stretchability (%)	Transparency (%)	Sheet Resistance (Ω/sq)	Cyclic Durability	Line width (μm)	Substrate	Fabrication method	Mesh structure	Application	Reference
2025	Ag grid/ Ag Nanowire	flexible	67.9	9	5,000 (bending)	15	NOA63	Photolithography/ Bar-coating	Square	OLED	[13]
2025	Ag metal mesh	flexible	73.1	1.52	1,000 (bending)	-	PET	Nanosphere lithography	circle	Heater, EMI sheilding	[14]
2025	Cu metal mesh	60%	83	0.22	20,000 (bending)	4.3	PDMS	Photolithography (Transfer)	Serpentine	Film heater	[15]
2025	Ag grid	100%	84.8	29.9	5,000 (50% stretching)	35-50	PDMS	Inkjet printing	Serpentine	Touch panel	[16]
2024	Liquid metal/ Cu metal mesh	800%	78.9 – 95.1	1.52 – 7.76	10,000 (300% stretching)	35	SEBS	Laser ablation	Serpentine	Haptic interface/Heater	[17]
2024	Cu metal mesh	30%	85.8	0.18	1,000 (bending)	1-2	PDMS	Self-forming crackle template method	Irregular	Heater	[18]
This work	**Au mesh**	50%	77.17	83.7	1,000 (30% stretching)	10	**Ultrathin SEBS (5 μm)**	**In-situ vacuum-deposition, phtolithography**	**Square (Intrinsically stretchable)**	**Electrophysiological electrode, ECD, Tactile senor, Integrated display system**	

Supplementary Table 2 | Comparison of T-iSPV with state-of-the-art literature on metal mesh-based deformable transparent electrodes.

Supplementary Video

Supplementary Video 1. Real-time demonstration of the integrated bioelectronics system. A fully assembled wearable platform integrating T-iSPV-based ECG electrodes, a stretchable electrochromic display (sECD), and a tactile sensor was mounted on human skin. Upon tactile stimulation, the system activates in real time, toggling the sECD to visually indicate operation. Concurrently, ECG signals are acquired via the T-iSPV electrode, processed through the data acquisition module, and used to control the second sECD, which turned on when the measured heart rate falls below a predefined threshold. This demonstration validates the seamless integration and functional responsiveness of the system under dynamic conditions.

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