Supporting Information

Materials and Fractal Designs for 3D Multifunctional Integumentary Membranes with Capabilities in Cardiac Electrotherapy

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Supplementary Note: FEA results

ABAQUS commercial software was used to study the elastic modulus and the stretchability of the device. The silicone elastomer (Ecoflex, ~150 μm in thickness, with modulus ~60 kPa) was modeled by the hexahedron element (C3D8R), while the device is modeled by the composite shell element (S4R). A submodel was established for the fractal electrode to obtain its effective mechanical properties. Figure S1 shows the stress-strain relation of the silicone elastomer with and without the fractal electrode. The modulus of silicone elastomer with the fractal electrode increases to 130 kPa for vertical stretching and 114 kPa for horizontal stretching. Figure S2 and Figure S3 show the deformation and strain distribution of the overall device subject to (0%, 5%, 10%, 15% and 20%) horizontal stretching and (0%, 5%, 10% and 15%) biaxial stretching, respectively. The optical image in Figure S2(a) agrees well with that obtained by FEA in Figure S2(b) for horizontal stretching. The maximum strain in the interconnect (Figure S2(c)), fractal electrode (Figure S2(d)) and sensor (Figure S2(e)) are all <0.3%. Figure S3 displays similar characteristics of the device subject to biaxial stretching.

FEA was used to study the distribution of contact pressure for a 3D-MIM (~150 μm thickness, and modulus ~74kPa from Figure 2d) wrapped around a heart. The volume change associated with integration of 3D-MIM was modeled by the thermally coupled shell element (S3T). Figure S4 shows the contact pressure (a) in the unexpanded state and (b) 145% volume of the unexpanded state, which corresponds to the diastolic state of the heart.

FEA was used to study the temperature field associated with the operation of heater #5. The substrate (myocardium, ~4 mm in thickness, with thermal conductivity ~0.5 W/mK [S1]) was modeled by the heat transfer brick element (DC3D8), while the device was modeled by the heat transfer shell element (DS4). The ambient temperature is 38 °C, and the heater 5 was heated to 70.8 °C. Table S1 shows the average temperature for each of the 9 temperature sensor/heater array.

[S1] D. Schutt, E. J. Berjano, D. Haemmerich, *Int. J. Hyperthermia* **2009**, *25*, 99.

Table S1. The average temperature on the 9 temperature sensor/heater array by FEA.

Sensor 1: 38.2℃	Sensor 4: 39.6℃	Sensor 7: 38.2℃
Sensor 2: 38.5℃	Heater 5: 70.8℃	Sensor 8: 38.5℃
Sensor 3: 38.4℃	Sensor 6: 39.6℃	Sensor 9: 38.4℃

Figure S1. FEA results for the stress-strain relation of the silicone elastomer with and without integrated fractal electrodes.

Figure S2. (a) Optical images and (b) FEA results for the device with up to 20% horizontal strain. The corresponding strain distribution in (c) interconnect, (d) fractal electrode and (e) sensor.

Figure S3. (a) Optical images and (b) FEA results for the device with up to 15% biaxial strain. The corresponding strain distribution in (c) interconnect, (d) fractal electrode and (e) sensor.

Figure S4. The contact pressure exerted on the heart by 3D-MIM for 145% of the contracted volume, which corresponds to the diastolic state of the heart.

Figure S5. Calibration data for the temperature sensors array.

Figure S6. Improvements in electrochemical impedance by fractal electrode design.

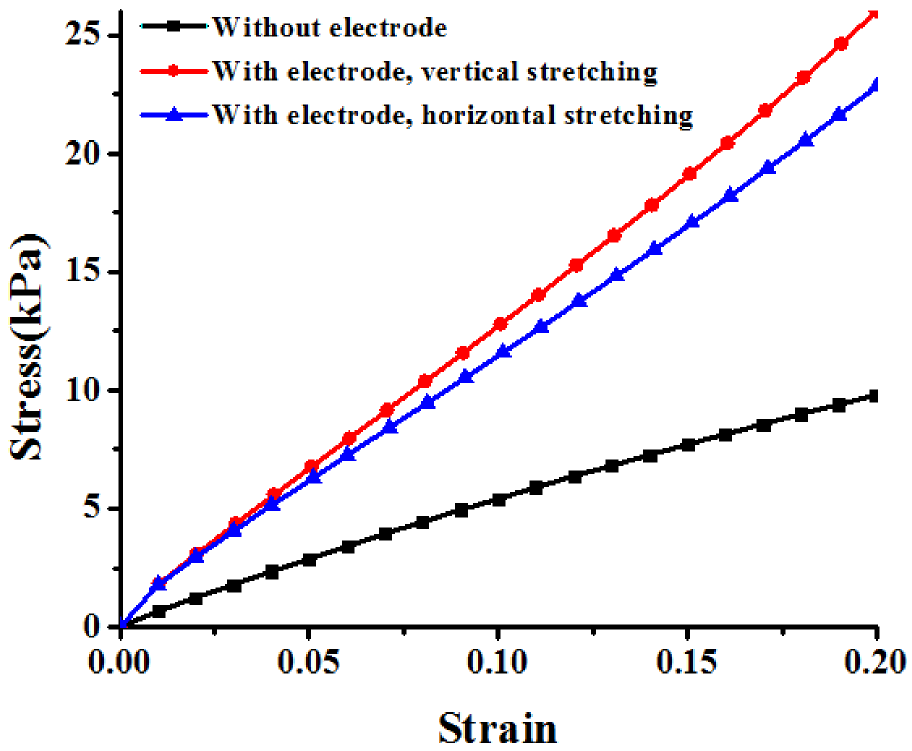

Without electrode
With electrode, vertical stretching
With electrode, horizontal stretching
Stress(kPa)
Strain
0
5
10
15
20
25
0.00
0.05
0.10
0.15
0.20

Figure S1

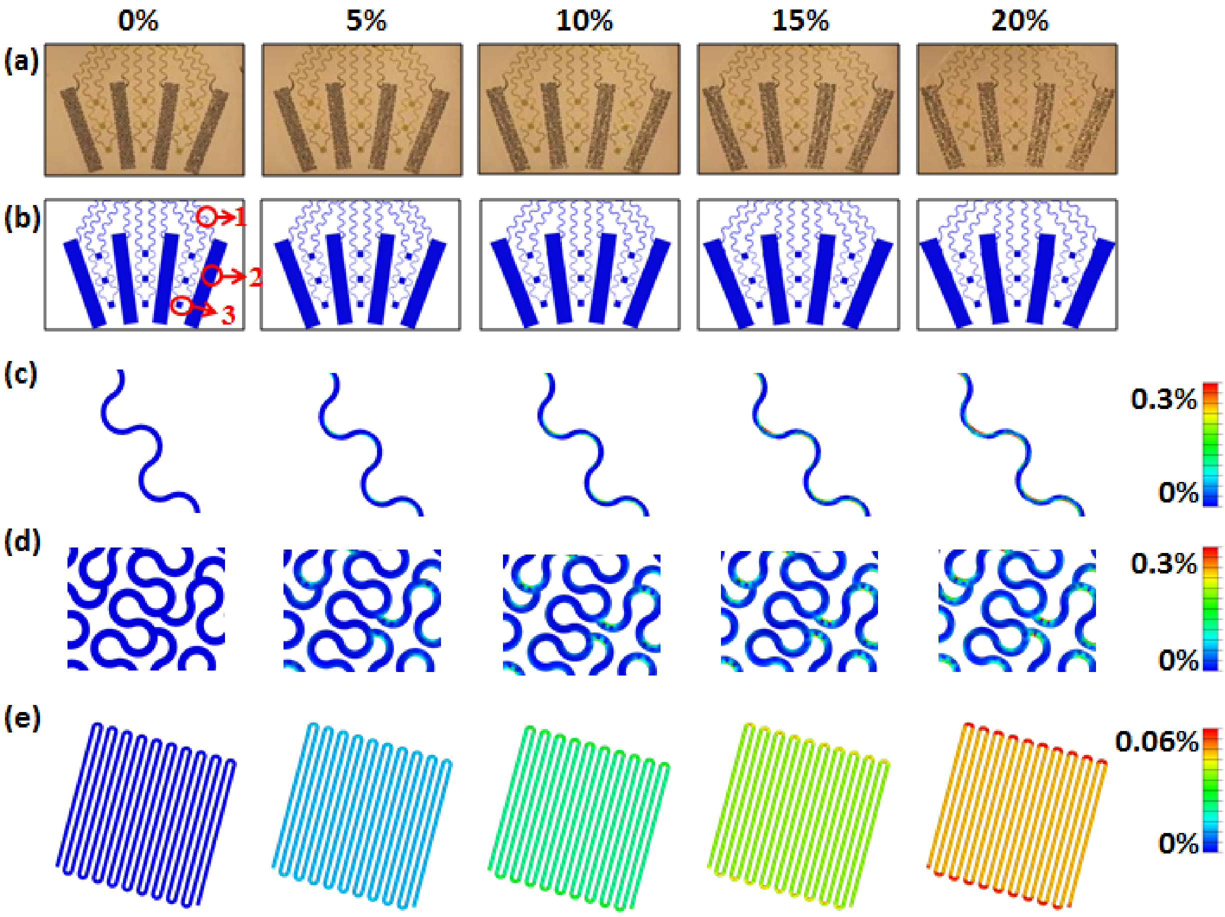


Figure S2

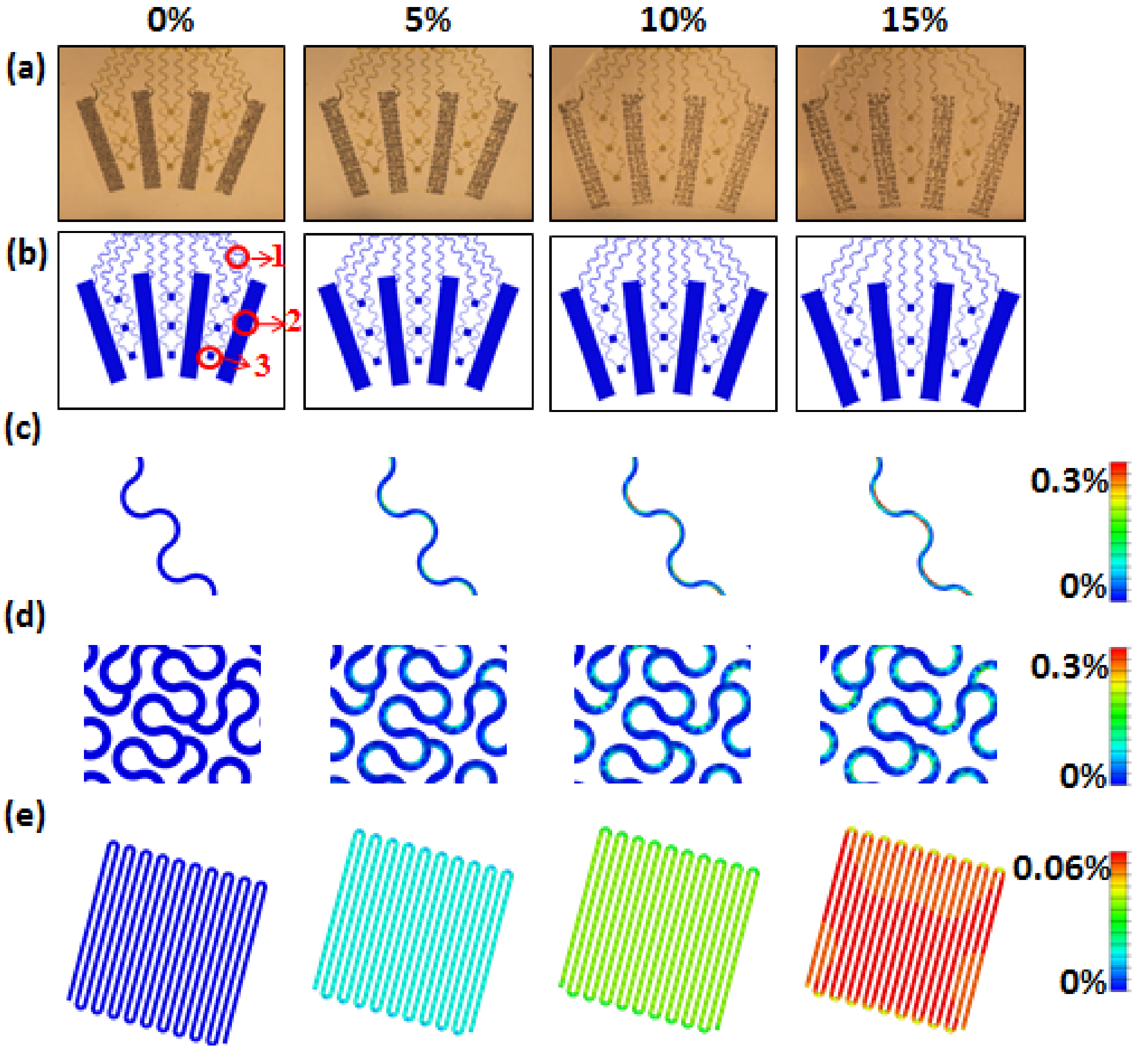
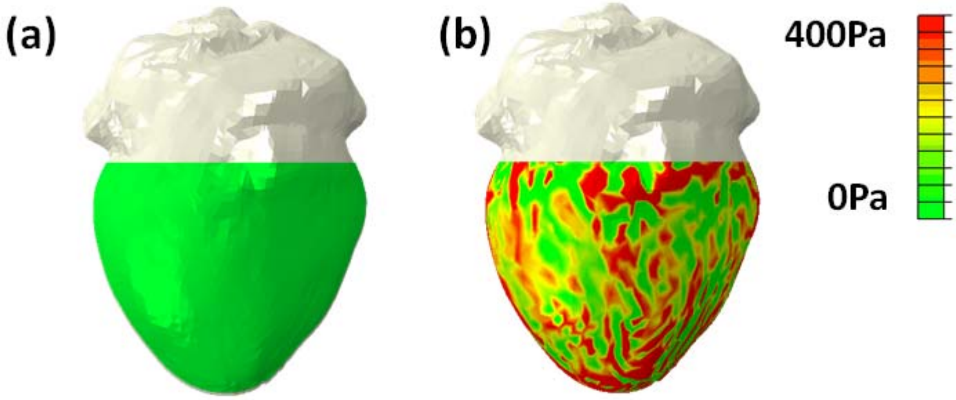


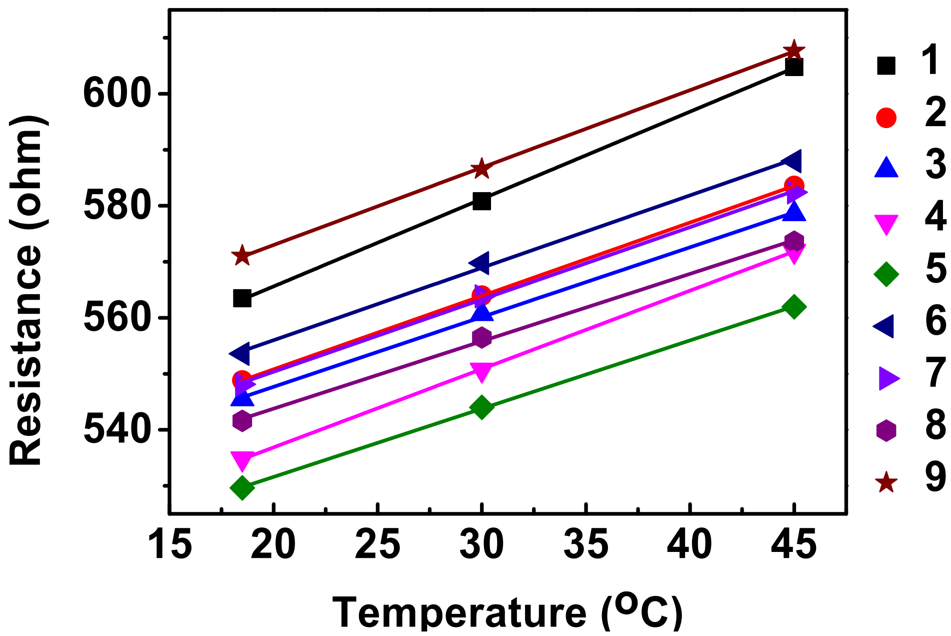
Figure S3



Expanded (100% volume)
Average pressure=0 Pa

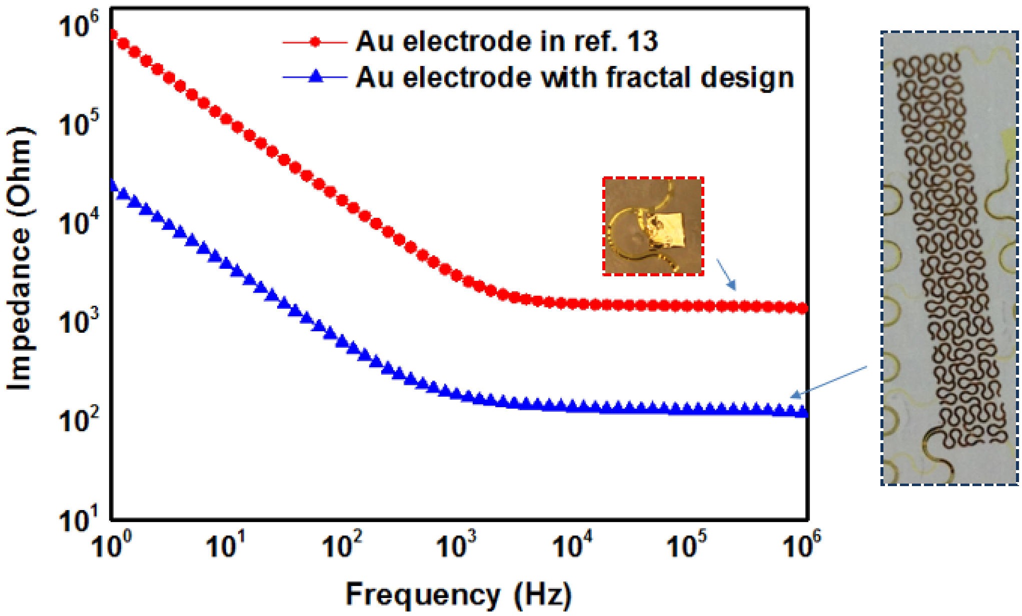
Expanded (145% volume)
Average pressure=273 Pa

Figure S4



600
580
560
540
15
20
25
30
35
40
45
Resistance (ohm)
Temperature (^{O}C)
1
2
3
4
5
6
7
8
9

Figure S5



Au electrode in ref. 13
Au electrode with fractal design
Impedance (Ohm)
Frequency (Hz)
10^6
10^5
10^4
10^3
10^2
10^1
10^0

Figure S6