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Supplementary Information

Highly Stretchable and Oxidation-resistive Cu Nanowire Heater for the Replication of Heat Feeling in a Virtual World

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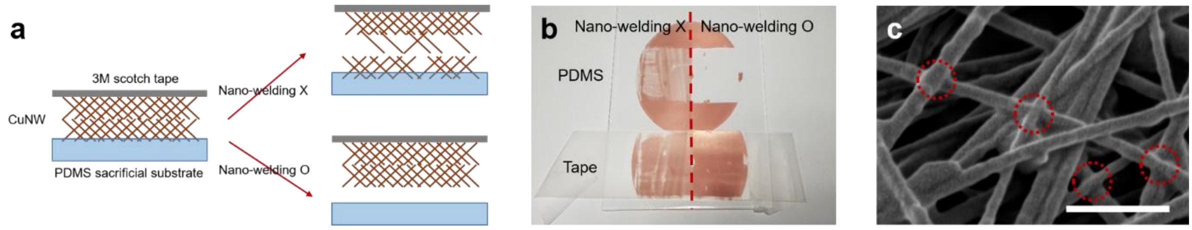

Figure S1. Comparison of CuNW networks with and without nano-welding. a) Schematic of tape test results according to the nano-welding process. b) Optical image of tape test results. Only the right side of the sample was nano-welded. c) A SEM image of a CuNW network nano-welded. The red circles mean the nano-welded parts (Scale bar = 500nm).

The nano-welding process for the whole CuNW makes the CuNW network function as a chunk since the contact areas between the CuNWs go through instantaneously melting and soldering[20]. When removes the CuNW network with a tape, it carries many CuNWs, but some of them remain on the substrate owing to the partial embedement[9] (**Figure S1a**). However, the nano-welding process enables to detach the CuNW network functioning as a one chunk. **Figure S1b** shows that the nano-welded region only exhibits cleanly removed surface (right) due to the constraint between CuNWs (**Figure S1c**).

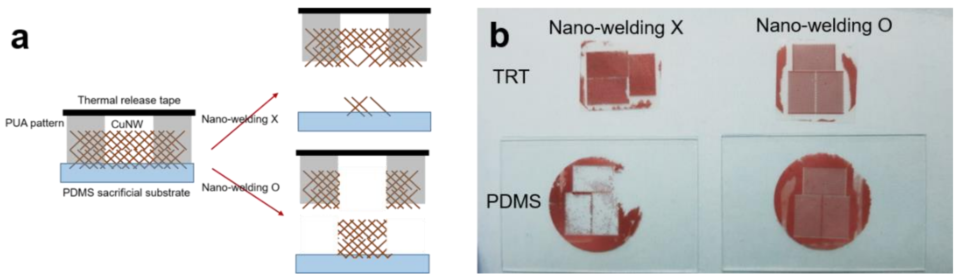

Figure S2. a) A schematic of difference in pattern according to the nano-welding when transferring CuNW-PUA pattern by TRT. b) Comparison of CuNW remaining on PDMS substrate after removing patterned CuNW-PUA electrode with TRT.

The nano-welded CuNW network considerably eases a separation of the CuNW-PUA pattern from remained CuNWs. Without nano-welding process, CuNW-PUA patterns carry the non-patterned CuNWs on the sacrificial substrate. However, the non-patterned CuNW embedded in PDMS leaves in one chunk after the nano-welding process.

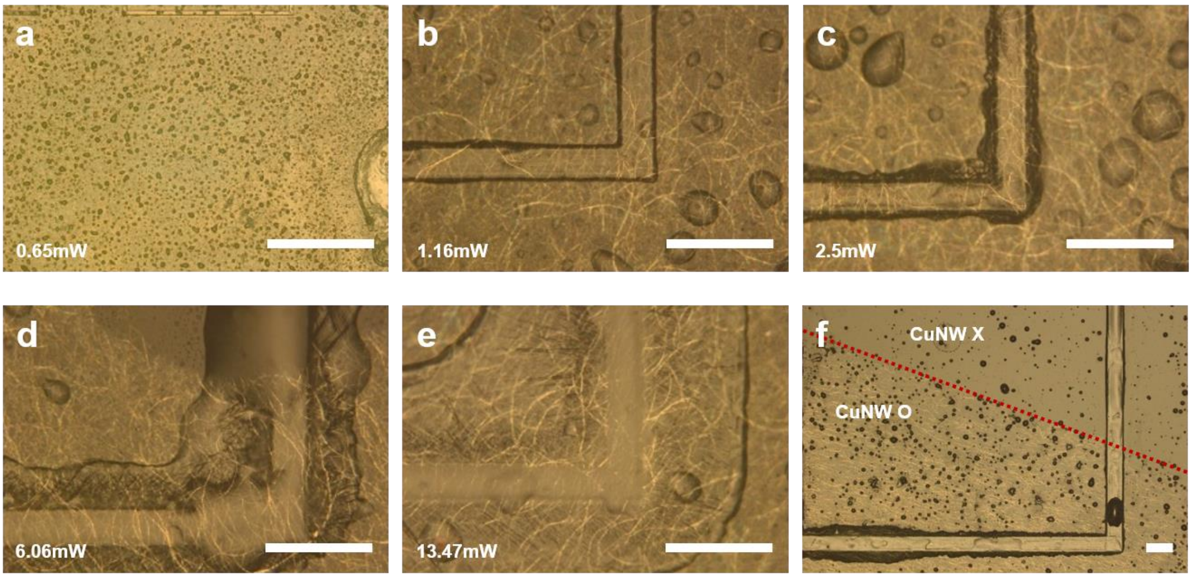

Figure S3. Change of shape of rectangular pattern according to 355nm laser power when scan speed is fixed at 100mm/s. a ~ e) Optical microscope image of the result of square patterning according to the laser power from 0.65mW to 13.47mW. f) Optical microscope image of the smudgy pattern according to the CuNW network (All scale bars = 200nm).

In the patterning process, the proper power of the UV laser is important to obtain intended patterns, since the photon energy of UV laser induces the PUA curing. Excessively low power of the laser is unable to cure the PUA while high power generates the pattern, which unintentionally results in greater in dimension (**Figure S3a**). As the power increased from more than 2.5mW, the unintended large pattern occurred (**Figure S3d, e**). The problem appears only on CuNWs, since a portion of the laser reflected on the CuNW surface solidify the PUA around the intended pattern (**Figure S3f**). The laser power of 1.16mW produces a neat pattern (**Figure S3b**).

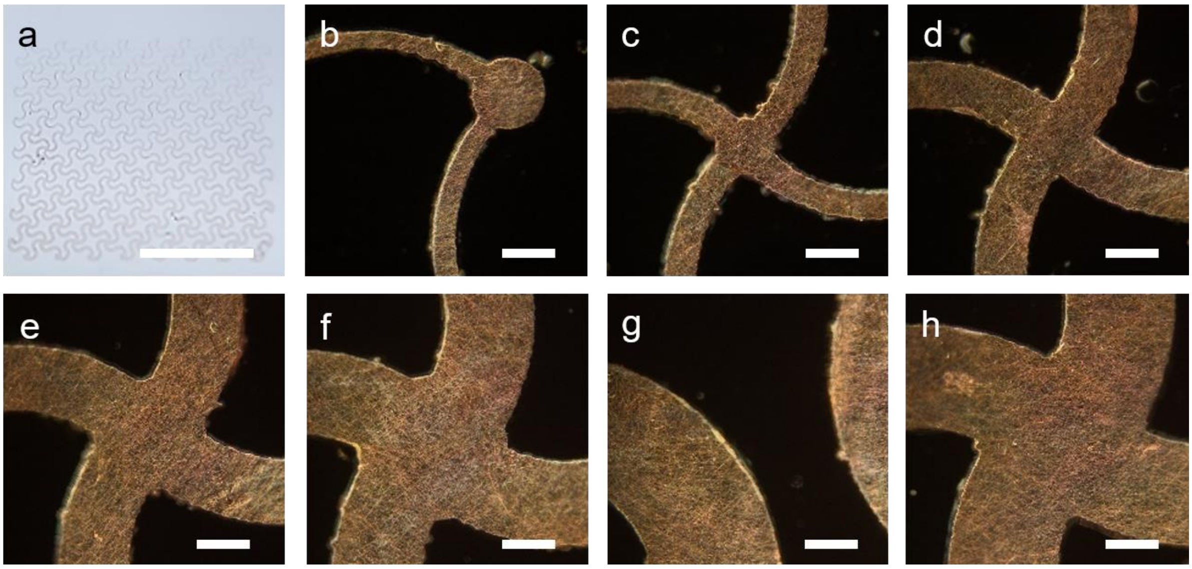

Figure S4. Resolution test of CuNW-PUA pattern. a) Increasingly thinning patterns for resolution studies. It gets thinner to the top. b-h) Images of **Figure S4a** enlarged by an optical microscope.

	CAD file line width	Real line width	Difference
b	17.62 µm	37.90 µm	20.28 µm
c	35.24 µm	58.00 µm	22.76 µm
d	70.48 µm	90.90 µm	20.43 µm
e	105.71 µm	126.90 µm	21.19 µm
f	140.95 µm	164.50 µm	23.55 µm
g	176.19 µm	198.90 µm	22.71 µm
h	211.43 µm	236.00 µm	24.58 µm

Table S1. Comparison of the line width of cad file and the line width of actual pattern of the pattern of Figure S4b-h.

Figure S4 shows the result of the resolution study to see the limits of the laser pattern. The thinnest line retains thickness of 38µm, which is about 20µm thicker than the intended linewidth in the CAD file (**Table S1**). This tendency does not change even if the pattern becomes thick, since the beam size is about 20µm. In other words, all patterns were created along the intended CAD file image, except for beam size errors.

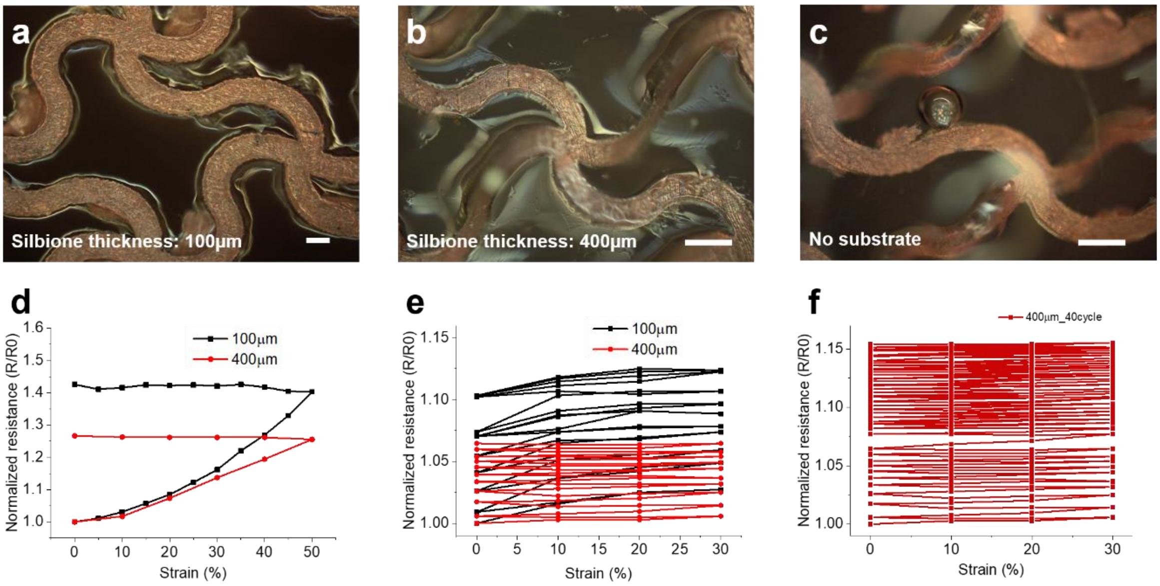

Figure S5 The resistance change of the CuNW-PUA pattern under stretching according to the adhesive substrate thickness. a, b) Optical microscope image of the stretched pattern when the thickness of Silbione is 100μm and 400μm (Scale bar = 100μm). c) Optical microscope image of the pattern is stretched without substrate (Scale bar = 100μm). d) Resistance change of patterned CuNW-PUA electrode according to strain when Silbione thickness is 100μm and 400μm. e, f) The resistance change of the electrode during cyclic tensile test with Silbione thickness of 100μm and 400μm (10, 40cycles).

Although Silbione retains too low modulus to prevent the electrode from being restrained on a plane[22], freeing the electrode is based on enough amount of Silbione. Silbione with a thickness of 100μm makes the pattern stretch without twisting, causing the electrode to be partially torn (**Figure S5a**). On the other hand, 400μm-thick Silbione assists the electrode in avoiding a mechanical damage, as it appeared to stretch with twisting (**Figure S5b**). The sample on thick Silbione deforms in a similar way that the sample without the substrate due to the low modulus (**Figure S5c**). The twisted and stretched pattern shows less resistance change when its strain increased by 50% but no resistance recovery when it returns to its original position (**Figure S5d**). The problem continues during repeated tensile test of 10-cycles. The thicker the Silbione thickness, the less resistance change but the resistance is still not recovered (**Figure S5e**). Instead, after 10-cycles of repeated tensile tests, the resistance increasing is reduced, confirming the aging (**Figure S5f**).

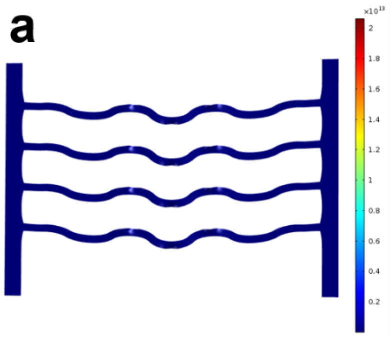

Figure S6. Strain energy density distribution of CuNW-PUA pattern (a) and Cu foil pattern (b) under 50% strain using COMSOL.

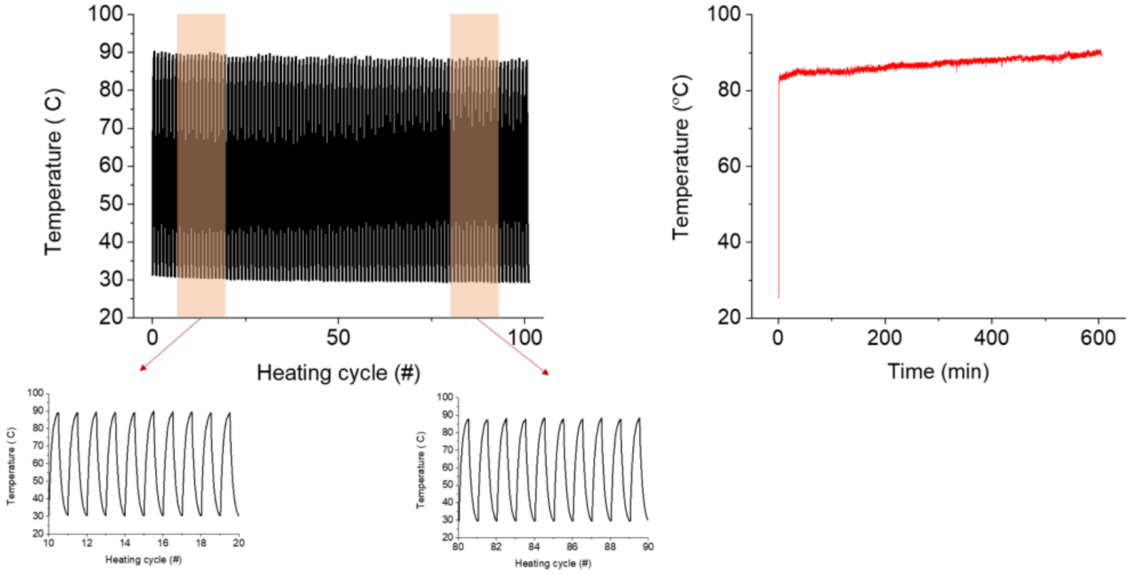

Figure S7. a) Detailed graphs of the Figure 4b results of repeated heating experiments. b) The measured resistance changes for the long term stability of the heater under 5.5V.

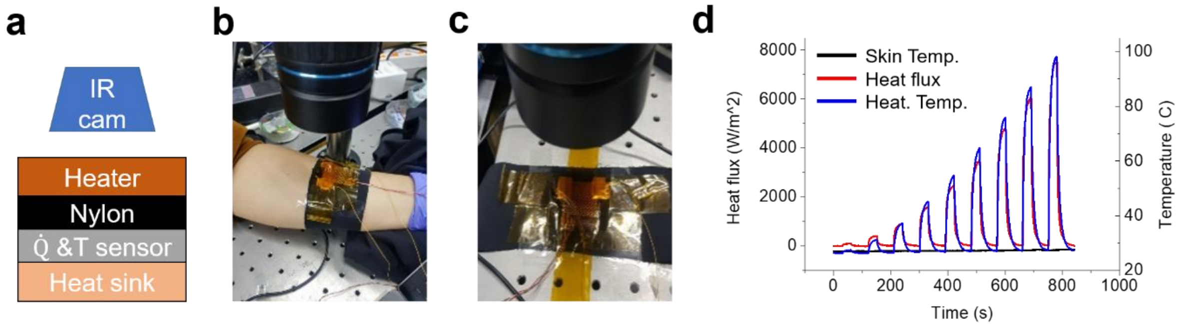

Figure S8. Experiments to investigate the relationship between temperature and heat flux from a heater. a) Experimental schematic. b) Actual state of the experiment to measure the heater and skin temperature and heat flux delivered to human arm skin. c) Actual state of the experiment which measured heater and table temperature and heat flux transferred to optical table. d) The result of the experiment conducted in c.

To verify the temperature of the heater without distortion, the Kapton tape (3M) was chosen due to its thin thickness.

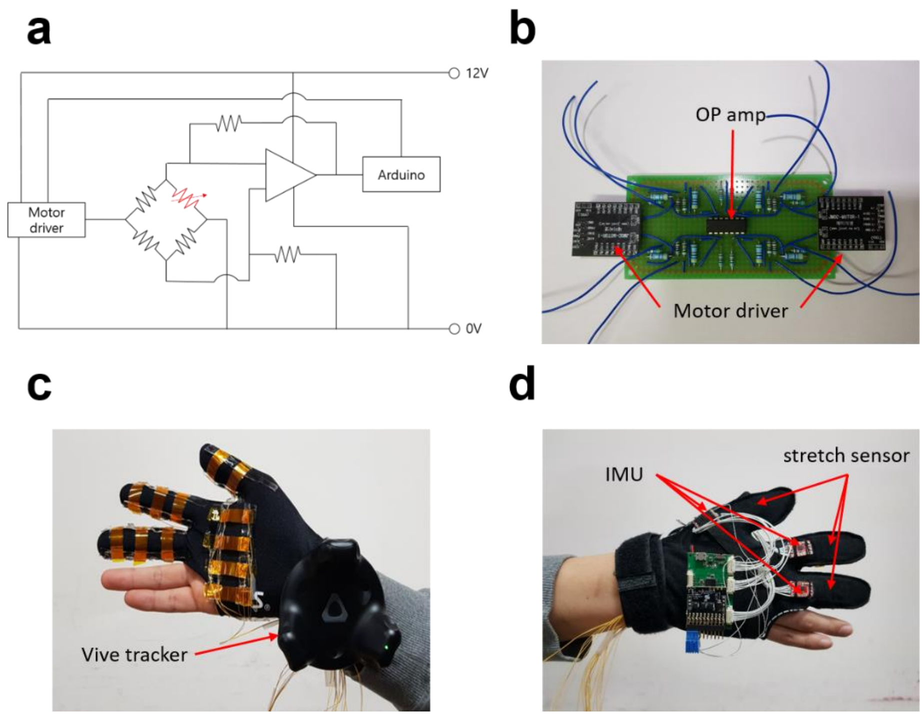

Figure S9. a) Arduino based thermo-haptic device circuit for the PID control. b) The implemented circuit for 4-devices control. c, d) The 12-THDs on a nylon glove with a motion tracker (Vive, Vive tracker), IMUs (MPU-9250, Sparkfun), and strain sensors (Stretch sense, Stretch sensor).

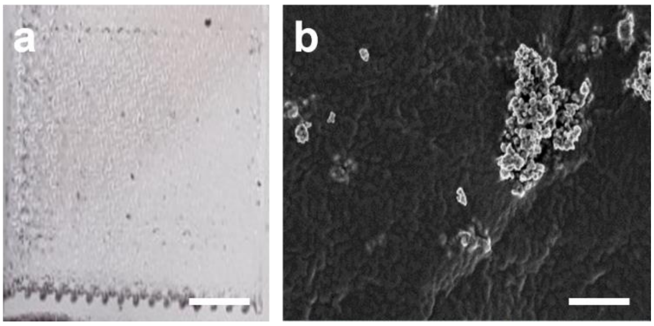

Figure S10. Results of CuNP-PUA electrode fabrication. a) Actual image of CuNP-PUA electrode. Most CuNPs are peeled off (Scale bar = 250μm). b) SEM image of CuNP-PUA electrode (Scale bar = 500nm).

The embedded structure comes from the fact that CuNW network has many empty spaces and the PUA permeate between the gaps. In addition, the PUA between the nanowires is also cured because of the laser beam scattered on the surface of the nanowires. On the contrary, it is hard to encapsulate the CuNP – based thin film with PUA by the process described above (**Figure S10**). A CuNP film has few pores and it stays on the transfer tape not on PUA (**Figure S10a**). **Figure S10b** shows that CuNP is barely attached to the PUA.