Electronic Supplementary Information

Strain sensors on water-soluble cellulose nanofibril paper by polydimethylsiloxane (PDMS) stencil lithography

Lingju Meng,[a] Seyed Milad Mahpeykar[a], Qiuyang Xiong [a], Behzad Ahvazi[b] and Xihua Wang*[a]

a. Department of Electrical and Computer Engineering, University of Alberta, Edmonton, T6G 2V4. Email: xihua@ualberta.ca

b. Biomass Processing & Conversion-BioResources, Alberta Innovates Technology Future, Edmonton, T6N 1E4.

Corresponding author: Prof. Xihua Wang

Reproducibility and reliability tests of PDMS stencils:

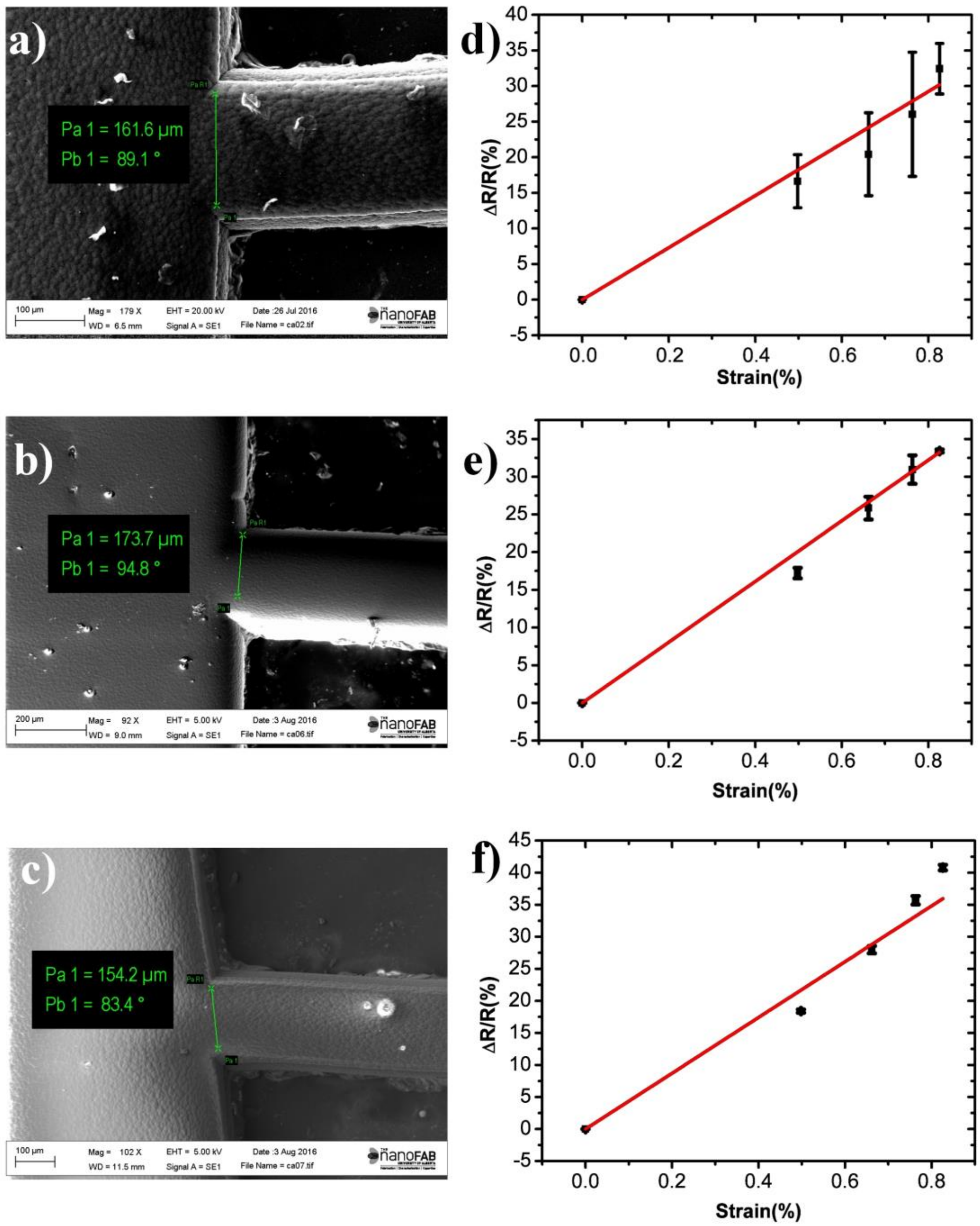

Fig S1. a)-c) SEM images of various PDMS stencils made by the same mold. The three PDMS stencils were selected when the silicon mold had been used for 15, 20 and 25 times, respectively. **d)-f)** Resistance change - strain characteristics of devices fabricated using the stencils shown in a)-c), respectively.

In experiments, we produced more than 25 PDMS stencils from the same silicon mold. Some PDMS stencils were selected to fabricate strain sensors. The width of the imaged

PDMS stencils for conducting channel is around 160 μm. It is noted that the PDMS stencils were soft and slightely tilted on sample holders in SEM imaging.

Resistance change - strain characteristics of strain sensors made by the same PDMS stencil:

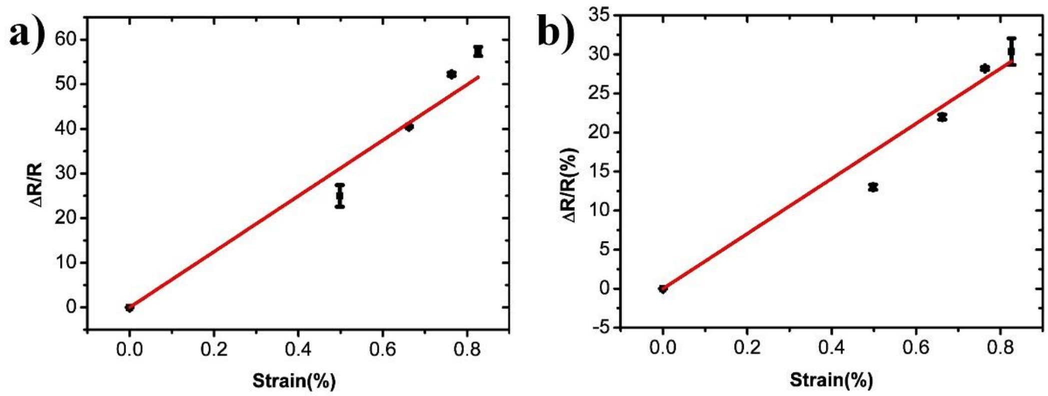

Fig. S2. The resistance change - strain characteristics of strain sensors made by the same PDMS stencil as the device shown in Fig. 5 in the manuscript.

Repeated bending tests:

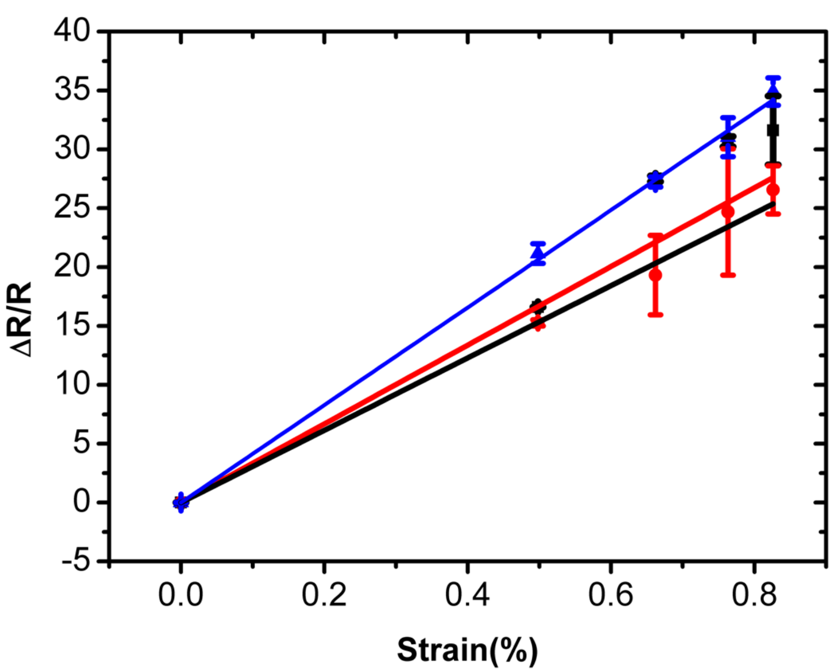

Fig. S3. Resistance change – strain characteristics of a device after repeated bending. The red, black, and blue curves show data of the device going through 0, 10 and 40 bending cycles, respectively.

Bending strain calculation:

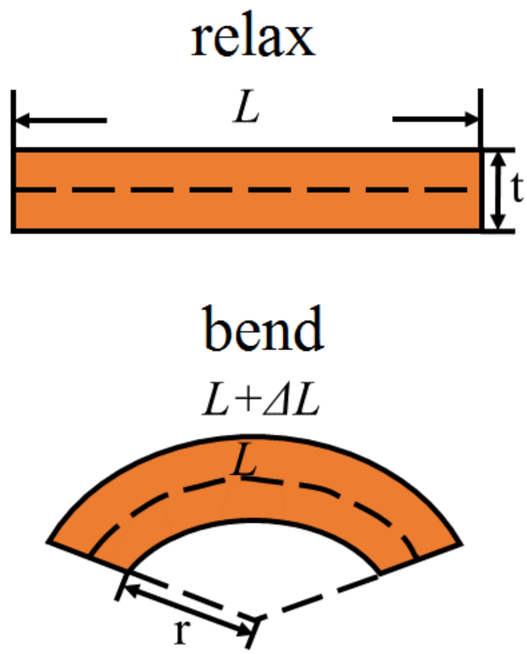

Fig. S4. Illustration of bending strain calculation

The commercially available strain sensors – strain gauges – are usually characterized by bending strain. According to the previous report[1], the strain on a bended substrate with the bending radius r can be calculated as shown in Fig. S4. At relax condition, the length of the substrate can be expressed as L and the thickness is t. After being bent on a stainless steel block with a radius of r, the condition of the substrate is shown as the bottom graph in Fig. S4. It is common to assume that the centre of the substrate will not be stretched or compressed. The length of the central line is still L. However, the top is stretched and the bottom is compressed. The top of the substrate is stretched to $L+\Delta L$. The top and bottom of the substrate are bended to radius of $r+t/2$ and $r+t$. Thus we can get equations as below:

$$\frac{L}{r+t/2} = \frac{L+\Delta L}{r+t}$$

It is derived to get:

$$\frac{t/2}{r+t/2}=\frac{\Delta L}{L}$$

$$\varepsilon=\frac{t/2}{r+t/2}$$

Where ε represents the strain of the top. The calculated results are shown in the table below.

Bending radius	**Top surface strain**
2.0 cm	0.498%
1.5 cm	0.662%
1.3 cm	0.763%
1.2 cm	0.826%

Tab. S1. Calculated results of the relation between top surface strain and bending radius

Explanation of electron transport in strain sensors:

According to the former reports, the electron transportation in metal nanoparticle matrix granular metals system[2] could be described as thermally activated tunneling[3–5]. The conduction is determined by several parameters such as particle radius, interparticle distance and so on. According to the model in former reports, the thermally activated tunneling conductivity is described as the Arrhenius equation:

$$\sigma=\sigma_0\exp(-\beta d)\exp[-\frac{0.5e^2}{4\pi\varepsilon\varepsilon_0 RT}\left(\frac{1}{r}-\frac{1}{r+d}\right)]$$

Where σ_0 is the intrinsic conductivity of the silver nanoparticles defined by $\sigma_0 = ne\mu$, β is a particle size and temperature dependent electron coupling term usually varying from 1 nm^{-1} to 10 nm^{-1}, d is the interparticle distance, ε is the relative dielectric constant of the interparticle medium and r is the particle radius. Under uniaxial strain, the interparticle distance will change from d_1 to d_2. So the resistance ratio for the stretched device and the relaxed device should be:

$$\frac{R_2}{R_1}=\exp[\beta(d_2-d_1)]\exp[-\frac{0.5e^2}{4\pi\varepsilon\varepsilon_0 RT}\left(\frac{1}{r+d_2}-\frac{1}{r+d_1}\right)]$$

Which can be rewritten as:

$$\frac{\Delta R}{R} = \exp(\beta \varepsilon_s d_1) \exp\left[-\frac{0.5e^2}{4\pi\varepsilon\varepsilon_0 RT}\left(\frac{1}{r+(1+\varepsilon_s)d_1} - \frac{1}{r+d_1}\right)\right] - 1$$

Where ε_s is the strain applied to the device, and the second exponential term in this formula can be used to extract the activation energy of metal nanoparticles. In our experiments, the non-linear curve-fitting of our data is shown in Fig. 5 in the manuscript, and we get that d is 36.2 nm and β is 1.21 nm^{-1}.

References:

1 J. Yin, P. Hu, J. Luo, L. Wang, M. F. Cohen and C. J. Zhong, *ACS Nano*, 2011, **5**, 6516–6526.

2 J. Herrmann, K. H. Müller, T. Reda, G. R. Baxter, B. Raguse, G. J. J. B. De Groot, R. Chai, M. Roberts and L. Wieczorek, *Appl. Phys. Lett.*, 2007, **91**, 89–92.

3 I. S. Beloborodov, a. V. Lopatin, V. M. Vinokur and K. B. Efetov, *Rev. Mod. Phys.*, 2007, **79**, 469–518.

4 M. Huth, *J. Appl. Phys.*, 2010, **107**, 5–12.

5 B. Abeles, P. Sheng, M. D. Coutts and Y. Arie, *Adv. Phys.*, 1975, **24**, 407–461.