Supporting Information

Conductance-Strain Behavior in Silver-Nanowire Composites: Network Properties of a Tunable Strain Sensor

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SI 1. Stretching Setup

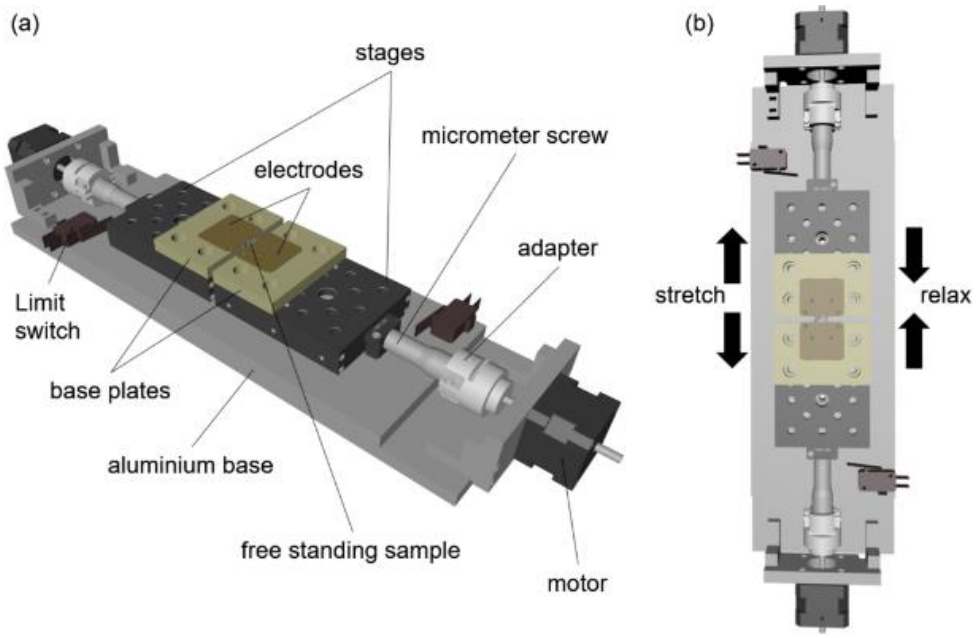

Figure S1: Stretching setup consisting of an aluminum base plate on which two single-axis micrometer translation stages are mounted. Both stages are driven by encoder-controlled stepper motors. Two limit switches are used to reference the motion of the translation stages. The sample is clamped with electrodes containing gold contacts for conductivity measurements (see SI 4). (a) Side view of the stretching setup and its components. (b) Top view with stretching directions.

The stretching setup consists of an aluminum base plate on which two single-axis micrometer translation stages (PT1/M, Thorlabs®) are mounted. Both have a travel range of 25 mm with a translation of 0.5 mm per revolution and a vertical load capacity of 4 kg. Each stage is connected to a stepping motor (0.9-NEMA 17, Nanotec®). The stepping motors are controlled by a closed-loop-stepping motor-controller (SMCI33-2, Nanotec®). For further details of the electrical setup and the wiring we refer to the construction manuals of Nanotec®. The two stages can be automatically moved to stretch the sample with an effective resolution of 1 µm limited by the resolution of the optical encoder. Two limit switches can be used for an internal and external reference drive to readjust the position of the translation stages between different measurements. Polyether ether ketone (PEEK) base plates on top of the translation stages enable the sample to be clamped with the electrodes for conductivity measurements. In Figure S2, photographs of the setup and the samples are shown.

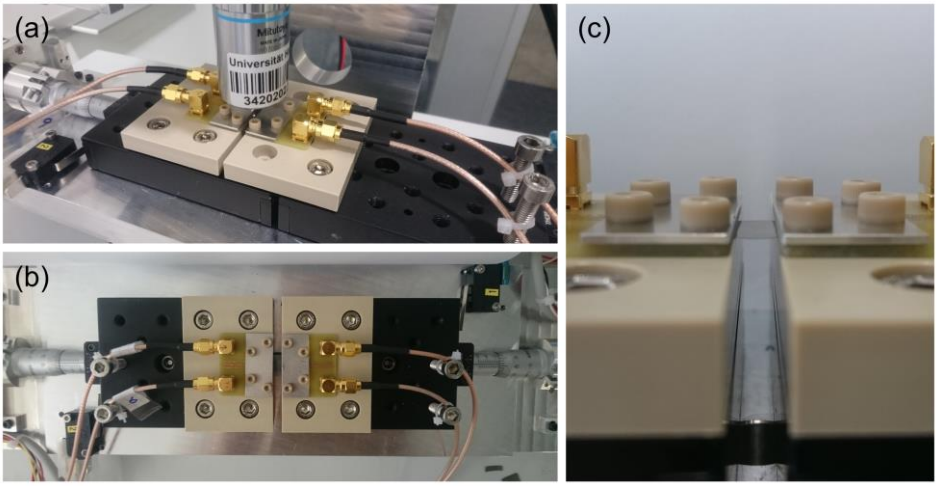

Figure S2: Photographs of the stretching setup. (a) Setup with light microscope above the sample. (b) Stretching setup top view. (c) Pre-stretched composite sample.

SI 2. Synthesis of Silver Nanowires

Silver nanowires were synthesized using the polyol method.[1] 6 mL $C_2H_6O_2$ (Sigma Aldrich, anhydrous, 99.8 %) were stirred and preheated in an oil bath at a temperature of 155 °C for 50 min. 3 µL $CuCl_2$ (Sigma Aldrich, 99.999 % purity) were added to a solution of 0.03 g Polyvinylpyrrolidone (PVP) MW = 55000 (Sigma Aldrich), 0.06 g PVP MW = 360000 (Carl Roth), and 3 mL $C_2H_6O_2$. This mixture was added to the preheated $C_2H_6O_2$. The mixture was heated for further 15 minutes. A solution of 0.03 g $AgNO_3$ (Carl Roth, > 99.9 % purity) in 2 mL $C_2H_6O_2$ was filled in a 2.5 mL syringe. After 65 min the stir bar was removed from the reaction solution and the injection of the $AgNO_3$ solution was started with a flow rate of 1.88 mL/h. The reaction was quenched after a total reaction time of 235 min. The product was centrifuged (2000 rpm, RT, 10 min) and washed six times in a row: two times with isopropanol, two times with acetone and two times with isopropanol again. The synthesized nanowires had an average diameter of 200 nm and their length varied from 4 µm up to 180 µm.[2]

SI 3. Stretching Process

The stepping motors were operated in half step-mode. As the step angle of each motor is 0.9°, one rotation equals 360°/0.45°= 800 steps. This corresponds to a stretching distance of 1 mm per rotation as one translation stage moves 500 µm per full turn. The initial distance between the stages was 3 mm. The samples were stretched step by step uniformly from both sides. Each sample was stretched in steps of 100 µm up to a total strain of 0.7 mm which equals an elongation of 23.33 %. Subsequently, we relaxed the sample in 100 µm steps back to the initial distance.

SI 4. Line and Sheet Resistance Measurements

For resistance measurements each electrode has two contacts as shown in Fig. S3. To measure the line resistance a current was applied on the contacts A and D and the voltage drop was recorded between B and C. To determine the sheet resistance the Van Der Pauw method was used as it derives the resistivity of a two-dimensional sample despite its shape.[3] A constant current of 0.6 mA was applied for all measurements. 12 single measurements were carried out and averaged. The experimental results for three samples with different concentrations (40 µg cm^{-2}, 80 µg cm^{-2}, and 120 µg cm^{-2}) are summarized in Table S1, Table S2, and Fig. S4 - Fig. S6.

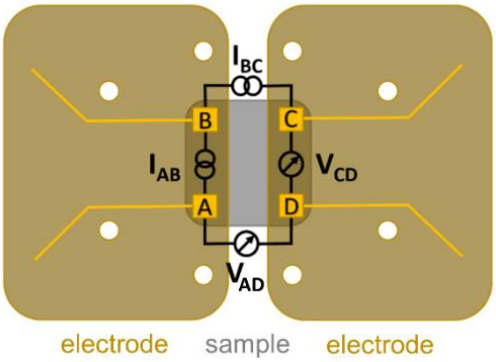

Figure S3: Sketch of the two electrodes and their respective electrical contacts (A, B, C, D). The composite sample is depicted in grey. The input currents (AB/AD) and the voltage drop (CD/BC) of the Van der Pauw measurement are shown.

Table S1.: Hysteresis as a function of stretching cycle. The difference Δ in line- (R_L) and sheet (R_S) resistance upon stretching and relaxation of the three samples (40 µg cm^{-2}, 80 µg cm^{-2}, and 120 µg cm^{-2}) are listed. ΔR_L as well as ΔR_S are decreasing with increasing number of stretching cycles.

	Cycle number:	1	2	3	4	5
40 µg cm^{-2} at 13.3 %	Δ R_L [Ω/mm]	1489.7	769.1	467.6	277.7	138.0
	Δ R_S [Ω/sq]	795.4	254.5	260.1	163.2	177.1
80 µg cm^{-2} at 13.3 %	Δ R_L [Ω/mm]	1306.8	746.7	608.5	356.0	121.4
	Δ R_S [Ω/sq]	918.3	1088.9	942.9	397.3	126.8
120 µg cm^{-2} at 6.6 %	Δ R_L [Ω/mm]	10.1	3.3	1.7	1.1	0.8
	Δ R_S [Ω/sq]	14.6	25.2	13.0	8.3	5.0

Table S2.: Line ($R_{L,max}$) and sheet ($R_{S,max}$) resistance of the three samples (40 µg cm^{-2}, 80 µg cm^{-2}, and 120 µg cm^{-2}) at maximum elongation (23.3 %) depending on the stretching cycle. In the last column the percentage of the fifth cycle on the initial $R_{L/S,max}$ of the first cycle are listed. R_L as well as R_S are decreasing with stretching cycle for all samples.

	Cycle number	1	2	3	4	5	percentage of initial value
40 µg cm^{-2}	$R_{L,max}$	3536.4	2665.7	2328.2	2185.3	2030.9	57.4 %
	$R_{S,max}$	3322.6	2499.7	2197.8	2080.9	1874.9	56.4 %
80 µg cm^{-2}	$R_{L,max}$	5051.1	4380.1	4518.0	4052.7	3506.2	69.4 %
	$R_{S,max}$	4331.5	3938.5	3967.9	3353.9	3098.9	71.5 %
120 µg cm^{-2}	$R_{L,max}$	32.1	27.1	19.2	19.2	17.0	52.9 %
	$R_{S,max}$	177.6	134.1	88.2	162.7	124.7	70.2 %

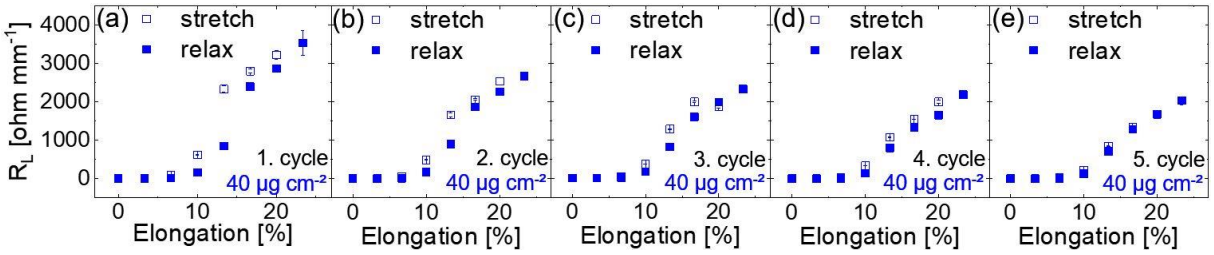

Figure S4: Line resistance during stretching the Ag-NW composite with a concentration of 40 µg cm^{-2} five times in a row. The initial line resistance $R_{L,0}$ before stretching was 0.9 Ω mm^{-1}. The line resistance at maximum elongation $R_{L,max}$ and the final resistance $R_{L,f}$ after each stretch are decreasing with each cycle. $R_{L,0} - R_{L,max} - R_{L,f}$ for each cycle is: (a) 0.9 – 3536.4 – 1.4 Ω mm^{-1}. (b) 1.4 – 2665.7 – 1.0 Ω mm^{-1}. (c) 1.0 – 2328.2 – 1.0 Ω mm^{-1} (d) 1.0 – 2185.3 – 0.8 Ω mm^{-1} (e) 0.8 – 2030.9 – 0.8 Ω mm^{-1}.

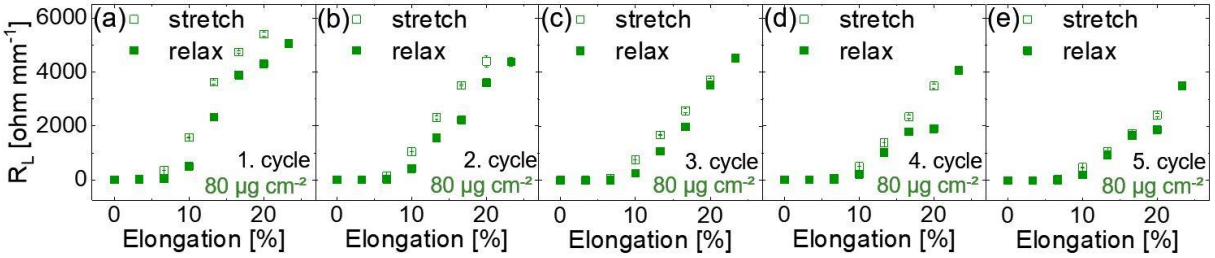

Figure S5: Line resistance during stretching the Ag-NW composite with a concentration of 80 µg cm^{-2} five times in a row. The initial line resistance before stretching $R_{L,0}$ was 2.9 Ω mm^{-1}. The line resistance at maximum elongation $R_{L,max}$ and the final resistance $R_{L,f}$ after each stretch are decreasing with each cycle. $R_{L,0} - R_{L,max} - R_{L,f}$ for each cycle is: (a) 2.9 – 5051.1 – 4.6 Ω mm^{-1}. (b) 4.6 – 4380.1 – 3.4 Ω mm^{-1}. (c) 3.4 – 4518.1 – 2.1 Ω mm^{-1} (d) 2.1 – 4052.7 – 1.8 Ω mm^{-1} (e) 1.8 – 3506.2 – 1.8 Ω mm^{-1}.

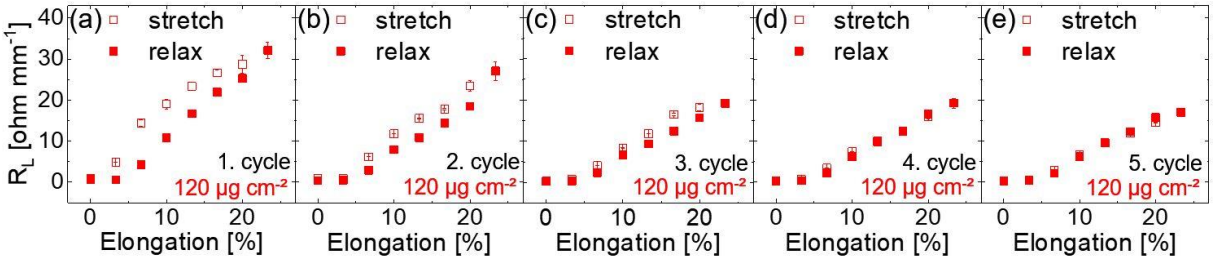

Figure S6: Line resistance during stretching the Ag-NW composite with a concentration of 120 µg cm^{-2} five times in a row. The initial line resistance $R_{L,0}$ before stretching was 0.7 Ω mm^{-1}. The line resistance at maximum elongation $R_{L,max}$ and the final resistance $R_{L,f}$ after each stretch are decreasing with each cycle. $R_{L,0} - R_{L,max} - R_{L,f}$ for each cycle is: (a) 0.7 – 32.1 – 0.8 Ω mm^{-1}. (b) 0.8 – 27.1 – 0.3 Ω mm^{-1}. (c) 0.3 – 19.2 – 0.3 Ω mm^{-1} (d) 0.3 – 19.2 – 0.2 Ω mm^{-1} (e) 0.2 – 17.0 – 0.2 Ω mm^{-1}.

SI 5. Composite Cross Section

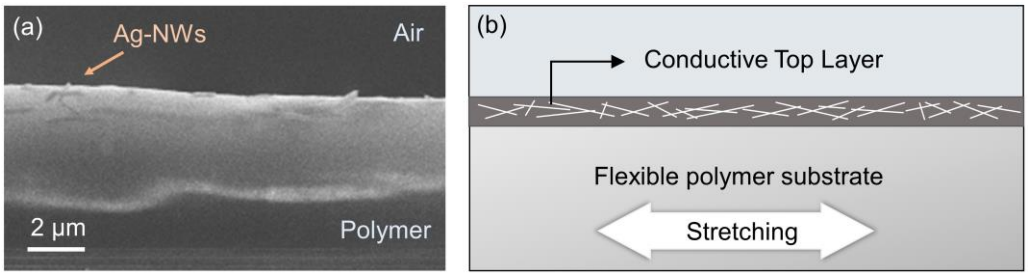

Figure S7: (a) SEM image of a cross section of an exemplary silver-nanowire composite with a concentration of 80 µg cm^{-2}. One can see the nanowires embedded in the polymer matrix forming the conductive top layer, as well as the pure flexible polymer below. Please note that both, the Ag-NW composite layer and the pure polymer layer have been fabricated and cured in one step, leading to a chemical crosslinking between the conductive top layer and the polymer layer. (b) Schematic representation of the cross section.

References

[1] Y. Sun, B. Gates, B. Mayers, Y. Xia, *Nano letters* **2002**, *2*, 165-168.

[2] T. E. Glier, L. O. Akinsinde, M. Paufler, F. Otto, M. Hashemi, L. Grote, L. Daams, G. Neuber, B. Grimm-Lebsanft, F. Biebl, D. Rukser, M. Lippmann, W. Ohm, M. Schwartzkopf, C. J. Brett, T. Matsuyama, S. V. Roth, M. Rübhausen, *Sci. Rep.* **2019**, *9*, 6465.

[3] L. J. Van der Pauw, *Philips technical review* **1958**, *20*, 220-224.