Supporting Information

Reversible Sliding in Networks of Nanowires

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Experimental

Nanowire network electrode preparation. Copper nanowires were donated from NanoForge Corp. The mean length of the nanowires was 38 ± 11.2 μm (one standard deviation on n = 40 wires). The mean diameter of the nanowires was 107 ± 20 nm. The copper nanowires were washed 3 times in an aqueous solution of 3 wt% hydrazine, and dispersed in DI water with vortexing.

Silver nanowires were synthesized according to the method reported by Wiley et al.[1] The mean length of the silver nanowires was 14 ± 5.3 μm, and the mean diameter was 119 ± 28 nm. After washing 1 time using acetone and 3 times DI water, the silver nanowires were stored in DI water at room temperature.

The process for making transparent nanowire actuators is illustrated in Figure S2. The nanowires were diluted with DI water to make solutions with different concentrations in order to obtain different transmission values for the nanowire networks. The well-dispersed nanowire solution was diluted in DI water and filtered using 0.45 mm MF-Millipore membrane filters (Millipore 0.45 mm, HAWP04700) to form a homogeneous nanowire network on the filter membrane. The nanowire-covered membrane was then immediately cut into a circle with a diameter of 10 mm, leaving a strip of nanowire-coated membrane for connection to the voltage supply. The cut membranes for both top and bottom electrodes were then put into contact with VHB that was biaxially pre-stretched to a strain of 300%. The transfer of the nanowires from the membrane to the VHB was enhanced by gently pressing by hand before peeling the membranes away. The entire filter and transfer process was completed within 10 minutes.

Measuring Actuation. A high voltage power supply (Matsusada, Japan) was used to apply the voltage between the nanowire electrodes on the top and bottom sides of the VHB. Area expansions of the copper nanowire actuator were recorded by a digital camera.

Measuring Transmittance. The transmittance of copper and silver nanowire electrodes was measured using a UV/VIS/NIR spectrometer (Cary 6000i, USA) at a wavelength from 400 to 1800 nm. The baseline on the UV/Vis/NIR spectrometer was corrected using a blank film of VHB biaxially prestretched to 300%.

Observing Nanowire Sliding. The study of nanowire sliding was carried out using an Olympus BX41M-LED optical microscope equipped with a 50x objective. The variation of strain was achieved by stretching the laminate with a biaxial stretcher.

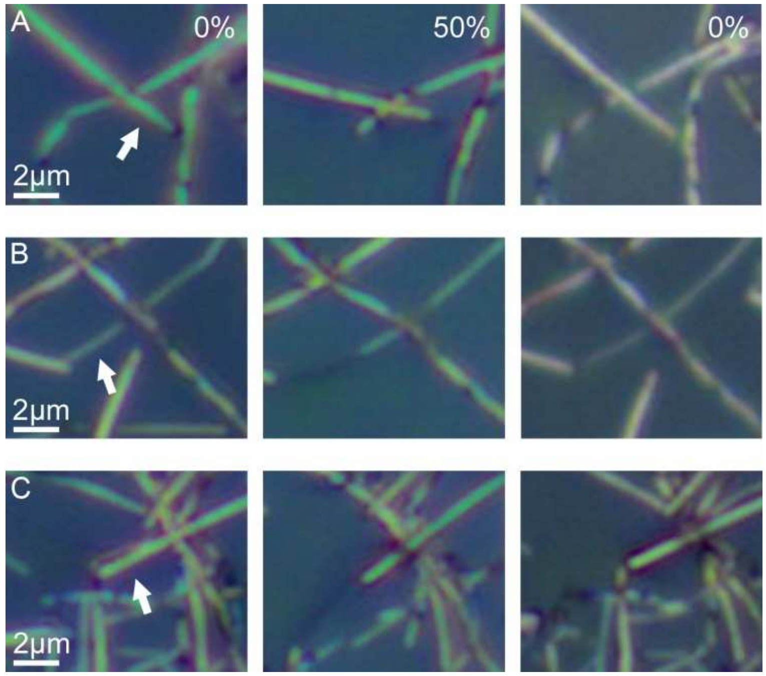

Figure S1. A series of optical microscope images showing three different copper nanowires sliding as the area strain is increased to 50%, and relaxed back to 0%.

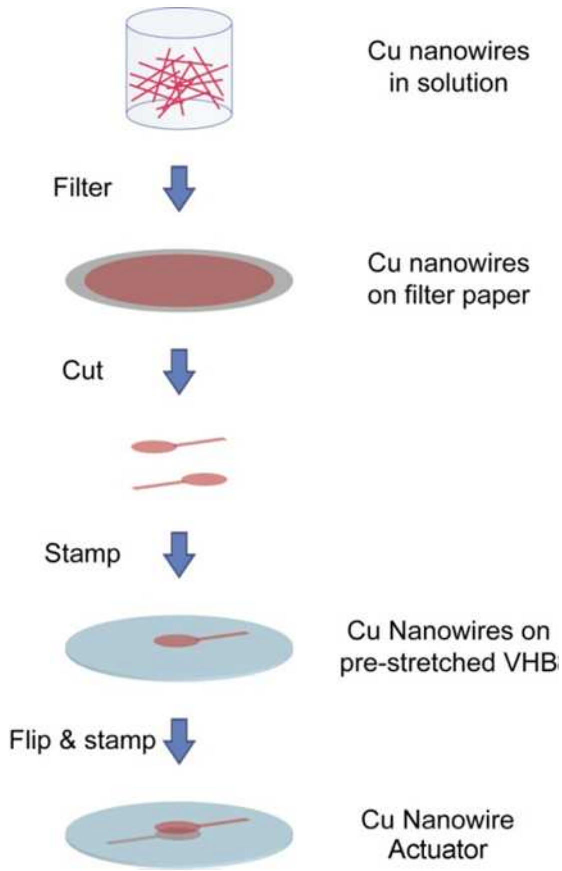

Figure S2. Schematic of the processes used for making the copper nanowire actuator.

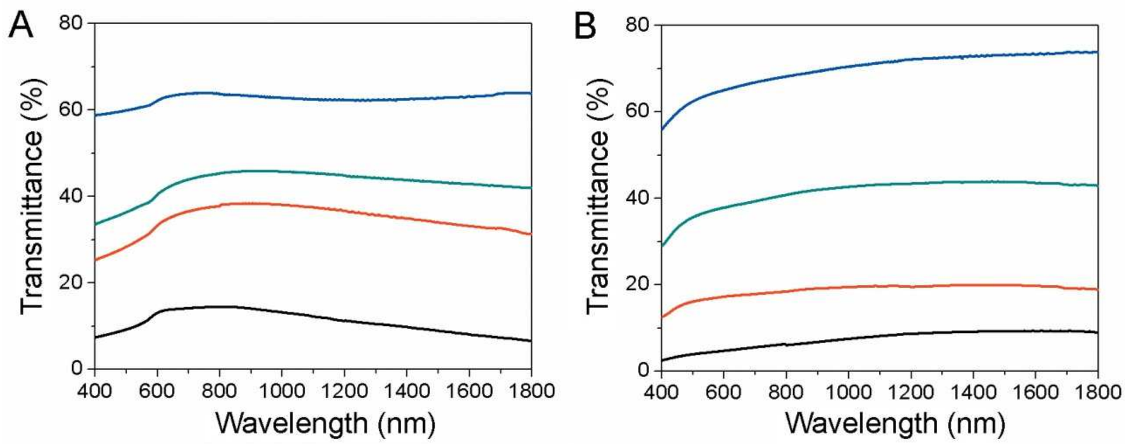

Figure S3. Broadband optical transmittance spectra of (A) copper nanowire and (B) silver nanowire actuators at different densities.

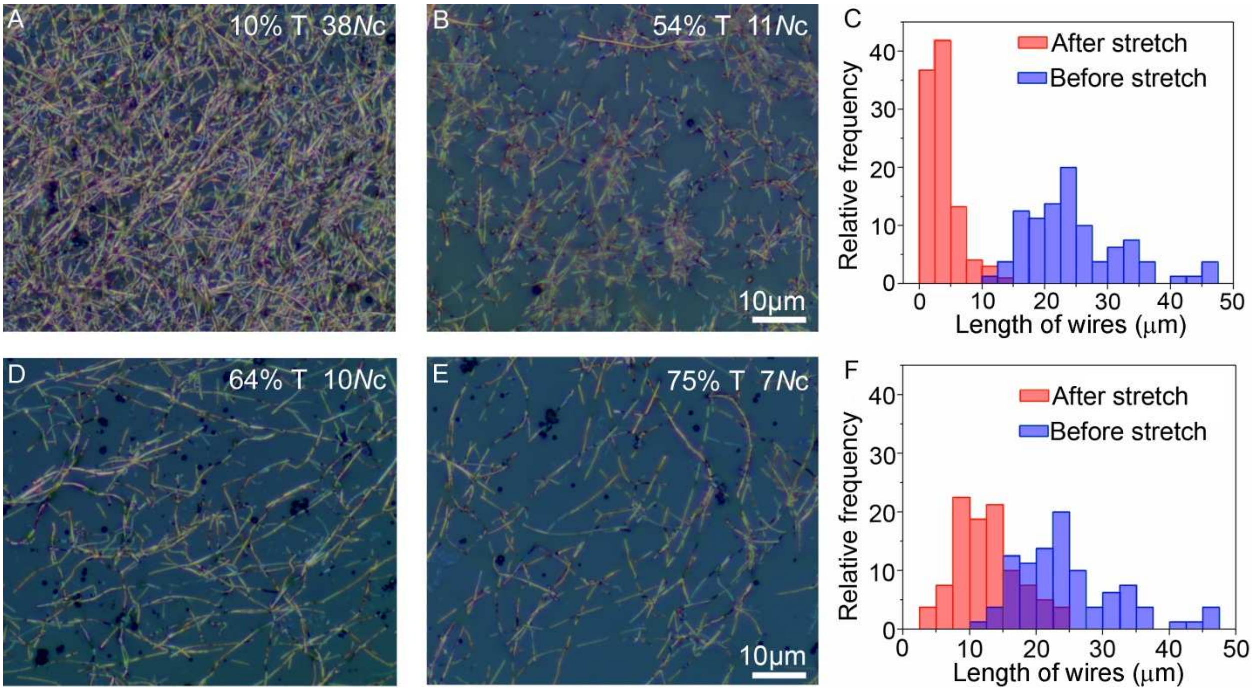

Figure S4. Microscope images of copper nanowire networks (A&D) before and (B&E) after actuation to the maximum strain (225% for B 50% for E). Nanowire entanglement at high nanowire densities led to clumps of nanowires (B) that were not apparent at low nanowire densities (E). C&F) Histograms of nanowire length before and after stretching indicate that high nanowire densities led to greater fracture of nanowires than low nanowire densities, likely due to nanowire entanglement. The initial length of the nanowires of 25 ± 7.7 μm decreased to μm 4 ± 2.4 at a density of 11*Nc* and 13 ± 4.7 μm at a density of 7*Nc*.

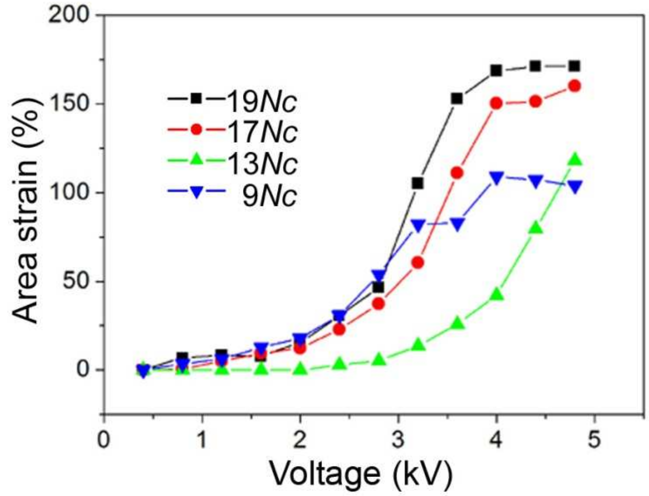

Figure S5. Performance of silver nanowire actuators with different number densities of nanowires. Here N_c is the critical density required for percolation, which in this case is 2.7×10^{10} nanowires m^{-2}.

Table S1. Summary of data for copper nanowire actuators

%T		Number density (# m^{-2})		$N_c = 4\times10^9$		Maximum strain
start	end	start	end	start	end	
10	54	1.5×10^{11}	4.6×10^{10}	$38N_c$	$11N_c$	225%
20	56	1.1×10^{11}	3.9×10^{10}	$28N_c$	$10N_c$	183%
40	65	6.4×10^{10}	2.8×10^{10}	$16N_c$	$7N_c$	134%
52	65	4.6×10^{10}	2.7×10^{10}	$12N_c$	$7N_c$	69%
64	75	3.2×10^{10}	2.1×10^{10}	$8N_c$	$5N_c$	50%

Table S2. Summary of data for silver nanowire actuators

%T		Number density (# m^{-2})		$N_c = 2.7\times10^{10}$		Maximum strain
start	end	start	end	start	end	
18	50	5.1×10^{11}	1.9×10^{11}	$19N_c$	$7N_c$	171%
21	48	4.7×10^{11}	1.8×10^{11}	$17N_c$	$7N_c$	160%
30	46	3.6×10^{11}	1.7×10^{11}	$13N_c$	$6N_c$	117%
53	73	2.5×10^{11}	1.2×10^{11}	$9N_c$	$4N_c$	104%

REFERENCES

(1) Bergin, S. M.; Chen, Y. H.; Rathmell, A. R.; Charbonneau, P.; Li, Z. Y.; Wiley, B. J. *Nanoscale* **2012,** 4, 1996-2004.