Supporting Information

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CNT–AgNP Patterning on PDMS Substrates

CNT–AgNP lines were patterned on the PDMS substrates by either a painting (i.e., dip-pen writing) or printing (i.e., silk printing) approaches. The two techniques resulted in similar performance in terms of resistivity and strain sensitivity of the obtained films. The sample in Fig. 1 was made by printing and the other data were obtained by the painting approach. The detailed procedure for each technique is summarized below and depicted in Fig. S1.

Approach 1: Printing (Fig. S1*A*).

i) The surface of the PDMS substrate is oxygen plasma treated (40 W, 1 min).
ii) A shadow mask with the desired pattern is prepared using a Kapton substrate (~70 μm in thickness) and brought in contact on the PDMS substrate.
iii) The CNT–AgNP mixture ink is poured over the PDMS substrate with the mask on top.
iv) A glass blade is swept on the surface of the substrate at ~45° angle to remove the extra ink.
v) The mask is removed the PDMS surface, leaving behind ink that is deposited only in the patterned regions.
vi) The sample is baked at 70 °C for 1–2 h.

Approach 2: Painting (i.e., Dip-Pen Writing; Fig. S1*B*).

i) The surface of the PDMS substrate is oxygen plasma treated (40 W, 1 min).
ii) A sharp plastic tip (~160 μm in diameter) is dipped into the ink mixture and dragged on the surface of the PDMS substrate to write the desired pattern.
iii) The sample was baked at 70 °C for 1–2 h.

Control Experiment—Devices with Symmetric CNT–AgNP Composite Films

Symmetric CNT–AgNP (30 wt % AgNP loading) composite films were painted on the top and bottom of a PDMS fiber to serve as a control device as shown in Fig. S2*A*. Fig. S2*B* shows the output signal of this device, exhibiting no resistance change as the fiber is bent up and down, corresponding to ~1.5% strain. This is expected because the films exhibit resistivity change that is nearly identical in magnitude but opposite in sign in response to compressive and tensile strain. Because under bending conditions, the top and bottom surfaces exhibit opposite strain (Fig. S3), the resistance change of the films cancels out, resulting in no net response. The results highlight the importance of using asymmetric composite films on top and bottom surfaces to obtain maximum device sensitivity for e-whisker applications.

Mechanical Simulations of E-Whiskers

To understand the stress distribution over the e-whisker structure, mechanical simulations were conducted by using a finite-element method (Comsol Multiphysics 4.2) as shown in Fig. S3. In this simulation, the tip of the e-whisker is displaced downward by 1 mm and holding the base at a fixed location. Here, the active layer is assumed to be a pure AgNP film for simplicity. Young's moduli of 40 GPa and 0.75 MPa were used for AgNP (1) and PDMS (2) layers, respectively. The structure assumes 2-μm-thick AgNP layers on the top and bottom surfaces of PDMS (thickness of 250 μm; and length of 15 mm). The simulation depicts the highest tensile and compressive stresses are in the Ag layers at the base of the e-whisker (Fig. S3*B*). The stress strength at the top and bottom surfaces is symmetric with tensile and compressive strains, respectively.

Spring Constant of E-Whisker

The e-whiskers can be viewed as highly elastic cantilevers. From our experiments, the displacement of the PDMS whiskers is linearly proportional to the applied force, for the explored range of up to $F \sim 50$ μN. Specifically, a force of ~22.5 μN leads to a tip displacement of $d \sim 3$ mm. The experimentally extracted spring constant, $k = F/d$, is ~7.5 mN/m. This value is consistent with that obtained from Comsol simulations. From simulation, we obtained spring constants between 2 and 5.4 mN/m according by using PDMS Young's modulus in the range of 0.75–3 MPa. It should be noted that the small spring constant of the PDMS fibers is essential in obtaining high sensitivity because minimal force leads to large displacement and thereby strain.

1. Park J, Lee DJ, Kim SJ, Oh JH (2009) Dynamic characteristics measurements of inkjet-printed thin films of nanosilver suspensions on a flexible plastic substrate. *J Micromech Microeng* 19:095021.
2. Armani D, Liu C, Aluru N (1999) Re-configurable fluid circuits by PDMS eleastomer micromachining. *Proceedings of the International Conference MEMS 99,* 222–227.

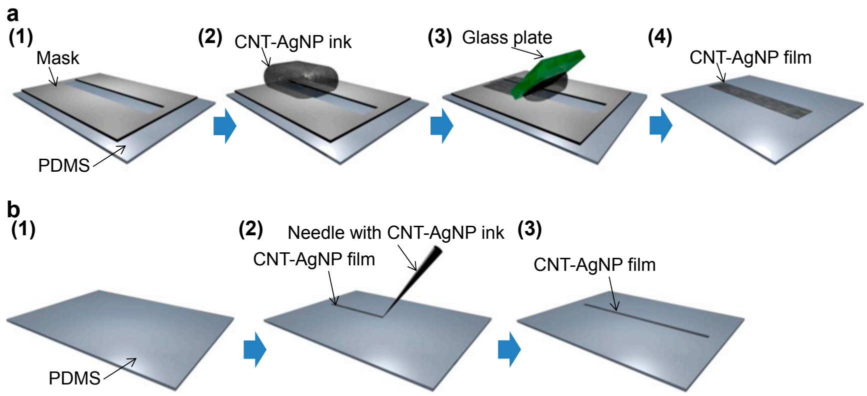

Fig. S1. Patterning techniques for CNT–AgNP composite films used in this work. (*A*) Silk printing using a line-patterned plastic mask. (*B*) Painting (i.e., dip-pen writing) using a sharp (~160 μm in diameter) plastic tip.

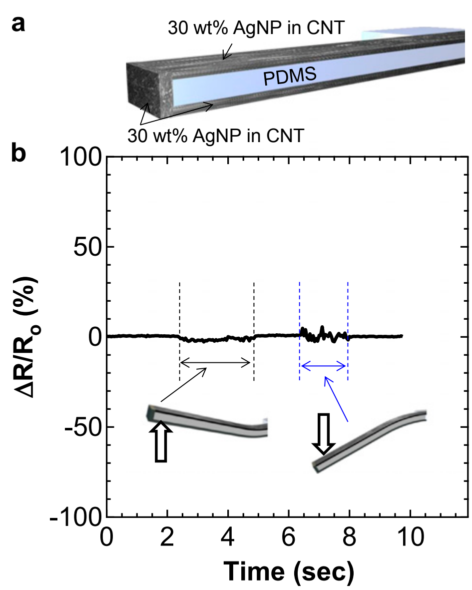

Fig. S2. (*A*) Schematic of a symmetric device where the same CNT–AgNP (30 wt % AgNP loading) composite film is patterned on the top and bottom surfaces of a PDMS fiber; (*B*) $\Delta R/R_o$ by applying compressive and tensile strains (~1.5%) on the device, showing minimal response.

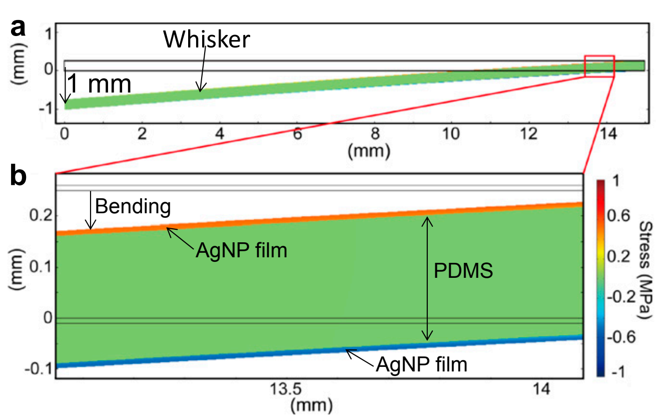

Fig. S3. Mechanical simulation of stress distribution for the e-whisker structure. (*A*) Stress distribution through the entire e-whisker structure with 15 mm length and 250 μm thickness with 2-μm-thick AgNP film for top and bottom PDMS surfaces. (*B*) Zoomed-in image of the root of AgNP film area.