Electronic Supplementary Material (ESI) for Nanoscale.

Supplementary Information

Paper-Based Silver-Nanowire Electronic Circuits with Outstanding Electrical Conductivity and Extreme Bending Stability

Gui-Wen Huang,[a,b] Hong-Mei Xiao,[*,a] and Shao-Yun Fu[*,a]

[a] Technical Institute of Physics and Chemistry, Chinese Academy of Sciences, Beijing 100190, China

[b] University of Chinese Academy of Sciences, Beijing 100039, China

* Correspondence to: syfu@mail.ipc.ac.cn

Videos

Video 1: A rolling test is ongoing for the five circuits.

Video 2: The PFP paper-based UHF RFID tag is read by a RFID reader. "EPC" in the video is the abbreviation of electronic product code.

Video 3: The PFP paper-based flexible cable is used to connect a micro-camera to a cell phone.

Synthesis of Silver Nanowires

Silver nanowires were synthesized via a solvothermal method. Typically, $AgNO_3$ (0.01 mol) was dissolved in ethylene glycol (100 ml) to form solution A. Polyvinylpyrrolidone (PVP, 0.015 mol) as active agent was dissolved in ethylene glycol (100 ml) and KCl (2.22×10^{-5} mol) was added to form solution B. Then, the solution B was added to solution A drop wise with vigorous stirring. After that, the mixture was moved to a 5L autoclave and heated in an oven at 160℃ for 3h. Finally the silver nanowires were obtained by rinsing with a large amount of acetone. **Fig. S1** shows the SEM images of the as-synthesized silver nanowires, which have an average length of 25.7 μm and an average diameter of 187 nm. The data were obtained from 100 stochastic measurements in terms of the SEM images of Ag-NWs using Nano Measure software.

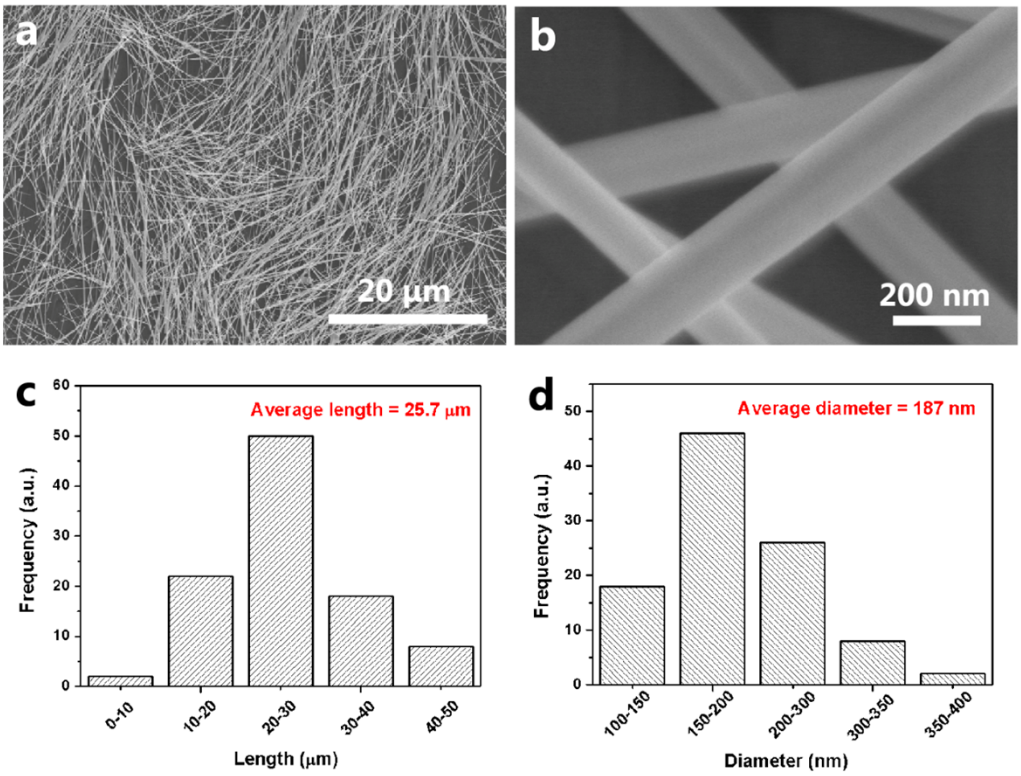

Fig. S1. (a) Low and (b) high magnification SEM images of the as-synthesized silver nanowires; histograms for (c) the length and (d) the diameter of the Ag-NWs.

Printing-Filtration-Press (PFP) Technique

In the PFP technique, negative pattern of the designed circuit was first printed on the paper substrate through screen printing. The ink used is the solvent-based black printing ink and the mesh count of the nylon screen is 400/inch. After screen printing, the printed area on paper was covered by the black ink after printing, and the pores in these areas were completely blocked, leaving the designed circuit areas blank. After the ink wad dried, the substrate was sucked by vacuum on a filter board. Ag-NW ethanol solution (0.1 mg/ml) was then poured on the paper substrate and a frame is usually needed to limit the liquid in the printed area during vacuum filtration. Since the liquid could only be sucked through the un-printed areas, the Ag-NWs were finally spontaneously deposited on the designed circuits. After deposition, Ag-NWs were evenly distributed on the designed areas and nearly no Ag-NWs were left in the printed areas. This proves that this technique can produce high quality electronic circuits. Lastly, the circuits were compacted by a pressing machine (769YP-24B, Ke-Qi technology Co. Ltd., Tianjin, China) and then the PVA was coated as the protecting layer. As a contrast, the same paper-based electronic circuit was made using commercial silver micro-flake filled conductive adhesive as the conductive material. Moreover, paper based Ag-NW circuits were prepared according to the previously reported spray and drop-casting techniques.[1,2]

Folding Test

The PFP Ag-NW circuit on paper, the spray Ag-NW circuit on paper, the drop-casting Ag-NW circuit on paper, the commercial etched copper circuit on PET and the commercial conductive adhesive circuit on paper were folded to test their bending stability. 50 g folding force was applied to the three circuit samples. The circuits were repeatedly folded from -180° to +180° and the conductivity was measured with Keithley source meter 2400 after each folding cycle. **Fig. S2** shows the ratio of the measured conductivity (C_m) to the initial conductivity (C_0) of the circuits versus the folding number. As can be seen, both the etched copper circuit on PET and the conductive adhesive circuit on paper fail after only a few cycles of folding; the spray circuit and drop-casting circuit failed after 23 and 34 folding cycles, respectively; while the PFP Ag-NW circuit on paper performs a very robust response to folding. The conductivity remains almost unchanged even after 50 folding cycles. This indicates that the PFP paper-based Ag-NW circuit has a much better folding-resistance performance than the other four flexible circuits. **Fig. S3** shows the digital images of the circuits after folding. The conducting network of Ag-NWs in the PFP circuit was still continuous even after 50 cycles of folding and only left a crease on the circuit. In contrast, other four circuits fail after a much smaller number of folding cycles.

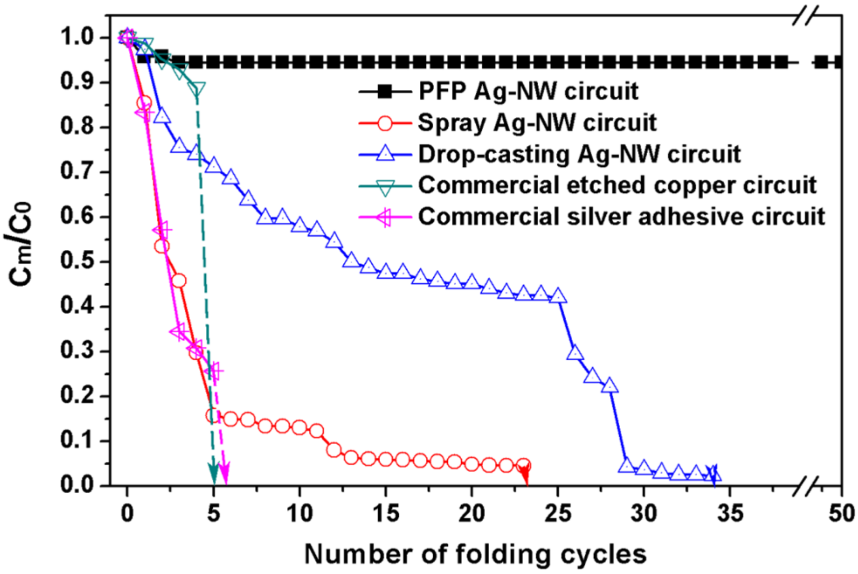

Fig. S2. The ratio of the measured conductivity (C_m) to the initial conductivity (C_0) of the five flexible circuits versus number of folding cycles.

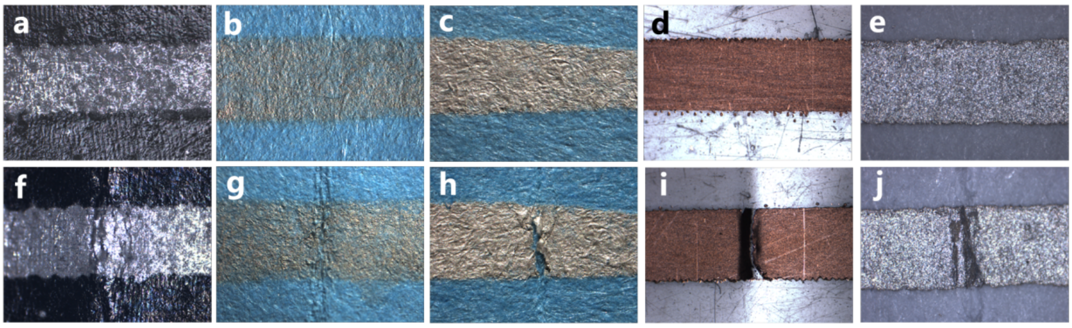

Fig. S3. Digital images of (a) the PFP Ag-NW circuit on paper, (b) the spray Ag-NW circuit on paper, (c) the drop-casting Ag-NW circuit on paper, (d) the etched copper circuit on PET and (e) the conductive adhesive circuit on paper before folding; (f-j) are respectively the corresponding images for (a-e) after the 50, 23, 34, 4 and 5 folding cycles.

Air Humidity Test

In order to investigate the effects of air humidity on the electrical property of the PFP circuits, one UHF antenna samples are placed in the environments with various air humilities adjusted by a humidifier for 1 h and then the resistance of the circuits are measured. The environmental temperature is fixed at 30 ℃. The results are shown in the Fig. S4. It shows that the resistance of the circuit keeps almost constant as the air humility changes from 20 % to 80 %, which demonstrates that the water content in the ambient may not cause obvious effects on the electrical property of the PFP circuits.

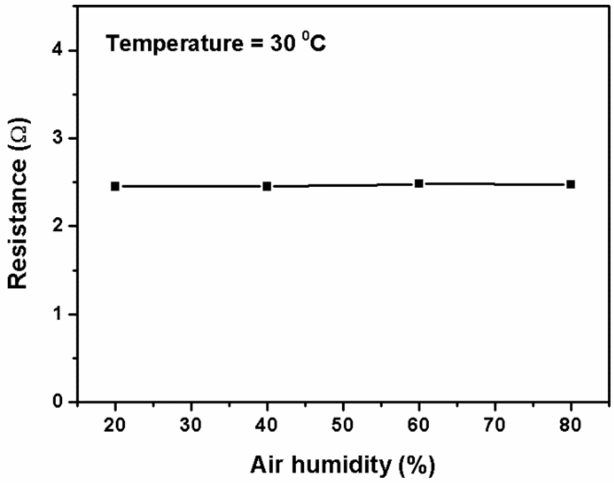

Fig. S4. Resistance of the PFP circuits as a function of air humidity. Where the temperature is fixed at 30 ℃.

REFERENCES

1. A. C. Siegel, S. T. Phillips, M. D. Dickey, N. Lu, Z. Suo and G. M. Whitesides, *Adv. Funct. Mater.*, 2010, **20**, 28-35.

2. C. Yang, H. Gu, W. Lin, M. M. Yuen, C. P. Wong, M. Xiong and B. Gao, *Adv. Mater.*, 2011, **23**, 3052-3056.