

Supplementary Information

Programmable Contact Printing Using Ballpoint Pens with a Digital Plotter for Patterning Electrodes on Paper

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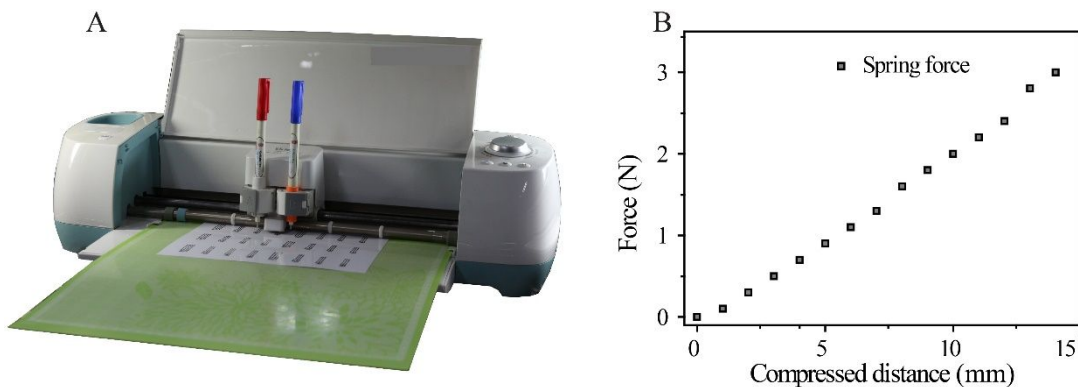


Figure S1. A) Image of the contact printing system containing: a digital plotter, two ballpoint pens with CNT ink (red) and AgNP ink (blue), printed ECSs on a paper substrate, and the adhesive mat (green). B) Relation between force and compressed distance of the metal spring which is used for the ballpoint pens.

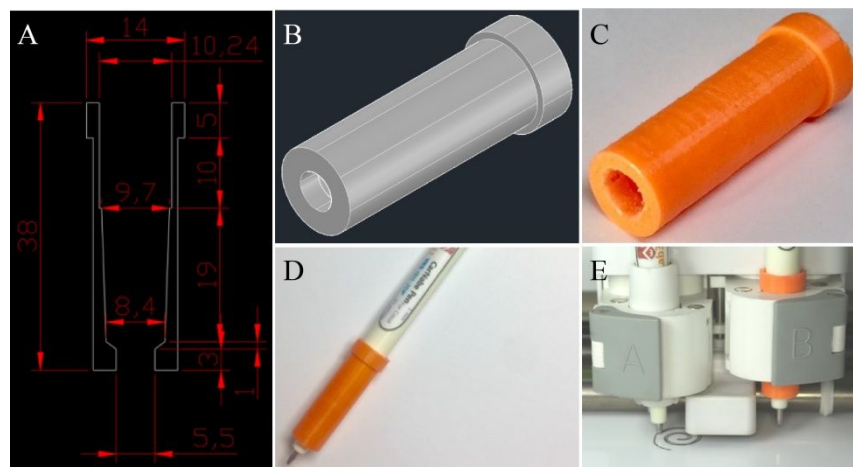


Figure S2. Preparation of a pen holder for clamp B. A) Schematic and a (B) 3D computer rendering of the design model. C) 3D printed pen holder. D) Picture of a ballpoint pen placed inside the 3D printed pen holder. E) Picture of the ballpoint pens that they are placed into clamp A and clamp B for sequentail contact printing.

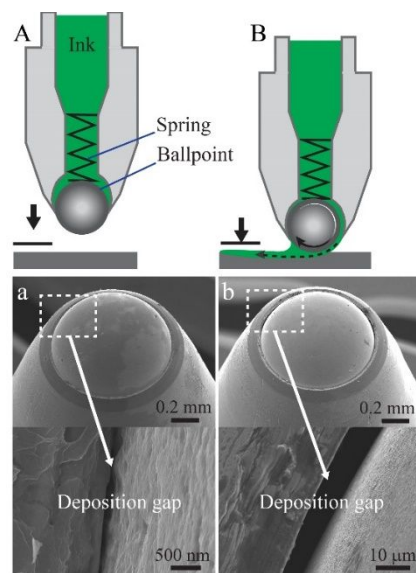


Figure S3. **A)** Schematics and **(a)** SEM images for the ballpoint tip without contact pressure. **B)** Schematics and **(b)** SEM images of the ballpoint tip with mimic contact pressure. The mimic contact pressure was mimicked in the way by removing the inner spring (a part of the commercial ballpoint pen), releasing the tension between the tip and nozzle.

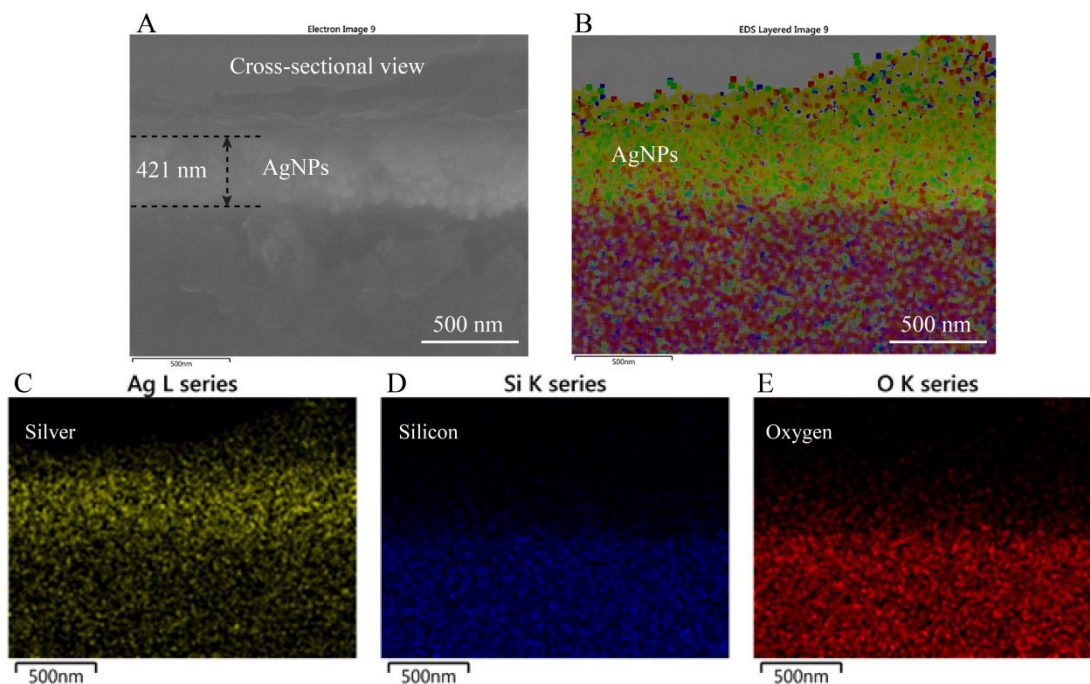


Figure S4. **A)** Cross-sectional view SEM image of an AgNP pattern printed by a ballpoint pen with a diameter of 1.0 mm. **B)** A merged element composition and its split element mapping, **(C)** Silver, **(D)** Silicon, **(E)** Oxygen, by EDS for the cross-sectional view of the AgNP pattern in **(A)**.

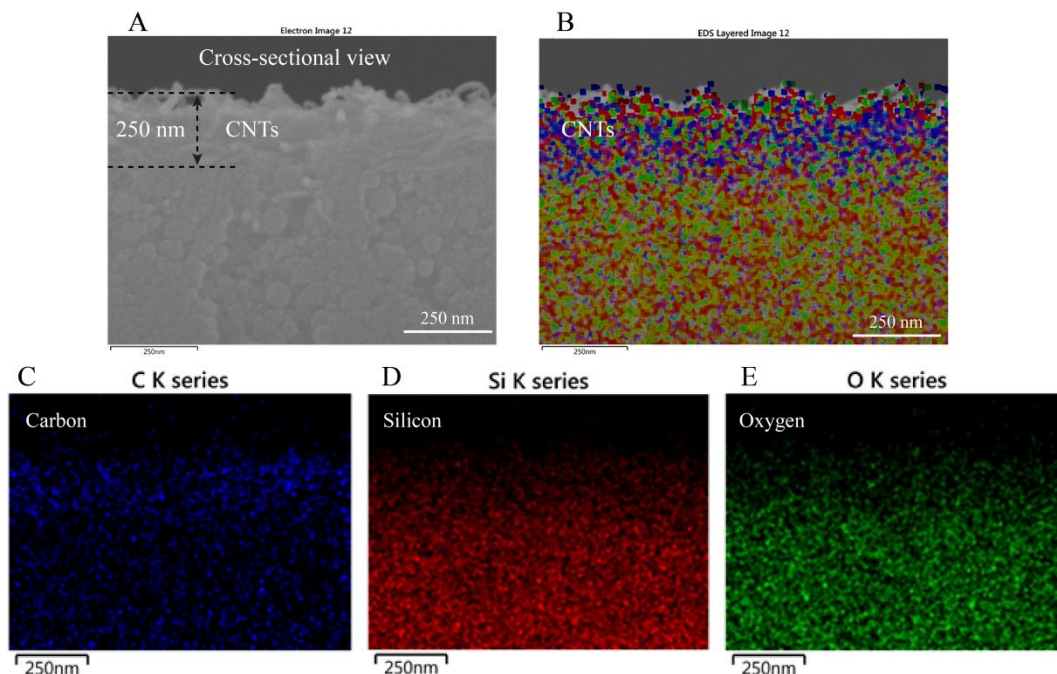


Figure S5. **(A)** Cross-sectional view SEM image of a CNT pattern printed by a ballpoint pen with a diameter of 1.0 mm. **(B)** A merged element mapping and its split element mapping, **(C)** Carbon (CNTs), **(D)** Silicon, **(E)** Oxygen, by EDS of the cross-sectional view for the CNT pattern in **(A)**.

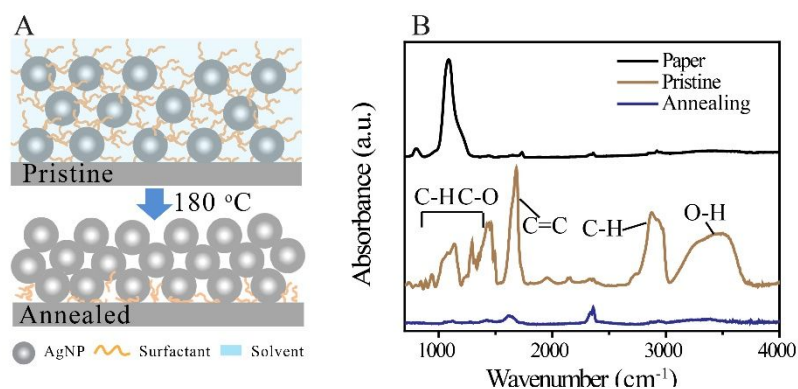


Figure S6. Effect of annealing on the printed AgNP pattern. **(A)** Schematics and **(B)** FTIR spectra of the printed AgNP patterns before and after annealing at 180 °C for 30 minutes.

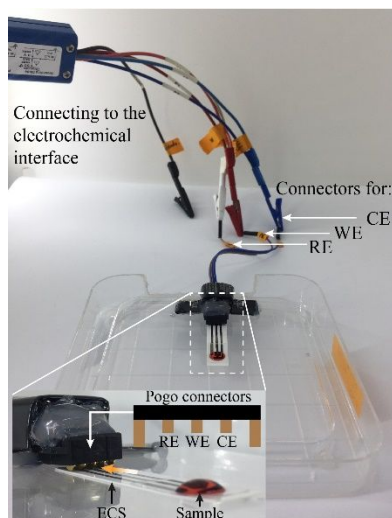


Figure S7. An electrochemical measurement setup. A lab-made platform for connecting between the ECS and the electrochemical interface was prepared with five pogo pins.

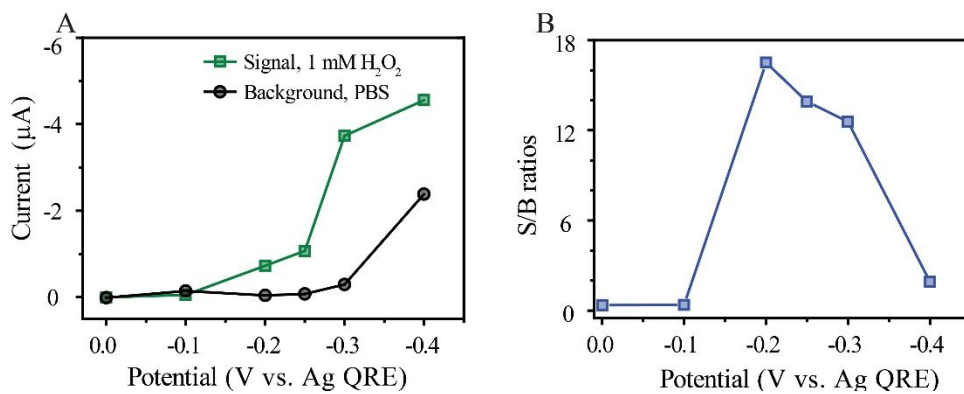


Figure S8. A) Hydrodynamic voltammograms for 1-mM H_2O_2 (Signal) and PBS (Background) and the current was selected at 60 s. B) Signal to background (S/B) ratios were taken from the data shown in (A).

Cost of component		Estimate cost of component per sensor	
Component	Cost (USD)	Cost (USD)	
Digital plotter	230/unit	NA	
Ballpoint pen	1/unit (x 2)	0.001 (x 2)	
AgNP ink	3/mL	0.006	
CNTs ink	2/mL	0.004	
Photo paper (A4)	0.25/pcs	0.001	
Adhesive film (A4)	0.2/pcs	0.001	
Total	237.45	0.014	

Table S1. Cost of components and estimated cost of component per sensor for the direct print using a digital plotter with ballpoint pens to fabricate the electrochemical sensors. Note: All cost of each component is based on market price in South Korea.