Highly transparent and flexible circuits through patterning silver nanowires into microfluidic channels

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Methods

PDMS film preparation. PDMS was prepared using Momentive RTV615 by mixing solution A with solution B at a mass ratio of 10:1. After degassing with a vacuum desiccator and curing at 80 °C for 2 hrs, solidified PDMS films were formed.

Surface modification of PDMS. The PDMS film was cleaned by a 3M tape and a UVO cleaner (Jelight, Irvine, CA). Then the PDMS film was immersed into a mixture of 2% poly(vinyl alcohol) (PVA) and 5% glycerol (Gly) solution for 20 min and vacuum dried at 60 °C for 2 hrs for three times. The PVA/Gly layer was peeled off from one side of the PDMS by a transparent tape and the PDMS film was vacuum dried at 100 °C for 20 min, resulting in immobilized PVA/Gly hydrophilic modification of the PDMS surface.

Spin coating of AgNWs. AgNWs (XFNano, Nanjing, China) were 30 nm in diameter and 100 – 200 μm in length. 60 μL of AgNWs ethanol solution (0.6 mg mL^{-1}) was applied onto the modified PDMS surface by pipetting. Spin coating was performed with a spin processor (Laurell Technologies, North Wales, PA) with the following optimized parameters: deposition layers, 8; spin acceleration, 30 rpm s^{-1}; spin speed, 1,000 rpm; spin time, 50 s.

Palladium particles (PdNPs) deposition on AgNWs circuits. PdNPs were deposited onto the AgNWs in the square-wave shaped circuits by cyclic voltammetry with a scan rate 25 mV/s in the potential window ranging from -0.25 V to 0. 4 V using 5 mM $PdCl_2$ dissolved in 0.2 M acetate/sodium acetate buffer.

Silicon mold and PDMS microcircuits preparation. Microcircuits silicon mold were obtained through a standard photolithography protocol with SU8-2050 on a 4-in. silicon substrate with a microcircuit height of 150 μm. The mixture of solution A and solution B (mass ratio of 10:1) was poured over the silicon mold, which was degassed and heated at 80 °C for 2 hrs. The solidified PDMS was formed and peeled off from the mold.

Transmittance and sheet resistance measurements. Transmittance was measured by a Lambda 35 UV-Vis spectrometer (PerkinElmer, Waltham, MA). A PDMS film without AgNWs coating was used as a reference. Sheet resistance was measured with an M-3 four-probe measurement system (Suzhou Jingge Electronic, Suzhou, China). The average values of at least 10 measurements on each sample were adopted as sheet resistance.

Glucose measurements. 0.1 M glucose dissolved in 0.2 M NaOH was measured by cyclic voltammetry with a scan rate 50 mV/s in the potential window ranging from -0.6 to 0.8 V. The AgNWs/PdNPs square-wave circuits were taken as the working electrode, Ag/AgCl as the reference electrode, and platinum as the counter electrode.

SEM and SEM–EDS mapping. Scanning electron microscope (SEM) images were acquired by SU8220 (Hitachi High-Tech, Japan). SEM–EDS (energy dispersive spectroscopy) mapping was performed with X-Max^{N} (Horiba, Japan).

Supplementary Figures

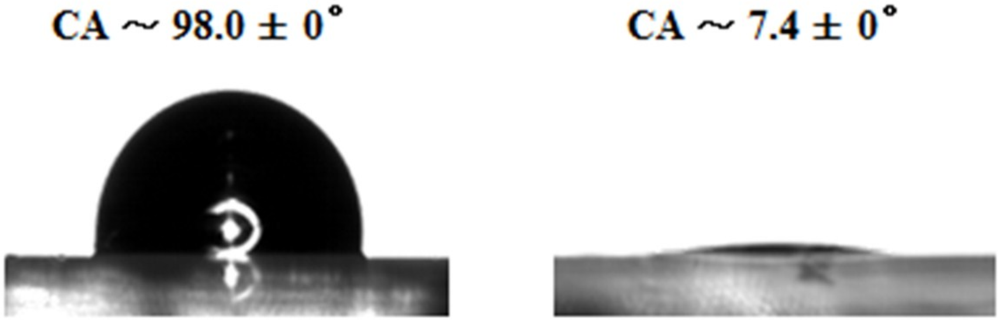

Figure S1. The surface wettability was investigated by water contact angle (CA) for native PDMS and three-layer PVA/Gly modified PDMS. The water CA of native PDMS was 98.0 ± 0°, exhibiting hydrophobicity. The water CA of PDMS reduced to 7.4 ± 0° after three layers of PVA/Gly modification, indicating that the surface was super hydrophilic.

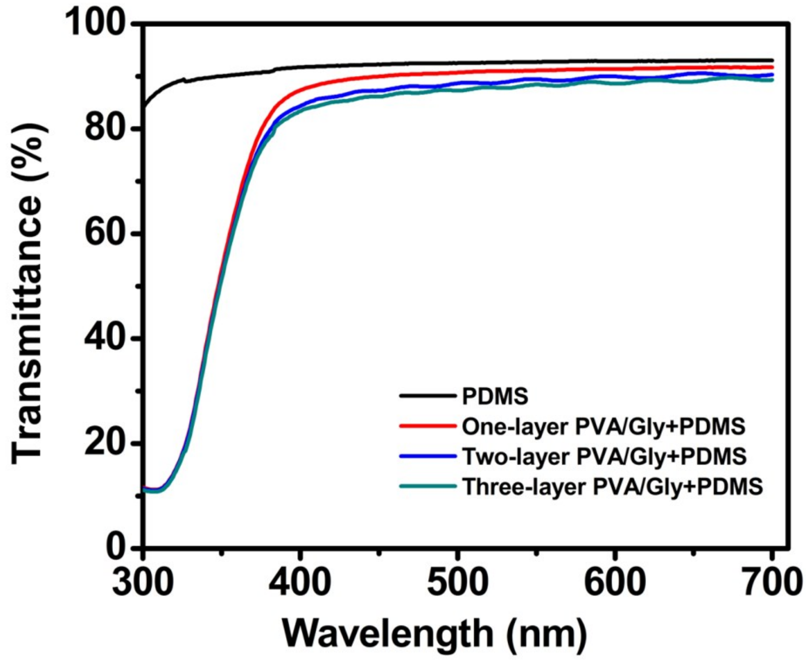

Figure S2. Transmittance measurements. The transparency of native PDMS, one layer PVA/Gly modified PDMS, two-layer PVA/Gly modified PDMS, and three-layer PVA/Gly modified PDMS were monitored by UV-vis spectra from 300 nm to 700 nm. The results showed that the PDMS transparency decreased about 4.3% after three layers of PVA/Gly modification according to the transmittances at 550 nm.

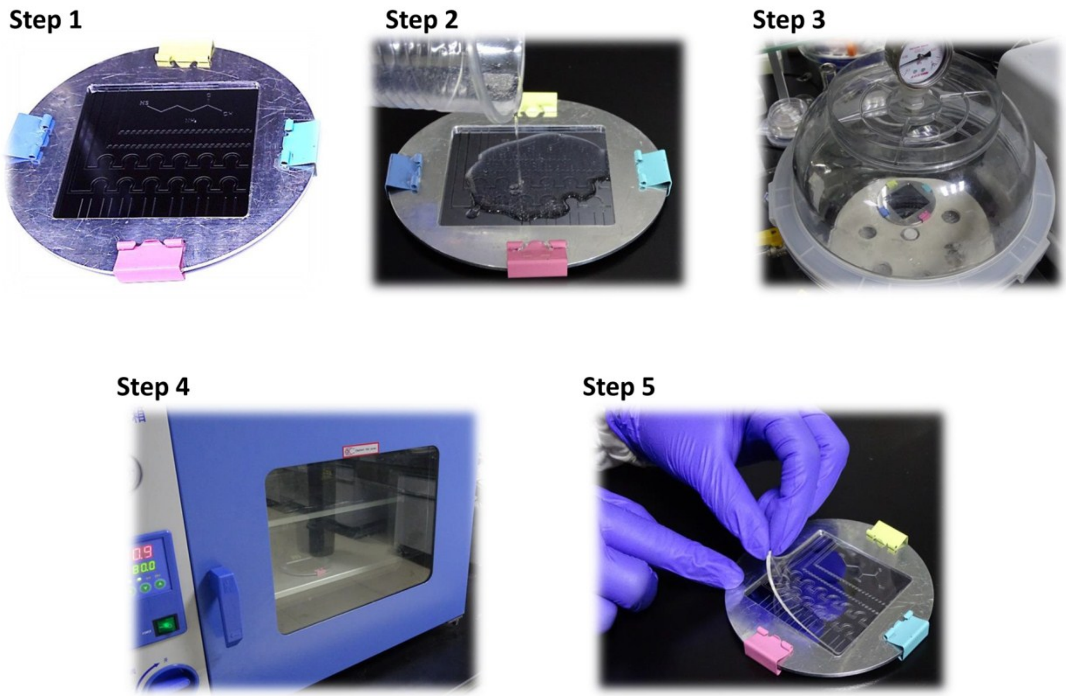

Figure S3. The silicon mold preparation. A silicon mold with fine-designed convex patterns was prepared by standard photolithography (Step 1). Liquid PDMS was poured onto the silicon mold (Step 2) and further treated by degassing (Step 3) and curing (Step 4). The solidified PDMS was peel off from the silicon mold to form a PDMS film with precisely designed concave patterns (channels) (Step 5).

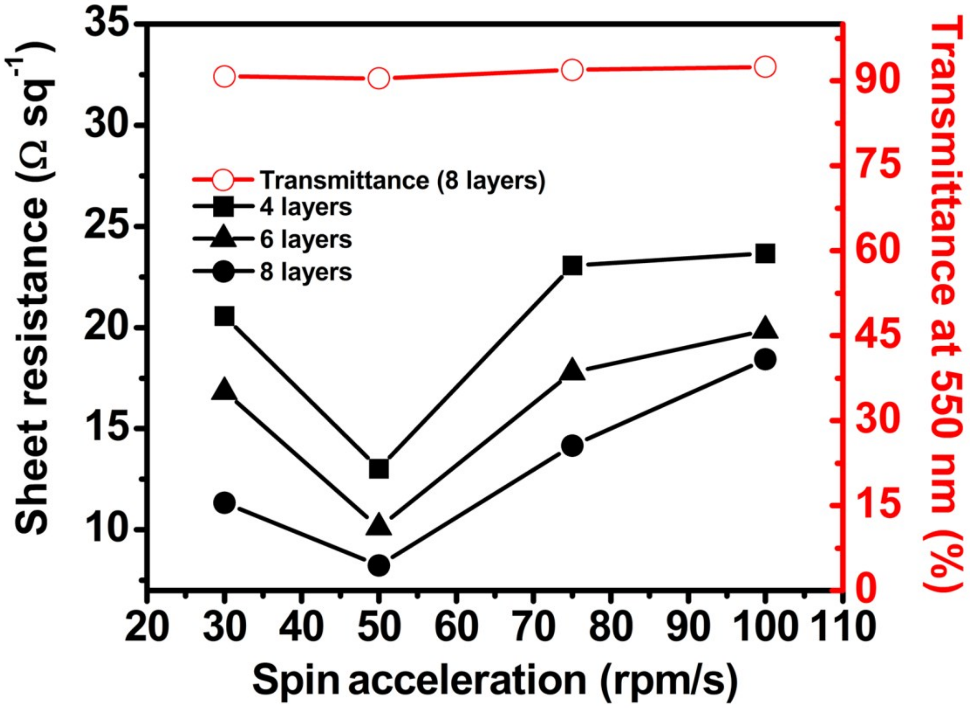

Figure S4. The influence of spin acceleration on sheet resistance and transmission. Various layers (4, 6, or 8) of AgNWs were deposited onto PDMS. Within the spin acceleration tested (30 – 100 rpm/s), sheet resistance at 50 rpm was the lowest for all the layers of AgNWs (13.01 Ω sq^{-1}, 10.12 Ω sq^{-1}, and 8.23 Ω sq^{-1} for the 4, 6, and 8 layers, respectively). Film transparency measured as transmittance at 550 nm light was consistent at all of the spin acceleration. The transmittances for the thickest AgNWs deposition (8 layers) were 90.77%, 90.38%, 94.85%, and 92.50% at 30 rpm/s, 50 rpm/s, 75 rpm/s, and 100 rpm/s spin acceleration, respectively.

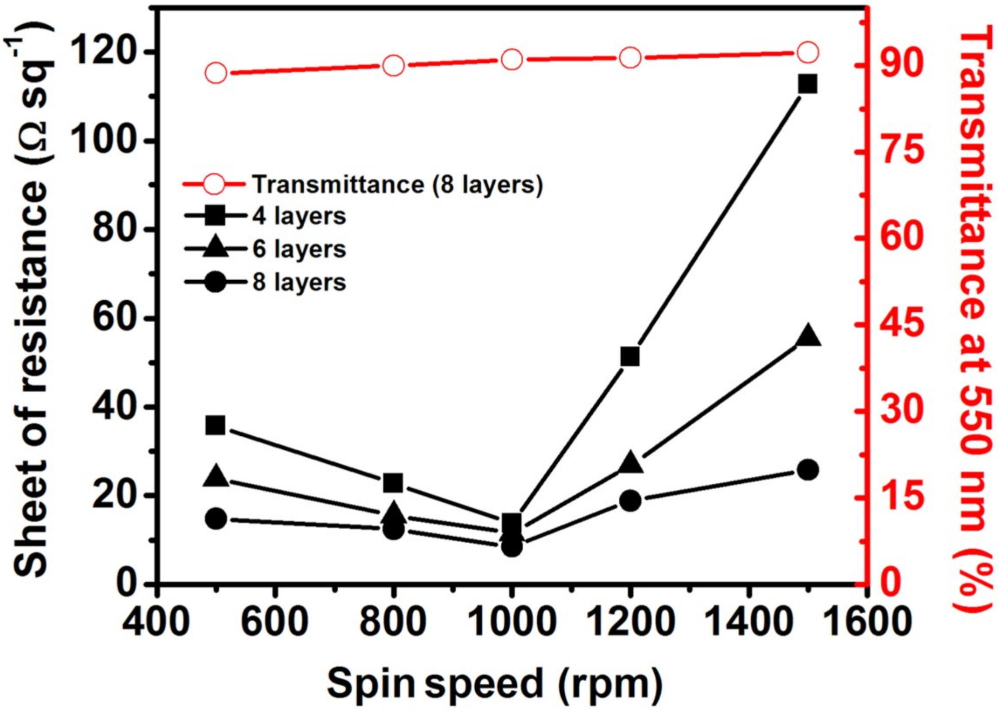

Figure S5. The influence of spin speed on sheet resistance and transmission. Spin speed test results showed that sheet resistance first reduced when the speed was increased from 500 rpm to 1,000 rpm no matter what deposition layers (4, 6, or 8 layers) were applied. However, further increase of the speed up to 1,500 rpm resulted in upsurges of the sheet resistance. Transmittance changed only slightly at all the tested spin speeds (88.64%, 89.92%, 90.98%, 91.30%, and 92.18% at 500 rpm, 800 rpm, 1,000 rpm, 1,200 rpm, and 1,500 rpm spin speed, respectively).

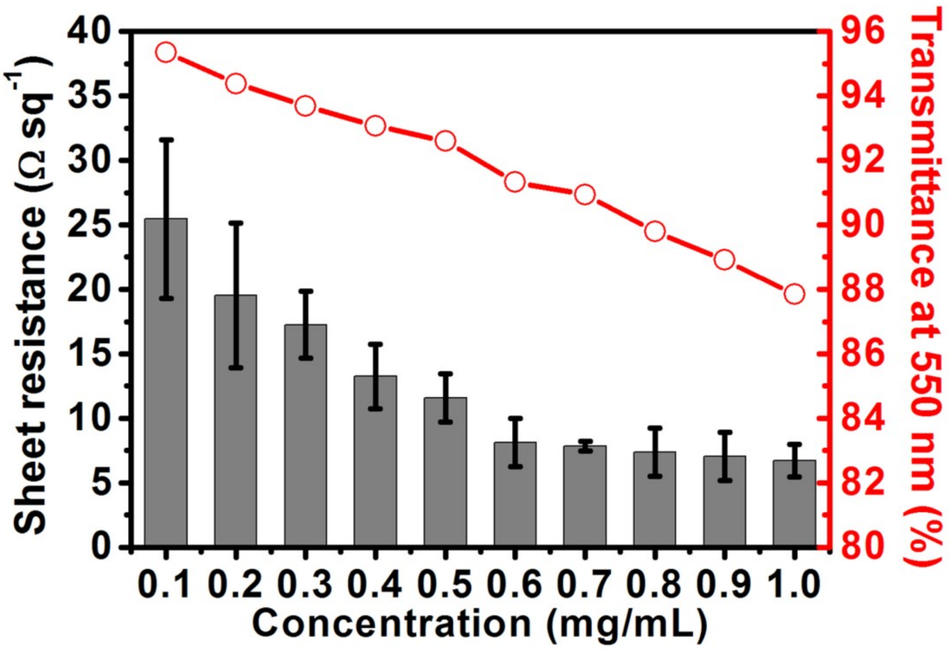

Figure S6. The influence of AgNWs concentrations on sheet resistance and transmission. Different concentrations (from 0.1 to 1.0 mg/mL) of AgNWs were spin coated onto PDMS to generate 8-layer AgNWs films, after which sheet resistance and transmittance were measured. While the AgNWs concentration increased, both sheet resistance and transmittance declined.

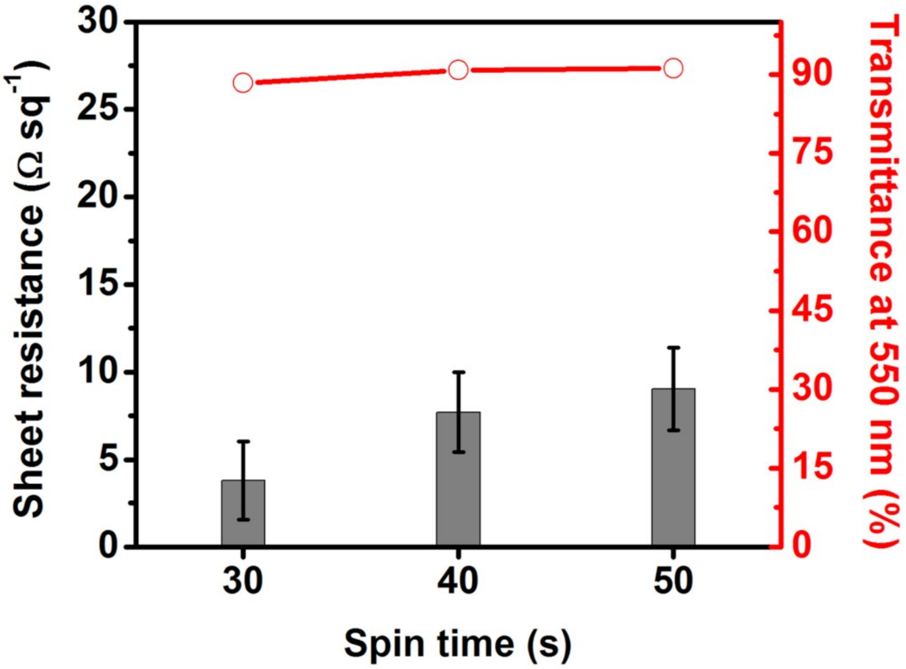

Figure S7. The influence of spin time on sheet resistance and transmission. Spin time analysis showed that the sheet resistance increased sharply with longer spin time, while the transparency slightly, 3.79 Ω sq^{-1}/88.35%, 7.70 Ω sq^{-1}/90.86%, and 9.03 Ω sq^{-1}/91.16% for 30 s, 40 s, and 50 s spin time, respectively.

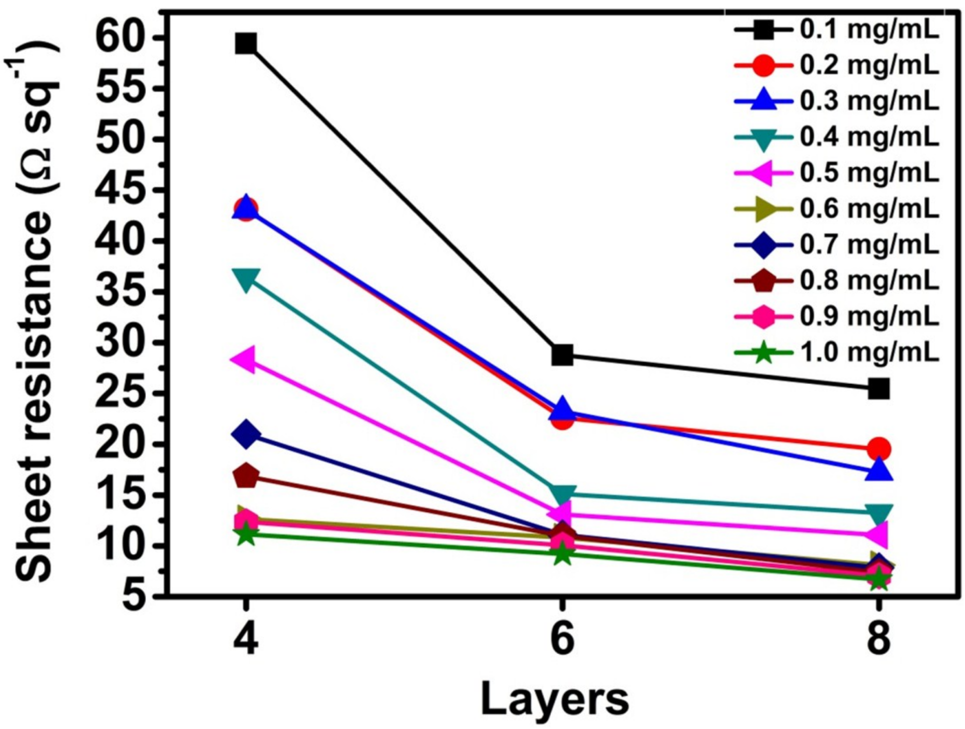

Figure S8. AgNWs deposition and sheet resistance. The effects of deposition layers and AgNWs concentrations on sheet resistance were investigated. More layers and higher AgNWs concentrations resulted in lower resistance.

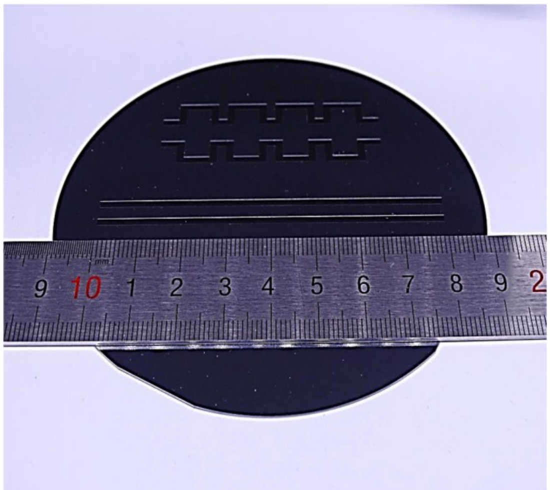

Figure S9. Line and square-wave shaped patterns on a 4-in. silicon mold by photolithography.

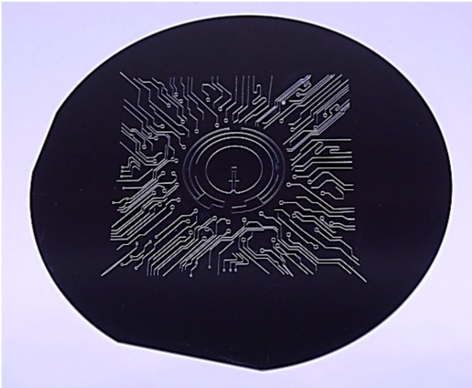

Figure S10. Precisely designed fine circuit patterns on 4-in. silicon molds by photolithography.

Table S1. Optimal AgNWs spin coating parameters

Acceleration (rpm/s)	Speed (rpm)	Time (s)	Concentration (mg/mL)
30	1,000	50	0.6

Table S2. Measurements of sheet resistance and transmittance.

Sheet resistance (Ω sq^{-1})					Transmittance (%)				
Test 1	Test 2	Test 3	Average	Standard deviation	Test 1	Test 2	Test 3	Average	Standard deviation
2.80	3.65	3.20	3.22	0.43	90.30	91.48	90.80	90.86	0.59