Electronic Supplementary Information

Inkjet-printed capacitive sensor for water level or quality monitoring theoretically and experimentally

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The file includes:

Variables:

w: width of electrodes;
s: spacing between electrodes;
l: length of electrode pairs;
$K(\kappa)$: elliptical integral of the first kind in terms of κ;
κ: the modulus of the complete elliptic integral;
N: the number of electrode pairs;

ε_0: the permittivity of free space, or the dielectric constant of vacuum, which is 8.85×10^{-12} F/m;

ε_x: relative dielectric constant of material x;

q: filling factor;
h: thickness of film;
C: capacitance;
A: cell constant;
ρ: resistivity;
R: resistance;
f: frequency;
ω: angular frequency;
d: thickness of assumed conductive layer in the interface of liquid and packing film;
c: concentration of ionic solution;
K: dissociation constant;

Λ_m^0: critical molar conductivity;

a: a complementary parameter to complement the error between the simulation and experimental results;
x: level of water;

Subscript:
i: the i^{th} one or the ionic solution;
sub: substrate;
pac: packing film;
ea: effective dielectric constant of capacitor in air;
ew: effective dielectric constant of capacitor in water;
ei: effective dielectric constant of capacitor in ionic solution;
0: the reference one or the control one;
if: interface;
w: water;
x: level;
m: mol;

1. Experiments

Coplanar capacitive sensor fabrication: The silver ink (40 wt%, Novacentrix) was inkjet printed on Kapton (HN, 3 mils, Dupont) by inkjet printer (Fujifilm Dimatix). Before printing, the Kapton film was cleaned by DI water, ethanol, acetone and ethanol in sequence to remove the dust and oil contaminates, and then soaked in isopropyl ethanol for 2 hours to remove the oil grease on the surface to enhance the adhesion between the ink and the substrate. The as-prepared capacitive sensors were sintered for 1 hour under 200 ^{o}C, and then sealed with adhesive tape (Scotch Desktop Tape, thickness, 50 μm). The sensors with different electrode width, length and spacing were designed and the drop spacing of inkjet printing was set to 20 μm.

Characterization and measurement: The electrode morphologies were characterized by SEM. The capacitance of the sensors was obtained by an electrochemical work station (VSP from Bio-Logic). The measurement parameters were set with voltages from -2.5V to 2.5 V, and frequency of 10^3 Hz. Every data was the average of at least 5 times measurement. In addition, a liquid tank fitted for the sensors was 3D-printed (Ultimaker^3) and the sensors were stuck on it. For the water quality monitoring, the tap water was from the tap in the lab, the filtered water was from the water picking-up device in the campus, the bottle water was purchased and the river water was from the near river.

2. Relationship of Linewidth between Designed and Measured

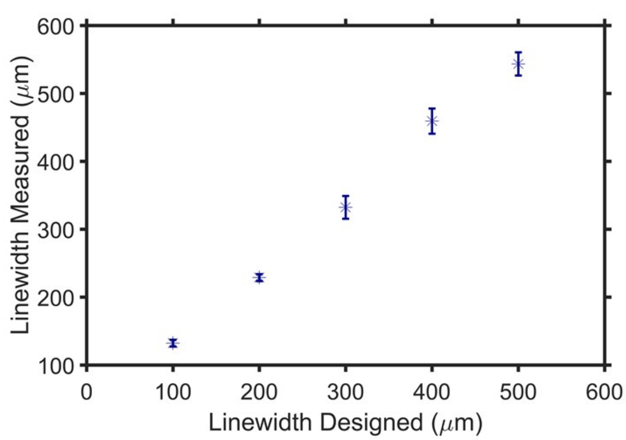

Fig. S1: The relationship of linewidth between designed and measured. The measured lines of the as-printed electrodes are wider than the designed ones. The phenomenon is attributed to the larger spread area of inkjet drops compared to the set ones.

3. Microscopic Image for the inkjet printed electrodes

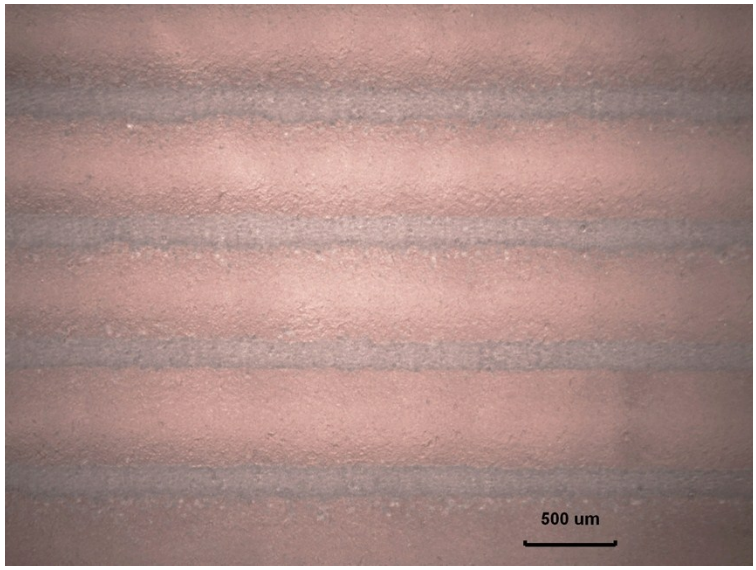

Fig. S2: Microscopic Image for the inkjet printed electrodes. For these electrodes, the linewidth was set 100 μm, spacing of electrodes was set 500 μm, the substrate was Kapton and the sample was sintered for 1 hour under 200 ^{o}C. The measured linewidth here was 132.2 ± 5.0 μm.

4. Schematic demonstration of measuring the dielectric constant of adhesive tape

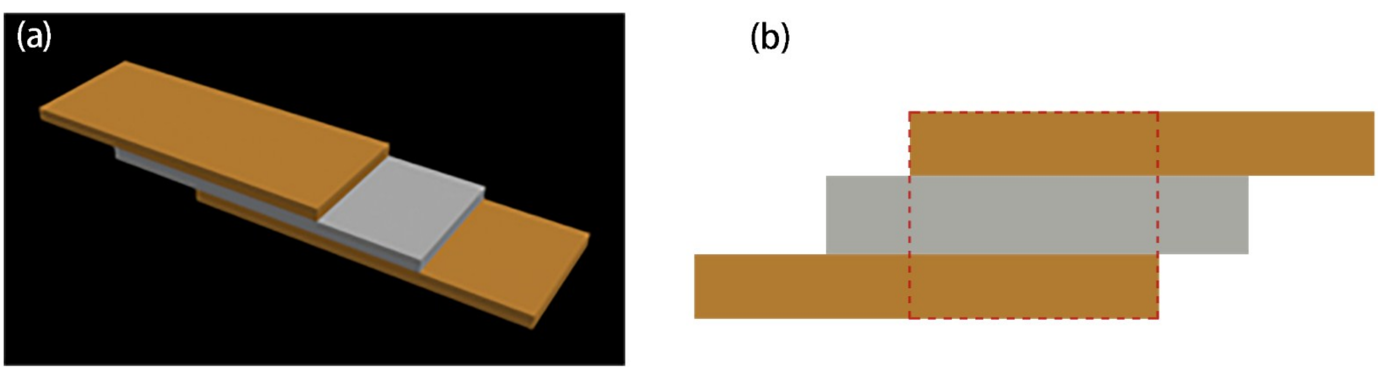

Fig. S3: Schematic demonstration of measuring the dielectric constant of adhesive tape **(a)** the 3D scheme and **(b)** the cross-view structure. The red dash square is the effective capacitor, whose electrode size is 1 cm × 1 cm.

5. EIS for the as-prepared sensor

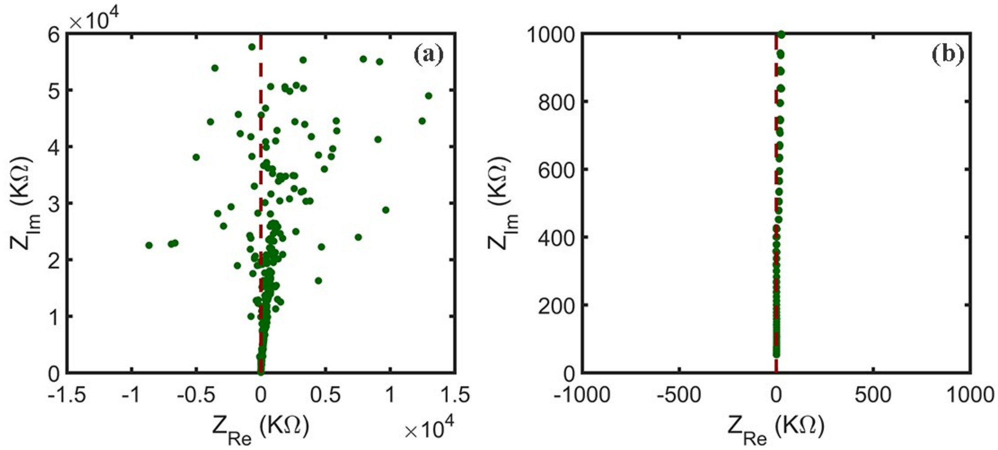

Fig. S4: EIS of the as-prepared capacitive sensor. **(a-b)** The EIS of the as-prepared capacitive sensor in full frequency ranging from 100 Hz to 100 kHz **(a)** and the high frequency part ranging from 1 kHz and 100 kHz **(b).** As the capacitive sensor was a single capacitor, the EIS curve should be a vertical line, which is reflected on the above figures. However, the error in the low frequency was very large.

6. Liquid tank to measure the liquid level and water quality

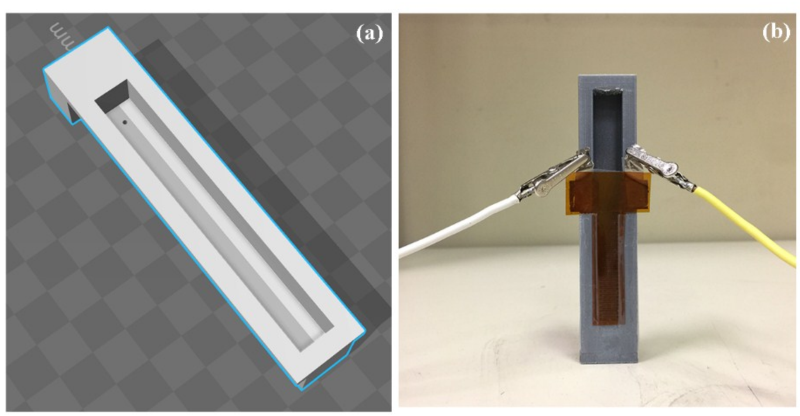

Fig. S5: Setup for measuring the water level. (a) the 3D-printed water tank and (b) the setup for the measuring system.

7. Resistivity estimation of KCl solution with the its concentration

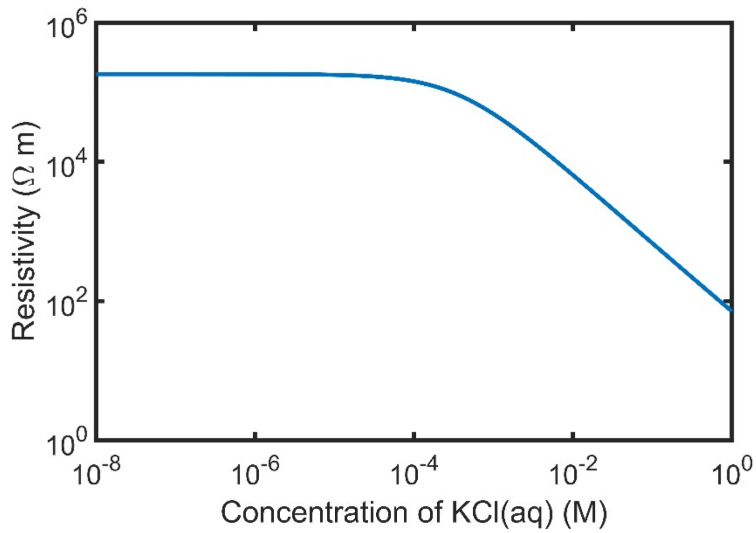

Fig. S6: Resistivity estimation of KCl solution with the its concentration

8. Table of sensors with different parameters and their capacitances.

Table S1: Capacitances of sensors with different parameters.

Sample	Electrode width w (μm)	Spacing between Electrodes s (μm)	Thickness of Packing Film t (μm)	Electrode Length l (mm)	Capacitance C (pF)
w1*	132.2±5.0	467.8±5.0	50	5	3.82±0.21
w2	228.8±5.1	471.2±5.1	50	5	5.02±0.24
w3	332.2±16.8	467.8±16.8	50	5	5.59±0.10
w4	459.2±18.5	440.8±18.5	50	5	5.76±0.21
w5	543.4±17.1	456.6±17.1	50	5	6.03±0.05
s1*	132.2±5.0	467.8±5.0	50	5	3.82±0.21
s2	126.6±7.6	573.4±7.6	50	5	3.85±0.23
s3	147.6±8.4	652.4±8.4	50	5	3.38±0.21
s4	135.0±9.9	765.0±9.9	50	5	2.90±0.19
s5	130.5±12.4	869.5±12.4	50	5	2.56±0.17
t1*	132.2±5.0	467.8±5.0	50	5	3.82±0.21
t2	132.2±5.0	467.8±5.0	100	5	4.29±0.17
t3	132.2±5.0	467.8±5.0	150	5	5.59±0.18
t4	132.2±5.0	467.8±5.0	200	5	6.09±0.49
t5	132.2±5.0	467.8±5.0	250	5	6.09±0.32

*The samples are the same one

9. Table of properties of different water

Table S2: Properties and main facts of different water[1]

DI water	Filtered water	Tap water	Bottled water	River water	KCl (0.1M)
$2*10^{-7}$ mol/L H^{+} 10^{-7}M OH^{-} 10^{-7}M	$3.04 \pm 3.56*10^{-3}$ mol/L Na^{+}: 35 ± 41 mg/L (1.52 ± 1.78 mM)	$5.5 \pm 5.27*10^{-3}$ mol/L Ca^{2+}: 34 ± 21 mg/L (0.83 ± 0.525 mM) Mg^{2+}: 10 ± 8 mg/L (0.42 ± 0.33 mM) Na^{+}: 35 ± 41 mg/L (1.52 ± 1.78 mM)	0.5~4.88 $*10^{-3}$ mol/L Ca^{2+}: 3.9~67 mg/L (0.1~ 1.7 mM) Mg^{2+}: 0.89 ~9.1 mg/L (0.04 ± 0.38 mM) Na^{+}: 2.6 ~ 8.3 mg/L (0.11 ~ 0.36 mM)	>10^{-2} mol/L Various ions , bacteria and organic contaminates	$2*10^{-1}$ mol/L K^{+} 10^{-1}M Cl^{-} 10^{-1}M

10. Reference

1. A. Azoulay, P. Garzon, and M.J. Eisenberg, *J. Gen. Intern. Med.,* 2001. **16**, 168-175.