Supplementary Information

The Effective Energy Harvesting Method from Natural Water Motion Active Transducer

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Here, C_f and C_s are the capacitances of first electrode-droplet capacitor and second electrode-droplet capacitor, respectively. V_f and V_s are voltages on C_f and C_s, respectively. ε is the effective electrical permittivity of the medium between dielectric layer and hydrophobic layer. The sum of thickness of dielectric layer and hydrophobic layer is d. A_f and A_s are the overlapping areas of water droplet with first and second electrodes, respectively. In Figure S1, there is electrode-electrode capacitor with capacitance C_0. The ratio of two capacitance values is

$$\frac{C_0}{C_f + C_s} = \frac{\varepsilon_0 \frac{A_0}{d_0}}{\varepsilon_f \frac{A_f}{d_f} + \varepsilon_s \frac{A_s}{d_s}} \fallingdotseq 10^{-5},$$

Where ε_k is the electrical permittivity of a dielectric material. This means C_0 is negligible. Therefore, the total capacitance varied much more dynamically than results in high electric output.

$$C_{tot} = \frac{\varepsilon}{d} \frac{A_f A_s}{A_f + A_s}, \qquad (\because \varepsilon_f = \varepsilon_s \equiv \varepsilon, \quad d_f = d_s \equiv d)$$

Neglecting friction, the droplet's contact area with upper electrode is

$$A_f(t) = A_f(t=0) - \int h(x)dx \qquad ;\ x = x(t) = v_o t + \frac{1}{2} g \sin\theta\, t^2$$

$$= A_f(t=0) - R^2 \left[cos^{-1}\left(\frac{d_0 - R}{R}\right) - cos^{-1}\left(\frac{d_0 - R + x(t)}{R}\right) \right.$$

$$\left. + \left(\frac{d_0 - R}{R}\right)\sqrt{1 - \left(\frac{d_0 - R}{R}\right)^2} + \left(\frac{d_0 - R + x(t)}{R}\right)\sqrt{1 - \left(\frac{d_0 - R + x(t)}{R}\right)^2} \right]$$

Also, that with lower electrode is

$$A_s(t) = \int h(x)dx$$

$$= R^2 \left[-cos^{-1}\left(\frac{x(t)}{R} - 1\right) + \sqrt{1 - \left(\frac{x(t)}{R} - 1\right)^2}\left(\frac{x(t)}{R} - 1\right) + \pi \right]$$

R is the radius of a droplet.

Output voltage is given by following equation.

$$\mathrm{V} = i(\mathrm{t})\mathrm{R_V},$$

Where $i(\mathrm{t})$ that is flowing current when measured voltage is given by following equation.

$$i(t)(\mathrm{R_V} + \mathrm{R_W}) = \mathrm{V}_f - \mathrm{V_s} = d\left(\frac{Q_f}{C_f}\right) - d\left(\frac{Q_s}{C_s}\right),$$

Where $\mathrm{R_V}$ and $\mathrm{R_W}$ are resistance across the voltmeter and the water droplet, respectively $(\mathrm{R_V} \fallingdotseq 3\mathrm{R_W})$. $d\mathrm{Q_f}$ and $d\mathrm{Q}_s$ are the electric charges variation in upper capacitor and lower capacitor, respectively, during the infinitesimal time, dt.

The output current is given by following equation.

$$\mathrm{I}(t) = \frac{\mathrm{V}_f - \mathrm{V_s}}{\mathrm{R_W}}.$$

As the droplet moved to the bottom the relative amount of overlapped area for each electrode varied according to the position of droplet. Since the speed of ions in the droplet is slower than that of the electrons in electrodes, there is potential variation in each capacitor. The

different amount of electric charges variation in each capacitor made potential difference ($V_f - V_s$). The electric charges moved to the other electrode for neutralizing the potential difference. As a result, on droplets passing between the electrodes, AC mode electric output was generated by the different variation rates between droplet's overlapped area with upper electrode and that with lower electrode. Here, $\varepsilon = 5.1\,\varepsilon_0$, $d = 290$ nm, $d_0 = 2$ mm, $R = 4.5$ mm, $A_f(t = 0) = 15.90\ mm^2$, $v_o = 0.5\ ms^{-2}$, $g = 9.8\ ms^{-2}$, $\theta = 45^{\circ}$, $R_V = 1\ M\Omega$, $R_W = 320\ k\Omega$ where ε_0 electrical permittivity of vacuum.

Experimental Section

Fabrication of Water Motion Active Tranducer by solution process

For WMAT using flowing water, the ITO layer was etched with HCl for electrode patterning. In pushing/releaseing type WMAT was not etched. PVP which was a blend of Poly(4-vinylphenol), Propylene glycol monomethyl ether acetate, and Poly(melamine-co-formaldehyde) methylated/butylated (Sigma aldrich) with mass ratio 2:1:17 was spin-coated at 3000 rpm for 35 s (acceleration speed at 500 rpm for 2 s) after ultraviolet ozone (UVO, λ = 185 and 254 nm, 100 mW/cm^2) exposure for 30 min, and then dried at 200 °C for 20 min. To prevent water droplet from attaching to the substrate, EKG-6015 (ETC company, Germany) was spin-coated at 4000 rpm for 35 s (acceleration speed at 500 rpm for 2 s) after UVO (λ = 185 and 254 nm, 100 mW/cm^2) exposure for 30 min and then dried at 200 °C for 15 min.

Performance characterization of water motion active transducer (WMAT)

The morphology of the hydrophobic layer surface and the cross-section of the dielectric layer was investigated using a field emission scanning transmission electron microscope

(FE-SEM) (JSM-7000F, JEOL). To operate the pushing/releasing motion, a pushing machine was made autonomously. The water flow was ejected using a syringe pump (Legato 200, KdScientific Inc.) The output voltage and current were detected by using 6½-digit digital multi-meter and 1.8 MS/s Isolated Digitizers (NI 4070, National Instruments). 100 data points were obtained in one second. Voltmeter or ammeter was connected directly to the electrodes to detect electric signals.

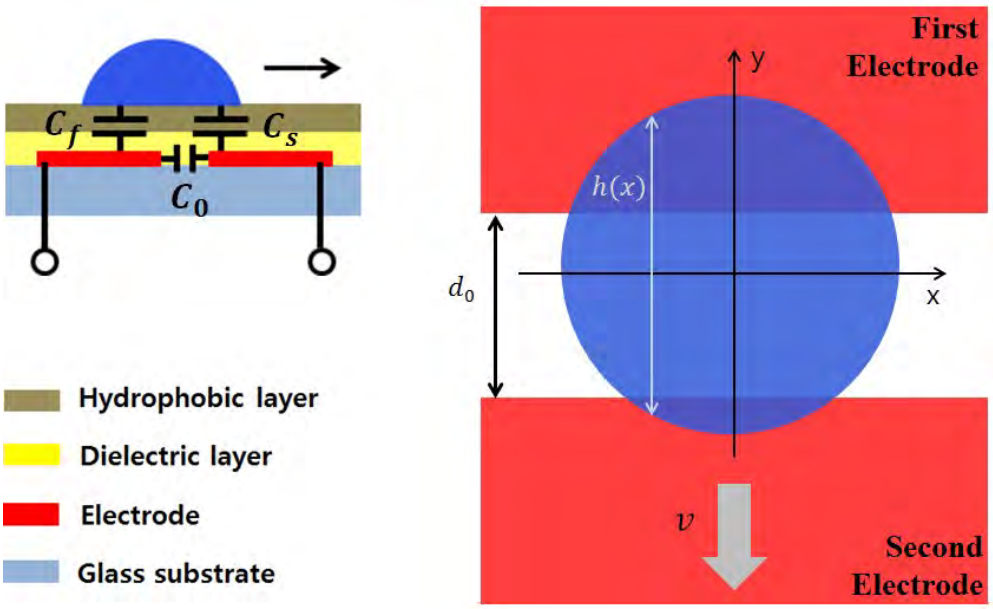


Figure S1. Schematic cross-section and top view image of device at the moment which droplet is located at around intermediate place between two electrodes. Assume droplet is a perfect sphere. $h(x)$is the droplet length of y-axis direction, where $v = v_o + g\,sin\,\theta\,t, v_o$ is initial velocity of droplet, g is acceleration of gravity, θ is tilted angle of device.

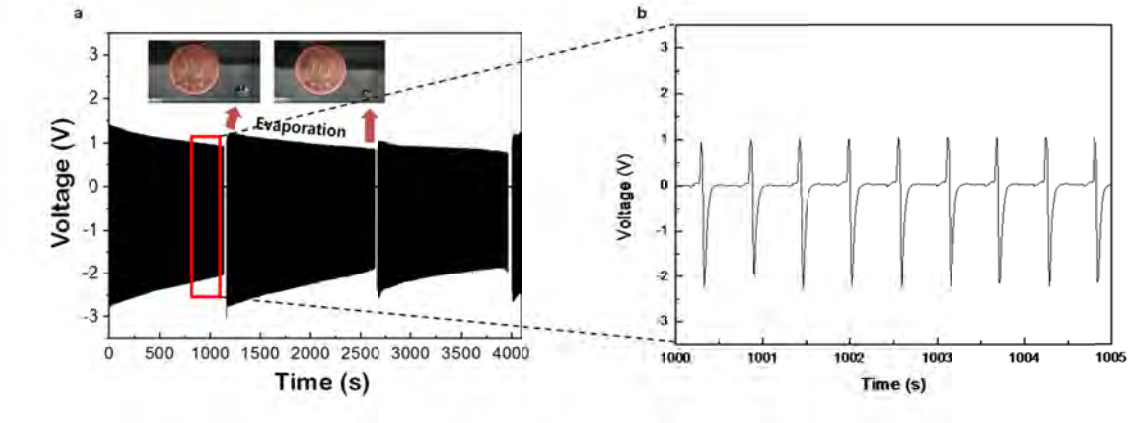


Figure S2. (a) Output voltage was measure by pushing/releasing motion. A water droplet with 40 µl volume was periodically flattened at the rate of 100 rpm (revolutions per minute). Inset images show initial droplet (40 µl) and evaporated droplet (~20 µl). (b) Magnified voltage peaks of stability experiment.

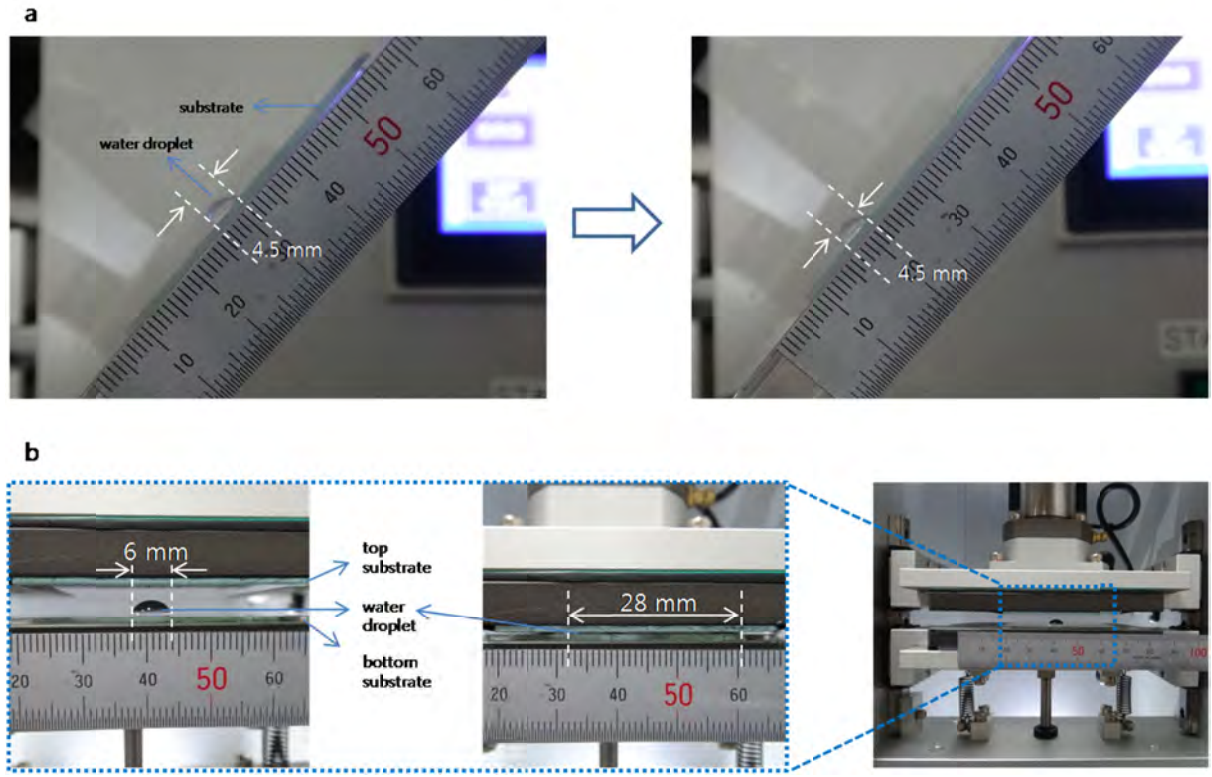


Figure S3. (a) The size of water droplet with flowing type of WMAT. (b) The size of water droplet with pushing/releasing type of WMAT (diameter of released state : 6mm, pushed state : 28 mm) and pushing/releasing machine used in this experiment.

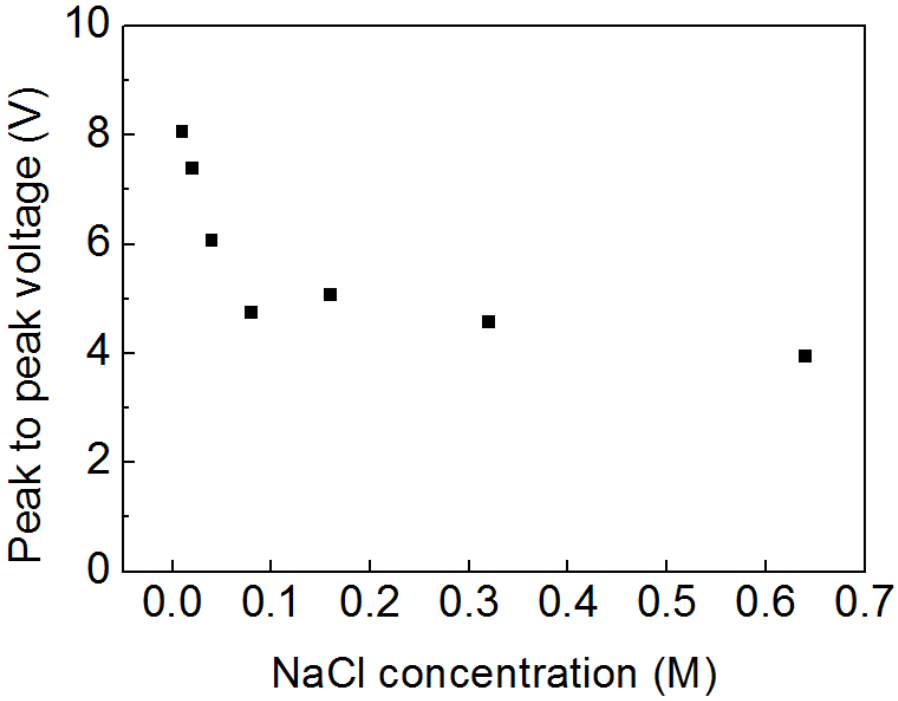
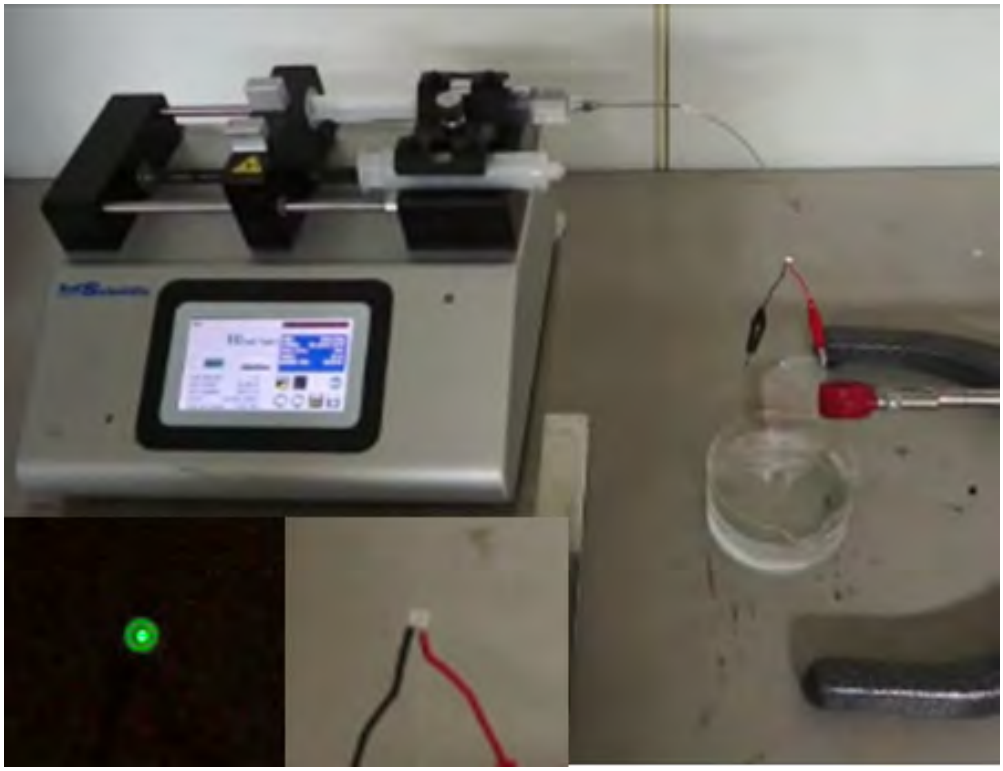
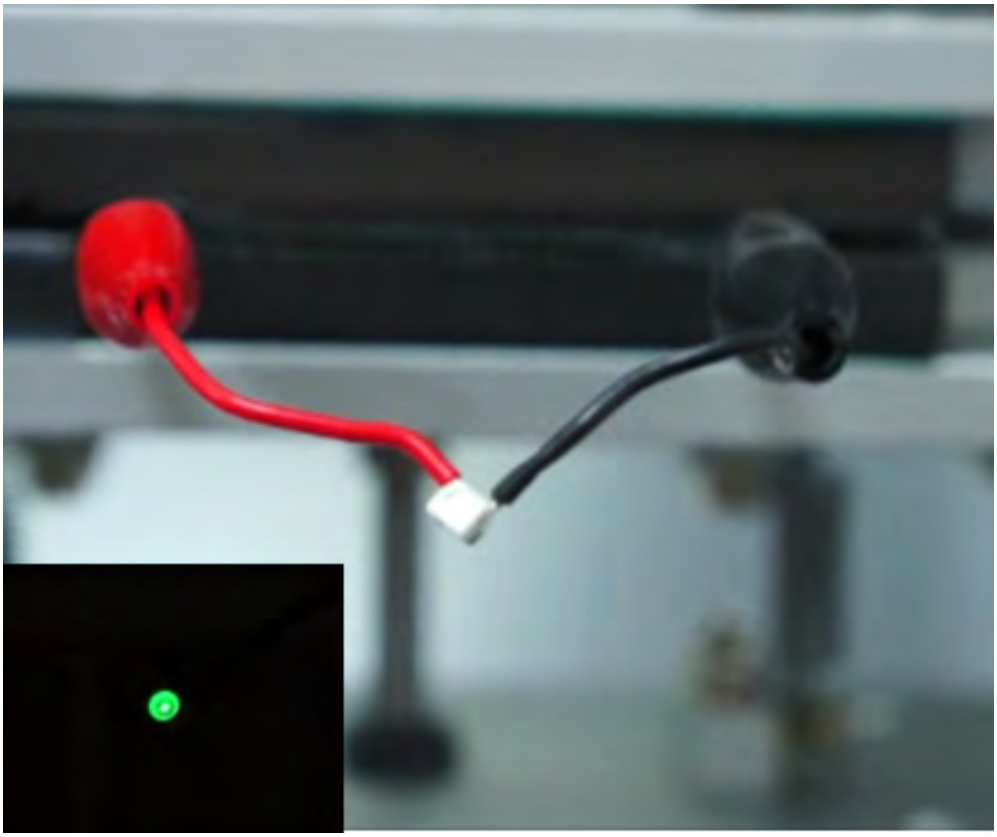


Figure S4. The comparison of voltage output according to the NaCl concentration. Measured by pushing/releasing motion.

Captured image from Movie S1 : Flowing type of WMAT.



Captured image from Movie S2 : Pushing and releasing type of WMAT.



Captured image from Movie S3 : Dipping type of WMAT.