Supporting Information

Agarose hydrogel-based power source: Electrode potential engineering and flow system integration for enhanced and sustained performance

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1. Derivation of output voltage in AGIPS derived from GHK equation

The Nernst–Planck equation describes ion flux across a membrane under the combined influence of concentration gradients and electrical potential differences,

$$J_S = -D_S\left(\nabla C_S + \frac{FZ_S}{RT} C_S \nabla \varphi\right) \#(1)$$

where D_S (m^2 s^{-1}) is the diffusion coefficient of *ion species s in its medium*, C_S (mol m^{-3}) is the molar concentration of *s*, F (C mol^{-1}) is Faraday's constant, Z_S is the charge of *s*, R (J mol^{-1} K^{-1}) is the gas constant, T (K) is the temperature, and φ (V) is the electrical potential. This equation describes ion flux driven by both the ion concentration gradient (first term) and the electric field (second term). The current generated as ions pass through the cell membrane can be described by the Goldman–Hodgkin–Katz current equation;

$$I_S = P_S V F^2 Z_S^2 \frac{C_{S_{in}} - C_{S_{out}} e^{-VF\frac{Z_S}{RT}}}{RT\left(1 - e^{-VF\frac{Z_S}{RT}}\right)} \#(2)$$

I_S (A m^{-2}) is the current density carried by *s* across the charge-selective membrane, P_S (m s^{-1}) is the permeability of *s* through the membrane, V (V) is the generated voltage across the membrane, and $C_{S_{in}}$ and $C_{S_{out}}$ (mol m^{-3}) are the concentrations of *s* inside and outside the cell.

In our system, since Na^+ and Cl^- were used as the primary ions, the current can be expressed as:

$$I = \frac{VF^2}{RT\left(1 - e^{\frac{-VF}{RT}}\right)}\left[\left(P_{Na^+}C_{Na^+_{in}} + P_{Cl^-}C_{Cl^-_{out}}\right) - \left(P_{Na^+}C_{Na^+_{out}} + P_{Cl^-}C_{Cl^-_{in}}\right) e^{\frac{-VF}{RT}}\right] \#(3)$$

The open-circuit voltage is obtained when *I*=0, and the above equation can be rearranged with respect to V to yield:

$$V_{OC} = \frac{RT}{F} \ln\left(\frac{P_{Na^+}C_{Na^+_{out}} + P_{Cl^-}C_{Cl^-_{in}}}{P_{Na^+}C_{Na^+_{in}} + P_{Cl^-}C_{Cl^-_{out}}}\right) \#(4)$$

According to this equation, V_{oc} is strongly influenced by the permeability and concentration ratios of Na^+ and Cl^- ions.

2. Measurement of current-voltage responses and power density of AGIPS

Figure 2e shows the current–voltage characteristics of the hydrogel-based energy device measured by connecting a series of external load resistors[1]. The IV curve exhibits a linear relationship between voltage and current, indicating Ohmic behavior across the measured range. This result demonstrates that the device can be effectively modeled as an equivalent circuit consisting of an open-circuit voltage source (V_{OC}) in series with an internal resistance (R_{int}). The simplified circuit diagram is shown in Figure S1. The maximum power transfer theorem states that the electrical power delivered to an external load resistor (R_{load}) is maximized when the load resistance matches the internal resistance of the device:

$R_{int} = R_{load} \# (5)$ The power delivered to the external load can be derived by first expressing the current as:

$$I = \frac{V_{oc}}{R_{int} + R_{load}} \# (6)$$

The voltage across the load resistor is given by:

$$V_{load} = I \times R_{load} = \frac{V_{oc} R_{load}}{R_{int} + R_{load}} \# (7)$$

By substituting the above two equations into P=IV and assuming $R_{int}=R_{load}$, the following expression for power can be derived:

$$P_{max} = \frac{V_{load}^2}{R_{load}} = \frac{V_{oc}^2}{4R_{int}} \# (8)$$

Using this relationship, the power density of the device can be calculated. Its variation with load resistance is illustrated in Figure 2e.

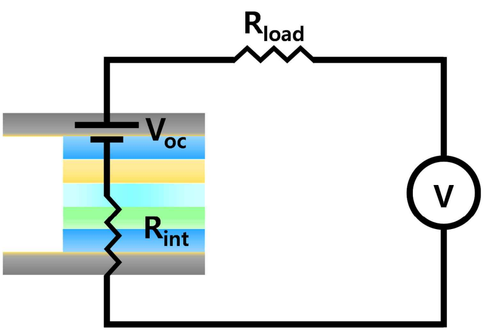

Figure S1. Equivalent circuit of AGIPS connected in series with an external load resistor (R_{load}) and a voltmeter.

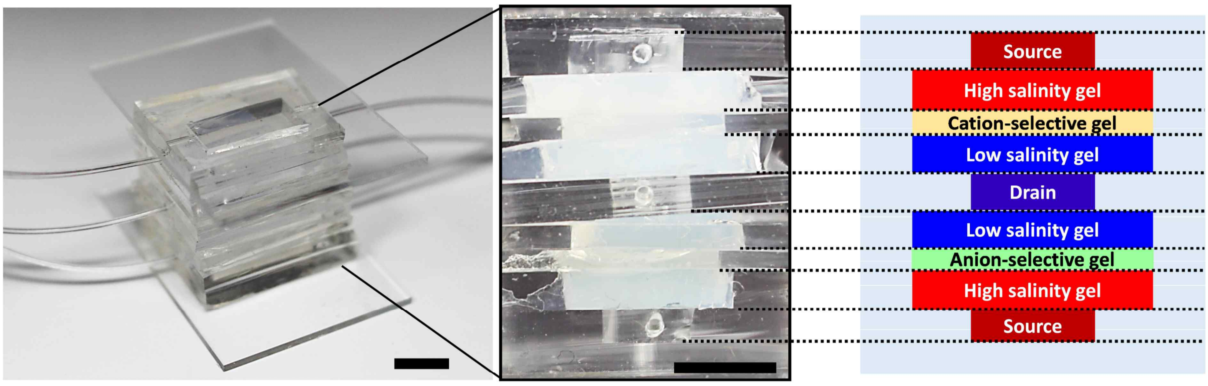

Figure S2. Pictures of the fabricated AGIPS device, integrated with a flow system. Scale bars = 5 mm.

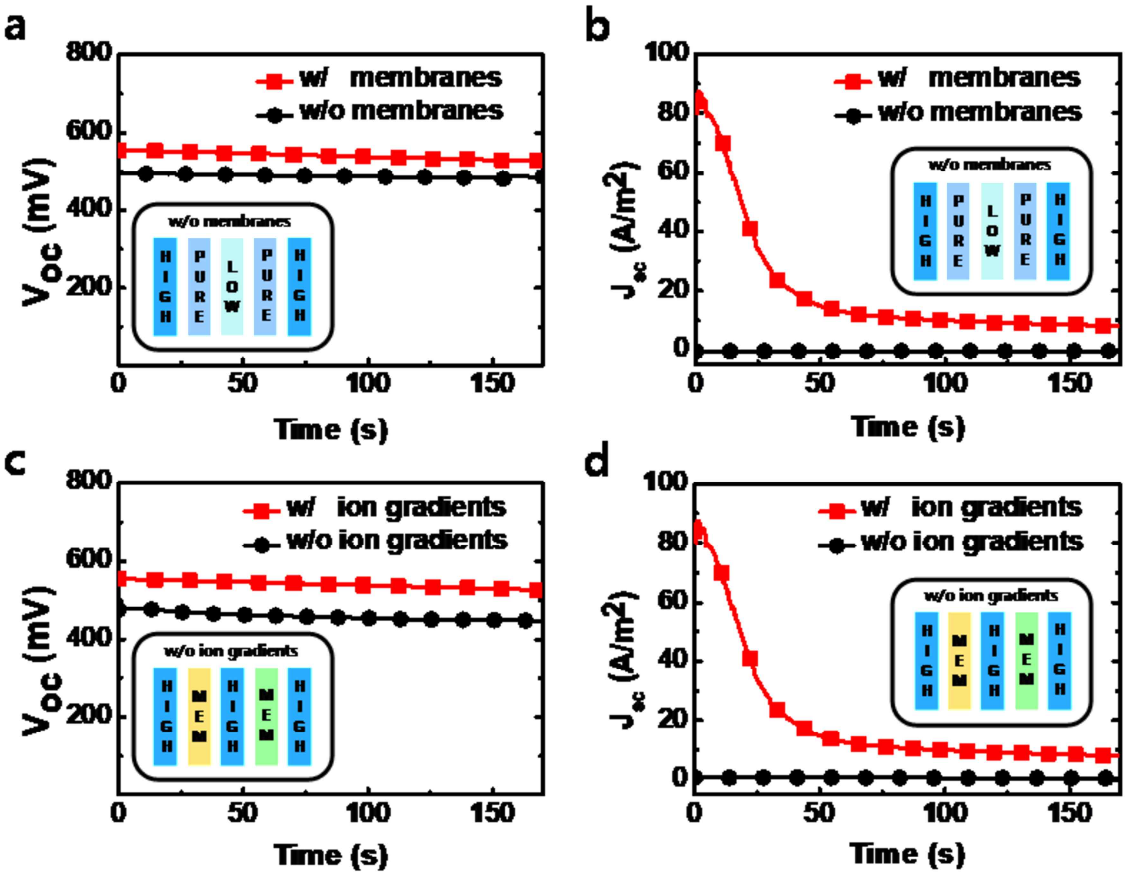

Figure S3. (a) V_{oc} and (b) J_{sc} of AGIPS devices employing asymmetric redox pairs with and without ion-selective membranes. (c) V_{oc} and (d) J_{sc} of AGIPS devices employing asymmetric redox pairs with and without ion concentration gradients

Reference

[1] T. B. H. Schroeder, A. Guha, A. Lamoureux, et al., "An electric-eel-inspired soft power source

from stacked hydrogels," Nautre 552 (2017): 214-218