Ultra-sensitive coplanar dual-Gate ISFETs for point-of-care biomedical applications

Authors: Jin-Hyeok Jeon (JH Jeon), Won-Ju Cho* (WJ Cho)
Affiliation: Department of Electrical Materials Engineering, Kwangwoon University, Seoul 139-701, Korea
E-mail address: chowj@kw.ac.kr

Supporting information

Figure

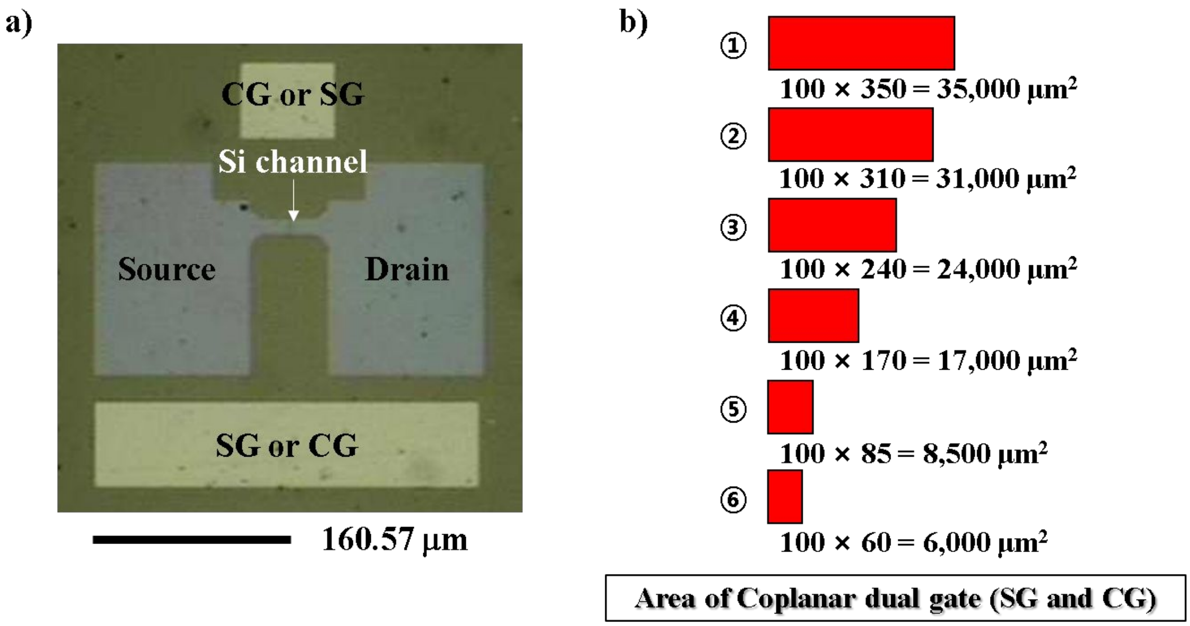

Figure S1. (a) Micrograph of FET transducers and (b) images of coplanar dual gates (SG and DG).

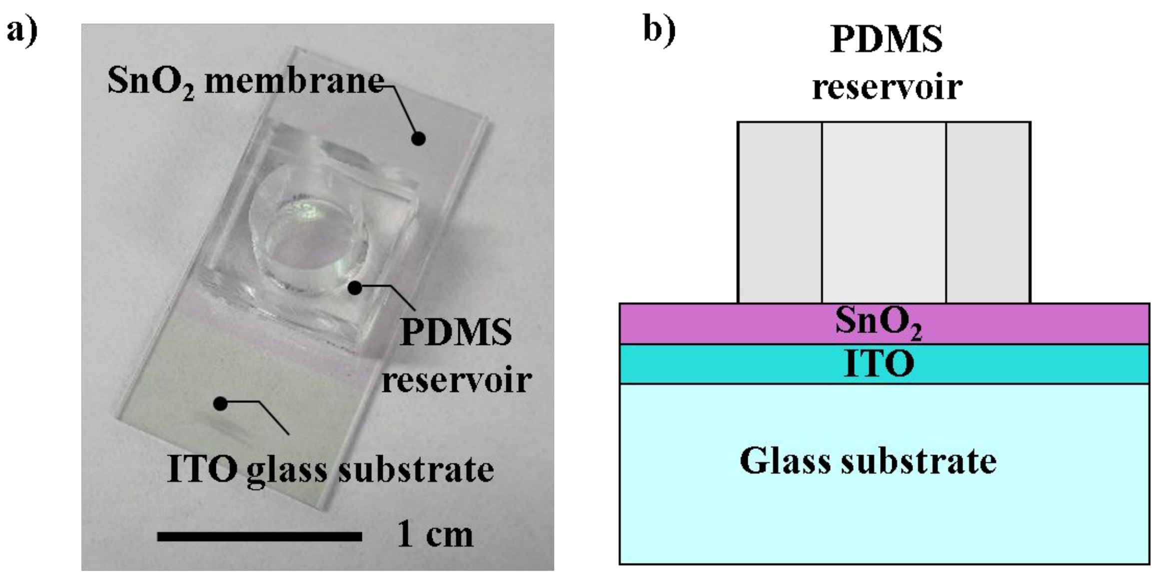

Figure S2. (a) Photograph of fabricated EG and (b) cross-sectional schematic of EG on glass substrate.

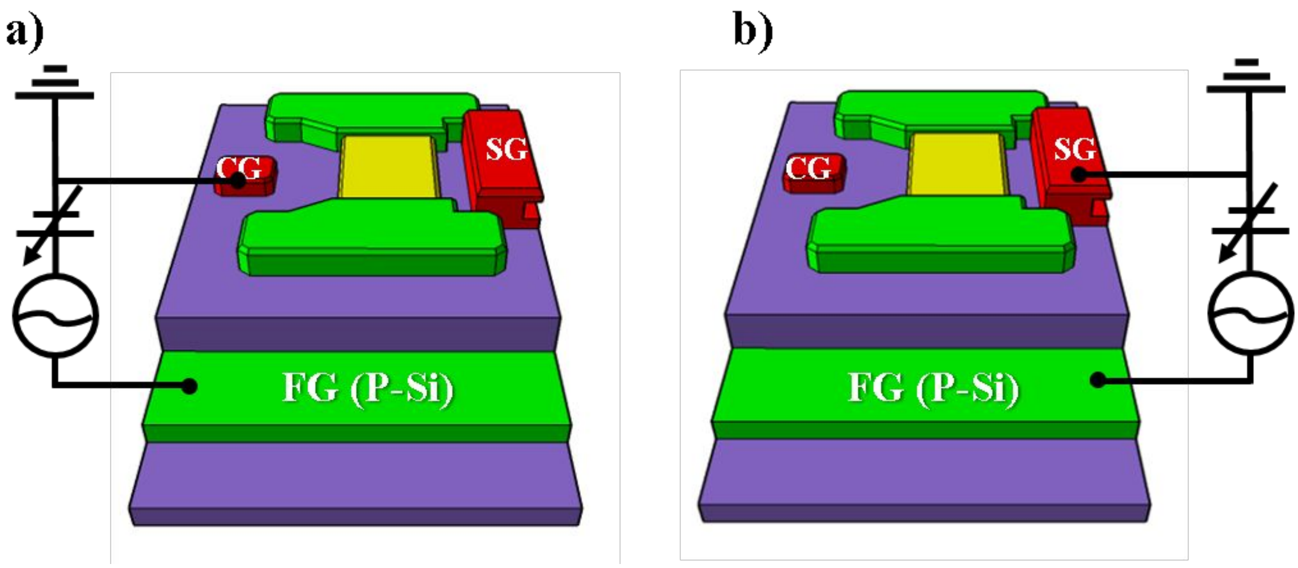

Figure S3. Measurement scheme of Cop-DG ISFETs pH sensor: C-V characteristics for coplanar dual-gate for (a) CG and (b) SG.

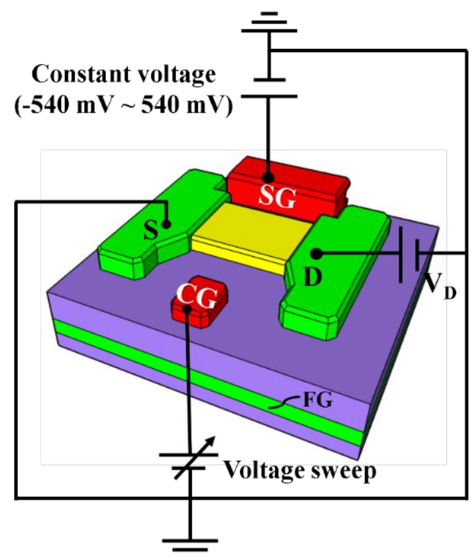

Figure S4. Measurement scheme of Cop-DG ISFETs pH sensor: capacitive coupling ratio between SG and CG.

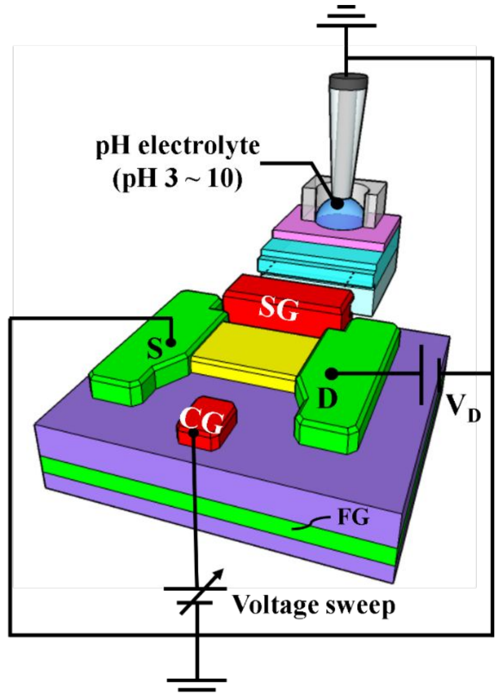

Figure S5. Measurement scheme of Cop-DG ISFETs pH sensor: sensitivity of pH electrolyte.

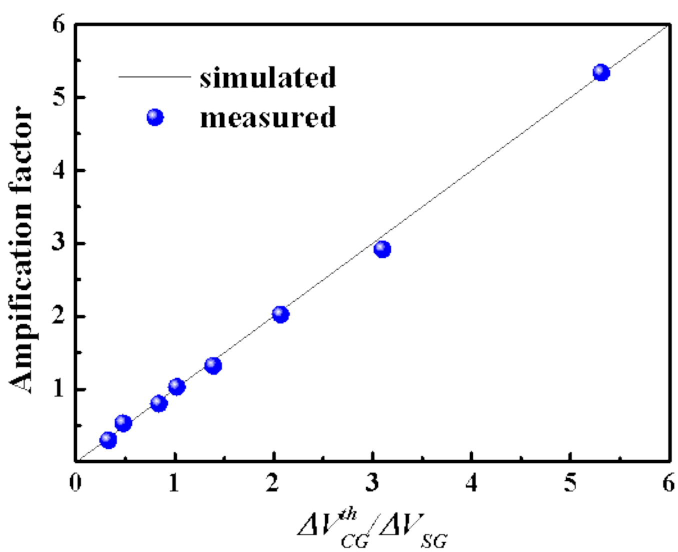

Figure S6. Comparison of amplification factor of pH sensitivity and coupling ratio of Cop-DG ISFETs sensor. The solid line and circles represent the simulation results obtained using TCAD simulation and experimentally measured results, respectively.

2. Development of equation 5 and 6 from equation 4 in manuscript

The equation 5 and 6 can be developed by equation 3 in manuscript. For reader's easier understanding, we developed the equation elaborately.

$$Q_{FG} = \sum_i (\mathrm{V}_{FG} - \mathrm{V}_i)\mathrm{C}_i \quad (4)$$

$$Q_{FG} = V_{FG}C_{TOT} - (V_{SG}C_{SG} + V_{CG}C_{CG} + 0 \cdot C_{OX})$$

$V_{FG} = \frac{V_{SG}C_{SG} + V_{CG}C_{CG}}{C_{TOT}} + \frac{Q_{FG}}{C_{TOT}}$, because only V_{SG} and V_{CG} are variables, equation 4 are defined as following.

$$\Delta V_{FG} = \frac{C_{CG}}{C_{TOT}}\Delta V_{CG} + \frac{C_{SG}}{C_{TOT}}\Delta V_{SG} \quad (5)$$

Therefore, V_{CG}, which can make channel in active region (V_{CG}^{th}) are defined by V_{FG}^{th} and V_{SG}. V_{CG} is swept by semiconductor parameter analyzer and V_{SG} is a surface potential of sensing membrane according to pH concentration.

$$\Delta V_{CG}^{th} = \frac{C_{TOT}}{C_{CG}}V_{FG}^{th} - \frac{C_{SG}}{C_{CG}}\Delta V_{SG} - \frac{Q_{FG}}{C_{CG}}, \ \Delta V_{SG} = \Delta\psi \quad (6)$$

So, we can develop the equation 5 to extract the pH sensitivity.

3. Extraction method of threshold voltage (V_{th})

V_{th} is calculated by using transconductance (g_m) extrapolation method in linear region (GMLE) (**method 1**). This method suggests that V_{th} corresponds to the gate voltage axis (x-axis) intercept of the linear extrapolation of the g_m–V_g characteristics at its maximum first derivative (slope) point. [1] Fig. S7 present the application of this method to the g_m–V_g characteristics producing an apparent value for V_{th} of only 0.44 V, which is figure of reference paper S1.

Moreover, we have to calculate the V_{th} using another method to justified this method. We calculate the V_{th} from constant current (CC) method (**method 2**). The CC method defines V_{th} as the gate voltage (V_g) required to achieve a chosen drain current (I_D) in the device's linear region of operation. I_D is determined by $(W/L)\times I_{con}$, where W and L are the channel width and length respectively, I_{con} is the arbitrary value assigned by users. Typical value of I_{con} is 1×10^{-8}. I_{con} may be different for different process nodes. [1] CC method is widely adopted because of its simplicity. The procedure of CC method is shown as Fig. S8, which is figure of reference paper S1.

Fig. S9 shows the variation of extracted sensitivity and linearity using two different methods. The sensitivity from method 2 is similar with sensitivity from method 1. In addition, the all linearity from method 1and method 2 is higher than 98 %.

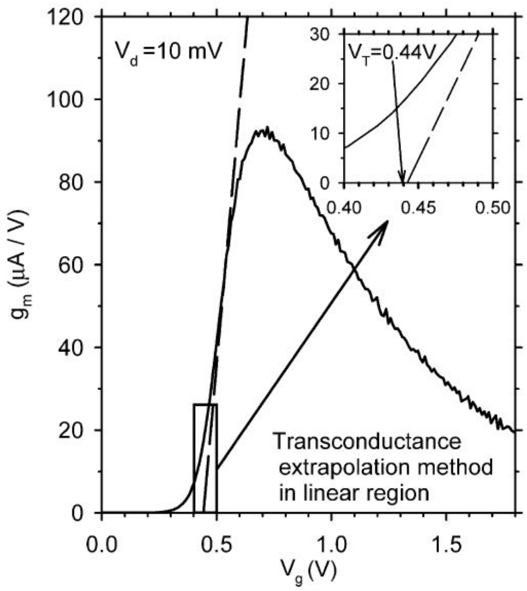

Figure S7. Transconductance extrapolation method (GMLE) implemented on the $g_m = dI_D/dV_g$ versus V_g characteristics of the test bulk device measured at V_d=10 mV. This method suggests that the threshold voltage corresponds to the gate voltage axis intercept of the linear extrapolation of the g_m–V_g characteristics at its maximum slope point.

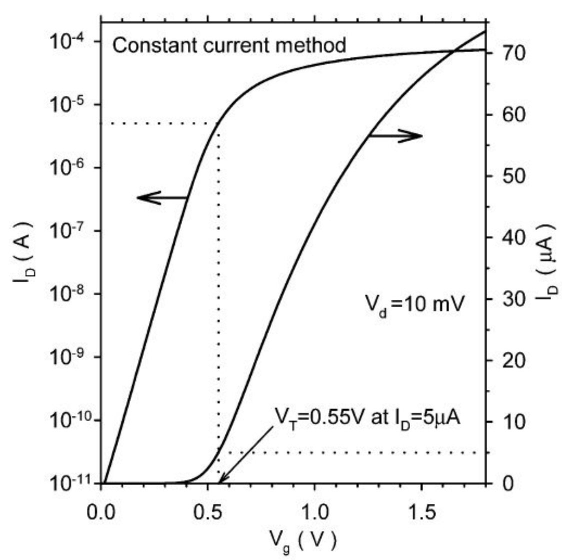

Figure S8. CC method implemented on the I_D–V_g transfer characteristics of the test bulk device measured at V_d = 10 mV. This method evaluates the threshold voltage as the value of the gate voltage corresponding to a given arbitrary constant drain current.

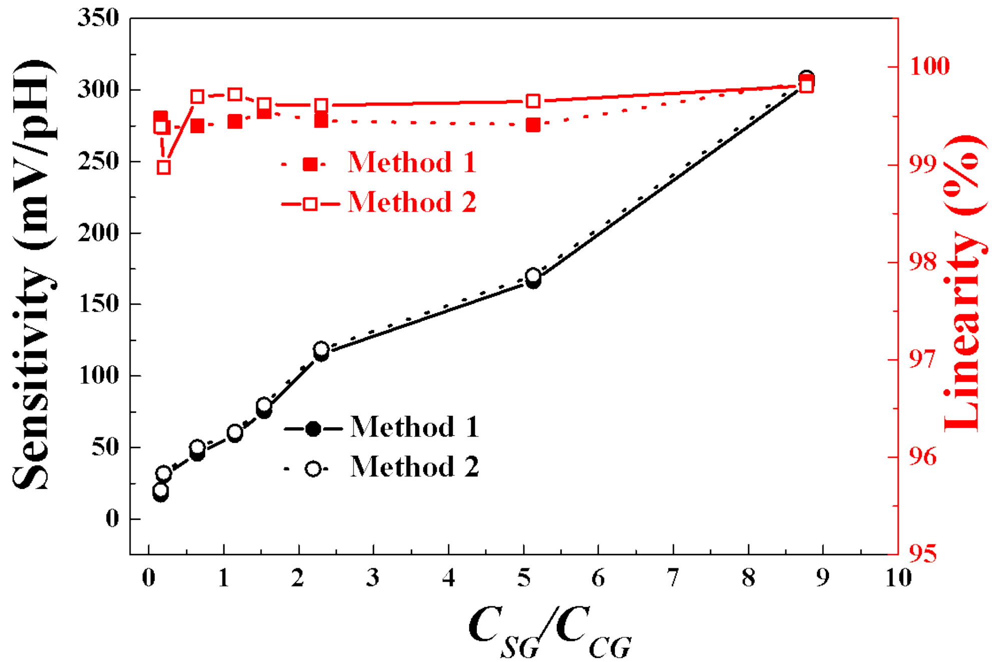

Figure S9. Comparison of pH sensitivity and linearity of Method 1 and 2 according to C_{SG}/C_{CG}.

4. Comparison of Cop-DG ISFETs and vertical structure dual-gate (V-DG) ISFETs

To compare the vertical dual-gate (V-DG) ISFETs and the proposed coplanar dual-gate (Cop-DG) ISFETs, **Fig. S10** shows the cross-section and gate capacitance of (a) V-DG ISFETs versus (b) Cop-DG ISFETs. Both devices have in common that they use the capacitive coupling effect. However, in the case of V-DG ISFETs in (a), the capacitance of the top and bottom gate oxides of the channel is used to determine the capacitive coupling ratio, and the capacitance ratio is controlled by adjusting the thickness of each gate oxide. Therefore, to improve the capacitive coupling ratio of V-DG ISFETs, a thinner top gate oxide or thicker bottom gate oxide is required. However, the thin top gate oxide increases the gate leakage current, and the thick bottom gate oxide is not efficient because the buried oxide (BOX) layer thickness must be increased in the manufacturing step of the SOI substrate, resulting in an increase in processing time and process cost. [2,3]

On the other hand, in the case of the Cop-DG ISFET, since the principle of controlling the capacitive coupling ratio through the relative area ratios of the coplanar gates (SG and CG), the problem of the thinner top oxide and the thicker bottom oxide of the V-DG ISFETs can be easily avoided. Moreover, the coplanar gates (SG and CG) can be formed simultaneously, which greatly simplifies the manufacturing process. As a result, the Cop-DG ISFETs proposed in this study not only amplify the sensitivity more efficiently than the previous V-DG ISFETs, but also allow the manufacturing process easier, providing a promising POC platform for biomedical applications.

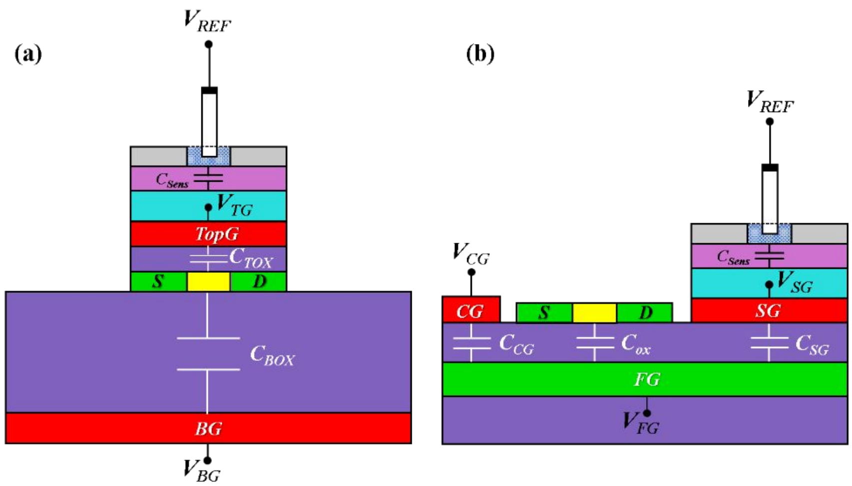

Figure S10. Cross-section view of the (a) vertical structure dual-gate (V-DG) ISFETs and (b) Cop-DG ISFETs.

5. The drain current (I_{DS}) of the Cop-DG ISFETs sensor by considering its relationship to the control gate voltage (V_{CG}) and I_{DS}-T curve measurements.

Cop-DG ISFETs sensor were n-channel enhancement-type MOSFETs and the drain current (I_{DS}) of the proposed device by considering its relationship to the control gate voltage (V_{CG}) is expressed as follows :

$$I_{DS} = k\left(V_{CG} - V_{CG}^{th}\right)^2 \tag{1}$$

And :

$$I_{DS(\mathrm{on})} = k\left(V_{CG(\mathrm{on})} - V_{CG}^{th}\right)^2, k = \frac{I_{DS(\mathrm{on})}}{\left(V_{CG(\mathrm{on})} - V_{CG}^{th}\right)^2} \tag{2}$$

The drain current is zero for levels of V_{CG} less than the threshold voltage of control gate (V_{CG}^{th}), as shown in **Fig. S11**.

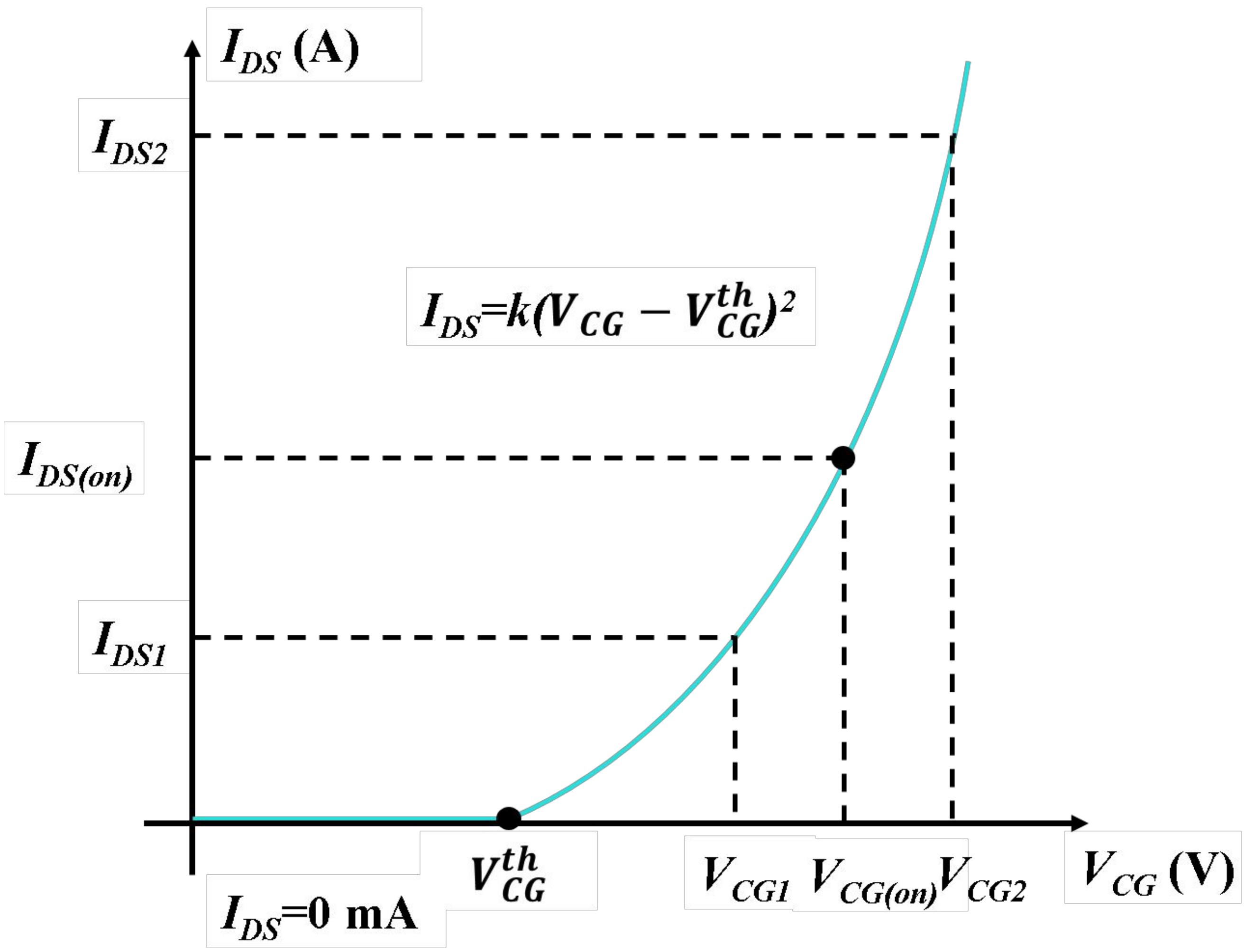

Figure S11. The transfer curve and the drain current equation of n-channel enhancement-type MOSFETs .

The threshold voltage of CG shifts according to the potential of SG, i.e., the magnitude of the biological signal, causing a change in I_{DS}. This can be confirmed easily when drain current (I_{DS}) vs. time (T) curves of Cop-DG ISFETs sensor for various pH electrolyte solution is measured.

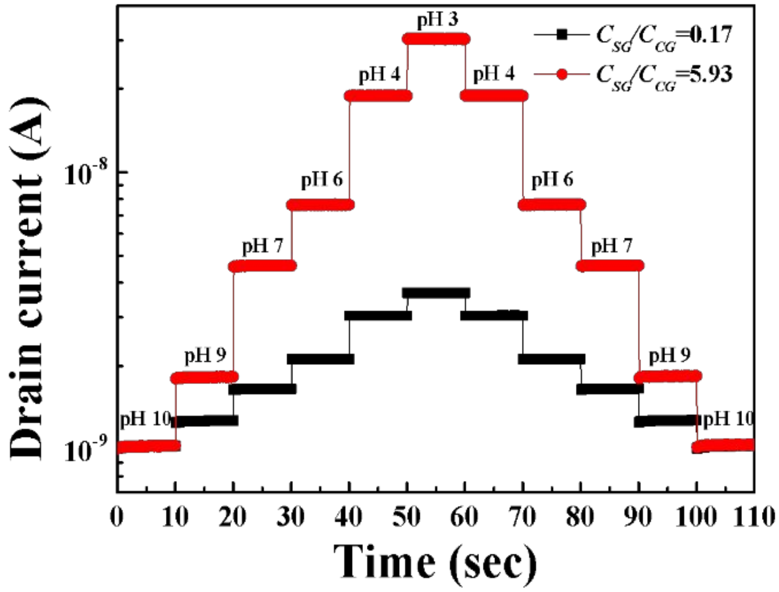

Figure S12. The drain current (I_{DS}) vs. time (T) curve of Cop-DG ISFETs according to various pH electrolyte.

Figure S12 shows the I_{DS}-T curves of the fabricated Cop-DG ISFETs sensor for various pH electrolyte solution, where C_{SG}/C_{CG} = 5.93 and 0.17. In the I_{DS}-T curve measurements, the V_{CG} was constant voltage, V_{CG} =9 V and 1 V, where C_{SG}/C_{CG} = 5.93 and 0.17, respectively. The time interval is 0.1 sec and the measurement time is 10 sec per each pH electrolyte solution. As threshold voltage shift of control gate (ΔV_{CG}^{th}) is larger, the change in I_{DS} is larger. That is, the sensitivity of Cop-DG ISFETs sensor determined the change in I_{DS}.

<Reference in supporting information>

1. Ortiz-Conde, A.; Sánchez, F.G.; Liou, J.J.; Cerdeira, A.; Estrada, M.; and Yue, Y. A review of recent MOSFET threshold voltage extraction methods. *Microelectron. Reliab.* **2002**, *42*, 583-596.
2. Yeo, Y.C.; King, T.J.; and Hu, C. Direct tunneling leakage current and scalability of alternative gate dielectrics. *Appl. Phys. Lett.* **2002**, *81*, 2091-2093.
3. Jang, H.J.; and Cho, W.J. Performance enhancement of capacitive-coupling dual-gate ion-sensitive field-effect transistor in ultra-thin-body. *Sci. Rep.* **2014**, *4*, 5284.