DOI 10.5162/IMCS2018/FE.4

Inkjet-Printed PEI FET-Type Humidity Sensor Having a Horizontal Floating-Gate

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Abstract:
In this paper, a field-effect transistor (FET) humidity sensor having horizontal floating-gate (FG) and control-gate (CG) is investigated. Branched polyethylenimine (PEI) is formed on the FET platform for the humidity detection. The inkjet printing process is adopted to deposit the sensing layer, which is convenient and low cost. The humidity sensing properties of the proposed sensor are measured at room temperature. The response, response time and recovery time of the sensor are 415%, 3 min and 13 min for 20% relative humidity (RH), respectively. The sensing mechanism is also explained from the perspective of the ion motions in the sensing material.

Key words: PEI, inkjet printing, FET gas sensor, humidity detection, room temperature.

Experimental

The structure of the proposed metal-oxide-semiconductor field-effect transistor (MOSFET) humidity sensor is shown in Fig. 1. Fig. 1 (a) and (b) are the microscopic images of the sensor without and with printed sensing material, respectively. Fig. 1 (c) and (d) show the 2D schematic cross-sectional views cut along line A-A' and B-B' in (a), respectivley. The formula of PEI is also shown in (c). The interdigitated FG and CG are formed horizontally to increase the coupling ratio between them. In this paper, *p*MOSFET sensor platform is adopted. Brenched PEI, which has primary, secondary, and tertiary amines, is deposited on the surface of the platform by inkjet printing process to serve as the sensing material. For preparing a PEI ink, Wt. 50% branched PEI aqueous solution (number average molecular weight 1200) is diluted by D.I. water to Wt. 1% to reduce the viscosity of the solution because ink with 1~10 cps viscosity is suitable for inkjet printing [1]. A humid gas sample is obtained by running the dry N_2 through a bubbler filled with D.I. water and the reference gas is dry N_2. All electrical measurements were carried out with an Agilent B1500A at room temperature.

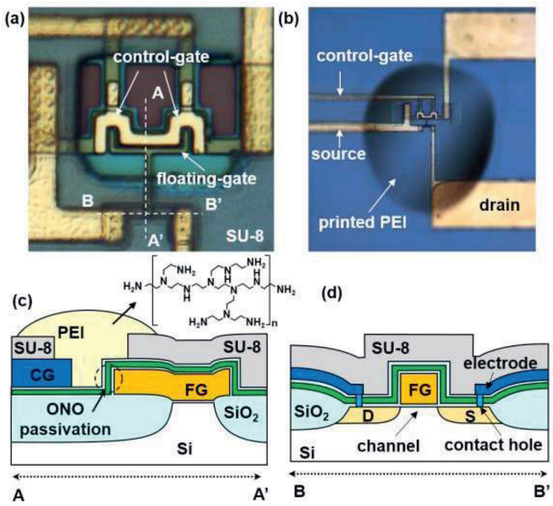

Fig. 1. (a) and (b) show the microscopic images of the sensor without and with printed PEI, respectively. (c) and (d) show the 2D schematic cross-sectional views cut along line A-A' and B-B' in (a), respectively. The formula of PEI is shown in (c).

Results and Discussion

Fig. 2 and Fig. 3 show the drain-current versus gate-voltage (I_D-V_{GS}) curve on a log scale and gate-current versus gate-voltage (I_G-V_{GS}) curve on a linear scale of the sensor, respectively. I_G-V_{GS} curves on a log scale are also plotted in Fig. 2 for a comparison with I_D-V_{GS} curves. In Fig. 2, the subthreshould swing (*SS*) and off-state I_D increase as RH increases from zero to 40%. In addition, the gate leakage current (I_G) also becomes larger with RH in Fig.3.

Fig. 4 shows the transient humidity sensing performance of the sensor. Dry and 20% RH N_2 gases are introduced into the measurement chamber, alternatively. The $|I_D|$ before humidity sensing is initialized to 2 nA with V_{GS}=0.1 V and V_{DS}=-0.5 V in dry N_2. The $|I_D|$ increases with the increasing humidity. We define the response (S) of a sensor as eq. (1). I_D and I_D' represent the drain current in dry and humid N_2, respectively. The response time (t_{RES}) and recovery time (t_{REC}) are defined as the rise time of $|I_D|$ to 90% of its maximum value and the fall time to 10% of the difference between the maximum and reference currents. The S, t_{RES} and t_{REC} of the proposed sensor are 415%, 3 min and 13 min, respectively.

$$S = \frac{|I_D| - |I_D'|}{I_D} \times 100\% \quad (1)$$

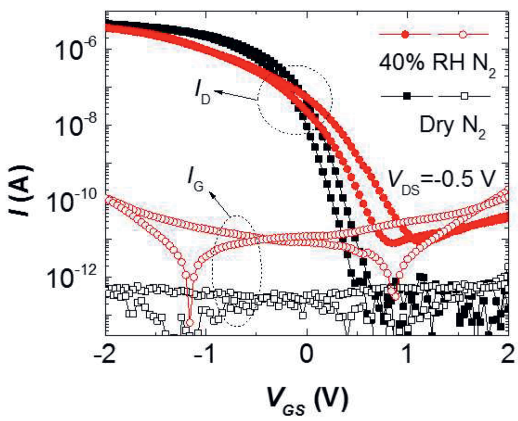

Fig.2. Double sweep I_D-V_{GS} and I_G-V_{GS} curves on a log scale of the sensor in dry and 40% RH N_2 gases.

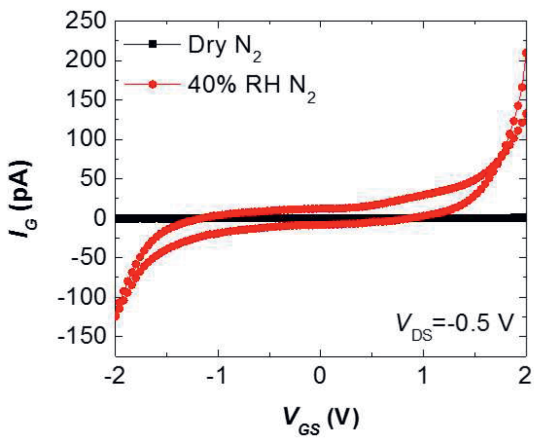

Fig.3. Double sweep I_G-V_{GS} curves on a linear scale of the sensor in dry and 40% RH N_2 gases.

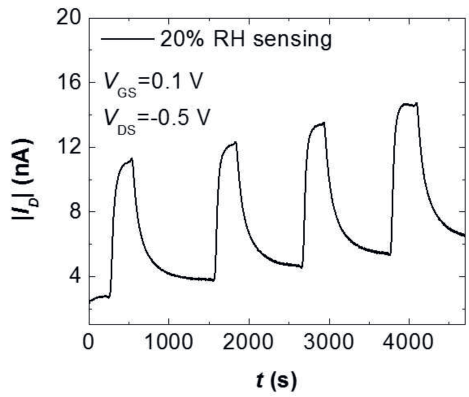

Fig.4. Transient humidity sensing performance of the sensor at room temperature.

During humidity sensing, water molecules adsorbe in PEI due to the hydrogen bond basic character of PEI [2], and partially protonate the aminies of PEI by donating protons [3]. The reactions can be discribed as eq. (2), (3), and (4) for primary, sencondary, and tertiary amines of PEI, respectively. The "R" denotes alkyl groups. As a result, the number of ions in PEI increases and their motions induce the large off state I_D and the *SS*. The high I_G in humid N_2 is also attributed to the displacement current caused by moving ions. In Fig. 2, $|I_D|$ increases with humidity in the subthreshold region of I_D-V_{GS} curve. Therefore, as $|I_D|$ is initialized to 2 nA, it increases with RH as shown in Fig. 4.

$$RNH_2 + H_2O \leftrightarrow RNH_3^+ + OH^- \quad (2)$$

$$R_2NH + H_2O \leftrightarrow R_2NH_2^+ + OH^- \quad (3)$$

$$R_3N + H_2O \leftrightarrow R_3NH^+ + OH^- \quad (4)$$

Acknowledgements

This work was supported by the National Research Foundation of Korea (NRF-2016R1A2B3009361) and the Brain Korea 21 Plus Project in 2018.

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