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Metal-oxide-semiconductor field effect transistor humidity sensor using surface conductance

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This letter presents a metal-oxide-semiconductor field effect transistor based humidity sensor which does not use any specific materials to sense the relative humidity. We simply make use of the low pressure chemical vapor deposited (LPCVD) silicon dioxide's surface conductance change. When the gate is biased and then floated, the electrical charge in the gate is dissipated through the LPCVD silicon dioxide's surface to the surrounding ground with a time constant depending on the surface conductance which, in turn, varies with humidity. With this method, extremely high sensitivity was achieved—the charge dissipation speed increased thousand times as the relative humidity increased. © *2012 American Institute of Physics*. [http://dx.doi.org/10.1063/1.3691936]

As the metal-oxide-semiconductor field effect transistor (MOSFET) technology advanced dramatically,[1,2] there has been an increased number of trials for using MOSFET as a sensor beyond its traditional usage as a memory or logic device.[3–7] This is because the MOSFET can directly be integrated with the read–out circuit, and sometimes, the MOSFET itself showed better performance as a sensing element.[3,4]

In this perspective, MOSFET sensors have been researched for detecting various measurands, such as bio material,[3] pressure,[4] temperature,[5] and various gases.[6,7] Also, several studies have been made on a humidity sensor.[8–11] However, instead of using the MOSFET directly for detecting humidity, various materials have been introduced to sense the relative humidity changes in the atmosphere. For example, dielectric constant change of carbon nitride film,[8] polymer swelling induced piezoelectric nanobelt (ZnO) strain,[9] and mobility change of a pentacene film were used to measure relative humidity change.[10,11] Unfortunately, no studies have been done for using the MOSFET as a humidity sensing element so far.

In this letter, we propose a humidity sensing method directly utilizing MOSFET as a sensing device which does not use any specific materials to sense the humidity.

Fig. 1 shows the mechanism of how we measured the humidity in the atmosphere using MOSFET. It consists of the four steps.

Step 1: As shown in the "before floating" part in Fig. 1(a), appropriate voltages to turn the transistor on are applied to the gate, source, and the drain by using a probe tip so as to conduct the drain-to-source current.

Step 2: The gate is electrically floated by detaching the probe tip as demonstrated in the "after floating" part in Fig. 1(a). The gate charges start to dissipate to the drain and source electrodes through the surface of the low pressure chemical vapor deposited (LPCVD) oxide, as shown in Fig. 1(b). Since the drain current is determined by the gate voltage, the drain current starts to decrease as the gate voltage drops. This event is described in the "after floating" part in Fig. 1(a).

Step 3: The drop rate of the gate voltage depends on how fast the gate charges are dissipated through the LPCVD

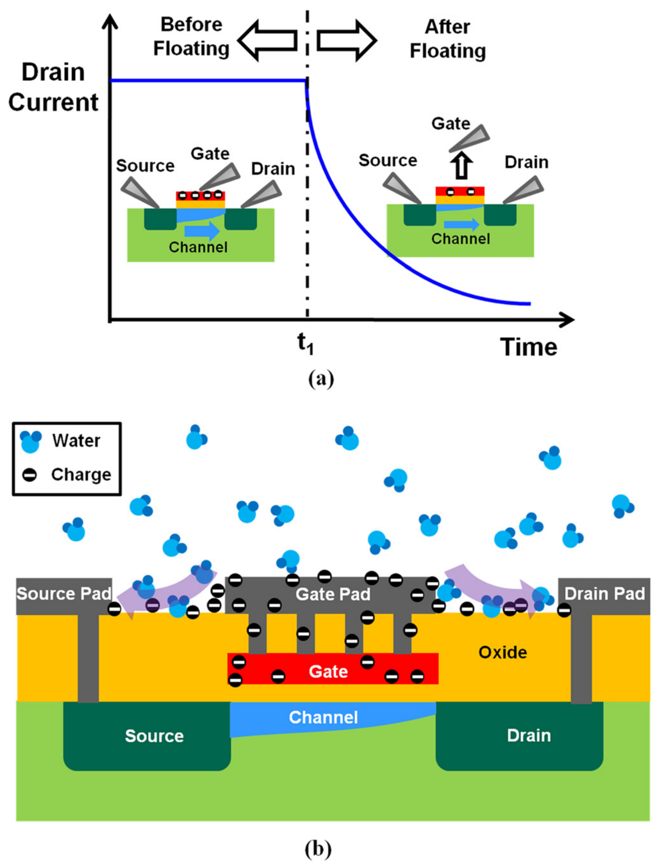

FIG. 1. (Color online) Schematic illustration of the drain current drop when the gate bias is electrically floated. (a) Drain current drops once the gate voltage is floated by lifting up the gate probe due to the dissipation of the gate charges. (b) The gate charges are dissipated to the surrounding electrodes through the oxide surface helped by the water molecules adhere to the surface.

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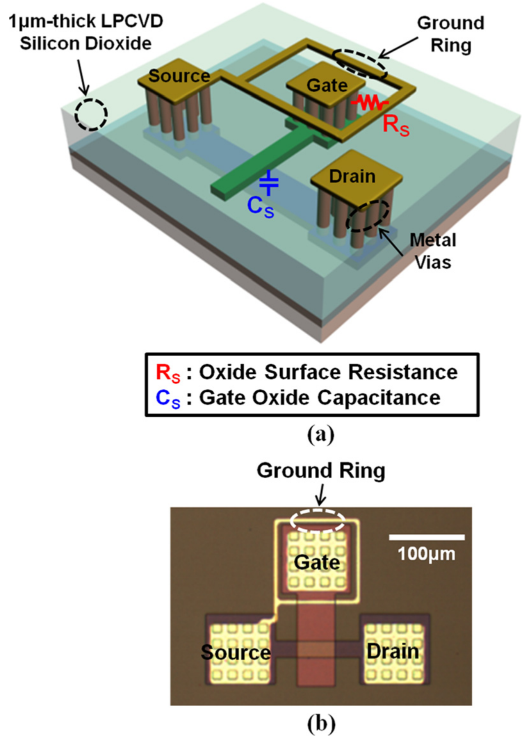

FIG. 2. (Color online) (a) The device structure including the ground ring surrounding the gate electrode. (b) Top view of the fabricated MOSFET humidity sensor.

oxide's surface from the gate pad to the surrounding electrodes.

Step 4: The surface conductance of the LPCVD oxide changes according to the humidity in the atmosphere.[12–16] Different humidity in the atmosphere results in different gate voltage drop rate. Thereby, we can sense the humidity change by measuring the drain current drop rate which is affected by the decreasing rate of the gate voltage.

Fig. 2 shows the schematic view of the proposed MOSFET humidity sensor and the image of the fabricated MOSFET humidity sensor. The device size is 340 μm by 280 μm. In this special design, we put a ground ring surrounding the gate electrode to gather the dissipated gate charges efficiently. All the electrodes were made of 1 μm thick aluminum, and the probing pad size was 80 μm by 80 μm.

The separation gap between the gate electrode and the surrounded ground ring was 15 μm and the circumference of the ground ring was 340 μm. The gate to channel overlap area was 50 μm by 20 μm, and 30 nm-thick of the thermal silicon dioxide was used as the gate oxide.

Decrease of the gate voltage can be described using the equation below

$$\frac{\partial V(t)}{\partial t} + \frac{V(t)}{R_S C_S} = 0, \tag{1}$$

where V is the gate voltage, R_S is the silicon dioxide surface resistance, C_S is the gate oxide capacitance (Fig. 2(a)). According to Eq. (1), the gate voltage drops exponentially as time proceeds,

$$V = V_0 e^{-\frac{t}{\tau}}, \tag{2}$$

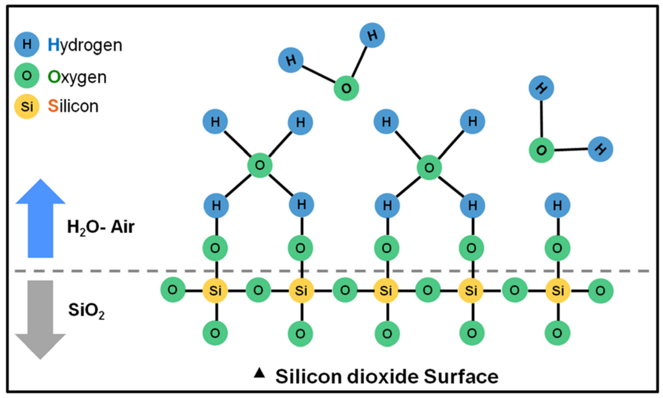

FIG. 3. (Color online) Schematic illustration that describes how H_2O molecules are adsorbed on the silicon dioxide surface.

where τ equals to $R_S C_S$ which is the decay time constant determining the decreasing rate of the gate voltage. We have noted that the surface conductance of the silicon dioxide changes by the relative humidity in air.

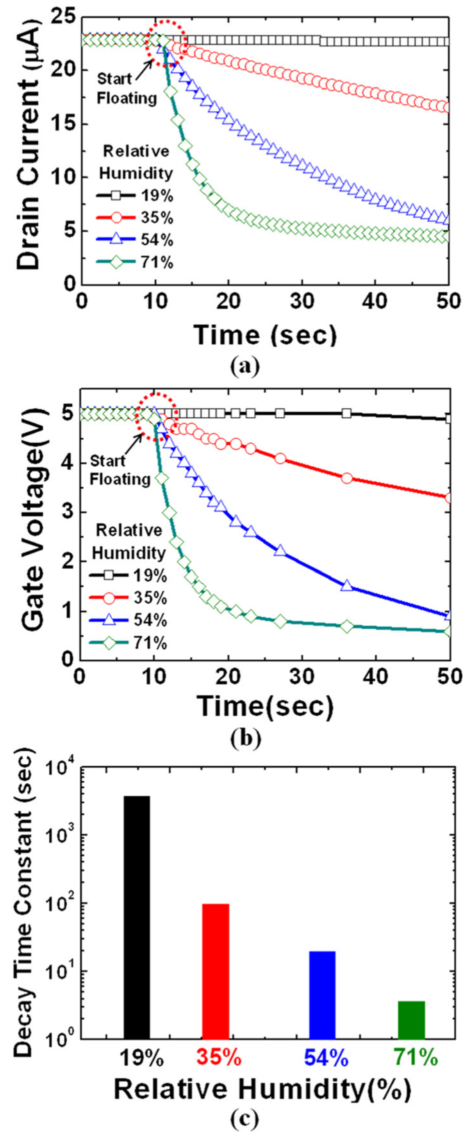

FIG. 4. (Color online) (a) Measured drain current drop at different relative humidity. (b) Measured gate voltage drop at different relative humidity. (c) Measured decay time constant at different relative humidity.

Many studies have shown that the silicon dioxide surface conductance changes by powers of ten according to the relative humidity in the surrounding air.[12–16]

Shockley *et al*. reported surface conductance changes according to the partial pressure of polar gases in the surrounding air.[16] H_2O molecule is the major polar gases in the air which can change the surface conductance. Fig. 3 shows how surface conductance changes according to the relative humidity in the air. On the silicon dioxide surface, silanol groups ($-OH$) are formed by chemisorptions of H_2O molecules in the surrounding air.[14] Then the silanol groups adsorb the H_2O molecules. As the humidity increases, more H_2O molecules stick to the silicon dioxide surface, and thereby the surface conductance increases. This increase makes the decay time constant decrease which, in turn, leads to a faster drop of the gate voltage. The change of the surface conductance for different humidity level was previously described by the Brunauer-Emmett-Teller (BET) theory.[14]

In order to measure the humidity, we applied 5 V to the gate, 0.05 V to the drain, and 0 V to the source by using the probe tips, respectively. The threshold voltage of the MOSFET was 0.81 V. The on-current of the device was 22.9 μA. The Fig. 4(a) depicts the drain current decrease once the gate is floated by detaching the probe tip. The drain current has dropped as soon as the probe tip is detached from the gate. The decreasing rate of the current varied according to the relative humidity in the air. In order to calculate the decay time constant, we converted the drain current to the gate voltage as shown in Fig. 4(b). In accordance with Eq. (2), we calculated the decay time constant from each of the relative humidity values. Fig. 4(c) shows the decay time constant (τ) according to the relative humidity which represents the decreasing rate of the gate voltage. The decay time constant (τ) varied from 3.67 s to 3650 s when the relative humidity changed from 71% to 19%. Depending on the design of the ground ring surrounding the gate electrode, we can further reduce the decay time constant.

In comparison with the previously reported FET humidity sensors,[8–11] whose maximum characteristic value changed as much as seven times when the relative humidity changed from 10% to 70%,[10] the characteristic value change obtained from the proposed method was 970 times when the relative humidity changed from 19% to 71%. From this result, we can speculate that the surface conductance change mechanism provides a more sensitive way to measure the humidity change than any other method reported to date.

In summary, we suggested a very sensitive MOSFET humidity sensor using the surface conductance change, which does not need any specific materials to sense the humidity in the air. This surface conductance change of the LPCVD oxide is responsible for the decrease of the gate voltage when the gate is electrically floated which can be measured by the drain current. This humidity sensing method is very simple and provides a very sensitive way to measure the relative humidity in air.

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