Sensors and Actuators B 236 (2016) 654–658

Contents lists available at ScienceDirect

Sensors and Actuators B: Chemical

journal homepage: www.elsevier.com/locate/snb

Chemical gating experiment of a nano-field-effect transistor sensor using the detection of negative ions in air

Kook-Nyung Lee[a,*], Yeong-Tai Seo[a,b], Sumi Yoon[a], Min-Ho Lee[a], Yong-Kweon Kim[b], WooKyeong Seong[a]

[a] HumanCare System Research Center, Korea Electronics Technology Institute, Korea
[b] School of Electrical Engineering & Computer Science, Seoul National University, Korea

ARTICLE INFO

Article history:
Received 26 February 2016
Received in revised form 23 May 2016
Accepted 9 June 2016
Available online 11 June 2016

Keywords:
NanoFET sensor
Chemical gating
Air anion detection
FET sensing behavior
Back-gate biasing

ABSTRACT

We detected negative ions in air using a nano-field-effect transistor (nanoFET) sensor. We experimentally demonstrated that the concentration of anions in air could be detected by the conductance change of the field-effect channel induced by the chemical gating caused by the adsorption of charged particles on the gate surface of the nanoFET sensor. The characteristics of chemical gating – the operating mechanism of the nanoFET biosensor – were measured from the anion detection experiments in air. In this paper, we demonstrated the operating mechanism of chemical gating by measuring and analyzing both the conductance change and response characteristics of the nano-field-effect channel using the various anion concentrations in air.

1. Introduction

Numerous approaches have been introduced recently to implement the nano-field-effect transistor (nanoFET) in biosensors because of its many advantages [1]. Not only are nanoFET sensors highly sensitive and label-free because of their direct detection mechanism, they allow real-time measurement of the biomolecular adsorption [2–7]. Additionally, nanoFET sensors are both optimal as a point-of-care testing diagnostic sensor through integration of electronic systems, and cost-effective through semiconductor mass production. However, the working characteristics by the adsorption of charged molecules on the FET gate, which is called chemical gating, have not been demonstrated experimentally because the pH level, salt concentration, and solution potential could cause a change in nanochannel conductance in a liquid environment [7–11]. Therefore, it is hard to differentiate the signal by the adsorption of charged molecules from noise or fake signal induced by other interferences existing in the liquid [7,10,11].

In this paper, we experimentally demonstrated for the first time the mechanism of chemical gating induced by the adsorption of charged substances on an FET gate by measuring the conductance change of the nanoFET using anion detection in air. As there was no need to consider pH variation, Debye screening, and solution potential in air, it was easy to characterize the electrical field-effect from the adsorption of charged substances. In a previous study, we reported that the nanoFET sensor can detect anions in air by the chemical gating induced by ion adsorption or charging [12,13]. In this study we analyzed further the operating characteristics of chemical gating in a nanoFET sensor with various anion concentrations. By controlling back-gate potentials, the characteristics of the nanoFET channel were analyzed in the off-, subthreshold-, and turn-on regions.

2. Material and methods

The structure of a nanoFET sensor is similar to previous silicon-oxide-insulator (SOI)-based devices (Fig. 1) [3,4,12]. The nanochannel was fabricated on an SOI wafer (5 μm × 1 μm × 20 nm in width, length, and thickness, respectively) by using the semiconductor process. The fabrication process was similar to a previously reported study [3,12]. The floating gate of Ti/Au (10/100 nm) was additionally fabricated on top of the nanochannel with a thermal deposition and lift-off process. Fig. 1 shows a side-view of the nanoFET structure. The Ti/Al layer was used as a contact electrode for the source and the drain. The gate oxide of the nanochannel was 15 nm thick and the buried oxide (BOX) of the SOI wafer was 145 nm thick. The inset of Fig. 1 is a scanning electron microscope

* Corresponding author at: Korea Electronics Technology Institute (KETI); #68, Yatap-dong, Bundan-gu, Seongnam-si, Gyeonggi-do 463-816, Korea.
E-mail address: plummy@keti.kr (K.-N. Lee).

http://dx.doi.org/10.1016/j.snb.2016.06.057
0925-4005/

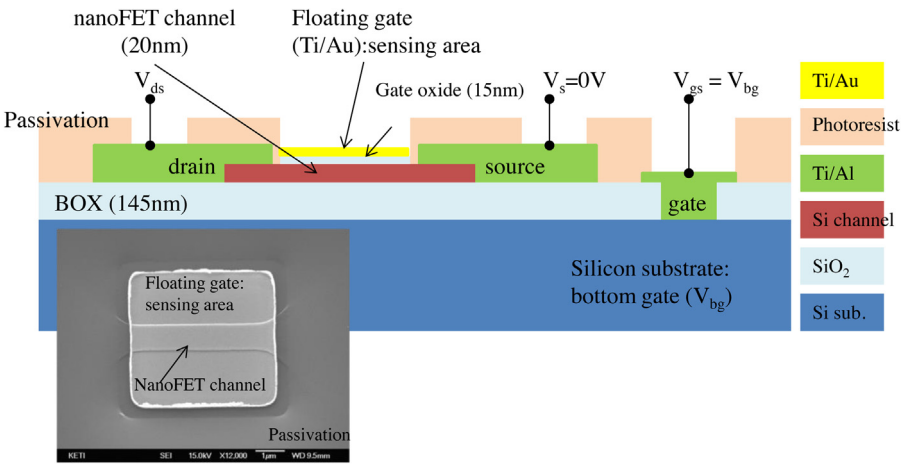

Fig. 1. Cross-sectional view of the nanoFET device and SEM micrographs of its sensing area.

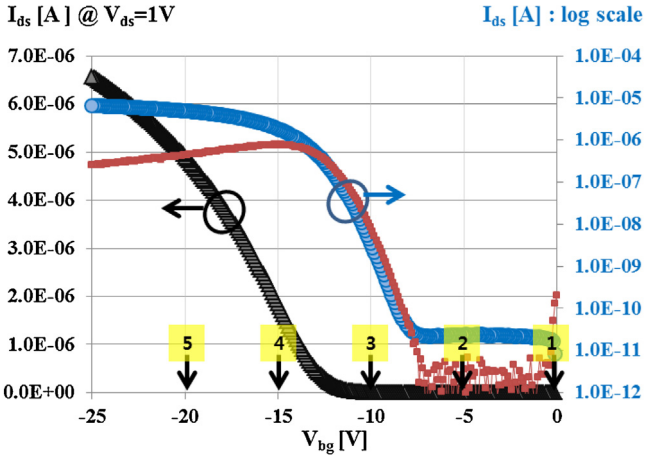

Fig. 2. I–V characteristics of the nanoFET device by back-gate (V_{bg}) sweep from 0 to −25 V at a constant V_{ds} of 1 V. The black triangular-dots line represents I_{ds} versus V_{gs} is in a linear-scale (the left *y*-axis) and the blue round dots line is in logarithmic scale (the right *y*-axis). The red square dots represent the transconductance of the device. The 1–5 positions on the V_{bg} axis represent bias voltage value in evaluating the device sensitivity according to the V_{bg} bias voltage. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

(SEM) micrograph of the fabricated nanoFET sensor showing the floating gate, the nanochannel, and the passivation layer.

The I–V characteristics of the nanoFET are shown in Fig. 2. The I_{ds} versus V_{bg} curve was plotted in both linear scale (left *y*-axis) and logarithmic scale (right *y*-axis). The nanoFET shows a typical p-type channel device with a high I_{on}/I_{off} ratio of over 10^5, and a transconductance (g_m) of 790 nS/V at V_{ds} = 1 V. We selected five back-gate bias values of V_{bg} from −20 to 0 V with 5 V intervals to evaluate the sensitivity of the nanoFET sensor according to the FET channel region of the nanoFET. At the V_{bg} values of −20 and −15 V, the channel was in the turn-on and linear region and the g_m of the device was maximized at the V_{bg} value of −15 V. At the V_{bg} value of −10 V, the device was in the subthreshold region. At the V_{bg} values of −5 and 0 V, the device was in the fully depleted and turn-off region. We evaluated experimentally which region of the nanoFET channel was optimal for maximizing the sensitivity of the nanoFET sensor. We compared the sensitivity in five different channel regions of the nanoFET to be determined by the back-gate bias potential as linear, subthreshold, and depleted channel states, respectively, as marked on the *x*-axis in Fig. 2.

The experimental set-up for detecting negative ions in air using a nanoFET sensor is shown in Fig. 3. Negative ions were generated and spread in air by the commercial ionizer. The anion concentration at the sensor position was adjusted by controlling the position of the ion generator from the nanoFET sensor. The place position of the ion generator from the sensor was set at 10–70 cm with 10 cm intervals. The air ion counter (Andes Electric Co., Japan) monitored the anion concentrations at the sensor position simultaneously. The shutter in front of the sensor was used to expose or block the anions that spread out from the ion generator. To make real-time measurements, the shutter opened at intended times after the measurement became ready. Using a SourceMeter (Keithley, USA), I_{ds} was measured in real time while a V_{ds} of 1 V was constantly applied to the nanoFET sensor. The V_{gs} of the device or the back-gate potential V_{bg} was applied with one of five different potential values representing typical regions of the nanoFET channel indicated as 1–5 on the *x*-axis (Fig. 2). The measurements were performed in sequence at several V_{bg} conditions. For long-term and continuous measurement, the developd hand-held circuit was used to read-out the nanoFET sensor [13].

3. Results and discussion

Fig. 4(a) shows the results of real-time conductance change of the nanoFET sensor. The conductance change was measured twice for five different back-gate potential regions with a constant anion concentration of approximately 40,000 ions/cm^3 (see Fig. 2). A shutter in front of the nanoFET sensor had a 5 s delay opening from the start of the measurement. The initial I_{ds} level varied and was determined by the relevant back-gate bias voltage and the I_{ds} values were known from the I_{ds}–V_{bg} characteristics curve (Fig. 2, the triangular dotted black line plotted on a linear scale). The real-time measurement results give information about the behavior of the nanoFET sensor. Firstly, the conductance of the p-type nanoFET sensor increased and gradually reached saturation, which indicates the accumulation of negative anions on the sensor surface through negative ion adsorption. Secondly, the device responding to ion exposure in air shows immediate changes in the subthreshold, as well as in the bias condition in the turn-on region of the nanoFET sensor. However, in the off region of the nanoFET sensor, the conductance change induced by the exposure of anions shows a delay and a larger delay for a more depleted condition. The delay in the off-region indicates that the accumulation of negative ions by adsorption or the charging on the sensor surface to turn on the nanochannel is a time-consuming process. The sensitivity of the