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Ion balance detection using nano field-effect transistor with an extended gate electrode

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Abstract

We developed a nano field-effect transistor (nanoFET) sensor for detecting ions in the air. Air ions can be measured using a commercial ion counter; however, it is large and expensive equipment, requires airflow to be through a cylinder type electrode or the plate electrode. NanoFET sensor is suitable for monitoring the ion generator module in home appliances like air purification. A nanoFET sensor can continuously measure the ion balance to monitor the performance of the ion generators which do static electricity elimination in electronics manufacturing lines. In this study, we developed a semiconductor sensor that can measure the ion balance in the air. The sensor is a nanoFET device with an extended gate electrode. The polarity of the ions adsorbed on the extended gate electrode is measured, and consequently, the ion imbalance is quantitatively estimated. The developed device enables reset with a switch connected to the extended gate. The sensor reads out with a current to voltage converting operational amplifier, a reset switch, and a microprocessor. We expect that the developed nanoFET sensor is practically applied to monitor the malfunction of ion generators in the air cleaner and in the static electricity elimination in electronics manufacturing lines.

Keywords: nanoFET, Extended gate electrode, Ion detection, Ion balance monitoring

Introduction

A nano field-effect transistor (nanoFET) device has been widely studied as a biosensor for detecting pH level, proteins, biomarker molecules, anions, and gas molecules in environments such as a solution or the air [1–7]. This is due to their advantages such as rapid response time, low-cost, ease of integration with electronic parts, and miniaturization. It can detect target substances in label-free with the conductance change of the nanochannel due to the electric field effect induced by the adsorption of a charged target substance on the gate electrode [6–10]. Electronic products using anions have attracted much attention recently because they can clean and remove dust, pollutants, and viruses by charging the ultrafine particles in the air [11–14]. Moreover, ion blowers have been used to remove static electricity in the manufacturing industry of electronic devices [15–17]. The ion blower

simultaneously generates anions and cations above 30,000 ea/cm³ each and releases them in the air with a fan. However, the amount of generated ions would be relatively unbalanced since the electrode in the ion generator ages over time and do malfunction during its usage in various environments. Therefore, the monitoring of the ion concentration and the ion balance in the air is crucial. To address this, authors developed a small-sized nanoFET device that can measure the number of ions in the air as an alternative to the commercial ion counter or electrostatic field-meter, which is huge and expensive equipment. However, previous nanoFET device has some limitations such as they have relatively longer measurement cycles, lower sensitivity, and they are inconvenient because of back-gate voltage sweep to reset the device [18–21].

In this study, we adopt a large-size extended gate electrode interconnected to the gate electrode of the nanoFET device, which increases the probability that ions in air adsorb on the sensor electrode. The extended gate electrode plays an essential role in providing the fast

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response of the sensor. The results show that the response of the sensor gets more rapid with the larger extended gate electrode for the sensing area. Besides, the device can be reset by grounding and removing the adsorbed charges on the extended gate in the sensing area using a switch. Furthermore, it is possible to monitor and measure quantitatively ion balance by the simultaneous use of n-type and p-type nanoFET devices sharing the extended gate electrode. We show that the conductance change of the nanochannel of the nanoFET device to the adsorption of air anions can be simply readout with an operational amplifier circuit.

Fabrication

The nanoFET device was fabricated with a silicon-on-insulator (SOI) wafer. The device has the nanochannel of $1\ \mu\text{m} \times 5\ \mu\text{m} \times 20\ \text{nm}$ with the top gate and the bottom substrate gate on it. The thickness of the oxide layer on the top gate, and that of the buried oxide on the SOI substrate used as the bottom gate, is 20 nm and 100 nm, respectively. The fabrication process and the structure of the nanoFET device are detailed in our previous work [18]. The gate electrode on the top of the nanochannel is a $200\ \mu\text{m}$ -sized pad to connect it to an extended gate electrode outside the device by a wire bonding. The bottom gate electrode also can be interconnected similarly to the extended gate electrode, which is the sensing electrode. The sensing electrode is itself in an electrically floating state and can be grounded using a switch. Figure 1 shows a schematic of the nanoFET device and the configuration of the read-out circuit. The extended gate

electrode is an Au electrode formed on a printed circuit board substrate and has several sizes of 6×6 to $30 \times 30\ \text{mm}^2$. The material or surface area of the extended gate electrode can be easily changed because it is a connectable part with the nanoFET device. The nanoFET device, except the extended gate electrode, is protected by epoxy to prevent its exposure to the environment.

Results and discussions

Figure 2 shows the $I_{ds}-V_g$ characteristics of the nanoFET device by the gate voltages (V_g) sweep of the top and bottom gate electrodes. The threshold voltages of the p-type and n-type nanoFET devices are $-2.5\ \text{V}$ and $-1\ \text{V}$, respectively, and the on/off ratio exceeds 10^6 . G_m is a trans-conductance that reflects the relationship between V_g and the current in the nanochannel (I_{ds}), as shown in Eq. (1). We use both p-type and n-type devices interconnected to the same extended gate electrode. By analyzing the output changes of p-type and n-type devices, the polarity of the dominant ions is confirmed, and the difference in relative amounts is calculated. This configuration allows us to compare the outputs of the two types under the same amount of ions adsorbed on the gate electrode, and ion balance is analyzed. The electrical charges in the gate electrode accumulate with the adsorption of airborne ions. Moreover, the increase or decrease of the number of charges calculates considering the amount of ions adsorption on the sensing electrode per hour, which is related to voltage, electrical charges, and the device capacitance. The metal–oxide–semiconductor structure of the nanoFET device is assumed to be that of a plate

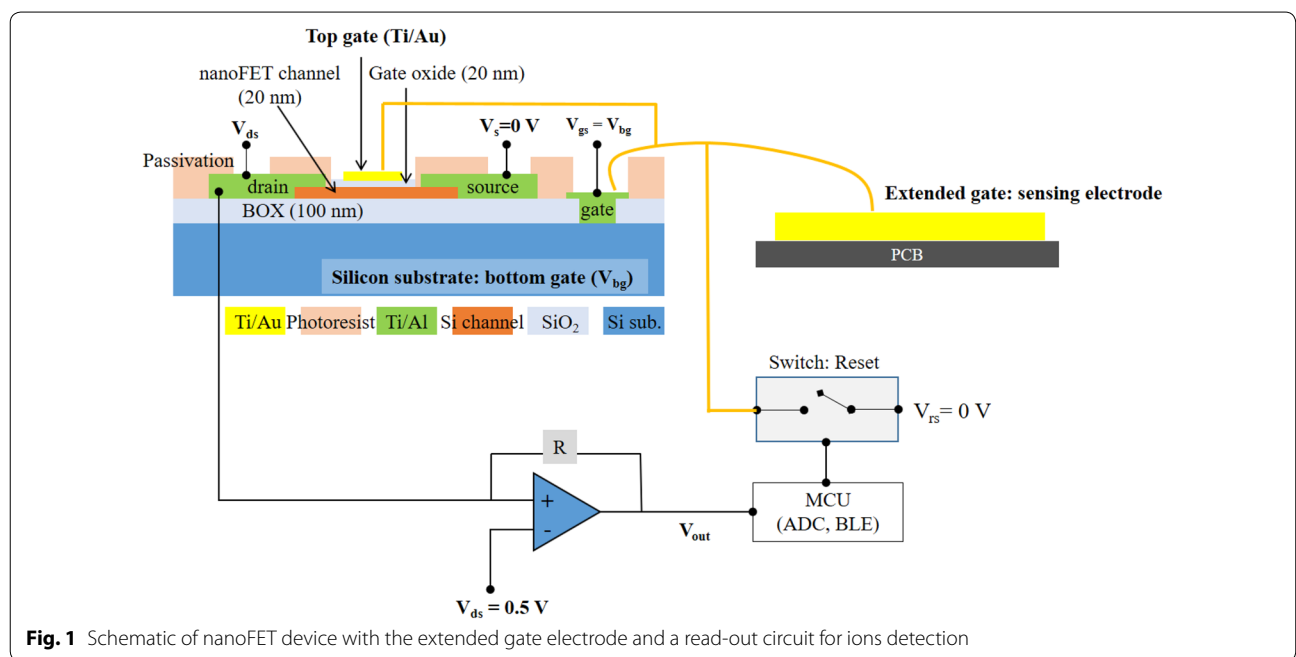
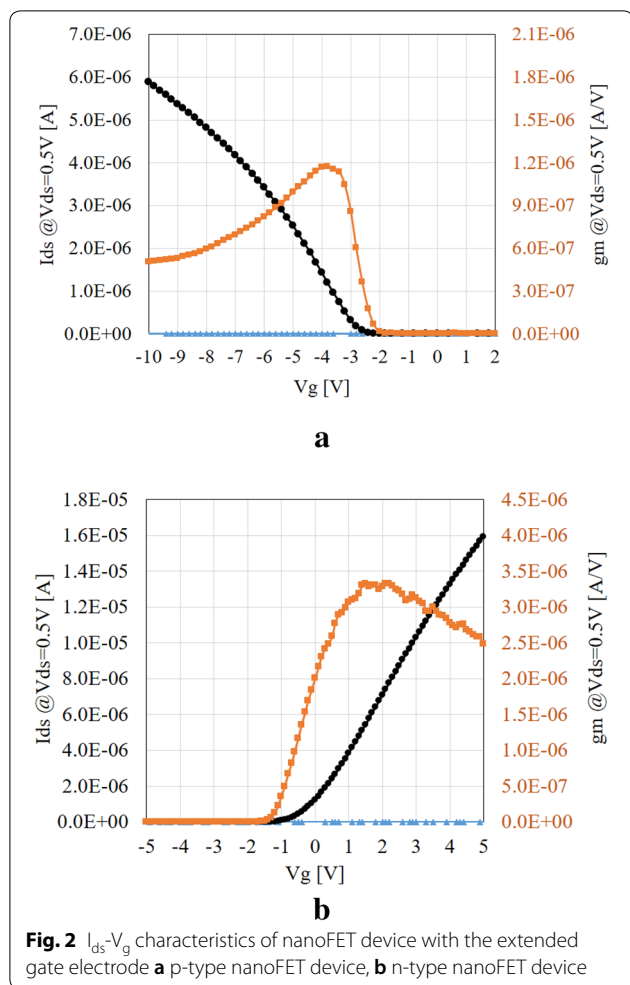


Fig. 1 Schematic of nanoFET device with the extended gate electrode and a read-out circuit for ions detection



capacitor, which is based on the general formula provided in Eq. (2). If Q is the amount of the accumulated charge of the gate electrode, C is the capacitance between the gate electrode and the nanochannel, and V_{gs} is the potential of the gate electrode, then the change in Q gives the effect of V_{gs} on the nanochannel. The I_{ds} is turned into a voltage value using Eq. (3) by a simple read-out circuit as shown in Fig. 1, where R is the resistance value of the operational amplifier integrated circuit to convert I_{ds} current to the voltage. The commercial operational amplifier integrated circuits device (OPA2380, Texas Instruments) is used. As described above, we can approximately measure the polarity and the number of ions adsorbed on the sensing electrode using the output voltage (V_{out}) and the simple equations provided below.

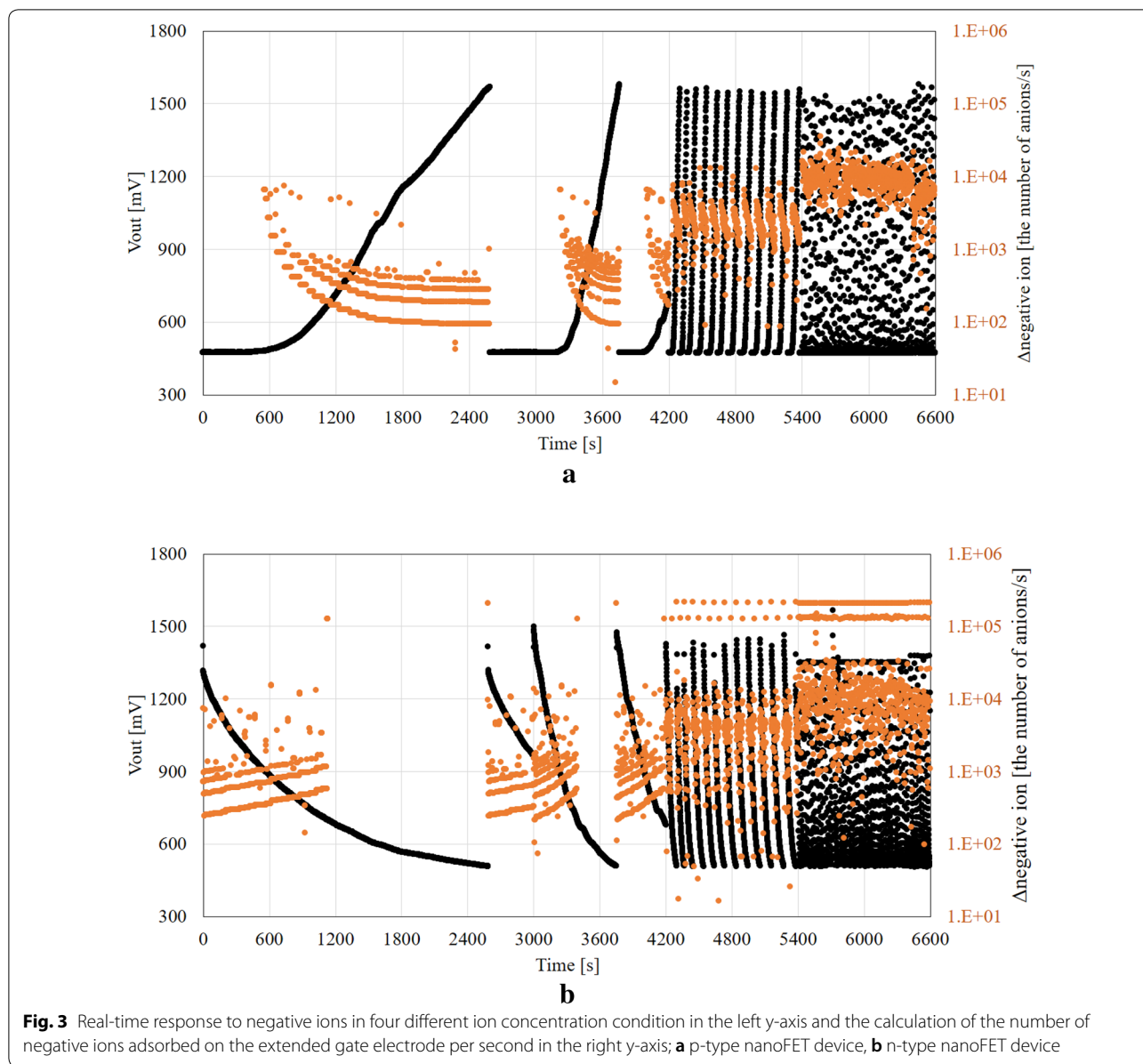
$$V_g = I_{ds}/G_m \tag{1}$$

$$Q = CV_{gs} \tag{2}$$

$$V_{out} = V_{ds} + I_{ds} \cdot R \tag{3}$$

Figure 3 shows the ion measurement results of the developed nanoFET sensor with an extended gate electrode. For the four different concentrations of negative ions from a few thousand to a few million anions/cm³, the real-time response of the sensor was recorded. The output voltage of the p-type device increase and that of the n-type decrease as the anions are adsorbed on the common sensing electrode. The number of anion increase per second is calculated using the method described above. The real-time output of the sensor and the calculation results at each anion concentration are represented in the left and right y-axis, respectively, in Fig. 3. The calculated anion increase is around 100 to 100,000 anions per second, which can interpret that approximately 10% of the concentration of ions in the air accumulates in the extended gate electrode. In the experiment, the sensor resets by grounding the extended gate electrode with a switch when the accrued charges by the ion adsorption reach the upper limit level. The action for reset occurs a drastic change in V_{out} as shown in Fig. 3a, b. The response of the p-type nanoFET device shows a short delay while the n-type device reacts immediately after every reset. That is caused by the threshold voltage of the p-type device, - 2.5 V. That is, the p-type device requires negative charge accumulation to turn-on while the n-type device turns on already in the initial level of the gate electrode. The simultaneous use of p-type and n-type devices allows the measurement range to extend to detect air ions due to cover over and compensation for the off area of each device. Consequently, the developed nanoFET sensor can detect anions as low as 1,000 anions/cm³.

Figure 4 shows the comparison results of the output voltage of the p-type nanoFET sensor, considering that the anion concentration is maintained at around 20,000 anions/cm³, and only the size of the sensing electrode is varied. The real-time responses of the nanoFET sensor when the size of the extended gate electrode is 6 × 6 mm², 20 × 20 mm², and 30 × 30 mm², respectively, are shown in Fig. 4. From the results, it is confirmed that the larger the size of the extended gate electrode, the faster the sensor output reaches the upper limit level. It is because of the amount of adsorbed charges per second increase as the adsorption area that ions in the air can adsorb increase. However, it should be noted that the adsorption efficiency of ion is constant regardless of the size of the extended gate electrode considering the unit size of the gate electrode. We predict that the adsorption efficiency of ions may vary depending on the material of the electrode or airflow and so on. Figure 5 shows the measurement of the ion balance emitted from the



ion blower, using which, the feasibility of the developed nanoFET sensor with the extended gate electrode, and that of the read-out circuit can be verified. The output voltage of the nanoFET device can be used to identify the relative imbalance of anions and cations. As a result, the output voltage of the p-type and the n-type devices immediately increases or decreases when the polarity of the charge accumulated in the extended gate electrode is biased to either the positive or the negative side. In other words, we could find which of the polarities dominate the nanoFET device, and the degree of ion imbalance could be determined using the method explained in Fig. 3. The small-sized nanoFET sensor is suitable for checking the

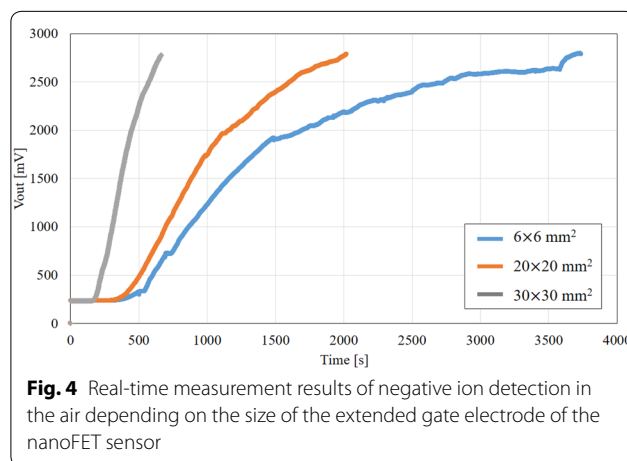
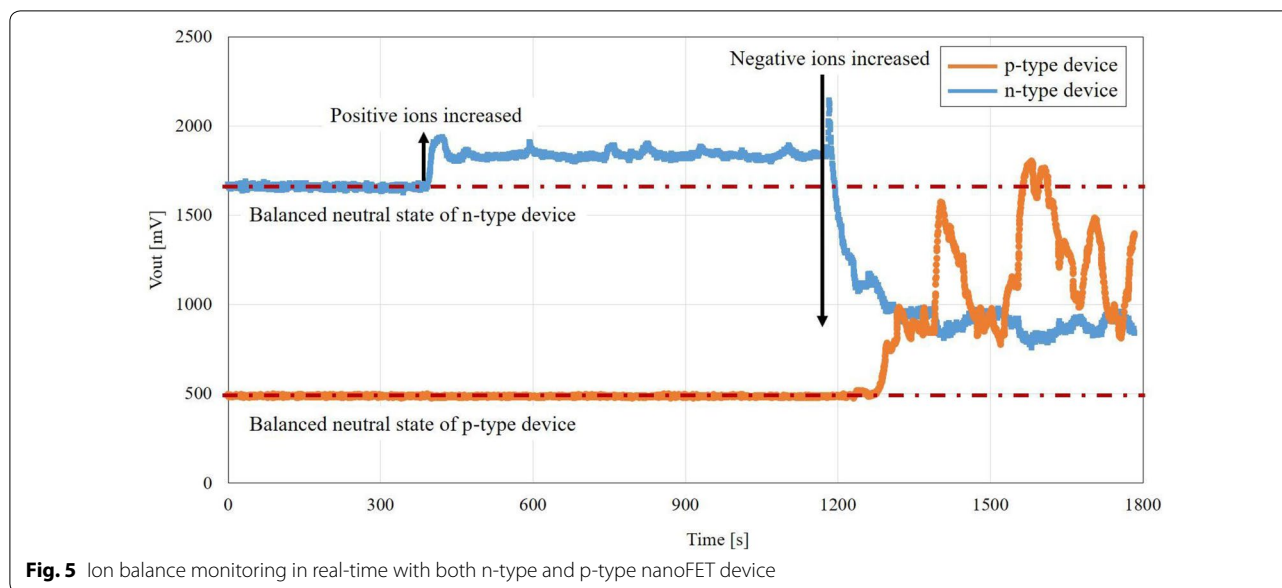


Fig. 4 Real-time measurement results of negative ion detection in the air depending on the size of the extended gate electrode of the nanoFET sensor



ion balance in real-time at the antistatic target position, where is affected by the ion blower.

Conclusions

In this paper, we showed that the nanoFET device with the extended gate electrode could measure ions in the air. We demonstrated that the sensor with a simple read-out circuit can monitor the number of air ions in real-time, and can reset the accumulated charges on the floating gate electrode to connect to the ground by a switch. The nanoFET ion sensor is a small semiconductor device compared with commercialized equipment such as air ion counter or hand-held electrostatic field-meter. We expect that these ion sensors able to be employed for home appliances or to monitor the malfunction of the ion blowers.

Abbreviations

NanoFET: Nano field-effect transistor; SOI: Silicon on insulator.

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Authors' contributions

HLK and SY, they designed the nanoFET device and did the experiment. Both summarized the experimental data and wrote the manuscript of the paper. DH, he designed and fabricated the read-out circuits and performed the measurement experiment. KNL, he brought the ideas and designed the concept and experimental setup. He wrote the manuscript of the paper. He is the corresponding author of the paper. WHK, and WKS, they supported the research with valuable advice and gave valuable comments and discussion on the research direction. All authors read and approved the final manuscript.

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Availability of data and materials

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Competing interests

The authors declare that they have no competing interests.

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