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Investigation of Feasibility of Tunneling Field Effect Transistor (TFET) as Highly Sensitive and Multi-sensing Biosensors

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***Abstract*—In this letter, we propose the use of tunneling field effect transistors (TFET) as a biosensor that detects bio-molecules on the gate oxide. In TFET sensors, the charges of target molecules accumulated at the surface of the gate oxide bend the energy band of p-i-n structure and thus tunneling current varies with the band bending. Sensing parameters of TFET sensors such as threshold voltage (V_t) shift and on-current (I_D) change are extracted as a function of the charge variation. As a result, it is found that the performances of TFET sensors can surpass those of conventional FET (cFET) based sensors in terms of sensitivity. Furthermore, it is verified that the simultaneous sensing of two different target molecules in a TFET sensor can be performed by using the ambipolar behavior of TFET sensors. Consequently, it is revealed that two different molecules can be sensed simultaneously in a read-out circuit since the multi-sensing is carried out at equivalent current level by the ambipolar behavior.**

***Index Terms*—Tunneling field-effect transistor (TFET), TFET biosensors, ion-sensitive field-effect transistor (ISFET), multiplexed biosensing**

I. INTRODUCTION

The biosensors based on ion-sensitive field effect transistors (ISFET) have been widely researched due to label-free, highly sensitive and real-time detection of biological entities, such as DNA, virus, and proteins. Various experimental works have been reported on ISFET sensors with different sensing concepts [1, 2]. Furthermore, CMOS-compatible device structures of ISFET sensors have received great attention for good uniformity, high reproducibility and low-cost fabrication for mass production [1-4]. The principle of electrical detection in ISFET sensors is based on the gating effect of the charged biomolecules on the gate oxide, which can be converted directly to the change in electrical properties such as current, conductance, and threshold voltage [5, 6]. Our group has developed silicon nanowire (SiNW) biosensors that can be completely co-integrated with CMOS readout circuit [7, 8]. However, conventional FET (cFET) based biosensors have suffered from theoretical limitations on the maximum sensitivity because MOSFET cannot implement sub-60mV/dec subthreshold swing (SS) at room temperature. Tunneling field effect transistors (TFETs) are known for their low power operation and good SS [9]. The advantages of TFET devices can also be applied to biosensors and thus TFET sensors can have the possibility for improved sensitivity over cFET sensors. Furthermore, TFET devices show ambipolar behavior [10]. Thus, the simultaneous sensing of two different target molecules in a TFET sensor can be performed by utilizing the ambipolar characteristics. In cFET sensors, Gate-

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Table 1. Parameters used in these simulations

Width	1 μm
Channel Length	1 μm
Oxide Thickness T_{ox}	4 nm
Channel Thickness T_{ch}	20 nm
Helmholtz Layer Thickness T_h	0.5 nm
Box Thickness T_{box}	100 nm
Source /Drain Doping	2×10^{20} cm^{-3}
Channel Doping	10^{17} cm^{-3}

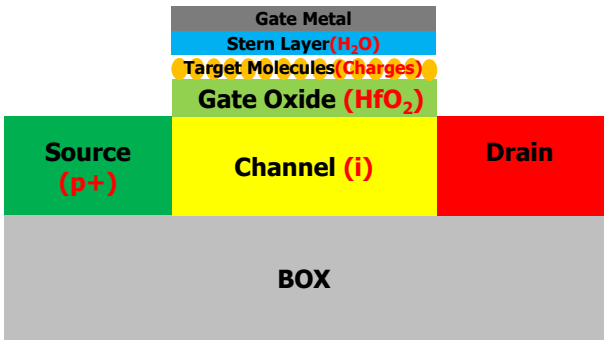

Fig. 1. Device structure of TFET sensor used in these simulations.

Induced-Drain-Leakage (GIDL) current and on current can be used when sensing two different target molecules in a cFET sensor respectively [11]. However, it is difficult that two different molecules can be sensed in a read-out circuit due to the low current of GIDL as compared to the on-current. In TFET sensors, the multi-sensing can be simply performed in a read-out circuit since each molecule is sensed at almost equivalent current level by the symmetric nature of ambipolar characteristic.

In this study, we adopt TFETs as a pH or biomolecule sensor. Through TCAD simulations, the sensitivities of TFET and cFET sensors are compared rigorously.

Additionally, the simultaneous detection of two different target molecules in a TFET sensor is performed in common-source amplifier read-out circuit.

II. Device Structure and Simulation Conditions

The device architecture and physical parameters of the TFET sensor used in this work is shown in Fig. 1 and Table 1 respectively. The proposed device has a conventional p-i-n structure. The channel length and width of the device are 1 μm. The source and drain

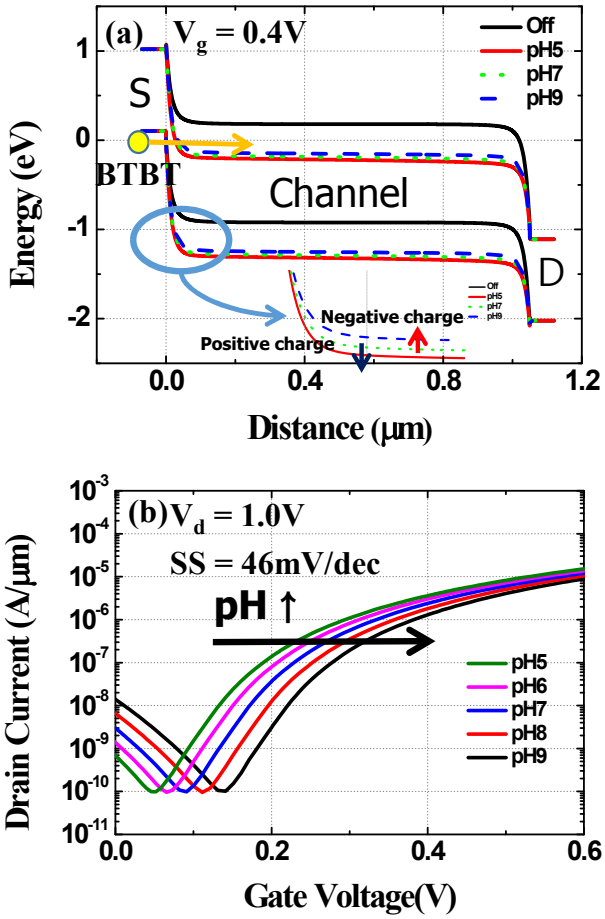

Fig. 2. (a) Energy band diagram change of n-type TFET pH sensor according to pH level, (b) Transfer curves of n-type TFET pH sensor according to pH level.

regions are doped with 2×10^{20} cm^{-3} boron and arsenic respectively, and channel doping concentration is 1×10^{17} cm^{-3}. In addition, we assume that Helmholtz layer can be considered as a dielectric layer with a few angstrom thickness [12]. Biomolecules are modeled as positive and negative charges on the gate oxide. Site-binding theory is used to model sensing mechanisms of target molecules with charges [13]. In multi-sensing simulations, negative/positive charges are attached on the source/drain side of the gate oxide respectively. All the simulations are conducted with Sentaurus™ TCAD simulator of Synopsys Inc.

III. Results and Discussion

1. Basic Operation of TFET Sensor

Fig. 2(a) shows the sensing mechanism of a TFET pH

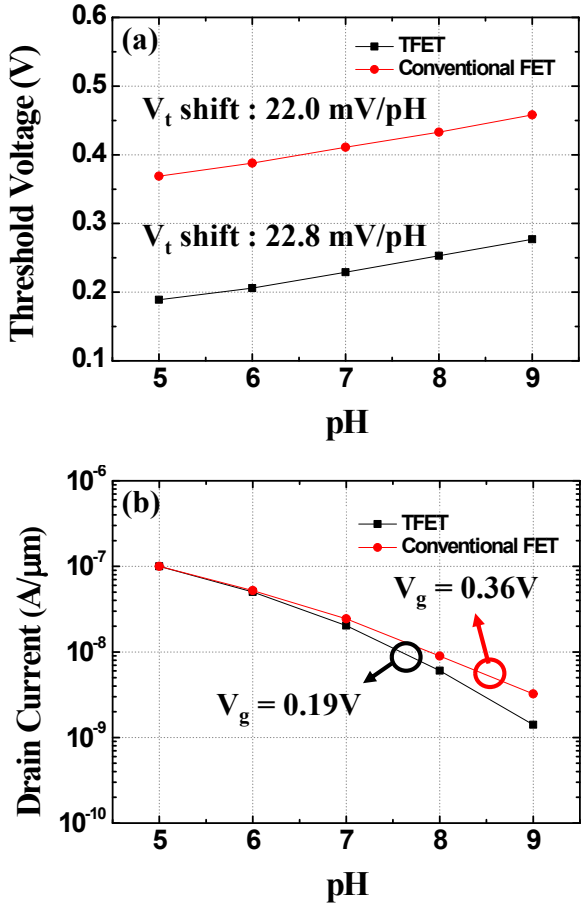

Fig. 3. Comparison of TFET and conventional FET pH sensor in terms of (a) Threshold voltage shift, (b) Current sensitivity at fixed gate voltage (V_t at pH level 5).

sensor. When pH increases and molecules with negative charges are attached to the gate oxide near the junction between source and channel, the energy band of the channel is elevated. That makes the potential barrier between source and channel thicker. As a result, tunneling rate decreases and tunneling current is reduced. Fig. 2(b) indicates the transfer curves of the simulated TFET pH sensor at different pH levels. The drain bias voltage is 1 V. Threshold voltage is extracted by constant current method and defined as the gate voltage when normalized drain current ($I_d \times$ L/W) matches 10^{-7} A. The proposed TFET device has the SS of about 45 mV/dec and the V_t of 0.23 V in pH 7. The V_t shift of 22 mV/pH occurs as pH increases. Fig. 3(a) shows that the threshold voltage shift of the TFET sensor by pH change is almost same as that of the cFET sensor. However, sensing current versus pH extracted at the threshold voltage of pH 5 shows that the TFET pH sensor has the improved sensitivity due to steeper SS as shown in Fig. 3(b).

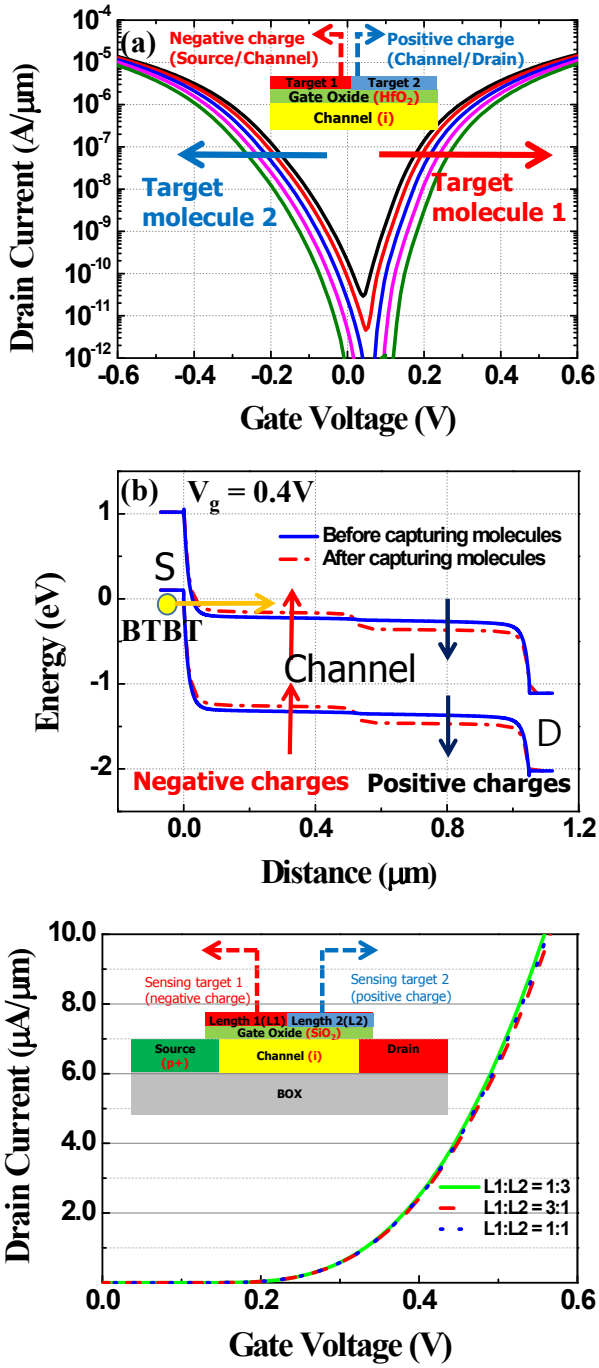

Fig. 4. (a) Multi-sensing of biomolecules with opposite charge in a TFET sensor, (b) Energy band diagram change by different charges at source/drain side, (c) Dependency on the total length of the attached target molecules.

2. Multi-sensing Performance of TFET Sensor

Ambipolar characteristics enable TFET sensors to sense two different biomolecules in one device. Fig. 4(a) shows the multi-sensing behavior of a TFET sensor. The biomolecule with negative charges can be sensed at

positive gate voltage region, whereas the biomolecule with positive charges can be detected at negative gate voltage region. As the proposed device has a long channel, we can easily attach different molecules to source/drain side gate oxide. Fig. 4(b) shows the energy band diagram of the TFET sensor when molecules with different charges are attached to each end of the gate oxide. The energy band of the channel is slightly separated. The source side with negative charges is elevated and the drain side with positive charges is moved downward. The mechanism of the multi-sensing can be explained by the variation of tunneling barrier thickness at source/channel or channel/drain junction. When positive gate voltage is applied, the ascended energy band makes the tunneling barrier thicker between source and channel, which results in the positive-shifted on-current. Likewise, when applying negative gate voltage, the descended energy band prevents electrons from tunneling at channel/drain junction, which leads to the negative-shifted ambipolar current. Here, it should be noted that two different molecules can be sensed at almost equivalent current level by the symmetric nature of ambipolar current. Also, the sensing of one molecule does not disturb that of the other. Fig. 4(c) illustrates that the length of attached one molecule has negligible effect on the sensing of the other molecule. In readout circuit application, TFET sensors also can achieve superiority over cFET sensors in terms of sensitivity and multi-sensing. To verify the superiority, common-source (CS) amplifier (one of read-out circuits) is simulated. Fig. 5 shows the bias condition for sensing and the circuit diagram of the CS amplifier with the TFET sensor/TFET or the cFET sensor/MOSFET. When target molecules are sensed in the CS amplifier, the conductance of the sensing device is changed by the attached molecules and the output voltage of the CS amplifier is shifted in the consequence. In multi-sensing operations, voltage transfer curves should be positive-shifted by the negative charges attached near source/channel junction, while voltage transfer curves should be negative-shifted by the positive charges attached near channel/drain junction. Moreover, sensitivity can be modified by adjusting the conductance of amplifier device [14]. Fig. 6(a) shows the output voltage change of TFET based amplifier by the gate voltage variation of sensing device. Similar to the characteristics of single sensor without additional

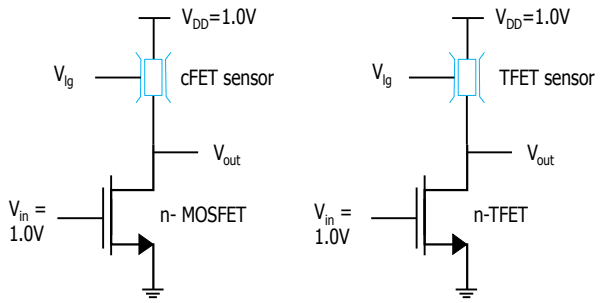

Fig. 5. Circuit diagram of common-source amplifier with a TFET sensor and a conventional FET sensor.

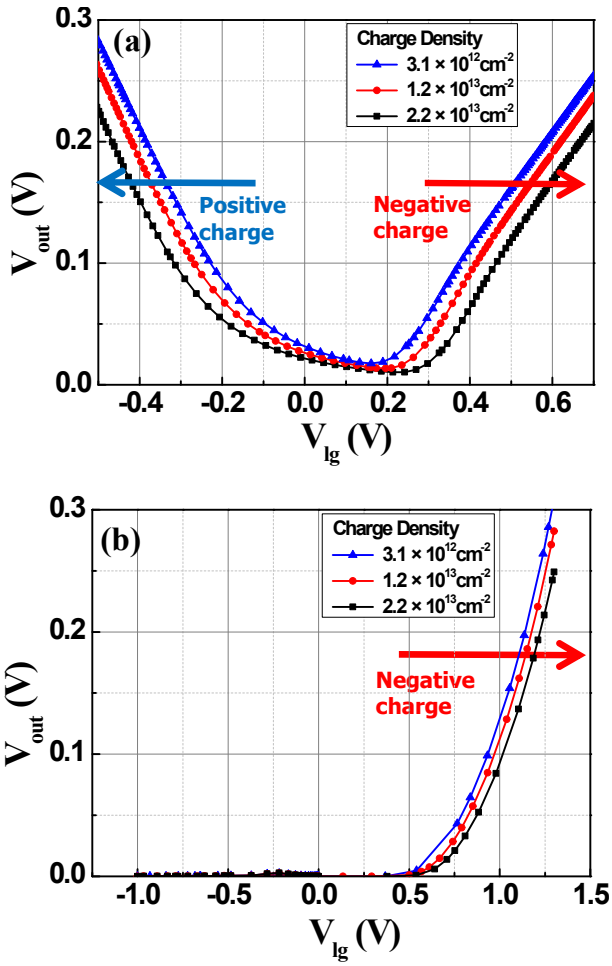

Fig. 6. Voltage transfer curves of common-source amplifiers for different charge density (a) Output voltage in TFET sensor, (b) in conventional FET sensor.

circuitry, the sensing of target molecules can be performed at positive and negative gate bias regions. Also, the amount of output voltage shift is similar at the two gate bias regions. It means that multi-sensing is performed successfully in TFET based amplifier due to the ambipolar characteristics of TFET sensors. It is

reported that single cFET sensor is also able to sense target molecules at positive and negative bias regions. In the cFET sensor, on-current is used at positive bias region, while GIDL current is used at negative bias region [11]. However, in cFET based CS amplifier, it may be difficult that two different molecules are sensed at positive and negative gate bias regions due to the low current of GIDL as compared to the on-current. Such high resistance of sensing device does not fit with that of other MOS amplifier device. Fig. 6(b) shows that output voltage shift is hardly observed at negative bias region due to this resistance difference in cFET based amplifier.

IV. CONCLUSIONS

In this paper, we have demonstrated a TFET based pH sensor. From TCAD simulations, it is found that TFET sensors have smaller subthreshold swing and threshold voltage than those of cFET sensors. Also, TFET sensors have the improved sensitivity due to their steeper subthreshold slope. Furthermore, TFET sensors can sense two different molecules with opposite charges in one device. By using two types of tunneling such as source-to-channel and channel-to-drain tunneling, the detection of two different target molecules is conducted successfully at the same sensing current level due to the ambipolar behavior of TFETs. In common-source amplifier circuit, it is confirmed that two different target molecules can be also sensed with equivalent sensitivity. Based on these results, we expect that TFET biosensors could open a new prospect in the bio-sensing applications.

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