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Fabrication of AlGaN/GaN MOS HEMT-based high-sensitivity EGFET pH sensor with coplanar gate structure

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Abstract

In this study, we deveolped a coplanar gate AlGaN/GaN MOS high electron mobility transistor (HEMT) based pH sensor platforms using resistance coupling effect to overcome the Nernst limit of 60 mV/pH of conventional ion-sensitive field-effect transistor (ISFET). The implemented HEMT-based EGFET pH sensors not only showed sensitivity far exceeding the Nernst limit depending on the ratio of the resistors connected to the coplanar gates, but also had excellent stability against long-term exposure in the pH buffer solutions. Therefore, our proposed coplanar gate HEMT-based pH sensors are expected to be a useful method for the next generation biosensor platform.

1. Introduction

Recent developments in big-data, Artificial Intelligence, Deep Learning, and IoT in the 4th industrial Revolution have led to increasing interaction between humans and devices, requiring the miniatuization, advancement, and funtionalization of all electronic devices. Sensors are actively studied as a core technology of interaction. However, the conventional ISFET has a Nernst limit of 60 mV/pH at room temperature, which makes it difficult io commercialize it. In order to onvercome this problem, a double-gate (DG) structure of ISFETs using a silicon-on-insulator (SOI) substrate has been proposed [1-2]. However, the DG-structured ISFET can overcome the Nernst limit by capacitive coupling of the upper and lower gate oxides, but has the disadvantage that it is only possible in metal-oxide-semiconductor (MOS) devices. Therefore, this study proposed a resistance coupling that can be used not only for MOS structure but also for metal-semiconductor (MES) and high electron mobility transistor (HEMT). First, the change of the sensing charateristic was confirmed through simulation. Finally, we fabricated a coplanar gate HEMT-based pH sensor to verify excellent pH sensing performance and sensitivity amplification, and to confirm non-ideal behaviors such as hysteresis and drift effect.

2. General Instructions

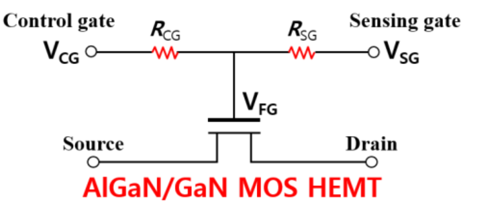

Fig. 1 Simplified circuit of AlGaN/GaN MOS HEMT-based coplanar gate pH sensor using resistance coupling.

Fig. 1 shows the simplified equivalent circuit of AlGaN/GaN MOS HEMT-based coplanar gate pH sensor. Here, the parasitic resistance and capacitance components are ignored. V_{CG} is the control gate, which is the voltage applied to the device. The total resistance (R_T) of coplanar gate can be expressed as the eq. (1).

$$R_T = R_{CG} + R_{SG} \quad (1)$$

where R_{CG} and R_{SG} are control gate resistance and sensing gate resistances, respectively. Then, the gate voltage (V_{FG}) of the MOS HEMT is given by eq. (2) the resistive coupling between the control gate and the sensing gate, and the voltage between the control gate and the sensing gate is summarized as eq. (3). Eventually, the potential change ΔV_{SG} of the sensing gate is amplified by R_{CG}/R_{SG} times, resulting in a change in the control gate voltage ΔV_{CG}.

$$V_{FG} = \frac{R_{SG}}{R_T}V_{CG} + \frac{R_{CG}}{R_T}V_{SG} \quad (2)$$

$$V_{CG} = \frac{R_T}{R_{SG}}V_{FG} - \frac{R_{CG}}{R_{SG}}V_{SG} \quad (3)$$

$$\therefore \Delta V_{CG} \propto \frac{R_{CG}}{R_{SG}}\Delta V_{SG} \quad (4)$$

This means that a very small potential change of the sensing gate is amplified by the resistance coupling effect and can be sensed at the control gate.

Fig. 2(a) shows the Silvaco TCAD simulation results for transfer curves of a coplanar gate HEMT with R_{CG}:R_{SG} = 2:1. As predicted in eq. (4), it can be seen that the change in ΔV_{CG} for ΔV_{SG} = 2 V is 4 V, which increased by the resistance ratio of R_{CG}/R_{SG} = 2. Fig. 2(b) shows the dependence of the amplification factor ($\Delta V_{CG}/\Delta V_{SG}$) on R_{CG}: R_{SG} = 1: 2, 1: 1, 2: 1 and 3: 1. ΔV_{CG} was determined at drain current I_D = 1 nA. The amplification coefficients are 0.5, 1, 2 and 3, respectively, and are determined by the resistance ratio R_{CG}/R_{SG}.

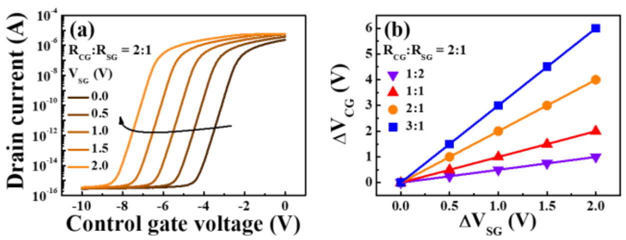

Fig. 2 Silvaco TCAD simulation results for AlGaN/GaN MOS HEMT-based coplanar gate pH sensor. (a) Transfer curve shift as a function of ΔV_{SG}. (b) Dependence of amplification factor ($\Delta V_{CG}/\Delta V_{SG}$) on R_{CG}:R_{SG}.

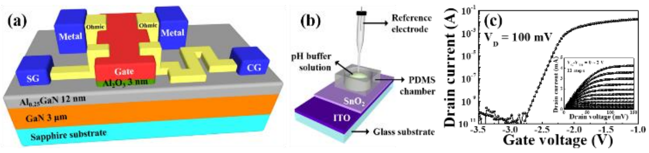

Fig. 3 Schematics of (a) MOS-HEMT with coplanar gate and (b) extended gate. (c) Transfer and output curves (inset).

The coplanar AlGaN/GaN MOS HEMTs were fabricated by the following procedure. AlGaN/GaN heterostructures have been grown by metal organic chemical vapor deposition (MOCVD) reactor on a 4-inch (0001) sapphire substrates. A 25-nm-thick low-temperature GaN nucleation layer was grown on the substrate, followed by successively growing 1-µm-thick high-resistance GaN layer and 1.8-µm-thick unintentionally doped GaN layer. Subsequently, an $Al_{0.25}GaN$ layer about 12-nm-thick was grown. After the AlGaN/GaN heterostructure was cleaned by acid solutions, a 3-nm-thick Al_2O_3 gate dielectric was deposited by atomic layer deposition (ALD). The active region was defined by BCl_3/Cl_2 gas and inductively coupled plasma etching, and Ti/Al/Ni/Au (20/100/25/50 nm) metal electrodes were formed for the source, drain, gate of HEMT and coplanar gate (sensing gate, control gate) electrodes. In addition, the resistors between the coplanar gates and the HEMT gate were formed using 30 nm thick Ni wire. In order to fabricate a separate extended gate (EG), a 150-nm-thick ITO and a 50-nm-thick SnO_2 films were sequentially deposited on a glass substrate, and then a poly dimethyl siloxane reservoir was attached. EGFET is a cost-effective sensing platform that can be used permanently only by replacing EG when the membrane is damaged. Figs. 3(a) and (b) are schematics of HEMT pH sensors with coplnaer gate and seperate extended gate on a glass. Fig. 3(c) shows the transfer curves of fabricated AlGaN/GaN MOS HEMTs, and the inset is the output curves.

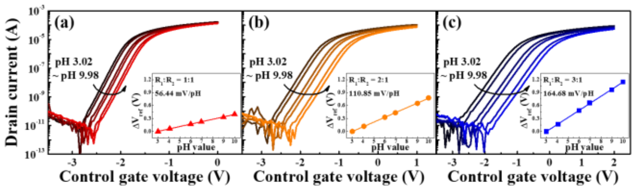

Fig. 4 Transfer curves of coplanar gate HEMT-based pH sensors for $R_{CG}:R_{SG}$ ratio of (a) 1:1, (b) 2:1, and (c) 3:1. Insets are change in V_{CG} of pH sensors as a function of pH solutions.

Fig. 4 shows the transfer curves of a coplanar gate HEMT-based pH sensor with a ratio of $R_{CG}:R_{SG}$ = 1:1,2:1 and 3:1. For this measurement, the EG was configured to connect directly to the SG using a cable to input the potential of the pH solution into the SG. We measured the sensing properties for buffer solutions with various concentrations of pH 3.07, 4.08, 5.99, 6.95, 8.97 and 9.87. The transfer curves shifted in the positive voltage direction as the pH value increased. The insets in (a)-(c) shows ΔV_{CG} as a function of pH. For $R_{CG}:R_{SG}$ = 1:1, the pH sensitivity is 56.44mV/pH, which is lower than the Nernstian limit of 59.16mV/pH. However, for $R_{CG}:R_{SG}$ = 2:1 and 3:1, the pH sensitivity was 110.85 mV/pH and 164.68 mV/pH, respectively, exceeding the Nernstian limit. Consequently, we demonstrated that the pH sensitivity is adjustable by the ratio of R_{CG}/R_{SG}.

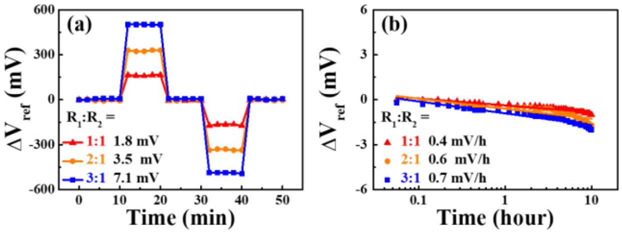

Fig. 5 (a) Hysteresis and (b) drift effect of coplanar gate HEMT-based pH sensor for various $R_{CG}:R_{SG}$.

Finally, we evaluated non-ideal behaviors such as hysteresis and drift effects of a coplanar gate HEMT-based EGFET pH sensor. Fig. 5(a) shows the hysteresis voltage after a pH loop of 7 → 10 → 7 → 4 → 7, which was 1.8, 3.5 and 7.1 mV for $R_{CG}:R_{SG}$ = 1:1, 2:1 and 3:1, respectively. Fig. 5(b) shows the drift rate by exposure to pH 7 buffer solution for 10 hours, which was 0.4, 0.6 and 0.7 mV/h for $R_{CG}:R_{SG}$ = 1:1, 2:1 and 3:1, respectively.

3. Conclusions

In this study, we fabricated the coplaner gate AlGaN/GaN MOS HEMT based EGFET pH sensors to amplify the sensitivity using a resistive coupling effect. Based on the results of the Silvaco TCAD simulation, we predicted that the practical voltage applied to the sensing gate can be amplified by R_{CG}/R_{SG} times through the resistance ratio between the control and sensing gate. To achieve high pH sensitivity, we controlled the $R_{CG}:R_{SG}$ ratio of the sensor and demonstrated that the pH sensitivity is amplified by R_{CG}/R_{SG} times through the resistance coupling effect. In addition, through the evaluation of non-ideal behaviors, we have verified that the pH sensor works stably. In conclusion, the coplanar gate AlGaN/GaN MOS HEMT based EGFET pH sensor with resistive coupling effect is expected to be a useful biosensor platform due to easy controllability of pH sensitivity and expandability to various transistor-based devices.

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