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Performance of open-gate AlGaN/GaN HFET in various kinds of liquids

Takuya Kokawa, Taketomo Sato and Tamotsu Hashizume

Research Center for Integrated Quantum Electronics (RCIQE) and
Graduate School of Information Science and Technology, Hokkaido University, Japan.
E-mail: kokawa@rciqe.hokudai.ac.jp

1. Introduction

GaN-based materials are very promising for various chemical and biological sensor applications, because of their superb chemical stability and capability of high-temperature operation owing to their widegap nature. The pH response of GaN surfaces using ion-sensitive field-effect transistor (ISFET) structures was recently reported by Steinhoff and co-workers [1]. However, no work on the pH response to AlGaN surfaces was done, and mechanism of pH response is not fully understood yet. In addition, the sensing properties of open-gate AlGaN/GaN heterostructure FET (HFET) to polar liquids have not systematically been investigated so far.

The purpose of this paper is to investigate pH- and liquid-phase sensing characteristics of open-gate AlGaN/GaN HFET structures.

2. Fabrication process and electrochemical cell

As shown in **Figure 1**, we used AlGaN/GaN heterostructures with an Al composition of 0.23 and AlGaN thickness of 22 nm, grown on sapphire by metal-organic vapor phase epitaxy (MOVPE). The electron mobility and density of the two dimensional electron gas (2DEG) were 950 cm^2/V and 8.0 x 10^{12} cm^{-2}, respectively, at room temperature.

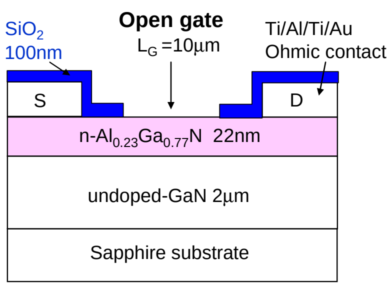


Fig1. The structure of the open-gate AlGaN/GaN HFET

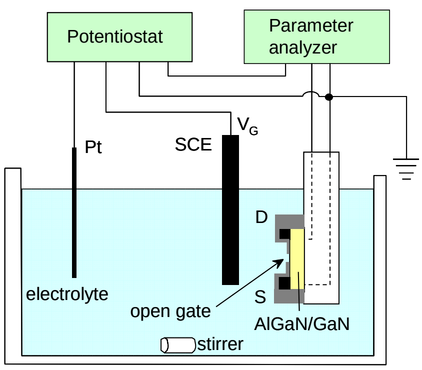


Fig2. Electrochemical cell

The device fabrication process started with isolation patterning using electron-cyclotron resonance-assisted reactive ion beam etching. The drain and source electrodes were formed by deposition of Ti/Al/Ti/Au multilayers. Then, the device surface was covered with SiO_2 film to a thickness of 100 nm using plasma-enhanced chemical vapor deposition. The open-gate area, length 10 µm and width 500 µm, was formed through photolithography and wet etching processes in a buffered HF solution. The final structure is shown in **Fig. 1**.

Figure 2 shows an electrochemical cell and a measurement circuit consisting of a potentiostat (EG&G, 273AEC) and a semiconductor parameter analyzer (Agilent, 4156C). The open-gate devices were set on a teflon holder, and the source and drain electrodes were covered by negative-type photoresist. The gate bias was applied from the semiconductor parameter analyzer to the electrolyte/AlGaN interface at the open-gate area via a saturated calomel electrode (SCE). For pH sensing measurements, we prepared deionized (DI) water and a mixed solution with HCl and NaOH in DI water. The pH values in solutions were measured using a digital pH meter (CyberScan, pH100). For polar liquids, we used ethanol and acetone. All measurements in solutions were performed at 24 ^oC under dark conditions.

3. Results and discussion

Figure 3 shows typical drain I-V characteristics of the open-gate HFET in DI water at 24 ^oC under dark conditions.

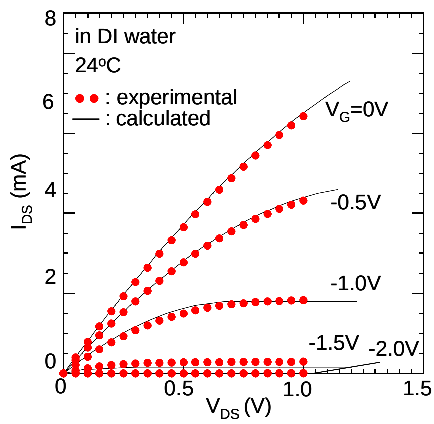


Fig3. Typical drain I-V characteristics of open-gate HFET in DI water

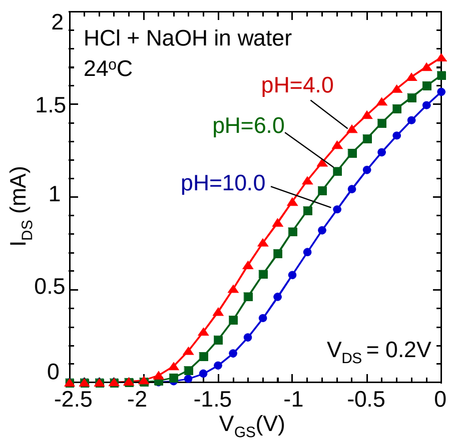
The device clearly exhibits current saturation and pinchoff behavior, which is very similar to I-V characteristics of typical Schottky-gate HFET. This shows that the potential of the AlGaN surface in the open gate can effectively be controlled by the solution potential. The solid lines in Fig. 3 indicate the calculated curves based on the gradual-channel approximation together with a field-dependent mobility formula. The experimental I-V curves were reproduced very well by the calculation. From the calculated results, we estimated the value of 1.5 eV for the flat-band potential at the water/AlGaN interface, which is very close to the charge neutrality level (CNL) of 1.6 eV for $Al_{0.23}Ga_{0.77}N$ [3].

Figure 4 shows the transfer characteristics of the open-gate HFET in a mixed solution of HCl and NaOH in water with different pH values. To evaluate the transfer characteristics in the linear region, we set the drain bias at 0.2 V. A fine parallel shift was observed in the transfer curves, when the pH value changed from 4.0 to 10.0, indicating the corresponding potential change at the AlGaN surface. The sensitivity for the potential change is 57.5 mV/pH, very close to the theoretical value of 58.9 mV/pH at 24 °C for the Nernstian response to H^+ ions.

The exact mechanism of how these changes occur is still unknown. For electrolyte-insulator interfaces (SiO_2, SiN_x, Al_2O_3, AlN, etc.) in Si-based ion-sensitive FETs, however, a site-binding model is generally accepted [4, 5]. According to this model, hydroxyl groups (MOH: M represents Si or metals) are formed at insulator surfaces in contact with aqueous solutions, and can dissociate to or combine with H^+, depending on the H^+ concentration and the equilibrium constants for the relevant reactions, as follows:

$$MOH \rightleftarrows MO^- + H^+ \qquad (1)$$
$$MOH + H^+ \rightleftarrows MOH_2^+ \qquad (2)$$

When the H^+ concentration decreases in solution, the right-direction reaction in the equilibrium equation (1) becomes dominant, resulting in negative charges at the insulator surfaces due to deprotonized hydroxyls (MO^-). On



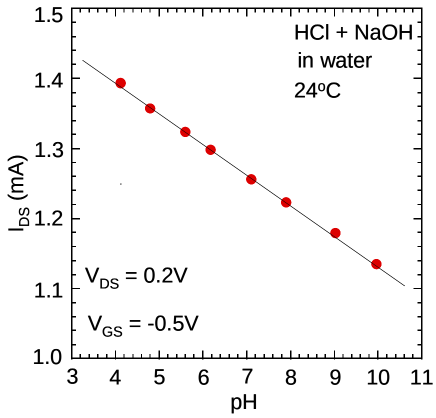


Fig5. Drain current as a function of pH value

the other hand, the increase of H^+ can induce positive charges at the surfaces due to protonized hydroxyls (MOH_2^+), represented by equation (2). This leads to a pH-dependent net charge at the insulator surfaces, and the liquid-solid interfacial potential thereby follows the Nernstian equation.

The simplest model for the present open-gate HFET is an analogy of this mechanism. On the other hand, there still remains the possibility that the potential at the solution-AlGaN interface is governed by direct adsorption of ions at the given sites of the AlGaN surface.

Figure 5 shows the drain current measured under V_{GS} = -0.5V and V_{DS} = 0.2V as a function of pH value. As expected from the result in Fig. 4, the drain current decreased with the pH value. A linear behavior was clearly observed, reflecting systematic change in potential at the AlGaN surface in the linear bias region. In addition, we obtained a large current change, over 200 μA, when the pH value was changed from 4.3 to 10.0, because of high mobility and 2DEG density of the AlGaN/GaN HFET.

The results obtained indicated that the open-gate AlGaN/GaN HFET are very promising for high-sensitive liquid phase sensors.

References

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