



Title	Al <sub>2</sub> O <sub>3</sub> Insulated-Gate Structure for AlGa <sub>N</sub> /Ga <sub>N</sub> Heterostructure Field Effect Transistors Having Thin AlGa <sub>N</sub> Barrier Layers
Author(s)	Hashizume, Tamotsu; Anantathanasarn, Sanguan; Negoro, Noboru; Sano, Eiichi; Hasegawa, Hideki; Kumakura, Kazuhide; Makimoto, Toshiki
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## Al<sub>2</sub>O<sub>3</sub> Insulated-Gate Structure for AlGaN/GaN Heterostructure Field Effect Transistors Having Thin AlGaN Barrier Layers

Tamotsu Hashizume<sup>1\*</sup>, Sangan Anantathanasarn<sup>1</sup>, Noboru Negoro<sup>1</sup>, Eiichi Sano<sup>1</sup>, Hideki Hasegawa<sup>1</sup>, Kazuhide Kumakura<sup>2</sup> and Toshiki Makimoto<sup>2</sup>

<sup>1</sup>Research Center for Integrated Quantum Electronics (RCIQE), Hokkaido University, Sapporo, 060-8628, Japan

<sup>2</sup>NTT Basic Research Laboratories, NTT Corporation, 3-1 Morinosato Wakamiya, Atsugi, 243-0198, Japan

(Received

An Al<sub>2</sub>O<sub>3</sub> insulated-gate (IG) structure was utilized for controlling the surface potential and suppressing the gate leakage in Al<sub>0.2</sub>Ga<sub>0.8</sub>N/GaN heterostructure field effect transistors (HFETs) having thin AlGaN barrier layers (less than 10 nm). In comparison with Schottky-gate devices, the Al<sub>2</sub>O<sub>3</sub> IG device showed successful gate control of drain current up to V<sub>GS</sub>= +4 V without leakage problems. The threshold voltage in the Al<sub>2</sub>O<sub>3</sub> IG HFET was about -0.3 V, resulting in the quasi-normally-off mode operation.

KEYWORDS: AlGaN, GaN, Al<sub>2</sub>O<sub>3</sub>, HFET, normally-off, insulated gate

Although significant progress has been achieved in the GaN-based high-power/high-frequency electronic devices such as AlGaN/GaN heterostructure field effect transistors (HFETs) [1-3], it is necessary to use thinner AlGaN layer for achieving higher transconductance ( $g_m$ ) and more precise control of threshold voltage in HFETs. To develop normally-off (enhancement) mode devices which are attractive for gaining in flexibility of circuit and/or system design, in addition, very thin AlGaN barrier thickness less than 10nm is required. A gate-recessing process is one of the actual approaches to reduce the effective thickness of a barrier layer.

However, Schottky contacts fabricated on GaN and AlGaN still suffer from serious leakage problems [4-9]. Although some models associated with the trap-assisted tunneling [10], the defect-related thin surface barrier (TSB) [8] and the dislocation-related hopping transport [11] have been proposed, the leakage mechanism through GaN and AlGaN Schottky interfaces has not yet been clarified, and thereby there is still no solution to suppress leakage currents. For Schottky-gate (SG) structures on AlGaN/GaN HEMTs with thinner AlGaN barrier layers or recessed-gate structures, leakage problems can be enhanced, making the gate control of drain current very difficult.

An FET device having an insulated gate (IG) structure is expected to suppress the gate leakage. Moreover, an insulator film can act as a passivation layer, making the surface more stable in the device. An Al<sub>2</sub>O<sub>3</sub> IG structure is very attractive for the application to AlGaN/GaN HFETs [12-14], since it has relatively high dielectric constant (~ 9) and a large conduction-band offset at the Al<sub>2</sub>O<sub>3</sub>/AlGaN interface [12]. In fact, the Al<sub>2</sub>O<sub>3</sub> IG AlGaN/GaN HFETs exhibited good gate control of drain current with low leakage currents, and suppressed current collapse under both drain stress and gate stress [12].

In this letter, we demonstrate the controllability of an Al<sub>2</sub>O<sub>3</sub> insulated-gate structure in the AlGaN/GaN HFETs

having a thin AlGaN barrier layer (7 nm).

The Al<sub>0.2</sub>Ga<sub>0.8</sub>N/GaN heterostructures was grown by metal organic vapor phase epitaxy on n-type 6H-SiC substrates, as schematically shown in **Fig.1**. A very thin AlGaN layer (7 nm) was grown with doping of Si ( $2 \times 10^{18} \text{ cm}^{-3}$ ). The electron concentration and mobility of the sample at room temperature (RT) were  $4.0 \times 10^{12} \text{ cm}^{-2}$  and  $830 \text{ cm}^2/\text{Vs}$ , respectively. The device isolation was carried out by an electron-cyclotron-resonance (ECR) assisted reactive ion beam etching using a gas system consisting of CH<sub>4</sub>, H<sub>2</sub>, Ar and N<sub>2</sub> [15]. As an ohmic contact, a Ti/Al/Ti/Au layered structure was formed on the surface of AlGaN/GaN followed by annealing at 800 °C for 1 min in N<sub>2</sub> ambient. A Ni/Au contact was used as a Schottky gate.

The Al<sub>2</sub>O<sub>3</sub>-based surface passivation structure was fabricated through the following *in-situ* steps [16]: The AlGaN surface was treated in ECR-N<sub>2</sub> plasma at 280 °C for 30 s. Then an Al layer with a nominal thickness of 3 nm was deposited by molecular beam deposition on the AlGaN surface at RT in the molecular beam epitaxy (MBE) chamber. Subsequently, the top Al layer was oxidized using ECR-excited O<sub>2</sub> plasma at 150 °C for 5 min. Finally, the sample was annealed at 700 °C for 5 min in the UHV annealing chamber. Through this *in-situ* process, the Al<sub>2</sub>O<sub>3</sub> IG HFETs schematically shown in **Fig. 1 (b)** were fabricated.

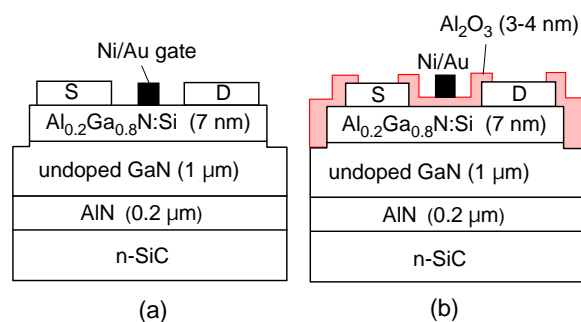


Fig.1 Schematic illustrations of (a) Schottky-gate and (b) Al<sub>2</sub>O<sub>3</sub> insulated-gate HFETs.

\*E-mail address: hashi@rciqe.hokudai.ac.jp

**Figure 2** shows the comparison of drain I-V characteristics between the Ni/Au SG and the Al<sub>2</sub>O<sub>3</sub> IG HFETs with device size of 1.0 μm x 60 μm. The drain-source spacing was 3 μm. The SG HFET showed pinch-off behavior at around V<sub>GS</sub>= -1 V, consistent with the result of a 2D potential calculation. Even when the positive gate bias was applied to the SG HFET, the drain current remained in the low magnitude. This seems to be attributed to poor controllability of the Schottky gate. Another possibility is that high-density surface states cause serious Fermi level pinning at the free AlGa<sub>0.8</sub>N surface in the region between gate and drain [17], blocking the modulation of the 2DEG channel. Moreover, the pronounced gate leakage behavior appeared at V<sub>GS</sub> = +2V in the I<sub>DS</sub>-V<sub>DS</sub> characteristics, as shown in Fig. 2 (a), due to the difficulty of a good Schottky barrier gate on the AlGa<sub>0.8</sub>N layers with thickness less than 10 nm.

In comparison, the Al<sub>2</sub>O<sub>3</sub> IG HFET exhibited good gate control even in the positive gate voltage range, as shown in Fig. 2 (b). A separate capacitance-voltage characterization of the Al<sub>2</sub>O<sub>3</sub>/n-GaN structure showed low interface state densities in the range of 10<sup>11</sup> cm<sup>-2</sup>eV<sup>-1</sup>. The present Al<sub>2</sub>O<sub>3</sub>/AlGa<sub>0.8</sub>N structure could have a similar interface quality, leading to good control of the AlGa<sub>0.8</sub>N surface potential and the modulation of the 2DEG density even at the positive gate bias. In addition, the drain current for the Al<sub>2</sub>O<sub>3</sub> IG HFET at V<sub>GS</sub>=0V is much larger than that for the SG HFET. This indicated that the band bending at the AlGa<sub>0.8</sub>N surface due to the Fermi level pinning could be reduced by the Al<sub>2</sub>O<sub>3</sub> passivation [16], thereby increasing the 2DEG density at zero bias.

**Figure 3** (a) shows the typical DC transfer characteristics of the fabricated Al<sub>2</sub>O<sub>3</sub> IG HFET. From the gate-bias intercept of the extrapolation of the drain current curve (broken line) in the transfer characteristics, the threshold voltages of the Al<sub>2</sub>O<sub>3</sub> IG HFET were determined in the range of -0.2 V to -0.4 V depending on the drain bias. Thus the quasi-normally-off mode operation was realized in the present device.

Khan et al [18] first reported the normally-off mode Al<sub>0.1</sub>Ga<sub>0.9</sub>N/GaN HFET with a Schottky gate and an AlGa<sub>0.8</sub>N thickness of 10 nm. Although the threshold voltage

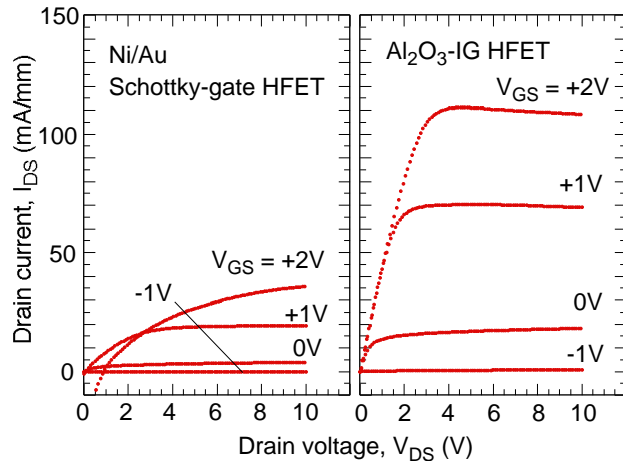


Fig.2 Drain I-V characteristics of the Ni/Au Schottky-gate and Al<sub>2</sub>O<sub>3</sub> IG HFETs with device size of 1 μm x 60 μm.

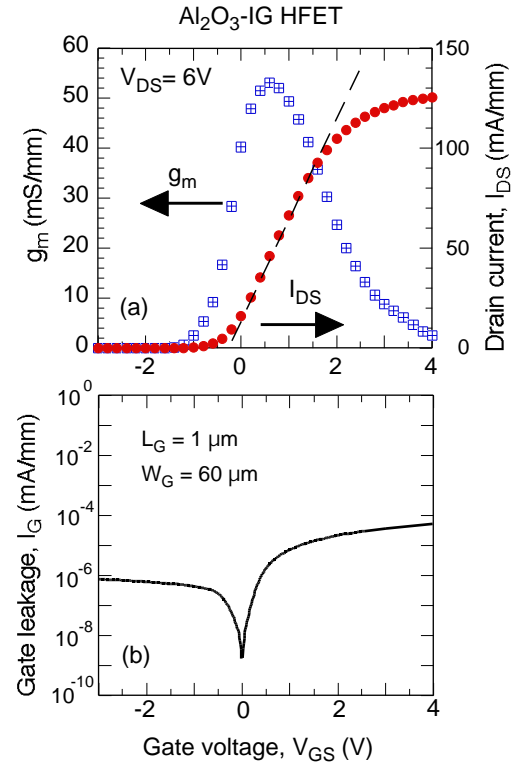


Fig.3 (a) DC transfer characteristics and (b) gate leakage characteristics of the Al<sub>2</sub>O<sub>3</sub> IG HFET.

of 0.05V was achieved, the maximum values of  $g_m$  and drain current were only 23 mS/mm and 40 mA/mm, respectively, for a device with 1 μm gate length. Hu et al [19] fabricated a normally-off mode Al<sub>0.2</sub>Ga<sub>0.8</sub>N/GaN HFET using selectively-grown pn junction gate. However, the device showed high knee voltages and low  $g_m$  values. Recently, Lee et al. [20] demonstrated quasi-normally-off mode operation in undoped Al<sub>0.25</sub>Ga<sub>0.75</sub>N/GaN HFETs with an AlGa<sub>0.8</sub>N thickness of 20 nm. The device exhibited relatively high values of  $g_m$  and drain current. Kumar et al [21] also reported high  $g_m$  and drain current values in the normally-off mode HFET fabricated by using a gate-recessing process. However, the sweeping range of gate voltage in those devices was limited below +2 V due to the serious leakage currents through the Schottky gates.

In comparison, our Al<sub>2</sub>O<sub>3</sub> IG device can control the drain current up to V<sub>GS</sub>= +4V without the gate leakage, as shown in **Fig.3** (b), indicating the advantage of utilizing an insulated gate. The maximum values of the drain current and the extrinsic  $g_m$  were 127 mA/mm and 54 mS/mm, respectively. There is a possibility that the gateless region between drain and source could limit the current transport in the present device structure. With further optimization of device structures, quasi-normally-off mode HFETs with better device performances are expected. The present results indicate that the Al<sub>2</sub>O<sub>3</sub> IG structure is a powerful tool for the gate control in AlGa<sub>0.8</sub>N/GaN HFETs with thin AlGa<sub>0.8</sub>N barrier layers.

In summary, the Al<sub>2</sub>O<sub>3</sub>-insulated gate structure was applied to the Al<sub>0.2</sub>Ga<sub>0.8</sub>N/GaN HFET with a AlGa<sub>0.8</sub>N barrier thickness of 7 nm. In comparison with the Schottky-gate devices, the fabricated Al<sub>2</sub>O<sub>3</sub> IG device showed successful gate control of drain current up to V<sub>GS</sub>= +4 V

without leakage problems. The threshold voltage was about -0.3 V, resulting in the quasi-normally-off mode operation. The Al<sub>2</sub>O<sub>3</sub> IG structure is promising for the gate control in AlGa<sub>0.2</sub>N/GaN HFETs having thin AlGa<sub>0.2</sub>N barrier layers.

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