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Al_2O_3 Insulated-Gate Structure for AlGaN/GaN Heterostructure Field Effect Transistors Having Thin AlGaN Barrier Layers

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An Al_2O_3 insulated-gate (IG) structure was utilized for controlling the surface potential and suppressing the gate leakage in $Al_{0.2}Ga_{0.8}N$/GaN heterostructure field effect transistors (HFETs) having thin AlGaN barrier layers (less than 10 nm). In comparison with Schottky-gate devices, the Al_2O_3 IG device showed successful gate control of drain current up to V_{GS}= +4 V without leakage problems. The threshold voltage in the Al_2O_3 IG HFET was about -0.3 V, resulting in the quasi-normally-off mode operation.

KEYWORDS: AlGaN, GaN, Al_2O_3, 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_2O_3 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_2O_3/AlGaN interface [12]. In fact, the Al_2O_3 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_2O_3 insulated-gate structure in the AlGaN/GaN HFETs having a thin AlGaN barrier layer (7 nm).

The $Al_{0.2}Ga_{0.8}N$/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 x 10^{18} cm^{-3}). The electron concentration and mobility of the sample at room temperature (RT) were 4.0 x 10^{12} cm^{-2} and 830 cm^2/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_4, H_2, Ar and N_2 [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_2 ambient. A Ni/Au contact was used as a Schottky gate.

The Al_2O_3-based surface passivation structure was fabricated through the following in-situ steps [16]: The AlGaN surface was treated in ECR-N_2 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_2 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_2O_3 IG HFETs schematically shown in **Fig. 1 (b)** were fabricated.

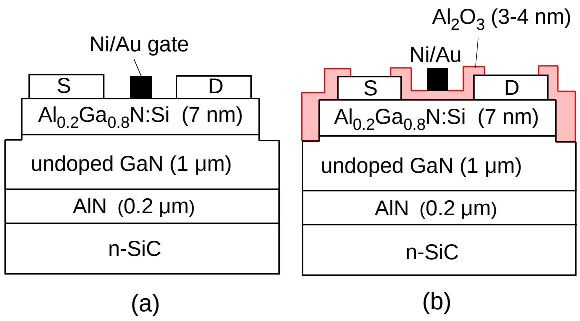

Fig.1 Schematic illustrations of (a) Schottky-gate and (b) Al_2O_3 insulated-gate HFETs.

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Figure 2 shows the comparison of drain I-V characteristics between the Ni/Au SG and the Al_2O_3 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_{GS}= -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 AlGaN 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_{GS} = +2V in the I_{DS}-V_{DS} characteristics, as shown in Fig. 2 (a), due to the difficulty of a good Schottky barrier gate on the AlGaN layers with thickness less than 10 nm.

In comparison, the Al_2O_3 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_2O_3/n-GaN structure showed low interface state densities in the range of 10^{11} $cm^{-2}eV^{-1}$. The present Al_2O_3/AlGaN structure could have a similar interface quality, leading to good control of the AlGaN surface potential and the modulation of the 2DEG density even at the positive gate bias. In addition, the drain current for the Al_2O_3 IG HFET at V_{GS}=0V is much larger than that for the SG HFET. This indicated that the band bending at the AlGaN surface due to the Fermi level pinning could be reduced by the Al_2O_3 passivation [16], thereby increasing the 2DEG density at zero bias.

Figure 3 (a) shows the typical DC transfer characteristics of the fabricated Al_2O_3 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_2O_3 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 $Al_{0.1}Ga_{0.9}N$/GaN HFET with a Schottky gate and an AlGaN thickness of 10 nm. Although the threshold voltage

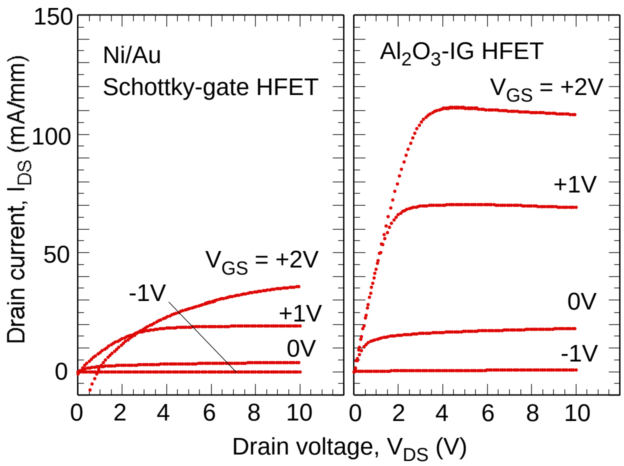

Fig.2 Drain I-V characteristics of the Ni/Au Schottky-gate and Al_2O_3 IG HFETs with device size of 1 μm x 60 μm.

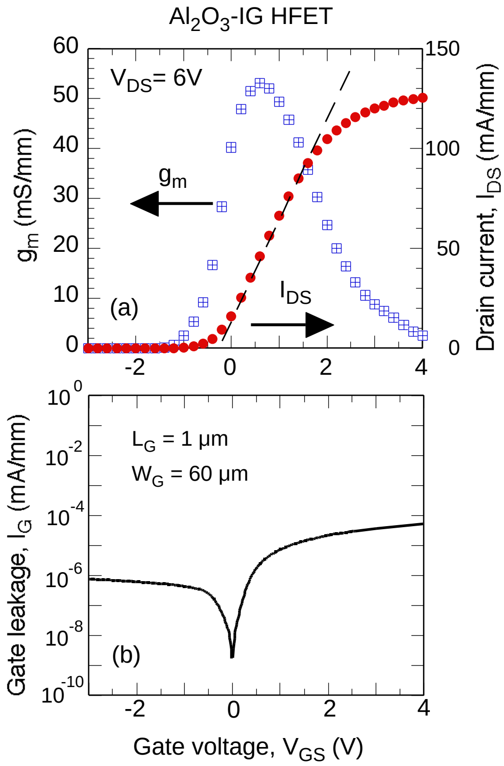

Fig.3 (a) DC transfer characteristics and (b) gate leakage characteristics of the Al_2O_3 IG HFET.

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 $Al_{0.2}Ga_{0.8}N$/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 $Al_{0.25}Ga_{0.75}N$/GaN HFETs with an AlGaN 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_2O_3 IG device can control the drain current up to V_{GS}= +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_2O_3 IG structure is a powerful tool for the gate control in AlGaN/GaN HFETs with thin AlGaN barrier layers.

In summary, the Al_2O_3-insulated gate structure was applied to the $Al_{0.2}Ga_{0.8}N$/GaN HFET with a AlGaN barrier thickness of 7 nm. In comparison with the Schottky-gate devices, the fabricated Al_2O_3 IG device showed successful gate control of drain current up to V_{GS}= +4 V without leakage problems. The threshold voltage was about -0.3 V, resulting in the quasi-normally-off mode operation. The Al_2O_3 IG structure is promising for the gate control in AlGaN/GaN HFETs having thin AlGaN barrier layers.

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