

Demonstration of undoped quaternary AlInGaN/GaN heterostructure field-effect transistor on sapphire substrate

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Undoped AlInGaN/GaN heterostructure field-effect transistors (HFETs) have been demonstrated on sapphire substrate. The maximum drain current of 758 mA/mm and extrinsic transconductance of 123 mS/mm were obtained from the device with 2 μm gate length and 15 μm gate width. Such performance was comparable to that of a conventional modulation-doped (MOD) AlGaIn/GaN HFET fabricated at same the condition. In spite of the high-density two-dimensional electron gas formed at the heterointerface, the AlInGaIn/GaN HFET structure showed relatively low Hall mobility (689 cm^2/Vs at 300 K), which was due to the high concentration background doping in the undoped AlInGaIn barrier region. Encouragingly, both the gate leakage current and drain current collapse showed lower values than that of the MOD-AlGaIn/GaN HFET, which implied the potential application of quaternary AlInGaIn to high-power and high-frequency devices.

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Since the first demonstration of the AlGaIn/GaN heterostructure field-effect transistor¹ (HFET), impressive progress has been made in the field of high-power and high-frequency electronic applications.² The high performance of GaN-based HFETs is due primarily to the existence of high-mobility two-dimensional electron gas (2DEG) at the AlGaIn/GaN interface, which is created by a large conduction band offset, and by the strong piezoelectric and spontaneous polarization effects in the heterostructure.³ Further improvement of HFET performance can be expected by increasing the Al content of the AlGaIn barrier layer. However, with further increase of Al content, the increasing lattice mismatch between AlGaIn and GaN will decrease the critical thickness of a fully strained AlGaIn barrier, resulting in uncontrolled local relaxation at the heterointerface via generation of misfit dislocation and cracks. To solve the problem, quaternary AlInGaIn was proposed^{4,5} to replace AlGaIn as the barrier because of the following two advantages. First, the quaternary can allow the independent adjustments of the bandgap and lattice constant, by which the built-in strain can be controlled below the critical value before the occurrence of relaxation. Second, larger polarization may be expected in the quaternary AlInGaIn barrier via significant Al incorporation (increasing mainly spontaneous polarization) because theoretical research⁶ predicted that the spontaneous polarization was as large as the piezoelectric polarization in wurtzite group-III nitrides increasing from GaN (−0.029) over InN (−0.032) to AlN (−0.081 C/m²). Recently, spontaneous polarization-induced high-density 2DEG was observed on lattice-matched AlInGaIn/GaN heterojunction interface,⁷ which was direct experimental evidence of aforementioned theoretical prediction. Up to now, although numerous researches have been conducted with respect to quaternary AlInGaIn, most of them concentrated on the luminescence applications of AlInGaIn (see Refs. 8–13) rather than on its electronics applications. There is no report available concerning the research of AlInGaIn/GaN HFET. In this letter, undoped quaternary

AlInGaIn/GaN HFET (hereinafter referred to as Q-HFET) was demonstrated. The performance of the Q-HFET was comparable to that of the conventional AlGaIn/GaN HFET; both lower current collapse and gate leakage current were observed. The result indicates that AlInGaIn is a promising candidate for high-power and high-frequency applications.

A 30 nm thick undoped AlInGaIn epilayer was grown on a 3 μm thick *i*-GaN layer on *c*-plane sapphire substrates by Taiyo Nippon Sanso SR2000 metalorganic chemical vapor deposition system. The growth details of AlInGaIn can be found elsewhere.⁸ The compositions of In and Al were estimated by electron probe microanalysis to be 2% and 22%, respectively, on a separately grown, thick AlInGaIn sample, and verified by x-ray diffraction (XRD) measurement. For comparison, a conventional modulation-doped (MOD) ternary Al_{0.2}Ga_{0.8}N-HFET (hereinafter referred to as T-HFET) structure was utilized, in which the carrier density of Si-doped Al_{0.2}Ga_{0.8}N supply layer is as high as $4 \times 10^{18} \text{ cm}^{-3}$. The growth conditions of two HFET structures were exactly same except for the barrier layers. Pseudomorphic growth of both AlInGaIn and AlGaIn barrier layer were confirmed by XRD asymmetrical reciprocal lattice mappings. Figure 1 shows the XRD ω - 2θ scan for both HFET structures, from

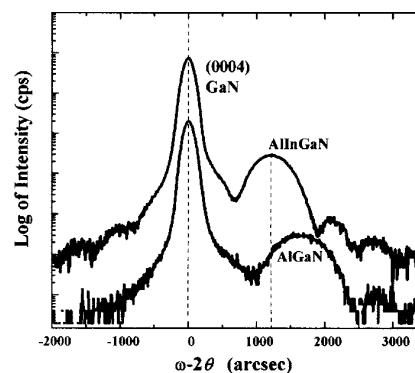


FIG. 1. XRD (0004) ω - 2θ scan of AlInGaIn/GaN and AlGaIn/GaN HFET structures.

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TABLE I. (a) Material and (b) device properties of AlInGaN/GaN and AlGaIn/GaN HFET structures at room temperature, in which $\Delta a/a_0$ is in-plane strain, the R_d is source-drain resistance, and V_{th} is the threshold voltage. The dimension of HFET used here is as following: $L_{sd}/W_g/L_g/L_{gs}=9/15/2/3 \mu\text{m}$. Both HFET structures were passivated with electron-beam-evaporated SiO_2 .

(a)	μ_H (cm ² /V s)	n_S (cm ⁻²)	R_{sh} (Ω/□)	E_g (eV)	$\Delta a/a_0$	ΔP_{SP} (10 ⁻⁴ C/m ²)	ΔP_{PZ} (10 ⁻⁴ C/m ²)	$\Delta P = \Delta P_{SP} + \Delta P_{PZ}$ (10 ⁻⁴ C/m ²)	$\Delta P_{SP}/\Delta P_{PZ}$
Al _{0.22} In _{0.02} GaN/GaN	689	1.04 × 10 ¹³	873	3.833	0.31%	115	46.9	161.9	2.5
MOD-Al _{0.2} Ga _{0.8} N/GaN	926	1.46 × 10 ¹³	464	3.851	0.50%	106.9	73.8	180	1.4
(b)	I_{dmax} (mA/mm) at $V_g = 1.5$ V		g_{mmax} (mS/mm)	R_s (Ω mm)		R_d (Ω mm)	V_{th} (V)	I_{gLeak} (mA/mm) at $V_{DS} = 20$ V	
Al _{0.22} In _{0.02} GaN/GaN	758		123	3.0		8.9	-5.0	6.1 × 10 ⁻³	
MOD-Al _{0.2} Ga _{0.8} N/GaN	772		187	2.2		5.2	-2.9	12.0	

which we believe that the AlInGaIn epilayer suffered from less tensile strain than AlGaIn epilayer. The bandgaps (E_g) of the two barrier layers were estimated by photoreflectance measurement¹⁴ to be 3.833 (AlInGaIn) and 3.851 eV (AlGaIn), respectively. Hall measurement revealed that the AlInGaIn/GaN heterostructure exhibited n -type properties; mobility (μ_H) and sheet carrier density (n_s) were 689 ($1132 \text{ cm}^2/\text{Vs}$) and 1.04×10^{13} ($9.83 \times 10^{12} \text{ cm}^{-2}$) at room temperature (77 K), respectively. The material properties of both HFET structures were listed in the Table I(a). As shown, in spite of high sheet carrier density, the mobility value was lower than that of the AlGaIn/GaN HFET structure, which accounted for the higher sheet resistance (R_{sh}) of $873 \Omega/\square$.

The device isolation was accomplished by mesa dry etching down to i -GaN by BCl_3 plasma reactive ion etching. A 100 nm thick SiO_2 passivation layer was then deposited by electron-beam evaporation. The Ti/Al/Ni/Au (15/70/12/40 nm) and Pd/Ti/Au (40/20/60 nm) were used as Ohmic contact and Schottky gate contact, respectively. The dimensions of the devices used in this study are as follows: source-drain distance (L_{sd}) = $9 \mu\text{m}$; gate width (W_g) = $15 \mu\text{m}$; gate length (L_g) = $2 \mu\text{m}$, and source-gate distance (L_{gs}) = $3 \mu\text{m}$. The dc and pulse characteristics were measured using Agilent 4156c semiconductor parameter analyzer. To measure the 2DEG density as a function of channel depth, capacitance-voltage (C - V) measurements were carried out at 1 MHz on Schottky diodes using HP4845A inductance, capacitor, and resistance meter. The device properties were summarized in the Table I(b).

Figure 2(a) shows the drain current (I_{DS}) versus drain-source voltage (V_{DS}) characteristics of the Q-HFET for different values of gate-source voltage (V_G). The maximum drain current (I_{Dmax}) of about 758 mA/mm was obtained with good pinch-off characteristics, which was comparable to the properties of the T-HFET (see Table I). Encouragingly, the Q-HFET exhibited extremely low gate leakage current (I_{gLeak}) compared to the T-HFET, which was shown in Fig. 2(b). The measurements were performed at subthreshold voltage for both HFETs. I_{gLeak} of the Q-HFET is about four orders of magnitude less than that of the T-HFET.

To evaluate the current collapse properties, pulsed measurements¹⁵ were performed, in which V_{DS} was fixed at a value well in the saturation regime and the gate was driven by pulsed bias with $1 \mu\text{s}$ duration and 50% duty cycle [see the inset of Fig. 3(a)]. The pulsed bias amplitude varied from 0 V to a value (V_{G-base}) below the device threshold voltage

(V_{th}). The pulsed drain current (I_{p-DS}) was measured when the pulsed gate voltage returned to the zero. To facilitate the comparison, the plot of the pulse current normalized to the dc current (I_{dc-DS}) at zero gate bias versus the gate voltage (V_{G-base}) normalized to the threshold voltage shown in Fig. 3(a). It can be seen that the Q-HFET showed a smaller decrease of I_{DS} than the T-HFET at pulsed mode, indicating a smaller current collapse effect in the Q-HFET. Both low gate leakage current and low current collapse in the Q-HFET imply the potential application of AlInGaIn in the high-frequency field. Further study is needed to understand the mechanism behind it.

The transfer characteristic of the Q-HFET device was shown in Fig. 3(b). The peak extrinsic transconductance (g_{mmax}) was obtained to be 123 mS/mm at a gate voltage of -2.8 V and a drain-source voltage of 6 V. The intrinsic transconductance value (g_{m0}) of the device was calculated to be 195 mS/mm from the expression $g_{m0} = g_m / (1 - R_s g_m)$, where R_s , the source resistance, is higher than that of T-HFETs (see Table I). We believe the possible reasons for the lower peak extrinsic transconductance are due to the lower mobility of the Q-HFET structure and the thicker AlInGaIn barrier layer.

In order to understand this phenomenon, C - V measurements were conducted on Schottky diode fabricated on Q-HFET structure. Figure 4 shows the carrier concentration profile as a function of depth from AlInGaIn surface, which was calculated from C - V data.¹⁶ The result indicated that the high density of the 2DEG channel had been formed at the AlInGaIn/GaN interface with peak of electron concentration

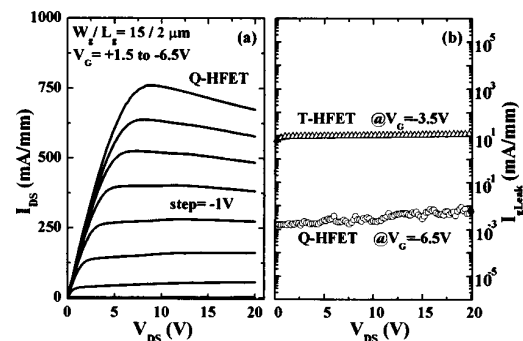


FIG. 2. (a) Drain current-voltage characteristics of AlInGaIn/GaN HFET. (b) Plot of gate leakage currents of both AlInGaIn and AlGaIn/GaN HFETs as a function of V_{DS} at subthreshold voltage.

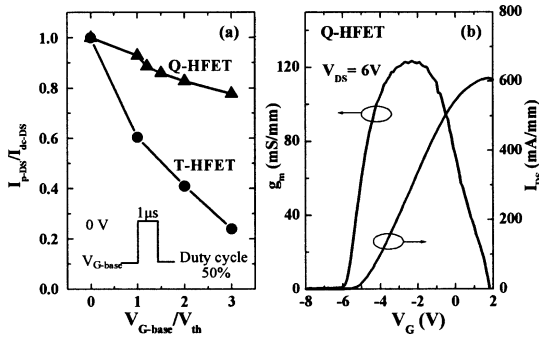


FIG. 3. (a) Plot of the pulse current (I_{p-DS}) normalized to the dc current (I_{dc-DS}) at zero gate bias versus the gate voltage (V_{G-base}) normalized to the threshold voltage; the inset shows the details of pulsed bias applied to the gate. (b) Plot of extrinsic transconductance (g_m) and drain current (I_{DS}) as a function of gate voltage (V_G).

of $2.3 \times 10^{19} \text{ cm}^{-3}$ at about 34 nm below the surface. The sheet carrier density obtained from the integration of above carrier profile¹⁶ was about $1 \times 10^{13} \text{ cm}^{-2}$, which was consistent with the room-temperature Hall data. Such high sheet carrier density was attributed to both conduction band offset and polarization discontinuity in the AlInGaN/GaN interface. To distinguish the contribution of piezoelectric and spontaneous polarization to the 2DEG, the discontinuity of piezoelectric (ΔP_{PZ}) and spontaneous (ΔP_{SP}) polarization in the AlInGaN/GaN interface was calculated³ assuming the validity of Vegard's law (see Table I). The ratio of ΔP_{SP} and ΔP_{PZ} ($\Delta P_{SP}/\Delta P_{PZ}$) was as high as 2.5, which was due to relatively less tensile strain in Q-HFET structure. This indicated that, in the Q-HFET structure, the spontaneous polarization contributed much more to the formation of the 2DEG than piezoelectric polarization. In comparison with the T-HFET structure, the value of the sheet carrier density of the Q-HFET structure was smaller. The difference may be due to both higher Si doping density and larger piezoelectric polarization in the T-HFET structure, since the bandgaps were almost same for two barrier layers.

It is worth mentioning that the electron concentration in the undoped AlInGaN region (labeled with an arrow in Fig. 4) is as high as $1.5 \times 10^{18} \text{ cm}^{-3}$. Such high background donor concentration was verified from another thicker AlInGaN sample grown at the same condition, which was believed to be due to the native defects or impurity-related donors. Thus, the lower mobility value of the Q-HFET structure may be explained in terms of the scattering from the native defects or impurities. Similar high background doping had been observed in GaN and InN, whose origin is still under debate. Further improvement of the Q-HFET's performance can be expected by optimizing the device structure, increasing the Al content in the barrier layer, and reducing AlInGaN background doping.

In summary, undoped AlInGaN/GaN HFET had been demonstrated with a maximum drain current of 758 mA/mm and extrinsic transconductance of 123 mS/mm. Such performance was comparable to that of conventional MOD-Al_{0.2}Ga_{0.8}N/GaN HFET fabricated at the same condition. Although the AlInGaN barrier layer suffered from less strain than the AlGaIn barrier layer, the high-density 2DEG profile was also observed at the AlInGaN/GaN interface by C-V

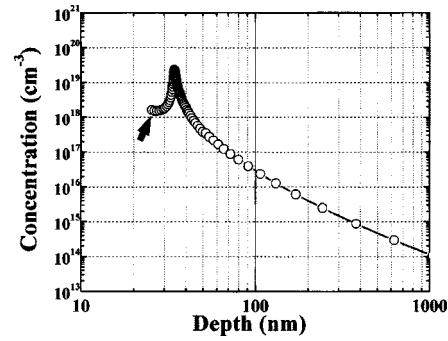


FIG. 4. C-V characteristics of Schottky diode on the AlInGaN/GaN HFET structure.

measurement, which was due to the larger spontaneous polarization in the AlInGaN layer. In spite of the high-density 2DEG, the AlInGaN/GaN heterostructure exhibited relatively low carrier mobility, which was due to the higher background doping in the AlInGaN barrier layer. Encouragingly, both the gate leakage current and drain current collapse showed lower values than that of the AlGaIn/GaN HFET, which implied that AlInGaN would be a promising candidate in high-power and high-frequency applications.

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