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A novel high-current density GaN-based normally-off transistor with tensile strained quaternary InAlGaN barrier

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Abstract
In this paper, we present a novel GaN-based normally-off transistor with high-current density using a tensile-strained quaternary InAlGaN barrier layer. The InAlGaN barrier layer is selectively removed and a p-AlGaN layer is formed for a gate electrode to obtain the normally-off operation with high-maximum drain current. The obtained threshold voltage of the device is + 1.1V. The maximum drain current reaches as high as 0.73 A/mm, which is almost twice higher than that of AlGaN-based conventional normally-off Gate Injection Transistor (GIT).

1. Introduction
III-nitrides are very promising materials for heterostructure field effect transistors (HFETs) since an InAlGaN/GaN heterojunction enables high current density and low on-state resistance caused by polarization-induced carriers. In order to increase sheet carrier density and to avoid generation of cracks in a conventional AlGaN/GaN heterostructure, a lattice-matched $In_{0.18}Al_{0.82}N$ on GaN structure is proposed [1]. Furthermore, slight increase of Al composition of an InAlGaN layer with slight addition of Ga is expected to increase sheet carrier density due to the addition of piezoelectric polarization induced charge by a tensile strain. Meanwhile, a normally-off operation used to be a critical issue for GaN-based HFETs. We have reported the normally-off GaN-based HFET using a p-AlGaN gate on an AlGaN barrier layer called Gate Injection Transistor (GIT) [2]. In this structure, a normally-off operation can be obtained since the p-AlGaN lifts up the potential and depletes the channel under the gate.

In this study, we propose a normally-off transistor using the tensile strained InAlGaN barrier layer with high sheet carrier density. In order to obtain a normally-off operation, the InAlGaN barrier layer is selectively removed under the gate and the p-AlGaN layer is formed on the AlGaN layer, so that the structure under the gate is the same as the conventional GIT [2]. The fabricated InAlGaN-based HFETs shows a normally-off operation with the threshold voltage (V_{th}) of + 1.1 V with high maximum drain current (I_{max}) of 0.73 A/mm.

2. Experimental Procedure
InAlGaN layers were grown on Si (111) substrates by a metalorganic chemical vapor deposition (MOCVD) reactor. Trimethyl aluminium (TMA), trimethyl gallium (TMG), trimethyl indium (TMI), cyclopentadienyl magnesium (Cp_2Mg) and ammonia (NH_3) were used as the source gas, respectively. The carrier gases employed were H_2 and N_2. In, Ga, and Al composition in the InAlGaN layer was evaluated by secondary ion mass spectrometry (SIMS). The thickness of the InAlGaN layer was determined by high-resolution X-ray diffraction (HR-XRD) measurement. The surface morphology was investigated by an atomic force microscope (AFM).

3. Structural design and fabrication of the InAlGaN-based HFET
Fig. 1 shows a calculated electron density (N_s) at the heterointerface between 15nm-thick-InAlGaN and GaN induced by piezoelectric polarization and spontaneous polarization. Electron density is calculated by using the value of spontaneous polarization, bandgap energy, piezo-electric constant, dielectric constant, lattice constant, elastic constant of the AlN, GaN and InN, respectively [3, 4]. Larger electron density can be obtained with increasing Al composition due to increase of the difference of spontaneous polarization between InAlGaN and GaN, and increase of piezoelectric polarization. Thus we used $In_{0.10}Al_{0.85}Ga_{0.05}N$ for the barrier layer on GaN which induces about 25 % larger N_s as compared to the lattice-matched $In_{0.18}Al_{0.18}N$ barrier layer shown in Fig. 1.

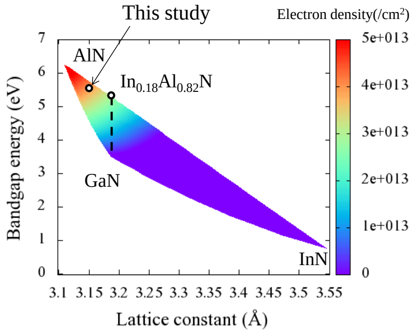

Fig. 1. Calculated electron density of the InAlGaN (15nm)/GaN heterointerface.

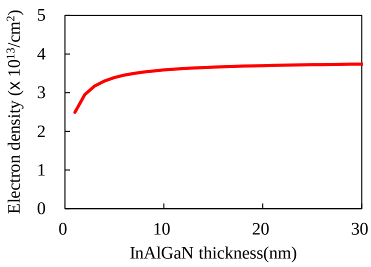

Fig. 2. Calculated electron density of the thickness-dependence of the $In_{0.10}Al_{0.85}Ga_{0.05}N$ on GaN.

Fig. 2 shows a calculated N_s of the strained $In_{0.10}Al_{0.85}Ga_{0.05}N/GaN$ heterointerface dependence on the thickness of the $In_{0.10}Al_{0.85}Ga_{0.05}N$ layer. N_s of the $In_{0.10}Al_{0.85}Ga_{0.05}N/GaN$ heterostructure reaches 3.0×10^{13} cm^2 when the thickness of the $In_{0.10}Al_{0.85}Ga_{0.05}N$ is 10 nm, and N_s almost saturates at the thickness of the $In_{0.10}Al_{0.85}Ga_{0.05}N$ above 10 nm.

AFM images of the $In_{0.10}Al_{0.85}Ga_{0.05}N$ layer grown on the GaN/Si (111) shown in Fig. 3, and a thickness dependence of the electron mobility of the $In_{0.10}Al_{0.85}Ga_{0.05}N$ layer on the GaN/Si (111) is shown in Fig. 4. The value of the electron mobility monotonically decreases as the thickness of the $In_{0.10}Al_{0.85}Ga_{0.05}N$ increases. Decreasing of the electron mobility is attributed to increasing of the roughness of the surface morphology as shown in Fig. 3.

Fig. 5 shows the cross-sectional schematic diagram of the fabricated InAlGaN-based HFET. It is difficult to deplete under the gate by p-AlGaN layer if $In_{0.10}Al_{0.85}Ga_{0.05}N$ exists due to the too much carrier density as shown in Fig. 2. Therefore, in order to obtain V_{th} more than 0V, the $In_{0.10}Al_{0.85}Ga_{0.05}N$ layer is removed and the p-AlGaN is formed on the AlGaN layer under the gate. The structure of the gate region is same as conventional GIT [2].

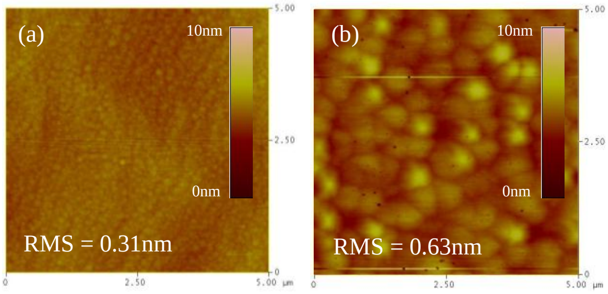

Fig. 3. AFM images for the $In_{0.10}Al_{0.85}Ga_{0.05}N$ ((a) 15nm (b) 25nm) grown on the GaN/Si (111).

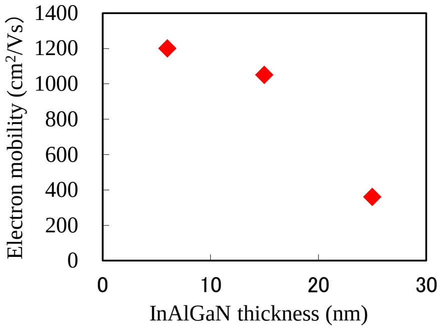

Fig. 4. Thickness dependence of the electron mobility of the $In_{0.10}Al_{0.85}Ga_{0.05}N$ on the GaN/Si (111).

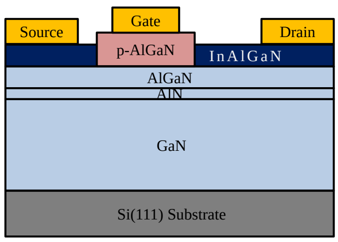

Fig. 5. Cross-sectional schematic diagram of the InAlGaN-based HFET.

Fig. 6 shows the V_{ds}-I_{ds} curves of the InAlGaN-based HFET and conventional AlGaN-based GIT. The gate length (L_g), gate-source spacing (L_{gs}) and gate-drain spacing (L_{gd}) of the InAlGaN-based HFET and conventional GIT is 2 um, 1.5 um and 2 um, respectively. The V_{th} of the InAlGaN-based HFET is + 1.1 V which is the same as conventional GIT. The off-state breakdown voltage (BV_{ds}) of the InAlGaN-based HFET is 80 V. The on-state resistance and I_{max} of the InAlGaN-based HFET is 6.9 Ω·mm and 0.73 A/mm, respectively. The on-state resistance of the InAlGaN-based HFET is reduced rather than conventional GIT and the I_{max} of the InAlGaN-based HFET is almost twice higher than conventional GIT. The on-state resistance and the I_{max} of the InAlGaN-based HFET shows a dramatic improvement with respect to the conventional GIT due to the increase of N_s.

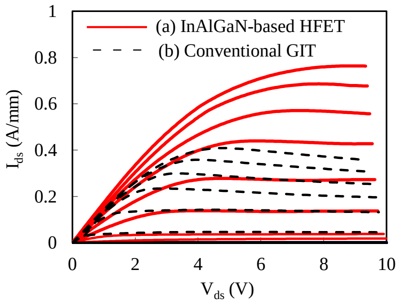

Fig. 6. V_{ds}-I_{ds} curves of the (a) InAlGaN-based HFET (V_{gs} = -1 to 9 V, in steps of 1 V)
(b) Conventional GIT (V_{gs} = -1 to 6 V, in steps of 1 V).

4. Conclusions

We have demonstrated a high-current GaN-based normally-off HFET with a quaternary InAlGaN barrier layer. In order to obtain normally-off operation in the InAlGaN-based HFET, the InAlGaN barrier layer is selectively removed and the p-AlGaN layer is formed under the gate region. The threshold voltage of the InAlGaN-based HFET is + 1.1 V, the on-state resistance is 6.9 Ω·mm, the off-state breakdown voltage is 80V and the maximum drain current is 0.73 A/mm. The drain current value of the InAlGaN-based HFET is almost twice higher than the conventional normally-off AlGaN-based GIT.

Acknowledgements

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