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Performance Comparison of Lattice-Matched AlInN/GaN/AlGaIn/GaN Double-Channel Metal–Oxide–Semiconductor High-Electron Mobility Transistors with Planar Channel and Multiple-Mesa-Fin-Channel Array

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Abstract: In this work, Al_{0.83}In_{0.17}N/GaN/Al_{0.18}Ga_{0.82}N/GaN epitaxial layers used for the fabrication of double-channel metal–oxide–semiconductor high-electron mobility transistors (MOSHEMTs) were grown on silicon substrates using a metalorganic chemical vapor deposition system (MOCVD). A sheet electron density of $1.11 \times 10^{13} \text{ cm}^{-2}$ and an electron mobility of $1770 \text{ cm}^2/\text{V}\cdot\text{s}$ were obtained. Using a vapor cooling condensation system to deposit high insulating 30-nm-thick Ga₂O₃ film as a gate oxide layer, double-hump transconductance behaviors with associated double-hump maximum extrinsic transconductances (g_{mmax}) of 89.8 and 100.1 mS/mm were obtained in the double-channel planar MOSHEMTs. However, the double-channel devices with multiple-mesa-fin-channel array with a g_{mmax} of 148.9 mS/mm exhibited single-hump transconductance behaviors owing to the better gate control capability. Moreover, the extrinsic unit gain cutoff frequency and maximum oscillation frequency of the devices with planar channel and multiple-mesa-fin-channel array were 5.7 GHz and 10.5 GHz, and 6.5 GHz and 12.6 GHz, respectively. Hooge's coefficients of 7.50×10^{-5} and 6.25×10^{-6} were obtained for the devices with planar channel and multiple-mesa-fin-channel array operating at a frequency of 10 Hz, drain–source voltage of 1 V, and gate–source voltage of 5 V, respectively.

Keywords: double-channel epitaxial structure; double-hump transconductance; Ga₂O₃ gate oxide layer; metal–oxide–semiconductor high-electron mobility transistors

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1. Introduction

In recent decades, silicon (Si)-based electronic devices have become dominant power devices used in various systems. To enhance their capability of operating at a higher voltage, higher current, higher temperature, higher frequency, and with better energy efficiency, gallium nitride (GaN)-based electronic devices have played the mainstream role of power semiconductor devices, which have recently benefited from their superior electrical and physical properties [1–3]. Despite the success of depletion-mode and enhancement-mode GaN-based single-channel metal–oxide–semiconductor high-electron mobility transistors (MOSHEMTs), active development of high-performance compelling devices is still needed. In general, the enhancement of both electron mobility (μ_n) and sheet electron density (n_{ch}) has been widely explored with the aim of improving the performances of GaN-based MOSHEMTs. However, it is technically difficult to grow an AlGaIn layer with high Al content to achieve high μ_n and n_{ch} simultaneously. Recently, to simultaneously obtain both the enhanced μ_n and n_{ch} , multiple-channel structures were explored [4–7]. Furthermore, superior performances of higher current drive, low resistance, low-frequency noise, and

improved linearity were demonstrated in multiple-channel MOSHEMTs [8–10]. Nevertheless, since lattice-matched heterostructured structures could reduce the failure caused by the inverse piezoelectric effect [11], lattice-matched barrier layers in multiple-channel structures remain a promising candidate for enhancing performance [12–14]. In this work, double-channel epitaxial layers of lattice-matched $\text{Al}_{0.83}\text{In}_{0.17}\text{N}/\text{GaN}/\text{Al}_{0.18}\text{Ga}_{0.82}\text{N}/\text{GaN}$ were grown on Si substrates using a metalorganic chemical deposition (MOCVD, AIXTRON Group, Herzogenrath, Germany) system. Although several gate oxide layers were used in GaN-based MOSHEMTs [15–20], gallium oxide (Ga_2O_3)-based materials have become promising gate oxide layers due to their superior properties of high breakdown voltage, high radiation resistance, high thermal and chemical stability, high Baliga's figure-of-merit, and better interface properties between Ga_2O_3 film and GaN-based semiconductors [21–23]. Furthermore, because high-quality and high-insulating amorphous Ga_2O_3 films could be deposited using a vapor cooling condensation system [24,25] and were successfully used in GaN-based MOSHEMTs previously [25,26], the system was used to deposit a 30-nm-thick Ga_2O_3 film as a gate oxide layer in this work. In addition, to improve interface properties, surface preparation was employed previously [27]. In this study, before depositing the Ga_2O_3 gate oxide layer, an $(\text{NH}_4)_2\text{S}_x$ chemical solution was used to treat the sample surface to completely remove the undesired native oxide residing on the surface of the GaN-based semiconductors [28]. Recently, lattice-matched double-channel $\text{AlInN}/\text{GaN}/\text{AlGaIn}/\text{GaN}$ MOSHEMTs with multiple-mesa-fin-channel array were reported [29]. Although the compared performances of signal-channel MOSHEMTs with planar channel and multiple-mesa-fin-channel array were reported previously [30,31], a comparison of the performances of the multiple-channel MOSHEMTs with planar channel and multiple-mesa-fin-channel array has not yet been carried out. In this work, to compare the performances of the planar channel structure with the multiple-mesa-fin-channel array of double-channel MOSHEMTs, lattice-matched double-channel $\text{Al}_{0.83}\text{In}_{0.17}\text{N}/\text{GaN}/\text{Al}_{0.18}\text{Ga}_{0.82}\text{N}/\text{GaN}$ MOSHEMTs with planar channel were fabricated and studied.

2. Epitaxial Growth and Results

A MOCVD system was utilized to grow epitaxial layers of $\text{Al}_{0.83}\text{In}_{0.17}\text{N}/\text{GaN}/\text{Al}_{0.18}\text{Ga}_{0.82}\text{N}/\text{GaN}$ double-channel structure on Si substrate. The epitaxial structure included an AlN nucleation layer (250 nm), a graded AlGaIn buffer layer (1.1 μm), a trimethylgallium (TMGa)-grown undoped GaN buffer layer (1.9 μm), a triethylgallium (TEGa)-grown GaN channel 1 layer (100 nm), an AlN spacer layer (1 nm), an $\text{Al}_{0.18}\text{Ga}_{0.82}\text{N}$ barrier layer 1 (25 nm), a TEGa-grown GaN channel 2 layer (10 nm), an AlN spacer layer (1 nm), an $\text{Al}_{0.83}\text{In}_{0.17}\text{N}$ barrier layer 2 (8 nm), and a GaN cap layer (2 nm). In the epitaxial growth, trimethylgallium (TMAI) and trimethylindium (TMIn) were used as the precursors for Al and In sources to grow the $\text{Al}_{0.18}\text{Ga}_{0.82}\text{N}$ barrier layer and the $\text{Al}_{0.83}\text{In}_{0.17}\text{N}$ barrier layer, respectively. In addition, ammonia (NH_3) and hydrogen (H_2) were respectively used as the nitrogen source and carrier gas for growing the 1.1- μm -thick graded AlGaIn buffer layer and 1.9- μm -thick GaN buffer layer. The H_2 carrier gas was replaced by nitrogen gas just before and at the end of the growth of the GaN buffer layer without growth interruption. Furthermore, by using a TEGa precursor to grow the GaN channel, the residual carbon concentration could be reduced to improve electron mobility due to the lower channel trapping [32].

Regarding the simulation of a one-dimensional (1D) Schrödinger–Poisson solver, double two-dimensional electron gas (2-DEG) channels were formed at the polarized $\text{Al}_{0.18}\text{Ga}_{0.82}\text{N}/\text{GaN}$ interface and the band-discontinued lattice-matched $\text{Al}_{0.83}\text{In}_{0.17}\text{N}/\text{GaN}$ interface [29]. Using a Hall measurement (Ecopia Crop., Anyang, Korea) at room temperature, the equivalent electron mobility of 1770 $\text{cm}^2/\text{V}\cdot\text{s}$ and the equivalent sheet electron density of $1.11 \times 10^{13} \text{ cm}^{-2}$ were measured. To compare the performances of double-channel MOSHEMTs with planar channel and multiple-mesa-fin-channel array, the same epitaxial layers were used in this work.

3. Results and Discussion

Figure 1a,b present the 3D schematic configuration of the double-channel $\text{Al}_{0.83}\text{In}_{0.17}\text{N}/\text{GaN}/\text{Al}_{0.18}\text{Ga}_{0.82}\text{N}/\text{GaN}$ MOSHEMTs with planar channel and multiple-mesa-fin-channel array, respectively. Under the protection of a patterned 500-nm-thick Ni metal mask, the mesa isolation region ($310\ \mu\text{m} \times 320\ \mu\text{m}$) of MOSHEMTs was etched down to Si substrate using a reactive-ion etching system with a BCl_3 etchant. After removing the Ni mask using an HCl chemical solution, the sample surface was treated by an $(\text{NH}_4)_2\text{S}_x$ chemical solution at $60\ ^\circ\text{C}$ for 30 min to completely remove undesired native oxide. Using a standard photolithography system to open windows of the source electrode and drain electrode, laminated Ti/Al/Pt/Au (25/100/50/400 nm) metals were sequentially deposited and were then lifted off. By annealing the sample in a nitrogen environmental rapid-thermal annealing system at $850\ ^\circ\text{C}$ for 1 min, an ohmic-contacted source electrode and drain electrode with a specific contact resistance of about $7.5 \times 10^{-6}\ \Omega\text{-cm}^2$ were obtained. The separation between the source electrode and the drain electrode was $10\ \mu\text{m}$. After depositing a ZnO film (300 nm), the gate windows (length = $1\ \mu\text{m}$ and width = $50\ \mu\text{m}$) placed at the central region between the source electrode and drain electrode were etched using a diluted HCl chemical solution under a photoresist mask. When the sample was repeatedly treated with a $(\text{NH}_4)_2\text{S}_x$ chemical solution, a 30-nm-thick Ga_2O_3 film was deposited at about 80 K as the gate oxide layer using a vapor cooling condensation system. The deposition process and electrical properties of the amorphous Ga_2O_3 films deposited using this system were reported previously [25,33]. Prior to removing the ZnO mask, laminated Ni/Au (20/300 nm) gate metals were sequentially deposited by an electron beam evaporator. The double-channel planar $\text{Al}_{0.83}\text{In}_{0.17}\text{N}/\text{GaN}/\text{Al}_{0.18}\text{Ga}_{0.82}\text{N}/\text{GaN}$ MOSHEMTs have a channel length of $10\ \mu\text{m}$ and a channel width of $50\ \mu\text{m}$. In the same batch process, two samples of the double-channel MOSHEMTs with planar channel and multiple-mesa-fin-channel array were fabricated. Every sample included more than 200 devices. The uniformity and performance reproducibility of the MOSHEMTs were good.

In addition to the 500-nm-wide strip channel array patterned using an He-Cd laser interference photolithography system, similar fabrication processes of planar devices were utilized for fabricating devices with multiple-mesa-fin-channel array. However, within the same channel width of $50\ \mu\text{m}$, the total real channel width in the multiple-mesa-fin-channel array was $25.2\ \mu\text{m}$ [29].

Figure 1. Cont.

Figure 1. Epitaxial structure and three-dimensional schematic configuration of double-channel MOSHEMTs with (a) planar channel and (b) multiple-mesa-fin-channel array.

Using the measurement of an Agilent 4156C semiconductor parameter analyzer, Figure 2a,b respectively illustrate the typical drain–source current (I_{DS})–drain–source voltage (V_{DS}) characteristics of the devices with planar channel and multiple-mesa-fin-channel array operating at various gate–source voltages (V_{GS}). By normalizing the channel width of 50 μm , the normalized saturation drain–source current (I_{DSS}) of the planar devices operating at $V_{GS} = 5$ V and $V_{DS} = 10$ V was 520.0 mA/mm, in which the real drain–source current was 26.0 mA. For the devices with multiple-mesa-fin-channel array, the I_{DSS} was 842.7 mA/mm, in which the real drain–source current was 21.2 mA. It was worth noting that the real drain–source current in the devices with multiple-mesa-fin-channel array was less than that of the planar devices. When the on-resistance (R_{on}) of the devices was defined as the inverse slope of the I_{DS} – V_{DS} characteristics at $V_{DS} = 0$ V and $V_{GS} = 5$ V, the $R_{on} = 10.2$ $\Omega\text{-mm}$ of the planar devices was calculated and compared with the $R_{on} = 6.1$ $\Omega\text{-mm}$ of the devices with multiple-mesa-fin-channel array [29].

Figure 2. Typical drain–source current–drain–source voltage characteristics of double-channel MOSHEMTs with (a) planar channel and (b) multiple-mesa-fin-channel array [29].

Figure 3 presents the I_{DS} – V_{GS} characteristics and the extrinsic transconductance (g_m)– V_{GS} characteristics of the devices with planar channel and multiple-mesa-fin-channel array operating at $V_{DS} = 10$ V. In the g_m – V_{GS} characteristics shown in Figure 3, a double-hump transconductance performance was clearly observed in the planar devices; it corresponded to the effective gate modulation of the upper channel 2 and the lower channel 1,

respectively. The maximum extrinsic transconductance (g_{mmax}) of the double-hump behavior was 89.8 and 100.1 mS/mm, respectively. It was worth noting that the double-hump transconductance performance was not found in the devices with a multiple-mesa-fin-channel structure due to the better gate control capability caused by the modulation of the side-wall electrical field in the fin-channel [31]. In addition, the g_{mmax} of 148.9 mS/mm was obtained in the single-hump transconductance. Compared with the performances of the devices with planar channel, the higher normalized saturation current, higher maximum extrinsic transconductance, and lower on-resistance in the devices with multiple-mesa-fin-channel array were contributed by the lower real drain–source current and the better heat dissipation driven by lateral heat flow within the fin-channel array [31]. If the threshold voltage (V_{th}) of the devices was defined as the V_{GS} corresponding to the $I_{DS} = 1 \mu A/mm$, the V_{th} of the planar devices was -3.8 V. Compared with a V_{th} of -3.2 V in the devices with a multiple-fin-channel array structure, the V_{th} was pushed toward a more positive value due to the early pinched-off effect [30,34].

Figure 3. Drain–source current–gate–source voltage characteristics and extrinsic transconductance/gate–source voltage characteristics of double-channel MOSHEMTs operating at drain–source voltage of 10 V.

An Agilent 8510C network analyzer (Agilent, CA, USA) was used to measure small-signal high-frequency performances of the MOSHEMTs. Figure 4 illustrates frequency-dependent short-circuit current gain and frequency-dependent maximum available power gain of the devices with planar channel and multiple-mesa-fin-channel array. The extrinsic unit gain cutoff frequency (f_T) of 5.7 GHz and the maximum oscillation frequency (f_{max}) of 10.5 GHz of the planar devices were obtained. For the MOSHEMTs with multiple-mesa-fin-channel array, the f_T and f_{max} were 6.5 GHz and 12.6 GHz, respectively [29].

Figure 4. Short-circuit current gain and maximum available power gain as a function of frequency of double-channel MOSHEMTs.

In general, the low-frequency noise behaviors could be used to evaluate electron trapping and electron detrapping effects induced by traps, defects, and interface states in electronic devices [35]. The low-frequency noise characteristics of both the devices were measured using an Agilent 4156C low-noise bias supply, an HP 35670A dynamic

signal analyzer, and a BTA 9812B noise analyzer. Figure 5 presents the normalized low-frequency noise power density ($S_{IDS}(f)/I_{DS}^2$)–frequency (f) characteristics of the devices with planar channel and multiple-mesa-fin-channel array operating at $V_{DS} = 1$ V. As shown in Figure 5, the normalized noise power density decreased with an increase in V_{GS} voltage. The $S_{IDS}(f)/I_{DS}^2$ was about $5.4 \times 10^{-13} \text{ Hz}^{-1}$ and $8.7 \times 10^{-14} \text{ Hz}^{-1}$ for the devices with planar channel and multiple-mesa-fin-channel array operating at $V_{GS} = 5$ V and $V_{DS} = 1$ V at $f = 10$ Hz. Under the same operating conditions, the higher normalized noise power density in the planar devices was attributed to the larger channel area. Generally, Hooge's coefficient α provided a useful figure-of-merit for evaluating electronic devices. The α value could be calculated as follows [36]:

$$\alpha = \left(S_{IDS}(f)/I_{DS}^2 \right) \cdot f \cdot (L_G W_G n_{ch} (V_{GS} - V_{th}) / |V_{th}|) \quad (1)$$

where $L_G = 1 \text{ } \mu\text{m}$ is gate length and $n_{ch} = 1.11 \times 10^{13} \text{ cm}^{-2}$ is channel electron density. In the planar devices, the gate width W_G is $50 \text{ } \mu\text{m}$ and the threshold voltage V_{th} is -3.8 V, while W_G is $25.2 \text{ } \mu\text{m}$ and V_{th} is -3.2 V in the devices with multiple-mesa-fin-channel array. The calculated α value of 7.50×10^{-5} and 6.25×10^{-6} for the MOSHEMTs with planar channel and multiple-mesa-fin-channel array operating at $f = 10$ Hz, $V_{GS} = 5$ V, and $V_{DS} = 1$ V was obtained. In addition to the result of low Hooge's coefficient, the normalized noise power density was well fixed at $1/f$. This behavior could imply that the flicker noise was the dominant noise in the devices.

Figure 5. Frequency-dependent normalized noise power density spectra of double-channel MOSHEMTs operating at drain–source voltage of 1 V.

4. Conclusions

Recently, planar channel structures and multiple-mesa-fin-channel array structures have been widely used for the fabrication of MOSHEMTs. In this study, to compare the performance of planar channel and multiple-mesa-fin-channel array used in double-channel MOSHEMTs, double-channel $\text{Al}_{0.83}\text{In}_{0.17}\text{N}/\text{GaN}/\text{Al}_{0.18}\text{Ga}_{0.82}\text{N}/\text{GaN}$ epitaxial layers were grown on Si substrates using an MOCVD system. The performance comparisons of the double-channel MOSHEMTs with planar channel and multiple-mesa-fin-channel array are listed in Table 1. Compared with the performance of the double-channel MOSHEMTs with multiple-mesa-fin-channel array, double-hump transconductance behavior was observed in the double-channel planar MOSHEMTs owing to the effective gate modulation of the upper channel 2 and the lower channel 1 by the only top-side electrical field. However, in addition to the modulation of the top-side electrical field, the side-wall electric field in the multiple-mesa-fin-channel could perform at a better gate control capability. Consequently, the transconductance collapse was paved in the multiple-mesa-fin-channel. It was expected that the pavement efficiency could be enhanced by using narrower fin-channel. The extrinsic maximum double-hump transconductances of the double-channel planar MOSHEMTs were 89.8 and 100.1 mS/mm, respectively. In addition, the extrinsic maximum

transconductance of the double-channel MOSHEMTs with multiple-mesa-fin-channel array was 148.9 mS/mm. Furthermore, compared with the performances of MOSHEMTs with a planar channel structure, better heat dissipation driven by the lateral heat flow in the parallel fin-channels could improve the direct-current performances and high-frequency performances [37]. The extrinsic unit gain cutoff frequency and maximum oscillation frequency of the MOSHEMTs with planar channel and multiple-mesa-fin-channel array were 5.7 and 10.5 GHz, and 6.5 and 12.6 GHz, respectively. Owing to the screening effect of the trapping probability, better noise performances were obtained in the MOSHEMTs with multiple-mesa-fin-channel array [31,38]. Hooge's coefficient of the MOSHEMTs with planar channel and multiple-mesa-fin-channel array was 7.50×10^{-5} and 6.25×10^{-6} , respectively. Although the multiple-mesa-fin-channel array exhibited superior advantages to the MOSHEMTs, its real drain-source current was less than that in the planar devices with the same channel width. Evaluating the power performances of devices with multiple-mesa-fin-channel array remains a challenging task.

Recently, planar channel structures and multiple-mesa-fin-channel array structures have been widely used for the fabrication of MOSHEMTs. In this study, to compare the performance of planar channel and multiple-mesa-fin-channel array used in double-channel MOSHEMTs, double-channel $\text{Al}_{0.83}\text{In}_{0.17}\text{N}/\text{GaN}/\text{Al}_{0.18}\text{Ga}_{0.82}\text{N}/\text{GaN}$ epitaxial layers were grown on Si substrates using an MOCVD system. The performance comparisons of the double-channel MOSHEMTs with planar channel and multiple-mesa-fin-channel array are listed in Table 1. Compared with the performance of the double-channel MOSHEMTs with multiple-mesa-fin-channel array, double-hump transconductance behavior was observed in the double-channel planar MOSHEMTs owing to the effective gate modulation of the upper channel 2 and the lower channel 1 by the only top-side electrical field. However, in addition to the modulation of the top-side electrical field, the side-wall electric field in the multiple-mesa-fin-channel could perform at a better gate control capability. Consequently, the transconductance collapse was paved in the multiple-mesa-fin-channel. It was expected that the pavement efficiency could be enhanced by using narrower fin-channel. The extrinsic maximum double-hump transconductances of the double-channel planar MOSHEMTs were 89.8 and 100.1 mS/mm, respectively. In addition, the extrinsic maximum transconductance of the double-channel MOSHEMTs with multiple-mesa-fin-channel array was 148.9 mS/mm. Furthermore, compared with the performances of MOSHEMTs with a planar channel structure, better heat dissipation driven by the lateral heat flow in the parallel fin-channels could improve the direct-current performances and high-frequency performances [37]. The extrinsic unit gain cutoff frequency and maximum oscillation frequency of the MOSHEMTs with planar channel and multiple-mesa-fin-channel array were 5.7 and 10.5 GHz, and 6.5 and 12.6 GHz, respectively. Owing to the screening effect of the trapping probability, better noise performances were obtained in the MOSHEMTs with multiple-mesa-fin-channel array [31,38]. Hooge's coefficient of the MOSHEMTs with planar channel and multiple-mesa-fin-channel array was 7.50×10^{-5} and 6.25×10^{-6} , respectively. Although the multiple-mesa-fin-channel array exhibited superior advantages to the MOSHEMTs, its real drain-source current was less than that in the planar devices with the same channel width. Evaluating the power performances of devices with multiple-mesa-fin-channel array remains a challenging task.

Table 1. Performance comparisons of the double-channel MOSHEMTs with planar channel and multiple-mesa-fin-channel array.

Characteristics	MOSHEMTs	Planar Channel	Multiple-Mesa-Fin-Channel Array
Drain–source current, I_{DS} at $V_{DS} = 10$ V and $V_{GS} = 5$ V		520.0 mA/mm	842.7 mA/mm
on-resistance, R_{on} at $V_{DS} = 0$ V and $V_{GS} = 5$ V		10.2 Ω -mm	6.1 Ω -mm
Transconductance, g_m at $V_{DS} = 10$ V		89.8 and 100.1 mS/mm	148.9 mS/mm
Threshold voltage, V_{th} at $I_{DS} = 1$ μ A/mm		−3.8 V	−3.2 V
Unit gain cutoff frequency, f_T		5.7 GHz	6.5 GHz
Maximum oscillation frequency, f_{max}		10.5 GHz	12.6 GHz
Hooge’s coefficient, α		7.50×10^{-5}	6.25×10^{-6}

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References

1. Roccaforte, F.; Greco, G.; Fiorenza, P.; Iucolano, F. An overview of normally-off GaN-based high electron mobility transistors. *Materials* **2019**, *12*, 1599. [\[CrossRef\]](#)
2. Lee, H.Y.; Lin, C.H.; Wei, C.C.; Yang, J.C.; Chang, E.Y.; Lee, C.T. AlGaIn/GaN enhancement-mode MOSHEMTs utilizing hybrid gate-recessed structure and ferroelectric charge trapping/storage stacked LiNbO₃/HfO₂/Al₂O₃ structure. *IEEE Trans. Electron Devices* **2021**, *68*, 3768–3774. [\[CrossRef\]](#)
3. Zhang, S.; Ma, B.; Zhou, X.; Hua, Q.; Gong, J.; Liu, T.; Cui, X.; Zhu, J.; Guo, W.; Jing, L.; et al. Strain-controlled power devices as inspired by human reflex. *Nat. Commun.* **2020**, *11*, 326. [\[CrossRef\]](#) [\[PubMed\]](#)
4. Heikman, S.; Keller, S.; Green, D.S.; DenBaars, S.P.; Mishra, U.K. High conductivity modulation doped AlGaIn/GaN multiple channel heterostructures. *J. Appl. Phys.* **2003**, *94*, 5321–5325. [\[CrossRef\]](#)
5. Chu, R.; Zhou, Y.; Liu, J.; Wang, D.; Chen, K.J.; Lau, K.M. AlGaIn-GaN double-channel HEMTs. *IEEE Trans. Electron Devices* **2005**, *52*, 438–446. [\[CrossRef\]](#)
6. Erine, C.; Ma, J.; Santoruvo, G.; Matioli, E. Multi-channel AlGaIn/GaN In-plane-gate field-effect transistors. *IEEE Electron Device Lett.* **2020**, *41*, 321–324. [\[CrossRef\]](#)
7. Chen, X.; Lv, D.D.; Zhang, J.F.; Zhou, H.; Ren, Z.Y.; Wang, C.; Wu, Y.; Wang, D.; Zhang, H.; Lei, Y.Y. Model of electron population and energy band diagram of multiple-channel GaN heterostructures. *IEEE Trans. Electron Devices* **2021**, *68*, 1557–1562. [\[CrossRef\]](#)
8. Kamath, A.; Patil, T.; Adari, R.; Bhattacharya, I.; Ganguly, S.; Aldhaheri, R.W.; Hussain, M.A.; Saha, D. Double-channel AlGaIn/GaN high electron mobility transistor with back barriers. *IEEE Electron Device Lett.* **2012**, *33*, 1690–1692. [\[CrossRef\]](#)
9. Wei, J.; Liu, S.; Li, B.; Tang, X.; Lu, Y.; Liu, C.; Hua, M.; Zhang, Z.; Tang, G.; Chen, K.J. Low on-resistance normally-off GaN double-channel metal–oxide–semiconductor high-electron-mobility transistor. *IEEE Electron Device Lett.* **2015**, *36*, 1287–1290. [\[CrossRef\]](#)
10. Jha, S.K.; Surya, C.; Chen, K.J.; Lau, K.M.; Jelencovic, E. Low-frequency noise properties of double channel AlGaIn/GaN HEMTs. *Solid-State Electron.* **2008**, *21*, 606–611. [\[CrossRef\]](#)

11. Joh, J.; Gao, F.; Palacios, T.; del Alamo, J.A. A model for the critical voltage for electrical degradation of GaN high electron mobility transistors. *Microelectron. Reliab.* **2010**, *50*, 767–773. [\[CrossRef\]](#)
12. Lim, T.; Aidam, R.; Waltereit, P.; Henkel, T.; Quay, R.; Lozar, R.; Maier, T.; Kirste, L.; Ambacher, O. GaN-based submicrometer HEMTs with lattice-matched InAlGaN barrier grown by MBE. *IEEE Electron Device Lett.* **2010**, *31*, 671–673. [\[CrossRef\]](#)
13. Mojaver, H.R.; Gosselin, J.L.; Valizadeh, P. Use of a bilayer lattice-matched AlInGaN barrier for improving the channel carrier confinement of enhancement-mode AlInGaN/GaN hetero-structure field-effect transistors. *J. Appl. Phys.* **2017**, *121*, 244502. [\[CrossRef\]](#)
14. Shrestha, N.M.; Li, Y.; Chen, C.H.; Sanyal, I.; Tarnag, J.H.; Chyi, J.I.; Samukawa, S. Design and simulation of high performance lattice matched double barrier normally off AlInGaN/GaN HEMTs. *IEEE J. Electron. Devices Soc.* **2020**, *8*, 873–878. [\[CrossRef\]](#)
15. Chiou, Y.L.; Lee, C.T. Band alignment and performance improvement mechanisms of chlorine-treated ZnO-gate AlGaIn/GaN metal-oxide-semiconductor high-electron mobility transistors. *IEEE Trans. Electron Devices* **2011**, *58*, 3869–3875. [\[CrossRef\]](#)
16. Kim, H.S.; Kang, M.J.; Kim, J.J.; Seo, K.S.; Cha, H.Y. Effects of recessed-gate structure on AlGaIn/GaN-on-SiC MIS-HEMTs with thin AlO_xN_y MIS gate. *Materials* **2020**, *13*, 1538. [\[CrossRef\]](#) [\[PubMed\]](#)
17. Lee, C.T.; Yang, C.L.; Tseng, C.Y.; Chang, J.H.; Horng, R.H. GaN-based enhancement-mode metal-oxide-semiconductor high-electron mobility transistors using LiNbO₃ ferroelectric insulator on gate-recessed structure. *IEEE Trans. Electron Devices* **2015**, *62*, 2481–2487. [\[CrossRef\]](#)
18. Eller, B.S.; Yang, J.; Nemanich, R.J. Electronic surface and dielectric interface states on GaN and AlGaIn. *J. Vac. Sci. Technol. A* **2013**, *31*, 050807. [\[CrossRef\]](#)
19. Zhang, S.; Wei, K.; Zhang, Y.C.; Chen, X.J.; Huang, S.; Yin, H.B.; Liu, G.G.; Yuan, T.T.; Zheng, Y.K.; Wang, X.H.; et al. Well-suppressed interface states and improved transport properties of AlGaIn/GaN MIS-HEMTs with PEALD SiN gate dielectric. *Vacuum* **2021**, *191*, 110359. [\[CrossRef\]](#)
20. Zheng, Z.; Zhang, L.; Song, W.; Feng, S.; Xu, H.; Sun, J.; Yang, S.; Chen, T.; Wei, J.; Chen, K.J. Gallium nitride-based complementary logic integrated circuits. *Nat. Electron.* **2021**, *4*, 595–604. [\[CrossRef\]](#)
21. Pearton, S.J.; Yang, J.; Cary IV, P.H.; Ren, F.; Kim, J.; Tadjer, M.J.; Mastro, M.A. A review of Ga₂O₃ materials, processing, and devices. *Appl. Phys. Rev.* **2018**, *5*, 011301. [\[CrossRef\]](#)
22. Oon, H.S.; Cheong, K.Y. Recent development of gallium oxide thin film on GaN. *Mater. Sci. Semicond. Process.* **2013**, *16*, 1217–1231. [\[CrossRef\]](#)
23. Shih, H.Y.; Chu, F.C.; Das, A.; Lee, C.Y.; Chen, M.J.; Lin, R.M. Atomic layer deposition of gallium oxide films as gate dielectrics in AlGaIn/GaN metal-oxide-semiconductor high-electron mobility transistors. *Nanoscale Res. Lett.* **2016**, *11*, 235. [\[CrossRef\]](#)
24. Lin, C.H.; Lee, C.T. Ga₂O₃-based solar-blind deep ultraviolet light-emitting diodes. *J. Lumines.* **2020**, *224*, 117326. [\[CrossRef\]](#)
25. Lee, H.Y.; Chang, T.W.; Lee, C.T. AlGaIn/GaN metal-oxide-semiconductor high-electron mobility transistors using Ga₂O₃ gate dielectric layer grown by vapor cooling condensation system. *J. Electron. Mater.* **2021**, *50*, 3748–3753. [\[CrossRef\]](#)
26. Lee, H.Y.; Chang, T.W.; Chang, E.Y.; Rorsman, N.; Lee, C.T. Fabrication and characterization of GaN-based fin-channel array metal-oxide-semiconductor high-electron mobility transistors with recessed-gate and Ga₂O₃ gate insulator layer. *IEEE J. Electron Devices Soc.* **2021**, *9*, 393–399. [\[CrossRef\]](#)
27. Chakraborty, A.; Maher, M.; Al Alam, E.; Souifi, A.; Aimez, V.; Arès, R.; Jaouad, A. Optimized pre-treatment process for MOS-GaN devices passivation. *IEEE Electron Device Lett.* **2014**, *35*, 318–320. [\[CrossRef\]](#)
28. Lin, Y.J.; Lee, C.T.; Chang, H.C. Changes in activation energies of donors and carrier concentration in Si-doped n-type GaN due to (NH₄)₂S_x treatment. *Semicon. Sci. Technol.* **2006**, *21*, 1167–1171. [\[CrossRef\]](#)
29. Lee, H.Y.; Liu, D.S.; Chyi, J.I.; Chang, E.Y.; Lee, C.T. Lattice-matched AlInN/GaN/AlGaIn/GaN heterostructured-double-channel metal-oxide-semiconductor high-electron mobility transistors with multiple-mesa-fin-channel array. *Materials* **2021**, *14*, 5474. [\[CrossRef\]](#)
30. Lee, C.T.; Guo, J.C. Fin-gated nanochannel array gate-recessed AlGaIn/GaN metal-oxide-semiconductor high-electron-mobility transistors. *IEEE Trans. Electron Devices* **2020**, *67*, 1939–1945. [\[CrossRef\]](#)
31. Jia, J.J.; Lin, C.C.; Lee, C.T. Scaling effect in gate-recessed AlGaIn/GaN fin-nanochannel array MOSHEMTs. *IEEE Access* **2020**, *8*, 158941–158946. [\[CrossRef\]](#)
32. Sanyal, I.; Lee, Y.C.; Chyi, J.I.; Lin, K.L. High electron mobility AlInGaIn/AlN/GaN heterostructures grown on 150-mm silicon substrate. *SPIE Photonics West Proc.* **2018**, *10532*, 1053213. [\[CrossRef\]](#)
33. Lee, H.Y.; Lin, C.H.; Lee, C.T. Whole metal oxide p-i-n deep ultraviolet light-emitting diodes using i-Ga₂O₃ active emissive film. *IEEE Photon. Technol. Lett.* **2020**, *32*, 941–943. [\[CrossRef\]](#)
34. Lu, B.; Matioli, E.; Palacios, T. Tri-gate normally-off GaN Power MISFET. *IEEE Electron Device Lett.* **2012**, *33*, 360–362. [\[CrossRef\]](#)
35. Levinshtein, M.E.; Rumyantsev, S.L.; Gaska, R.; Yang, J.W.; Shur, M.S. AlGaIn/GaN high electron mobility field effect transistors with low 1/f noise. *Appl. Phys. Lett.* **1998**, *73*, 1089–1091. [\[CrossRef\]](#)
36. Hooge, F.N.; Kleinpenning, T.G.M.; Vandamme, L.K.J. Experimental studies on 1/f noise, *Rep. Prog. Phys.* **1981**, *44*, 479–532. [\[CrossRef\]](#)
37. Mikulics, M.; Kordoš, P.; Fox, A.; Kočan, M.; Lüth, H.; Sofer, Z.; Hardtdegen, H. Efficient heat dissipation in AlGaIn/GaN heterostructure grown on silver substrate. *Appl. Mater. Today* **2017**, *7*, 134–137. [\[CrossRef\]](#)
38. Vodapally, S.; Theodorou, C.G.; Bae, Y.; Ghibaudo, G.; Cristoloveanu, S.; Im, K.S.; Lee, J.H. Comparison for 1/f noise characteristics of AlGaIn/GaN FinFET and planar MISHFET. *IEEE Trans. Electron Devices* **2017**, *64*, 3634–3638. [\[CrossRef\]](#)