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Investigation of the impact of the GaN cap layer on DC and RF performance in N-polar AlGaIn/GaN HEMTs

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In this paper, we investigated the logic and RF performance of nanostructure N-polar AlGaIn/GaN high-electron mobility transistors (HEMTs) with and without GaN cap layer. It's found that devices without the GaN cap layer exhibit superior performance, the maximum drain current density of 0.99 mA/μm at $V_{GS} = 2$ V and a corresponding on-state resistance (R_{on}) of 0.88 Ω·mm. The GaN HEMT without GaN cap layer leads to a peak transconductance of 0.75 S/mm at $V_{DS} = 3$ V. Varying the drain doping concentration significantly affects both the current density and transconductance. At a doping concentration (N_D) of 10^{22} cm⁻³, the device without GaN cap layer achieves a maximum current density of 0.98 mA/μm at $V_{DS} = 1$ V, and the maximum cut-off frequency (f_T) of 183.8 GHz at $V_{DS} = 3$ V. These findings highlight the potential of N-polar AlGaIn/GaN HEMTs without the GaN cap layer for high-power, high-frequency, and micro- and nano-electromechanical system (M/NEMS) sensors applications.

KEYWORDS

HEMTs, 2DEG density, g_m , quantum tunneling, cut-off frequency, output characteristics

1 Introduction

AlGaIn/GaN HEMTs are highly effective for high-power, and high-frequency applications. This effectiveness arises from their outstanding material properties, characterized by a wide energy bandgap, saturation velocity, high breakdown voltage, and a substantial density of two-dimensional electron gas (2DEG) at the AlGaIn/GaN heterointerface [1–4]. The strong mechanical stability of epitaxial films enables the III-N materials HEMTs for micro-electromechanical system (MEMS) sensors and oscillators [5–7]. The size of nano electromechanical device can be scaled [8]. The wurtzite crystal structure of GaN causes polarization in the c-direction. Thus, the orientation of the substrate can result in epitaxial structures with either N-polarity or Ga-polarity. Currently, most commercial AlGaIn/GaN HEMTs utilize Ga-polar orientation because it's simplifying epitaxial growth process and more mature processing techniques [9]. However, the reversed polarization found in N-polar epitaxial structures that may offer advantages for N-polar HEMTs. In N-polar HEMTs, unlike Ga-polar HEMTs, the barrier layer is situated below the channel. This arrangement enables the gate-to-channel distance to be scaled further without reducing the density of the 2DEG [10, 11]. N-polar GaN HEMTs exhibit superior performance as higher-frequency and higher-power amplifiers than their Ga-polar [12]. Additionally, due to its position beneath the channel, the barrier layer acts as a built-in back barrier, enhancing the device's pinch-off performance [13]. Furthermore, in N-polar

GaN, a thick GaN-cap layer can be applied. The N-polar HEMT epi structure featuring a GaN cap is often termed a “deep recess HEMT” due to its requirement for recess etching to position the gate in closer proximity to the channel [14, 15]. The GaN cap layer reduces the vertical electric field in the GaN channel, leading to an increase in 2DEG charge density and improved mobility [16]. Additionally, the GaN cap helps control dispersion by shifting surface states away from the channel and increasing the threshold voltage (V_{TH}) in the access regions [17]. This voltage shift results from the higher sheet charge density induced by the polarization effects of the GaN layer.

Despite these benefits, deep recess N-polar HEMTs face certain challenges. The interface between the gate and GaN, particularly at the trench sidewalls, can lead to higher leakage currents due to damage caused by dry etching [18]. Additionally, the deep recess structure introduces fringing capacitance from the gate recess through the GaN cap layer, limiting the device gain [19] which can degrade RF performance [20]. Furthermore, incorporation of a GaN cap layer in N-polar HEMTs creates challenges such as increased surface roughness, complexities in managing polarity reversal during growth, and potential interfacial strain and defects [21, 22]. Removing the GaN cap layer in N-polar HEMTs can offer several significant advantages, primarily related to improved device performance and fabrication simplicity. Without the GaN cap layer, the overall surface roughness of the device can be reduced, leading to better electron mobility and enhanced high-power performance [23]. The absence of the cap layer also simplifies the growth process, reducing the complexity and potential for polarity inversion issues during fabrication [24]. To improve dispersion control and environmental stability, a thin layer of *ex-situ* SiN is used as passivation layer. To fabricate a thin passivation layer bubble electrospinning can be used to enhance device performance [25]. By utilizing multiple jets formed from polymer solution bubbles, insulation can be improved, and leakage currents can be reduced. Although some research is done on GaN cap layer, further research is needed to understand the RF performance of AlGaN/GaN HEMTs in detail.

In this work, a novel nanostructure N-polar GaN HEMT without a GaN cap layer is proposed, where a 3 nm HfO₂ layer is used for passivation. The passivation layer is used to control dispersion and environmental stability, particularly at higher operating voltages. Evaluated the device's behavior, DC, and small-signal performance. The findings revealed GaN HEMTs without a GaN cap layer improved the output current density, transconductance, and maximum cut-off frequency. The drain doping concentration significantly affects the current density and transconductance. The principal contributions of this article include:

1. The impact of GaN cap layer of AlGaN/GaN HEMTs on DC performance has been studied.
2. The comparison of the RF performance of GaN HEMTs with and without GaN cap layer.
3. The impact of drain doping concentration on output characteristics, transfer characteristics, transconductance, and cut-off frequency has been investigated.

The paper is organized as follows: Section 2 provides a detailed explanation of the device structure and simulation methodology. In Section 3, the results and discussions are

thoroughly discussed. Finally, Section 4 presents the conclusions drawn from the findings.

2 Device structure and simulation methodology

The cross-sectional view of the conventional and proposed AlGaN/GaN HEMTs are shown in Figures 1a,b, respectively. The proposed structure has a sapphire substrate over which a 1.5 μm thick Fe-doped GaN buffer layer is placed. This buffer layer plays a critical role in minimizing lattice mismatch between GaN layer and the substrate, thereby reducing strain and defect density in the subsequent layers. Above the buffer, a 150 nm unintentionally doped (UID) GaN layer is introduced, followed by a 20 nm thick Al_{0.32}Ga_{0.68}N barrier layer with a donor concentration of $3.8 \times 10^{18} \text{ cm}^{-3}$. The UID GaN layer helps to prevent electron leakage from the two-dimensional electron gas (2DEG) into the substrate, while the barrier layer ensures carrier confinement within the channel, improving overall device performance. A 0.7 nm AlN spacer layer is incorporated to further confine the 2DEG and enhance electron mobility. Above the spacer, a 12 nm UID GaN channel layer is employed. To facilitate selective etching, a 3 nm thick layer of Al_{0.26}Ga_{0.74}N serves as an etch-stop layer. For the gate dielectric, a 3 nm HfO₂ layer is used due to its high-k properties, which provide excellent gate capacitance while minimizing gate leakage current without compromising gate control. Below the drain/source region placed an n⁺ GaN layer with a donor concentration of 10^{20} cm^{-3} . The device features 750 nm source-to-drain spacing, 250 nm source-to-gate recess spacing, 200 nm source-to-gate, and 300 nm drain-to-gate metal distances.

The Fermi-Dirac statistics model was employed to capture the effects of elevated doping levels, along with the Shockley-Read-Hall (SRH) recombination-generation model, and incomplete ionization models used, offered by Silvaco TCAD [26]. The SRH recombination model consists of four different stages: initially, electrons and holes are captured, followed by their subsequent emission. To manage the carrier transport field-dependent mobility and concentration-dependent mobility models were incorporated. Other essential models, including drift-diffusion, continuity, quantum tunneling, the high-field velocity saturation, and the Schrödinger-Poisson equations [27], were utilized to regulate electron and hole transport, as well as their dynamics throughout the simulations. Newton's method was employed to solve the physics-based models over multiple triangular mesh regions of the HEMT. The simulation models were validated using experimental data sample, as reported by Odabasi et al. [9]. Figure 2 shows that, the simulated results closely align with the experimental data, confirming the simulation environment feasible for comparative analysis.

3 Results and discussion

Figure 3 illustrates the impact of the GaN cap layer on the performance of high-electron mobility transistors. At V_{GS} of 0 V and 2 V, HEMTs without the GaN cap layer exhibit higher I_{DS} values, reaching 0.8 mA/ μm and 0.99 mA/ μm , and the corresponding to on-state resistance (R_{on}) of 1.02 $\Omega\cdot\text{mm}$ and 0.88 $\Omega\cdot\text{mm}$, respectively.

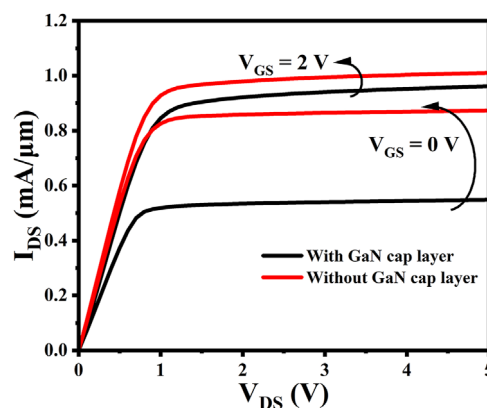
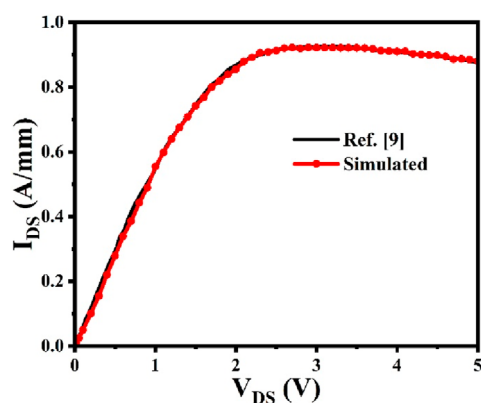
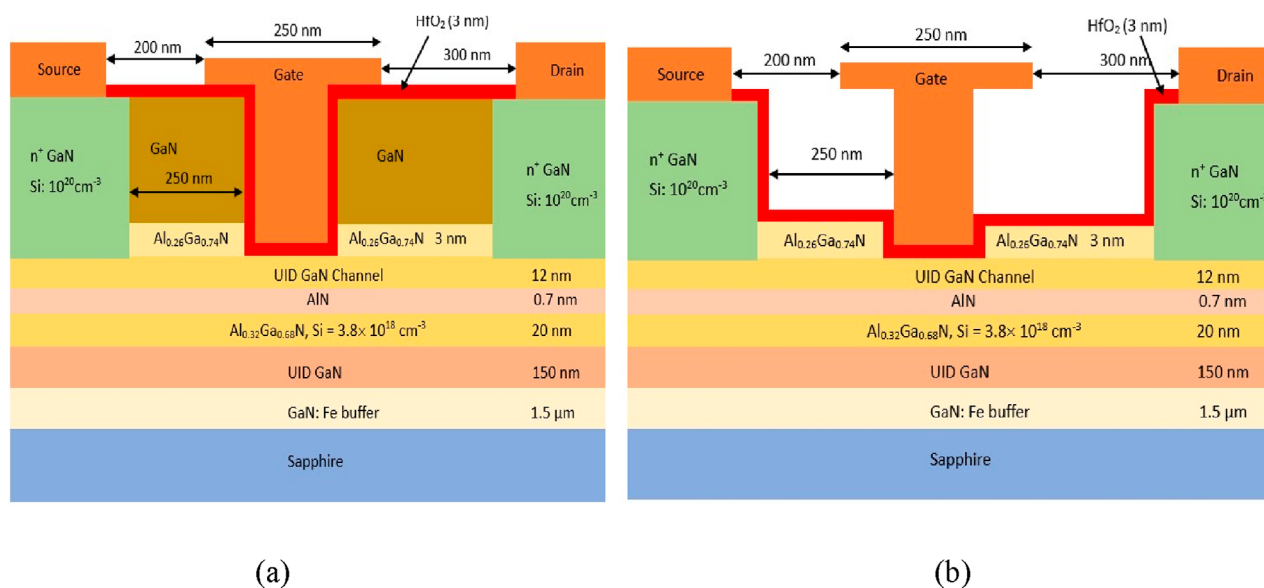


Figure 5 shows the transconductance (g_m) of GaN HEMTs with and without a GaN cap layer as a function of V_{GS} at a constant V_{DS} of 3 V. The transconductance curve for HEMTs without the GaN cap layer demonstrates a higher peak g_m value compared to those with the GaN cap layer, indicating improved electron mobility and channel control in the absence of the GaN cap layer. The device

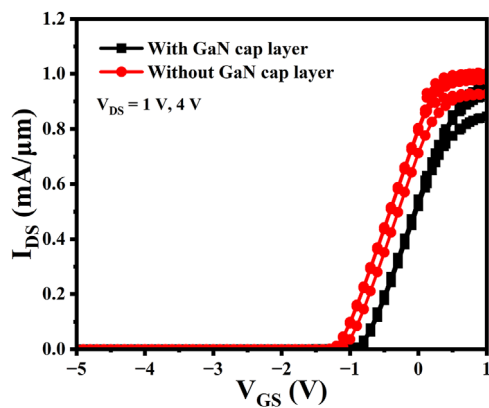


FIGURE 4 Transfer characteristics at $V_{DS} = 1$ V and $V_{DS} = 4$ V for GaN HEMTs with and without GaN cap layer.

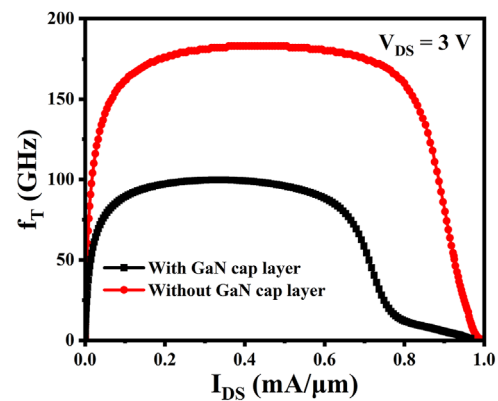


FIGURE 6 f_T Vs I_{DS} of GaN HEMTs with and without GaN cap layer at $V_{DS} = 3$ V.

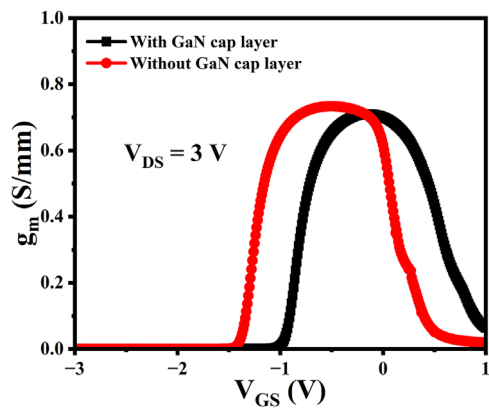


FIGURE 5 Transconductance (g_m) characteristics of GaN HEMTs with and without GaN cap layer at $V_{DS} = 3$ V.

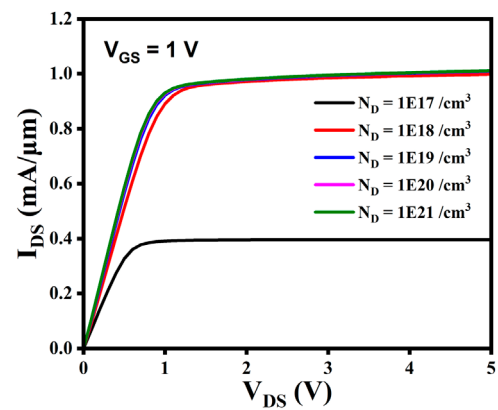


FIGURE 7 Variation of output characteristics for different drain doping concentrations at $V_{GS} = 1$ V in GaN HEMTs without GaN cap layer.

without the GaN cap layer reaches a peak transconductance (g_{m_max}) of 0.75 S/mm at $V_{GS} = -0.51$ V, whereas the device with the GaN cap layer achieves a slightly lower peak g_{m_max} . This improvement can be attributed to the absence of the GaN cap layer, which reduces surface scattering and traps, thereby enhancing the overall device performance.

Figure 6 shows cut-off frequency (f_T) as a function of I_{DS} with and without GaN cap layer at constant drain to source voltage of 3 V. The device without and with cap layer exhibits higher cut-off frequency ($f_{T,max}$) of 183 GHz and 99.79 GHz, respectively. Both devices experience a decline in f_T at high I_{DS} , but the non-capped device maintains better performance. The GaN cap layer introduces parasitic effects that degrade RF performance. Thus, the without GaN cap configuration offers superior high-frequency behavior.

Figure 7 illustrates the output characteristics of GaN HEMTs without a GaN cap layer with varying drain doping concentrations (N_D) from 10^{17} cm $^{-3}$ to 10^{21} cm $^{-3}$ at a constant V_{GS} of 1 V. The results show a clear trend, as the doping concentration increases,

the drain current (I_{DS}) also increases. For $N_D = 10^{17}$ cm $^{-3}$, the I_{DS} reaches 0.385 mA/μm, whereas for $N_D = 10^{21}$ cm $^{-3}$, I_{DS} reaches nearly 0.97 mA/μm, indicating improved conductivity with higher doping levels. This enhancement in current with increasing doping is due to the higher carrier concentration, which reduces the resistance in the channel.

Figure 8 illustrates the transfer characteristics of GaN HEMT for different drain doping concentrations at a constant V_{DS} of 1 V. The drain concentrations (N_D) range from 10^{17} cm $^{-3}$ to 10^{22} cm $^{-3}$. As the donor concentration increases the I_{DS} also increases, and the maximum current of approximately 0.98 mA/μm around $V_{GS} = 0.5$ V for $N_D = 10^{22}$ cm $^{-3}$, due to the enhanced electron mobility and conductivity at higher doping levels. This behavior highlights how donor concentration improves device performance by increasing the current-carrying capability.

Figure 9 shows the transconductance (g_m) characteristics as a function of V_{GS} at a constant $V_{DS} = 3$ V. The graph shows a significant change in g_m for different N_D levels. The higher donor concentrations result in higher peaks in transconductance.

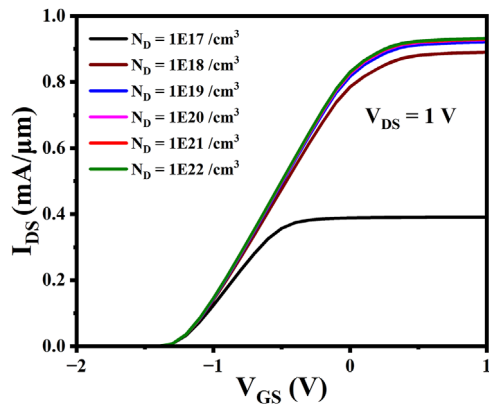


FIGURE 8
Variation of Transfer characteristics for different drain doping concentrations at $V_{DS} = 1$ V in GaN HEMTs without GaN cap layer.

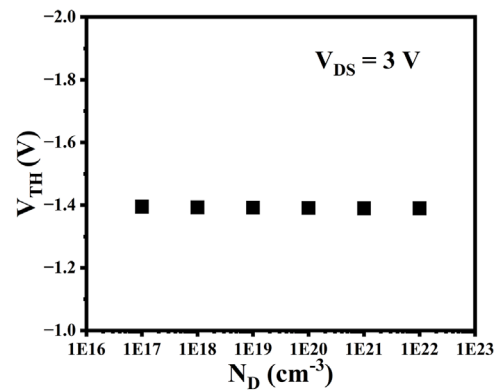


FIGURE 10
Variation of threshold voltage (V_{TH}) for different drain doping concentrations at $V_{DS} = 3$ V in GaN HEMTs without GaN cap layer.

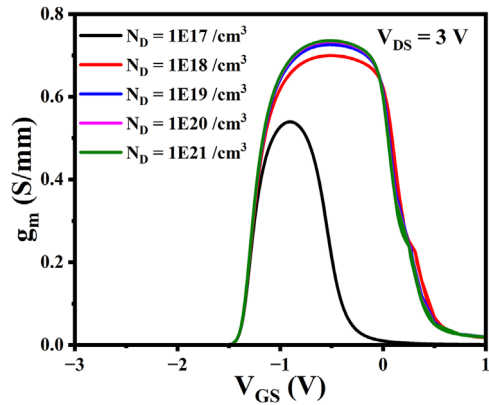


FIGURE 9
Variation of Transconductance (g_m) characteristics for different drain doping concentrations at $V_{DS} = 3$ V in GaN HEMTs without GaN cap layer.

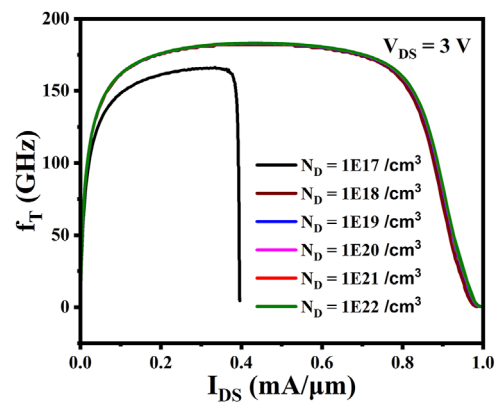


FIGURE 11
Variation of cut-off frequency (f_T) for different drain doping concentrations at $V_{DS} = 3$ V in GaN HEMTs without GaN cap layer.

The result suggests that higher doping levels improve the device's electrical characteristics by enhancing charge carrier mobility, thereby increasing the transconductance.

From Figure 10 observed that the threshold voltage remains nearly constant at approximately -1.4 V for $N_D = 10^{17} \text{ cm}^{-3}$ to $N_D = 10^{22} \text{ cm}^{-3}$. This indicates that the threshold voltage is not significantly influenced by changes in donor concentration within this range. The stability of V_{TH} suggests that the device maintains consistent switching characteristics regardless of variations in doping levels, which can be advantageous for ensuring uniform performance in applications where device consistency is crucial.

Figure 11 illustrates the relationship between the cut-off frequency (f_T) and the drain current density (I_{DS}) for different doping at $V_{DS} = 3$ V. These results indicate that the cut-off frequency is approximately same for $N_D = 10^{18} \text{ cm}^{-3}$ to for $N_D = 10^{22} \text{ cm}^{-3}$. At $N_D = 10^{17} \text{ cm}^{-3}$, the cut-off frequency reaches a peak value of 165 GHz. However, beyond this point, as I_{DS} continues to increase, f_T decreases significantly, due to parasitic effects such as self-heating

or increased channel resistance. For $N_D = 10^{22} \text{ cm}^{-3}$, the maximum cut-off frequency of 183.8 GHz at $V_{DS} = 3$ V.

To evaluate the significance of our findings, we performed a comparative analysis between GaN HEMTs without cap layer and state-of-the-art GaN HEMTs with cap layer. Table 1 presents the details of device parameters and performance metrics [9, 28, 29]. Our study highlights the exceptional DC performance of GaN HEMTs without GaN cap layer, achieving a peak drain current of $0.99 \text{ mA}/\mu\text{m}$ at $V_{GS} = 2$ V and a cut-off frequency of 183.8 GHz at $V_{DS} = 3$ V. Additionally, the devices exhibit a notably low on-state resistance, which plays a critical role in reducing power losses and improving overall efficiency. These findings suggest that, GaN HEMT without GaN cap layer have the potential to surpass existing RF transistor performance limits, paving the way for next-generation semiconductor technology in high-frequency, and MEMS applications.

TABLE 1 Comparison between GaN HEMT without cap layer and state-of-the-art GaN HEMTs with cap layer.

Parameters	This work (without GaN cap layer)	N-polar ALD HEMT [9]	High breakdown voltage N-polar HEMT [28]	N-Polar GaN/AlN MIS-HEMT [29]
L_G (nm)	100	200	1000	112
I_{DS} (mA/ μ m)	0.99 ($V_{GS} = 2$ V)	0.9 ($V_{GS} = 1$ V)	0.575 ($V_{GS} = 1$ V)	1.1 ($V_{GS} = 1$ V)
R_{on} (Ω . mm)	0.88 ($V_{GS} = 2$ V)	2 ($V_{GS} = 1$ V)	10 ($V_{GS} = 1$ V)	4 ($V_{GS} = 1$ V)
g_m (S/mm)	0.75 ($V_{DS} = 3$ V)	0.46 ($V_{DS} = 3$ V)	0.18 ($V_{DS} = 5$ V)	0.115 ($V_{DS} = 6$ V)
V_T (V)	−1.4	−1.75	−4.8	−8
f_T (GHz)	183.8 ($V_{DS} = 3$ V)	30.5 ($V_{DS} = 3$ V)	-	95 ($V_{DS} = 6$ V)

4 Conclusion

In summary, we have investigated the performance of nanostructure N-polar AlGaIn/GaN HEMTs with and without GaN cap layer, and focused on the effects of drain doping concentration. Devices without the GaN cap layer demonstrated improved electron mobility, reduced on-state resistance, and enhanced transconductance. The GaN HEMT without the cap layer achieved a peak drain current of 0.99 mA/ μ m and R_{on} of 0.88 Ω .mm at $V_{GS} = 2$ V. Additionally, higher doping concentrations improved current density and transconductance, reaching a peak current of 0.98 mA/ μ m at $N_D = 10^{22}$ cm^{−3} at $V_{DS} = 1$ V. The devices without the GaN cap layer exhibited enhanced high-frequency characteristics, with the maximum cut-off frequency reaching 183.8 GHz at $V_{DS} = 3$ V. Thus, it is conclude that the N-polar GaN HEMTs without a GaN cap layer, show strong potential for high-power, high-frequency, and N/MEMS sensor applications. These finding is crucial for optimizing the doping levels in semiconductor devices to achieve desired electrical performance.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

CD: Investigation, Methodology, Validation, Writing – original draft. KM: Formal Analysis, Supervision, Writing – review and editing.

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Conflict of interest

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