Characterization of GaN-based HEMTs Down to 4.2 K for Cryogenic Applications

Bolun Zeng, Haochen Zhang, Zikun Xiang, Chao Luo, Member, IEEE, Yuanke Zhang, Mingjie Weng, Qiwen Xue, Sirui Hu, Yue Sun, Lei Yang, Haiding Sun, Senior Member, IEEE, and Guoping Guo
University of Science and Technology of China, China
Email: lc0121@ustc.edu.cn, haiding@ustc.edu.cn

Abstract—The cryogenic performance of GaN-based HEMTs (high-electron-mobility transistors) is systematically investigated by the direct current (DC) and low-frequency noise (LFN) characteristics within the temperature (T) range from 300 K to 4.2 K. The important electrical merits of the device, including drain saturation current (I_{Dss}), on-resistance (R_{ON}), transductance, subthreshold swing (SS), gate leakage current, and Schottky barrier height, are comprehensively characterized and their temperature-dependent behavior was statistically analyzed. In addition, the LFN of the device shows an evident behavior of 1/f noise from 10 Hz to 10 kHz in the measured temperature range and can be significantly reduced at cryogenic temperature. These results are of great importance to motivate further studies into the GaN-based cryo-devices and systems.

Index Terms— cryogenic temperature, GaN-based HEMT, low-frequency noise, power spectral density.

I. INTRODUCTION

The prosperity of quantum computing technologies in recent years has greatly boosted the vigorous development of cryogenic electronics. Among the various device technologies, the wide bandgap semiconductor GaN-based HEMTs recently have emerged as one of the promising candidates in cryo-systems thanks to their superior material and device properties [1]-[3]. Several previous investigations have reported the electrical performance of GaN-based cryo-HEMTs operating at ~100 K temperatures[4]-[6]. In addition to the electrical properties, the LFN level of devices is regarded as a key parameter in the cryogenic electronic system, since it would contribute to the main part of the transistor comprehensive noise, given that the thermal noise and shot noise decrease at cryogenic temperature [7], [8]. Besides, the LFN measurements can evaluate the defect states in the devices and the device reliability [9]. Nevertheless, there are few studies into the LFN characteristics of GaN HEMTs in the cryogenic environment, especially at extremely low temperature down to 4.2 K.

In this work, we comprehensively investigated the DC and LFN behavior of the GaN-based HEMTs within the temperature range from 300 K to 4.2 K. As the temperature decreases, the devices exhibited an overall improved electrical performance, featuring a 60% increased I_{Dss}, steeper SS, suppressed leakage current by an order of magnitude, and a decreased R_{ON}. All these merits can be attributed to the suppressed lattice scattering and enhanced carrier mobility under cryogenic environments. Furthermore, the LFN of the devices is analyzed as a function of temperature, showing an evident behavior of 1/f noise. More importantly, the LFN level can be significantly reduced at cryogenic temperatures because of the reduced leakage current. In short, our work provides analysis of DC and LFN characterizations of GaN HEMTs down to 4.2 K, providing insights for the design of the future GaN-based cryo-HEMTs and electronic systems.

II. EXPERIMENTAL DETAILS

The HEMT structure was grown on GaN-on-sapphire template via metal-organic chemical vapor deposition (MOCVD), consisting of a unintentionally doped GaN, a 1 nm AlN spacer layer, a 20 nm Al_{0.3}Ga_{0.7}N barrier layer, and a 3 nm GaN cap layer, as shown in Fig. 1(a). The device fabrication started with the Cl_{2}-based dry etching for mesa isolation. The metal schemes for source/drain Ohmic contacts and gate Schottky contacts are Ti/Al/Ni/Au and Ni/Au and deposited by the e-beam evaporator. The gate width (W_g), gate length (L_g), and source-to-drain distance (L_{SD}) of the device under test (DUT) are 50/3/14 μm. The DC characteristics and LFN performance were tested by Keysight semiconductor device analyzer B1500A and Primarius Fs-Pro 380. The measurements were performed on Lakeshore probe station (Fig. 1(b)).

III. TEMPERATURE-DEPENDENT ELECTRICAL PERFORMANCE

Fig. 2(a) and (b) plot the output characteristics of the DUT at 300 K and 4.2 K, showing a 1.6-times-increased maximum I_{DS} from 500 to 808 mA/mm, thanks to the suppressed lattice scattering and enhanced carrier mobility at cryogenic
temperature [10]. Fig. 2(c) further compares the output curves at $V_{GS} = 1$ V under various $T$. Obviously, the current droop behavior at high drain voltage ($V_{DS}$), which is caused by self-heating effects [11], [12], is weakened under low temperature and nearly unobservable at $T \leq 100$ K.

![Graph](image)

**Fig. 2.** DC characteristics of the DUT under various $T$. Output characteristics at (a) 300 K and (b) 4.2 K. (c) Comparison of the output curves at $V_{GS} = 1$ V from 300 K to 4.2 K. The $T$-dependent (d) $I_{Dsat}$ and (e) $\Delta I_{Dsat}$ at $V_{GS} = 1$ V and $V_{DS} = 15$ V. Extracted (f) $R_{ON}$ and (g) $G_{DS}$ as a function of $T$.

We further extract the temperature-dependent behavior of the key parameters including $I_{Dsat}$ at $V_{GS} = 1$ V, $V_{DS} = 15$ V (Fig. 2(c)), $I_{Dsat}$ gain $\Delta I_{Dsat}$ (defined as $[I_{Dsat}(T) - I_{Dsat,300K}] / I_{Dsat,300K}$, Fig. 2(b)), $R_{ON}$ (Fig. 2(e)), and output conductance $G_{DS}$ (Fig. 2(d)), highlighting the significantly improved output characteristics of GaN-based HEMTs under cryogenic environments. Notably, it can be found that the change of $I_{Dsat}$ becomes slight when $T < 100$ K, as shown in Fig. 2(d) and Fig. 2(e), indicating that the carrier mobility would “saturate” at extremely low $T$ [10]. The extracted $R_{ON}$ at 4.2 K was 3.4 times reduced compared with that at 300 K, as shown in Fig. 2(f), showing the great potential of GaN HEMTs to realize low-loss switching in the cryo-system. In addition, the $G_{DS}$ at varied $T$ are smooth in the entire measured $V_{DS}$ range, benefiting the analog and RF applications to avoid harmonic signals [13].

Fig. 3(a) shows the temperature-dependent transfer characteristics ($I_{DS} - V_{GS}$) and calculated $G_{m} - V_{GS}$ curves of the DUT operating at the linear region ($V_{DS} = 0.5$ V). The $G_{m}$ peak was found improved with the decreased temperature and changed slightly when $T < 100$ K, conforming to the trend of $I_{Dsat}$. The transconductance efficiency ($G_{m} / I_{DS}$) shown in Fig. 3(b) manifests an evident enhancement at 4.2 K at the weak inversion bias.

In addition, a zero-temperature coefficient (ZTC) point of approximately $-4.5$ V can be obtained in Fig. 3(a). When $V_{GS} > ZTC$ point, $I_{DS}$ increases along with the decreased temperature due to the enhanced carrier mobility at cryogenic temperatures. Notably, $I_{DS}$ slightly drops at $V_{GS}$ close to 1 V due to the gate leakage current and can be suppressed at low temperature. When $V_{GS} < ZTC$ point, a positively shifted threshold voltage ($V_{TH}$) of 0.45 V from 300 K to 4.2 K can be observed, as plotted in Fig. 3(e). This temperature-dependent $I_{TH}$ can be attributed to the decreased two-dimensional electron gas (2DEG) density at low temperature caused by the inhibited detrapping process [14]. Plus, the electrons at cryogenic temperature would have insufficient energy to transport through the depletion region formed in the conductive channel, leading to a more positive $V_{TH}$. Furthermore, we extracted the low-field electron mobility ($\mu_0$) by a direct transconductance method [15], as plotted in Fig. 3(f). It can be observed that $\mu_0$ increases and gradually saturates at extremely low temperatures, conforming the same trend of $I_{Dsat}$.

![Graph](image)

**Fig. 3.** (a) The temperature-dependent $I_{DS} - V_{GS}$ and $G_{m} - V_{GS}$ curves in linear region ($V_{DS} = 0.5$ V). (b) The calculated transconductance efficiency ($G_{m} / I_{DS}$) at varied $T$ versus $V_{GS} - V_{TH}$ (c) The semi-logarithmic $I_{DS} - V_{GS}$ biased at linear region ($V_{DS} = 0.5$ V) and saturation region ($V_{DS} = 10$ V) at 4.2 K to calculate DIBL effect. (d) The temperature-dependent $I_{DS} - V_{GS}$ curves with floating $V_{TH}$. Extracted (e) $V_{TH}$, (f) $\mu_0$, (g) SS, and (h) $\phi$ as a function of $T$.

In Fig. 3(e), the semi-logarithm $I_{DS} - V_{GS}$ curves are depicted. The off-state drain leakage current ($I_{OFF}$) is found to be suppressed as the temperature decreases. This positive temperature coefficient (PTC) of $I_{OFF}$ is commonly observed in the GaN-based devices and can be normally explained by the two mechanisms: the bulk subthreshold leakage current and the Schottky-gate reverse bias tunneling leakage current [16]. The extracted subthreshold swing (SS) was improved by 64% at 4.2 K compared with that at 300 K, as shown in Fig. 3(g), suggesting the desirable potential for decreasing energy consumption and faster switching speed.
barrier lowering (DIBL) effect was characterized under 4.2 K as shown in the inset of Fig. 3(c), with a value of 4.21 mV/V. This value is significantly smaller than that of the Si-based MOSFETs [17, 18], which is one of the advantages of the power devices based on wide bandgap GaN over Si.

To further study the mechanisms of gate leakage, the temperature-dependent gate current curves ($I_G-V_{GS}$) are characterized in Fig. 3(d). The device was biased with floating $V_{DS}$ $(I_{DS} = 0 \ A)$. At the forward state ($V_{GS} > 0 \ V$), $I_G$ values are linear and negatively shifted with the increased temperature, indicating that the electron transport through the Ni/AlGaN junction is a thermally activated process conforming to the thermal emission (TE) model [19], as given by Equation 1,

$$I_G = A_e A' T^2 \exp\left(-\frac{q \phi_B}{kT}\right)\left(\exp\left(\frac{qV}{nkT}\right)-1\right)$$

where $A_e$, $A'$, $q$, $k_B$, and $n$ represent the Schottky contact area, Richardson constant (36 Å·cm$^{-2}$·K$^{-2}$ in this calculation), electronic charge, Boltzmann’s constant, and ideality factor, respectively. We further fitted the $I_G-V_{GS}$ curves using TE model and extracted Schottky barrier height ($\phi_B$) as plotted in Fig. 3(h). It is found that the $\phi_B$ value increases at high temperature. Such a $\phi_B$ variation is generally observed in the GaN-based HEMTs and Schottky barrier diodes (SBDs) and is normally explained by the interface inhomogeneity of the metal/AlGaN junction [19, 20]. At lower temperatures, carriers flow through the lower level of inhomogeneous Schottky contact. As the temperature rise, more electrons would gain enough energy to surmount the higher level of Schottky barrier, causing the Schottky barrier height to increase with the increment of temperature. More importantly, at the reverse state ($V_{GS} < 0 \ V$), $I_G$ reduces as the temperature decreases from 300 K to 4.2 K, as shown in Fig. 3(d), which might be attributed to the suppressed defect-assisted tunneling [21, 22] and/or thermal emission [5] at cryogenic temperature.

After analyzing the temperature-dependent electrical performance as well as the underlying physics mechanisms of the GaN-based HEMTs, we further investigated the LFN of the fabricated devices from 300 K to 4.2 K as below. Fig. 4(a) and (b) demonstrate the drain current power spectral density (PSD) as a function of frequency ($S_{IDS}$) for $V_{GS}$ varied from $-4.5 \ V$ to 1 V operating at $T = 300 \ K$ and 4.2 K, respectively. The value of $S_{IDS}$ demonstrates an evident flicker noise (1/f$^\gamma$, where $\gamma = 1$) behavior within the low-frequency range between 10 Hz and 10 kHz. In addition, the $S_{IDS}$ amplitude increases along with the $V_{GS}$, indicating a positive dependence of 1/f noise level of HEMTs on the drain current. This $S_{IDS} - I_{DS}$ correlation can further explain the phenomenon that the $S_{IDS}$ span of the device operating at 4.2 K is obviously larger than that at 300 K, which can be attributed to larger current variation within the measured $V_{GS}$ range, as shown in Fig. 3(c).

Fig. 5(a) and (b) display the drain current power spectral density normalized by the drain current squared as a function of frequency ($S_{IDS}/I_{DS}^2$) when the DUT were biased at the linear and saturation regions, respectively. The value of $S_{IDS}/I_{DS}^2$ also conforms the behavior of 1/f noise. The $\gamma$ is extracted and plotted in the inset of Fig. 5(a) and (b), showing constant ideal value of 1 from 300 K to 4.2 K, indicating that there is no Generation-Recombination (GR) noise in the fabricated devices. $S_{IDS}/I_{DS}^2$ was found to be reduced by about one order of magnitude at temperature down to 4.2 K, which can be explained by the lowered leakage current, together with the suppressed lattice scattering. This can be significantly beneficial to reduce the noise level of HEMTs at cryogenic temperature.

![Figure 4](image)

**Fig. 4.** The drain current power spectral density ($S_{IDS}$) versus frequency ($f$) acquired at (a) 300 K and (b) 4.2 K when the device was biased at different $V_{GS}$ ranging from $-4.5 \ V$ to 1 V, $V_{DS} = 0.1 \ V$.

Fig. 5(c) further plots the relationship of $S_{IDS}/I_{DS}^2$ against $I_{DS}$, considering that the LFN spectra at lower currents can be informative to analyze the trapping-detrapping of defect states in the devices due to the slower processes of carrier recombination process. It can be found that the $S_{IDS}/I_{DS}^2$ decreases with the increment of $I_{DS}$. In addition, the $S_{IDS}$ tends to be independent of temperature at higher current, which is probably because the noise dominated by series resistance in that region. Fig. 5(d) shows the drain voltage power spectral density as a function of frequency ($S_{VDS}$) at $V_{DS} - V_{TH} = 0.1 \ V$ and $V_{DS} = 0.1 \ V$ down to 4.2 K. $S_{VDS}$ also follows 1/f noise law and decreases with the temperature reduction about an order of magnitude.

![Figure 5](image)

**Fig. 5.** The normalized drain current power spectral density ($S_{IDS}/I_{DS}^2$) versus frequency ($f$) acquired from 300 K to 4.2 K when the device was biased at $V_{GS} - V_{TH} = 0.5$, $V_{GS} = (a) 0.1 \ V$ and (b) 10 V, respectively. Inset: $\gamma$ as a function of temperature with (a) $V_{GS} = 0.1 \ V$ and (b) $V_{GS} = 10 \ V$. (c) $S_{IDS}/I_{DS}^2$ as a function of $I_{DS}$, varying $T$, $V_{DS} = 0.1 \ V$, $f = 10 \ Hz$ during measurements. (d) The drain
voltage power spectral density \( S_0 \) at \( V_{DS} = 0.1 \, \text{V}, V_{GS} - V_{TH} = 0.5 \, \text{V} \) and varying \( T \) versus \( f \).

IV. CONCLUSIONS

In this work, we have performed a comprehensive characterizations and analysis into the DC and LFN properties of GaN-based HEMTs down to 4.2 K, demonstrating that GaN-based cryo-HEMTs possess superior device merits including the decreased drain current, decreased on-resistance, weakened self-heating effects, steeper SS, as well as significantly suppressed leakage current and reduced LFN level. Furthermore, the DIBL effect, SBH inhomogeneity, and LFN behavior within the temperature of 300 K to 4.2 K are characterized and investigated. Our results provide the insights into the physical mechanisms of GaN-based power devices under cryogenic environments and further highlight the great potential of such technologies for the cryo-systems.

REFERENCES

[1] H. Zhang, C. Huang, K. Song, H. Yu, C. Xing, D. Wang, Z. Liu, and H. Sun, “Compositionally graded III-nitride alloys: building blocks for effecient ultraviolet optoelectronics and power electronics,” Rep. Prog. Phys., vol. 84, no. 4, p. 044401, Mar. 2021, doi: 10.1088/1361-6633/abde93.

[2] C. Huang, H. Zhang, and H. Sun, “Ultraviolet optoelectronic devices based on AlGaN-SiC platform: Towards monolithic photonics integration system,” Nano Energy., vol. 77, p. 105149, Jul. 2020, doi: 10.1016/j.nanoen.2020.105149.

[3] L. Nela, N. Perera, C. Erine, and E. Matioli, “Performance of GaN Power Devices for Cryogenic Applications Down to 4.2 K,” IEEE Trans. Pow. Electron., vol. 36, no. 7, pp. 7412-7416, Jul. 2021, doi: 10.1109/TPele.2020.3047466.

[4] Y. Wang, Y. Gu, X. Lu, H. Jiang, H. Guo, B. Chen, K. M. Lau, and X. Zou, “Comparative Study on Dynamic Characteristics of GaN HEMT at 300K and 150K,” IEEE J. Electron Devices Soc., vol. 8, pp. 850-856, Aug. 2020, doi: 10.1109/EDS.2020.3013656.

[5] D. Bisi, S. Wienecke, B. Romanczyk, H. Li, E. Ahmadi, S. Keller, M. Guidry, C. De Santi, M. Meneghini, G. Meneghesso, U. K. Mishra, and E. Zanoni, “Observation of \( I_{D}-V_{G} \) Kink in N-Polar GaN MIS-HEMTs at Cryogenic Temperatures,” IEEE Electron Device Lett., vol. 41, no. 3, pp. 345-348, Mar. 2020, doi: 10.1109/LED.2020.2968875.

[6] H. Guo, J. Zhou, M. Wang and X. Zou, “Output Phase and Amplitude Analysis of GaN-Based HEMT at Cryogenic Temperatures,” IEEE Microwave Wireless Compon. Lett., vol. 31, no. 11, pp. 1219-1222, Nov. 2021, doi: 10.1109/LMWC.2021.3079222.

[7] T. Struck, A. Hollmann, F. Schauer, O. Fedorets, A. Schmidbauer, K. Sawano, H. Riemann, N. V. Abrosimov, L. Cywiński, D. Bougeard, and L. R. Schreiber, “Low-frequency spin qubit energy splitting noise in highly purified \( \text{Si}/\text{SiGe} \),” npj Quantum Inform., vol. 6, no. 1, pp. 1-7, May 2020, doi: 10.1038/s41534-020-0276-2.

[8] K. Takeda, T. Ohata, and Y. Fukaoaka, “Characterization and suppression of low-frequency noise in \( \text{Si}/\text{SiGe} \) quantum point contacts and quantum dots,” Appl. Phys. Lett., 2013, vol. 102, no. 12, p. 123113, Mar. 2013, doi: 10.1063/1.4799287.

[9] S. Mouetis, F. Zouache, and D. Rechem, “Flcker noise in AlGaAs/GaAs of high electron mobility heterostructure field-effect transistor at cryogenic temperature,” 48th International Convention on Information and Communication Technology, Electronics and Microelectronics (MIPRO), pp. 53-56, 2017, doi: 10.23919/MIPRO.2017.7973390.

[10] I. P. Smorchkova, C. R. Elsasser, J. P. Ibbetson, R. Vetur, B. Heying, P. Fini, I. Haus, S. P. DenBaars, J. S. Speck, and U. K. Mishra, “Polarization-induced charge and electron mobility in AlGaN/GaN heterostructures grown by plasma-assisted molecular-beam epitaxy,” J. Appl. Phys., vol. 86, pp. 4520-4526, 1999, doi: 10.1063/1.371396.

[11] A. W. Curtin, E. Gebara, J. Laskar and H. M. Harris, “Study of self-heating effects, temperature-dependent modeling, and pulsed load-pull measurements on GaN HEMTs,” IEEE Trans. Microw. Theory Tech., vol. 49, no. 12, pp. 2413-2420, Dec. 2001, doi: 10.1109/22.971629.

[12] S. Garcia-Sanchez, I. Iniguez-de-la-Torre, S. Perez, K. Ranjan, M. Agrawal, R. Lingaparthi, D. Nethaji, K. Radhakrishnan, S. Arulkumaran, G. I. Ng, T. Gonzalez, and J. Mateos, “Non-linear thermal resistance model for the simulation of high power GaN-based devices,” Semicond. Sci. Technol., vol. 36, no. 5, p. 055002, Mar. 2021, doi: 10.1088/1361-6641/abe883.

[13] B. Patra, “CMOS circuits and systems for cryogenic control of silicon quantum processors,” TU Delft. 2021. doi: 10.4233/uid/cce59727-fda2-41e1-ba87-9404e22202d.

[14] A. Chakraborty, S. Ghosh, P. Mukhopadhyay, S. Das, and D. Biswas, “Effect of trapped charge in AlGaN/GaAs and AlGaN/InGaN/GaN heterostructure by temperature dependent threshold voltage analysis,” Superlattice Microst., vol. 113, pp. 147-152, Oct. 2018, https://doi.org/10.1016/j.spmi.2017.10.033.

[15] B. L. Anderson and R. L. Anderson, “Fundamentals of Semiconductor Devices,” New York, NY, USA: McGraw-Hill, 2005.

[16] E. Bahat-Treidel, “GaN-Based HEMTs for High Voltage Operation Design, Technology and Characterization”, PhD. Dissertation, Berlin University, 2012.

[17] Y. Zhang, T. Lu, W. Wang, Y. Zhang, J. Xu, C. Luo, and G. Guo, “Characterization and Modeling of Native MOSFETs Down to 4.2 K,” IEEE Trans. Electron Devices, vol. 68, no. 9, pp. 4267-4273, Sptet, 2021, doi: 10.1109/TED.2021.3099775.

[18] C. Luo, Z. Li, T. Lu, J. Xu, and G. Guo, “MOSFET characterization and modeling at cryogenic temperatures,” Cryogenics., vol. 98, pp. 12-17, Mar. 2019, doi: 10.1016/j.cryogenics.2018.12.009.

[19] T. Tu, X. Li, J. Wu, J. Yang, Y. Lu, X. Liu, and J. P. Ao, “Recessed Anode AlGaN/GaN Schottky Barrier Diode for Temperature Sensor Application,” IEEE Trans. Electron Devices., vol. 68, no. 10, pp. 5162-5166, Oct. 2021. doi: 10.1109/TED.2021.3105498.

[20] J. P. Sullivan, R. T. Tung, M. R. Pinto, and W. R. Graham, “Electron transport of inhomogeneous Schottky barriers,” J. Appl. Phys., 1991, vol. 70, no. 12, pp. 7403-7424, doi: 10.1063/1.349737.

[21] B. Ssa, B. Of, and B. Hm, “Effects of current transportation and deep traps on leakage current and capacitance hysteresis of AlGaN/GaN HEMT,” Mater. Sci. Semicond. Process., vol. 115, pp. 1369-8001, Apr. 2020, doi: 10.1016/j.mssp.2020.105100.

[22] S. Saadouni, M. B. Salem, M. Gissoumi, H. Maaref, and C. Gaquiere, “Anomaly and defects characterization by I-V and current deep level transient spectroscopy of Al\(_{0.5}\)Ga\(_{0.5}\)N/GaN/SiC high electron-mobility transistors,” J. Appl. Phys., vol. 111, no. 7, p. 073713, Apr. 2012, doi: 10.1063/1.3702458.