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Abstract

This paper presents a simulation study to achieve wide-linear-range transconductance of T-gate GaN HEMTs by introducing a o-doped layer and a p-GaN back barrier. With optimized o-doping density and location, the transconductance (gm) and current gain cutoff frequencies (fr) are ultra-flat and remain close to their peak values over a wide range of gatesource voltages (Vgs). In addition, a smaller absolute gm3 (thirdorder derivative of the Ids-Vgs curve) over a wide range of Vgs is obtained in proposed HEMTs. These features are valuable in designing highly linear RF AlGaN/GaN HEMTs.

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Simulation of GaN HEMT with Wide-Linear-Range Transconductance

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***Abstract*—This paper presents a simulation study to achieve wide-linear-range transconductance of T-gate GaN HEMTs by introducing a δ-doped layer and a p-GaN back barrier. With optimized δ-doping density and location, the transconductance (g_m) and current gain cutoff frequencies (f_T) are ultra-flat and remain close to their peak values over a wide range of gate-source voltages (V_{gs}). In addition, a smaller absolute g_{m3} (third-order derivative of the I_{ds}-V_{gs} curve) over a wide range of V_{gs} is obtained in proposed HEMTs. These features are valuable in designing highly linear RF AlGaN/GaN HEMTs.**

***Keywords*—GaN HEMTs, Delta-doping, Back-barrier, Linear transconductance**

I. Introduction

With excellent performance in high-power, high-voltage operations at microwave frequencies, GaN-based high electron mobility transistors (HEMTs) have been regarded as one of the most promising candidates for next-generation RF/microwave power amplifiers. Linearity is an important factor for RF power amplifiers due to the large dynamic range in the high variable envelop of the modulation signals. An ideally linear FET device would possess constant drain transconductance (g_m) over a wide range of input gate–source voltages [1]. The problems in achieving flat transconductance include (1) small absolute distance between 2DEG channel and gate [2], (2) increase of the access resistance at high drain current levels caused by quasi-saturation of electron velocity [3], and (3) large transverse electric-field (E-field) perpendicular to the channel and at high current levels [4]. It is reported that linearity can be enhanced by enlarging the absolute distance between 2DEG channel and gate through controlling the barrier thickness of GaN HEMT or implementing n-doped GaN cap above AlGaN barrier or a combination [2]. Other methods of improving the linearity are reported by using field plate [5] or modifying the access resistance [3]. Moreover, a composite-channel design by inserting an AlGaN layer with low-Al composition in the channel region was shown to exhibit higher linearity [4], due to the formation of a secondary channel that reduces transverse electric field in the 2DEG channel.

Another possible way to create a secondary channel is by introducing heavy n-type doping in the GaN layer close to 2DEG channel. Linearity improvement has been reported in AlGaN/GaN HEMT with buffer structure of i-GaN/n-GaN/i-GaN layers (i-n-i buffer) [6], where the thin n-GaN in the buffer modulates the band diagram to achieve a wider region of g_m profile. However, due to low uniform doping density of the n-GaN in the buffer, a secondary channel is not formed and the improvement of device linearity is limited. Delta doping (δ-doping) is an attractive technique to significantly increase doping density [7]. Si δ-doping in GaN layer can reach a sheet concentration as high as 1×10^{12} cm^{-2} to 2×10^{13} cm^{-2} [8, 9], while the Si uniform-doping in GaN can only achieve concentration up to a few 10^{19} cm^{-3} (sheet concentration of a few 10^{12} cm^{-2}) [10, 11]. In addition, high density uniform doping in GaN film would introduce significant amount of strain which can cause cracking of layers [10], while Si δ-doping is a method to reduce tensile stress while obtaining high doping density [12].

In this work, we propose a T-gate AlGaN/GaN HEMT with n-type δ-doped GaN buffer layer and p-GaN back barrier. The n-type δ-doping creates a secondary channel close to the 2DEG channel while the conduction band deep into the buffer is lifted up by the p-GaN back barrier to suppress buffer leakage and short channel effect. The most important feature for the proposed HEMT is that the transcondutance (g_m) and cutoff frequencies (f_T) are ultra-flat and remain close to their peak values over a wide range of gate–source voltages (V_{gs}). In addition, a smaller magnitude of g_{m3} (third-order derivative of the I_{ds}-V_{gs} curve) over a wide range of V_{gs} has been obtained in the proposed HEMTs, which would be beneficial to achieve a higher third-order intercept point (IP3).

II. SIMULATION STRUCTURE

The schematic cross-section of the proposed T-gate AlGaN/GaN HEMT is shown in Fig. 1. The sample includes a 1.8 μm p-GaN back barrier with doping density of 1×10^{17} cm^{-3}, followed by an unintentionally-doped (UID) GaN buffer and AlGaN barrier layer. The barrier layer consists of a 3 nm UID $Al_{0.3}Ga_{0.7}N$ spacer, a 20 nm $Al_{0.3}Ga_{0.7}N$ n-doped region ($N_d = 2\times10^{18}$ cm^{-3}), and a 2 nm UID $Al_{0.3}Ga_{0.7}N$ cap layer. In this work, a heavily n-type δ-doped layer of 1 nm and doping densities of 6×10^{19} cm^{-3} (sheet doping density of 6×10^{12} cm^{-2}) is introduced in GaN buffer with distance of 25 nm away from the AlGaN/GaN interface. A conventional HEMT with 25 nm UID-$Al_{0.3}Ga_{0.7}N$ barrier on 2 μm UID-GaN buffer is also simulated for comparison. For all the simulated structures, the source/gate spacing (L_{gs}) is fixed at 1.0 μm and gate/drain spacing (L_{gd}) is 2.0 μm. The left/right part of T shape gate

L_g1/L_g3 are fixed at 0.05/0.1 μm, respectively, and center part of gate L_g2 varies from 0.1 to 0.3 μm. Moreover, the height of source/drain (H_2) is 0.2 μm, and the lower/upper height of gate (H_1/H_3) is 0.1/0.2 μm, respectively. The whole device is covered by 0.5 μm Si_3N_4 as surface passivation. The numerical simulations are carried out by SILVACO ATLAS. Shockley–Read–Hall, Fermi–Dirac statistics, Auger Recombination and self-heating models are enabled. The primary channel 2DEG density of the proposed HEMT is calculated by ATLAS to be 1.3×10^{13} cm^{-2}, which agrees well with the sheet electron density reported from experiment [4].

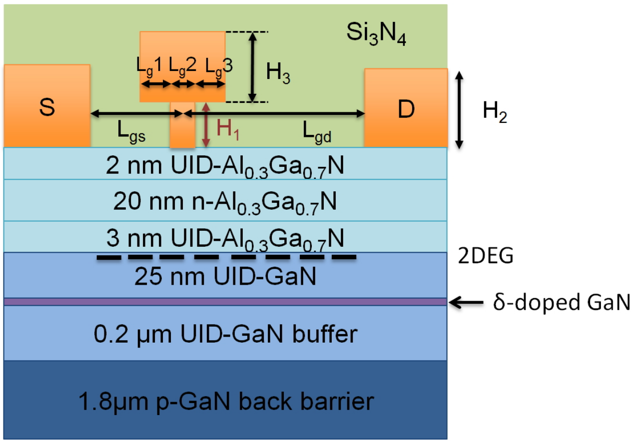

Figure 1 Schematic cross section of the proposed T-gate AlGaN/GaN HEMT.

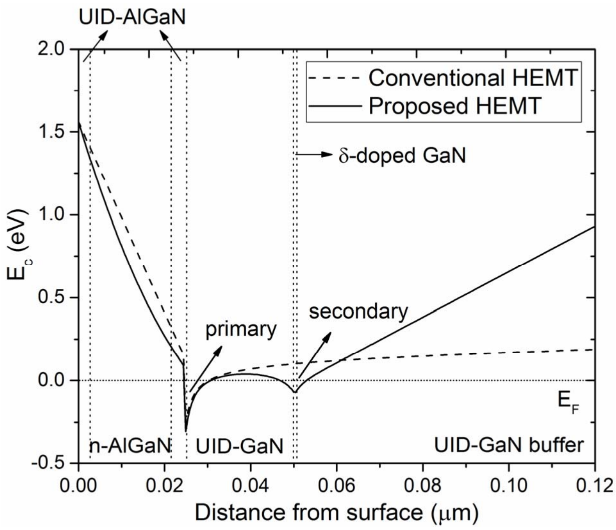

Figure 2 Conduction band diagrams of the proposed structure and conventional structure.

III. Characteristics and Discussion

Fig. 2 shows the simulated conduction band diagram under the gate of the proposed HEMT and conventional HEMT. In the conventional HEMT, carriers are only located at the primary channel at AlGaN/GaN interface. By inserting an n-type δ-doped GaN layer in the buffer, a secondary channel is created in the proposed HEMT. Under on-state condition, carriers can transit smoothly between the primary and secondary channels due to very low barrier height between them. On the other hand, the conduction band of conventional HEMT is relatively flat in GaN buffer. Therefore, the electrons in the 2DEG channel would easily spill over to the buffer region under bias condition, leading to current flowing within the GaN buffer. The situation would be more serious when the gate length is small (under 0.2 μm), in which short channel effect would dominate. By introducing a p-GaN back barrier [13], the conduction band of proposed HEMT is pulled up, resulting in much better electron confinement in both primary and secondary channels. The carrier spill-over and short channel effect can be suppressed to some extent.

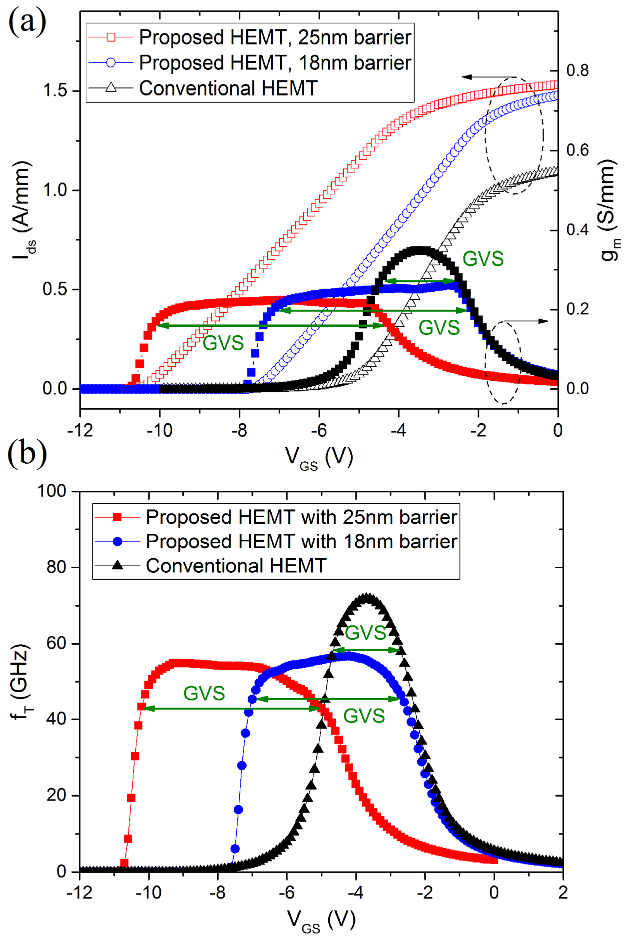

Figure 3 (a) transfer characteristics, (b) current gain cutoff frequencies of conventional structure and proposed structure with 18 or 25nm barrier, L_g2=0.2 μm. The ac simulation was conducted at f = 1 MHz.

The transfer characteristics of the proposed HEMTs and conventional HEMT at V_{ds} = 3V are plotted in Fig. 3 (a). The thickness of AlGaN barrier layer in conventional HEMT is 25 nm, while two different barrier thicknesses of 18 nm and 25 nm are introduced in the proposed HEMTs (13 nm and 20 nm n-AlGaN n-doped layers) for comparison. The threshold voltages (V_{th}) of conventional HEMT and proposed HEMT with 18 nm and 25 nm barrier are -5.8 V, -7.9 V and -10.8 V, respectively. The negative shift of threshold voltages in proposed HEMTs is due to the formation of the secondary channel and therefore, more electrons under the gate electrode. It can be seen that nearly flat g_m are achieved over a wide gate bias (V_{gs}) range in the two proposed HEMTs, which is a desirable feature for linear operation. It has been demonstrated that the increase in the access resistance as drain current increasing plays an important role in the decrease of g_m in AlGaN/GaN HEMTs [14]. The flatter g_m in proposed HEMT can be ascribed to tailor of access resistance by forming the secondary channel, make it more independent of the drain current [3]. To quantitatively compare the linearity of transcondutance, we adopt figure of merit of gate-voltage swing (GVS), which is defined as the range of the gate voltage where the device parameter drops to 80% of its peak value [15]. The corresponding GVS for g_m of the proposed HEMTs with 25 nm and 18 nm barrier are 5.6 V (from -10 to -4.4 V) and 4.8 V (from -7 to -2.2 V), which are ~2 and ~1.5 times higher than the 1.9 V (from -4.4 to -2.5 V) observed in the conventional HEMT, respectively.

The intrinsic cutoff frequency f_T is defined as the frequency when the current gain is unity and it is an important measurement for RF applications. Device transfer characteristics are simulated in ac mode, and g_m and gate capacitances C_{gd} and C_{gs} were extracted as a function of V_{gs}. The intrinsic cutoff frequency f_T was calculated by [13]

$$f_T = \frac{g_m}{2\pi C_{gs}\sqrt{1+2(C_{gd}/C_{gs})}} \quad (1)$$

Fig. 3 (b) shows f_T as a function of V_{gs} for conventional HEMT and proposed HEMTs. Relatively flat f_T is obtained for the two proposed HEMTs from low to high current levels, while the conventional HEMT shows the peak at V_{gs} = -3.7 V and drops significantly at high current levels. The corresponding GVS for f_T in the conventional HEMT is 2.1 V (-4.7 to -2.6 V). And GVS in the proposed HEMTs with 18 nm and 25 nm barrier are 4.4 V (from -7 to -2.6 V) and 5.1 V (from -10.2 to -5.1 V), respectively. The highly flat f_T of proposed HEMTs is associated with higher linearity for both g_m and gate-source capacitance.

The δ-doping density and location to the primary channel has to be carefully optimized to achieve flat g_m over wide range of V_{gs}. Fig. 4 (a) and Fig. 4 (b) show simulated g_m as a function of δ-doping density and delta doping location in proposed HEMT with 25 nm barrier. The g_m of conventional HEMT is also added for comparison. Firstly, the delta doping location is fixed at 25 nm away from AlGaN/GaN interface (primary channel). As the sheet density of delta doping increases from 4×10^{12} cm^{-2} to 6×10^{12} cm^{-2}, it can be seen in Fig. 4 (a) that the original g_m peak around V_{gs} = -5 V reduces and another g_m peak at negative side of V_{gs} increases gradually, which is due to the modulation of access resistance by conduction in secondary channel. However, as delta doping density further increases to 8×10^{12} cm^{-2}, g_m shows a two-peak behavior rather than a flat region. This double-hump behavior in the g_m versus gate bias curve is commonly observed in double channel GaN HEMTs [16], which corresponds to the effective gate modulation of the primary and secondary channel respectively. The two-peak behavior would cause large on-resistance and kinks in the linear region of the I_{ds}-V_{ds} output curves [17], which is harmful for device linearity. On the other hand, the two-peak behavior is also observed when δ-doping density is fixed at 6×10^{12} cm^{-2} while δ-doping location to primary channel is beyond 30 nm (shown in Fig. 4 (b)). To achieve linear transconductance, the optimized δ-doping sheet density and location to AlGaN/GaN interface are determined to be 6×10^{12} cm^{-2} and 25 nm, respectively.

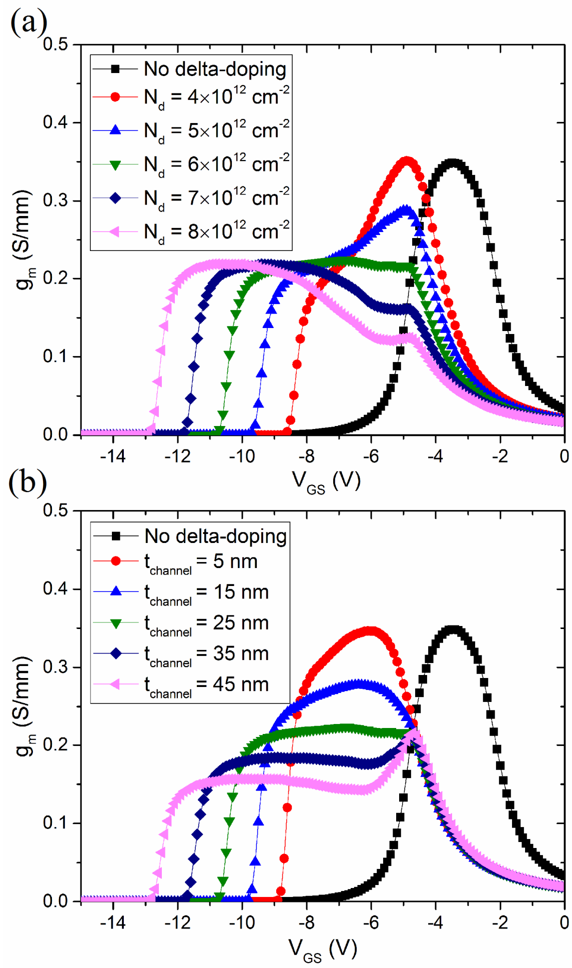

Figure 4 Simulated transconductance (g_m) as a function of (a) delta doping density in buffer and (b) delta doping location to AlGaN/GaN interface in proposed HEMT with 25 nm barrier.

In order to achieve a high third-order intercept point (IP3) for linear power amplifier application, the magnitude of third derivative of the I_{ds}-V_{gs} curve (g_{m3}) should be minimized [18]. Fig. 5 (a) plots the g_{m3} as a function of V_{gs} in conventional HEMT and proposed HEMT without p-GaN back barrier. It can be seen that the proposed devices without back barrier has an overall lower magnitude g_{m3} curve over a wider range of V_{gs} than it in conventional device. The g_{m3} peak reductions are ~73% and ~65% in devices with 25 nm and 18 nm barrier, respectively. For the proposed HEMTs with back barrier, the carrier confinement is enhanced thus subthreshold slope of transfer curve becomes sharper. This results in an increase of g_{m3} peak near the threshold voltage (shown in Fig. 5 (b)), however, the g_{m3} peak value is still at least ~28% and ~36% lower in proposed HEMT with 18 nm and 25 nm than in conventional HEMT, respectively. It should be noted that more detailed two-tone intermodulation characteristics has to be carried out to further confirm linearity improvement for power amplifier application.

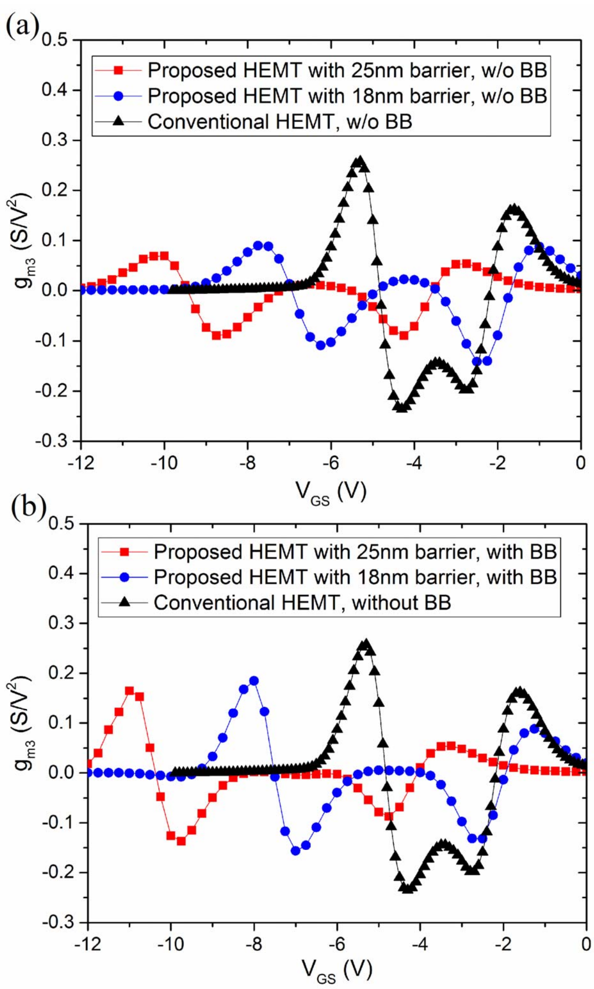

Figure 5 Simulated g_{m3} as a function of gate–source voltage in conventional HEMT and proposed HEMT (a) without back barrier and (b) with back barrier

IV. CONCLUSION

In conclusion, we proposed an AlGaN/GaN HEMT with an n-type delta-doped GaN buffer layer and a p-GaN back barrier. DC and AC simulations show that transconductance (g_m) and cutoff frequencies (f_T) can be maintained near their peak values with wide range of V_{gs} (from low to high current levels). And the flat region of g_m can be modified by delta-doping location and density. A lower magnitude g_{m3} over a wide range of V_{gs} has been obtained in proposed HEMTs than conventional HEMT. These results are especially valuable for designing highly linear RF AlGaN/GaN HEMTs.

REFERENCES

[1] W. Nagy, J. Brown, R. Borges, and S. Singhal, "Linearity Characteristics of Microwave-Power GaN HEMTs", *IEEE Trans. Microw. Theory Techn.*, vol. 51, no. 2, pp. 660-664, Feb. 2003.

[2] I. Khalil, E. B. -Treidel, F. Schnieder, and J. Würfl, "Improving the Linearity of GaN HEMTs by Optimizing Epitaxial Structure", *IEEE Trans. Electron Devices*, vol. 56, no. 3, pp. 361-364, March 2009

[3] T. Palacios, A. Chini, D. Buttari, S. Heikman, A. Chakraborty, S. Keller, S. P. DenBaars, and U. K. Mishra, "Use of Double-Channel Heterostructures to Improve the Access Resistance and Linearity in GaN-Based HEMTs", *IEEE Trans. Electron Devices*, vol. 53, no. 3, pp. 562-565, March 2006

[4] J. Liu, Y. Zhou, R. Chu, Y. Cai, K. J. Chen, and K. M. Lau, "Highly Linear $Al_{0.3}Ga_{0.7}N$–$Al_{0.05}Ga_{0.95}N$–GaN Composite-Channel HEMTs", *IEEE Electron Device Lett.*, vol. 26, no. 3, pp. 145-147, March 2005

[5] Y. F. Wu, A. Saxler, T. Wisleder, M. Moore, R. P. Smith, S. Sheppard, P. M. Chavarkar, and P. Parikh, "Linearity performance of GaN HEMTs with field plates," in *Proc. Device Research Conf.*, Notre Dame, IN, 2004, pp. 35–36.

[6] K. Inoue, H. Yamamoto, K. Nakata, F. Yamada, T. Yamamoto, and S. Sano, "Linearity Improvement of GaN HEMT for RF Power Amplifiers", in *IEEE Compound Semiconductor Integrated Circuit Symposium (CSICS)*, Monterey, CA, 2013, pp. 1-4.

[7] C. Tang, J. Shi, "Influence of delta doping on intersubband transition and absorption in AlGaN/GaN step quantum wells for terahertz applications", *Physica E,* vol. 69, pp. 96-100, May 2015.

[8] H. P. D. Schenk, A. Bavard, E. Frayssinet, X. Song, F. Cayrel, H. Ghouli, M. Lijadi, L. Naim, M. Kennard, Y. Cordier, D. Rondi, and D. Alquier, "Delta-Doping of Epitaxial GaN Layers on Large Diameter Si(111) Substrates", *Appl. Phys. Expr.* vol. 5, no. 2, pp. 025504, Feb. 2012.

[9] S C P Rodrigues, A L Rosa, L M R Scolfaro, D Beliaev, J R Leite, R Enderlein and J L A Alves, "Miniband structures and effective masses of n-type δ-doping superlattices in GaN", *Semicond. Sci. Technol.* vol. 13, no. 9, pp. 981-988, Sep. 1998.

[10] J. Sánchez-Páramo, J. M. Calleja, M. A. Sánchez-García and E. Calleja, "Optical investigation of strain in Si-doped GaN films", *Appl. Phys. Lett.* vol. 78, no. 26, pp. 4124-4126, Jun. 2001.

[11] S. Fritze, A. Dadgar, H. Witte, M. Bügler, A. Rohrbeck, J. Blasing, A. Hoffmann, and A. Krost, "High Si and Ge n-type doping of GaN doping - Limits and impact on stress", *Appl. Phys. Lett.* vol. 100, pp. 122104, 2012

[12] P. Xiang, Y. Yang, M. Liu, W. Chen, X. Han, Y. Lin, G. Hu, G. Hu, H. Luo, J. Jiang, J. Lin, Z. Wu, Y. Liu and B. Zhang, "Influences of periodic Si delta-doping on the characteristics of n-GaN grown on Si (111) substrate", *J. Cryst. Growth*, vol. 387, pp. 106–110, 2014

[13] S. Adak, A. Sarkar, S. Swain, H. Pardeshi, S. K. Pati, and C. K. Sarkar, "High performance AlInN/AlN/GaN p-GaN back barrier gate-recessed enhancement-mode HEMT," *Superlattices Microstruct.*, vol. 75, pp. 347–357, Nov. 2014

[14] T. Palacios, S. Rajan, A. Chakraborty, S. Heikman, S. Keller, S. P. DenBaars, and U. K. Mishra, "Influence of the dynamic access resistance in g_m and f_T linearity of AlGaN/GaN HEMTs," *IEEE Trans. Electron Devices*, vol. 52, no. 12, pp. 2117–2123, Dec. 2005

[15] Z. H. Liu, G. I. Ng, S. Arulkumaran, Y. K. T. Maung, K. L. Teo, S. C. Foo, and V. Sahmuganathan, "Improved Linearity for Low-Noise Applications in 0.25-μm GaN MISHEMTs Using ALD Al_2O_3 as Gate Dielectric", *IEEE Electron Device Lett.*, vol. 31, no. 8, pp. 803-805, Aug. 2010

[16] R. Chu, Y. Zhou, J. Liu, D. Wang, K. J. Chen, and K. M. Lau, "AlGaN-GaN Double-Channel HEMTs", *IEEE Trans. Electron Dev.*, vol. 52, no. 4, pp. 438-446, April. 2005

[17] R. Gaska, M. S. Shur, T. A. Fjeldly, and A. D. Bykhovski, "Two-channel AlGaN/GaN heterostructure field effect transistor for high power applications", *J. Appl. Phys.*, vol. 85, no. 5, pp. 3009-3011, Mar. 1999

[18] S. A. Maas. *Nonlinear microwave and RF circuits*. Norwood, MA: Artech House, 1988