# 30-GHz Low-Noise Performance of 100-nm-Gate-Recessed n-GaN/AlGaN/GaN HEMTs

Chia-Ta Chang, Heng-Tung Hsu, *Senior Member, IEEE*, Edward Yi Chang, *Senior Member, IEEE*, Chien-I Kuo, Jui-Chien Huang, Chung-Yu Lu, and Yasuyuki Miyamoto, *Senior Member, IEEE*

***Abstract*—We demonstrate a 100-nm-gate-recessed n-GaN/AlGaN/GaN high-electron mobility transistor (HEMT) with low-noise properties at 30 GHz. The recessed GaN HEMT exhibits a low ohmic-contact resistance of 0.28 $\Omega \cdot$ mm and a low gate leakage current of 0.9 $\mu$A/mm when biased at $V_{GS} = -3$ V and $V_{DS} = 10$ V. At the same bias point, a minimum noise figure of 1.6 dB at 30 GHz and an associated gain of 5 dB were achieved. To the best of our knowledge, this is the best noise performance reported at 30 GHz for gate-recessed AlGaN/GaN HEMTs.**

***Index Terms*—AlGaN/GaN, high-electron mobility transistor (HEMT), noise figure, recessed gate.**

## I. Introduction

THE NEED for on-demand broadband capacity for all types of communication has led to the development of a broadband radio-based access network communication system that is capable of providing tens of megabits per second in the downlink stream [1]. The local multipoint distribution system (LMDS) with frequency bands allocated at 28–29 GHz in the U.S. and at 40.5–42.5 GHz in Europe is one such system based on cellular architecture offering flexible high-capacity connections.

In point-to-point LMDSs, RF front-end technology is the key for such systems to meet the stringent requirements of broadband performance; this is particularly true in the case of the receiving chain where minimum signal distortion is a must for the received signals. Thus, low-noise amplifiers with high linearity play a critical role in such systems. Toward this purpose, low-noise GaN device technology is certainly a promising candidate because it can provide low-noise and high-power performance by biasing at high drain voltages.

Manuscript received October 5, 2009; revised November 9, 2009. First published December 22, 2009; current version published January 27, 2010. This work was supported in part by the National Science Council under Contracts NSC98-2923-E-009-002-MY3 and NSC98-2221-E-155-069 and in part by the Ministry of Education, Culture, Sports, Science and Technology (MEXT), Japan, through the Nanotechnology Network Project. The review of this letter was arranged by Editor J. A. del Alamo.

C.-T. Chang, C.-I Kuo, J.-C. Huang, and C.-Y. Lu are with the Department of Materials Science and Engineering, National Chiao Tung University, Hsinchu 300, Taiwan (e-mail: picben.mse93g@nctu.edu.tw; g904514@alumni.nthu.edu.tw; crazyfighter.mse90g@nctu.edu.tw; tzongywh.mse91g@nctu.edu.tw).

E. Y. Chang is with the Department of Materials Science and Engineering and the Department of Electronics Engineering, National Chiao-Tung University, Hsinchu 300, Taiwan (e-mail: edc@mail.nctu.edu.tw).

H.-T. Hsu is with the Department of Communications Engineering, Yuan Ze University, Chung-Li 32003, Taiwan (e-mail: htbeckhsu@saturn.yzu.edu.tw).

Y. Miyamoto is with the Department of Physical Electronics, Tokyo Institute of Technology, Tokyo 152-8552, Japan (e-mail: miya@pe.titech.ac.jp).

Color versions of one or more of the figures in this letter are available online at http://ieeexplore.ieee.org.

Digital Object Identifier 10.1109/LED.2009.2037167

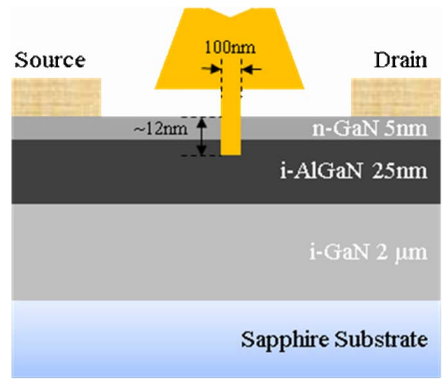


Fig. 1. Cross section of the 100-nm-gate-recessed n-GaN/AlGaN/GaN HEMT.

The power performance of gate-recessed AlGaN/GaN high-electron mobility transistors (HEMTs) at 30 GHz has been reported, and the results demonstrate that they are suitable for high-frequency and high-power applications [2]. For low-noise performance, GaN-based HEMTs can achieve a minimum noise figure $(NF_{\min})$ of less than 2 dB over the frequency of 10–20 GHz [3]–[6]. These results were achieved without a recessed gate, and short-channel effects were observed when the gate length was scaled down to the deep-submicrometer range. This letter proposes a heavily Si-doped GaN cap layer and a recessed gate to demonstrate the potential of GaN-based HEMTs for low-noise applications up to 30 GHz.

## II. Device Fabrication

The AlGaN/GaN heterostructure was grown on a 3-in (0001) sapphire substrate using metal–organic chemical vapor deposition. The epitaxial structure consisted of a nucleation layer, a 2-$\mu$m-thick GaN buffer layer, a 25-nm-thick $Al_{0.25}GaN_{0.75}N$ barrier layer, and a 5-nm-thick Si-doped $(3 \times 10^{18}\ \text{cm}^{-3})$ GaN cap layer, as shown in Fig. 1. The heavily Si-doped cap layer was proposed to reduce contact resistance [7].

The HEMT device fabrication started with ohmic-contact formation. Ti/Al/Ni/Au metal stacks (20/120/25/100 nm) were evaporated as ohmic metals and subsequently annealed at

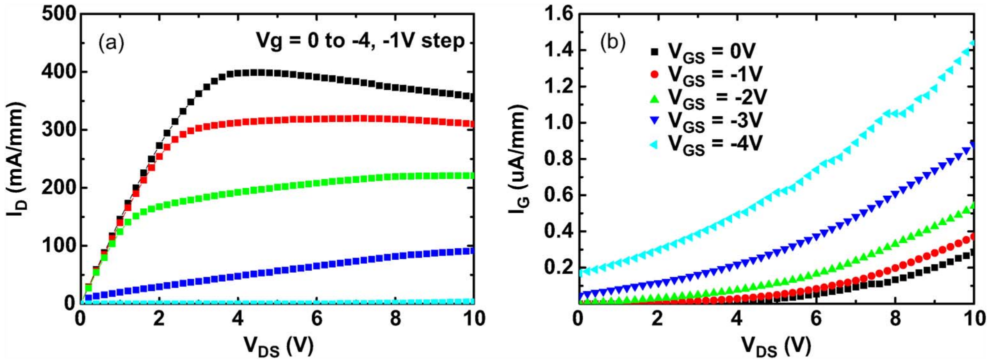


Fig. 2. (a) DC forward characteristics of the 100-nm-gate-recessed n-GaN/AlGaN/GaN HEMT. The source–drain spacing and device size are 7 $\mu$m and 2 × 50 $\mu$m, respectively. (b) Gate leakage current density during the device operation.

800 °C for 60 s in ambient $N_2$. An ohmic-contact resistance of 0.28 $\Omega \cdot$mm was obtained using the TLM method. Mesa isolation was formed utilizing an inductively coupled plasma etcher with $Cl_2$-based gas. For the T-shaped gate process, it was defined in the center of the 7-$\mu$m drain–source spacing by a 50-kV JEOL electron-beam lithography system (JBX 6000 FS) with trilayer e-beam resist. The e-beam resist was also used as a mask for recess etching afterward. Before Ni/Au (20-nm/300-nm) gate metal deposition, gate recess was performed using an inductively coupled plasma etcher with $BCl_3$ gas. The recess etching rate was controlled at 0.05 nm/s. In this letter, approximately 12-nm recess depth was etched to enhance the aspect ratio to around 5.5. Finally, the gate metal was lifted off by acetone and dimethylacetamide to form a 100-nm T-shaped recessed gate. The gate width of the devices in this letter was 2 × 50 $\mu$m.

## III. Results and Discussion

The dc performance of the device was measured by Agilent E5270B. As shown in Fig. 2(a), the drain-current characteristics of the device with a 100-nm recessed gate exhibit a good pinchoff behavior, which is due to the enhanced aspect ratio by the gate recess technique. The OFF-state breakdown voltage is 90 V, as defined by the drain leakage current up to 1 mA/mm. Fig. 2(b) shows the gate leakage current $(I_G)$ during the device operation. It can be seen that the gate leakage current is lower than 2 $\mu$A/mm at each bias point. Such a low leakage current might be attributed to the extremely low recess etching rate that helps reduce the damage caused during the dry etching process. After recessing, more than one-order reduction in the reverse leakage current was observed using a Schottky diode (not shown here). This finding was in agreement with that of Okamoto *et al.* [8]. They suggested that the reduction of leakage current after recessing is due to the suppression of the tunneling component of the gate leakage current by slight removal of the surface n-type AlGaN. However, the mechanism is not understood clearly and needs further study.

The $S$-parameters of the fabricated device were measured using an on-wafer probing system with an Agilent E8361A network analyzer. The standard LRRM calibration method was adopted to calibrate the measurement system with reference planes set at the tips of the probes. Fig. 3 shows the frequency dependence of the current gain $H_{21}$ and Mason's unilateral gain

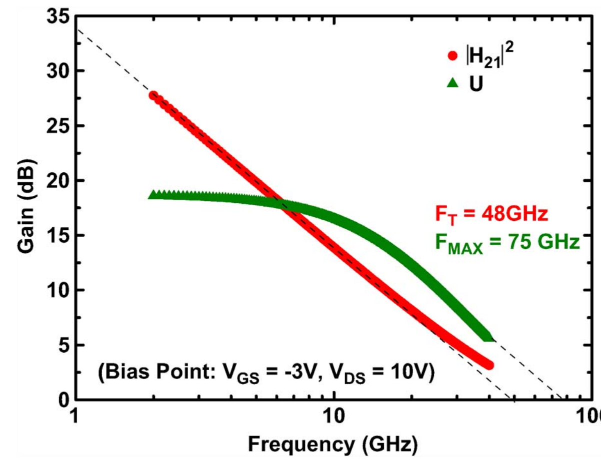


Fig. 3. Intrinsic $S$-parameter performance of the device at the bias point of $V_{\rm GS} = -3$ V and $V_{\rm DS} = 10$ V.

$U$ of the device measured at $V_{\rm DS} = 10$ V and $V_{\rm GS} = -3$ V. The parasitic effects (mainly capacitive) due to the probing pads have been carefully removed from the measured $S$-parameters using the same method as that in [9] and the equivalent circuit model in [10]. The unity-current-gain cutoff frequency $(F_T)$ and the maximum frequency of oscillation $(F_{\rm MAX})$ were extrapolated as 48 and 75 GHz, respectively, using $-20$-dB/dec regression.

High-frequency noise properties at room temperature were measured over the frequency range of 18–40 GHz using an Auriga noise measurement system with an Agilent 8975A noise figure analyzer. Fig. 4 shows the minimum noise figure $(NF_{\rm min})$ and the associated gain $(G_{\rm ass})$ as a function of frequency at the bias point of $V_{\rm GS} = -3$ V and $V_{\rm DS} = 10$ V, where the lowest noise figure was achieved. An $NF_{\rm min}$ value of 1.2 dB (1.6 dB) with $G_{\rm ass} = 6.5$ dB (5 dB) at 20 GHz (30 GHz) was observed. Such a low noise could be attributed to the low contact resistance of 0.28 $\Omega \cdot$mm, the source resistance of 2.5 $\Omega$ extracted from $S$-parameters, and also the low gate leakage current of 0.9 $\mu$A/mm during the device operation. To the best of our knowledge, this 30-GHz noise performance is the best reported so far for GaN-based HEMTs with a recessed gate. Another important figure of merit used to characterize the performance of a broadband low-noise amplifier is the equivalent noise resistance $R_n$ normalized to the optimal noise matching impedance $|Z_{\rm opt}|(|R_n/Z_{\rm opt}|)$ [11]. The fabricated

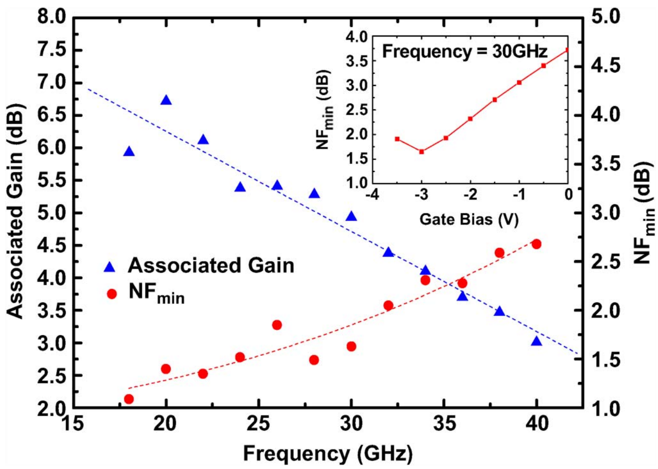


Fig. 4. Frequency dependence of minimum low-noise figure $(NF_{\min})$ and associated gain of the device at the bias point of $V_{\rm GS} = -3$ V and $V_{\rm DS} = 10$ V. The inset shows $NF_{\min}$ against gate bias at $V_{\rm DS} = 10$ V.

device exhibited 0.47 (0.57) of $|R_n/Z_{\rm opt}|$ at 20 GHz (40 GHz) and an average value of 0.53 from 20 to 40 GHz, indicating an excellent potential for broadband low-noise amplifier applications.

## IV. Conclusion

A 100-nm-gate-recessed AlGaN/GaN HEMT device has been reported for 30-GHz low-noise application. A minimum noise figure of 1.6 dB was obtained at 30 GHz, which could be attributed to the low gate leakage current and the low contact resistance due to the use of a heavily Si-doped GaN cap layer. Furthermore, an average value of 0.53 for $|R_n/Z_{\rm opt}|$ from 20 to 40 GHz was obtained, suggesting that such a device is a promising candidate for broadband low-noise amplifier applications in modern communication networks.

## Acknowledgment

The authors would like to thank Hitachi Cable Corporation, Japan, and ULVAC Corporation, Taiwan Branch, for their technique support. The authors would also like to thank Mr. T. Yamaguchi for his support on the e-beam lithography process. C.-T. Chang would also like to thank the Interchange Association, Japan, for its sponsorship of the 2009 Summer Program.

## References

[1] A. Nordbotten, "LMDS systems and their application," *IEEE Commun. Mag.*, vol. 38, no. 6, pp. 150–154, Jun. 2000.

[2] J. S. Moon, S. Wu, D. Wong, I. Milosavljevic, A. Conway, P. Hashimoto, M. Hu, M. Antcliffe, and M. Micovic, "Gate-recessed AlGaN-GaN HEMTs for high-performance millimeter-wave applications," *IEEE Electron Device Lett.*, vol. 26, no. 6, pp. 348–350, Jun. 2005.

[3] W. Lu, J. Yang, M. A. Khan, and I. Adesida, "AlGaN/GaN HEMTs on SiC with over 100 GHz $f_T$ and low microwave noise," *IEEE Trans. Electron Devices*, vol. 48, no. 3, pp. 581–585, Mar. 2001.

[4] J. S. Moon, M. Micovic, A. Kurdoghlian, P. Janke, P. Hashimoto, W.-S. Wong, L. McCray, and C. Nguyen, "Microwave noise performance of AlGaN–GaN HEMTs with small DC power dissipation," *IEEE Electron Device Lett.*, vol. 23, no. 11, pp. 637–639, Nov. 2002.

[5] W. Lu, V. Kumar, E. L. Piner, and I. Adesida, "DC, RF, and microwave noise performance of AlGaN–GaN field effect transistors dependence of aluminum concentration," *IEEE Trans. Electron Devices*, vol. 50, no. 4, pp. 1069–1074, Apr. 2003.

[6] H. Sun, A. R. Alt, H. Benedickter, and C. R. Bolognesi, "High-performance 0.1-$\mu$m gate AlGaN/GaN HEMTs on silicon with low-noise figure at 20 GHz," *IEEE Electron Device Lett.*, vol. 30, no. 2, pp. 107–109, Feb. 2009.

[7] W. K. Wang, P. C. Lin, C. H. Lin, C. K. Lin, Y. J. Chan, G. T. Chen, and J. I. Chyi, "Performance enhancement by using the n+-GaN cap layer and gate recess technology on the AlGaN–GaN HEMT fabrication," *IEEE Electron Device Lett.*, vol. 26, no. 1, pp. 5–7, Jan. 2005.

[8] Y. Okamoto, Y. Ando, T. Nakayama, K. Hataya, H. Miyamoto, T. Inoue, M. Senda, K. Hirata, M. Kosaki, N. Shibata, and M. Kuzuhara, "High-power recessed-gate AlGaN/GaN HFET with a field-modulating plate," *IEEE Trans. Electron Device*, vol. 51, no. 12, pp. 2217–2222, Dec. 2004.

[9] Y. Yamashita, A. Endoh, K. Shinohara, M. Higashiwaki, K. Hikosaka, T. Mimura, S. Hiyamizu, and T. Matsui, "Ultra-short 25-nm-gate lattice match InAlAs/InGaAs HEMTs within the range of 400 GHz cutoff frequency," *IEEE Electron Device Lett.*, vol. 22, no. 8, pp. 367–369, Aug. 2001.

[10] A. Jarndal and G. Kompa, "A new small signal model parameter extraction method applied to GaN devices," *IEEE Trans. Microw. Theory Tech.*, vol. 53, no. 11, pp. 3440–3448, Nov. 2005.

[11] H. Fukui, "Design of microwave GaAs MESFETs for broad-band low-noise amplifiers," *IEEE Trans. Microw. Theory Tech.*, vol. MTT-27, no. 7, pp. 643–650, Jul. 1979.