Received 4 March 2022; accepted 25 March 2022. Date of publication 30 March 2022; date of current version 8 April 2022.
The review of this article was arranged by Editor M. Chan

Digital Object Identifier 10.1109/JEDS.2022.3163379

Bias-Dependence of Electroluminescence in AlGaN/GaN High-Electron-Mobility Transistors on SiC Substrate

QIANG MA [1], SHIYO URANO [1], ATSUSHI TANAKA [2,3], YUJI ANDO [4] (Member, IEEE), AND AKIO WAKEJIMA [1] (Senior Member, IEEE)

1 Graduate School of Engineering, Tsukuri College, Nagoya Institute of Technology, Nagoya 466-8555, Japan
2 Institute of Materials and Systems for Sustainability, Nagoya University, Nagoya 464-8601, Japan
3 National Institute for Materials Science, Tsukuba 305-0044, Japan
4 Department of Electronics, Nagoya University, Nagoya 464-8601, Japan

CORRESPONDING AUTHOR: A. WAKEJIMA (e-mail: wakejima.akio@nitech.ac.jp)

This work was supported by MEXT "Research and Development of Next-Generation Semiconductor to Realize Energy-Saving Society" Program under Grant JPJ005357.

ABSTRACT This paper investigates bias-dependence of electroluminescence (EL) in an AlGaN/GaN HEMT fabricated on a SiC substrate. The HEMT exhibited a low-intensity reddish EL at the gate electrode at a drain voltage (V_{ds}) of 30 V, which was confirmed with combination of a top-side view using a CMOS sensor camera and a back-side view using a silicon-intensified CCD. As V_{ds} was increased to 48 V, color change from low-intensity red to high-intensity white was accompanied with shift of the location from the gate to the drain edge. The changes in the EL are attributed to a shift of the high electric field from the gate to the drain electrode and a concentration of electric field near the drain edge.

INDEX TERMS GaN, HEMT, electroluminescence, electron trap, current collapse, electric field.

I. INTRODUCTION

AlGaN/GaN high-electron-mobility transistors (HEMTs) on a SiC substrate have been expected to be used in power and high frequency applications because of their high breakdown voltage, high mobility, and high thermal conductivity [1]–[6]. In spite of these advantages, the development of AlGaN/GaN HEMTs suffers from current collapse, associated with electron trapping. Under high voltage biasing conditions, electrons are accelerated by a concentrated electric field at a gate edge towards a drain electrode, and trapped at an interface between a passivation film and AlGaN or somewhere in epi layers [7]–[14]. To address the current collapse, it is crucial to comprehensively understand the relationship between electron trapping and the electric field of AlGaN/GaN HEMTs under biasing conditions.

Electroluminescence (EL) measurement is a powerful method for analysis of electric field distribution in AlGaN/GaN HEMTs [15]–[25]. The high electric field region in HEMTs can be identified by EL location. In the case of HEMTs with severe current collapse, EL was observed at the drain edge. By contrast, luminescence in HEMTs with a low current collapse occurred at the drain-side edge of the gate. Furthermore, some literatures mentioned when HEMTs was under continuous biasing, EL shifted from the gate edge toward the drain electrode, indicating a transition of the high electric field region [17]–[19].

In addition, EL color was used to explore a distribution of an electron energy. HEMTs with high energy hot electrons exhibited a high-intensity whitish EL, whereas HEMTs with relatively low energy hot electrons exhibited a weak reddish EL [19]. On the other hand, in our study, we successfully observed EL color changed from a low-intensity reddish to a high-intensity whitish in one HEMT with increased V_{ds} [21]. These changes in EL color are attributed to a shift of high electric field from the gate to the drain edge. High energy hot electrons are generated by the concentrated electric field at the drain edge, resulting in strong whitish EL. Therefore, EL location in one HEMT is expected to shift during the EL color change.

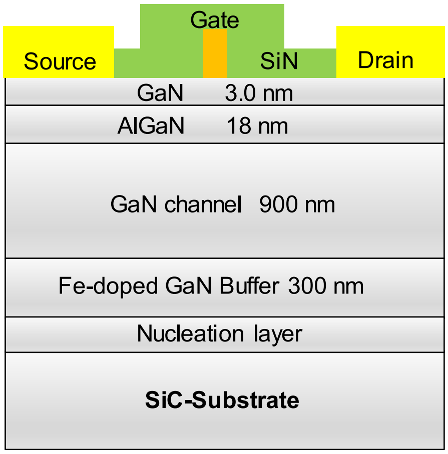

FIGURE 1. Schematic of cross-sectional structure of an AlGaN/GaN HEMT on a SiC substrate.

In this work, we investigate change of EL color and transition of EL location in a HEMT under an increased V_{ds}. Especially, we observe EL from a back side of the HEMT through the SiC substrate to exactly confirm the location of EL.

II. DEVICE FABRICATION

A cross-sectional structure of the AlGaN/GaN HEMT investigated in this study is shown in Fig. 1. Ohmic contacts for source and drain and Schottky contacts were composed by Mo/Al/Mo/Au and Ni/Au, respectively. A gate length (L_g), a source-gate distance (L_{sg}), and a gate-drain distance (L_{gd}) were fixed to 0.8, 1.0 μm, and 2.0 μm, respectively. A 60-nm-thick SiN film with a stress of +26.5 MPa was deposited on the HEMT with plasma-enhanced CVD for passivation [26].

III. DEVICE CHARACTERIZATION

A. ELECTRICAL CHARACTERISTICS OF ALGAN/GAN HEMT

Figure 2 displays dc and pulsed I_d-V_{ds} characteristics of an AlGaN/GaN HEMT on a SiC substrate at room temperature. The maximum drain current (I_{dmax}) is 350 mA/mm under a V_{gs} of 0 V. The threshold voltage (V_{th}) is −1.85 V.

A synchronous gate and drain pulsed-bias sequence was used in this work. A width and duty of the pulse were fixed at 10 ms and 10%, respectively. The quiescent bias of gate (V_{gq}) was set at −10 V and the quiescent bias of drain (V_{dq}) was increased from 10 to 48 V, which was an off-state. As shown in Fig. 2 (a), severe current collapse of the I_d is observed under a V_{dq} of 48 V. Fig. 2 (b) shows a dependence of dynamic on-resistance (R_{on}) on the V_{dq}. As the V_{dq} is changed from 40 to 48 V, the R_{on} obviously increases, which indicates a significant current collapse [27].

B. ELECTROLUMINESCENCE CHARACTERISTICS OF ALGAN/GAN HEMT

Figures 3 (a)-(c) display true color EL images of the AlGaN/GaN HEMT on the SiC substrate at room temperature, taken by a CMOS sensor camera from top side of the HEMT under an increased V_{ds} from 30 to 48 V. The CMOS camera (SONY α6100) is combined with an optical microscope. Because for the low minimum shutter speed of the camera, a fairly intricate long-exposure shot can be achieved. An integration time of 20 s was used for all measurements. During observation, the V_{gs} was kept at −1.7 V and I_d was approximately 75 mA/mm. The color of EL was identified by using an optical filter, which is transparent in different spectral bands from 400 to 710 nm. In Fig. 3 (a) and (b), the HEMT exhibits a low-intensity reddish EL under a V_{ds} of 40 V. As V_{ds} increases to 48 V, the HEMT exhibits a high-intensity whitish light, shown in Fig. 3 (c). This result is identical to our previous report about the changes in EL color of the HEMT with a different SiN film stress [21].

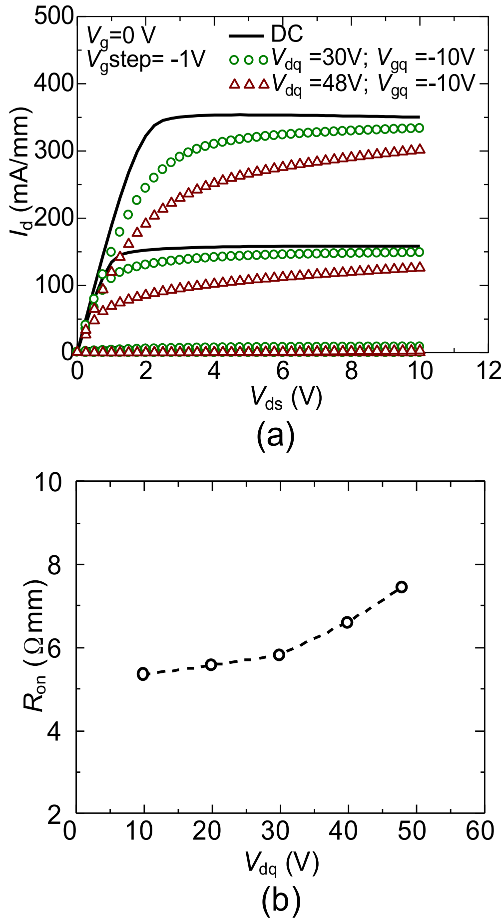

FIGURE 2. (a) The dc and pulsed I_d-V_{ds} characteristics of an AlGaN/GaN HEMT on a SiC substrate. (b) The relation between the dynamic on-resistance (R_{on}) and the quiescent bias of drain (V_{dq}).

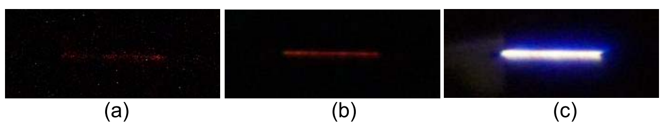

FIGURE 3. True color EL images of the AlGaN/GaN HEMT on the SiC substrate taken by a CMOS sensor camera under an increased V_{ds}: (a) 30 V; (b) 40 V; (c) 48 V.

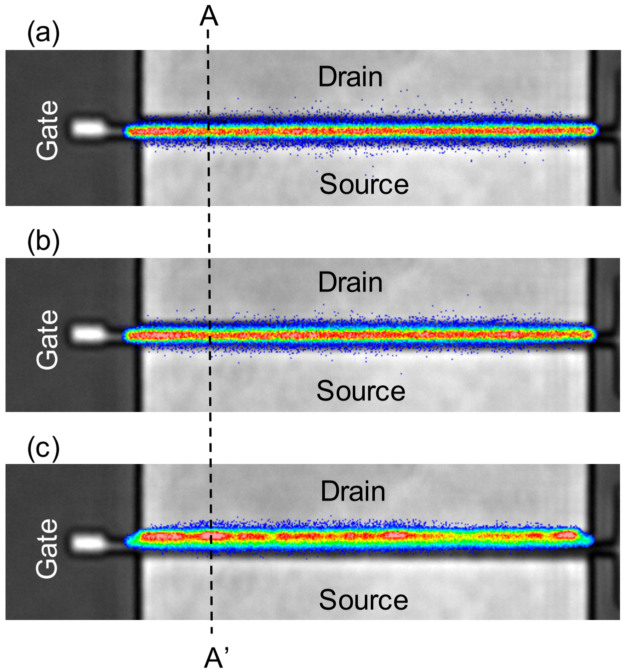

FIGURE 4. **False color EL images of the AlGaN/GaN HEMT on the SiC substrate taken by a SI-CCD under an increased V_{ds}: (a) 30 V; (b) 40 V; (c) 48 V.**

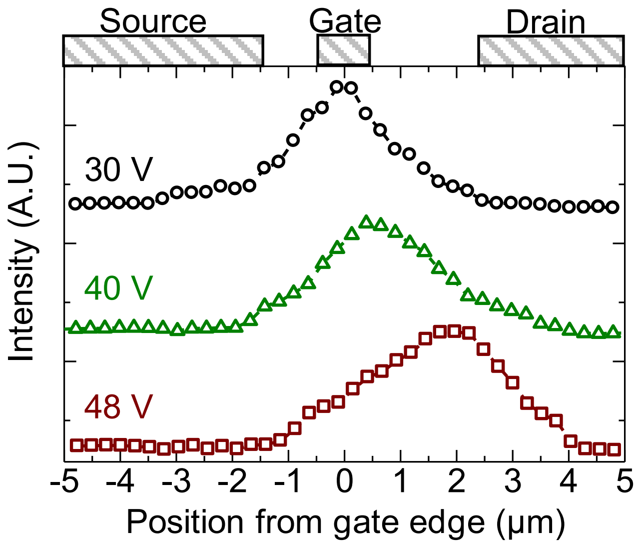

FIGURE 5. **Line scan of the EL along A–A' in Fig. 4. The three lines from top to bottom correspond to the EL under a V_{ds} of 30, 40, and 48 V.**

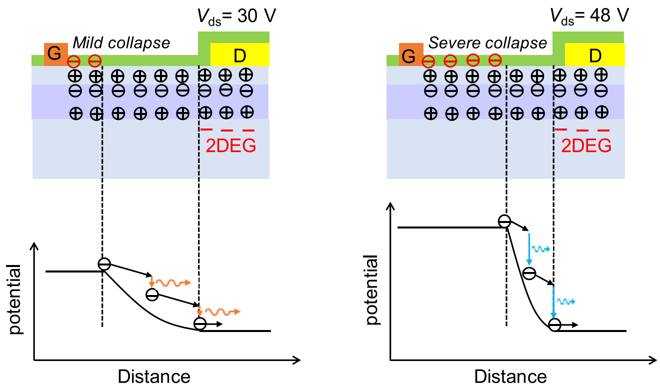

FIGURE 6. **Schematic illustration of electric field distribution in the gate-drain region of an AlGaN/GaN HEMT on a SiC substrate with mild or severe current collapse.**

An emission microscope (Hamamatsu Photonics PHEMOS-1000) for identifying the EL location consists of a silicon-intensified CCD (SI-CCD), whose features are sub-micro level spatial resolution and high sensitivity of the light [28]. The detectable wavelength range of the SI-CCD camera is 300–1100 nm, so the EL related with the hot electrons in HEMTs can be observed with the PHEMOS-1000 [19]–[20].

Figures 4 (a)-(c) show false color EL images of the AlGaN/GaN HEMT on the SiC substrate at room temperature, taken by the SI-CCD from back side of the HEMT under a V_{ds} ranged from 30 to 48 V. Figure 5 depicts the pixel-by-pixel intensity of EL along A–A' in Fig. 4. Because for the sub-micro level spatial resolution of the PHEMOS-1000 and a L_{gd} of 2.0 μm in HEMT, it is possible to identify a shift of EL peak between the gate and the drain electrode. As shown in Fig. 4 (a), a straight line-shaped EL is observed along the gate finger of the HEMT under a V_{ds} of 30 V. Based on Fig. 5, the EL emission peak is at the gate. When the V_{ds} increases from 30 to 40 V, the EL of the HEMT shifts 0.5 μm from the gate center toward the drain edge, shown in Fig. 4 (b) and Fig. 5. When the V_{ds} is 48 V, the EL peak of the HEMT shifts 2.1 μm from the gate center and reaches near the drain edge, shown in Fig. 4 (c) and Fig. 5. The result indicates a transition of the highest electric field toward the drain edge under an increased V_{ds}.

C. DISCUSSING BIAS-DEPENDENCE OF EL

Origins of the EL shift in one HEMT under an elevated V_{ds} are attributed to a transition of high electric field from the gate electrode to the drain electrode [18]. The change in EL color is related with the density of trapped electrons, which affects the potential profile in the gate–drain access region [19], [21]. As shown in Fig. 6 (a), under a V_{ds} of 30 V, small amount of electrons is trapped near the gate, which results in a low current collapse in the HEMT, depicted in Fig. 2 (a). Under this condition, the highest electric field in the HEMT is at the gate electrode and the electric field widely distributes between the gate and the drain electrode. Therefore, hot electrons with relatively low energy are generated, resulting in a low-intensity reddish EL. On the other hand, as shown in Fig. 6 (b), under a V_{ds} of 48 V, more electrons are trapped on surface states, which causes a severe current collapse in the HEMT, shown in Fig. 2 (a). The increase in the trapped electrons results in a shift of the highest electric field region from the gate toward the drain edge [29]. Hence, high energy hot electrons are generated by the concentrated electric field around the drain edge, leading to a high-intensity whitish EL.

According to the references, a change in EL color from red to white is attributed to severe current collapse and a concentrated electric field in HEMT [19], [21]. Severe current collapse and a strong electric field in the gate-drain access region can result in a degradation of HEMT performance. Therefore, it can be conceived that a change in EL color is correlated with a degradation of HEMT.

IV. CONCLUSION

In this work, bias-dependence of EL in one HEMT on a SiC substrate was investigated using a CMOS sensor camera and a SI-CCD. As V_{ds} was increased from 30 V to 48 V, EL color of the HEMT turned from low-intensity red to high-intensity white, meanwhile the EL location of the HEMT shifted from the gate to the drain electrode. The results are attributed to a shift of highest electric field and a formation of a concentrated electric field at the drain edge.

REFERENCES

[1] R. S. Pengelly, S. M. Wood, J. W. Milligan, S. T. Sheppard, and W. L. Pribble, "A review of GaN on SiC high electron-mobility power transistors and MMICs," *IEEE Trans. Microw. Theory Techn.*, vol. 60, no. 6, pp. 1764–1783, Jun. 2012, doi: 10.1109/TMTT.2012.2187535.

[2] N. Tipirneni, A. Koudymov, V. Adivarahan, J. Yang, G. Simin, and M. A. Khan, "The 1.6-kV AlGaN/GaN HFETs," *IEEE Electron Device Lett.*, vol. 27, no. 9, pp. 716–718, Sep. 2006, doi: 10.1109/LED.2006.881084.

[3] R. Gaska *et al.*, "Electron transport in AlGaN–GaN heterostructures grown on 6H–SiC substrates," *Appl. Phys. Lett.*, vol. 72, no. 9, pp. 707–709, Aug. 1998, doi: 10.1063/1.120852.

[4] Y.-F. Wu, D. Kapolnek, J. P. Ibbetson, P. Parikh, B. P. Keller, and U. K. Mishra, "Very-high power density AlGaN/GaN HEMTs," *IEEE Trans. Electron Devices*, vol. 48, no. 3, pp. 586–590, Mar. 2001, doi: 10.1109/16.906455.

[5] L. Baczkowski *et al.*, "Thermal characterization using optical methods of AlGaN/GaN HEMTs on SiC substrate in RF operating conditions," *IEEE Trans. Electron Devices*, vol. 62, no. 12, pp. 3992–3998, Dec. 2015, doi: 10.1109/TED.2015.2493204.

[6] D.-Y. Chen *et al.*, "Microwave performance of 'buffer-free' GaN-on-SiC high electron mobility transistors," *IEEE Electron Device Lett.*, vol. 41, no. 6, pp. 828–831, Jun. 2020, doi: 10.1109/LED.2020.2988074.

[7] H. Chandrasekar *et al.*, "Buffer-induced current collapse in GaN HEMTs on highly resistive Si substrates," *IEEE Electron Device Lett.*, vol. 39, no. 10, pp. 1556–1559, Oct. 2018, doi: 10.1109/LED.2018.2864562.

[8] R. H. Hao *et al.*, "Breakdown enhancement and current collapse suppression by high-resistivity GaN cap layer in normally-off AlGaN/GaN HEMTs," *IEEE Electron Device Lett.*, vol. 38, no. 11, pp. 1567–1570, Nov. 2017, doi: 10.1109/LED.2017.2749678.

[9] M. T. Hasan, T. Asano, H. Tokuda, and M. Kuzuhara "Current collapse suppression by gate field-plate in AlGaN/GaN HEMTs," *IEEE Electron Device Lett.*, vol. 34, no. 11, pp. 1379–1381, Nov. 2013, doi: 10.1109/LED.2013.2280712.

[10] I. Hwang *et al.*, "Impact of channel hot electrons on current collapse in AlGaN/GaN HEMTs," *IEEE Electron Device Lett.*, vol. 34, no. 12, pp. 1494–1496, Dec. 2013, doi: 10.1109/LED.2013.2286173.

[11] R. Stradiotto, G. Pobegen, C. Ostermaier, M. Waltl, A. Grill, and T. Grasser, "Characterization of interface defects with distributed activation energies in GaN-based MIS-HEMTs," *IEEE Trans. Electron Devices*, vol. 64, no. 3, pp. 1045–1052, Mar. 2017, doi: 10.1109/TED.2017.2655367.

[12] Q. Ma, T. Yoshida, Y. Ando, and A. Wakejima, "Transient response of drain current following biasing stress in GaN HEMTs on SiC substrates with a field plate," *Jpn. J. Appl. Phys.*, vol. 59, no. 10, pp. 1–6, Sep. 2020, doi: 10.35848/1347-4065/abb7e2.

[13] Q. Ma, Y. Ando, and A. Wakejima, "Dynamic characteristics after bias stress of GaN HEMTs with field plate on free-standing GaN substrate," *Electron. Lett.*, vol. 57, no. 15, pp. 591–593, May 2021, doi: 10.1049/ell2.12201.

[14] X. Y. Zhou *et al.*, "Dynamic characteristics of AlGaN/GaN Fin-MISHEMTs with Al_2O_3 dielectric," *IEEE Trans. Electron Devices*, vol. 65, no. 3, pp. 928–935, Mar. 2018, doi: 10.1109/TED.2018.2792060.

[15] M. Meneghini *et al.*, "Electron and hole-related luminescence processes in gate injection transistors," *Appl. Phys. Lett.*, vol. 97, no. 3, pp. 1–3, Jul. 2010, doi: 10.1063/1.3467039.

[16] G. Meneghesso *et al.*, "Reliability of GaN high-electron-mobility transistors: State of the art and perspectives," *IEEE Trans. Device Mater. Rel.*, vol. 8, no. 2, pp. 332–343, Jun. 2008, doi: 10.1109/TDMR.2008.923743.

[17] M. Meneghini *et al.*, "Time-and field-dependent trapping in GaN-based enhancement-mode transistors with p-gate," *IEEE Electron Device Lett.*, vol. 33, no. 3, pp. 375–377, Mar. 2012, doi: 10.1109/LED.2011.2181815.

[18] A. Wakejima, A. F. Wilson, S. Mase, T. Joka, and T. Egawa, "Evaluation of electron trapping speed of AlGaN/GaN HEMT with real-time electroluminescence and pulsed *I–V* measurements," *IEEE Trans. Electron Devices*, vol. 60, no. 10, pp. 3183–3189, Oct. 2013, doi: 10.1109/TED.2013.2273796.

[19] S. Ohi, T. Yamazaki, J. Asubar, H. Tokuda, and M. Kuzuhara, "Correlation of AlGaN/GaN high-electron-mobility transistors electroluminescence characteristics with current collapse," *Appl. Phys. Exp.*, vol. 11, no. 12, pp. 1–4, Jan. 2018, doi: 10.7567/APEX.11.024101.

[20] T. Yamazaki, J. T. Asubar, H. Tokuda and M. Kuzuhara, "Impact of rounded electrode corners on breakdown characteristics of AlGaN/GaN high-electron mobility transistors," *Appl. Phys. Exp.*, vol. 11, no. 5, pp. 1–5, Apr. 2018, doi: 10.7567/APEX.11.054102.

[21] Q. Ma, S. Urano, Y. Ando, A. Tanaka, and A. Wakejima, "Impact of SiN passivation film stress on electroluminescence characteristics of AlGaN/GaN high-electron-mobility transistors," *Appl. Phys. Exp.*, vol. 14, no. 9, pp. 1–3, Sep. 2021, doi: 10.35848/1882-0786/ac1f40.

[22] T. Narita, A. Wakejima, and T. Egawa, "Local gate leakage current induced by inhomogeneous epitaxial growth in AlGaN/GaN high-electron-mobility transistors," *Appl. Phys. Exp.*, vol. 9, no. 3, pp. 1–3, Feb. 2016, doi: 10.7567/APEX.9.031002.

[23] Y. Ohno, T. Nakao, S. Kishimoto, K. Maezawa, and T. Mizutani, "Effects of surface passivation on breakdown of AlGaN/GaN high-electron-mobility transistors," *Appl. Phys. Lett.*, vol. 84, no. 12, pp. 2184–2186, Mar. 2004, doi: 10.1063/1.1687983.

[24] Z. Tang, S. Huang, X. Tang, B. Li, and K. J. Chen, "Influence of AlN passivation on dynamic ON-resistance and electric field distribution in high-voltage AlGaN/GaN-on-Si HEMTs," *IEEE Trans. Electron Devices*, vol. 61, no. 8, pp. 2785–2792, Aug. 2014, doi: 10.1109/TED.2014.2333063.

[25] A. F. Wilson, A. Wakejima, and T. Egawa, "Step-stress reliability studies on AlGaN/GaN high electron mobility transistors on silicon with buffer thickness dependence," *Appl. Phys. Exp.*, vol. 6, no. 5, pp. 1–3, Apr. 2013, doi: 10.7567/APEX.6.056501.

[26] Y. Ando, H. Takahashi, Q. Ma, A. Wakejima, and J. Suda, "Impact of film stress of field-plate dielectric on electric characteristics of GaN-HEMTs," *IEEE Trans. Electron Devices*, vol. 67, no. 12, pp. 5421–5426, Dec. 2020, doi: 10.1109/TED.2020.3029540.

[27] R. Vetury, N.-Q. Zhang, S. Keller, and U. K. Mishra, "The impact of surface states on the DC and RF characteristics of AlGaN/GaN HFETs," *IEEE Trans. Electron Devices*, vol. 48, no. 3, pp. 560–566, Mar. 2001, doi: 10.1109/16.906451.

[28] "Emission Microscope PHEMOS-1000." [Online]. Available: http://www.hamamatsu.com.cn/UserFiles/DownFile/Product/SSMS0003E_PHEMOS1000.pdf (Accessed: May, 2019).

[29] Y. Hori, M. Kuzuhara, Y. Ando, and M. Mizuta, "Analysis of electric field distribution in GaAs metal-semiconductor field effect transistor with a field-modulating plate," *J. Appl. Phys.*, vol. 87, no. 7, pp. 3483–3487, Mar. 2000, doi: 10.1063/1.372370.