

Article

A Novel GaN:C Millimeter-Wave HEMT with AlGa_N Electron-Blocking Layer

You-Chen Weng ¹, Yueh-Chin Lin ², Heng-Tung Hsu ³ , Min-Lu Kao ² , Hsuan-Yao Huang ³, Daisuke Ueda ³, Minh-Thien-Huu Ha ², Chih-Yi Yang ³, Jer-Shen Maa ¹, Edward-Yi Chang ^{2,3,4,*} and Chang-Fu Dee ⁵ 

¹ College of Photonics, National Yang Ming Chiao Tung University, Tainan 71150, Taiwan; ycweng.cop00g@nctu.edu.tw (Y.-C.W.); jershenmaa@mail.nctu.edu.tw (J.-S.M.)

² Department of Materials Science and Engineering, National Yang Ming Chiao Tung University, Hsinchu 30010, Taiwan; nctulin@yahoo.com.tw (Y.-C.L.); b9904133@gmail.com (M.-L.K.); thienhuu84@gmail.com (M.-T.-H.H.)

³ International College of Semiconductor Technology, National Yang Ming Chiao Tung University, Hsinchu 30010, Taiwan; htshu@nctu.edu.tw (H.-T.H.); axiarll44@gmail.com (H.-Y.H.); daisuke@ieee.org (D.U.); abx50131@gmail.com (C.-Y.Y.)

⁴ Department of Electronics Engineering, National Yang Ming Chiao Tung University, Hsinchu 30010, Taiwan

⁵ Institute of Microengineering and Nanoelectronics (IMEN), University Kebangsaan Malaysia, Level 4, Research Complex, Bangi 43600, Malaysia; cfdee@ukm.edu.my

* Correspondence: edc@mail.nctu.edu.tw

Abstract: An AlGa_N/Ga_N/Si high electron mobility transistor (HEMT) using a GaN:C buffer with a 2 nm AlGa_N electron-blocking layer (EBL) is investigated for the first time for millimeter-wave applications. Compared with the double heterostructure field effect transistor (DHFET), the AlGa_N/Ga_N HEMT with the GaN:C/EBL buffer has a lower vertical leakage, higher thermal stability, and better RF performance. In addition, AlGa_N EBL can prevent carbon-related traps from GaN:C and improve electron confinement in 2DEG during high-frequency operation. Finally, a P_{out} of 31.2 dBm with PAE of 21.7% were measured at 28 GHz at 28 V. These results demonstrated the great potential of HEMTs using GaN:C with AlGa_N EBL epitaxy technology for millimeter-wave applications.

Keywords: GaN; HEMT; electron-blocking layer



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1. Introduction

Due to the wide bandgap and high mobility nature of the GaN material, AlGa_N/Ga_N HEMTs have become one of the most popular devices for high-frequency and high-power applications, including 5G applications, in recent years. In the past decade, AlGa_N/Ga_N HEMTs on SiC have shown efficiency over 40% [1–3], and a high output power density of 8.2 W/mm at Ka band [4]. However, the fabrication cost of AlGa_N/Ga_N HEMTs on SiC is very high. Recently, AlGa_N/Ga_N HEMTs on Si substrate for Ka band applications have become popular [5], since GaN-on-Si substrate technology has the benefit of fabricating devices on large wafers (up to 8 inch) with silicon-compatible processes [6,7] to reduce manufacturing costs as compared with GaN-on-SiC technology.

Nevertheless, RF loss caused by the buffer layers for AlGa_N/Ga_N HEMTs on Si substrate results in a lower output power when the device is used for millimeter-wave applications. Several issues have to be addressed for the buffer layer's epitaxy for RF loss improvement, including AlN/Si interface issues, and different kinds of buffers, including the buffer (thickness usually around 0.5~2 μm) and back-barrier layer (thickness usually around 0.5~1 μm) in the epitaxial structure. For AlN/Si interface properties, parasitic channel formation at the Al/Si interface [8] is usually encountered due to the diffusion of Al and Ga atoms into Si substrate. Furthermore, a buffer was grown to balance the lattice and thermal mismatch between GaN and Si for stress control, three major types of buffer structures have been studied in the past [9], namely, the step AlGa_N buffer, the

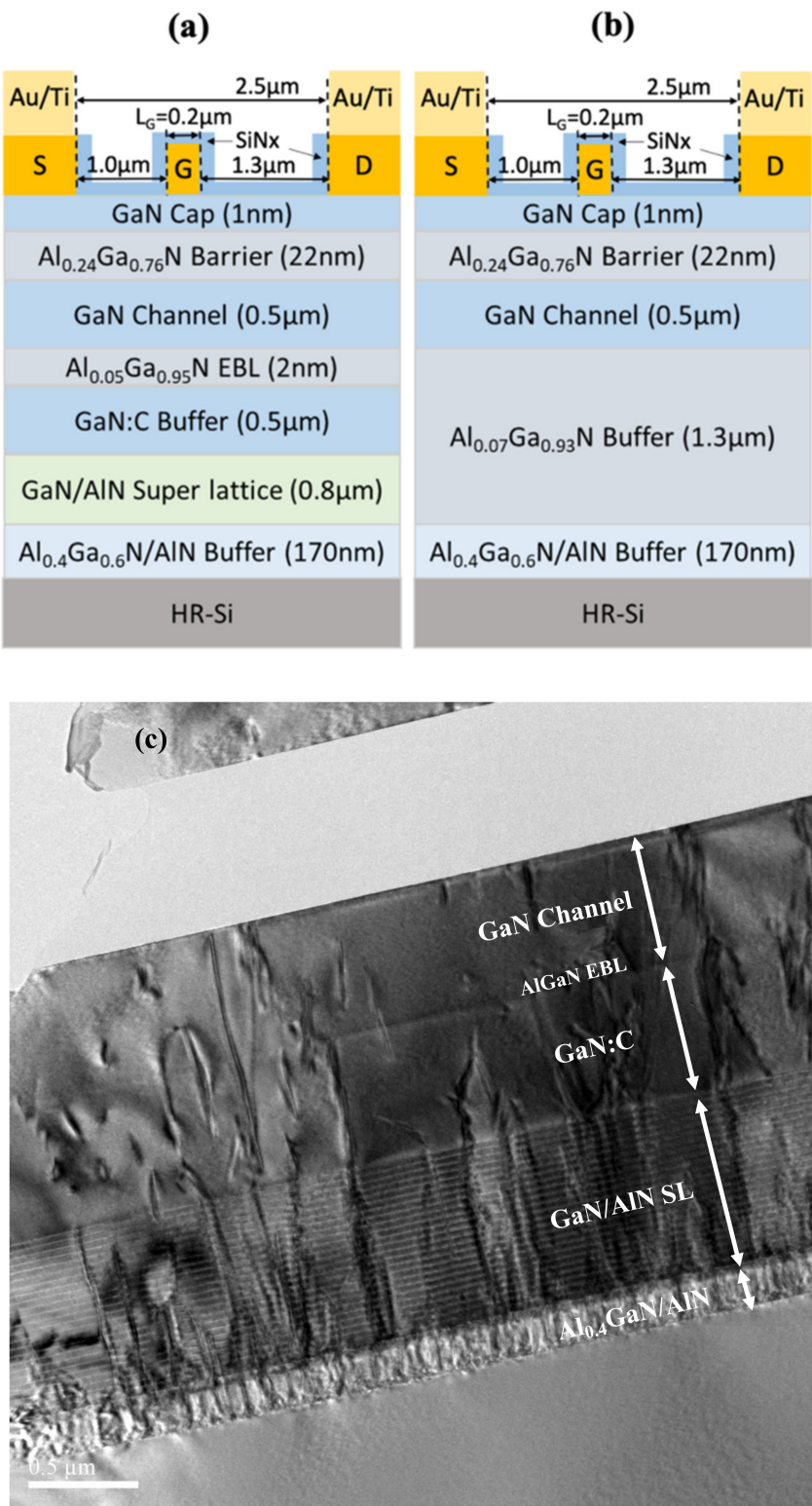
low-temperature interlayer (LT-interlayer) buffer, and the (Al)GaN/AlN superlattice buffer. The step AlGaN buffer has multi-AlGaN layers, each layer typically around 100 to 300 nm thick, and each AlGaN layer with decreasing Al%. The LT-interlayer buffer includes some transitions layers (e.g., AlGaN, carbon doped, and iron doped), and the thin LT-Al(GaN) layer was used to introduce compressive stress. The superlattice buffer uses a thin layer of (Al)GaN/AlN to build up compressive stress. However, some defects still form during the growth of the thick layer. Finally, with the back-barrier layer being the first layer under the undoped GaN channel, different doping profiles may act as the acceptors or donors which may degrade the channel conductivity, resulting in current collapse [10–13].

Recently, DHFET on Si substrate was investigated for RF applications [14]. DHFET usually adopts a thick AlGaN as the back-barrier (thickness usually over 1 μm) with 4~10% Al content to achieve high breakdown voltage due to better electron confinement with low trapping effects [5,15,16]. Using the GaN:C buffer as back-barrier is widely used in high power switching applications [17,18] with low memory effect [19]. However, the transfer of hot carriers from the channel to the GaN:C buffer occurs at high drain bias levels, which causes device degradations for millimeter-wave applications [11–14]. Some papers report positive results using the AlGaN back-barrier combined with the GaN:C buffer to enhance the channel conductivity of the device, and to reduce the current collapse effect [20–23]. Moreover, according to [24], W. Liu et al. reported when $10 < \text{Al}\% < 90$, poor thermal conductivity of the AlGaN layer will cause a self-heating effect in the device, thus increasing the channel temperature during the device operation. In addition, the device's current collapse for different types of buffers was also evaluated [9], and this showed that a low current collapse effect can be achieved by using a superlattice as a buffer.

In this paper, an AlGaN/GaN HEMT with a GaN:C buffer, combined with low Al content $\text{Al}_{0.05}\text{Ga}_{0.95}\text{N}$ EBL and a AlN/GaN superlattice buffer was grown on Si substrate. The result is compared to the AlGaN/GaN/AlGaN DHFET on Si substrate for RF applications.

2. Materials and Methods

The AlGaN/GaN HEMTs structure with the GaN:C/EBL buffer were grown by the Veeco Propel Metal Organic Vapor Deposition (MOCVD) system on high resistivity 6-inch Si (111) substrate ($R = 3000 \text{ ohm-cm}$). From the bottom to the top, the epitaxial layer structure of the device consisted of a 120 nm AlN seed layer, a 50 nm $\text{Al}_{0.4}\text{Ga}_{0.6}\text{N}$ buffer layer, an 800 nm AlN/GaN super-lattice buffer layer, a 500 nm GaN:C back-barrier layer, a 2 nm $\text{Al}_{0.05}\text{Ga}_{0.95}\text{N}$ electron blocking layer, a 500 nm unintentionally doped (UID) GaN channel layer, a 22 nm $\text{Al}_{0.24}\text{Ga}_{0.76}\text{N}$ barrier layer, and a 1nm GaN cap layer; the structure is as shown in Figure 1a. The room-temperature electron mobility of $1700 \text{ cm}^2/\text{V}\cdot\text{s}$ and a sheet carrier density of $8.5 \times 10^{12}/\text{cm}^2$ were achieved for the AlGaN/GaN HEMT device structure with the GaN:C/EBL buffer. The structure of DHFETs on Si substrate was shown in Figure 1b, and the room-temperature electron mobility of $1750 \text{ cm}^2/\text{V}\cdot\text{s}$ and a sheet carrier density of $8.0 \times 10^{12}/\text{cm}^2$ were measured. Figure 1c shows the cross-sectional transmission electron microscopy (TEM) images of the GaN:C/EBL buffer HEMT device; the interfaces of the buffer were quite smooth, as shown in this figure. Figure 1d shows the sharp and smooth interface between the GaN channel, AlGaN EBL, and the GaN:C back-barrier, and the threading dislocations in the GaN:C were effectively bent by the AlGaN EBL. Additionally, this is first time using a TEM image to verify the AlGaN EBL thickness in a AlGaN/GaN HEMT epitaxy structure. The 2 nm AlGaN EBL is shown in Figure 1e, Figure 1f shows the root mean square roughness of the AlGaN/GaN HEMTs structure with the GaN:C/EBL buffer surface morphology measured by the Atomic Force Microscope (AFM). The surface roughness was 0.264 nm.



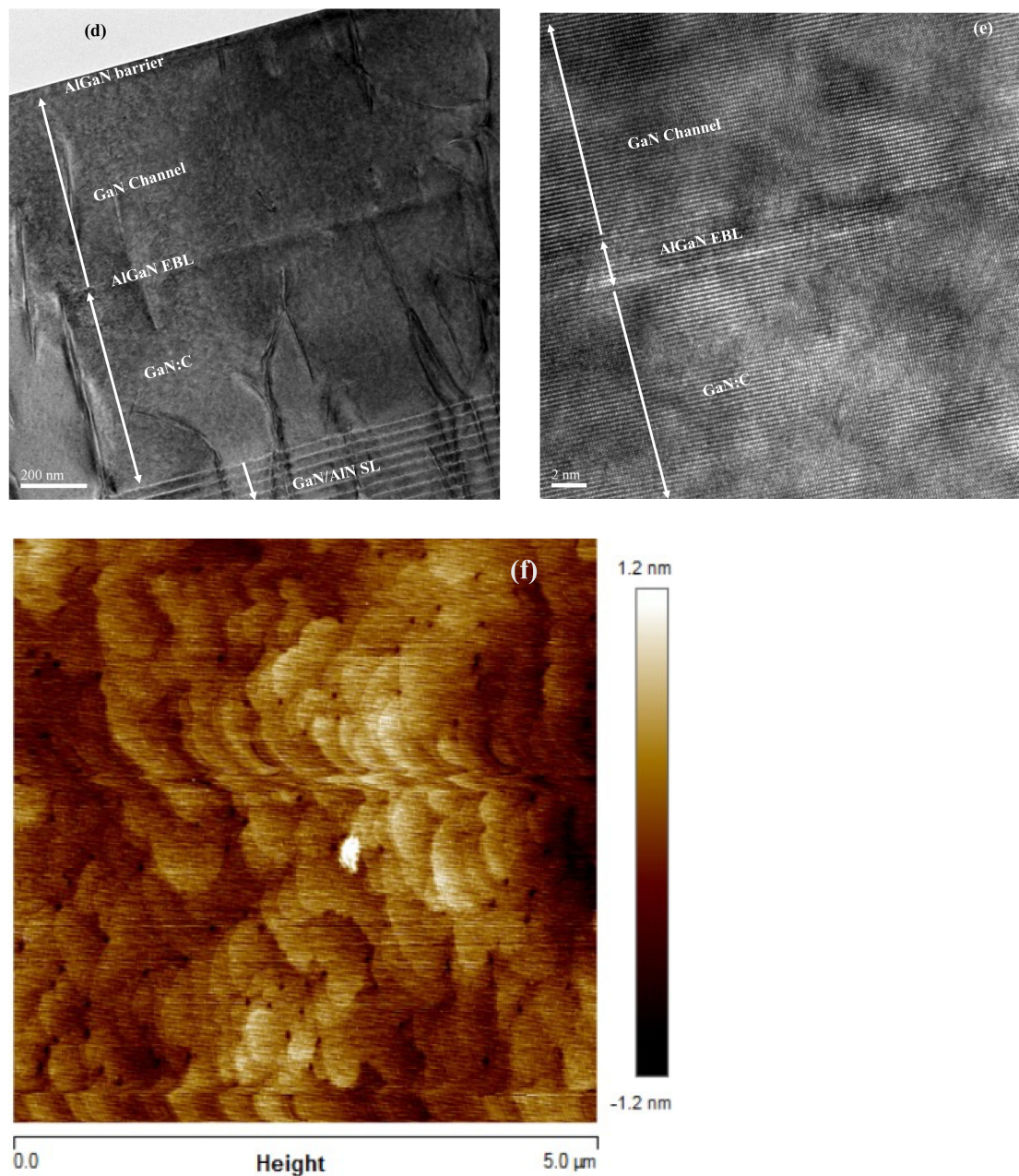


Figure 1. (a) The device structure of the GaN:C buffer AlGaIn/GaN HEMT with AlGaIn EBL; (b) the device structure of the AlGaIn/GaN/AlGaIn DHFET; (c) cross-section of the TEM image of the AlGaIn/GaN HEMT with GaN:C buffer with AlGaIn EB; (d) the TEM image of the GaN channel/AlGaIn EBL/GaN:C; (e) The TEM image of the AlGaIn EBL; (f) surface morphology of the GaN:C buffer AlGaIn/GaN HEMT with AlGaIn EBL.

The HEMT device process consisted of four major steps: ohmic contact formation, ion implantation isolation, gate formation, and interconnecting formation. First, the fabrication process starts with ohmic contact formation. Ti/Al/Ni/Au ohmic metal was deposited by E-gun evaporation, followed by the lift-off process, and then annealed at 850 °C for 30 s in an N₂ ambient environment by a rapid thermal annealing system (RTA). After that, an ion implantation isolation process using 3×10^{13} B11⁺ with 190 keV ion implantation energy was performed to define the active region. For device gate formation, a 100 nm SiN_x passivation layer was deposited using plasma-enhanced chemical vapor deposition (PECVD). The gate stem was fabricated by E-beam lithography and SiN_x etching by

was performed with ICP, and the gate metal Ni/Au was deposited by E-gun evaporator, followed by the lift-off process. The gate length was around 200 nm in this study. Finally, a 100 nm SiN_x layer was deposited for passivation with nitride via the open-to-the-device pad region; finally, the thick metal stacks with Ti (30 nm)/Au (1000 nm) were deposited by E-gun evaporator.

3. Results and Discussion

To verify the material compositions of each layer, the secondary ion mass spectrometry (SIMS) analysis was performed. The composition profiles of the AlGaN/GaN HEMT device structure with AlGaN EBL are shown in Figure 2. From the depth profiles, C and Al atoms were observed at a distance of 500 nm below the surface, showing evidence that an amount of Al atoms existed between the GaN:C and UID GaN channel. It was found that inserting an AlGaN EBL between the UID GaN channel and the GaN:C buffer can be used to prevent carbon-related traps from the GaN:C buffer; however, the Ga and Al signals were used only for quality analysis, not for quantitative analysis. From Figure 2 and the insert of Figure 2, a 2 nm thick AlGaN EBL can be clearly observed from the TEM image.

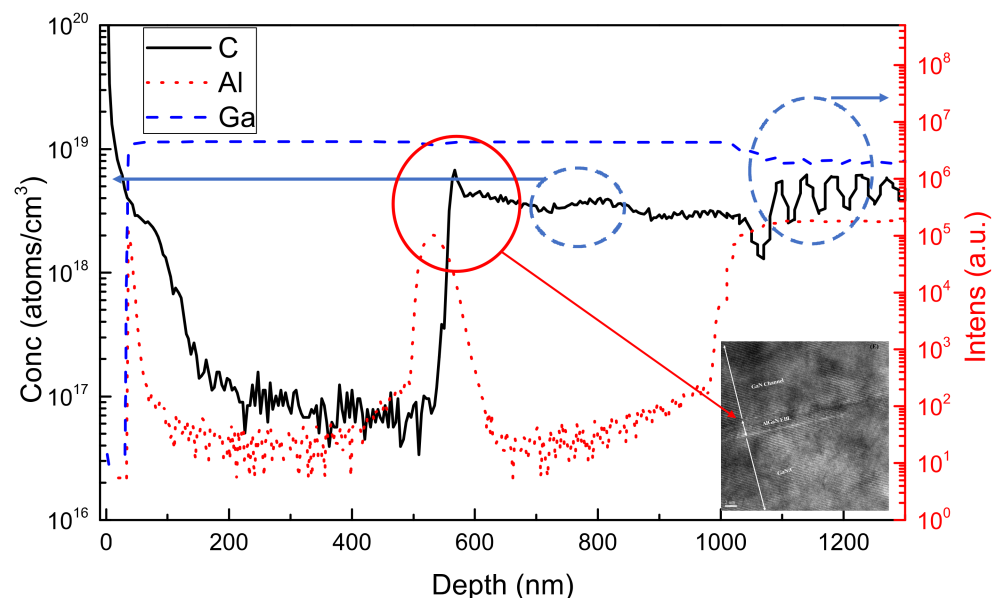


Figure 2. SIMS depth profiles of C, Ga, Al for the AlGaN/GaN HEMT with GaN:C and AlGaN EBL buffer, the insert shows AlGaN EBL between GaN:C and UID GaN channel.

Figure 3 shows the temperature-dependent forward (AlGaN/GaN surface to Si substrate) and reverse (Si substrate to AlGaN/GaN surface) vertical leakage currents between the GaN channel and the Si substrate. The forward bias was swept up from 0 V to 400 V (step is 1 V), the reverse bias from 0 V to −300 V (step is −1 V), with temperature ranging from 25 °C (room temperature) to 150 °C. The vertical breakdown voltage (V_{bd}) was defined at the leakage current of 10^{-5} A/mm². The V_{bd} of the device with GaN:C/EBL buffer decreased from 305 to 280 V (9% decrease) at forward bias, and −270 to −230 V (15% decrease) at reverse bias, as shown in Figure 3a. However, asymmetric characteristics were observed in reverse and forward characteristics in Figure 3b. The Si substrate formed a barrier at AlN/Si interface, but multi-AlGaN buffer could not prevent the electrons from injecting into the buffer layer. The V_{bd} of the DHFET decreased from 195 to 170 V (13% decrease) at forward bias, and −160 to −130 V (19% decrease) at reverse bias, as shown in Figure 3b. Thus, the device with the GaN:C/EBL buffer had a higher V_{bd} field strength (1.5 times higher than DHFET) and higher thermal stability at high temperatures.

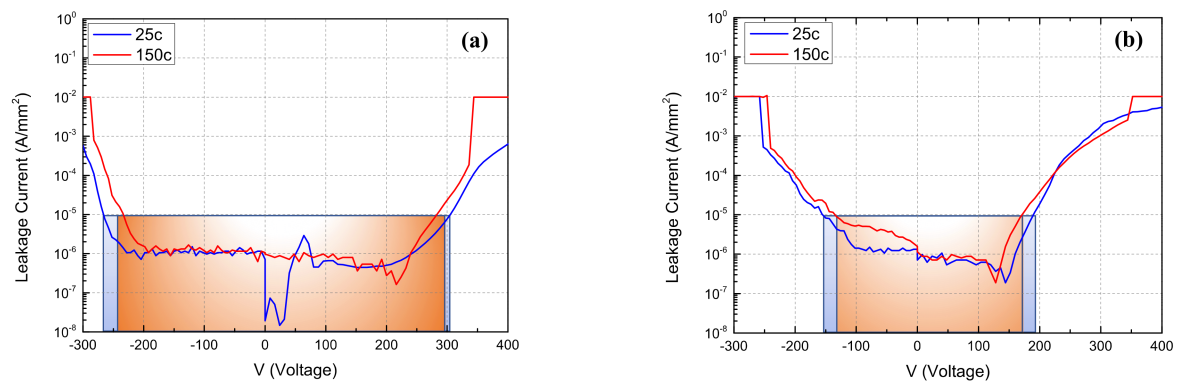


Figure 3. Vertical buffer leakage currents under forward and reverse bias (@Temperature: 25 °C and 150 °C) for (a) the GaN:C/EBL buffer device, and (b) the DHFET.

Figure 4a,b show the DC characteristics including the current–voltage (I_{DS} - V_{GS}) curve and the transfer curve (G_m - V_{GS}) of the $2 \times 50 \mu\text{m}$ GaN:C/EBL buffer device. The GaN:C/EBL buffer device exhibits an I_{DS} of 611 (mA/mm) and a maximum G_m of 258 mS/mm at $V_{DS} = 20$ V. Compared with the GaN:C/EBL buffer device, the DHFET showed a lower I_{DS} of 594 mA/mm and a lower maximum G_m of 250 mS/mm at $V_{DS} = 20$ V, as shown in Figure 4c,d, due to lower sheet carrier density for the DHFET. Pulsed I_{DS} - V_{DS} characteristics were extracted from the off-state with quiescent bias (V_{GSQ}) of -4 V to on-state at 0 V in 200 ns with 1% duty as shown in Figure 5a,b. As observed, current collapse occurred in both samples. The quiescent drain bias (V_{DSQ}) was swept from 3.3 to 20 V (3.3 , 5 , 10 , 15 , 20 V). The dynamic on-resistance increased from 2.1 to $5.2 \Omega \cdot \text{mm}$ and increased from 2.3 to $5.2 \Omega \cdot \text{mm}$ when V_{DSQ} varied from 3.3 to 20 V for the GaN:C/EBL buffer device and the DHFET, respectively. From the pulsed IV results, the device with the GaN:C/EBL buffer had similar results with the DHFET device after the drain lag test, because the electrical field shielding effect of the AlGaIn EBL, which effectively suppressed the capture of electrons in the channel by carbon-induced acceptor, trapped them in the GaN:C buffer [21].

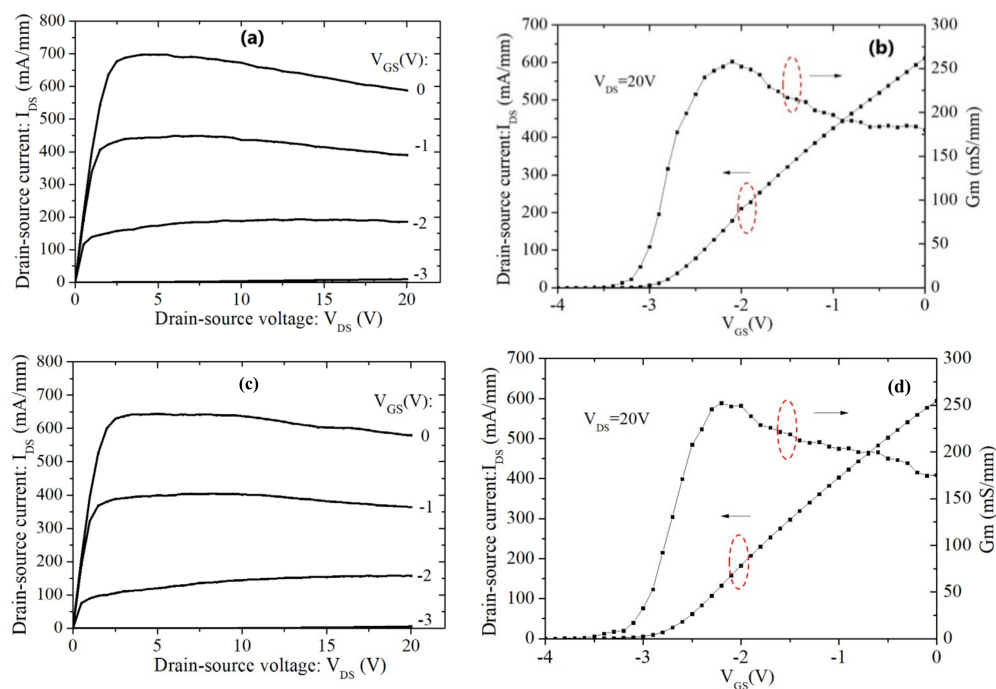


Figure 4. (a) I_{DS} - V_{DS} , and (b) I_{DS}/G_m - V_{GS} characteristics of the $2 \times 50 \mu\text{m}$ GaN:C/EBL buffer device. (c) I_{DS} - V_{DS} , and (d) I_{DS}/G_m - V_{GS} characteristics of the $2 \times 50 \mu\text{m}$ DHFETs.

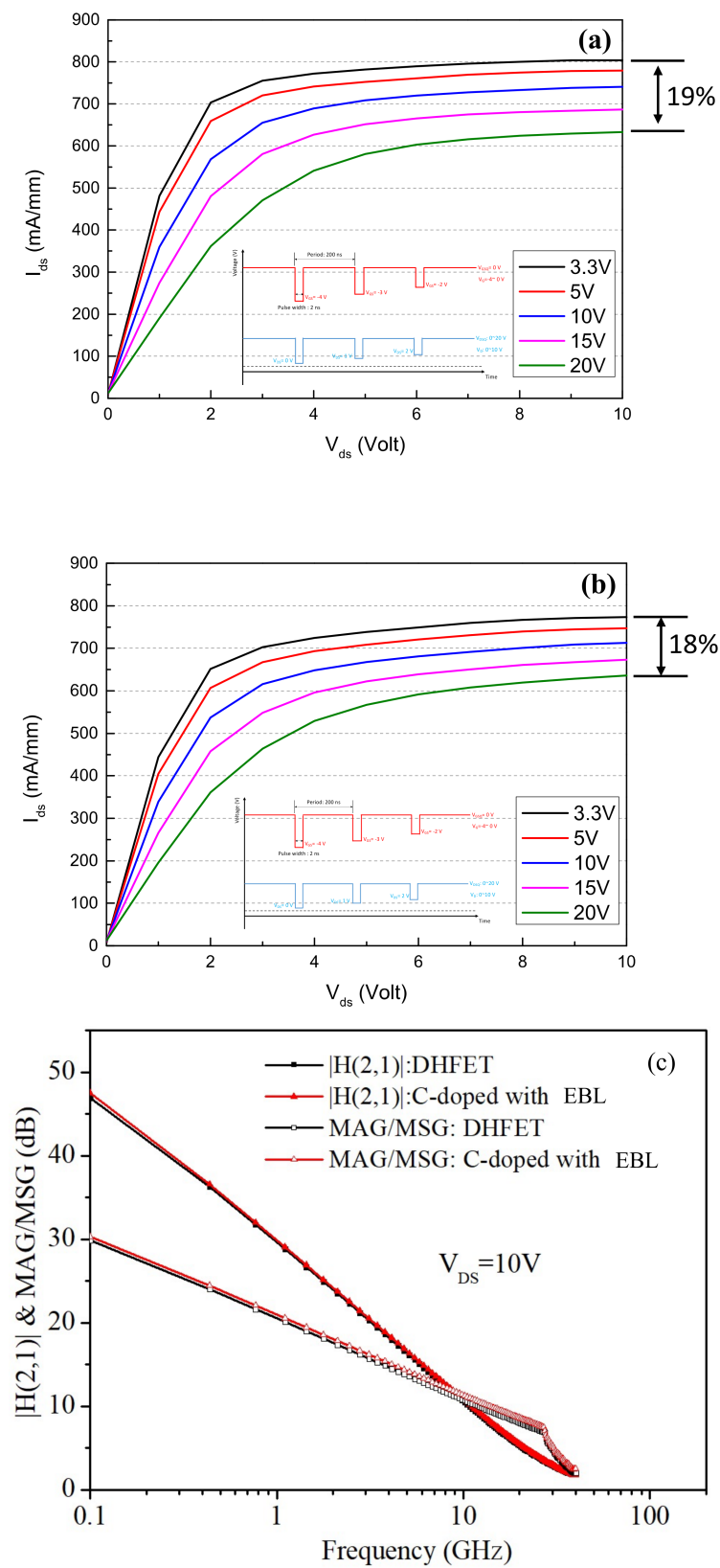


Figure 5. Pulsed I-V characteristics of the device with different buffers: the data show the drain lag under different drain biases (pulse width 200 ns, duty 1%); (a) the $2 \times 50 \mu\text{m}$ GaN:C/EBL buffer device; (b) the $2 \times 50 \mu\text{m}$ DHFETs; (c) MSG/MAG gain of the GaN:C/EBL buffer device and the DHFET (device size $8 \times 50 \mu\text{m}$).

Figure 5c shows the comparison of the measured small-signal maximum available (stable) gain (MAG/MSG) and current gain (H21) for the $8 \times 50 \mu\text{m}$ device of the device with GaN:C/EBL buffer and DHFET. The measurements were performed using vector network analyzer on the on-wafer probing system up to 40 GHz. The GaN:C/EBL buffer device showed a consistent improvement of about 1 dB in MAG/MSG up to 30 GHz, evidencing that the AlGaIn EBL could reduce the current collapse effect observed for the device using only the GaN:C buffer.

On-wafer load-pull measurement for the device with large gate peripheries of $8 \times 50 \mu\text{m}$ at 28 GHz were performed: Γ_{source} tuning of the device for max Gain and Γ_{load} tuning for max Power. The measurement results of the device at $V_{\text{DS}} = 28 \text{ V}$ are shown in Figure 6. The device with the GaN:C/EBL buffer exhibited a high Pout of 31.2 dBm, with a power density over 3 W/mm and PAE of 21.7% at $V_{\text{DS}} = 28 \text{ V}$; these results demonstrate the GaN:C/EBL buffer has a high breakdown field strength, and can reduce the hot electron trapping effect even at high V_{DS} when operated at high frequencies.

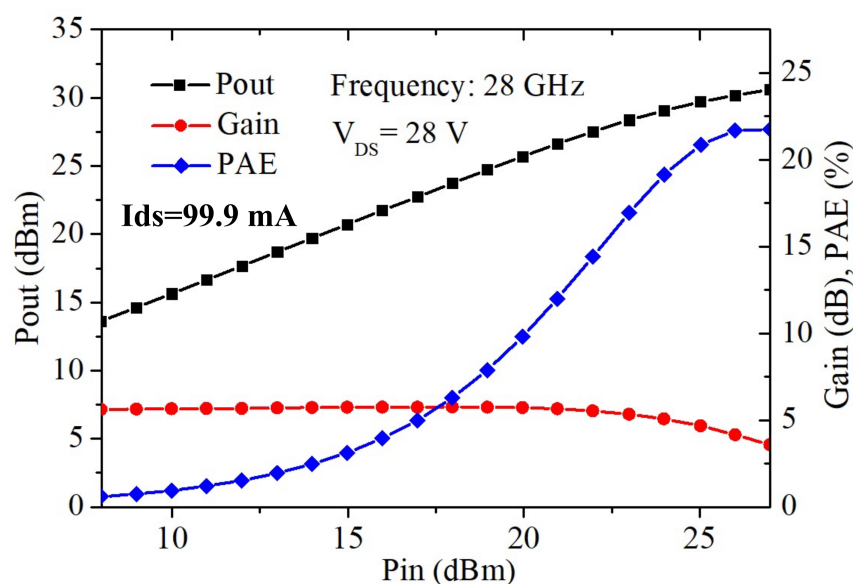


Figure 6. Power performance at 28 GHz for the $8 \times 50 \mu\text{m}$ GaN:C/EBL buffer device with $V_{\text{DS}} = 28 \text{ V}$.

4. Conclusions

The AlGaIn/GaN HEMTs on Si substrate using the GaN:C buffer with AlGaIn EBL is fabricated and evaluated for millimeter-wave applications. Compared with the DHFET, the GaN:C/EBL buffer device has a higher breakdown strength, higher thermal stability and better RF performances. This is because the GaN:C buffer can reduce the leakage current, and the insertion of an AlGaIn EBL in the GaN:C buffer can prevent carbon proximity effects from the buffer for the device. An output power of 31.2 dBm with a PAE of 21.7% was observed at 28 GHz when the drain was bias at 28 V for the $8 \times 50 \mu\text{m}$ GaN:C/EBL buffer device. The results demonstrate that the AlGaIn/GaN HEMTs on Si with GaN:C/EBL buffer is suitable for high-frequency device applications up to millimeter-wave. In the future, we will be using the GaN:C buffer with different AlGaIn EBLs to achieve a GaN device for V band applications.

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Data Availability Statement: The data presented in this paper are available on request from the corresponding author.

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References

- Piotrowicz, S.; Jardell, O.; Chartier, E.; Aubry, R.; Baczowski, L.; Casbon, M.; Dua, C.; Escotti, L.; Gamarra, P.; Jacquet, J.C.; et al. 12 W/mm with 0.15 μm InAlN/GaN HEMTs on SiC technology for K and Ka-Bands applications. In Proceedings of the 2014 IEEE MTT-S International Microwave Symposium (IMS2014), Tampa, FL, USA, 1–6 June 2014; pp. 1–3.
- Kolluri, S.; Keller, S.; DenBaars, S.P.; Mishra, U.K. Microwave Power Performance N-Polar GaN MISHEMTs Grown by MOCVD on SiC Substrates Using an Al_2O_3 Etch-Stop Technology. *IEEE Electron Device Lett.* **2012**, *33*, 44–46. [\[CrossRef\]](#)
- Higashiwaki, M.; Pei, Y.; Chu, R.; Mishra, U.K. Effects of Barrier Thinning on Small-Signal and 30-GHz Power Characteristics of AlGaIn/GaN Heterostructure Field-Effect Transistors. *IEEE Trans. Electron Devices* **2011**, *58*, 1681–1686. [\[CrossRef\]](#)
- Lin, Y.C.; Chen, S.H.; Lee, P.H.; Lai, K.H.; Huang, T.J.; Chang, E.Y.; Hsu, H.-T. Gallium Nitride (GaN) High-Electron-Mobility Transistors with Thick Copper Metallization Featuring a Power Density of 8.2 W/mm for Ka-Band Applications. *Micromachines* **2020**, *11*, 222. [\[CrossRef\]](#) [\[PubMed\]](#)
- Medjdoub, F.; Zegaoui, M.; Grimbert, B.; Ducatteau, D.; Rolland, N.; Rolland, P.A. First Demonstration of High-Power GaN-on-Silicon Transistors at 40 GHz. *IEEE Electron Device Lett.* **2012**, *33*, 1168–1170. [\[CrossRef\]](#)
- Egawa, T. Heteroepitaxial Growth and Power Devices Using AlGaIn/GaN HEMT on 200 mm Si (111) Substrate. In Proceedings of the 2013 IEEE Compound Semiconductor Integrated Circuit Symposium (CSICS), Monterey, CA, USA, 13–16 October 2013; pp. 1–4.
- Ishida, M.; Ueda, T.; Tanaka, T.; Ueda, D. GaN on Si Technologies for Power Switching Devices. *IEEE Trans. Electron Devices* **2013**, *60*, 3053–3059. [\[CrossRef\]](#)
- Luong, T.T.; Lumbantoruan, F.; Chen, Y.Y.; Ho, Y.T.; Weng, Y.C.; Lin, Y.C.; Chang, S.; Chang, E.Y. RF loss mechanisms in GaN-based high-electron-mobility-transistor on silicon: Role of an inversion channel at the AlN/Si interface. *Phys. Status Solidi A* **2017**, *214*, 1600944. [\[CrossRef\]](#)
- Stoffels, S.; Zhao, M.; Venegas, R.; Kandaswamy, P.; You, S.; Novak, T.; Saripalli, Y.; Van Hove, M.; Decoutere, S. The physical mechanism of dispersion caused by AlGaIn/GaN buffers on Si and optimization for low dispersion. In Proceedings of the 2015 IEEE International Electron Devices Meeting (IEDM), Washington, DC, USA, 7–9 December 2015; pp. 35.4.1–35.4.4.
- Lopatiuk, O.; Osinsky, A.; Dabiran, A.; Gartsman, K.; Feldman, I.; Chernyak, L. Electron trapping effects in C- and Fe-doped GaN and AlGaIn. *Solid-State Electron.* **2005**, *49*, 1662–1668. [\[CrossRef\]](#)
- Klein, P.B.; Binari, S.C.; Ikossi, K.; Wickenden, A.E.; Koleske, D.D.; Henry, R.L. Current collapse and the role of carbon in AlGaIn/GaN high electron mobility transistors grown by metalorganic vapor-phase epitaxy. *Appl. Phys. Lett.* **2001**, *79*, 3527–3529. [\[CrossRef\]](#)
- Hilt, O.; Bahat-Treidel, E.; Cho, E.; Singwald, S.; Würfl, J. Impact of buffer composition on the dynamic on-state resistance of high-voltage AlGaIn/GaN HFETs. In Proceedings of the 2012 24th International Symposium on Power Semiconductor Devices and ICs, Bruges, Belgium, 3–7 June 2012; pp. 345–348.
- Meneghesso, G.; Meneghini, M.; Bisi, D.; Silvestri, R.; Zanandrea, A.; Hilt, O.; Bahat-Treidel, E.; Brunner, F.; Knauer, A.; Würfl, J.; et al. GaN-Based Power HEMTs: Parasitic, Reliability and High Field Issues. *ECS Trans.* **2013**, *58*, 187–198. [\[CrossRef\]](#)
- Kabouche, R.; Derluyn, J.; Püsche, R.; Degroote, S.; Germain, M.; Pecheux, R.; Okada, E.; Zegaoui, M.; Medjdoub, F. Comparison of C-Doped AlN/GaN HEMTs and AlN/GaN/AlGaIn Double Heterostructure for mmW Applications. In Proceedings of the 2018 13th European Microwave Integrated Circuits Conference (EuMIC), Madrid, Spain, 24–25 September 2018; pp. 5–8.
- Corrion, A.L.; Shinohara, K.; Regan, D.; Milosavljevic, I.; Hashimoto, P.; Willadsen, P.J.; Schmitz, A.; Wheeler, D.C.; Butler, C.M.; Brown, D.; et al. Enhancement-Mode AlN/GaN/AlGaIn DHFET with 700-mS/mm g_m and 112-GHz f_T . *IEEE Electron Device Lett.* **2010**, *31*, 1116–1118. [\[CrossRef\]](#)
- Hsiao, Y.L.; Chang, C.A.; Chang, E.Y.; Maa, J.S.; Chang, C.T.; Wang, Y.J.; Weng, Y.C. Material growth and device characterization of AlGaIn/GaN single-heterostructure and AlGaIn/GaN/AlGaIn double-heterostructure field effect transistors on Si substrates. *Appl. Phys. Express* **2014**, *7*, 055501. [\[CrossRef\]](#)
- Geens, K.; Li, X.; Zhao, M.; Guo, W.; Fahle, D.; Aktas, O.; Odnoblyudov, V.; Decoutere, S. 650 V p-GaN Gate Power HEMTs on 200 mm Engineered Substrates. In Proceedings of the 2019 IEEE 7th Workshop on Wide Bandgap Power Devices and Applications (WiPDA), Raleigh, NC, USA, 29–31 October 2019; pp. 292–296.
- Besendörfer, S.; Meissner, E.; Zweipfennig, T.; Yacoub, H.; Fahle, D.; Behmenburg, H.; Kalisch, H.; Vescan, A.; Friedrich, J.; Erlbacher, T. Interplay between C-doping, threading dislocations, breakdown, and leakage in GaN on Si HEMT structures. *AIP Adv.* **2020**, *10*, 045028. [\[CrossRef\]](#)
- Uren, M.; Moereke, J.; Kuball, M. Buffer Design to Minimize Current Collapse in GaN/AlGaIn HFETs. *IEEE Trans. Electron Devices* **2012**, *59*, 3327–3333. [\[CrossRef\]](#)

20. Cho, E.; Brunner, F.; Zhytnytska, R.; Kotara, P.; Würfl, J.; Weyers, M. Enhancement of channel conductivity in AlGaIn/GaN heterostructure field effect transistors by AlGaIn:Si back barrier. *Appl. Phys. Lett.* **2011**, *99*, 103505. [[CrossRef](#)]
21. Lee, J.H.; Ju, J.M.; Atmaca, G.; Kim, J.G.; Kang, S.H.; Lee, Y.S.; Lee, S.H.; Lim, J.W.; Kwon, H.S.; Lisesivdin, S.B.; et al. High Figure-of-Merit (V₂BR/RON) AlGaIn/GaN Power HEMT With Periodically C-Doped GaN Buffer and AlGaIn Back Barrier. *IEEE J. Electron Devices Soc.* **2018**, *6*, 1179–1186. [[CrossRef](#)]
22. Yang, L.; Zhang, M.; Hou, B.; Mi, M.; Wu, M.; Zhu, Q.; Zhu, J.; Lu, Y.; Chen, L.; Zhou, X.; et al. High Channel Conductivity, Breakdown Field Strength, and Low Current Collapse in AlGaIn/GaN/Si δ -Doped AlGaIn/GaN:C HEMTs. *IEEE Trans. Electron Devices* **2019**, *66*, 1202–1207. [[CrossRef](#)]
23. Kaun, S.; Wong, M.; Lu, J.; Mishra, U.; Speck, J. Reduction of carbon proximity effects by including AlGaIn back barriers in HEMTs on free-standing GaN. *Electron. Lett.* **2013**, *49*, 893–895. [[CrossRef](#)]
24. Liu, W.; Balandin, A.A. Thermal conduction in Al_xGa_{1-x}N alloys and thin films. *J. Appl. Phys.* **2005**, *97*, 073710. [[CrossRef](#)]