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Enhanced Breakdown Voltage of AlGaN/GaN MISHEMT using GaN Buffer with Carbon-Doping on Silicon for Power Device

Naeemul Islam [a], Mohamed Fauzi Packeer Mohamed [a]*, Siti Fatimah Abd Rahman [a]*, Mohd Syamsul [b,c] , Hiroshi Kawarada [c] , and Alhan Farhanah Abd Rahim [d]

[a]School of Electrical and Electronic Engineering, Engineering Campus, Universiti Sains Malaysia, 14300 Nibong Tebal, Pulau Pinang, Malaysia
[b]Institute of Nano Optoelectronics Research and Technology (INOR), Universiti Sains Malaysia, Bayan Lepas 11900, Pulau Pinang, Malaysia
[c]Faculty of Science and Engineering, Waseda University, Tokyo 169-8555, Japan
[d]Electrical Engineering Studies, College of Engineering, Universiti Teknologi MARA, Cawangan Pulau Pinang, 13500 Permatang Pauh, Pulau Pinang, Malaysia.
∗Corresponding author. Tel.: +60193022707; e-mail: fauzi.packeer@usm.my (M.F.P.M.) and fatimahrahman@usm.my (S.F.A.R.)

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ABSTRACT

In recent years, Gallium Nitride (GaN)-based metal-insulator-semiconductor high-electron-mobility transistors (MISHEMTs) have attracted interest in high-power and high-frequency applications. The breakdown mechanism in E-mode GaN MISHEMTs with carbon doping in the GaN buffer grown on a Silicon (Si) substrate (Sub) was investigated using technology computer-aided design simulations. Results showed that GaN MISHEMTs without Si Sub had a breakdown voltage (BV) of 600 V. However, after adding Si Sub to the GaN buffer layer, the electric field (E_F) increased, creating a vertical breakdown through the total buffer thickness, therefore, BV was reduced to around 240 V. On the other hand, BV is increased to approximately >1100 V, and the Electric field is reduced after employing a carbon deep acceptor with the proper doping concentration in this device. The GaN MISHEMTs with Si Sub is presented as threshold voltage +1.5 V with transconductance of 700 mS/mm, which is an excellent result compared to GaN MISHEMTs without Si Sub. Eventually, the study device depicted higher BV performance compared to other C-doped GaN HEMT devices. This suggests that the designed GaN MISHEMTs device could effectively be used in power semiconductor devices with optimum performance.

Keywords: *Gallium Nitride, HEMT, Semiconductor devices, Breakdown voltage, Threshold voltage, Transconductance*

1. INTRODUCTION

In the last ten years, Gallium Nitride (GaN) has remarkable performance properties, including a large band gap, large breakdown field, large electron mobility, large saturation velocity, low noise, and low thermal impedance, and has become a popular material for fabricating semiconductor devices [1]. Thus, several market-driven industries, such as high-frequency communication, RF power devices, high-power conversion, photonics, and control, have reported the use of GaN-based devices [1, 2]. However, the fundamental drawback of the high-electron-mobility transistor (HEMT) structure is that, owing to the native two-dimensional electron gas (2DEG) channel, the device is intrinsically normally-on (depletion-mode type), which is undesirable for many high-power applications. Therefore, normally-off (enhancement-mode type) is preferred.

Metal-insulator-semiconductor HEMTs (MISHEMTs) based on GaN have recently drawn significant attention because they have the lowest gate leakage current, and by thinning the barrier layer below the gate, enhancement-mode devices can be implemented. GaN devices on the Silicon (Si) substrate help to solve the substrate's cost and heat sink capability [2, 3]. This is due to the Si substrate's affordable price and big size. However, GaN-based MISHEMTs face reliability issues that may eventually cause degradation, such as high-temperature environments, high electric fields or thin films, high leakage current, current collapse, and low breakdown voltage [4].

There were found to be two sources of the current dispersion. First, the 2DEG density in the channel is modulated by a "virtual gate," which is created by surface donor-like traps close to the drain side edge of the gate. Thus, surface passivation, such as Al_2O_3 and HfO_2, can reduce surface trap-induced current collapse. Within the semi-insulating buffer layer, a consequence of deep levels of charge trapping is called the second number. Here, by using a 15 nm layer of HfO_2 as the gate dielectric/surface passivation layer, the current collapse induced by surface states is predicted to be significantly decreased[5]. Additionally, different dielectric materials such as SiO_2, SiN_x, and Al_2O_3 have been implemented to overcome those issues. For SiO_2, the breakdown voltage (BV) achieved 810 V [6], 451 V [7], and 100 V [8], while for SiN_x, the BV achieved 600 V [9] and 400 V [10], respectively. The BV of SiON was 640 V [11] and 428 [12], and Al_2O_3 had a BV of 993 V [13] and 930 V [14]. Furthermore, with suitable designs, acceptor-like traps in the buffer can minimize leakage current and short-channel effects, which makes them crucial for device performance [15].

Therefore, this study used a deep acceptor to minimize the large electric field (E_F), which increased after the Si Sub was included in the GaN buffer layer. Consequently, the BV increased to approximately >1100 V. It was observed that from our founding, BV shows better results than other C-doped GaN HEMTs devices. Furthermore, the GaN MISHEMT Si Sub device illustrates the threshold voltage (V_{TH}) and transconductance (G_M) of approximately +1.5 and 700 mS/mm respectively.

2. DEVICE DESIGN

The E-mode AlGaN/GaN MISHEMT device with a Si Sub was designed using technology computer-aided design (TCAD) simulation software, such as Silvaco, as shown in Figure 1. The transistor building consisted of an $Al_{0.25}Ga_{0.75}N$ barrier layer with a thickness of 25 nm, a GaN channel with a thickness of 10 nm, and a doped GaN buffer layer with a thickness of 1.5 µm on a Si Sub. The AlGaN barrier layer doping concentration was assumed to be 10^{15} cm^{-3}. However, 10^{21} cm^{-3} was the concentration of carbon doping in the GaN buffer layer. From the top, the proper electron confinement towards the channel is provided by the $Al_{0.25}Ga_{0.75}N$ barrier layer. Due to piezoelectric and spontaneous polarization effects, numerous electrons spontaneously emerge at the GaN channel without intentional doping, producing a 2DEG. In the channel, it was found that the sheet electron gas density was 9.45 x 10^{12} cm^{-2}. The surface states which created the current collapse are thought to be effectively reduced using Hafnium Oxide (HfO_2) as the surface passivation layer and gate dielectric. The parameters for HfO_2 dielectric are 15 nm of thickness, a permittivity of 25, a bandgap of 6 eV, and an electron affinity of 2.4 eV [16].

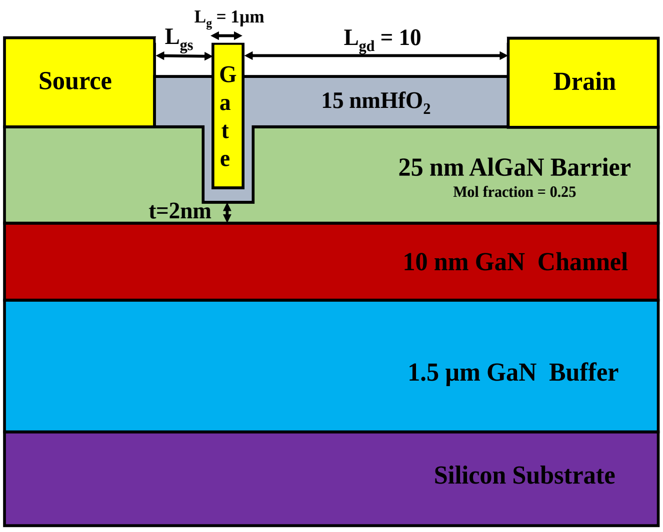


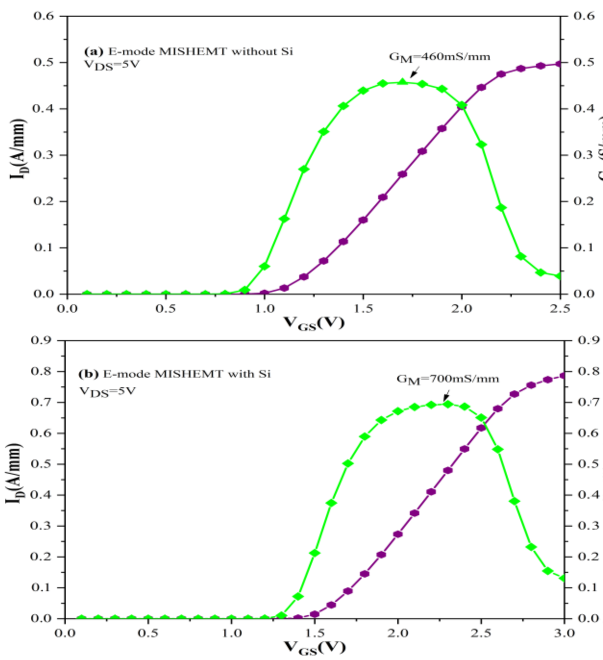
Figure 1. Schematic of the simulated AlGaN/GaN MISHEMT with Silicon substrate.

Moreover, the 2 nm AlGaN barrier is left under a 23 nm depth recess. The device has a 1 µm gate length and 5.5 eV work function; the gate electrode created for the structure is assumed to be made of metal. 1.5 µm was the distance from the gate to the source, and from the gate to the drain was 10 µm. Both the drain and source contacts have a length of 7 µm. As for simulation, various models have been incorporated for it, such as the Drift-Diffusion model, which takes into consideration the transit of carriers in the channel; The Fermi-Dirac model uses Fermi statistics. For carrier generation and recombination, the Shockley-Read-Hall model is used; the Statement of the Albrct model to take into account the effects of mobility and saturation velocity; a Trap parameter to set up the trap effect; the Impact Ionization model to calculate the breakdown characteristics, and for the epitaxial strain caused by lattice mismatch and spontaneous polarization, calculated strain and polarization are evoked. Subsequently, the built-in equations in Atlas TCAD are solved using Newton's technique, which includes the transport equation and Poisson's equation [17].

3. RESULTS AND DISCUSSION

3.1. Characteristic Curve

The transfer characteristic curves for an E-mode MISHEMT without a Si Sub are displayed in Figure 2 (a)[5], where the threshold voltage (V_{TH}) and transconductance (G_M) were obtained as +1.2 V and 460 mS/mm, respectively. In comparison, the transfer characteristic curves for an E-mode MISHEMT with a Si Sub are illustrated in Figure 2 (b). The threshold voltage (V_{TH}) and transconductance (G_M) have increased to approximately +1.5 V and 700 mS/mm for the MISHEMT Si Sub device because carbon concentration in the GaN buffer layer impacts mobility and 2DEG concentration. So, it is reported that 2DEG concentration will rise when in GaN buffer layer carbon dopant, which is a donor. As a result, the 2DEG layer with more electrons influences the transconductance and threshold voltage. Besides, mobility will be affected by the carbon dopant because it assists in enhancing the mobility of the charge carriers; for example, carbon doping reduces scattering events, limiting the charge carrier's movement. As a result, electrons can move more freely through the material [18].



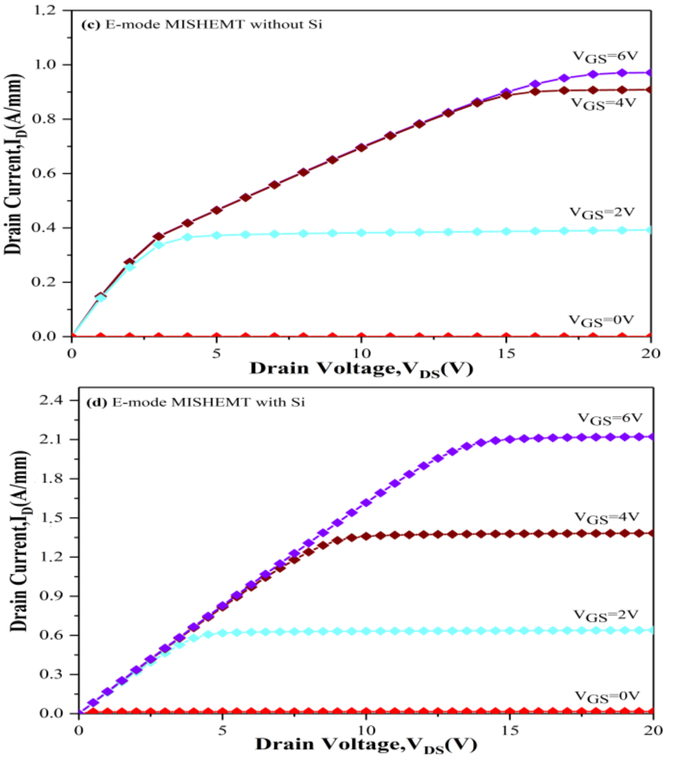


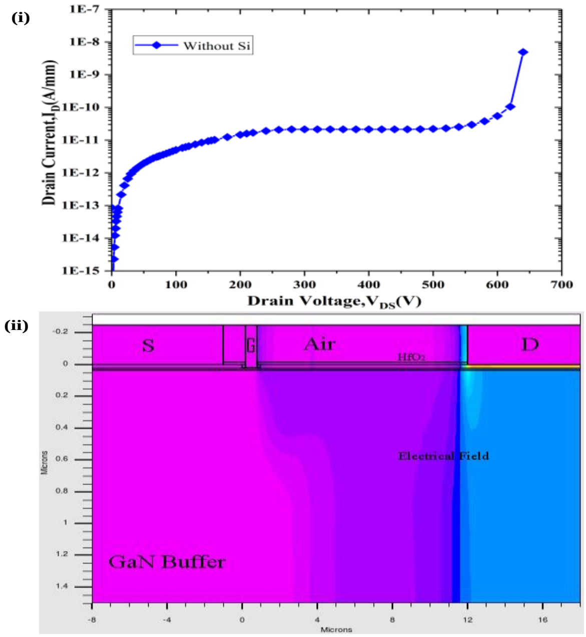
Figure 2. (a) Transfer characteristics and transconductance curve of AlGaN/GaN MISHEMT without Si and (b) AlGaN/GaN MISHEMT with Si. (c) Current vs Voltage characteristics curve of AlGaN/GaN MISHEMT without Si and (d) AlGaN/GaN MISHEMT with Si.

In the characteristic curves of the drain current (I_D) vs. drain-source voltage (V_{DS}), the MISHEMT without the Si Sub presented a maximum drain current of 0.950 (A/mm) at V_{GS} = 6 V, whereas 2.1 (A/mm) was indicated by the Si Sub MISHEMT devices, as shown in Figure 2 (c) and 2 (d). Note that a better Atomic Layer Deposition (ALD) HfO_2 gate dielectric prevents undesirable leakage and dielectric breakdown in HfO_2-based MIS structures when the gate bias is set to 6 V because a passivation layer with the large permittivity might reduce the effects of charge trapping by dispersing charges more effectively which minimizes chances of current collapse being caused by the accumulation of trapped charges while the device is in operation. Moreover, the relative permittivity of HfO_2(25) is higher than other dielectrics such as SiO_2 (3.7), SiN_x (7.5), AIN (8.5), and Al_2O_3 (9.3) [16, 19].

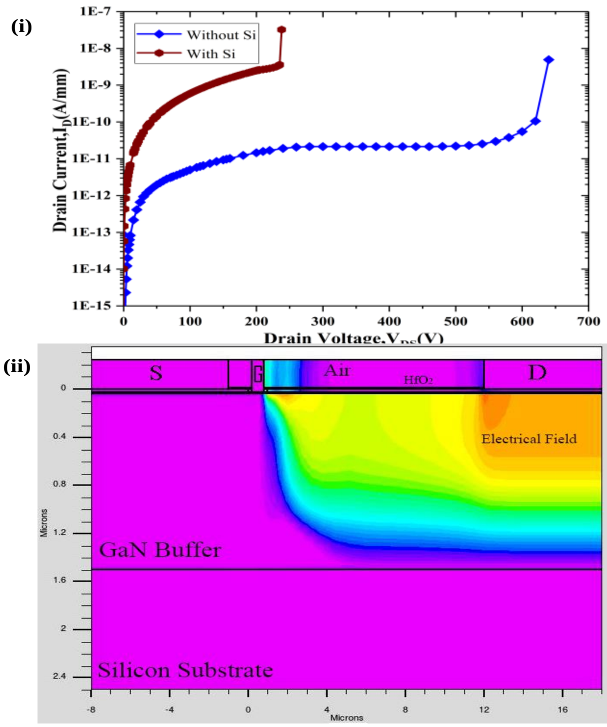
3.2. Breakdown Voltage

A crucial variable in GaN power devices is the off-state BV. It is defined by two widely accepted methods: when the leakage current is beginning to rapidly rise at the condition of the off-state drain current, and when a critical value, like 1×10^{-6} A/mm, is exceeded by the drain leakage current, the drain voltage is in the off-state situation.

However, E-mode MISHEMT without Si Sub achieved the BV at 600 V, where acceptor doping iron (Fe^{2+}/Fe^{3+}) in GaN buffer layer with energy level 0.7 eV and trap density 7×10^{17} cm^{-3} was used; furthermore, the degeneracy factor for the deep-level trap was set to 1.0[5], as illustrated in Figure 3(a)(i). Moreover, the E_F condition can be demonstrated in Figure 3(a)(ii), where it is noticed that electron injection from the drain to the buffer layer reduces the leakage current.



(a)



(b)

Figure 3. (a) AlGaN/GaN MISHEMT without Si. (i) BV and (ii) Electric Field of the device. (b) AlGaN/GaN MISHEMT with Si. (i) BV and (ii) Device drain side significant electric field.

On the contrary, after adding the Si Sub to this structure, at the drain-side gate edge, the E_F grew dramatically, as indicated in Figure 3(b)(ii). Because of the significant E_F near the edge of the gate, the gate tunnel electron enters the surface states, which fills surface donor states near the gate terminal. The 2DEG density in the channel is impacted by the filled states, and surface conduction is caused by hopping effects. Therefore, the BV reduces from approximately 600 V to 240 V; this comparison is displayed in Figure 3(b)(i).

Thus, GaN HEMT devices with Si Sub have a few of the primary causes of leakage current and associated BV. Firstly, between GaN and Si, an enormous difference in the thermal expansion coefficient (56 %) and an immense lattice mismatch of 17 % both induced the growth of tensile stress. Secondly, Figure 4(a) illustrates the reflecting electrons injected into the buffer by parasites, called the punch-through effect. Thirdly, the leaking current is due to surface-related conduction and/or through the passivation layer, as displayed in Figure 4(b). Finally, owing to the poor doping compensation of the buffer, the vertical breakdown happens across the entire buffer thickness, as indicated in Figure 4(c). Subsequently, by displacing an electron in the valence band and advancing it to the conduction band, the electrons in the 2DEG channel become so energetic in high electric field circumstances that they can produce an electron-hole pair, causing a sudden rise in the drain current. Source and gate injections are two different ways that electrons can start the impact ionization process. [18]. Nevertheless, to raise the BV of GaN HEMTs, more research work has been done. Hence, different solutions to solve the Si Sub issue in AlGaN/GaN HEMTs are presented in Table 1.

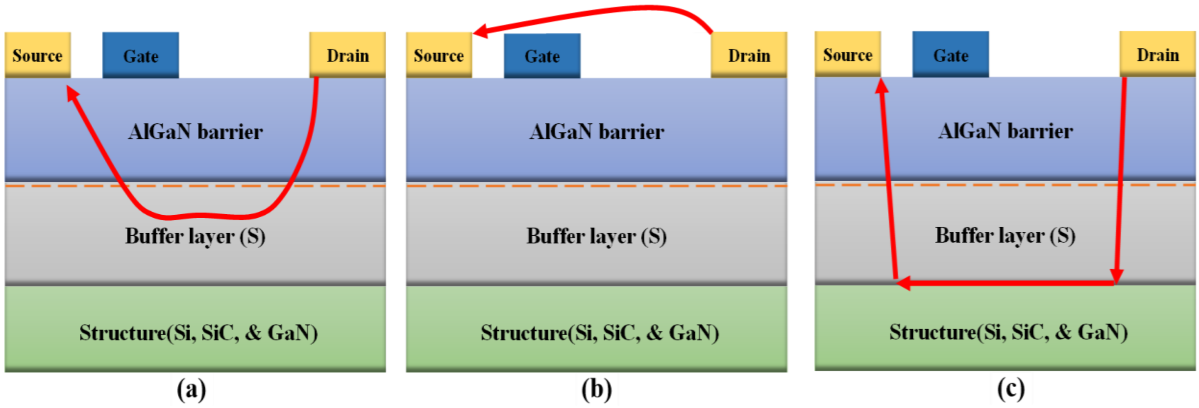
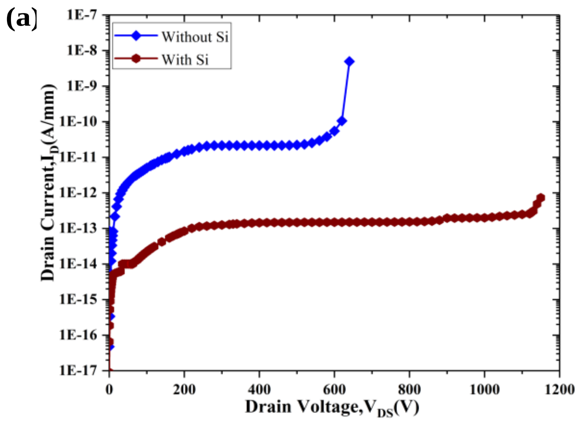


Figure 4. The primary source of leakage current is shown in the figure and associated BV for GaN HEMT device with the Si Sub.

Table 1 Different types of techniques for enhancing the breakdown voltage.

No.	Technique for Improving the Breakdown Voltage	Ref.
1	For surface passivation, when a high-quality dielectric is utilized, the amount of leakage that occurs both at the interface and the surface of the barrier is reduced.	[20, 21]
2	Increase the buffer resistance and, consequently, prevent carrier injection by properly compensating the doping into the buffer layers, which are usually carbon or iron doping.	[15, 22]
3	The back barrier approach has used materials with a graded AlGaN or AlN structure.	[23, 24]
4	To reduce the current collapse, implement of Field plate structures.	[25]
5	The use of superlattice buffer for suppressing trapping effects.	[26]
6	The silicon substrate removal method for suppressing the parasitic condition.	[27]
7	The vertical leakage characteristics are significantly influenced when a resistive Si substrate is used.	[28]
8	Implementing a buffer layer that is much thicker for the purpose of preventing the collapse of the current.	[29]
9	The use of SiN interlayer at AlN/Silicon substrate.	[30]
10	P^{++} doping implementation in the Si at the Si/AlN interface for reducing the vertical leakage.	[31]

In this study, a high-k dielectric HfO_2 was used to enhance the BV [16]. In addition, deep-level acceptors have been used in the buffer layer, such as carbon and iron, which are essential for suppressing buffer leakage, punch-through, and short-channel effects. However, we used the C deep-acceptor here because it is more strongly dispersed than the F deep-acceptor, which shows a marginal impact on the dispersion under pulse situations [32]. For the carbon doping GaN buffer layer, we used 10^{21} cm^{-3} C-doping concentration with acceptors 0.9 eV above the valence band. The Fermi level will be positioned close to this energy in the bottom half of the gap, and the material will be p-type if its density is greater than that of any donor state. Hence, using the mentioned methods, Figure 5(a) shows the BV increased to approximately >1100 V for MISHEMT with Si Sub compared to Figure 3(b)(i) which BV only 240 V. Figure 5(a) also demonstrates a further comparison of BV between MISHEMT with and without Si Sub.



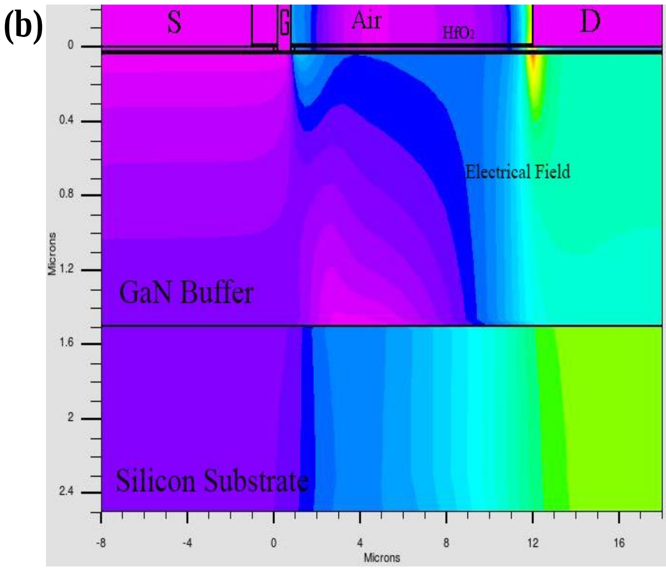


Figure 5.(a) Breakdown voltage and (b) electric field of AlGaN/GaN MISHEMT device.

In addition, the E_F condition after applying the proper C-doping concentration with acceptors to the buffer is displayed in Figure 5(b). The E_F was available on the drain side, but the drain current could move to the buffer layer. To reduce the E_F, we need to use a field plate that will be implemented in our subsequent research. Additionally, in Table 2, we add some C-doped GaN HEMT devices with their respective BV and compare them with our E-mode AlGaN/GaN MISHEMT silicon device. It can be observed that our device exhibits a higher BV than other devices.

4. CONCLUSION

The enhanced breakdown voltage of E-mode AlGaN/GaN MISHEMT silicon devices using the C-doping method has been studied using SILVACO TCAD simulation. It was observed that the AlGaN/GaN MISHEMT without silicon exhibits a BV of approximately 600 V. However, the BV is reduced to approximately 240 V after including Silicon in the AlGaN/GaN MISHEMT buffer layer because of the high electric field on the drain side of the device. Therefore, a deep acceptor 0.9 V with a doping concentration of 10^{21} cm^{-3} is applied to the buffer layer. Consequently, the BV increased to >1100 V. Moreover, the GaN MISHEMT Si Sub device illustrates the threshold voltage (V_{TH}) and transconductance (G_M) approximately +1.5 and 700 mS/mm, respectively. The proposed device also has a higher BV than other C-doped GaN HEMT devices, indicating that the method could be extended to power device applications.

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Table 2 Comparison between carbon doping concentration and breakdown voltage

No.	C-doping concentration (cm^{-3})	Breakdown voltage (V)	Ref.
1.	4×10^{19}	1000	[33]
2.	$1\times10^{19} – 1\times10^{20}$	650	[34]
3.	8×10^{18}	800	[20]
4.	1.2×10^{20}	>900	[35]
5.	4×10^{19}	1000	[36]
6.	8×10^{17}	450	[37]
7.	1×10^{18}	>1000	[38]
8.	1×10^{19}	670	[39]
9.	1×10^{19}	800	[40]
10.	1×10^{19}	1000	[41]
11.	1×10^{21}	>1100	This work

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