Enhancing Breakdown Voltage in Normally-OFF p-GaN HEMTs through Heterostructure Engineering

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***Abstract*—This work investigates the influence of key heterostructure parameters on the breakdown voltage of normally-OFF p-GaN HEMTs using Synopsys Sentaurus TCAD simulations. The results demonstrate that employing SiC substrates and increasing the aluminum content in the AlGaN barrier layer significantly improve breakdown performance. A maximum breakdown voltage of 1118V was achieved with a SiC substrate and GaN buffer, offering valuable insights for the design and optimization of GaN-based high-power electronic devices.**

***Index Terms*—GaN, AlGaN, Breakdown voltage, Electric field.**

I. Introduction

GaN is a highly promising semiconductor material for high-power and high-frequency applications due to its wide bandgap, high breakdown voltage, and superior electron mobility [1]. Conventional GaN-based HEMTs are normally-ON devices; however, for high-power applications, normally-OFF operation is preferred. This is achieved using the p-GaN gate technique [1]. The breakdown characteristics of HEMTs play a crucial role, as they directly impact the operating voltage, power density, and overall efficiency of the device [1].

In this study, we examine the effects of various heterostructure parameters on the breakdown voltage of AlGaN/GaN-based normally-OFF HEMTs. Despite maintaining a constant gate-to-drain length ($12\mu m$), our analysis reveals that structural variations significantly influence the breakdown voltage.

II. Theoretical Details and Validation

The simulations presented in this work were carried out using Synopsys TCAD [2] and schematic of simulated device shown in Fig. 1. The device structure includes a $5\mu m$ substrate, followed by a 150 nm AlN nucleation layer and a $3\mu m$ GaN/AlGaN buffer layer. Above this, a 200 nm GaN channel and an AlGaN barrier layer are implemented, topped with a 100 nm p-GaN layer doped with magnesium. A 200 nm Si_3N_4 passivation layer is added at the top.

Variabilities of hetrostructure parameters include the buffer layer material (GaN and $Al_{0.4}Ga_{0.6}N$), AlGaN barrier thicknesses (t_B) (10 nm, 13 nm, and 15 nm), and aluminum mole fractions (X_B) (0.25 and 0.30). Additionally, the Mg doping concentration in the p-GaN region was taken to be $2.0 \times 10^{19} cm^{-3}$. Each of these configurations was simulated using three different substrates silicon (Si), silicon carbide (SiC), and sapphire allowing us to analyze the impact of substrate variation as well. Fig. 2 demonstrates the validation of our work by comparing the drain current versus gate voltage characteristics with those reported by Hwang et al. [3].

III. Results and Discussion

In this variabilities the thickness of the AlGaN barrier is selected based on the aluminum mole fraction. For $X_B = 0.25$, a relatively thicker barrier is typically employed, leading to the selection of 13 nm and 15 nm thicknesses [4]. In contrast, for $X_B = 0.30$, a thinner barrier is preferred, and therefore, 13 nm and 10 nm thicknesses were chosen [5]. Breakdown voltage and maximum electric field for all simulated devices with the specified variations, are summarized in Table 1. In most cases, higher breakdown voltages were achieved when the electric field was more evenly distributed—indicated by a lower peak electric field, as seen in the table. Additionally, Table 1 shows that the combination of a SiC substrate with a GaN buffer yields the highest breakdown voltage compared to the other configurations.Fig. 3 and Fig. 4 illustrate the breakdown voltage and electric field characteristics, respectively, for the configuration that achieved the highest performance among all variations. This optimal result was achieved with a SiC substrate, a GaN buffer, and an AlGaN barrier with an aluminum mole fraction of 0.3. Such variability in heterostructure design plays a crucial role in optimizing HEMTs for high-power applications.

IV. Conclusion

Among all configurations, the combination of a SiC substrate with a GaN buffer delivered the highest breakdown voltage. Notably, a maximum breakdown voltage of 1118V was achieved with a fixed gate-to-drain length of $12\mu m$, highlighting its potential for high-power device applications.

References

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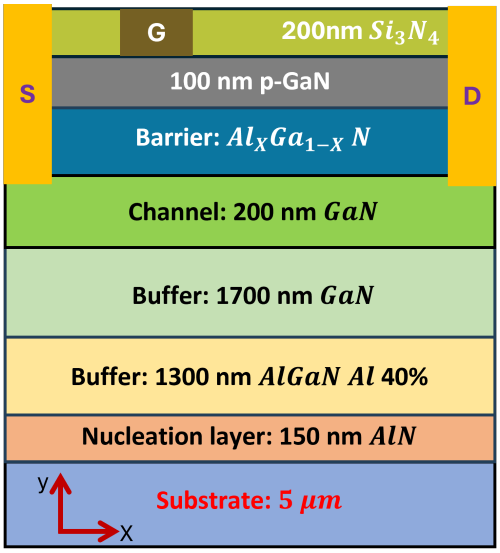

Fig. 1: Schematic of simulated HEMT device.

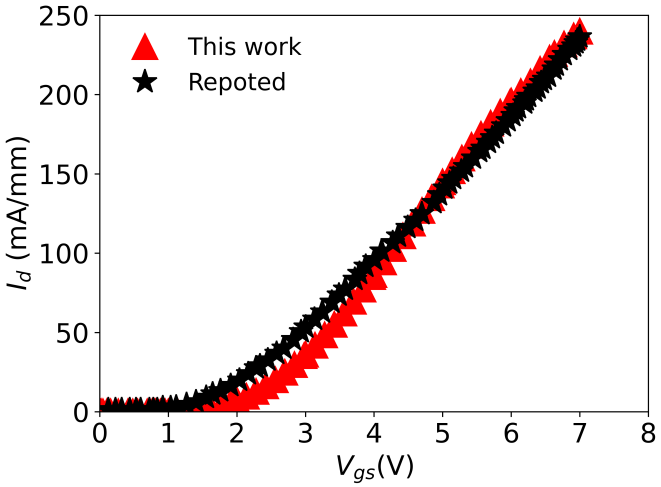

Fig. 2: Validation of drain current (I_d) vs gate voltage (V_{gs}) [3].

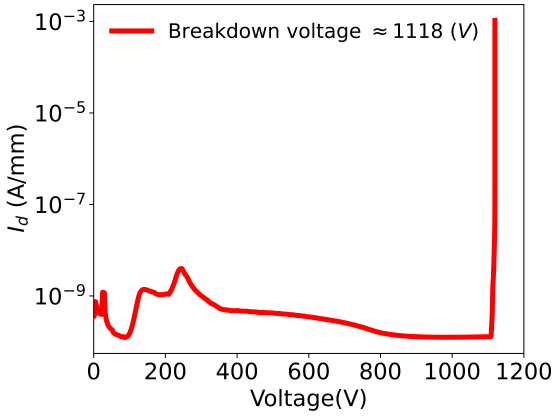

Fig. 3: Breakdown characteristics of the simulated structure that exhibits the highest breakdown voltage.

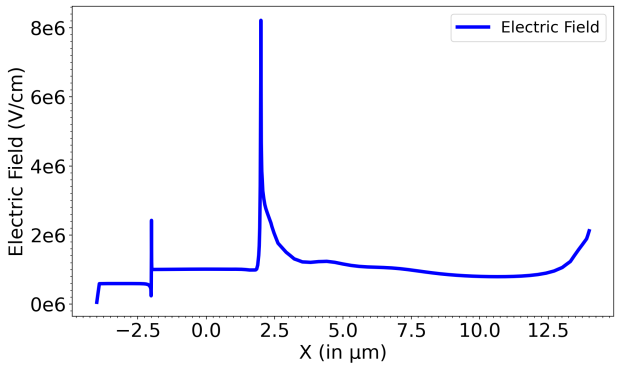

Fig. 4: Electric field distribution over heterostructure that exhibits the highest breakdown voltage.

TABLE I: Simulated Breakdown Voltage (V_{Br}) and Maximum Electric Field (E_{max}) for Different Heterostructure Configurations

Substrate	X_B	t_B (nm)	V_{Br} (V)		E_{max} (MV/cm)	
			AlGaN Buffer	GaN Buffer	AlGaN Buffer	GaN Buffer
Silicon	0.25	13	386	631	4.6	7.8
		15	391	640	4.6	7.7
	0.30	10	428	715	4.8	8.8
		13	430	729	4.5	6.5
SiC	0.25	13	387	890	4.6	8.9
		15	390	901	8.4	8.2
	0.30	10	435	1118	4.7	8.3
		13	436	1091	4.6	6.3
Al_2O_3	0.25	13	370	1010	4.6	9.0
		15	376	1012	4.5	8.4
	0.30	10	422	806	4.6	5.8
		13	425	379	6.1	5.9