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EFFECT OF SILICON NITRIDE AND SILICON DIOXIDE PASSIVATION FILMS ON THE PERFORMANCE OF OFF-STATE FIELD-PLATED AlGaN/GaN HEMT

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Abstract. The effect of Si_3N_4 and SiO_2 passivation films on the off-state breakdown performance of the AlGaN/AlN/GaN high electron mobility transistor with a source- or gate-connected field plate was investigated using TCAD simulations. It was discovered that the breakdown voltage of the field-plated device structure passivated by SiO_2 is noticeably higher compared to Si_3N_4, which contrasts with the results usually observed for transistors without field plates. It was also determined that the intrinsic stress in Si_3N_4 passivation films of certain thickness (250–300 nm) exerts a significant influence on the breakdown characteristics, with tensile-stressed layers allowing to increase the breakdown voltage. Finally, the device structure with a combined Si_3N_4/SiO_2 passivation stack and a gate field plate was analyzed.

Keywords: breakdown, electric field, field plate, gallium nitride, heterostructure, high electron mobility transistor, impact ionization, leakage current, passivation, simulation, stress.

Conflict of interests. The authors declare that there is no conflict of interests.

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ВЛИЯНИЕ ПАССИВАЦИОННЫХ СЛОЕВ НА ОСНОВЕ НИТРИДА КРЕМНИЯ И ДИОКСИДА КРЕМНИЯ НА ХАРАКТЕРИСТИКИ AlGaN/GaN-ТВПЭ С ПОЛЕВОЙ ОБКЛАДКОЙ В ЗАКРЫТОМ СОСТОЯНИИ

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Аннотация. В статье представлены результаты исследования в рамках компьютерного моделирования влияния пассивационных слоев на основе Si_3N_4 и SiO_2 на напряжение пробоя в закрытом состоянии транзистора с высокой подвижностью электронов на основе AlGaN/AlN/GaN с полевыми обкладками, подключенными к истоку или затвору. Выяснено, что напряжение пробоя приборной структуры с полевой обкладкой при использовании пассивационного слоя на основе SiO_2 заметно выше, чем при использовании Si_3N_4, что контрастирует с результатами, обычно получаемыми для транзисторов без полевых обкладок. Также обнаружено, что внутренние механические напряжения в пассивационных слоях на основе Si_3N_4 определенной толщины (250–300 нм) оказывают существенное влияние на пробивные характеристики, и применение слоев, имеющих механические напряжения на растяжение, может приводить к повышению напряжения пробоя. Проведен анализ характеристик приборной структуры с двойной пассивацией на основе Si_3N_4/SiO_2 и полевой обкладкой, подключенной к затвору.

Ключевые слова: пробой, электрическое поле, полевая пластина, нитрид галлия, гетероструктура, транзистор с высокой подвижностью электронов, ударная ионизация, ток утечки, пассивация, моделирование, напряжение.

Конфликт интересов. Авторы заявляют об отсутствии конфликта интересов.

Для цитирования. Влияние пассивационных слоев на основе нитрида кремния и диоксида кремния на характеристики AlGaN/GaN-ТВПЭ с полевой обкладкой в закрытом состоянии / В. С. Волчёк [и др.] // Доклады БГУИР. 2025. Т. 23, № 6. С. 5–11. http://dx.doi.org/10.35596/1729-7648-2025-23-6-5-11.

Introduction

Since the advent of solid-state electronics, silicon has continued to be the main semiconductor material for power devices. However, standard silicon technology is gradually approaching its fundamental physical and theoretical limits [1]. For that reason, there is an ongoing shift in the development of power devices, with manufactures now focusing on wide band gap semiconductors. One of these promising materials is gallium nitride (GaN), a representative of unique group-III nitrides. Among the advantages of GaN transistors are low on-state resistance, high breakdown voltage, high operational switching frequency, exceptionally good thermal and radiation stability. One of the most appealing devices for power electronics is high electron mobility transistor (HEMT) based on group-III nitrides [2]. Although GaN HEMT technology has recently made substantial progress [3, 4] there still remain critical problems that must be resolved to transform them to reliable and economically viable devices. It is well established that dangling bonds and other defects on the surface of a (Al,Ga)N heterostructure act as traps. When a large negative gate-source voltage is applied to turn the transistor off electrons are injected from the drain and captured by these surface state in the gate-drain access region. This accumulated negative charge reshapes the electric field distribution along the AlGaN barrier layer and creates a local electric field peak whose magnitude may be above the limit the device can safely withstand. Common techniques to cure surface traps include high-quality passivation and formation of field plates [5]. In this paper, we study the effect of Si_3N_4 and SiO_2 passivation films on the off-state breakdown characteristics of the AlGaN/AlN/GaN HEMT with a source- or gate-connected field plate using TCAD simulations.

Device structure

A two-dimensional representation of the AlGaN/AlN/GaN HEMT augmented with a source-connected field plate is shown in Fig. 1. The device structure consists of a 16 nm thick $Al_{0.2}Ga_{0.8}N$ barrier layer, a 1 nm AlN spacer layer and a 5.2 µm GaN buffer layer deposited on a sapphire substrate and covered by a 2 nm GaN cap layer and by a passivation film. Iron-induced deep-level acceptor trap states with an associated energy of 0.7 eV below the conduction band with a maximum concentration of $1 \cdot 10^{18}$ cm^{-3} are introduced into the buffer layer to control the off-state drain current. The source and drain electrodes are set to be ohmic contacts. The workfunction of 4.55 eV is specified to the gate electrode treated as a Schottky contact. This value is chosen so that the off-state drain current would be in a range from 10^{-9} to 10^{-8} A. The lengths of the source and drain electrodes are 1 µm, while the gate length equals to 2 µm. The source-gate and gate-drain access regions are 4.5 and 16 µm respectively. The source field plate is 15.5 µm long.

Since GaN HEMT is a unipolar device the hole transport, generation and recombination processes were fully neglected in our simulations. As to electrons, we employed the Farahmand temperature and composition-dependent low-field mobility model [6]. The spontaneous and piezoelectric components of polarization were calculated for all (Al,Ga)N heterointerfaces. Simulation of avalanche breakdown was performed using the Selberherr impact ionization model [7].

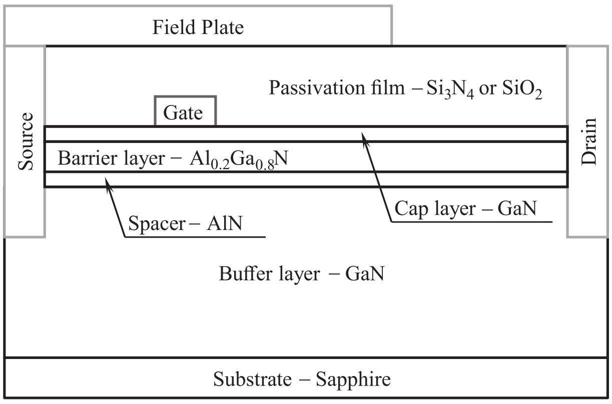

Fig. 1. AlGaN/AlN/GaN HEMT with a source field plate

Results and discussion

In order to investigate the influence of Si_3N_4 and SiO_2 passivation films on the performance of a field-plated AlGaN/AlN/GaN HEMT, a series of DC and off-state breakdown simulations was performed. In the first stage, a conventional device structure featuring a stress-free Si_3N_4 passivation layer but lacking a field plate of any type was studied. Its current-voltage characteristics at a gate-source voltage of –5 V calculated for 50, 200 and 400 nm thick passivation films are presented in Fig. 2. The thicker passivation layer provides a higher breakdown voltage, with the 400-nm film giving a 286 V value, which is larger by 68 V than the value obtained for the 50-nm film. The breakdown voltage grows as the passivation thickness is increased because the electric field weakens at the drain side of the gate. A larger available area allows to spread out the voltage drop along the device structure reducing the peak electric field that can induce breakdown [8].

The effect of the permittivity of the passivation material on the breakdown voltage resembles that of the thickness. When an insulator where the applied voltage tends to propagate more uniformly in general is deposited on a semiconductor, the voltage drop across the latter becomes smoother at the drain side of the gate. If the permittivity of the insulator is increased, the influence of the passivation film becomes more significant [8]. This implies that Si_3N_4 passivation would be a better choice for high-breakdown applications in comparison with SiO_2 since the permittivity of Si_3N_4 equals to 7.4, almost twice as large as 3.9 of SiO_2 [9]. However, several papers [10, 11] claim that the breakdown characteristics of GaN transistors passivated by SiO_2 can surpass those of Si_3N_4 passivated devices.

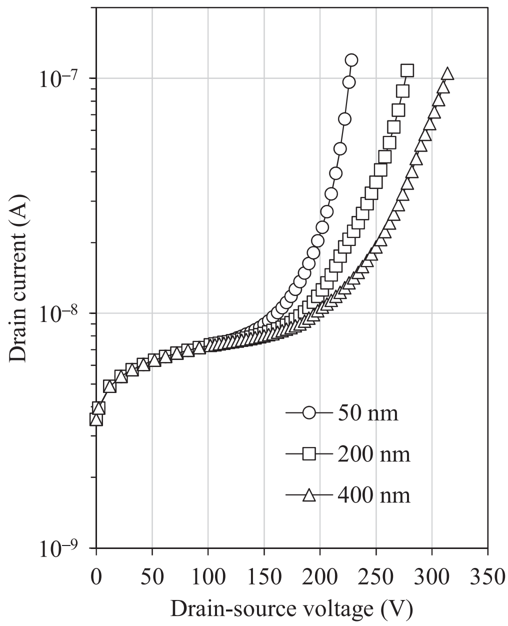

Fig. 2. Current-voltage characteristics of the device structure without a field plate at various Si_3N_4 passivation thickness values

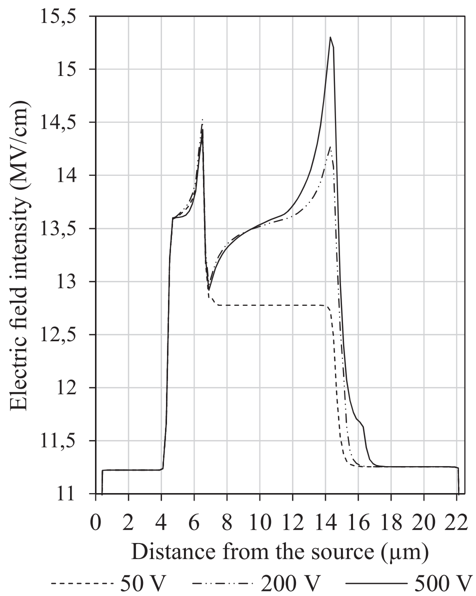

Fig. 3. Electric field distributions along the AlN spacer layer at various drain-source voltages

Figure 3 shows the profiles of the electric field along the AlN spacer layer of the off-state AlGaN/AlN/GaN HEMT with a source-connected field plate at drain-source voltages of 50, 200 and 500 V. The thickness of the Si_3N_4 passivation layer is 250 nm. As it can be seen from Fig. 3, a peak of the electric field forms in the area situated underneath the drain edge of the gate and its intensity remains invariable regardless of the magnitude of the applied voltage. At the same time, as the drain-source voltages is raised a second local maximum of the electric field starts to gradually form in the area below the drain side of the field plate. While no second peak is observed at 50 V, it reaches a value of 15.3 MV/cm at 500 V, greatly exceeding 3.1 MV/cm found near the gate. Similar results [5] were previously reported for gate-connected field plates.

The evolution of the electric field at different bias points is mirrored by the variation of the impact ionization rate, as demonstrated in Fig. 4. At a drain-source voltage of 500 V, the maximum rate becomes as high as $4 \cdot 10^{22}$ $1/(cm^3 \cdot s)$ and the area of the AlN spacer layer situated below the drain side of the field plate becomes the critical region of the device structure where avalanche breakdown can occur. According to our simulation data, both the electric field and impact ionization rate evolve much more slowly with increasing drain-source voltage if the passivation films are sufficiently thick. In Fig. 5, the effect of the passivation thickness on the breakdown characteristics is presented. When the AlGaN/AlN/GaN HEMT without a field plate is considered, the extension of the Si_3N_4 layer thickness from 50 to 400 nm leads to an increase in the breakdown voltage by around 10 V per every 50 nm. The SiO_2 passivation provides somewhat lower values, giving a breakdown voltage of 250 V for a 400 nm film. The basic physical mechanism that underlies these results was discussed earlier. It is further evident that the addition of a field plate connected to the source contact improves dramatically the off-state performance and enhances the significance of passivation thickness. In case of Si_3N_4, the breakdown voltage increases by 84.6 V per every 50 nm in a thickness range from 50 to 400 nm, reaching a maximum of 865 V. It is interesting to note that the device structure passivated by SiO_2 shows even better performance as the breakdown voltage increases by 96.7 V per every 50 nm and peaks at 970 V. This contrasts with the results obtained for transistors without field plates. The reason is that SiO_2 being a material with a lower permittivity stores a higher electric field compared to Si_3N_4 and reduces indirectly the field intensity in the AlN spacer layer where the critical region is generated.

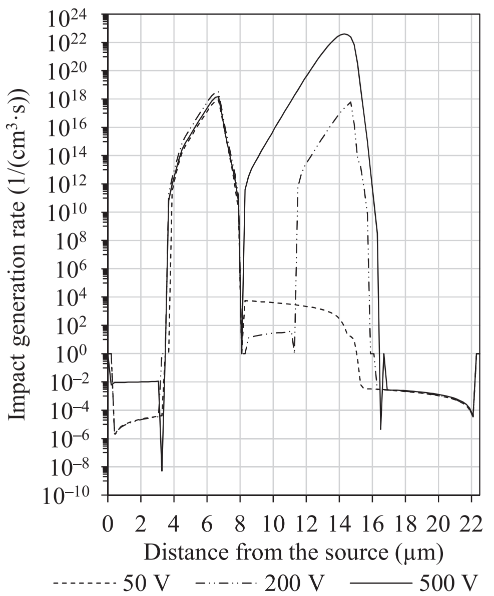

Fig. 4. Impact generation rate distributions along the AlN spacer layer at various drain-source voltages

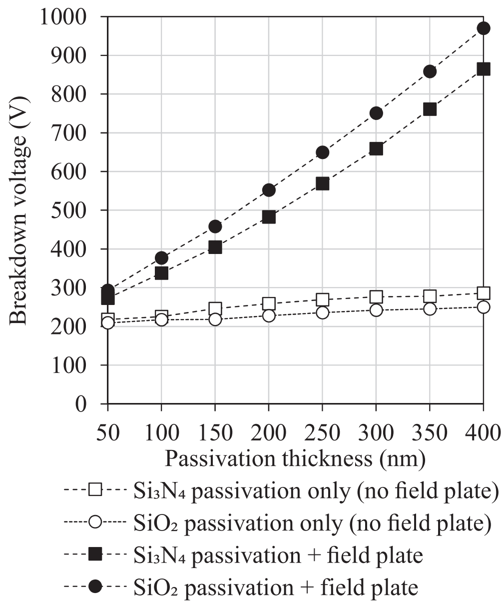

Fig. 5. Effect of the passivation thickness on the off-state breakdown voltage

If a Si_3N_4 passivation film is thick enough it can become intrinsically strained and consequently induce mechanical stress in underlying (Al,Ga)N layers [12]. Depending on deposition conditions, intrinsic, or built-in, stress in Si_3N_4 films can be either compressive (–) or tensile (+). Figure 6 shows the distributions of the longitudinal stress component along the AlN spacer layer of the AlGaN/AlN/GaN HEMT compressively strained by Si_3N_4 passivation films with –0.5 GPa ($-5 \cdot 10^9$ dyn/cm^2) intrinsic stress. The thickness of the Si_3N_4 layers is varied from 50 to 400 nm. On the graph, one can notice a remarkable feature – two distributions corresponding to 250- and 300-nm films have distinct spikes located precisely in the region of the device structure where avalanche breakdown is highly probable. As a result, a noticeable dependence (Fig. 7) of the breakdown characteristics on internal stresses in a passivating film with a thickness of 50 to 400 nm is observed. If a 250-nm Si_3N_4 layer with a tensile built-in stress of +0.5 GPa is deposited on the top device structure surface it allows to increase the breakdown voltage up to 598 V. On the contrary, the compressive stress of the same magnitude results in a value, which is lower by 62 V. The tensile and compressive intrinsic stresses in the 300-nm Si_3N_4 layer give 639 and 627 V respectively.

The dependence of the leakage current on the intrinsic stress in the Si_3N_4 passivation film at a drain-source voltage of 200 V is shown in Fig. 8. The thickness of the Si_3N_4 layers is again varied from 50 to 400 nm. In most cases, the tensile/compressive built-in stress leads to a higher/lower leakage current.

For example, the AlGaN/AlN/GaN HEMT passivated by a 400-nm tensile film exhibits an off-state current of $7.19 \cdot 10^{-9}$ A and a value of $6.85 \cdot 10^{-9}$ A is obtained for a 400-nm compressive film. The data points corresponding to the 50-nm film look to be inconsistent with the overall tendency. This is because the device structure passivated with such a film is in a state close to avalanche breakdown when biased at 200 V.

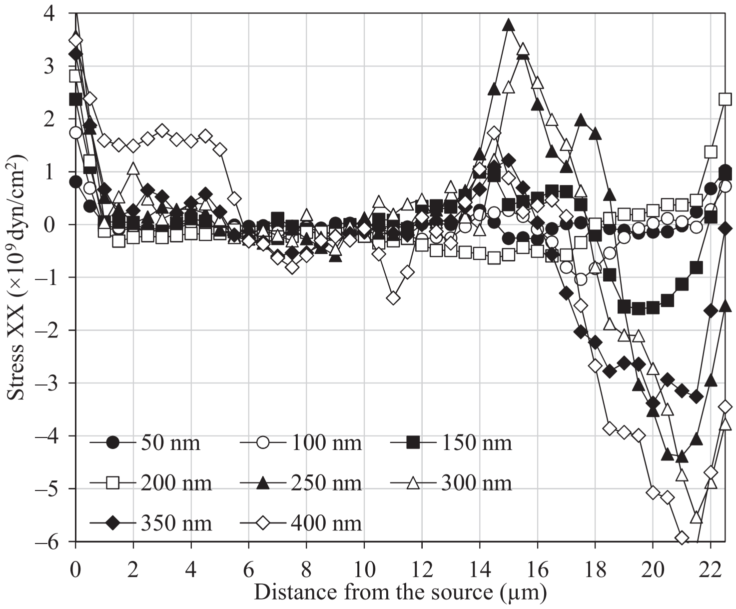

Fig. 6. Simulated distributions of the longitudinal stress component along the AlN spacer layer

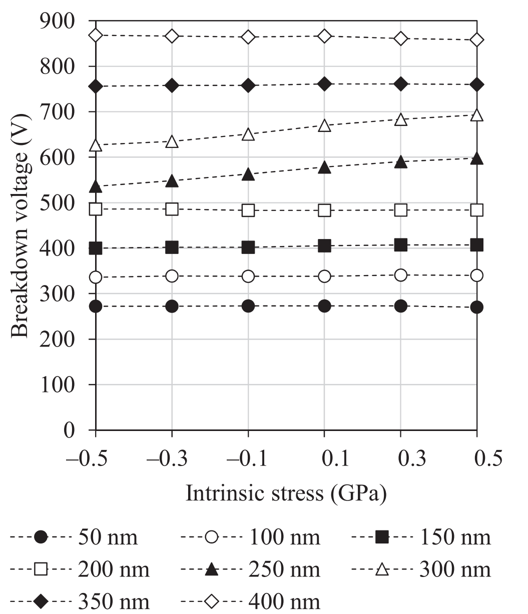

Fig. 7. Effect of the intrinsic stress in the Si_3N_4 passivation film on the off-state breakdown voltage

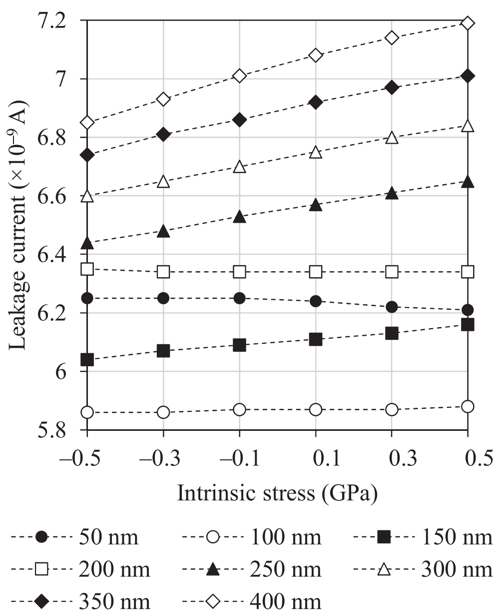

Fig. 8. Effect of the intrinsic stress in the Si_3N_4 passivation film on the off-state leakage current

After completing a series of supplementary simulation runs for the AlGaN/AlN/GaN HEMT with a gate-connected field plate, we found out that both types of field plates provide almost identical characteristics. Provided that the gate-to-drain distance is relatively long (16 μm) and the drain edges of the field plates sit halfway between the gate and the drain, these results seem quite reasonable [13]. In Fig. 9, a comparison of electric field profiles along the AlN spacer layer at various lengths of the gate field plate is presented. Here, we used a bilayer Si_3N_4/SiO_2 (250/50 nm) passivation stack where the SiO_2 film is inserted between the (Al,Ga)N epitaxial structure and the Si_3N_4 film to improve the poor adhesion of the latter [14]. As clearly seen in Fig. 9, the elongation of the field plate towards the drain leads to a redistribution of the electrostatic potential in the gate-drain access region causing the electric field peak associated with the field plate end to shift further away from the gate. However, the magnitude of this peak remains unchanged and equals to 14.3 MV/cm. This results in a very small fluctuation of the breakdown voltage within just 13 V when the length of the gate field plate is varied from 5 to 15 µm, as shown in Fig. 10. If the length exceeds 15 µm the field plate end appears to be critically close to the drain contact and the breakdown voltage eventually drops. Moreover, the simulation results correlate fairly well with the experimental data obtained on HEMT test structures.

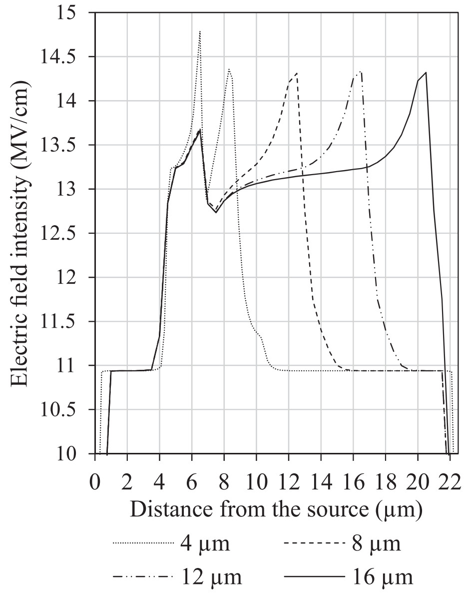

Fig. 9. Electric field distributions along the AlN spacer layer at various gate field plate length values

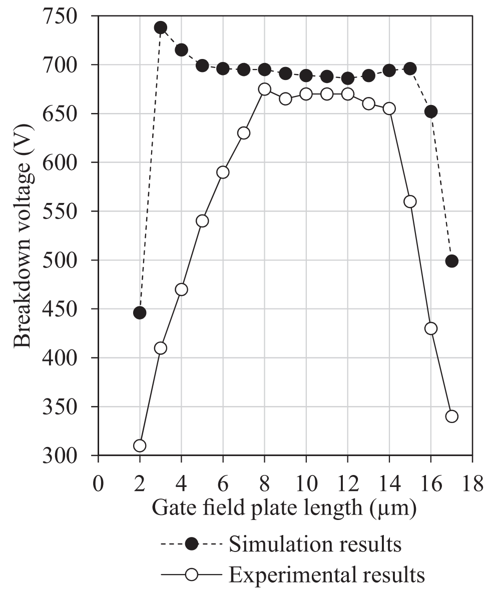

Fig. 10. Variation of the breakdown voltage with the gate field plate length

Conclusions

1. In this paper, we studied the effect of Si_3N_4 and SiO_2 passivation films on the off-state breakdown performance of the AlGaN/AlN/GaN HEMT with a source- or gate-connected field plate using TCAD software. It was shown that the breakdown voltage of the field-plated device structure passivated by SiO_2 is noticeably higher compared to Si_3N_4 (970 vs 865 V for 400 nm thick films). It was determined that the intrinsic stress in Si_3N_4 passivation films of certain thickness (250–300 nm) has a significant influence on the breakdown characteristics, with tensely strained layers allowing to increase the breakdown voltage. We also analyzed the device structure with a combined Si_3N_4/SiO_2 passivation stack and a gate field plate which made it possible to obtain HEMT test structures with a breakdown voltage above 650 V.

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Author's contribution

Volcheck V. performed simulation runs and prepared the manuscript of the article.
Lovshenko I. analyzed the results.
Yunik A. analyzed the results and prepared the manuscript of the article.
Hulikava K. performed simulation runs and analyzed the results.
Solovjov Ja. carried out the task setting for the study.

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