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Field plates design optimization to increase breakdown voltage of GaN HEMT

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Abstract. This article presents the results of modeling the heterostructure of a normally-off n-channel transistor with various designs of field plates on electrodes. The use of field plates makes to possible to effectively control the distribution of the field in the channel and increases the breakdown voltage. The optimal design parameters of field plates to achieve maximum BV were determined by study of the current-voltage characteristics, the distribution of the field in the channel and the concentration of the majority carriers in the channel.

Keywords: GaN, power transistor, field plate, breakdown voltage

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Оптимизация конструкции экранирующих электродов для повышения напряжения пробоя GaN HEMT

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Аннотация. В данной статье представлены результаты моделирования гетероструктуры нормально закрытого n-канального транзистора с различными конструкциями экранирующих электродов. Использование экранирующих электродов позволяет эффективно управлять распределением поля в канале и повышает напряжение пробоя. С помощью исследования вольт-амперных характеристик, характера распределения электрического поля и концентрации основных носителей заряда в канале были определены оптимальные конструкционные параметры экранирующих электродов.

Ключевые слова: GaN, силовой транзистор, экранирующий электрод, напряжение пробоя

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Introduction

A breakdown in high electron mobility transistor (HEMT) is a critical event, as it can lead to irreversible damage to the device [1]. Therefore, when designing such transistors, special attention is paid to their ability to withstand high voltages. Over the past two decades, in the course of research in the field of GaN HEMT, experts have proposed and implemented design solutions that allow an order of magnitude increase in breakdown voltage (BV). For example, the use of field plates (FP) allows the electric field (EF) to be redistributed in the transistor channel between gate and drain. The shift of strong fields from critical areas to less significant areas of transistor leads to an increase in the BV [2, 3]. Due to the uniform distribution of the electric field, the FP helps reduce probability of occurrence of an avalanche breakdown, improve the thermal stability of the transistor, preventing local overheating, and also increase the reliability and durability of HEMT. The scientific community has proposed and studied various designs of field plates [2–4]. The variety of design approaches leads to the need for systematization and selection of the best. The geometric dimensions of multiple FPs have a huge number of combinations. Even the search for the optimal ratio of the sizes of dual FPs turns into a lengthy search of geometric parameters. A possible solution may be use of computer simulation, algorithms and artificial neural networks that optimize the design of complex FPs [5]. In the work, the effect of different FP designs on the BV of normally-off GaN HEMT was investigated by computer simulation.

Materials and Methods

The study was carried out by Sentaurus TCAD. The command file for modeling the electrophysical characteristics included a piezoelectric polarization model, drift-diffusion model, thermionic emission mechanism at heterojunctions, avalanche generation model, SRH recombination, etc. The equations were solved by Newton's iteration method. The 2D model mesh included 12,500 nodes densified in channel area. Drain voltage was limited to the range from 0 to 3000 V. The limit of current in the channel was 1 A/mm. The heterostructure design of GaN HEMT was taken from a previous study in which the optimal mole fraction of aluminum in the buffer layer was determined to achieve maximum BV [6]. The heterostructure consisted of a 50 nm AlN nucleation layer, a 2 μm $Al_{0.05}Ga_{0.95}N$ buffer layer, a 300 nm GaN channel layer, a 15 nm $Al_{0.25}Ga_{0.75}N$ barrier layer, a 1 nm AlN spacer layer and a 100 nm p-GaN cap layer (Fig. 1). Si_3N_4 was used as a dielectric. The heterostructure was located on a silicon substrate. The model took into account a background impurity (Si, 1×10^{15} cm^{-3}) in the heterostructure. The Mg concentration in the cap layer is 5×10^{17} cm^{-3}. The study of the influence of FPs on the BV was carried out for most common designs with FP-source, FP-gate, grating FP-gate, FP-drain, and dual FPs (Fig.1). The distance between source and drain is 21 μm, between source and gate 1 μm, between gate and drain 18 μm. The design of the FPs varied in length, height from the barrier layer, and presence of a trench. In GaN HEMTs with a gFP-gate, the distance from the gate edge to the edge of the last FP finger on the drain side is constant. The grating parameters satisfied the ratio $L_{GG}:L_{GB} = 3:1$, where L_{GG} is length of finger in the grate, L_{GB} is the distance between the FP fingers. The GaN HEMT without FPs in the design has a BV of about 311 V.

Results and Discussion

Modeling of GaN HEMT with FP-source (Fig. 1, *a*) demonstrated an increase in the BV with increasing FP-source length (L_S) due to the redistribution of the peak EF strength from the gate edge towards the drain (Fig. 2, *a*). However, a further increase in the L_S leads to a decrease in BV. Increasing the L_S reduces the dielectric layer between the drain edge and the FP edge, which causes breakdown through dielectric layer at lower drain voltages [7]. In addition, an excessive field shift from the gate edge increases the EF peak at the drain edge, which can lead to an avalanche breakdown. Reducing the distance between barrier layer and FP-source leads to an increase in the efficiency of EF redistribution in the channel and an increase in BV. Since the minimum distance (1 μm) between FP-source and barrier layer (H_S) is limited by height of the gate (400 nm), a trench with a length of 4 μm was used on the FP-source edge, which reduced the distance between FP-source and barrier layer (H_{ST}) and increased the BV (Fig. 2, *a*). The optimal FP-source design to achieve maximum BV included L_S 9.5 μm and H_{ST} 50 nm. Similar field distributions were demonstrated in modeling of GaN HEMTs with FP-gate (Fig. 3). The BV and the nature of the BV versus L_G dependence were approximately the same as in the case of the FP-source (Fig. 2, *b*). It is worth noting that when the L_G reaches 6 μm and the trench at the FP-gate edge approaches the barrier layer (H_{GT}) to 50 nm, the BV drops, as a result of which the center of the “parabolic” dependence of the BV on the L_G acquires a valley. This is due to the fact that according to the reduction of H_{GT}, the EF peaks at the gate and drain edges are reduced, whereas the EF peak beneath the FP-gate edge increase [7]. Therefore H_{GT} or L_G to be selected so that the EF peaks at the gate and drain edges and the FP-gate edges are leveled. The optimal FP-gate design for leaving the valley and achieving maximum BV at H_{GT} of 50 nm and trench length of 0.9 μm requires L_G of 5 or 7 μm.

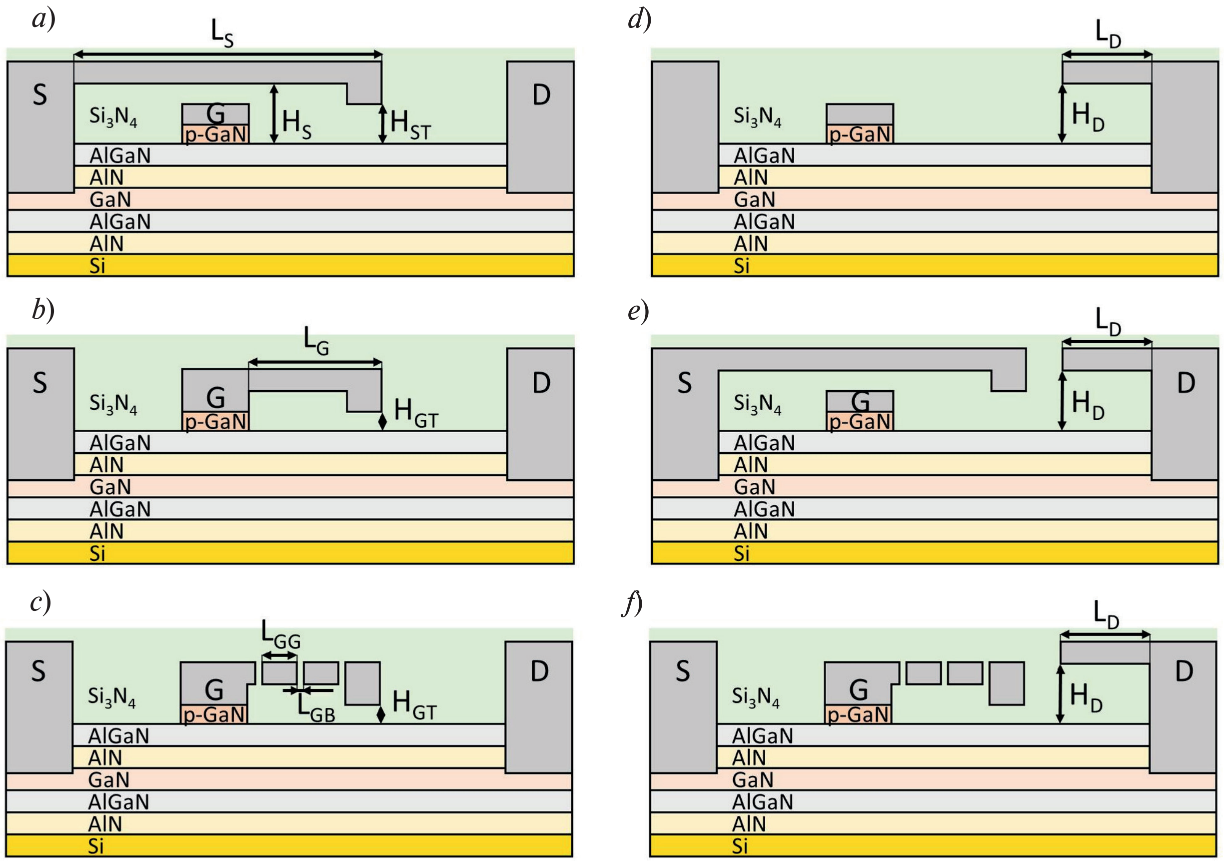

Fig. 1. Cross-section GaN HEMT with a FP-source (*a*), with a FP-gate (*b*), with a gFP-gate (*c*), with a FP-drain (*b*), with dual FPs: FP-drain and FP-source (*e*), with dual FPs: FP-drain and gFP-gate (*f*)

Converting FP-gate into grating FP-gate was applied to increase the BV (Fig. 2, *c*). The gFP-gate has more EF peaks due to charge induction between each finger. More points with electric charge located at the finger edges are generated, which redistribute and reduce the peak EF strength. The EF distribution in GaN HEMT with gFP-gate becomes smoother than in other designs. The maximum BV was achieved for gFP-gate length of 5 μm using a two-finger design and for gFP-gate length of 6 μm using a three-finger design (Fig. 2, *f*).

Reducing the H_{GT} to 50 nm leads to an increase in the BV in comparison with FP-gate, but does not allow one to overcome the valley at 6 μm. The optimal gFP-gate design to achieve

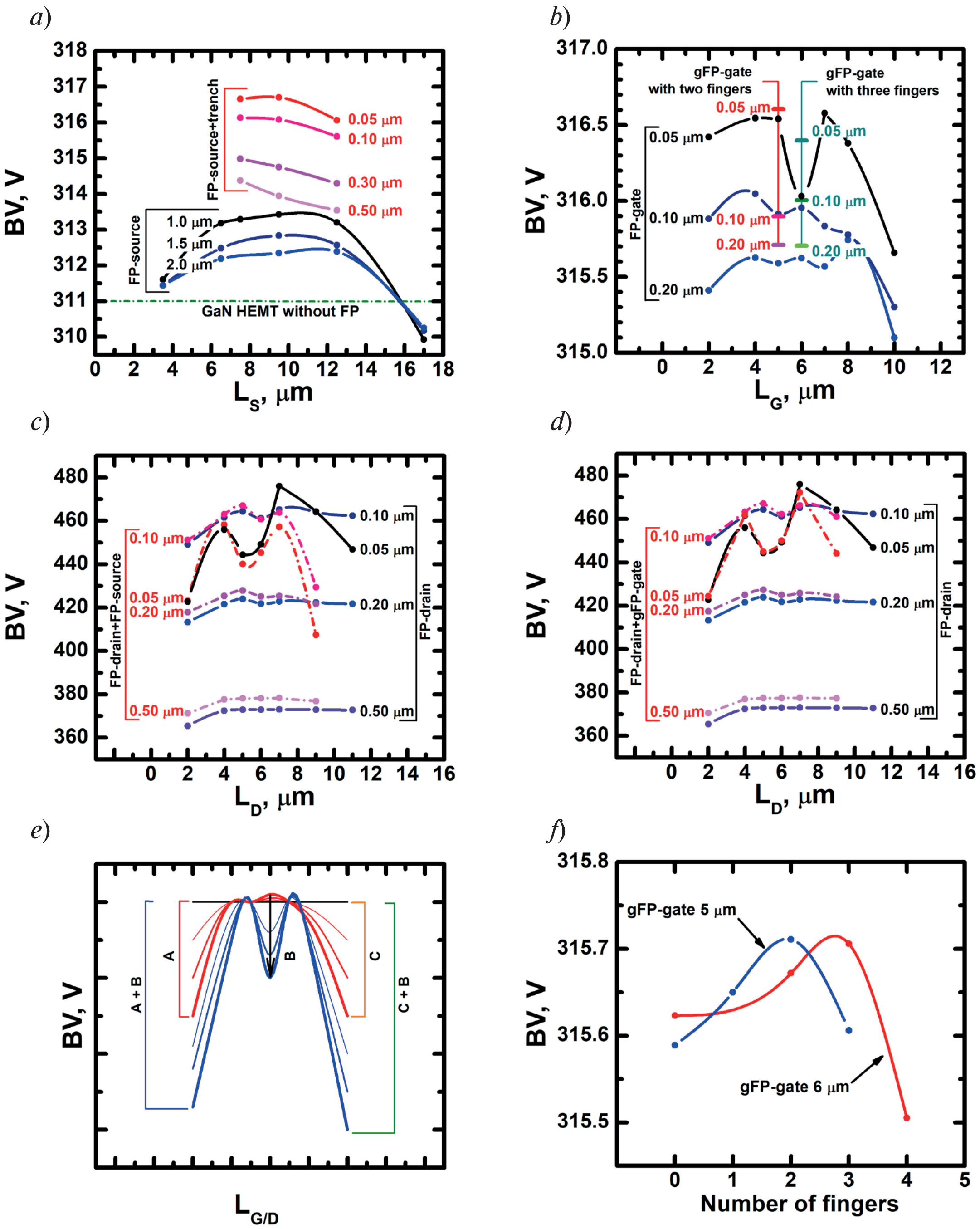

Fig. 2. Dependence of BV on length FP-source (*a*), FP-gate (*b*), FP-drain (dual FPs with FP-source) (*c*), FP-drain (dual FPs with gFP-gate) (*c*). The alleged influence of a close distance from FP edge to the own electrode (A) and to the opposite electrode (C) and peak states of the EF (B) on the dependence of BV on the FP length (*e*). The influence of the number of fingers in the gFP-gate on the BV (*f*)

maximum BV included two fingers, L_G 5 μm, L_{GG} 1.125 μm, L_{GB} 0.375 μm and H_{GT} 50 nm. The modulation of electric fields for GaN HEMT with FP-drain and gFP-drain is shown in Figure 3. As a result of the modeling, a significant increase in the BV was revealed when using a FP-drain in the GaN HEMT design (Fig. 2, *c*, *d*). The characteristic peak of the EF under the drain edge was significantly suppressed (Fig. 3). Similar to FP-source and FP-gate, the insufficient length of FP-drain leads to insignificantly shift the peak EF away from the source, and the excess length leads to a very close distance to the gate, which reduces the BV. Similar to FP-gate, the approach of FP-drain to the barrier layer leads to the appearance of a valley. Adding FP-source to GaN HEMT leads to a greater FP-drain length limitation than adding FP-gate. The previously found optimal designs of FP-source and FP-gate were used to modeling GaN HEMT with dual FPs. The use of dual FPs makes it possible to increase the BV, but does not solve the problem of the appearance of a valley at small H_D. The optimal FP-drain design to achieve maximum BV included L_D 7 µm and H_D 50 nm. The optimal dual FPs design to achieve maximum BV was obtained at L_D of 5 µm and H_D of 100 nm.

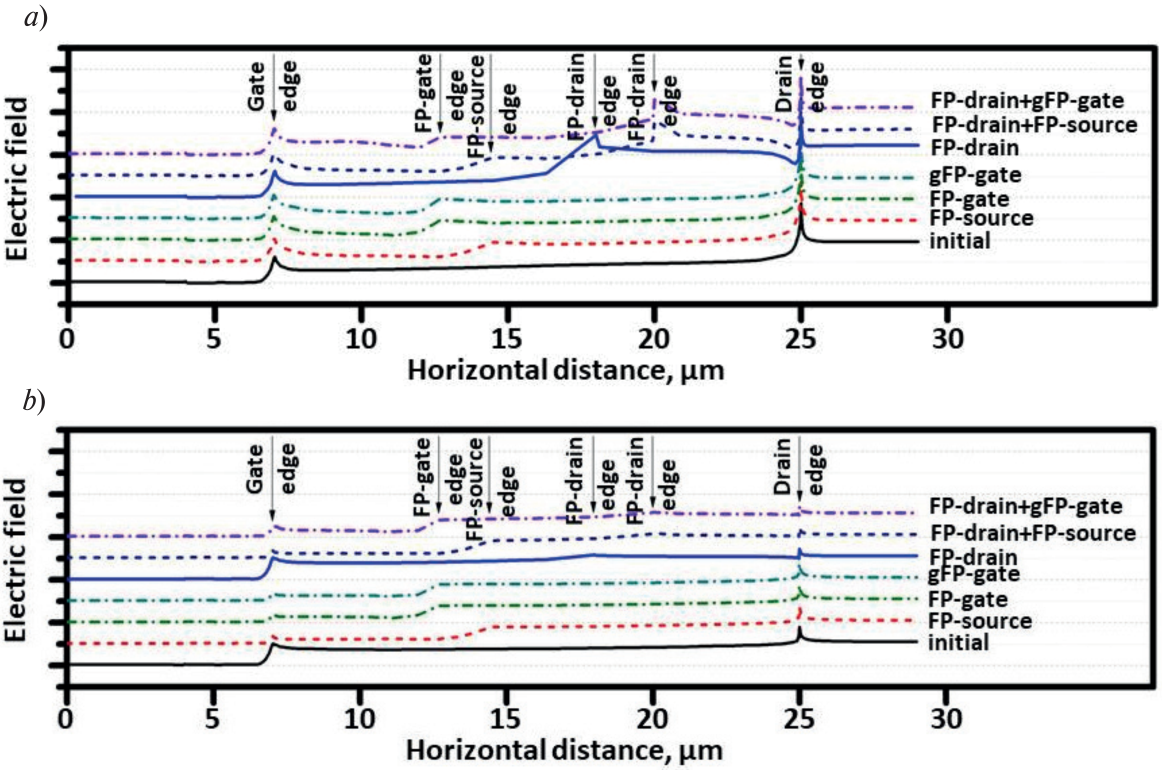

Fig. 3. The influence of different FP designs on field distribution in the GaN HEMT at BV (*a*) and 200 V (*b*). Field distribution is demonstrated for each type of FP with optimal dimensions and maximum BV

Conclusion

The work demonstrated the modeling results of GaN HEMT by Sentaurus TCAD. A characteristic change in the dependence of the BV on the FP length was established (Fig. 2, *e*). The close distance from the FP edge to the edge of its electrode (FP-gate and FP-drain) or to the edge of the gate (FP-source) leads to decrease of the BV due to increase of non-uniformity of EF (Fig. 2, *e*, A). The close distance of the FP edge to the edge of opposite electrode or FP leads to decrease of the BV due to breakdown through the dielectric layer between the FP edge and the opposite electrode. Thus, when designing the FP length, it is necessary to take into account the EF of an insulator breakdown and prevent excessive approaching of the elements of opposite electrodes. In addition, excessive field shift from the gate/drain edge increases the EF peak at the drain/gate edge, which can lead to avalanche breakdown (Fig. 2, *e*, C). Reducing the distance between the FP and the barrier layer increases the possibility of modulating the electric field, but contributes to the appearance of a valley with a low BV due to an increase in the EF peak at the FP edge (Fig. 2, *e*, B). The valley formation is not typical for a GaN HEMT with FP-source. Reducing the distance between the FP and the barrier layer at a minimum and maximum FP length leads to the overlap of two effects and a greater BV reduction (Fig. 2, *e*, A+B, C+B). Studying the influence of FPs design on BV made it possible to select the optimal FPs parameters to achieve maximum BV of GaN HEMT.

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