# The Influence of AlGaN Barrier-Layer Thickness on the GaN HEMT Parameters for Space Applications

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**Abstract** The results of simulation of field-effect microwave high-electron-mobility transistors (HEMTs) based on GaN/AlN/AlGaN heterostructures are presented. The research allowed to determine the optimal thickness of the AlGaN barrier layer for achieving high microwave capacity implementation.

**Keywords** Gan · Hemt · Heterostructure · Thickness · Space application Numerical simulation

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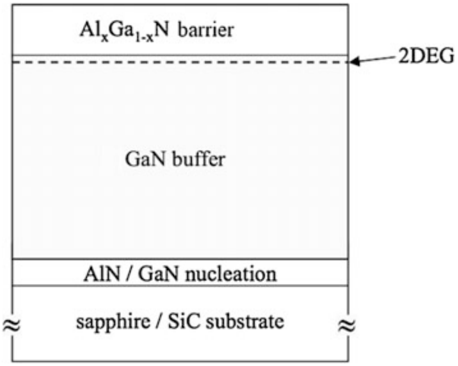
GaN transistors allow to significantly extend the capabilities of microwave devices. Electron mobility in combination with a high-electron density in the region of the 2D electron gas makes it possible to implement high current densities in the transistor-channel cross-section and high gain. However, optimization of heterostructure transistors still remains a complicated and expensive procedure [1–3]. The results of numerical simulation and calculation for the AlGaN barrier layer of high-electron-mobility transistors (HEMTs) are shown in this paper.

We have chosen typical heterostructure GaN HEMT transistor as the object of model. Briefly, it consists of a substrate, made of sapphire or silicon carbide SiC, a buffer layer of undoped GaN (thickness of several microns), a barrier layer of AlGaN (thickness of 10 nm) and a passivating silicon nitride layer SiN, which may be absent in a simplified case. This structure is represented on the Fig. 1.

According to the recommendations from the working [4], we have optimized the used mathematical models for the analysis of our heterostructures working. We have chosen two-dimensional hydrodynamical mathematical model, that often is used in many industrial simulation systems [5, 6], which, combining with the original physical models of the behavior of electrons in dielectrics and semiconductors, gave the good results. The same approaches are described in many workings [7–9]. Choosing the model of electron transporting, we took account balance between speed of calculations and sufficient accuracy. Nowadays it is clear that calculations of the drift—diffusion model cannot satisfy the demands of practice in the calculations of submicron transistors [10–16]. Accounting of the results by the Monte Carlo method in conjunction with the existing hydrodynamic model is the best choice in many cases, in our opinion. In general, we solve the system of three differential equations in partial derivatives. The Poisson's equation, describing the field, the current continuity and electron energy balance equation are solved self-consistently. This system of equations is supplemented by the specific equations for material medias, for example, the mobility of the charge carriers, the electron density, etc. The most important advantage is of complex analyze opportunity of ionization processes, defect formatting, and electron transport in the active area of the transistors.

**Fig. 1** The typical diagram of heterostructure for producing of GaN HEMT



Effects of ballistic and quasi-ballistic movement of electrons in strong heterogeneous electric fields become significant with reducing of semiconductor devices working area length to 30–300 nm [17–19]. The sizes of structures lead to fundamental changes in the physics of the devices when designing devices for working in conditions of radiation. It happens because characteristic spatial scales of variation of the electric field are compared with relaxation lengths of the energy, with electron impulse and with electron mean free path, the characteristic dimensions of devices workspace are comparable with the distance between the areas of defects, also the characteristic dimensions of devices workspace are comparable with the sizes of the defects. In this case analysis of radiation resistance supposes a using of the two-dimensional approach and considering of a number of new effects, connected with the heating of the electron gas under radiation exposure and scattering of carriers on the radiation defects. To analyze the radiation exposure on the submicron semiconductor devices was used quasihydrodynamic method of the charge carriers movement describing.

Studying effect of a heterostructure barrier layer on transistor's static characteristics in an equipment of space application, should consider a potential effect of specific external factors such as intensity of ionizing radiation on conductivity of two-dimensional electron gas and a number of the other GaN heterostructure parameters and investigated field-effect transistor, including the effect of metallization contacts topology [12, 20, 21].

Because of great amount of works with suggestion to drop heterostructure layers with Si, it is important to take into account the results of experimental investigations of the conductivity of GaN epitaxial structures, doped with a Si, concentration $1 \times 10^{18}$ cm$^{-3}$ and $1.8 \times 10^{18}$ cm$^{-3}$. Usually, electrical measurements are carried out by van der Pauw method in a wide temperature range 40–300 K. The effect of electron irradiation with energy of 1 meV in a dose range $10^{14}$–$10^{16}$ cm$^{-2}$ on the conductivity of such structures is interesting. Today it is known that in the range of low temperatures, 40 K conductivity with low activation energy E2, depending on the initial level of doping is observed. In the sample with a lower concentration of $1 \times 10^{18}$ cm$^{-3}$, the activation energy is greater and it is equal to 0.08 meV. Half of activation energy E2 = 0.04 meV is observed in a sample with a higher concentration, equal to $1.8 \times 10^{18}$ cm$^{-3}$. This behavior is typical for strongly doped semiconductors with conductivity in the impurity band. In the range of high temperatures 77–300 K extrinsic conductivity with activation energy E1, having a small dependence on the impurity concentration is observed. It is possible to connect the value of this energy that is equal to 2.5 meV with the transition of carriers from the impurity conduction band to the lower edge of the GaN conduction band. Conducted researches showed that the conductivity of strong doped epitaxial GaN structures in the temperature range 40–300 K is characterized with two activation energies, E1 and E2. The conductivity activation energy E2 can be associated with conductivity of impurity band within which the transitions of carriers with localized states of the impurity band in the states above conduction band edge. Quantity of this energy has strong dependence on the level of doping and decreases with increasing of dopant concentration. The activation energy E1 characterizes the transitions of carriers from the impurity band to the conduction band edge of the GaN crystal and is almost independent on the concentration of silicon impurities. The main static electrical characteristics of the material turned out to be resistant to radiation exposure with electrons, but decreasing of the charge carrier mobility in the area of two-dimensional electron gas channel forming gives grounds to refuse doping heterostructure for using in the space application equipment and to achieve high concentration of electrons using piezodoping effect layers of AlGaN/GaN.

A simplified scheme of two-dimensional section of GaN HEMT transistors for simulation is shown in Fig. 2.

In the first stage of the study, the numerical models [2, 22, 23] were adapted to the specific features of the configuration and fabrication technology of actual device structures. It is well known that the parameters of the undoped AlGaN barrier layer located near the two-dimensional electron channel have a significant effect on the characteristics of a HEMT. Versions of the HEMT heterostructure configuration with AlGaN barrier-layer thicknesses within 10–25 nm range and a fixed Al mole fraction of 25% were calculated, and ways of its optimization were studied.

The calculations revealed the strong effect of the barrier-layer thickness on the transconductance (Gm) (Fig. 3).

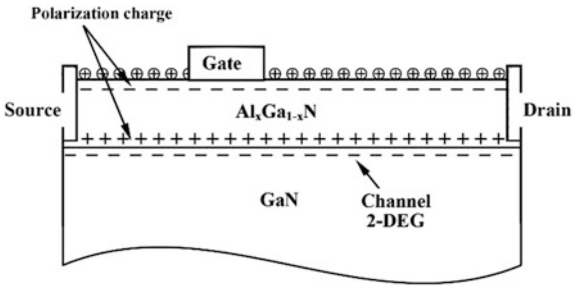


**Fig. 2** Simplified scheme of two-dimensional cross-section of AlGaN / GaN HEMT transistors for simulation of accounting charges on the interfaces

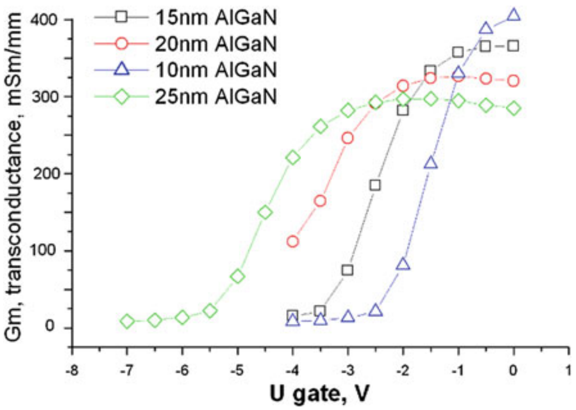


**Fig. 3** Calculated dependences of the transconductance (Gm) and gate potential with different AlGaN barrier layer thickness

It is easily seen that the drain current significantly increases as the AlGaN barrier-layer thickness increases from 10 to 25 nm. At the same time, a decrease in the barrier-layer thickness leads to a significant increase in the transconductance. However, a decrease in the drain current in the region of small thicknesses of the AlGaN barrier layer means that it is impossible to achieve a sufficiently high power density in a transistor produced from such structure even regardless of current-collapse effects. At the same time, the fabrication of a thin barrier layer is very attractive for improving the high-frequency characteristics of the transistors and reducing short channel effects at a sub micrometer gate length. Considering the above, for purposes of clarity, we can build on the one graph the dependence of the drain current on the thickness of the barrier layer (Fig. 4) and dependence of the outer slope on the thickness of the barrier layer. It is clear that the trends have different directions and it needs to find the balance between current density, received from the device and its reinforcing properties.

Choosing thickness of barrier layer should to consider the other effect, specific only for GaN HEMT heterostructures. Especially it can be important in the design of onboard equipment of space application. Numerical calculations show the presence of strong electric field domain under the gate, more precisely, at the edge of the gate stock. Using the typical operating conditions of the GaN heterostructure transistor the drain voltage is in the range of 30–60 V. Also, electric field intensity distribution is strongly heterogeneously. In the area at the age of the gate stock, the field intensity can reach many megavolts per centimeter. However, this inevitably leads to the appearance inverse piezoelectric effect in the thin barrier layer that can cause significant mechanical stresses at the surface and in the bulk structure [4, 24]. The appearance of the inverse piezoelectric effect is especially dangerous in a strong electric field. Even with very good heat removal from the transistors when

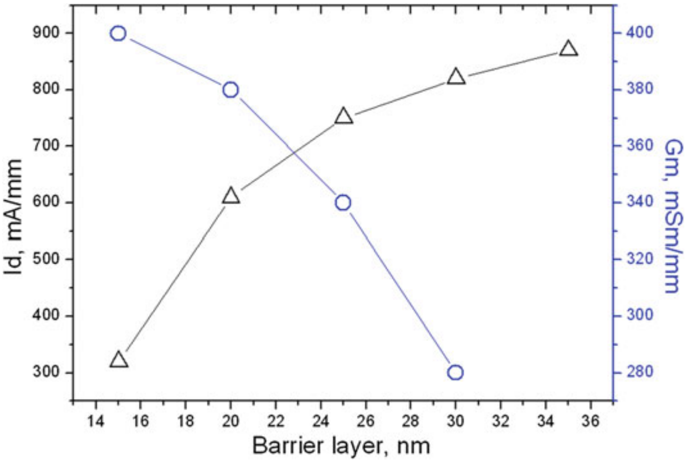


**Fig. 4** Calculated dependences of the transistor drain current (Id) at a drain potential of 6 V and the I–V characteristic transconductance (Gm) on the AlGaN barrier layer thickness

the temperature in GaN HEMT channel does not exceed tens of degrees Celsius, it is possible mechanical damage to the heterostructure because of the existence of the inverse piezoelectric effect. In the more favorable case, it can lead to the significant and unexplained by conventional factors (electrical degradation of the structure, external heating, self-heating, the effect of structural defects, the effect of plating defects contacts and so forth) reducing of the equipment life based on the powerful GaN electronics, or what is even more dangerous, to the sudden failures of such equipment, especially in space technologies.

We plan to investigate the described effect in subsequent works described effect in details, but we already can give some important recommendations to the equipment designers. It is important pre-mathematical modeling of specific processes in the GaN heterostructure layers, in this case, imposes the limitations on the thickness of the layers and the necessity to inject additional field electrode in the GaN HEMT construction.

## Conclusion

It was shown a strong dependence of the transistor's drain current (Id) and the drain current (Id)—gate voltage (Ug) characteristic transconductance (Gm) on the thickness of the AlGaN barrier layer as a result of the study by numerical simulation.

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