Increasing efficiency of GaN HEMT transistors in equipment for radiometry using numerical simulation

V G Tikhomirov¹,², A G Gudkov³, S V Agasieva⁴,⁵, D D Dynaiev², M K Popov¹, S V Chizhikov³

¹ Saint-Petersburg State Electrotechnical University “LETI”, St. Petersburg 197376, Russia
² Closed Joint Stock Company “Svetlana-Electronpribor”, St. Petersburg 194156, Russia
³ Bauman Moscow State Technical University, Moscow 105005, Russia
⁴ Peoples’ Friendship University of Russia, Moscow 117198, Russia
⁵ “Microwave radiometry global excellence” ltd., Moscow 115201, Russia

Abstract. The numerical impact modeling of some external effects on devices based on AlGaN/GaN heterostructures (HEMT) was carried out. The mathematical model was created that allowed to predict the behavior of the drain current depending on condition changes in the heterostructure in the buffer region and to start the process of directed construction optimization of the devices based on AlGaN/GaN HEMT with the aim of improving their performances.

1. Introduction
The main advantage of GaN HEMT is the highest power density and the ability to achieve high efficiency during operation in amplifiers or MIC. However, in recent years, such devices have a lag in expected increasing efficiency with the quality improvement of the GaN buffer layer growth in the heterostructure. Optimization of such transistors production cycle is still a complicated and expensive procedure [1-4]. This paper presents the results of numerical simulation and calculation of the buffer layer features of GaN HEMT for increasing efficiency when they are operating as a part of amplifiers for passive radar equipment.

2. Simulation results
The reasons of impossibility of high efficiency achievement by these transistors were analyzed. It was found that improvement of GaN crystal quality was accompanied by the decreasing of traps and defects in the region near the channel [5]. It led to increasing of the buffer conductivity above some critical value. This created the conditions for the appearance of a noticeable current through the transistor in the state of maximum sub-gate region depletion and a large bias at the drain. This situation is shown in Fig.1. It shows that there can be the conditions for the current bypassing the depletion region when the buffer layer has sufficient conductivity. It causes an unexpected increase of leakage current in the range 30-50V, that corresponds to the operating mode of transistors in amplifiers-class AB.

In this paper, a numerical simulation of the current flow in these modes was carried out and ways...
to overcome this problem were offered.

It can be assumed that by using the research results, the doping of the buffer layer at the certain depth by acceptor impurities, for example, "C" or "Fe", allows to achieve a significant decrease of the leakage current through the buffer. It significantly increases the opportunity to achieve high efficiency that was predicted for these devices by theoretical calculations.

Figure 1. The image of the screen for the calculating of the leakage current through the transistor in the state of maximum depletion of the sub-gate region and a large bias in the drain.

It is planned to use a rectangular doping profile that means the concentration of the acceptor impurity will remain at the same level increasing the depth towards the substrate. In this case, the leakage current that flows between the source and the drain of the transistor through the buffer layer has to significantly reduce by this approach. As a result, the device efficiency will increase. It is assumed that the microwave characteristics of transistors with the doped buffer layer by iron or carbon will not degrade. In order to achieve the desired result, it is necessary to optimize the semiconductor structure by selecting the concentration of impurities and the doping profile by numerical experiment.

The results of computer simulation of HEMT’s semiconductor structure are given below. A microwave transistor based on GaN with a doped buffer layer was simulated. The current-voltage characteristic of the source-drain breakdown for different values of gate lengths was obtained. Obtained results confirmed the presence of a specific source-drain breakdown in these transistors. And it is necessary to find a way to solve this problem.

Figure 2. The image of the screen with the simulation results for doping of a small part of the buffer layer by carbon with the acceptor concentration $n = 10^{17}$ cm$^{-3}$.
Figure 2 shows the calculation of the semiconductor structure of HEMT based on gallium nitride with doping of the buffer layer by carbon with the acceptor concentration $n = 10^{17} \text{ cm}^{-3}$. The impurity is located quite deep in the buffer layer. The impurity is located in the depth of the structure in the range from about 0.9 microns to 1.2 microns. The current flows between the source and drain electrodes, that confirms the existence of the punch-through effect. The current begins to flow from the source, then it flows around the Schottky gate, under which a region depleted by carriers is formed, and then rushes by the shortest way to the channel where the two-dimensional electron gas is located, and already reaches the drain through the channel. The current density decreases with depth into the substrate. This is due to the presence of an acceptor impurity in the depth of the buffer layer, which prevents the flow of current through the GaN.

Figure 3 shows a similar calculation of the semiconductor structure except that the depth of the acceptor impurity (in this case of carbon) has been changed. The impurity is located in the depth of the structure in the range from about 0.6 µm to 1.2 µm. Comparing figure 2 and 3, it can be concluded that the source-drain breakdown current significantly decreases with a decreasing of the impurity in the depth (figure 3). In addition, the depth of the flowing current in the buffer layer also decreases. The current, as shown in figure 2, flows around the sub-gate region of the transistor structure and rushes to the drain through a channel containing two-dimensional electron gas. A strong decrease in the punch-through current is associated with a decreasing of the doping depth by acceptor impurities of the buffer layer GaN.
Figure 4. The image of the screen with the simulation results for doping of a greater part of the buffer layer by carbon with the acceptor concentration \( n = 10^{18} \text{ cm}^{-3} \).

The breakdown current of source-drain completely disappears with increasing of the acceptor impurity concentration to the value \( n =10^{18} \text{ cm}^{-3} \) at a constant doping depth compared to figure 3. In this case the transistor is in the closed state and does not have source-drain leakage on the buffer layer. Thus, the found concentration and the impurity depth are optimal to eliminate the phenomenon of source-drain punch-through in the buffer layer.

3. Conclusion

According to the research results it can be recommended doping of the buffer layer at a certain depth by acceptor impurities. It can be the introduction of “Fe” or “C” atoms at a concentration about \( 0.5 \times 10^{18} \text{ cm}^{-3} \) for the GaN buffer layer. In this way, a significantly increase of the device efficiency can be achieved. More researches are needed for the directional changes of the heterostructure and of the overall transistor design to increase its efficiency.

The research is carried out in the framework of the research project No. 19-19-00349 on the theme: “Development of a methodology and multi-channel multi-frequency microwave radiothermography based on monolithic integrated circuits for finding the 3D distribution and dynamics of the brightness temperature in the depths of the human body” (Russian Science Foundation).

References

[1] Uren M J et al. Buffer design in GaN-on-Si power devices, J. Phys. D: Appl. Phys. 51 (2018) 163001.
[2] Stutzmann M, Steinhoff G, Eickhoff M, Ambacher O, Nobel CE, Schalwig J, et al, Diamond Rel Mater 2002; 11:886.
[3] Duffy S J et al. Strain-reduction induced rise in channel temperature at ohmic contacts of GaN HEMTs, IEEE Access, vol. 6, pp. 42721–42728, 2018.
[4] Tikhomirov V, Zemlyakov V, Volkov V, Parnes Ya, Vyuginov V, Lundin W, Sakharov A, Zavarin E, Tsatsulnikov A, Cherkashin N, Mizerov M, and Ustinov V, Semiconductors, 2016, Vol. 50, N. 2, pp. 244–248.
[5] Benbakhti B, Soltani A, Kalna K, Rousseau M, and De Jaeger J. Effects of self-heating on performance degradation in AlGaN/GaN-based devices, IEEE Trans. Electron Devices, vol. 56, no. 10, pp. 2178–2185, Oct. 2009.