ECV profiling of GaN HEMT heterostructures

G Yakovlev and V Zubkov
Department of Micro and Nanoelectronics, St. Petersburg State Electrotechnical University “LETI”, Prof. Popov str. 5, St. Petersburg, 197376, Russia

E-mail: gy@etu.ru

Abstract. AlGaN/GaN high electron mobility transistor (HEMT) heterostructures were investigated by means of the electrochemical capacitance-voltage technique. The concentration profiles of free charge carriers across the samples were experimentally obtained. The features of 2D electron gas (2DEG) appearing in GaN HEMT in relation to spontaneous and piezoelectric polarization were described in detail, along with the factors affecting the density of free charge carriers in the channel and the performance of GaN HEMTs. The 2DEG density for various technological parameters of the interface, such as the mutual orientation of the AlGaN/GaN layers and Al\textsubscript{x}Ga\textsubscript{1-x}N composition, was calculated accounting for piezoelectric effects.

1. Introduction
Gallium nitride has a set of properties that make it possible to develop devices with superior parameters compared to devices based on conventional semiconductors [1]. GaN, as a material for high-temperature, high-voltage, and high-current applications, can significantly expand the operational capabilities of semiconductor technology. The unique combination of physical properties in GaN means that nitride semiconductors may be the most promising materials for designing new generation devices. That is why GaN is currently associated with a breakthrough in microwave and high-current electronics. However, it should be noted that the development and improvement of such devices steadily leads to high requirements for reproduction accuracy of the sequence, composition, and doping level of the layers. The heterostructures of GaN-based high electron mobility transistors (HEMT) occupy leading positions in high-power microwave devices, but the initial presence of a sufficiently large number of various GaN defects leads to the appearance of traps and the so-called effect of current collapse, decreasing frequency and power performance. For this reason, it is especially important to investigate and control both active and buffer layers. When developing solutions to eliminate these negative phenomena and optimize the parameters of heterostructures to increase the subthreshold slope characteristic, operating frequencies, and device power, the most productive approaches involve the presence and effective use of an appropriate diagnostic base for high-quality and reliable verification of the resulting structures.

The main objectives of this work were to precisely measure the depth distributions of free charge carriers, to calculate the density of a 2D electron gas (2DEG) at the Al\textsubscript{x}Ga\textsubscript{1-x}N/GaN interface at various technological parameters. and to make recommendations for optimizing the parameters of the samples.
2. Samples and experimental technique

In this work, a set of two types of GaN HEMT heterostructures (sample 1 without additional doping and sample 2 with additional doping of the donor layer) was investigated. Typically, additional doping of the donor layer is used to increase the channel conductivity and operating current of a HEMT device. The sequences of layers in the investigated samples are shown in figure 1. In such structures, a quantum well (QW) is formed due to the band offset at the AlGaN/GaN interface, while the 2DEG channel is located on the side of the GaN layer. The surface of sample 1 was passivated with a SiN\(_x\) film [2]. There were very thin (1–2 nm) GaN and AlN layers grown on both sides of the emitter layer for improving the structural properties and roughness. In particular, the presence of the AlN layer leads to sufficient improvement of the GaN/AlGaN interface quality and a noticeable increase in 2DEG mobility, respectively. In addition, heterostructures with an ultrathin AlN layer are recognized as the most suitable for the manufacture of ultra-high frequency (UHF) transistors due to the reduction of the effects of a short channel and low threshold voltage [3].

![Figure 1. The sequences of layers in the investigated samples.](image)

The measurements were performed at room temperature using an ECVPro profiler (Nanometrics) and 0.2M H\(_2\)SO\(_4\) [4]. The area of the electrolytic rectifying contact was 0.1 cm\(^2\). The etching current was maintained at a level of 0.3 mA/cm\(^2\). During electrochemical capacitance-voltage (ECV) profiling, the samples were etched gradually with a 1 nm step in a pulsed mode [5]. The frequency of an ac test signal was 100 Hz. In some of the experiments, an Agilent E4980A LCR meter was used.

The structure of HEMT consists of many layers of different materials, electrochemical etching of which occurs at different rates. Therefore, in the ECV etching process, it is important to check the amount of etched material at different stages of the measurement. The etching depth and the surface quality were verified by atomic force microscopy (Solver NEXT AFM).

3. The results and discussion

In this part of the paper, the results of the measured depth distributions of free charge carriers as well as the 2DEG density and built-in electric field simulation are presented.

3.1. GaN HEMT: ECV-profiling

Figure 2 shows the depth distribution profile of free charge carriers in sample 1. The peak of the concentration profile is located at a depth of 24 nm, which well coincides with the location of the triangular QW formed by the AlGaN/GaN heterojunction. At the same time, the concentration profile peak has a large amplitude (2.1·10\(^{13}\) cm\(^{-2}\)) due to polarization effects and a larger band offset. Thus, even without the use of doping, GaN HEMT allows achieving 2DEG densities of more than 10\(^{13}\) cm\(^{-2}\).

The generally accepted mechanism for increasing the steep of the subthreshold slope characteristic in HEMT devices is to reduce the thickness of the upper (donor) layers [6], in our case (sample 2) – the AlGaN layer. At the same time, the magnitude of the induced electric field also decreases with a decrease in the layer thickness, which results in a decrease in the number of charge carriers in the channel. In this case, it is necessary to compensate the lost amount of the charge (due to the thickness...
decreasing) in order to maintain the same device performance. This problem is solved by additional doping of AlGaN.

Figure 3 shows the observed concentration profile of sample 2 measured over a wide depth range. The peak concentration of free charge carriers is equal to $1.2 \cdot 10^{20}$ cm$^{-3}$ ($2.4 \cdot 10^{13}$ cm$^{-2}$) and located at a depth of 22 nm, which agrees well with the structure specification. It should be noted that due to additional doping, it is possible to increase the 2DEG density by no more than 20%, since almost the entire charge in the channel is associated with a large built-in polarization field [7]. This is confirmed by our measurements. The peak concentration in undoped GaN HEMT (sample 1) is equal to $1 \cdot 10^{20}$ cm$^{-3}$ versus $1.2 \cdot 10^{20}$ cm$^{-3}$ in the case of additional doping (sample 2).

![Figure 2. Apparent profile of free charge carriers in sample 1 (undoped GaN HEMT).](image1)

![Figure 3. Apparent profile of free charge carriers in sample 2 (doped GaN HEMT), measured in a wide depth range: blue – concentration of electrons, red – concentration of holes.](image2)

As shown in figure 3, we also observed a sharp increase in the carrier concentration from a depth of ~ 450 nm. We associate it with a parasitic conduction $p$-channel with deep acceptors introduced to compensate the background concentration of electrons in the buffer GaN layer. Such excessive compensation leads to a situation when deep acceptors behave like electronic traps. Therefore, a key technological solution for this type of trap is the optimization of the compensation process [7]. In ECV results, we observed a spontaneous change of conductivity from $n$- to $p$-type, which is evidence of a high degree of compensation of the main impurity by deep acceptors.

3.2. GaN HEMT: electric field and 2DEG simulation
The polarization field in GaN HEMT consists of two components - piezoelectric and spontaneous. The spontaneous polarization emerges due to the features of the wurtzite lattice and the nature of its chemical bond where the geometric centers of negative charges (electrons) do not coincide with the centers of positive charges (nucleus). This means that atomic bonds between neighboring atoms are not equivalent, and explains why most semiconductors lack spontaneous polarization [8]. The piezoelectric polarization is caused by the deformation of the crystal lattice due to the occurring stretching stress during the growth of the $\text{Al}_x\text{Ga}_{1-x}\text{N}$ strained layer on GaN. This leads to the formation of a large sheet charge density on both sides of the AlGaN layer. The spontaneous polarization of nitride structures is directed along the polar c-axis, which coincides with (0001) sapphire or SiC substrate orientation during the growth process.
The piezoelectric polarization magnitude and difference of the total polarization at the AlGaN/GaN interface were calculated depending on the composition and orientation angle of the Al\(_x\)Ga\(_{1-x}\)N layer relative to the (0001) plane [9]. Figure 4 shows the calculated value of the electric field induced by polarization at the AlGaN/GaN interface, depending on the composition and orientation angle of the AlGaN layer with respect to the (0001) plane. Here the dashed line indicates the curve corresponding to the Al\(_{0.33}\)Ga\(_{0.67}\)N alloy investigated in the current work (samples 1 and 2).

\[
\begin{align*}
\theta, \text{ deg} & \quad 0 \quad 15 \quad 30 \quad 45 \quad 60 \quad 75 \\
E, \text{ MV/cm} & \quad 10 \quad 8 \quad 6 \quad 4 \quad 2 \quad 0 \\
\text{Al}_{0.1}\text{Ga}_{0.9}\text{N/GaN} & \quad \text{AlN/GaN}
\end{align*}
\]

Figure 4. The calculated built-in electric field at the AlGaN/GaN interface as a function of the Al\(_x\)Ga\(_{1-x}\)N composition and layer orientation.

As expected, the maximum value of the electric field strength at the AlGaN/GaN interface is reached at a zero angle of the Al\(_x\)Ga\(_{1-x}\)N layer orientation relative to the (0001) plane. The charge calculation [9] at the Al\(_x\)Ga\(_{1-x}\)N/GaN interface shows that the 2DEG density in the channel of HEMT increases with aluminum fraction in the alloy (figure 5). The most significant growth is observed at compositions x up to ~ 0.35. It can therefore be concluded that sample 1 represents a good compromise between a large amount of the built-in charge and a relatively low mismatch of the crystal lattices. We note that the calculated 2DEG charge for sample 1 without additional doping of the Al\(_{0.33}\)Ga\(_{0.67}\)N layer was \(1.9 \times 10^{13} \text{ cm}^{-2}\), which correlates well with the experimentally determined value \((2.1 \times 10^{13} \text{ cm}^{-2})\).

4. Conclusion
In this work, a set of GaN heterostructures were investigated using the ECV technique. The apparent depth distribution profiles of free charge carriers were obtained. The nature of the 2DEG formation in GaN HEMT that is associated with spontaneous and piezoelectric polarization was considered along with factors affecting the density of charge carriers in the channel. It is shown that the ECV technique can be effectively used to control the quality of both the active and buffer layers of GaN HEMT heterostructures, for instance: the positions of the AlGaN/GaN heterojunction, the 2DEG density, the insulating properties of the buffer layer and the presence or absence of a parasitic conduction channel. The built-in field in GaN HEMT structures was calculated taking into account the spontaneous and piezoelectric polarization for different compositions of the Al\(_x\)Ga\(_{1-x}\)N layer. The calculation showed the possibility of changing the built-in electric field at the interface in the range from 0 to 10 MV/cm at a zero angle of Al\(_x\)Ga\(_{1-x}\)N layer orientation relative to the (0001) plane. The experimentally determined 2DEG charge value was \(1.9 \times 10^{13} \text{ cm}^{-2}\), which, within the error of the applied continuum approximation of the theory of elasticity, closely matches the experimental one \((2.1 \times 10^{13} \text{ cm}^{-2})\).
References

[1] Aadit M, Kirtania S, Afrin F, Alam K and Khosru Q 2017 Different Types of Field-Effect Transistors – Theory and Applications (Rijeka: InTech) ed M M Pejovic and M M Pejovic chapter 3 pp 45-64
[2] Zhuravlev K, Malin T, Mansurov V, Tereshenko O, Abgaryan K, Reviznikov D, Zemlyakov V, Egorkin V, Parnes Ya, Tikhomirov V and Prosvirin I 2017 Semiconductors 51 395
[3] Deen D, Storm D and Meyer D 2014 Appl. Phys. Lett. 105 093503.
[4] Knübel A, Polyakov V, Kirste L and Aidam R 2010 Appl. Phys. Lett. 96 082106
[5] Wolff T, Rapp M and Rotter T 2004 Phys. Stat. Sol. A 201 2067
[6] Yakovlev G and Zubkov V 2018 J. Phys. Conf. Ser. 993 012038.
[7] Binari S, Ikossi K and Roussos J 2001 IEEE Trans. Electron Devices 48 465
[8] King-Smith R and Van-Derbilt D 1993 Phys. Rev. B. 47 1651
[9] Romanov A, Baker T, Nakamura S and Speck J 2006 J. Appl. Phys. 100 023522-10