Impact of a superlattice on electrical properties of AlGaN/GaN/sapphire 2DEG structures

V Jakštas¹, V Janonis¹, A Bičiūnas¹, R Aleksiejūnas², A Kadys², T Malinauskas² and I Kašalynas¹

¹ Center for Physical Sciences and Technology, A. Gostauto 11, LT-01108 Vilnius, Lithuania
² Institute of Applied Research, Vilnius University, Sauletekio 9-III, LT-10222 Vilnius, Lithuania

E-mail: vytautas.jakstas@ftmc.lt, irmantas.kasalynas@ftmc.lt

Abstract. In this work we demonstrate the impact of the AlGaN/GaN superlattice (SL) on electrical properties of AlGaN/GaN heterostructures grown by MOCVD on sapphire substrate. Schottky diodes and high electron mobility transistors were processed of the AlGaN/GaN heterostructures with and without the SL. It was demonstrated that the presence of the SL increased the breakdown voltage and improved the saturation current and transistor transfer characteristics performance.

1. Introduction
AlGaN/GaN heterostructures are promising material for the high-frequency and high-power solid state electronic devices due to the unique physical properties of GaN, i.e. wide bandgap, high breakdown field, electron mobility, and good thermal stability and conductivity [1]. During the last decade a huge interest of scientist and technologist community to this material was shown towards the growth of higher quality heterostructures and the development of new electronic devices. One of expected is an efficient terahertz (THz) emitter development for THz spectroscopy and imaging applications at room temperature [2].

Successful designs require reliable electrical performance of AlGaN/GaN 2DEG structures, which in turn depends on the quality of the grown buffer and epitaxial layers. AlGaN/GaN heterostructures are usually grown on a foreign substrates, such as sapphire, Si, and SiC due to absence of the GaN substrates and requirement to maintain low budget. However, foreign substrates cause high threading dislocation density (TDD) in grown heterostructure layers. One of the possibilities to reduce the TDD is to insert a superlattice (SL) between the layers.

In this work we characterize differently grown 2DEG AlGaN/GaN heterostructures by deploying a Ni/Au contacts and investigating their electrical performance in temperature range 300-124 K. Temperature dependence of the I-V characteristics and C-V characteristics were investigated by measuring the Schottky barrier height, the ideality factor and the leakage current dependence on temperature for heterostructure grown on sapphire substrate with and without the SL.
2. Fabrication of samples
The AlGaN/GaN layers were grown by the metalorganic chemical vapour deposition (MOCVD) method providing two VU393 and VU394 samples with different heterostructures design on 2” diameter sapphire substrate. The first sample was consisted of n-type unintentionally-doped GaN layer, the AlN spacer and the AlxGa1-xN layer. The main difference for the sample VU394 was that the SL consisted of 5 pairs of AlGaN/GaN layers and an additional GaN buffer was grown beneath the AlN spacer. The thickness and the molar concentration of Al in the top AlxGa1-xN layer for the samples VU393 and VU394 were found of about 21 nm and 0.11, and 18 nm and 0.26, respectively.

The self-consistent design of the Schottky diodes and HEMTs were taken with the aim to reduce a complexity of production. A standard ultraviolet (UV) photolithography and e-beam thin films deposition system was used to obtain the electric contacts. The Ohmic contacts were formed of the Ti/Al/Ni/Au stack annealed at 830 °C in N₂ ambient for 30 s. The conditions of the Rapid Thermal Annealing (RTA) was experimentally optimised by using circular transmission line method (TLM) and determining the specific contact resistance [3]. The contact resistance and the specific contact resistivity were as low as 7.0 Ω and 3.4×10⁻⁵ Ω·cm², respectively.

The metals Ni/Au were processed afterward to form the Schottky contacts and finalize the fabrication process. SEM images of the electronic devices are shown in the figure 1. No mesa etching and no surface passivation were used. The proposed design with the minimized technological steps is very attractive for the fast and cheap prototyping of the electronic components.

3. Results
3.1. Performance of the Schottky diodes
Measured I-V characteristics of the Schottky diodes at the applied direct current (DC) bias from -2 V to +2 V are shown in figure 2. The maximum forward current was found strongly depending over the distance \(d\): at +2 V it changed from 146 A/cm² and 140 A/cm² when \(d = 5 \mu m\) to 396 A/cm² and 309 A/cm² when \(d = 40 \mu m\) for the samples VU393 and VU394, respectively. The leakage current for the diodes processed of VU394 sample has increased significantly above -1 V as it is seen in figure 2. The effect was explained by the different TDD measured with the atomic force microscope; for the samples VU393 and VU394 the TDD was of 1.6×10⁹ cm⁻² and 1.5×10⁹ cm⁻², respectively. It was observed that the SL contribution was the other way than expected. However, the on-off ratio of all the VU394 Schottky diodes was almost 10⁵, indicating that the increase of the leakage current was not critical for most applications.
3.2. Performance of the HEMTs

Figure 4 shows the DC characteristics of the HEMTs normalised to the gate width. The output characteristics were acquired at applied drain voltages from 0 V to +7 V. Maximum drain current density was obtained up to 188 mA/mm and 302 mA/mm for the samples VU393 and VU394, respectively. It was followed by the decrease of $R_{on}$ from 18 Ω to 10 Ω for the same samples indicating a significant improvement with the presence of the SL. In addition, the dependence of the leakage current over applied drain voltage, which was visible in the transfer characteristic of the
samples VU393, vanished in the sample VU394 and the absolute values slightly decreased. Finally, the transconductance characteristics were measured steeper and its maximum value was obtained higher and improved from 121 mS/mm to 152 mS/mm level. This comparative analysis of the DC characteristics shows the positive impact of the SL to the performance of the HEMTs.

![Graphs showing DC characteristics of HEMTs](image)

**Figure 4.** DC characteristics of the HEMT made of VU393 (parts a, b, and c) and of VU394 (parts d, e, and f) samples: (a, d) output characteristics at gate bias from +2 V to -3 V in the steps of 0.5 V, (b, e) transfer characteristics at the selected drain voltages, and (c, f) transconductance characteristics at the same drain voltages.

### 4. Conclusion

In summary, we have developed unpassivated surface Schottky diodes of the AlGaN/GaN structures grown with and without the SL on sapphire substrate. The results have shown higher leakage current of the Schottky diodes made of the sample with the SL, providing on-off current switching ratio up to $10^5$. Despite higher TDD in the sample with SL, devices demonstrated much higher breakdown voltage. The comparison of the HEMTs made of the samples with and without the SL has shown improved parameters of the HEMT: $I_{DS\, \text{MAX}}$ has increased 1.6 times, the $R_{ON}$ has decreased 1.8 times, $g_{m\, \text{MAX}}$ has increased 1.3 times, and the $I_{DS}$ dependence over $U_{DS}$ below $U_{th}$ was not significant. The overall results have suggested a need to optimize the growth conditions of the SLs in order to overcome issue of increase of the TDD and further improve the performance of the electronic devices.

### References

[1] Meng F, Zhang J, Zhou H, Ma J, Xue J, Dang L, Zhang L, Lu M, Ai S, Li X and Hao Y 2012 Transport characteristics of AlGaN/GaN/AlGaN double heterostructures with high electron mobility *J. Appl. Phys.* **112** 1–7

[2] Otsuji T, Watanabe T, Boubanga Tombet S A, Satou A, Ryzhii V, Popov V and Knap W 2014 Emission and detection of terahertz radiation using two-dimensional plasmons in semiconductor nanoheterostructures for nondestructive evaluations *Opt. Eng.* **53** 031206

[3] Jakštas V, Kašalynas I, Šimkienė I, Strazdienė V, Prystawko P and Leszczynski M 2014 Schottky diodes and high electron mobility transistors of 2DEG AlGaN/GaN structures on sapphire substrate *Lith. J. Phys.* **54** 227–32

[4] Tekeli Z, Altnal Ş, Çakmak M, Özçelik S, Çalışkan D and Özbay E 2007 The behavior of the I-V-T characteristics of inhomogeneous (Ni/Au) - Al 0.3Ga0.7N/AlN/GaN heterostructures at high temperatures *J. Appl. Phys.* **102** 0–8