Impact of nanomaterial arrangement on the reliability and the electron mobility in AlGaN/GaN HEMTs

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Abstract. The obtained results demonstrate that the improvement of nanomaterial arrangement in AlGaN/GaN HEMT structures quantitatively characterized with the use of a multifractal parameter (the degree of disorder) results in the increase at several times in the electron mobility values at 2DEG channel in HEMT structures and the reliability of HEMT parameters.

1. Introduction
AlGaN/GaN high electron mobility transistors (HEMTs) have received increased attention because of their prospective use in microwave power devices. Recently, the impressive progress in improving the performance of such devices for the use in RF-power amplifiers has been achieved. However, open points related to the output power/current collapse and the gate-drain leakage current and its relation to reliability issues still remain [1,2]. The origin of both phenomena limiting AlGaN/GaN HEMTs reliability is now under the study. Inverse piezo-electric effect, hot carriers, the creation of stress-induced percolation path across the AlGaN barrier by defect formation, the increase in material traps concentration due to high electric fields have been considered as the possible causes of HEMT reliability deterioration [2-4]. It seems that all causes have a common source related to the complicated nanomaterial arrangement (NA) of AlGaN/GaN HEMT structures. The complicated NA in nitrides is determined by the presence of extended defects system (EDS) piercing the device’s active layers and nano scale phase separation in AlGaN and InGaN alloys [5-7]. These peculiarities result in numerous NA forms with different nanomaterial disordering which are governed by crystallite coalescence of near 3D growth mode to near 2D one. It is well known that nanomaterial disordering causes current crowding effect, the local Joule overheating and degradation in light emitting devices based on III-N nano materials [8], the percolation paths in AlGaN and InGaN layers [6,7]. It also has an impact on the electron mobility values and electron transport mechanism in GaN layers [9]. However, the impact of nanomaterial disordering on AlGaN/GaN HEMT reliability and the electron mobility in two-dimensional gas (2DEG) channels has not been considered yet.

In this paper we will show some experimental results allowing us to clarify the correlation of the electron mobility in 2DEG channel and AlGaN/GaN HEMT’s reliability with the nanomaterial disordering, using the approach based on the concept that the nitrides have the complicated NA.
2. Experimental

The plates of HEMT structures were grown on (0001) sapphire substrates using a low-temperature GaN nucleation layer in the standard AIX2000HT MOVPE reactor equipped with an in situ optical reflectance monitoring the system. Ammonia, TMGa, TMAl, and SiH$_4$ were used as precursors, and H$_2$, N$_2$, and H$_2$N$_2$ mixtures were used as carrier gases for various stages of the growth. The heterostructure represents a standard HEMT structure consisting of 4 nm insulating GaN buffer, 1 nm AlN interface layer, 7 nm undoped Al$_{0.3}$Ga$_{0.7}$N spacer, 13 nm silicon doped Al$_{0.3}$Ga$_{0.7}$N layer (the Si concentration is approximately $1\times10^{19}$ cm$^{-3}$) and 5 nm undoped GaN cap layer. To suppress the formation of a conductive layer at GaN/sapphire interface, GaN nucleation layer was annealed in a hydrogen-free ambient, which resulted in quasi-2D growth mode of high-temperature GaN buffer from the very beginning of the growth. The growth regimes for the top of GaN buffer and AlN interface layer were optimized for suppression of interface erosion due to the GaN hydrogen interaction [10]. The change in the buffer layer growth conditions enables one to obtain AlGaN/GaN HEMT structures with different NA. The plates of AlGaN/GaN HEMT structures were grown in Ioffe Institute.

It was shown that the complicated NA is reflected at the surface morphology [9]. Surface monitoring by using atomic force microscopy (AFM) and the data processing by the multifractal analysis allow one to quantitatively characterize nanomaterial desodering [9]. The AFM investigation was carried out by using the SOLVER Pro set up produced by NT-MDT (Russia). The surface topography was recorded in the tapping mode using silicon cantilevers with a 10 nm radius tip. The procedure of image processing and of multifractal parameters’ extraction, such as the Renyi dimension (D) and the degree of disorder ($\Delta p$) at local level, includes several steps: the AFM images are converted to high-contrast rough images by using standard computer software for the image processing, these images are approximated by a binary matrixes containing “0” for bright spots and “1” for dark spots, the matrixes are processed by using the mathematical procedure based on multifractal analysis (MFA) in the MFRDrom program developed by Vstovsky [11]. In contrast with the conventional fractal analysis which uses only one level of self-similarity and only one correlation function of digit ensemble density for an entire system, MFA uses several levels of self-similarity and several correlation functions. As a result, the obtained multifractal parameters can characterize the complicated structure of nanomaterial more precisely. The lower $\Delta p$ value, the more ordered nanomaterial. The experimental application of MFA to study the properties of nitride based materials and the devices on their base has shown the effectiveness of the use of the degree of disorder [8,9]. The relative error in $\Delta p$ value determining is $\pm 0.002$ at simultaneous determination of $\Delta p$ in investigated materials with the use of AFM images of the same scale. HEMTs devices and the samples for the determination of the electron mobility values by the Van-der-Paw method were obtained from each plate. HEMTs devices were fabricated at JSC «Svetlana-Electronpribor». The reliability of HEMTs devices was controlled by step-stress test [12] which was performed at 300 K by sweeping the gate voltage from -20 to -100 V in steps of 5 V with the source and drain voltage set to 0 V. Step time is value 100 s.

3. Results and Discussion

The examples of the surface topology for two HEMT structure plates differing strongly by the nanomaterial arrangement are presented at figure 1 (a,b). The strong violation of layer by layer growth is typical for the HEMT structure with the higher value of the degree of disorder which is presented at figure 1 (a). It results in the heterogeneity of nanomaterial and the decrease in the values of electron mobility in 2DEG channels of HEMT structures to 500 cm$^2$ V$^{-1}$ s$^{-1}$ at 300 K and 800-1000 cm$^2$ V$^{-1}$ s$^{-1}$ at 77 K (Figure 2, curves 1,2). Moreover, the uniformity of electron transport at the same sample was revealed by the discrepancy in the electron mobility values for the same sample with the change of the current and potential contacts (Figure 2, curves 1,2).
Figure 1 (a,b). AFM views of AlGaN/GaN HEMT structures having different the degree of disorder - $\Delta_p$: (a) – 0.357; (b) - 0.345.

The improvement of nanomaterial arrangement (the decrease in $\Delta_p$ values) by the realization of nearly 2D growth mode (Figure 1, b) is accompanied by an increase in the electron moblility values in 2 DEG until 10 000 cm$^2$ V$^{-1}$ s$^{-1}$ at 77 K and 2000 cm$^2$ V$^{-1}$ s$^{-1}$ at 300 K. The density of 2DEG is 1.2·1013 cm$^{-2}$. HEMTs were fabricated from these structures. The dispersion of the leakage current of the gate values and drain current near one order is typical for HEMTs fabricated from structure with $\Delta_p = 0.357$. Moreover, the output power/current collapse and the increase of gate-drain leakage current were observed for many parts of devices after several switching without the reliability test. The reliability of HEMTs fabricated from the structure with $\Delta_p = 0.345$ is significantly higher. The degradation in these HEMTs occurs only after 250 hours working under the reliability test.

Figure 2. The temperature dependences of electron mobility in 2DEG channels of HEMT structures with different the degree of disorder ($\Delta_p$): 1 and 2 (at different couples of contacts) - 0.357; 3 - 0.345.

4. Conclusion
The obtained results demonstrate that the improvement of nanomaterial arrangement of AlGaN/GaN HEMT structures, quantitative characterized by the use of multifractal parameter, the degree of disorder, results in the increase by several orders of magnitude in the electron mobility values at 2DEG channel of HEMT structures and the reliability of HEMTs parameters. It seems that quantitative control of the nanomaterial disordering is one of the ways to optimize the grow process of AlGaN/GaN HEMT structures and HEMTs reliability.
Acknowledgments
This work was supported by the Ministry of Education and Science of Russian Federation on behalf of the Government of Russian Federation (the contract № 14.574.21.0116, the project identification number is RFMEFI57414X0116).

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