Nanomaterial disordering in AlGaN/GaN UV LED structures

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Abstract. Multifractal analysis was applied to characterize quantitatively nanostructural disordering in HVPE-grown AlGaN/GaN UV LED structures. A higher level of leakage currents shunting the active region of LEDs by an extended defect system is correlated with higher values of multifractal parameters (MFs). As a result, the concentration of injected carriers participating in radiative recombination in the active region is reduced. MFs and the conductivity of quasi-ohmic shunts localized in an extended defect system are higher in AlGaN/GaN structures than in InGaN/GaN structures. It is one of the reasons behind the low external quantum efficiency of AlGaN/GaN UV LEDs.

1. Introduction
AlGaN quantum well (QW) based ultraviolet (UV) light emitting diodes (LEDs) are expected to replace conventional UV lamps based on mercury vapor [1, 2]. Compact UV LEDs are environmentally friendly and are of interest in various applications such as air, water and surface sterilization and decontamination, bio-agent detection, UV curing, etc. The UV LED emission can be selected in a wide and continuous range of wavelengths as opposed to the fixed emission lines of the conventional UV lamps. Another prospective application of (Al)GaN/GaN (and InGaN/GaN) p-n structures is photoelectrochemical water splitting for H2 generation [3, 4].

During the last decade much efforts has been focused on developing high power and high efficiency AlGaN-based UV LEDs emitting at wavelength shorter than 365 nm [1, 2]. The major problems in UV AlGaN/GaN LEDs development are found to be low external quantum efficiency (about 2%) and short life-time (about 2000 hours) [5]. Development of high brightness InGaN-based blue LEDs has demonstrated that structural quality is one of the important factors to get higher external efficiency and longer life-time of LED lamps [6]. It has been reported for GaN layers and InGaN/GaN blue LEDs that the structural quality is not merely in a strict dependence on total dislocation density but also is connected with the peculiarities of nanomaterial disordering (nano-
structural arrangement (NA)) [7, 8]. It was found that changes of nanomaterial disordering caused by different angles of tilt and twist of the mosaic structure results in the existence of an extended defect system. This system contains different types of dislocations, V-defect among them, and domain boundaries enriched by dislocations. These features are apparent in the surface morphology. This allows examining the surface with the help of atomic force microscopy for quantitative characterization of nanomaterial disordering on the basis of multifractal analysis [7]. A correlation of nanomaterial disordering with multifractal parameters determined from the surface morphology examination of GaN layers and InGaN/GaN blue LEDs [7, 8] has been observed.

Quantitative estimation of nanomaterial disordering in UV AlGaN/GaN LED structures has not been assessed and its connection with the LED parameters has not been studied previously. In this work we apply a multifractal analysis for quantitative characterization of nanomaterial disordering in AlGaN/GaN UV LEDs with relation to their electrical and structural properties.

2. Experimental
The AlGaN-based UV LED structures were grown by hydride vapor phase epitaxy HVPE on c-plane 2-inch sapphire substrates. The growth procedure included in-situ sapphire substrate treatment and an AlN/AlGaN (∼0.6) buffer layer deposition followed by AlGaN/GaN multilayer p-n structure growth. Details of the structure growth and characterization can be found elsewhere [9]. The structures grown were processed to form mesas and deposit contacts. Fabricated chips had planar dimensions of 850 µm x 850 µm with light extraction through the surface. Electroluminescence (EL) peak emission was usually observed at 350-360 nm.

Three types of UV AlGaN/GaN LED structures having different nanomaterial disordering were grown by changing the buffer layer growth conditions. Quantitative estimation of nanomaterial disordering in the structures grown was performed by a technique certified earlier for InGaN/GaN blue LEDs [7]. The technique is based on the fact that surface morphology implies nanomaterial disordering of the material. The different tilt and twist angles of domains in the GaN-based mosaic structure result in co-existence of numerous forms of nano-structural arrangement (NA) that influences the surface morphology. Multifractal analysis of digital multitude obtained by atomic force microscopy (AFM) corresponding to the surface morphology of UV AlGaN/GaN LED structures makes it possible to evaluate two parameters (degree of disorder - Δp and level of self-organization – D) for quantitate characterization of the nanomaterial disordering. The AFM morphology of AlGaN/GaN UV LED structures having different multi-fractal parameters is given in figure 1. An AFM image of 450–460 nm InGaN/GaN blue LED structures with internal quantum efficiency of 45% is given for comparison.

![Figure 1. AFM views of surface morphology of AlGaN/GaN (a, b, c 2 µm × 2 µm scan) and InGaN/GaN (d: 3 µm × 3 µm scan) LED structures with different nanomaterial disordering (multifractal parameters Δp and D): (a) Δp = 0.390 and D=1.84; (b) Δp = 0.370 and D=1.78; (c) Δp = 0.348 and D=1.62; (d) Δp = 0.370 and D=1.78.](image-url)
I-V characteristics, EL spectra and dependencies of the spectral current-noise density (SI) on the forward current density (j) of UV AlGaN/GaN LEDs obtained from the LED structures having different nanomaterial disordering were studied. Low frequency noise analysis was also applied in the frequency range from 1 Hz to 10 kHz and the power spectra were measured at a current density of 10^{-3} – 10 A/cm^2 in all studied LEDs.

3. Results and Discussion

Increasing parameters of nanomaterial disorder are accompanied by an increase of direct and reverse currents at low voltage (U < 3 V) (figure 2).

![Figure 2. I-V characteristics of AlGaN/GaN UV LEDs fabricated from LED structures with different nanomaterial disordering (multifractal parameters Δр and D): (a) Δр = 0.390 and D=1.84; (b) Δр = 0.370 and D=1.78; (c) Δр = 0.348 and D=1.62. Respective AFM images are given in Figure 1.](image)

Moreover, I-V characteristics of all AlGaN/GaN LEDs demonstrated shunts in the p-n junction area whose conductivity becomes higher with increase of Δр and D values. A similar correlation has been reported in InGaN/GaN LEDs [8] and it was proposed that the shunts localize at an extended defect system. This suggestion is in a good agreement with data obtained by other methods [2, 10-12]. A comparison of AFM data of high-defect and defect-free areas has proved that leakage paths (shunts) are observed only in open-core threading dislocations [2]. By using a defect-sensitive etch technique, it was demonstrated that AlGaN-based UV LEDs having different densities of the open-core dislocations are also differ in values of leakage paths (shunts) [2, 10]. Higher density of leakage paths corresponds to higher density of this type of dislocation. The open-core dislocations known as nano-pipes or V-defects are 2-50-nm tubes with the (10-10) facets penetrating the epitaxial layer [11]. The nano-pipes were observed by means of AFM, conductive AFM, transmission electron microscopy (TEM), and even optical microscopy with the help of defect-sensitive etching [11, 12]. The density of this type of dislocation is two orders of magnitude lower than the total dislocation density. I-V characteristics at low voltage of AlGaN-based UV LEDs determine the cumulative level of leakage path (shunt) conductivity of the extended defect system. The interrelation of the open-core dislocation conductivity with nanomaterial disordering is thought to be due to the worse nano-structural arrangement that accompanies the enrichment of growing layers by indium or gallium metals. It has been reported indium or gallium segregation results in V-defects formation [13].

The results obtained in this work demonstrate the values of disordering and shunt conductivity in AlGaN/GaN structures are higher than that in InGaN/GaN structures with high external quantum efficiency, but similar to InGaN/GaN structures with low EQE values (less than 5%). Thus, as in the InGaN/GaN LED structures, multifractal parameters together with the shunt current at voltages less than 2 V can be used for quantitative estimation of nanomaterial disordering in AlGaN/GaN LED structures. It has been also demonstrated that high values of conductivity of quasi-ohmic shunts localized in the extended defect system lead to decreasing of EQE [14]. This is correct for both...
InGaN/GaN and AlGaN/GaN LEDs [8, 14]. Moreover, carrier leakage through the shunts was revealed in bulk GaN having low dislocation density of $10^6$ cm$^{-2}$ [15].

Thus, the higher nanomaterial disordering and higher values of conductivity of quasi-ohmic shunts in AlGaN/GaN LEDs than in InGaN/GaN LEDs is one of the reasons behind the low external quantum efficiency values. In addition, the correlation between nanomaterial disordering in AlGaN/GaN LEDs and the conductivity of the quasi-ohmic shunts can be applied for selection of LED lamps from different manufacturers by structural quality of the LED structure.

Figure 3 shows that the dependency of spectral noise density on current density has a near monotonic tendency $S_I(j) \sim j$ at a current density less than $10^9$ A/cm$^2$ and is similar to that in InGaN/GaN structures, which is, to a large extent, related to processes localized in an extended defect system shunting the p-n-junction.

**Figure 3.** The spectral noise density ($S_I$) in relation with forward current density ($j$). Curves 1, 2, 3 corresponds to I-V curves (a), (b), and (c) in figure 1, respectively.

4. **Conclusions**

Nanomaterial disordering of AlGaN/GaN UV LED structures grown by HVPE on sapphire substrates in comparison with InGaN/GaN LED structures has been studied. A correlation between nanomaterial disordering and conductivity of the quasi-ohmic shunts localized in the extended defect system and shunting the p-n-junction of LEDs was revealed. The shunt conductivity became larger with the value of nanomaterial disordering that can be represented by multifractal parameters. It was demonstrated that the disordering in AlGaN/GaN LED structures is higher than in InGaN/GaN ones. As a result, a concentration of injected carriers bypassing radiative recombination in the active region of AlGaN/GaN LEDs is much higher than that in InGaN/GaN LEDs and it is one of the reasons behind the low external quantum efficiency of AlGaN/GaN UV LEDs.

**Acknowledgments**

Work at University ITMO was supported by the Ministry of Education and Science of Russian Federation within the grant agreement 14.575.21.0054 (unique identifier of research activities is RFMEFI57514X0054).

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