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Correlation of mosaic structure peculiarities with electric characteristics and surface multifractal parameters for GaN epitaxial layers

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Abstract. The first successful results of multifractal analysis application to a quantitative description of mosaic structure peculiarities, which are typical of GaN epitaxial layer with hexagonal modification grown on (0001) sapphire substrates, have been obtained. Characteristic size of the mosaic structure has been measured to be 200–800 nm. The direct dependence of mobility on the multifractal parameters (the Renyi dimension and the degree of the order index) of the surface topology of the mosaic structure has been observed for all GaN layers investigated.

Introduction

GaN epitaxial layers are a basis of light-emitting devices and photodetectors operating over the short wavelength region. It well known, a high density ($10^8 - 10^{10} \text{ cm}^{-2}$) of dislocations, which form the mosaic (columnar) structure of the epitaxial layers with the domain size of 200–800 nm, is typical of hexagonal III-nitrides. The results concerning with the dislocation density effect on electrical characteristics of the layers are quite contradictory, while the data on the mosaic structure effect on these characteristics are a few in number.

Our first investigations [1, 2] of the GaN epitaxial layers demonstrated at a qualitative level that the mosaic structure peculiarities played an important role in the electrical properties of the layer and device parameters, including the Schottky barrier height, leakage current, and persistent photoconductivity. In this connection a quantitative characterization of the mosaic structure is required to investigate an influence of its peculiarities on the electrical properties of the layers.

However, the traditional characterization techniques do not allow the peculiarities of the mosaic structure to be described in detail. For instance, the average domain size along with the basic axes is evaluated by the X-ray diffraction analysis. The diagnostics of the GaN surface topology with a use of atomic-force microscope gives only quality characteristics of the mosaic structure. It has been known that the multifractal analysis of a surface structure can be used to compare the mosaic structure peculiarities of a complex system quantitatively. This method has been not applied for semiconductors [3]. In contrast with conventional techniques, the multifractal analysis allows the structure peculiarities to be characterized as a whole. As a result, the quantitative correlation between individual elements of the complex structure could be obtained using multifractal parameters.

In the present paper the potentialities of the multifractal parameterization method have been evaluated for the quantitative description of the structure peculiarities of the GaN epitaxial layers grown on sapphire substrates as well as for establishing the interrelation between the multifractal characteristics of the GaN surface structure and the GaN electro-physical properties.

1. Experiment

GaN epitaxial layers with a specular surface, which were grown by metal-organic chemical vapor deposition on (0001) sapphire substrates at pressure of 200 mbar, were investigated. The layers were of n -type conductivity with the concentration of $(1 - 2) \times 10^{17} \text{ cm}^{-3}$. They differed both in the buffer layer growth conditions and in carrier mobility from 20 to $600 \text{ cm}^2 \text{ V}^{-1} \text{ s}^{-1}$ (see Table 1). The mobility was determined by the Van-der-Pauw technique in the temperature range 78–300 K with a use of Ti/Al ohmic contacts. The dislocation density was about 10^9 cm^{-2} for all layers but the layer #598 had the dislocation density of one order of magnitude less.

The structural peculiarities of the mosaic structure (the domain size, the domain tilt and twist angles) were investigated by X-ray diffractometry [4]. An additional information on the mosaic structure (roughness and a lateral size of surface domains) was obtained with a use of an atomic force microscopy (AFM).

The approximated images of the topographic surface structure (TSS) for the layers investigated by AFM are presented in Fig. 1. The images were used to obtain multifractal parameters of TSS. For this purpose the original method based on generation of rough partitioning measures was applied using the computer program MFRDrom developed by G.B. Vstovskii [5]. According to previous theoretical and experimental studies [3], the multifractal parameters, like the Renyi dimension (D_q) and the degree of the order index (Δ_{100}), are reasonable for quantitative parameterization. The value of D_q carries the information on thermodynamic conditions for the structure formation and hence it can be used for recognition of material structures, which are slightly distinguished by conventional techniques.

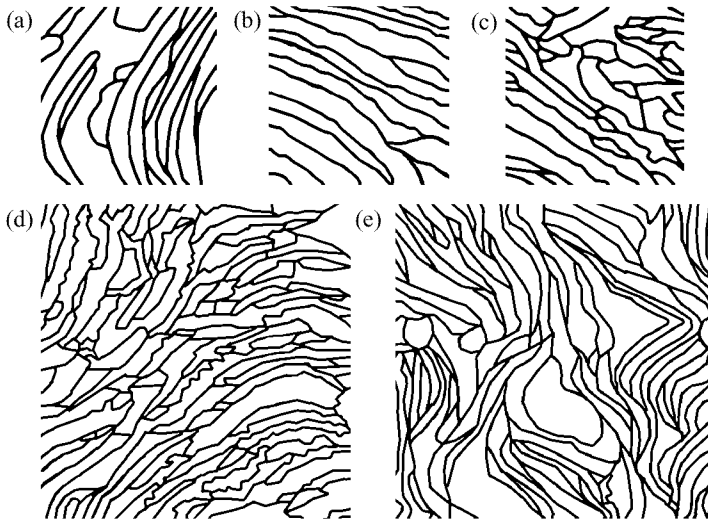


Fig. 1. The approximated images of the topographic surface structure for the GaN epitaxial layers: (a) #413, (b) #598, (c) #646, (d) #644, and (e) #776.

2. Results and discussion

The layers #413 and #598 differ dramatically in the mosaic structure peculiarities (see Table 1 and Fig. 1) as well as in the mobility (μ) and in a form of the temperature dependencies of μ and conductivity (σ) (see Fig. 2, curves 1 and 2). The other layers are not too distinct

Table 1. Basic characteristics of the GaN epitaxial layers.

	Epitaxial layer				
	#413	#598	#646	#644	#776
<i>X-ray data</i>					
Domain twist angle	20'	6'	18'	20'	25'
Average domain size, nm	2000	480	500	800	800
<i>AFM data</i>					
Surface domain size, nm	500–1500	200–300	200–500	200–500	300–1500
Roughness, nm	2.0	0.4	0.6	0.6	1.0
Electron mobility at room temperature, cm ² V ^{−1} s ^{−1}					
	55	600	400	30	50
Renyi dimension (<i>D_q</i>)					
	1.62	1.49	1.55	1.63	1.64

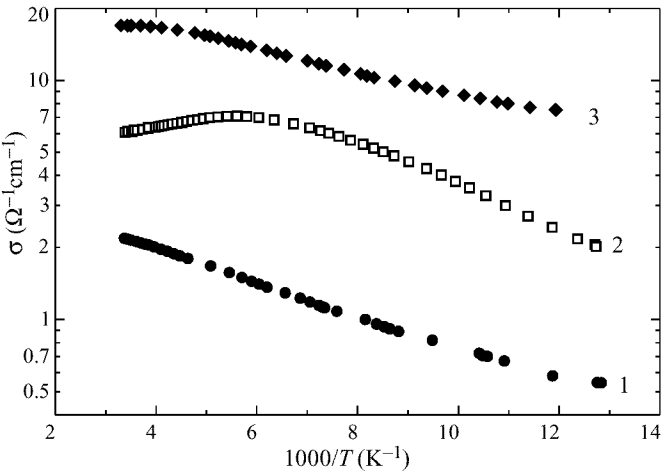


Fig. 2. Temperature dependence of conductivity for the GaN layers: (1) #413, (2) #598, and (3) #646.

in the mosaic structure peculiarities determined by the conventional techniques (AFM and X-ray diffractometry) as well as in the dislocation density.

These layers differ in the mobility, while their temperature dependence of conductivity points to unconventional carrier transport, that is typical both of the materials with localized charge defects and of low-dimensional structures.

The multifractal parameters of TSS allowed the GaN layers to be clearly distinguished. The direct dependence of μ on D_q and Δ_{100} was observed for all layers (see Fig. 3). That correlation was reasonable, because the carrier transport mechanism was unconventional and it depended on probability of the current channel formation. The values of D_q was the least for the most perfection layer #598. That was indicative of the more uniform conditions for the layer growth.

Therefore, the TSS multifractal parameters carry the information on the self-organization of the epitaxial layer mosaic structure. They allow the mosaic structure peculiarities to be quantitatively classified as a whole using the degree of the order index and the Renyi dimension. Moreover, the structure-properties correlation could be established, while the conventional techniques commonly manipulating the dislocation density and the averaged mosaic structure characteristics fail to do it.

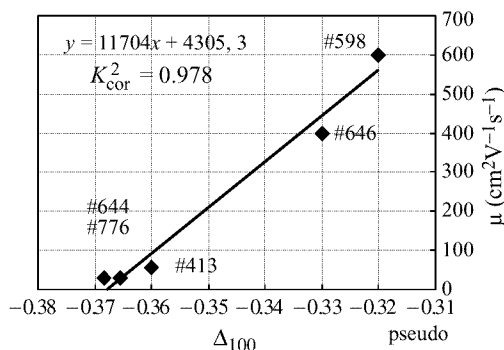


Fig. 3. Correlation between the degree of the order index (Δ_{100}) and the mobility (μ) at room temperature obtained from pseudo-multifractal computation. Correlation coefficient is 0.989.

The first successful results are indicative of great promise of the multifractal analysis to investigate III-nitrides.

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