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Mosaicity and electrical and optical properties of group III nitrides

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Abstract

It is demonstrated that the degree of mosaic structure domain coalescence has an influence on both the intensity of the yellow band and the blue-shift of the basic photoluminescence peak. Detectable differences between the electroluminescence spectra and the current–voltage characteristics of InGaN/GaN quantum well light-emitting structures with different degrees of order have been found. The possibility of using the new approach, based on multifractal parametrization, to analyse the mosaic structure properties has been demonstrated.

1. Introduction

It is well known that mosaic structure is typical of hexagonal group III nitrides. However, only limited numbers of works have been devoted to the study of the correlation of electrical and optical properties of III nitrides with their mosaicity.

A new approach to the analysis of mosaicity, viewed as a complex system of extended defects, was previously proposed [1, 2]. It was demonstrated that investigations of the surface topology followed by a multifractal analysis (MFA) allow the properties of such systems to be characterized quantitatively [3]. The multifractal parameters—namely, the self-organization degree (the Renyi dimension, D) and the degree of order (the disruption of both general and local symmetry, Δ)—could be used as characteristic properties of these systems. A direct correlation between a carrier mobility μ in GaN epilayers and the multifractal parameters has been shown. The less the disruption of the local symmetry, the higher the mobility of the charge carriers [1, 2]. The linear dependences of μ versus D and Δ are reasonable, because the carrier transport mechanism is unconventional (for most of the layers, the temperature dependence of the conductivity corresponds to materials with localized charge defects or to low-dimensional structures). The mechanism depends on the probability of current channel

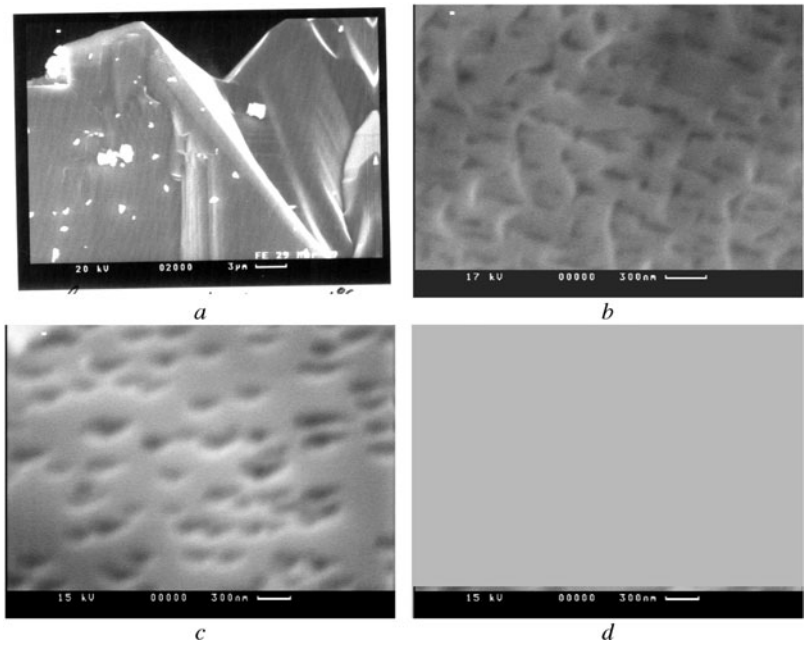

Figure 1. SEM views of surfaces of the GaN layers with different degrees of domain coalescence of the mosaic structure.

formation. Therefore, the layers with a higher self-organization level of the mosaic structure (i.e. with a small value of D_{100}) have higher mobility.

In the present paper experimental results which demonstrate the correlation between the optical properties of GaN layers and MQW InGaN/GaN light-emitting structures and the mosaic structure peculiarities (the degree of order and the self-organization level) are presented. The contribution of the mosaicity to the carrier transport in the p–n junction region is discussed.

2. Experimental details

The photoluminescence features of n-GaN epilayers grown by the MOVPE, HVPE, and MBE techniques on (1000) sapphire substrates were investigated. The photoluminescence was excited by a He–Cd laser with an intensity of 25 W cm^{-2}. The morphology of these epilayers was investigated with scanning electron microscopy (SEM). SEM views of their surfaces are shown in figure 1.

Partially coalescent domains with various forms were observed for all growth techniques. The layers with the best coalescent domains were basically grown by the MOVPE technique. In this case the domain boundaries were not revealed in the SEM view (figure 1(*d*)).

The light-emitting structures based on InGaN/GaN MQW with an active region consisting of five periods of (3 nm InGaN and 7 nm GaN) [4] and p$^+$-GaN/n-GaN were grown by means of MOVPE on (0001) sapphire substrates. To obtain various degrees of order, there were different regimes of nucleation layer growth. Substrates from different manufacturers with a high quality of surface treatment were used. Mosaicities of the light-emitting structures were characterized by multifractal parametrization. The parameters (D and Δ) were determined from the atomic force microscopy data [1].

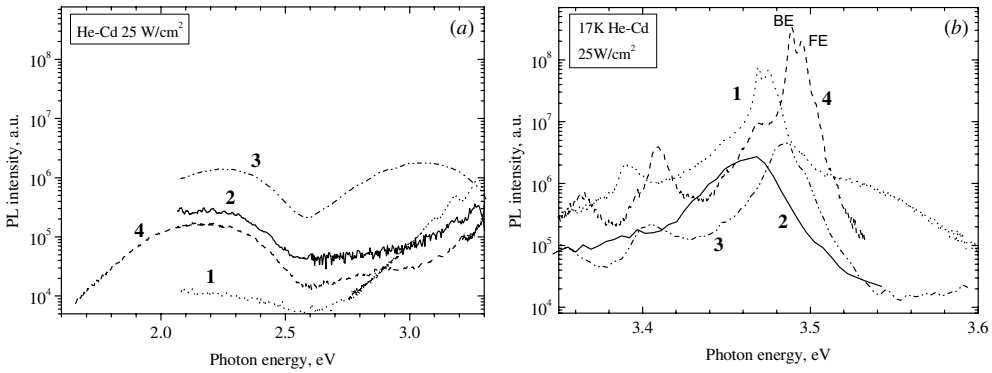

Figure 2. Photoluminescence spectra of GaN epilayers, whose SEM views are presented in figure 1: 1: see figure 1(*a*); 2: see figure 1(*b*); 3: see figure 1(*c*); 4: see figure 1(*d*).

The AFM data were treated using the MFA. It can associate with the structure quantitative parameters characterizing the structure as a whole; it is used in addition to the conventional methods of description. In particular, the original technique involves the multifractal parametrization of a surface structure on the basis of a new mathematical–theoretical interpretation of the multifractal formalism [1, 5] and allows the degree of order of the structures to be indexed, and the Renyi dimension to be introduced and computed.

Unlike conventional fractal analysis, which uses only one level of self-similarity and only one distribution function of a digital ensemble density for the entire system, MFA uses several levels of self-similarity and several distribution functions for large boxes of the system. It allows the distribution functions to be compared both among themselves and with the whole system. The procedure allows the degree of disruption to be determined quantitatively for the local symmetry and the general symmetry of a complex system as a whole. Therefore, more detailed information on the system peculiarities can be obtained using MFA. The computations are performed using the MFRDrom program developed by Vstovsky [3]. The procedure was described in [1, 2] in detail.

3. Results and discussion

The photoluminescence (PL) spectra of the GaN epilayers presenting various degrees of the domain coalescence differ dramatically (figures 2(*a*) and (*b*)). For GaN with both individual and partly coalescent domains (figure 1(*a*)), the position of the basic PL peak is close to that for unstrained bulk GaN (figure 2(*b*), curve 1) and the yellow band is nearly absent (figure 2(*a*), curve 1). For GaN with more coalescent domains, the basic PL peak is also close to that for unstrained bulk GaN, but its intensity is one order of magnitude less. At the same time, these layers have very intense yellow bands. The basic PL peak of the GaN layers with well-coalesced domains is shifted; therefore the layers are stressed. The yellow band is less intense.

Therefore, as the domain coalescence improves, the blue-shift of the basic PL peak increases and the yellow band appears. The maximum shift is observed for well-coalesced and relaxed mosaic structure. The intensity of the yellow band is minimal for this structure. The results lead us to suppose that the blue-shift is associated not only with stresses, which are caused by lattice mismatch between the epilayer and the substrate and by differences of thermal expansion coefficients, but also with local strains concentrated in the mosaic structure domains.

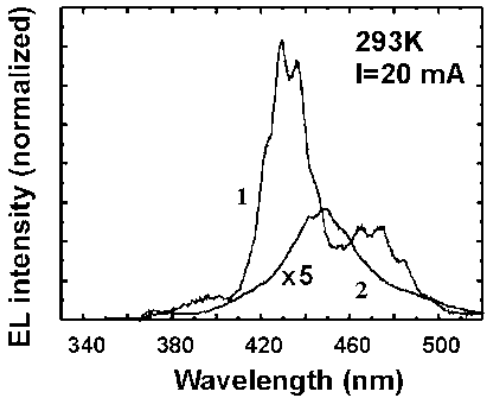

Figure 3. EL spectra of InGaN/GaN MQW light-emitting structures with different degree of order Δ: 1: 0.35; 2: 0.33.

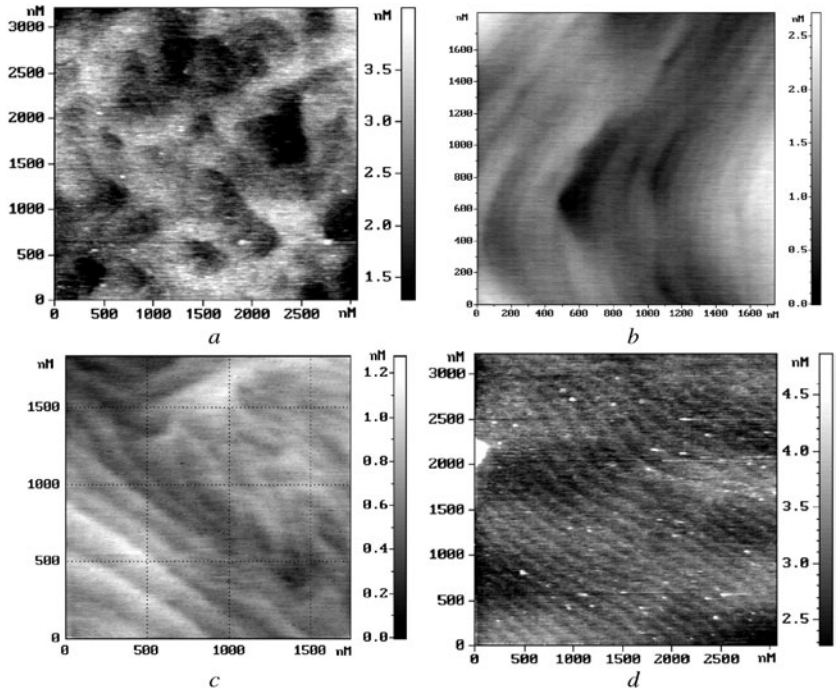

Figure 4. AFM views of InGaN/GaN MQW ((*a*), (*d*)) and p^+-GaN/n-GaN ((*b*), (*c*)) light-emitting structures with different degrees of order Δ: (*a*) 0.37; (*b*) 0.36; (*c*) 0.34; (*d*) 0.32.

A detectable difference between the electroluminescence (EL) spectra (figure 3) was found for the InGaN/GaN MQW light-emitting structures, which consist of layers with well-coalesced domains but with different values of the degree of order Δ.

AFM views of typical surfaces of InGaN/GaN MQW with different values of Δ are presented in figures 4 (*a*), (*d*). Different degrees of order ($\Delta = 0.33$ and 0.35) were obtained for the light-emitting structures grown in one process on the substrates from two manufactures. The

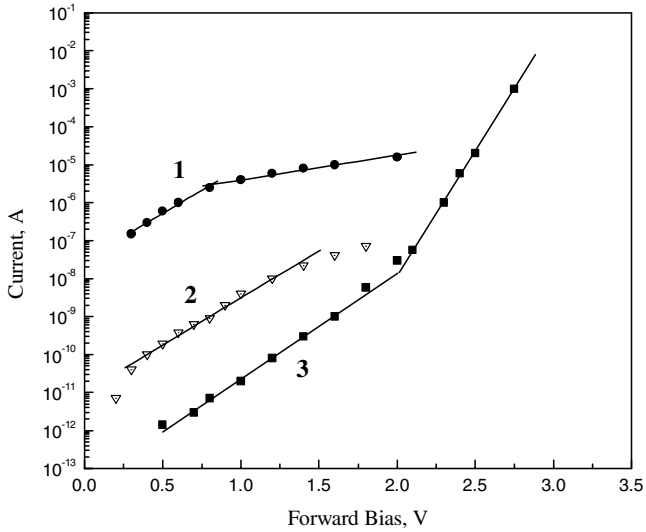

Figure 5. The I–V characteristics of the InGaN/GaN MQW (1, 3) and p^+-GaN/n-GaN (1, 2) light-emitting structures with different degrees of order Δ: 1: 0.37; 2: 0.34; 3: 0.32. (Curve 1 coincides for the two types of structure.)

structure with $\Delta = 0.33$ had the typical EL spectrum, while the other had a more complicated spectrum (figure 3, curve 2) because of the decomposition of InGaN.

The current–voltage (I–V) characteristics of the InGaN/GaN MQW and p^+-GaN/n-GaN light-emitting structures depend strongly on the degree of order of the mosaic structure. Their I–V characteristics are shown in figure 5. The tunnelling character of the current was found in [6] and associated with peculiarities of heterojunctions.

Our results demonstrate that the I–V characteristics are similar for homojunctions and heterojunctions. The largest current (figure 5, curve 1) was obtained for both p^+-GaN/n-GaN and InGaN/GaN MQW structures with the lowest degree of order of the mosaic structure. It should be noticed that these curves coincide (they are shown as the same curve, curve 1).

At $V > 1.5$ V, the series resistance is significantly higher for both types of structure with lower degrees of order of the mosaic structure. This fact is in good agreement with the data on the mobility [1, 2]. Therefore, the peculiarities of the I–V characteristics are likely to be determined by the mosaic structure, which forms a 3D conducting net in the p–n junction region.

4. Conclusions

The experimental results have shown that the mosaicity is one of the main factors determining the electrical and optical properties of group III nitrides. A new approach, based on multifractal parametrization, to the analysis of the mosaic structure properties proves very beneficial.

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