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Evaluation of AlGaN/GaN heterostructures properties by QMSA and AFM techniques*

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Atomic force microscopy and Quantitative Mobility Spectrum Analysis (QMSA) were applied for characterization and evaluation of the quality of AlGaN/GaN heterostructures. The structural uniformity, growth mode and electrical properties of the heterostructures were determined. The obtained results indicated that the time of growth of the low temperature GaN nucleation layer influenced the morphology and electrical properties of the AlGaN/GaN heterostructure.

Keywords: *AlGaN/GaN; Hall mobility; AFM; Quantive Mobility Spectrum Analysis*

1. Introduction

High mobility of electrons in two-dimensional electron gas (2DEG), which occurs at the aluminum gallium nitride/gallium nitride interface, makes the AlGaN/GaN heterostructure system a good candidate for the fabrication of high frequency and high power transistors. Gallium nitride layers are mainly grown heteroepitaxially on sapphire, silicon carbide and silicon substrates. The fabrication of such layers of very good quality (low concentration of structural defects, high resistivity of buffer GaN layer, uniformity of AlGaN layer, smooth AlGaN/GaN interface), which is necessary for obtaining 2DEG with high mobility and concentration, is a challenging task. The growth process of a high resistivity GaN buffer layer includes several steps: growth of a low-temperature nucleation/seed layer, island growth, coalescence and 2D growth of a high temperature layer. All of them have an influence on the electrical and structural properties of the heterostructure.

2. Experiment

The $Al_{0.2}Ga_{0.8}N$/GaN heterostructures investigated in this work were grown by MOCVD epitaxy (Aixtron CCS $3 \times 2''$) on c-plane sapphire substrates at 100 mbar pressure and H_2 used as a carrier gas. Trimethylgallium, trimethyaluminum and NH_3 were used as Ga, Al, and N sources, respectively. The growth was performed in the following stages: sapphire substrate annealing in hydrogen atmosphere, substrate nitridation in the mixture of H_2 and NH_3 (1:1), low temperature growth of GaN nucleation layer (LT-GaN NL) at 530 °C, coalescence of LT-GaN NL during temperature ramping, growth of high temperature GaN buffer layer at 1035 °C with V/III molar ratio equal to 1000 and growth of AlGaN layer at 1060 °C with V/III molar ratio equal to 1200.

Topography of the samples was investigated in air using Veeco Multimode V atomic force microscope (AFM) in tapping mode. The sample was scanned at the speed od 5 μm/s. With a standard silicon tip (nominal force constant – 42 N/m and tip radius <10 nm). Before calculations of surface roughness parameters, the data in AFM image was leveled by flat plane fitting.

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Mobility measurements at temperatures of 300 K and 77 K were performed using LakeShore 7604 equipment in a magnetic field changed in the range of 0.01 to 1.0 T. The samples used for Hall measurement were van der Pauw structures with soldered indium contacts. The Quantitative Mobility Spectrum Analysis was applied to investigate the electron transport properties in the AlGaN/GaN heterostructures. Mobility Spectrum Analysis was developed by Beck and Anderson in 1987 [1] and was expanded to Quantitative Mobility Spectrum Analysis by Meyer and Hoffman [2] and Antoszewski et al. [3]. This method was licensed and applied in data processing software of the Hall measurement system used in this work. In QMSA technique the measured Hall coefficient and resistivity are correlated to a unique mobility spectrum. The value of Hall coefficient and resistivity are measured in different applied magnetic fields and analyzed to extract a corresponding set of carrier mobilities and concentrations. The input data of Quantitative Mobility Spectrum Analysis are the values of the measured Hall coefficient and resistivity tensors at various strength of magnetic field. The elements of the field-dependent conductivity matrix are then calculated, and by numerical fitting of these elements, a type and spectrum of mobilities and densities for the individual carriers are extracted [2, 4]. Typical Hall measurements, which give only information about average values of carriers mobility and concentration in the sample, are not sufficient in case of systems like AlGaN/GaN, where multi carrier conduction mechanisms can appear [5]. This method has been used for describing electrical parameters of a number of materials systems with mixed conduction mechanism such as: InGaAs/InAlAs, GaAs/AlAs, HgCdTe [6], InAs [7], AlGaAs/GaAs [8], nanocrystalline Si [9] and AlGaN/GaN [5].

3. Results

Fig. 1 presents a schematic view of a fabricated AlGaN/GaN sample. All three heterostructures were grown at the same parameters of epitaxial process, except for the thickness of the LT-GaN NL, which was controlled by the growth time of that layer. The applied times were: 120 s for sample A, 160 s for sample B and 200 s for sample C.

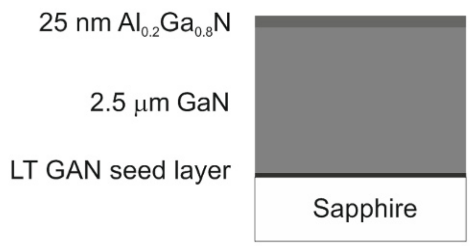

Fig. 1. Schematic view of the AlGaN/GaN heterostructure.

Topography images of the heterostructures obtained by AFM are presented in Fig. 2. The topography of samples B and C shows a step flow structure typical of good quality MOCVD AlGaN/GaN layers, with a number of pits in the places where threading dislocations reach the surface. The root mean square surface roughness (R_{RMS}) varies for these samples in the range of nanometer (Table 1). In case of sample A, the topography of the layer has a different structure with significant areas of deep pits (about 50 nm). The sample reveals much worse surface roughness (more than 10 nm). This indicates the poor structural quality of the heterostructure, which is a consequence of uncompleted coalescence of the layer, which in turn results in a three dimension mode of growth [10].

Mobility spectra of heterostructures A, B and C with different buffer layer thicknesses obtained at 300 K and 77 K are presented in Figs. 2a and 2b. In Table 1, carrier mobility and concentration in the measured peaks of conductivity are shown.

Conductivity of sample C shows only single peaks, at mobility of about 1590 cm^2/Vs at the temperature of 300 K and at mobility of 3870 cm^2/Vs at 77 K. This peak can be attributed to the conduction of 2DEG. In case of samples A and B at the temperature of 300 K, we can observe wider spectra of mobility, with two conductivity peaks at the mobility values of 860 cm^2/Vs and 1860 cm^2/Vs (sample B), and 360 cm^2/Vs and 1320 cm^2/Vs (sample A). In both cases the peak related to the lower mobility can be attributed to bulk conductivity of GaN buffer layer [11] whereas the peak

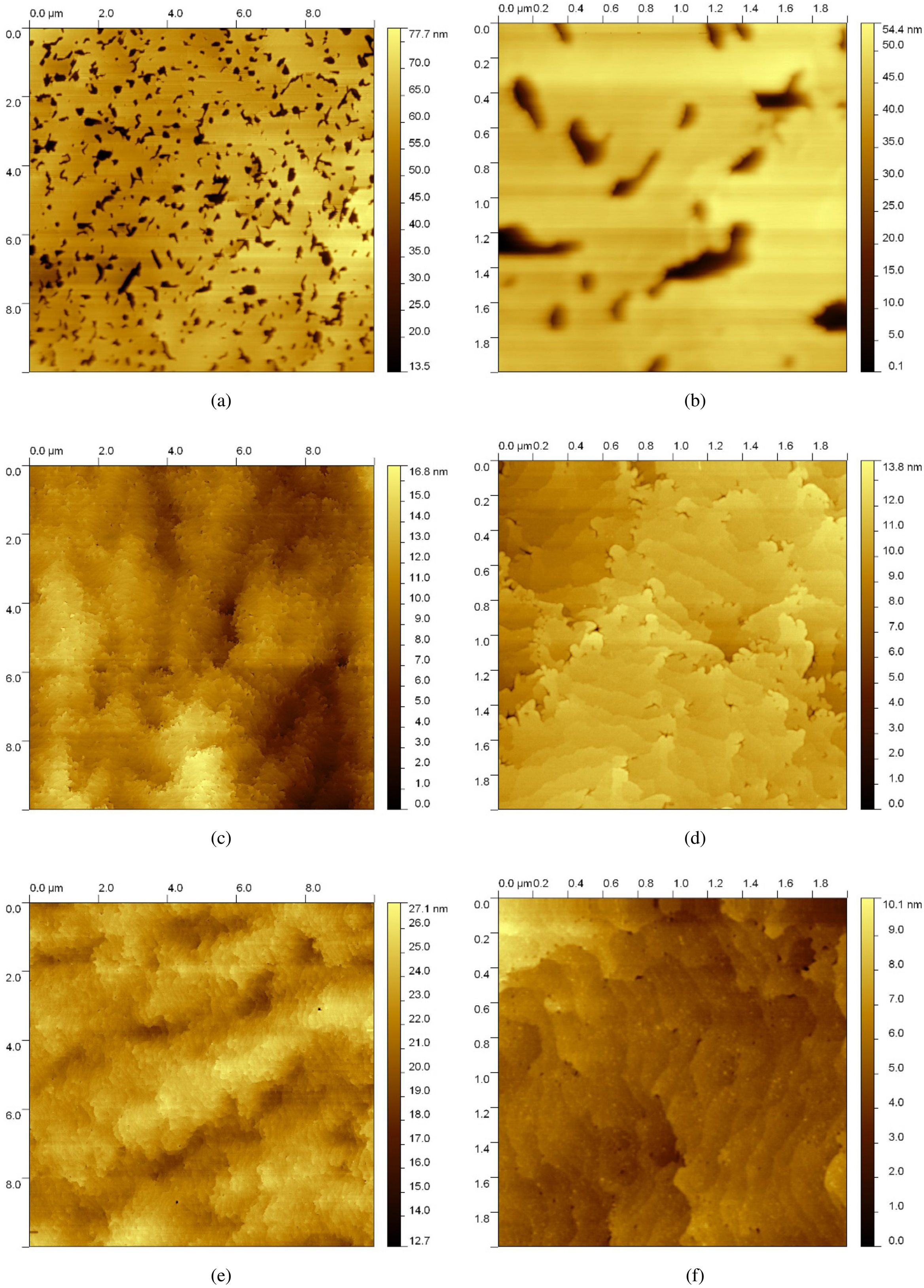

Fig. 2. AFM topography images of AlGaN/GaN heterostructures. Sample A: (a) 10 × 10 μm area, (b) 2 × 2 μm area. Sample B: (c) 10 × 10 μm area, (d) 2 × 2 μm area. Sample C: (e) 10 × 10 area μm, (f) 2 × 2 μm area.

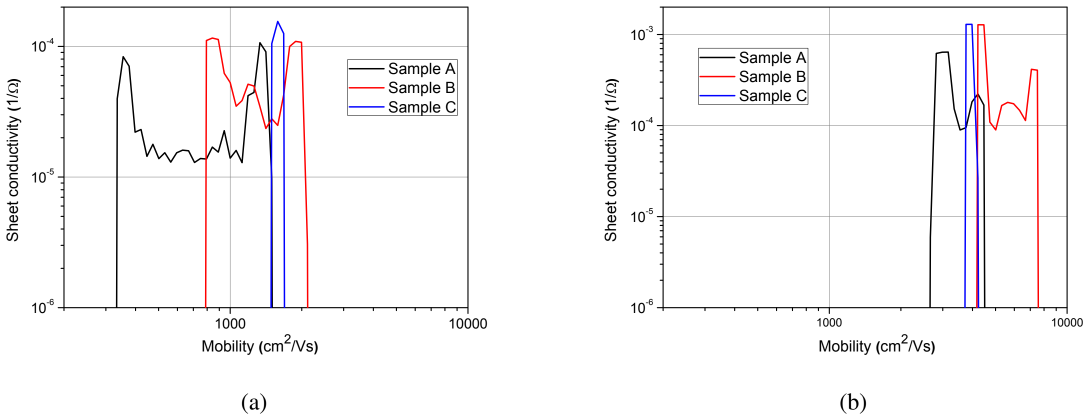

Fig. 3. Mobility spectra for AlGaN/GaN heterostructures at 300 K (a) and 77 K (b).

related to higher mobility can be attributed to electron transport in two-dimensional electron gas.

It can be stated that mobility of electrons in 2DEG correlates with the roughness of heterostructure surface – smaller R_{RMS} is connected with higher mobility. It seems that at 300 K, except the dominating role of phonon scattering mechanism, also structural properties of AlGaN/GaN interface have some influence on the mobility of 2DEG. Additionally, undesirable bulk conductivity occurs for samples A and B, for which the shorter nucleation layer growth time was applied. It can be concluded that short NL growth time results in larger grain size of GaN buffer layer and reduction of threading dislocation (TD) density [12, 13]. This could reduce the effect of unintentional doping compensation by the carbon impurities segregated at/or near the edge of the TDs and increases conductivity of gallium nitride layer [13].

At the temperature of 77 K two peaks of conductivity in both samples were also present: at the mobility of 4380 cm^2/Vs and 7080 cm^2/Vs for structure B and 3010 cm^2/Vs and 4100 cm^2/Vs for structure A. At this temperature, the low mobility peak cannot be attributed to the bulk conductivity because below 150 K all free electrons in GaN are frozen out [5]. It can be concluded that in the case of these samples, some electron mobility distribution exists within the 2DEG. This indicates that for these samples there are two populations of carriers whose electronic transport is governed by different possible scattering mechanisms, recognized for 2DEG in AlGaN/GaN: background impurity, alloy disorder [11], AlGaN/GaN interface roughness [14], polarization surface roughness (PSR) [15] and threading dislocation [16]. The mobility of electrons in the main conductivity peak at high electron concentrations for samples A and B and the single peak of sample C also follow the rule of increased mobility for smaller value of surface R_{RMS} parameter as for 300 K. The appearance of the additional conductivity peak at lower concentration of carriers but higher mobility indicates that in the samples A and B there exist a population of electrons, probably slightly remote from interface, whose transport mechanism is not influenced by the interface structure. Further study is needed to explain the carrier mobility distribution in AlGaN/GaN two dimensional electron gas.

The results obtained so far show that sample C is the most suitable for field effect transistor fabrication because of the lack of conductivity in the GaN buffer layer and the absence of carrier dispersion in 2DEG.

4. Conclusions

The presented results show the suitability of atomic force microscopy and variable magnetic field Hall measurements for the characterization and evaluation of the quality of AlGaN/GaN heterostructures. Observation of AFM topography images makes it possible to determine the condition of epitaxial growth of nitrides layer, which re-

Table 1. Roughness, mobility and carrier concentration in AlGaN/GaN heterostructures.

	R_{RMS} (nm)	$\mu_{p1\,(300\text{ K})}$ (cm^2/Vs)	$n_{p1\,(300\text{ K})}$ (cm^{-2})	$\mu_{p2\,(300\text{ K})}$ (cm^2/Vs)	$n_{p2\,(300\text{ K})}$ (cm^{-2})	$\mu_{p1\,(77\text{ K})}$ (cm^2/Vs)	$n_{p1\,(77\text{ K})}$ (cm^{-2})	$\mu_{p2\,(77\text{ K})}$ (cm^2/Vs)	$n_{p2\,(77\text{ K})}$ (cm^{-2})
A	10.5	1320	1.5×10^{12}	360	5.0×10^{12}	3010	4.4×10^{12}	4100	1.0×10^{12}
B	1.05	1860	1.4×10^{12}	860	3.4×10^{12}	4380	3.9×10^{12}	7080	1.8×10^{12}
C	1.20	1590	1.5×10^{12}	–	–	3870	4.2×10^{12}	–	–

sults in a smooth and uniform layer surface. By application of QMSA analysis, electrical properties (Hall electron mobility and concentration) of both GaN buffer layer and 2DEG at AlGaN/GaN could be obtained. Additionally, this technique allows us to observe the existence of dispersion of mobility in the layers. The applied techniques make it possible to infer that the deposition of thicker low temperature GaN seed layer results in better properties of AlGaN/GaN heterostructure.

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