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# MOVPE growth conditions optimization for AlGaN/GaN/Si heterostructures with SiN and LT-AlN interlayers designed for HEMT applications

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## Abstract

In this work we present the influence of in situ deposited non-continous SiN layer and the chemical precursors III/V mole ratio change during GaN buffer growth for AlGaN/GaN/Si(111) heterostructures with low temperature AlN interlayer on their crystalline quality and electrical mobility of two dimensional electron gas (2DEG). We show, that application of SiN layer resulted in a decrease of (0002) full width at half maximum of diffraction peak below 400 arcsec and build-in stress in 2 µm thick heterostructures below 200 MPa without any relaxation visible on the surface. In optimized AlGaN/GaN heterostructures, by altering V/III mole ratio during growth of GaN subbuffer, the maximum 2DEG mobility of 2057 $cm^2\ V^{-1}\ s^{-1}$, measured by impedance spectroscopy method, was obtained.

## 1 Introduction

AIII-N heterostructure based devices are of great interest in power and high frequency electronics due to their exceptional properties, primarily high breakdown field, high electron saturation velocity and high electron mobility of two dimensional electron gas in AlGaN/GaN heterostructures. Numerous publications devoted to growth and construction of high power p–n [1] or Schottky [2] diodes and high electron mobility transistors [3], as well commercially available devices grown on sapphire and silicon carbide clearly indicate that nitride based devices are serious alternative to the ones, i.e. silicon triacs, IGBTs, MOSFETs, SiC diodes, typically used in many areas of high power and high frequency electronics. In order to exploit the full potential of nitrides, in this context, devices with vertical current conduction need to be extensively investigated. In that respect, growth of high quality material on conducted substrates, that provide low resistive contact to nitrides heterostructure, is essential and in practice will be one of the fundamental factors that determines the devices parameters. The most widely used substrate for GaN-based power devices is SiC, that is characterized by very high thermal conductivity and good crystallographic match to nitrides [4, 5]. However, the high cost and limited availability of large diameter SiC substrates, effectively narrow down the use of high power GaN devices to dedicated, highly performed and expensive applications. In order to enable mass production and increase the widespread availability of affordable GaN-based vertical power diodes and transistors, it is necessary to step up research in the area of AIII-N growth on Si substrates. Silicon, with it's proofed reputation in semiconductor industry, is the ideal candidate for high volume and low cost GaN devices.

GaN growth on large area silicon substrates is still challenging due to fundamental limitations imposed by thermal and lattice mismatch of GaN and Si, and chemical incompatibility of both material systems. Direct growth of GaN on Si by metalorganic vapor phase epitaxy (MOVPE) resulted in parasitic reactions between substrate and growth precursors (typically $NH_3$ and TMGa) and crystallization of low quality strained layers with high defect density. Different approaches were proposed in order to minimize the occurrence of parasitic surface nitridation and melt-back etching of Si during MOVPE process [6–8] as well as strain incorporation in heteroepitaxial AIII-N structures [9, 10].

One of the known method of stress engineering in nitride-based heteroepitaxial structrures is the apllication of thin, several nanometers thick, low temperature (LT) AlN interlayers, which serves as a relaxation spacer

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between strained GaN layers [11, 12]. This method has been proved as a effective way of reducing tensile strain in thick (above 2 µm) GaN layers. In addition, the application of thin noncontinous SiN layer can enhance the three dimensional growth mode of GaN layer, which suppress formation of threading dislocation in the early sages of GaN crystallization [13–16]. Unfortunatelly, LT-AlN interlayers as well as SiN nanomask have significant impact on the surface morphology of deposited GaN, due to prolonged coalescence of epitaxial layer and delayed transition from the 3D to 2D growth mode. This problem can be partially solved by optimization of growth condition, i.e. V/III mole ratio during GaN growth. In this research we investigate the influence of growth process parameters, mainly V/III mole ratio of Ga and N precursors, during growth of GaN buffer layer on the structural and electrical properties of AlGaN/GaN/Si HEMT-type heterostructures grown by MOVPE technique with the use of in situ deposited SiN and LT-AlN interlayers.

The layer scheme of investigated heterostructures is presented in Fig. 1. Silicon substrate is protected against Ga and Si inter diffusion by high temperature (HT) AlN nucleation layer that is covered by in situ deposited noncontinuous layer of SiN that promotes required 3D growth mode of subsequent GaN buffer. LT-AlN act as a relaxing layer which introduce compressive stress in tensile strained heterostructure. The influence of SiN nanomask and the growth conditions of GaN buffer on the stress state in epitaxial structure was studied. Moreover, the results of electrical characterization of AlGaN/GaN heterostructures, grown on the optimized buffer layers, and the comparison of their parametes with the properties of AlGaN/GaN heterostructures deposited on sapphire was performed.

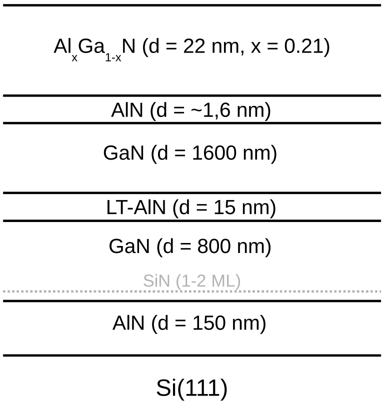

**Fig. 1** The layer scheme of investigated AlGaN/GaN heterostructures deposited on Si(111) with SiN mask and low temperature AlN layer between two GaN sub-buffers

## 2 Experimental details

Experimental work was divided in two parts. First, the influence of SiN nanomask on the built-in stress in AlGaN/GaN/Si heterostructures was investigated, second, the optimization of growth conditions (mole ratio of V/III group precursors), in order to enhance crystalline quality and electrical properties, was conducted. All samples were grown on 2 inch, 340 nm thick Si(111) substrates in AIXTRON CCS reactor, using trimethylgallium (TMGa), trimethylaluminium (TMAl), ammonia ($NH_3$) and sillane ($SiH_4$) chemical reagents as a source of gallium, aluminum, nitrogen and silicon atoms respectively. Total gas flow in the reactor during growth procedure was kept constant at 16 sl/min. Initial thermal cleaning of Si substrates, as well as subsequent growth stages were performed in $H_2$ atmosphere. In order to prevent formation of parasitic SiN on the Si surface, prior to AlN deposition, the TMAl preflow (20 s, 8.6 µmol/min) without $NH_3$ was applied. After that, using the same conditions (100 mbar, 1060 °C), $NH_3$ (67 mmol/min) was introduced and 150 nm thick AlN layer was grown. In the case of samples with SiN nanomask, HT-AlN was in situ covered by the noncontinuous SiN layer by switching from TMAl to $SiH_4$ (0.11 µmol/min) for 100 s. Subsequently, high temperature (Al,Ga)N layers were deposited at 1045 °C and 100 mbar with constant $NH_3$ (129 mmol/min) flow, whereas low temperature AlN layers at 650 °C with TMAl flow equaled to 9.4 µmol/min. In the first attempt, the impact of non-continous SiN subnanometer layer on the properties of subsequently grown AlGaN/GaN heterostructure was checked. The detailed layers structure scheme and growth parameters of the samples with and without SiN is shown in Table 1 (sample A and B). Application of this layer significantly reduce the built in stress in AlGaN/GaN heterostructure and enhance its crystalline quality (detailed results will be presented later in this manuscript). It led to following investigation of heterostructures containing SiN nanomask. Certain disadvantage of this approach is the increase of the surface defect density—so called micropits [17], however, by altering of $NH_3$ and TMGa mole ratio during the growth of GaN buffer, this issue can be effectively solved. High V/III ratios tend to enhance the lateral growth thus suppress formation of these defects on the SiN/GaN interface and in result their reveal on the samples surface. However, in this work, the focus is placed on the influence of V/III growth ratio on the mobility of 2DEG what is an indirect measure of material quality. The layer structure schemes and growth parameters of investigated samples are presented in Table 1 (samples B–E). Different V/III growth ratios were obtained by altering TMGa flow, keeping $NH_3$ flow constant. V/III mole ratios of 600,

**Table 1** The layer scheme and growth parameters of investigated AlGaN/GaN heterostructures with and without SiN mask (A, B) growth with different V/III mole ratios (B–E)

| Sample | A | B | C | D | E | F |
|---|---|---|---|---|---|---|
| HT-AlN thickness (nm) | 150 | 150 | 150 | 150 | 150 | 150 |
| SiN deposition time (s) | – | 100 | 100 | 100 | 100 | 100 |
| HT-GaN I thickness (nm); V/III ratio (mol/mol) | 800; 5000 | 800; 5000 | 800; 5000 | 800; 5000 | 800; 5000 | 800; 5000 |
| SiN deposition time (s) | – | 100 | 100 | 100 | 100 | 100 |
| HT-GaN I thickness (nm); V/III ratio (mol/mol) | 800; 5000 | 800; 5000 | 800; 5000 | 800; 5000 | 800; 5000 | 800; 5000 |
| LT-AlN thickness (nm) | 15 | 15 | 15 | 15 | 15 | 15 |
| HT-GaN II thickness (nm); V/III ratio (mol/mol) | 1600; 1200 | 1600; 1200 | 1600; 600 | 1600; 3000 | 1600; 5000 | 1600; 1200 |
| AlN thickness (nm) | ~ 1.6 | ~ 1.6 | ~ 1.6 | ~ 1.6 | ~ 1.6 | ~ 1.6 |
| $Al_xGa_{1-x}N$ thickness (nm); composition (x) | 22; 0.21 | 22; 0.21 | 22; 0.21 | 22; 0.21 | 22; 0.21 | 22; 0.28<br>$n_d = 2 \times 10^{17}$ $cm^{-3}$ |

1200, 3000 and 5000 correspond to TMGa flow of 217, 109, 43.5 and 21.7 µmol/min respectivelly at $NH_3$ flow of 129 mmol/min.

## 3 Results and discussion

### 3.1 Influence of SiN nanomask

Investigated heterostructures, with and without SiN nanomask (samples A and B), were characterized by SEM, AFM, room temperature PL and XRD. The FWHM values of GaN related PL peak decreased from 97 to 76 meV after SiN introduction in epitaxial structure, which indicates the improvement of material quality. XRD measurements also confirmed increase of GaN crystalline quality, the (0002) and (01-15) diffraction peaks FWHM decreased from 778.39 to 386.64 arcsec and from 700.88 to 362.56 arcsec respectively for sample with SiN layer (Fig. 2). Furthermore, built in stress in heterostructures, determined on the basis of GaN unit cell deformation measured by XRD, was much smaller in the sampe with SiN – 161 versus 872 MPa. Structural characterization was supplemented by the microscopic observations of investigated samples. SEM and AFM surface pictures of the heterostructures with and without SiN nanomask are shown in Fig. 3. Surface of the sample with SiN is much smoother, the RMS value equals to 1.3 nm, compared to the value of 5.8 nm measured for the sample grown without SiN. However, occurrence of hexagoanl micropits on the surface is observed in the case of sample with SiN. The mechanism of bending and recombination of threading dislocations (TDs) and reduction of tensile stress in GaN layers grown on SiN interlayer were widely described in literature [18–21]. Further information and analysis of micropits like defect formation mechanism in heterostructures grown on silicon with and without SiN interlayer can be found in authors previous publication [13].

### 3.2 Influence of III/V ratio

Surface AFM scans of samples B–E grown with different V/III mole ratio are presented in Fig. 4. It is clearly visible, that in ammonia rich atmosphere the density of hexagonal micropits is smaller. This can be partially attributed to the fact, that high V/III conditions result in enhanced lateral growth of GaN, that can suppress the formation of surface defects. XRD measurements of investigated samples showed strong correlation between growth conditions and crystalline

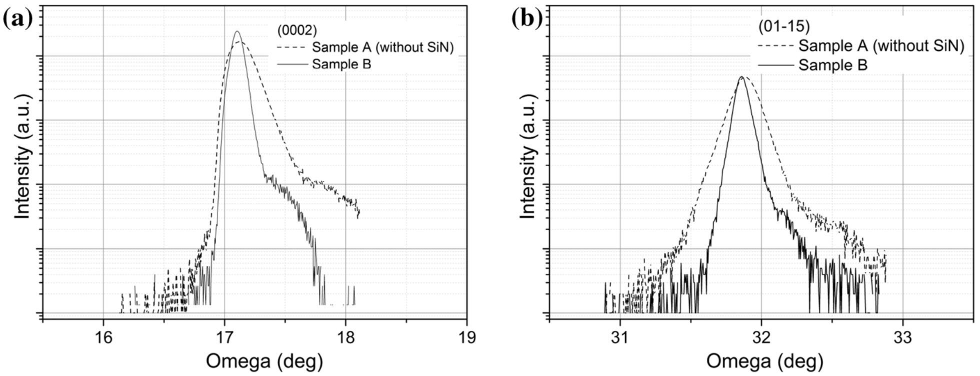

**Fig. 2** The XRD scans in the omega-2theta configuration of the (0002) reflex (**a**) and the asymmetric (01-15) reflex (**b**) of the investigated samples with and without SiN layer

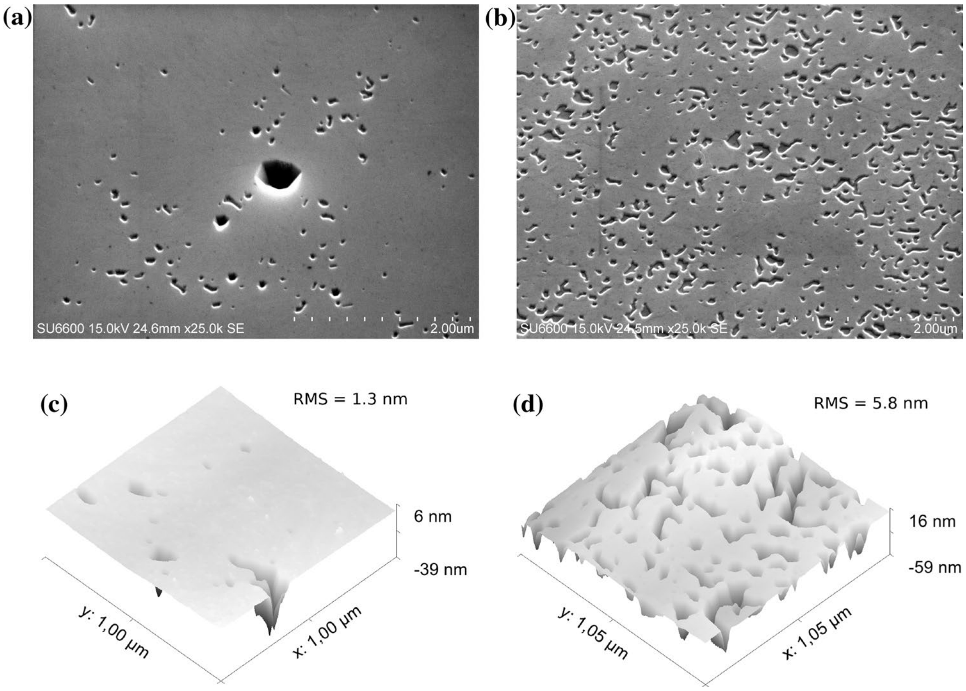

**Fig. 3** Surface SEM pictures (**a**, **b**) and AFM scans (**c**, **d**) of the samples grown with (**a**, **c**) and without (**b**, **d**) SiN interlayer

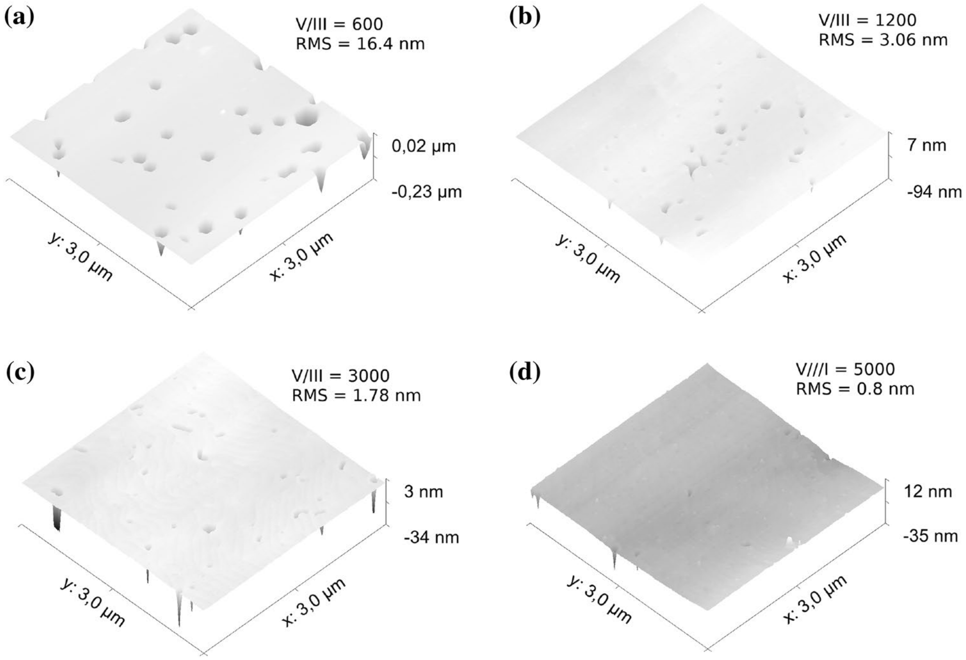

**Fig. 4** Surface AFM scans of the samples grown with different V/III mole ratio: 600 (**a**), 1200 (**b**), 3000 (**c**) 5000 (**d**)

quality. The relationship between V/III mole ratio and (0002) GaN FWHM peak is presented in Fig. 5. For reference, on the same graph the values of 2DEG mobility, measured by impedance spectroscopy [22] method, were indicated. In this case the crystal quality improvement are not reflected in the increase of electron mobility. The highest mobility (2057 $cm^2\ V^{-1}\ s^{-1}$) was observed in the sample grown with V/III = 1200. Unfortunately, the impedance spectroscopy measurements were impossible for sample grown in Ga rich conditions (V/III = 600) due to high surface deterioration by shallow micropits.

In order to enhance electrical properties (to decrease the 2DEG surface resistance), the heterostructure (sample F) with Si dopants and higher Al content in AlGaN barrier was deposited using the same buffer grown scheme

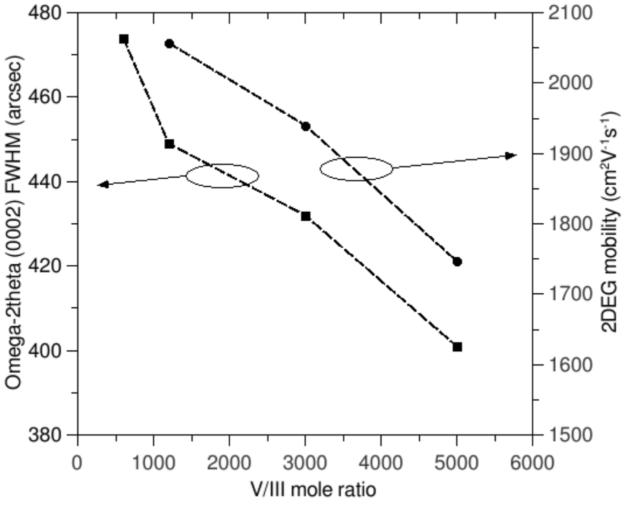

**Fig. 5** Dependence of V/III mole ratio during GaN growth on GaN (0002) diffraction peak FWHM and 2DEG mobility. Dashed lines are a guide to the eye

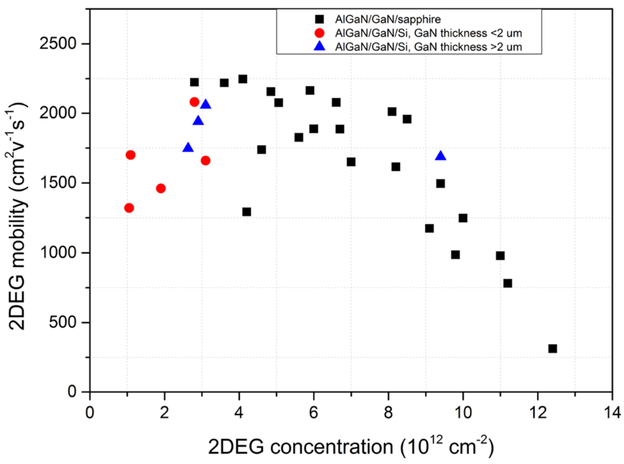

**Fig. 6** 2DEG mobility versus sheet charge concentration of different AlGaN/GaN heterostructures deposited on sapphire and silicon substrates (author's own results)

as sample B (III/V = 1200). CV and impedance spectroscopy measurements indicated very low sheet resistance of 392 Ω/sq for this sample. For reference, on the graph presented in Fig. 6, the comparison of sheet charge concentration and electron mobility of 2DEG of different heterostructures grown on sapphire and silicon with SiN interlayer, using different buffer thicknesses and V/III mole ratios during GaN growth, are shown. This proves usefulness of presented method in MOVPE deposition of high quality AlGaN/GaN heterostructures with thick GaN buffers on Si(111) without cracking.

## 4 Conclusions

The undertaken experimental studies have proved the usefulness of in situ grown non-continous sub-nanometer SiN layer in stress reduction and material quality improvement of AlGaN/GaN heterostructures deposited on Si(111) substrates. The fabricated sample with SiN nanomask exhibited good structural properties, with GaN (0002) diffraction peak FWHM equals to 362 arcsec and calculated basal plane stress lower than 200 MPa. Structural characterization of investigated samples confirmed the influence of V/III mole ratio, during growth of GaN buffer, on the crystalline quality of AlGaN/GaN heterostructures. Higher V/III mole ratios enabled growth the better quality material with smoother surface. Furthermore, the $NH_3$ to TMGa molar ratio has noticeable impact on the electrical parameters of 2DEG of AlGaN/GaN heterostructures. However, higher mobility was obtained for lower V/III mole ratios, what is not expected and may indicate another important factors, other than crystalline quality, that influence the scattering mechanism of 2DEG in these type of structures. Electrically optimized AlGaN/GaN heterostructures deposited on silicon showed similar performance to those grown on sapphire substrates. This indicates the suitability of discussed growth method in fabrication of AlGaN/GaN/Si heterostructures for lateral and vertical HEMTs.

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