Materials Letters 142 (2015) 335–338

Contents lists available at ScienceDirect

Materials Letters

journal homepage: www.elsevier.com/locate/matlet

High hole concentration Mg doped a-plane GaN with MgN by metal–organic chemical vapor deposition

Keun-Man Song [a], Jong-Min Kim [a], Je-Hyuk Choi [a], Dae-Hun Kang [a], Kahee Kim [a], Sung-Min Hwang [b], Bong-Kyun Kang [c], Dae-Ho Yoon [c,*]

[a] *Korea Advanced Nano Fab Center, Suwon, Gyeonggi 443-770, Republic of Korea*
[b] *Korea Electronics Technology Institute, 86 Yatap-dong, Seongnam, Republic of Korea*
[c] *School of Advanced Materials Science and Engineering, Sungkyunkwan University, 300 Cheoncheon-dong, Suwon, Republic of Korea*

ARTICLE INFO

Article history:
Received 23 September 2014
Accepted 14 December 2014
Available online 18 December 2014

Keywords:
GaN
Nonpolar
MgN
MOCVD
AFM

ABSTRACT

Mg doped a-plane GaN layers with MgN interlayers were grown on r-plane sapphire substrates by metal–organic chemical vapor deposition. Nonpolar Mg doped a-plane GaN without MgN exhibited a rough surface morphology, with both various sized, and large number of faceted pits. Meanwhile, nonpolar p-type GaN layers using MgN exhibited improved surface morphology, with typical stripe features along the [0 0 0 1] direction, and reduced faceted triangular pits on the surface, leading to increased hole concentration and crystal quality. The effect of insertion of MgN interlayers and their characteristics in Mg doped a-plane GaN were estimated by Hall-effect measurement, atomic force microscopy (AFM), cathode luminescence (CL), X-ray diffraction (XRD), and transmission electron microscope (TEM) measurement.

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1. Introduction

Significant progress of III nitride-based semiconductor technology has been made in the commercialization of GaN-based LEDs and LDs for solid state lighting. However, further improvement of device performance is hindered by the internal electric fields caused by spontaneous and piezoelectric polarization in GaN, which is based on the c-plane surface. Recently, nonpolar and semipolar GaN have been attracting increasing attention for resolving this drawback. They have reduced, or are free of polarization-induced effects in nitride-based devices, resulting in enhancement of the internal quantum efficiency by increased oscillator strength of the electrons and holes [1,2]. However, the growth of high quality nonpolar and semipolar GaN is extremely difficult, unlike the c-plane GaN growth, because of the large lattice mismatch and crystallographic anisotropy with sapphire substrate. This causes high density of threading dislocations, and undulating surface morphology. Additionally, another important technical challenge in the realization of nonpolar or semipolar III nitride devices is Mg doping for p-type GaN. It is difficult to achieve Mg doped p-type GaN with high hole concentrations, due to poor crystal quality and Mg activation efficiency. In previous study, the electrical properties of Mg-doped a-plane GaN have been investigated as a function of the growth rate, doping level, V/III ratio, and the growth temperature, resulting in a maximum hole concentration of $6.8\times10^{17}\ \mathrm{cm}^{-3}$ with 0.9% ionization [3]. Tsuchiya et al. demonstrated the growth of Mg-doped a-plane GaN using $Al_{0.5}Ga_{0.5}N/AlN$ buffer structure on $+0.5^{\circ}$-off r-plane sapphire, and showed a full width at half maximum of X-ray rocking curves of approximately 1000 arcsec, and maximum hole concentration of $2\times10^{18}\ \mathrm{cm}^{-3}$ with activation energy of 118 meV, which is lower than that of c-plane GaN ($\sim$170 meV) [4]. For high efficient device performance, it is essential to obtain p-type GaN with both higher hole concentrations and crystal quality, because it plays an important role in carrier injection into multiple quantum wells (MQWs), through low ohmic contact, and light extraction from MQWs. The attainment of higher hole concentration and higher crystal quality remains one of the biggest obstacles for nonpolar GaN-based applications. However, there are few studies on the growth of Mg doped a-plane GaN with both high hole concentrations and high crystal quality, even though nonpolar a-plane GaN shows different growth behavior, compared with c-plane GaN.

In this work, high quality Mg doped nonpolar a-plane GaN layers with MgN interlayers were grown on r-plane sapphire by metal–organic chemical vapor deposition (MOCVD). The electrical and physical characteristics of the Mg doped a-plane GaN epitaxial layers inserted MgN is reported.

2. Experimental

A planetary MOCVD system (Aixtron G3 2600HT) was used to grow nonpolar a-plane GaN on r-plane sapphire substrates with a

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[*] Corresponding author.
E-mail address: dhyoon@skku.edu (D.-H. Yoon).

http://dx.doi.org/10.1016/j.matlet.2014.12.072
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direct growth method [5]. Trimethylgallium (TMGa), and ammonia were used as the source precursors, and bis-cyclopentadienylmagnesium (CP_2Mg) as the p-type dopant. For high quality p-type nonpolar GaN, firstly, the high temperature undoped a-plane GaN layer with 4-μm thickness was directly grown on sapphire substrate at 1050 °C by a two-step growth scheme, which is initial 3D growth, and coalescence by 2D growth [6,7]. The subsequent growth of 550-nm-thick p-type nonpolar GaN was carried out at 930 °C. To investigate the effects of MgN interlayers on the properties of Mg-doped a-plane GaN, two sets of samples were prepared. The first set of Mg doped a-plane GaN layers were prepared with different MgN treatment time of 0, 3, 5, and 15 s, maintaining one MgN interlayer. The second set was prepared to study the effect of the number of MgN interlayers on the properties of Mg doped a-plane GaN, which has evenly spaced MgN interlayers in a constant 550-nm thickness. Fig. 1(a) and (b) schematically shows the structure of samples without and with MgN interlayers, respectively. MgN interlayers were inserted into the middle of the uniformly doped p-type GaN, varying the MgN treatment times, and the number of MgN interlayers. For hole activation, rapid thermal annealing (RTA) was carried out at 750 °C for 1 min, under N_2 ambient. After annealing, Hall-effect measurements were performed with the Van der Pauw method. The surface morphology, luminescence and crystal characteristics were estimated by atomic force microscopy (AFM), cathode luminescence (CL), X-ray diffraction (XRD), and transmission electron microscope (TEM) measurement.

3. Results and discussion

Fig. 2(a) shows the room temperature hole concentration of Mg doped a-plane GaN with different MgN treatment times for one MgN interlayer. The hole concentration of Mg doped a-plane GaN without MgN was 5.3×10^{17} cm^{-3}. By introducing the MgN treatment, the hole concentration increased, and showed the highest value of 8.6×10^{17} cm^{-3} at 5 s of MgN treatment time. With further increase of the MgN treatment time to 15 s, the hole concentration of Mg doped a-plane GaN with one MgN interlayer showed similar value, in spite of further MgN treatment time. This result reveals that MgN treatment can prominently improve the hole concentration. Fig. 2(b) shows the hole concentration of Mg doped a-plane GaN, as a function of the number of MgN interlayers. The hole concentration increased to 1.8×10^{18} cm^{-3}, with increase in the number of MgN interlayers from 0 to 2. However, with further increasing the number of MgN interlayers to 6, the hole concentration decreased to 1.1×10^{17} cm^{-3}. The decrease of hole concentration with further increasing MgN interlayers could be attributed to an additional formation of structural defects or compensation centers, as a result of incomplete coalescence, and growth of an Mg doped a-plane GaN layer on the MgN interlayer, because the growth of Mg-doped a-plane GaN between MgN interlayers is not thick enough for coalescence and recovery during the growth, as the number of MgN interlayers increase within the limited thickness of p-GaN (550 nm). Therefore, the short distance between MgN interlayers might cause a degradation of quality, rather than an improvement in Mg-doped a-plane GaN. For Mg-doped a-plane GaN, the decrease of hole concentration resulted from the formation of structural defects of Mg–N, or compensation centers such as nitrogen vacancies, or the incorporation of electrically inactive forms, such as clusters, and precipitates [3]. From the SIMS measurements, Mg concentration was 6.8×10^{19} cm^{-3} for Mg doped a-plane GaN without MgN interlayer. The activation efficiency of Mg dopants was 0.78% and 2.6% for Mg doped a-plane GaN without and with 2 pair of MgN interlayers on the assumption of zero compensation, respectively.

Fig. 3(a) and (d) shows the AFM surface morphology of Mg doped a-plane GaN without and with 2 pair of MgN interlayers, respectively. From the AFM measurement (10 μm × 10 μm), Mg doped a-plane GaN without MgN interlayer exhibited a rough surface morphology, with both various size, and large number of triangular faceted pits, which might originate from the underlying undoped a-plane GaN. In a-plane GaN, triangular pits with a vertical $(0\,0\,0\,\bar{1})$ facet and inclined $\{1\,0\,\bar{1}\,1\}$ facets on the growing surface

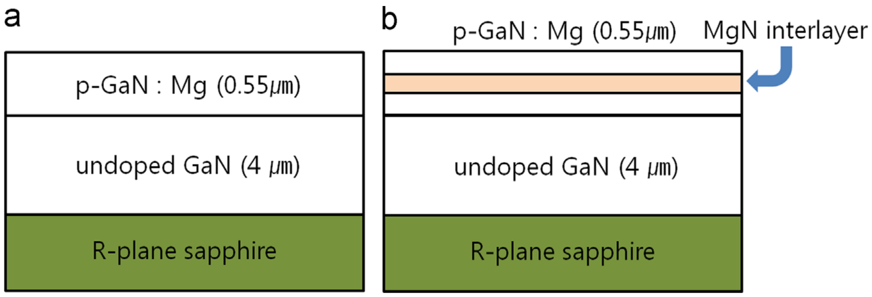

Fig. 1. Schematic diagram of samples (a) Mg doped a-plane GaN without MgN, and (b) with MgN interlayers inserted.

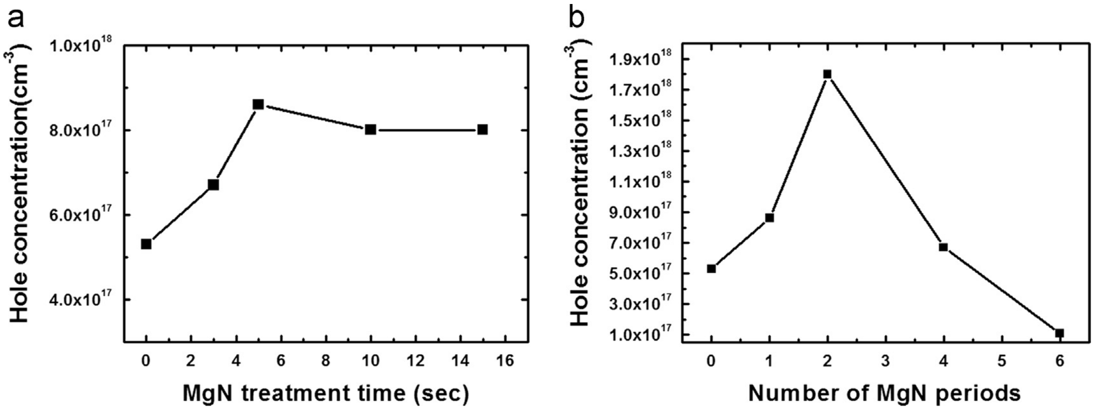

Fig. 2. Room temperature hole concentration of Mg-doped a-plane GaN with (a) different MgN treatment times, and (b) the number of MgN interlayers.

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