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Effect of periodic Si-delta-doping on the evolution of yellow luminescence and stress in *n*-type GaN epilayers

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A B S T R A C T

We report the effect of periodic Si-delta-doping on the yellow luminescence (YL) and stress evolution in *n*-GaN epilayers. Photoluminescence measurements indicated that the YL component could be effectively suppressed with increasing dopant flow rate or decreasing period length. X-ray diffraction, transmission electron microscopy and secondary ion mass spectroscopy measurements revealed that the variations of dislocation density and carbon concentration are not the responsible mechanisms for the of YL emissions. The reduction of Ga vacancy related defects seems to be the probable reason for the YL suppression by Si-delta-doping. Moreover, Raman spectroscopy showed no obvious stress variation among these samples with different equivalent electron concentration. These observed features are entirely different from those reported for uniformly Si-doped GaN.

1. Introduction

In the last decade, GaN and related compound semiconductors (InN, AlN and their ternary/quaternary compounds) have been extensively studied as the representation of the 3rd generation semiconductors [1–3]. To achieve high-performance nitride-based optoelectronic and electronic devices, both of efficient *n*- and *p*-type doping are essential. Unlike the *p*-type doping, *n*-type doping is easily obtained with Si incorporation in nitrides. However, heavy Si doping for achieving high conductivity usually accompanies with the increase of native defects and degradation of structural properties in *n*-GaN layer. The most commonly observed defect response in *n*-type GaN is the yellow luminescence (YL) of 2.20–2.25 eV, and the YL intensity increases with Si doping level [4,5]. Positron annihilation experiments evidence that the acceptor-like Ga vacancy (V_{Ga}), which has relatively low formation energy when the Fermi level is close to the conduction band, is abundantly formed in *n*-type GaN [5–9]. The increase of YL in Si-doped GaN is generally attributed to the increase of V_{Ga} concentration [4,5,10–13]. Acceptors around edge threading dislocation [14,15] and carbon (C) impurity [16–19], however, have also been proposed to be responsible for the YL. On the other hand, the Si-doped GaN grown on sapphire usually suffers from compressive stress and the stress gradually relaxes with Si doping level [10,20]. In a recent report, it was claimed that the stress evolution in Si-doped GaN was strongly related to free carrier concentration which was explained by the Fermi level effect on the surface mediated dislocation climb via V_{Ga} [21].

Si-delta-doping (Si-δ-doping) technique has attracted considerable attention in the epitaxial growth of *n*-GaN and GaN-based device structure [22–28]. Our recent work indicated that this approach assisted in enhancing the device performance of GaN-based light-emitting diodes in terms of output power and electrostatic discharge reliability [27]. Moreover, the *n*-type GaN samples grown using this doping method exhibited quite different electron mobility behavior from that in uniformly Si-doped *n*-GaN [28]. Despite these research findings, very little is known about the material properties of Si-δ-doped GaN in terms of native defects related YL and stress state. In this study, the effect of periodic Si-δ-doping on the YL and stress evolution in GaN epilayers is therefore investigated. According to the analysis on the structural and optical of these epilayers, it was confirmed that the YL component can be effectively suppressed with increasing dopant flow rate or decreasing period length, possibly due to the reduction of V_{Ga} density. On the other hand, the compressive stresses in the investigated samples were almost on the same level for different equivalent Si doping concentrations.

2. Experimental details

The GaN samples used in this study were grown on 2 in. *c*-face sapphire substrates in a metal organic chemical vapor deposition

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system with Thomas Swan close-coupled showerhead reactor. Trimethylgallium (TMGa) and ammonia (NH_3) were used as the gallium and nitrogen precursors, respectively. Silane (SiH_4) was used as n-type doping sources, and hydrogen was used as the carrier gas throughout the growth run. The sample structures consist of a 25-nm-thick low-temperature (530 °C) GaN nucleation layer, a 2-μm-thick high-temperature (1060 °C) unintentionally-doped (UID) GaN buffer layer, and several periods of Si-δ-doped layers with the total thickness of ~1 μm. During the deposition of δ-doped layers, the TMGa and SiH_4 sources were alternatively switched on and off, while NH_3 was kept on all the time. The growth conditions for the UID-GaN buffer layer and the Si-δ-doped layers were similar, with a V/III ratio of around 1000. Two series of samples have been grown. For series I, 20 periods of δ-doped layers were grown in the total 1-μm-thick Si-δ-doped GaN layers, while the Si flow rate in the doping planes was varied from 5.51 to 40.58 nmol/min. For series II, the period lengths (i.e., barrier thicknesses or period number) of the δ-doped layers were varied in the total 1-μm-thick Si-δ-doped GaN layers, while the Si deposition time and flow rate kept the same (10 s; 40.58 nmol/min) in each doping plane. The time series of the TMGa, NH_3 and SiH_4 precursors during growth and schematic diagram of the grown structure are illustrated in Fig. 1. Moreover, a 3-μm-thick UID-GaN with a background electron concentration of $\sim 8 \times 10^{16}\ \mathrm{cm}^{-3}$ was also grown for comparison.

Room temperature photoluminescence (RT-PL) measurements were carried out using a 266 nm Nd:YAG laser as the exciting source (laser power density $\sim 7.2\ \mathrm{W/cm^2}$). High-resolution X-ray diffraction (HR-XRD) measurements were performed using a Bruker D8 Discover instrument. Cross-sectional transmission electron microscopy (TEM) specimens were prepared by the focus-ion-beam method. TEM analysis was performed in a FEI Tecnai G2 F20 instrument operated at 200 kV. The carbon concentration profiles were determined by secondary ion mass spectroscopy (SIMS) measurements. Raman measurements were carried out by Horiba JY LabRAM HR800 system with 514 nm Argon ion laser (output power ~30 mW).

3. Results and discussions

To investigate the optical properties of the Si-δ-doped layers, RT-PL measurements were at first performed on the two series samples. Fig. 2 shows the PL spectra of the investigated samples normalized by the peak intensity of band-edge (BE) emission centered around 3.44 eV (~360 nm). Besides the BE emission peaks, whose integrated intensities are nearly on the same level with the variation less than 8% for the measured samples, the YL bands located around 2.25 eV (~550 nm) could also be clearly identified. Fig. 2(a) and (b) presents the results for the series I and II samples, respectively. The PL spectrum of the UID-GaN sample is not included in Fig. 2 as its luminescence behavior may be different from those of other samples. The insets of Fig. 2(a) and (b) plot the integrated PL intensity ratios of YL band to BE emission (I_{YL}/I_{BE}). The I_{YL}/I_{BE} ratio decreases from 0.14 to 0.06 when the Si flow rate in the doping plane increases from 5.51 to 40.58 nmol/min (for samples with 50 periods), and decreases from 0.11 to 0.02 when the period number increases from 8 to 62 (for samples with 40.58 nmol/min Si flow rate). It could be concluded that for samples with increased period number or higher Si doping level in each doping plane (i.e., with higher equivalent electron concentration [28]), the intensity of YL band emission becomes weaker compared to the BE emission. Moreover, because the integrated intensities of the BE emissions are nearly on the same level with no obvious changes related to Si-δ-doping level, the reduction of I_{YL}/I_{BE} ratio therefore indicates the weakening of YL emission due to the Si-δ-doping.

In contrast, for uniformly-Si-doped GaN samples, the incorporation of Si impurity with increasing Si doping level usually causes the deterioration of crystalline quality and demonstrates a monotonic

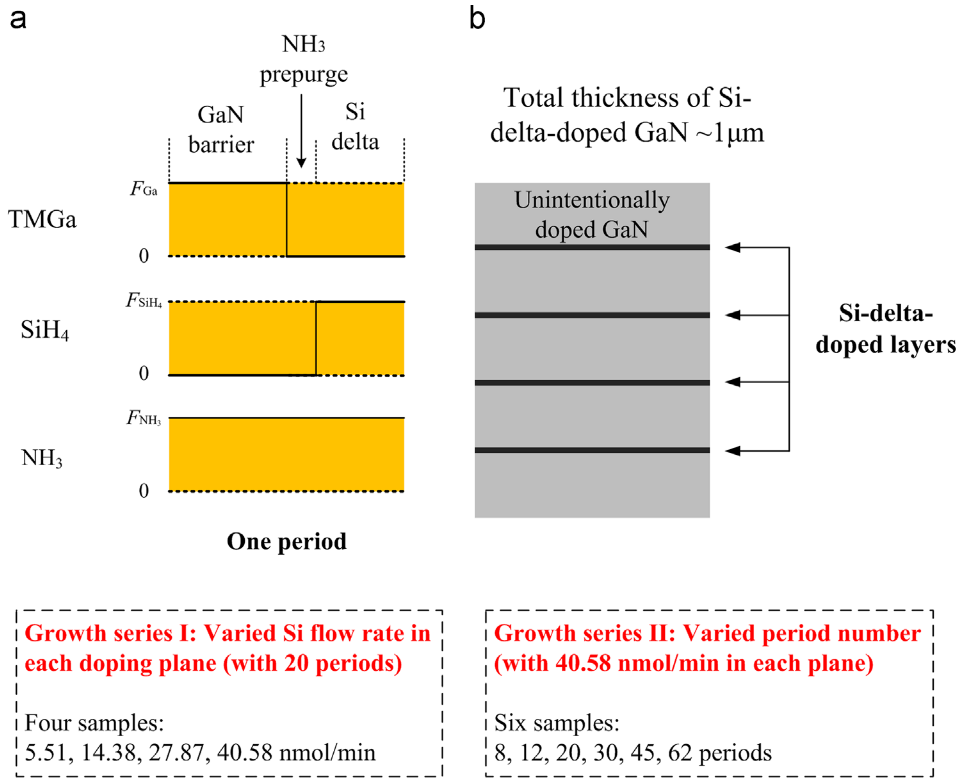

Fig. 1. (a) Time series of the TMGa, NH_3 and SiH_4 precursors during the growth. During the growth of Si-δ-doped layers, the TMGa and SiH_4 sources were alternatively switched on and off, while NH_3 was kept on all the while and (b) schematic diagram of the grown structure.