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Characterization of deep levels in *a*-plane GaN epi-layers grown using various growth techniques

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ABSTRACT

To study the correlation between defects and deep levels in *a*-plane GaN films grown on *r*-plane sapphire substrates, transmission electron microscopy (TEM) and deep level transient spectroscopy (DLTS) have been performed on three types of *a*-plane GaN samples grown using modified two-step growth (sample I), SiN_x interlayer (sample II), and patterned insulator on sapphire substrate (sample III). From the microstructure evolution in cross-sectional TEM images, it was shown that combination of growth techniques is highly efficient in the reduction of dislocation densities. Average dislocation densities of samples I, II, and III were about $2.2\times10^9\,cm^{-2}$, $1.1\times10^9\,cm^{-2}$, and $3.4\times10^8\,cm^{-2}$, respectively. The trap at $E_c–E_t\sim0.13$ eV (E1) was observed in only sample I, and three electron traps at 0.28–0.33 eV (E2), 0.52–0.58 eV (E3), and 0.89–0.95 eV (E4) from the conduction band edge were measured common to all the samples. The analysis of trap properties indicated that E2 and E3 trap levels are strongly associated with the partial dislocations in *a*-plane GaN films.

1. Introduction

Group III-nitrides such as GaN and related ternary compounds have been widely used for optoelectronic applications [1]. Since conventional GaN-based devices with polar orientation are affected by quantum-confined Stark effect decreasing the device efficiency, the studies on nonpolar GaN films are believed to improve the device performance [2–4]. It is expected that the strong polarization fields across the active region along polar direction could be eliminated using the nonpolar structure. In spite of several advantages of nonpolar structure, the nonpolar-based devices still could not be applied to commercial products, because the growth of the nonpolar structure is more difficult than that of the polar structure due to the high Ga-polar to N-polar wing growth rate ratio and large lattice-mismatch with hetero-epitaxial substrates [5]. In order to achieve a high quality epitaxial structure, the defect reduction and surface smoothing techniques, and the development of suitable substrates have been extensively studied. Some groups used low lattice-mismatched substrates such as nonpolar GaN bulk substrates [6,7]. However these homo-epitaxial substrates are too expensive to commercialize the product. Therefore, the growth techniques such as two-step growth process [8], lateral epitaxial overgrowth [9], and insertion of SiN_x interlayers [10] for lowering the threading dislocation density on sapphire substrates are attracting attentions. The extended defects as well as electrically active defects in semiconductors induce the formation of deep levels in energy band structure. However, despite the importance of the deep level characterization, only a few papers reported the measurement of the deep traps in nonpolar GaN layers. Therefore, identification and characterization of deep levels in nonpolar GaN films could provide useful information for understanding the properties of defects.

In this study, we have carried out a detailed investigation of the defects in *a*-plane GaN films by transmission electron microscopy (TEM) and deep level transient spectroscopy (DLTS) of three samples employing various growth techniques, which are modified two-step growth [11], SiN_x interlayer, and epitaxy on patterned insulator on sapphire substrate (EPISS). Threading dislocation densities in samples were estimated by TEM images with two-beam conditions. Origins of deep levels in *a*-plane GaN films were identified by filling pulse dependent behavior of trap levels, and then the influence of growth techniques on electrical properties and deep levels was intensively investigated by comparison of trap densities.

2. Experimental procedure

Three different series of *a*-plane GaN samples were grown by metal–organic chemical vapor deposition (MOCVD) on *r*-plane sapphire. For the first sample (sample I), the modified two-step

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growth process was employed. Sample I consisted of the high temperature nucleation layer, the first buffer layer for the 3D growth, the second buffer layer for the interlayer between 3D and 2D growth layer, and the third buffer layer for the 2D growth. Before the growth of GaN films, sapphire substrates were heated for nitridation in a flow of ammonia. The growth thickness of NLs was 120 nm with a growth rate of 2 μm/h. For the first buffer layer, growth parameters, such as reactor pressure, growth temperature, V/III ratio were 600 mbar, 1090 °C, and 840, respectively. During the growth of the first buffer layer, large GaN islands were formed. The coalescence of the large GaN islands and the surface smoothening were achieved using the second and the third buffer layers. The second buffer layer was grown at 1050 °C, 100 mbar, and a V/III ratio of 330. This intermediate layer was expected to reduce the density of threading dislocations, and the growth temperature of the third buffer layer increased to 1160 °C. These optimized growth conditions were verified in our previous report [11]. For the second sample (sample II), in-situ SiN_x interlayer was additionally inserted in between the second and the third buffer layers of the modified two-step growth layers. Facetted islands form in the self-assembled windows of the SiN_x mask and this selective area epitaxial growth process enhances the dislocation bending and annihilation process, resulting in epilayers with reduced threading dislocation densities. For the third sample (sample III), our own EPISS technique was used to minimize the dislocation density. Using lift-off process, a set of periodic hexagonal SiO_2 patterns are defined on the *r*-plane sapphire substrates, with the separations between the oxide patterns called "window". The periodic patterned substrate is loaded into the MOCVD system for direct GaN growth. During this procedure, epitaxial growth of GaN starts in the window regions, whereas no growth occurs above the masked area. The overgrown GaN will extend both vertically or laterally whose ratio highly depends on the growth conditions used. Laterally grown regions are called "wing" region, which contains much fewer defects. The area ratio of wing region to window region is about 3:1. And all samples have Si-doped *n*-type GaN layer as a top layer. For electrical characterizations of *a*-plane GaN films, the Ti/Au electrode of wide area for ohmic contacts and the 300 μm-diameter Pt electrode for Schottky contacts were fabricated on the top of samples using *e*-beam evaporator. To perform the DLTS analysis, temperature-dependent transient capacitance behavior was measured using low temperature cryostat system with a capacitance meter, and filling pulse width was controlled by a pulse generator. The plan-view TEM samples were prepared using an ion milling system, and multiple TEM images with two-beam conditions taken at random locations were analyzed for the estimation of defect densities in *a*-plane GaN films.

3. Results and discussion

For the three types of samples, microstructure evolution of threading dislocations is shown in Fig. 1. TEM images of each sample show characteristic features of two-step growth, SiN_x interlayer, and EPISS techniques. Fig. 1(a) shows the cross-sectional and plan-view (inset) TEM images of sample I with two-beam conditions. For the cross-sectional TEM image viewed along the *c*-direction of sample I, partial dislocations ($\boldsymbol{b}$= 1/5 < 20–23 >) and several types of threading dislocations could be observed with the two beam condition of $\boldsymbol{g}$=[11–20]. Threading dislocations were formed at the interface between the substrate and the GaN layer, and it was shown that the majority of the defect lines starts to change direction from (1–100) to (11–20) by the layer transition between three and two dimensional growth layers. It is obvious that the dislocation density confined

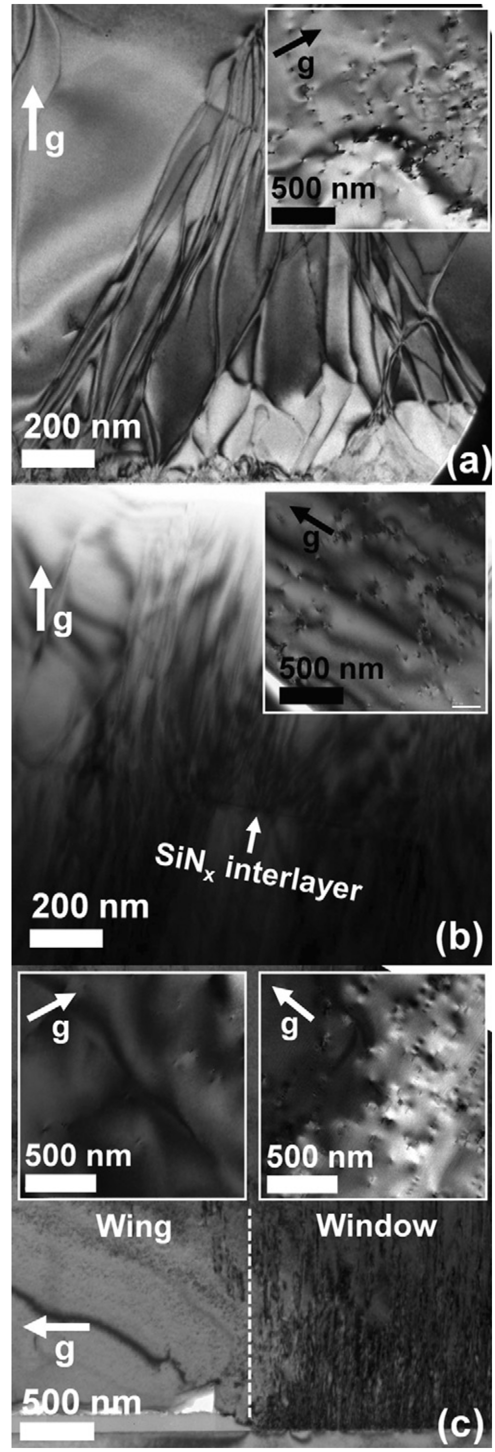

Fig. 1. Cross-sectional and plan-viewed (insets) TEM images of the samples I, II, and III: (a) For sample I, cross-section of the sample was viewed along (0001) with $\boldsymbol{g}$=[11–20], and plan-view image of the inset was taken with $\boldsymbol{g}$=[0002]. (b) Cross-sectional TEM image of sample II using SiN_x interlayer was viewed along (0001) with $\boldsymbol{g}$=[11–20]. Inset showed plan-view image with a two-beam condition of $\boldsymbol{g}$=[0002]. (c) The cross-section of sample III using EPISS was viewed along (1–100) with $\boldsymbol{g}$=[0002], and plan-view images of insets with a two-beam condition of $\boldsymbol{g}$=[0002] showed the difference between wing and window regions.

in *c*-plane decreases. Using the diffraction extinction rule, dislocation densities in *a*-plane GaN films could be calculated from plan-view TEM images with $\boldsymbol{g}$=[0002]. Under this two beam condition, partial dislocations ($\boldsymbol{b}$=1/6 < 20–23 >), *a*+*c*-type ($\boldsymbol{b}$= 1/3[11–23]), and *c*-type ($\boldsymbol{b}$=1/2 [0002]) threading dislocations are in