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ScienceDirect

Journal of Crystal Growth 310 (2008) 2514–2519

JOURNAL OF CRYSTAL GROWTH

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InGaN/GaN multi-quantum well and LED growth on wafer-bonded sapphire-on-polycrystalline AlN substrates by metalorganic chemical vapor deposition

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Received 13 September 2007; received in revised form 21 November 2007; accepted 17 January 2008
Communicated by R. Bhat
Available online 24 January 2008

Abstract

We report growth of InGaN/GaN multi-quantum well (MQW) and LED structures on a novel composite substrate designed to eliminate the coefficient of thermal expansion (CTE) mismatch problems which impact GaN growth on bulk sapphire. To form the composite substrate, a thin sapphire layer is wafer-bonded to a polycrystalline aluminum nitride (P-AlN) support substrate. The sapphire layer provides the epitaxial template for the growth; however, the thermo-mechanical properties of the composite substrate are determined by the P-AlN. Using these substrates, thermal stresses associated with temperature changes during growth should be reduced an order of magnitude compared to films grown on bulk sapphire, based on published CTE data. In order to test the suitability of the substrates for GaN LED growth, test structures were grown by metalorganic chemical vapor deposition (MOCVD) using standard process conditions for GaN growth on sapphire. Bulk sapphire substrates were included as control samples in all growth runs. *In situ* reflectance monitoring was used to compare the growth dynamics for the different substrates. The material quality of the films as judged by X-ray diffraction (XRD), photoluminescence and transmission electron microscopy (TEM) was similar for the composite substrate and the sapphire control samples.

Electroluminescence was obtained from the LED structure grown on a P-AlN composite substrate, with a similar peak wavelength and peak width to the control samples. XRD and Raman spectroscopy results confirm that the residual strain in GaN films grown on the composite substrates is dramatically reduced compared to growth on bulk sapphire substrates.

PACS: 81.15.Gh; 81.05.Ea; 85.60.Jb; 81.05.Je; 68.60.Dv; 68.35.Ct

Keywords: A1. Substrates; A3. Metalorganic vapor phase epitaxy; B1. Nitrides; B1. Sapphire; B2. Semiconducting III–V materials; B3. Light emitting diodes

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1. Introduction

Owing to the lack of low cost, large-diameter (2-in or greater) GaN substrates, GaN epitaxy is performed almost exclusively on non-lattice matched substrates [1]. For commercial InGaN/GaN LED devices the overwhelming substrate of choice is *c*-plane sapphire [2]. Growth techniques such as low temperature nucleation layers (NLs) [3] have been developed to improve the deposition of GaN films on sapphire resulting in adequate material for many devices despite the large differences in lattice constant and coefficient of thermal expansion (CTE). Continuing issues remain, in particular the CTE mismatch is known to cause film stress and wafer bowing during growth of InGaN/GaN LED structures on sapphire [4],

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doi:10.1016/j.jcrysgro.2008.01.022

Table 1
Comparison of thermal properties of GaN substrate materials

Material	CTE (20–1100 °C) (ppm/K)[a]	Thermal conductivity ($\mathrm{W\,m^{-1}K^{-1}}$)
c-Plane GaN	5.2	210 Ref. [1]
c-Plane sapphire	8.1	23 Ref. [1]
P-AlN	5.5	180[b]

[a] In-plane CTE averaged over the temperature range indicated, using data from Ref. [7].

[b] CeramTec North America Corp. Material Selection Guide, 2003.

leading for example to within-wafer and run-to-run wavelength non-uniformity. Strategies incorporating *in situ* curvature monitoring have been implemented on 2-in sapphire to improve the wavelength uniformity [4,5], however, even with such growth controls in place it is not possible to eliminate the CTE mismatch effects entirely. For example the issue of high residual stress upon cool-down [6] remains, which can impact the yield of post growth processing steps. Finally, in order to reduce production costs it will be important to use larger diameter substrates, however, the effects of wafer bowing on growth and processing are expected to be amplified and more difficult to control as the sapphire wafer diameter increases.

Here we present results of metalorganic chemical vapor deposition (MOCVD) growth of InGaN/GaN MQW (multi-quantum well) and LED structures on a composite substrate consisting of a thin laminate of *c*-plane sapphire attached to a polycrystalline aluminum nitride (P-AlN) support substrate. The sapphire layer provides an epitaxial template for the GaN growth, while the thermo-mechanical properties are controlled by the thick P-AlN substrate. As shown in Table 1, polycrystalline AlN has a CTE mismatch with *c*-plane GaN that is an order of magnitude smaller than the CTE difference between GaN and sapphire. The thermal conductivity of P-AlN is also approximately five times higher than that of sapphire. It is therefore expected that substrate bowing attributed to thermal gradients across the thickness of the sapphire substrate [5] as well as the CTE mismatch induced bowing experienced during growth on sapphire, can be substantially eliminated with these composite substrates. The reduced substrate bow and the higher thermal conductivity should result in improved temperature uniformity. Therefore using this composite substrate approach it should be possible to grow GaN LED's with good wavelength uniformity on a larger diameter substrate than is currently practical with bulk sapphire. Another advantage of the composite substrate is that the P-AlN support substrate is rapidly etched in hot KOH [8], so that epitaxial lift-off for flip chip bonded LED devices may be accomplished using a batch wet chemical process rather than laser lift-off techniques.

MQW and LED growth and device results for the composite substrates are compared to those obtained on traditional bulk sapphire substrates in the same growth run. Although previous work has reported GaN growth on composite substrates, for example silicon carbide-on-insulator substrates [9], this is the first report of MOCVD III-nitride device growth on a composite substrate engineered to have a close CTE-match with GaN.

2. Experimental details

The composite substrates are fabricated using wafer bonding and layer transfer techniques [10] and consist of a thin layer of *c*-plane sapphire bonded to a 500 μm thick, 50 mm diameter tape-cast P-AlN substrate. Prior to bonding, a SiO_2 bonding layer is deposited onto the P-AlN substrate by plasma-enhanced chemical vapor deposition (PECVD) using TEOS precursor. The PECVD oxide is densified in nitrogen at 1100 °C to remove hydrogen and is then polished to a sub-nanometer RMS surface roughness and a final thickness of approximately 1 μm. Fifty millimeter diameter, double-side polished (DSP) on-axis ($\pm 0.3^\circ$) *c*-plane sapphire substrates are co-implanted with H and He ions to facilitate layer transfer. The bonding and layer-transfer process is performed in a vacuum wafer bonder, and following transfer the composite substrate is annealed in nitrogen at 1100 °C to stabilize the transferred layer, which is typically about 1 μm thick. A CMP treatment is performed to reduce the surface roughness, after which the substrates are ready for growth.

The InGaN/GaN MQW and LED growths were performed in a Veeco D-125 MOCVD system. The films were grown simultaneously on single-side polished (SSP) and DSP sapphire, and the composite P-AlN/sapphire substrates. No modifications to the standard two-step growth conditions [3] were made for the composite substrates. The MQW test structure consists of a $\sim$2.5 μm thick Si-doped n-type GaN layer grown at 1050 °C followed by a 200 nm 2% InGaN layer grown at 790 °C, and a 5-period InGaN/GaN MQW grown at 770 °C. X-ray diffraction (XRD) analysis of the MQW indicates an InGaN well thickness and indium content of 2.5 nm and 12% indium, respectively, and a GaN barrier thickness of 9.0 nm. The 2% InGaN layer, which was added to enhance the PL intensity from the MQW test structure, is not included in the LED device growth. In addition to the n-type buffer layer and 5-period MQW, the LED structure includes a 30 nm thick $\sim$15% p-AlGaN layer after the MQW and a 200 nm thick p-type GaN contact layer grown at 970 °C. The well thickness and indium content for the LED growth were 2.5 nm and 13%, respectively, and the GaN barrier thickness was 8.3 nm according to XRD.

3. Results and discussion

Structural characterization was performed on the substrate before and after GaN growth. A RHEED image of the starting sapphire template layer is shown in Fig. 1(a).