Growth and characterization of lattice-matched InAlN/GaN Bragg reflectors grown by plasma-assisted molecular beam epitaxy

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We demonstrate six to ten period lattice-matched $In_{0.18}Al_{0.82}N$/GaN distributed Bragg reflectors with peak reflectivity centred around 400 nm, grown by molecular beam epitaxy. Thanks to the well-tuned ternary alloy composition crack-free layers have been obtained as confirmed by both optical and scanning electron microscopy. In addition, cross-sectional analysis by high resolution transmission electron microscopy reveals highly periodic structure with abrupt interfaces. When the number of DBRs periods increased from six to ten, peak reflectivity increased from 45% to 60%. This increase was found to be in reasonable agreement with theoretical simulations.

1 Introduction High quality distributed Bragg reflectors (DBRs), based on nitride-compounds quarterwave layers, have huge potential for near UV - blue - green vertical cavity devices such as vertical cavity surface emitting lasers, resonant cavity light emitting diodes and Fabry-Perot modulators. Though high-reflectivity DBRs based on both AlN/GaN and $Al_xGa_{1-x}N/Al_yGa_{1-y}N$ (for violet-blue-green and near UV applications, respectively) have been already demonstrated the high lattice mismatch between GaN and AlN binaries remains a key problem to grow high quality III-nitride heterostructures. This mismatch results in strain accumulation leading to plastic relaxation which can be detrimental to optoelectronic devices properties. Recent interest has been focused on the growth of high-quality InAlN layers *in-plane* lattice-matched to GaN. So far, state-of-the-art optoelectronic devices using lattice-matched InAlN/GaN heterostructures have been grown by metal organic vapour phase epitaxy (MOVPE) exclusively There have been a few reports of molecular beam epitaxy (MBE) growth of InAlN/GaN heterostructures though their well-controlled growth still remains fundamental challenge.

This work reports on the MBE growth and characterization of InAlN single layers and InAlN/GaN DBRs lattice-matched to GaN.

2 Experiment All samples were grown in a RIBER Compact 21 MBE system equipped with a radio-frequency (RF) plasma N source and standard Knudsen cells for gallium, aluminum and indium. As substrates, GaN templates grown by MOCVD on *c*-plane sapphire were used (Lumilog). The growth temperature was measured using an Ircon Modline 3 optical pyrometer and the growth was *in-situ* monitored by reflection high energy electron diffraction (RHEED). Before the growth of either the InAlN single layers or the DBRs structures, a high-temperature (700 ºC) GaN buffer layer ~ 100 nm thick was grown under intermediate Ga-rich growth conditions to bury possible impurities and to provide a smooth and flat surface

The alloy composition was measured by X-ray diffraction (XRD) scans around (0002) Bragg reflection. The crystal quality of the samples was assessed by JEOL JEM 3010 transmission electron microscopy (TEM) and by XRD rocking curve scans. The DBRs reflectivity was

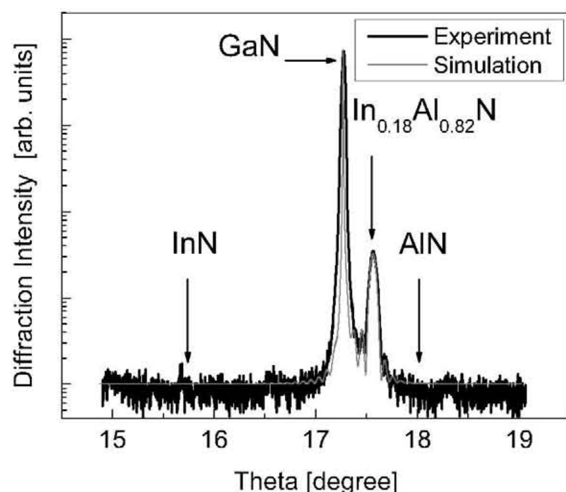

Figure 1 Measured and simulated (0002) θ-2θ XRD spectra of an ~80 nm thick $In_{0.18}Al_{0.82}N$ single layer grown on a MOVPE - grown GaN template.

measured at room temperature at normal incidence using a JASCO V-650 spectrophotometer. Data were normalized using a standard calibrating mirror.

3 Results and discussion As a previous step to achieve lattice-matched InAlN/GaN DBRs, MBE grown single InAlN layers were analysed as function of the growth conditions (i. e. substrate temperature and impinging fluxes) InAlN layers lattice-matched to GaN (18% In) were successfully grown at 535 ºC near the thermodynamical limit for indium droplets formation using a III/V flux ratio slightly lower than one

Figure 1 shows the typical measured and simulated profiles extracted from the (0002) θ-2θ XRD scan of a ~80 nm thick $In_{0.18}Al_{0.82}N$ layer lattice-matched to GaN. Apart from GaN and InAlN (0002) θ-2θ peaks, no additional peaks have been observed confirming that no phase separation occurred during the growth. The full width of half maximum (FWHM) values of rocking curve scans varied within the range of 390 to 420 arcsec indicating a low crystal mosaicity, comparable to that of the underneath GaN template (approximately 300 arcsec).

A sequence of six to ten period lattice-matched $In_{0.18}Al_{0.82}N$/GaN DBRs was designed with a target wavelength centred at 400 nm. Thus, the nominal thicknesses of InAlN/GaN half-periods were set to 43.5 and 40 nm, respectively. To grow the InAlN half-periods we used the same growth conditions as for the InAlN single layers discussed above. The GaN half-periods were grown at the same temperature (535 ºC) close to stoichiometric conditions (Ga/N ~ 1) using indium as surfactant. Due to negligible indium desorption at 535 ºC, it was required to increase the substrate temperature up to 600 ºC for ten minutes after each GaN half-period to allow for desorption of indium droplets formed during the growth of the GaN layers.

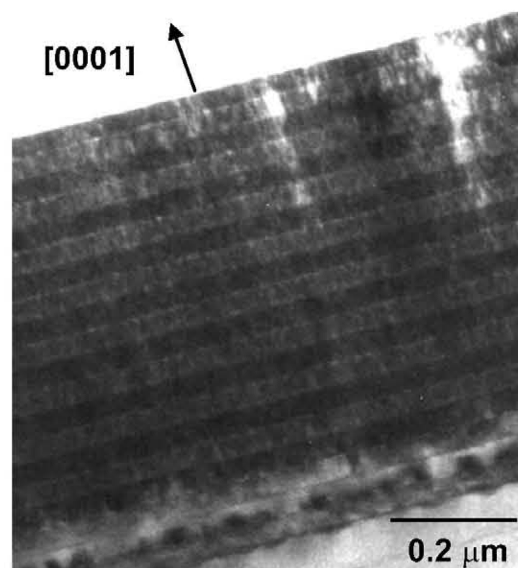

Figure 2 TEM cross-sectional view of a ten period lattice-matched InAlN/GaN DBR. Dark layers are GaN while light ones are InAlN.

During the growth of InAlN half-periods, the RHEED pattern was getting slightly streaky-modulated but recovered within tens of seconds during the GaN half-period growth. Additionally, the RHEED pattern was found to be somewhat dimmer at the end of each period. That was a consequence of a slight accumulation of droplets on the sample surface, as confirmed by optical microscopy. This points to indium droplets acumulation due to excess of indium not fully desorbed after each GaN half-period. No cracks were observed by either optical or scanning electron microscopy on the samples surface. Additionally, cross-sectional TEM images revealed the absence of micro cracks. The bright field TEM micrograph in Fig. 2 reflects the high periodicity of the InAlN/GaN DBR and the abrupt

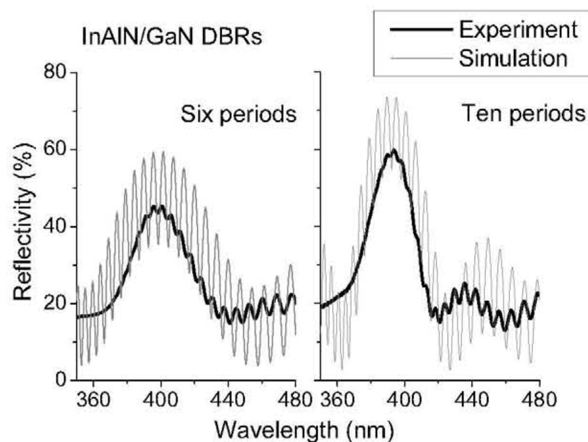

Figure 3 Measured and simulated reflectivity of six- and ten-period $In_{0.18}Al_{0.82}N$/GaN DBRs.

interfaces with no indications of extended phase separated precipitates.

Normalized reflectivity spectra of six and ten period DBRs are summarized in Fig. 3. Experimental data show that when the number of periods increased from six to ten, the peak reflectivity increased from 45% to 60%. The 60% reflectivity is significantly higher than the value reported by Ive et al. found to be around 38% for eleven-period InAlN/GaN DBR centred at 450 nm (also grown by MBE). It was speculated that such low reflectivity was obtained due to residual absorption and/or scattering by In-rich regions on submicroscopic scale. However, 60% reflectivity is still inferior to 76% reflectivity reported by Carlin et al for a ten-period InAlN/GaN DBR centred at 455 nm (grown by MOVPE). Thus we suppose that although residual absorption dramatically decreased when compared to results reported by Ive it is still somewhat present in our grown samples.

To interpret the reflectivity results, a transfer matrix method was applied to simulate the structure. The absorption in DBR layers was neglected and the thick sapphire substrate was assumed to be infinite. We found that simulation data were in best agreement with recorded spectra when refractive indexes of 2.34/2.5 for InAlN/GaN layers respectively were used. However, the refractive index contrast between the two materials is widely reported to be between 7-8% in the violet-blue range which is slightly higher than 6.4% value used in our simulation. This disagreement can also be explained by actual presence of residual absorption supposed to be zero in the simulations.

4 Conclusion In summary, we have demonstrated the growth of both $In_{0.18}Al_{0.82}N$ single layers and $In_{0.18}Al_{0.82}N$/GaN based DBRs lattice-matched to GaN by MBE. $In_{0.18}Al_{0.82}N$ single layers show a crystal mosaicity comparable to that of the underneath GaN template with minimal FWHM values of the (0002) rocking curve scans of 390 arcsec. The $In_{0.18}Al_{0.82}N$/GaN based DBRs show high periodicity and abrupt interfaces. The increase in reflectivity from 45% (6 periods) to 60% (10 periods) is found to be in reasonable agreement with theoretical simulations. However, the total reflectivity of 60% of ten-period lattice-matched DBR is still lower than the expected value ($> 70\%$). The background reason for this finding could be the presence of residual absorption by defects in our samples. Further work is required to confirm the actual origin of this discrepancy.

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