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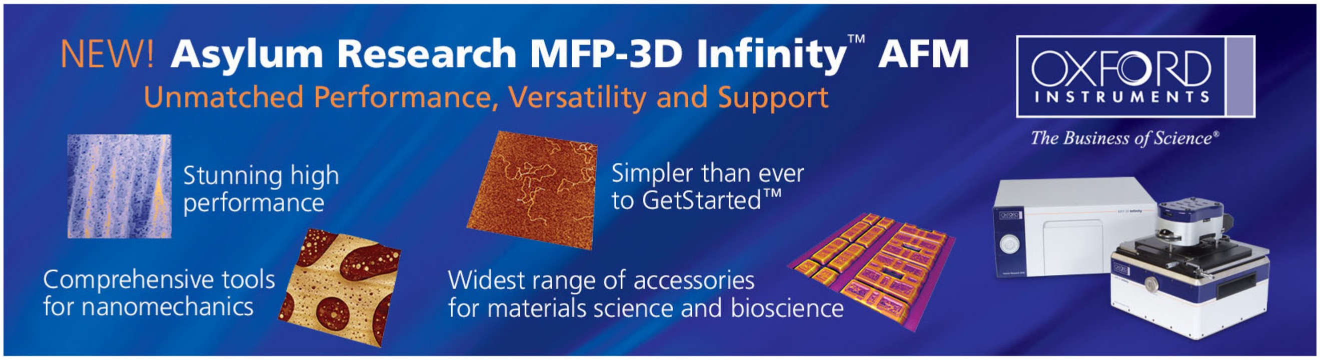

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Crack-free GaN/AlN distributed Bragg reflectors incorporated with GaN/AlN superlattices grown by metalorganic chemical vapor deposition

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A crack-free GaN/AlN distributed Bragg reflector (DBR) incorporated with GaN/AlN superlattice (SL) layers was grown on a *c*-plane sapphire substrate by metalorganic chemical vapor deposition. Three sets of half-wave layers consisting of 5.5 periods of GaN/AlN SL layers and GaN layer were inserted in every five pairs of the 20 pair GaN/AlN DBR structure to suppress the crack generation. The grown GaN/AlN DBRs with SL insertion layers showed no observable cracks in the structure and achieved high peak reflectivity of 97% at 399 nm with a stop band width of 14 nm. Based on the x-ray analysis, the reduction in the in-plane tensile stress in the DBR structure with insertion of SL layers could be responsible for the suppression of crack formation and achievement of high reflectivity. © *2006 American Institute of Physics*. [DOI: 10.1063/1.2172007]

GaN-based vertical cavity surface emitting lasers (VCSELs) have attracted great interest for various optical applications.[1] Highly reflective epitaxial distributed Bragg reflectors (DBRs), such as quarter-wave GaN/AlGaN multilayers, have played an important role in the operation of VCSELs.[2,3] Because of the relatively high contrast of the refractive index between GaN and AlN in comparison to the GaN/AlGaN DBRs, a small number of GaN/AlN DBR pairs is required to achieve a high reflectivity with a broad stop band width. However, the large lattice mismatch between GaN and AlN induces a lot of cracks in the DBR when the number of the epitaxial pairs increases. These cracks tend to grow into V-shaped grooves, which seriously affect the reflectivity of the DBR due to scattering, diffraction and absorption. Therefore, it is necessary to suppress crack generation to achieve a smooth surface and a high reflectivity. Shirasawa and our group have studied and reported a metalorganic chemical vapor deposition (MOCVD) grown GaN/AlN DBRs.[4,5] Ng, Moustakas, and Chu reported a molecular beam epitaxy grown GaN/AlN DBR with a reflectivity of 99%.[3] However, these samples exhibited extensive cracking surfaces. Many research groups have studied and reported the approaches of using GaN/AlGaN or AlN/AlGaN superlattice (SL) insertion layers to reduce the biaxial tensile strain and successfully suppress crack generation while growing high Al-contained structures.[6–10] Nakada *et al.* have reported a MOCVD grown 30-pair GaN/$Al_{0.41}Ga_{0.59}N$ DBR with a reflectivity of 98%. They employed 100 periods of GaN/AlGaN SL insertion layers prior to the growth of the GaN/AlGaN DBRs to decrease the tensile strain in the DBRs.[6] In this letter, we report the growth of the crack-free 20-pair GaN/AlN DBRs with insertion of three sets of 5.5 periods of GaN/AlN SL during the growth and the achievement of high reflectivity with wide stop band width.

The GaN/AlN DBRs were grown in a low pressure EMCORE D75 MOCVD system. (0001)-oriented, 2-in.-diam sapphire substrates were used for the growth of samples. Trimethylgallium and trimethylaluminum were used as group III source materials and ammonia as the group V source material. The growth pressure was kept at 100 Torr. The surface morphology of the DBRs was studied by the optical microscope. The thicknesses of the individual layers in the DBRs were investigated by transmission electronic microscopy (TEM). Measurements on the reciprocal space maps (RSMs) of x-ray diffraction intensity were performed on the Philips X'Pert material research diffraction system around an asymmetrical GaN $(10\bar{1}5)$ Bragg peak. The reflectivity spectrum of the GaN/AlN DBRs was measured by the n & k ultraviolet-visible spectrometer with normal incidence at room temperature.

Figure 1 shows two DBR layer structures grown and examined in this study. The normal DBR structure without the SL layers referred to as the non-SL sample was grown for

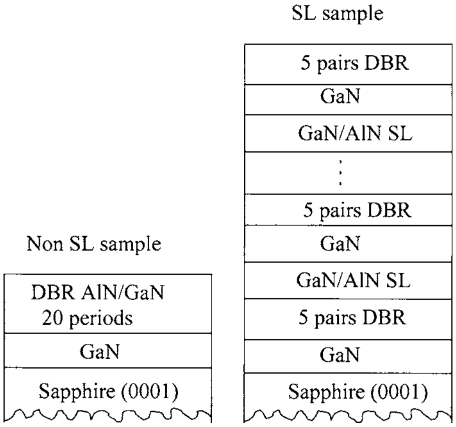

FIG. 1. Structures of the non-SL and SL samples grown and examined in this study. Non-SL sample is the normal 20-pair GaN/AlN DBR and the SL sample has been inserted with three sets of 5.5 periods of GaN/AlN SL in the 20-pair GaN/AlN DBR.

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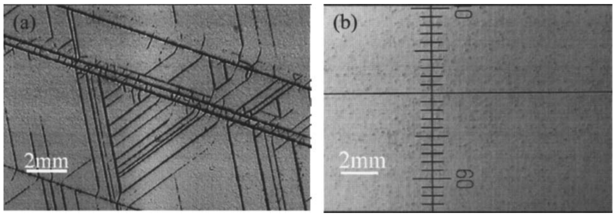

FIG. 2. Plane-view optical microscope images of the 20 periods of GaN/AlN DBRs for (a) non-SL sample and (b) SL sample.

comparisons. The non-SL DBR sample has the following layers: a 30-nm-thick GaN nucleation layer grown at 500 °C, a 2-μm-thick GaN bulk layer grown at 1100 °C, and 20 pairs of quarter-wave GaN/AlN layers grown at 1100 °C. The ambient gas was changed from hydrogen into nitrogen before the DBR layers were grown. For the DBR structure with SL layers, referred to as the SL sample, three sets of a half-wave layer consisting of 5.5 periods of GaN/AlN SL and GaN layer were inserted in every five pairs of the 20-pair GaN/AlN DBR structure, while keeping the other growth conditions the same as the non-SL sample. The center wavelength of these DBRs was designed to be around 400 nm.

Figure 2 shows the optical microscopy image of these two samples. For the non-SL sample, cracks were always observed when the number of DBR pairs is greater than 10 [Fig. 2(a)]. However, the cracks were not observed in our case when the number of DBR pairs is less than 5. As a result, we chose to insert three sets of a half-wave layer consisting of a quarter-wave GaN/AlN SL and a GaN layer in every five pairs of GaN/AlN DBRs in the SL sample. No cracks were observed for the SL sample as shown in Fig. 2(b).

Figure 3 shows cross-sectional TEM images of the SL sample. The lighter layers represent AlN layers while the darker layers represent GaN layers. In Fig. 3(a), no cracks can be observed in the TEM image. However, some V-shaped defects (dark spots) were still observed on the interfaces of GaN or AlN layers in Fig. 3(a). These V-shaped defects have been reported earlier to be due to various origins such as stacking mismatch boundaries and surface undulation.[11] Figure 3(b) shows the cross section of one set of 5.5 pairs of GaN/AlN SL insertion layers. The interface between GaN and AlN is sharp and abrupt. The GaN/AlN SL insertion layers were ended by one more AlN layer to identify the interface changing from the AlN layer to the GaN layer. Here a set of GaN/AlN SL insertion layers can be seen as a digital alloy of an $\mathrm{Al}_x\mathrm{Ga}_{1-x}\mathrm{N}$ layer ($x \sim 0.5$) for a low reflective index quarter-wave layer in the DBR structure because the wavelength of light being reflected was much longer (~400 nm) than the thicknesses of AlN and GaN layers (~3–5 nm) in SL.

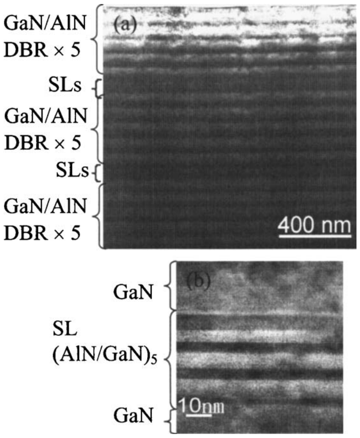

FIG. 3. TEM cross-sectional image of the SL sample for (a) top 17 pairs of DBR structure, and (b) one set of AlN/GaN SL.

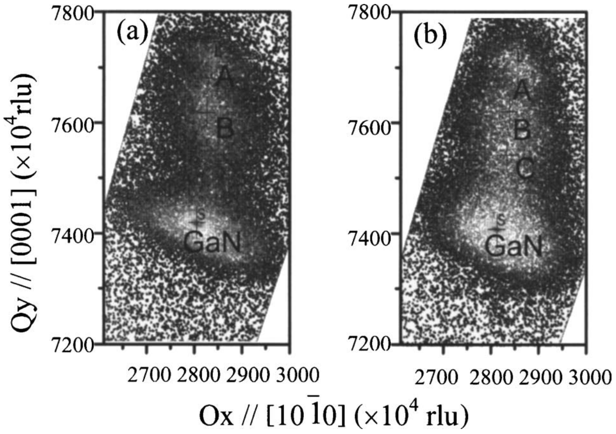

FIG. 4. Reciprocal space maps of (a) non-SL and (b) SL samples.

The effect of the SL insertion layers on the structural characteristics of these DBR samples was investigated based on the asymmetrical RSMs. Figures 4(a) and 4(b) show the $(10\bar{1}5)$ RSMs of the non-SL and SL samples. The perpendicular axis represents the reciprocal lattice c and the parallel axis represents reciprocal lattice a. The growth direction and in-plane strains of the epilayer can be calculated by the distances along two axes from the GaN reciprocal lattice point, respectively. The in-plane strain ε_{xx} for the epitaxial layer grown on GaN layer can be calculated from $q_x^{\mathrm{GaN}}/q_x^{\mathrm{Epi}}-1$, where q_x^{GaN} and q_x^{Epi} are the x positions of the GaN and the epitaxial layer to be determined, respectively. Compared with the RSM patterns of non-SL and SL samples in Figs. 4(a) and 4(b), the diffraction pattern around spots labeled A and B are due to the DBR layers for the high aluminum composition. In Fig. 4(b), the diffraction spot labeled C is due to the SL insertion layers. Both RSM patterns in non-SL and SL samples indicate that the DBR layers are under the tensile strain and the tensile strain is partially relaxed because the diffraction peaks do not align in a vertical straight line. The relaxation could be due to the creation of the misfit dislocation.[11] The biaxial tensile strain in AlN layer relative to GaN layer in non-SL sample is large (about 0.013 in ε_{xx}) thus the accumulation of this stress can lead to generation of cracks. However, the in-plane strain of spot A relative to that of spot C of the SL layers in the SL sample is 0.008, which is much smaller than the tensile strain of spot A (0.013) relative to the GaN bulk layer underlying the DBR layers in the non-SL sample. Based on these data the insertion of the SL layers during the growth of the DBR layers could act as strain buffers between DBRs and the underlying GaN bulk layer because the in-plane lattice constants of the SL layers are close to those of the AlN layers in the DBRs. As a result, the relative tensile stress in the AlN layers in the DBRs is reduced and the crack generation could be suppressed.

Figure 5 shows reflectivity spectra of two samples. They exhibit flattop stop bands, indicating high crystal quality of

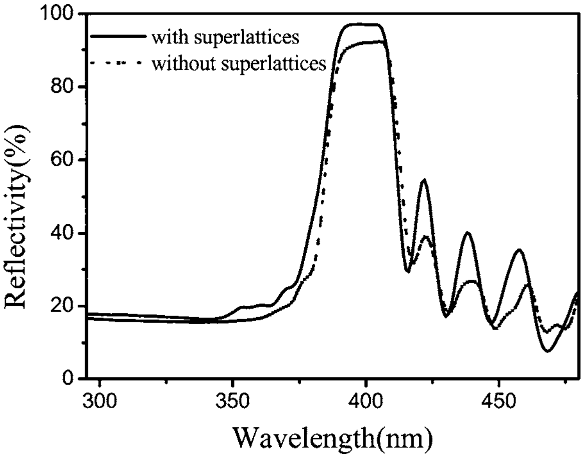

FIG. 5. Reflectivity spectra of 20-pair DBRs of (a) non-SL and (b) SL samples.

the samples. The peak reflectivity of the SL sample at 399 nm is 97%, and the stop band width is 14 nm. However, the peak reflectivity of the non-SL sample at 400 nm is only 92%, and the stop band width is 13 nm. The reduction of the cracks should be an important factor in obtaining a high reflectivity of SL sample.

In conclusion, we have fabricated and characterized a crack-free 20-pair GaN/AlN DBRs with the SL insertion layers. The DBR showed no observable cracks and high reflectivity of 97% compared to the 92% reflectivity of non-SL DBR samples. The stop band width was also increased from 13 to 14 nm. The RSM analysis indicated the reduction in the in-plane tensile stress in the SL sample that could be responsible for the crack suppression and improvement in the reflectivity of the SL DBRs. This technique should be applicable for the fabrication of GaN-based VCSELs requiring high reflectivity and broad stop band width AlN/GaN DBRs.

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