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The waveguide properties are reported for wide bandgap gallium nitride (GaN) structures grown by metal organic vapor phase epitaxy on sapphire using a AlN/GaN short period-superlattice (SPS) buffer layer system. A detailed optical characterization of GaN structures has been performed using the prism coupling technique in order to evaluate its properties and, in particular, the refractive index dispersion and the propagation loss. In order to identify the structural defects in the samples, we performed transmission electron microscopy analysis. The results suggest that AlN/GaN SPS plays a role in acting as a barrier to the propagation of threading dislocations in the active GaN epilayer; above this defective region, the dislocations density is remarkably reduced. The waveguide losses were reduced to a value around 0.65dB/cm at 1.55 μm, corresponding to the best value reported so far for a GaN-based waveguide. © *2011 American Institute of Physics*.
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Wide bandgap group III-V nitride compounds, e.g., gallium nitride (GaN) and its alloys such as AlGaN and InGaN have promising applications in optics, as in the fabrication of light emitting and detection devices.[1] With technology becoming more and more mature, there is a large demand for designing and analyzing optical waveguides to function as a basic building block for integrated optical circuits.[2,3] While optical waveguide technology is somewhat mature, and in certain instances well established in other material systems, there has been very little work done on GaN or its alloys in terms of optical waveguide applications. The development of new photonic devices requires the precise knowledge of optical properties such as refractive index, optical losses, electro-optic constants. The use of a variety of techniques for device characterization has become an integral part of research, consequently facilitating the understanding of material and their performance under diverse operating conditions. In order to improve device performance, high quality microstructures are required for the films involved. Major advances in GaN-based devices can be especially attributed to the progress that has been made in materials research, in particular with the introduction of buffer layers between the epitaxial films and the sapphire substrate.[4,5] Techniques of this type improved the crystallinity and the surface morphology of the grown layers. Since defects always exist in an epilayer and threading dislocations (TDs) at material interfaces, the epitaxial growth of films may be affected by them and, as a result, modify their optical properties.

This work reports a study of microstructure in GaN epilayers deposited on top of an original stack of layers with the aim of improving the waveguide properties. Transmission electron microscopy (TEM), atomic force microscopy (AFM), optical refractive indices [in transverse electric (TE)/transverse magnetic (TM) polarization] and waveguide planar loss measurements were conducted. An attempt to correlate the observed microstructure feature with the optical properties (as refractive index and planar losses) obtained from the prism coupling technique is reported.

AlN/GaN short period-superlattice (SPS) structures are employed in distributed Bragg reflectors (DBRs) which are considered to be a key element in nitride optoelectronic devices such as vertical cavity surface emitting lasers, resonant cavity surface emitting diodes resonant cavity and tunable detectors.[6] This type of an AlN/GaN superlattice also serves as an interlayer in order to compensate for the strain arising between two lattice mismatched layers such as in the case of GaN deposited directly on sapphire or silicon.

The structure used in this work is shown in Fig. 1(a) and was grown by metal-organic vapor phase epitaxy (MOVPE) on c-plane (0001) sapphire substrate. Trimethylaluminium

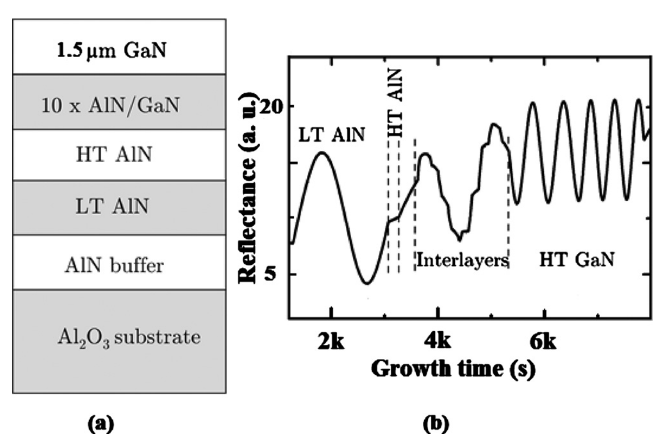

FIG. 1. Schematic depicting the sample structure (a) and *in situ* monitored laser reflectance signal arising from the surface during the growth of the sample (b).

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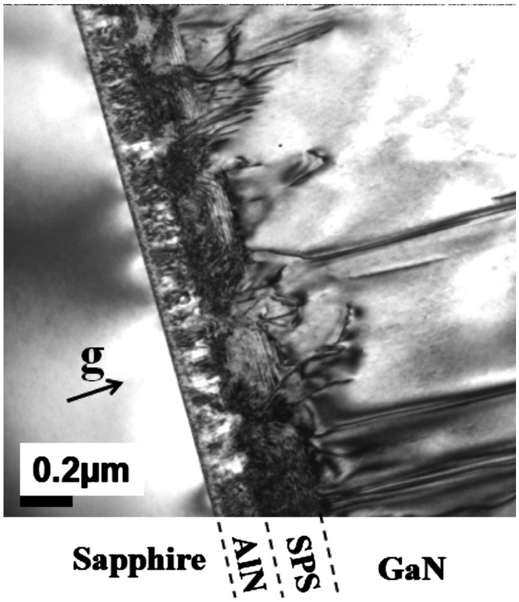

FIG. 2. Weak beam TEM cross-sectional image of the GaN based waveguide sample showing the TDs.

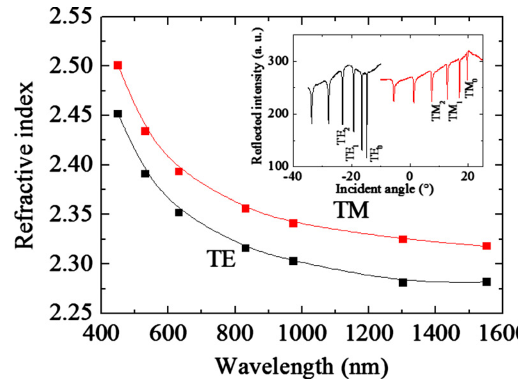

FIG. 3. (Color online) Dispersion of the refractive index in GaN optical waveguide structure deposited on sapphire substrate (for TE and TM polarizations) and guided mode spectrum in inset.

and trimethylgallium were used as aluminum and gallium sources and ammonia was used as nitrogen source. After the cleaning of the substrate at high temperature, a low temperature 150nm thick AlN layer was grown at 950 °C.[7] The temperature was consequently elevated to 1040 °C and the deposition of a 150 nm thick high temperature (HT) layer grown onto plane AlN. Finally, an interlayer consisting of 10× GaN/AlN layers having a total thickness of 200nm were carried out under the same HT conditions and 1.5 μm thick GaN was grown on top of the interlayer. Figure 1(b) presents the *in situ* laser reflectometry interferogram associated with the structure of this type. This interferogram demonstrates a pronounced difference in the growth rate of GaN and AlN during the interlayer growth. It also shows a good quality top GaN layer as indicated by the full recovery of the reflectance signal from the GaN surface.

TEM analysis permitted to probe into the microstructural properties of this sample with a Philips© CM30 microscope operated at 300 kV. Cross-sectional thin foils were prepared by focused ion beam milling technique. Figure 2 is a typical weak-beam cross-sectional micrograph obtained with g =(0002) for the 1.5 μm-GaN sample. Numerous dislocations are generated within the grown layers due to the high stress levels which are present in the structure. The filtering action of the buffer layer can be confirmed: confinement of the dislocations away from the GaN active layer and within the AlN and superlattice layers.[8,9] The micrograph shown in Fig. 2 reveals that this highly defective region, which starts from the top of the substrate, can locally extend to 300 nm within the GaN epilayer (see, for instance, the arrowed regions in this figure). Above this defective region, the TD density is remarkably reduced in the GaN active epilayer as in a reference layer with no SPS. Its average value was estimated to be as low as around 5×10^{8} cm^{-2} [deduced from (0002) and (11$\bar{2}$0) two-beam images]. For a structure deposited on basic AlN buffer layer, the TD's density is found to be 3×10^{9} cm^{-2}. AFM analysis performed on the samples has proved the existence of a very smooth surface and a density of defects in the same order (images not shown here). This is clearly about one order of magnitude lower dislocation density than if no SPS were used.

For studying the effect of the microstructure on the optical properties of the GaN epilayer, we used the guided-wave technique based on prism coupling,[10,11] consisting of a rutile (TiO_2) prism in a Metricon M2010 setup. By measuring the reflected intensity versus the angle of incidence to the normal of the prism α, it is possible to plot the guided-mode spectrum of the sample (inset in Fig. 3). The reflectivity dips observed at certain angles correspond to the excitation and propagation of guided modes in the film structure. These very sharp modes indicate a good film quality of the active GaN epilayer.[12,13] In case of the samples used in this study and with the optical axis normal to the surface, the ordinary and extraordinary modes are excited by using TE and TM polarized light. From the values of the angle α for the two propagation mode, we computed the corresponding effective-mode indices N_m, according to the Eq. (1) where A_p is the apex of the prism (A_p=43.40°) and n_p is the refractive index of the prism.

$$N_m = n_p\,.\,\sin\left\{A_p + \arcsin\left[\sin\left(\frac{\alpha}{n_p}\right)\right]\right\}, \tag{1}$$

We measured refractive indices for six wavelengths, namely, 450, 532, 633, 832, 1302, and 1550 nm with an accuracy of 10^{-3}. The dispersion of TE and TM refractive index is plotted in Fig. 3. Because of its plane wave, TM polarization refractive index values are more sensitive to the layer quality. The refractive index measured at 1.55 μm for the GaN layers were found to be $n_{TE}=2.282\pm0.001$ and $n_{TM}=2.318\pm0.001$, which is quite close to values reported in literature.[2,14,15] An approach using similar SPS system was studied by Schenk *et al.*[13] for GaN waveguides on Si with close values for indices. The introduction of an optimized AlN/GaN SPS does not influence the index value of the structure.

The role played by the TDs in the degradation of the optical characteristics of epitaxial GaN layers has already been reported by Natali *et al.*[16] about an AlN thin film grown on Si. In particular, it was shown that the impact of these dislocations on the measured refractive indices increased together with the TDs density and remained negligible as long as this density is lower than almost 10^{9} cm^{-2}. We presume that a similar description can be applied to GaN.

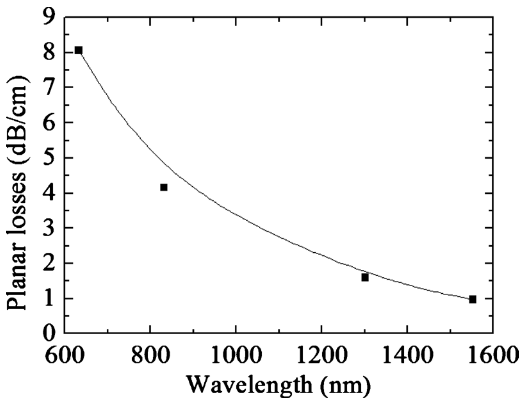

FIG. 4. Evolution of the propagation losses in GaN planar waveguide structure as a function of wavelength (TE polarization).

During the operation of waveguides, the optical losses of light injected into the waveguide are also a critical parameter.[17] The smaller the losses in the GaN structure, the better the performance of the waveguide device in transmitting light. By injecting light through a prism with the Metricon setup, we measured the propagating wave intensity in the GaN layer wherein we excite the fundamental effective guided mode in this layer. The accuracy is ± 0.1 dB/cm. Figure 4 presents the evolution of the optical losses in volume versus wavelength for TE polarization: we have obtained a value of 0.65 dB/cm at 1.55 μm, which is very low for such a planar structure. If a relation between refractive index and the dislocation density can be highlighted, we can maybe extend it to planar optical loss. In comparison, we have measured the optical loss into a basic GaN waveguide deposited onto a classical AlN nucleation layer. The loss is close to 4 dB/cm at 1.55 μm, clearly showing the advantage of such an optimized SPS structure. As a reference, Geiss *et al.*[18] conducted planar loss measurements in a freestanding GaN waveguide and they reported an absorption loss coefficient of 0.82 dB/cm for the same condition. Our structure, presenting refractive index in the same order to literature, reduces the optical loss in volume close to freestanding values. This exhibits the use of an SPS enables to get the best propagating properties with a thin film. Thus, this kind of a GaN based structure with low optical loss values will be highly beneficial in fabricating low-loss structure for photonic and optoelectronic applications.

In summary, GaN planar waveguides grown on (0001) sapphire by MOVPE were studied using an AlN/GaN SPS system. Both the microstructure and optical properties of these structures were studied using TEM and guided wave prism coupling technique. The study allowed the establishment of a correlation between the TDs density and the optical properties. The index dispersion and the optical propagation losses of the materials have been fully characterized and a reduction in the optical planar loss values has been observed by using such an AlN/GaN SPS (α=0.65 dB/cm at 1.55 μm).

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