

Crack-Free Thick GaN Layers on Silicon (111) by Metalorganic Vapor Phase Epitaxy

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The tensile strain in GaN epitaxial layers grown on silicon (111) substrates by metalorganic vapor phase epitaxy was investigated. Thick (0.9–2.5 μm) GaN layers without any crack were deposited on Si(111) using AlN/GaN superlattices as templates. X-ray diffraction and photoluminescence measurements were used to determine the effect of these AlN/GaN superlattices on the strain in the subsequent GaN layer. Evolution of strain as a function of the GaN layer thickness is also determined. Dislocation reduction (from 10^{10} to $2.5 \times 10^9 \text{ cm}^{-2}$) is observed by transmission electron microscopy and atomic force microscopy when such superlattices are used. Strong band edge photoluminescence of GaN on Si(111) was observed, with full width at half maximum of the I_2 line as low as 6 meV at 10 K. The 500 arcsec linewidth on the (002) X-ray rocking curve attests the high crystalline quality of GaN on Si(111), when AlN/GaN superlattices are used.

The growth of nitrides on silicon is of great interest because of the numerous advantages of this substrate: low cost, large scale availability with high quality, good thermal and electrical conductivities, and possible removing by chemical etching. The first nitride devices fabricated on silicon such as light emitting diodes [1–3] and high electron mobility transistors [4], have demonstrated the great possibilities offered by this substrate. The performance of these devices depend on their thicknesses and on the density of defects and impurities in the material. The large lattice mismatch and the difference in thermal expansion coefficients between GaN and silicon lead to the formation of cracks when the thickness of the deposited layer exceeds a critical value (depending on the process used). The highest crack-free thicknesses reported for GaN layer grown on silicon is 3 μm using molecular beam epitaxy [4, 5]. But, due in part to the ~ 300 K higher growth temperature, the thickest crack-free GaN layers deposited using metalorganic vapor phase epitaxy (MOVPE) are only 1.4 μm (on a SiC buffer layer) up to now [6]. In this paper, we show that using AlN/GaN superlattices, the critical thickness for appearance of cracks in GaN layers grown on Si(111) by MOVPE can be increased to 2.5 μm , giving the opportunity to grow thicker device structures with better material quality.

Our study of strain in GaN layers grown on Si(111) is based on structures composed of an AlN intermediate layer (buffer) followed by a 0.9 μm thick GaN. As seen in the inset of Fig. 1, we have inserted between the AlN and the thick GaN layers, several AlN/GaN superlattices separated from each others by a thin (200 nm) GaN layer. The introduction of such superlattices aims at creating an additional compressive stress, in

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order to counterbalance the tensile strain present in nitrides deposited on silicon. All measurements presented in this paper were performed on uncracked samples.

Trimethyl-gallium and trimethyl-aluminium were used as precursors for GaN and AlN, and NH_3 was the nitrogen source. Growth was achieved in a home-made vertical reactor operating at low pressure (300 mbar). Our process starts with a desoxidation of the substrate surface under an H_2 flow at high temperature (1120°C), then an AlN (~ 40 nm) buffer layer is deposited on silicon before any deposition of GaN, since GaN does not nucleate on Si(111). The AlN buffer thickness must be sufficient to prevent diffusion of Si from the substrate to the GaN layer, but we have observed an increase of the tensile strain in the following GaN layer with the thickness of this AlN buffer. A deposition of about $0.2\text{ }\mu\text{m}$ of GaN follows the AlN buffer, before starting the growth of the first ten-period superlattice. The typical temperature used for the growth of GaN and AlN on silicon is 1060°C . Optimization of the AlN and GaN thicknesses in the superlattices has shown that layers as thin as 3 and 4 nm for the AlN and the GaN, respectively (see Fig. 1), increase the compressive effect of the superlattice.

Figure 1 shows a cross-sectional transmission electronic microscopy (TEM) image of a ten-period AlN/GaN superlattice (which was inserted in a sample to minimize the tensile strain in the upper GaN layer). It can be noticed that superlattices seem also to act as filters for threading dislocations, by bending some of them. Atomic force microscopy (AFM) has been used to characterize the surface morphology of the samples and the threading dislocation density. The roughness of the GaN layer is considerably improved by the use of superlattices. The roughness measured on a $10 \times 10\text{ }\mu\text{m}^2$ scan is only 0.6 nm, which is comparable to those obtained for GaN on sapphire. An AFM study of samples with and without superlattices shows a decrease of the dislocations density with the succession of superlattices ($\sim 1.5 \times 10^{10}\text{ cm}^{-2}$ for sample without any superlattices). We have found a dislocation density of $2.5 \times 10^9\text{ cm}^{-2}$ for our best uncracked sample (with four superlattices).

As the energy of the free exciton associated to the Γ_9 valence band (E_A) varies linearly with the in-plane biaxial strain [7, 8], optical studies are an easy method for strain monitoring in GaN layers grown on silicon. Figure 2 shows typical temperature depen-

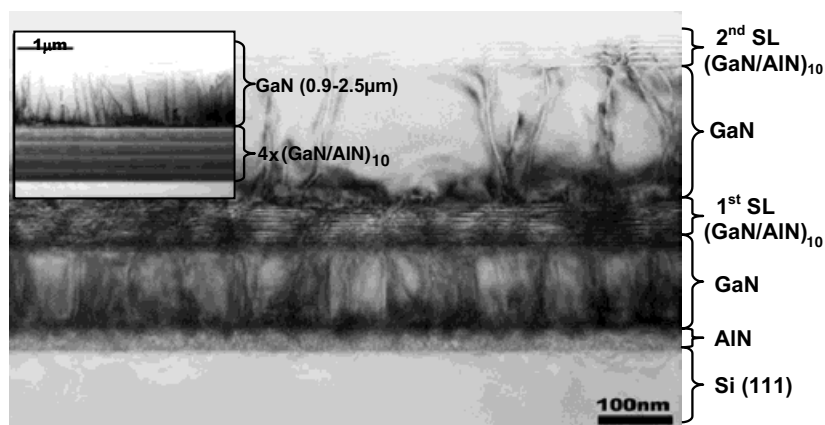


Fig. 1. Cross-sectional transmission electron microscopy image of a ten-period AlN/GaN superlattice

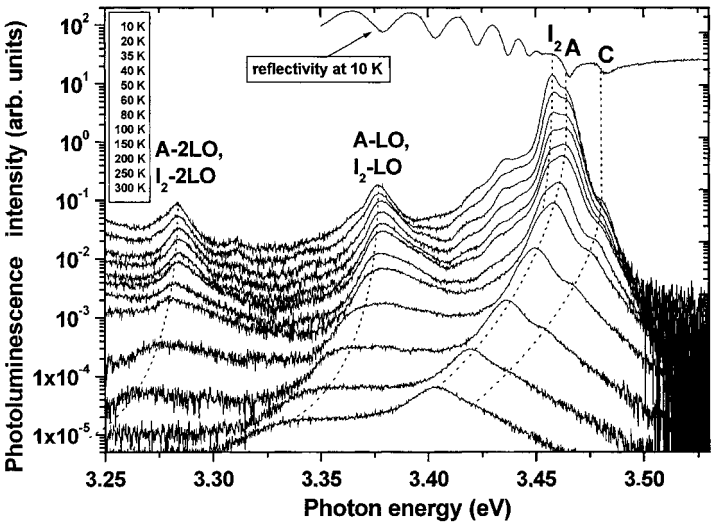


Fig. 2. Typical temperature dependent PL spectra together with the reflectivity spectrum at 10 K of a 2.5 μm thick GaN layer grown on Si(111)

dent photoluminescence spectra, together with the reflectivity spectrum at 10 K of a 2.5 μm thick GaN layer on Si(111). The linewidth of the GaN exciton recombination peak at 3.403 eV of the room temperature spectrum is 33 meV, similar to that of GaN on sapphire. We observe an A band gap increase of 62 meV when cooling from 300 to 10 K, which is significantly smaller than that for GaN on sapphire (typically 70 meV).

The low temperature spectra are dominated by neutral donor bound exciton recombinations (I_2) line centered at 3.459 eV with a full width at half maximum (FWHM) of 6 meV. The larger FWHM of the I_2 line of GaN on Si(111) than on sapphire is attributed to larger strain inhomogeneity in the epilayer, due to the large dislocations density. The C free exciton recombination and phonon replica of the exciton lines are also recorded.

Figure 3 demonstrates the effect of the superlattices on the strain

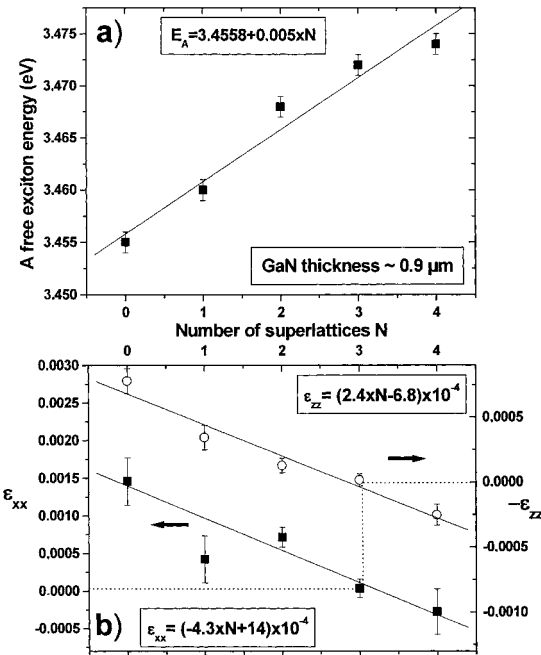


Fig. 3. a) Free exciton energy vs. number of superlattices. b) In-plane and on-axis strains of GaN layer vs. the number of superlattices

measured in the final GaN layer (with a constant thickness of 0.9 μm). For a sample without any superlattice, the energy of the free A exciton determined by photoluminescence and reflectivity at 10 K is 3.455 eV which corresponds to typical values reported for GaN on Si(111) without any cracks [5, 9] (Fig. 3a). The position of the free exciton of the thick GaN layer increases approximately linearly with the number of superlattices inserted between this layer and the substrate. With four superlattices (separated by 200 nm thick GaN layers), a 0.9 μm thick layer of GaN on silicon is nearly totally relaxed ($E_A = 3.474$ eV). The band gap versus strain relation $\partial E_A / \partial \epsilon_{xx} \approx -9$ eV [7, 8] gives a compressive biaxial stress of 230 MPa obtained with the insertion of each superlattice. Using a structure with four superlattices, we have been able to grow up to 2.5 μm thick GaN on silicon without any cracks (the total thickness deposited on Si(111) is 3.8 μm including the superlattices).

The determination of the a and c crystal parameters using X-ray rocking curve measurements on some ($h0l$) symmetric and asymmetric reflections confirms the evolution of strain with the number of superlattices determined by PL and reflectivity. The in-plane and the on-axis strains of the GaN layer versus the number of superlattices used in the structure are reported in Fig. 3b. Both strains decrease linearly with the number of superlattices, and an additional in-plane compressive stress of 215 MPa is achieved with the introduction of each superlattice.

As seen in Fig. 4, the in-plane and on-axis strains in the GaN layer depend directly on the sample thickness. The energy of the A free exciton versus the thickness of the GaN layer (deposited on one or four superlattices) is plotted in Fig. 4a. On one superlattice, the free exciton energy of the upper GaN layer varies linearly from 3.473 eV for a 250 nm thick GaN layer to 3.463 eV for a 1.3 μm thick GaN layer. With one superlattice, cracks appear in the layers with thicknesses superior to 1.3 μm . For GaN thicknesses in the 1–2.5 μm range, crack formation occurs for an in-plane stress exceeding 800 MPa.

Using four superlattices, the variation of E_A with the thickness is similar for the first 1.5 μm , but the increase of stress seems to be slower for higher thicknesses. However, E_A decreases from 3.474 eV for a 0.9 μm thick layer to 3.465 eV for a 2.5 μm thick layer, which corresponds to a 440 MPa increase of the tensile stress. These measurements indicate that the

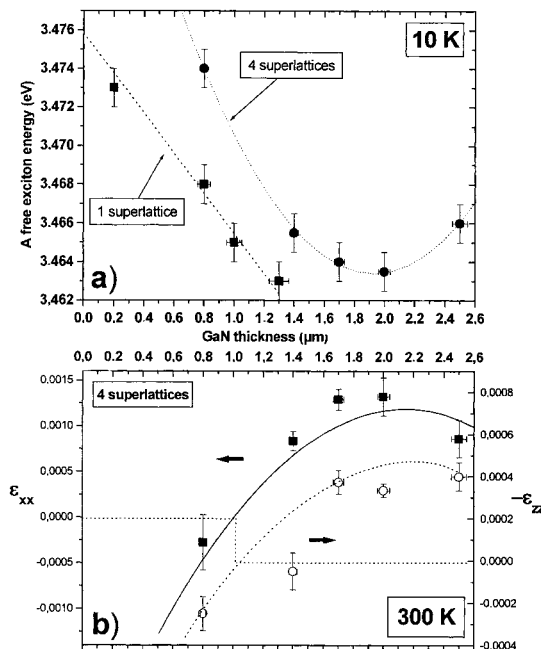


Fig. 4. a) Energy of the A free exciton vs. thickness of GaN layer, deposited on one and four superlattices. b) In-plane and on-axis strains vs. GaN layer thickness for four superlattices

compressive strain in GaN induced by the superlattices is compensated progressively during the growth of GaN as the thickness increases.

X-ray measurements (Fig. 4b) on the same samples (with four superlattices) show that an increasing of the thickness of GaN from 0.9 μm to 2.5 μm results in a biaxial tensile stress increase as high as 470 MPa. The evolution of strain measured on these layers is the same as that observed with PL and reflectivity. For a 2.5 μm GaN layer, we have measured a FWHM of the X-ray rocking curve of 500 arcsec which is the narrowest value ever reported for GaN on silicon. This value is partially due to the high curvature of the sample ($\sim 1 \text{ m}^{-1}$) and is characteristic of the high crystalline GaN quality on Si(111), even though it is still higher than that obtained for GaN on sapphire (~ 350 arcsec) grown in the same reactor.

In conclusion, high quality GaN layers on silicon have been grown by EPVOM using the insertion of AlN/GaN superlattices. These superlattices can efficiently counteract the tensile stress usually observed in GaN layers deposited on Si(111), and improve as well the crystalline quality. Our process enables the growth of thick GaN layers on silicon without any crack. Relaxed GaN layers have been obtained on Si(111). The variation of stress in the GaN layers deposited on silicon was investigated over a large range of thicknesses. The gradient of strain seems to be larger in the first micrometer of the layers.

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