Growth of buffer structures for AlGaN/GaN HEMT on Silicon Substrates

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Abstract

GaN buffers were deposited on (111)−oriented silicon (Si) by AIXTRON metal organic vapour phase epitaxy (MOVPE) reactors using a buffer structure of low temperature (LT) AlN layers and high temperature (HT) layer stacks, consisting of AlN, AlGaN and GaN. Structures with two− and three−fold LT/HT layer combinations were investigated. The films were characterized by atomic force microscopy (AFM) (minimum root mean square roughness (rms) = 0.4 nm), high resolution X−ray diffraction (HRXRD), LT photoluminescence (PL) measurements (minimum FWHM = 10 meV) and circular transmission line measurements (CTLM) (R_{sheet} = 0.8 − 1 M Ohm/sq). The GaN buffers were used for the subsequent deposition of AlGaN/GaN modulation−doped and undoped high electron mobility transistors (HEMT). Room temperature (RT) mobilities of up to 1170 cm^2/Vs and sheet carrier concentrations of up to $1.26 \cdot 10^{13} cm^{-2}$ were measured. Round−HEMT devices (unpassivated, gate length 1 µm, gate width 150 µm) showed a maximum transconductance of 148 mS/mm at U_{DS} = 4 V and a maximum current of 439 mA/mm at U_{GS} = 1 V.

Introduction

The GaN−based material system and its devices have gained much attention for electronic applications due to their outstanding electrical properties such as high breakdown voltages, high peak electron velocities and high sheet electron concentrations, especially in two−dimensional electron gas structures. A current focus of device research are AlGaN/GaN high electron mobility transistors (HEMT). Due to their high impedance levels as well as their resistance against elevated ambient temperatures, AlGaN/GaN HEMT are very promising candidates for RF power applications like plasma generation, microwave heating, phased−array radars and mobile communications. However, especially for applications in high−volume low−cost market segments, the choice of substrate is still an open question. Due to the lack of suited homosubstrates, sapphire and silicon carbide (SiC) are commonly used for commercial applications. Because of disadvantages like the high substrate price of SiC, the low thermal conductivity of sapphire and difficulties in substrate handling like etching, alternative substrates are required. The low cost, the large−area availability, the high thermal conductivity, the mature processing technology, the possibility to integrate GaN−based high−power electronics with Si−based logical circuits and the excellent quality render Si the substrate of choice especially for the epitaxy of GaN.

However, the main challenge for the growth of GaN on Si is to accomplish the large mismatch in lattice constants (−16.9%), which leads to dislocations, and the mismatch in the thermal expansion coefficients (~ 57%) between GaN and Si, which causes tensile strain especially during the cooling−down phase resulting in cracks in the nitride layers. Additionally, the Si surface must be protected from nitridation. The reaction of nitrogen with Si and the poor nucleation of GaN on the Si surface result in a migration of Si to the surface of the GaN layers subsequently deposited at higher temperatures [1, 2]. The most established method to prevent the nitridation is starting the growth process with AlN. This leads to the best results and is used by many researchers [3 − 5]. One further advantage of AlN is that it can be grown in the same conventional reactor. In this work, GaN was deposited on Si using a two− and three−fold LT/HT layer combination, and the resulting GaN buffer layers were investigated in terms of their electrical, optical and structural properties. The LT and HT layers were used to grow GaN on Si of a crystalline quality comparable to that of GaN layers deposited on sapphire and SiC. The LT AlN layers are essential for strain reduction and defect blocking from the underlying AlN and GaN layers due to the LT nucleation of the AlN. The HT layers are composed of AlN, AlGaN and GaN and create a crossover of thermal expansion coefficients from Si to GaN because the thermal expansion coefficient of AlN is between those of Si and GaN. One additional advantage of AlN both as LT and HT layer is its insulating character, which is useful to prevent parallel current through the layer structure in the Si substrate. The AlGaN layers cause a compressive strain in the following GaN layers, which lowers the tensile strain in the GaN layers resulting from the Si substrate during the cooling down phase. On the GaN buffers with a three−fold HT/LT layer combination, AlGaN/GaN modulation−doped and undoped HEMT were deposited. The deposition of all samples was monitored by reflectance spectroscopy.

Experimental

All samples were grown in AIXTRON MOVPE reactors at low pressures (200 hPa and 50 hPa) on 2−inch (111)−oriented Si substrates. Trimethylgallium (TMGa), Trimethylaluminium (TMAl), ammonia (NH3) and silane (SiH4) were used as precursors and H_2 and N_2 as carrier gases. Prior to the growth process, the substrates were cleaned by an etch process consisting of two steps. First, the substrate was etched with a solution of H_2O, H_2O_2 and H_2SO_4 (3:1:1) for two minutes to remove organic contaminations and to oxidize the surface homogeneously. In the following second step, the created thin oxide layer was removed by HF (2%). After rinsing with deionized water, these two steps were repeated. The cleaning process was finished by drying with N_2 and loading the substrate into the reactor.

As mentioned before, starting the epitaxial process with AlN leads to the best growth results. In this work, a thin AlN film deposited at 720°C preceded the growth of the layer structure on the Si wafer. On this nucleation layer, 100 nm thick HT AlN was grown followed by HT AlGaN and GaN layers. The AlGaN layers were grown with decreasing Al content starting at 30%. The HT layers were followed by a second LT AlN nucleation layer. In this way, structures were grown consisting of two and three LT and HT layer stacks before the final GaN layer of the buffer structure was deposited, with the intention to get a highly resistive GaN buffer layer. The second and (if present) third LT AlN layers were grown at 635°C based on previous works [3]. The HT layer stacks were grown at temperatures which are typical for HT layer growth of GaN on sapphire. The thicknesses of the AlGaN layers in the structure with the three−fold combination were 150 nm in all stacks. In the last HT layer stack, no HT AlN was used. The top GaN layer exhibits a thickness of 800 nm. The samples grown with a double HT/LT layer sequence were grown with 150 nm for the first AlGaN layer and 450 nm for the second. In this case, the top GaN layer offers a thickness of 1.6 µm.

Results and Discussion

As mentioned before, all growth processes were monitored by in−situ reflectivity measurements. In figure 1, the reflectivity at 800 nm and the reactor temperature taken during a growth process of a structure with a double LT/HT layer sequence are shown as functions of growth time. In this graph, the growth of the two HT layer stacks can be observed precisely by their oscillations. The oscillations attributed to the first GaN layer show increasing amplitudes. This layer was finished by a LT AlN layer before saturation in the oscillations was achieved. This indicates that the GaN film is not fully coalesced retaining an elastic character of the first HT layer stack. The oscillations of the second GaN layer show a saturated character indicating fully coalesced films.

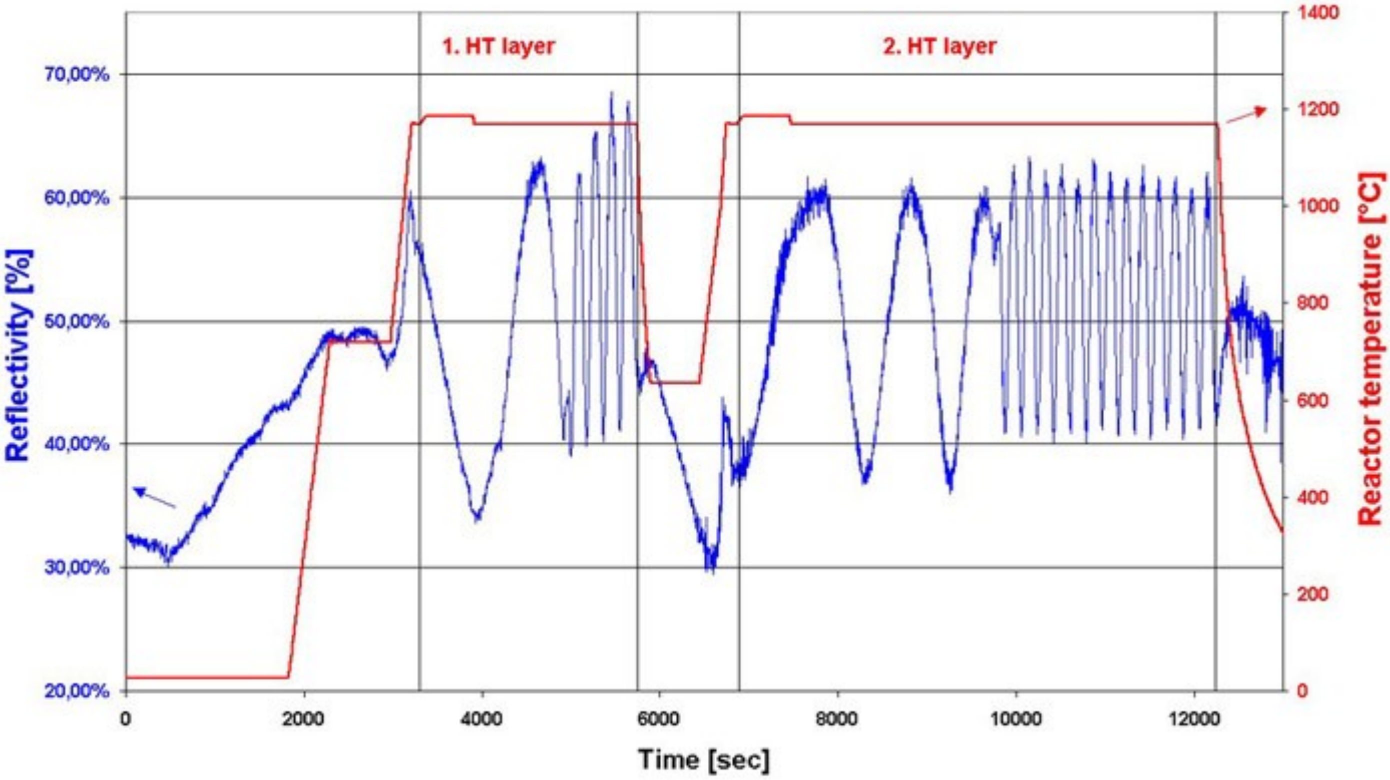

Figure 1: Reflectance measurement taken during the growth process at a wavelength of 800 nm. The two HT layer stacks can be observed by their oscillations.

The layers were investigated by AFM, CTLM, RT and LT PL and HRXRD. The AFM images showed no perceivable defects. The rms roughness of a 2 x 2 µm^2 scan area was obtained to 0.4 nm for the structure with three−fold layer sequence and 0.7 nm for the double layer sequence. The grown structures were free of cracks. One GaN buffer layer was grown on a low resistive Si substrate (specific resistance < 0.01 Ohm cm). By measuring the resistivity of the epitaxial layer, the insulating properties of the buffer structure against the conductive Si substrate can be investigated. The GaN buffer layers on low resistive Si substrates have shown a sheet resistance of 0.8 to 1 M Ohm/sq by CTLM. These results prove the insulating properties of the buffer structure and the GaN buffer layer on top, which is important in electronic devices to prevent parallel current in the buffer layers. The PL measurements of the GaN buffer layer on Si result in a full width at half maximum (FWHM) of 10 meV and 14 meV at 77 K and 18 K, respectively, which is similar to [5] and even better than [4]. In the first reference, an additional SiN interlayer for defect reduction was used. In the second reference, selective area growth for crack reduction was utilized. The samples showed a band edge emission at 358 nm at 18 K. The band edge emission of a 4 µm thick GaN buffer layer on sapphire was determined under the same conditions to 356 nm. The red shift of the GaN buffer layer on Si is caused by the fact that the GaN film on sapphire is slightly biaxially compressed whereas the layer on Si is relaxed or slightly biaxially expanded resulting from the different thermal expansion coefficients of GaN, sapphire and Si [6]. The samples showed a very low yellow band emission which suggests a comparably low defect density in these samples and the low intensity of donator−acceptor pair emissions demonstrate the high quality of the GaN films. HRXRD (Philips X'Pert MRD) was employed to examine the structural properties of the buffer structures. The (0002) reflection was measured in three configurations: with an open detector, with a 1 mm anti−scatter slit and in triple−axis geometry. The appearance of all peaks, even in the triple−axis geometry, the low FWHM of the GaN peak (with 1 mm anti−scatter slit) of 292 arcsec and 360 arcsec for the two−fold and three−fold structures, respectively. The sturcture with the two−fold LT/HT layer sequence exhibits a fine modulation of the AlGaN peaks indicating on the good structural properties of this sample.

A comparison of the peak heights in the three different configurations can be taken as a rough measure of the crystalline quality of each material including the defect density. The relative difference of the peak intensities is smallest for the GaN peak which proves the good quality of this material. Relatively, AlN has the lowest structural quality and the highest defect density which is naturally connected with its application in LT nucleation and HT lattice constant transition layers.
The GaN buffers grown with a three−fold LT/HT layer sequence were used for the subsequent deposition of AlGaN/GaN HEMT. For a scan area of 5 x 5 μm^2, the HEMT samples showed an AFM roughness of 0.9 nm to 1.8 nm. Compared to the roughness of the GaN buffer layers this roughness is more than twice as high and results from the high Al content in the uppermost AlGaN layer. The structures showed RT mobilities of μ = 1170 cm^2/Vs and 994 cm^2/Vs with sheet carrier concentrations of $n_S = 8.86 \times 10^{12}$ cm^{-2} and $n_S = 1.26 \times 10^{13}$ cm^{-2}, respectively. Round−HEMT technology was used for fast characterization. The unpassivated devices have a gate length of 1 µm and a gate width of 150 µm. The ohmic contacts were prepared by evaporating Ti/Al/Ni/Au layers and annealing at 900 °C for 10 s. The best specific contact resistance was measured to 3.8 x 10^{-6} Ohm cm^2. The Schottky contacts consist of Ni layers covered by Au. The HEMT show a maximum transconductance of 148 mS/mm at U_{DS} = 4 V and a maximum current of 439 mA/mm at U_{GS} = 1 V. I−V−characteristics up to U_{DS} = 70 V were taken. Maximum breakdown voltages of U_{DS} > 100 V were measured.

Conclusion and Outlook

Highly resistive and crack−free GaN buffer layers (R_{sheet} = 0.8 – 1 M Ohm/sq) on Si(111) using a two− and three−fold LT/HT layer sequence were presented. The capability of these films as buffers for the subsequent deposition of AlGaN/GaN HEMT was demonstrated. The HEMTs exhibit good properties in terms of sheet resistance, surface roughness and DC/RF data. Taking substrate quality, price and availability into consideration, Si is the substrate of choice for certain applications. To enhance the crystalline quality and to reduce the strain in the grown films, the influence of the growth rate needs to be further addressed.

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