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GaN/AlGaN Two-Dimensional Electron Gas Grown by Ammonia-MBE on MOCVD GaN Template

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The growth of high quality GaN/AlGaN two-dimensional electron gas on MOCVD GaN template substrates by ammonia-MBE is reported. The homoepitaxial growth required a significantly lower growth temperature than that needed for growth on SiC or sapphire substrates, and yielded significantly improved surface smoothness, and consequently improved electrical characteristics of the two-dimensional electron gas. A low temperature Hall mobility of 14300 $cm^2/V\,s$ and quantum mobility of 2000 $cm^2/V\,s$ were obtained, representing the highest values observed in the GaN/AlGaN structures grown by the ammonia-MBE technique. A correlation between the surface roughness and increased Hall mobility to quantum mobility ratio was observed, suggesting that the surface roughness could be a source of small-angle scattering in these structures.

Introduction The quality of GaN materials and devices grown with the ammonia-molecular-beam epitaxy (ammonia-MBE) and plasma-assisted MBE techniques has seen continued improvement over the past few years. For example, the GaN bulk films and GaN/AlGaN two-dimensional electron gas (2DEG) grown by MBE have shown transport mobilities comparable to the best results from the metal–organic chemical vapour deposition (MOCVD) technique [1–5]. In fact, the MBE technique has demonstrated effectiveness and advantages for growth of GaN/AlGaN heterostructure field-effect transistors (HFETs) in terms of device performance and reproducibility [6–8]. However, in the case of ammonia-MBE, the direct growth on sapphire or SiC substrates via an AlN buffer layer generally yields films with significant surface roughness with RMS values in the order of 10 nm or more. This may be partly due to the high growth temperature regime (around 900 °C) employed in order to achieve large grain size and low defect density. Though the rough surface morphology apparently has little effect on the transport mobilities, which can be high even for quite rough GaN/AlGaN 2DEG samples, it could have adverse impact on other figure-of-merit parameters such as the quantum mobility and the quality of the Schottky barrier. In contrast, the MOCVD grown GaN layers typically exhibit an atomically smooth surface with generally quite large grain size, thus providing a desirable template for homoepitaxy by MBE. In this work, the growth by ammonia-MBE on such MOCVD GaN templates has been investigated with the aim of improved surface and interface smoothness and electrical characteristics of the GaN/AlGaN 2DEG.

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Experimental The MOCVD GaN/sapphire template layers were undoped with background electron concentrations in the range of 10^{16} to 10^{17} cm^{-3}. The template substrates were degreased in boiling chloroform, dipped in H_2O : HF (10 : 1) solution for one minute, rinsed in deionised water for 10 min, and dried with nitrogen. The MBE system was the SVTA N35S nitride growth system. The substrate temperature was ramped at 10 °C/min to the set growth temperature under a 50 sccm flow of ammonia. Different growth temperatures were studied with respect to the influence on the growth results. The surface condition of the substrate template layer and the growing layer was monitored using a 10 KV RHEED gun. The GaN/AlGaN 2DEG structure was grown with 200 nm undoped GaN followed by 30 nm AlGaN. The ammonia flow rate was kept at 50 sccm throughout the growth. The Al concentration in the AlGaN layer was about 7% as estimated from the respective growth rates of Al and Ga components. The surface morphology of the GaN/AlGaN 2DEGs was imaged using an atomic force microscope operating in a tapping mode. The electrical characteristics were studied by low temperature Hall and magnetoresistance measurements in fields up to 8 T.

Results and Discussion The starting surface of the MOCVD GaN template layers invariably showed intense and streaky RHEED patterns at ambient temperature, indicating smooth surface and high crystalline quality of the MOCVD grown material. The strong and streaky pattern was maintained up to certain temperature when the substrate temperature was ramped up under 50 sccm ammonia. At the typical growth temperature of 900 °C, however, the streaky RHEED pattern turned spotty and weaker even before the MBE growth could occur. The surface roughening was apparently due to the thermal decomposition of the GaN layer at this temperature. The successive MBE growth could not restore the streakiness nor the intensity of the RHEED pattern. The AFM image of the resulting GaN/AlGaN structure showed an RMS roughness of 12 nm and quite small grain size, as illustrated in Fig. 1a.

However, when a lower growth temperature of 800 °C was used, no surface roughening of the template layer was observed, and the streaky, intense RHEED pattern was maintained throughout the MBE growth. This indicates that there was no significant thermal decomposition at this lower growth temperature, yet the crystalline order was

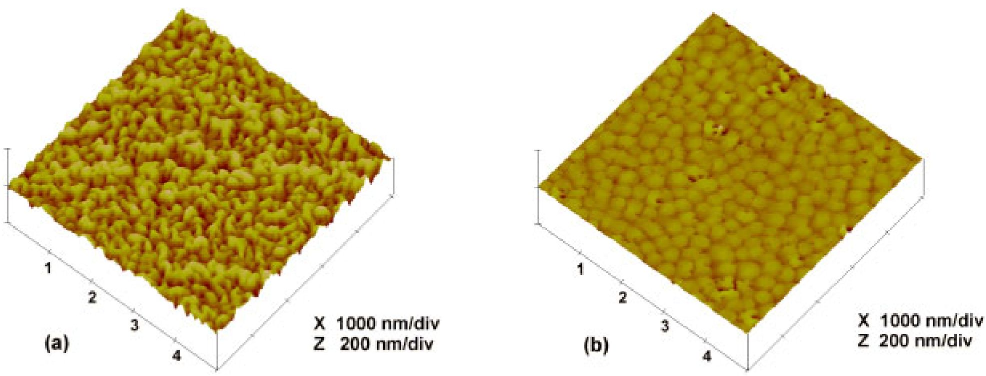

Fig. 1 (online colour). AFM images of GaN/AlGaN 2DEG structures grown on MOCVD GaN templates by ammonia-MBE at growth temperature of a) 900 °C and b) 800 °C maintained. The AFM image of the resulting AlGaN/GaN structure showed an RMS roughness of only 2.2 nm measured from 5 × 5 μm scans, and relatively large grain size, as illustrated in Fig. 1b. This is the best smoothness we have observed with the ammonia-MBE growth technique in our laboratory. Previously, the smallest RMS roughness was 10 nm for samples grown on sapphire substrates, and 8 nm for samples grown on SiC substrates. Clearly, the lack of lattice mismatch in homoepitaxy on GaN template layers made it possible to achieve significantly smoother morphology by ammonia-MBE while not compromising the crystalline quality of the materials grown.

The rough sample in Fig. 1a showed a Hall mobility of only 3000 cm^2/Vs at 77 K and a sheet electron density of 3.6×10^{12} cm^{-2}. No Shubnikov de-Haas oscillations were observed in the low temperature magnetoresistance measurement. The disintegrated surface of the GaN template due to thermal desorption prevented proper nucleation and growth of the GaN/AlGaN layers, leading to the deteriorated electrical characteristics.

The smooth sample in Fig. 1b, in contrast, showed a Hall mobility of 14300 cm^2/Vs at a density of 3.3×10^{12} cm^{-2} at 1.2 K. This is the highest Hall mobility that we have observed in the GaN/AlGaN 2DEG structures grown by the ammonia-MBE technique. Moreover, as shown in Fig. 2, the magnetoresistance of this sample exhibited strong Shubnikov de-Haas (SdH) quantum oscillations starting at fields as low as 2.0 T. Such high intensity of the SdH oscillations has not been observed previously in the GaN/AlGaN 2DEGs grown on sapphire or SiC substrates. From the Dingle plot of the amplitude of the oscillations [9], a quantum mobility of 2000 cm^2/Vs is found for this GaN/AlGaN 2DEG grown on the MOCVD GaN template. This is significantly higher than the best quantum mobility value of 1260 cm^2/Vs found in the GaN/AlGaN 2DEGs grown on SiC substrates [2], or the best value of 780 cm^2/Vs in those grown on sapphire substrates by ammonia-MBE in our laboratory. Note that the intensity of the SdH quantum oscillations is an extremely sensitive function of the quantum mobility. A moderate decrease in the quantum mobility can strongly dampen or even wash out the quantum oscillations.

The markedly improved electron quantum mobility in the smooth GaN/AlGaN 2DEG grown on the MOCVD GaN template suggests a direct impact of the surface roughness on this figure-of-merit parameter. The quantum mobility is limited by all scattering events including small-angle scatterings, whereas the Hall (or transport) mobility is limited mostly by large-angle scattering events. As a result, the Hall mobility to

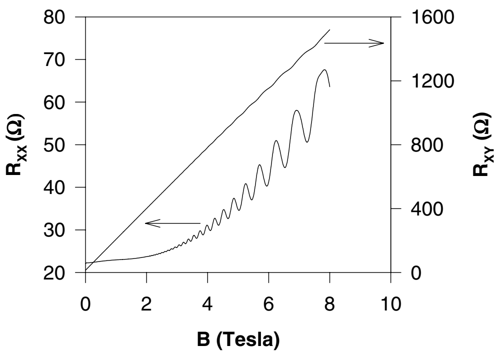

Fig. 2. Hall and magnetoresistance at 1.2 K of the GaN/AlGaN 2DEG sample in Fig. 1b, grown by ammonia-MBE on an MOCVD GaN template

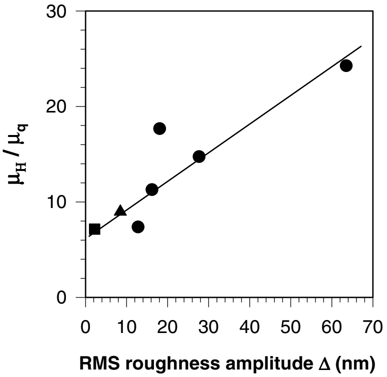

Fig. 3. The Hall mobility to quantum mobility ratio against the surface roughness amplitude for a series of GaN/AlGaN 2DEG samples grown by ammonia-MBE on various substrates including sapphire (circle), SiC (triangle), and MOCVD GaN templates (square)

quantum mobility ratio is usually larger than unity, and will increase if the small-angle scattering becomes more important. Figure 3 shows the correlation between the Hall mobility to quantum mobility ratio and the surface roughness amplitude for a series of GaN/AlGaN 2DEG samples grown on various substrates including the MOCVD GaN templates, SiC and sapphire. All the samples shown were grown by ammonia-MBE. A clear trend is observed that this ratio increases with increasing surface roughness. This result suggests that the interface roughness is an important source of small-angle scattering, and that improving surface smoothness is key to the enhancement of the quantum mobility in these 2DEG structures.

Conclusions Growth of high quality GaN/AlGaN 2DEG structures on MOCVD GaN template substrates by ammonia-MBE was achieved using a growth temperature significantly lower than that required for direct growth on non-GaN substrates (SiC or sapphire). The homoepitaxially grown GaN/AlGaN structures show significantly improved surface smoothness, and consequently improved electrical characteristics. The Hall mobility of 14300 cm^2/Vs and quantum mobility of 2000 cm^2/Vs measured of such a sample at low temperature are the highest values observed in the GaN/AlGaN 2DEG structures grown by ammonia-MBE on different substrates. The surface smoothness was found to have strong impact on the quantum mobility and could be a major source of small-angle scattering in these structures.

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