The role of AlN and GaN nucleation layers on the performance of doped and undoped nitride HEMT structures grown by MOCVD

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High electron mobility transistors (HEMT) based on AlGaN/GaN structures are very attractive candidates for high-power, high voltage and high-frequency microwave devices. The influence of AlN and GaN nucleation layers on their electrical, optical and structural properties was studied. Four different types of structures including doped and undoped structures each with a set of experiments were grown and investigated. For optimized and processed structures transit frequencies of up to 35 GHz, maximum frequencies of 70 GHz were measured in transistors with gate lengths of 200 nm. Those devices exhibited a transconductance of 175 mS/mm and a maximum source-drain current density of 700 mA/mm.

Introduction

Nitride semiconductors have gained widespread attraction due to their exceptionally good electrical properties and their ability to operate at high temperatures and in caustic and radiation rich environments. Two types of HEMT structures, doped and undoped, are believed most promising for actual applications. Undoped HEMT in comparison to doped HEMT are interesting due to lower noise, higher mobility and lower electric field under the gate at the pinch off condition, while doped HEMT offer higher sheet carrier concentration in the two-dimensional electron gas (2DEG) compared to undoped structures. Hence, doped and undoped 2DEG structures were grown and investigated in this work. However, the growth of GaN structures on sapphire substrates requires the careful matching of the GaN lattice to the substrate, involving the engineering of suitable nucleation layers between the substrate and the buffer layer. The influence of this nucleation layer on the electrical properties of the HEMT structures was at the focus of this work.

Experimental

All samples presented here were grown by MOCVD in AIXTRON reactors on 2 inch c-plane sapphire wafers, using TMGa, TMAl, NH_3 and SiH_4 as precursors. Two types of HEMT structures, doped and undoped, were grown employing both AlN and GaN nucleation layers. The types of layers will be denominated D_A, D_G, U_A, and U_G in this work (D = _d_oped, U = _u_ndoped, A = _A_lN nucleation, G = _G_aN nucleation). Temperature resolved Hall measurements were used to determine the electrical data, while the sample roughness was assessed by atomic force microscopy (AFM) and in-situ reflectometry measurements (Filmetrics). The Al concentration and thickness of the barrier and n-type electron supply layers were determined by Rutherford back scattering (RBS). Optimized structures were processed into HEMT devices.

Results and Discussion

Firstly undoped GaN buffer layers were investigated. Optimized layers exhibited free A-, B- and C-excitons in low temperature photoluminescence. Fig. 1 shows a sheet resistance mapping of such an undoped GaN buffer layer. The high value of sheet resistance of 31830 Ω/sq proves the suitability of the undoped buffer, allowing for low parallel shunt conductance and good pinch-off. The high uniformity of the layer allows high yield which is important for mass production of these structures.
With these prospects complete HEMT structures with AlGaN high bandgap layers were grown. Hall measurements at room temperature show lower mobilities and higher sheet carrier concentrations for

D_A in comparison to D_G (D_A: μ(300 K) = 1080 cm^2/Vs, n(300 K) = 9×10^{12} cm^{-2}, D_G: μ(300 K) = 1200 cm^2/Vs, n(300 K) = 8×10^{12} cm^{-2}). The same value for mobilities (μ(300 K)=1350 cm^2/Vs) as well as sheet carrier concentrations (n(300 K) = 3×10^{12} cm^{-2}) were measured for U_A and U_G at 300 K, while lower sheet carrier concentrations and nearly the same mobility could be achieved for U_A in comparison to U_G (U_A: n(77 K) = 4×10^{12} cm^{-2}, U_G: n(77 K) = 5×10^{12} cm^{-2}, U_A and U_G: μ(77 K) = 6000 cm^2/Vs) at 77 K. An explanation for the increase of carrier concentrations at low temperature for U_A and U_G may be that, the deep defects of the structures act as acceptors. At low temperature these defects freeze out and thus a higher sheet carrier concentration can be measured. This could be proved in structures on which T-resolved measurements were performed.

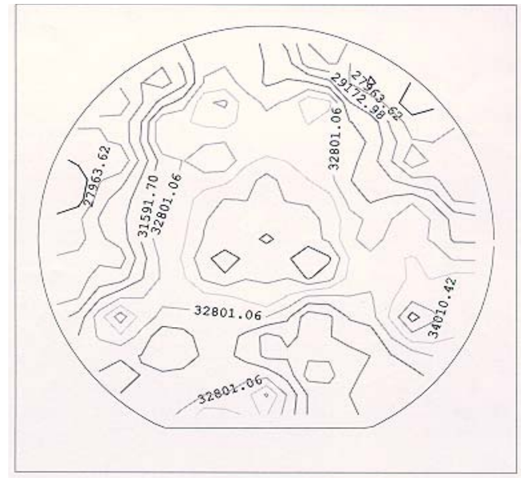

Fig. 1: Sheet resistance mapping of undoped buffer layer (31830 Ω/sq).

The AFM measurement shows a small difference in the surface roughness between the samples grown on AlN (D_A and U_A) and GaN (D_G and U_G) nucleation layers (D_A and U_A: rms ca. 0.9 nm, D_G and U_G: rms ca. 0.3 nm).
From the optimized D_G structures first HEMTs were processed and a transconductance of 175 mS/mm and a maximum source-drain current density of 700 mA/mm, as well as, a transit frequency of 35 GHz and a maximum frequency of 70 GHz were measured for samples with 200 nm gate length. In structures of the type D_G excellent electrical data (sample I: μ(300 K)= 1540 cm^2/Vs, n(300 K)= $1.03\text{x}10^{13}$ cm^{-2}), (sample II: μ(77 K)= 6380 cm^2/Vs, n(77 K)= $8\text{x}10^{12}$ cm^{-2}, μ(5 K)= 7500 cm^2/Vs) could be achieved with the variation of relevant process parameters in D_G structures for still unprocessed and unoptimized HEMT structures.
To test the reproducibility of these results both doped and undoped structures were re-grown several times. RBS data showed a reproducibility of the Al-concentration in the AlGaN layer of 17.5% $\pm$ 0.5%. Room temperature and liquid nitrogen temperature Hall effect measurements of the 2DEG exhibited extremely high reproducibility of the sheet carrier concentration and the corresponding electron mobility.

Conclusion

Through optimization of the nucleation and buffer layers excellent 2DEG performance was achieved. HEMT structures based on these structures exhibited transit frequencies of up to 35 GHz and transconductances of up to 175 mS/mm were achieved. The reproducibility and on-wafer uniformity results prove the AIXTRON systems suitable for the production of such devices for future high frequency applications.

The correlation of all relevant process parameters to the electrical, optical and structural properties will be presented. In addition, reflectometry results will be discussed.