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Compositional variation of nearly lattice-matched InAlGaN alloys for high electron mobility transistors

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Quaternary InAlGaN semiconductors with AlN mole fractions between 40% and 81% and respective InN contents of 7% and 19% including InAlN as a ternary border case have been grown by plasma-assisted molecular beam epitaxy. The electron mobility in InAlGaN-based heterostructures increases with Ga concentration in the barrier up to 1460 $cm^2/V\,s$ at a sheet electron density of 1.9×10^{13} cm^{-2}. An advanced spacer comprising an AlN/GaN/AlN triple-layer sequence is inserted between the GaN-buffer and the InAlGaN-barrier. Transistors with thin quaternary barrier show a large current density of 2.3 A/mm and an excellent transconductance of 675 mS/mm. © *2010 American Institute of Physics*. [doi:10.1063/1.3456561]

Among all types of semiconductor power amplifying devices, GaN-based high electron mobility transistors (HEMTs) can currently offer the highest power density at microwave frequencies.[1] This kind of device is commonly manufactured using AlGaN/GaN heterostructures which can be grown with high material quality. However, the AlGaN-barrier in such structures is always strained and prone to relaxation effects for high Al-contents restricting the epitaxial design particularly for high-frequency applications. During recent years, the ternary compound InAlN has been intensively investigated as an alternative barrier material. For an InN mole fraction of approximately 18%, InAlN is lattice-matched to GaN and can provide high sheet electron densities owing to its high spontaneous polarization. Despite the impressive results realized with InAlN-based heterostructures,[2,3] an inherent disadvantage of this alloy is its immiscibility which severely impedes the growth of high-quality material.

In view of the crystallographic and thermochemical properties in the III-N system,[4,5] quaternary compounds with suitable Al/In-ratio can be expected to be better miscible than $In_{0.18}Al_{0.82}N$ while simultaneously retaining lattice-matching conditions on GaN. Moreover, such InAlGaN alloys offer an additional degree of freedom to independently adjust bandgap and strain state. In spite of the potential advantages of quaternary nitride compounds, there exist only a few reports on transistor structures and actual devices using InAlGaN-barriers.[6,7] Here, we present the molecular beam epitaxy (MBE) growth and characterization of nearly lattice-matched quaternary nitride heterostructures and investigate the influence of the barrier composition on electrical properties. MBE is specifically capable to grow compounds with poor intrinsic miscibility as well as sharp interfaces and is therefore highly suitable to fabricate both the InAlGaN-barriers and the AlN/GaN/AlN triple-layer spacers utilized here. Based on these results, we further demonstrate HEMT devices with quaternary barriers including both dc and rf characteristics.

Epitaxial growth has been performed in a Veeco GEN20A MBE system with a UNI-Bulb rf plasma source for nitrogen supply. GaN templates grown by metal-organic chemical vapor deposition (MOCVD)[8] on sapphire or 4H–SiC substrates have been used as substrates, except for processed devices which have been grown on 4H–SiC completely by MBE. The epitaxial layer sequence (Fig. 1) always comprises a GaN-buffer[9] of about 1.5 μm overall thickness including the channel for the two-dimensional electron gas (2DEG), a spacer consisting of a nominally 0.7/1.1/0.7 nm thick AlN/GaN/AlN stack (0.8/1.1/0.8 nm on processed wafers), and the InAlGaN-barrier. The triple-layer spacer allows a higher separation between the 2DEG and the barrier than a single AlN interlayer and therefore further reduces alloy scattering. According to Poisson–Schrödinger simulations, no second 2DEG is confined in the spacer GaN layer. The buffer and spacer layers have been grown at a substrate temperature of 740 °C measured using optical pyrometry and a growth rate of about 350 nm/h. For the barrier layers, the temperature has been ramped down to about 420 °C except for $In_{0.07}Al_{0.40}Ga_{0.53}N$ which has been grown at about 580 °C. An approximately stoichiometric III/N-ratio has been used for all layers.

High-resolution x-ray diffraction (HRXRD) has been used to determine the lattice parameters of the InAlGaN alloys investigated and to subsequently calculate the composition assuming Vegard's Law. For this procedure, either the GaN mole fraction in the quaternary material has been estimated based on the MBE Ga-flux or a pair of an InAlGaN layer and an additional AlGaN sample has been investigated. This additional AlGaN wafer has been grown without In but equally to the InAlGaN wafer in other respects so that the Al/Ga-ratio is the same in both samples owing to complete incorporation of Al and Ga.[10] In this way, the InAlGaN com-

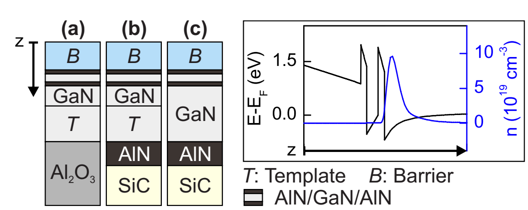

FIG. 1. (Color online) Epitaxial layer sequences (not to scale) for growth on sapphire templates (a), SiC templates (b), and blank SiC substrates (c). The graph on the right shows the conduction band profile for an exemplary structure with 7.2 nm thick $In_{0.18}Al_{0.82}N$-barrier.

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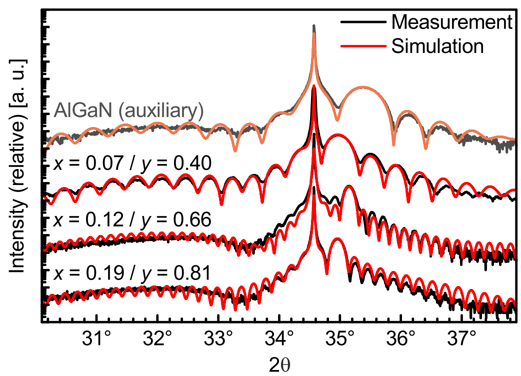

FIG. 2. (Color online) HRXRD θ-2θ-scans of the 00.2 reflex range. The mole fractions of InN (x) and AlN (y) are given for each barrier. In addition, an auxiliary AlGaN wafer with the same Al/Ga-ratio as in $In_{0.07}Al_{0.40}Ga_{0.53}N$ has been measured to be able to determine the quaternary composition.

position is accessible by the two HRXRD measurements. Atomic force microscopy (AFM) has been utilized to characterize the surface morphology. For the electrical characterization, room temperature Hall measurements in Van der Pauw geometry have been used. To fabricate HEMT devices[11] Ti/Al/Ni/Au-based ohmic contacts, dry-etched mesas for lateral isolation, SiN_x-passivation layers, and Ni/Au-based Schottky T-gates have been processed.

HRXRD θ-2θ-scans across the 00.2 reflex range on 20–50 nm thick barrier layers grown using templates on sapphire show clearly distinct reflexes and Pendellösung fringes (Fig. 2) providing compositions and thicknesses (Table I). The increased intensity around $2\theta=32°$ is caused by the AlN/GaN/AlN sequence according to dynamic scattering simulation.

Hall measurements at room temperature on HEMT structures show a strong influence of the barrier composition on 2DEG properties (Table II). A wafer using a quaternary nearly lattice-matched $In_{0.07}Al_{0.40}Ga_{0.53}N$-barrier achieves a sheet electron density of 1.9×10^{13} cm^{-2} and an electron mobility of 1460 cm^2/V s. The latter value is much higher than in heterostructures from the same series with lower GaN mole fraction in the barrier which can most evidently be explained by the improving miscibility of the corresponding InAlGaN alloys.[4,5] For $In_{0.18}Al_{0.82}N$, spinodal decomposition is expected to occur at temperatures below 1500–2500 °C in equilibrium whereas for 50% GaN content and lattice-matching on GaN the limit is estimated to be around 700–1300 °C. Therefore, the driving force for phase separation and other miscibility-related material deterioration at typical growth temperatures will be much lower for an intermediate quaternary compound than for ternary InAlN which probably results in the different electron transport properties observed.

TABLE I. Properties of thick barrier layers. The compositions and the thicknesses (d) have been determined by HRXRD. Roughness (rms) values (r) over 5×5 μm^2 have been measured using AFM.

x(In)	y(Al)	z(Ga)	d (nm)	r (nm)
0.19	0.81	0.00	41	0.4
0.12	0.66	0.22	53	0.9
0.07	0.40	0.53	21	0.5

TABLE II. Sheet electron density (n_s) and electron mobility (μ) of HEMT structures with thin barrier layers (d). All thicknesses are estimated based on the growth rate as determined by HRXRD.

y(Al)/z(Ga)	d (nm)	Substrate	n_s (10^{13} cm^{-2})	μ (cm^2/V s)
0.82/0.00	~8	Al_2O_3	1.7	570
0.66/0.22	~7	Al_2O_3	2.0	900
0.40/0.53	~9	Al_2O_3	2.0	1280
0.40/0.53	~7	4H–SiC	1.9	1460

Compared to previous reports on nearly lattice-matched III-N heterostructures,[7,12,13] the 2DEG properties presented here are among the best results with respect to electron mobility. One distinctive feature here is the use of MBE as a growth method whereas most other comparable reports are based on heterostructures grown by MOCVD. It is notable that most published electron mobilities for MBE-grown ternary InAlN-barrier heterostructures[14–16] do not attain the best values achieved with MOCVD which is consistent with the observations in this work. In contrast, by utilizing quaternary InAlGaN compounds, which have rarely been studied until now, barrier-related restrictions in 2DEG mobility can be overcome while retaining both lattice-matching on GaN and higher sheet electron densities than in AlGaN-based heterostructures with comparable barrier thickness.

To further investigate the promising InAlGaN alloys with intermediate Ga concentration, HEMT devices have been fabricated from wafers with nominally 5.6 nm thick $In_{0.07}Al_{0.40}Ga_{0.53}N$-barrier.[17] The transistors present excellent dc characteristics with a maximum current density of 2.3 A/mm and a peak extrinsic transconductance of 675 mS/mm for 150 nm gate length and 2×30 μm device width (Fig. 3). These results combining both a high current density and a high transconductance are primarily enabled by the high 2DEG density and mobility with simultaneously low gate-to-2DEG distance in our InAlGaN-barrier heterostructures. A good suitability for microwave power applications is demonstrated in load-pull measurements at 10 GHz where larger transistors on the same wafer with a width of 2×150 μm and 250 nm gate length achieve up to 47% power added efficiency (PAE) at a drain-source voltage of $V_{DS}=10$ V and an output power density of 5.6 W/mm at an increased bias of $V_{DS}=30$ V.

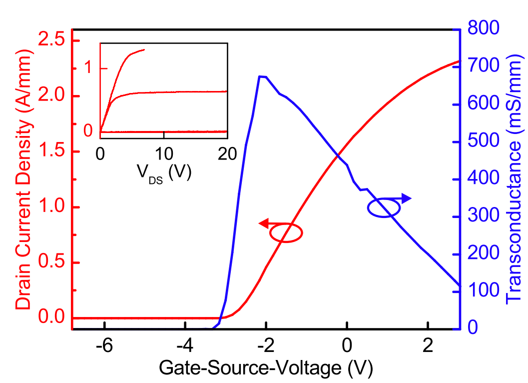

FIG. 3. (Color online) Transfer characteristics of a device with 150 nm gate length and a width of 2×30 μm at a bias of $V_{DS}=5$ V. The inset shows exemplary dc characteristics [drain current density (ampere per millimeter) on left axis] at gate-source-voltages of 1, −1, −3, and −5 V (latter two graphs nearly congruent) from top to bottom.

In conclusion, we have presented nearly lattice-matched InAlGaN-barrier heterostructures with varied barrier composition grown by MBE. Transistor structures comprising an $In_{0.07}Al_{0.40}Ga_{0.53}N$-barrier exhibit a sheet electron density of 1.9×10^{13} cm^{-2} and an electron mobility of 1460 cm^2/V s. HEMT devices fabricated from such wafers provide a current density of 2.3 A/mm, an extrinsic transconductance of 675 mS/mm, as well as a good performance at 10 GHz with up to 47% PAE qualifying well for microwave power applications.

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