InAlN/AlN/GaN heterostructures for high electron mobility transistors

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Abstract. The results of development of InAlN/AlN/GaN heterostructures, grown on sapphire substrates by metal-organic chemical vapour deposition, and high electron mobility transistors (HEMTs) based on them are presented. The dependencies of the InAlN/AlN/GaN heterostructure properties on epitaxial growth conditions were investigated. The optimal indium content and InAlN barrier layer thicknesses of the heterostructures for HEMTs were determined. The possibility to improve the characteristics of HEMTs by in-situ passivation by Si\textsubscript{3}N\textsubscript{4} thin protective layer deposited in the same epitaxial process was demonstrated. The InAlN/AlN/GaN heterostructure grown on sapphire substrate with diameter of 100 mm were obtained with sufficiently uniform distribution of sheet resistance. The HEMTs with saturation current of 1600 mA/mm and transconductance of 230 mS/mm are demonstrated.

1. Introduction
Currently the high electron mobility transistors (HEMTs) based on InAlGaN material system are most promising for production of electronic components for high-power amplifiers operating at high frequencies in extreme conditions at high temperatures, in the near-Earth space environment, at exposure to ionizing radiation \[1\]. High values of the band gaps, conduction band discontinuities at heterojunctions of AlGaN/GaN or InAlN/GaN, high electron saturation velocities and breakdown voltages and other features of the InAlGaN material system allow to produce HEMTs with the parameters exceeding achievable for transistors based on III-As or Si material systems.

The lattice-mismatched heterostructures AlGaN/GaN are traditionally used for HEMTs. Two dimensional channel is formed in the heterostructure on the interface between AlGaN barrier layer and GaN buffer layer both by difference in the coefficients of spontaneous polarization and piezoelectric polarization caused by strain. The increase of the mobility and charge carrier concentration in HEMT AlGaN/GaN heterostructures to achieve maximal output characteristics requires the increase of the Al content and variation of the barrier layer thickness. The increase of the Al content and AlGaN layer thickness leads to increase of the elastic strain, which reduces the material quality and in turn causes deterioration of the transistors parameters and lifetime.
The implementation of InAlN layer as a barrier in HEMT structures instead of AlGaN allows to control the strain in the InAlN/GaN heterostructures. Since In$_{x}$Al$_{1-x}$N layer with indium content of about 18% is lattice matched to GaN it allows to realize strain-free InAlN/GaN heterostructures [2, 3]. The formation of the two-dimensional channel at the interface is caused not only by difference of band gap energies, but also by electric field induced by difference of the coefficients of spontaneous polarization and piezoelectric polarization caused by strain in lattice mismatched case. The variation of indium content below/above 18% allows to obtain tensile/compressive strained barrier layers which in turn permits to control charge carrier concentration.

It should be noted that the InAlN alloy is the most technologically complicated material among the III-nitrides due to difference in the optimal growth conditions for the AlN (growth temperature over 1100 °C) and InN (~600 °C) which is related to the low mobility of Al adatoms and desorption of In atoms. The optimization of the relatively thick epitaxial layer growth regimes, carried out previously [4], allows us to determine growth parameters and to obtain high-quality InAlN layers, which permits to produce InAlN/GaN distributed Bragg reflectors with reflectivity more than 99% in a wide range from blue (460 nm) to red (610 nm) spectral regions [5]. Implementation of the InAlN layers for modification of the active region based on InGaN/GaN quantum wells allows to expand the range of emission of light emitting diodes [6].

2. Experiment
The InAlN/AlN/GaN heterostructures were grown on (0001) oriented sapphire substrates by metal-organic chemical vapour deposition (MOCVD) in Dragon-125 setup with horizontal reactor equipped with induction-heated graphite susceptor [7]. Nitrogen, hydrogen and nitrogen-hydrogen mixtures were used as carrier gases and ammonia, trimethylgallium (TMGa), trimethylindium (TMIn), trimethylaluminum (TMAI) and monosilane (SiH$_4$) - as precursors.

The heterostructures (Table 1) consist of GaN nucleation layer, GaN insulating buffer layer of 2 µm thick, AlN layer of ~1 nm thick and undoped In$_{x}$Al$_{1-x}$N barrier layer with varied thickness and indium content. InAlN layers were grown under reduced reactor pressure of 200 mbar without implementation of the intentional doping by silicon. A detailed description of the epitaxial growth conditions of the InAlN and GaN layers by MOCVD method was described previously in the studies [4 - 6]. The use of the nanometer-thick AlN layer at the interface allows to increase the mobility of electrons in the channel by improving the interface quality and by increasing of the charge carriers wave function localization in the channel region [8, 9]. The growth conditions of the GaN and AlN layers for all the heterostructures were selected the same and growth temperature for InAlN varied (Table 1) from 820°C (structure H1) to 880°C (structure H5).

| Structure | $T_{gr}$, °C | $d_{InAlN}$, nm | $T=300$ K |
|-----------|-------------|-----------------|------------|
|           |             | $\sigma$, (Ohm cm)$^{-1}$ | $\mu$, cm$^2$/V s | $n_e$, $10^{13}$ cm$^{-2}$ |
| H1        | 820         | 19              | 24.3       | 746         | 2.03       |
| H2        | 835         | 18              | 30.6       | 837         | 2.28       |
| H3        | 850         | 17              | 36.5       | 747         | 3.05       |
| H4        | 865         | 16              | 30         | 559         | 3.35       |
| H5        | 880         | 15              | 20.3       | 372         | 3.41       |
| H6        | 850         | 12              | 36.6       | 795         | 2.88       |
| H7        | 850         | 12              | 38         | 840         | 2.82       |

The structural properties of the grown samples were investigated by the scanning electron microscopy and high-resolution X-ray diffraction (HRXRD) using Bruker D8 Discover (Bruker AXS,
Germany) diffractometer. The $\omega$-2$\theta$ rocking curves for symmetric Bragg reflection (0002) were analyzed [10]. Approximation of experimental data was carried out using LEPTOS software [10]. Measurements of the electrical parameters of conductivity $\sigma$, charge carrier concentration $n$, and carrier drift mobility $\mu$ in the channel were performed by Hall effect measurements by van der Pauw method. The sheet resistance measurements and maps of resistance distribution on the wafer were carried out by LEI 1510A SA (Lehighton Electronics) contactless measurement system. Structural and electrical parameters of the heterostructures versus growth temperature ($T_{gr}$) of In$_{x}$Al$_{1-x}$N are summarized in Table 1.

3. Results and Discussion

3.1. InAlN/AlN/GaN heterostructures for high electron mobility transistors

Set of samples was grown on 2 inch wafers with variation of growth temperature of the In$_{x}$Al$_{1-x}$N barrier layer from 820 to 880 °C (structures H1 - H5), maintaining the same growth time. It was observed that the increase of growth temperature from 820° to 880° C leads to simultaneous reduction of thickness from 20 to 15 nm and to nearly twice decrease of indium content from 18 % to 9 % (Figure 1 (a)). No evidence of phase separation in the InAlN layers was revealed for all investigated heterostructures from the high-resolution X-ray diffraction studies as shown in Figure 1 (b). The comparison of the variation of the InAlN and partial AlN thicknesses, calculated as the product of layer thickness on Al content, with increasing of $T_{gr}$ shows that the reduction of the InAlN layer thickness occurs mostly due to decrease of the indium incorporation. The highest values of conductivity 36.5 (Ohm cm)$^{-1}$ and mobility of 837 cm$^2$/V s were observed for heterostructures with InAlN layer grown at temperatures of 835 (H2) and 850 °C (H3) with indium content of about 14-16 %. Increase of the barrier layer growth temperature up to 880 °C (H5) leads to significant increase of the charge carrier concentration in the channel and to decrease of the mobility more than twice to 372 cm$^2$/V s, resulting in decrease of conductivity. Despite being strained at room temperature the In$_{x}$Al$_{1-x}$N layers of the heterostructures H2 and H3 contain less defects, originating during epitaxy due to higher temperature and during cooling due to the difference of thermal expansion coefficients of the In$_{x}$Al$_{1-x}$N, AlN and GaN.

![Figure 1](image_url)

Figure 1. HRXRD rocking curves (a), InAlN barrier layer (open circles) and AlN layer (solid circles) thicknesses and indium content (open squares) (b) of the InAlN/AlN/GaN heterostructures with barrier layer grown at different temperatures from 820° (structure H1) to 880° C (H5).

Hence, In$_{x}$Al$_{1-x}$N barrier layers with indium content of about 14-16 % are optimal for HEMT based on InAlN/AlN/GaN heterostructures. The structure H6, grown at $T_{gr}$ = 850 °C with reduced InAlN barrier layer thickness (12 nm), demonstrates characteristics similar to those of H3 structure. So the
variation of InAlN barrier layer thickness from 12 to 20 nm does not significantly affect the performance of InAlN/AlN/GaN HEMT heterostructures.

To study the effect of surface passivation, a pair of identical structures were grown with \textit{in-situ} deposited 5 nm thick Si$_3$N$_4$ layer (H7) and without one (H6). The protective passivation layer was grown \textit{in-situ} in the same epitaxial process using ammonia and SiH$_4$ after the deposition of the In$_x$Al$_{1-x}$N barrier layer \cite{11, 12}. The values of charge carrier concentration obtained for the structures H6 and H7 were found to be very close, some variation may be due to surface modification of the InAlN layer or by the addition strain caused by deposition of Si$_3$N$_4$ layer.

In order to analyze the possibility of growth of InAlN/AlN/GaN heterostructures on larger diameter substrates, the structure with identical to H7 growth regimes was grown on (0001) oriented sapphire substrate with diameter of 100 mm. The distribution of sheet resistance $R_s$ over the wafer is shown on Figure 2. The sheet resistance $R_s$ measured in different regions of the wafer is found to be uniform and varied in the range from 211 to 216 Ohms/square with mean value of 213 ± 1.5 Ohms/square.

3.2. \textit{InAlN/AlN/GaN transistor test structures}

Heterostructures with the highest electrical parameters (H2, H6 and H7) were processed using optical photolithography (Figure 3). Standard metallization sequence of Ti/Al/Ni/Au was used for ohmic and Ni/Au for barrier contacts. Gate length (L) and gate width (W) were 1 and 90 microns, respectively. The gates of the transistors were passivated by Si$_3$N$_4$ layer, deposited by plasma-enhanced chemical vapor deposition method. In order to increase the drain saturation current ($I_{dss}$), transconductance ($g_m$), and breakdown voltage ($U_{br}$) of HEMT structures the distance between the drain (D) and the gate (G) were selected larger (3.5 $\mu$m) than the distance (1.5 $\mu$m) between the gate and the source (S) \cite{13}.

The output characteristics of the test transistor structures T1 (Figure 4 (a)), T2 (Figure 4 (b)) and T3 (Figure 4 (c)) are shown in Figure 4. The parameter determined from the analysis of the current-voltage characteristics are summarized in Table 2. Transistor structures are opened at zero gate-to-source voltage ($U_{gs}$) and almost open at $U_{gs}>0$ V. The increase of the negative $U_{gs}$ leads to decrease of the drain-to-source current ($I_{ds}$) until the total cut-off of the transistor channel.
Figure 4. The output current-voltage characteristics drain current versus drain-to-source voltage of the transistor structures T1 (a), T2 (b) and T3 (c).

It should be noted that the channel of the structure T1 does not close completely at $U_{gs}<0$ possibly due to inhomogeneous indium distribution in the InAlN barrier layer. Barrier heights $\varphi_b$, determined from the analysis of the current-voltage characteristics of the gate current ($I_{gs}$) versus the gate-to-source voltage ($U_{gs}$), were 1.7, 1.5 and 2.5 eV for the structures T1, T2 and T3, respectively. The breakdown voltages ($U_{br}$) were determined from the forward source-gate and reverse gate-drain diode characteristics (Table 2).

Table 2. Parameters of the HEMT transistors based on In$_x$Al$_{1-x}$N/AlN/GaN heterostructures.

| Transistor structure | Structure | $d_{Si3N4}$, nm | $d_{InAlN}$, nm | $\varphi_b$, eV | $U_{br}$, V | $I_{dss}$, A/mm | $g_m$, mS/mm |
|----------------------|-----------|-----------------|-----------------|---------------|-------------|----------------|-------------|
| T1                   | H2        | -               | 16              | 1.7           | 10          | 1.35           | 100         |
| T2                   | H6        | -               | 12              | 1.5           | 40          | 1.2            | 230         |
| T3                   | H7        | 5               | 12              | 2.5           | 80          | 1.6            | 217         |

The transconductance ($g_m$) and saturation current ($I_{dss}$) for the HEMT structure T1 are 100 mS/mm and 1350 mA/mm, respectively. The comparison of the HEMT structures T2 and T3 allows to reveal that the structure T3, grown with in-situ Si$_3$N$_4$ passivation layer, shows higher electron mobility than structure without Si$_3$N$_4$ layer with nearly the same values of carrier concentration. Also despite the high barrier height of 2.5 eV structure T3 demonstrates better output characteristics and maximal saturation current reaching 1600 mA/mm (Figure 5). Breakdown voltage $U_{br}$ significantly increases from $\sim$40 V to $\sim$80 V. The maximal value of $g_m$ slightly decreases from 230 to 217 mS/mm. As shown in Figure 5, cut-off voltage and the region of the maximal transconductance shifts towards the negative $U_{gs}$. The fact that deposition of the ~5 nm thick in-situ Si$_3$N$_4$ layer leads to increase of the distance between the 2D channel and the gate and to passivation of the InAlN/AlN/GaN heterostructure surface, which reduces the density of surface states.
4. Conclusions
The optimal design of the InAlN/AlN/GaN heterostructures: indium content and InAlN barrier layer thicknesses were determined. InAlN/AlN/GaN heterostructure grown on sapphire substrate with diameter of 100 mm were obtained with very high uniformity of sheet resistance distribution with 3% standard deviation. The InAlN/AlN/GaN heterostructures with high electron mobility up to 837 cm²/(V s) and high charge carrier concentration up to 3.05 10¹³ cm⁻² were used for HEMT fabrication. The optimal design for InAlN/AlN/GaN heterostructures and HEMTs was found to be slightly different. High electron mobility transistors with transconductance over 200 mS/mm were demonstrated. Transistor structure, grown with in-situ Si₃N₄ passivation layer, demonstrates improved output characteristics and maximal saturation current of 1600 mA/mm.

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