InAlN/GaN and AlGaN/GaN HEMT technologies comparison for microwave applications

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Abstract. High electron mobility transistors (HEMTs) technologies based on AlGaN/GaN and InAlN/GaN heterostructures have been developed. The research focused on influence of epitaxial growth conditions and buffer doping profiles on electrical properties HEMTs. An output power density of 4W/mm at 17 GHz was demonstrated for InAlN/GaN HEMTs and 7W/mm at 10 GHz for AlGaN/GaN HEMTs.

1. Introduction

GaN-based high electron mobility transistors (HEMTs) have potential for successful application in MMIC technology for various frequencies including mm-wave range. InAlN/GaN and AlN/GaN based heterostructures have a higher, compared to AlGaN/GaN, spontaneous polarization induced electric field and, hence, a higher electron concentration in 2DEG \cite{1–3}. The electron density in 2DEG for InAlN-based heterostructures reaches 2.5\textasciitilde3\cdot10^{13} \text{cm}^{-3}, more than 2 times of typical AlGaN/GaN 2DEG value. Among them, In\textsubscript{0.17}Al\textsubscript{0.83}N/GaN heterostructure was of special interest because of its lattice matched, unstrained InAlN barrier, which may lead to improved device reliability \cite{4}. In addition to a higher electron concentration in 2DEG, an electron mobility of 1800\text{cm}^{2}/\text{V·s} was reported for InAlN/GaN heterostructure, which is comparable to the values for AlGaN/GaN heterostructures \cite{5}. A high electron concentration in 2DEG in InAlN/GaN heterostructures is expected to extend the frequency range of HEMTs \cite{6, 7}. Reducing the gate length is the main step to increase the operation frequency of the FETs, but this leads to an increase of the electric field in transistor channel and force to decrease operating voltage. To achieve high output power levels for this type of devices one should increase the maximum current range, which is possible with high Al-content InAlN/GaN and AlN/GaN based heterostructures. A thin barrier layer is essential for short gate length high frequency devices, since a high ratio between the gate length and the gate to channel distance is a key factor suppressing the short channel effects in HEMTs \cite{8}.

A good confinement of 2DEG in the heterostructure near the threshold voltage even for high drain voltages is important to achieve high power performance of short channel HEMTs because drain leakage at high Vds at \[|V_{gs}|>|V_T|\] affects such an important parameter as Power Added Efficiency (PAE). Possible solutions include AlGaN and InGaN back barriers and adjustment of dopant profiles in the GaN buffer layer \cite{9–15}. Despite the excellent electrophysical properties, some issues regarding the stability of thin InAl(Ga)N barrier layers were reported \cite{16–19}. Most of them are related to traps generated...
during reliability tests, which are located at the surface or in the InAlN barrier layer causing degradation of the RF performances of the devices. The impact of traps becomes more severe for low thickness barriers, since a decrease in the distance between the 2DEG and traps increases the effect of trap charges on the 2DEG in the channel. Utilizing an optimized SiN in-situ passivation along with other passivation techniques (ALD of Al2O3 or SiO2) is necessary to achieve high DC and RF parameters [20].

The development of GaN-based HEMT and MMIC technologies for frequencies above 30GHz requires several technological and design steps that allows achieving comparable to GaAs-based devices RF parameters by compensating a lower than in GaAs HEMTs electron mobility in the 2DEG. To date, technologies developed by leading companies use gates with lengths of 60-150nm, low resistance non-alloyed ohmic contacts, AlGaN, InAlN and InAlGaN-based heterostructures with in-situ SiN passivation and scaling of device sizes [21–23].

2. Samples preparation and experimental results
AlGaN/GaN and InAlN/GaN heterostructures were grown by MOVPE on 100mm diameter silicon carbide (SiC) substrates. The epi layers included an AlN nucleation layer, an insulating buffer layer, a 1nm thick AlN interlayer, an AlGaN or InAlN layer, and a 5nm in-situ SiN layer. The sheet electron concentration and the electron mobility for the AlGaN/GaN and InAlN/GaN heterostructures were around 1800cm2/V·s, 1.15cm2/V·s and 1100cm2/V·s, 2.5cm2/V·s, respectively.

Device fabrication started with alignment marks and ohmic contacts formation. Device isolation was carried out by ion implantation of boron. The alloyed ohmic contacts were formed by evaporation of Ti/Al/Mo/Au-based metallization followed by short (15–20sec) rapid thermal annealing at 780–800°C [24]. 0.1μm-length T-gates were fabricated using electron-beam lithography followed by ICP-RIE of a 0.1μm-thick SiN layer in a fluorine-based plasma. The top of the T-gate was formed by photolithography. Then, a Schottky contact was formed by deposition of Ni/Pt/Au.

Figure 1. Comparison of the pulsed Id (Vd) characteristics at Vg = 0 V of the AlGaN/GaN HEMT with C- doped (a) and Fe-doped (b) buffer layers at the different quiescent bias points (Vg = 0V, Vd = 0V), (Vg = -6V, Vd = 5 ÷ 25V). The pulse length is 250ns.

Pulse I-V, S-parameters and load pull measurements were used to characterize the obtained AlGaN/GaN and InAlN/GaN HEMTs. AlGaN/GaN and InAlN/GaN HEMTs with a source-drain spacing of 2.5 and 3.5μm and 2x50μm or 2x100μm gate fingers were fabricated and characterized. Short (≤0.15μm) gate lengths required for millimeter wave range devices imposes strict requirements on leakage current values of the GaN buffer layers. To achieve a high breakdown voltage in transistors along with a minimal current collapse effect, an optimization and comparison of buffer layers with different design was carried on, namely, the transistors with undoped, C-doped and Fe-doped buffer layers were fabricated and compared. The highest (≥180V) breakdown voltages were observed in samples with C-doped and Fe-doped buffer layers. To evaluate the current collapse effect, pulsed I-V characteristics were measured on the AlGaN/GaN HEMTs, fabricated on the C- and Fe-doped buffer layers. Curves measured at Vg = 0V, were measured at various quiescent bias points and compared
The smallest values of current collapse were observed in transistors with Fe-doped buffer layers.

InAlN/GaN is a structure with complex epitaxy requirements (the conditions for the growth of Al-containing and In-containing layers are different - the optimum temperatures for InN are ~600°C, and for AlN are ~1200°C), which makes an uniform In concentration along the InAlN layer not easily obtained. Also, an unintentional incorporation of Ga atoms into the InAlN layer was reported [25, 26]. Still, a layer-to-layer analysis of the composition of our InAlN/AlN/GaN samples by X-ray photoelectronic spectroscopy (Figure 2) showed that the In content corresponds to the target value of 12% and is almost the same over the entire thickness of the InAlN layer, as well as no Ga incorporation in the InAlN layer is observed.

**Figure 2.** Atomic concentration profile obtained by layer-by-layer etching of SiN/InAlN/AIn/GaN heterostructure samples. The In concentration shown in the graph is 8 times increased.

The investigation of the effect of the InAlN molar fraction on the electrophysical parameters of a two-dimensional electron gas showed the InAlN layer conductivity is highest for indium content of 13\(\text{-}15\)% with a relatively good mobility of 1100 cm\(^2\)/V·s, so this content was used in further experiments.

A significant effect of the trimethylindium (TMI) flow rate during InAlN growth on the current collapse effect was also observed (Figure 3), showing a lowest collapse for a low TMI flow rate, which can be attributed to changes in the spectrum and/or concentration of the deep centers in the InAlN layer and on the surface. 0.1μm gate length HEMTs based on this heterostructures demonstrates a maximum drain current \(I_{d_{\text{max}}}=1.4\text{A/mm}\), a transconductance \(g_m=600\text{mS/mm}\) with \(V_{th}=-1.5\text{V}\).

**Figure 3.** Current collapse effect on InAlN/GaN HEMTs fabricated on InAlN barriers grown with different TMI flow. Current collapse calculated as \([I_d(0,0)-I_d(1.2V_t, 25V)]/I_d(0,0)\). TMI flow is normalized.
Reducing the gate length without a proportional decrease of the thickness of the wide-gap AlGaN barrier layer of the transistor leads to a significant short-channel effect. Due to the greater than in the AlGaN/GaN heterostructures conduction-band discontinuity and the spontaneous polarization charge density of InAlN/GaN heterostructures, the latter type of heterostructures allows the drain current density to be increased up to $2\div 3\, \text{A/mm}$, which was confirmed in our experiments. Thanks to this, InAlN-based heterostructures allows to reduce the wide-gap InAlN layer thickness whilst keeping $I_{\text{max}}$ higher than in AlGaN/GaN heterostructures based HEMTs [23]. As a result, it is possible to compensate for the decrease in the operating voltage of thin barrier layer short-channel transistors by higher maximum current in InAlN/GaN heterostructures and to obtain high output power levels in the millimeter wavelength range [27].

The Ti/Al/Mo/Au-based alloyed ohmic contacts technology, developed for AlGaN/GaN was applied to fabricate contacts for InAlN/GaN heterostructures. This allowed to fabricate low-resistance ohmic contacts ($R_c\leq 0.25\, \Omega\cdot\text{mm}$) on AlGaN/GaN and InAlN/GaN heterostructures along with decreasing the gate-drain distance up to $1.5\, \mu\text{m}$ due to the low thickness of contacts metallization ($0.12\, \mu\text{m}$) and low surface roughness ($\text{RMS}\approx 14\, \text{nm}$ for AlGaN/GaN and $24\, \text{nm}$ for InAlN/GaN). The carried out experiments revealed the effect of an electrophysical parameters degradation during rapid thermal annealing at $825^\circ\text{C}$ and above (Figure 4).

![Figure 4. The dependence of carrier mobility (top) and concentration (bottom) in the channel on the annealing temperature (measurements were carried out at room temperature).](image)

InAlN/GaN heterostructures proved out to be sensitive to another process as the gate foot was fabricated. A surface low energy ion treatment during ICP RIE of SiN and an oxygen plasma ashing of photosist residues may strongly affect the sheet resistance of 2DEG and $R_{\text{on}}$ in fabricated HEMTs. Figure 5 shows the results of InAlN/GaN heterostructure surface treatment. Processing time was 2 minutes. As can be seen from the results, an increase of the plasma power leads to an increase in the semiconductor layer resistance and, consequently, to a decrease of the current in InAlN/GaN-based HEMTs. Therefore, an additional adjustment of the process parameters is required for successful processing of InAlN/GaN-based heterostructures.

![Figure 5. Effect of oxygen plasma surface treatment on InAlN/GaN heterostructure parameters.](image)
Fabricated AlGaN/GaN HEMT and InAlN/GaN HEMT have demonstrated DC characteristics that are in good agreement with their design and 2DEG parameters. AlGaN/GaN HEMT had $I_D \approx 1.0A/mm$, $V_T \approx -3.2V$, $g_m \approx 280mS/mm$, while InAlN/GaN HEMT had $I_D \approx 1.3A/mm$, $V_T \approx -1.3V$, $g_m \approx 550mS/mm$. The I-V characteristics of 0.1μm gate length AlGaN/GaN HEMTs shows a low short channel effect which can be attributed to the buffer and T-gate design (Figure 6).

**Figure 6.** Pulse I-V curves for 0.1x100μm gate length InAlN/GaN HEMT, $V_g = +1.5\div-4V$.

Comparison of small-signal microwave characteristics of InAlN/GaN and AlGaN/GaN HEMT with a 0.1μm gate length and different source-drain spacing, shown in Figure 7 confirms that, being fabricated in the same process and topology and measured at the same bias and current, AlGaN/GaN HEMT demonstrated a higher gain than InAlN/GaN HEMT. This advantage disappears when AlGaN/GaN HEMT is compared with InAlN/GaN HEMT with a 1μm smaller source-drain spacing, giving similar MaxGain vs frequency curve.

**Figure 7.** Comparison of MSG/MAG for 0.1μm gate length InAlN/GaN and AlGaN/GaN HEMTs with different source-drain spacing.

A comparison of power characteristics of the devices (Figure 8) using pulsed load pull measurements, carried out at a 17GHz on 100μm gate width for AlGaN/GaN and 200μm gate width for InAlN/GaN devices, showed that both type of devices demonstrated comparable levels of power parameters.
Figure 8. Comparison of loadpull data for 0.1μm gate length InAlN/GaN (a) and AlGaN/GaN (b) HEMTs.
InAlN/GaN demonstrated a high-power density of 3.5÷4W/mm at a lower V_{ds}=15V supply voltage while the same power level was obtained for AlGaN/GaN devices at V_{ds}=20V. As expected from small signal data, AlGaN/GaN-based transistors have a higher power gain. A lower PAE in InAlN/GaN devices may be attributed to the higher leakage at high drain voltages at pinch-off.

3. Conclusion
The results of the study showed that high quality InAlN/GaN can compete with AlGaN/GaN-based HEMTs for use in millimeter wave range power applications. Using low-resistance alloy contacts in combination with a 0.1μm gate and an optimized design of the buffer layer allows to achieve high microwave parameters required for operation in the selected frequency ranges.

However, further improvement of the RF parameters of the InAlN/GaN transistors is required to reach typical values of small and large signal gain in AlGaN/GaN HEMTs. Besides increasing of 2DEG mobility, an increase in gain can be achieved utilizing short a source-drain and gate length dimensions, non-alloyed regrown ohmic contacts and optimization of the heterostructure. In this case, it will be possible to realize the potential of the InAlN/GaN heterostructure in achieving high values of the output power in the mm-wave frequency ranges.

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