Comparison of Metamorphic InGaAs/InAlAs HEMT's on GaAs with InP based LM HEMT's

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Introduction

InP based HEMT's have already shown to be the best performing three-terminal devices [1], with excellent performance in the microwave and millimeter wave range. The combination of high gain and low noise has been demonstrated by many realized devices and circuits with operating frequencies up to 100 GHz and beyond [2,3].

A drawback of the InP based system is the substrate itself. Because it is a fairly young technology with limited maturity, the crystal quality is less than for GaAs, resulting in increased brittleness and limited size availability. Up to now, only 2" and 3" substrates are available at relatively high cost per square inch, whereas for GaAs already 6" substrates are available. Additionally, wafer thinning and backside processing have become mature technologies for GaAs.

To combine the advantages of the GaAs substrate with the advantages of InP based heterostructures, metamorphic (MM) InGaAs/InAlAs quantum well structures can be grown on GaAs. The lattice constant of GaAs can be transferred into the one of InP with an appropriate buffer (typically 1 to 2 μm thick), on which the layer stack can be grown lattice matched. The quality of the final heterostructure and thus the device performance, depends fully on the buffer type and quality.

In this paper we will present the results of devices, based on two types of buffer and compare them with the original InP based HEMT's. Both a quaternary buffer (AlGaAsSb) and a ternary buffer (InAlAs) on GaAs will be discussed. All structures have been grown with MBE (Molecular Beam Epitaxy).

I. Device Processing

The HEMT processing technology used in this work, has been developed over the last years within IMEC [4] on Lattice Matched (LM) layer structures on InP, purchased from commercial suppliers. The used epilayer consists of a 250 nm $In_{.52}Al_{.48}As$ buffer layer with the 20 nm $In_{.53}Ga_{.47}As$ channel grown on top, followed by the high bandgap $In_{.52}Al_{.48}As$. At this interface a 2-dimensional electron gas (2-DEG) will arise in the channel layer as a consequence of the discontinuity in the conduction band. The channel is provided with electrons by the $5 \cdot 10^{12}$ cm^{-2} Si delta-doping, separated from the channel by a 6 nm spacer layer. The following 20 nm $In_{.52}Al_{.48}As$ layer will act later on as a Schottky barrier for the gate. Finally, a 7 nm $6 \cdot 10^{18}$ cm^{-3} Si-doped $In_{.53}Ga_{.47}As$ cap layer is applied to facilitate the forming of ohmic contacts and to prohibit oxidation of the Schottky layer.

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At room temperature this epitaxial sequence results in an electron density $n_e = 2.1 \cdot 10^{12}$ cm^{-2} and a low-field mobility $\mu = 10500$ cm^2/V·s.

Mesa isolation is done in a phosphoric acid based solution for removal of the active layer, followed by an etch step in a succinic acid based mixture to reduce the sidewall leakage from gate to channel [5].

The Ni/Au/Ge/Ni/Au ohmic contacts are applied by e-beam and result after lift-off and alloy in an ohmic contact resistance of about 0.2 • ·mm [6]. This value also depends on the exact layer structure on which the contact is applied.

For definition of the gate e-beam lithography is used. With this tool, a gate length down to 0.15 μm can be obtained, combined with a T-shaped gate for reduced gate resistance, using two-level resist.

For the recess etch of the cap layer an etchant based on succinic acid is used. This mixture etches $In_{.53}Ga_{.47}As$ with a selectivity of approximately 23:1 over $In_{.52}Al_{.48}As$. After the etchant has reached the Schottky layer only lateral etching is performed, increasing the gate isolation. Gate leakage current and gate-drain breakdown voltage can be improved by overetching, although the increased source and drain resistances reduce the HF performance.

Finally, after gate metal (Pt/Ti/Pt/Au) deposition and lift-off, the devices are passivated by PECVD of Si_3N_4 to stop oxidation of the recessed area and stabilize the gate mechanically. A cross-section made by Focused Ion Beam (FIB) of the source-drain region of a finished device is given in Figure 1. The dark region at the bottom is the substrate with the epi-layer (grey) on top. The gate is shifted towards the source (left side in the figure) to reduce source resistance. At the outer left the contacting metallization on top of the ohmic metal is visible. Dirt on top of the device is originating from Au sputtering to avoid charging during imaging.

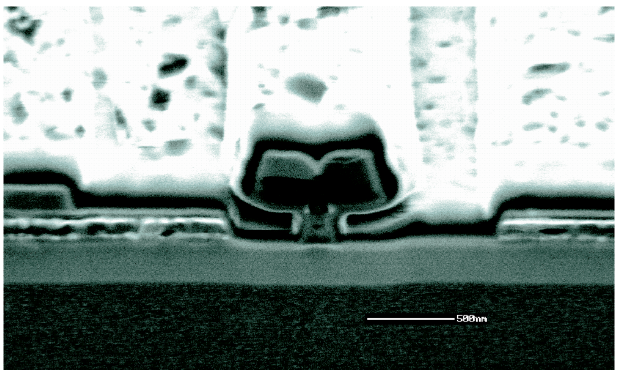

Fig. 1. Cross-section of passivated InP HEMT with 0.15 µm T-gate. Source contact on the left side and drain on the right.

This technology, developed on InP based epilayers, is also used to fabricate devices on the MM layer structures. No changes in the process are needed, as can be expected because the active layers are identical for all substrate types.

II. Metamorphic layers

II.a Quaternary buffer

A first type of MM layer structures is one with a quaternary buffer based on AlGaAsSb [7]. Although four elements are more complex to control from a growing point of view, it gives an additional degree of freedom with respect to bandgap energy.

Figure 2 displays the Sb content in AlGaAsSb to be lattice matched with InAlAs and InGaAs. Also displayed (right axis) is the corresponding bandgap energy. To meet the lattice matching condition with InAlAs and InGaAs with Indium contents of 50%, The Sb content of the buffer has to be 45%. Below the buffer a 5nm AlAs and 35 nm AlSb nucleation layers are grown at 550 °C, to ensure good starting conditions. Next, the approximately 2 µm thick buffer is grown at 500 °C. Because of the large lattice mismatch many defects will be initiated at the start of the buffer, which will be overgrown during the rest of the buffer growth. The top of the buffer consists of a crystal with a lattice constant equal to InP, with low defect density. On top of this, all structures can be grown, which are possible on InP. The GaAs substrate has been transferred into a virtual InP substrate. For comparison, an identical heterostructure as discussed for InP has been grown metamorphic on GaAs.

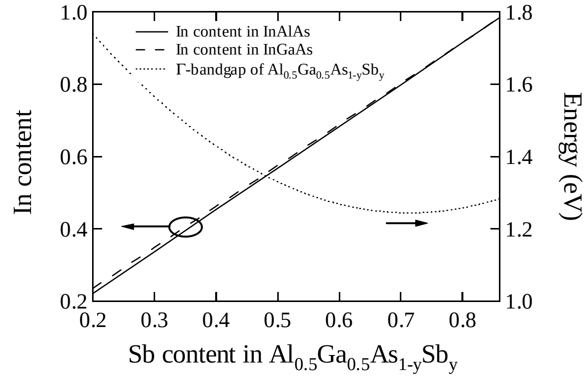

Fig. 2. Indium content of InAlAs and InGaAs for lattice-matching condition to a strain-relaxed $Al_{.5}Ga_{.5}As_{1-y}Sb_y$ layer (right axis: calculated direct bandgap at 300 K of $Al_{.5}Ga_{.5}As_{1-y}Sb_y$ as a function of the Sb content).

The structural quality and composition of the quaternary AlGaAsSb buffer layer was determined by (400) x-ray diffractometry. Figure 3 shows a high-resolution x-ray diffraction rocking curve of the discussed layer structure. Two peaks are clearly resolved: At a smaller diffraction angle than the GaAs substrate (33.03°) the quaternary AlGaAsSb buffer layer (31.62°) can be identified. The rocking curve full width at half maximum of 260 arcsec demonstrates the good structural quality and in-depth homogeneity in composition of the buffer layer, taking the large lattice mismatch into account.

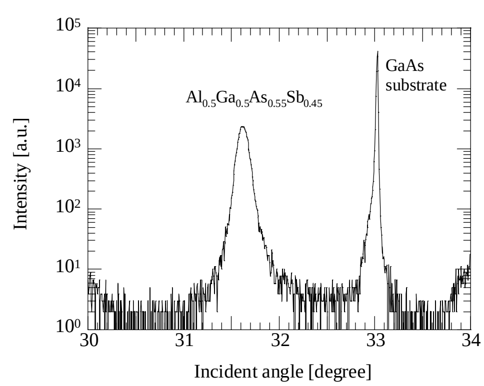

Fig. 3. Cu Kα1 (400) x-ray diffraction pattern of an AlGaAsSb buffer layer on a GaAs substrate.

By Hall measurements and using the Van der Pauw method the electron mobility and density of the modulation-doped InGaAs/InAlAs quantum well structure are determined. At room temperature this layer showed an electron mobility of 8500 $cm^2/V\cdot s$ and a sheet concentration of $3.5\cdot10^{12}$ cm^{-2}.

II.b Ternary buffer

A second type of buffer layer for MM growth on GaAs consists of the ternary InAlAs compound and is based on a gradual change in lattice constant instead of the abrupt approach. By starting with 0 % In, the AlAs is fully lattice matched to the GaAs substrate. During the following 800 nm the In content is increased gradually to 57 %, which is beyond the value to be LM to InP (52 %). This overshoot is in the next 100 nm linearly brought back to the LM value of 52%. This inverse step [8] in the buffer allows a high relaxation of the mismatch strain, improving the crystal quality of the layers to be grown on top of this.

To allow mutual comparison, the identical heterostructure has been grown on this buffer as well. At room temperature the layer on this ternary buffer yields the following properties: The electron mobility is 9300 $cm^2/V \cdot s$ and the electron density amounts $3.0 \cdot 10^{12}$ cm^{-2}.

For both types of buffer the layer characteristics are comparable to the InP values, with slightly reduced mobilities for the metamorphic structures due to the higher defect density. The electron density is significant higher for both GaAs based heterojunctions due to a higher doping level in the Si δ-layer.

III. Device performance

On all three presented layers, LM to InP and MM on GaAs with quaternary abrupt and ternary gradual buffer, HEMT's have been processed. All devices are fabricated with an identical process. For both metamorphic buffers a comparison with the InP based devices is made.

III.a Quaternary buffer

Firstly, 100 µm devices have been processed on the layer with the abrupt quaternary buffer structure. Figure 4 shows the transfer characteristics of such a device at V_{ds} = 1 V, with a gate length of 0.25 µm.

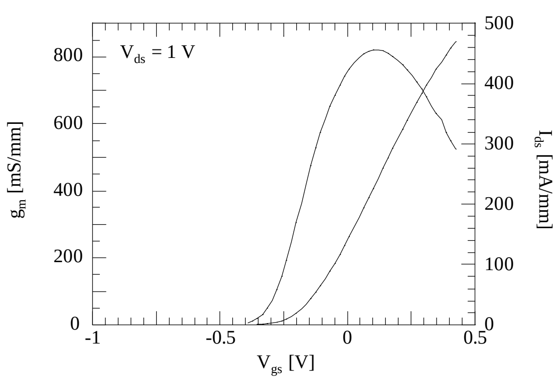

Fig. 4 Drain-source current and transconductance as a function of gate-source voltage, for a 0.25 x 100 μm^2 MM HEMT with a quaternary buffer.

A maximum transconductance of just over 800 mS/mm is obtained at V_{gs} = 0.1 V, whereas the channel current reaches a saturation value close to 500 mA/mm. A sharp pinch-off can be seen at a threshold voltage of V_t = - 0.3 V.

When looking at the output characteristics of the same device, we see well-behaved I-V curves, showing no traces of impact ionization, combined with a low output conductance (g_{ds} = 40 mS/mm). Combined with the transconductance, this results in a DC voltage gain of g_m/g_{ds} = 20.

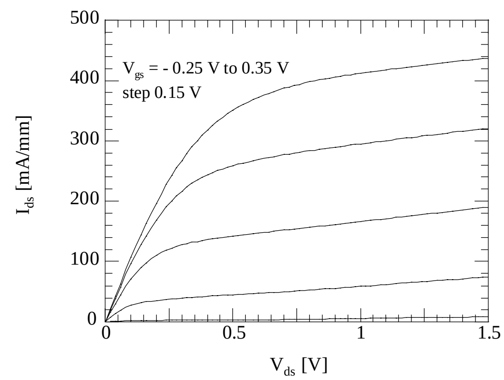

Fig. 5 Output characteristics for a 0.25 x 100 μm^2 metamorphic transistor, showing a low output conductance at normal bias conditions of g_{ds} = 40 mS/mm.

Furthermore, S-parameter measurements revealed a current gain cut-off frequency f_T of 87 GHz and a maximum oscillation frequency f_{max} of 140 GHz.

Values for the devices on InP substrates, processed in parallel, are: g_m = 800 mS/mm, g_{ds} = 65 mS/mm, f_T = 100 GHz and f_{max} = 150 GHz.

III.b Ternary buffer

With the identical mask set (not optimized for HF performance) the GaAs wafers with the ternary buffer structure have been processed. In Figure 6 the transfer characteristics of such a device at V_{ds} = 1 V is depicted. The gate length is 0.25 µm.

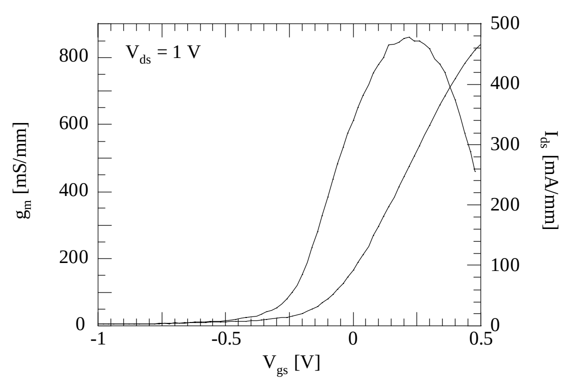

Fig. 6 Drain-source current and transconductance as a function of gate-source voltage, for a 0.25 x 100 μm^2 MM HEMT with a ternary buffer.

The transconductance reaches a maximum of 860 mS/mm at Vgs = 0.2 V and the open channel current exceeds 460 mA/mm. These are excellent DC values which exceed the values for the InP based HEMT's.

Figure 7 displays the output characteristics of the HEMT with a ternary buffer. Also for this layer the output conductance is limited (g_{ds} = 35 mS/mm) by the high bandgap of the thick InAlAs buffer material (1.55 eV versus 1.34 eV for InP), whereas the InP based layers have an only 250 nm thick InAlAs buffer on the InP substrate.

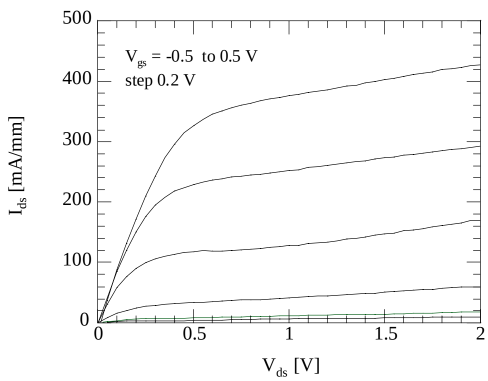

Fig. 7 Drain-source current and transconductance as a function of gate-source voltage, for a 0.25 x 100 μm^2 MM HEMT with a ternary buffer.

A drawback of this specific layer is the low breakdown voltage of BD_{gd} = 2.5 V, which is expected to be a consequence of an In content higher than the projected 52%. The resulting gate leakage current also limits the HF performance; The cut-off frequency is extracted to be f_T = 75 GHz with a maximum oscillation frequency of f_{max} = 115 GHz. Considering the gate length and the high gate leakage current, these are competitive values. When adjusting the In content towards 52% the performance is expected to further improve.

VI. Conclusions

In this paper we have shown the possibilities of GaAs based metamorphic layers. An abrupt quaternary and a gradual ternary buffer layer have been presented, demonstrating that the performance of InP based HEMT's can be met up to 90%. This technique results in a virtual substrate, with a lattice constant that can be chosen freely in a wide range.

Additionally, the fabrication process developed on InP can be directly transferred, without the adjustment of any process parameter.

This gives the opportunity of introducing a new family of extremely high performant devices on GaAs, combining the improved performance of InP based heterostructures with the advantages of GaAs as substrate material.

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