High-Performant High-Gain Amplifiers
Based on Metamorphic GaAs HEMT's

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Introduction

For almost a decade InP based HEMT's have shown to be the best performing three-terminal devices [1]. It combines high gain with low noise levels, resulting in excellent performance in the microwave and millimeter wave range. MMIC's with operating frequencies up to 100 GHz and beyond [2,3] have been realized and demonstrate the applicability of this technology.

Despite its convincing performance level, InP is unlikely to break through in mass-market applications such as automotive radar and LAN's because of several practical reasons. First of all, there is the availability of only 2" and 3" substrates at a high cost per square inch. In combination with its brittleness, this strongly limits the manufacturability of InP, resulting in a significant higher cost level compared to GaAs.

Over the last years, the technology of metamorphic GaAs based HEMT's has matured, demonstrating performance levels close to InP with f_T values of typically 200 GHz [4]. In these devices, the advantages of the GaAs substrate are combined with the performance level of InP based heterostructures, yielding way for production for consumer applications.

Until now, research efforts were mainly on device level. In this paper, we first will present the results of metamorphic devices based on a double delta-doped heterostructure, grown by MBE on GaAs with a ternary graded InAlAs buffer. Secondly, we integrate these devices monolithically into high-gain amplifiers in the Q- and W-band. These coplanar M^4IC's (metamorphic MMIC's) have been fabricated with a mask set, originally designed for InP based devices. A performance comparison between MMIC's on LM InP and MM GaAs is made.

I. Layer growth

The large 4% lattice mismatch between GaAs and InP can be overcome with a buffer. Although quaternary AlGaAsSb buffers have been used as well [5], ternary buffers are most commonly used [6]. This is mainly due to the complexity of growth of quaternary material by molecular beam epitaxy (MBE).

In this work we used a graded InAlAs buffer of 1 µm to relax the built up strain. Figure 1 schematically displays the grown metamorphic heterostructure on GaAs. After an initial GaAs nucleation layer the 1 µm InAlAs buffer grades from 0% to 57% Indium. Most of the defects originating from the change in lattice constant are overgrown in this layer. A 100 nm reverse step towards $In_{.52}Al_{.48}As$ is added to further improve the crystalline quality of the grown top layer. The actual heterostructure commences with a 100 nm $In_{.52}Al_{.48}As$ buffer and a first Si δ-doping of $2.5 \cdot 10^{12}$ cm^{-2}, followed by a 5 nm $In_{.52}Al_{.48}As$ spacer layer.

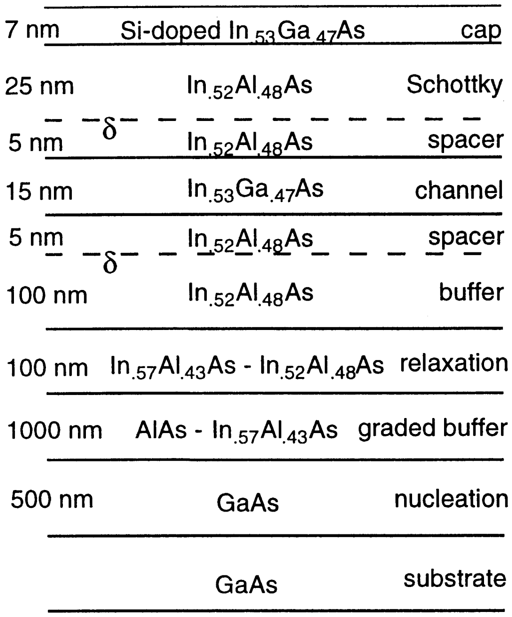

Fig. 1. Schematic sequence of the double delta-doped InAlAs/InGaAs HEMT layer on a streain-relaxed InAlAs graded buffer on a GaAs substrate.

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The top Si δ-doping of $5 \cdot 10^{12}$ cm^{-2} is separated from the 15 nm $In_{.53}Ga_{.47}As$ channel by a 5 nm $In_{.52}Al_{.48}As$ spacer layer. A 25 nm $In_{.52}Al_{.48}As$ Schottky layer and a 7 nm Si-doped $In_{.53}Ga_{.47}As$ cap layer complete the structure.

Table 1 shows the low field characteristics at room temperature of the MM structure on GaAs and the results of a similar layer, LM to InP.

@ room temp.	LM on InP	MM on GaAs
μ [cm^2/V·s]	5480	6850
n_e [10^{12} cm^{-2}]	5.1	5.7
R_{sqr} [Ω]	223	159

Table 1. Low-field characteristics at room temperature of double δ-doped heterojunction on both InP (lattice matched) and GaAs (metamorphic).

The MM GaAs structure displays excellent values of μ = 6850 cm^2/V·s and $n_e = 5.7 \cdot 10^{12}$ cm^{-2}, which even compare favorably with InP based layers. The differences in values can largely be attributed to the fact that the InP layer is delivered from a commercial supplier, whereas the metamorphic layer is grown in-house. Small deviations in effective doping levels, layer thickness and composition can occur. These results show that high-quality metamorphic structures can be grown on GaAs.

II. Device performance

II.a Processing

For the fabrication of MM HEMT's the exact process is taken, as used for the production of LM HEMT's on InP. This process is developed within IMEC and has previously been described in more detail in literature [7].

Mesa isolation is done in a phosphoric acid based solution followed by e-beam deposition of the Ni/Au/Ge/Ni/Au ohmic contacts. After an alloy step this results alloy in an ohmic contact resistance of about 0.2 Ω·mm [8]. For definition of the gate e-beam lithography is used. With this tool, a gate length of typically 0.20 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.

II.b Performance

With the described process devices have been fabricated on the metamorphic GaAs based heterostructure. Figure 2 shows the DC characteristics of a 0.20 μm long device. A maximum transconductance of g_m = 670 mS/mm at V_{gs} = -0.55 V is combined with a maximum channel current I_{ds} = 660 mA/mm. All measurements are performed at V_{ds} = 1 V.

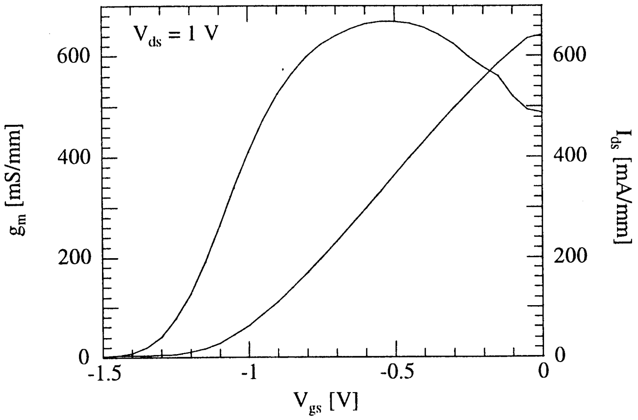

Fig. 2. Drain-source current and transconductance as a function of gate-source voltage, for a 0.20 x 100 μm^2 metamorphic device at V_{ds} = 1 V.

These characteristics resemble very strongly the ones obtained on LM InP HEMT's.

Additionally, S-parameter measurements up to 50 GHz reveal an extrinsic cut-off frequency of f_T = 90 GHz and a maximum frequency of oscillation f_{max} = 130 GHz. It has to be noted that these results are obtained on devices, processed with a mask-set not optimized for RF application (large pad capacitance). Only extrinsic values are given to make a direct comparison between different layer structures. These values reach typically up to 90% of InP based devices (f_T = 102 GHz and f_{max} = 154 GHz). These results already indicate that the metamorphic technology can find its application in MMIC's at microwave and millimeterwave frequencies.

III. Circuit design and performance

In this Section, two examples of coplanar M^{4}IC's (metamorphic MMIC's) will be presented and discussed. Both are narrow-band high-gain amplifiers, originally designed to be processed on LM InP heterostructures. This mask-set is used on metamorphic layers without any adjustment in design and process, and this effort is therefore just a first-order approximation of the possible performance level of M^{4}IC's. Both a Q-band and a W-band circuit will be presented and compared with the InP based original, which have been extensively described in literature [7,9].

III.a Q-band amplifier

The first metamorphic demonstrator is a single-stage narrow-band amplifier, designed for maximum gain around 40 GHz. Figure 3 displays an SEM picture of the fabricated device. The coplanar lay-out comprises of transmission lines, MIM capacitors and resistors. The active device is based on a cascode design, making use of dual gate technology for tuneability after fabrication.

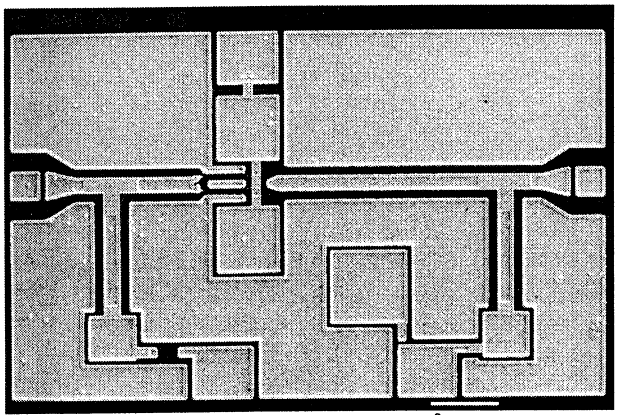

Fig. 3. SEM picture of the 800 x 500 μm^2 Q-band high-gain amplifier. RF in- and output are at left and right. DC bias pads are at top (DC gate) and bottom (gate and drain) of the circuit.

After manufacturing with the InP based process, RF measurements display the following results: A maximum gain of 17.5 dB is reached at a frequency of 40.5 GHz, combined with an excellent in- and output matching of –19 dB and –27 dB, respectively. Figure 4 gives an overview of the RF results between 30 GHz and 50 GHz.

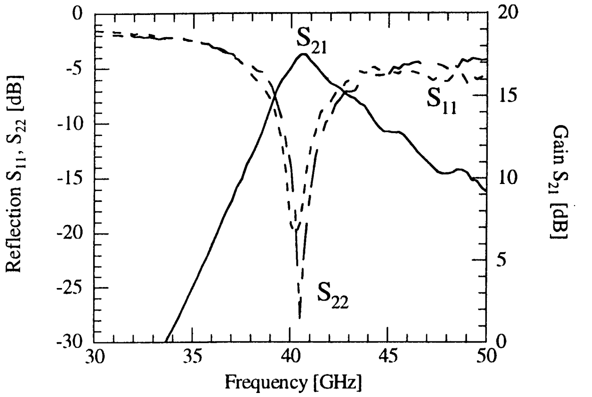

Fig. 4. Gain (S_{21}) and in- and output reflection (S_{11} and S_{22}) of the M^4IC betweeen 30 and 50 GHz. DC bias conditions are V_{g1s} = -0.55 V, V_{g2s} = 0.35 V and V_{ds} = 2 V.

The corresponding values for the original InP based circuit are a maximum gain of 17 dB and an in- and output matching of –15 dB and –20 dB, respectively. These values are obtained at the same operating frequency as the M^4IC.

Comparison of the figures of both technologies show that there is little difference in performance level at this frequency level.

III.b W-band amplifier

To become a competitor with InP, the metamorphic technology has to demonstrate its abilities at frequencies higher than 80 GHz. For that reason, a W-band amplifier has also been processed and compared with InP. Figure 5 shows an SEM picture of this circuit, designed in the identical technology as the Q-band amplifier.

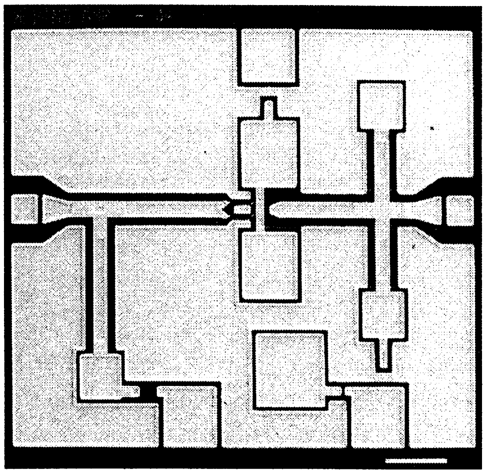

Fig. 5. SEM picture of the 600 x 700 μm^2 metamorphic 1-stage dual-gate W-band amplifier. RF in- and output are at left and right. DC bias pads are at top (DC gate) and bottom (gate and drain) of the circuit.

In Figure 6 the gain and output reflection of this circuit is displayed for operating frequencies between 75 GHz and 100 GHz. A maximum gain of 10.5 dB is obtained at an operating frequency of 84 GHz, in combination with an output matching of –15 dB.

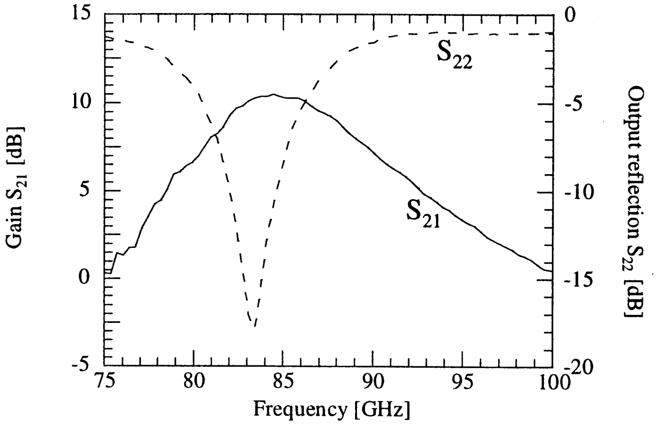

Fig. 6. Gain (S_{21}) and output reflection (S_{22}) of the W-band M^4IC between 75 GHz and 100 GHz. Input reflection was below detection limit, due to used attenuation.

The original InP circuit demonstrates a gain of 12.4 dB at 94 GHz with an output reflection below –11 dB. The shift in frequency can be largely attributed to a lower output conductance in the MM layer due to the second doping layer (the LM InP layer has only a single delta-doping). An adjustment of the matching network would be required to obtain maximum gain at 94 GHz.

VI. Conclusions

In this paper we have shown that metamorphic heterojunctions can be grown on GaAs, with similar layer characteristics as obtained from lattice matched structures on InP. Devices have been fabricated on these layers with the identical process as developed for InP based layers, with an RF performance level reaching up to 90% of the InP results.

In a next step, two metamorphic MMIC's (M^4IC's) have been fabricated to demonstrate the abilities of this technology in the millimeter wave range. Although the design of the circuits and the used mask-set were based on InP LM HEMT's, the performance level was in the range of InP based circuits. A Q-band M^4IC slightly outperformed its InP based counterpart, whereas at the W-band a 2 dB lower gain was obtained (10.5 dB instead of 12.4 dB) in combination with a frequency shift. Because these differences can be strongly reduced by adapting the design, we can conclude that the metamorphic technology is a strong competitor of InP for cost-driven mass-market applications.

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