Fabrication of 160-nm T-gate metamorphic AlInAs/GaInAs HEMTs on GaAs substrates by metal organic chemical vapour deposition*

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The fabrication and performance of 160-nm gate-length metamorphic AlInAs/GaInAs high electron mobility transistors (mHEMTs) grown on GaAs substrate by metal organic chemical vapour deposition (MOCVD) are reported. By using a novel combined optical and e-beam photolithography technology, submicron mHEMTs devices have been achieved. The devices exhibit good DC and RF performance. The maximum current density was 817 mA/mm and the maximum transconductance was 828 mS/mm. The non-alloyed Ohmic contact resistance R_c was as low as 0.02 Ω-mm. The unity current gain cut-off frequency (f_T) and the maximum oscillation frequency (f_{max}) were 146 GHz and 189 GHz, respectively. This device has the highest f_T yet reported for a 160-nm gate-length HEMTs grown by MOCVD. The output conductance is 28.9 mS/mm, which results in a large voltage gain of 28.6. Also, an input capacitance to gate-drain feedback capacitance ratio, Cgs/Cgd, of 4.3 is obtained in the device.

Keywords: GaAs, metamorphic, high electron mobility transistor, metal-organic chemical vapour deposition

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1. Introduction

There has been an intense interest in the fabrication of GaAs-based high-speed devices for digital and microwave applications by molecular beam epitaxy (MBE) or metal organic chemical vapour deposition (MOCVD). High electron mobility transistors (HEMTs) based on the lattice-matched InAlAs/InGaAs/InP material system have demonstrated the highest gain and lowest noise figure for any three-terminal device at millimeter wave frequencies. Although InP-based devices have been shown to have superior performance in higher frequency and power applications, the InP industry has not experienced similar demand and growth. The downturn of the photonics industry, a major driving force behind the InP-based devices and circuits, did not help. Without large volume consumption, the cost of InP substrates and chip manufacturing remains high, making InP-based devices less competitive in the market place.

The emergence of metamorphic devices in the past few years shed light on this new approach of improving RF device performance at a lower cost. There are different buffering schemes on GaAs substrate allowing the growth of structure for high-quality RF devices traditionally grown on InP substrates. MBE has been extremely successful in developing metamorphic technology. There have been many reports on mHEMTs and mHBTs grown by MBE, with devices results comparable to those on InP substrates.[1−4] Metamorphic technology by MOCVD is much lagged behind. Although growth of structures for RF devices by MOCVD has always been at a slower development pace than MBE, the commercial success of a few epitaxial material suppliers using MOCVD demonstrated the manufacturing advantages of MOCVD. One of the difficulties of growing metamorphic RF devices by MOCVD is to suppress the buffer leakage. Slight buffer leakage tends to degrade the RF operation of

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HEMTs with parasitic components.[5−7] With a 4% lattice mismatch between InP and GaAs, the common metamorphic growth technique is to grow a thick buffer with graded alloy compositions or superlattices. Unintentional impurities incorporated in these layers decrease the resistivity of the buffer, resulting in devices that cannot be pinched off. We have developed a growth technique of a comparatively thin multi-stage buffer to obtain high resistivity in the buffer layer leading to good device performance. This sets the stage for potential high volume production of mHEMTs by MOCVD.

2. Material growth and device fabrication

The wafers were grown by MOCVD on about 10 cm [001] oriented semi-insulating GaAs substrates in an Aixtron AIX-200/4 MOCVD system. The composite buffer stack consists of a low-temperature (LT) InP nucleation layer (110 nm), high-temperature (HT) undoped InP (650 nm) as buffer 1; LT-InP:C (100 nm) as buffer 2, and undoped LT-$Al_{0.49}In_{0.51}As$ (200 nm) and HT-$Al_{0.49}In_{0.51}As$ (100 nm) as buffer 3 and buffer 4. A 25-nm undoped $Ga_{0.47}In_{0.53}As$ channel was grown on the buffer layer and is followed by a 5-nm undoped $Al_{0.49}In_{0.51}As$ spacer layer, a Si-doping plane (4×10^{12} cm^{-2}), a 25-nm undoped $Al_{0.49}In_{0.51}As$ Schottky contact layer and a 15-nm $Ga_{0.47}In_{0.53}As$ cap layer. All the layers are compositional lattice matched to InP. The metamorphic layer structures grown on GaAs substrates have been characterized and demonstrated with good electrical properties in our previous works.[8−10] With the cap layer removed, a room-temperature two-dimensional electron gas (2DEG) electron concentration of 4.6×10^{12} cm^{-2} and mobility of 8300 cm^2/V·s were measured for this hetero-structure. The root-mean-square (RMS) value of the surface roughness is 2.5 nm across a scan area of (10×10) μm^2.

The devices were fabricated with mesa isolation and six-layer metal system (Ni/Ge/Au/Ge/Ni/Au) Ohmic contacts. Using the transmission line model (TLM), the non-alloyed Ohmic contact resistance R_c was as low as 0.02 Ω·mm, which is due to the higher doping concentration in cap layer and optimization of Ohmic contact metal systems. Nanoscale T-gate devices were fabricated by a two-stage electron beam lithography process as shown in Fig. 1. A 10-nm-thick SiN_x film was deposited by plasma enhance chemical vapour deposition (PECVD) to define the gate footprint, and to mechanically support the T-shaped gate. After etching of the SiN_x film with CF_4/O_2 reactive ion etching (RIE), the gate-head pattern was formed by a bi-layer PMMA/P(MMA-MAA) process. The high selectively citric acid-based etchant was used to remove the highly doped GaInAs cap layer in order to stack T-shaped gates on the AlInAs barrier layer. Finally, Ti/Pt/Au was deposited as the Schottky gate contact. The space between gate-source (G-S) and gate-drain (G-D) was 1.0 μm and 2.0 μm.

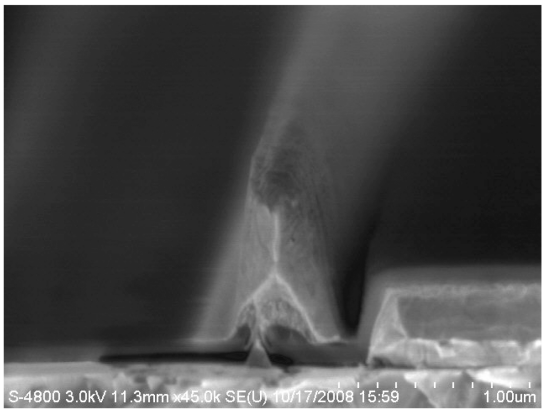


Fig. 1. Cross-section scanning electron microscopy (SEM) graph of 160-nm T-shaped gate mHEMTs.

3. Results and discussion

The DC characterization of the 160-nm gate length mHEMTs was performed using an Agilent 4155 semiconductor parameter analyser. Figure 2 shows the I–V characteristics of a 160-nm mHEMT. The maximum drain current is 817 mA/mm. Figure 3 shows the transfer characteristics. The maximum extrinsic transconductance is 828 mS/mm at $V_{GS} = -0.65$ V and $V_{DS} = 1.0$ V, and the device

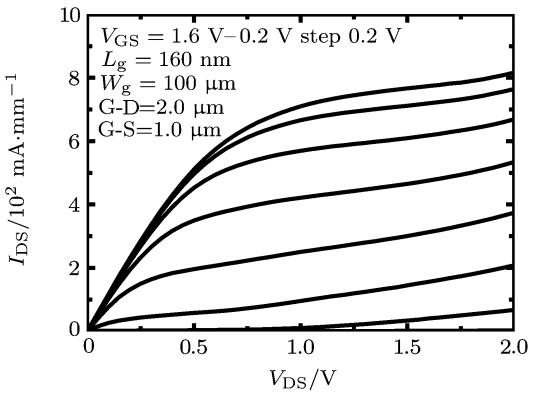


Fig. 2. Typical I–V characteristics of 160-nm mHEMTs.

threshold voltage is −0.95 V. Figure 4 shows the gate leakage current characteristics of the mHEMT. The device with composite buffer stack growth exhibites good pinch-off characteristics and little buffer leakage current, which will be further improved by optimizing the growth of buffer layer.

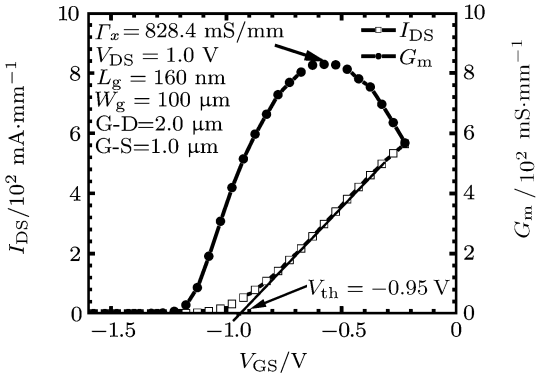


Fig. 3. Transfer characteristics of 160-nm mHEMTs.

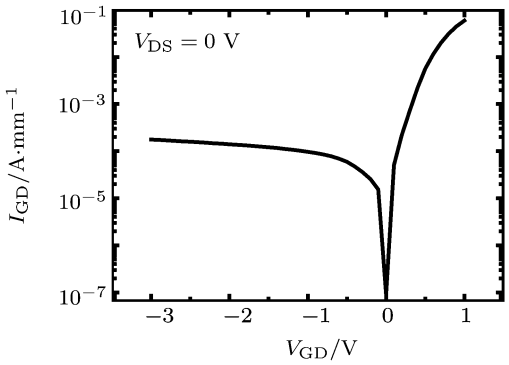


Fig. 4. Gate leakage current characteristics of mHEMTs at V_{DS} = 0 V.

On-wafer RF measurements were carried out on a 160-nm×100-μm mHEMT using a Cascade Microtech Probe Station and an HP8722 network analyser from 0.1 GHz to 39.5 GHz. Open on-wafer de-embedding structures were used to determine the parasitic capacitance of the probe pads and to de-embed the short circuit current gain $|h_{21}|$. Figure 5 shows the current gain and MSG/MAG as a function of frequency. The current gain cut-off frequency (f_T) and the maximum oscillation frequency (f_{max}) are 146 GHz and 189 GHz, respectively, the former value is the highest f_T yet reported for similar device grown by MOCVD. The optimum bias condition for maximum unity current gain cut-off frequency is determined to be V_{GS} = −0.5 V and V_{DS} = 1.0 V. The dependencies of f_T and f_{max} on the gate bias are shown in Fig. 6. Both f_T and f_{max} are relatively constant at both low and high gate biases, indicating a good linearity.

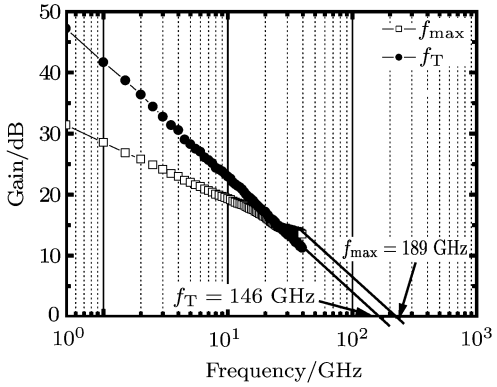


Fig. 5. Typical current gain and MSG/MAG as a function of frequency for 160-nm mHEMTs.

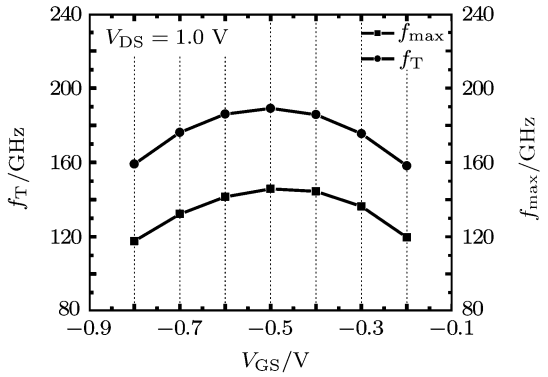


Fig. 6. Dependencies of f_T and f_{max} on gate bias for 160-nm mHEMTs, where V_{DS} is fixed at 1.0 V.

Table 1 shows the comparison of different AlInAs/GaInAs HEMTs performance, which were grown by MBE on GaAs or InP substrate with similar gate-length HEMTs. The performance of mHEMTs grown by MOCVD is comparable to that of HEMTs grown by MBE technology. These results are very encouraging toward the manufacturing of metamorphic devices on GaAs substrates by MOCVD.

We also analysed input capacitance to gate–drain feedback capacitance ratio, C_{gs}/C_{gd} and voltage gain, G_m/G_{ds} as shown in Table 2. They are much important RF parameters and have a strong influence on the value of f_{max}. C_{gs}/C_{gd} and G_m/G_{ds} were determined by equivalent circuit modeling of measured 10 GHz∼30 GHz S-parameters (V_{DS} = 1.0 V). The device has an extrinsic transconductance (G_m) of 828 mS/mm, and an output conductance (G_{ds}) of 28.9 mS/mm, G_m/G_{ds} is 28.6. The extremely low output conductance is a result of the large gate–drain recess distance (L_{gd}). An input capacitance to gate–drain feedback capacitance ratio, C_{gs}/C_{gd}, is 4.3.

Table 1. Comparison of AlInAs/GaInAs HEMTs performance.

Hetero-structure	Sub.	Growth	Mob.	L_g/nm	G_m/(mS/mm)	f_T/GHz	f_{max}/GHz	Date	Ref.
$In_{0.53}GaAs/In_{0.52}AlAs$	GaAs	MBE	N/A	100	750	154	300	2004	[11]
InGaAs/InAlAs	GaAs	MBE	N/A	100	690	189	334	2004	[12]
$In_{0.53}GaAs/In_{0.52}AlAs$	GaAs	MBE	9100	150	740	150	240	2003	[13]
InGaAs/InAlAs	InP	MBE	8800	150	800	151	172	2006	[14]
$In_{0.53}GaAs/In_{0.52}AlAs$	GaAs	MOCVD	8300	160	828	146	189	2010	HK PTC

Table 2. Small signal equivalent circuit model parameters of 160-nm mHEMTs.

C_{gs}/fF	C_{gd}/fF	C_{ds}/fF	G_m/mS	G_{ds}/mS	C_{gs}/C_{gd}	G_m/G_{ds}
149.86	34.89	64.5	82.8	2.89	4.3	28.6

4. Conclusion

In summary, we have successfully grown metamorphic AlInAs/GaInAs HEMTs with good device performance by the MOCVD technique, through the introduction of a multi-stage buffer. Our developed metamorphic device structure is lattice-matched to InP. With 160-nm gate-length devices, f_T and f_{max} of 146 GHz and 189 GHz respectively were obtained. The result is comparable to the structure of mHEMT grown by MBE. We believe these results are the best reported for MOCVD grown mHEMTs, and sufficient for high frequency, and high-speed applications. With the anticipated demand of commercial high-speed and high-performance transistors, mHEMTs technology by MOCVD is very attractive for manufacturing.

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