High Performance Metamorphic HEMTs on 100-mm GaAs Substrate

M. Kao, E. A. Beam III, M. Muir, P. Saunier, H. Tserng, and W. R. Frensley*

TriQuint Semiconductor
P. O. Box 833938, Richardson, Texas 75083-3938, USA
Phone: (972) 994-8556, e-mail: mkao@tqtx.com

*University of Texas at Dallas, Richardson, Texas 75083-0688, USA

ABSTRACT

We report the development of Metamorphic HEMTs (MHEMTs) with 43 to 63% InAs mole fraction channels on 100-mm GaAs substrates. A MHEMT with a 0.15μm gate length and a composite channel of $In_{0.63}GaAs$ and $In_{0.53}Ga_{0.47}As$ yielded an extrapolated f_T of 150GHz at a drain bias of 1.5 volts. Furthermore, excellent noise performance was achieved on devices from several 100-mm MHEMT wafers. At 26GHz, a noise figure of 0.73dB with an associated gain of 12.6dB was measured on a 100-μm wide MHEMT with an $In_{0.43}Ga_{0.57}As$ channel. This is the first report of MHEMTs fabricated on 100-mm substrates. To our knowledge, these results also represent the best noise performance yet reported for MHEMTs at this frequency band.

INTRODUCTION

While the gate lengths of FETs can be scaled down to enhance device RF performance, it does require high cost advanced lithography and has its practical scaling limitation of around 0.1-micron. The alternative approach of fabricating improved HEMTs is to build devices of same or more relaxed gate lengths on an epitaxial layer with a high indium channel on the GaAs substrate. The $In_xGa_{1-x}As$ channel layers of conventional GaAs PHEMT structures are typically limited to compositions of $x < 0.24$. To achieve the higher indium concentrations needed for higher performance applications InP-based lattice matched HEMT structures and/or GaAs-based structures incorporating lattice relaxed (metamorphic) buffer layers are required. Due to the maturity of GaAs processing and lower substrate cost, the Metamorphic HEMT (MHEMT) structure is a very attractive alternative to the InP-based materials approach.

Early work on MHEMTs was built on the conception of using compositionally graded antimony-based buffer (AlGaAsSb) as the transition layer from the GaAs substrates to the high indium active layer [1]. In recent years, excellent MHEMTs were also demonstrated based on graded AlInAs buffers, which is more compatible with conventional MBE systems [2]. In this study, we adopt the latter approach for the potential of easy production transfer.

The purpose of the present investigation is a demonstration of 100-mm MHEMT development in a production facility and a comparison of these technologies (PHEMT, MHEMT and InP HEMT) with respect to DC and small signal microwave performance.

MATERIAL GROWTH AND FABRICATION

A conventional pulse-doped pHEMT structure was used as a baseline for comparisons. 100-mm InP lattice-matched HEMT and mHEMT layers were grown in the same MBE reactor. The MHEMT buffer layers consisted of compositionally graded layers of $In_xAl_{1-x}As$, grown at low temperatures. The compositions of the topmost buffer layers ranged from $x = 0.40\text{-}0.53$. Symmetric and asymmetric X-ray diffraction rocking curves were used to verify the composition and degree of relaxation of the buffer layers. Similar active layers were grown for both the InP HEMT and MHEMT at a common growth temperature. Room temperature Hall mobilities in excess of 10,000 $cm^2/Vsec$ were obtained for both structures at sheet charge densities of $3.3\text{-}3.5 \times 10^{12}$ cm^{-2}. This is a 50-percent improvement in Hall mobility and a 10-percent improvement in sheet charge densities over conventional PHEMTs.

We have fabricated 0.15-micron T-gate devices on 100-mm MBE-grown MHEMT layers with either a single $In_{0.43}Ga_{0.57}As$ channel or a composite channel of 100 Å $In_{0.63}Ga_{0.37}As$ and 130 Å $In_{0.53}Ga_{0.47}As$. The layer

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structure of MHEMT layer with composite channel is shown in the Fig. 1.

$In_{0.45}GaAs$ Cap Layer	
$In_{0.45}AlAs$ Schottky	
Silicon Delta Doped	
$In_{0.45}AlAs$ Spacer	
$In_{0.63}GaAs$ Channel	100 Å
$In_{0.53}GaAs$ Channel	130 Å
$In_{0.45}AlAs$	
InAlAs Graded Layer	
GaAs Substrate	

Fig. 1. The layer structure of an InAlAs/InGaAs MHEMT wafer with graded InAlAs buffer of InAs mole fraction up to 45%.

The exact composition of $In_{0.63}Ga_{0.37}As/In_{0.53}Ga_{0.37}As$ channel was verified by comparing the X-ray diffraction rocking curves and model as shown in the Fig. 2. The layer also exhibits very close to 100-percent relaxation based on the comparison of the X-ray data on the (004) and (115) planes.

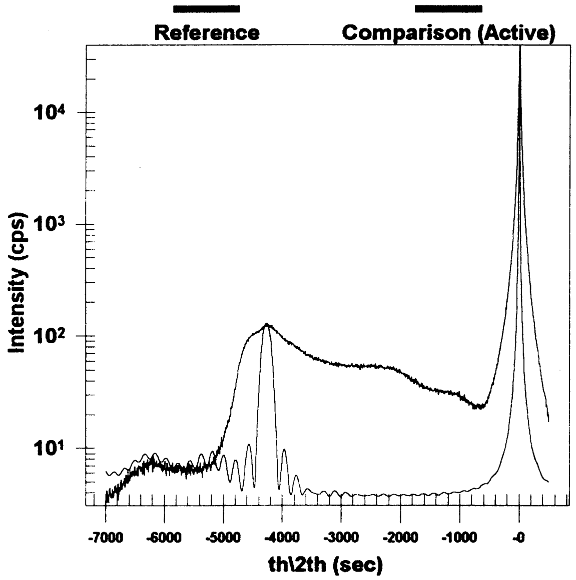

Fig. 2. Plots of simulation model and X-ray diffraction rocking curves on the (004) plane.

The entire wafer processing was done in a 100-mm GaAs foundry facility. Engineering supervision on fabrication is needed in only a few process steps, i. e. gate recessing. Device ohmic metal for the source and drain contacts is an alloyed Au/Ge-based metal stack. It is followed by a shallow mesa etch using wet chemicals and ion implantation for device isolation. 0.15-μm gate length T-shaped gates were defined by E-beam lithography. Low voltage automatic SEM was used to make sure that uniform and desired resist openings were achieved across wafers. A selective gate recessing etch was performed to remove the heavily doped cap layer and to reach the top of the InAlAs layer. Ti/Pt/Au metals were deposited to form the Schottky contact. Silicon nitride layers of 500 Å or 2000Å are deposited on the same wafer for evaluation of the effect of passivation on the RF performance.

DC CHARACTERISTICS

As shown in Fig. 3, the peak g_m of 150-micron wide MHEMT with 43% indium channel is 700mS/mm and the pinch-off voltage is 0 volts. The I-V curves with drain bias up to 3 volts of same size device are plotted in the Fig. 4. It exhibits a very low knee voltage of less than 0.4 volts.

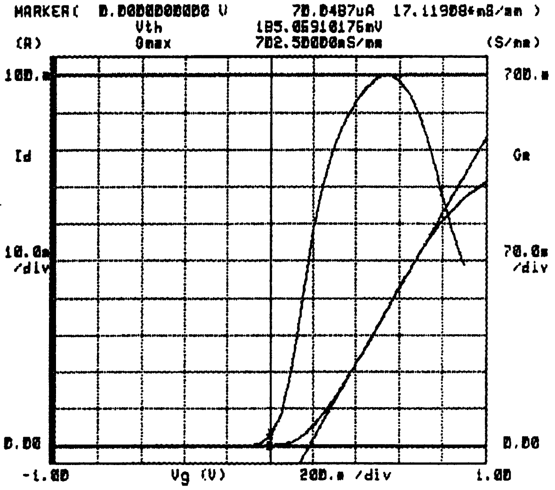

Fig. 3. Plots of g_m and I_d as a function of gate voltages for a 0.15μm x 150μm MHEMT at a drain voltage of 1.5 volts.

Typical device gate to drain breakdown voltages are measured to be 5.5 to 6.8 volts at I_{gd} = 1mA/mm. The standard deviation of pinch-off voltages that is evaluated at I_d = 1mA/mm is less than 50mV across the wafer.

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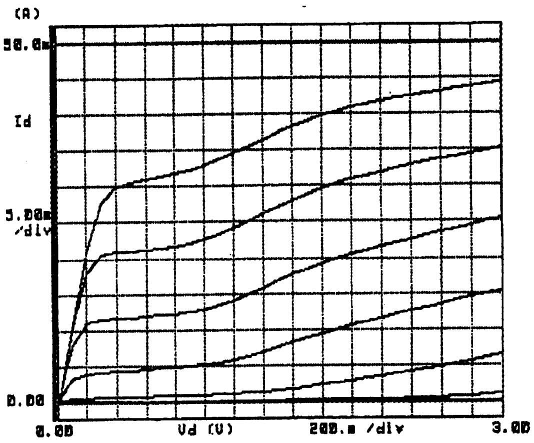

Fig. 4. I-V curves of a 150μm wide MHEMT. V_g of top curve is 0.5 volts and each gate voltage step is 0.1 volts.

SMALLL SIGNAL AND NOISE PERFORMANCE

S-parameters up to 50GHz were measured on 200-micron MHEMTs at a drain bias of 1.5 Volts and at a drain current of 100mA/mm. Gain-bandwidth frequencies (f_T) of 126 and 150GHz were extrapolated from $|H_{21}|^2$ curves using a 20dB per decade slope for MHEMTs with $In_{0.43}Ga_{0.57}As$ or $In_{0.63}Ga_{0.37}As$, respectively. This represents more than an 80-percent improvement in f_T in comparison with regular PHEMTs of 80GHz. Devices with thicker passivation of 2000Å nitride have gain-bandwidth frequencies of 6 to 12GHz lower in general. The lattice-matched InP HEMTs with an $In_{0.53}Ga_{0.67}As$ channel that were processed at the same time delivered comparable performance to the best MHEMTs with 43% indium channel.

On-wafer noise measurements were performed on the devices from three MHEMT wafers with single InGaAs channel. The best noise performances at 26GHz measured to be 0.73dB noise figure and 12.6 dB associated gain for a 100-micron MHEMT at V_d = 1.5 volts and I_d = 5 mA. In comparison with regular PHEMTs of the same gate length, the MHEMT yields about a 0.3 dB lower noise figure and 2 to 3dB higher gain at 26GHz. The noise performance as a function of drain current of a 100μm MHEMT from the second wafer with an $In_{0.43}Ga_{0.57}As$ channel is illustrated in the Figure 5. It shows the lowest noise figure of 0.74dB at I_d = 75mA/mm and the gain increases as drain current goes up.

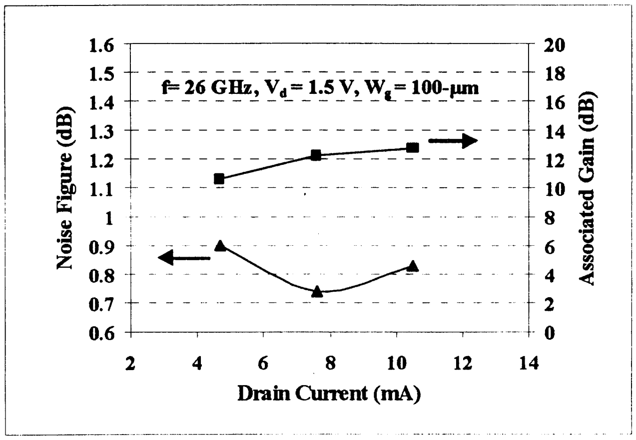

Fig. 5. Plots of noise figure and associated gain versus drain current at 26GHz of a 0.15μmx100μm MHEMT.

CONCLUSIONS

MHEMTs on 100-mm GaAs substrate were fabricated in a production line. MHEMTs with higher indium mole fraction exhibit much superior gain-bandwidth frequency response and noise performance to their PHEMT counterpart. We have demonstrated that MHEMTs on GaAs are an excellent device technology for low-noise millimeter wave applications.

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