W-band Penta-Composite Channel InAlAs/InGaAs Metamorphic HEMT for High Power Application and Comparison with Pseudomorphic HEMT

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Abstract

Advance device design of novel penta-composite channel of 0.25 µm InAlAs/InGaAs MHEMT has been reported for the first time in composite channel HEMT. Highest Indium mole fraction of 0.78 in channel and total channel thickness of 140 Å was found to be an optimized structure. It has both higher I_D of 1029 mA/mm and flatterer g_m of 648 mS/mm at V_{DS} of 1.3 *V*. AC analysis results f_T of 125 GHz and f_{max} of 250 GHz, which makes the device useful for W-band Power amplifier applications. Comparison between MHEMT and PHEMT has also been emphasized with respect to transconductance (g_m) and drain current (I_D).

INTRODUCTION

Superior carrier transport and other favorable electronic properties of InAlAs/InGaAs High Electron Mobility Transistor (HEMT) have the capability to achieve high power at very high frequency with high linearity. The prime motivation behind the increasing Indium mole fraction in channel is to increase conduction band discontinuity by reducing the bandgap of the channel. It increases the quantum well depth, confining more carriers in the channel, leading to rise in the possibility of forming multiple sub-band energy levels in quantum well below the equilibrium Fermi level, hence almost complete removal of three-dimensional carrier movement effects. Higher Indium percent in the material also has lower electron effective mass which enhances the mobility. However, higher Indium in channel results in phase in-homogeneities due to the onset of kink effect and both breakdown voltage (BV) and g_m flatness degrade [1, 2]. This problem can be solved by using composite channel structure where multiple materials are used with linear grading in channel to increase Indium mole fraction and accommodate the lattice mismatch at the same time [3]. We introduce the use of the MBE grown composite channel InGaAs/InAlAs/GaAs MHEMT of 0.25 µm gate length and 1 µm source to drain spacing. Our device structure design was focused towards the optimization of In%, δ-doping & spacer thickness to achieve high current with higher linearity at high frequencies. This high performance five channel device is well suited for power applications in a variety of W-band Front-Ends. Performance of MHEMT & PHEMT with respect to transconductance (g_m) and drain current (I_D) are also competed.

MHEMT DEVICE STRUCTURE

Due to metamorphic buffer, MHEMT allows wider range of channel design which results better maximum oscillation frequency, cut-off frequency and low frequency noise characteristics. Composite channel structure [4] fulfills the low noise, high linearity requirements while maintaining gate-drain BV. Our penta channel MHEMT device structure is shown in Fig 1, in which the top and bottom of $In_xGa_{1-x}As$ (x ~ 0.53) channel layers has high drift velocity and lower impact ionization under high electric field [4]. Relatively high bandgap of the lower indium mole of InGaAs channel (0.75 eV) limits impact ionization effects and the high band gap of the InAlAs Schottky layer (2 eV) improves the turn-on voltage [5], which results in a better on-state Breakdown Voltage (BV), a main limiting factor for power devices. High channel indium content is optimized by the aluminum content in spacer to avoid the kink effect while second next channel layer (x ~ 0.65) helps to introduce further indium content in the middle channel and middle $In_xGa_{1-x}As$ (x ~ 0.78) channel layer improves the electron mobility under low electric field.

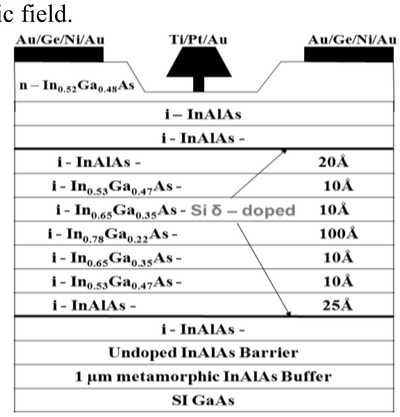

Fig 1: $In_{0.78}Ga_{0.22}As$ penta-composite channel structure MHEMT

RESULT AND DISCUSSIONS

We have designed the optimized penta-composite channel InAlAs/InGaAs structure, keeping in view the Matthews and Blakeslee model [4]. This aggressive channel design has been implemented, with Indium mole fraction as in Fig 1 with varying total channel thicknesses between 120Å to 250 Å. 140 Å has been found to be optimum with average Indium mole fraction of 0.7; resulting in high ΔE_C i.e. further confinement of free carriers in quantum well (QW). The transfer characteristics of 0.25 µm MHEMT is shown in Fig 2, where g_m is 648 mS/mm at V_{DS} of 1.3 V. The output characteristic is shown in Fig 3 with output saturation current (I_D) of 1029 mA/mm. At saturation the value of drain resistance, $R_{DS} = dV_D/dI_D \approx 10k\Omega$ and increases to 74 kΩ at V_D of 5 V.

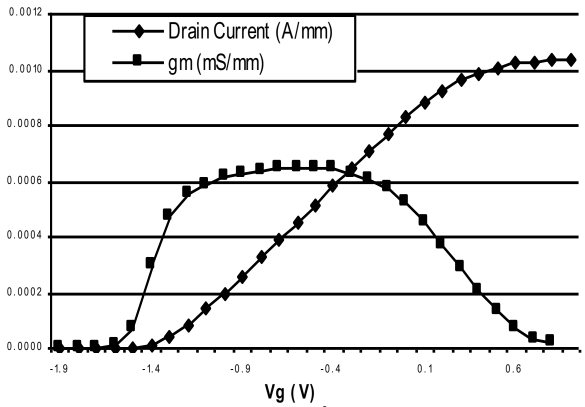

Fig 2: I_D & g_m vs V_D curve of 140Å InAlAs/InGaAs MHEMT

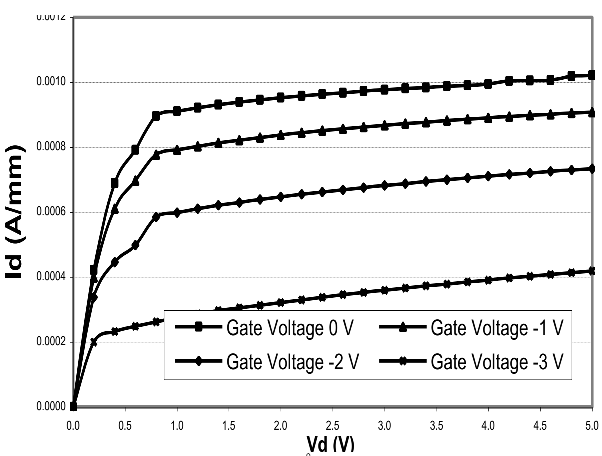

Fig 3: I_D vs V_D curve of 140Å InAlAs/InGaAs MHEMT

By varying channel thickness we have studied the same structure, with respect to g_m and output saturation current for two different values of delta doping (9×10^{18} / 3×10^{18} cm^{-3} and 8×10^{18} / 2×10^{18} cm^{-3} top/bottom respectively). The comparative results are shown in Fig 4, from where it can be said that 140 Å channel structure is the optimized one among others. Though 120 Å has greater g_m but it has much lower current which can be due to the scattering effect in narrow channel width. On the other hand in QW, 3D effect may arise in case of wider channels and result in lower current and g_m.

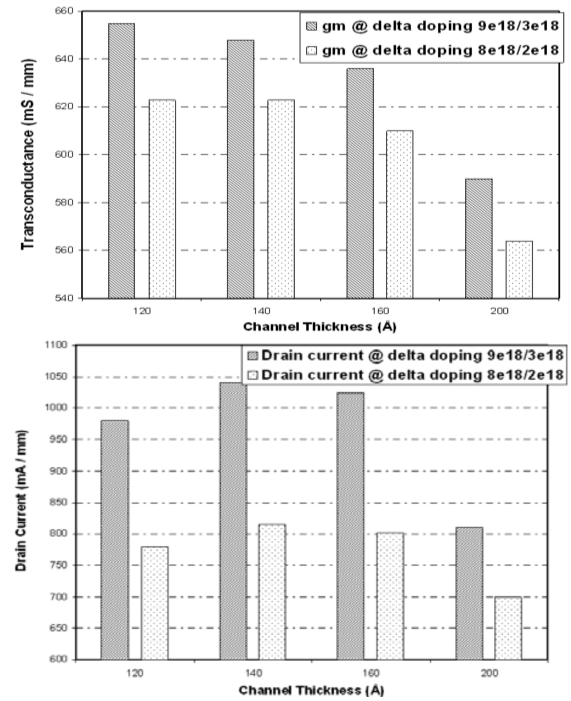

Fig 4: I_D and g_m vs. channel thickness of penta-composite MHEMT with two different δ-doping

The cut-off frequency f_T is estimated at 125 GHz and the expected maximum frequency of oscillation f_{max} is 250 GHz as shown in Fig 5.

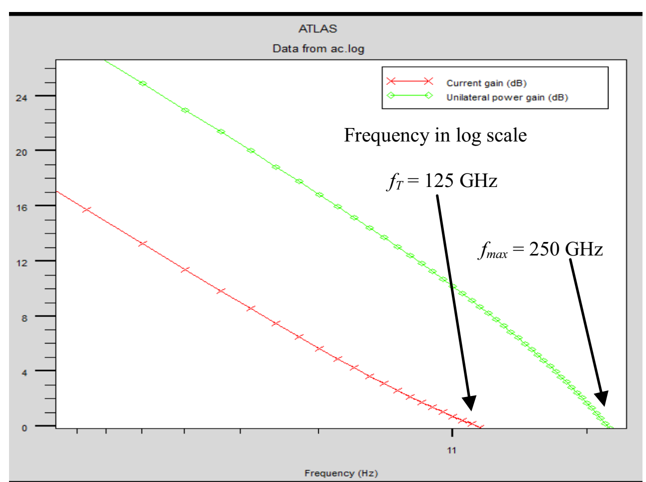

Fig 5: Frequency response of 140 Å InAlAs/InGaAs penta-channel HEMT

Table 1 shows the summary of the comparative results of the all optimized structure created in our design environment. It helps to determine the optimized structure and get the optimized values of both I_D and g_m for each structure.

Table 1: Comparative study among the optimized structures

Material Scheme	**Diff.. Channel Structure scheme**	**Optimized structure**	I_D	g_m
AlGaAs/InGaAs/ AlGaAs PHEMT (varying from 100Å to 250 Å)	Single (In% - 22) & Three channel (In% - 22/35/22 top/mid/bottom)	120 Å tri-composite channel	525 mA/ mm	440 mS/ mm
InAlAs/InGaAs/ InAlAs Metamorphic HEMT (varying from 100 Å to 250Å)	Single (In% - 53) and Three channel (In% - 53/67/53 top/mid/bottom)	100 Å tri-composite channel	760 mA/ mm	640 mS/ mm
	Penta-Composite channel Structure	140 Å penta-composite channel	1029 mA/ mm	648 mS/ mm

Ratio of third-order sideband power to fundamental power (IP3) is proportional to (g_m''/g_m). Reduction of this ratio (close to zero) presents improvement in linearity of the devices [7]. The comparative study of g_m and IP3 curve among these three optimized structures, as defined in Table 1, is shown in Fig 6 and 7 respectively. The results show that in both cases, 140 Å penta-composite channel MHEMT is better than conventional PHEMT as well as three-channel MHEMT.

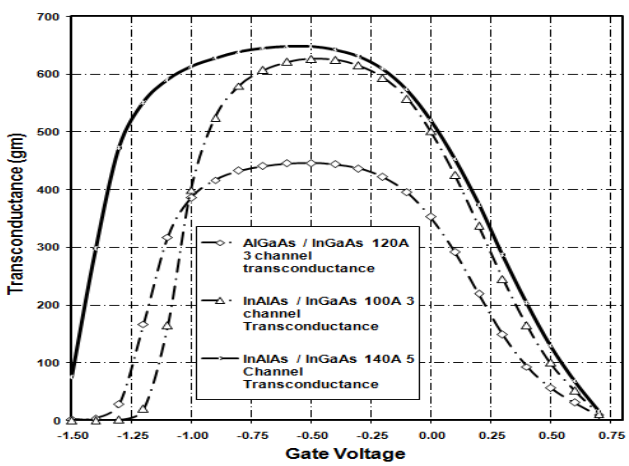

Fig 6: Comparative study of gm curve of penta and tri-composite channel InAlAs/InGaAs MHEMT and AlGaAs/InGaAs PHEMT

Since we are involved in optimization of design of multi-channel FETs for delivering superior Power, frequency and linearity performance in one structure, it is rather important for our model to be sensitive to the several alloy compositions of the alternate barrier and channels for both lattice matched and mismatched structure.

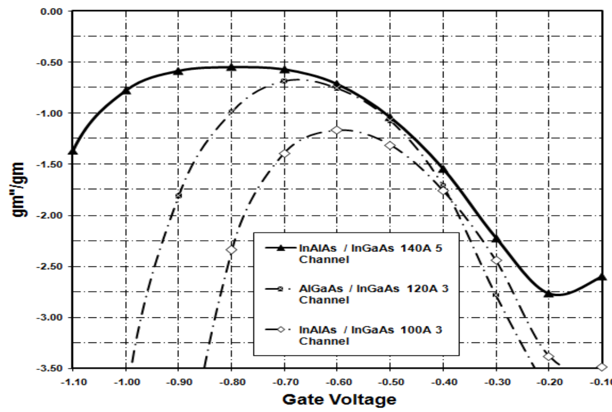

Fig 7: Comparative study of IP3 of MHEMT and PHEMT

CONCLUSION

We have designed InAlAs/InGaAs metamorphic HEMT with multi-layer channel structure to achieve high current of 1029 mA/mm and high g_m of 648 mS/mm while operating at high frequency, f_T of 125 GHz and f_{max} of 250 GHz. This structure shows high drain resistance i.e. less fluctuation at high voltage and high linearity than conventional PHEMTs and MHEMTs. Our structure has gate length, L_g of 0.25 µm, which is much higher than current technology, while achieving very high f_T which is remarkable. It can be attributed to the efficient device structure and choice of materials. This higher gate length leads to lower process costs with high performance devices which can be valuable for low cost wireless / space communications.

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