THEORETICAL ANALYSIS OF MATERIAL AND HIGH FREQUENCIES PERFORMANCE OF METAMORPHIC $In_yAl_{1-y}As/In_xGa_{1-x}As$ ($0.3 < x < 0.6$) HEMT DEVICES ON GaAs SUBSTRATE.

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Abstract:
A theoretical analysis is made of Metamorphic HEMT structures (MM-HEMT) versus InAs molefraction. The material properties are analysed, as are the modeling of dc, ac, noise and high frequency performance of a device with 0.25 µm gate length. This analysis shows that an InAs molefraction of 0.40 is an optimum composition in terms of low noise and power applications. In other ways, the performance of MM-HEMT structures are similar to those obtained with InP substrate devices.

INTRODUCTION

The operating frequency of monolithic integrated circuits have recently been extended into the millimeter wave range [1][2]. To reach this frequency range of operation, HEMTs grown on GaAs or InP substrates are used because these are the only active devices showing high cut-off frequencies, low noise figure, and high power-handling capabilities. In addition, the development of millimeter wave integrated circuits for use in large quantities requires a high performance device with low production cost. In this respect, the GaAs substrate shows two main advantages with respect to the InP substrate. First, it is less fragile and less expensive than the InP substrate. Secondly, diameters as large as 6 inches are now available. However, InP based HEMTs offer higher cut-off frequencies and lower noise figure than GaAs HEMTs. To solve this dilemma, another structure called metamorphic HEMT has been proposed [3]. The metamorphic HEMT (MM-HEMT) uses an unstrained $In_yAl_{1-y}As/In_xGa_{1-x}As$ material system grown on GaAs. High performance devices have been already obtained in the field of low noise and power amplifiers [4],[5],[6].

Using MM-HEMT structures, high conduction band discontinuity can be obtained in the large InAs molefraction range. The InAs molefraction of the channel ($In_xGa_{1-x}As$) has a large influence on material properties and device performance. Consequently, as the InAs molefraction increases, certain material parameters increase, such as the low field mobility and peak velocity, while others decrease, like band gap discontinuity, which greatly influences the sheet carrier density. So it is still an open question as to what the optimum composition is, for high device performance fore low noise and power applications.

The aim of this paper is to study the theoretical effect of the material composition on the MM-HEMT device performance, using a physical model. This study is based on the quasi-two-dimensional (Q2D) approach [7],[8],[9].

The material properties of the device layer are first studied versus indium molefraction. The transport parameters like average velocity and energy are calculated by the Monte Carlo technique in a bulk material. The charge control law (C-V characteristic) of the active layers is obtained using a self-consistent solution of Poisson's and Schrödinger's equation. These results are used to model the performance of a device with 0.25 µm gate length. This is analysed using the new version of the commercial HELENA software [10],[11]. In terms of device performance, we find that an InAs molefraction of x = 0.4 in the MM-HEMT device is the optimum structure if low noise and power amplifiers have to be realized on the same IC.

DEVICE MODELING

The device performance is calculated using a modified version of the commercial HELENA software [10],[11] for PC. The new version of the HELENA software operates on UNIX. In this version there is no limitation on layer structure. All material parameters are calculated automatically. The transport properties of any layer are calculated using a Monte Carlo module described in [12], and the charge control law is obtained by solving consistently Schrödinger's and Poisson's equations.

In the HELENA software (PC and UNIX version) the physical device model is based on the quasi-two-dimensional (Q2D) approach. Figure 1 shows the flowchart of the new version of HELENA software (UNIX version). The two main phases of the Q2D approach appear in this flowchart: layer analysis followed by device modeling. For any kind of HEMT or MESFET, HELENA provides the DC, AC, noise and non linear performance in a broad frequency range from the physical and technological parameters.

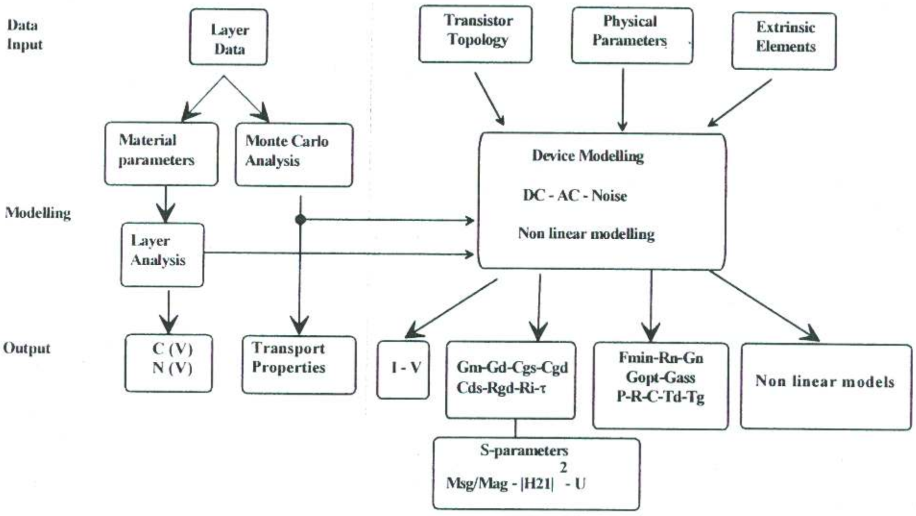


Figure 1 : HELENA flowchart - UNIX version

The layer structure used is shown in Figure 2. A delta-doped layer of 5 10^{12} cm^{-2} is used. Four InAs molefractions (x=0.3, 0.4, 0.53 and 0.6) are investigated. The same doping level and layer structure are used for all alloy compositions used in this analysis. The device has a 0.25 µm gate length and (2x50) µm gate width. The extrinsic parameters used are given in Figure 3. The same extrinsic parameters are used everywhere in order to make a realistic comparison of the different devices.

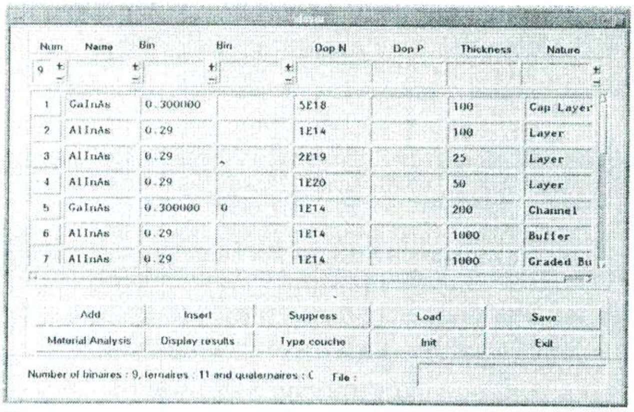


Figure 2 : Example of layer used (InAs 30%)

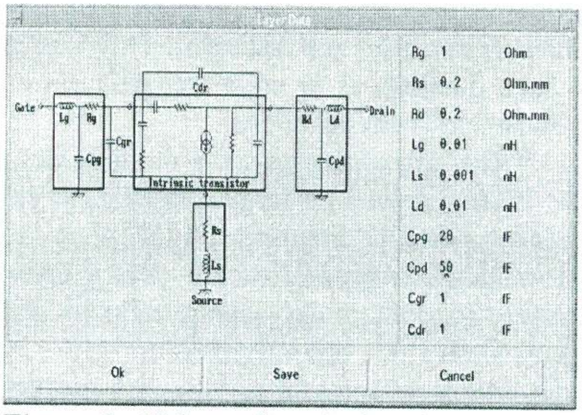


Figure 3 : Values of extrinsics elements

DEVICE PERFORMANCE

The extrinsic transconductance and drain-to-source current for different indium molefractions are shown in Figure 4 versus gate voltage for a bias point Vds = 1.5V. Similar maximum Gm values of about 1.4 S/mm are obtained. This value mainly depends on the gate-to-channel distance which is the same for the differents InAs molefractions. The transconductance remains relatively constant versus Vgs for the lower InAs molefraction. This characteristic improves the power gain linearity, as is shown in [13], so the 0.30 InAs molefraction is suitable for power device applications.

The high frequency device performance is calculated from 2GHz to 110GHz. The cut-off frequencies Fc, Ft, and Fmax are shown in Table 1. The cut-off frequencies increase with indium molefraction. The Fmax value of 285 GHz is obtained with a 0.6 InAs molefraction. This composition also shows the ratio fmax/ft close to 3. This result is obtained with a gate length of 0.25 μm. The device speed is primarily determined by the gate length, the material properties, and the extrinsic elements. Since the gate length and the parasitics are the same, it appears that the cut-off frequencies are improved by the electron transport properties as the InAs molefraction increases.

In order to estimate the potentiality of a 0.60 InAs molefraction of MM-HEMT devices in millimeter-wave range, the simulation of the 0.1μm gate length using the same extrinsic parameters shows Fmax at about 500 GHz and Ft of 180 GHz.

In terms of noise performance, Figure 5 shows the advantage of the 0.4 InAs molefraction over other compositions in terms of minimum noise figure, by plotting Fmin versus indium molefraction at 94 GHz and 110 GHz. The lower minimum noise figure obtained for this composition can be explained by the counteracting variations of sheet carrier densities and transport properties as the InAs molefraction increases. The potentiality of MM-HEMT structures in terms of minimum noise figure is also shown versus gate length at 60 GHz and 94 GHz for InAs mole fraction of 0.40 using the same previous parasitics and the same bias point (Ids = 50 mA/mm) -Figure 6-. These results shows that, using the MM-HEMT structures, the minimum noise figure of 1.2 dB and 1.8 dB can be expected at 60 GHz and 94 GHz respectively with a 0.1 μm gate length device. These results, obtained with the devices on GaAs substrate, are similar to some reported measurements on InP substrate [14]. So the metamorphic HEMT structures are well suited to the production of low production cost, low noise, and high-power amplifiers.

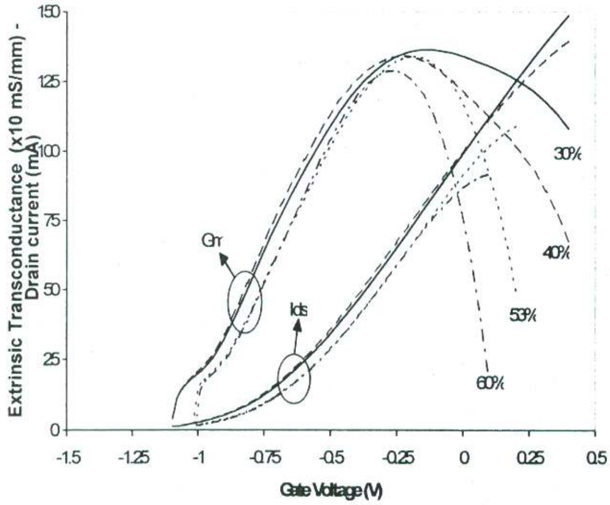
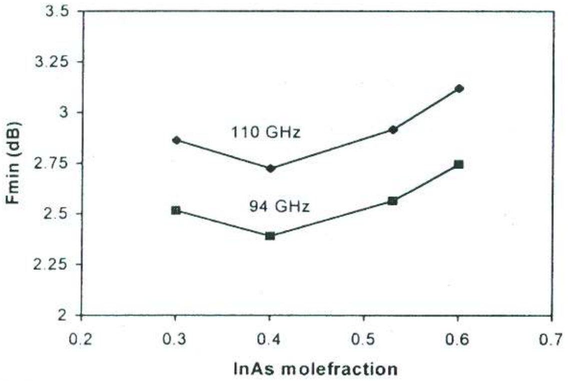


Figure 4 : Gm-Ids versus - Vds=1.5V

%In	Vb(V)	Fc (GHz)	Ft (GHz)	Fmax GHz
30	0.75	210	94	246
40	0.65	222	98	261
53	0.55	233	100	268
60	0.45	236	104	285

Table 1 Cut-off frequencies of devices



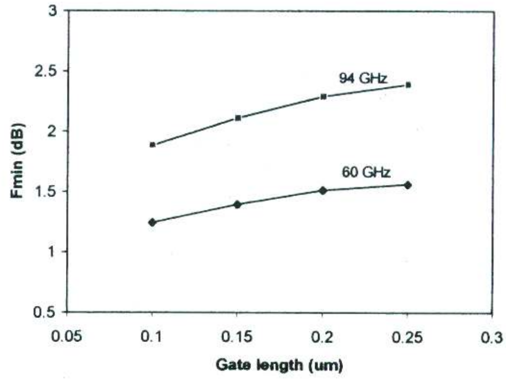


Figure 5 :

Figure 6 : InAs molefraction 0.40

Bias point : Ids = 50 mA/mm, Vds = 1.5 V

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