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f_T=152 GHz and f_{MAX}=196 GHz in a 130nm Gate InP HEMT

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Abstract

In this paper the physics of pseudomorphic Indium Phosphide “High Electron Mobility Transistor” or pHEMT, its DC and RF characteristics and the possibility of operating the device in terahertz region has been studied by numerical simulation based on the Chalmers HEMT design. The designed HEMT produce a record for current gain cutoff frequency and maximum frequency of oscillation for the specified gate length.

Keywords: HEMT, $f_{T,}$ f_{MAX}

I. INTRODUCTION

InP HEMT is the most advanced device for terahertz monolithic integrated circuits. Field effect transistors or FETs are important solid state sources of terahertz technology because when gate lengths are decreased, the plasma frequencies are in the terahertz region and are tunable by the gate voltage. The terahertz frequency range operation from transistors has been observed at room temperature. The main challenge is to reduce the effect of parasitics, short channel effect and impact ionization as the gate length is reduced. Maintaining the Integrity of the Specifications.

II. DEVICE PHYSICS AND SPECIFICATIONS

I have taken ’Chalmers HEMT’ model for reference HEMT and modified that pHEMT structure to reach the ultimate goal for terahertz HEMT. A structure of the reference HEMT is shown in figure1. The feature that primarily distinguishes the HEMT from other types of FETs is the use of a hetero-structure consisting of a wide band-gap and a narrow band-gap semiconductor. In InP HEMT currents between drain and source are flowed through a channel of indium-rich indium gallium arsenide (InGaAs) where contact with the channel is made by highly n-doped and low-resistive drain and source contacts. 2DEG is defined as a thin layer of electrons trapped in a sandwich like structure of compound semiconductor like InAlAs/InGaAs. The barrier is n-doped and it donates electrons to the surrounding material for current conduction. Using delta doping, we can get reduced short channel effects (SCEs). Delta-doped layer is separated from the channel by a region called spacer. As the 2DEG increase the electron mobility in channel, it controls the amount of electrons participating in current flow and thus it also control the operating principle of HEMT.

Table I. Material characteristics

Electron Parameters	**$In_{0.53}Ga_{0.47}As$**	**$In_{0.52}Ga_{0.48}As$**	**$In_{0.70}Ga_{0.30}As$**	**InP**
μ_{max}	11599	4220	22700	4917
μ_{min}	3372	220	5000	300
E_{critn}	-	-	9×10^5	-
N_{critn}	10^{17}	10^{17}	10^{18}	10^{17}

III. METHODOLOGY

Silvaco's ATLAS/BLAZE is an important tool for optimizing designs without fabrication. In my work, TCAD based modeling and optimization of $In_{0.7}Ga_{0.3}$ As/$In_{0.52}Al_{0.48}$As/InP pHEMT has been done.

Table 1 specifies the electron parameters used for the simulation. The highly doped delta layer forms Ohmic contacts with source and drain regions of HEMT. The metal gate forms a Schottky contact with the supply layer of un-doped wideband gap InAlAs layer. The Indium content in the $In_{0.7}Ga_{0.3}$As channel and the conduction band discontinuity at the interface mainly determine the two dimensional electron gas density and mobility. Physics based models used for this simulations are concentration dependent Shockley-Read-Hall recombination(CONSRH), Boltzmann statistics, and doping and parallel field dependent mobility. For the highly doped delta and cap layers Fermi-Dirac statistics model is implemented. Also to minimize kink effect for this device in the InGaAs channel and InAlAs layers, the impact ionization and trap effects are used respectively.

IV. RESULTS

TCAD structure simulation is done according to the table 1 specifications. The simulated structure is shown in the figure 1.

Gate length is 130 nanometer and width of the device is 1000 micrometer. The source to drain spacing is optimized to be of 790 nanometer where passivation layer is of silicon nitride. Optimization is done to minimize the parasitic delay effect while determining the current gain cut-off frequency f_T and thus f_{MAX} . Here I have taken recess gate length to be 80 nanometer.

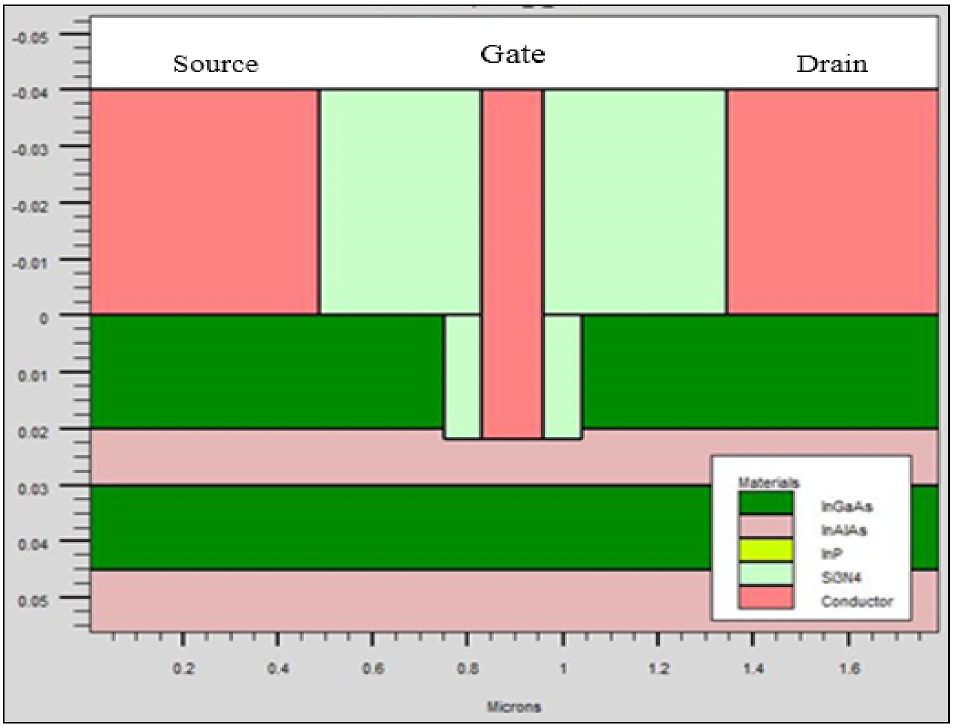

Fig. 1. Zoomed structure of the major area

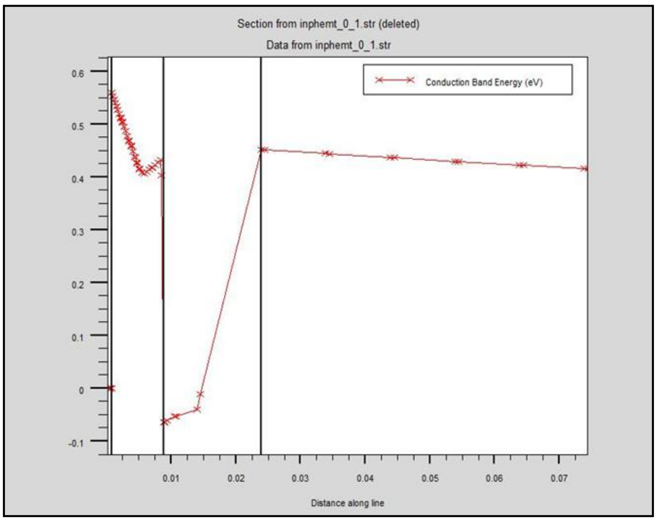

Fig. 2. 2D electron gas formation in the conduction band energy profile

Here I have taken silicon nitride to be the choice for passivation material because it prevents gate leakage currents better than other materials like silicon di-oxide etc. and it also gives us better transconductance value which is one of the major deciding factor for noise lass HEMT [2]. Electron concentration is of 10^{18}cm^{-3} in this structure. In the figure 2, 2D electron gas formation in the conduction band energy profile is shown.

Current voltage characteristics for 1000 micrometer width InGaAs HEMT is shown in figure 4 and 5. The currents are described in the units of mA per unit length of mm.

Velocity saturation is one of the major factor for this. Drift velocity of the charge carriers are proportional to the electric field applied to them. Interaction of the carriers with the lattice causes them to lose kinetic energy and their speeds to saturate if electric field is increased after some critical level.

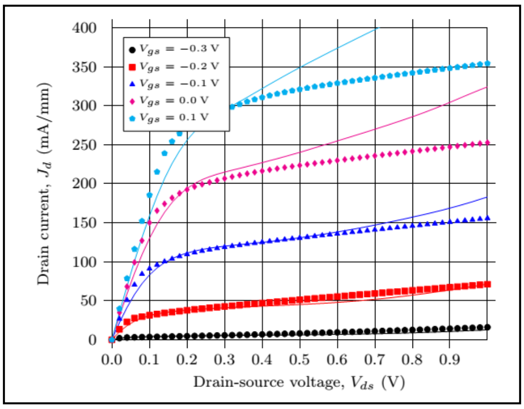

Fig. 3. Reference device's drain current vs drain source voltage [1]

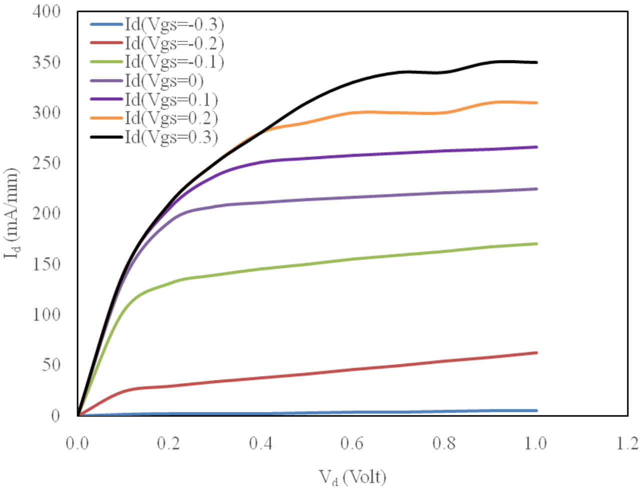

Fig. 4. Simulated I_d -V_d characteristics

In figure 3, reference device's drain current changes is shown if drain to source voltage is changed from 0 to 1 V in steps of 0.1 V where high field velocity saturation is enabled. It is shown for comparison with the simulated structure's I_d-V_d characteristics as shown in the figure 4. Both the results are almost identical. It proves the result simulated by ATLAS Silvaco TCAD is correct as well as our assumptions for material specifications as it is nearest to the fabricated Chalmers HEMT result.

Figure 5 shows the I_d -V_g characteristics of the simulated HEMT when gate voltage is changed from -0.6 to 0.6 V in steps of 0.1 V and high field velocity saturation enabled. As shown in the figure the maximum current is almost 400 mA/mm for gate voltage of 0.5 volt and it is also has to be noted as the drain voltage is increased, the drain current also increases.

To measure RF characteristics or small signal gain, one needs to understand the concept of unilateral power gain, maximum available gain, maximum stable gain and current gain. A unilateral device is one whose scattering parameter $s_{12} = 0$, that means no internal feedback. This particular property is tough to get at microwave frequency. Theoretically, an external circuit can remove the feedback effect of internal feedback. However, the result of this technique is valid only when operating frequency is in very high frequency range.

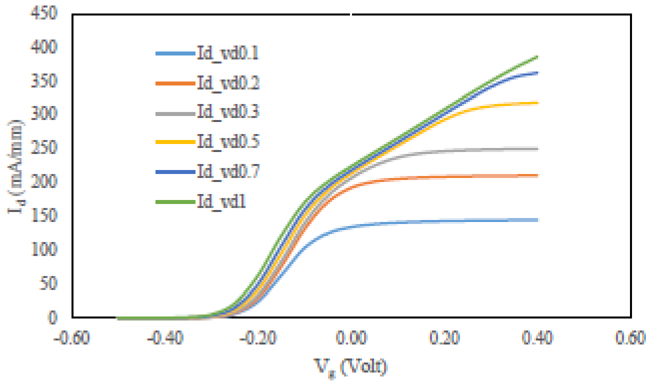

Fig. 5. Simulated I_d -V_g characteristics

U is invariant, so it is inherent to the device. Most importantly, U is a useful figure of merit of the device specially in RF frequencies. Mason's paper [3] does not fully indicate its contents and applicability.

$$U = \frac{|Z_{12} - Z_{21}|^2}{4(\mathrm{Re}[Z_{11}].\mathrm{Re}[Z_{22}] - \mathrm{Re}[Z_{12}].\mathrm{Re}[Z_{21}])} \qquad (1)$$

The significance of the unilateral power gain U can be obtained by comparing it with other kinds of power gain used in microwave work, from which Mason's unilateral power gain should be deduced, like the maximum available power gain Gma , Rollet's maximum stable power gain G_{ms}, and Kotzebue's maximally efficient power gain G_{me}. These power gain maxima are different in application and condituon of utility. At low frequencies, where Rollet's stability factor k <1, G_{ma} becomes infinite and is therefore defined only at higher frequencies where k > 1. U is defined even if the device is stable or potentially unstable.

$$G_{ma} / MAG = \frac{S_{21}}{S_{12}}\left(k \pm \sqrt{k^2 - 1}\right) \tag{2}$$

$$G_{ms} / MSG = \frac{S_{21}}{S_{12}} = \frac{Y_{21}}{Y_{12}} \tag{3}$$

- Current gain H_{21}=0 at frequency of f=f_T
- The current gain cut-off frequency

$$f_T = \frac{1}{2\pi}\frac{g_{mi}}{C_{gs} + C_{gd} + g_{mi} + (R_s + R_D)\left[C_{gd} + \left(C_{gs} + C_{gd}\right)\frac{g_{oi}}{g_{mi}}\right]} \tag{4}$$

As the unilateral power gain is a monotonic function of frequency, f_{MAX} is a single-valued and well defined parameter. It is usually used to measure the high-frequency performances of an active device. Its significance is that U exceeds unity for an active device. So the maximum frequency of oscillations is also therefore maximum available frequency.

$$U(f)\,|_{\,f\,=\,f_{MAX}} = 1 \tag{5}$$

$$f_{MAX} = \frac{f_T}{\sqrt{4g_{ds}(R_i + R_s + R_g) + \frac{2C_{gd}}{C_{gs}}\left(\frac{C_{gd}}{C_{gs}} + g_m\left(R_i + R_s\right)\right)}} \tag{6}$$

g_{ds}=output conductance, R_i=channel resistance.

The measurement is done by an automatic network analyzer to measure the S parameters of the two-port. From

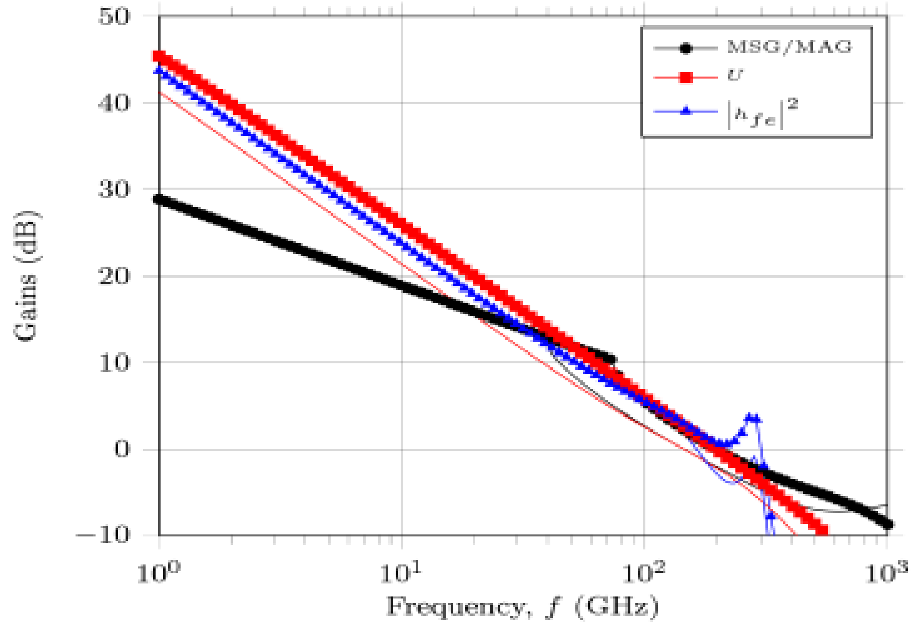

Fig. 6. Chalmers HEMT: measured [1]

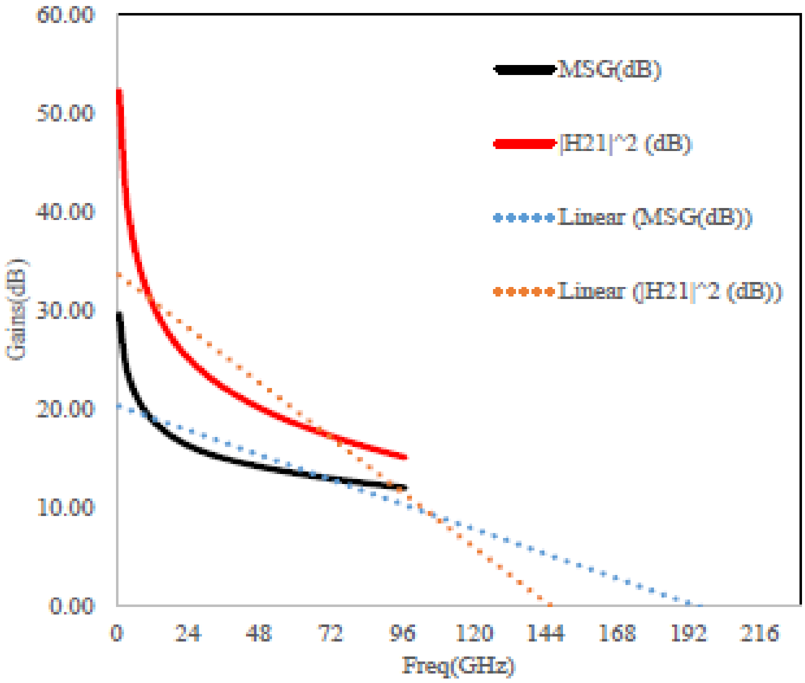

Fig. 7. Simulated HEMT RF characteristics

that the unilateral power gain can be calculated. Then the frequency at which it is one thus can be found which is nothing but the f_{MAX}.

Interestingly, the frequency at which U attains the value of 1 is also the frequency at which the maximum stable gain and the maximum available gain of the device also become unity. As a result, through alternative approach one can get fmax. So the maximum frequency of oscillation in a circuit in which the following three conditions are met:

- only one active device present in the circuit
- the device is embedded in a passive network, and
- only single sinusoidal signals are of interest.

The small signal performance of reference HEMT in figure 6 is compared with the result of the simulated HEMT in figure 7. The RF characteristics is taken at a low noise bias point of gate voltage -0.14 V and drain voltage of 0.6 V. In the reference HEMT, the f_T and f_{MAX} is 152 GHz and 196 GHz. In figure 7 it is shown clearly that the simulated result is very close to the reference HEMT result. In the simulated HEMT the f_T and f_{MAX} is 144 GHz and 192 GHz.

V. CONCLUSIONS

We got more f_T and f_{MAX} than the reference HEMT device fabricated in Chalmers University. Many modifications can be done on this structure by gate scaling, channel length reduction and most importantly introducing a InP etch stop layer to get more stable HEMT device which can operate in the terahertz region.

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