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Effect of Carrier Concentration Dependant Mobility on the Performance of High Electron Mobility Transistors

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Abstract

The influence of the sheet carrier concentration dependence on mobility on the performance of High Electron Mobility Transistor (HEMT) structures is theoretically modeled. The model basically takes into account both the drift and diffusion part of the overall drain current. The normalised drain current and normalised transconductance are found to be greatly affected by the carrier concentration dependant mobility.

1. Introduction

High Electron Mobility Transistor (HEMT) structures have been the focus of intense research, with particular focus on high speed and high frequency semiconductor devices, since the introduction of the devices in 1980 [1]. This device has demonstrated some unusually higher transconductance, lower noise and extremely fast switching speeds. In order to obtain optimum device parameters and to attain even higher performance, some considerable amount of effort has gone into the more realistic modeling of the HEMT devices [2-7], each dealing with different aspects of them. Among the findings, some works have clearly demonstrated, both theoretically and experimentally, that the mobility of the channel electrons depend strongly on the carrier concentration [8]. However, the effects of the carrier concentration dependent mobility, as well as the diffusion part of the total current, have not yet been simultaneously taken into account. This paper, hence, aims to model the effect of the carrier concentration dependant mobility on the characteristics and on the transconductance of the devices, by simply employing the diffusion portion of the drain current as well as the drift part.

2. The Model

The $Al_{0.3}Ga_{0.7}$ As in a HEMT structure is fully depleted under normal operating conditions and the electrons are confined to a triangular like potential well, at the GaAs side of the heterointerface. The sheet carrier concentration at a point x along the channel is hence given by, [2]

$$n_s(x) = \frac{\varepsilon}{qd^*}[V_g - V_T - V(x)] \tag{1}$$

where ε is the dielectric permittivity of $Al_{0.3}Ga_{0.7}$ As, q is the electronic charge, d^* is the total effective distance between the metal gate and the actual channel, V_T denotes the threshold voltage of the device, and finally $V(x) = \int E(x)dx$ is the position dependant potential within the channel. Note here that $d^* = d + \Delta d$ is larger than the actual physical distance, d, because of the field induced variation in the Fermi Energy of the two-dimensional electron gas (2DEG) and the difference is considered to be about $\Delta d = 80\mathring{A}$.

The model presented here is valid for the range in which the charge control is linearly changing with the gate voltage. It is however well known that, as V_g starts to saturate, a second parasitic channel is eventually created in the doped $Al_{0.3}Ga_{0.7}$ As layer. Hence a so-called three-dimensional electron gas becomes reality instead of a two-dimensional one [9]. At gate voltages closer to the threshold voltage, the V_g dependence of the sheet carrier concentration becomes superlinear. This effect is also to be excluded in the model in order to reach the result in the shortest way. These effects however can be included to obtain even better results.

The drain current is in general given by the sum of two components, namely drift and diffusion parts [7],

$$I_d = qWn_s(x)v(x) + qWD(x,T)\frac{d}{dx}n_s(x) \tag{2}$$

where W is the width of the gate, v(x) denoting the position dependant velocity and D(x,T) denotes the diffusion constant for the conducting 2DEG electrons.

Various velocity-field characteristic curves have been proposed in the modeling of the devices [3-5]. Yokoyama and Sakaki have pointed out that the electric field may not always be high enough for the electrons to move at their saturation velocity in the vicinity of the source under the gate and mentioned the importance of the low field mobility in the modeling of HEMT and other FET devices [10]. Following that, the effect of the low field mobility on the performance of the FET devices was tackled by Sakaki et al. [11]. We, therefore, try to concentrate only on the n_s dependant mobility and its influence on both drain current and transconductance. For the velocity-field relation, we intend to employ the one most commonly used that is [12]

$$v(x) = \frac{\mu(x)E(x)}{1 + \frac{\mu(x)E(x)}{v_s}} \tag{3}$$

where E(x) is the electric field at point x, v_s is the saturation velocity of the electrons and μ(x) is the position dependant mobility of the electrons. The mobility is position dependant because the sheet carrier concentration n_s(x) varies along the channel. The mobility of the electrons along the channel is strongly affected by the sheet carrier concentration. So the relation is expressed in simplest manner as follows [13]:

$$\mu(x) = \mu_0 \frac{n_s^\alpha(x)}{n_{s0}^\alpha} \tag{4}$$

where μ_0 is the low field mobility, a very important parameter for the device performance; and n_{s0} is the equilibrium sheet carrier concentration of the heterostructure. The crucial exponent α on the other hand, depends strongly on the operating temperature and the internal structure of the HEMT devices but typically ranging from 0.3 to 2. The appearance of the parameter α in fact mostly originates from the ionised impurity scattering. For the HEMT structures having about 200 $\mathring{A}$ of spacer layer, the parameter α is found to be about 0.7 at 4.2 K [14], and for the devices having no spacer layer, it is about 1.1, 0.5 and 0.3 at 10,77 and 300 K, respectively [13].

Substitution of D(x,T)=μ(x)kT/q, μ(x), v(x) and n_s (x) into the equation (2) and integrating it from $V(x) = 0$ ($x = 0$ at the source end) to $V(x) = V_d$ ($x = L$ at the drain end), gives us the following equation for the overall drain current which includes both linear and saturation regions inside:

$$I_d = \frac{A(\alpha)[V_p^{\alpha+2} - (V_p - V_d)^{\alpha+2}] - B(\alpha)[V_p^{\alpha+1} - (V_p - V_d)^{\alpha+1}]}{1 + C(\alpha)[V_p^{\alpha+1} - (V_p - V_d)^{\alpha+1}]} \tag{5}$$

where

$$A(\alpha) = \frac{qW\mu_0}{Ln_{so}^\alpha(\alpha+2)}(\frac{\varepsilon}{qd^*})^{\alpha+1} \tag{6}$$

$$B(\alpha) = \frac{WkT_{\mu_0}}{Ln_{s0}^\alpha}(\frac{\varepsilon}{qd^*})^{\alpha+1} \tag{7}$$

$$C(\alpha) = \frac{\mu_0}{Lv_s n_{s0}^\alpha(\alpha+1)}(\frac{\varepsilon}{qd^*})^{\alpha} \tag{8}$$

and k is the Boltzmann's constant, T is the absolute temperature, L is the gate length and W is the gate width. By doing so we obviously ignore both source and drain contact resistances, which makes the situation quite straightforward to understand. Equation (5) is to be employed for the case prior to "quasi pinchoff". In this situation, the electric field at the drain end of the gate remains finite, which means the carrier concentration at the drain end is not zero but has a finite value. The situation beyond the quasi pinchoff can easily be obtained by substituting $V_d = V_p = V_g - V_T$. So the drain current for the saturation region can be given by,

$$I_{ds} = \frac{A(\alpha)V_p^{\alpha+2} - B(\alpha)V_p^{\alpha+1}}{1 + C(\alpha)V_p^{\alpha+1}}. \tag{9}$$

The influence of the parameter α on the transconductance is even more important and must also be significant. In order to obtain an equation for the transconductance beyond the quasi pinchoff, we employ the actual definition for the transconductance, that is

$$g_m = \frac{dI_d}{dV_g}. \tag{10}$$

By doing so, we finally obtain the following equation for the transconductance,

$$g_m = \frac{(\alpha+2)A(\alpha)V_p^{\alpha+1} - (\alpha+1)B(\alpha)V_p^{\alpha} + A(\alpha)C(\alpha)V_p^{2(\alpha+1)}}{(1+C(\alpha)V_p^{\alpha+1})^2}. \tag{11}$$

This equation now gives us the actual relation between the parameter α and the transconductance for a certain gate voltage.

3. Results and Discussion

Figure 1 is plotted by using equations (5) and (9), and provides information about the drain voltage dependence of the normalized drain current. A brief examination of the figure, makes a few points clear that are worth mentioning. Firstly, the influence of the parameter α depends somehow on the gate voltage or the pinchoff voltage. When V_p less than 0.6 V or V_g is negative, the drain saturation current decreases as the parameter increases. However, when V_p is larger than 0.6 V which means V_g positive, the drain saturation current goes up in direct propotion with the parameter α. Secondly, the effect previously seen by others [11], namely, the occurence of the saturation at lower drain voltages, is not observed here. This is presumably due to the diffusion part of the current.

In Figure 2, the normalised trasconductance (g_m/W) is plotted versus the gate voltage or the pinchoff voltage. The points extracted from the Figure 1 is more pronouncingly caught here. At a certain gate voltage, the transconductance increases as the parameter α goes up, because the mobility of the electrons increases. What happens however when V_p is less than 0.45 V is not very clear. We beleive that the increase in the mobility is supressed by the change in the actual channel length. The other point worth noting here is the dependence of the transconductance on the pinchhoff voltage. For the case in which α=0, the dependence seems to be quite linear. For positive α values, as α increases, the dependence on the other hand becomes more and more superlinear. The saturation in the transconductance as the gate voltage increases, is not seen here, because the employed charge control model does not include that effect.

In summary, the carrier concentration dependence of the mobility influences the performance of the HEMT structures significantly, Especially, at normal operating voltages the parameter α greatly increases the transconductance.

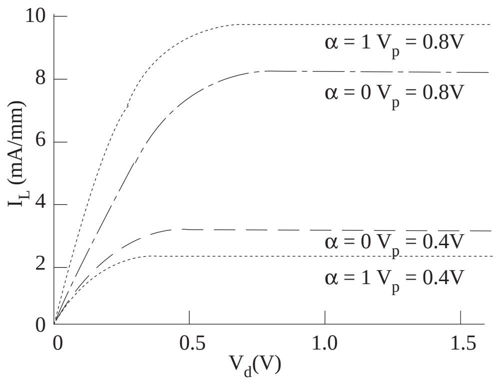

Figure 1. Normalised drain current (I_L=I_d/W) plotted versus drain voltage (V_d) using equations (5) and (9). The values used here are L=35 μm, W=65 μm, n_{s0}=3.4x10^{15}m^{-2}, μ_0 = 0.825 m^2/Vs, v_s=2.5x10^5 m/s, d*=95nm, ε=1.05x10^{-10}Nm^2/C^2 and V_T=-0.6V.

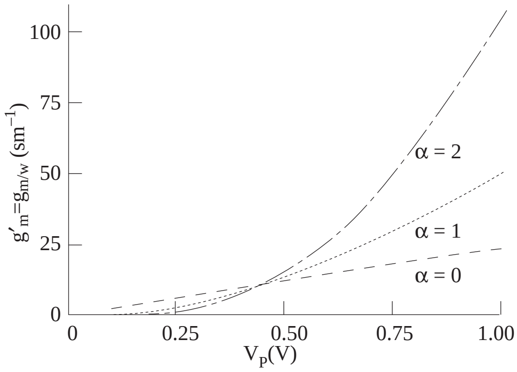

Figure 2. Gate voltage dependence of the normalised transconductance (g'_m = g_m/W) plotted by using the Equation (11). The same numbers, as in the Figure 1, are used in the calculation.

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