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Analytical Admittance and Noise Calculations in InGaAs transistor channels

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Abstract

In this contribution, we analysis the small-signal admittance and the corresponding noise of the high electron mobility transistors under a continuation branching of the current between channel and gate. The analytical approach takes into account the linearization of the 2D Poisson equation and the drift current along the channel. The real part of admittance and the noise spectra exhibit resonances in high frequency associated to the oscillations in the channel. The appearance of the resonances is discussed as function of the geometrical channel parameters (length, thickness and doping concentration).

Keywords: high electron mobility transistor, admittance, noise spectra, high frequency, resonances.

INTRODUCTION

In the last years, the research is directed to develop an electronic devices operating at room temperature and useful for emission and detection of terahertz (THz) radiations [1]. The development of transistors with a high mobility channel became an interesting terahertz devices employed at room temperature [2]. More recently, the high electron mobility transistors (HEMTs) have considered as important competitors due to the existence of the plasma oscillations in the channel [3]. Several works show that the oscillations in transistors channels can be controlled in high frequency by varying the gate effect and can exhibit a terahertz range by the short gate-length transistors [4]. In particular, the experiments have shown that the high-frequency noise spectra of HEMTs contain excess noise related to electronic excitation of plasma modes [1].

The analytical admittance characterization of high mobility channel is now integrated in many physics factors characterizations such as the behavior study of the microwave modern transistors (FETs, HEMTs) [2], the noise calculation and therefore the improvemen of the detectivity level. Usually the main task of such an analysis is to determine the parameters of the intrinsic small-signal equivalent circuit elements, the density of the current fluctuations, the gain and cutoff frequency and the transconductance.

In this contribution, we propose an analytical approach to characterize the admittance at the drain and source-drain terminals of high electron mobility transistors. The analytical model can perform the hydrodynamic results by using the linearization of the 2D Poisson equation. The analytical results discuss the frequency dependence of the admittance and the noise spectra on the geometrical channel parameters. In particular, the small-signal admittance exhibits a series of the resonant peaks corresponding to electronic excitation of plasma waves where the resonances are interpreted as function of the length, thickness, doping and operating temperature.

ANALYTICAL MODEL OF ADMITTANCE CALCULATION

We consider the transistor structure in figure 1 of the channel length L, thickness δ and the doping concentration n_0. We suppose that the gate covered the entire channel and the distance channel-gate is d.

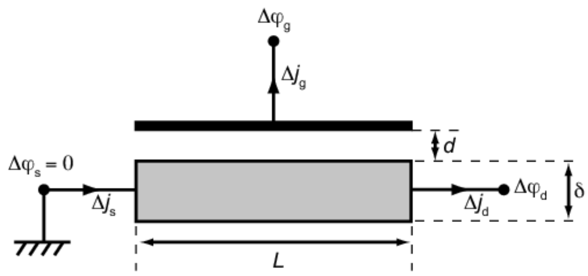

Figure 1: The transistor structure with channel length L and the gate effect is under distance d.

For this analytical approach, we suppose that the channel is subdivided into n cells of length Δx connected in series and the current flows along the channel is in one-dimensional (1D) direction (the channel current depends to x). The differential equation that describes the potential distribution along the channel written as [4], [5]:

$$\varepsilon_c \frac{\partial^2}{\partial x^2} \Delta\varphi(x) + \frac{\varepsilon_d}{d\delta}\left[\Delta\varphi_g - \Delta\varphi(x)\right] = \frac{-1}{\varepsilon_0}\rho^{3D}(x) \qquad (1)$$

Where ε_c is the channel dielectric constant, ΔU_g is the small-signal gate potential, d is the distance gate-channel, δ is the channel thickness and the charge density in the channel is approximated as $\rho^{3D} = en^{2D}/\delta$. The equation (1) presents the one-dimensional (1D) approximation of the generally adopted 2D Poisson equation and takes into account the gate influence (ΔU_g) on the potential distribution $\Delta\varphi(x)$ along the transistor channel. By using the conservation law of charge density ρ^{3D} in the channel and going to the spectral representation, the free electron surface density n^{2D} is [5]:

$$e\Delta n^{2D}(x) = \frac{-\delta}{i\omega}\frac{\partial}{\partial x}\Delta J_c^{drift}(x) \tag{2}$$

The drift current in the channel determined by the free-electrons, which flow under an applied voltage [6]:

$$\Delta J_c^{drift}(x) = \varepsilon_0\varepsilon_c \frac{\omega_p^2}{i\omega+\nu}\left(f - \frac{\partial}{\partial x}\Delta\varphi(x)\right) \tag{3}$$

Where ν is the velocity relaxation rate, f is the Langevin source of the thermal fluctuations $f = \delta(x-x_0)\delta(t)/n_0$ where x_0 is the local perturbation induced by the Langevin force and $\omega_p = \sqrt{e^2 n_0/\varepsilon_0\varepsilon_c m^*}$ is the plasma frequency of the electrons in the channel volume (here n_0 is the donor concentration in the channel).

The solution of equation (1) when we introduce the equations (2) and (3) can carried out on two parts: the homogeneous solution (the first term of equation (4)) and the Green function solution (second term of equation (4)). The general solution of equation (1) can be approximated as [3]:

$$\Delta\varphi(x) = \frac{\Delta U_s \sinh\beta(L-x) + \Delta U_d \sinh\beta x}{\sinh\beta L} + \int_0^L G(x,x_0)\left[-\beta^2\Delta U_g + \alpha\frac{\partial}{\partial x}f(x_0)\right]dx_0 \tag{4}$$

Here the Green function of equation (4) is:

$$G(x,x_0) = \frac{1}{\beta}\left(-\frac{\sinh\beta(L-x_0)\sinh\beta x}{\sinh\beta L} + \theta(x-x_0)\sinh\beta(x-x_0)\right) \tag{5}$$

Where $\alpha = \omega_p^2/\left(\omega_p^2 + i\omega(i\omega+\nu)\right)$ depends to frequency, $\beta = \lambda^2 i\omega(i\omega+\nu)/\left(\omega_p^2 + i\omega(i\omega+\nu)\right)$ and $\lambda = \sqrt{\varepsilon_d/\varepsilon_c d\delta}$ is the plasma wavelength. Here $\theta(x-x_0)$ is the Heaviside step function and ΔU_s is the potential of source contact. The fluctuations of the total current along the channel are given by [5] :

$$\Delta J(x) = \varepsilon_0\varepsilon_c \frac{\omega_p^2}{i\omega+\nu}\left[f - \frac{\omega_p^2 + i\omega\nu - \omega^2}{\omega_p^2}\frac{\partial}{\partial x}\Delta\varphi(x)\right] \tag{6}$$

The total currents at the source ΔJ_s and the drain ΔJ_d are obtained by using the boundary values of channel length at $x=0$ and $x=L$ in equation (6) respectively. The relations between the currents and the potentials of channel transistor terminals can be rewritten in the matrix form as [7]:

$$\begin{bmatrix}\Delta J_s\\ \Delta J_d\end{bmatrix} = \begin{pmatrix}Y_{11} & Y_{12}\\ Y_{21} & Y_{22}\end{pmatrix}\begin{bmatrix}\Delta U_s\\ \Delta U_d\end{bmatrix} \tag{7}$$

The detailed expressions of the matrix elements are: $Y_{11} = \frac{\gamma\cosh\beta L}{\sinh\beta L}$, $Y_{12} = -\frac{\gamma}{\sinh\beta L}$, $Y_{21} = \frac{\gamma}{\sinh\beta L}$ and $Y_{22} = -\frac{\gamma\cosh\beta L}{\sinh\beta L}$ where $\gamma = \frac{\varepsilon_0\varepsilon_c\omega_p^2}{i\omega+\nu}\frac{\beta}{\alpha}$. We notice that we have a symmetric matrix $Y_{11} = -Y_{22}$ and $Y_{12} = -Y_{21}$.

NOISE SPECTRUM

In thermal equilibrium, the regular and spontaneous small-signal responses represented, respectively, by the real part of admittance and spectral density of current fluctuations are related by the Nyquist relation as [6], [7]:

$$S_{JJ}^{ij} = 4kT\,\mathrm{Re}\left[Y_{ij}(\omega)\right] \tag{8}$$

RESULTS AND DISCUSSIONS

For the results calculations, we consider the transistor $In_{0.53}Ga_{0.47}As$ based on n^+nn^+ structure with channel length *L* = 400 nm, thickness *δ* = 15 nm, channel-gate distance *d* = 100 nm, the electron concentration in the channel $n_0 = 8\times10^{17}cm^{-3}$, the relaxation rate $\nu = 2\times10^{12}s^{-1}$ and the effective mass $m^* = 0.048m_0$.

The figure 2 presents the frequency dependence of the admittance at drain and source-drain terminals for the reported channel length *L*, *2L* to *3L*.

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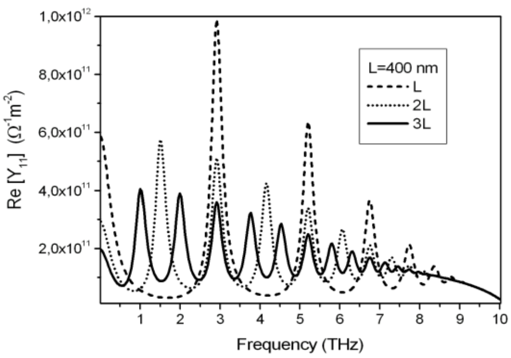
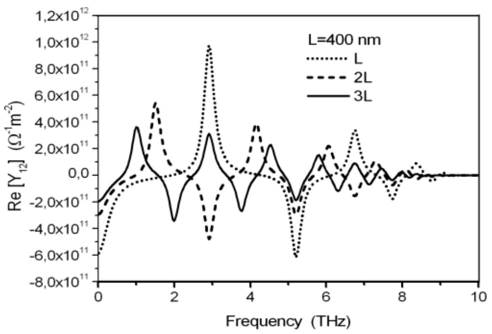


(a)



(b)

Figure 2: Real parts of the admittance at: (a) the drain terminal and (b) the source-drain terminal for the different length value. With: the distance d = 100 nm, the concentration n_0 =8×1017 cm^{-3}, the velocity ν= 2×10^{12} s^{-1} and the temperature T=200 K.

In figure 2, we remark the appearance of a series resonance peak caused by thermal excitation of plasma waves (see figure 2 (a)). For the figure 2 (b), the admittances Y_{12} presents the symmetric curves with the up down of the resonances appearance (equation (7)) due to the voltage source connection.

The frequency positions of the resonance peaks fitted by the empirical expression given by:

$$\omega_{res}(q) = \frac{q\omega_p}{\sqrt{(\lambda L/\pi)^2 + q^2}} \qquad (9)$$

where $q = 0, 1, 2, 3, 4, 5$….. .

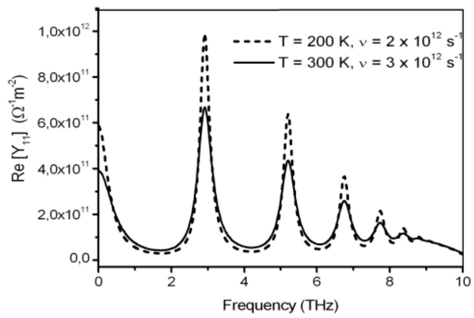
In the case of a length channel 3L, the resonance peaks calculated by the empirical expression corresponding to the frequencies: 0, 1 THz, 2 THz, 2.7 THz, 3.6 THz, 4.3 THz, 5 THz and 5.6 THz which are similar to that found in the solid line curve (see figure 2). Moreover, the increasing of the channel length increases the number of the resonance peaks and decreases the amplitude of the admittance. For example, in the frequency range from 0 to 3 THz the admittance exhibits three resonance peaks (see solid line), two resonance peaks (see point line) and one resonance (dashed line) for the length values 3L, 2L and L, respectively. Therefore, the increasing of the channel length from L to nL leads to increase the resonance number to n peaks.

The figure 3 illustrates the dependence of the admittances Y_{11} and Y_{12} on the temperature effect. The relaxation rate is obtained by: $\nu = q / m^{*}\mu$ where the electron mobility μ depends on the temperature. Therefore, the variation of the temperature introduces a significant variation in the relaxation rate due to the thermal mobility variation. The corresponding mobility of figure 3 is presented in table 1.

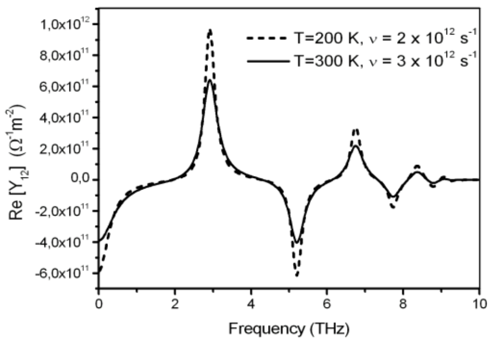
Table 1. The mobility and temperature effect.

Mobility (10^3 cm^2Vs)	Temperature (K)
12.2	300
19	200
56	100

We observe that the admittance value decreases in the moderate temperature compared to the low temperature 200 K.



(a)

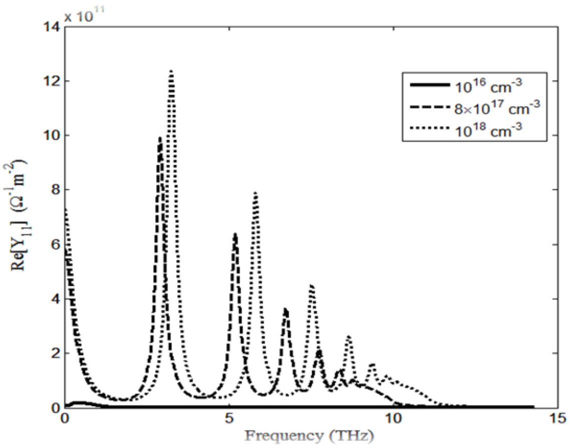


(b)

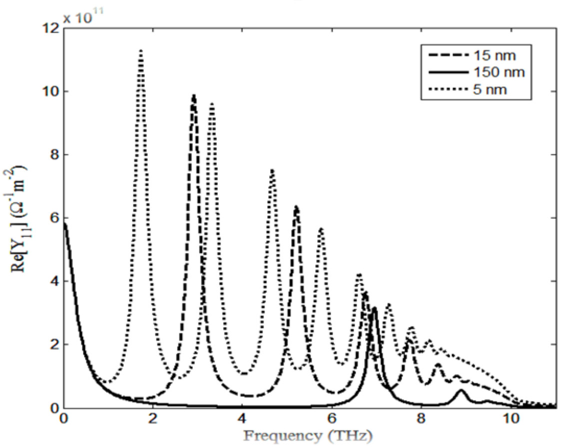
Figure 3 -The real parts of admittance for different relaxation rate value. (a) At drain terminal and (b) at source-drain terminal.

In addition, the temperature effect is neglected for the frequency position of resonances due to the plasma frequency ω_p which does not depend on the temperature.

The figure 4 reports the real part of admittance for different electron concentration and thickness of channel. The high resonance frequencies is obtained by the increasing of the concentration to the degeneration doping 10^{18} cm^{-3} (see dot line in figure 4 (a)). For the doping concentration 10^{16} cm^{-3}, we remark the disappearance of the resonances associated to the the low electron concentration in the channel. The deceasing of the effective number of electrons leads to low plasma oscillations in the channel.



(a)

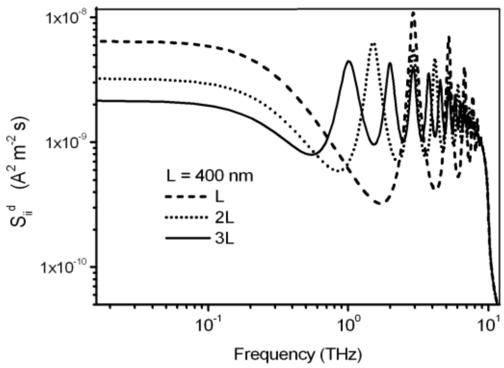


(b)

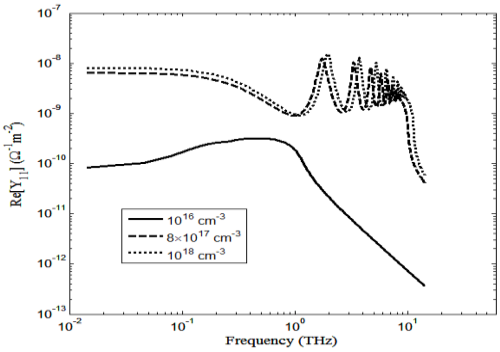
Figure 4 -The real parts of admittance for the reported: (a) doping concentration n_0 and (b) thickness of channel δ.

In figure 4 (b) the high oscillations is due to the some anometric thickness of channel (δ = 5 nm). The inceasing of the thickness decreases the number of resonances (low oscillations) where the electrons motion is distributed over the thickness and the one dimensional channel supposition is no valid.

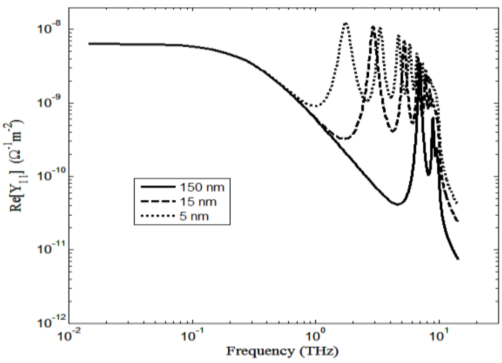
The spectral density of drain current fluctuations obtained by equation (8) is represented in figure 5 where the drain admittance Y_{11} is calculated in figure 3. The results of figure 5 are similar to that calculated by the hydrodynamic equations in Ref [6].



(a)



(b)



(c)

Figure 5 -The real parts of admittance for different: (a) channel length L, (b) doping concentration n_0 and (c) thickness of channel δ.

We observe that the spectral current density exhibits resonance peaks corresponding to the frequencies of plasma oscillations in the channel. The similar resonance peaks is appeared in the admittance curve and depends on the channel length by equation (8). As discussed above in figure 2 (a), the high noise is obtained by the short channel length (see figure 5 (a)). The increasing of the length channel increase the oscillations of the resonance due to increasing of the free carrier plasma frequency (ω_p). For the concentration effect, the noise behavior of the transistor disappears for a low doping channel (see figure 5 (b)). According to the equation (8), the high oscillations corresponding to the high number of resonances is obtained by thin thickness (see figure 5 (c)).

The figure 6 presents the tmodification from transistor to diode behavior by considering the distance between the channel and the gate tends to infinity (see figure 1). In this case, the structure of figure 1 modifies to a diode channel without gate effect.

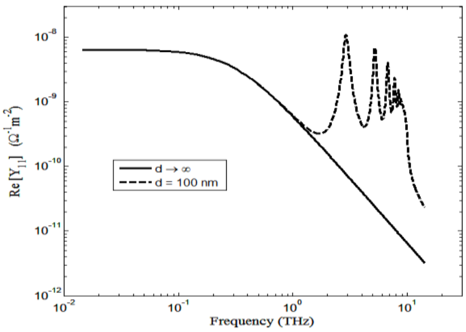


Figure 6 - Spectral current density in the transistor (under gate effect d=100 nm) and in the diode (ungated d $\rightarrow\infty$).

We remark that the diode exhibits a Lorentzian spectral density (solide line) compared to the resonances oscillations in current spectral of transistor.

CONCLUSION

In this paper, we present analytical calculations of admittance and noise for InGaAs channel of HEMTs. Additionally, the model determines the channel admittance characteristics and describes the terahertz frequency part of the noise spectrum.

The admittance exhibits a resonance peak investigated for different channel length, temperature, thickness and doping concentration in the frequency range f < 10 THz. The results show that the length of the channel has a significant effect on the appearance of the resonance peaks. In particular, the transistor with low nano-channel length can present high frequency resonances peaks when the appearance of an additional resonance is controlled by the free carries concentration and the channel thickness. More oscillation in the current noise spectra is obtained by the high doping concentration and thin channel thickness. Therefore, the admittance of high electron mobility channel can reach a terahertz domain by the degenerate doping, thin thickness and nanometric length of channel.

For the temperature effect, the calculations found that the admittance depends on all thermal parameters such as the velocity relaxation rate and the mobility of carriers. The thermal effect keeps the resonance frequency position constant this means that the temperature does not lead to change the plasma frequency of free carriers.

The variation of the channel-gate distance d leads to change the transistor behavior to diode with two terminals when the Lorentzian noise spectrum is obtained.

The discussion of the channel parameters effects on admittance is useful for optimizing the transistor behavior for the high frequency appearance of resonance.

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