Electronic, optical and thermal excitation of plasma waves in HEMTs: a theoretical study

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Abstract. We investigate the influence of collective plasma modes in a field-effect transistor channel under different excitations and biasing conditions. First, we study the case of a device externally-excited by a harmonic optical beating or an electronic excitation and current-driven at the drain. The harmonic and continuous responses of the transistor are calculated using a pseudo-two-dimensional hydrodynamic approach. They show sharp resonances related to the first odd plasma modes, whose frequencies and amplitudes can be modified by playing on the drain bias. Then, through the generalized impedance-field method we calculate also the spectral density of drain voltage fluctuations in the absence of external excitations. Also these noise spectra exhibit peaks corresponding to the odd plasma modes.

1. Introduction
Two-dimensional plasma waves in quasi-ballistic nanometric transistors are considered a very promising physical phenomenon which can be exploited for the conception of terahertz (THz) devices operating at room temperature. Recent experiments have shown the possibility of exciting plasma modes in HEMTs by means of a THz radiation, useful for detection applications [1], or by means of a beating photoexcitation which could provide a possible THz emitter [2]. In addition, it has been shown that the high-frequency noise spectra of HEMTs contain excess noise related to thermal excitation of plasma modes [3].

We propose to investigate theoretically these three situations by using a numerical pseudo-two-dimensional hydrodynamic (HD) approach. This model allows us to simulate nanometric field-effect transistors from ohmic to saturation conditions by taking into account nonequilibrium conditions, presence of access regions, etc. [4]. The two cases of external excitation (electronic and optical) of plasma modes are studied by calculating the deterministic frequency responses of the transistor working in different operation modes. On the other hand, the thermal excitation is treated in the framework of the impedance-field method based on noise sources calculated by Monte-Carlo simulations [3].

Thus, this article constitutes a synthesis on the influence of plasma resonances on the high-frequency transistors operation with or without an external excitation, and a very useful tool to
achieve a detailed comprehension of the plasma mechanism.

2. Numerical model

We couple the one-dimensional HD equations relative to the electron density \( n(x,t) \), the mean velocity \( v(x,t) \) and the mean energy \( \epsilon(x,t) \), with an approximation of the Poisson equation described in [3, 4]:

\[
\begin{align*}
\frac{\partial n}{\partial t} &= \frac{\partial (nv)}{\partial x} + G + \delta G \\
\frac{\partial v}{\partial t} &= -v \frac{\partial v}{\partial x} - \frac{eE}{m^*} - \frac{1}{n} \frac{\partial (\delta v^2 n)}{\partial x} - n_v + \dot{f} \\
\frac{\partial \epsilon}{\partial t} &= -v \frac{\partial \epsilon}{\partial x} - \frac{eE \epsilon}{m^*} - \frac{1}{n} \frac{\partial (\delta \epsilon \delta n)}{\partial x} - (\epsilon - \epsilon_0) n_v \\
\epsilon c \frac{\partial^2 V}{\partial x^2} + \epsilon s V_g + \delta V_g - V &= e (n - N_D) 
\end{align*}
\]

(1)

Here \( e \) is the elementary charge and \( E \) the \( x \) electric field component. \( \epsilon_0 \) is the equilibrium mean energy. \( \epsilon_s \) and \( \epsilon_c \) are the dielectric constants of, respectively, the Schottky layer and the channel. \( d \) is the gate-to-channel distance and \( \delta \) the channel thickness. \( N_D \) is the effective donor concentration in the channel. The velocity and energy relaxation rates \( n_v, \nu_c \), the electron effective mass \( m^* \), the velocity variance \( \delta v^2 \) and the energy-velocity covariance \( \delta \epsilon \delta v \) depend on the local mean energy and they were calculated by a Monte-Carlo simulation of InGaAs bulk material at room temperature.

Three source terms can be included in the equations: (i) a beating optical excitation through the term \( G + \delta G = G_0[1 + \cos(2\pi ft)] \) [4]; (ii) an electronic excitation on the gate which may describe the coupling between a THz radiation and an antenna connected to the gate [1], \( \delta V_g = \Delta V_g \cos(2\pi ft) \); (iii) a local source of thermal fluctuations in the channel \( \dot{f} \), described by the spectral density \( S_{ff} = 4k_bT n_v / m^* \) obtained by Monte Carlo simulations [3].

3. External excitation of plasma modes

It has been experimentally shown that the plasma resonances can be efficiently excited by external stimulations [1, 2]. In this section, we study the resonant response of a transistor channel to an optical beating and an electronic oscillating voltage on the gate.

We simulate a \( \text{In}_{0.53}\text{Ga}_{0.47}\text{As}/\text{InAlAs} \) HEMT, with \( d = 22 \text{ nm} \) and \( \delta = 10 \text{ nm} \), composed of a \( L_g = 100 \text{ nm} \) long gated part \( (N_D' = 1 \times 10^{18} \text{ cm}^{-3}) \) surrounded by two 50-nm-long ungated sections \( (N_D' = 5 \times 10^{18} \text{ cm}^{-3}) \). The threshold voltage \( V_{th} \) calculated by the Poisson equation in (1) gives a value \( V_{th} = -\frac{eN_{D'}d}{\epsilon_s} = -300 \text{ mV} \). By taking \( V_g = 0 \text{ mV} \), the swing voltage is \( V_0 = V_g - V_{th} = 300 \text{ mV} \).

In order to be in the optimal static conditions for plasma wave excitation, the source voltage and the drain current are fixed. Under this constant current operation, the response of the transistor to an external oscillating excitation can be described by the drain voltage harmonic and continuous variations, \( \delta V(f) \cos(2\pi ft) \) and \( \delta V(f) \), respectively [4].

3.1. Optical excitation

In this case, \( \Delta V_g = 0 \), \( \dot{f} = 0 \) and \( G_0 \) is taken equal to \( 1 \times 10^{27} \text{ cm}^{-3} / \text{s} \) which corresponds to typical conditions of photomixing experiments [5]. The harmonic and average photoresponse are reported on Fig. 1. For both quantities, two resonances corresponding to the first plasma modes are observed at THz frequencies. At increasing \( V_{DS} \), the resonance frequency of the peaks decreases significantly. This can be explained by the global growth of the mean velocity.
in the channel leading to an increase of the plasma transit time along the channel. Moreover, we observe that the amplitude of the resonant photoresponse can be maximized by playing on the drain voltage. As discussed in [4], this effect is mainly due to the optimization of the wave increment of the forced oscillator constituted by the photoexcited channel.

Figure 1. Calculated harmonic (a) and average (b) photoresponses under optical excitation as functions of the beating frequency and for the reported $V_{DS}$.

3.2. Electronic excitation

In this subsection, $G_0 = 0$, $\bar{f} = 0$ while $\Delta V_g = 1$ mV. Figure 2 shows the frequency-dependent harmonic and average responses of the transistor to the harmonic oscillating gate voltage for different $V_{DS}$. The behavior is very similar to that observed in the case of optically excited channels: the same resonance frequencies are observed at the different drain voltages and the variation of resonance qualities with the drain bias is identical. Even if the carrier modulation in the channel is induced by two very different physical mechanisms, the excited plasma modes, whose properties only depends on static parameters (gate length, gate and drain biases), are similar.

Figure 2. Calculated harmonic (a) and continuous (b) responses under electronic excitation as functions of the frequency of electronic excitation and for the reported $V_{DS}$.

The main difference between the two kinds of excitation stands into the fact that high order modes are better excited by an electronic excitation, and this especially at low voltages. Indeed,
an optical illumination controls the carrier generation velocity while an oscillating gate-to-
channel voltage is almost proportional to the electron concentration [see Eq. (1) for low $\partial^2 V / \partial x^2$].
Thus, the oscillating optical excitation is less efficient at high-frequency than the electronic
stimulation.

4. Thermal excitation of plasma modes
In this section, we consider a similar HEMT without any external excitation. We solve the first
two hydrodynamic equations taking $\nu_v = 3 \times 10^{12}$ s$^{-2}$, $m^* = 0.04 m_0$, $G_0 = 0$ and $\Delta V_g = 0$.

The drain current is fixed at zero value and we calculate the spectral density of voltage
oscillations at the drain in the framework of the generalized impedance-field method [3]. The
result is reported on Fig. 3.

![Figure 3](image)

Figure 3. Spectral density of voltage fluctuations at the drain terminal as a function of
frequency.

Since the noise sources are considered white and not correlated in space, they can excite
the different odd plasma modes whatever their wavelength or frequencies. As a consequence,
sharp peaks related to the odd plasma modes, already seen in Fig. 1 and 2, appear in the high-
frequency noise spectra. The larger peak around 25 THz can be attributed to the 3D plasma
resonance of the access region.

5. Conclusion
We studied the most common cases where plasma wave resonances manifest themselves in field
effect transistor channels. This theoretical investigation is carried out by means of an original
hydrodynamic pseudo-2D numerical model. We demonstrate that the first plasma resonances
can be efficiently excited by an optical or electronic excitation. In this latter case, the high-order
harmonics are significantly more stimulated. In both cases, the first resonance can be optimized
and tuned by playing on the static bias. Finally, even in the absence of an external excitation,
these plasma resonances are evidenced in the noise spectrum as an excess contribution.

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