Plasmonic Noise of Field-Effect Transistors Operating at Terahertz Frequencies

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I. INTRODUCTION

The use of nanometer field-effect transistors (FETs) for the development of low-cost THz detectors and emitters working at room temperature is one of the most promising trends in ultrafast modern electronics. Such devices should open the way to a large number of applications and may greatly benefit from the development of integrated systems[1]. Mainly, this is associated with the possibility of easy tuning the 2D plasma excitation spectrum inside the transistor channel by changing the external conditions, namely: gate voltage, drain voltage, operation regime, etc.[2–4]. Indeed, under special excitation and biasing conditions, stream-plasma instabilities leading to the emission of THz radiation may be created in the transistor channel[5]. On the other hand, it has been proved both by experiments and numerical simulations that the excitation of plasma modes in the transistor channel increases significantly the efficiency of room-temperature direct and heterodyne detection in the THz frequency range[6,7].

It is well known that the characteristics of the internal electronic noise of a device reflect the information related to both the eigen-frequency spectrum[2] and the state of the free carrier system and its changes (for example, in going from equilibrium to nonequilibrium conditions). Such a dependence of the internal noise characteristics on the physical behavior of free carriers can also be used as a precursor of the transition from a first physical state to another one such as, for instance, the transition from a static to a dynamic state, onset of generation processes, etc.. In this contribution we present a critical overview of the main features of electronic noise spectra of FETs operating in the THz frequency range : in particular, we discuss the possible influence of external excitations and the role of the transistor geometry.

II. THEORETICAL MODEL

Carrier transport and related fluctuations are modeled as a one-dimensional (1D) process by using simple hydrodynamic (HD) equations[2]

$$\frac{\partial n}{\partial t} + \frac{\partial nv}{\partial x} = 0 \qquad (1)$$

$$\frac{\partial v}{\partial t} + \frac{\partial}{\partial x}\left[\frac{v^2}{2} + \frac{e}{m^*}\varphi\right] + e\nu D\frac{\partial n}{\partial x} + v\nu = \tilde{f} \qquad (2)$$

where n and v are the concentration and velocity of electrons in the channel, respectively, ν is the velocity relaxation rate, m^* the electron mass, D the longitudinal diffusion coefficient, and $\tilde{f}$ the Langevin force which describes the source of thermal fluctations at the lattice temperature T with the spectral density

$$S_{ff} = \frac{4k_BT\nu}{m^*} \qquad (3)$$

The self-consistent potential $\varphi(x)$ inside the channel is described by a 1D approximation of the 2D Poisson equation[8]:

$$\varepsilon_c\frac{\partial^2}{\partial x^2}\varphi + \varepsilon_s\frac{U_g-\varphi}{d(x)\delta} = \frac{e}{\varepsilon_0}[n(x) - N_D(x)] \qquad (4)$$

where δ is the channel width, U_g the gate potential, N_D the effective donor concentration in the channel, $d(x)$ the effective gate-to-channel distance. A dependence of $d(x)$ on the coordinate in the channel allows us to describe in the framework of Eq. (3) both gated regions where $d(x)$ has certain finite value and ungated regions where $d(x) \to \infty$ is supposed to tend to infinity.

III. PLASMA RESONANCES EXCITATED BY THERMAL FLUCTUATIONS

The system of Eqs. (1) to (4) is closed and it allows to calculate numerically the spectral densities of current and voltage fluctuations, $S_{JJ}(\omega)$ and $S_{UU}(\omega)$, respectively at the transistor terminals as:

$$S_{\xi\xi}(\omega) = \int_0^L n(x_0)|G_\xi(\omega, x_0)|^2 S_{ff}(x_0)dx_0 \qquad (5)$$

where L is the full length of the channel, $G_\xi(\omega, x_0)$ the spectral representation of the response function ($\xi = J, U$) to a local $\delta-$like excitation at $x = x_0$ induced by the Langevin force $\tilde{f}(x_0)$.

Therefore, it is possible to calculate the spectral density of current fluctuations in source-drain (SD) and source-gate (SG) circuits. A typical result calculated at constant voltage operation, that is for $\Delta U_g = 0$ and $\Delta U_d = 0$, is reported in Fig. 1. We observe that, as expected, oscillations in the noise spectra which are related to the resonant excitation of spatial modes of plasma waves in the dielectric layer separating the channel from the gate.

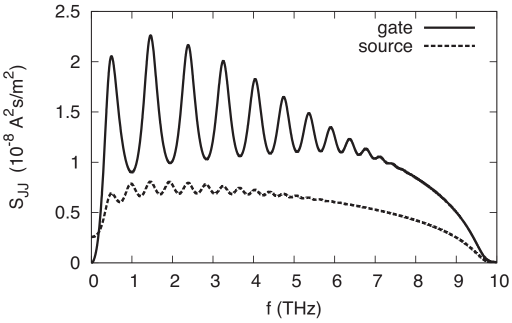

FIG. 1. Calculated spectral density of current fluctuations in source-drain and source-gate circuits calculated with $U_d = 0$ and $U_g = 0$.

IV. CRITICAL ANALYSIS AND OPEN QUESTIONS

Using the previously described model we will present a critical analysis of the main features of noise spectra and a discussion of the following debated questions in the literature:

1. To which extent the widely employed Dyakonov-Shur model can describe correctly the noise spectra and the associated plasma resonances?

2. What happens if the transistor channel is not a perfect 2D gas, i.e. which is the role of the channel thickness?

3. Which is the effect of a realistic topology, i.e. channel regions whose electrostatic potential is not directly controlled by the gate electrode?

4. Which is the effect of the embedding circuit, i.e. can the plasma resonances be tuned by playing on external discrete elements?

5. Can the noise be suppressed or enhanced by using external electromagnetic excitations ?

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