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Effect of gate-length shortening on the terahertz small-signal and self-oscillations characteristics of field-effect transistors

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ABSTRACT

We investigate the shortening of the gate-length in submicrometric and nanometric field-effect transistors as a powerful tool to improve their self-oscillations performances in the terahertz frequency region due to the appearance of the Dyakonov–Shur instability. The theoretical model is based on the numerical solution of hydrodynamic equations for the electron transport in FETs/HEMTs channels. We show that a decrease of the gate length allows, on the one hand, to increase the intrinsic resonant frequencies near 1 THz and, on the other hand, to improve the conditions for the onset of the Dyakonov–Shur instability and related phenomena. The small-signal characteristics calculated under constant drain-voltage operation are compared with the drain-voltage self-oscillations calculated under constant drain-current operation.

1. Introduction

During the last 3 decades various current instabilities and possibilities to obtain THz/sub-millimeter (0.3–3 THz or 1–0.1 mm) radiation generation in semiconductor electronic structures have been widely investigated both theoretically and experimentally. Historically, these investigations can be subdivided into two groups.

The former group concerns instabilities in diode structures where the main attention has been paid to plasma instabilities assisted by the Gunn-effect and low-temperature optical phonon emission in new materials (GaN, SiC, InGaAs, etc. [1–4]), resonant tunneling diodes [5,6], Bloch oscillations [7,8], etc.

The latter group has started in recent years together with the development of modern Field Effect Transistors (FETs) and High Electron Mobility Transistors (HEMTs) which, compared to diodes, allow to decrease the level of relaxation processes (remote impurity scattering [9]) and to govern the 2D-plasma frequency by the voltage applied to the gate contact [10,11]. Current investigations of FETs/HEMTs try to exploit not only the effects typical for diodes but also to use the additional possibilities inherent to these structures such as the Dyakonov–Shur effect and optical excitation of 2D plasma waves [10–16]. Moreover, recent experimental results and their theoretical interpretations [15,16] seems to indicate that THz radiation generation due to Dyakonov–Shur (DS) instability could be achieved. Therefore, below we shall concentrate on the DS-instability and associated phenomena based on the excitation of 2D-plasma waves. In short, we refer to the DS instability as the self-oscillations of the drain voltage associated with the reflection of plasma waves traveling in a FET channel by the source and drain boundaries that can be achieved under particular material, bias and geometry conditions.

First, in Section 2, we discuss the general physical requirements to obtain the DS instability and the different ways to realize them in the channel of a FET or HEMT. Then, in Section 3, we describe the details of the theoretical model and the equations used to simulate the transistors. As a probe to investigate the presence of this instability it is possible to use the small-signal response of the device to different kinds of perturbations. In our case we concentrate on the frequency analysis of the small-signal admittance $Y(f)$ describing the device current response under voltage driven operation: as we will show below this is the appropriate quantity for our situation. Indeed, negative values of the real part of the admittance $\Re[Y(f)]$ are generally used as an indicator of possible instabilities in the corresponding frequency range. In addition, it can be easily demonstrated that $\Re[Z(f)] = \Re[Y(f)]/Y^2$ thus showing that if $\Re[Y(f)]$, calculated in the constant voltage operation, is negative in a certain frequency range, $\Re[Z(f)]$, calculated in the constant current operation, is also negative in the same frequency range. For the case of 2D plasma waves in FETs, previous works and also our simulations show that the situation is stable under the

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constant voltage operation while it becomes unstable for the constant current operation. However we stress that, by definition, small-signal characteristics can be calculated only under stable operation conditions. Since the DS instability can be obtained only when a constant current is forced to flow through the drain contact, it is possible to investigate this phenomenon through the frequency analysis of the real part of the small-signal admittance calculated in the voltage driven operation mode; the calculation of the real part of the small-signal impedance under constant current operation would not be possible because the device is unstable. We remark that for other devices the situation can be the opposite one, i.e. if the device is stable under current driven operation the calculation of the small-signal impedance would be more appropriate (see for instance Ref. [17]). For these reasons, in the first part of Section 4, we calculate the frequency dependence of the real part of the small-signal admittance under constant drain voltage conditions. This investigation provides the possible oscillation frequency bands as functions of the applied drain voltage and gate length. Moreover a comparison with the theoretical conditions for the achievement of the instability can be made. Then, in the second part of Section 4, the appearance of the DS instability is directly simulated through the time evolution of the drain voltage under constant drain-current conditions. If an initial voltage perturbation, due to a small current step-like variation, is progressively growing in time instead of being damped, we can consider this evolution as a clear signature that the transistor enters a self-oscillation regime related to the plasma instability. Finally a comparison between the frequency associated with the negative values of the real part of the small-signal admittance and that of the self-oscillations is performed. The agreement between these frequencies clearly indicates the common origin of these phenomena, i.e. the DS instability.

2. Condition of instability

2.1. General trends

Let us imagine the system characterized by: (i) some resonant frequency ω_{res} corresponding to an instability which can appear under certain conditions and (ii) some velocity/momentum relaxation time τ caused by free-carrier scatterings by ionized impurities, acoustic and optical phonons, etc. which tend to destroy the instability.

In the general case, as a first estimation of the critical point for the instability onset, one can consider the condition:

$$\omega_{res}\tau = 1 \tag{1}$$

If $\omega_{res}\tau < 1$ the relaxation processes prevail and the instability cannot develop. In the opposite case, $\omega_{res}\tau > 1$ one can expect a favorable situation for the instability development. To fulfill the latter condition obviously one should either increase ω_{res} or increase $\tau = 1/\nu$, i.e. decrease the intensity of scatterings and the associated momentum relaxation rate ν.

2.2. Dyakonov–Shur instabilities

Let us specify the case of the DS instabilities which can occur in the gated channel of a short FET/HEMT. Such instabilities appear when the amplitudes of plasma waves, after propagation and reflection by the boundaries, instead of being damped are progressively growing in time. Let us note R_s and R_d the voltage-wave reflection coefficients on source and drain terminals, respectively. During a roundtrip, the amplitude of the voltage perturbation is multiplied by a factor:

$$\alpha = \exp(-T_{res}/\tau)|R_s||R_d| \tag{2}$$

where $T_{res} = 1/f_{res}$ is the duration of the roundtrip, and consequently the period of plasma oscillation.

Then, an instability can only occur for a asymmetrically biased channel because:

- for a voltage-driven operation, the boundary condition impose $R_d = R_s = -1$, therefore $\alpha = \exp(-1/(f_{res}\tau)) < 1$, the oscillation are unconditionally damped and the system is stable.
- for a current-driven operation, we now have $R_d = \frac{s+v_d}{s-v_d}$, where s is the plasma velocity and v_d the drift velocity (see Ref. [10] for a calculation under the assumption of uniform static potential and velocity or Ref. [18] for a more general approach). In these conditions, α can exceed 1 for high drift velocities and thus an instability can occur.

In this latter case, the instability condition is therefore $\alpha = \exp(-1/(f_{res}\tau))R_d > 1$ which can be rewritten:

$$\omega_{res}\tau > 2\pi/\ln R_d \tag{3}$$

However, it is difficult to precisely define and estimate R_d in far-from-equilibrium conditions when the velocity and potential profiles inside the channel are non uniform. Nevertheless, we can assume that, under usual operating conditions, the order of magnitude of the dimensionless coefficient $2\pi/\ln R_d$ is around 1. The specific instability condition is similar to the general one described by Eq. (1) and consequently the value of the $\omega_{res}\tau$ is the one of interest to explain or predict a resonant or unstable behavior.

2.3. Setting off the Dyakonov–Shur instability

For the DS instability considered here, the first way corresponds to increasing the frequency of the 2D-plasma waves. Usually this implies increasing the electron concentration in the FET/HEMT channel since the resonance frequency $\omega_{2D} \propto \omega_p/L_g$ where ω_p is the 3D plasma frequency and L_g the length of the gate. If the maximum possible free-electron concentration n in the transistor channel is controlled by the donor concentration N_d, then $\omega_p^2 \propto n \leqslant N_d$ while the relaxation rate due to impurity scattering $\nu_I \propto N_d$. As a result, an increase of the frequency of eigen plasma oscillations deteriorates automatically the conditions for the instability development $\nu_I/\omega_p \propto N_d/\sqrt{n} \geqslant \sqrt{N_d}$.

In part this problem is removed in HEMTs where the free electrons come from the δ-doped layer placed outside the channel so that only the remote impurity scattering [9] remains as interaction mechanism with impurities in the channel. Nevertheless, as we can see from the literature, the generation regime is not achieved yet and it is necessary to discuss other strategies to improve the possibilities for the onset/development of the DS instability.

(i) The most direct way is to decrease the lattice temperature, and thus, to decrease the scattering intensity and the momentum relaxation rate $\nu = 1/\tau$. For example, in a recent work [16] a significant narrowing of the emission line has been experimentally observed in lowering the temperature from 300 to 200 K. These results agree with theoretical calculations of the resonant detection spectra behavior performed under similar conditions [16].

(ii) Another way consists in increasing the resonant frequency by an enhancement of the free-electron concentration in the portion of the channel under the gate when a positive potential $U_g > 0$ is applied to the gate [19]. Such an effect can be realized in FET/HEMT transistors by using the MOS-technology for the galvanic gate-to-channel separation. In this case the level of impurity scattering at doping centers remains at a minimum level determined by the level