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Multi-input intrinsic and extrinsic field effect transistor models beyond cutoff frequency

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ABSTRACT

This work expands the classical theory of operation of FETs beyond cutoff frequency. Using an electron drift transport model, the responsivity of a FET working in the linear region of operation within the semi-classical transport region is derived. Different DC circuit configurations are included in the analysis, as well as multiple AC input signals. Separating the model into intrinsic and extrinsic parts enables better analysis of the effect of multiple input AC signals. A new treatment of the concept of symmetry/asymmetry in FETs beyond the cutoff frequency is presented. The origin of symmetry and factors affecting it are analyzed. The effects of asymmetries from various origins within the FET system are taken into account. The analytical results are used to qualitatively explain published experimental results of symmetry points in FET THz detectors.

1. Introduction

For long time, the cutoff frequency has been considered the limiting factor for the operation of any transistor. The transistor was considered blind above this frequency, which can be as high as few hundreds of gigahertz for channel lengths below 100 nm. AC input signals with frequencies higher than the cutoff frequency are highly attenuated within the channel and blocked from reaching the output port.

In recent works, however, field effect transistors (FETs) have been used for Terahertz (THz) signal detection beyond its transit-time cut-off frequency [1,2]. This phenomenon is explained in terms of the simultaneous nonlinear modulation of the carrier density and velocity within the transistor channel due to incoming THz radiation [3-5]. THz electric field is rectified, like in square law detectors, and a constant (DC) source-to-drain voltage appears. This voltage is the detection signal and is called the photovoltaic response or the photo-response. More details about the detection mechanism can be found in the literature [6]. Different kinds of FETs with gate length of the order of hundreds of nanometers exhibit good broadband responsivities for the THz radiation. Examples are GaAs high electron mobility transistors (HEMTs) [7,8], GaN HEMTs [9], InGaAs HEMTs [10] and silicon metal–oxide-semiconductor-FETs (MOSFETs) [11,12] when modeling FETs operating beyond their cutoff frequency (THz FET detectors) the input signal was assumed from only one input port [13]. Practically, this is not feasible. This is so because of the long wavelength of incident THz radiation compared to the FET channel length. Therefore the presence of multiple AC inputs is sometimes unavoidable experimentally. The effect of multiple-AC-inputs has been noticed through the existence of points of null responsivity. These null (symmetry) points were attributed to symmetry between the two input signals. Conclusions were drawn from experimental results that operating around the symmetry point must be avoided for Proper operation of FET THz detectors. However no analysis on the conditions and parameters affecting this symmetry point operation were found in the available literature.

This work presents two models for FET operation beyond cutoff: the intrinsic and the extrinsic FET models. The intrinsic model (Section 2) describes the nonlinear operation of a FET 2DEG channel beyond cutoff. Drift electron transport equations are used to model the electron nonlinear response within the channel. Multi-AC input signals are assumed through proper boundary conditions. Different biasing conditions are assumed also through the DC boundary conditions. In each case, the multi-AC input intrinsic FET responsivity is derived. The extrinsic FET model (3) describes

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coupling the externally applied/read signals to intrinsic FET ports (2DEG channel ports). These signals include AC input signals and DC readout signal. However this work is focusing on the AC input coupling because of its effect on the symmetry phenomenon. Once both the extrinsic and intrinsic models are established, the analysis of symmetry effects in FET THz detectors can follow (0). The present analysis offers a novel analytical treatment for the effects of symmetry/asymmetry on the operation of FET THz detectors. The origin of symmetry and parameters affecting it are discussed based on the analytical derivation presented in Sections 2 and 3. Finally in order to estimate the validity of these equations the presented analysis is compared with experimental data of THz FET detectors that included symmetry points (5). A qualitative comparison between these results and the presented analysis will show significant agreement between them. This verifies the validity of the presented analysis of multi-AC input symmetry effects in THz FET detectors.

2. Intrinsic drift electron transport model

This model uses the electron drift transport equation to model the electron transport within the 2DEG channel of the FET. This model is valid within the semi-classical transport which is limited by frequencies below the momentum relaxation rate ($1/\tau$), where τ is the momentum relaxation time. The other limit for the validity of this model is the FET cutoff frequency, which is the practical case for FET THz detectors. Therefore the scope of validity of the present work is defined by:

$$\omega_T < \omega < \frac{1}{\tau} \tag{1}$$

This range coincides with the range of operation of broadband terahertz FET detectors. Operation of such detectors have been previously analyzed by applying Euler hydrodynamic equation [14,13] to model the response of damped plasma waves within the nonlinear FET channel.

A typical FET structure that is studied within the scope of this work is shown in Fig. 1. HEMTs and MOSFETs are examples of FET structures that fall within the scope of this work. For a typical FET structure two equations can be used to describe the 2DEG electron transport within the channel: carrier continuity and drift equations. For a FET channel with an electric field $F(x)$ applied along the x axis the charge continuity equation can be written as [15]

$$\frac{\partial I(x,t)}{\partial x} = W_g C_g \frac{\partial U_{gc}}{\partial t} \tag{2}$$

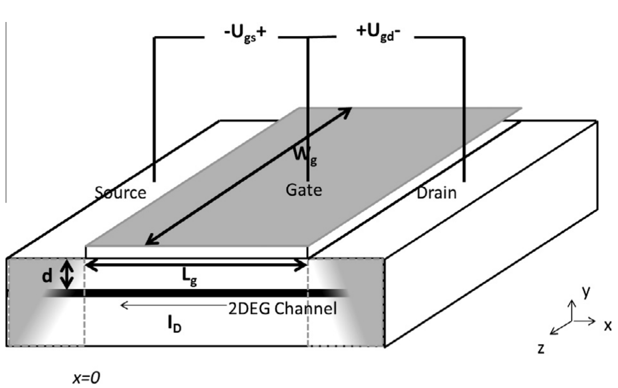

Fig. 1. Schematic representation of the FET structure.

where W_g is the gate width (z direction), $U_{gc}(x,t) = U_{GC}(x,t) - V_T$ is the local gate to channel (at a distance x from the source) potential, U_{GC} is the gate to channel potential, V_T is the threshold potential of the FET (considered constant), and $C_g = \epsilon/d$ is the gate capacitance per unit area, where ϵ is permittivity of the dielectric between the gate and the channel (oxide in MOS and semiconductor in MODFET), and d is the distance between the gate and the FET channel. The above equation is valid under the gradual channel approximation. This is valid within the scope of this work for FETs operating in the linear region of operation.

For a FET 2DEG channel where the relaxation time approximation is valid and no diffusion is assumed (gated part of the channel for $V_G > V_T$), the current transport can be simplified to the drift current equation:

$$I_D \cong W_g \mu C_g (U_{GC} - V_T) \frac{dU_{CS}}{dx} \tag{3}$$

where $U_{CS}(x,t)$ is the potential within the channel at distance x from the source ($U_{CS} = U_{gs} - U_{gc}$, $U_{gs} = U_{GS} - V_T$, U_{gs} is the gate/source potential), and μ is the electron drift mobility within the FET channel. The two equations above are valid for FETs within the linear region of operation. Under this condition the electric field within the channel does not exceed the critical field value $F_c = \upsilon_S/\mu$, at which the electron gas reaches its effective saturation velocity υ_S. From Eqs. (2) and (3) the potential wave equation within the FET channel can be written as

$$\frac{\partial^2}{\partial x^2} U^2(x,t) = \frac{2}{\mu} \frac{\partial U(x,t)}{\partial t} \tag{4}$$

where $U(x,t) = U_{gc}(x,t)$. This equation is similar to the one presented in the hydrodynamic model, and it can be solved using similar steps [4,13]. The wave equation is divided into DC and AC equations that are given by:

DC:

$$\frac{d^2\left(V_0^2 + \frac{1}{2}|V_1|^2\right)}{dx^2} = 0 \tag{5}$$

$$I_0 = -\frac{\beta}{2} \frac{d\left(V_0^2 + \frac{1}{2}|V_1|^2\right)}{dx} \tag{6}$$

where $\beta = W_g C_{g\mu}$

and AC (small signal)

$$\frac{d^2(V_0(x)V_1(x))}{dx^2} = \frac{i\omega}{\mu} V_1(x) \tag{7}$$

$$I_1 = -\beta \frac{d(V_0 V_1)}{dx} \tag{8}$$

where subscripts 0/1 refer to DC/AC parts of the potential and current signals respectively. The DC boundary conditions depend on the driver of the FET. The two most common FET configurations can be described as follows:

$$\text{voltage driven FET} \quad V_0(0) = V_{gs0}, V_0(L_g) = V_{gd0} \tag{9}$$

and

$$\text{current driven FET} \quad V_0(0) = V_{gs0}, I_0(L_g) = I_{D0} \tag{10}$$

$$\text{and the AC boundary conditions} \quad V_1(0) = V_{gs1}, V_1(L_g) = V_{gd1} \tag{11}$$

a. **DC anaylsis**

The solution of Eq. (5) has been presented in the hydrodynamic model in [13]. The solution gives the DC readout signal (respon-