Solid-State Electronics 126 (2016) 143–151

Contents lists available at ScienceDirect

Solid-State Electronics

journal homepage: www.elsevier.com/locate/sse

Circuit model for single-energy-level trap centers in FETs

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ARTICLE INFO

Article history:
Received 4 June 2016
Received in revised form 27 August 2016
Accepted 30 August 2016
Available online 3 September 2016

The review of this paper was arranged by S. Cristoloveanu

Keywords:
Trapping
Microwave FET
GaN HEMT
Semiconductor device measurement
Semiconductor device modeling

ABSTRACT

A circuit implementation of a single-energy-level trap center in an FET is presented. When included in transistor models it explains the temperature-potential-dependent time constants seen in the circuit manifestations of charge trapping, being gate lag and drain overshoot. The implementation is suitable for both time-domain and harmonic-balance simulations. The proposed model is based on the Shockley-Read-Hall (SRH) statistics of the trapping process. The results of isothermal pulse measurements performed on a GaN HEMT are presented. These measurement allow characterizing charge trapping in isolation from the effect of self-heating. These results are used to obtain the parameters of the proposed model.

1. Introduction

When charge trapping is present in a field-effect transistor (FET), the DC characteristics of the FET are not representative of high-frequency operation [1]. Charge trapping is a process in an FET that is characterized by a characteristic frequency that is dependent on temperature and the terminal potentials of the FET. In large-signal, broadband applications, the difference frequencies in these signals can fall in the region of the trapping characteristic frequency [2], resulting in a dramatic drop in the intrinsic gain of the transistor, which then severely affects the linearity of the transistor [3]. The design of circuits for these applications cannot rely on narrow-band, low-frequency, or small-signal assumptions. Instead, a full spectral view of the frequency-dependent high-order nonlinearity of FETs needs to be considered, so a comprehensive model is required to fully describe behavior from DC to RF [4]. Such a model should incorporate the low-frequency charge-trapping phenomenon [5].

Charge trapping in FETs is attributed to the presence of so-called "trap centers" [6]. These are formed in FETs as a result of a perturbation of the bonding structure of the semiconductor material, from which the FET is fabricated, leading to the formation of energy levels in the bandgap of the semiconductor. A trap center is either an acceptor or a donor [7], and is either a single-energy-level trap center or a multiple-energy-level trap center [8,9]. This work is concerned with single-energy-level trap centers, and so for simplicity, a "single-energy-level trap center" is referred to, hereafter, as a "trap center".

A trap center can either be an electron- or hole trapping center or a carrier generation or recombination center [8]. At thermal equilibrium, a trap center acts either as an electron-trapping center or as a hole-trapping center. In a non-equilibrium condition, the concentrations of the available electrons and holes for capture at a trap center can be quite arbitrarily varied, and so a trap center acts as a generation or recombination center in one non-equilibrium condition, but as an electron or hole trapping center in another non-equilibrium condition. In an FET, a non-equilibrium condition corresponds to the condition where the FET is biased.

To incorporate charge trapping in an FET model, many models have been proposed. Unlike other empirical models for charge trapping [10–16], in [4] a model is proposed for a trap center that is based on Shockley-Read-Hall (SRH) [17] statistics of the trapping process. When included in transistor models it explains the potential- and temperature-dependent time constants seen in the circuit manifestations of charge trapping, being gate lag and drain overshoot. This model, however, captures the trapping behavior only when the trap center acts as a donor electron trapping center or as an acceptor hole trapping center. This can be non-realistic in FETs because a trap center in an FET can be subject to the injection of electron current at one bias condition [18] and to the injection of hole current at a different bias condition [19,20], and to the injection of both electron and hole currents at a third bias condition.

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http://dx.doi.org/10.1016/j.sse.2016.08.005
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By relaxing the simplifying assumptions of the model of [4], we develop, in this paper, a comprehensive model of a trap center in an FET that can capture the trapping behavior at various bias conditions. In this model, the trapping phenomenon is represented in terms of controlled current sources that can be handled by a circuit simulator. This model is implemented in an FET model as a feedback network: The terminal potentials of the FET dictate the input potentials of the model, and the output potential of the model modifies the pinch-off potential and/or the drain and source parasitic resistances of the FET, depending on the location of the trap center in the FET. The proposed model can be extended to a model for a multiple-energy-level trap center. This will be dealt with in a future work.

In [4], an empirical approach is taken to set a single functional form for the dependence of the input potential of the trap-center model, on which the trapping time constant depends, on the terminal potentials of the FET. Unlike this approach, we demonstrate, in this paper, that by identifying the current-injection mechanism that triggers the trapping process in the FET and exploring the functional form for the current that is injected into the trap-center region, it becomes possible to obtain the actual dependence of the trapping behavior on the terminal potentials of the FET, which varies depending on what injection mechanism is responsible for the trapping process. This paper presents results of measurements performed on a GaN high-electron-mobility transistor (HEMT) that confirm the theory. In particular, this paper reports results of pulse measurements that show that the state of charge trapping in the device under test is completely determined by a linear combination of the terminal potentials of the device, called the "controlling potential". Transient responses that are obtained by performing pulse measurements from several bias points to a final bias point are identical if the bias points before the step change correspond to the same controlling potential.

This paper finally presents the results of isothermal measurements [21] performed on the device under test, by which the trapping behavior in the device was characterized, and the parameters of the proposed trapping model were obtained, in isolation from the effect of the self-heating process in the device.

Section 2 reviews the charge-trapping mechanism in FETs. The equations developed in this section are used, in Section 3, to develop a comprehensive circuit model of a trap center in FETs. Section 4 presents the results of pulse measurements performed on a GaN HEMT. These results are used to obtain the parameters of the proposed trapping model for the trap centers in the device under test. Finally, Section 5 draws some conclusions.

2. Trap center

2.1. Rates of charge capture and emission

There exists four competing processes for hole and electron capture and emission at the energy level E_X of a trap center. These processes are electron capture, electron emission, hole capture and hole emission. In a Shockley-Read-Hall (SRH) trapping process [17], which is the concern of this paper, these processes are governed by Fermi-Dirac statistics. There is a rate associated with each process. These rates are defined, respectively, as the rate of electron capture from the conduction band, R_{cn}, the rate of electron emission to the conduction band, R_{en}, the rate of hole capture from the valence band, R_{cp}, and the rate of hole emission to the valence band, R_{ep}.

Let n_X [m^{-3}] and p_X [m^{-3}] denote, respectively, the concentrations of the captured electrons and holes at a trap center. For a unit volume of material, the net rate of electron accumulation at the energy levels of a trap center is given by

$$dn_X/dt = U_n - U_p, \tag{1}$$

where $U_n \equiv R_{cn} - R_{en}$ and $U_p \equiv R_{cp} - R_{ep}$ are, respectively, the total rate of electron and hole capture at E_X, and are given by [17]

$$U_n = e_n[p_X \exp(\phi_n) - n_X] \text{ and} \tag{2}$$

$$U_p = e_p[n_X \exp(\phi_p) - p_X], \tag{3}$$

where e_n [s^{-1}] and e_p [s^{-1}] are, respectively, the characteristic frequencies of electron and hole emissions, and

$$\phi_n \equiv (F_n - E_X)/kT \text{ and} \tag{4}$$

$$\phi_p \equiv (E_X - F_p)/kT, \tag{5}$$

where F_n [eV] and F_p [eV] are, respectively, the quasi-Fermi-levels for electrons and holes, k [J/K] is the Boltzmann constant and T [K] is temperature.

The characteristic frequencies of electron and hole emissions $e_{n,p}$ in (2) and (3) are temperature and bias dependent. The temperature dependence of $e_{n,p}$ is given by [4]

$$e_{n,p} = A_{n,p}T^2 \exp(-\Delta E_{en,ep}/kT), \tag{6}$$

where $\Delta E_{en} \equiv E_C - E_X$ and $\Delta E_{ep} \equiv E_X - E_V$ are the activation energies of the electron and hole emissions respectively, where E_C [eV] and E_V [eV] are, respectively, the conduction-band-edge energy and the valence-band-edge energy, and the pre-exponential factors $A_{n,p}$ are proportionality constants. The field-dependent of $e_{n,p}$ is, on the other hand, dictated by the Poole-Frenkel mechanism [22,23].

2.2. Acceptor versus donor trap center

A trap center is either an acceptor or a donor [7]. An acceptor trap center is a trap center that is neutral when all the energy levels of the trap center are empty, and negatively charged and, therefore, ionized, when one or more energy levels of the trap center are occupied by electrons. On the other hand, a donor trap center is a trap center that is neutral when all the energy levels of the trap center are occupied by electrons, and positively charged and, therefore, ionized, when one or more energy levels of the trap center are empty. If the trap center is an acceptor, then (1) corresponds to the ionization rate of the trap center, and if it is a donor, then (1) corresponds to the de-ionization rate of the trap center.

2.3. Available charge for capture

The concentrations of electrons and holes available for capture at a trap center, denoted respectively as n [m^{-3}] and p [m^{-3}], are given by [8]

$$n = \hat{n} \exp(\phi_n) \text{ and} \tag{7}$$

$$p = \hat{p} \exp(\phi_p), \tag{8}$$

where $\hat{n}$ [m^{-3}] is the concentration of the electrons in the conduction band when F_n falls at E_X, and $\hat{p}$ [m^{-3}] is the concentration of the holes in the valence band when F_p falls at E_X.

2.4. Control potentials

From (2) and (3), ϕ_n and ϕ_p act as controlling potentials for the net rate of electron accumulation at a trap center, normalized to the thermal energy kT. From (7) and (8), ϕ_n and ϕ_p act as controlling potentials for the available charge for capture at a trap center. This leads to an interpretation of the terms ϕ_n and ϕ_p as the normalized control potentials of a trap center to the thermal energy (in eV). For simplicity, ϕ_n and ϕ_p will be referred to as the control potentials of a trap center.