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RF dynamic and noise performance of Metallic Source/Drain SOI n-MOSFETs

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ABSTRACT

This paper presents a detailed study of the RF and noise performance of n-type Schottky barrier (SB) MOSFETs with a particular focus on the influence of the Schottky barrier height (SBH) on the main dynamic and noise figures of merit. With this aim, a 2D Monte Carlo simulator including tunnelling transport across Schottky interfaces has been developed, with special care to consider quantum transmission coefficients and the influence of image charge effects at the Schottky junctions. Particular attention is paid to the microscopic transport features, including carrier mean free paths or number of scattering events along the channel for investigating the optimization of the device topology and the strategic concepts related to the noise performance of this new architecture. A more effective control of the gate electrode over drain current for low SBH (discussed in terms of internal physical quantities) is translated into an enhanced transconductance g_m, cut-off frequency f_T, and non-quasistatic dynamic parameters. The drain and gate intrinsic noise sources show a noteworthy degradation with the SBH reduction due to the increased current, influence of hot carriers and reduced number of phonon scatterings. However, the results evidence that this effect is counterbalanced by the extremely improved dynamic performance in terms of g_m and f_T. Therefore, the deterioration of the intrinsic noise performance of the SB-MOSFET has no significant impact on high-frequency noise FoMs as NF_{min}, R_n and G_{ass} for low SBH and large gate overdrive conditions. The role of the SBH on Γ_{opt}, optimum noise reactance and susceptance has been also analyzed.

1. Introduction

Schottky barrier (SB) MOSFETs have a device structure similar to conventional MOSFETs in which heavily doped source and drain regions are replaced by metals or silicides to form Schottky contacts [1–3]. These devices have recently attracted a huge interest due to their remarkable features, which have situated them as potential candidates to solve some of the problems of conventional downscaled MOS transistors [4]. For example, SB-CMOS technology is fully compatible with Silicon CMOS technology, can be fabricated in a low-temperature process including high-*k*/metal-gate [5] and eliminates the need for ultra-shallow junctions and complicated channel doping steps [6]. It has been already demonstrated that CMOS circuits fabricated with SB-MOSFET technology can compete with a highly doped S/D MOSFET structure [7]. The use of silicide source and drain offers at the same time inherently reduced values of contact resistivity [4], even lower than the target values indicated in the ITRS for the year 2016 [8]. Therefore, from the point of view of the device performance, this in turn yields to a higher scalability, reduced short channel effects due to the junction abruptness [1,8], a lower sub-threshold swing [9] and high transconductance [10]. Also some authors defend the immunity of these devices to the latchup phenomena [11,12]. Thus, SB-MOSFETs appear quite attractive as promising candidates for the design of analogue applications featuring sub-100 nm nanoscaled transistor devices [3,13]. For a detailed overview and status of the SB-MOSFET technology, see [5,8,14–16].

In an accumulation mode SB-MOSFET, the injection of carriers in the channel is controlled by the metal (silicide) – semiconductor Schottky junction at the source, which is reverse biased [8]. Thus tunnelling across the potential barrier plays a crucial role to set the transition between the *on* and *off* states [1,17]. Consequently, accurate modelling of SB-MOSFETs involves the treatment of non-classical phenomena, like direct quantum tunnelling across the Schottky barrier. However, the potential barrier modulation induced by the gate severely compromises the use of one-dimensional diode equations to describe the injection at the source [18–21]. Furthermore, the study of the RF performance of SB-MOSFETs is a major issue to find out the possibilities of metal S/D MOS devices to replace doped S/D transistors in the short and mid terms [9,17,22–24]. Within this context, the high frequency noise performance of SB-MOSFETs needs to be elucidated.

In this work we have developed a two-dimensional Monte Carlo (MC) device simulator to study the influence of the main topology parameter of this architecture (the Schottky barrier height, SBH) on

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the high-frequency *ac* and noise properties of SB-MOSFETs, including the most relevant figures of merit (FoMs). It must be noticed that the stochastic nature of the Monte Carlo approach mimics the real, noisy movement of carriers inside the device [25,26] in a microscopic fashion. These features make this method to be particularly well suited for the study of submicrometric devices, since far-from-equilibrium phenomena, non-stationary and ballistic transport, short channel effects, intrinsic noise sources, etc. are intrinsically included [27]. Moreover, an exhaustive analysis of the electronic transport in SB-MOSFET devices is also carried out, including the investigation of the microscopic features of the carrier movement (transit times, mean free paths, local densities of scattering mechanisms, etc.) [27]. The procedure involves tracking any particular electron movement to obtain a recording of the characteristic transport parameters (time of free flights, scattering undergone, etc.) of the ensemble of carriers along the channel. This type of information, closely related to the microscopic transport of the carrier ensemble, is usually not accessible by other types of simulators, including commercial ones. The connection of such microscopic quantities to the intrinsic noise sources and the dynamic and noise figures of merit has not been performed up to date on a Metallic Source/Drain MOSFET.

The paper is organized as follows. Section 2 presents the topology of the devices under study, together with the main characteristics of the model developed and its implementation in the 2D MC simulator. In Section 3 the small-signal performance of the device is presented, while the high-frequency noise is discussed in Section 4, with particular attention to the influence of the Schottky barrier height (SBH) on the noise figures of merit. Finally, the main conclusions of our work are presented.

2. Simulated structure and Monte Carlo approach

2.1. Monte Carlo approach

Injection phenomena in Schottky source and drain contacts of an SB-MOSFET are mainly related to quantum effects. This means that in order to determine the charge to be injected, transmission coefficient (*TC*) must be calculated along the path perpendicular to the Schottky contacts. However, solving in a self-consistent manner the potential profiles provided by the solution of Poisson's equation and the transmission coefficients achieved by the solution of Schrödinger's equation is a rather complicated task. As a consequence, Monte Carlo simulations related to this technology have been scarcely reported (e.g. the work by Winstead and Ravaioli [21], Xia et al. [23] and the publications from the group of the Peking University [20,28]). For this purpose, we have exhaustively improved our in-house 2D Monte Carlo device simulator to be able to model in an appropriate way the physics of SB-MOSFETs and the electronic transport across the Schottky interfaces. We solve Schrödinger's equation by means of the Wenzel–Kramers–Brillouin (WKB) approach [29] which determines the *TC* along the whole silicide/silicon surfaces including in a self-consistent manner the image charge effects responsible for the Schottky Barrier Lowering (SBL). The effect of the Schottky Barrier Lowering is incorporated internally by considering it in the potential profile for the calculation of the quantum transmission coefficient, as pointed out by Winstead and Ravaioli [21]. Even though the solution of the WKB approach can present some inaccuracies for sharp barriers, careful tuning of the WKB model parameters allows obtaining similar current values to those obtained by calculating the transmission coefficient by means of more exact solutions of Schrödinger's equation as the Airy Transfer Matrix method [30]. Our model has been exhaustively calibrated to properly reproduce experimental data of Schottky barriers under the most unfavourable conditions of high inverse polarization in Schottky diodes [31] and back-to-back Schottky diodes [32] for a wide temperature range and several values of the SBH. The procedure that accounts for thermionic and tunnel injection/absorption mechanisms has been carefully developed for the two-dimensional case. It is worth to mention that thermionic and quantum tunnelling currents are calculated by accounting the number of particles crossing the Schottky barrier in both senses, injection and absorption components (and not by analytical or numerical calculations for the current at the contact). The Schottky barrier interface is considered to be ideal in the simulations. Since effects such as interface traps or dipole fluctuations must play a role mainly in the low-frequency regime, this shall not significantly modify the conclusions presented in this paper. As our approach is fully two-dimensional, not only the SBL but also the potential energy profile is different at each vertical position of the mesh, yielding to different local quantum transmission coefficients. The 2D thermionic-and-tunnel-injection/absorption procedure is detailed in [33], in which the physical principles of operation of SB-MOSFETs (with a constant barrier height of 0.20 eV) have been studied as well as the transition of the device from triode to saturation regime by means of the study of internal quantities such as the potential, carrier density or average carrier velocity.

We solve Poisson's equation each 1 *fs*. The mesh size in the channel or in the buried oxide is consistently fitted to consider the characteristic shape of the electron concentration. The number of simulated particles is around 50,000, and may vary depending on the bias point. The main aspects of our two dimensional MC simulator (band structure, scattering mechanisms, etc.) can be found in [26,27]. The longitudinal profiles along the channel of the different internal quantities (carrier concentration or velocity, etc.) are obtained properly weighting each 2D quantity over the channel by the local concentration along the vertical axis [27]. In this work we show different quantities related to the stochastic movement of the electron in the channel (as the average transit time across the channel, or mean free path between scatterings) that are provided by our Monte Carlo simulator following the procedure detailed in [27]. In parallel, we will describe also the high-frequency performance in the RF and microwaves frequency domain [34], thanks to our all-in-one modelling tool which is particularly adequate for investigating the optimization of the SB-MOSFET topology.

The use of silicides with low SB heights together with dopant-segregation (DS) layer close to the Schottky contact in the SB-MOSFET transistor is a promising solution to lower the effective SB of the structures [20,22,32,35]. This causes a substantial increase of the drain current that has been measured experimentally [5,35,36] and also observed by means of simulations of transistors and back-to-back diodes [22,32,35,37]. Important efforts are being devoted in the last few years to the DS Schottky junction engineering [15,16]. This leads to several technological possibilities, with different features of the DS layer, to finally achieve a given low effective SBH [32,38], which is the parameter considered in this work.

2.2. Simulated structure

The simulated structure consists of an n-channel accumulation-mode SB-MOSFET on SOI substrate presented in Fig. 1. As we can observe, the topology is similar to that of a conventional SOI-MOSFET, but the source and drain doped regions have been replaced by Schottky junctions. A differential factor of the SB-MOSFET architecture which can be also noticed in the figure is the *underlap* length, L_{un}, (instead of the overlap region of conventional MOSFETs). The main characteristics of the device (geometry, channel doping, etc.) are detailed in Table 1 and were chosen following the SB