Novel TCAD oriented definition of the off-state breakdown voltage in Schottky-gate FETs: a 4H SiC MESFET case study

Novel TCAD-Oriented Definition of the OFF-State Breakdown Voltage in Schottky-Gate FETs: A 4H–SiC MESFET Case Study

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***Abstract*—Physics-based breakdown voltage optimization in Schottky-barrier power RF and microwave field-effect transistors as well as in high-speed power-switching diodes is today an important topic in technology computer-aided design (TCAD). OFF-state breakdown threshold criteria based on the magnitude of the Schottky-barrier leakage current can be directly applied to TCAD; however, the results obtained are not accurate due to the large uncertainty in the Schottky-barrier parameters and models arising above all in advanced wide-gap semiconductors and to the need of performing high-temperature simulations to improve the numerical convergence of the model. In this paper, we suggest a novel OFF-state breakdown criterion, based on monitoring the magnitude (at the drain edge of the gate) of the electric field component parallel to the current density. The new condition is shown to be consistent with more conventional definitions and to exhibit a significantly reduced sensitivity with respect to physical parameter variations.**

***Index Terms*—Breakdown voltage, FETs, physics-based simulation, wide-bandgap semiconductors.**

I. INTRODUCTION

WIDE-GAP compound semiconductors are the material of choice for advanced next-generation power electronics both for high-frequency (RF and microwave) and for high-speed and/or high-voltage power-switching applications. In fact, wide-gap compounds such as silicon carbide (SiC) and gallium nitride (GaN) and related alloys (InGaN and AlGaN) exhibit frequency and power figures of merit by far superior to silicon. Moreover, recent developments in field-plate (FP) microwave FET technology have markedly increased the power levels achievable also in gallium arsenide (GaAs) and related alloys (AlGaAs, InGaAs, and InGaAsP). Taking into account that most RF and microwave power transistors are Schottky-gate FETs (MESFETs, HFETs, HEMTs, and PHEMTs) and that Schottky-based contacts also are the main building block in a number of switching devices (e.g., power Schottky diodes), the definition and investigation of breakdown voltage in such structures have been the object of particular interest in the literature, traditionally concerning GaAs heterojunction FETs; for a comprehensive and rather recent review, the reader is referred to [1].

The physical origin of the drain breakdown voltage $\mathrm{BV_{DS}}$ in advanced Schottky-gate FETs is somehow more complicated than in other field-effect devices. While in JFETs and MOSFETs failure is commonly due to channel or drain avalanche, the breakdown behavior of Schottky-gate FETs is quite different, since it is commonly accepted that in such devices, the OFF-state high-voltage behavior is dominated by a complex interplay between tunneling (or field emission) and impact ionization beneath the Schottky-gate contact in the device region facing the drain (see, e.g., [1], [2]). The experimental characterization of $\mathrm{BV_{DS}}$, on the other hand, has to be based on indirect criteria so as not to bring the device out of the safe operating area, thus avoiding irreversible damage. In particular, the definition of $\mathrm{BV_{DS}}$ is usually based on a direct threshold check on the gate and drain–currents (practically equal at the onset of breakdown for these devices), such as $|I_G(\mathrm{BV_{DS}})| \approx |I_D(\mathrm{BV_{DS}})| \approx I_{\mathrm{th}}$, where $I_{\mathrm{th}} = 1 - 2\ \mathrm{mA} \cdot \mathrm{mm}^{-1}$ [2]–[6]. Among the available experimental techniques, we mention the so-called Bahl approach [7] (see also Section II), where a constant drain–current is injected into the device and $\mathrm{BV_{DS}}$ is determined by inspecting the $V_{\mathrm{GS}}(V_{\mathrm{DS}})$ characteristic.

Moreover, in physics-based simulations, a similar paradigm for the definition of the breakdown voltage has to be applied for a number of reasons. First, physics-based simulation in full breakdown conditions is often fraught with numerical convergence problems, thus making it virtually impossible to numerically recover $\mathrm{BV_{DS}}$ from the position of the VI curve asymptotes. Second, structure optimization with the aim of increasing $\mathrm{BV_{DS}}$ should possibly exploit criteria that can be closely compared with experimental ones. Unfortunately, the extension of current-based breakdown criteria to physics-based simulation is not straightforward for two main reasons. First, the reverse Schottky contact current is strongly dependent on modeling choices and the related parameters, namely, the Schottky-barrier height (SBH) and the electron and hole effective masses. In the case of SiC or III-N compounds, the limited precision in the estimation of the SBH (due, e.g., to technological immaturity, the presence of traps, and/or SBH

Manuscript received February 25, 2008; revised July 29, 2008. Current version published November 26, 2008. This work was supported by the Italian Ministry of University and Research under the PRIN 2005 project "High breakdown voltage FETs for high power and efficiency applications" (FPFET). The review of this paper was arranged by Editor M. Anwar.

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Digital Object Identifier 10.1109/TED.2008.2006774

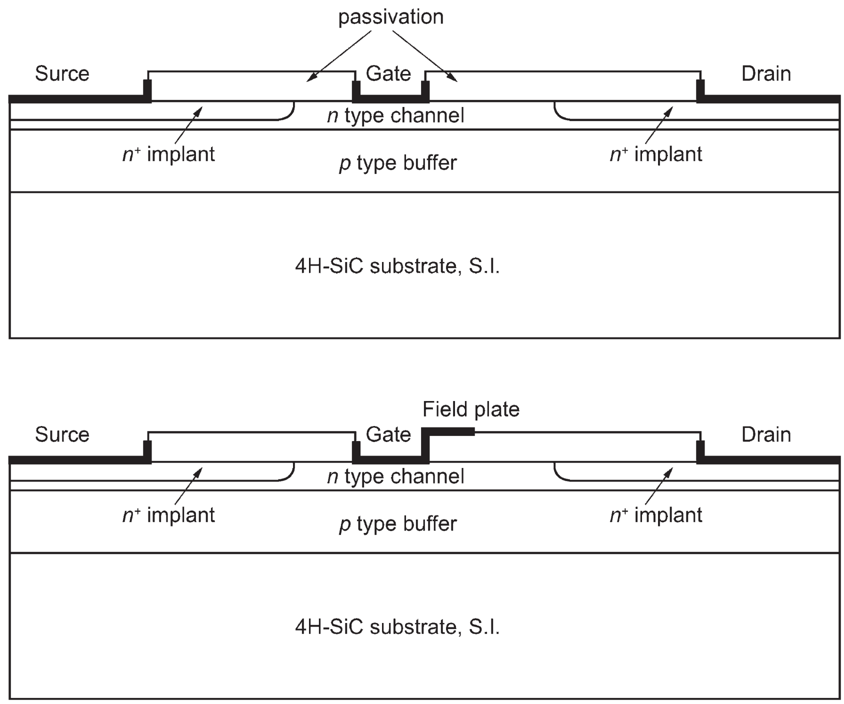

Fig. 1. Structure of the simulated devices. (Top) Conventional MESFET. (Bottom) FP-MESFET.

inhomogeneities, see [8]–[13]) or of the carrier effective masses can lead to a large spread in the simulated results. Second, the reverse current is also strongly (exponentially) dependent on temperature; this makes the absolute threshold criteria difficult to apply due to the common practice of simulating wide-gap semiconductor devices at an artificially increased temperature, in order to alleviate numerical problems related to the extremely low minority carrier concentration at ambient temperature [14]–[16]. For such reasons, an absolute threshold criterion on the reverse Schottky contact current is hardly applicable in defining the simulated breakdown conditions and may lead to completely unrealistic results.

In this paper, we propose a novel alternative method for the estimation of the simulated breakdown voltage BV_{DS} not affected by the problems discussed earlier. The method is based on monitoring the behavior of the magnitude of the electric field component parallel to the current density in a section located at the drain edge of the gate; clearly, the use of microscopic variables makes this approach well suited for simulation rather than for the experiment where only the external variables can be observed. The simulation approach and field-based criterion are introduced in Section II, using 4H–SiC MESFETs with both conventional and FP electrodes as a case study. Results from different current-based techniques for the evaluation of the breakdown voltage of such devices are also presented and compared with the field-based definition, with good agreement. Furthermore, Section III is devoted to discussing the sensitivity of the present definition with respect to variations of the parameters of the Schottky-barrier models; as a result, we show that the field-based breakdown definition has low sensitivity and can be safely exploited also when the material parameter uncertainty is large. Finally, conclusions are drawn in Section IV.

II. Defining the Breakdown Voltage: A 4H–SiC MESFET Case Study

To introduce the novel definition of the breakdown voltage, we will start from the physics-based simulation of RF planar 4H–SiC MESFETs, considering both a standard and an FP gate electrode layout (see Fig. 1). The device structure considered consists of a semiinsulating 4H–SiC substrate, a 1.5-μm-thick p-type buffer layer with $N_A = 5 \times 10^{16}$ cm^{-3}, and a 0.2-μm n-type channel layer with $N_D = 3 \times 10^{17}$ cm^{-3}. The Schottky-gate metal is titanium. The gate length is 0.5 μm, and the gate–source and gate–drain spacings are 0.5 and 1 μm, respectively. A 0.2-μm-thick silicon nitride passivation layer is placed on top of the uncontacted device surface, and n^+ implants are added below the source and drain ohmic contacts. Such a layout can be considered as representative of a standard silicon carbide RF and microwave technology, see e.g., [2], [17]–[21].

Simulations were performed by means of Synopsys Sentaurus Device [22]. We carried out 2-D drift-diffusion simulations, taking into account doping-dependent mobility, high-field velocity saturation, and impact ionization. The physical models and the numerical parameters for 4H–SiC drift-diffusion simulations are collected in Table I (see also [9]). In order to include gate leakage, we used the WKB-based model implemented into the device simulator. Since, as discussed earlier, the gate current in SiC MESFETs is strongly affected by tunneling through the Schottky gate, we carefully determined the numerical parameters of the tunneling model [34], namely, the carrier effective masses and effective SBH, exploiting the results achieved in our previous experimental [25], [35] and theoretical [8], [9] works on Schottky-barrier diodes. Finally, for the sake of simplicity and due to the unavailability of experimental data, we neglected traps at the buffer–epilayer or at the epilayer–passivation interfaces.

TABLE I
PHYSICAL MODELS AND PARAMETERS FOR ROOM-TEMPERATURE 4H–SiC MESFET SIMULATIONS. MOBILITY AND IMPACT IONIZATION VALUES ARE RELATIVE TO CARRIER TRANSPORT IN THE 4H–SiC BASAL PLANE [9]

Model	Parameters
Bandgap energy [23]	$E_{g,0} = 3.34$ eV, $\alpha = 3.3 \times 10^{-4}$ eV K^{-1}, $\beta = 0$ K [24], [25]
DOS masses	$N_{C,300} = 1.83 \times 10^{19}$ cm^{-3}, $N_{V,300} = 4.07 \times 10^{19}$ cm^{-3} [24]
Dielectric constant	$\epsilon_r = 9.63$ [9], [24]
Low-field mobility [26]	$\mu_e^{max} = 947$ cm^2 V^{-1}s^{-1}, $\mu_e^0 = 0$ cm^2 V^{-1}s^{-1}, $\mu_e^1 = 0$ cm^2 V^{-1}s^{-1},
	$C_e^r = 1.94 \times 10^{17}$ cm^{-3}, $\alpha_e = 0.61$ [27]
	$\mu_h^{max} = 117$ cm^2 V^{-1}s^{-1}, $\mu_h^0 = 16$ cm^2 V^{-1}s^{-1}, $\mu_h^1 = 0$ cm^2 V^{-1}s^{-1},
	$C_h^r = 1.76 \times 10^{19}$ cm^{-3}, $\alpha_h = 0.34$ [28]
High-field saturation [29]	$v_e^{sat} = 2.01 \times 10^7$ cm s^{-1}, $\beta_e^{sat} = 0.9$ [9], [30]
	$v_h^{sat} = 1.07 \times 10^7$ cm s^{-1}, $\beta_h^{sat} = 0.9$ [9], [31]
Impact ionization [32]	$a_e = 2.10 \times 10^7$ cm^{-1}, $b_e = 1.70 \times 10^7$ V cm^{-1} [33]
	$a_h = 2.96 \times 10^6$ cm^{-1}, $b_h = 1.60 \times 10^7$ V cm^{-1} [33]
Electron tunneling mass	$m_{t,e}^* = 0.3 * 9.1 \times 10^{-31}$ Kg [8]
Schottky barrier height	$\phi_B = 0.9$ eV [8]

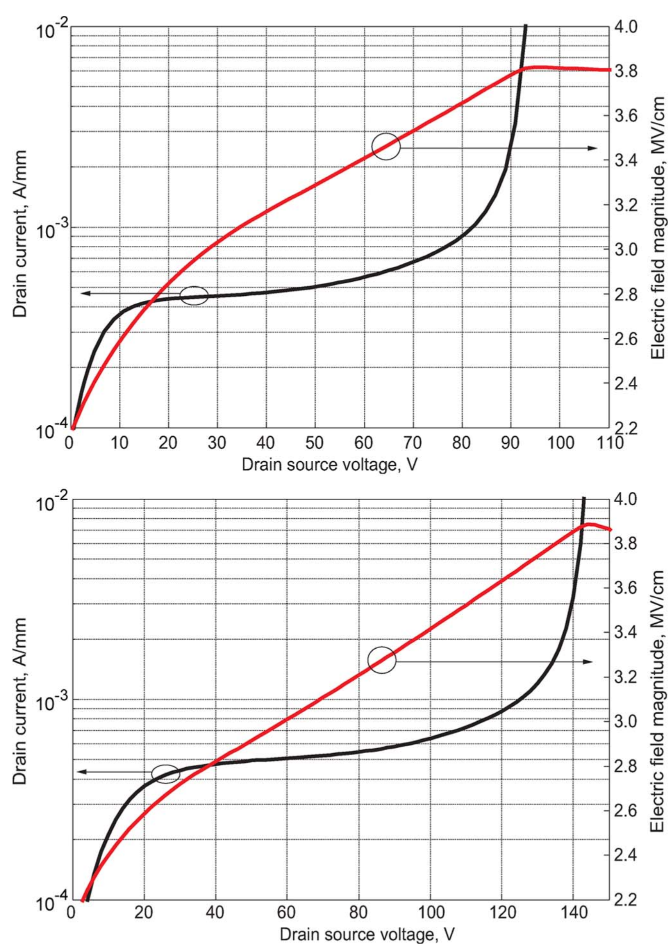

Fig. 2. OFF-state characteristic and peak magnitude of the electric field a the gate edge for $V_{GS} = -15$ V. (Top) Conventional MESFET. (Bottom) FP-MESFET.

We begin the analysis by examining the OFF-state output characteristics of the conventional-gate MESFET, shown in Fig. 2. The gate–source voltage was set to $V_{GS} = -15$ V, while the device threshold voltage is $V_{th} = -10$ V. The drain reverse leakage current is essentially due to carrier tunneling at the edge of the gate contact facing the drain electrode. By exploiting the standard fixed threshold definition of the breakdown voltage ($I_D = 1$ mA $\cdot$ mm^{-1}), BV$_{DS} = 82$ V. If the maximum current criterion is set to 2 mA $\cdot$ mm^{-1}, the extracted BV$_{DS}$ will rise up to 90 V, thus showing a 10% increase.

For the purpose of device optimization and *quantitative* prediction of the effects of layout variations by exploiting physics-based simulation tools, the approach described previously cannot be considered as satisfactory. We propose a more rigorous but simple technique based on the analysis of the values of microscopic variables within the device. Taking into account the discussions presented in [3] and [36] (for the case of 4H–SiC MESFETs) and in [37]–[39] (for III-nitride lateral devices), we monitored the internal variables in a critical point in the device structure, located close to the surface of the epitaxial layer in correspondence of the edge of the gate electrode facing the drain.

By monitoring, as a function of V_{DS}, the magnitude of the peak electric field component parallel to the current density at the gate edge, we obtained the field-voltage characteristic shown in Fig. 2. It can be observed that the field monotonically increases up to $V_{DS} = 90$ V, whereas for a larger voltage, the electric field is either constant or slightly decreasing. Thus, the field-voltage characteristics can be decomposed into two parts. In the first one, the electric field increases monotonically due to the increase in the bias voltage applied to the drain electrode; in these conditions, the reverse leakage current collected at drain is the sum of the electron flux coming from the source and of the electrons tunneling through the gate electrode. In the second part of the characteristic, the electric field saturates (or slightly decreases) with increasing V_{DS}. Such a behavior is a clear indication that impact ionization is taking place at the gate edge. In fact, when the number of carriers generated by avalanche multiplication becomes significant, any further increase of V_{DS} is effectively screened by the larger free carrier

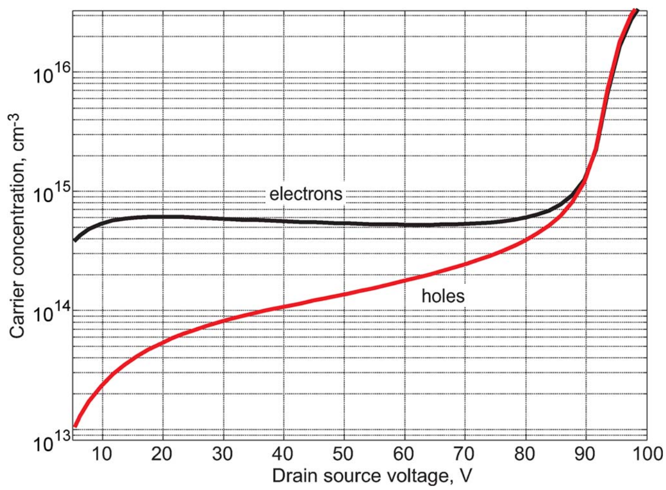

Fig. 3. Electron and hole concentrations at the drain edge of the gate electrode. Conventional MESFET, $V_{\rm GS} = -15$ V.

density. Such a conclusion is supported by the analysis of other microscopic variables in the same device region, such as carrier concentrations, impact ionization generation rate, and current densities. As an example, Fig. 3 shows the electron and hole concentrations at the edge of the gate electrode as a function of $V_{\rm DS}$. A steep increase in carrier concentrations, which is due to generation by impact ionization, is observed for $V_{\rm DS} = 90$ V. As a consequence, we can exploit this behavior by defining the breakdown voltage $\mathrm{BV_{DS}}$ of the device as the $V_{\rm DS}$ value for which the electric field at the gate edge shows a maximum. Moreover, this bias value must be considered as the ultimate upper limit at which the device can be safely biased, since for a larger $V_{\rm DS}$, avalanche multiplication assumes levels which may lead to a destructive failure of the device.

To check for the consistency of the definition, we consider the MESFET device with a 0.2-μm gate FP extension over the silicon nitride passivating layer. Based on the peak field criterion we are proposing, the breakdown voltage of the device is (unambiguously) estimated to be 140 V. Such value is in complete agreement with the trends in [3], [40], and [36]. When exploiting a current-based method (1 mA/mm), $\mathrm{BV_{DS}}$ would lie in the range 130–140 V.

In order to further validate the novel definition, we compare our results with the so-called drain–current injection approach proposed by Bahl [7], very popular in the experimental characterization of the breakdown voltage of Schottky-gate transistors. In this method, a fixed current level is injected into the drain of the device with $V_{\rm GS} = 0$ V (the source terminal is grounded); the gate electrode is then biased toward negative values in order to close the conductive channel, and the corresponding drain–source voltage is measured. $\mathrm{BV_{DS}}$ is defined as the maximum $V_{\rm DS}$ value measured during the gate bias sweep. We reproduced this approach with the physics-based simulator by exploiting a current boundary condition at the drain electrode. The results for the 4H–SiC MESFET with conventional gate are shown in Fig. 4 for two different levels of injected drain–current, namely, 1 and 2 $\mathrm{A \cdot mm^{-1}}$. As previously discussed, the extracted values for $\mathrm{BV_{DS}}$ significantly depend on the level of injected current. For $V_{\rm GS} = V_{\rm th} = -10$ V, a 10% variation is observed (100 and 108 V for $I_D = 1$ and

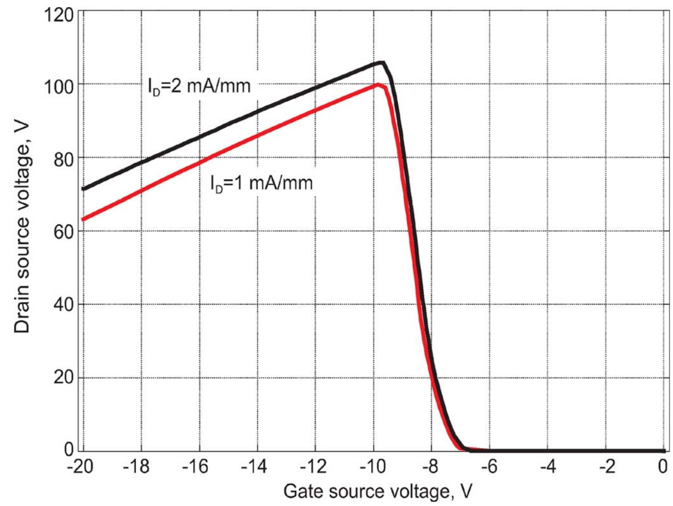

Fig. 4. Gate bias dependence of the drain bias of the conventional device for fixed injected drain–current. Simulations are shown for $I_D = 1$ and 2 $\mathrm{mA \cdot mm^{-1}}$.

2 $\mathrm{A \cdot mm^{-1}}$, respectively). Consistent with the previous results obtained with the conventional voltage boundary conditions, for $V_{\rm GS} = -15$ V, values for $\mathrm{BV_{DS}}$ are 82 and 90 V for $I_D = 1$ and 2 $\mathrm{A \cdot mm^{-1}}$, respectively. Similar remarks apply to the case of the FP device.

III. Sensitivity of $\mathrm{BV_{DS}}$ on Simulation Parameters

We have shown that our approach is better suited for device optimization with physics-based simulation tools than current-based criteria, which are commonly used in breakdown measurements. In this section, we will also demonstrate that our approach is more reliable than other techniques whenever some of the physical parameters of the device are subject to uncertainty.

Let us consider a typical situation in the development of a novel device and/or technology. The general features of the device are known with a certain degree of approximation; however, some parameters (particularly the physical ones) are not known with accuracy. One critical parameter in Schottky-gate devices is the contact potential barrier height; moreover, it is well assessed that SBH inhomogeneities play a major role in determining the (tunneling dominated) reverse bias behavior of Schottky contacts on wide-bandgap semiconductors (see [8]–[11] in the case of SiC and [12] and [13] for GaN). Here, we assume a 0.1-eV uncertainty on the value of the SBH at the gate contact, which we consider a reasonable value for the device/technology under examination.

Fig. 5 shows the output characteristics (for $V_{\rm GS} = V_{\rm th} - 0.5|V_{\rm th}|$) of the conventional device simulated with two values of the SBH: 0.8 and 0.9 eV. A large difference in the drain–currents is observed, thus leading to a corresponding uncertainty in the estimation of $\mathrm{BV_{DS}}$ if the fixed drain–current criterion is exploited. A 100% or more discrepancy in $\mathrm{BV_{DS}}$ is observed at the fixed current value $I_D = 1$ mA $\mathrm{mm^{-1}}$, both for the conventional and the FP devices. This is confirmed by the curves shown in Fig. 6, where the results of fixed drain–current simulations are shown (Bahl's approach). The

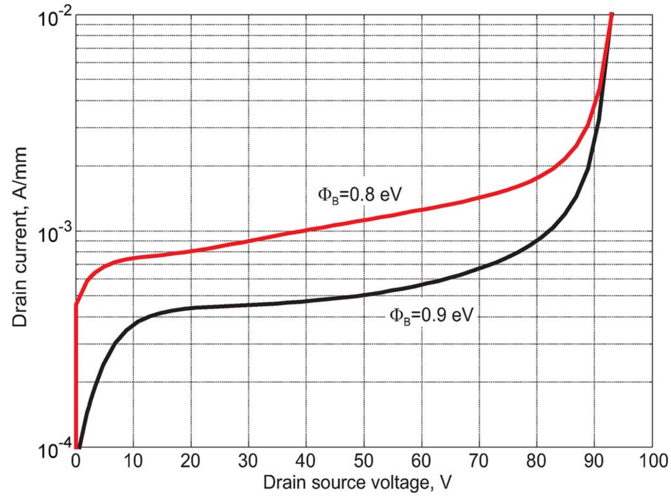

Fig. 5. Output characteristics of the conventional device for different values of the SBH. $V_{\mathrm{GS}} = V_{\mathrm{th}} - 0.5|V_{\mathrm{th}}|$.

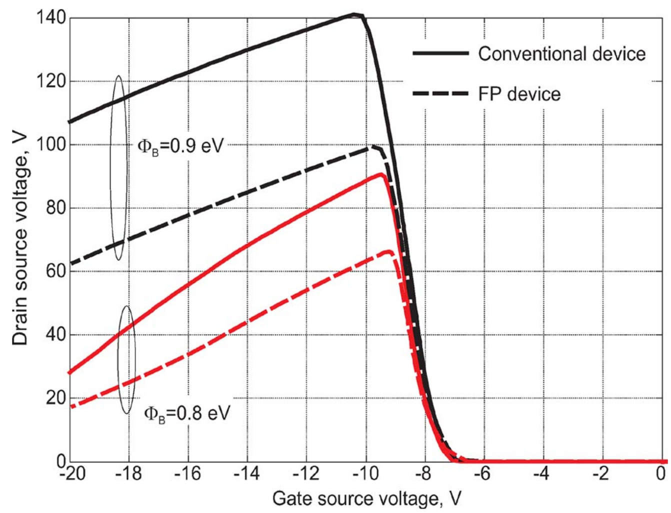

Fig. 6. Gate bias dependence of the drain bias of the conventional and FP devices for fixed injected drain–current. Simulations are shown for $I_D = 1$ mA/mm and two values of the SBH.

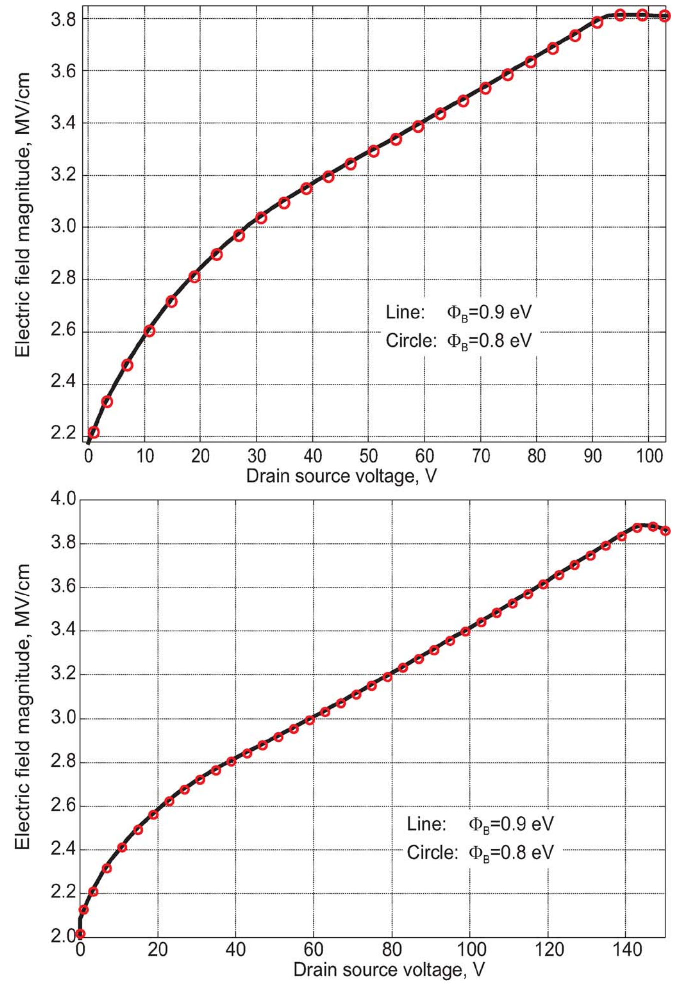

Fig. 7. Drain bias dependence of the peak electric field at the edge of the gate contact. $V_{\mathrm{GS}} = V_{\mathrm{th}} - 0.5|V_{\mathrm{th}}|$. (Top) Conventional MESFET. (Bottom) FP-MESFET.

large discrepancies observed when employing current-based criteria is related to the exponential dependence of the tunneling current of the reverse-biased Schottky junction on the barrier height, see [8]–[10]. Therefore, a large uncertainty on the gate SBH value dramatically affects the evaluation of the device breakdown voltage at a fixed current threshold. The same effect can be observed when performing simulations at a higher temperature, to alleviate numerical issues.

By exploiting our field-based definition of $\mathrm{BV}_{\mathrm{DS}}$, on the other hand, the effect of the uncertainty of the effective SBH is minimal, as shown in Fig. 7 for the conventional device. It can be observed that the field-voltage characteristics are practically unaffected by the uncertainty in the SBH. This behavior can be intuitively explained by considering, for example, the conventional analytical formula for the calculation of the maximum electric field $E_{\max}$ at a metal–semiconductor interface within the depletion approximation (see, e.g., [41])

$$E_{\max} = \sqrt{\frac{2qN_D}{\epsilon_s}(V_{\mathrm{bi}} - V_a)}$$

where V_{bi} is the junction built-in potential and V_a is the externally applied reverse bias. If $V_a < 0$ and $|V_a| \ll V_{\mathrm{bi}}$, the contribution of the SBH to the maximum junction field is negligible. For this reason, our approach enables one to optimize the breakdown behavior of the devices considered independently from the detailed and accurate knowledge of the Schottky-barrier parameters, a feature which is particularly useful when considering devices on immature technologies.

IV. Conclusion

We have discussed the physics-based evaluation of the OFF-state breakdown voltage in wide-gap semiconductor Schottky-based field-effect transistors, exploiting, as a case study, 4H–SiC MESFETs. We have shown that conventional leakage-current-based criteria to define the breakdown voltage (derived from experimental techniques) fail to provide reliable results when considering parameter uncertainties. In particular, this applies to uncertainties in the Schottky-barrier model characterization or, even worse, high-temperature simulations carried out to improve the model numerical conditioning. We have proposed, instead, a field-based breakdown criterion, which can be readily implemented in physics-based simulations (although it is, of course, not amenable to experimental characterization). The criterion exhibits a low sensitivity with respect to the Schottky-barrier model parameters and provides results consistent with the experimental criterion. Aside from the 4H–SiC MESFET device case study, the technique proposed can, in principle, be applied to any Schottky-gate compound semiconductor FETs, such as HFETs, HEMTs, and PHEMTs, both on III-V and III-N wide-gap compounds.

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