Threshold Voltage Statistical Variability and Its Sensitivity to Critical Geometrical Parameters in Ultra-Scaled InGaAs and Silicon FETs

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Abstract— We investigate the statistical variability of the threshold voltage and its sensitivity to critical geometrical parameters in Ultra-Scaled $\text{In}_{0.53}\text{Ga}_{0.47}\text{As}$ and Si MOSFETs by means of 3D quantum-corrected drift-diffusion simulations. Dual-Gate Ultra-Thin-Body and FinFET device structures are analyzed for both channel materials. To assess the variability and sensitivity effects also from the scaling perspective, we consider devices belonging to two technological nodes with gate lengths 15 nm and 10.4 nm, designed according to ITRS specifications. Variability sources included in our analysis are Random Dopant Fluctuation (RDF), Work Function Fluctuation (WFF), as well as Body- and Gate- Line-Edge Roughness (LER). Sensitivity to critical geometrical parameters is assessed by varying gate length, channel thickness, and oxide thickness. Results point out the major detrimental effect of WFF and Body-LER for InGaAs FETs, whereas WFF dominates in Si counterparts. Moreover, the sensitivity analysis shows that control over gate length and channel thickness in InGaAs technology is fundamental in order to keep variability within tolerable values. Scaling of the InGaAs technology highlights the importance of abiding to ITRS projections regarding LER control improvement. Furthermore, a tight channel thickness control is required in ultra-scaled devices due to the large sensitivity of the threshold voltage to the channel thickness combined with increased variability.

Index Terms— III-V MOSFET, InGaAs, Line-Edge Roughness, Random Dopant Fluctuations, Sensitivity, Variability, Work-Function Fluctuations.

I. INTRODUCTION

THE relentless scaling of CMOS technology is nowadays facing challenges in keeping up with Moore's law predictions. Among different alternatives to overcome the intrinsic limitations of Si-based devices, a very promising solution is replacing the thin Si channel with III-V materials [1]. Particularly, $\text{In}_{0.53}\text{Ga}_{0.47}\text{As}$ is being extensively explored as a potential constituent of the channel in nMOS devices due

to its superior electron mobility [2-4], which allows further dimension scaling, higher switching speed, and lower power consumption [1]. InGaAs superior mobility depends on the smaller electron effective mass that, however, has the side effect of enhancing quantization effects in the thin body and reducing the quantum capacitance (i.e., DOS bottleneck) [5, 6]. This makes InGaAs MOSFETs potentially more prone to both local and global variations of body thickness [7]. A smaller quantum capacitance reduces the overall gate capacitance and leads to stronger short-channel effects, which in turn can worsen the impact of gate-length fluctuations. In addition, substituting InGaAs for Si in the standard CMOS process flow poses major technological challenges to obtain the desired control on key process parameters (e.g., physical gate length - L_G , channel thickness - T_{CHAN}) [8]. In addition, the impact of technology scaling toward end-of-the-roadmap nodes deserves careful consideration, as L_G and T_{CHAN} become comparable with the critical dimensions associated with intrinsic fluctuations (e.g., line-edge roughness amplitude and correlation length) [9]. All of these considerations call for an intensified effort towards the comprehension and the quantitative assessment of both statistical and systematic process variations in ultra-scaled InGaAs MOSFETs in view of their possible introduction into CMOS logic technology.

In this work, InGaAs FETs at the two technological nodes ($L_G = 15$ nm, $V_{\text{DD}} = 0.63$ V) and ($L_G = 10.4$ nm, $V_{\text{DD}} = 0.59$ V) are explored in terms of threshold voltage statistical variability and its sensitivity to systematic geometrical parameter variations, extending our recent conference report in [10]. Two types of device architecture are considered, namely the Dual-Gate Ultra-Thin-Body (DG-UTB) MOSFET and the FinFET. A comparison between InGaAs devices and their Si equivalent at the node ($L_G = 15$ nm, $V_{\text{DD}} = 0.63$ V) is also included for benchmarking purposes.

Variability is evaluated by using the statistical Impedance Field Method (IFM) [11] within the framework of quantum corrected drift-diffusion (QDD) three-dimensional device simulations. While unable to fully capture effects like mutual interactions among different variability sources as well as random location of discrete dopants and gate metal grains (which require more detailed atomistic simulations [12]), this

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Fig. 1. Schematic representation of (a) Dual Gate - Ultra Thin Body (DG-UTB) and (b) FinFET devices

Fig. 2. Simulated I_D - V_{GS} curves for the InGaAs DG-UTB device obtained using QDD (curves) and higher-order models (symbols) for $L_G = 15$ nm.

Fig. 3. Simulated I_D - V_{GS} curves for the InGaAs FinFET device obtained using QDD (curves) and higher-order models (symbols) for $L_G = 15$ nm.

Fig. 4. Simulated I_D - V_{GS} curves for the InGaAs DG-UTB device obtained using QDD (curves) and higher-order models (symbols) for $L_G = 10.4$ nm.

Fig. 5. Silicon FinFET QDD simulations (curves) calibrated over measurements data from Intel [13] (circles).

Fig. 6. Simulated I_D - V_{GS} curves including variability (red curves, WFF effect on the InGaAs DG-UTB) over the ones of reference device (white circles).

approach can be considered an acceptable trade-off between accuracy and computational efficiency. Comparison of our total variability predictions for the Si devices with experimental data from a comparable gate-length technology [13] gives us comforting indications about the dependability of our approach.

The methodology used in our analysis is an advancement over the approaches previously reported in literature, in that we simultaneously considered all the relevant sources of statistical variability, as well as their dependence on the most critical geometrical parameters. Previous works considered only Si channel material [12, 14-20], fewer variability sources and/or sensitivity parameters [17, 19-24], and devices not as aggressively scaled as in our investigation [12, 15, 17].

The paper is organized as follows. In Section II, we describe the methodology used to assess the variability and its sensitivity to geometrical parameter variations. In Section III, we show the results obtained for the different channel materials and device architectures. A discussion of the critical aspects emerging from our analysis is reported in Section IV. Conclusions follow.

II. METHODOLOGY

Ultra-scaled transistor technologies are susceptible to both 1) local fluctuations of dimensions/doping/material parameters ultimately related to discreteness of matter and charge, and 2) global variations of critical geometrical parameters and doping profiles induced by systematic process imperfections [15]. In the following, we will refer to effects 1) and 2) as statistical variability, or simply variability, and sensitivity to geometrical

TABLE I
GEOMETRICAL AND DOPING PARAMETERS OF REFERENCE DEVICES

Symbol	Quantity	Value (15 nm – 10.4 nm)
L_G	Physical Gate Length	15 nm – 10.4 nm
L_{UND}	Gate Underlap	2 nm
T_{CHAN}	Channel Thickness or Fin Width	7 nm – 4 nm
$W_G/H_{CHAN}^\dagger$	Gate Width/Fin Height	26 nm – 14 nm
T_{OX}	Oxide Thickness	3.84 nm* – 3.3 nm
N_{CHAN}	Channel Doping	10^{17} cm^{-3}

*Value for DG-UTB devices. FinFETs have $T_{OX} = 3.75$ nm.

$^\dagger W_G$ refers to DG-UTB devices, H_{CHAN} to FinFETs.

parameter variations, or simply sensitivity, respectively. In this Section is described the complete methodology used in our investigation, including analyzed device structures, calibration of simulations tools, and computational approaches adopted for the assessment of variability and sensitivity effects.

A. Calibration

The DG-UTB and FinFET structures for the two nodes (15 nm and 10.4 nm) are implemented in the Synopsys Sentaurus DeviceTM simulator according to ITRS projections, with geometrical and process parameters defined in Fig. 1 and Tab. I. These structures will be referred to as “reference devices” in the following. 3D numerical device simulations of these structures are carried out using the quantum-corrected drift-diffusion transport model (QDD) with quantum effects accounted for by means of the modified local density approximation (MLDA) model [25]. The calibration of the material-related properties (metal workfunction, effective channel electron mobility, saturation velocity) for InGaAs and

Si devices is performed separately. For all the investigated InGaAs devices (DG-UTB and FinFET at both nodes), it is possible to correctly reproduce the transfer characteristics in both linear and saturation regimes as obtained by higher-order transport models [26] with a unique set of QDD parameters, see Figs. 2-4 (where V_T and short-channel parameters are also shown). Calibration for Si devices is performed by comparison with experimental data available in the open literature for a Si FinFET with $L_G = 20$ nm [13], see Fig. 5 (again including V_T and short-channel parameters). The overall satisfactory agreement achieved for all materials and structures indicates that the adopted quantization model allows accurately describing the confinement effects in the ultra-thin body of these scaled devices.

B. Variability

Variability at the two technological nodes has been assessed by using the statistical Impedance Field Method (IFM) [11] available in Sentaurus DeviceTM. Within the IFM, random device variations are treated as small perturbations of the nominal device. The full (3D) self-consistent device simulation is only performed once for each reference device, whereas current fluctuations at the device contacts can be calculated for a very large number of randomized realizations as the linear response to the applied device perturbations using a Green's function based approach. From the computed contact current fluctuations, a set of varied transfer curves can be constructed, from which the threshold voltage (V_T) distribution is extracted. All the main microscopic variability sources of relevance for ultra-scaled MOSFETs [23] have been taken into account, namely: Random Dopant Fluctuations (RDF), Gate-metal Workfunction Fluctuations (WFF), Body-surface or Fin-Sidewall Roughness (Body-LER), and Gate Line Edge Roughness (Gate-LER). RDF, caused by inherent discreteness of impurity atoms, is modeled assuming spatially uncorrelated doping both in the body and in the source/drain regions. The number of dopant atoms in a given volume follows the Poisson distribution with an average value equal to the nominal number of dopants in that volume [27]. WFF is caused by intrinsic granularity of the gate metal, and modeled by assuming TiN gate metal characterized by two major grain orientations with a workfunction difference of 0.2 eV and an associated probability of 0.4/0.6 for the lowest/highest workfunction, respectively [12, 18]. The number of metal grains in the gate region follows a Poisson distribution with an average value calculated using the average grain size. Each grain can have different shape and size, according to the procedure found in [27]. It is known that WFF variability increases with greater grain size, eventually saturating as grain size approaches the gate size itself [12]. Nonetheless, we consider an average grain size of 5 nm for both grain orientations as representative of the typical value achievable in present gate-first processes with TiN as the gate metal [28, 29]. Moreover, the grain random location also affects WFF variability; while our IFM-based approach is partially able to describe this effect, atomistic simulations are required for a more accurate analysis [12]. Line edge

TABLE II
PARAMETERS OF LINE EDGE ROUGHNESS VARIABILITY SOURCE

LER Parameters (15 nm)	LER Parameters (10.4 nm)
$\Delta_{rms} = 1.8$ nm	$\Delta_{rms} = 1.2$ nm
$\Lambda = 15.5$ nm	$\Lambda = 8.3$ nm

roughness, inherent to patterning steps of CMOS technology, results in local variations of the gate length (Gate-LER) and of the body or fin thickness in DG-UTB and FinFET devices, respectively (Body-LER). These effects are modeled by means of a Gaussian autocorrelation function [9, 30], with r.m.s. roughness amplitude (Δ_{rms}) and correlation length (Λ) set in accordance with ITRS projections for the nodes under consideration [31]. For Gate-LER, the roughness at the two gate edges have been assumed uncorrelated, so that the combined, worst-case variability effects are taken into account. The same applies to roughness on the two body surfaces of the DG-UTB device or on the two fin sidewalls of the FinFET. The parameters used for WFF and Gate-/Body-LER are summarized in Tab. II (the model for RDF does not require any additional input parameter other than the doping profile). For each of the above variability sources, we consider 10000 randomly varied device realizations. V_T is always evaluated at $V_{DS} = 0.05$ V with the constant current method at a reference current of 10 μ A/ μ m.

C. Sensitivity

Statistical variability is evaluated not only for the “reference devices” but also for varied devices resulting from the application of critical geometrical parameter variations, so that their interplay can be assessed. This is of paramount importance since classical analytical models of this interplay become inaccurate in ultra-scaled devices [14]. The effects of systematic variations are evaluated by applying uniform, global variations to the following parameters: gate length (L_G), body thickness or fin width (T_{CHAN}), and gate oxide thickness (T_{OX}). Variations as large as $\pm 10\%$ and $\pm 20\%$ are applied to nominal values of these parameters. The variability analysis described in Section II-B is performed on all varied device realizations to extract the corresponding V_T average and standard deviation values. In this paper, we purposely focus on V_T variability/sensitivity effects, for which our modeling approach is best suited. The accurate estimation of the ON-state current variability would require higher-order transport models, accounting for quasi-ballistic transport and self-consistent channel-mobility dependence on variability sources.

III. RESULTS

A. Variability

Bar plots in Fig. 7(a) provide a quantitative assessment of statistical variability at the 15-nm node for both Si and InGaAs devices (DG-UTB and FinFET), showing extracted V_T standard deviation value, $\sigma(V_T)$, for each variability source. The variability sources are considered separately from each other for the purpose of quantifying and comparing their individual contributions. Notably, only small differences

Fig. 7. (a) Bar plots of $\sigma(V_T)$ for the four variability sources and the four reference devices at the 15-nm node. (b) RDF variability for the InGaAs DG-UTB device, when considering body doping variations only and both body and S/D doping variations, for two different S/D doping concentrations, namely $5 \times 10^{19} \text{ cm}^{-3}$ (white bin) and 10^{20} cm^{-3} (red bin). (c) WFF variability for the DG-UTB devices, with varying metal grain size for the InGaAs (15-nm and 10.4-nm node) and Si technology.

between DG-UTB and FinFET architectures arise, regardless of the considered variability source. It is evident from Fig. 7(a) that InGaAs devices show higher Body-LER and Gate-LER as well as RDF variability than Si FETs. This can be understood by considering that InGaAs has a smaller effective mass than Si, resulting in: *i*) larger quantum confinement effects, making V_T more susceptible to channel thickness fluctuations (larger Body-LER variability) [32]; *ii*) reduced effective inversion capacitance, that makes V_T more sensitive to modulation of gate length and associated short-channel effects (larger Gate-LER variability). Interestingly, RDF is affected by the lower InGaAs density of states, leading to a non-negligible dependence of V_T on source/drain doping concentration (i.e., “source-starvation effect” [6]). This can be appreciated in Fig. 7(b), where $\sigma(V_T)$ is shown for the InGaAs DG-UTB device, with RDF activated in the body region only and in the entire device (body + S/D) for two different $N_{S/D}$ values (namely $N_{S/D} = 5 \times 10^{19}, 10^{20} \text{ cm}^{-3}$). Remarkably, $\sigma(V_T)$ decreases at increasing $N_{S/D}$, and it is minimum when RDF is accounted for in the body region only.

Figure 7(c) shows the effect of different metal grain size (in the range of 2 to 20 nm [33, 34]) on the WFF variability for the DG-UTB devices. Results show that for grain size > 5 nm $\sigma(V_T)$ only slightly increases. In addition, specific works in the literature focusing on the WFF variability show that, by adopting a more realistic tessellation of the gate area, the forecasted increase of WFF variability at grain size > 5 nm is further reduced, see [34]. On the other hand, grain size < 5 nm causes WFF variability to drop considerably. Nevertheless, this reduction can only be achieved with processes preventing the crystallization of the metal [35], i.e., gate-last flow, or with different materials, such as TaSiN, that remain amorphous even in gate-first flows [36]. Hereafter, we consider $\sigma(V_T)$ at 5 nm grain size to be representative of WFF variability for the typical gate-first processes in the devices under study, with

Fig. 8. Bar plots of $\sigma(V_T)/V_T$ for the four variability sources and the two InGaAs DG-UTB reference devices at two technological nodes.

TiN as the gate metal. In general, WFF has comparable effects on InGaAs and Si devices due to the same device geometries. Another important point about $\sigma(V_T)$ data shown in Fig. 7(a) is that WFF and Body-LER have comparable and predominant variability effects on V_T of InGaAs devices, whereas WFF is the only predominant source of variability in Si.

Bar plots in Fig. 8 provide a quantitative comparison of statistical variability at the 15-nm and 10.4-nm nodes, showing the extracted $\sigma(V_T)$ values for the different variability sources, similarly to what reported in Fig. 7(a). Note that, for the sake of comparison, standard deviation values are normalized to corresponding average values $\mu(V_T)$. Notably, the relative variability of V_T is not dramatically affected by L_G scaling. More specifically, *i*) RDF- and WFF-induced variability slightly increases at the 10.4-nm node mostly due to the small nominal V_T reduction; *ii*) Body-LER and Gate-LER variability actually decreases with L_G scaling due to the reduction in both Δ_{rms} and Λ parameters projected by ITRS and employed in our simulations (see Tab. II). In this scenario, the detrimental impact of Body-LER on V_T variability evident for the 15-nm node is attenuated, leaving to WFF the role of dominant variability source (as for Si devices). However, this encouraging scaling perspective holds true only if the LER control improvements forecasted by ITRS are effectively attained.

B. Sensitivity

The overall promising picture emerging from the variability analysis needs to be confirmed also when considering the effects of systematic geometrical parameter variations. For this purpose, we have considered all the varied and reference devices and evaluated how $\mu(V_T)$ and $\sigma(V_T)$ are affected by systematic variations. We focus the analysis only on DG-UTB devices, as they exhibit comparable variability with respect to their FinFET counterparts, as reported in Fig. 7(a). Results are reported in Fig. 9 for the InGaAs DG-UTB devices at the 15-nm and 10.4-nm nodes as well as for the Si DG-UTB device at the 15-nm node. Figures 9(a)-9(c) show the dependence of $\mu(V_T)$ on L_G , T_{chan} and T_{ox} . For the sake of comparison, $\mu(V_T)$ values are normalized to the V_T of the reference device.

As it can be noted, the 15-nm node InGaAs device exhibits worse or, at most, similar V_T sensitivity than the Si FET, for all varied parameters. This is still a consequence of the reduced quantum capacitance of the InGaAs MOSFET making the device more prone to short-channel effects and therefore translating to:

Fig. 9. Plots of the sensitivity of $\mu(V_T)$ normalized to the V_T of the reference device to (a) L_G , (b) T_{CHAN} , and (c) T_{OX} . Plots of $\sigma(V_T)$ sensitivity to (d-g-j-m) L_G , (e-h-k-n) T_{CHAN} , and (f-i-l-o) T_{OX} due to (d-e-f) RDF, (g-h-i) WFF, (j-k-l) Body-LER, and (m-n-o) Gate-LER. Filled (empty) black symbols refer to InGaAs 15-nm (10.4-nm) node DG-UTB devices. Red symbols refer to Si DG-UTB devices.

- 1) a more significant V_T roll-off with L_G decrease, Fig. 9(a);
- 2) a larger V_T increase with shrinking of T_{CHAN} , see Fig. 9(b), this being the predominant variation effect in both the InGaAs and the Si device;
- 3) a larger V_T increase upon decreasing in T_{OX} , see Fig. 9(c). It is worth noticing that an increase in V_T at decreasing T_{OX} is indeed opposite to what generally expected and can be ascribed to strong quantization effects in these ultra-narrow channel devices [37].

The observed larger $\mu(V_T)$ sensitivity to geometrical parameter variations in InGaAs devices, as compared to Si ones, at the 15-nm node raises concerns about the scaling potential of InGaAs devices. Our analysis shows that node scaling weakly affects $\mu(V_T)$ sensitivity to variation of critical geometrical parameters, as far as L_G and T_{OX} are concerned. This can be appreciated in Fig. 9(a) and 9(c) showing that the $\mu(V_T)$ curves versus L_G and T_{OX} almost rigidly shift to smaller dimensions upon scaling. T_{CHAN} scaling causes instead more concern, as the $\mu(V_T)$ roll-off at increasing T_{CHAN} becomes steeper upon node scaling, see Fig. 9(b). In this case, for a

20% increase above the nominal value (i.e., a 0.8 nm change), $\mu(V_T)$ drops below 50 mV. The sensitivity of $\sigma(V_T)$ on systematic geometrical parameter variations is illustrated in Figs. 9(d)-9(o), for the different statistical variability sources. InGaAs and Si DG-UTB MOSFETs are again compared. As can be noted, qualitatively similar $\sigma(V_T)$ dependence on varying parameters are predicted for the two materials at the 15-nm node. However, similarly to what is observed for the nominal structures (see Fig. 7(a)), the InGaAs devices always display worse or, at most, comparable $\sigma(V_T)$ than Si ones, regardless of the varying parameter and the statistical variability source considered. This holds true also for the FinFET structure [10]. Most of the $\sigma(V_T)$ -vs-parameter trends shown in Figs. 9(d)-9(o) actually confirm results for ultra-thin-channel devices, already pointed out by studies on Si MOSFETs [9], indicating that: *i*) WFF variability has very small dependence on geometrical systematic variations; *ii*) statistical V_T variability worsens at decreasing L_G as well as increasing T_{CHAN} and T_{OX} for RDF, Body-, and Gate-LER. The latter is the most crucial aspect, as it emphasizes the

Fig. 10. Sensitivity of the overall variability $\sigma_{TOT}(V_T)$ (i.e., sum of all variability sources) to L_G , T_{CHAN} and T_{OX} for the 15-nm node Si (red), 15-nm and 10.4-nm node InGaAs DG-UTB devices (black filled and hollow symbols, respectively). Experimental data is included for the Si technology (purple star) for the 14-nm node ($L_G = 20$ nm).

importance of appropriate scaling and accurate control of involved critical geometrical parameters. In this context, the sensitivity of $\sigma(V_T)$ to geometrical parameter variations in InGaAs devices is, in most cases, not appreciably worsened by scaling.

A notable exception to this picture is evidenced in Fig. 9(h) for the 10.4-nm node InGaAs device, which displays a worsening of the $\sigma(V_T)$ sensitivity to T_{CHAN} due to WFF. This $\sigma(V_T)$ increase for increasing T_{CHAN} , combined with corresponding $\mu(V_T)$ decrease observed in Fig. 9(b) may be a critical issue for device scaling. In any case, scaling to the 10.4-nm node results in an increased sensitivity of $\sigma(V_T)$ to T_{CHAN} also for Body-LER variability (which is the dominant variability source along with WFF). This indicates that, despite ITRS projections on LER control are followed when scaling to the 10.4-nm node (see Tab. II), the $\sigma(V_T)$ sensitivity to T_{CHAN} worsens. Eventually, the combination of the increased sensitivity to T_{CHAN} for both $\mu(V_T)$ and $\sigma(V_T)$ can be a showstopper for this technology, highlighting the critical role of T_{CHAN} control, which is discussed in the next Section.

IV. DISCUSSION

To assess the overall tolerance of a technology to process variations, it is necessary to evaluate the total V_T variability by considering the combined effect of all variability sources. Here we assume sources to be mutually independent, thus evaluating the total variability, $\sigma_{TOT}(V_T)$, by using equation (2) in [15]. A comparison between the $\sigma_{TOT}(V_T)$ of InGaAs and Si DG-UTB devices is reported in Fig. 10, along with its dependence on L_G , T_{CHAN} , and T_{OX} variations. Remarkably, our results are in good agreement with recent experimental data showing a $\sigma_{TOT}(V_T)$ of about 18 mV for Si FinFETs at the 14-nm node [13] (purple star symbol in Fig. 10).

Interactions among different variability effects can in principle result in either over- or under-estimation of total variability, and their evaluation requires atomistic approaches to be adopted [12]. In [38], authors investigate InGaAs-based FinFETs and show that considering the LER/WFF coupling can result in a larger variability, as compared to the case in

Fig. 11. Sensitivity of V_T distributions obtained from the sum of all variability sources to T_{CHAN} for the 15-nm node InGaAs DG-UTB device.

Fig. 12. Sensitivity of V_T distributions obtained from the sum of all variability sources to T_{CHAN} for the 10.4-nm node InGaAs DG-UTB device. An increase of T_{CHAN} might lead to a significant chance of having normally-on devices.

which the coupling is neglected. However, the effect is non-negligible only when the two sources are independently characterized by comparable σ values. Since this could be the case of InGaAs 15-nm devices, see Fig. 7(a), the total variability could be worse than the predictions in Fig. 10. Conversely, in the case in which one source is dominant, the coupling effect can be safely ignored. On the other hand, RDF and LER components have been suggested to be statistically independent [12, 39]. Overall, our analysis leads to reasonable values, as demonstrated by the comparison with experimental results for Si, which improves our confidence on the dependability of our variability predictions also for InGaAs devices, for which experimental data is not yet available on statistically meaningful data sets.

Regardless of the geometrical parameter under consideration, InGaAs devices exhibit higher $\sigma_{TOT}(V_T)$ than the Si equivalent at the 15-nm node, and show a larger $\sigma_{TOT}(V_T)$ dependence on all parameters. Interestingly, scaling InGaAs devices to the 10.4-nm node negligibly affects their overall variability and also results in significantly better $\sigma_{TOT}(V_T)$ sensitivity to all parameters, with the exception of T_{CHAN} . The critical role of T_{CHAN} control upon scaling is further illustrated in Figs. 11 and 12, showing the V_T distributions of InGaAs DG-UTB devices for the different T_{CHAN} values (nominal, $\pm 10\%$, and $\pm 20\%$ changes) at the two technological nodes, respectively. Specifically, a T_{CHAN} increase can be critical due to the I_{OFF} increase associated with V_T reduction, a scenario which is further worsened by the associated $\sigma_{TOT}(V_T)$ increase (standard deviation of the distributions in Figs. 11 and 12). In particular, our results show that, at the 15-nm node, a 10% T_{CHAN} increase results in an almost 30% probability to obtain a device with $V_T < 100$ mV (see Fig. 11), which implies a $>10\times$ increase in I_{OFF} . This picture is exacerbated at the 10.4-nm node: a T_{CHAN} increase of 10% results in almost 30% chance to get a device with V_T

<70 mV (see Fig. 12), which implies a >50x increase in I_{OFF} . At this node, a further T_{CHAN} increase (i.e., +20%) might even lead to a significant chance to get a normally-on device (critical tail highlighted in Fig. 12). On the other hand, a T_{CHAN} decrease results in obvious gate overdrive and I_{ON} current reduction. Particularly, for both technological nodes a $\approx 20\%$ reduction in I_{ON} is observed for a 10% T_{CHAN} reduction. Likewise, the observed I_{ON} decrease is larger than 40% considering a 20% T_{CHAN} reduction. Therefore, T_{CHAN} control appears to be the most stringent constraint for InGaAs technology when variability/sensitivity effects are considered. Approaches that rely on T_{CHAN} definition by epitaxy rather than etching, like in [40] and [41] for UTB and FinFET devices, respectively, might represent a viable solution to reduce T_{CHAN} sensitivity as well as related LER effects.

V. CONCLUSIONS

In this work, we investigated the effects of both statistical variability and systematic geometrical parameter variations on InGaAs DG-UTB and FinFET devices at two technological nodes ($L_G = 15$ nm, $V_{\text{DD}} = 0.63$ V) and ($L_G = 10.4$ nm, $V_{\text{DD}} = 0.59$ V). For the 15nm-node, the analysis has been extended to Si-based devices for benchmarking purposes. Our simulations show that InGaAs devices have comparatively higher V_T variability than Si ones as a result of stronger quantization effects in the ultra-thin device channel. Moreover, InGaAs devices exhibit worse V_T sensitivity to systematic variations. Nevertheless, the overall variability, due to the combined effects of all variability sources, appears still manageable at the 15-nm node (i.e., smaller than 30 mV considering $\pm 10\%$ deviation on L_G or T_{CHAN}). Scaling to the 10.4-nm node negligibly affects V_T variability, if ITRS projections regarding LER control are attained. On the other hand, scaling strongly affects V_T sensitivity to T_{CHAN} , thus configuring the control over T_{CHAN} as the most critical issue for InGaAs devices scaling.

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