

Al-Ameri, T. (2017) Statistical Variability in 5 nm Vertically Stacked Lateral Si Nanowire Transistors. 12th IEEE Nanotechnology Materials and Devices Conference (NMDC 2017), Singapore, 2-4 Oct 2017.

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Deposited on 17 October 2017

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Statistical Variability in 5 nm Vertically Stacked Lateral Si Nanowire Transistors

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Abstract In this work, we present a comprehensive computational study of the impact of the principle sources of statistical variability, i.e., random dopant fluctuations, wire edge roughness, and metal gate granularity, on the threshold voltage, drain-induced barrier lowering, and drive current. Furthermore, we investigated the position dependent performance and geometrical variation of the lateral nanowires in the stack as new sources of process variability.

I. INTRODUCTION

The vertically stacked lateral (VSL) gate-all-around (GAA) nanowire transistor (NWT) was introduced as a novel structure to tackle the challenges of degraded performance of Si NWT for 7 nm technology and beyond. It enabled significant current leakage reduction and is expected to pave the way to Si for high-performance or ultra-low-power 5 nm CMOC applications [1]. In current nanoscale transistor technology, the variability is becoming important due to process deviation and the intrinsic properties of semiconductor materials and interfaces. There are numerous sources of statistical variability (SV) such as random discrete dopants (RDD), wire edge roughness (WER), and metal gate granularity (MGG), which dominate the NWT behaviour [2]. The NWT geometry has a significant impact on electrostatic driven performance, i.e., the variation in the cross-sectional shape of the NWT may enhance process variability, furthermore, the vertical position of lateral NWTs in the vertical stack significantly dominate the performance of VSL NWT due to series resistance between the source/drain contacts and the lateral channels, causing enhancement in the process variability.

II. METHODOLOGY

In this work we used ensemble Monte Carlo (EMC) simulations with Poisson-Schrödinger (PS) quantum corrections as a reference [3]; we calibrated our drift-diffusion simulations to this reference. The quantum corrected EMC simulations accurately captured the nonequilibrium charge transport. A simplified workflow is presented in Fig. 1. The results of the EMC+PS simulations were used to accurately calibrate the drift-diffusion (DD) simulations employed to study process and SV.

III. RESULTS AND DISCUSSION

The simulated NWTs considered in this work have an elliptical cross-sectional shape with an aspect ratio (the ratio of major axis to the minor axis) close to the golden ratio (Phi)

8.1 nm/5 nm and <110> channel orientation. Fig. 2 shows the structure and material information of the VSL with two lateral channels.

The analysis of the SV and reliability involving RDD, WER, MGG, critical dimension variability, and contact resistance variability are introduced individually in combination with two levels of interface trapped charge ITC in the simulations for VSL NWT. The FOM are extracted at high drain voltage V_D=0.7V, gate voltage V_G=0.7V, and contact resistance $R=1K\Omega$. With an average grain diameter of 5 nm, the WER is modelled with the assumption that it follows a Gaussian autocorrelation function. Fig. 3 presents the distributions of I_{on} and V_T for 960 different devices. The lateral NWT position in the vertical stack is formed by randomly changing the vertical position of the nanowire with a range of +/- 2 nm considering the initial device. The probability distributions were a binomial distribution for both I_{on} and V_T . The I_{on} and V_T vary between 2.56 and 2.32 mA/µm, and 95.6 and 95.83 mV respectively. In Fig. 4, the impact of the variability of the cross-sectional shape on DIBL, SS, and Ioff for an ensemble of 3700 (device) VSL NWT with three lateral NWTs is illustrated. The crosssectional shape of the nanowire has significant influence over the main figures of merit. Fig. 5 illustrates the normal probability distribution of I_{on} and V_T for an ensemble of 3700 VSL NWT with three lateral NWTs. It is clear that when the DIBL is increasing the SS and the I_{off} also increase. Hence, the cross-sectional shape of the nanowire has significant influence over the main figure of merit. The solid red line on the figure presents normal probability distribution while the blue circles are the devices' sample. For V_{T} the results do not follow the normal distribution, which proves the point that statistical TCAD simulations are important to accurately represent the device's behaviour. The situation for ION is somehow different. The device results follow the normal distribution very closely. However, only the tails of the blue circles are not on the top of the red line. We also studied the SV for VSL NWT with double lateral channels. Fig. 6 illustrates the normal probability QQ-plot of DIBL, Ion, Ioff, and V_T distributions due to individual SV sources (RDD, LER, MGG, and R), and in their combination with $1x10^{12}$ cm^{-2} and $7x10^{12} cm^{-2}$ ITC. As we can observe from data in Fig. 6, the interaction between the source of variability and the interface traps increase the standard deviation from 1.24 to 3.44 mV/V for DIBL and 3.41mV to 21.49mV in the V_T case. This shows that the interplay between variability sources and the interface trap will significantly increase the variability of important device parameters. Fig. 7 shows the distribution of and correlations between extracted FOM from the TCAD simulations of individual ITC $1x10^{12}$ cm⁻² and 4x10¹² cm⁻² with the main SV effect (RDD, WER, MGG, and R=1K Ω). The results show a similar correlation between I_{off}

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and VT for both the triple and double NWT. The anticorrelation is observed for a combination between I_{on} , I_{off} , and V_T . The magnitudes of the coefficients are very similar to the data for ITC2 = $8x10^{12}$ cm⁻².

In conclusion, our work shows that considering various sources of SV is mandatory to obtain a realistic and comprehensive prediction of the behaviour of the next generation ultra-scaled transistors.



Fig. 1. Simplified simulation tool flow chart.



Fig. 2. 3D schematic view of simulated Si transistor (NTW) and material information.



Fig. 4. The impact of geometry process variability on the shape of the cross section on DIBL, SS, and $I_{\rm off}$ for 3700 ensembles VSH NWT with **three** lateral VSL NWTs.



Fig. 5. The normal probability distribution of Ion and V_T for 3700 ensemble VSL NWT with three lateral NWTs subject to SV in the shape of cross-sectional.



Fig. 3. The distributions of I_{ON} subject to lateral NWT position in the stack, an ensemble of 960 devices with random lateral NWT positions subjugated to +/- 2nm distribution around the standard device.



Fig. 6. Normal probability QQ-plot of DIBL, I_D sat, I_{Off} , and V_T distributions due to individual VS effect of RDD, combined (RDD, LER, MGG, and R), and in their combination with 1×10^{12} cm⁻¹ and 8×10^{12} cm⁻¹ ITC for an ensemble of 1000 VSL NWT with double lateral NWTs.



Fig. 7. Distribution of and correlations between extracted FOM from the TCAD simulations of individual ITC1= 1×10^{12} cm⁻¹ and ITC2= 8×10^{12} cm⁻¹ with SV effect (RDD, WER, MGG, and R=1K Ω) for an ensemble of 1000 VSL NWT with double lateral NWT (right) and for triple lateral NWT (left).

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