Accurate prediction of device performance in sub-10nm WFIN FinFETs using scalpel SSRM-based calibration of process simulations.

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Abstract—In this paper, we illustrate how high resolution two-dimensional (2D) carrier maps obtained from scalpel scanning spreading resistance microscopy (s-SSRM) can be applied to calibrate a technology computer aided design (TCAD) simulator in order to predict and understand the performance of sub-10nm WFIN FinFETs. In the proposed approach, process simulations are calibrated such that the resulting simulated carrier profiles match the quantified s-SSRM profiles. Upon reaching satisfactory agreement, they can be used as input for device simulators in order to predict more accurately key device parameters such as the linear on-state resistance ($R_{ON,LIN}$), and the threshold voltage ($V_{TH,SAT}$) roll-off to name few. This also allows us to accelerate the development of devices towards new technology nodes (as N7 and N5) by identifying parameters to be improved and technological options to be selected.

Keywords—FinFET, SSRM, metrology, calibration

I. INTRODUCTION

The aggressive downsizing of FinFET devices in past years has put a great emphasis on the need to characterize two-(2D) and even three-dimensional (3D) carrier profiles for the correct understanding of device behavior. In such scaled devices even the smallest variations of the structure dimensions (ie. fin width or length, local interconnect, spacer, etc.), carrier distribution and/or activation rate can cause significant variations in the electrical properties of the devices. As physical mechanisms involved in scaled devices are complex, adequate 2D and 3D characterization techniques have been identified as a necessity by process/device engineers to achieve an accurate modeling and calibration of TCAD simulators.

To fulfill these needs, scanning spreading resistance microscopy (SSRM) has been used extensively and has demonstrated its usefulness. In essence, SSRM consists of a conductive tip mounted on an atomic force microscope (AFM) which is scanned in contact mode over the area of interest, and whereby one measures the current flowing through the sample while a DC bias is applied between the tip and a back-contact (Fig. 1). SSRM is performed at a large pressure (GPa range) which leads to a good (near ohmic) electrical contact between the tip and the sample. The contact resistance is then dominated by the current spreading in the point contact and scales directly with the local resistivity and hence with the carrier concentration. In order to optimize the tip-sample electrical nano-contact, measurements are typically performed in a low humidity chamber (<0.1 ppm H2O and O2). The resulting current varies over a broad dynamic range (typically 10 pA to 0.1 mA) and is measured using a logarithmic current amplifier. The successful implementation of SSRM is intimately linked to the emergence of wear resistant probes based on doped diamond. Its sub-nanometer spatial resolution combined with a doping sensitivity ranging over 5 orders of magnitude with good quantification accuracy make SSRM unique [1-4].

In this work we have utilized its most recent mode, named scalpel-SSRM (s-SSRM), wherein one is exploiting the possibility to use diamond based AFM-tips as scalpel, removing material layer by layer while scanning. s-SSRM is allowing to perform successive 2D carrier mappings [5] with a sub-2nm resolution along X-Y and Z directions. 2D carrier maps parallel to the fin in the center of sub-10nm WFIN FinFETs were generated using the s-SSRM (Fig. 2).
II. CALIBRATION OF PROCESS SIMULATOR USING S-SSRM

A. Comparison between s-SSRM and default TCAD results

We have analyzed two different n-FinFET devices (samples S1 and S2). Key process differences (Fig. 3) between these devices are the doping procedure of recessed source-drain epi (implanted undoped Si epi in sample S1 vs. in-situ doped Si:P 4% epi in sample S2), anneals (1200°C laser anneal and 1.5s 1000°C rapid thermal annealing in S1 vs. 1100°C laser annealing in sample S2) and the local interconnect (Ni silicided contact in sample S1 vs. direct Ti contact in sample S2).

The 2D s-SSRM resistance maps (along the sub-10nm fin and in its center as illustrated in Fig. 2) are presented in Fig. 4. Vertical and lateral resistance section lines (corresponding to the left-hand side scale-bar) as well as the quantified active dopant concentration section lines (right-hand side scale-bar) are presented in Fig. 5. They demonstrate a larger overlap in the case of sample S2 (12 vs. 6nm) while the extension conditions are the same for both samples.

All the process differences have been carefully included in the TCAD decks resulting in noticeable differences in the simulated carrier maps (Fig. 6). In particular, we observe in sample S2 that the extension could be covered (higher concentration and more lateral diffusion) by the carriers coming from the pre-doped source-drain epi. Difference in overlap length is confirmed by the $V_{T,SAT-LG}$ (at $V_{DS}=V_{DD}=0.8V$) exhibiting more roll-off for sample S2 (Fig. 7).

However, major differences may still be observed between these default TCAD simulations and both the s-SSRM maps and the electrical characteristics. In particular, the maximum carrier concentration (in epi and extensions) is too high in the simulations (vs. experimental s-SSRM results) and the $R_{ON,LIN}$ is too low (vs. measured values), in particular for sample S1. This is a clear indication that the process simulations are not yet properly calibrated.
B. Impact of active dose variation in extensions and source-drain

As compared to the default TCAD results, carrier (or active dopant) concentrations measured with s-SSRM (Figs. 5 and 6) exhibit lower values in the extensions (10x for sample S1 and 2x for sample S2) as well as in the source-drain epi (5-10x for sample S1 and 3x for sample S2). Hence we have investigated the impact of (active) dose loss in the extensions and variation in the source-drain epi (Table 1).

The dose loss in the extensions may originate from the resist strip step from the lithographic process performed prior to the epi growth (a softer processed is utilized for sample S2). The higher dose in the epi source-drain of sample S2 arises from the ability to incorporate very high dopant concentrations (above 1E21 at/cm³) into in-situ doped Si:P epi.

Both dose variations are impacting the \( I_{D,LIN} \) current (measured at \( V_G=0.8V \), \( V_DS=0.05V \)) and \( R_{ON,LIN} \) (\( V_G=V_{T,LIN}+0.5V \), \( V_DS=0.02V \)) even if their effect remains relatively limited. For instance, based on our simulations, 90% of dopant deactivation in both extensions and source-drain leads to a current decrease of 43% in sample S1.

C. Impact of local interconnects (LI)

We have investigated the impact of the LI depth since experimentally a deeper (8nm) LI (larger recess prior to epi growth) is observed in sample S2. Including this deeper recess in TCAD (Fig. 8) we can however observe that the impact on the \( I_{D,LIN} \) current is not large (~5%).

We have also analyzed the impact of the probable presence of a thin oxide layer at the interface between LI and source-drain in sample S1 revealed by a resistance peak in the s-SSRM sections (red circle in Fig. 5) and confirmed by energy-dispersive X-ray spectroscopy (EDX) measurements (see in [5]). Introducing a thin (0.4nm) oxide layer at the interface (Fig. 9) is impacting the \( I_{D,LIN} \) current significantly (+ 100%). Note that
such a thin oxide may originate from a not optimized cleaning process prior to the LI silicide formation.

D. Calibration of process simulator and analysis of TCAD results

Taking into account all these indications, we have calibrated our process simulations. For sample S1, corresponding to the implanted source-drain epi, we introduce a dose loss of 90% for the extension and 80% for the epi s/d, with a 0.4nm interfacial oxide. For sample S2, we introduce a dose loss of 50% for the extension and of 66% in the epi s/d. In the optimized 2D TCAD carrier maps as well as the lateral section we obtain a very good agreement with the s-SSRM profiles (Fig. 10). The simulated $V_{T,SAT-LG}$ are in much better agreement with measurements for both samples S1 and S2 (Fig. 11) as the roll-off is reduced (less dopant diffusion into the channel). For sample S2, this also leads to a far better agreement between measured and simulated $R_{ON,LIN-LG}$. For sample S1, however, matching carrier profiles (dose loss) doesn’t lead to agreement for $R_{ON,LIN-LG}$ ($I_{D,LIN}$ remains too high). Hence we have to consider the presence of a residual oxide at the contact.

III. PROSPECTIVE WORK AND CONCLUSIONS

Introducing a softer resist strip process at extension and reducing the thermal budget of the epitaxial growth of source-drain, one should be able to further increase the carrier concentration (in particular in the extensions), to reduce the extension overlap and to increase its lateral steepness. Hence roll-off characteristics should be improved and access resistance ($R_{ON,LIN}$) reduced.

The s-SSRM technique has been successfully utilized in order to calibrate process simulations. Impacts of dose loss, thermal budget during epitaxial growth and possible interfacial layers at the LI-epi interface have been highlighted. Tuning these parameters to match the 2D carrier TCAD maps with the s-SSRM maps, we are able to predict more accurately important device parameters and to provide strategy for further improvements in view of the stringent N7 and N5 requirements.

### TABLE 1

<table>
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<tr>
<th>Dose</th>
<th>Def S1</th>
<th>Def S2</th>
<th>Ext &amp; SD loss S1</th>
<th>Ext &amp; SD loss S2</th>
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<tr>
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<td>x</td>
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<td>x</td>
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<tr>
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<td>x</td>
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<td>$I_{D,LIN}$ (μA)</td>
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<td>$R_{ON,LIN}$ (Ω.μm)</td>
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<td>364</td>
<td>420</td>
<td>625</td>
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</table>

ACKNOWLEDGMENTS

The imec SPM and TEM teams, the TCAD team, the pilot line and amsimec (testlab) are acknowledged for their support.

REFERENCES