Analysis of uncertainties in the Self-Heating Extraction by RF technique in FD-SOI Transistors

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Abstract: This work provides a deep assessment of RF technique for self-heating (SH) extraction in advanced FD-SOI MOSFETs focusing on the uncertainties introduced by the extraction procedure. Particularly, we investigate the impact of i) choice of thermal resistance, R_{th} formula and ii) extraction of drain current variation with temperature, $g_t = dI_D/dT$. We show that the two valid output conductance g_{ds}-based formulations for thermal resistance, when applied to experimental data, exhibit discrepancies that increase at higher gate voltages and shorter gate lengths. Extracted uncertainty ranges from ~3% for 100 nm device to ~22% for the shortest lengths, underlining the importance of both consistent formulation and accurate g_t extraction at aggressively scaled nodes.

Introduction and Method: Enhanced self-heating in FD-SOI MOSFETs, w.r.t. their bulk counterparts, originates from the buried oxide (BOX) enhanced thermal isolation, and the higher power densities at advanced technology nodes [1]. The RF technique proved its advantages for SH extraction in advanced devices [1]. It extracts R_{th} from g_{ds} difference at high and low frequency: $g_{ds,sh}$ - $g_{ds,iso}$, combined with g_t computation (Figure 1) [2]. Depending on whether g_t is taken from I_D vs T_{amb} or T_{ch}, four R_{th} formula can exist (Figure 2(a)). We show that only two of the proposed formula, $R_{th,F1}$ and $R_{th,F2}$, originally derived in [2], are mathematically correct. Confusion in the definition of g_t or g_{ds} may lead to using incorrect forms $R_{th,F1p}$ and $R_{th,F2p}$, as mentioned for $R_{th,F1p}$ in [3]. In this work, we combine experimental results with analytical modeling to validate the correctness of $R_{th,F1}$ and $R_{th,F2}$, and to quantify the relative uncertainty in R_{th} arising from g_t extraction and formula selection.

Results and Discussion: DC and RF S-parameters measurements were carried out on 28FD-SOI nMOSFETs with gate lengths L from 30 to 100 nm, T_{amb} from 298 to 353 K, and V_{DS} = 1 V. The characterized devices are considered representative of the typical 28FD-SOI device behavior. The validity of the R_{th} formulas is evaluated in Figure 2(b) using a simple transistor model with a user-specified R_{th}^{user}. As shown, only $R_{th,F1}$ and $R_{th,F2}$ correctly recover R_{th}^{user}, whereas the alternative $R_{th,F1p}$ and $R_{th,F2p}$ formulas introduce errors of up to 7%. Figure 2(c) illustrates $R_{th}W$ values extracted using four formulas for experimental 40 nm-long device, together with error bars reflecting the g_t uncertainty (given by assumption of linear $I_D(T)$ dependence). From the experimental data, even if $R_{th,F1}$ and $R_{th,F2}$ do not coincide exactly, they remain the closest pair. The observed separation between $R_{th,F1}$ and $R_{th,F2}$ exceeds the uncertainty associated with g_t extraction, showing that g_t uncertainty: σ_{gt} alone cannot explain the deviation. We therefore examine how this deviation ($R_{th,F1}$–$R_{th,F2}$) evolves with L and V_{GS}, to gain further insight into its physical origin. We define $R_{th,mean} = (R_{th,F1}+R_{th,F2})/2$, and use $\sigma_{formula} = |R_{th,F1}-R_{th,F2}|/2$ as a measure of uncertainty due to formula choice. As shown in Figure 3(a), σ_{gt} rises sharply near $V_{ZTC} \approx 0.65$ V, where $g_t \rightarrow 0$, while $\sigma_{formula}$ increases with V_{GS}. Figure 3(b) shows that both contributions grow as the channel length decreases, with σ_{tot} increasing from ~3.5% at L = 100 nm to ~11% for the shortest device, where σ_{gt} and $\sigma_{formula}$ become comparable. The increase of $\sigma_{formula}$ with higher V_{GS} and shorter L strongly suggests that enhanced self-heating amplifies the discrepancy between $R_{th,F1}$ and $R_{th,F2}$. A plausible explanation is that R_{th} is temperature-dependent [2], an effect that was not included in the model. Finally, Figure 3(c) shows that using an incorrect formula (i.e. $R_{th,F1p}$ or $R_{th,F2p}$) significantly increases the relative uncertainty, reaching up to 20% for the shortest gate lengths 30-40 nm).

Conclusion: This work analyzed various uncertainty sources in R_{th} extraction using the RF method. We analytically confirmed that $R_{th,F1}$ and $R_{th,F2}$ are the only mathematically correct g_{ds}-based formulations, while $R_{th,F1p}$ and $R_{th,F2p}$ introduce a systematic error. A residual $R_{th,F1}$–$R_{th,F2}$ discrepancy is observed in measurements, increasing with both V_{GS} and L^{-1}, while the uncertainty in g_t extraction also grows with L^{-1}. Notably, $\sigma_{formula}$ dominates over σ_{gt} for most geometries, except at L = 30 nm where both contributions become comparable underlining the need for both consistent formula selection and accurate g_t extraction at the shortest nodes. Further studies, including temperature-dependent R_{th} characterization, are needed to fully clarify the origin of experimentally observed differences between $R_{th,F1}$ and $R_{th,F2}$. This room-temperature analysis is only a first step toward a more complete temperature-dependent study, as those uncertainties are expected to exacerbate at cryogenic temperatures, where T_{amb} and T_{ch} differ much more strongly.

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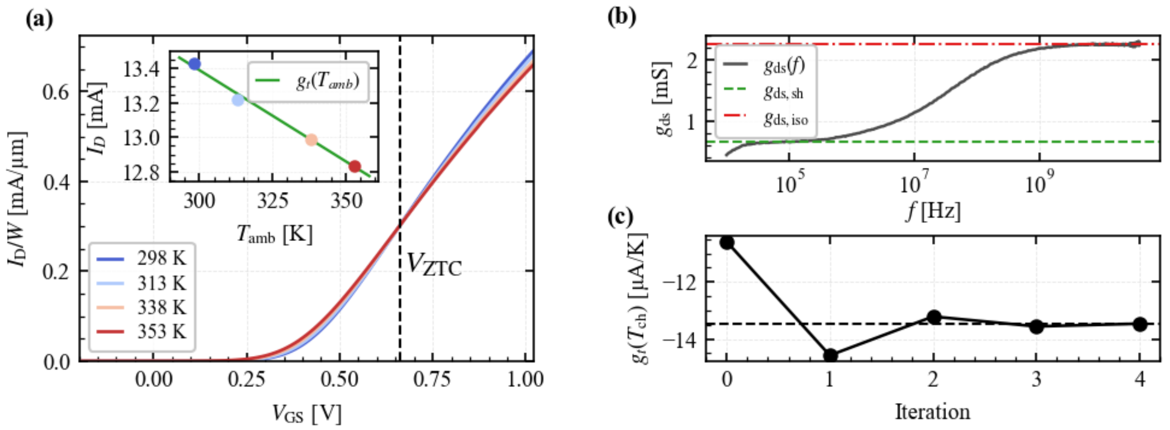

Figure 1 : (a) I_d/W vs V_{GS} at multiple T_{amb} (L = 40 nm, V_{DS} = 1 V). Inset: $g_t(T_{amb})$ at V_{GS} = 1 V from linear fit. (b) RF-extracted g_{ds} after open-short de-embedding and back-gate correction [4]. (c) Iterative convergence of $g_t(T_{ch})$ at V_{GS} = 1 V: starting from $g_t(T_{amb})$, R_{th} and $T_{ch} = T_{amb} + R_{th}V_{DS}I_D$, update $g_t(T_{ch})$, repeat until convergence.

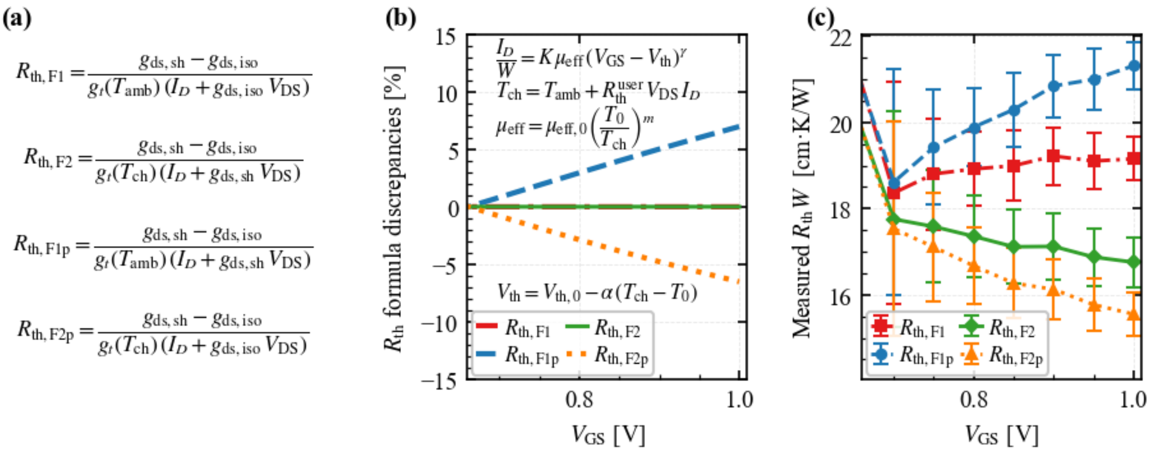

Figure 2 : Four R_{th} formula definitions (a), R_{th} formula verification using an analytical model with R_{th}^{user} = 18 cm·K/W (b), measured $R_{th}W$ versus V_{GS} for L = 40 nm, V_{DS} = 1 V (c).

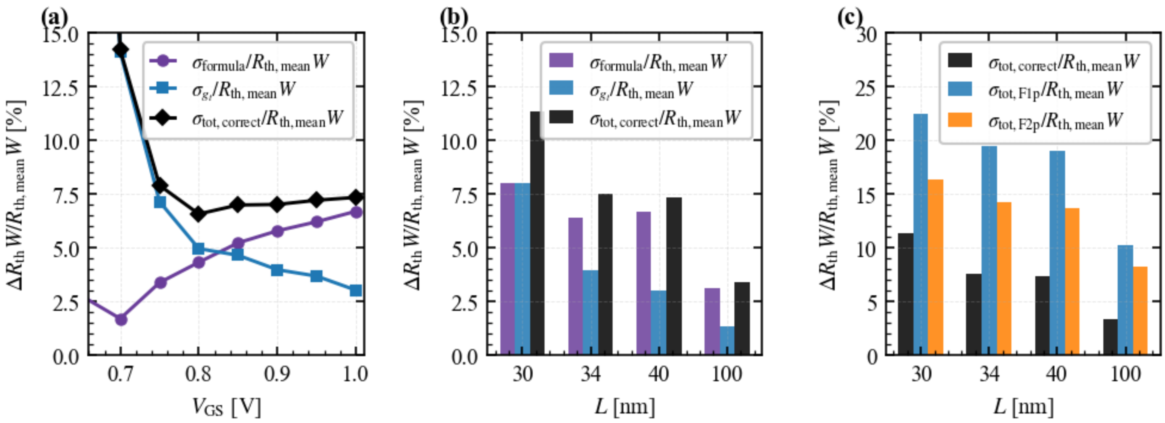

Figure 3: Extracted relative $R_{th}W$ uncertainty versus (a) V_{GS} (L = 40 nm) and (b) L (V_{GS} = 1 V) showing $\sigma_{formula}$, σ_{gt} and $\sigma_{tot,correct}$ (total uncertainty: $\sigma_{tot}^2 = \sigma_{formula}^2 + \sigma_{gt}^2$). (c) Total relative $R_{th}W$ uncertainty if one uses $R_{th,F1p}$ or $R_{th,F2p}$ to extract R_{th} (total uncertainty: $\sigma_{tot,F1p}^2 = |R_{th,F1p} - R_{th,mean}|^2 + \sigma_{gt,F1p}^2$ and $\sigma_{tot,F2p}^2 = |R_{th,F2p} - R_{th,mean}|^2 + \sigma_{gt,F2p}^2$).

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Acknowledgements: The authors would like to thank STMicroelectronics for chip fabrication and research support. This work is partially supported by Chips JU projects "SOIL" (#101139785) and "ARCTIC" (#101139908). The following states have contributed to the funding of that project: Belgium, Austria, Germany, Estonia, Finland, France, Ireland, Netherlands, Sweden, Czechia, Italy, Romania and Switzerland). Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or CHIPS. Neither the European Union nor the granting authority can be held responsible for them.