Unifying Self-heating and Aging Simulations with TMI2

Wai-Kit Lee, Kasa Huang, Jim Liang, Juan-Yi Chen, Cheng Hsiao, Ke-Wei Su, Chung-Kai Lin, Min-Chie Jeng
Taiwan Semiconductor Manufacturing Company
168, Park Ave 2, Hsin-Chu Science Park, Hsin-Chu County, Taiwan 308-44, R.O.C
Phone: 886-3-5636688 ext 7228220; Fax: 886-3-6668166;

Abstract— **In this paper, we discuss how to implement the self heating and aging models with TMI. Various examples about self heating and aging simulations with TMI methodology are shown in this paper. Without trading-off the accuracy, the one with proposed TMI approach for self heating simulations takes much shorter simulation time.**

I. INTRODUCTION

The geometry of FinFET devices confines the generated heat in a narrow Fin. Since the heat cannot be dissipated effectively, self-heating effect (SHE) is common in FinFET devices [1]. SHE not only affects the device electrical characteristics but also its reliability. To model the device aging characteristics, SHE has to be taken into account in the aging simulations. Most compact models use an auxiliary R-C network to simulate SHE as shown in Fig.1 [2], [3].

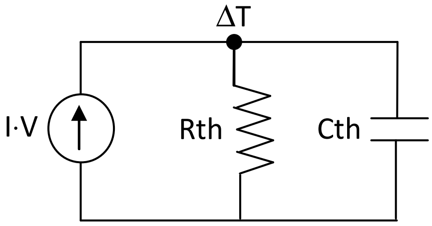


Fig.1 R-C Network for SHE calculation

The current source in the R-C network refers to the device power, such as |Ids·Vds| of a MOS device while Rth and Cth are the device thermal resistance and thermal capacitance respectively, which are determined by simulations or measurements [4]. The value of the simulated nodal voltage (ΔT) is equal to the temperature change due to SHE and has to be taken into account in the device temperature. With this modeling methodology, not only the device branch current, nodal voltage but also the device temperature are kept updated for each iteration in a simulation. This complicated relation not only slows down simulation efficiency significantly and may even cause convergence issues [5]. Even worse this approach is not straightforward to integrate into most reliability simulation flows.

TSMC Model Interface (TMI) has been demonstrated for aging simulations [6] and various model extensions on top of built-in models in simulators. We propose a novel solution to model SHE by TMI. With this methodology, SHE can be either modeled independently or naturally integrated into existing TMI aging simulation flow. Using a unified TMI structure, the drawbacks of traditional R-C network approach have been avoided. This paper explains the concept of modeling SHE by TMI and demonstrates some examples.

II. TMI BASED AGING MODEL WITH SELF-HEATING

Since TMI2 was elected as an industry standard interface specification between model and circuit simulators by CMC [7], it has been implemented in many EDA tools. With TMI specifications, model developers can develop a shared library to communicate with simulators to access simulation information (such as nodal voltages and time steps) and modify model/instance parameters. This feature has been used to enhance the simulator built-in models to include the layout effect and to reflect device aging behavior. A simplified TMI simulation flow is shown in Fig.2.

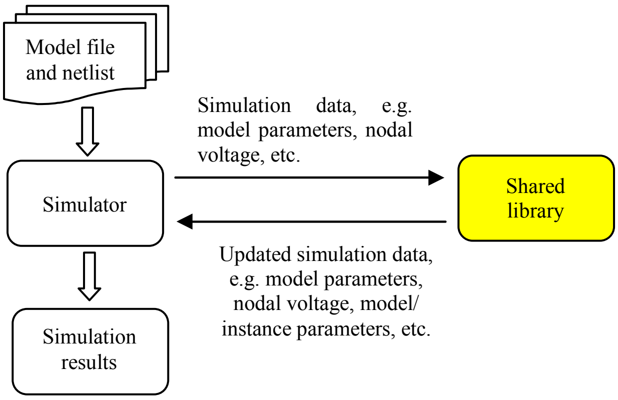


Fig.2 A simplified TMI operation flow

A general TMI-based aging simulation flow involves two simulations [6]. The first simulation evaluates the degradation rate of each device, projects the degradation to a given future time, and updates the instance/model parameters to reflect the degradation to be incurred. The second simulation is run with

978-1-4799-5288-5/14/$31.00 © 2014 IEEE

the updated model parameters to simulate the aged circuit performance.

In advanced technologies, SHE becomes more severe due to higher current density in the device and so it cannot be neglected in simulations. Power dissipation speed (inversely proportional to the thermal constant in a thermal R-C network) is usually much slower than the signal speed. It's a good approximation to assume that device temperature raised by SHE is proportional to the average power dissipated in the device during a transient simulation period. Therefore, SHE simulation flow can be similar to that of aging simulation flow. In the first simulation, without considering any SHE, based on the converged *I, V* data of each device at every single time point, TMI calculates the accumulated power of each device. After the simulation, the total accumulated power is converted to the average power, which is then used to find the temperature change (ΔT_{ave}) due to SHE as described in Fig.3.

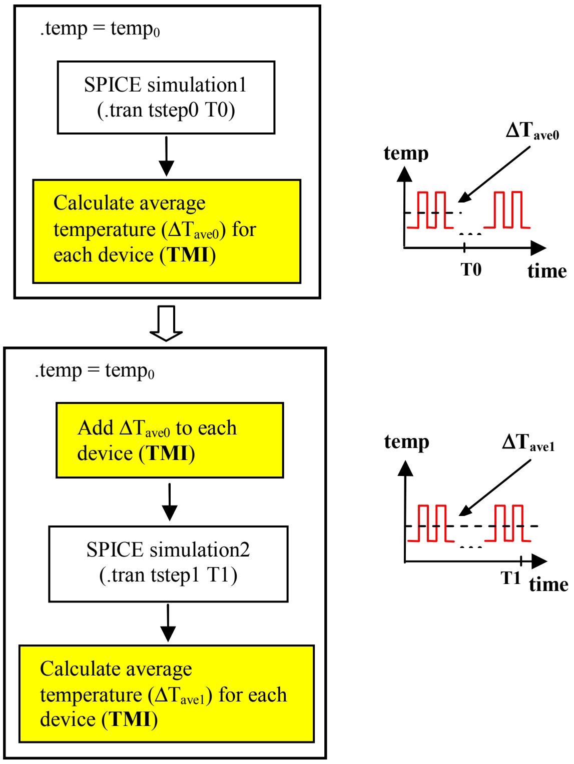


Fig.3 In step 1, the TMI shared library evaluates the average temperature (ΔT_{ave0}) for each device for a time interval T_0 and stores them in a file. In step2, the shared library will load in the stored SHE data for each device to take SHE into account in the simulation.
Users can run these 2 simulations manually or let the simulator run these 2 steps one by one automatically through the TMI settings.

Unlike the R-C network approach, this methodology doesn't need to update device temperature for each iteration and time step, hence has little impact on simulation efficiency. Device degradations and lifetimes are usually temperature sensitive. When SHE cannot be neglected, it has to be taken into account in the aging simulation flow.

The similar SHE and aging TMI simulation flows allow us to evaluate both effects either independently or combined together in a unified simulation flow and environment as depicted in Fig.4. SHE is taken into account in evaluating the device degradation in Fig.4b.

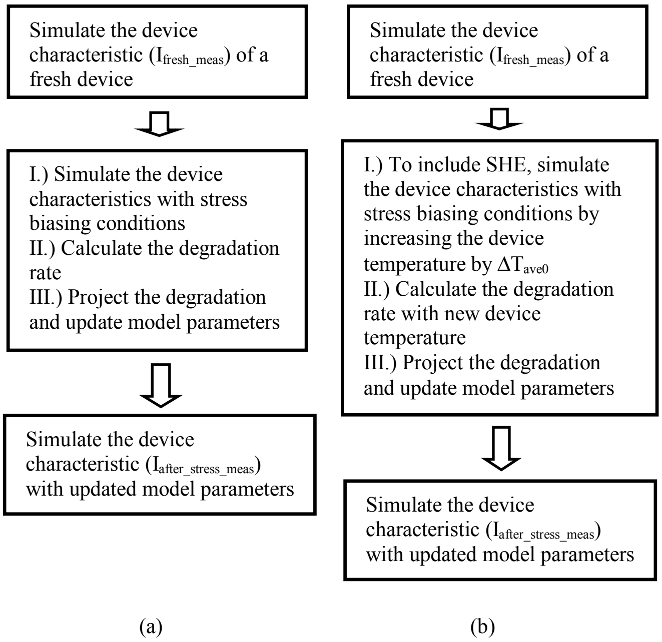
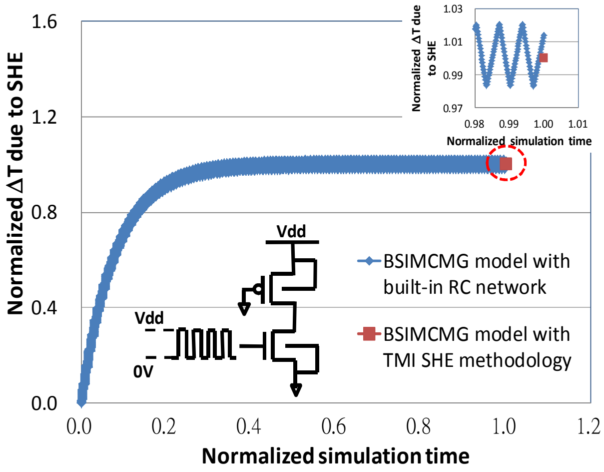


Fig.4a The TMI aging simulation flow without SHE (before and after stressing). Fig. 4b The TMI aging simulation flow with SHE (before and after stressing). ΔT_{ave0} is the average temperature evaluated by TMI shared library as shown in Fig.3

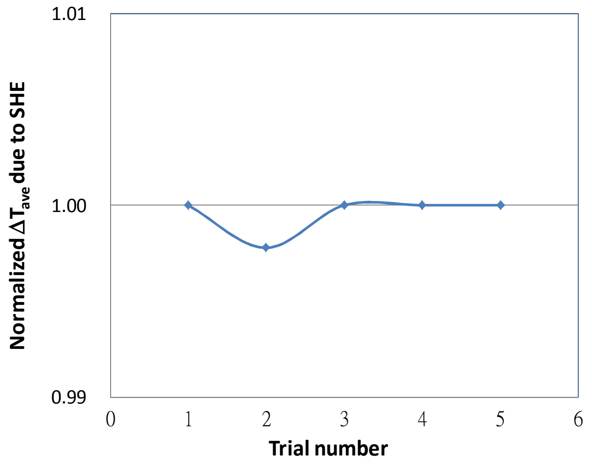
Furthermore, this simulation flow works for all simulators supporting TMI specifications without extra license cost.

III. TMI BASED AGING SIMULATION WITH SELF-HEATING EXAMPLES

The first example demonstrates SHE only. The circuit used in a transient simulation is shown in Fig.5a. A pulse chain is applied at the gate of the nFinFET device. To validate our approach, we also used BSIMCMG's built-in R-C network [3] to calculate the temperature rise ΔT. The temperature rise by our approach ΔT_{ave} is consistent with the ΔT in the steady state.



(a)



(b)

Fig.5a The ΔT of the nFinFET due to SHE varies with time by BSIMCMG built-in RC network and the ΔT_{ave} evaluated by the TMI SHE methodology. The ΔT_{ave} matches to the steady ΔT. Fig.5b shows ΔT_{ave} converges to the steady value in a few trials

Although this approach requires two simulations, the total simulation time is still faster than the one-step thermal R-C network approach without introducing extra convergence issues. Like aging simulation, SHE simulation accuracy can be improved by adopting more simulations with each simulation taking the previous generated ΔT_{ave} of each device as input as shown in Fig.5b. However, we found that two or three simulations are usually sufficient as ΔT_{ave} converges to a steady value very quickly as shown in the figure.

The next example demonstrates aging simulations with and without SHE. Although the degradation trends with and without SHE are similar as shown in Fig. 6, degradations are more severe when self-heating exists.

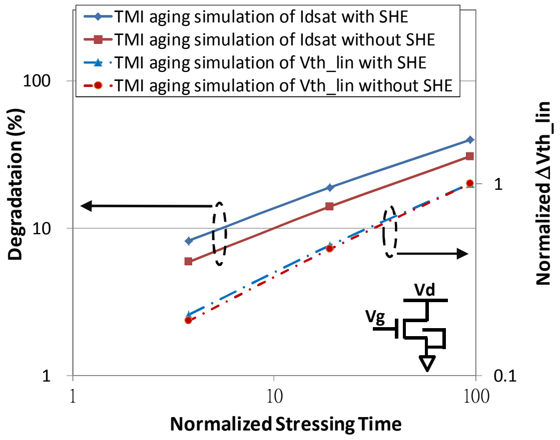


Fig.6 The degradation of an nFinFET device against stressing time with and without considering SHE using TMI aging simulation methodology.
The stressing conditions: Vd and Vg are biased at 1.1xVdd and Vdd respectively while Vs and Vb are at 0V.
The measurement conditions: Vd and Vg biased at Vdd while Vs and Vb are at 0V. The temperature at stressing and measurement are both at 25°C

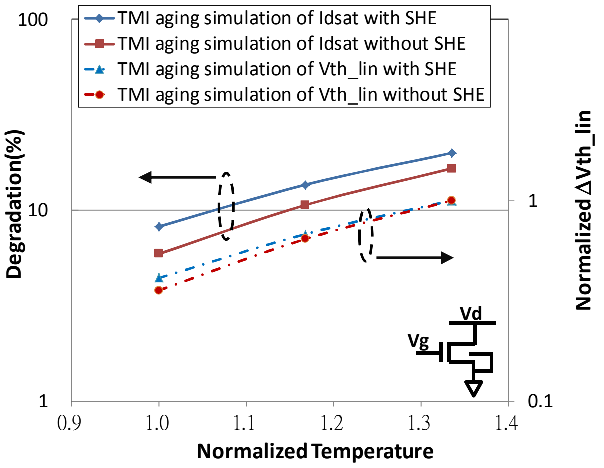


Fig.7 The degradation of an nFinFET device against temperature with and without considering SHE using TMI aging simulation methodology.
The stressing conditions: Vd and Vg are biased at 1.1xVdd and Vdd respectively while Vs and Vb are at 0V.
The measurement conditions: Vd and Vg biased at Vdd while Vs and Vb are at 0V. 25°C is applied at both stressing and measurement.

This fact is also observed in circuits as shown in Fig.7, where degradations at several temperature were simulated.

Aging simulations of a three-staged NAND ring oscillator with FinFET devices are shown in Fig.7.

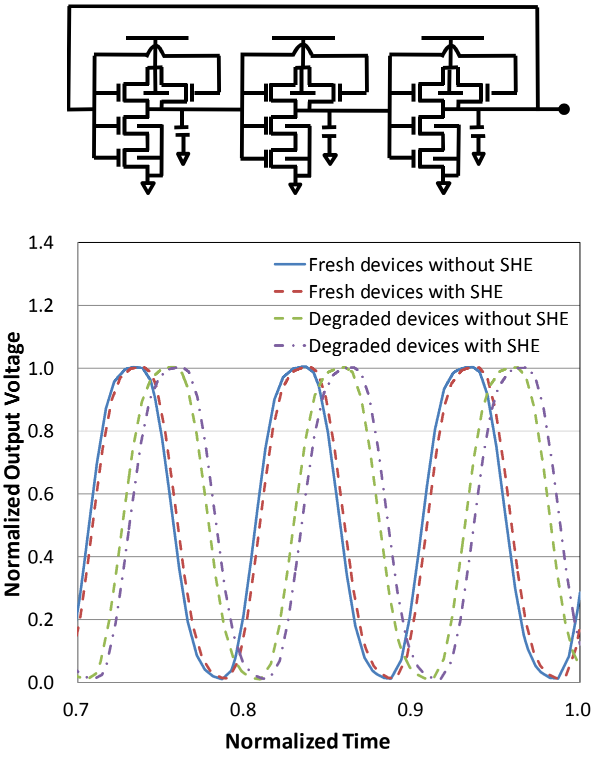


Fig.8 Simulation results of a 3-staged NAND ring oscillator – fresh without SHE, fresh with SHE (TMI), degraded without SHE and degraded with SHE (TMI). The stressing conditions: 1.1 x Vdd at 25 °C

SHE significantly affects the operation frequency for both the fresh and aged states. Table 1 lists the CPU times used for this approach and the traditional thermal R-C network approach of a ring oscillator SHE simulation.

SHE Simulation	CPU time (S)
BSIMCMG model with built-in RC network	131.22
BSIMCMG model with TMI methodology	0.43

Table1 The CPU time required for a 3-staged fresh NAND oscillator to achieve the steady ΔT by different methodologies.

Our proposed approach has notable efficiency improvement. Combining aging simulation with SHE, we can identify the reliability weak spots in the circuits more quickly and accurately as TMI can output ΔT_{ave} of each device together with HCI and BTI degradations in sorted manner for further analysis. One result is shown in Table2.

Device	Normalized ΔT_{ave} for fresh devices	Normalized device degradation Δidsat, (HCI + BTI)
p1	1.00	1.00
p2	1.00	1.00
n1	0.40	0.01
n2	0.14	0.00

Table2 n1 and n2 show lower ΔT_{ave} and device degradation as they are connected in series. The output voltage and the stressing voltage are shared between these two devices. This gives lower Vds across n1 and n2, which in turn results in lower power consumption and lower stressing voltage.

IV. CONCLUSIONS

Aging simulations with SHE considered are necessary for advanced technologies. Without sacrificing the simulation accuracy, we have developed a more efficient SHE simulation flow and integrated with existing aging simulation into a unified simulation flow through TMI.

REFERENCES

[1] C. Xu, S.K. Kolluri, K. Endo, K. Banerjee, “Analytical Thermal Model for Self-Heating in Advanced FinFET Devices With Implications for Design and Reliability”, IEEE Trans. on Computer-Aided Design of Integrated Circuits and Systems, vol.32, pp.1045-1058, 2013;

[2] P.Su, S.K.H. Fung, S. Tang, F. Assaderaghi, C. Hu, “BSIMPD: a partial-depletion SOI MOSFET model for deep-submicron CMOS designs”, IEEE CICC, pp.197-200, 2000;

[3] http://www-device.eecs.berkeley.edu/bsim/?page=BSIMCMG;

[4] W. Jin, S.K.H. Fung, W. Liu, P.C.H Chan, C.Hu, “Self-heating characterization for SOI MOSFET based on AC output impedance”, IEEE IEDM, pp.175-178, 1999;

[5] S. Maas, “Ill conditioning in self-heating FET models”, IEEE Microwave and Wireless Components Letters, vol.12, pp.88-89, 2003;

[6] M.C. Jeng, C. Hsiao, K.W. Su, C. K. Lin, “Circuit reliability simulation using TMI2”, IEEE CICC, pp.1-7, 2013;

[7] http://www.si2.org/;