Technology Black Box: A Pioneering Tool for Semiconductor Technology Development in the Automotive Industry

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***Abstract*— During last years the automotive industry is driving substantial changes in the semiconductor value chain, seeking for specialized products tightly bounded to their application space. Therefore even if the Automotive Electronics Council (AEC) states different “grades” for the compliance of microelectronics chips, under different uniform environmental temperature stress, still an agreement on actual Mission Profiles (MP) is missing. The MP remains nowadays customer specific, therefore the assessment of a semiconductor technology against such customized specifications has to be insured on a case-by-case standpoint.**

In this paper we present the Technology Black Box (TBB) as a new effective tool for the assessment of the microelectronics technology to the specific automotive requirements. Combinations of stresses derived from MPs and physical parameters are used in the TBB for realistic calculations and to identify the technology limitations. Such limitations can be afterwards fine-tuned, before technology qualification, so that TBB can be also used as an effective tool for technology development.

The use cases of TBB, presented in this paper, come from the assessment of 28SLP (28nm Super Low Power) against different automotive grades, and the development of 22FDX (Fully-Depleted Silicon-On-Insulator (FD-SOI)) technology from GLOBALFOUNDRIES.

***Index Terms*— Automotive electronics, Mission profile, Semiconductor reliability, Cumulative stress modeling, Effective stress, Lifetime requirement, Semiconductor technology, Automotive suitability, Technology assessment, Technology Black Box, TBB.**

I. INTRODUCTION

Innovative challenges like driver assistance systems, autonomous driving, electric mobility and car connectivity are together the driving force of microelectronics in the automotive industry. In order to realize such ambitious innovative features, the usage of leading-edge semiconductor technologies is essential. But nowadays, there is no “standard” applied to automotive requirements except what exists in AEC documents. It should be noticed however that the AEC [1] does not consider the Mission Profile (MP) requirements. Such requirements are typically customer specific and feature variable temperature stress profiles, reflecting the actual stress that the Electronic Component Unit have to withstand without “on field” failure. This work presents a new effective tool called the Technology Black Box (TBB) for the unified development and assessment of the automotive compliance of specific technologies. The TBB indeed can be used in various technological maturity phases, from the paper model, where no component is available yet, to first silicon and eventually the pre-production. A technology manufacturer can via the TBB verify the first electrical readouts against the MP requirements of different customers, and spend effort in optimizing the technology.

The TBB can also be shared among different tiers of the automotive value chain, as essentially a “black-box” aiming to fast response on the matching between technologies versus requirements, without a full awareness of technological parameters, existing in model cards.

The TBB therefore will help in saving time on the entire technology development for specific automotive customers as shown in Fig. 1. This will be achieved by the early alignment of the development plans along the supply chain.

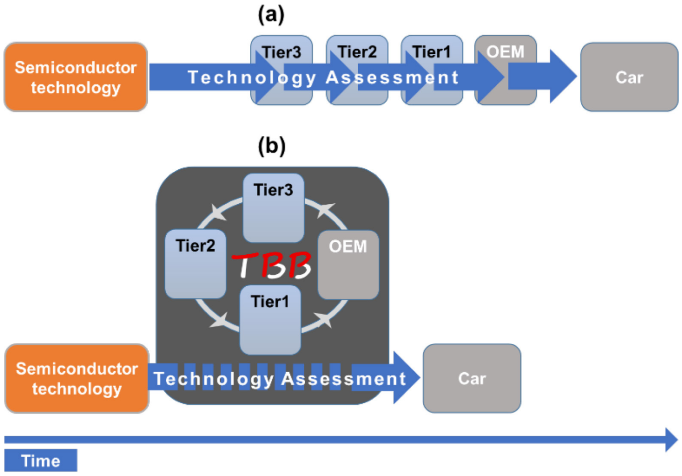

Fig. 1: Comparison of technology assessment without (a) and with (b) using the TBB. The expected time reduction is clearly visible

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To satisfy the needs of each actor of the automotive value chain the output of TBB are adjusted with different levels of information.

As seen in Fig. 1 TBB serves as a central tool and assesses reliability on the wafer level based on failure mechanisms. This is done according to defined criteria of physical models and characteristic parameters of the respective technology. The TBB analyzes the technology and shows the limiting aspects dependent on the defined lifetime requirements.

The TBB has been developed within the autoSWIFT project [9] for automotive applications. Nevertheless the TBB tool can be exploited for all other semiconductor applications, such as consumer, military/space industry.

II. THE KEY FEATURES OF THE TBB

At the moment, it is only one model for each failure mechanism considered and implemented in the TBB construction. All implemented failure mechanisms and models of the TBB are summarized in table 1. To demonstrate the working principle, the TBB currently focuses only on the intrinsic failure mechanisms of the CMOS technology, namely: Time Dependent Dielectric Breakdown (TDDB), Bias Temperature Instability (BTI) and Hot-Carrier Injection (HCI) for the Front End of Line (FEoL), ElectroMigration (EM) and TDDB for the Back End of Line (BEoL). More details of the models are explained in Refs of [5] and [6].

TABLE 1

FAILURE MECHANISMS AND MODELS IN THE TBB

	Failure mechanism	Voltage/Current acceleration model
FEoL	TDDB	Power law model
	BTI	Power law model
	HCI	Power law model
BEoL	EM	Black's model
	TDDB	Square-root-E-model

It is possible to implement more failure mechanisms and models in the next version of TBB in order to cover more critical mechanisms for CMOS semiconductor technology or other technologies such SiC, carbon nanotubes and new devices such as Tunneling Field Effect Transistors (TFETs), SOI and FINFETs. That means: Depending on the models other technologies can be evaluated with the TBB, too.

To demonstrate the idea and benefits, the concept of the TBB is programmed within a widely common software. Therewith, it is comfortable to change a parameter or to integrate a new model or add other failure mechanisms already in the current version. For the future application of the TBB, it will be preferred to program the TBB concept in a higher programming language. With that, it will be easier to use the TBB in all levels of the supply chain.

Fig. 3 presents basic input and output of the TBB software. In the TBB input area it is possible to consider specific design requirements (it can be called as technology requirements too) as Ac/Dc factor for each failure mechanism, specific devices dimensions (depending on the Failure mechanism and device type), targets and criteria. All of those design requirements are presented in orange block in the Fig. 3.

The mission profile belongs to the TBB input too. A simple example of a MP, to which the technology has to match, can be found in the "Handbook for Robustness Validation of Semiconductor Devices in Automotive Applications" from German Electrical and Electronic Manufacturers' Association (ZVEI), this is presented in Fig. 2.

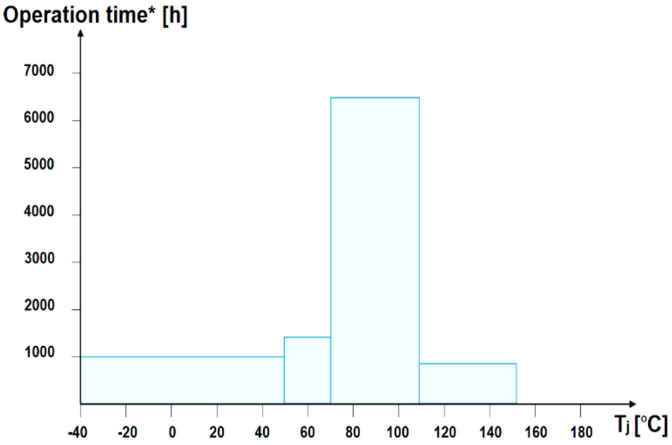


Fig. 2: Temperature mission profile [10]

In this example the distribution of temperature stress over the device lifetime (e.g. MP) is shown in Fig. 2. A conservative approach for a failure mechanism associated with high temperature would link each bin to its maximum temperature. In this case this would result in the values given in table 2.

TABLE 2

MISSION PROFILE EXAMPLE [10]

Duration (h)	**Percentage (%)**	**T_j component (°C)**
1000	10	48
1600	16	71
6500	65	108
890	9	150

However, in industry, only the effective MP has been used as equivalent to the daily MP which has been proven correct by our work. For the first time in reliability calculations, it is proven that a classified MP can be reduced to an effective stressor level and stressor time [4]. It has been shown that both input types produce the same result. Therefore, the stressors in the TBB can be entered either as an effective MP (only one value for 100 % of the whole operating time and the others 0 % of the whole operating time) or as a classified MP.

For a quick overview, the output of the TBB is integrated in traffic light form. Colors red, yellow and green indicate fail, marginality and pass. It is also possible to reflect more details, like the calculated life times, in the output or to customize it depending on a specific device or technology. Fig. 3 shows the concept of the TBB and its component: the input (the MP and the technology requirements), the technology card and the output (traffic light form).

TBB serves as a central tool and assesses reliability on the wafer level based on failure mechanisms. This is done according to defined criteria of physical models and characteristic parameters of the respective technology. The TBB analyzes the technology and shows the limiting aspects dependent on the defined lifetime requirements.

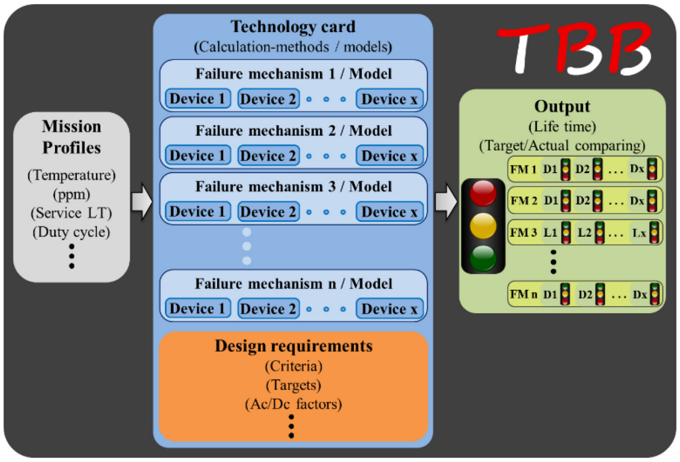


Fig. 3: Scheme of the TBB; in the output block D means “device” and FM means “failure mechanism” (for details see text).

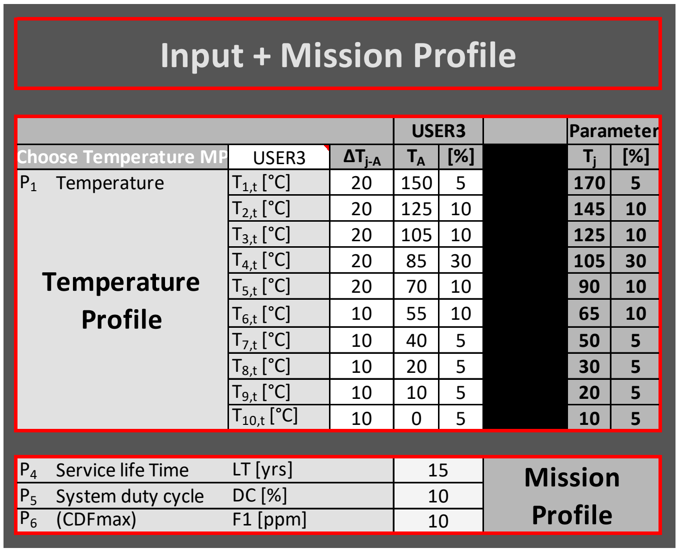
III. FUNCTIONALITY AND STRUCTURE OF THE TBB

In this chapter is following the actual representation of TBB to the user.

A. *Input area of the TBB*

The first step of using the TBB is the definition of the proposed mission profiles. This enables the possibility for all partners in the supply chain to communicate their requirements for future products from beginning of technology and product development. An additional advantage is achieved, because all partners can start nearly simultaneously with the development of their own products. In the MP, the temperature or temperature histogram, the voltage or voltage histogram, the desired lifetime, system duty cycle and the maximum allowed failure rate can be included. For example, according to internal company standard VW 80000: 2013-06 (LV 124) table 47 [2], the requirements are specified as follows: The service life is 15 years, the service lifetime is 8000 h and the mileage is 300,000 km. Figure 4 shows the structure of the input area including the MP input area. It shows the ability to enter the stressors in the TBB either as an effective MP (only one value for 100 % of the whole operating time and the others as 0 %) or as a classified MP.

The lower part of the input area in Fig. 4 describes the other system requirements, like the service life time, system duty cycle and the maximum allowed failure rate of the components.



Input + Mission Profile

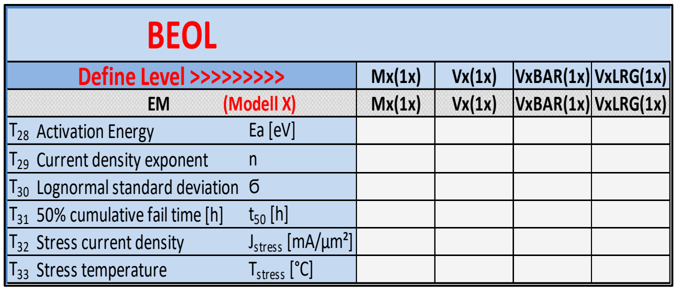
			USER3			Parameter	
Choose Temperature MP	USER3	$\Delta T_{j\text{-}A}$	T_A	[%]		T_j	[%]
P_1 Temperature	$T_{1,t}$ [°C]	20	150	5		**170**	**5**
	$T_{2,t}$ [°C]	20	125	10		**145**	**10**
	$T_{3,t}$ [°C]	20	105	10		**125**	**10**
	$T_{4,t}$ [°C]	20	85	30		**105**	**30**
Temperature Profile	$T_{5,t}$ [°C]	20	70	10		**90**	**10**
	$T_{6,t}$ [°C]	10	55	10		**65**	**10**
	$T_{7,t}$ [°C]	10	40	5		**50**	**5**
	$T_{8,t}$ [°C]	10	20	5		**30**	**5**
	$T_{9,t}$ [°C]	10	10	5		**20**	**5**
	$T_{10,t}$ [°C]	10	0	5		**10**	**5**

P_4 Service life Time	LT [yrs]	15	**Mission Profile**
P_5 System duty cycle	DC [%]	10	
P_6 (CDFmax)	F1 [ppm]	10	

Fig. 4: The input area of the TBB containing the MP and the service life requirements. Specifically, T_A is the ambient temperature at the Power Control Unit (PCU) and T_J is the junction temperature and $\Delta T_{J\text{-}A}$ is the temperature difference between them.

B. *Technology card*

At this point, the technology data must be taken into account. In particular, the technology card of a specific technology contains the failure models and their technological parameters. So it is necessary to adapt the models and their parameters together with their associated technological requirement. These data in the technology card will be filled by the technology manufacturer (e.g. tier 3). Depending on the IP-status within the supply chain from tier 3 to OEM, these data may be disclosed or just the final overall result (see next section) may be delivered. Usually the technology input parameters are not disclosed and also later through the development the exact model equation or output values, therefore all these data and models stay hidden (therefore “Black Box”) in the TBB.



BEOL

Define Level >>>>>>>>>		Mx(1x)	Vx(1x)	VxBAR(1x)	VxLRG(1x)
EM	(Modell X)	Mx(1x)	Vx(1x)	VxBAR(1x)	VxLRG(1x)
T_{28} Activation Energy	Ea [eV]				
T_{29} Current density exponent	n				
T_{30} Lognormal standard deviation	б				
T_{31} 50% cumulative fail time [h]	t_{50} [h]				
T_{32} Stress current density	J_{stress} [mA/µm²]				
T_{33} Stress temperature	T_{stress} [°C]				

Fig. 5: An example of electromigration model in TBB technology card. M_x, V_x…, are different line/via test structures.

An example of the technology card can be seen in Fig. 5, which refers to electromigration failure mechanism in BEoL. As mentioned in table 1, the Black's acceleration model for electromigration [7] is used in the TBB to calculate the Median Time To Fail MTTF defined as

$$\mathrm{MTTF} = A \cdot J_{\mathrm{stress}}{}^{-n} \cdot EXP\left(\frac{E_{\mathrm{a}}}{k_{\mathrm{b}} \cdot T}\right) \tag{1}$$

where, A is constant, n is the current density exponent, J_{stress} is the stress current density, E_a is the activation energy for metal diffusion, k_b is Boltzmann constant and T is the interconnect temperature.

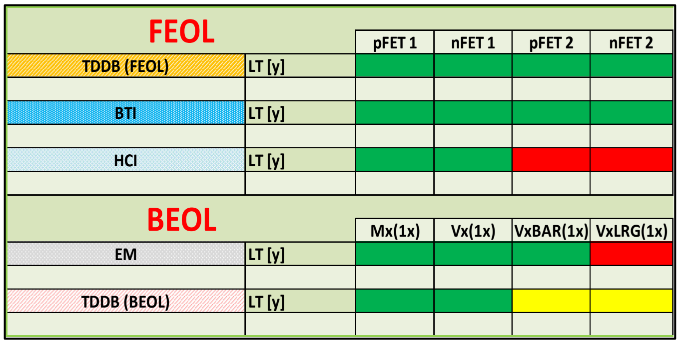
The maximum allowable operating current density J_{use} for a given interconnect may be calculated for example as done by Li [8]:

$$J_{\mathrm{use}} = J_{\mathrm{stress}} \cdot \left(\frac{t_{50}}{t_{\mathrm{EOL}}}\right)^{\left(\frac{1}{n}\right)} \cdot \exp\left[\frac{E_{\mathrm{g}}}{n \cdot k_{\mathrm{b}}}\left(\frac{1}{T_{\mathrm{use}}} - \frac{1}{T_{\mathrm{stress}}}\right)\right] \tag{2}$$

where J_{stress} is the stress current density, T_{stress} the stress temperature, T_{use} the operating temperature, n, k_{b} and E_{a} have the same meaning as in the equation (1) and T_{50} is the 50 % cumulative fail time at stress condition. It should be mentioned that the presented basic equation is usually modified by the technology card owner (e.g. tier 3) for their purposes (and may be subject to IP-protection).

C. Output area of the TBB

The final component of the TBB concept is the comparison of the values calculated by the models for each failure mechanism with the respect to the associated requirements criteria. These calculated values may be lifetime, voltage shift, current deviation or other quantities. In the case of electromigration for example, we have calculated the devices lifetime depending on the equation 1. Fig. 6 presents an example of the traffic light output for a specified use case. The output should be implemented with different degrees of detail depending on the level of engagement with tier (1 … n) or customer.



FEOL		pFET 1	nFET 1	pFET 2	nFET 2
TDDB (FEOL)	LT [y]	🟩	🟩	🟩	🟩
BTI	LT [y]	🟩	🟩	🟩	🟩
HCI	LT [y]	🟩	🟩	🟥	🟥
BEOL		Mx(1x)	Vx(1x)	VxBAR(1x)	VxLRG(1x)
EM	LT [y]	🟩	🟩	🟩	🟥
TDDB (BEOL)	LT [y]	🟩	🟩	🟨	🟨

Fig. 6: An example output of TBB (based on fictive technology parameters).

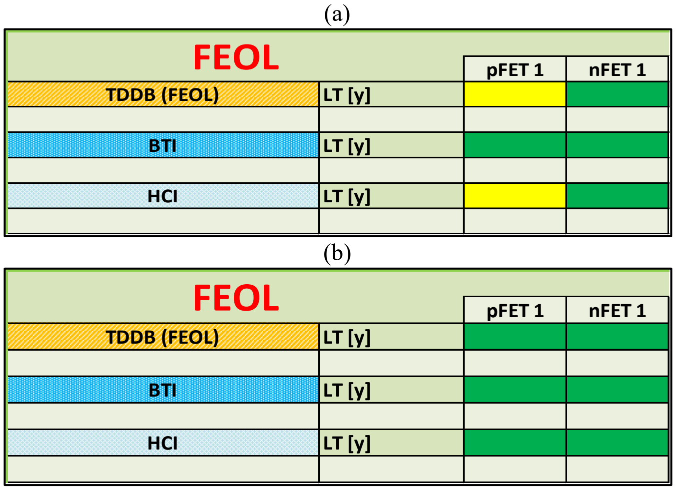
IV. EXAMPLES OF THE TBB FUNCTIONALITY

In this section, two examples of TBB usage are presented. The goal being in the first case to assess a mature technology against different MPs, while in the second case to help improving the maturity of a technology in development, through fast assessment against a defined MP.

A. Example of reliability evaluation against different automotive grades

In the first example, we compare two MPs which correspond to the AEC-Q100 grade 1 and AEC-Q100 grade 3 requirements (of the High Temperature Operating Life (HTOL)). That means, maximum ambient temperatures of 125 °C and 85 °C, respectively, are considered at a Power Control Unit (PCU) [1], while the temperature shift from ambient temperature at the PCU to junction temperature is set to 20 °C (see fig. 4, $\Delta T_{J\text{-}A}$).

At the same time, the maximum allowed failure rate is fixed at 10 ppm. The lifetime of the components will be calculated on the basis of a system lifetime of 15 years (standard system requirements of OEMs) and a duty cycle of 10 %. The TBB calculates the lifetime for both AEC-Q100 grades with the same model and parameters, which are based on 28SLP GLOBALFOUNDRIES data.



(a)

FEOL		pFET 1	nFET 1
TDDB (FEOL)	LT [y]	🟨	🟩
BTI	LT [y]	🟩	🟩
HCI	LT [y]	🟨	🟩

(b)

FEOL		pFET 1	nFET 1
TDDB (FEOL)	LT [y]	🟩	🟩
BTI	LT [y]	🟩	🟩
HCI	LT [y]	🟩	🟩

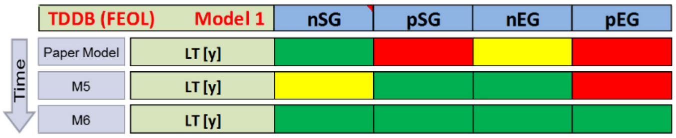
Fig. 7: Output of TBB for (a) AEC-Q Grade 1 (b) AEC-Q grade 3.

The TBB allows to compare reliability projections from a measured AEC-Q100 grade 3 (at $T = 85$ °C) to a proposed AEC-Q100 grade 1 (at $T = 125$ °C). It is shown in Fig. 7 that the output changes accordingly to the criteria and the AEC-Q100 grades conditions.

In Fig. 7, we demonstrate the two device types, pFET and nFET, only for illustration purposes. In Fig.6 (a), it can be seen that the pFET 1 device has a marginal pass versus AEC-Q100 Grade 1 requirements regarding the TDDB and HCI failure mechanisms. While against the conditions of AEC-Q100 grade 3, the devices show a "robust" pass (see Fig. 7 (b)).

B. Example of reliability changes during product development

In the second example, the life time of the devices is calculated at three different milestones of the 22FDX technology of GLOBALFOUNDRIES starting from the paper model stage till to the finished qualification. For the calculations, the same MP is considered for all milestones. That means, the ambient temperature at the PCU, the temperature shift, the maximum allowed failure rate, the expected system lifetime and the system duty cycle are fixed requirements during the technology development. On the other hand the technology cards are evolving from one milestone to the next one, because the technology itself grows in maturity and becomes more and more robust against automotive specifications. The first TBB calculation is carried out on paper model, where technology parameters are theoretical values, e.g. from the design manual, or derived from data of previous technology node. At milestone M5, the process is frozen and the technology parameters are measured values from test chips. Finally, a TBB calculation is carried out at M6, where the technology qualification is done and at this point the production can be started. In Fig. 8, the output of the TBB for TDDB (FEoL) at three different technology milestones is shown. It can be clearly seen how the technology robustness is improving with respect to the milestones (i.e. technology maturity), based on the results from lifetime calculation.



TDDB (FEOL)	Model 1	nSG	pSG	nEG	pEG
Paper Model	LT [y]	🟩	🟥	🟨	🟥
M5	LT [y]	🟨	🟩	🟩	🟥
M6	LT [y]	🟩	🟩	🟩	🟩

Fig. 8: Output of the TBB for TDDB (FEoL) at three different technology milestones and the fulfillment of specifications on the different devices at the end of the technology development phase.

V. CONCLUSION

We have presented a new tool – called the Technology Black Box (TBB) - for the development & assessment of semiconductor technologies with respect to custom-based automotive specifications. TBB allows to discriminate the dominant failure mechanisms within a specific technology, thus it allows to improve the technology, if still under development, saving time through a direct comparison of custom-based requirements along the automotive value chain. Through the clear definition of MPs, the TBB enables the possibility for all partners in the supply chain to communicate their requirements for future products, already at the beginning of their development. And technology manufacturers on their own side can amend the technology toward requirement compliance.

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