Experimental Characterization of Electromigration-Induced Stress Evolution in a 22nm-Technology

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***Abstract*—Electromigration research has experienced a paradigm shift within the last years, moving from conventional current-density verification to physics-based modeling to measure for EM robustness. However, the new models lack practical validation and established methods to experimentally characterize the modeling parameters. In this work, we analyze existing characterization schemes and propose a novel and simplified approach to experimentally obtain the EM parameters for physics-based modeling. We validate both our new method and a previously published interpolation method with experimental lifetime data for 80 nm-pitch Cu(Mn) metallization using GlobalFoundries 22FDX® FDSOI (fully depleted silicon-on-insulator) technology.**

***Index Terms*—electromigration, experimental characterization, Korhonen model, physics-based modeling, stress, interconnect lifetime**

I. INTRODUCTION

Electromigration (EM) is a well-known reliability phenomenon in integrated circuits (ICs). Driven by high current density and accelerated by high temperature, it causes interconnect degradation and, thus, potential circuit failure.

In standard process design kits (PDKs), EM robustness is ensured by current-density limits. However, in the last decade, research has showed that the underlying models are pessimistic and, hence, the design freedom is unnecessarily constrained.

Novel physics-based models that apply hydrostatic stress as a measure for EM robustness (instead of current-density) promise more precise EM verification. Specifically, they avoid over-designs and are capable to evaluate local EM risks. Hence, global current-density limits can be replaced by local constraints and moreover, targeted EM countermeasures can efficiently be implemented in the layout.

Unfortunately, these novel models have not yet been included into the IC design flow. There are several obstacles toward their use in IC design, including the lack of commercial verification tools facilitating physics-based EM simulation. In order to apply physics-based modeling in practice, two prerequisites have to be fulfilled:

- The modeling parameters (i. e., material properties) have to be known and
- the models need to be validated and tested for their reliability and limitations.

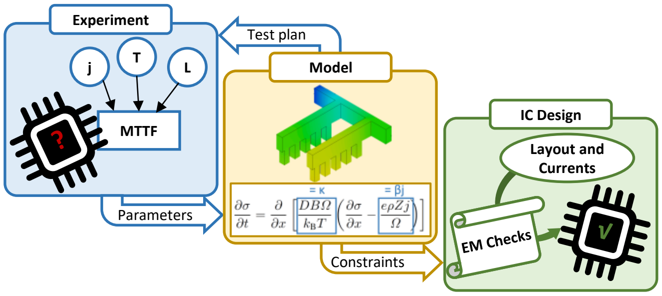

Fig. 1. Enabling reliable electromigration modeling and subsequent verification rely on thorough experimental technology characterization. The resulting material parameters can then be applied in the models to derive constraints for IC design and verification. In this work, we focus on the experimental parameter characterization for physics-based models, including the test plan and parameter derivation (marked in blue).

Finding the modeling parameters (Fig. 1) is a task that has been addressed in recent publications. Specifically, [1] proposes a method leveraging TEM imaging for EM parameter derivation and provides experimental validation. The approach introduced in [2] relies on standard lifetime testing with an extended set of test structures. However, it does not include experimental data and results.

Both methods exceed the experimental effort currently invested in EM characterization. Such an extensive EM characterization might challenge lab capacity and time schedules for technology qualification. Ideally, EM characterization for physics-based modeling should cause the fabs no extra effort.

This is where our work comes in. We aim to significantly improve experimental EM parameter characterization by focusing on time and effort as well as by providing lifetime data for model validation. With this approach, our work aims to overcome one of the major obstacles that have thus far hindered the application of physics-based models in practical IC design flows.

Our main contributions are:

- A facilitated method to derive EM modeling parameters from standard lifetime tests using the test structures and routines already in place for most technologies and
- experimental validation and discussion of both our new facilitated method and the recently published interpolation method [2].

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II. State of the Art

A. Electromigration Modeling

There are three important models to quantify EM: The Black equation [3], the Blech criterion [4], and the Korhonen equation [5]. In this section, we will introduce them and show their purpose, strengths, and disadvantages.

We will use the following symbols: L is the line length, j is the current density, σ is the stress, σ_{crit} is the critical stress for failure, t is the time, t_{50} is the median time to failure, x is the location on the interconnect, $\varOmega$ is the atomic volume, e is the elementary charge, ρ is the specific resistivity, Z is the effective charge number, B is the Bulk modulus, $D = D_0 \cdot \exp\left(-E_{\text{a}}/\left(k_{\text{B}}T\right)\right)$ is the diffusivity with D_0 being the diffusion constant, E_{a} the activation energy, k_{B} the Boltzmann constant, and T the temperature.

The industry standard to ensure EM robustness is current-density verification which is based on the empirical Black equation [3]

$$t_{50} = Aj^{-n} \cdot \exp\left(-\frac{E_{\text{a}}}{kT}\right). \tag{1}$$

This equation is based on lifetime measurements of long single-segment wires that are used to fit the empirical scaling parameters A and n. The Black model is used to derive global current-density limits that must not be exceeded at any location of an interconnect. The current-density limits based on the Black equation represent a worst-case assumption ensuring EM lifetime in any case and regardless of interconnect geometry, topology, and local current densities. This disadvantage of setting unnecessarily strict EM constraints comes with the benefit of a very simple and safe EM verification where the design has to be checked for just one global current-density limit.

Some technologies offer relaxed current-density limits for wires not exceeding a specified length limit. These short-length constraints are based on the Blech equation [4] and the concept of interconnect immortality. The Blech equation is given by

$$jL_{\text{Blech}} = \frac{\Delta\sigma \cdot \varOmega}{e\rho Z} = \frac{2 \cdot \sigma_{\text{crit}}}{\beta} \tag{2}$$

with

$$\beta = e\rho Z/\varOmega. \tag{3}$$

It describes the equilibrium of EM and stress migration (SM) in a single-segment finite wire where the stress reaches a steady state and does not grow any further (as shown in Fig. 2). If the maximum stress in the steady-state case does not exceed the critical stress, the wire can be classified as *immortal*; it will not fail due to EM. This applies to wires where the product of length and current density is lower than the technology-specific critical Blech product jL_{Blech} which is experimentally characterized for many semiconductor technologies.

Even if the steady-state stress exceeds the critical stress, the interconnect is not necessarily EM violated. Transient analysis is used to find the time when the critical stress is reached (cf. Fig. 2). This is usually understood as the lifetime of the wire[1]. As long as the lifetime of the interconnect is longer than the specified lifetime of the chip, the interconnect can be treated as EM robust because it will not fail during operation.

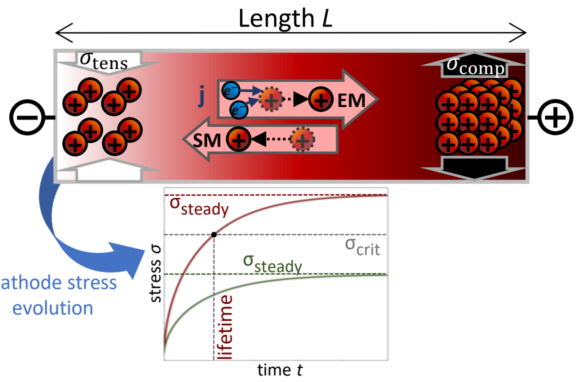

Fig. 2. Principle of migration-induced stress evolution and interconnect failure [6], [7]. Instead of applying current-density values to evaluate EM reliability, these new physics-based models uses hydrostatic stress built up by EM to evaluate the lifetime of an interconnect.

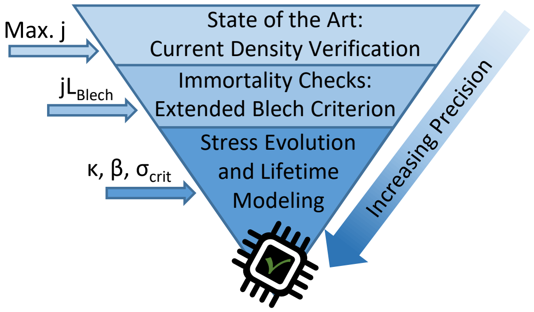

Fig. 3. Scheme of a three-stage EM verification to filter what interconnects have to undergo more complex verification steps in order to achieve a more precise EM verification. The third and last stage requires EM parameters that are not yet characterized by the fabs.

This transient stress modeling, which is the foundation of the new physics-based models (Fig. 2), is enabled by the Korhonen equation [5]. It describes stress evolution in a finite single-segment line with boundary conditions (BCs) as

$$\frac{\partial\sigma}{\partial t} = \frac{\partial}{\partial x}\left[\kappa\left(\frac{\partial\sigma}{\partial x} - \beta j\right)\right], \quad \text{BCs:} \quad \left.\frac{\partial\sigma}{\partial x}\right|_{x=0,L} = \beta j \tag{4}$$

with:

$$\kappa = DB\varOmega/k_{\text{B}}T. \tag{5}$$

The parameters κ and β as well as the critical stress σ_{crit} are technology-specific and, to our knowledge, not yet characterized for semiconductor technologies.

Both the Blech method and the Korhonen method have been extended to general multi-segment interconnects [8], [9].

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[1] This simplification neglects the phase of void growth until the wire resistance is critically increased. However, the void growth phase is short compared to the time until the critical stress is reached. In this work, we apply this common simplification. Still, it can cause errors and must be further evaluated in the future.

To minimize computation-intensive verification effort, it is often proposed to apply a three-stage verification scheme as shown in Fig. 3. Only interconnects that fail a step have to be considered in the following (more complex) stages of EM verification.

While the first two stages rely on established EM parameters, the third stage demands additional technological information, which has proven difficult to obtain. Developing a novel, time- and effort-efficient approach to acquiring this information is the central focus of this paper as outlined next.

B. Interpolation Method for Experimental Parameter Characterization

In [2], a method has been proposed to experimentally characterize the material parameters κ and $\sigma_{\text{crit}}/\beta$. It reduces the numerous technology parameters of the Korhonen equation (4) to only these two which are sufficient to perform physics-based EM modeling. By this simplification, the method enables deriving the parameters from standard EM lifetime tests.

It exploits the solution of the Korhonen equation for finite lines as given in [5]:

$$\sigma(x,t) = \beta j L\Bigg(0.5 - \frac{x}{L} - 4\sum_{m=0}^{\infty}\frac{\cos((2m\pi+\pi)\frac{x}{L})}{(2m\pi+\pi)^2\exp\left((2m\pi+\pi)^2\kappa\frac{t}{L^2}\right)}\Bigg). \quad (6)$$

In a finite line, the stress profile grows symmetrically and the maximum stress will be reached first at the two ends of the wire (anode and cathode). As a reasonable simplification, [2] expects the stress at the cathode of the wire to equal the critical stress in the moment of failure. Thus, $\sigma(x=0, t_{\text{life}}) = \sigma_{\text{crit}}$. Substituting this into Eq. (6), and solving for jL results in

$$jL = \frac{\sigma_{\text{crit}}}{\beta}\left(0.5 - 4\sum_{m=0}^{\infty}\frac{\exp\left(-(2m\pi+\pi)^2\kappa\frac{t_{\text{life}}}{L^2}\right)}{(2m\pi+\pi)^2}\right)^{-1}. \quad (7)$$

This method relies on the length dependency of the lifetime that can be observed in medium-length wires. *Medium-length* means that

- the wire is short enough to benefit from back stress and
- the wire is long enough to exceed the Blech product and, thus, is mortal.

These two criteria are dependent on current density: Wires stressed with higher current density need to be shorter in order to be classified as *medium-length*.

Stressing a set of medium-length wires with multiple current densities results in lifetime data depending on both length and current density $t_{\text{life}}(L, j)$. Writing these data points as $(t_{\text{life}}/L^2, jL)$, we can now use Eq. (7) for curve fitting. In order to do that, the infinite sum in Eq. (7) has to be terminated, [2] suggests termination at $m = 1$.

In [2], this method has only been demonstrated using FEM simulation data.

III. FACILITATED PARAMETER CHARACTERIZATION

The interpolation method for characterizing the parameters κ and $\sigma_{\text{crit}}/\beta$ presented in [2] and described in the previous Section II-B has been designed for low experimental effort and relies on standard EM tests. However, it still requires more test structures and lab capacity than today's standard procedure to find the parameters for the Black equation (1) and the critical Blech product jL_{Blech} (2). Moreover, the termination of the infinite sum in Eq. (7) necessarily introduced an error that varies in size depending on the material parameters and can thus impact the precision of the results.

Hence, we further improved it to reduce that effort. This facilitated approach for EM parameter characterization relies on two parameters that are already known for most semiconductor technologies:

- The lifetime of a long wire at a certain current density, and
- the Blech product jL_{Blech}.

A. Obtaining the Parameter $\sigma_{\text{crit}}/\beta$

Though the Blech product is not characterized for all technologies and only sometimes provided in the PDK, there are well-known and established techniques on how to obtain it from short-length lifetime measurements [10], [11].

The Blech equation (2) can be applied to calculate the first of the two necessary EM parameters $\sigma_{\text{crit}}/\beta$ from the Blech product:

$$jL_{\text{Blech}} = \Delta\sigma \cdot \mathit{\Omega}/e\rho Z = 2 \cdot \sigma_{\text{crit}}/\beta \quad (8)$$

which results in:

$$\sigma_{\text{crit}}/\beta = jL_{\text{Blech}}/2. \quad (9)$$

B. Obtaining the Parameter κ

The second parameter, κ, can be derived from measurements that are usually used to find the parameters for the Black equation (1). In this case, long wires are tested, where the back-stress does not impact lifetime, anymore. Consequently, the lifetime of such wires is independent from their length. In the Korhonen model, this corresponds to the case where the stress growth does not reach the middle of the wire within the lifetime because the diffusion length is too short.

In this case, the solution of the Korhonen equation for finite lines equals the one for semi-infinite lines at the start of the line ($x = 0$). The solution for the semi-infinite line is given in [5] as

$$\sigma(x,t) = \beta j\left[\sqrt{4\kappa t/\pi}\cdot\exp\left(-x^2/4\kappa t\right) - x\cdot\text{erfc}\left(x/\sqrt{4\kappa t}\right)\right] \quad (10)$$

In the test line, the critical stress σ_{crit} will first be reached at the location $x = 0$ (the cathode end). The time when the critical stress is reached can be understood as the lifetime $t = t_{\text{life}}$. Substituting this into Eq. (10) yields a significantly simplified equation:

$$\sigma(0, t_{\text{life}}) = \sigma_{\text{crit}} = \beta j\sqrt{4\kappa t_{\text{life}}/\pi}. \quad (11)$$

TABLE I

NUMBER OF STRUCTURES PER TEST, APPLIED STRESS CONDITIONS, AND NUMBER OF FAILED DEVICES (IN BRACKETS) AT THE END OF THE EXPERIMENT.

	L [µm]				
j [mA/µm^2]	***15***	***25***	***30***	***35***	***200***
29.24		12 (6)	12 (9)	10 (10)	11 (9)
37.59		10 (9)	12 (12)	10 (10)	13 (13)
41.77	10 (1)	12 (12)			
50.13	10 (4)				

Consequently, κ can be calculated as:

$$\kappa = \frac{\pi}{4t_{\text{life}}} \left(\frac{\sigma_{\text{crit}}}{\beta j} \right)^2 . \tag{12}$$

where $\sigma_{\text{crit}}/\beta$ corresponds to the parameter derived from the Blech product in Sec. III-A.

IV. TEST SETUP FOR EXPERIMENTAL VALIDATION

Our test was performed at 80 nm-pitch Cu(Mn) metallization using GlobalFoundries 22FDX® FDSOI (fully depleted silicon-on-insulator) technology [12] with short line length of [15, 25, 30, 35] µm and long lines of 200 µm at current densities in the range of 30 to 50 mA/µm^2. We consider only upstream configurations. Measurements were conducted at an oven temperature of 300 °C. We do not consider temperature dependency in this experiment. To obtain the temperature dependency of the EM parameters, the experiment would have to be conducted at more than just one temperature which exceeded the available lab capacity.

Stressed with the above-mentioned current densities, most of the short-length test structures should exceed the critical Blech product but still benefit from back stress compared to the commonly tested long 200 µm-lines stressed at around 30 mA/µm^2. Still, we expect some test structure to be immortal. The failure criterion was set to a 10 % increase in line resistance. All test structured include an extrusion monitor. We applied four-terminal sensing.

Table I provides an overview over the structures that have been measured and what test conditions where applied. The number of structures per test varies due to initial failures and re-assembly. As the short-length structures have relatively long lifetimes and some test configurations are close to the immortality limit, we terminated the test after most structures have failed. Tests, where only one device has failed within the test time, we consider immortal. For all other structures, the derived mean time to failure will be discussed in the next section.

V. RESULTS AND DISCUSSION

A. Lifetime Experiment Results

Figure 4 shows the measured lifetimes of the samples in a probability plot. From the data, we derived a lognormal distribution (also shown in Fig. 4) which is used to obtain the mean time to failure t_{50} as given in Tab. II.

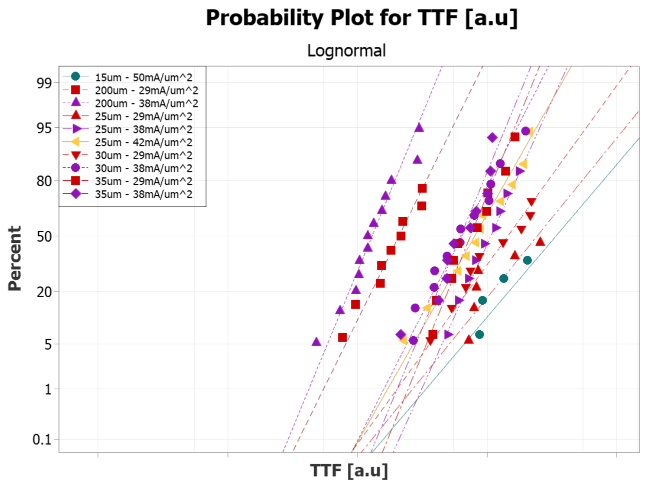

Fig. 4. Lifetime data obtained from the EM experiments. We show tests with more than one failed device within the duration of the experiment. The plot also shows the fitted lognormal distribution for each test.

TABLE II

LIFETIME EXPERIMENT RESULTS: WE PROVIDE THE MEDIAN TIME TO FAILURE T$_{50}$ [A.U.] AND THE STANDARD DEVIATION OF THE LOGNORMAL DISTRIBUTION.

	L [µm]				
j [mA/µm^2]	***15***	***25***	***30***	***35***	***200***
29.24		11.28 0.952	6.70 0.848	3.44 0.477	0.97 0.577
37.59		4.95 0.529	2.96 0.597	2.89 0.486	0.60 0.484
41.77	x	3.72 0.666			
50.13	15.77 0.995				

Qualitatively, the experiments show the expected results: Shorter wires stressed with lower current densities have a higher lifetime. The decrease in lifetime with growing length is steep for shorter wires and lower for longer wires. This represents the decreasing impact of back stress.

From the short-length data, we obtained the critical Blech product $jL_{\text{Blech}} = 6839$ A/cm as described in [10] and shown in Fig. 5.

B. Parameter Derivation Applying the Interpolation Method

We applied the interpolation method described in Sec. II-B to our short-length data in order to obtain the EM parameters κ and $\sigma_{\text{crit}}/\beta$. In contrast to the example in [2], we directly used the values of t_{50} as given in Tab. II and not the individual lifetime of each test structure. Thus, we better represent the lognormal distribution of the lifetime and also avoid errors due to the lower number of failed structures in some tests.

However, the results from the curve fit deviate strongly from the lifetime experiment data.

We were able to improve the interpolation by adding two more data points that represent “extreme” cases:

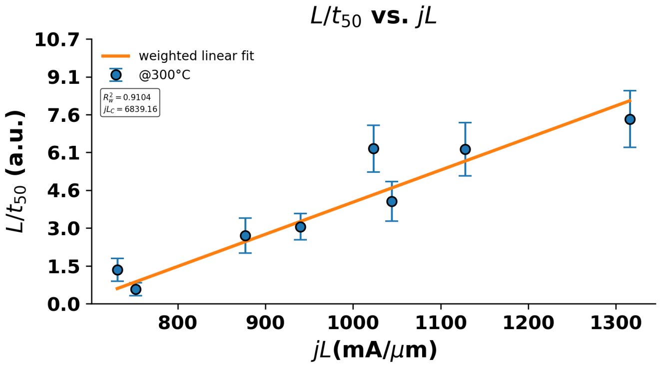

Fig. 5. Short-length data and linear fit to obtain the critical Blech product.

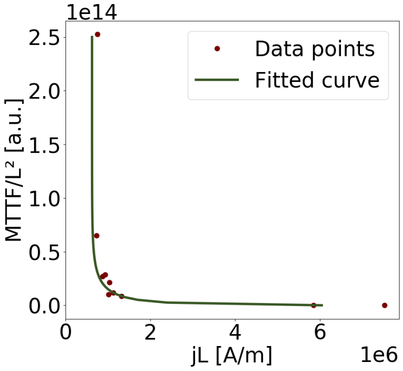

Fig. 6. Measurement data and fitted curve using the approach from [2].

TABLE III
SIMULATION RESULTS AND RELATIVE ERROR δ APPLYING THE PARAMETERS FROM THE INTERPOLATION METHOD [2]. WE PROVIDE THE MEDIAN TIME TO FAILURE T_{50} [A.U.].

	L [µm]				
j [mA/µm²]	***15***	***25***	***30***	***35***	***200***
29.24		5.90 (-48 %)	5.10 (-24 %)	4.91 (43 %)	4.84 (401 %)
37.59		3.02 (-39 %)	2.94 (0 %)	2.93 (1 %)	2.93 (389 %)
41.77	x	2.40 (-35 %)			
50.13	1.94 (-88 %)				

- A wire that is barely mortal and has a very high lifetime and
- a 200 µm line stressed with a current density of 29.24 mA/µm^2.

Specifically, we added the 15 µm wire with a current density 41.77 mA/µm^2 (corresponding to the immortal test structure from our experiment) with a very high lifetime and a 200 µm line stressed with a current density of 29.24 mA/µm^2 (corresponding to our measurement of long wires).

Stabilized with these two values, the interpolation yields EM parameters of $\kappa = 1.87 \cdot 10^{-11}$ m^2/a.u. and $\sigma_{\text{crit}}/\beta = 3137$ A/cm. The latter, according to Eq. (9), corresponds to a Blech product of $jL_{\text{Blech}} = 6274$ A/cm which is approximately 10 % lower than the Blech product obtained in Sec. V-A using the conventional method.

Figure 6 shows the experimentally obtained data points and the fitted curve. In Tab III, we provide the lifetime values, that the Korhonen model yields applying the EM parameters obtained from the interpolation. Also, we show the error compared to the experimental lifetime data. The error is calculated by

$$\delta = \frac{t_{\text{sim}} - t_{\text{exp}}}{t_{\text{exp}}} \cdot 100\,\%. \tag{13}$$

We observe a decent fit of the model with the short-length measurements. However, the model with the obtained parameters fails to calculate the lifetime of long wires. This leads to significant over-estimation of the lifetime which corresponds to an overly optimistic reliability assessment. Thus, EM violations might not be caught resulting in critical circuit degradation and possible failure.

C. Parameter Derivation Applying the Novel Facilitated Method

For our novel, facilitated approach, we obtain $\sigma_{\text{crit}}/\beta$ from the Blech product that has been derived in Sec. V-A from the short-length data using the conventional industry-standard method. Thus, applying Eq. (9), we find $\sigma_{\text{crit}}/\beta = 3420$ A/cm.

Furthermore, we calculate κ using Eq. (12). We use the 200 µm test structure from our experiment stressed with current densities of 29.24 mA/µm^2 and 37.59 mA/µm^2. While one data point would be enough, we calculate κ for both as this enables us to compare the results. Ideally, they would be identical.

This results in two very similar values: $\kappa = 1.11 \cdot 10^{-10}$ m^2/a.u. (for j = 29.24 mA/µm^2) and $\kappa = 1.09 \cdot 10^{-10}$ m^2/a.u. (for j = 37.59 mA/µm^2), which are both significantly higher than for the interpolation method.

Table IV shows the results for the lifetime that the Korhonen model yields using the EM parameters $\kappa = 1.11 \cdot 10^{-10}$ m^2/a.u. and $\sigma_{\text{crit}}/\beta = 3420$ A/cm. We can observe that the model significantly underestimates the short-length lifetime. Though, compared to the results in Sec. V-B, this is less critical for reliability assessment as this correspond to an overly pessimistic verification, it is still evident, that the Korhonen model fails to correctly predict lifetimes.

D. Comparison of the Parameter Derivation Applying the Interpolation Method and the Facilitated Method

From our results, we can observe that both of the methods find the parameter $\sigma_{\text{crit}}/\beta$ within the same order of magnitude with only a minor deviation. However, we observe a difference of about one order of magnitude in the parameter κ obtained with both approaches. While the parameters found with the interpolation method are more suitable to represent the short-length lifetime data, our novel facilitated approach better represents the lifetime of long wires and conservatively assesses

TABLE IV

SIMULATION RESULTS AND RELATIVE ERROR δ APPLYING THE PARAMETERS FROM THE NEW FACILITATED METHOD PROPOSED IN THIS PAPER. WE PROVIDE THE MEDIAN TIME TO FAILURE T_{50} [A.U.].

	L [µm]				
j [mA/µm^2]	***15***	***25***	***30***	***35***	***200***
29.24		1.45 (-87 %)	1.07 (-84 %)	1.00 (-71 %)	0.97 (0 %)
37.59		0.62 (-87 %)	0.60 (-80 %)	0.59 (-80 %)	0.59 (-2 %)
41.77	x	0.49 (-87 %)			
50.13	0.45 (-97 %)				

short interconnects. Both methods fail to predict all lifetime data with equal precision.

The interpolation method needs more data points and, thus, more test structures and lab capacity. In this work, the facilitated approach also benefits from this data for obtaining the Blech product. In standard tests, the jL product can be obtained using fewer data points.

Also, the interpolation relies on the truncation of the infinite sum, which may introduce errors. Our facilitated approach resolves this issue by directly applying the analytical equations.

In summary, our novel facilitated approach for obtaining the parameters for physics-based EM models requires lower experimental effort and is based on the exact analytical equations for EM. It relies on established lifetime measurement setups and evaluation. However, further experiments have to clarify, to what extend the Korhonen model alone is suitable to predict the lifetime of real interconnects as both our tested methods failed to predict interconnect lifetimes over a large range of lengths.

VI. SUMMARY AND CONCLUSION

We proposed a novel, facilitated approach to experimentally characterize the modeling parameters for physics-based EM verification. This approach is based on the analytical equations for stress evolution and the standard lifetime tests that are already performed in the fabs. Thus, our characterization method does not require additional experimental effort.

We validated both our novel approach and a previously published interpolation method using experimental lifetime data for interconnects with varying length and current density. The measurement data qualitatively fits the expected behavior. However, we found that while our facilitated method significantly underestimates the lifetime of short wires, the interpolation method fails to predict the lifetime of long wires.

We were not able to find a model parameter combination that correctly fits the Korhonen equation into the full set of measurement data. Thus, further experimental effort has to be invested in order to clarify the limitations of the one-dimensional Korhonen model and how it is able to represent migration mechanisms in real interconnects. Potential other failure mechanisms impacting lifetime have to be analyzed and included into the model. Also, the model's scalability over temperature, large ranges of current density and wire width, and in branched, multi-segment interconnects has to be studied in more detail.

Our work provides the basis for further experimental validation of the physics-based models. This will build trust and practical knowledge, hopefully paving the way toward their beneficial and successful application in IC design.

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