Validity of power cycling lifetime models for modules and extension to low temperature swings

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Keywords

Power cycling, Lifetime models, Elastic deformation, Plastic deformation

Abstract

Various papers in power electronics contain a part of lifetime estimation depending on power cycles in application. The used model is often the CIPS08 lifetime model published at the conference CIPS 2008. In many applications, a lot of cycles with low temperature swings occur. The used model, however, is only valid for temperature swings above 40 K. For temperature swings < 30 K, there are strong deviations, since some materials are now approaching the elastic region. First experimental power cycling results are gained below 30 K temperature swing. Also an approximation for the reliability of low temperature swing is given in this paper.

Introduction

Power electronic devices are exposed to high thermo-mechanical load in field. During operation, lateral and vertical temperature gradients evolve in the layers of the modules. It leads to expansion and deformation of each layer, especially due to the different coefficients of thermal expansion (CTE) of the involved materials. The resulting mechanical stress causes degradation in the interconnection interfaces, which finally leads to failure and to a limited lifetime in application. Bond wires and soldered interconnections were found to be weak points limiting the lifetime in application, which can be reproduced using the power cycling test.

The first large-scale research on power cycling capability of power module was the LESIT project [1]. It delivered a data base and an equation to calculate the lifetime of the that-time standard power modules: Base plate, soldered substrate with Al_2O_3 ceramics, soldered chip and aluminum wire bonding on top. The LESIT results have been widely used for power system designs in following. In 2008, an improved empirical model for the same type of packages was given with the CIPS08 equation, considering the meanwhile progress in technology, based on a large number of tests and containing more parameters [2]. With the application of power modules in motor drives for hybrid- and electric cars, the interest on power cycling lifetime of power modules is increasing.

The CIPS 2008 Model

Based on a large number of power cycling results of power modules, Bayerer et al. [2] derived the equation:

$$N_f = K \cdot \Delta T_j^{\beta 1} \cdot \exp\left(\frac{\beta 2}{T_{min}}\right) \cdot t_{on}^{\beta 3} \cdot I^{\beta 4} \cdot V^{\beta 5} \cdot D^{\beta 6} \quad (1)$$

N_f is the number of cycles to failure. The first term, the Coffin-Manson-term, describing the dependency on the temperature swing ΔT_j, as well as the second term, the Arrhenius term describing the dependency on the operation temperature are already contained in [1]. As parameter K the value $9.30 \cdot 10^{14}$ is given in [3]. The other parameters ß2 ... ß6 are given in Table I [2].
The parameters for a high-power DAB module were derived in [4] and are discussed in the section Results of this paper.

Table I. Parameters for calculation of power cycling capability according to Eq. (1)

	CIPS08 [2]	DAB module [4]
K	9.3E14	**5.65E14**
β_1	-4.416	**-4.1**
β_2	1285	1285
β_3	-0.463	**-0.484**
β_4	-0.716	-0.716
β_5	-0.761	-0.761
β_6	-0.5	-0.5

Equation (1), which is known as CIPS 08 model, contains additionally the dependence on the heat-up time t_{on} in seconds, the current per bond stitch on the chip I in A, the voltage range of the device V in V/100 (reflecting the impact of the semiconductor die thickness), and the bond wire diameter D in µm. The CIPS 08 model holds for standard power modules with Al_2O_3 substrates, it is not valid for high-power traction modules which are built with the AlN substrate and AlSiC baseplate.
Equation (1) was a result of purely statistical analysis and is not a result of physics-based models [2]. The paper has 328 citations in Scopus, however many of them do not consider the validity range of the parameters, despite it is mentioned: “As this is an empirical approach, the formula is limited to the test data range and cannot be used for extrapolation” [2]. The range for ΔT_j reaches from 43 K to 130 K, the range for ton from 1 s to 15 s. Since at 15 s the temperature profile in the module is assumed to be stationary, for t_{on} >15 s the value 15 should be used in Eq. (1). Nevertheless it is more often used outside the defined range (e.g. [5], [6]), these results have to undergo a critical review.
The Coffin-Manson-term in (1) describes crack propagation. It used in mechanical engineering for plastic deformation. It is well known that many materials have a transition from plastic to elastic deformation for low deformation amplitudes. In this point of view, a model from Hartmann et al. for bond wires was published [7] which contains a “cut-off line” for low temperature swings, where no lifetime is consumed by power cycles. The range for ΔTj reaches from 40 K to 75 K in the data used in [7].

Measurement delay time and delay time correction

At turn-off of I_{load} and the measurement of the temperature sensitive electrical parameter $V_j(T)$, there is the delay time t_d between turning-off the load current and the instant of measurement, as shown in Fig. 1. This delay time is necessary for several reasons. First, there can occur some ringing due to unavoidable parasitic inductances in the circuit, as to be seen in Fig. 1. Second, the measurement current source I_{sense} is exposed to a load leap if the voltage at its output changes from on-state voltage at high current to low measurement current. A current source I_{sense} with fast response behavior is necessary. Thirdly, what is less known: If a bipolar device is used, there is a necessary recovery time for the internal charge carriers.
The time delay t_d leads to a systematic measurement error ΔT_d. The cooling-down ΔT_d in this interval lies for Si devices in the range of 2 K for usual power density, and up to 4 K for modules with high power density and advanced cooling systems. For tests executed for the models [1] [2], this measurement

error was neglected. However, if the temperature swing range < 30 K is addressed, this is a significant error. A correction of this measurement error is possible with the square-root-t method [8]. It holds under

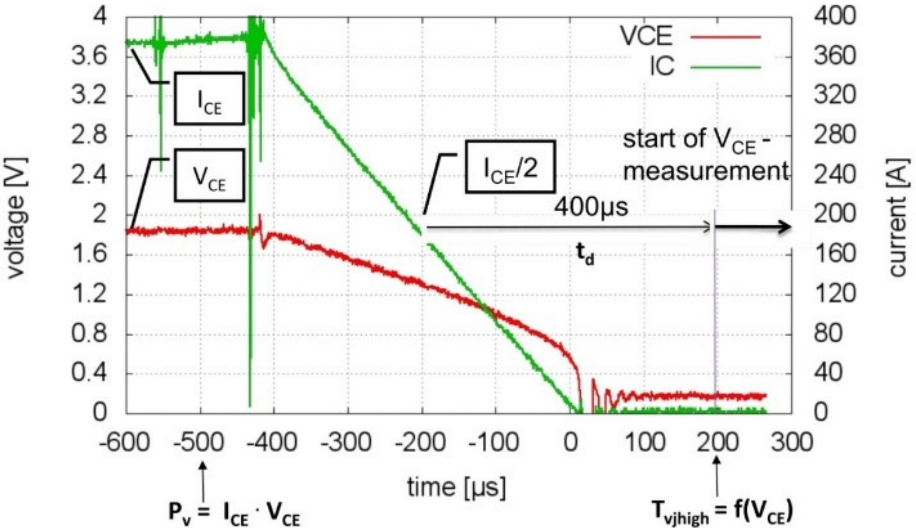

Fig. 1 Detail of measurements at turn-off of the load current with an IGBT. Fig. from [3]

boundary condition of a planar heat source at the surface of a semi-infinitely thick cylinder assuming one-dimensional heat flow. Since the heat source in SiC devices is in a narrow region close to the device surface, that method is found to hold for SiC devices with good accuracy [9]. However, for Si-IGBTs the use of the square-root-t method leads to a significant error, since there the heat generation is across the whole thickness of the device. For IGBTs, the correction can be done with thermal FEM simulation. It is possible to simulate only the layers close to the device, since during the short t_d they are dominating.

First results for short on-time and low temperature swings

A high-current power cycling test-bench for short load pulse duration was described in [10] and first results for a t_{on} time down to 10 ms were published in [4]. For low temperature swings, the short heating time is essential since a large number of cycles is expected. The devices under test were fabricated with copper-substrates DCB or with Al-substrates DAB.
Modules with DAB substrate have reached lower power cycling lifetime as the modules with the DCB substrate. However there are more differences in the packaging technology of these two tested modules. The difference in the substrate is not solely responsible for the difference in the power cycling lifetime. But several results were gained with the DAB based modules. It was found that for DAB the power cycling lifetime does not change anymore, if t_{on} is reduced from 40 ms to 20 ms or even smaller. A saturation of the t_{on}-dependency was found in the very small t_{on} range. The lifetime strongly increased below 30 K, if one approximates the region from plastic to elastic deformation. Results are summarized in Fig. 2.
There is a strong lifetime increase for T_{jmean} 100 K below ΔT 30 K. Three of 6 devices failed, 3 were still within the limits. The N_f is lower than predicted by the hyperbolic model in [7], and the Coffin-Manson exponent ß1 is approximated as -10.1. All failures are due to V_{CE} increase by bond wire lift-off. After the test with more than 500 Mio cycles, reported in [4], several parts of the test bench had to be renewed and the test with the 3 still functioning devices was continued up to $1.17 \cdot 10^9$ cycles (green circles in Fig. 2). No further device failed.

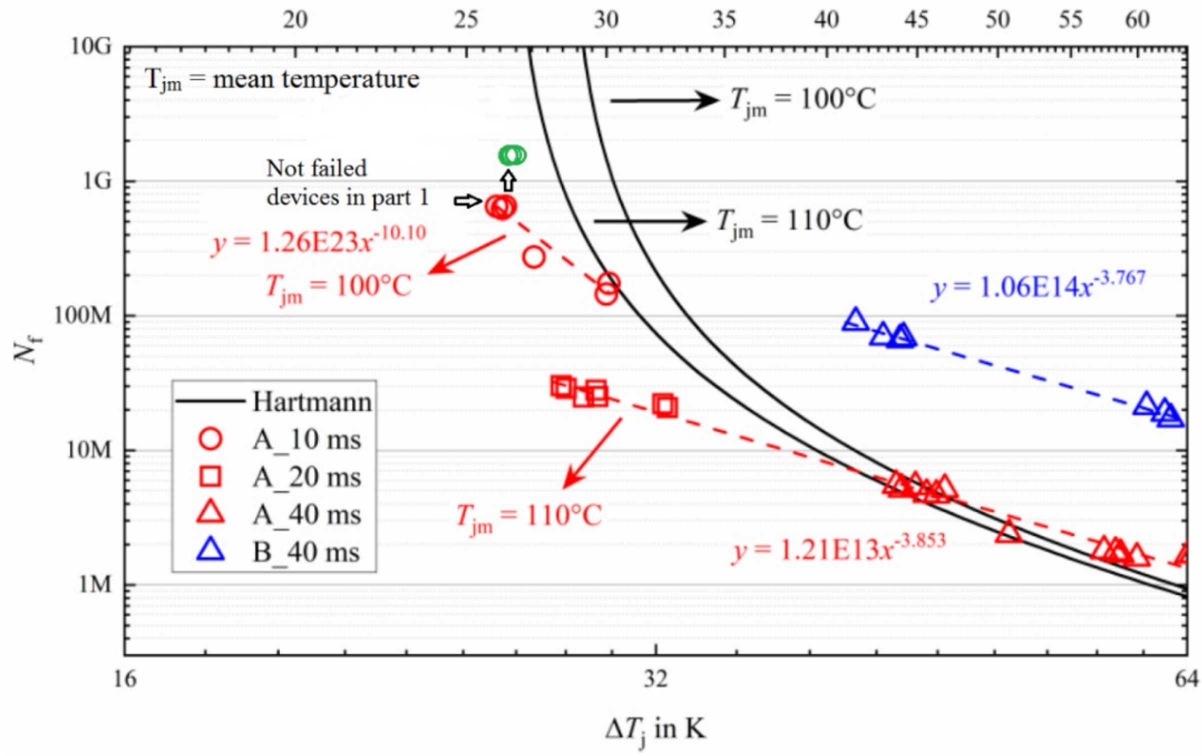

Fig. 2 Power cycling capability at low temperature swings, taken from [4]. Compared are results with DCB (B) and DAB (A) and the model of Hartmann [7], while $T_{jm} = T_{jmin} + \Delta T/2$. Not failed devices in part 1 [4] actualized (green circles)

Table II: Test conditions for continuation (t_{on} = 0,01 s, t_{off} = 0.02 s, T_{inlet} = 22 °C)

	ΔT_j in K	T_{jmin} in °C	P_V in W	I_L in A	ΔT_j in K (corr)	cycles	status
A_020_Sys2_D	23.7	80.4	2554	755	27,3	1,169,199,601	Not EOL
A_022_Sys3_D	23.2	76.6	2475	755	26,7	1,169,199,601	Not EOL
A_026_Sys1_D	26.0	105.4	2580	755	29,6	1,169,199,601	Not EOL

The failed modules (Fig.2) and the not failed were inspected regarding number of lifted-off bond wires and the adhesive force of the remaining bond wires. For the failed modules, 60.3 % were lifted-off, and the adhesive force of the remaining bond wires was in average 0.8 N. For the “Not EOL” modules the result is given in table III. For evaluation a self-constructed bond pull tester was designed (see Fig. 3). It is a force measuring equipment in a rack, to ensure vertical load. A hook is attached in the bond wire loop and pulled upwards. The remaining force of the bond interconnection is measured.

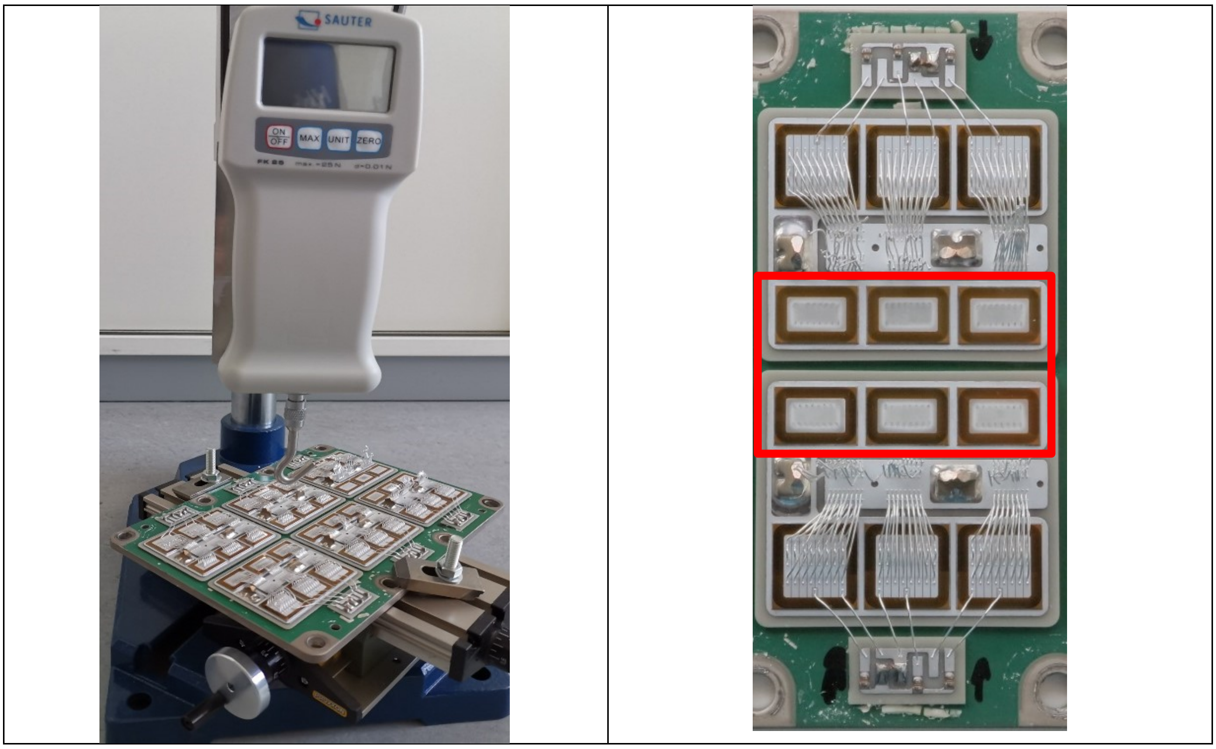

Fig. 3 Bond pull tester on the left and module scheme on the right with the 6 diode chips in the middle

D2_1

0,00	x	0,29	0,27	0,40	0,64	0,22	4,18
x	x	x	x	x	0,00	x	x

D2_2

2,10	1,62	x	0,90	1,11	1,51	1,45	0,88
0,00	0,00	0,00	x	x	x	x	x

D2_3

6,05	3,92	2,81	1,69	2,14	1,84	2,97	4,10
1,54	0,00	0,00	0,00	0,00	0,00	0,00	1,31

D2_4

1,06	0,00	x	0,00	0,00	0,13	0,67	4,39
2,42	1,78	1,50	1,31	0,99	1,74	2,61	6,13

D2_5

0,90	x	x	x	x	x	x	0,00
7,10	4,44	2,51	2,29	2,49	2,83	3,25	2,80

D2_6

0,11	x	0,00	x	x	x	x	0,64
1,86	1,56	1,13	1,31	0,58	1,13	1,64	2,44

Fig. 4 Example of bond pull forces in N for the 6 diode chips with color scheme from blue → lifted off during test to green → still good contact force

Table III: Evaluation of bond wires and estimation final EOL

	Lifted-off wires in %	Lifetime consumption for lift-off	adhesive force, average in N	Lifetime consumption adhesive force in %	Expected EOL in Gigacycles „worst-case“
A_020_Sys2_D	31.2	51.8	1.7	47.1	**2.26**
A_022_Sys3_D	32.2	53.6	1.1	72.7	**1.61**
A_026_Sys1_D	39.6	65.6	2.2	36.4	**1.79**

The expected lifetime in table III is calculated with the lower value of lifetime consumption from lifted wires and from adhesive force. The lifetime model Eq. (1) holds for standard DCB modules, for the DAB high-power modules a lifetime model was derived in [4]. The equation is the same, some parameters are different, and they are given in table I. They hold for $\Delta T_j > 43$ K.
With focus on the temperature swing the Coffin-Manson relation can be described as:

$$N_F \sim K' \cdot \Delta T_j^{\beta 1'} \qquad (2)$$

Considering the data in Fig. 2 and the estimated lifetimes for the remaining devices in table III, the parameter $\beta 1'$ can be approximated with the equation:

$$\beta 1' = e^{-\frac{\Delta T_j - 27{,}1\,K}{2{,}08\,K}} + \beta 1 \quad (3)$$

All other parameters for the DAB modules are used from table I. ß1' approximates to -4.1 for $\Delta T_j > 43K$. It was also considered that the t_{on}-influence saturates for $t_{on} < 0.04$ s [4] and therefore for 0.01 s in the experiment, the value of 0.04 s is used in Eq. (1).
The comparison of the Eq. (1) with the parameters for DAB modules table I and the extension for temperature swings below 30 K is given in Fig. 6. It becomes visible that soon a failure of one to two decades will occur if the original model of CIPS2008 [2] is used and the approximation to the elastic range is not considered.
With equation (3) and the CIPS08 model with the parameters for DAB module (see table I), it is possible to normalize the results and to do statistical analysis. Fig. 5 shows a Weibull plot for the experimental results. The confidence interval with the upper and lower percentile of 95 % of the probability distribution is quite large, due to the small amount of data points. The results are normalized to $T_{jmin} = 90$ °C and $\Delta T = 28$ K for the statistical analysis to allow a comparison between the cycles until failure.

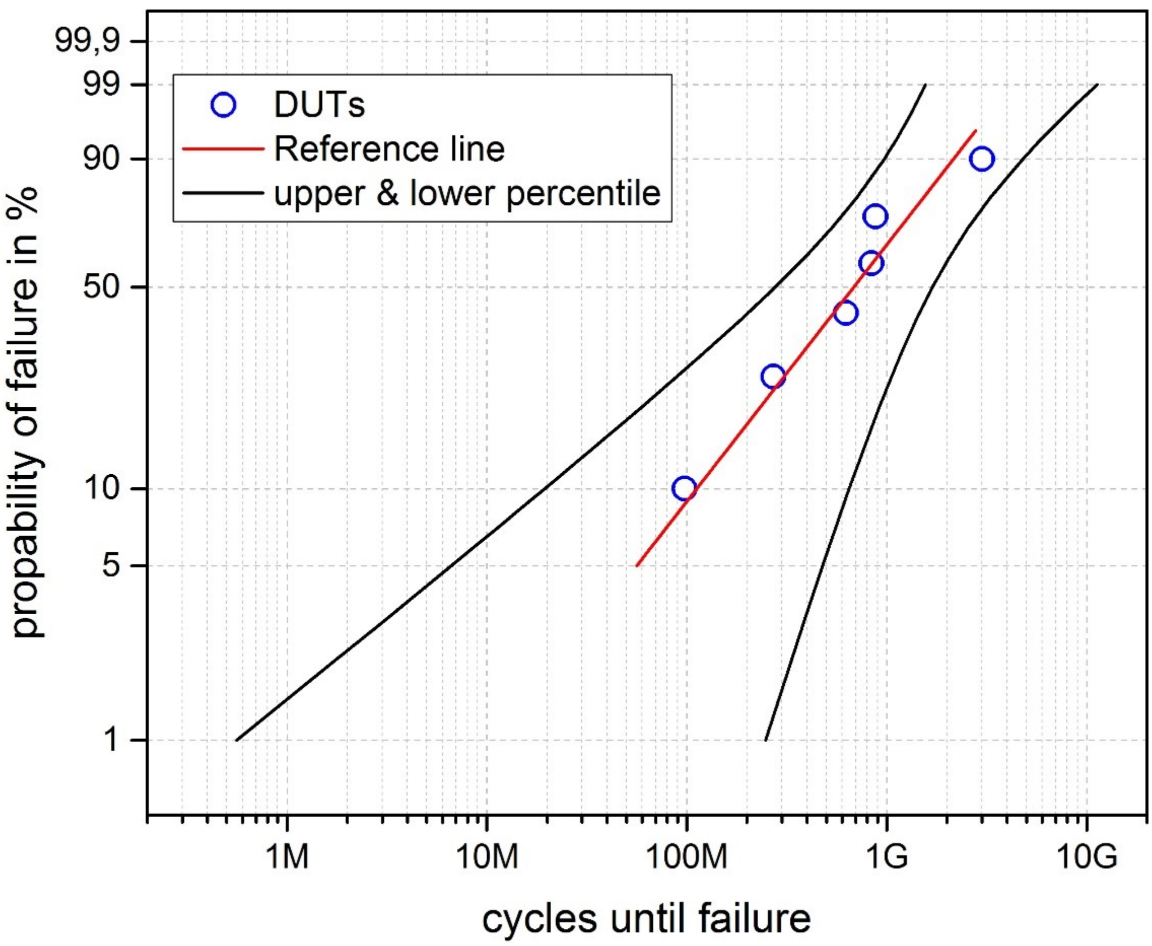

Fig. 5 Weibull-Plot for the experimental results normalized to T_{jmin} 90 °C and ΔT = **28 K**

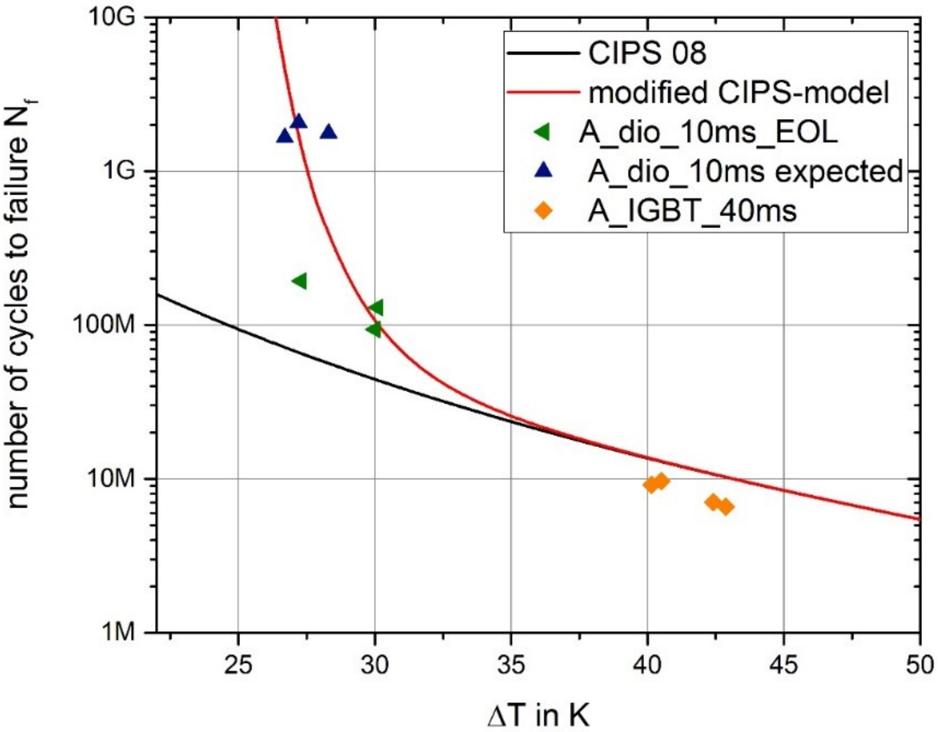

Fig. 6 Comparison of CIPS08 model and exp. data, normalized for T_{jmin} 90 °C, and modified CIPS-Model with Eq. 3 for β1'

Since there are slightly different conditions for the devices, the experimental values in Fig. 6 are normalized to T_{jmin} 90 °C using the Arrhenius-term in Eq. (1) with the data in table I. This allows a better comparison between the results.

Discussion of the results

Fig. 5 and Fig. 6 show that only six experimental values were determined for N_f, three of them are expected values. The data also showed significant scattering. On the other hand, this is to our knowledge the first time that a power cycling test up to more than 10^9 cycles was executed. Therefore even this low amount of data is valuable. All devices failed due to bond wire ageing. The analysis of the three failed modules and the three not failed modules are consistent. Besides, the measured ΔT_j is in the range of 23 K to 26 K, which raises a much higher requirement on the accuracy of the chip temperature measurement compared to the classical power cycling test with ΔT_j in the range of 80 K to 150 K. Further, the data are in agreement with material science which gives an elastic and no-linear elastic and plastic range for material deformation. This is already contained in the model of Hartmann et al. [7]. However in [7] the approximation is hyperbolic,

$$N_f = K2\left(\frac{1}{c_\Delta \Delta T_j + c_T T_{j,max} - c_0}\right)^m \tag{4}$$

with $c_\Delta = 7.6\cdot10^{-6}$ K^{-1}, $c_T = 1.7\cdot10^{-6}$ K^{-1} , $c_0 = 4.1\cdot10^{-4}$, m = 2.4. This model has a pole at

$$c_\Delta \Delta T_j + c_T T_{j,max} = c_0 \tag{5}$$

at which the lifetime becomes infinite. The approximation (3) presented in this paper is an exponential approach where the lifetime never becomes infinite. This is in agreement with [11] where an exponential approach for the elastic behavior is assumed, where the material never becomes ideal elastic, however approaches to this region exponentially. The results in Fig. 2 already show that the lifetime becomes very high, but not as high as calculated by Eq. (4).

The results are gained with DAB based modules. Fig. 2 shows that DCB based high-power modules reach one decade higher No. of cycles in the range $\Delta T_j > 43$ K. The root cause is supposed to be the found Al-reconstruction in the Al layer of the DAB which increases the temperature swing in the center of the chips. However, since the failures are always the bond wires, we can assume that the approximation (3) can also be used for DCB based high-power modules, however with a different K in Eq. 1, which is given in [4].
For standard DCB-based modules, whose lifetime is described in Eq. (1) for temperature swings above 40 K, we preliminary suggest to use Eq. (3) for extension down to $\Delta T_j > 25$ K. Table 1 is to be considered, and the second factor in (3) must be replaced by -4.416 to be in agreement with the CIPS2008 equation for cycles $\Delta T_j > 43$ K.
We have also to consider that 160 % of rated current had to be used to achieve a significant temperature swing for the short t_{on} of 10 ms. Because the current density is of influence, the results are probably worst-case, and the real lifetime for rated current will be higher. In the next step, a power cycling test with standard DCB modules is running, where the power for heating is generated by an adjustable part of switching losses [12]. Due to the high experimental effort and the expected cycles to failure of above 10^9, it will take some time for the next experimental data.

Conclusion

The model published at CIPS 2008 [2] is only valid for temperature swings above 40 K. For temperature swings < 30 K, the error becomes more than a factor of 10. Using the assumption of exponential approaching the ideal elastic behavior, the factor of underestimation of lifetime increases exponentially if used for temperature swings < 25 K. A first preliminary approximation for low temperature swings is given in this paper. Further work is in progress, however to gain more data is extremely time consuming.

References

[1] M. Held, P. Jacob, P. Scacco und M. H. Poech, „Fast power cycling test of IGBT modules in traction application,“ in *Proc. of PEDS*, 1997.

[2] R. Bayerer, T. Licht, T. Herrmann, J. Lutz und M. Feller, „Model for Power Cycling lifetime of IGBT Modules – various factors influencing lifetime,“ in *Proceedings of the 5th International Conference on Integrated Power Electronic Systems*, p 37-42, 2008.

[3] J. Lutz, H. Schlangenotto, U. Scherumann und R. De Doncker, Semiconductor Power devices - Physics, Characteristics, Reliability, 2nd edition: Springer, 2018.

[4] G. Zeng, R. Alvarez, C. Künzel und J. Lutz, „Power cycling results of high power IGBT modules close to 50 Hz heating,“ in *Proc. of EPE 2019, p. 1-9*, Genova, 2019.

[5] H. Wang, K. Ma und F. Blaabjerg, "Design for Reliability of Power Electronic Systems", Montreal : IEEE , 2012.

[6] Y. Zhang, H. Wang, Z. Wang, Y. Yang und F. Blaabjerg, „Impact of Lifetime Model Selections on the reliability prediction of IGBT modules,“ in *IEEE Energy Conversion Congress and Exposition (ECCE)*, 2017.

[7] S. Hartmann und E. Özkol, „Bond wire life time model based on temperature dependent yield strength,“ in *Proc. PCIM Europe*, Nuremberg, 2012.

[8] D. Blackburn und F. Oettinger, „Transient Thermal Response Measurement of Power Transistors,“ in *IEEE Transactions Electrical and Control Instrumentation*, Vol. IECI-22 , pp.134-141.

[9] C. Herold, J. Franke, R. Bhojani, A. Schleicher und J. Lutz, „Requirements in power cycling for precise lifetime estimation," in *Microelectronics reliability*, 2015.

[10] G. Zeng, C. Herold, M. Beier-Möbius, S. Kubera, R. Alvarez und J. Lutz, „High-current power cycling test bench for short load pulse duration and first results," in *Proc. of PCIM Europe*, Nuremberg, 2016.

[11] W. Illg, „Fatigue tests on notched and unnotched sheet specimens of 2014-T3 and 7075-T6 aluminum alloys and of SAE 4130 Steel with special consideration of the life range from 2 to 10`000 cycles," NACA Technical Note 3866, 1956.

[12] P. Seidel, C. Herold, J. Lutz, C. Schwabe und R. Warsitz, „Power Cycling with switching losses," ECPE final report, Nuremberg, 2017.