Early Damage Detection in Power Electronics Using Thermal RC Networks

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Early Damage Detection in Power Electronics Using Thermal RC Networks

- Motivation
  - Development Tasks
    - Results and Insights
      - Conclusions and further research priorities

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Motivation

Importance of Early Damage Detection

- Autonomous systems demand ultra-reliable electronics
- Critical for ensuring reliability and safety in electronic components
- E.g. autonomous driving
  - can only be achieved via redundant systems
  - Redundant systems add weight and high costs of the vehicle
  - Bulky monitoring limits practical on-board integration

Challenges in Power Electronics

- High currents, thermal loads require efficient dissipation
- Addresses challenges in algorithm performance, power management, and system complexity

New Technology Approaches and Methods "**On-Board Thermal Spectroscopy**"

- Thermal spectroscopy and electrothermal models for monitoring, but not detecting, faults in power MOSFETs
- Development of algorithms that leverage thermal impedance curves to identify and classify damage types
- Integration of virtual simulations to replicate damage scenarios

Early Damage Detection in Power Electronics Using Thermal RC Networks

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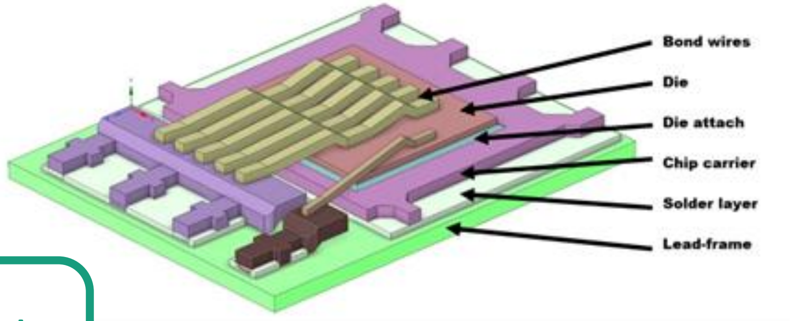
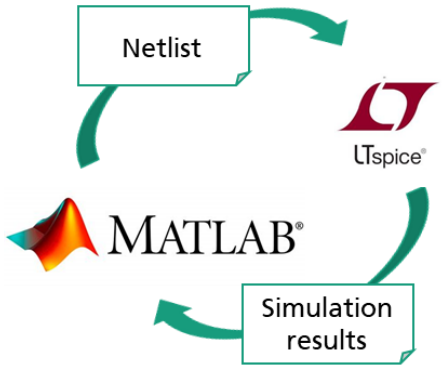
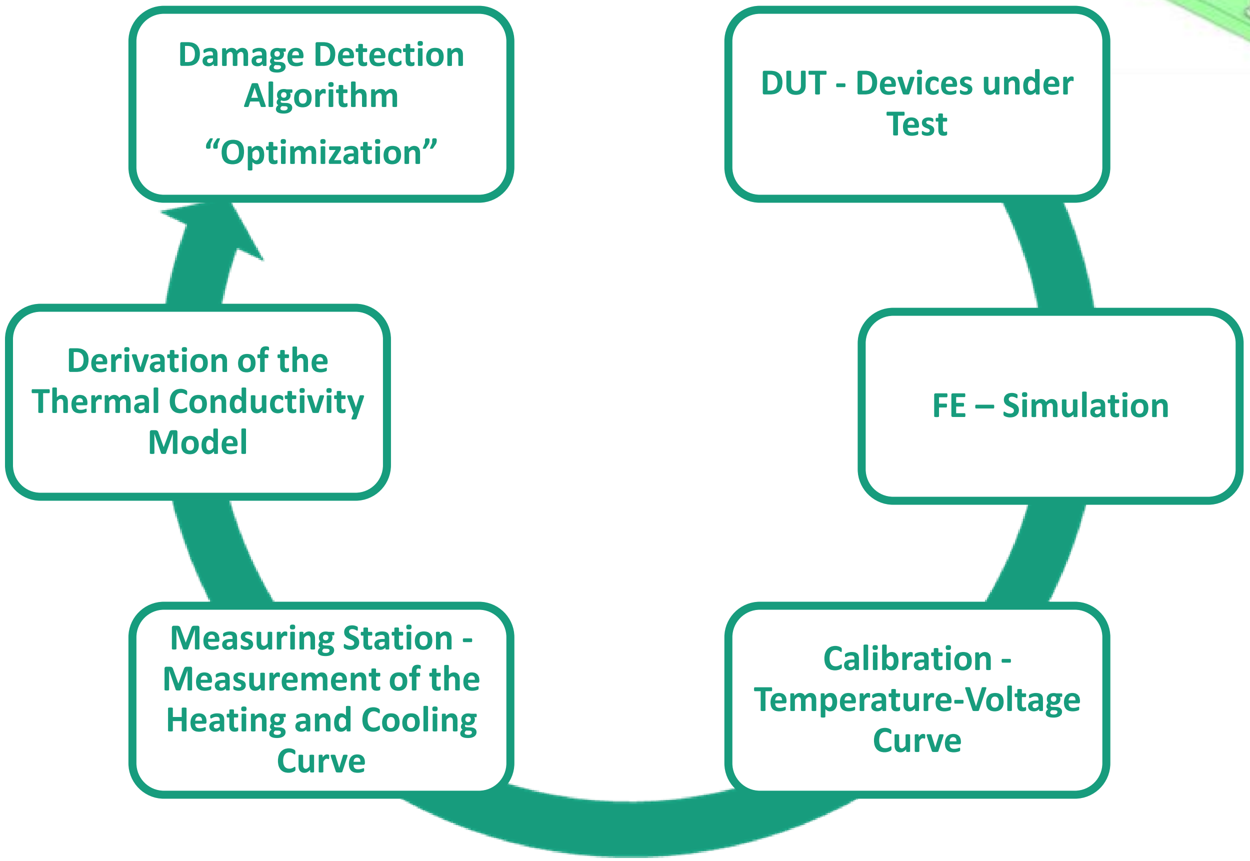
- Development Tasks
- Results and Insights
- Conclusions and further research priorities

Development Tasks

Our Approach - Concept






Damage Detection Algorithm
"Optimization"

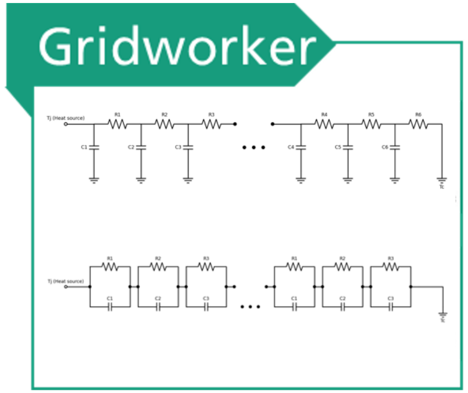
DUT - Devices under Test

FE – Simulation

Calibration - Temperature-Voltage Curve

Measuring Station - Measurement of the Heating and Cooling Curve

Derivation of the Thermal Conductivity Model



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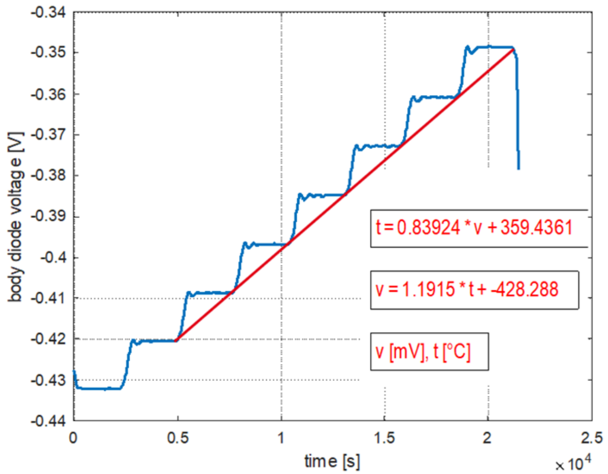


Development Tasks

Our Approach - Concept

Research objectives

- Development of an early damage detection method based on on-board thermal spectroscopy
- Investigation of different manufacture variants in relation to the derived RC model
- Investigation of ageing effects in the context of early damage detection

Key challenges

- Derivation and optimization of the thermal resistance model (1D heat transfer) of the system
- Evaluation of different manufacturing variants in relation to the derived RC model

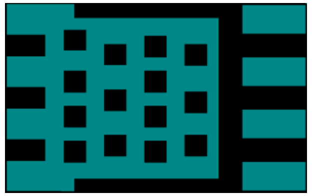
Development Tasks

DUT - Devices under Test

GLD

B30

E30



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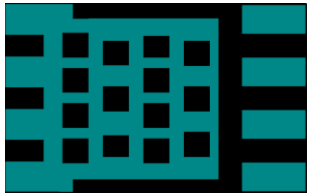
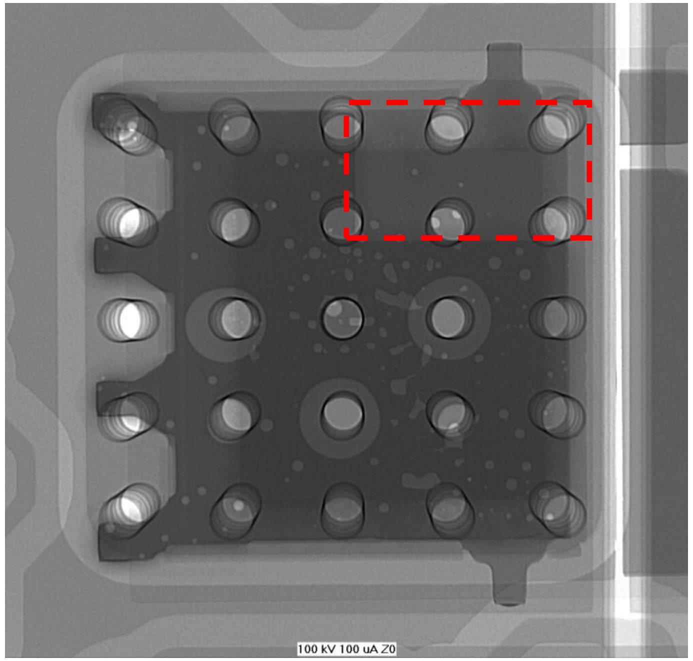
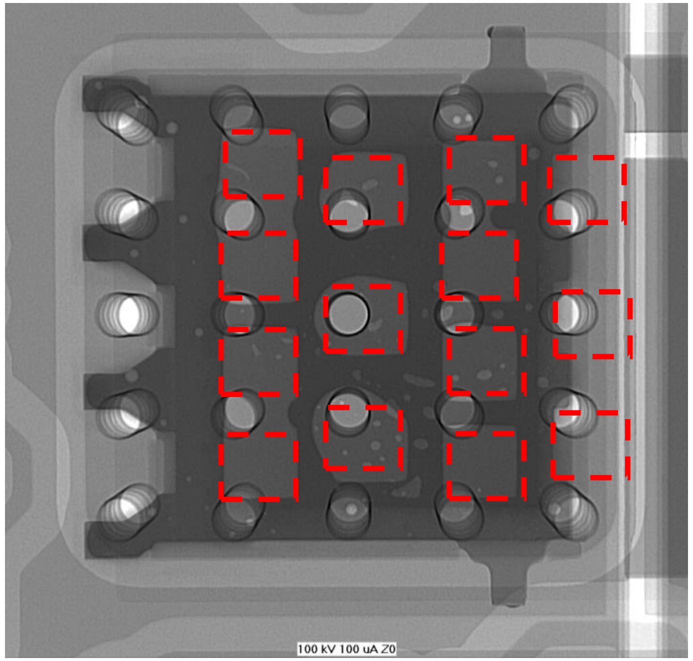
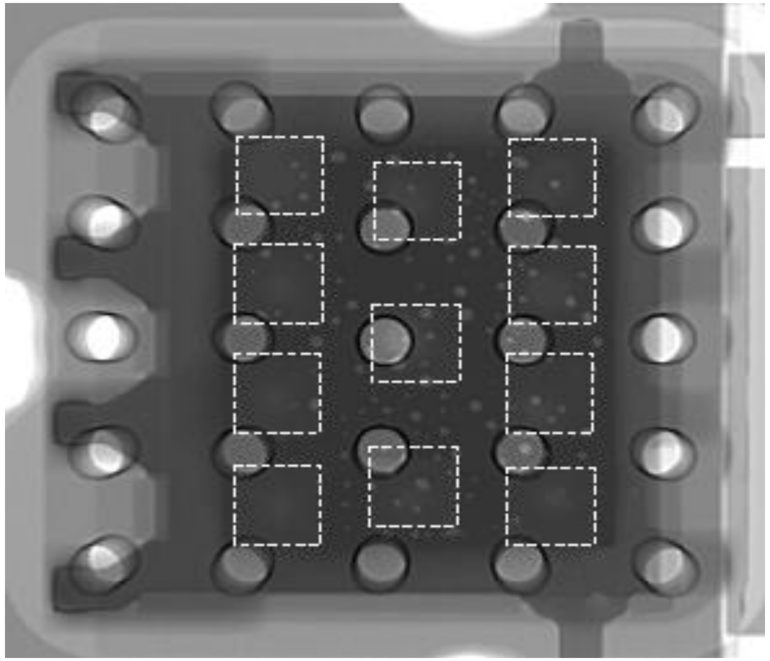


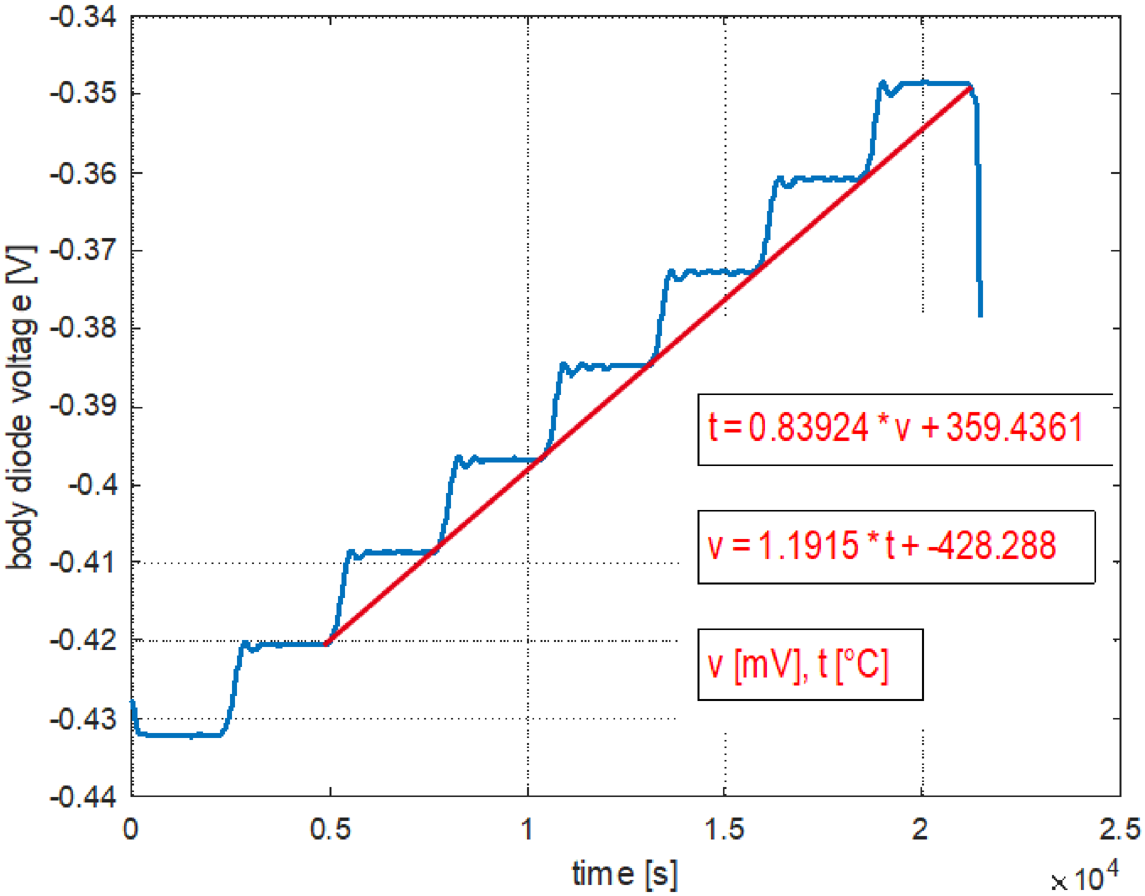






Development Tasks

Calibration – Temperature - Voltage Curve



Development Tasks

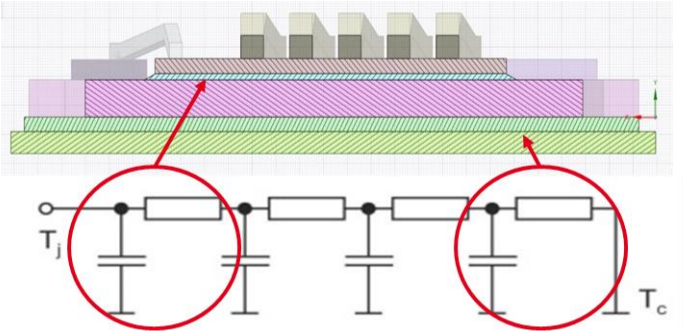
Measuring Station – Heating and Cooling Curve

Development Tasks

Derivation of the Thermal Conductivity Model

Physically based mesh

- Derivation or determination of the mesh nodes via the layer geometry and the material properties



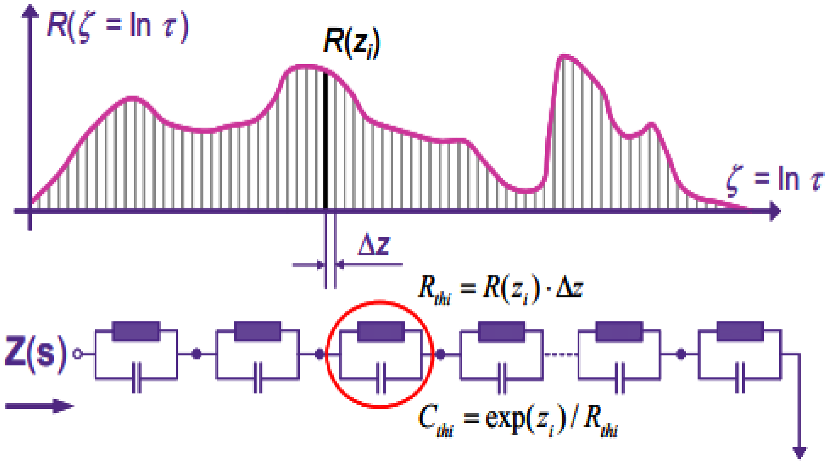
$$R_{th} = \frac{d}{\lambda \cdot A}$$

$$\tau = R_{th} \cdot C_{th} = \frac{c_p \cdot \rho \cdot d^2}{\lambda}$$

$$C_{th} = c_p \cdot \rho \cdot A \cdot d$$

Mathematically based mesh

- Derivation or determination of the network nodes using the time-constant spectrum “derivation of the impedance function”
- No physical reference => pure optimization challenge



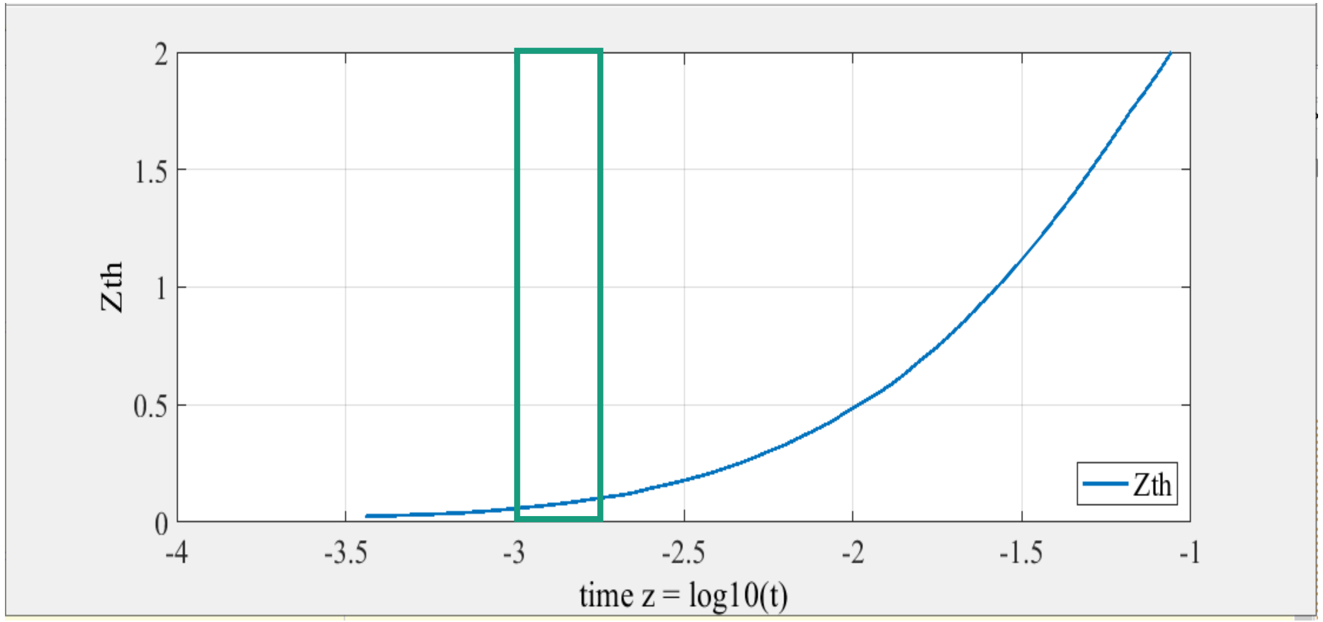
Development Tasks

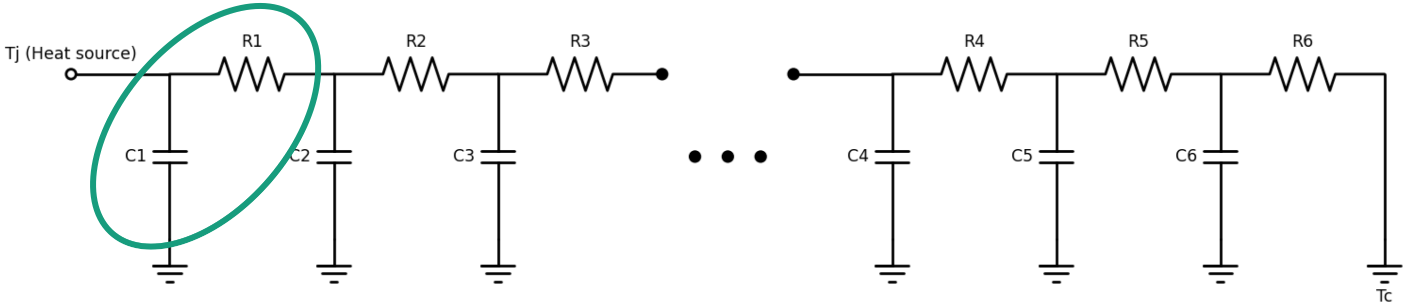
Derivation of the Thermal Conductivity Model

Key challenges / milestones

- Determination of the required number of RC nodes
- Definition of the optimization strategy and the restriction conditions
- Determination of the values of the individual RC nodes

$$Z_{th} = \frac{(T_J(t) - T_J(t=0))}{P_H}$$





Development Tasks

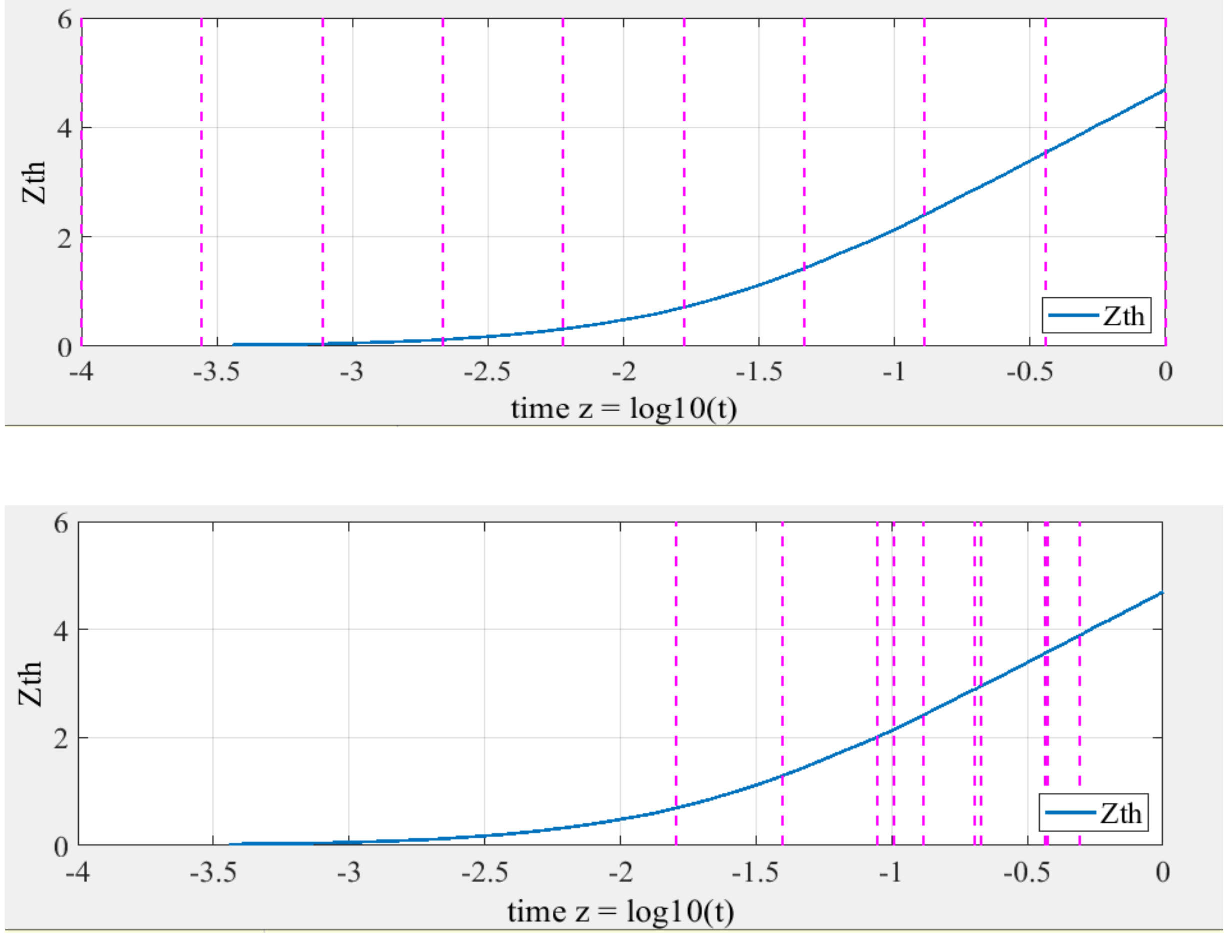
Derivation of the Thermal Conductivity Model

Optimization procedures

- FSQP - Feasible Sequential Quadratic Programming
- Powell

Optimization methods

- Uniform distribution
- Optimization within defined limits
- Free distribution of tau's



Development Tasks

Derivation of the Thermal Conductivity Model

Specific analysis

- Manufacturing tolerances result in sample specific configuration

Model based analysis

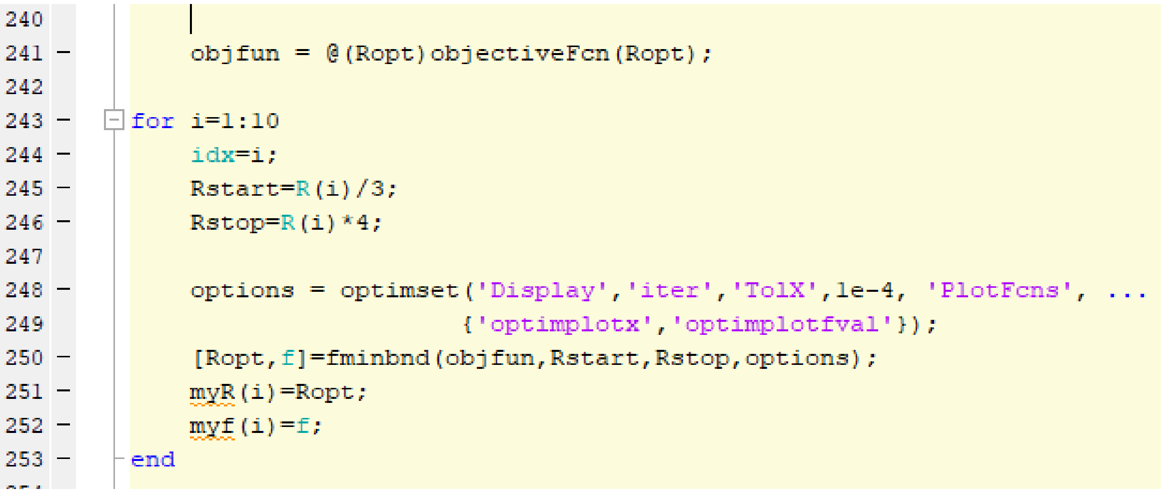
- Based on an idealized sample (average of all individual measurements)

DUT	R1	R2	R3	R4	R5	R6	R7	R8	R9	R10
1	0.8167	1.0482	0.8970	0.6444	0.6416	0.5245	0.2690	0.1583	0.5555	0.7346
2	0.8018	1.0992	0.8977	0.6362	0.6699	0.5177	0.2587	0.1628	0.5887	0.7620
3	0.8247	1.1281	0.9329	0.6521	0.6827	0.5264	0.2663	0.1845	0.5378	0.7001
4	0.8013	1.0875	0.9077	0.6277	0.6479	0.5324	0.2514	0.1739	0.5679	0.7473
5	0.8095	1.0979	0.9272	0.6189	0.6787	0.5365	0.2563	0.1626	0.5887	0.7681
6	0.8058	1.0741	0.9049	0.6577	0.6349	0.5032	0.2647	0.1848	0.5224	0.6632
7	0.8482	1.1772	0.9430	0.6501	0.6828	0.5260	0.2652	0.1616	0.5666	0.7579
8	0.8199	1.0709	0.8959	0.6497	0.6479	0.5299	0.2793	0.1433	0.6347	0.8506
9	0.8239	1.2108	0.7989	0.9497	0.4432	0.4168	0.5546	0.0958	0.6799	0.8551
10	0.7994	1.1421	0.8318	0.8384	0.4904	0.4779	0.4998	0.0957	0.7333	0.9383
11	0.8004	1.0834	0.7980	0.8235	0.4712	0.4730	0.4521	0.1066	0.6380	0.8434
12	0.7812	1.1093	0.7957	0.8331	0.4703	0.4359	0.5547	0.0837	0.7706	0.9943
13	0.8422	1.2213	0.8372	0.8703	0.4873	0.4429	0.5267	0.0896	0.7166	0.9154
14	0.8033	1.1226	0.8592	0.7196	0.6003	0.4919	0.4049	0.1047	0.7143	0.9097
15	0.7976	1.1202	0.8958	0.6526	0.6486	0.5247	0.2794	0.1482	0.5682	0.7731
16	0.8569	1.2366	0.8761	0.8337	0.5307	0.4333	0.5278	0.0863	0.9092	1.2419
17	0.8433	1.1389	0.8351	0.8569	0.5005	0.4367	0.5173	0.0959	0.7154	0.9248
18	0.6119	1.2517	0.6112	1.0998	0.3292	0.4246	0.4895	0.0924	0.6864	0.8953
19	0.7821	1.1408	0.7692	0.9033	0.4229	0.4524	0.5758	0.0788	0.7092	1.1195
20	0.8322	1.1606	0.8343	0.8663	0.4673	0.4504	0.5613	0.0750	0.8712	1.3763

R	.*1	.*2	.*3	.*4	.*5	.*6	.*7	.*8	.*9	.*10
Z(Tau)	-1.7955	-1.4008	-1.0541	-0.9910	-0.8832	-0.6933	-0.6685	-0.4356	-0.4258	-0.3087
Ø	0.8064	1.1329	0.8525	0.7703	0.5543	0.4833	0.4047	0.1225	0.6692	0.8926
σ^2	0.0469	0.0556	0.0707	0.1262	0.1005	0.0398	0.1250	0.0371	0.1025	0.1699

Development Tasks

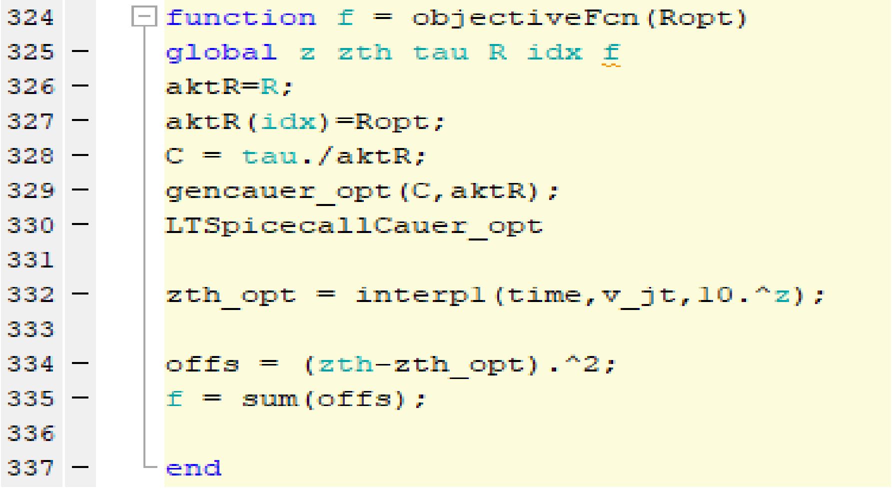
Damage Detection Algorithm “Optimization”



```
    objfun = @(Ropt)objectiveFcn(Ropt);

for i=1:10
    idx=i;
    Rstart=R(i)/3;
    Rstop=R(i)*4;

    options = optimset('Display','iter','TolX',1e-4, 'PlotFcns', ...
                      {'optimplotx','optimplotfval'});
    [Ropt,f]=fminbnd(objfun,Rstart,Rstop,options);
    myR(i)=Ropt;
    myf(i)=f;
end
```

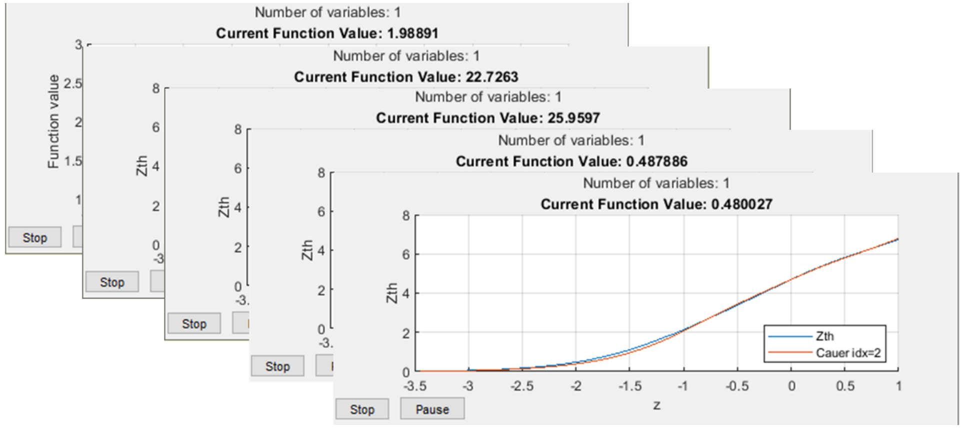


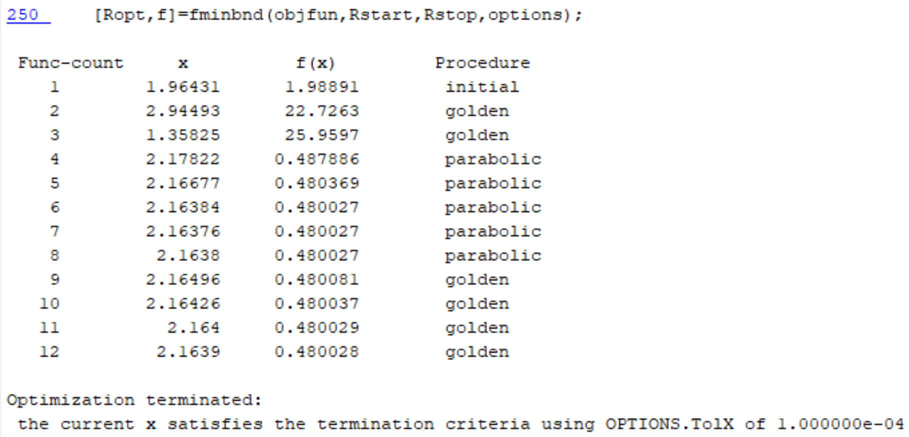
```
function f = objectiveFcn(Ropt)
global z zth tau R idx f
aktR=R;
aktR(idx)=Ropt;
C = tau./aktR;
gencauer_opt(C,aktR);
LTSpicecallCauer_opt

zth_opt = interp1(time,v_jt,10.^z);

offs = (zth-zth_opt).^2;
f = sum(offs);

end
```





```
250      [Ropt,f]=fminbnd(objfun,Rstart,Rstop,options);

 Func-count     x          f(x)         Procedure
    1         1.96431     1.98891        initial
    2         2.94493     22.7263        golden
    3         1.35825     25.9597        golden
    4         2.17822     0.487886       parabolic
    5         2.16677     0.480369       parabolic
    6         2.16384     0.480027       parabolic
    7         2.16376     0.480027       parabolic
    8          2.1638     0.480027       parabolic
    9         2.16496     0.480081       golden
   10         2.16426     0.480037       golden
   11           2.164     0.480029       golden
   12          2.1639     0.480028       golden

Optimization terminated:
 the current x satisfies the termination criteria using OPTIONS.TolX of 1.000000e-04
```

Early Damage Detection in Power Electronics Using Thermal RC Networks

- Motivation
- Development Tasks
- **Results and Insights**
- Conclusions and further research priorities

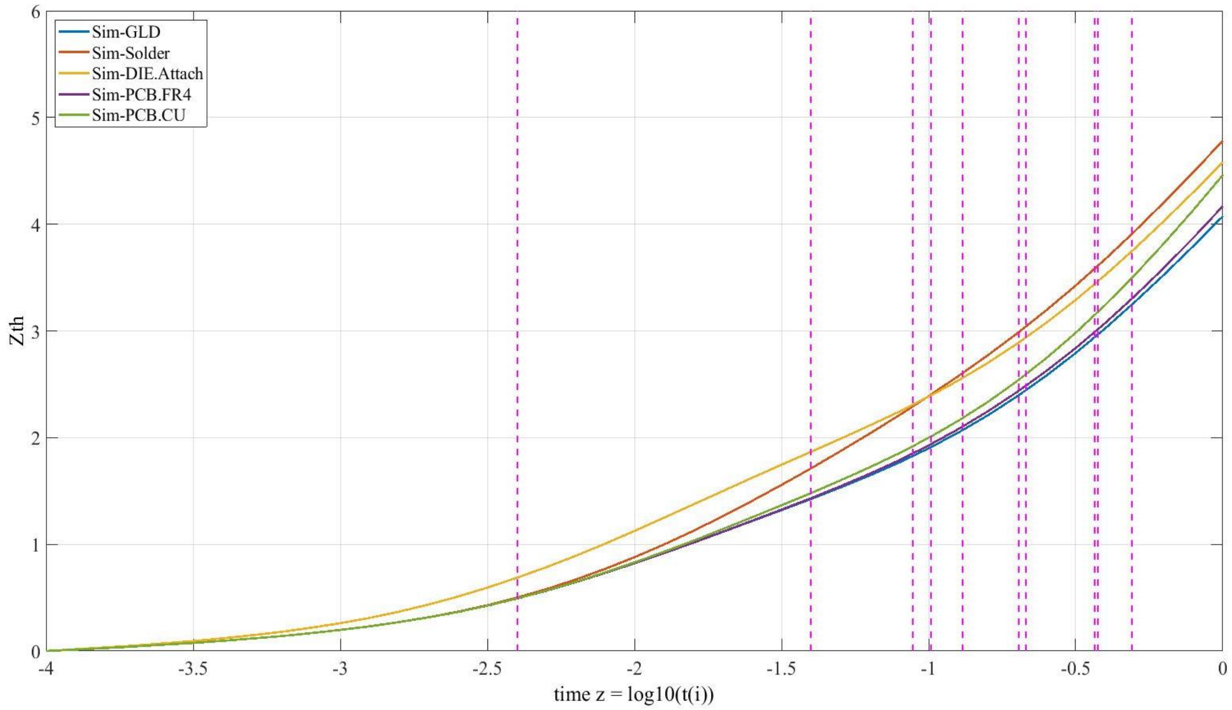
Results and Insights

FE - Simulation

- FE model allows simulation of thermal system behaviour for different damages

Specific time deviation

- Die attach - Network element 1 🟨
- Solder - Network element 2 🟥
- PCB.CU - Network element 4 🟩
- PCB.FR4 - Network element 5 🟪



Interpretation of the results

Investigation of ageing effects in the solder => change of the curve Sim-GLD to Sim-Solder

	F(R1)	F(R2)	F(R3)	F(R4)	F(R5)	F(R6)	F(R7)	F(R8)	F(R9)	F(R10)
B30	5.1608	0.3508	2.0542	5.7488	8.7950	12.4074	13.8380	17.4637	20.2662	20.7935
A20DA	0.4731	1.8692	4.8533	7.2362	8.9040	10.7621	11.4483	12.5958	14.0917	14.4117
PCB-FR4	1.2967	0.9235	0.4931	0.1965	0.1712	0.2575	0.3516	0.5213	1.2037	1.4122
PCB-CU	5.8050	3.1911	1.0893	0.2710	0.7567	2.2374	3.1047	6.4467	9.2951	9.8471

Results and Insights

Investigation and Evaluation of Various Causes of Faults in the Solder

The starting point

- Idealised RC mesh

Routine

- Initial adjustments to the individual samples (measurements of the basic state)

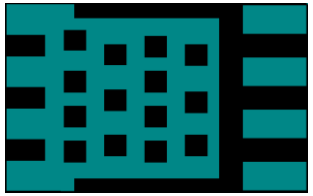
Interpretation of the results

- Differentiation between the failure variants could only be proven to a limited extent

B30

	F(R1)	F(R2)	F(R3)	F(R4)	F(R5)	F(R6)
.*744	0.0206	0.0214	0.0199	0.0197	0.0201	0.0208
.*759	0.1024	0.0281	0.0918	0.1999	0.2989	0.3988
.*804	0.1171	0.0138	0.0634	0.1694	0.2675	0.3659
.*819	0.2545	0.0197	0.0435	0.1720	0.3044	0.4434
.*834	0.5750	0.0446	0.1296	0.4613	0.7949	1.1404

E30



Nr	F(R1)	F(R2)	F(R3)	F(R4)	F(R5)	F(R6)
.*741	0.0283	0.0100	0.0088	0.0130	0.0182	0.0234
.*756	0.0048	0.0310	0.0489	0.0639	0.0736	0.0827
.*801	0.0447	0.0188	0.0127	0.0150	0.0205	0.0264
.*816	0.0167	0.0370	0.0854	0.1491	0.1972	0.2402
.*831	0.0658	0.0158	0.0227	0.0599	0.0996	0.1419

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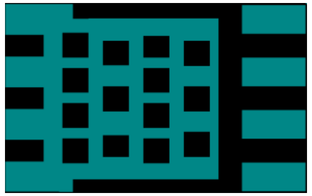


Nr	F(R1)	F(R2)	F(R3)	F(R4)	F(R5)	F(R6)
.*743	0.0167	0.0052	0.0147	0.0290	0.0399	0.0487
.*758	0.0073	0.0149	0.0188	0.0211	0.0227	0.0241
.*803	0.0103	0.0135	0.0289	0.0476	0.0636	0.0796
.*818	0.0793	0.0214	0.0866	0.1901	0.2811	0.3707
.*833	0.2099	0.0461	0.1813	0.4201	0.6340	0.8457

Results and Insights

Evaluation of the Ageing Measurements

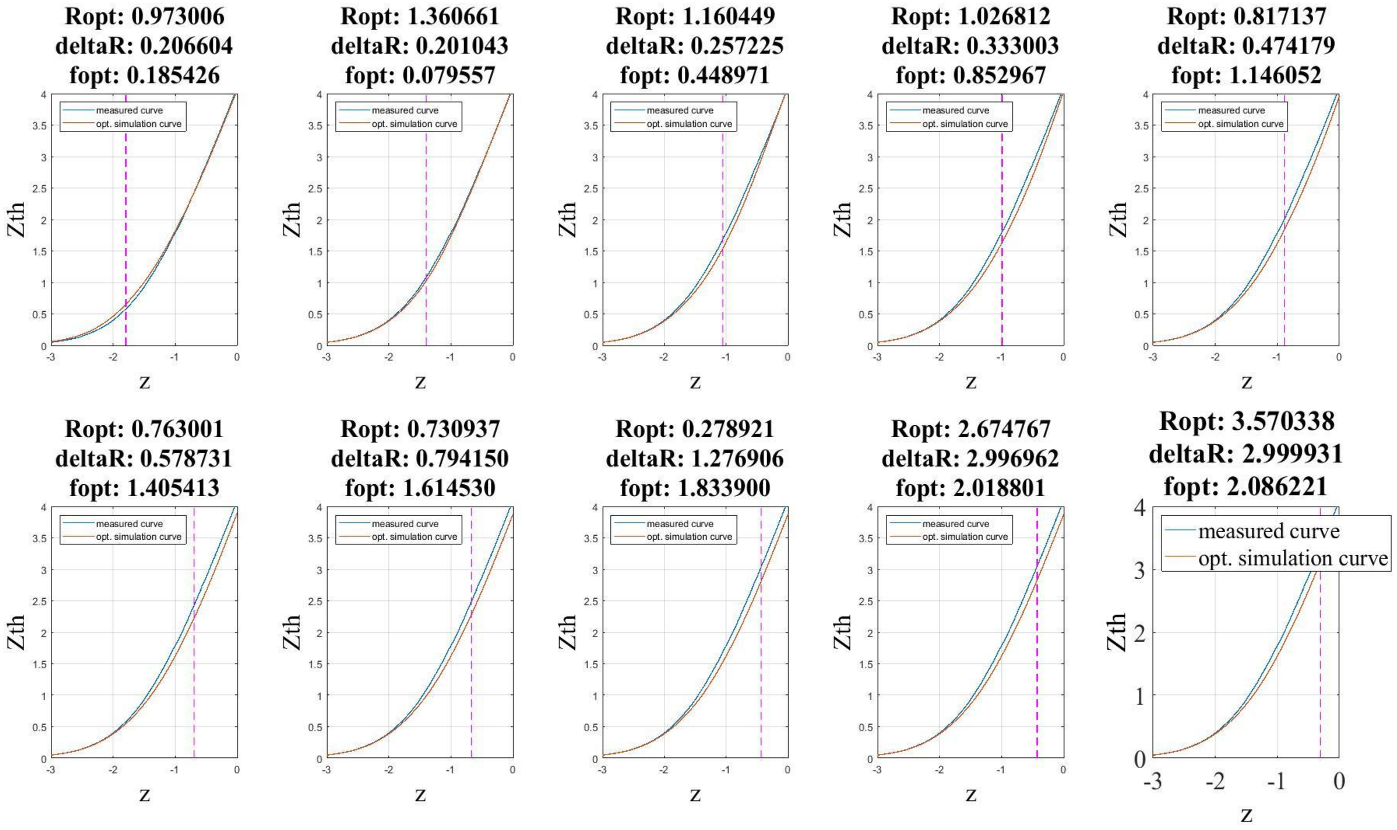
The starting point

- Idealised RC mesh

Routine

- Initial adjustments to the individual samples (measurements of the basic state)
- Iterative resistance variation ‘optimisation’ incl. the associated deviation error

- Determination of limits % change in resistance
- Determination of limits of the fault tolerance ‘fopt’


Ropt: 0.973006 deltaR: 0.206604 fopt: 0.185426

Ropt: 1.360661 deltaR: 0.201043 fopt: 0.079557

Ropt: 1.160449 deltaR: 0.257225 fopt: 0.448971

Ropt: 1.026812 deltaR: 0.333003 fopt: 0.852967

Ropt: 0.817137 deltaR: 0.474179 fopt: 1.146052

Ropt: 0.763001 deltaR: 0.578731 fopt: 1.405413

Ropt: 0.730937 deltaR: 0.794150 fopt: 1.614530

Ropt: 0.278921 deltaR: 1.276906 fopt: 1.833900

Ropt: 2.674767 deltaR: 2.996962 fopt: 2.018801

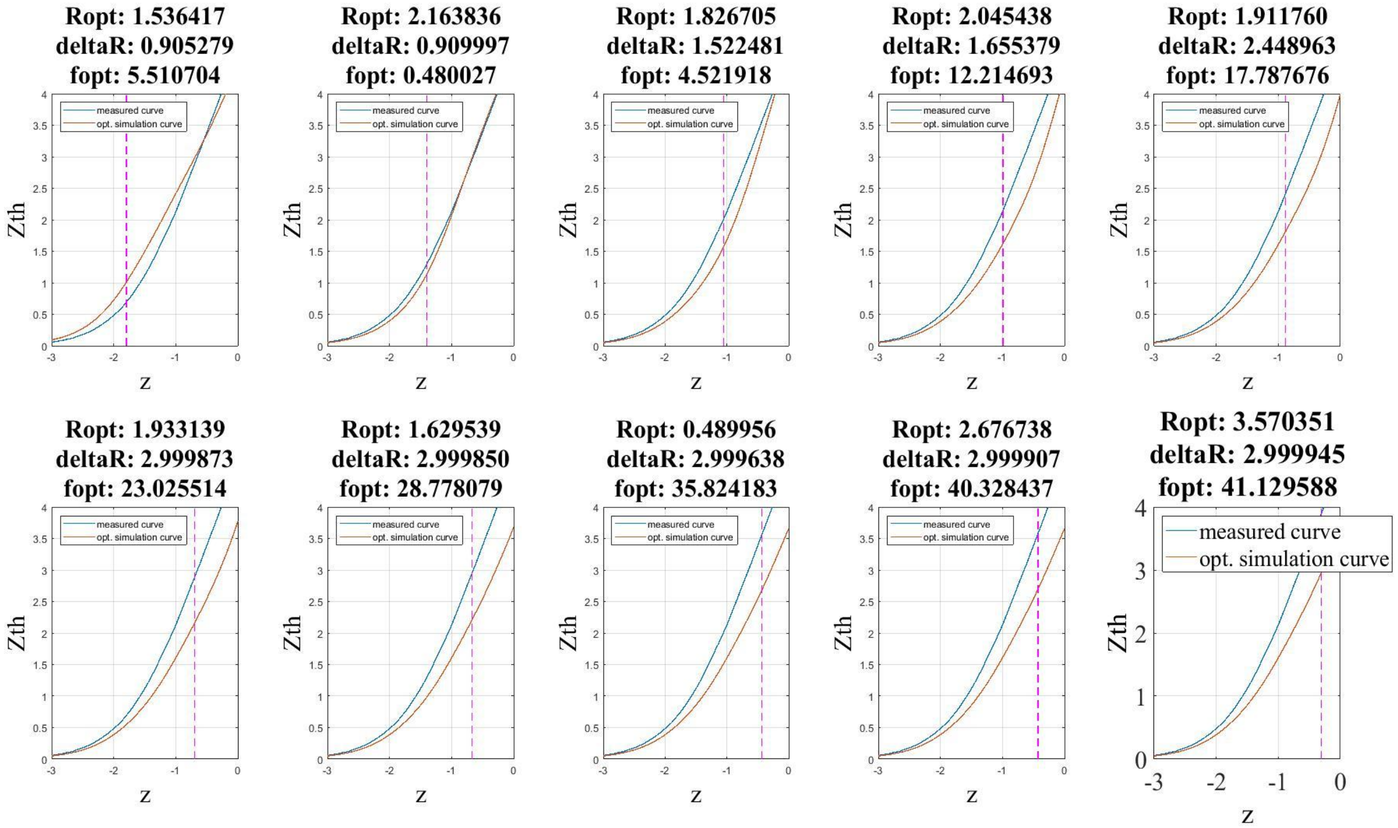
Ropt: 3.570338 deltaR: 2.999931 fopt: 2.086221

Results and Insights

Evaluation of the Ageing Measurements

Interpretation of the results

- Ageing effects lead to significant changes in the coefficient values (1.133 Ω -> 2.164 Ω)
- Reliable assessment based on the ‘fopt’ quality criterion
- Decision criteria such as a percentage change of 20% of R could further improve clarity



Ropt: 1.536417
deltaR: 0.905279
fopt: 5.510704

Ropt: 2.163836
deltaR: 0.909997
fopt: 0.480027

Ropt: 1.826705
deltaR: 1.522481
fopt: 4.521918

Ropt: 2.045438
deltaR: 1.655379
fopt: 12.214693

Ropt: 1.911760
deltaR: 2.448963
fopt: 17.787676

Ropt: 1.933139
deltaR: 2.999873
fopt: 23.025514

Ropt: 1.629539
deltaR: 2.999850
fopt: 28.778079

Ropt: 0.489956
deltaR: 2.999638
fopt: 35.824183

Ropt: 2.676738
deltaR: 2.999907
fopt: 40.328437

Ropt: 3.570351
deltaR: 2.999945
fopt: 41.129588

Results and Insights

Evaluation of the Ageing Measurements

	F(R1)	F(R2)	F(R3)	F(R4)	F(R5)	F(R6)	F(R7)	F(R8)	F(R9)	F(R10)
.*700	3.3144	1.5123	2.7242	8.5850	9.5289	13.0708	17.3180	20.5412	22.1616	22.7546
.*702	0.3110	0.1285	0.1495	0.2665	0.4182	0.6340	0.8686	1.1313	1.3674	1.4433
.*716	0.5303	0.1002	0.8796	1.9571	2.7920	3.3624	3.9605	4.5563	4.8788	4.9860
.*731	0.2604	0.0346	0.3279	0.7672	1.1389	1.3618	1.6267	1.8082	1.9140	1.9627
.*747	0.1695	0.0601	0.0410	0.0741	0.1336	0.2180	0.3181	0.3804	0.4975	0.5396
.*761	5.1858	0.5936	5.4936	13.3250	20.1104	25.5624	34.2510	38.9909	40.6542	41.2345
.*791	0.4257	0.1429	0.1327	0.2807	0.4837	0.7626	1.0674	1.4260	1.7218	1.8126
.*796	0.0987	0.0427	0.2010	0.3968	0.5309	0.6154	0.6936	0.7387	0.7659	0.7766
.*822	0.0955	0.0734	0.0889	0.1229	0.1732	0.2339	0.3192	0.3597	0.4465	0.4846
.*841	1.0035	0.1963	1.5496	3.3488	4.7957	5.9421	7.0490	8.4507	9.1310	9.3726

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Conclusions and further Research Priorities

- The investigations show
  - The measurement of the voltage of the body diode can be used to determine the thermal impedance curve of the component
  - The evaluation was carried out using validated finite element models and on test boards with various integrated defect patterns
  - Test measurements proved that the developed method recognises changes to the package and responds selectively
- Further work
  - Variability in manufacturing and measurement inaccuracies can obscure damage detection
  - Testing the methods and the algorithm on real ageing methods or in field tests
  - Investigation and derivation of threshold values - anomalies, deviations and malfunctions

Thank You for Your Attention

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