Mastering challenges in automotive electronics – from technology to standardization

Aug 2023

AE/EAI1-Henneken, -Welzel

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Enabling Connected, Electrified and Automated Mobility
Challenges for assembly and interconnect technology

Connected mobility

Automated mobility

Powertrain systems and electrified mobility

Mission-critical ECU* (Class 3)

Harsh environment (Class 3)

High-volume production

*** ECU = electronic control unit**

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Enabling Connected, Electrified and Automated Mobility
Challenges for assembly and interconnect technology

Connected mobility

Automated mobility

Powertrain systems and electrified mobility

High-speed design: ‘server on wheels’

24/7
5G
Miniaturization
New package styles
Power density logic
ASIL
FIT rates
Data transmission and protocols
Supply chain
High-speed design
Commodity components

high voltage/high power

Switching frequency
High voltage
New AIT
24/7
Power density power semiconductors

High-volume production / Harsh environment (Class 3) / Mission-critical ECU* (Class 3)

Sustainability

Rework

* ECU = electronic control unit

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Enabling Connected, Electrified and Automated Mobility

Functional requirements - examples

▶ Trend to higher operation voltage at small box volume	Increase of voltages up to > 1000 V (Battery systems) Reduction of isolation distance < 75 µm (for signals)	electrified connected automated
▶ Trend to devices with smaller pitch (~ 0.35 mm for area array) and higher I/O count (~ 3000)	Increase of necessary layer count (~ 20) and reduction of line/space and via ∅ (~60 µm, 80 – 90 µm µvias) for PCB	connected automated
▶ Trend to high-speed applications like image processing, ADAS	Impedance & loss control; high-speed materials up to > 10 Gbit/s (today 100 Mbit/s – 1 Gbit/s)	connected automated
▶ Power electronics on organic substrates	Increase of Cu in substrates (e.g. thick Cu, busbar) and local anisotropic heating around power lines	electrified automated
▶ Increasing currents and switching loss reduction for WBG power semiconductors	Low-inductance design Higher temperature capability to enable higher T_j	electrified automated

New functional requirements require advanced highly integrated logic PCBs, power PCBs and new AIT concepts (e.g. welding, sintering).

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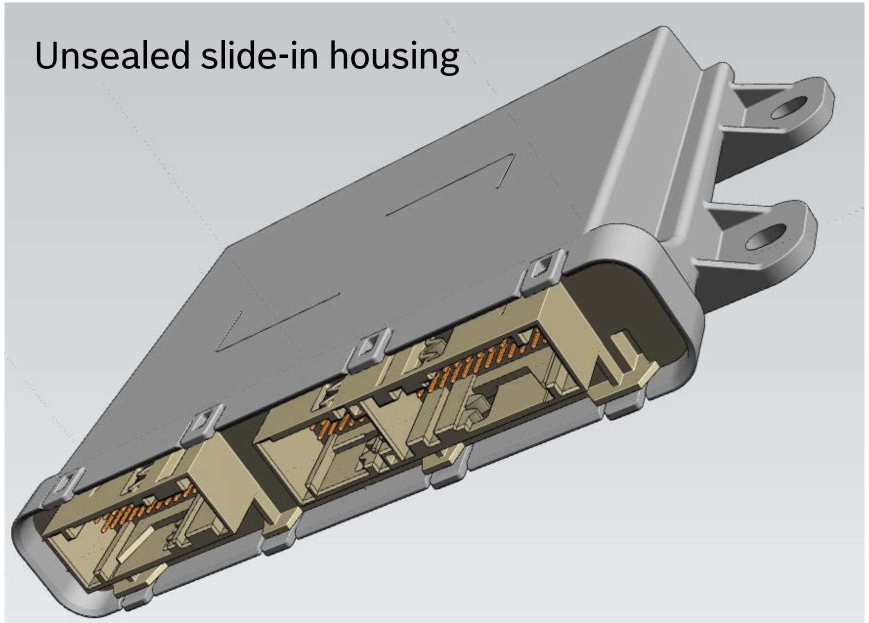
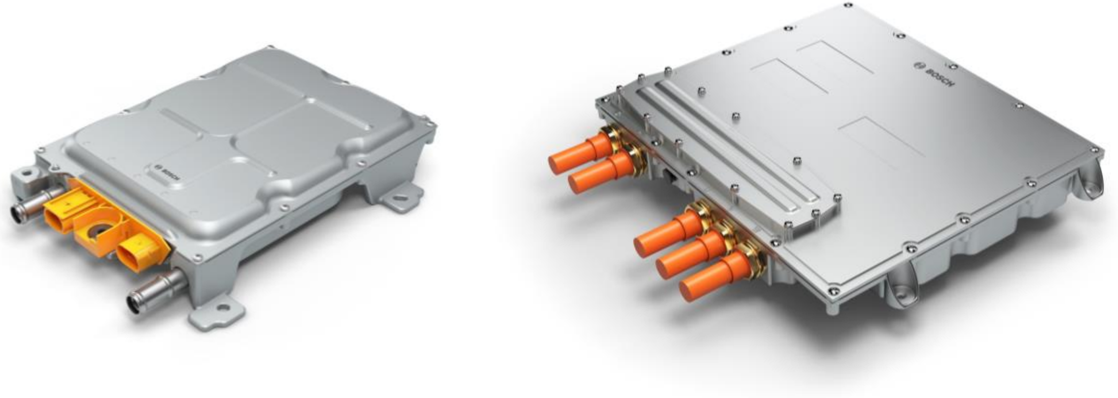
Electrochemical Reliability
Next Generation of ECUs

- More units with open housing
  - Open plastic housing in passenger room
  - Change in microclimate and 24/7 requirements



- More units with high power / high voltage
  - Water tight housing with water cooling inside
  - Change in microclimate and 24/7 requirements
  - Change in operation time from 5.000h to 130.000h
  - Circuits with 470V, 850V, 1200V



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Enabling Connected, Electrified and Automated Mobility
Environmental & internal loads - examples

- Trend to plastic housings or even open housings and Asian market → **Increase of humidity load on and in ECU and short dewing periodes on PCB/substrate** — connected, automated, electrified
- Trend to longer operational time (charging) and always-on mode → **Longer Temperature/Humidity/Bias (THB) impact (up to 130.000 h instead of 8000 h)** — connected, electrified, automated
- Trend to hotter applications and hotspots on PCB due to higher power dissipation and less cooling → **Increase of temperature load and temperature cycle load (160 – 175 °C) over whole ECU or at hotspots** — automated, electrified

Increasing environmental and internal loads require adaptions of materials and concepts for automotive electronics. Very good understanding of cause & effect relationships is essential!

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Standards
Automotive addenda/standards/documents

Dedicated automotive standards → Harmonization of requirements throughout the supply chain

Focus on common targets → Acceleration of innovation, reduction of time-to-market and cost

Automotive addenda/standards	TG/TC	Status
Automotive Addendum to IPC-6012EA Automotive Applications Addendum to IPC-6012E Qualification and Performance Specification for Rigid Printed Boards	IPC D-33AA	Published
IPC J-STD-001HA/IPC-A-610HA Automotive Addendum to IPC J-STD-001H Requirements for Soldered Electrical and Electronic Assemblies and IPC-A-610H Acceptability of Electronic Assemblies	IPC 7-31BV	Published
IPC-9797A Press-fit Standard for Automotive Requirements and Other High-Reliability Applications IPC-HDBK- 9798 Handbook for Press-fit Standard for Automotive Requirements and other High-Reliability Applications	IPC 5-21N IPC 5-21M	Published
IPC-TM-650 2.5.7.4 High Voltage Moisture and Insulation Resistance Test of Fabricated Printed Board Test Patterns	IPC D-33AA	Pending
IPC-WP-027 Understanding Control and Assessment of Voiding in Surface Mount Technology Connections for Automotive Applications	IPC 7-31BV-Ghost	Pending
IPC-WP-028 Guidance on Objective Evidence for Validating the Acceptability of Bubbles in Conformal Coatings	IPC 5-22A-AT-Champagne	Pending
IEC 61191-8 Printed board assemblies - Part 8: Voiding in solder joints of printed board assemblies for use in automotive electronic control units - Best practices	IEC TC 91 WG2	Published
IEC TR 61191-9 Printed board assemblies - Part 9: Electrochemical reliability and ionic contamination on printed circuit board assemblies for use in automotive applications - Best practices	IEC TC 91 WG2	Published

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automotive electronics – humidity robustness

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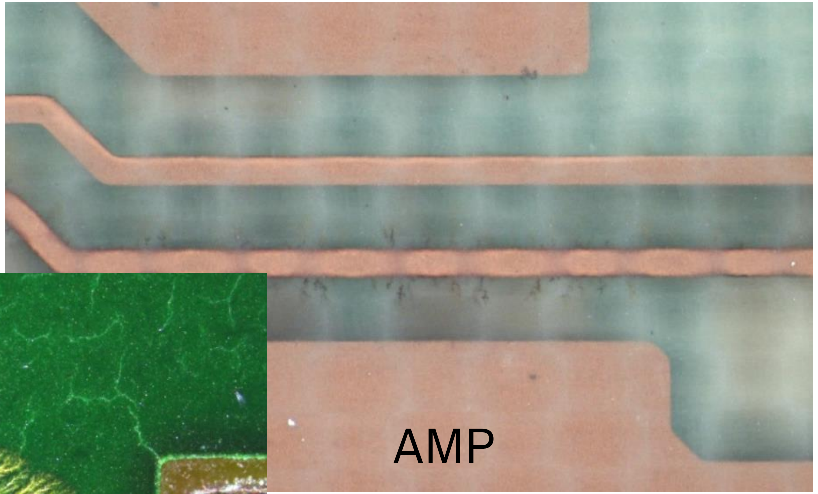
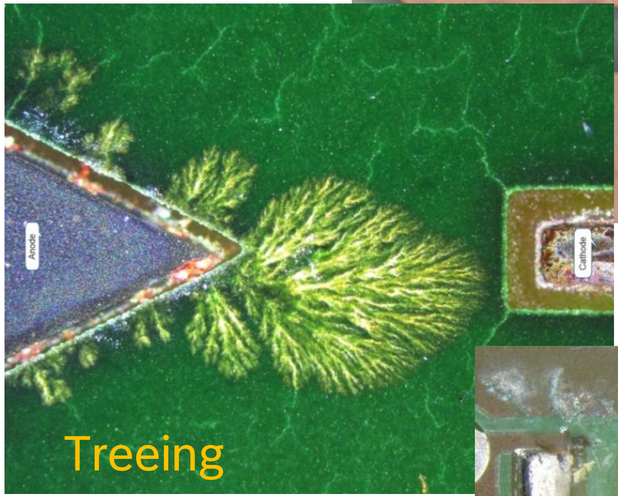
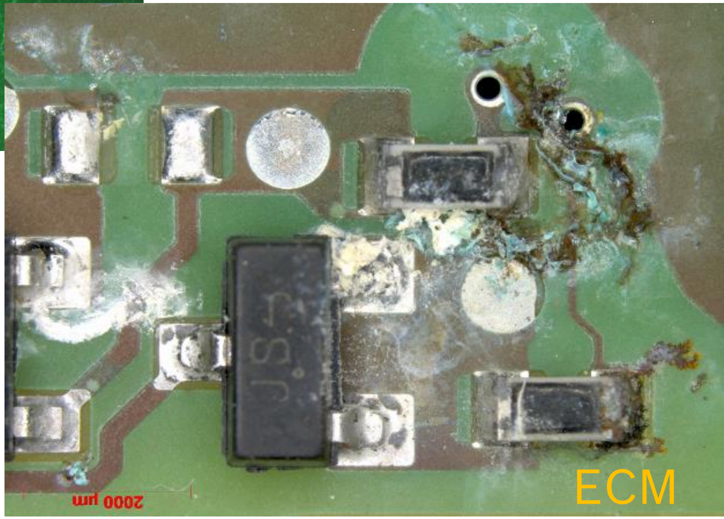
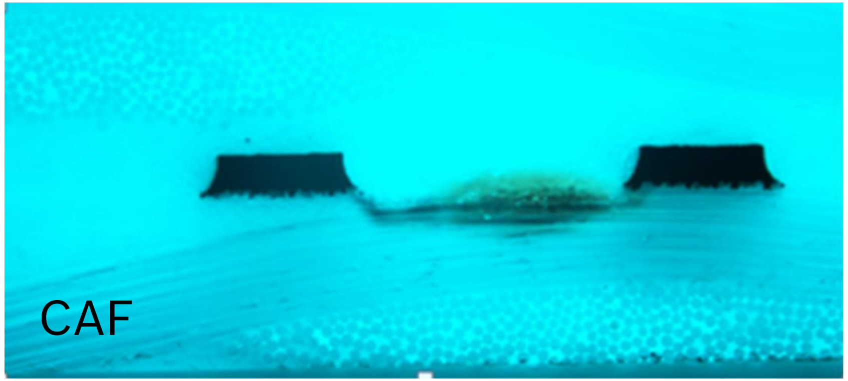
Electrochemical Reliability
Definition – What is really the topic?

- Electrochemical reliability of electronics:
  - Correct operation of electronic products under realistic humidity **and** voltage loads (intended end-use) without overstress conditions that would change the failure mechanism,
  - Synonym for all failures like ECM, CAF, AMP,
  - Different failure modes, different timeline, no single life time model.









ECM: Electrochemical migration (Electrochemical failure mode)
PD: Partial Discharge
AMP: Anodic Migration Phenomena
SIR: Surface Insulation Resistance
CAF: Conductive Anodic Filament
THB: Temperature-Humidity-Bias

Electrochemical Reliability
Definition – Electrochemical Failure Modes

- At low voltage (ca. < 300V) failures based on electrochemical principles are predominant,
  - pH-shift, anodic dissolution of metals, migration along cracks, migration across surfaces, electron “wind”,
  - Subsequent failures are initiated by this mechanism (e.g. leakage, shorts),
- At higher voltages (300V – 3000V) ionization can take place across or inside the materials. Discharge mechanism are changing the dielectric properties of the materials additionally to the LV-failures.

	Outer layer PCB	Inner layer PCB
Low Voltage	Dendrites	Electromigration (fine line)
	Creepage	CAF
	Electrochemical Migration	Anodic Migration
High Voltage	Tracking	Treeing
	Arc-, Corona-discharge	Partial discharge
	Flashover	Dielectric breakdown
	Subsequent LV failures	Subsequent LV failures

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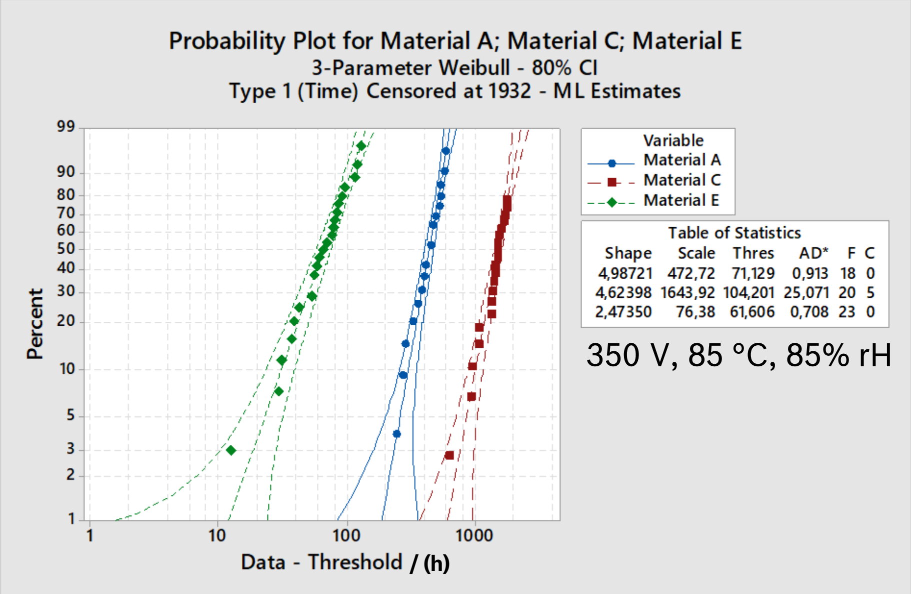
Electrochemical Reliability

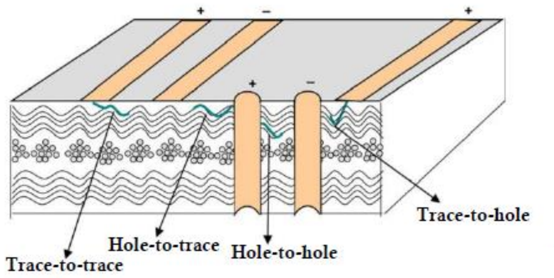
Inner Layer – Conductive anodic filament CAF

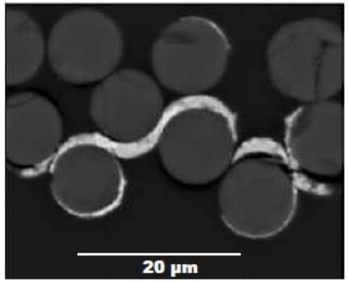
- CAF (Conductive anodic filament)
- Growth from Anode to Cathode inside PCB with formation of semi-conductive salt Atacamite $Cu_2(OH)_3Cl$
- Why are CAF lifetime models available?
  - Slow degradation of material (hydrolysis, rate determining)
  - Followed by fast ECM

$$TTF = BM \times f(H;T) \times \frac{(L-D)^2}{U}$$



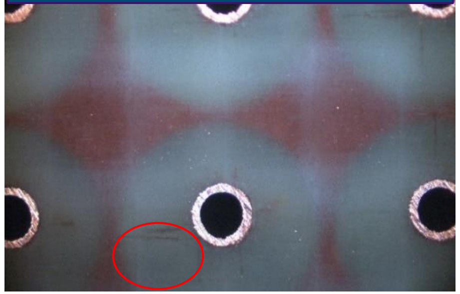
350 V, 85 °C, 85% rH



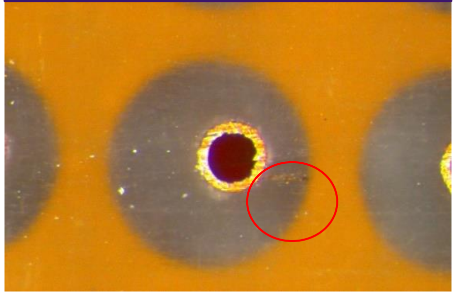


TTF: time to failure
BM: Base material
H: humidity
T: Temperature
L: distance
D: distorted zone
U: Voltage
EoL: End of life

CAF H-IL failure, material A



CAF H-IL failure, material E



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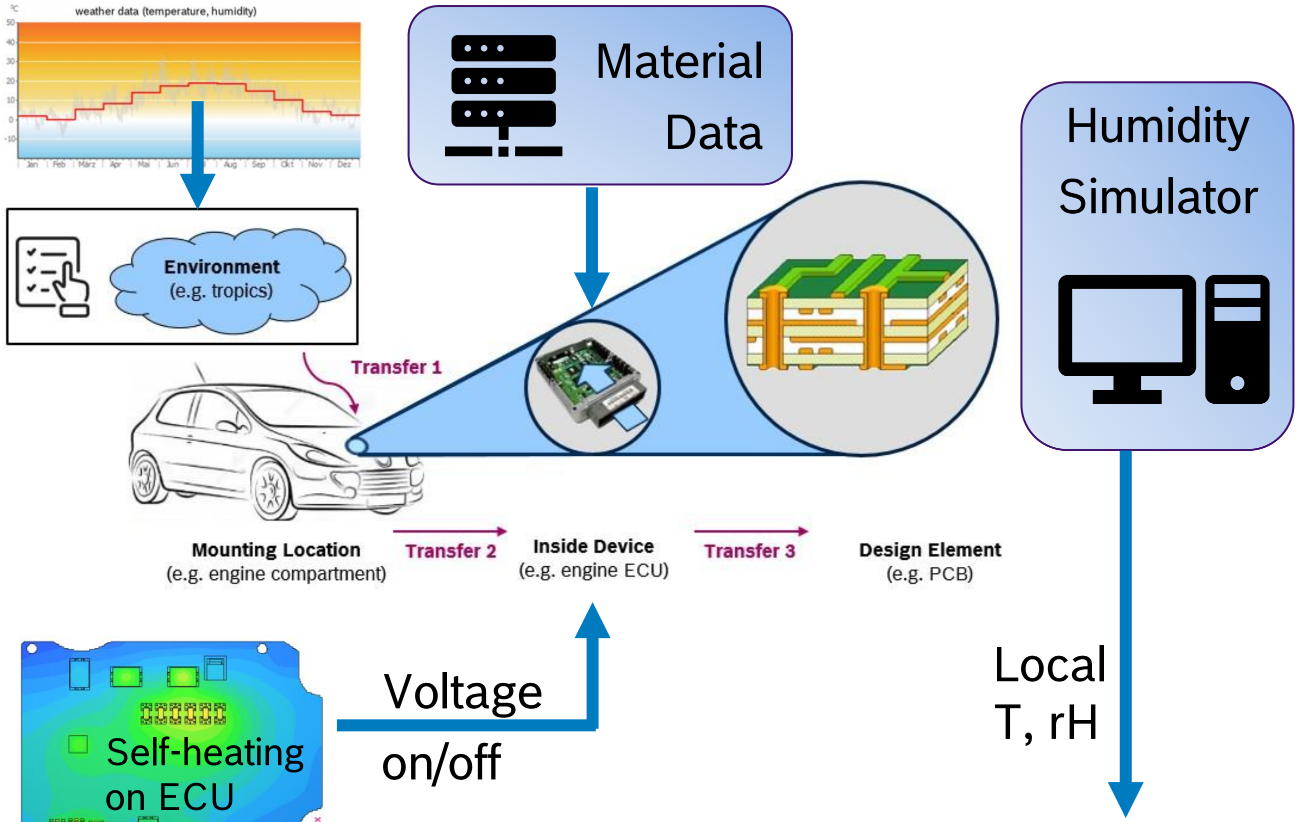
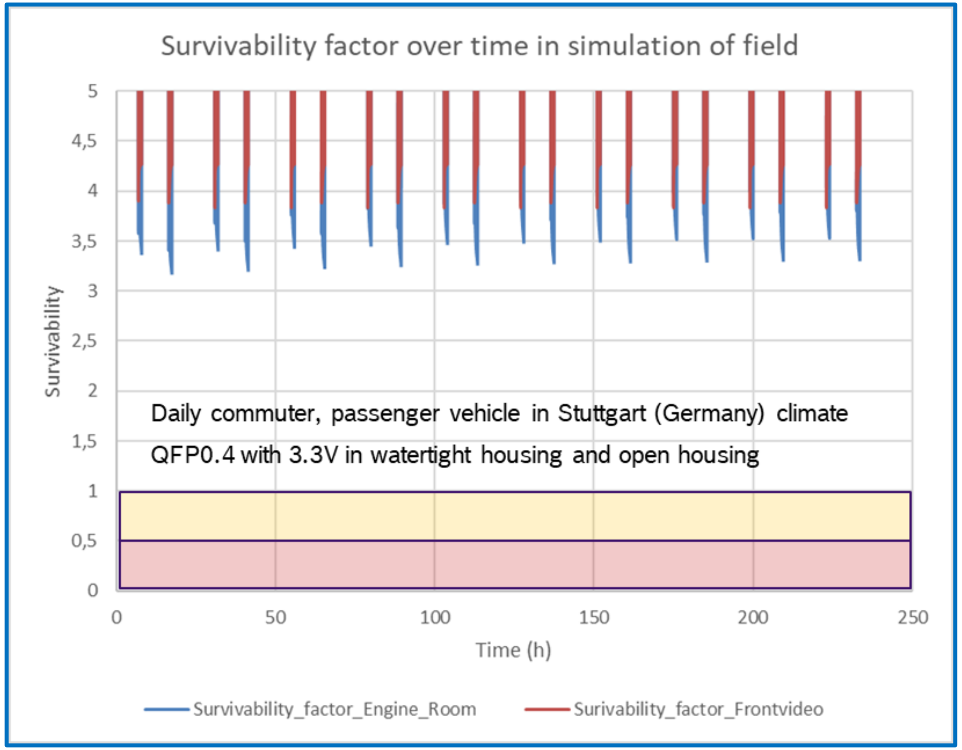
Electrochemical Reliability
Humidity robustness – Electrochemical migration @ PCB surface





$$\mathbf{ECM_{risk} = r[SIR\ as\ f(T, rH) - SIR_{limit}\ as\ f(U)] \cdot r(U/d^2) \cdot r(contamination)}$$

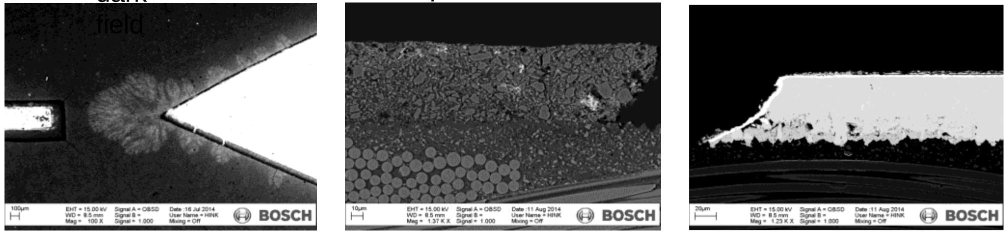
Source: L. Henneken, Proceedings of IPC APEX EXPO 2023

Electrochemical Reliability

Bias, distance for high voltage application

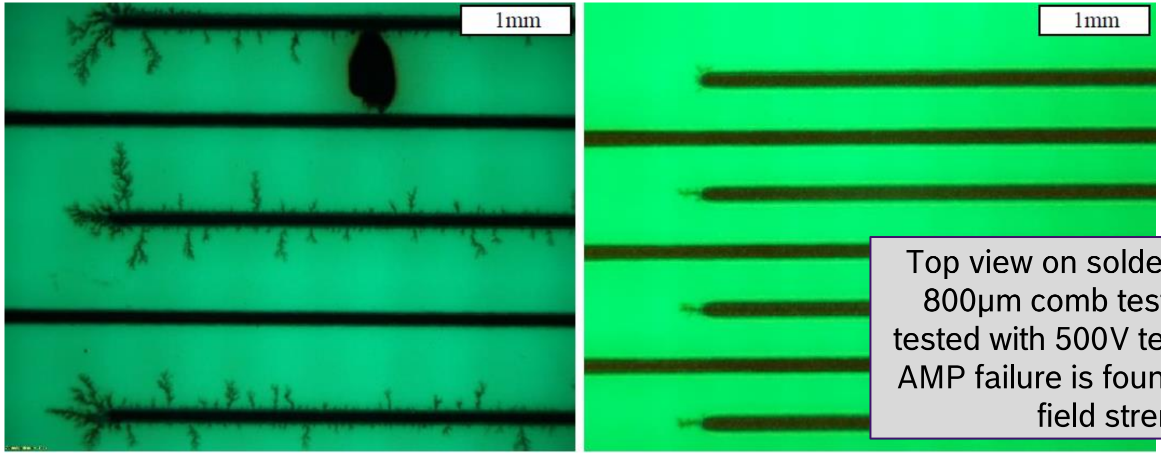
- With high voltage applications (> 300V) a change in failure modes is observed,
- Partial discharge mechanisms causing AMP failures become increasingly dominant,
- Thus E-field and Voltage are determining the risk of electrochemical failures:
  - $ECM_{risk} \approx U^2 f(t) / d$ (for HV-defects)

dark field | polarized | UV



overview SEM | Cross section S/M near anode | Cross section Cu tip at anode

Electrochemical treeing with HV-load:
1000h at 1000V, 85 °C, 85 % rH;
A semi-conductive Cu-Oxide salt is formed from anode



Top view on solder mask covered test structures with UV light. Left: 800µm comb tested with 1000V test voltage. Right: 400µm comb tested with 500V testing voltage under 85°C, 85% rH. A more distinct AMP failure is found with 1000V than with 500V at identical electrical field strength for same materials and application.

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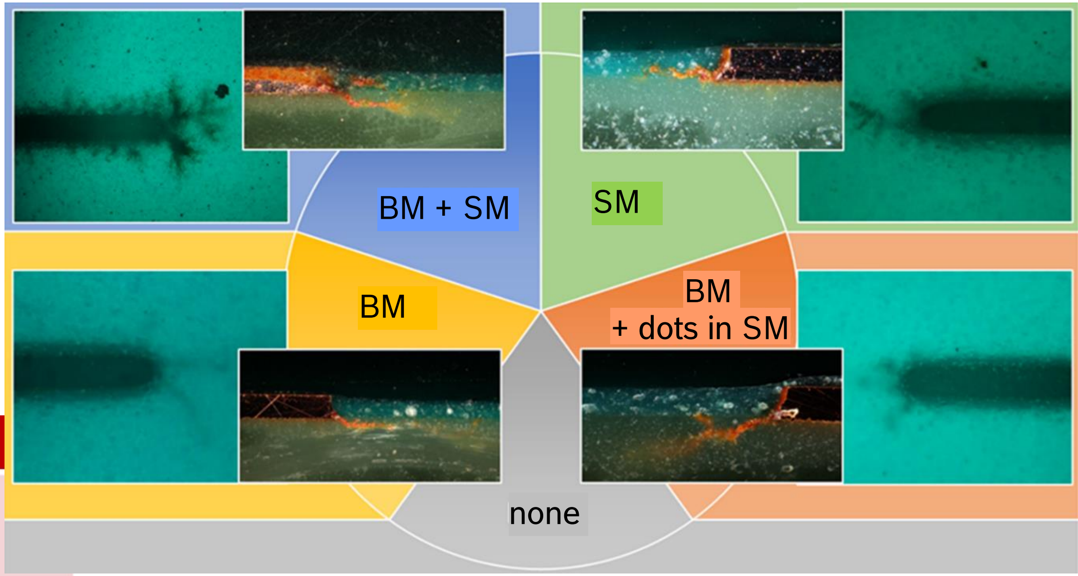
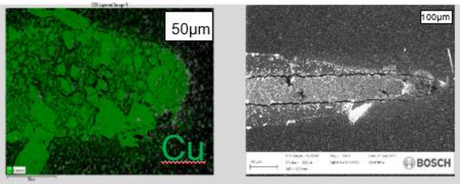
Electrochemical Reliability
Material Properties – Polymers (solder resist)

- Polymer composition becomes predominant factor in HV testing,
  - Cross linking, Hardener,
  - Fillers, Dispersing agents,
- They way of water path formation determines the failure mode (e.g. for solder resist as insulator).

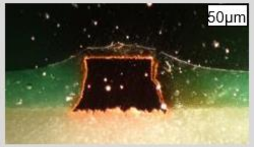


THB test with 1000V at 85 °C, 85% rH:
AMP is strongly material dependent,
Cu-Oxide(Cl) compound is formed along the water, path formation. The path of least resistance is taken.

Cathode (-)



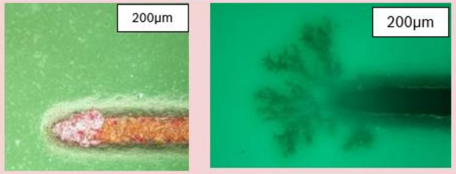
PCB surface SEM/EDX analysis



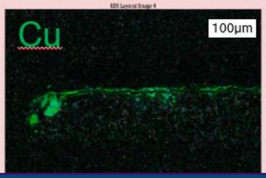
Cross section PCB

Cracks in solder mask SM
Hydrolysis reaction at (-)
“Cu-cloud” in around track

Anode (+)



PCB surface | PCB surface (UV light)



Migration in SM
(AMP treeing)
Cu-salt on SM

THB test: 500V, 85 °c, 85% rH

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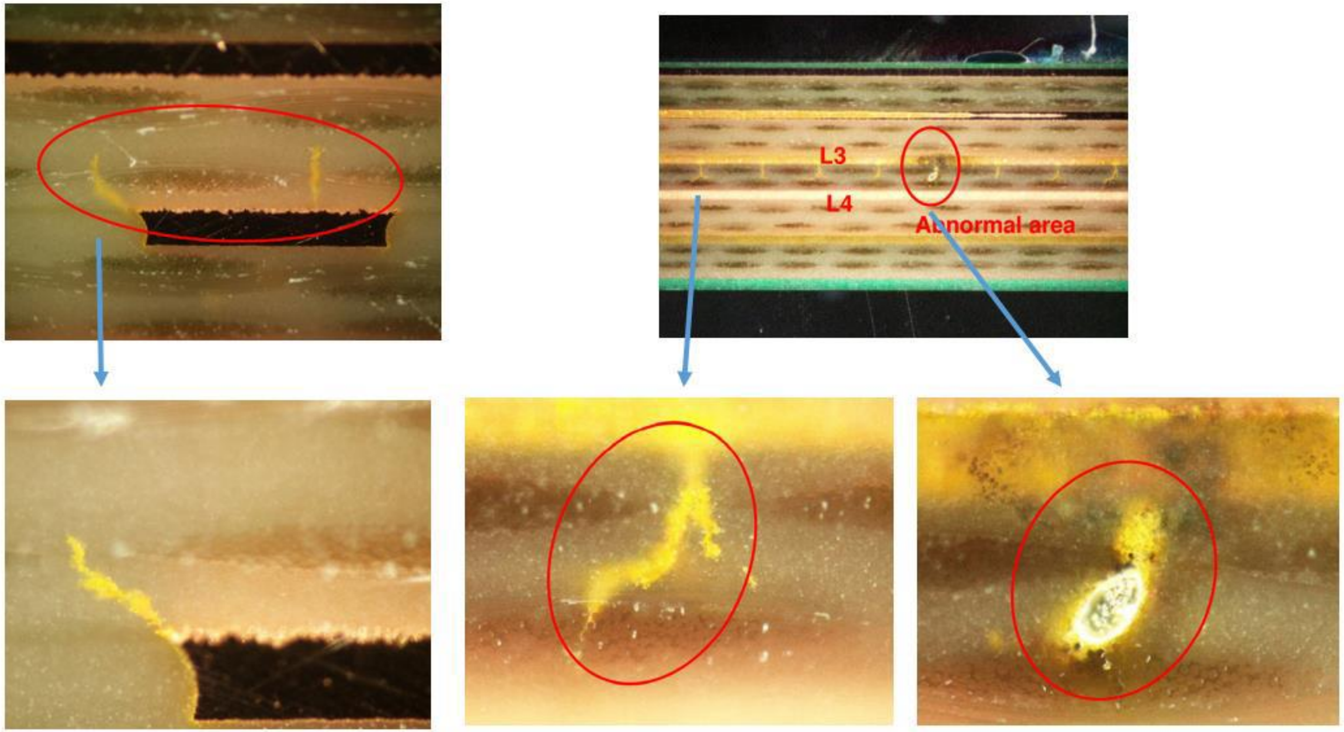
Electrochemical Reliability
Bias, distance for high voltage application

- With high voltage applications (> 300V) new failure modes are observed.
- Example: z-axis failures in 85°C/85% R.H. test w/ 1000 V applied bias.



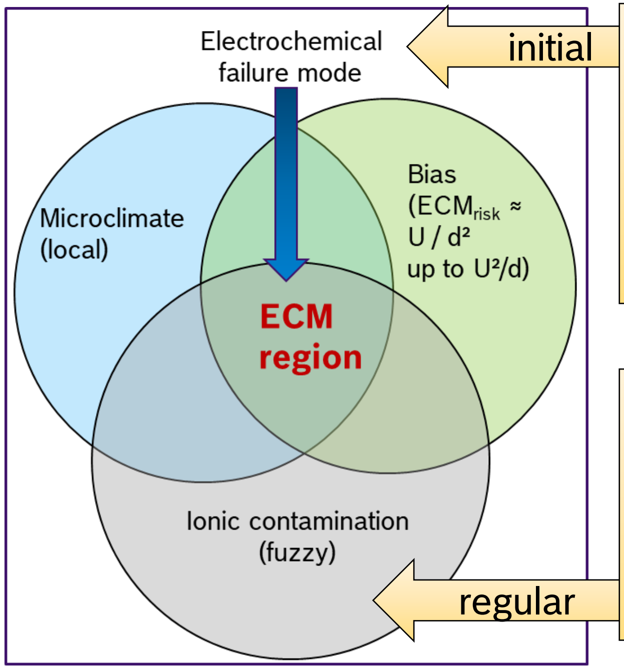
Migration stage

Breakdown stage

Source: W. Olbrich (TTM) Proceedings of IPC APEX EXPO 2023

Electrochemical Reliability
Way towards humidity robust products

- Level 1: Comprehensive THB-testing (e.g. CAF, SIR) for principal material- and process release
- Level 2: Active tests of products before SOP by reasonable climate conditions
- Level 3: Keep the materials and processes constant for series production



(1) Design
- Validation of ECM-robustness on design element level by comprehensive THB-testing,
- Complemented by active humidity tests on product level.

Qualification of robust materials & processes

Overstress test with units (heat damp cyclic)

Freeze of processes and materials

(2) Production
- <u>Standard:</u> Monitoring of released process windows by implemented stringent Q-system,
- <u>Optional:</u> Monitoring of ionic contamination on PBA (as agreed between Manufacturer and User).

Q-systems ensure constant processing; ROSE, IC, FTIR… optional as check with former fingerprint

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Electrochemical Reliability
Comprehensive THB testing

- Low voltage THB tests are well defined:
  - IEC TR 61191-9, IPC-9202, IPC-9203, IPC TM650, 2.6.25, IPC-9691,
  - Test coupons are available (ICP-B52, IPC-B53, IPC-9253…),
  - The right pre-ageing and climate conditions are ongoing topics of discussions.
- Aligned test procedure for high voltage testing of PCBs is still missing,
  - IPC task group D-33AA-HV has drafted a HV-test method to make users aware of the topic, ➔ IPC TM650, 2.5.7.4
  - ECPE 2022 PC29 is evaluating currently a new 1000V test coupon (outer layer).

Adapted from IEC TR 61191-9

Test Type	Condition	Purpose
T-shock test passive, option	1x, 2x or 3x reflow 1000h at 150 °C 100 cycles, -40 °C to +125 °C	Pre-aging of material
Constant climate SIR	1000h, 40 °C, 93% rH, 50V	Test for realistic material degradation (IPC-9202, IEC 60068-3-4)
Constant climate SIR, option	1000h, 65 °C, 93% rH, 50V	Preferred for polymer encapsulation (accelerated degradation)
Cyclic damp heat SIR	6 cycles, 25-55 °C, 96% rH, 50V	Test for short term dewing events (IEC 60068-3-4)
Constant climate CAF	1000h, 85 °C, 85% rH, 100V	For understood cases so that failure mechanism are not changed

Universität Bremen

BOSCH SEMIKRON innovation+service

Humidity-robust Printed Circuit Board Technologies for eMobility Solutions, 2022/PC29

Alexander Brunko

peters Coating Innovations for Electronics

ZESTRON High Precision Cleaning

ECPE Competence Centre

Institute for Electrical Drives, Power Electronics and Devices IALB

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Electrochemical Reliability
Acknowledgement

Teamwork

- Influence of Humidity on PCBAs is teamwork at Bosch-AE. Many thanks to all the Bosch-AE colleagues who are deeply involved in this work.
- Thanks for your attention.

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