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2024 AUSTIN

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# Wide-Bandgap Qualification:

# Meet Relevant Industry Standards

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# The big change!

# Our world is power electronics

- Green energy is linked to electrical power

- E-Mobility is the definition of “power electronic” today

- Power electronic is a luxury good when we think of transportation, elevators, heat pumps or air conditioning

# Global energy hunger drives entire industry to limits

Where Si based transistors and IGBTs did a great job the last 40 years today's applications e.g. Heat pumps, PV (photo voltaic), EV (electrical vehicle) and even electric air vehicles like EVTOLs (electric vertical take of and landing) or local and decentralized smart grid networks require

- Higher voltage bands
- Higher current ratings
- Better thermal behaviour
- Less power losses
- Faster switching
- Reduced size and wight

**higher efficiency**

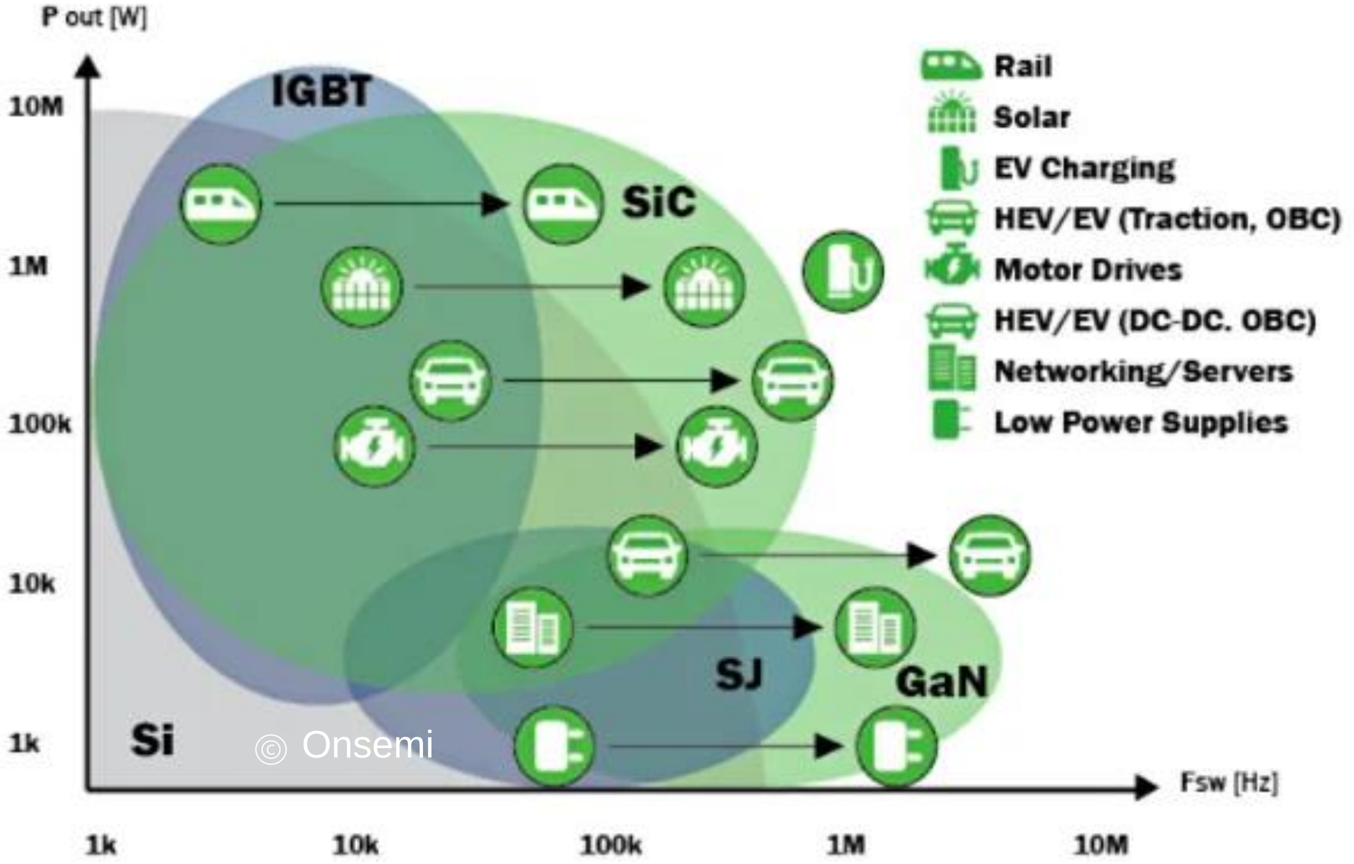
# The answer is easy & old: We move to WBG materials !

- In the mid 1970s SiC was under research for use as a new WBG material and late 1980s successfully applied under lab conditions

- Took another 20 years to release the first product to the market
  - in 2001 the first SiC Schottky diode by Infineon !!

# Power Semiconductor market: silicon vs. wide-bandgap

- Another 20years in the future the wide application of WBG devices is reality!
- We see a **massive shift from silicon to WBG** materials in high performance applications
- New technologies on old substrate like Super Junction MOSFETs bride the gap
- The **EV (electric vehicle) industry is THE main driver** for WBG power semiconductors, for both SiC and GaN

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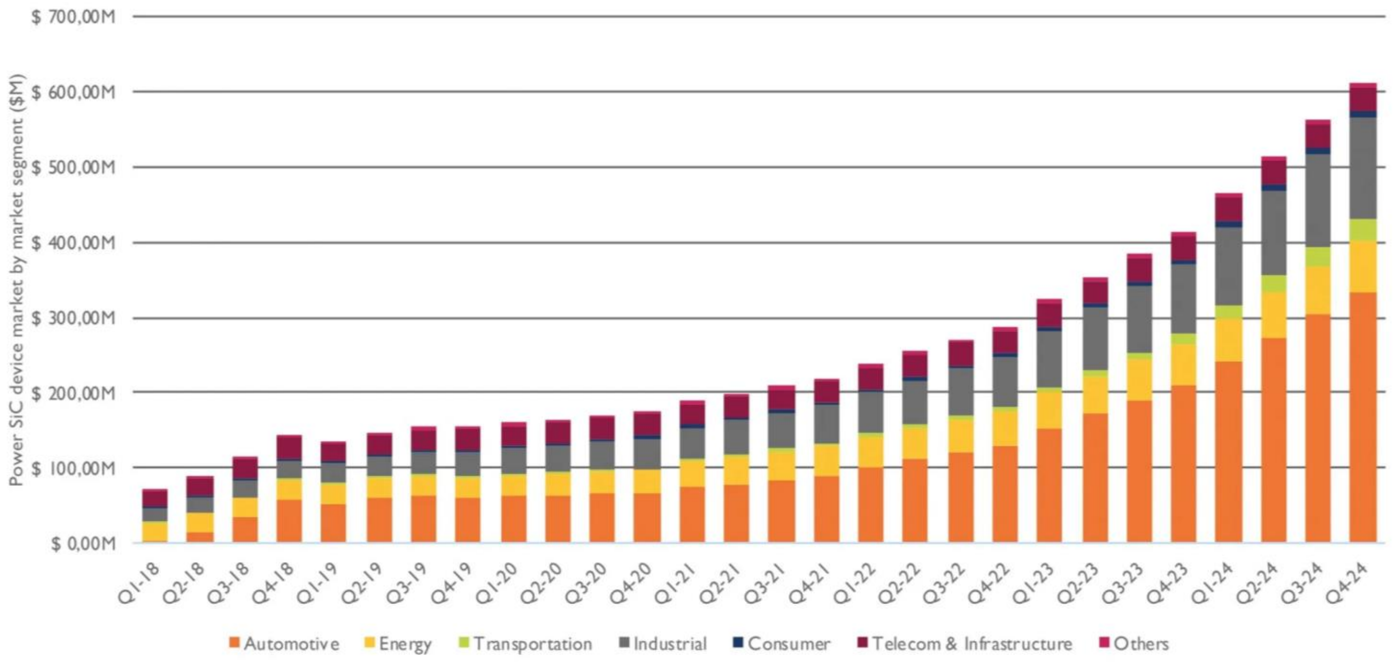
# Power Semiconductor device market for xEV

## Power SiC device market Forecast by segment

*(Source: CS Market Monitor, Yole Développement, Q4 2019)*




- This figure represents the estimated market for SiC devices, including both open and captive markets.
- The ramp up of automotive market in 2018 was mainly due to Tesla's adoption of SiC in its main inverter.
- Similar to automotive application, other applications such as industrial, energy and transportation are expected to grow.

YOLE Développement



- Especially the automotive sector drives the growth of SiC in the next recent years
- But other fields catch up since the energy market needs to gain efficiency in total
- Growth of the SiC market is limited by availability not by demand
- Massive investment around the world to increase production is ongoing

# Wide-Bandgap Qualification:

# How does it work ?

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# Reliability Tests Si vs. SiC

- There are decades of investigation and in-field experience available for SI, together with deep understanding of failure modes, acceleration factors and probabilities

- Based on that knowledge the qualification for SI could be optimized:
  - Tests with high acceleration factors
  - Tests only needed with small engineering samples
  - Tests not needed anymore

- The Situation is **fundamental** different for SiC or GaN!

# How does “reliability” work?

**Every application built in high numbers needs to be carefully designed:**

- What is the expected performance
  ➡ At the beginning and over lifetime

- How long will it work
  (Meantime between failure)

# How does “reliability” work?

Every application built in high numbers needs to be carefully designed:

Looking at Electric Vehicles:

- What is the expected car life?
- How efficient will the car run… over lifetime?
- What is the risk for recalls, in cost and reputation

➡ These questions carry billions of dollars $

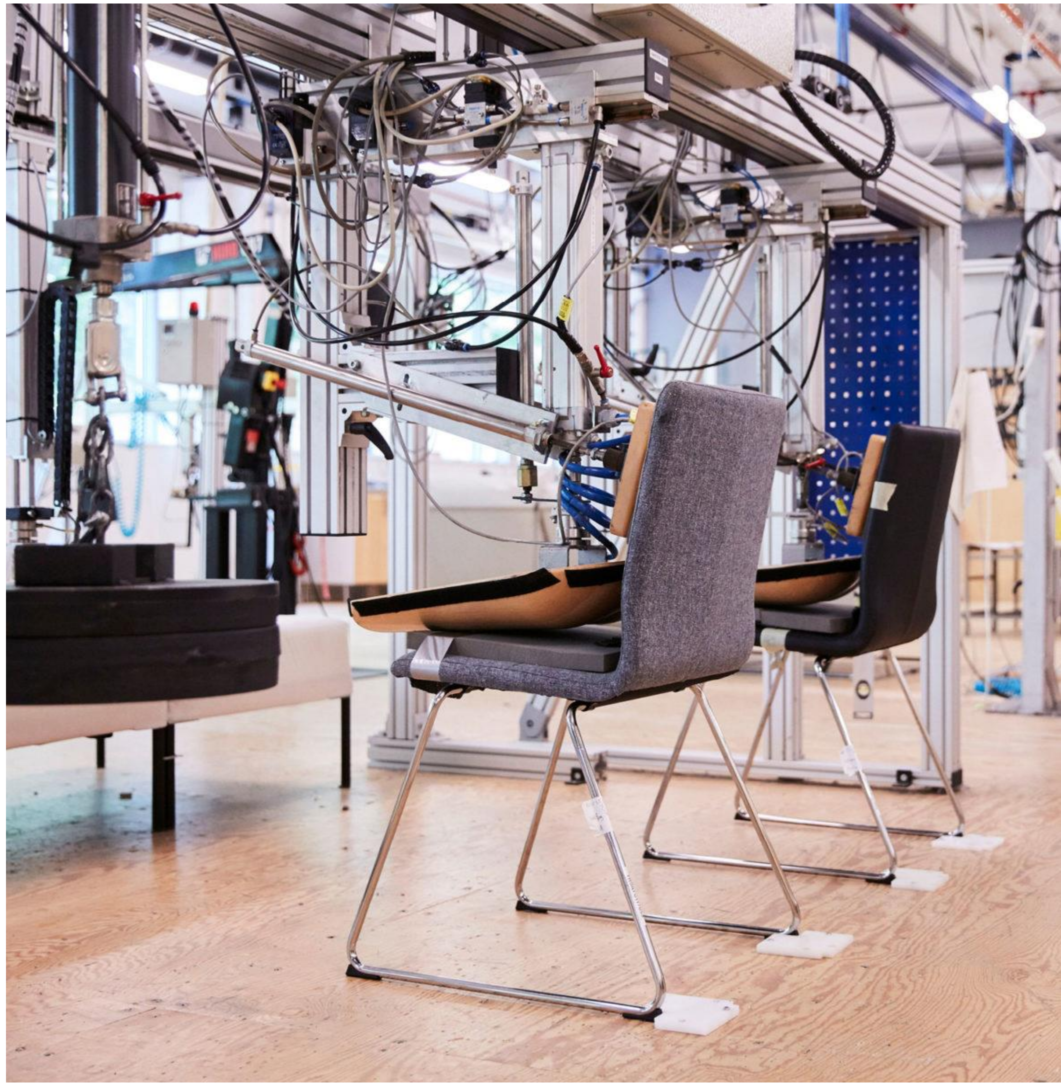
# How long will it keep the performance?

What are my possibilities to
…measure/calculate/whatever that?

Build and let it run?

Requirements:

- experience for first design (statistic/design rules from the past)
- Test subjects (sample size for statistics)
- Testability
- Time



Chair testing at IKEA

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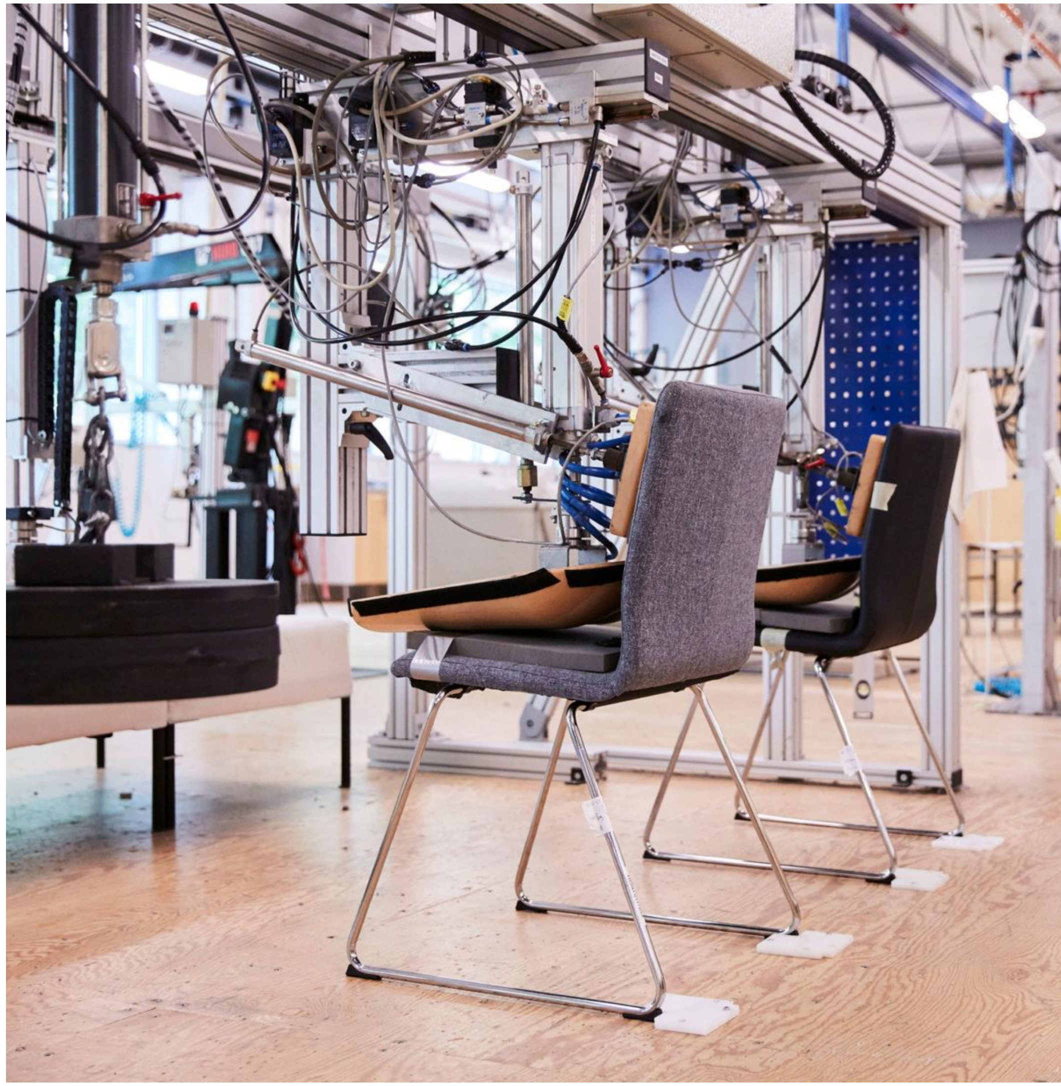
Time to market?
New technologies?



Chair testing at IKEA

# Disruptive EV WBG market!

Time to market is king,

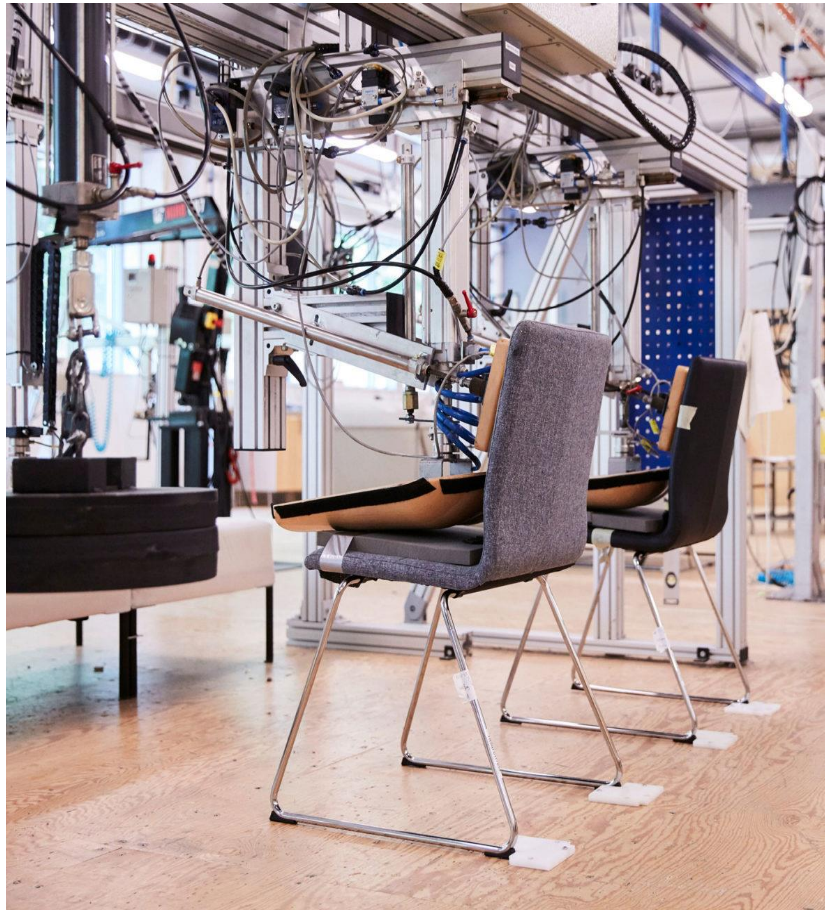
Power Semiconductor devices built into cars are not available in series form years in advance – EV runs on newest generation.

The challenge is to test ~20 years of car live within ~1 year!
Or 30 year green energy solar / wind inverter within ~1 year
… or train inverter, washing machine, etc etc

# Test 20 years within 1 year

We need to accelerate the testing – preferably 20 years within 1000 hour!
… that is an acceleration factor of **x175**
**(**for components that are always on)

➡ Can that be done like IKEA?
➡ In picture we have highly accelerated “chair sit down”
… but what about fabric UV light stability?



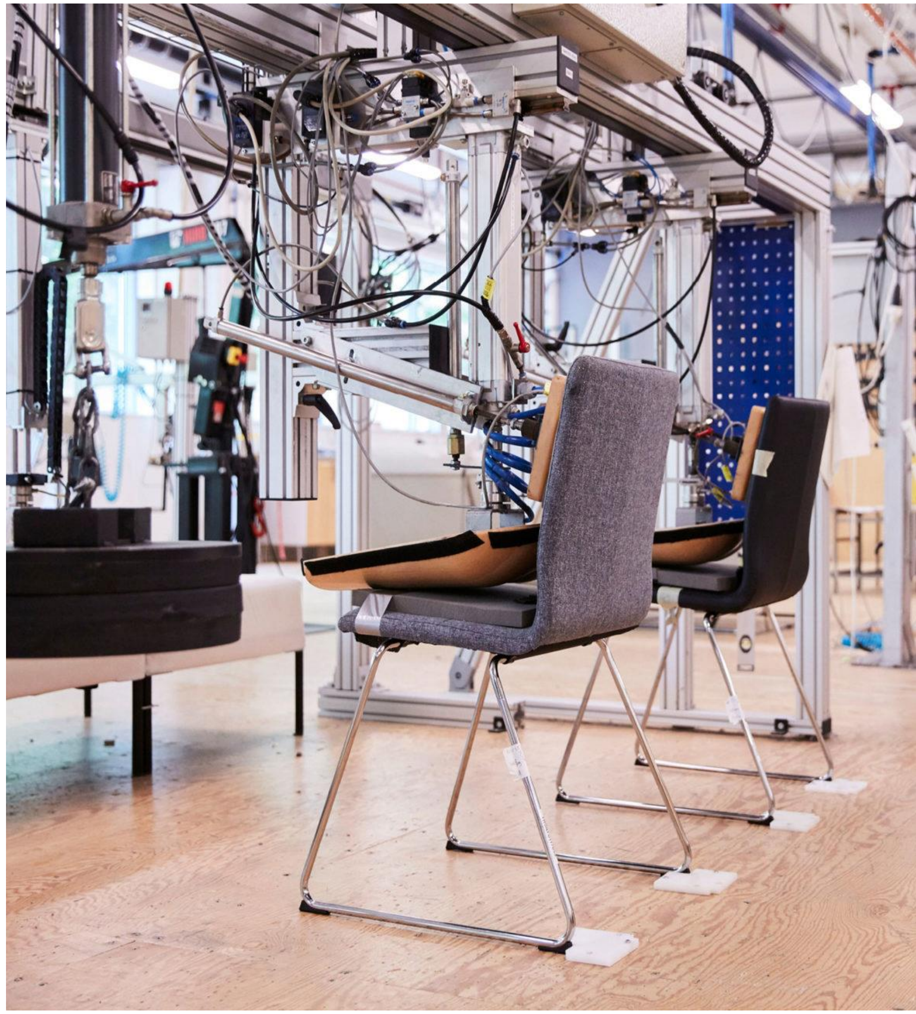
Chair testing at IKEA

# Test 20 years within 1 year

Accelerated testing can be done for
- people taking a seat
- UV light

in specialized setups but **not** together!

➡ We have different failure mechanics we need to look at!

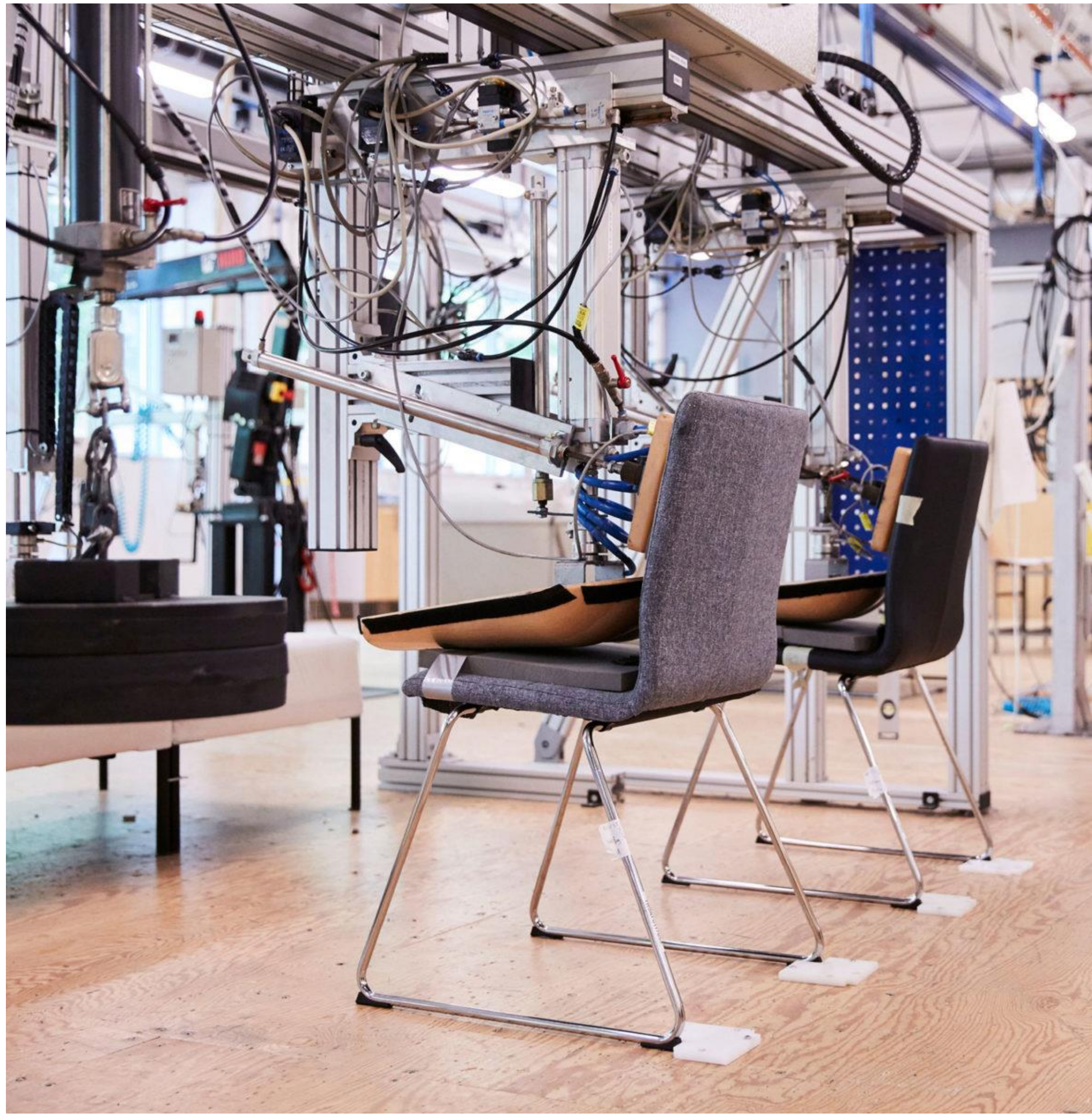


Chair testing at IKEA

# Test 20 years within 1 year

How to find out?

| | |
|---|---|
| Testsetup „seating“ | Lifetime: 30k seatings |
| Testsetup „Fabric UV Light“ | Lifetime: 100k Hours UV light |



Chair testing at IKEA

# Test 20 years within 1 year

How to find out?

**Mission Profile!**

| | |
|---|---|
| Dining table chair: | 6 sits & 4 hours direct sunlight a day |
| Outdoor chair: | 0.2 sits & 8 hours direct sunlight a day |

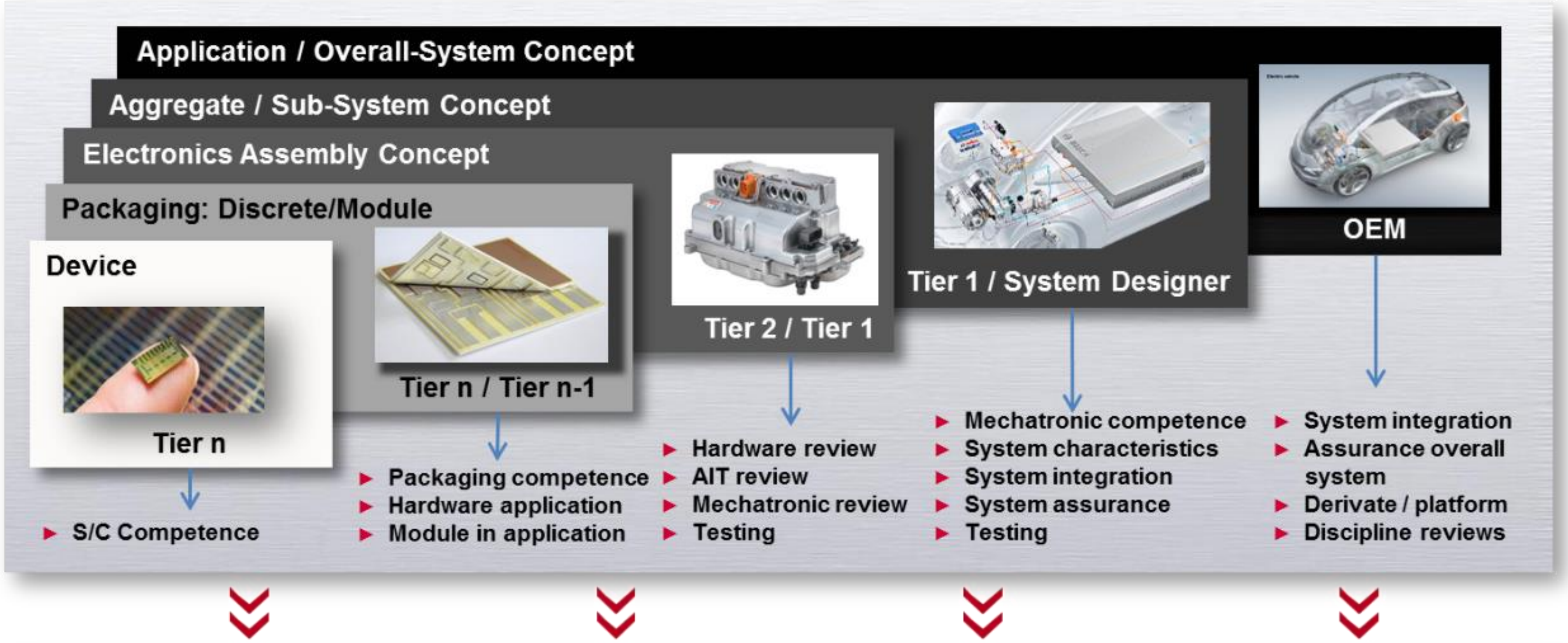
➡ Now we can calculate which failure mechanic limits the lifetime!
➡ Or how the chair fabric will look after 2 years!

# Wide-Bandgap Qualification:

# How does it work in automotive industries

# Packaging – Reliability Assessment

## 'Front-Loading' of Function and Robustness in Automotive Electronics




**Functionality and Robustness Validation on Electronics Design upon all chain links**

- **Design starts already upon device** (design, testing, screening / usage in application / life-time)
- **OEM competence mission down to Tier n**
  - Discussion about application and mission profile with S/C-manufacturer / hardware assembler
  - Expert's dialog along supply chain (Tier n… Tier 1)
- **Competence development at Tier n … Tier 1**

**Source:**
**B. Hellenthal, Audi AG, within the BMBF publicly funded project 'ProPower'**

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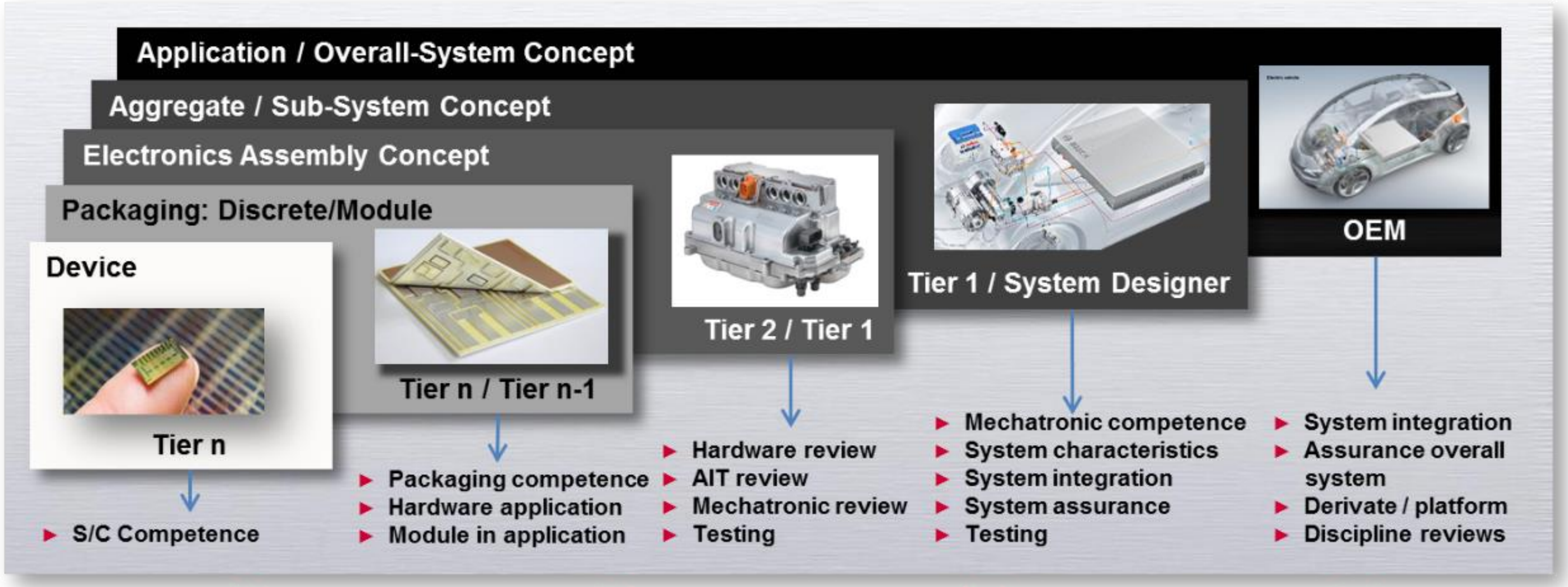
# Packaging – Reliability Assessment

## Test and Qualification Demands on each Link of the Supply Chain (incl. WBG specifics)




**(Sub-)Components' test and (delta-)qualification cycles**

| | | | |
|---|---|---|---|
| Require-ments | Require-ments | Require-ments | Mission Profile |
| AEC-Q, JEDEC, IEC, DeQuMa | AQG324, IEC, ISO IPC, DeQuMa | IEC, IPC, ISO, OEM-standards, HW-DQM | IEC, IPC, ISO, OEM-standards, HW-DQM, legal regulations |
| Supply | Supply | Supply | Final System |







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# Herculean Industry Task:

# Qualification Standards

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# General Aspects on Standardization

**Advantages**

- Description of a set of technological minimum requirements for all market participants
  - E.g. prevention of ‘windfall-gain due to opportunistic behavior‘
- Minimization of transactional costs
- Contribution on quality assurance
  - E.g. implementation of ‘Robustness Validation’ methodology
- Avoidance of reserves at introduction of technological innovation
- Market preparation
  - Fulfillment of customer expectations
- Triggering of external effects
  - Utilization for several industry branches

**Disadvantages**

- Necessary specific invests in equipment and competences
  - knowledge
  - experiences
- As the case maybe: depreciations on already performed, but misallocated specific invests
- Allocating portion of qualification / testing on production costs
- Typically: fixation of ‘state-of-the-art’
  - Well-anchored knowledge is a premise for a standard.
  - But, in an era of accelerated technology progresses more agile acting – in terms of faster revisions and updates – is necessary!



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# JEDEC

Global Standards for the Microelectronics Industry

# Qualification Standard

JEDEC®
Global Standards for the Microelectronics Industry

## Technology Focus Areas

For over 50 years, JEDEC has been the global leader in developing open standards and publications for the microelectronics industry.

JEDEC committees provide industry leadership in developing standards for a broad range of technologies. Current areas of focus include.

(JEDEC website)

**Guided Search**

Click a term to initiate a search.

**Committees**

- JC-10: Terms, Definitions, and Symbols (17)
- JC-11: Mechanical Standardization (626)
- JC-13: Government Liaison (35)
- JC-14: Quality and Reliability of Solid State Products (170)
- JC-15: Thermal Characterization Techniques for Semiconductor Packages (20)
- JC-16: Interface Technology (39)
- JC-22: Diodes and Thyristors (16)
- JC-25: Transistors (36)
- JC-40: Digital Logic (80)
- JC-42: Solid State Memories (158)
- JC-45: DRAM Modules (136)
- JC-63: Multiple Chip Packages (3)
- JC-64: Embedded Memory Storage & Removable Memory Cards (37)
- JC-65: RFID (1)
- JC-70: Wide Bandgap Power Electronic Conversion Semiconductors (13)

**Document Types**

- JESD (JEDEC Standards) (437)
- MO- (Microelectronic Outlines) (354)
- JEP (JEDEC Publications) (121)
- MODULE (4, 4.2, 4.3, 4.4, 4.5, 4.6, 4.7 Modules) (119)
- TO- (Transistor Outlines) (53)
- CO- (Carrier Outlines) (41)
- MS- (Microelectronic Standards) (34)
- SO- (Socket Outlines) (31)
- SPD (4.1.2 Serial Presence Detect) (26)
- SPP- (Standard Practices and Procedures) (25)
- DO- (Diode Outlines) (19)
- DG- (Design Guideline) (16)
- SDRAM (3.11 Synchronous Dynamic Random Access Memory) (16)
- More...

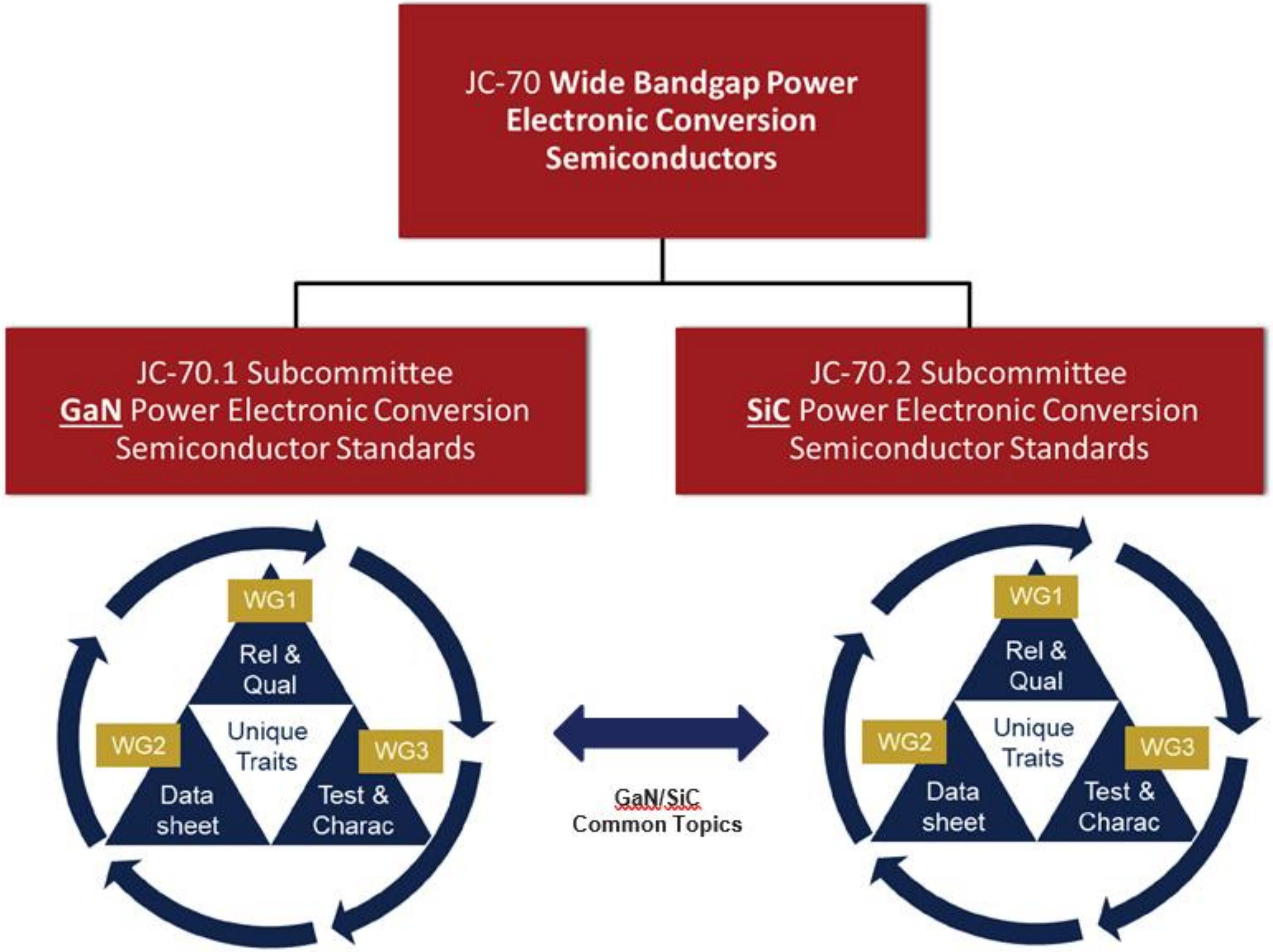
# JC -70 WBG Semiconductors Purpose

- **Develop guidelines** and **standards for wide bandgap (WBG) components**, covering unique behaviors of Silicon Carbide (SiC) and Gallium Nitride (GaN)

- **Set consistent expectations for reliability and qualification procedures, Test and Characterization Methods, and Datasheet Elements and Parameters** across different microelectronics suppliers

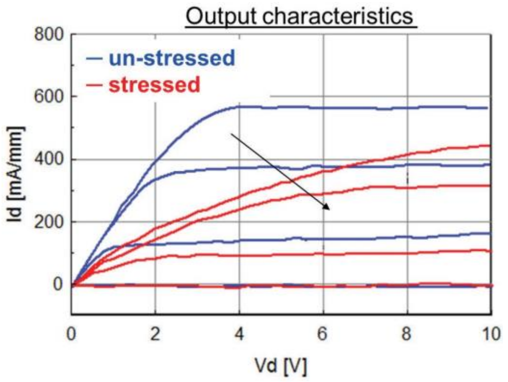
- **Facilitate the widespread adoption** and integration of WBG components **in various applications** like power electronics, automotive systems, and renewable energy

## JC-70 Structure for Wide Bandgap



# Examples for Published GaN Guidelines

How to address dynamic electrical effects due to trapped charges by test methods and procedures




JEP173


JEDEC PUBLICATION

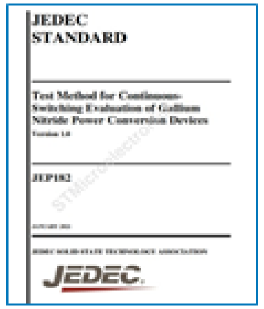
Dynamic ON-Resistance Test Method Guidelines for GaN HEMT based Power Conversion Devices, Version 1.0

JEP173

JEDEC

Dynamic RDS(on) Test Method

JEP182


JEDEC STANDARD

Test Method for Continuous-Switching Evaluation of Gallium Nitride Power Conversion Devices

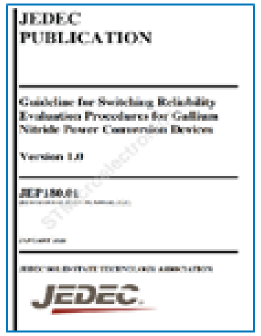
Version 1.0

JEP182

JEDEC

Continuous Switching Test Method

JEP180.01


JEDEC PUBLICATION

Guideline for Switching Reliability Evaluation Procedures for Gallium Nitride Power Conversion Devices

Version 1.0

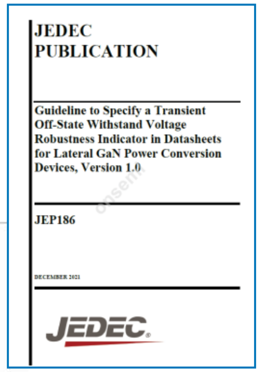
JEP180.01

JEDEC

Switching Reliability Evaluation Procedure

How to specify maximum allowed transient drain-source voltage peaks in datasheets (in absence of avalanche)

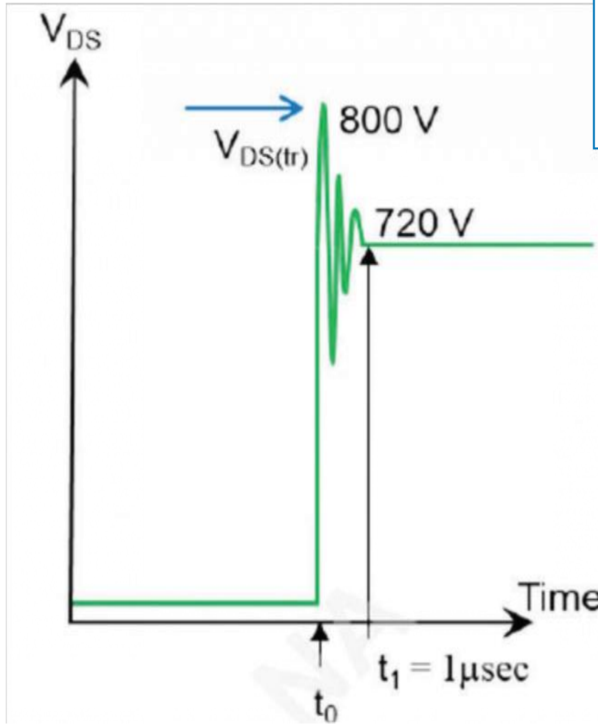
JEP186


JEDEC PUBLICATION

Guideline to Specify a Transient Off-State Withstand Voltage Robustness Indicator in Datasheets for Lateral GaN Power Conversion Devices, Version 1.0

JEP186

JEDEC

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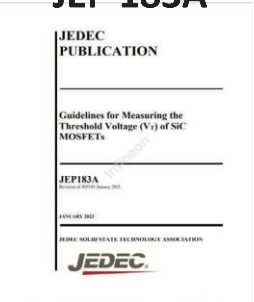
# Examples for Published SiC Guidelines

How to address electrical effects due to gate trapped charges.

Long term or more permanent
(Gate Switching Instability (GSI))

JEP 183A

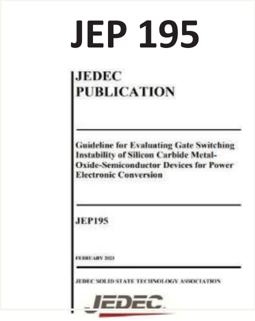



Measure VTH in a reproducible manner

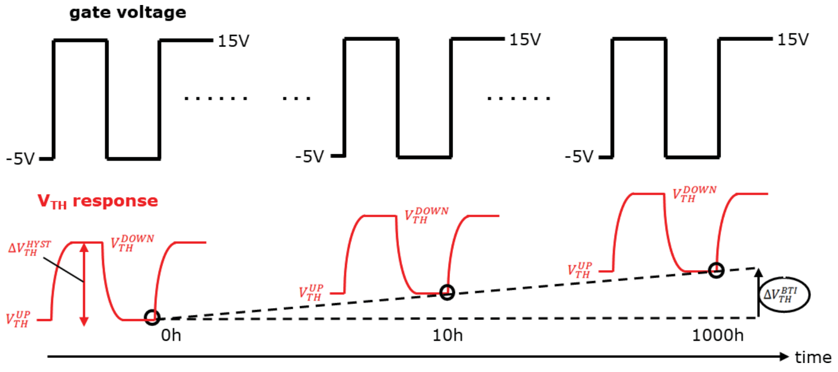
JEP 184


Understand VTH evolution under static gate bias conditions

JEP 195

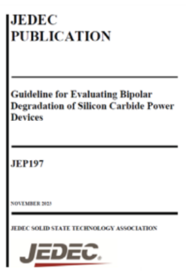



Understand VTH evolution under gate switching conditions




How to specify maximum allowed transient drain-source voltage peaks in datasheets (in absence of avalanche)

JEP197



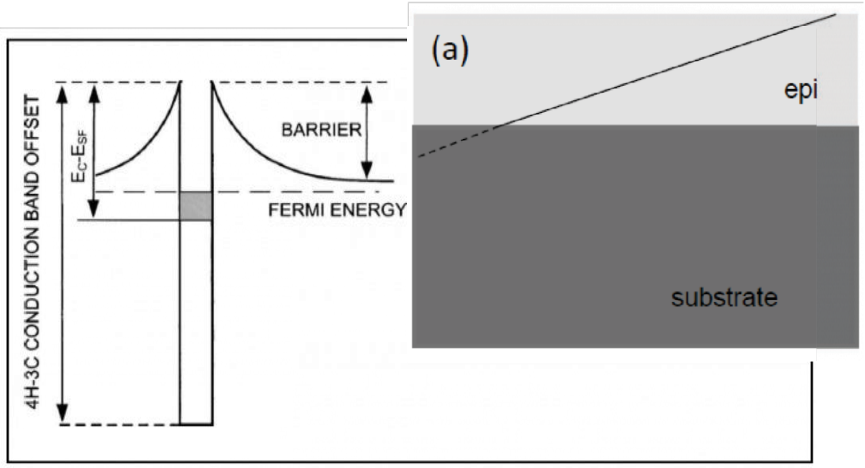
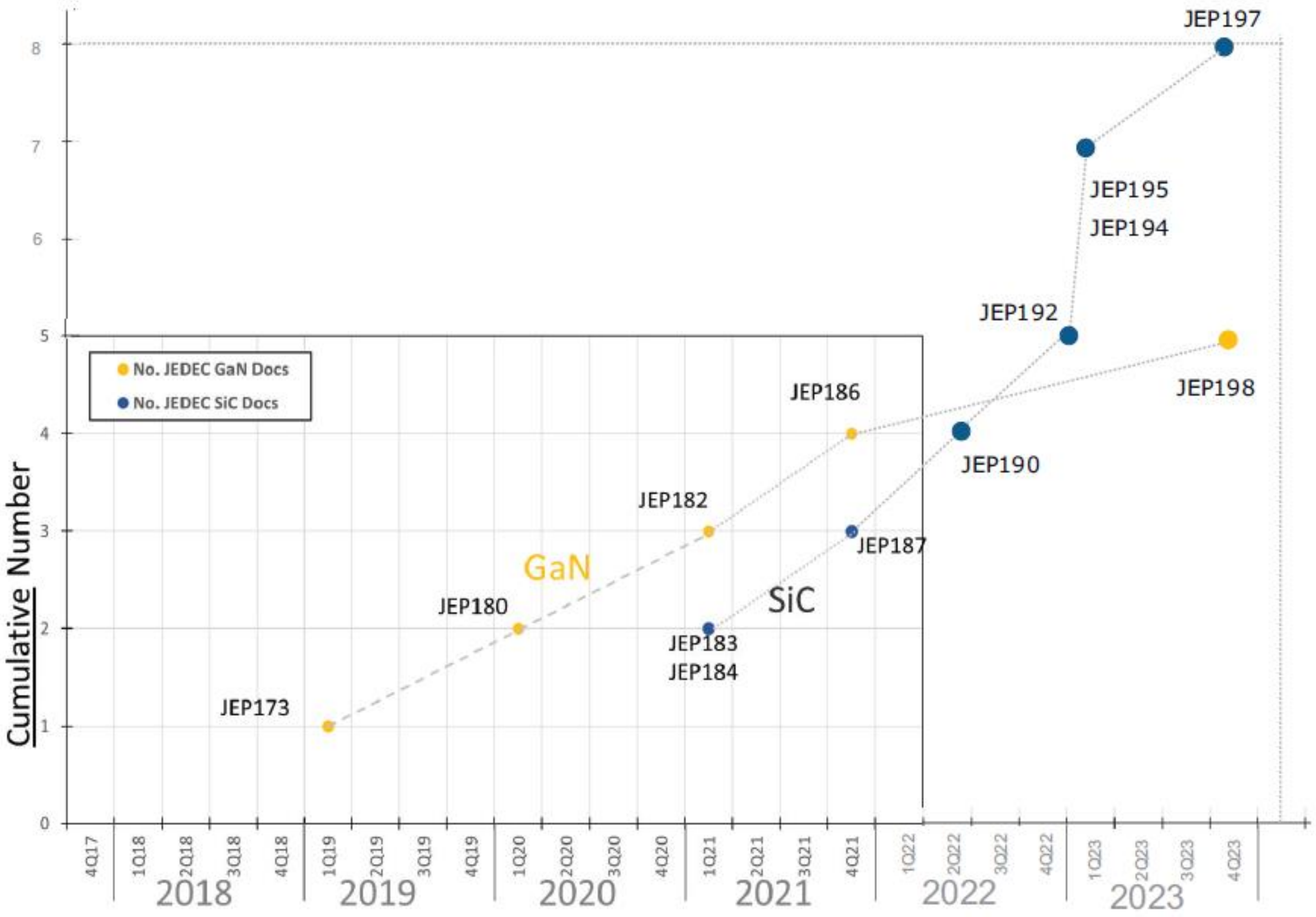




**Figure 3 — Quantum Well Representation of Shockley Stacking Fault**

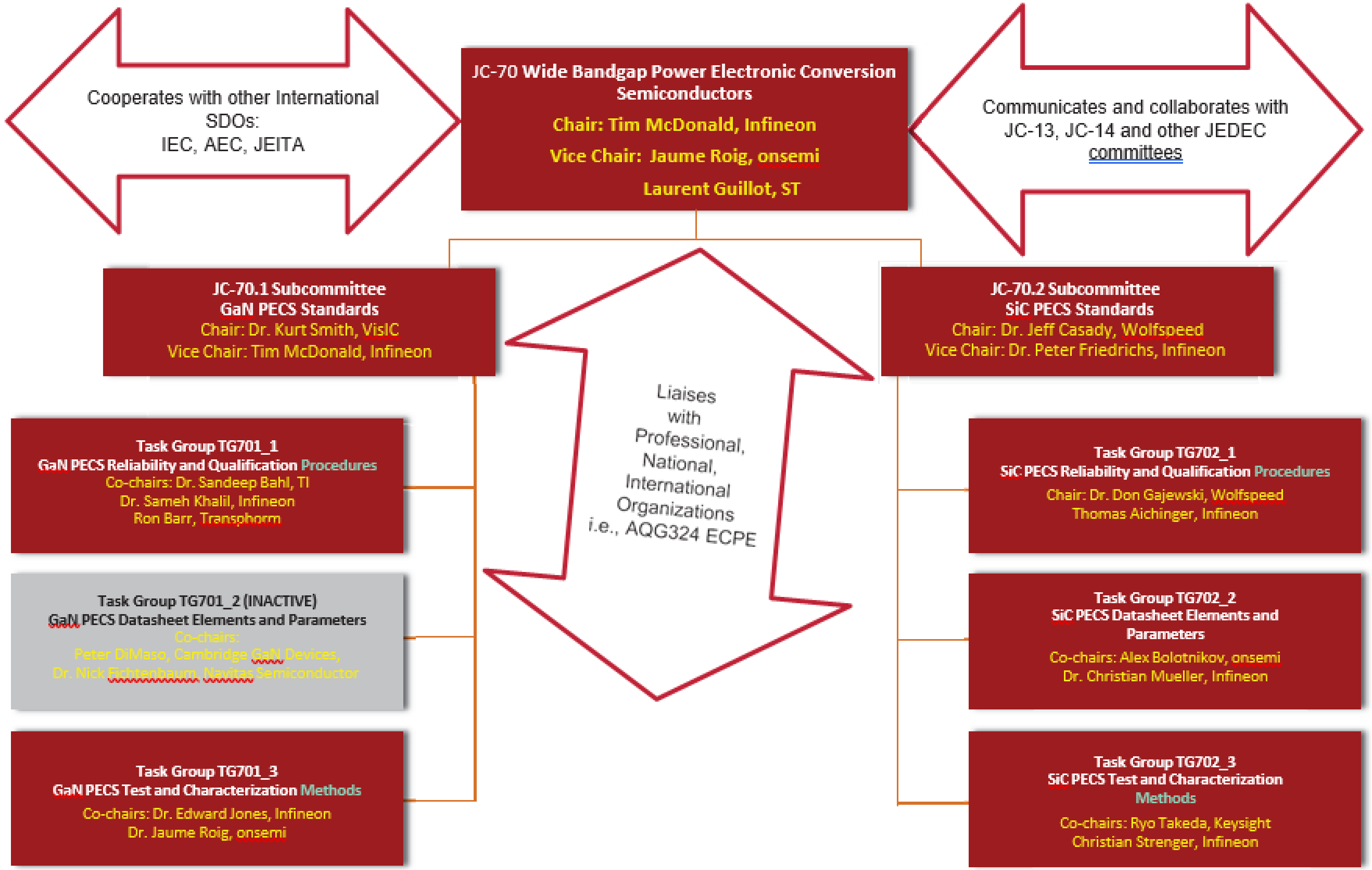
# JC-70 Publications to Date

| | | |
|---|---|---|
| Guideline for Evaluating Bipolar Degradation of Silicon Carbide Power Devices | JEP197 | Nov 2023 |
| Guideline for Reverse Bias Reliability Evaluation Procedures for Gallium Nitride Power Conversion Devices | JEP198 | Nov 2023 |
| Guideline for Gate Oxide Reliability and Robustness Evaluation Procedures for Silicon Carbide Power MOSFETs | JEP194 | Feb 2023 |
| Guideline for Evaluating Gate Switching Instability of Silicon Carbide Metal-Oxide-Semiconductor Devices for Power Electronic Conversion | JEP195 | Feb 2023 |
| Guidelines for Measuring the Threshold Voltage (VT) of SiC MOSFETs | JEP183A | Jan 2023 |
| Guidelines for Gate Charge (QG) Test Method for SiC MOSFET | JEP192 | Jan 2023 |
| Guideline for Evaluating dv/dt Robustness of SiC Power Devices, Version 1.0 | JEP190 | Aug 2022 |
| Guideline to Specify a Transient Off-State Withstand Voltage Robustness Indicator in Datasheets for Lateral GaN Power Conversion Devices, Version 1.0 | JEP186 | Dec 2021 |
| Guidelines for Representing Switching Losses of SiC MOSFETs in Datasheets | JEP187 | Dec 2021 |
| GUIDELINE FOR EVALUATING BIAS TEMPERATURE INSTABILITY OF SILICON CARBIDE METAL-OXIDE-SEMICONDUCTOR DEVICES FOR POWER ELECTRONIC CONVERSION | JEP184 | Mar 2021 |
| GUIDELINE FOR SWITCHING RELIABILITY EVALUATION PROCEDURES FOR GALLIUM NITRIDE POWER CONVERSION DEVICES | JEP180.01 | Jan 2021 |
| TEST METHOD FOR CONTINUOUS-SWITCHING EVALUATION OF GALLIUM NITRIDE POWER CONVERSION DEVICES | JEP182 | Jan 2021 |
| DYNAMIC ON-RESISTANCE TEST METHOD GUIDELINES FOR GaN HEMT BASED POWER CONVERSION DEVICES, VERSION 1.0 | JEP173 | Jan 2019 |

- 13 Documents Issued Since 2019 (5 for GaN, 8 for SiC)



# JC-70 Cooperations and Communications



# ECPE AQG 324

# Qualification (Quasi-) Standard

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# ECPE Working Group AQG324

## Representatives and Members

WG Chairman: Dr. Martin Rittner (Robert Bosch)

Vice Chairmen: Dr. Markus Thoben (UAS Dortmund)
Peter Dietrich (Richardson RFPD)
Frank Heidemann (National Instruments)

WG Members: > 30 industrial members including OEMs, tier 1suppliers, power semiconductor and module manufacturer, test equipment supplier

**AQG324: Board, Chairmen**
Dr. Rittner (Bosch)
Prof. Thoben (UAS Dortmund), Mr. Dietrich (Richardson RFPD), Mr. Heidemann (SET)

**Core-Team: Board + Sub-Group-Leaders + OEM representatives**

- **SG1 Endurance Tests (HTxy)** – Mr. Schmitt (Semikron)
- **SG2 Power Cycle Tests (PCT)** – Mr. Tüllmann (Infineon)
- **SG3 Scope & Advanced AIT** – Mr. Ewald (Fuji Electric), proxy: Mr. Farkas (Mentor)
- **SG4 Insulation & Environ. Tests** – Dr. Thieman (Valeo Siemens)
- **GaN Task Force** – Mr. Dietrich (Richardson RFPD)

# ECPE Working Group AQG324

## CV of (LV)AQG324

| Feb/ 2011: | Mar/2012 | Mar/2013 | Oct/2013 | May/2014 | Jun/2017 | April/2018 | 2018 | x/2021 |
|---|---|---|---|---|---|---|---|---|
| German OEMs to generate a standard for qualification of power modules that includes endurance tests | Draft version for OEM internal review | Version to align with the supplier industry via ZVEI and ECPE | Check global view → Establish cooperation with JEITA EDR-4711 | Release LV 324 as supplier regulation - each OEM uses individual Group Standard with identical content) | Mandate from OEMs to ECPE to host LV 324 → Kick-off for the ECPE Working Group AQG 324 | Release of 1st ECPE AQG 324 Doc.<br><br>**May/2019**<br>Release no.: 02.1/2019 | Check for further Standards: CATARC<br><br>**Oct/2019**<br>Exchange with JEDEC | next Release will cover SiC-based power modules |

2011 2012 | 2013 | 2014 2015 / 2016 | 2017 | 2018 2019 | 2020 2021

**Concept phase of LV324**

**Alignment phase**

**Application phase**
- The document was highly accepted from many suppliers
- Further feedback is continuously obtained for the further development

**Transfer to AQG 324 hosted by ECPE association**
- Further development of the Guideline
- Extension to new technologies

# ECPE AQG324 Main Document

## Some General ‘Mind Settings’ or Premises (Excerpt)

- Do not compete with any suitable already existing standard or ‘quasi-standard’
  - Identify robustness demands for multi-chip-power-module qualification
  - Re-use/adjust the existing, then fill up gaps/lacks
- Balance between detailed routine descriptions and flexibility in specificity of design and requirements
  - Provide an elaborated guideline to receive valid data of power module’s robustness performance, but leave space for specific alignments in the customer-supplier-relationship
- Routines und criteria shall be applicable independent of specific module design and technology
- Qualify the module and its ‘technology’, but not the semiconductor
  - Ideally, handle the chip in the power module as something like a ‘black box’.
  - Already Si-devices deviate from this ‘ideal model’: but the impacting effects are quite well understood and mirrored in the descriptions for qualifications routines
  - SiC-MOSFETs: which semiconductor and/or chip architecture related characteristic influence the routines or even has to be addressed as the qualification target by any routine?
  - This consideration is valid as well for the next ‚WBG-chapter‘ GaN-devices




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# ECPE AQG324 Main Document

## Essential Qualification Routines

| | | |
|---|---|---|
| Characterizing module tests | QC-01 Determination of parasitic stray inductance ($L_p$) | |
| | QC-02 Determ. of thermal resistance ($R_{th}$ value) | |
| | QC-03 Determ. of short-circuit resistance | |
| | QC-04 Insulation test | |
| | QC-05 Determ. of mechanical data | |
| Environmental tests | QE-01 Thermal shock (TST) | **'Check' for** |
| | QE-02 Contactability (CO)*) | **automotive** |
| | QE-03 Vibration (V) | **capability** |
| | QE-04 Mechanical shock (MS) | |
| Life tests | QL-01 Power cycle (PCsec) | **Determined by 'mind-setting'** |
| | QL-02 Power cycle (PCmin) | **of Robustness Validation** |
| | QL-03 High temperature storage (HTS) | **'Check' for** |
| | QL-04 Low temperature storage (LTS) | **automotive** |
| | QL-05 High temperature reverse bias (HTRB) | **capability** |
| | QL-06 High temperature gate bias (HTGB) | |
| | QL-07 High humidity high temperature reverse bias (H3TRB) | |

***)Due to technologies' complexities and minor meaning meanwhile withdrawn without been worked out.**

# ECPE AQG324 SiC-Chapters

## Excerpt of Essential Differences in Comparison to Si-Chapters

- Power Cycling (QL-01, QL-02)
  - Due to strong $R_{DS,on}$(T)-dependency of a SiC-MOSFET-device the definition of so-called $V_{DS,cold}$ measurement is necessary. Else, the $V_{DS}$ EoL-criteria (+5% raise to initial state) will be lost!
- High Temperature Rev. Bias (HTRB, QL-05) and High Humidity High Temp. Rev. Bias ($H^3$TRB, QL-07)
  - Obligatory use of $V_{DS} \geq 0.8\ V_{DS,max}$ instead of $V_{DS}$ = 80V (not so far WBG specific, but updated in parallel)
- Dynamic Reverse Bias (DRB, QL-05a)
  - Dynamic testing under reverse bias defined due to steeper switching gradient effects.
- Dynamic Gate Stress (DGS, QL-06a)
  - Extend of $V_{th}$-drift occurrence on chip-level will be influenced by module's design/switching characteristics.
- Dynamic $H^3$TRB (QL-07a)
  - Additional generic chip robustness test for the module technology.
- High Temperature Forward Bias (HTFB, QL-08) and dynamic HTFB (QL-08a)
  - Under discussion and construction; not finalized yet. When indicated part of next AQG 324 release.

# NI Reliability offering

# Systems to test for new Effects

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# NI/SET – Power Reliability Turn-key Solutions

General:

- Highly automated test sequencing, freely configurable
- COTS speed up lead times and maintenance
- Scalable whilst project or after delivery extension
- Standardized DUT-connection interfaces, minimizing custom adaptation efforts connecting a variety of DUT types, for example:
  - discrete packages
  - half-bridge, power modules
  - B6-bridge, inverters

**Solutions according to lifetime testing guidelines:**

- AQG-324: QL-01, QL-02
- AQG-324: QL-05, QL-06, QL-07
- AQG-324: QL-06a
- AQG-324: QL-05a, QL-07a
- AEC-Q101: #10

# Testing as a Service

- Extensive engineering support for test setup and execution
- Application / nonstandard tests on request
- Detailed test reports
- DUT adaption service


## Standard tests provided:

| | |
|---|---|
| • Power cycling: | AQG-324: QL-01, QL-02 |
| • HTRB: | AQG-324: QL-05, |
| • DRB: | AQG-324: QL-05a |
| • HTGB: | AQG-324: QL-06 |
| • DGS: | AQG-324: QL-06a |
| • H3TRB: | AQG-324: QL-07 |
| • Dyn. H3TRB: | AQG-324: QL-07a |
| • IOL: | AEC-Q101 |

# Thank you!!

# Questions??

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