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Reliability of WBG, results of a Pre-Scoping Study

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Keywords

«Wide bandgap», «Reliability», «Silicon Carbide (SiC)», «Gallium Nitride (GaN)», «Device application».

Abstract

This report contains the outcome of this first study on the reliability of Wide Band Gap (WBG) components and WBG-based applications. By summarizing key findings, it leads to an outlook and discusses the next steps.

Introduction

The overall goal of PECTA includes collecting and analyzing information about new WBG-based power electronic devices, coordinating internationally acceptable approaches that promote WBG-based power electronics, and developing greater understanding and action amongst governments and policy makers.
One of several activities of PECTA included the investigation of possible policy measures in relation to the development of WBG technology to suggest ambitious policy measures for selected product applications and within a reasonable timeline. A particular result of this work was, that one of the barriers (among others) identified for widespread application of WBG in systems/products is the limited knowledge of the reliability of the new technology, compared for instance, to IGBT technology applied for years with a considerably longer track record. Therefore, PECTA was interested for inputs on reliability of electronic components and systems with wide band gap technology.

Fig. 1 shows the historical development of power semiconductors, power electronics, and reliability engineering. Reliability is a crucial performance factor that is considered during the design, manufacturing, and field operation of power electronic converters. In recent years, there has been a shift in the industry's business model from product suppliers to holistic service providers, emphasizing the need for reducing life-cycle costs and optimizing the operation of power electronic converters [1]. This necessitates innovative design, a comprehensive understanding of failure mechanisms and high-reliability design, and reliability evaluation methodologies.

In this regard, it is critical and most relevant to better understand the reliability of power electronics in general, and for WBG technology specifically from different perspectives. The following guiding questions outline the aspects which have been addressed so far.

1) What are the main reliability issues (in general and for WBG), classified by level, from system to component?
2) What is the state of the art in designing reliable systems and components with WBG?

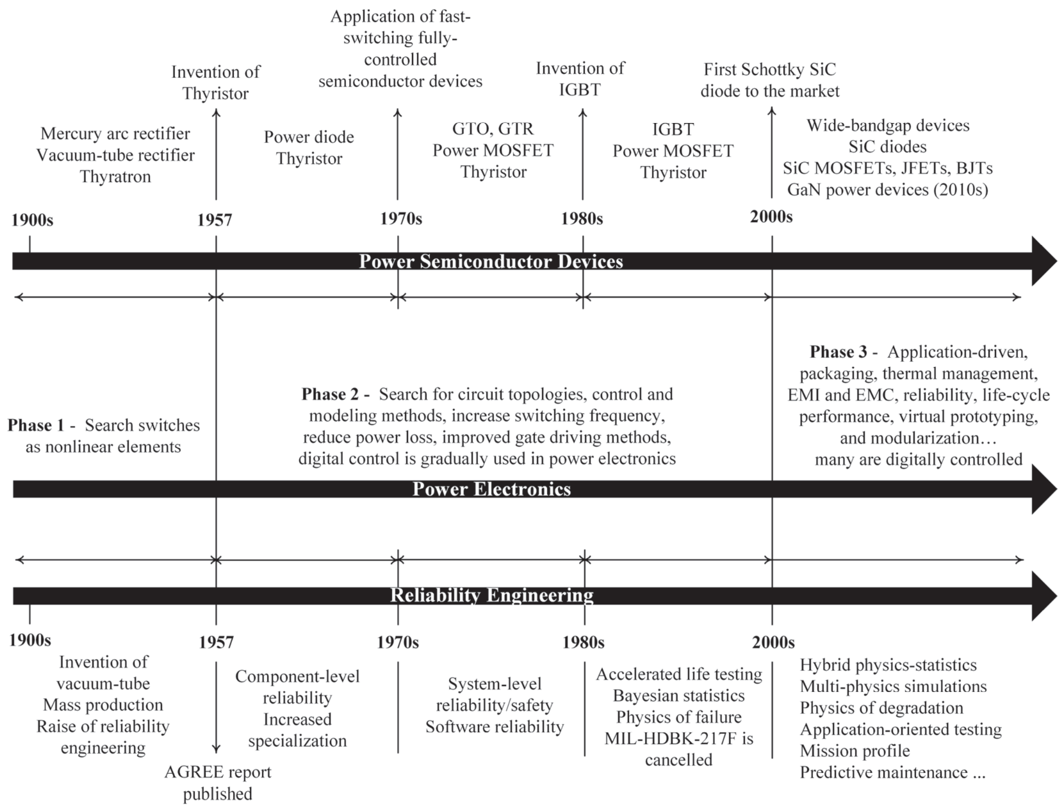

Fig. 1: Historical development of power semiconductors, power electronics, and reliability engineering [1].

3) What are the metrics/measures that define reliability in components and systems?
4) Which methodologies are available for determining the reliability of components and systems (general and WBG)?
5) What would be relevant for policymakers to address regarding the reliability of electronics to promote WBG for energy and resource-efficient systems and end-use products?

This article focuses on updating the power electronics reliability aspects of research with specific focus on WBG-relevant areas. It should be noted that this article limits its scopes in the following:

1) The main reliability issues/failure mechanisms of SiC MOSFETs and GaN devices and WBG-related applications.
2) Reliability assessment procedures for power electronics applications.
3) Trends and expectations on the reliability of power electronics.

Failure in WBG components and applications

SiC-based devices exhibit distinct failure modes and mechanisms in comparison to their Si counterparts. Therefore, a comprehensive review is critical to develop accurate lifetime prediction and extension strategies for SiC power converter systems [2]. The typical failure locations, causes, and indicators of SiC MOSFETs are summarized in the report. The failure locations indicate where specific failure modes occur, with two chip-level and two package-level failure modes summarized. The failure causes describe the stresses associated with different failure modes. Indicators, which are external electrical parameters reflecting internal failure modes, are utilized to determine the number of cycles to failure in Accelerated Life Tests (ALTs) when the indicator values meet the defined failure criteria [3].

GaN-based HEMTs are almost ideal devices for application in power converters. The reliability of these transistors can still be limited by the existence of specific degradation processes, that impact on the static and on the dynamic performance of the devices [4]. It has been mentioned that despite extensive research on this topic, work remains to be done to fully understand these mechanisms. For instance, various degradation mechanisms exist in GaN power HEMTs such as dynamic on-resistance, threshold voltage shift, and time-dependent dielectric breakdown, and these may depend on the specifics of the epitaxial growth and device processing [5]. In the report, the most critical degradation processes induced by off-state, on-state, and semi-on-state stress, along with their related failure modes, have been discussed. Additionally, the test methodologies employed for analyzing degradation mechanisms have also been presented.

Even though WBG devices can enhance converter performance, the field reliability of the WBG-based converter should still be further addressed. Furthermore, the lifetime models and lifetime extension strategies need to be enhanced. In the report, the reliability challenges of the WBG-based converter for applications like PV, wind turbine, and EV have been discussed correspondingly.

Reliability assessment methodologies

Numerous reliability assessment procedures based on mission profiles, integrating Design for Reliability (DfR) methods and Physics of Failure (PoF) principles specific to power electronics, have been proposed and effectively implemented across various applications. Examples include wind power converters, grid-connected PV inverters, variable frequency drives, and electric aircraft. Regarding EV/HEV applications, significant emphasis has also been placed on the reliability evaluation methodology for power modules employed in the electrical drive train inverter. Drawing from research conducted at the Center of Reliable Power Electronics (CORPE), Aalborg University, this discussion will explore two reliability assessment methodologies employed for power electronic systems.

A. Mission profile-based reliability assessment

Fig. 2 depicts a comprehensive six-step procedure based on mission profiles, which has been

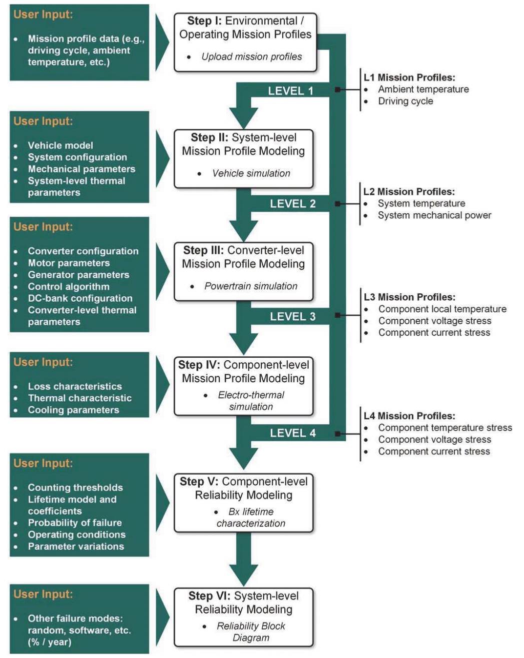

Fig. 2: Detailed framework of the proposed reliability assessment procedure for EV applications [6].

proposed to estimate the lifetime and assess the reliability of power electronics both at the component and system level. Each of the necessary steps within the reliability analysis are briefly introduced below, using the EV application as an example [6].

1) Environmental/Operating Mission Profiles: the mission profile includes a standard driving cycle and ambient temperature. These factors serve as inputs for the reliability assessment procedure, allowing for a comprehensive evaluation of reliability in the PE system.
2) System-level Mission Profile Modelling: to determine the mechanical power output of the motor shaft using mechanical models.
3) Converter-level Mission Profile Modelling: to determine the electrical loadings (e.g., voltage and current) of the components of interest.
4) Component-level Mission Profile Modelling: to calculate the thermal

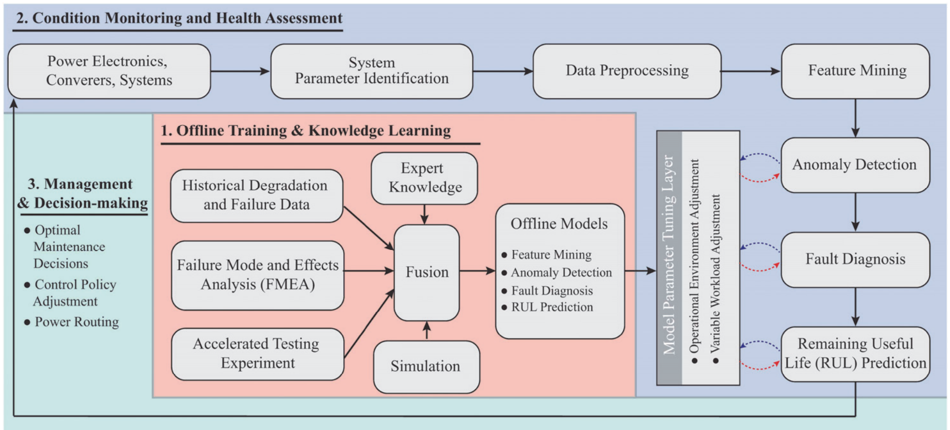

Fig. 3: Flowchart and procedures of AI methods of maintenance of power electronic systems [7].

behaviour of the devices under the given inputs.

5) Component-level Reliability Modelling: a rainflow counting algorithm is applied in order to represent the thermal loading data. After determining the damage inflicted by each thermal cycle, the total accumulated damage can be calculated by means of Miner's rule. Finally, by means of a Weibull cumulative distribution function (CDF) the unreliability curve of the power semiconductor components can be determined.
6) System-level Reliability Modelling: the reliability information of each component can be merged together through reliability block diagram (RBD) analysis in order to obtain the unreliability curve of the entire inverter sub-system.

B. *AI-based reliability assessment*

The implementation of AI in each life-cycle phase of the maintenance brings about flexible functional interactions, offering several benefits such as performance optimization and procedural simplification. Moreover, it enables efficient data flow management between electrical and other disciplines, such as the mechanical area. By utilizing AI-based system parameter identification, aging information can be seamlessly integrated into AI-based controllers, thereby enhancing system reliability. As a result, it is crucial to prioritize and explore the interconnected interactions empowered by AI, as they hold significant potential for advancing maintenance practices.

Fig. 3 illustrates the application of AI methods in maintenance activities within power electronic systems. This framework typically encompasses three key components: Offline Training and Knowledge Learning, Condition Monitoring and Health Assessment, and Management and Decision-Making. Below are the specific applications of AI in maintenance, exploring each of these three components, which have been discussed in detail in [7].

1) Condition Monitoring: it includes system parameter identification, data preprocessing, and feature mining. Condition monitoring information is applied to uncover hidden and informative insights, which serve as a basis for the subsequent prognostics and health management (PHM) applications.
2) Anomaly Detection and Fault Diagnosis: anomaly detection is responsible for identifying abnormal behavior and making a binary decision when the rated system characteristics or nominal parameters surpass the predefined safety range. Following this, fault diagnosis identifies and locates detailed failure modes.
3) RUL Prediction: it predicts the residual lifetime of an individual unit in service based on the condition monitoring information. RUL prediction is applied as an additional tool to reduce the

Table I: Prospects of Reliability in Power Electronics.

	Pre-history	Past	Present	(near) Future
Customer Expectations	- Replacement on failure - Years of warranty	- Low failure risk - Request for maintenance	- Peace of mind - Predictive maintenance	- On-time maintenance - Self-diagnostics
Reliability targets	Affordable returns (%)	Low return rates	Ppm return rates	Negligible returns
R&D approach	- Reliability testing - Avoid catastrophes	- Robustness tests - Weak-link approach	- Design for reliability - Smart derating	- Offline condition logging - Online condition monitoring
R&D key tools	Operating testing	Limit testing	Understanding failure mechanisms, mission profiles, root causes Multi-domain simulations	- Beyond Temperature - New concepts – challenge rainflow counting & Miner's rule - Physics of degradation - Digitalization - 100% traceability - CAD software with reliability plug-ins - Reduced testing time
Available technologies		Accelerated life testers CAD tools	Parallel computing Land-network communication (4G)	IoT Big data databases Cloud-/supercomputing AI Satellite communication (5G,..)

uncertainties for reliability-critical, safety-critical, or availability-critical applications.

Power electronics reliability outlook

Reliability challenges for electronic components in power electronics necessitate a paradigm shift. Power electronics, as an enabling technology for the green transition, require reliability engineers to exert extraordinary efforts in keeping pace with market demands. The convergence of modern demands and technologies highlights the need for reliability engineers to bridge the gap through dedicated efforts in specific directions. The trends and expectations regarding the reliability of power electronics and drives are presented in Table I [8].

1) Customer Expectations:
   - On-time maintenance: Maintenance intervention should be based on an accurate estimate of the state of wear. Too-early or too-late interventions should be avoided in the near future.
   - Self-diagnostics: The control unit has to be aware of the state of wear of power components, and report to the customer.
2) Reliability Targets:
   - The return should be negligible. The automotive market will be the driving application in the coming decade. As it is a sector with approximately a billion pcs. /year, a part-per-million return is not acceptable anymore. Other sectors, such as laptop power supplies and wireless mobile-phone chargers, are also experiencing significant growth, except for EV applications.
3) R&D Approach:
   - Offline condition logging: A remarkable cost decrease in non-volatile memory will enable massive data logging, providing significant benefits in terms of both diagnostics and knowledge.
   - Online condition monitoring: Condition monitoring is nowadays the most

promising method for increasing operability of power electronics. The two major hurdles are accessing to the electrical quantities without affecting the circuit reliability and building a cheap communication infrastructure.

4) R&D key tools:
   - Temperature is regarded as the most dangerous variable to keep under control, but what about the others?
   - The rainflow counting algorithm and Palmgren-Miner's rule are considered the only ways to get an estimate of the accumulated damage in power electronics, but are there any new concepts that could challenge rainflow counting & Miner's rule?
   - Physics of degradation: Before failure mechanisms, there are degradation mechanisms. However, there is a lack of knowledge about them, and further investigation into the physics of degradation is necessary.
   – Digitalization: Digital electronics can be used more and more effectively to monitor and diagnose power electronics and, more importantly, can be used to make fast decisions.
   - 100% traceability: Full backward traceability is demanded to investigate variation at the manufacturing level.
   - CAD software with reliability plug-ins: The most advanced CAD software for PE design does not even include rudimentary reliability prediction.
   - Reduced testing time: Power cycling is the most used technique to infer the expected life under certain conditions, which normally takes weeks or months for each condition tested.
5) Available technologies:
   - IoT: The IoT gives access to a huge local communication infrastructure that can be used, for example, for condition monitoring.
   - Big data databases: Large databases are now publicly available, offering the possibility to infer cause-effect relationships.
   - Cloud-/supercomputing: FEM simulations at submicron-level are simply impossible at a local computer level but become possible with cloud computing.
   - AI: The benefits of using AI in reliability prediction are massive, especially when combined with large training sets.
   - Satellite communication (5G, etc.): The missing link for communication from mobile power-electronics systems, such as electric vehicles.

Conclusion

This paper is focusing on the reliability of WBG components and WBG-based applications. Key findings have been summarized. The results will be considered in the PECTA work of exploring suitable policy measures for WBG-based power electronic devices. The article highlights the importance of addressing reliability concerns, particularly for WBG technology, in order to accelerate its market adoption. The article provides insights into the main reliability issues, failure mechanisms, reliability assessment procedures, and trends in power electronics reliability, with a specific focus on WBG-related areas.

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