May 2022
Volume 3

iRel40

Intelligent Reliability 4.0

Newsletter M24

"Intelligent Reliability 4.0" (iRel40) is a project with the ultimate goal of improving reliability of electronic components and systems by reducing failure rates along the entire value chain.

Welcome to the third newsletter from the project "Intelligent Reliability 4.0 (iRel40)". Today, the reliability concepts are at the doorstep of major changes, moving from stress-based and knowledge-based to application-based approaches. This is strongly supported by the current development of machine learning, digital twin-supported diagnostics or prognostics, and health monitoring. The partners in iRel40 are paving the road towards these reliability approaches and drive new concepts based on Physics of Degradation.

Based on current and expected changes in the reliability concepts the iRel40 project has defined "Five key research & development areas for reliability": i) Multi-scale & multi-physics simulations for physics of degradation; ii) AI-based control systems in advanced production; iii) Smart sensoring and big data analysis; iv) Reliable materials and reliability testing; v) Prognostic and Health Management digital twin for condition monitoring. All activities of the iRel40 project are associated with these five R&D areas aiming at the common ultimate goal of improving the reliability of electronic components and systems by reducing failure rates along the entire value chain.

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Facts & Figures

Partners: 75

Countries: 13

Budget: 101.8 Mio €

JU Funding: 24.5 Mio €

National funding 22.9 Mio €

Project Start: May 1st, 2020

Duration: 36 months

Coordinator: Infineon Technologies AG

ABOUT THE iRel40 PROJECT

Project objectives

iRel40 comprises 75 research and industrial partners from 13 countries that are joining their forces to improve the reliability of electronic components and systems by following 5 objectives:

Objective 1: Define needs and requirements for future ECS applicants to drive improvements and prediction of reliability along with the value chain chip, package, board/system - to foster Europe's competitiveness in ECS.

Objective 2: Implement data value chains and cross-component data analytics to speed up the learning curves by 30%.

Objective 3: Double the predicted lifetime for specific materials and load conditions for ECS applications.

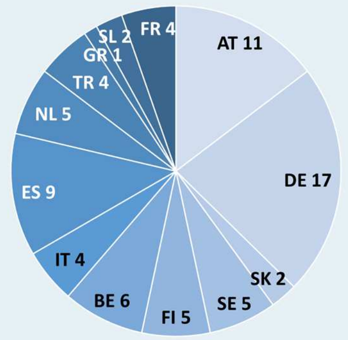
Objective 4: Early detection of unexpected quality relevant events along the ECS value chain by advanced and innovative control concepts.

Objective 5: Reduce the failure rates by 30% and enable lifetime prediction with connected and new test concepts along the ECS value chain.

Project organisation

The project is organized in **8 WP — Work Packages**, 6 of which focus on the technical content. In addition, iRel40 includes **16 UC** — Application Use Cases and **18 IP** — Industrial Pilots, which are worked out horizontally in the 6 technical work packages.

iRel40 consortium
(# of partners for each country)



Advanced reliability is a key differentiator of electronic components and systems.

The times they are a-changin'

"The times they are a-changin'", that is what Bob Dylan's song is about. And that is also what iRel40 is about. We are at the doorstep of major changes in reliability concepts. Simple FIT (Failure In Time), MTBF (Mean Time Between Failure), MTTF (Mean Time To Failure) concepts as well as standard-based component quality testing will become history in the future. Physics-of-failure, although a very strong concept, will see further improvements as well. Like Dylan sang: "As the present now, will later be past". And the past was characterized by three distinct waves (see Fig. 1):

Wave 1: Stress based

The first wave was characterized by the establishment of a test-to-failure approach based on standardized stress-based tests. Examples are thermal cycling, moisture testing and/or operational tests under combined conditions. Each of these tests got standardized in the semiconductors industry by dedicated bodies, like e.g. JEDEC, IEEE or IEC, to enable smooth comparison between suppliers and test houses. Understanding of possible failure modes gradually increased in several industries using semiconductor devices but the use of prediction models was still limited.

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Wave 2: Knowledge based

The second wave continued from all the test results obtained over a period of 30-40 years in the first wave. Companies started to understand the physics that caused failure modes in their products. Test schemes changed to test-to-failure instead of test-to-pass. Still standardized tests are used under the condition of similarity: if a previous product differed slightly from a new one, no new testing was required. This wave has been characterized as knowledge-based qualification. Models became commonly used in this wave, both analytical and / or numerical (using Finite Element Methods FEM) ones.

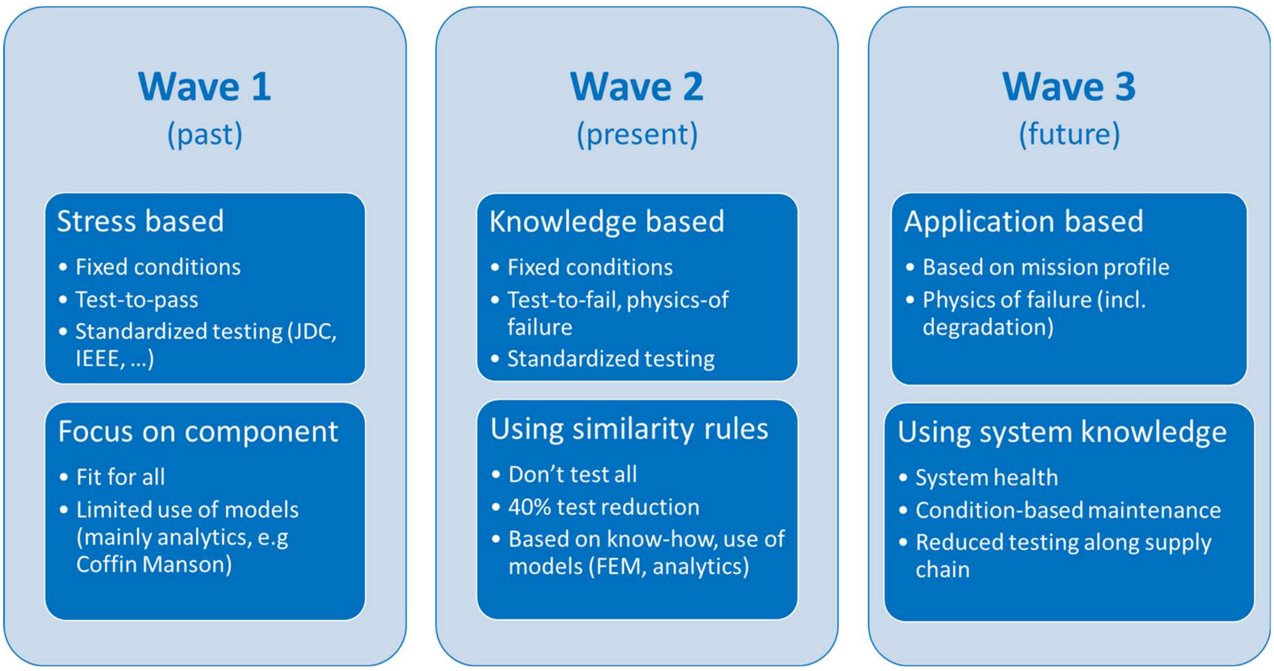


Fig. 1: Waves in reliability.

The times they are a-changin'

Wave 3: Application based

In the third wave, application conditions are considered. All industries performed a substantial amount of application studies in which dedicated sensors are used to measure the actual loading, in terms of temperatures, vibrations, and/or external forces. Here, measure, in some cases, means monitoring so that the data are logged continuously and send to an online database. Standards are not yet available, but some bodies did publish guidelines.

Per today, most industries are in the transfer coming from wave 2 towards wave 3. Wave 3 goes hand in hand with the current development of machine learning, digital twin driven diagnostics or prognostics and health monitoring. These technologies are needed to move to ***Wave 4: Physics of Degradation and Robustness***. Two new concepts will become available at a significant level of maturity:

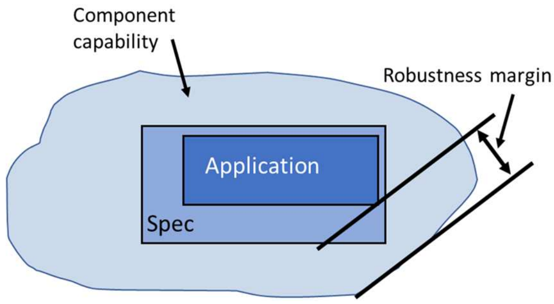


Fig. 2: Schematic illustration of basic idea of robustness validation (see W. Kanert – Robustness Validation, Microelectronics Reliability 54 (2014) 1648ff).

Physics of Degradation: Degradation is apparent in naturally occurring materials and structures as well as human-engineered materials and devices. In everyday experience, it is the ever-present phenomena of spontaneous loss of some quality, functionality, and order. This loss of order or degradation has many terms or phrases to label the phenomena, such as ageing, deterioration, devolution, and wear-out. Understanding the physics of degradation will also reduce the amount (and cost) of product release testing.

Robustness Validation: Today's standard qualification procedures for electronic components, assemblies and components for the automotive industry are based on the use of standardized tests at the end of the product development of parts and components. In contrast, Robustness Validation is a process that includes the entire product development process, as well as mass production. The qualification of the components based on the robustness analysis is thus implicit.

We are at the doorstep of major changes in reliability concepts, moving from stress-based, knowledge-based and application-based approaches towards a new reliability concept based on physics of degradation and robustness.

In this third iRel40 newsletter we present selected project outcomes related to data science (e.g. artificial intelligence models applied to production data, machine learning approaches, anomaly detection), digitalization (e.g. digital twins), as well as new test methods and processes for driving reliability. We show results from semiconductor and IC design topics like conditional burn-in (#1) or reliability assessment in IC design projects (#4) to application-related topics like big data streaming applied to electro motors (#14) and applying algorithms for fault detection in-wheel technology (#15). We start with chip/semiconductor and IC related topics (#1 to #5, with the last one a test equipment focus), continue with preassembly (#6) and package/board-related topics (#7 to #9, with the last one a test equipment focus), and finally close with application-related topics (#10 to #15).

The partners in iRel40 are paving the road towards the described new reliability concepts and are ready for Wave 4! In Dylan's lyrics: "Your old road is rapidly aging, please get out of the new one if you can't lend your hand for the times they are a-changing'".

#1. IP-6: Conditional burn-in

Industrial Pilot IP-6 provides a framework for the determination of lot-specific burn-in times. This allows for the reduction of burn-in (BI) costs, while still guaranteeing the defined quality target for early failures $\pi_{target} \in [0,1]$.

In order to achieve this aim, AI models are trained on production data to predict the health index $h \in R$ for each lot, see Fig. 1.1. This health index h serves as an input variable to a logistic regression model for the early life failure probability π, i.e.,

$$logit\ \pi(h) = \beta_0 + \beta_1 h$$

The regression model itself is learned based on a random sample that is put to BI; this is a so-called BI study. The health index h contains an uncertainty that propagates into the interval estimator of π.

At semiconductor devices, π is typically very low. Moreover, the acceptance criteria for BI studies is zero failures. This leads frequently to situations of sparse data, i.e., hardly any BI failures are available. For production lots, a threshold value of h can be combined with the Clopper-Pearson estimator for π. Alternatively, if in an ongoing BI study there are still failures and the actual lot has a lower health index than the average sampled lots, the improved health index h can be seen as a countermeasure and a fractional failure model can be applied.

Appropriate data from advanced process control and electrical product tests were extracted and are now used for training AI models such as Gaussian process regression, additive models, Long Short Term Memory (LSTM) based Autoencoders, etc. Once the model training is finalized, the trained models will be used to validate and refine above described concept for lot-specific burn-in times. Furthermore, burn-in times will be matched with time in field.

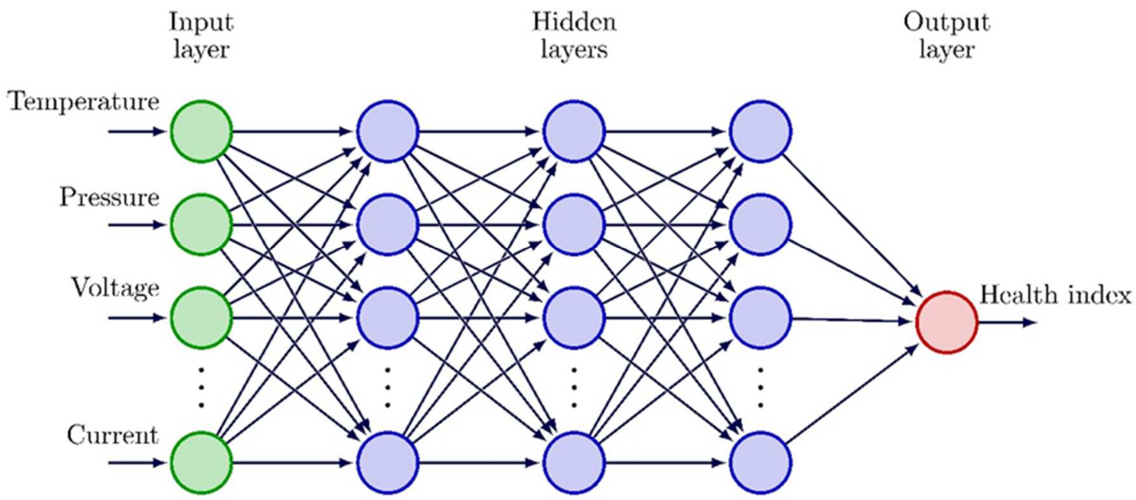


Fig. 1.1: Illustration of an AI model used to infer the health index h of lots.

SELECTED TECHNICAL INNOVATIONS

#2. Detection of unknown defects in semiconductor materials from a hybrid deep and machine learning approach

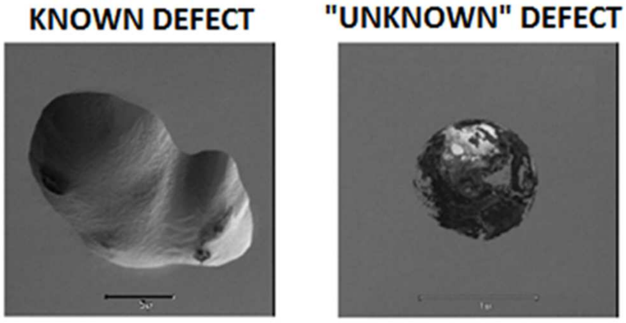


Fig.2.1: Known vs "Unknown" defect.

The semiconductor manufacturing environment, like many other industries, is not stationary. An example of a direct consequence of this constantly changing environmental conditions is the emergence of new, previously unseen defects. At the same time, machine learning (ML) and deep learning (DL) enter the way into manufacturing, which must deal with environmental changes as well. A common approach is to use supervised learning algorithms, where models are trained on instances (images) with known labels, i.e., different defect classes, visible on defect density images. These methods, which are known to achieve human-level performance in the defect classification task, are lacking in detecting or correctly classifying images of new, previously unseen defects into the correct defect class, since this defect class did not exist during supervised model training. Therefore, it is necessary to find a suitable methodology or strategy that reliably detects and classifies new defects, allowing manufacturers to react instantly to changes in production.

To face this challenge, within IP-2 a hybrid DL and ML pipeline for the detection of "unknown" defects has been developed. First, the different datasets (training, test, validation and "unknown") are generated. The test set is obtained from the original IP-2 dataset, while the training and validation sets are composed of original and augmented images from known classes. For the set of "unknown" images, a publicly available data set was chosen with images like plants, animals, planets, etc. and modified in a way that they look similar to the defect density images from IP-2 (same background, same color style...) (see Fig. 2.1). Next, a modified ResNet50 convolutional neural network (CNN) is used to extract the feature vectors of each image of the different datasets. The feature vectors of the training, test and half of the "unknown" dataset are then used to tune a Gaussian mixture model (GMM) through a grid search algorithm. Once the hyperparameters of the GMM are tuned, the GMM is evaluated with the remaining images of the "unknown" dataset and the images from the test set.

PREDICTED LABEL

TRUE LABEL	Class 100	Class 150	Class 200	Class 300	Class 350	Class 500	Class 550	"Unknown"
Class 100	100%	0%	0%	0%	0%	0%	0%	0%
Class 150	50%	50%	0%	0%	0%	0%	0%	0%
Class 200	0,25%	0%	99,75%	0%	0%	0%	0%	0%
Class 300	0%	0%	0%	99,09%	0%	0%	0%	0,91%
Class 350	0%	0%	0%	0%	75%	25%	0%	0%
Class 500	0%	0%	0%	0%	0%	100%	0%	0%
Class 550	0%	0%	0%	0%	0%	0%	100%	0%
"Unknown"	0%	0%	0%	0%	0%	0%	0%	100%

Fig. 2.2: Classification performance of the proposed algorithm.

The results obtained with the proposed algorithm are very promising, being able to classify 100% of the unknown images into the "unknown" class (see Fig. 2.2). Only one defect image from class 300 is wrongly classified as "unknown" due to the small error introduced by the GMM.

More information regarding this methodology for the detection of "unknowns" can be found in the congress paper "Detection of Unknown Defects in Semiconductor Materials from a Hybrid Deep and Machine Learning Approach" that will be submitted to the IWINAC 2022 conference.

#3. Laser equipment & systems cluster - enhancing reliability in semiconductor manufacturing processes

The Laser Equipment and Systems Cluster is a group organized in an iRel40 project task which is committed to increase the reliability of production processes for advanced wafer and material processing. Laser processes offer powerful methods in the semiconductor industry. A big challenge in the complex manufacturing process especially for power semiconductors is to avoid any cross contamination driven by metals, in particular contamination by noble metals. Infineon uses special substrate wafers as auxiliary material for some technology steps within semiconductor manufacturing. Today, these auxiliary substrates must be scrapped due to high risk of contamination. Teams from Infineon Dresden and Westsächsische Hochschule Zwickau (WHZ) jointly established a demonstrator in the WHZ laboratory which is able to remove noble metals from the outer edge of the substrate wafers. Based on several online and face-to-face meetings, the target processes for wafer cleaning and process requirements have been worked out. Fig. 3.1 below shows the current status of the demonstrator in Q1 2022.

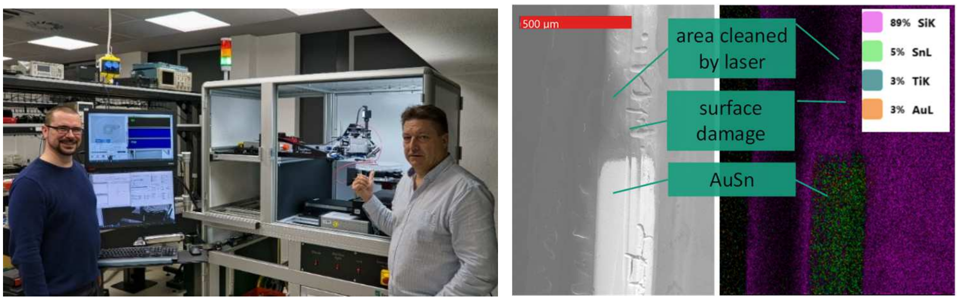


Fig. 3.1: Laser equipment & systems demonstrator discussions by Tobias Baselt (Fraunhofer) and Fred Kallweit (LEC) in the lab in Zwickau (left); Laser-based detection of the material composition of the sample and Microscope image of the surfaces selectively cleaned by laser (right).

The laser is cleaning the outer bevel of the wafer while a TXRF sensor is continuously controlling the amount of noble metals within the focus area. As soon as the concentration of noble metals is below the specification limits of Infineon, wafer processing is stopped, and the substrate wafers can be re-used.

The laser-based cleaning system which combines the selective cleaning of the wafers with an online monitoring system has been developed by the partners in a joint effort. Lasers with optical powers of up to 80 Watt in combination with fast deflection optics enable a scanning of the wafer surface with a speed of about 5 meters per second. In parallel, the plasma signal of the laser ablation process is spectroscopically analyzed for material specific peaks. This analysis ensures an effective and reliable cleaning of the wafer surface in real-time. Novel optical fiber solutions were developed to allow for simultaneous delivery of laser power and plasma signal. Additionally, the partners are working on in-line monitoring solutions in the fields of optical surface profilometry and industrial image processing to further enhance the laser processes. These measurement approaches will enable quality assessment of both surface roughness and cleanliness with nanometer resolution.

Infineon supported the research work with wafers and substrate material. The teams have shown by using this demonstrator that the first test wafers could be perfectly cleaned according to the specifications of the factory. The collaborative work on laser-based surface modification, on development of software and electronics for metrology, on laser equipment and systems, as well as on AI-enabled statistical analyses is ongoing. The results of these joint efforts offer strong benefits for recycling of expensive substrate wafers and assure high reliability. This will help to save both energy and materials to produce those advanced wafers. The outcome will have a strong positive impact on the way of Infineon Dresden to become a green factory.

SELECTED TECHNICAL INNOVATIONS

#4. Efficient reliability assessment in IC design projects

Durable electronic systems for long-living applications can only be realized when all their components are sufficiently reliable. This also holds for integrated circuits (ICs) found in these systems – independent of their detailed functionality and complexity.

In IC design, single-device lifetime models are well established for many devices and failure mechanisms. They can be used to predict the degradation of single transistors in their particular use scenario based on transient simulations of typical use conditions, so-called mission profiles. To assess the impact of the individual degradations onto circuit performance, aging simulations can be performed – but they cause a significant additional effort in IC verification.

The goal of our work is to support IC designers in achieving their reliability targets more efficiently. For this purpose, a low-threshold access to IC reliability is established and extended.

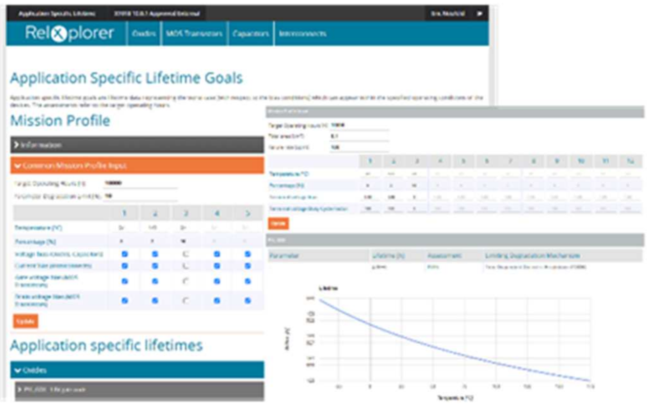


Fig. 4.1: RelXplorer main page and results.

X-FAB has been offering its RelXplorer tool for many 0.35 µm and 0.18 µm processes for many years already. After manually importing mission profile information for a single transistor, its degradation is predicted in terms of shift in important transistor characteristics, such as linear and saturation current (IDLIN and IDSAT), threshold voltage (VTH), and maximum transconductance (GMAX). In iRel40, additional functionality (saving of inputs mission profile and report generation) was added to increase usability, this is now available to iRel40 partners as a prototype. Also, additional models were developed and are now available to all XFAB customers.

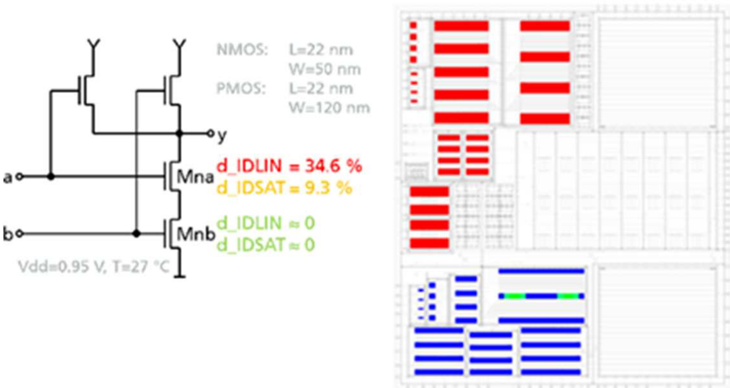


Fig. 4.2: ReliaVision w/ reliability information in schematic and layout.

To bring the reliability information into the designers' world, Fraunhofer IIS/EAS is working on the ReliaVision methodology. It enables an efficient assessment of IC reliability based on the main functionality of RelXplorer. Mission profiles are automatically extracted for all transistors in a circuit from transient simulations, and the individual degradations are determined by applying models and parameters from RelXplorer. These information is fed back into the design environment. The prototype implementation generates a color-coded overlay of reliability information over the circuit layout, and future developments target an annotation of reliability information to the schematic. A major part of the implementation work covered the exchange of reliability information, which is done by using an XML representation of the corresponding models and their parameters. This exchange format is setup to allow an easy extension to further process technologies in the future. The developments are supported by Hahn-Schickard with a use case in a 180nm X-FAB process. While the prototype of ReliaVision is running at Fraunhofer IIS/EAS, it will be tested by Hahn-Schickard and X-FAB in their ASIC development activities soon.

UNIVERSITÀ DEGLI STUDI DE L'AQUILA

#5. Investigation of the aging of CMOS based electronics circuits and interfaces subjected to thermal cycling conditions

UNIVAQ is investigating the aging of CMOS based electronics circuits and interfaces subjected to thermal cycling conditions by developing models and data acquisition systems. Reliability of aggressively scaled electronic systems is one of the most critical concerns of designers. It is being increasingly challenging to design systems that will provide users with the intended service over time: in particular, bias temperature instability (BTI) aging of MOS transistors, together with its detrimental effect for circuit performance and lifetime evaluation and mitigation through design techniques is the final goal when scaling discrete components. In this scenario a hotbox chamber has been fully custom designed (Fig. 5.1) and tested with a dedicated conditioning system and GUI. The system control phase is performed by voltage regulation of the electric resistances thanks to a full AC wave control circuit, managed by a trigger module.

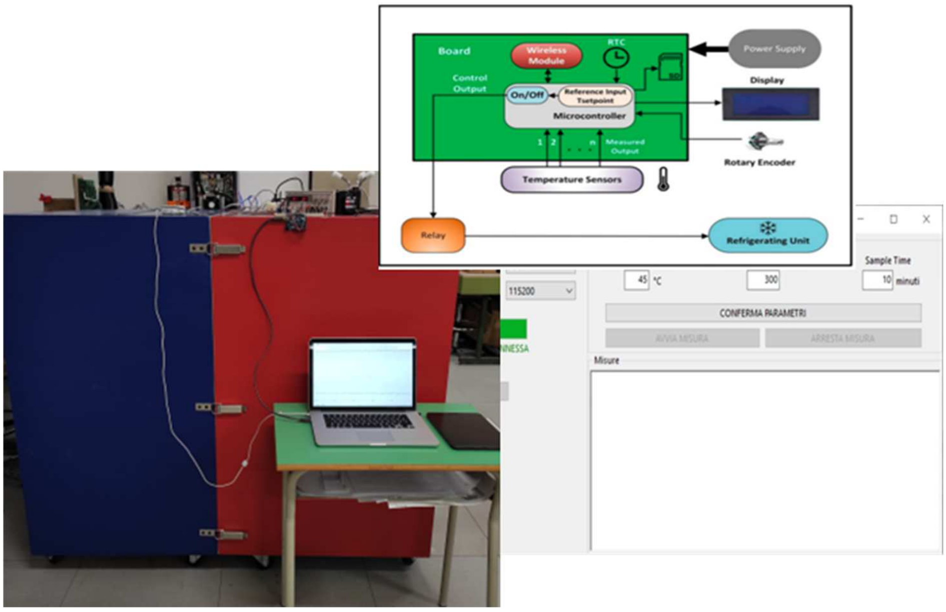


Fig. 5.1: Hotbox chamber with dedicated control interface.

The chamber has been used first for testing discrete standalone devices in simple electronic configurations and after discrete element boards circuits implementing those devices (Fig. 5.2) evaluating most important parameter variations. Actually, differential resistive interfaces for accurate, real-time measurement of voltage, current and temperature that have been designed using a standard 0.35um CMOS technology (IC implementation is underway) is under test.

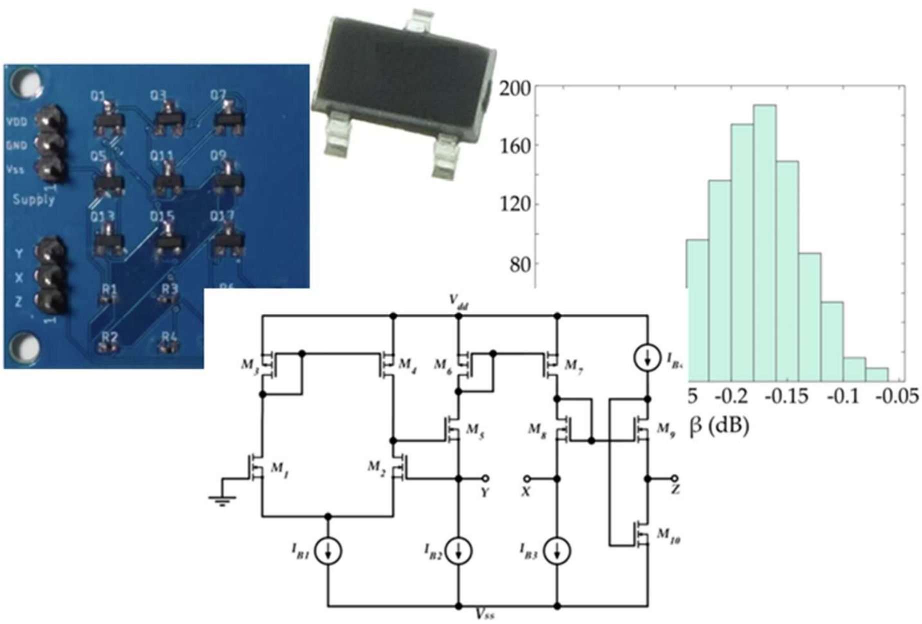


Fig. 5.2: Test circuits and histograms of device parameter variation.

#6. Avoiding Cu pad corrosion during or after mechanical dicing with possible impact on the bond interconnect

Increasing compactness of semiconductor devices leads to increasing thermal challenges and therefore requires new metallization systems. These metallization systems have significant impact on preassembly. Thus, preassembly becomes more challenging to reach reliably packaged dies. More research and development effort is needed to better understand dicing and grinding and their impact on reliability. Below we present research on the challenging example of Cu pads.

More frequently, chip pads are made out of Cu instead of AlCu. In some cases, the Cu pads cannot be protected by protecting layers (e.g. electroless plated layer), driven by assembly requirements and integration schemes. In such cases, the Cu surface might be oxidized during dicing of the wafer and when stored after dicing, as dicing water in general is very aggressive to open Cu surfaces. Target is to avoid Cu pad corrosion during or after mechanical dicing with possible impact on the bond interconnect.

A very common way to prevent oxidation of metal surfaces is the usage of surfactants in the dicing water. These substances are amphiphilic and form a molecular passivation monolayer on the metal surface that is able to prevent the direct reaction between dicing water and Cu metal. Also, the silicon dust that is generated during dicing will be covered by a monolayer. This prevents additionally the absorption of silicon on the metal surfaces.

Test vehicles have been prepared and tested under different conditions like dicing time, temperature or surfactant material. As shown in Fig. 6.1 a clear effect between the different surfactants can be seen in terms of optical appearance and structure of the Cu surface after the dicing process. This effect can even be locally different on the same wafer.

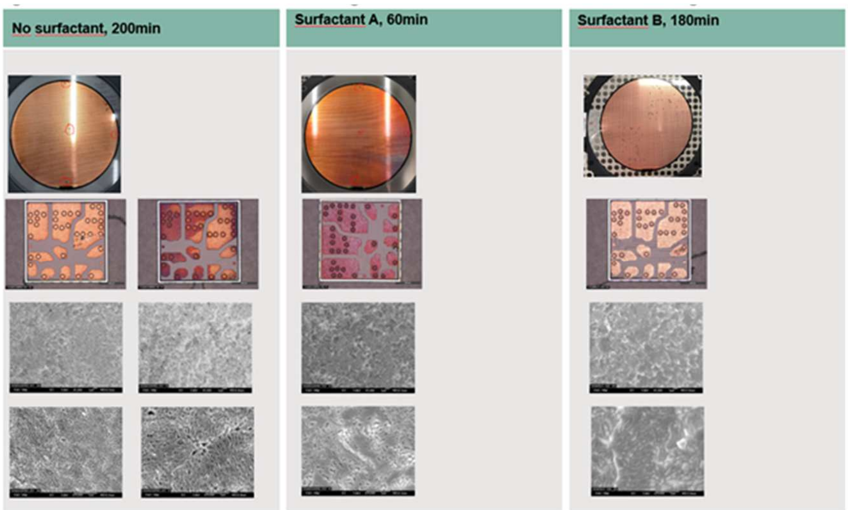


Fig. 6.1: Appearance of Cu metal surface after dicing with different dicing times and surfactants.

Different hypothesis for protection mechanism had been applied to explain this behavior. Further progress of this research on Cu pad corrosion applying mechanical dicing is restricted by incomplete surfactant information from suppliers. This problem was already identified in initial risk assessment. Standard analysis methods like atomic mass spectroscopy do not have the required capability to identify the substances in detail.

#7. Development of a standardized approach for using a stress sensing system for IC package development (IP-17 and T-9)

Internal stresses inside of microelectronic packages are a function of the package design, the used materials and processes during the assembly process as well as the material aging effects caused by the environments in the field (mission profile). The knowledge of the local stresses and their change inside the package for defined material, process and aging parameter can be used as input for FEM-Simulations of the investigated packages. This means the measurement result from stress sensing dies inside a defined package can be used to "calibrate" the FEM simulation model for the device optimization by defined parameter variation e.g. as DoE (Design of Experiment) or for the reliability prediction by applying known physics of failure (PoF).

Within the iRel40 project the known methodology using stress sensing dies in IC packages is applied to package types with different geometry (SO16 and TO263), materials and assembly technologies, but all these investigations should be done in a standardized manner. Besides these differences in the package the focus of interest varies, so for the SO16 test vehicle the stress change during the manufacturing process should be analyzed. On the other hand, for the TO263 test vehicle the stress change during accelerated reliability tests should be addressed.

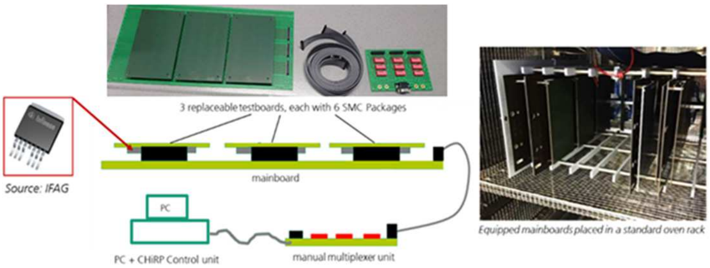


Fig. 7.1: Schematic overview of the manufactured test devices (testboards, mainboard, multiplexer unit).

For the efficient processing of both tasks at FhG ENAS the concept of standardized systems was developed. The basis is the bus system, organized data acquisition and processing with a standardized interface. This interface includes besides the definition of the electrical signals also the definition of the used PCB as substrate for the devices. The principle structure of this system is shown in Fig. 7.1. For instance, the PCB's with the devices under test (DUT's) can be placed in ovens or chambers for temperature or humidity loading and the data acquisition on different time also until End-of-Life (EoL) can be realized.

Parallel to the hardware definition and realization a new evaluation software helps to handle the bigger data amounts and supports a user-friendly post-processing as well as comparison of the measured data. It is now possible to load the raw data directly from the measurements into the analysis tool. In Fig. 7.2 some measurement results for the TO-263 test vehicle are shown. The x-y-plot of the stress distribution can be used to compare different stress changes in an easy way. Applying the measurements for each stress cell to an FEA model the results can be used for an advanced assessment, e.g. in a Digital Twin. So, the difference stress on the SMC can be used to validate the FEA model and to improve the material models included. The validated FEA model is afterwards used to compare results after reliability experiments and detect possible delamination and aging effects.

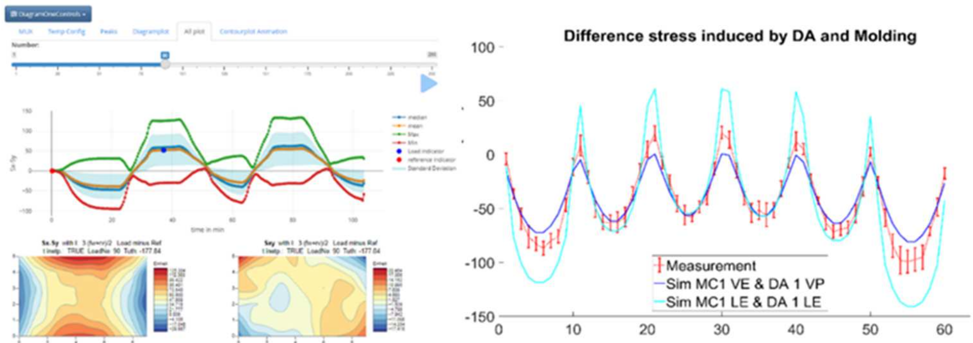


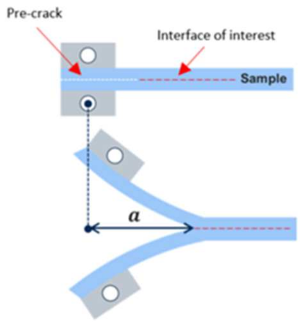
Fig. 7.2: Measurement results, left – stress distribution as surface plot and cell-wise x-y-plot, right –of the difference stress. Comparison of simulation and measurement results for FEA validation.

#8. Double cantilever beam test for quantitative characterization of FR4 resin/resin interfaces

AT&S

In multilayer PCBs or IC substrates interfaces such as resin/resin (R/R) or copper/resin (C/R) interfaces are strongly relevant for thermo-mechanical reliability performance of boards as well as systems. The actual quality of these interfaces is significantly depending on the applied materials as well the process history of the multilayer build-up.

In order to get a quantitative measure for the R/R interface strength a linear fracture mechanics based Double Cantilever Beam (DCB) test setup has been developed by AT&S. The DCB test is based on the standards ISO 15024 and ASTM D5528 which today are commonly applied to characterize interfaces in structural composite area. The basic principle of the DCB test is shown in Fig. 8.1. The DCB test provides a quantitative value characterizing crack propagation. For the tests AT&S has been customizing a DCB specimen with regard to thickness and dimensions so that it optimally fits the property range of FR4 resins and laminates. Preferred specimen dimension and proposed test conditions have been identified using a 2D simulation, featuring cohesive contact to represent crack behavior.



$$G_{IC} = \frac{3P\delta}{2B\,(a + |\Delta|)} * \frac{F}{N}$$

P load;
a_0 initial delamination length;
a total delamination length (a = a_0 + measured delamination
b width of specimen;
δ load line displacement;
N is the load block correction.
F is the large-displacement correction (described below);

Fig. 8.1: Concept for Double Cantilever Beam (DCB) testing. A beam featuring two laminate layers with approximately same thickness and a pre-crack is tested in a setup, where a normal force is applied by pinned load blocks in order to introduce crack growth.

In order to ensure high DCB specimen quality the samples have been manufactured on the standard AT&S PCB manufacturing line. The pre-cracks have been introduced by AT&S 2.5D technology which allows local layer separation. A picture of the real sample is shown in Fig. 8.2 (left). For crack length detection a digital image correlation system with optical crack length detection has been applied (Fig. 8.2, right).

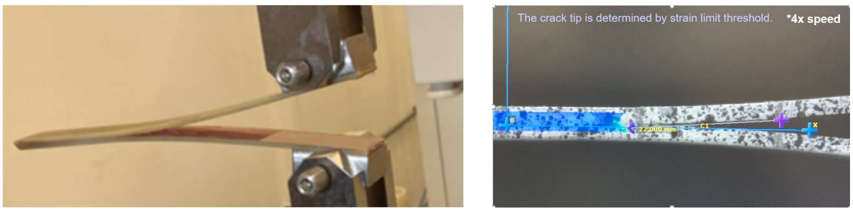


Fig. 8.2: Detailed view of applied DCB specimen during test in universal testing machine (left). Snapshot for automatic crack length detection during DCB test using DIC (right).

For first tests DCB samples have been manufactured featuring different surface treatment and lamination conditions. Samples have been tested in dry and humidity soaked conditions. In order to check for repeatability, the humidity soaking test has been repeated 4 weeks after the initial test.

The first experimental results had a good agreement with the simulation, showing lower variations of the test curves than experienced in pre-tests. This is mainly attributed to the highly standardized manufacturing conditions of the specimen. This methodology does not only allow to characterize the influence of humidity on the interface but also enables resolving process influences such as the impact of oxide replacement on the R/R interface quality or the impact of lamination pressure on interface strength. Thus the presented methodology is applicable to identify fast and reliably negative influences on the R/R interface such as systematic surface modification or contamination, material incompatibilities as well as non-optimum process conditions.

SELECTED TECHNICAL INNOVATIONS

#9. Application of a newly developed weathering set up for testing of semiconductor related metallization and coating materials

The characterization of materials and interfaces applied in the electronic- and semiconductor industry is a highly important task, which is required for suitable material selection for the development and construction of a functional and competitive device. A major part of this characterization lies within the investigation of aging and degradation properties under certain environmental conditions, as this is crucial for the robustness and the reliability of resulting products. In the course of iRel40 TU Wien has developed a special weathering setup (Fig. 9.1) to expose materials and interfaces to harsh environments as corrosive gases, high temperature and relative humidity. Together with the project partners KAI GmbH and Fraunhofer IFAM, various analytical techniques are applied to assess aging and degradation effects on weathered polymer coatings as well as the induced corrosion of metallization materials as Copper or Aluminum.

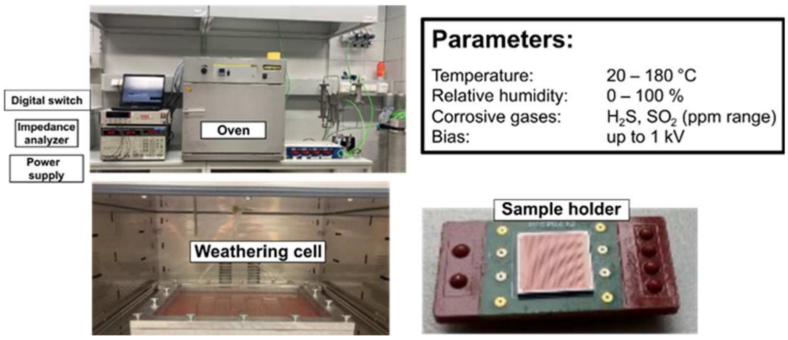


Fig. 9.1: Weathering setup developed at TU Wien.

Sulfur uptake of polymer films weathered with different temperature and humidity:

KAI GmbH has conducted weathering experiments with different polymer films and studied the sulfur uptake due to H_2S and SO_2 exposure with quantitative Laser Ablation Inductively Coupled Plasma Mass Spectrometry (LA-ICP-MS) measurements. Despite from determined bulk concentration which allows quick comparison of different materials, the measurement of quantitative depth profiles enables the assessment of uptake rates and diffusion of corrosive species through the polymer films. The weathering methodology together with the developed analysis methods will be applied in Use Case E-3 to evaluate the performance and protection capability of newly developed protective coatings by Fraunhofer IFAM.

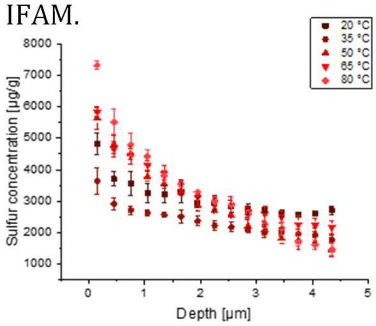


Fig. 9.2: Sulfur depth profile of PVA films weathered with different temperature. 100 ppm SO_2 and 0 % relative humidity for 24 hours.

Characterization of metallization materials under harsh environments:

At TU Wien, a wide range of different analytical techniques are used to characterize the corrosion phenomena of Copper and Aluminum after exposure to various sulfur containing atmospheres. Using XPS, formed species as well as elemental composition of the surface can be analyzed. Additionally, Raman Spectroscopy provides additional insights into formed species. Distribution of the elements of interest (Cu, Al, S, O, H) both lateral and in-depth are analyzed using SEM-EDX, LA-ICP-MS, and Laser-Induced Breakdown Spectroscopy (LIBS) giving additional insights into occurring corrosion phenomena.

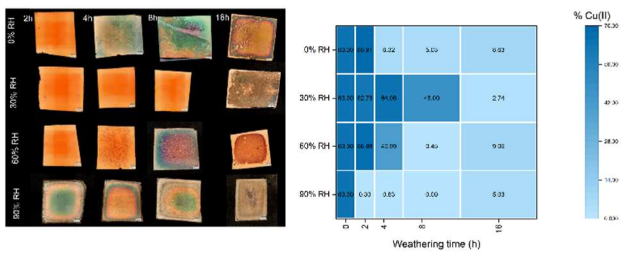


Fig. 9.3: Microscope pictures of Copper samples after exposure to different atmospheres and right: XPS analysis showing changes of oxidation state of copper.

SELECTED TECHNICAL INNOVATIONS

#10. Monitoring degradation of IGBTs in induction cooktops by artificial intelligence

B/S/H/

The demonstration of the reliability of the cooktop inverter is crucial given its importance for power conversion and transmission. One of the most critical components of the inverter is the Insulated gate bipolar transistor (IGBT), which is widely employed in induction cooktops due to its fast-switching speed, large current capacity and low on-stage power dissipation. Induction cooktop operation causes large thermal/electrical stress on the IGBTs. This results in thermo-mechanical fatigue and deterioration of the components electric properties, which, in turn, will influence the heat transfer inside the inverter and further aggravate the uneven internal thermal stress of IGBTs. Therefore, the evaluation of the IGBTs health state requires to estimate the temperature in the most critical locations, such as junction and case. Since the installation of temperature sensors in some critical locations of cooktops is not feasible, the objective is the development of a data-driven model for the estimation of the IGBTs case temperature during in-field operation of induction cooktops from measurements of other installed sensors. The proposed method is based on the selection of the measured signals to be used as input of the prediction model through a wrapper feature selection approach which employs a Non-dominated Sorting Genetic Algorithm (NSGA-II) based multi-objective (MO) optimization method. The optimization aims at the identification of a set of features, which allows obtaining a satisfactory trade-off between prediction accuracy, computational burden and memory demand, and cost of installation of the measurement system. Once the feature selection has been performed, an Artificial Neural Network (ANN) is developed to predict the case temperature.

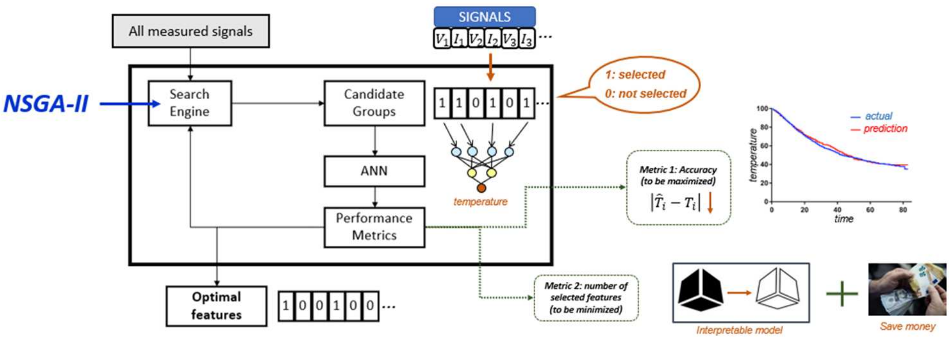


Fig. 10.1: Wrapper feature selection framework.

The proposed method has been verified using the data collected in laboratory tests within the framework of IP-3 (Induction cooktops). The obtained results in Fig. 10.2 show that the developed ANN model is able to provide accurate estimations of the case temperature using a reduced set of features. Therefore, the developed model constitutes the basis of the condition monitoring of the induction cooktop IGBTs.

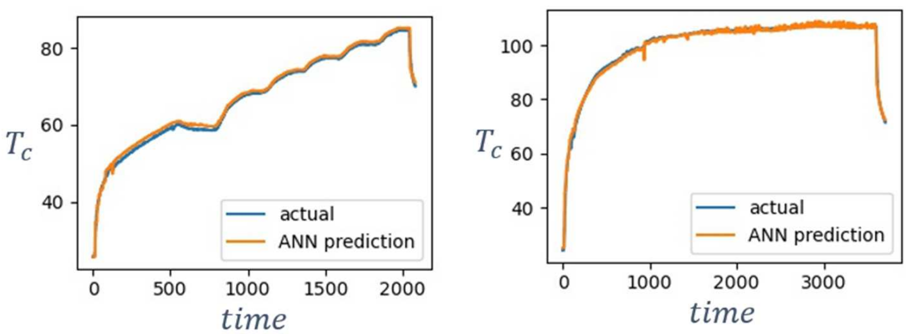


Fig. 10.2: IGBT case temperature predictions.

#11. Strategies to investigate the reliability of VCSEL application

The development of reliability models and the resulting lifetime prediction across a wide variety of operating conditions play an increasingly significant role for vertical-cavity surface-emitting lasers (VCSELs). The VCSEL technology provides compact and high-efficient solutions for applications such as proximity and ranging sensors, face identification, motion control, and many more. As the automotive certification standard exceeds the quality requirements of other application areas, the use of VCSELs in the automotive sector for driver monitoring, or sensors for (semi)autonomous driving demands additional requirements. One issue related to reliability is that any failure occurring to the component or subsystem leads to a shutdown of the system, as VCSELs are not designed with redundancy. These unscheduled interruptions not only cast significant safety concerns but also increase system operation costs and partially negate the benefits of introducing VCSEL systems.

VCSEL lifetime testing data are, in many cases, limited in terms of application conditions and not representative of the foreseen mission profile. Therefore, MCL together with ams OSRAM AG work on strategies for more robust, more universal, and easier-to-use VCSEL reliability models and useful lifetime prediction tools. Our main objective of that cooperation is to determine the lifetime of VCSELs as a function of their operating conditions as well as the application near temperature-driven boundary conditions.

MCL and ams OSRAM AG investigate different concepts to improve the lifetime prediction of VCSEL systems:

1) VCSEL quality tests at ams OSRAM AG to study the functionality under different high temperature operating life (HTOL) conditions by varying current and duty cycles.
2) Analysis of the interconnect technology (IcT) regarding their porosity – as a high porosity of the IcT can hinder heat dissipation, which results in a higher junction temperature.
3) Temperature-driven reliability tests at MCL to study the impact of thermal fatigue of the IcT by monitoring the junction temperature evolution over time.
4) Linking the production (functionality test data on wafer level) with the reliability of the system to determine the impact of the manufacturing process on the application's lifetime.

The combination of process data with the used reliability data will be applied as a tool to increase the quality of the VCSEL in their purposed application field. Thus, the investigation of the model's sensitivity and predictability in correlation with the application-specific mission profile is essential.

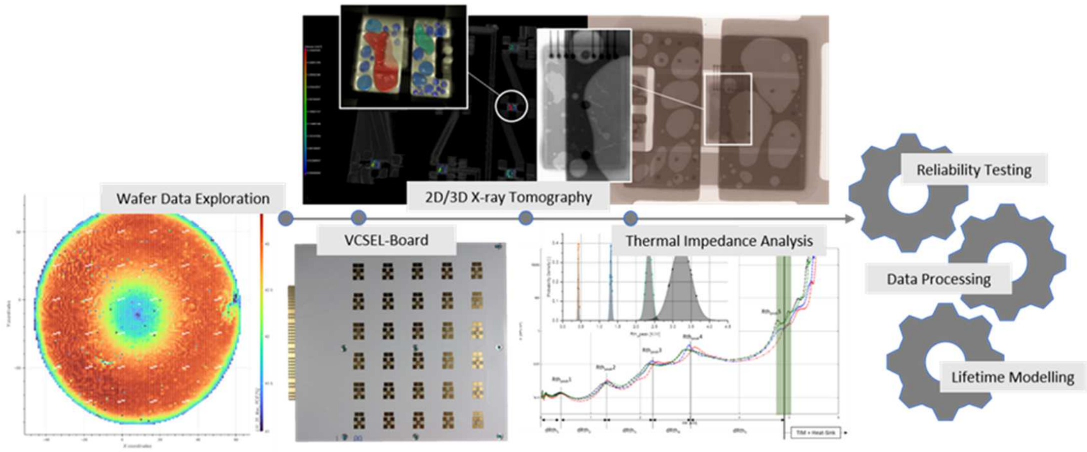


Fig. 11.1: VCSEL board intake inspection for lifetime modelling to improve model accuracy by the use of wafer level distribution data linked with board level heat path and porosity analysis.

SELECTED TECHNICAL INNOVATIONS

#12. Local current crowding monitoring in WBG power devices for induction cooking

Within the industrial pilot IP-3 dedicated to induction cooktops, CSIC is performing exploratory research around wide bandgap power semiconductor devices under short-time overcurrent events, identified as their worst operation condition in such an application. Such conditions could lead to current crowding phenomena, which consists in a current focalization effect due to non-homogenous conduction on top of a power semiconductor device. It usually occurs at local areas with a lowered resistance or concentrated electric field strength, which compromises the device performance and ruggedness. There is a demand for experimental means to describe the physics underlying current crowding conduction in such devices. As a promising solution to this end, CSIC has proposed the use of the Internal Infrared Laser Deflection (IIR-LD). As a proof of concept, the free-carrier profile in a 1.2 kV SiC Schottky diode has been measured under current crowding. Such results are assessed with simulation and the mainstream approach for free-carrier concentration profile measurement: Free Carrier Absorption (FCA).

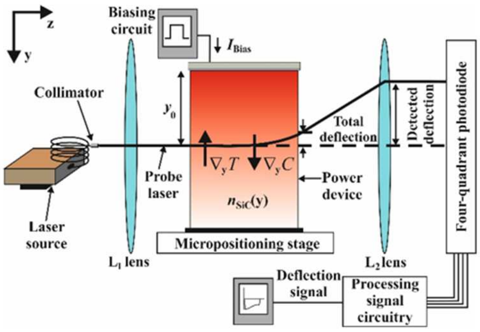


Fig. 12.1. Schematic view of the IIR-LD technique at a given lateral position

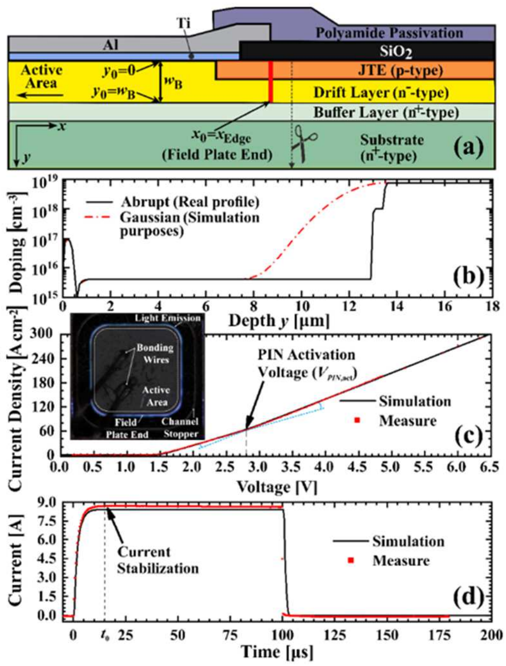


Fig. 12.2: a) JTE edge termination structure, highlighting $x_0 = x_{Edge}$ and the doping profile cut. b) Doping profile used in the simulations. Experimental and simulation results comparison at room temperature for: c) static I-V characteristic (normalized to device total area) and d) I_{Bias} waveform. Fig. 2c insert: blue electroluminescence at 3.3 V and 86 A/cm² by JTE bipolar activation.

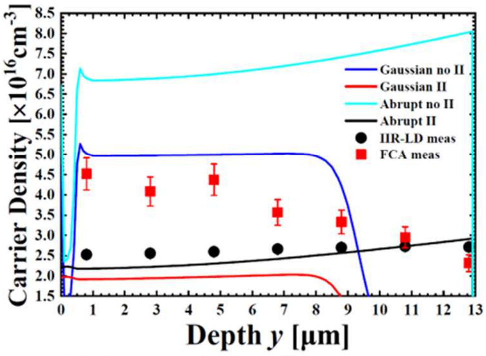


Fig. 12.3: Comparison of carrier profiles at $x_0 = x_{Edge}$ between experiments and various simulated doping profiles for $I_0 = 8.7$A.

Fig. 12.1 outlines the IIR-LD operation principle and its experimental set-up. An IR-laser beam passes through the biased device at a given depth y_0, perpendicularly striking on their opposite lateral sidewalls. During on-state, the free-carrier injection into the drift region and the resulting self-heating leads to the beam deflection induced by the refractive index n variation, due to the gradients of temperature T and free-carrier density C (∇T and ∇C). To monitor this, the following elements are required (see Fig. 12.1): a laser source, two converging lenses (L_1 and L_2), automated micro-positioning stages, a Germanium four-quadrant photo-detector, and a processing signal circuitry. To bias the device, a modified Buck converter is used to generate the short current pulses. The same experimental set-up shown in Fig. 12.1 is used to obtain the FCA measurements. Fig. 12.2 presents the location where current crowding occurs (Fig. 12.2a), the doping profiles used in the simulations (Fig. 2b) and the match between static and dynamic characteristics (see Figs. 12.2c and 12.2d). The insert demonstrates the current crowding conduction around the device by a bipolar mechanism. Fig. 12.3 presents the comparison of simulations and measurements by IIR-LD and FCA. IIR-LD matches the simulation results, while FCA are not predictive and cannot be used in WBG-based power devices.

ENFORMA

#13. Anomaly detection using audio signals

A review of supervised and unsupervised machine learning algorithms and applications suitable for anomaly detection on audio signals was presented recently during the International Aegean Scientific Research Symposium 2021 (IASRS 2021) that was held on 25-26 Dec.

The specific purpose of Enforma's paper was to investigate the audio signals obtained from a water pump motor. A more general goal of the company's research is to lay the groundwork in preparation of a transformation to a fully automatic quality test system at the end of a production line for white goods electric motors. Today's state of the art is that the test system greatly depends on human effort and subjective judgement. Our plan is to implement fully automatic quality test of electric motor based on artificial intelligence and machine learning.

In our published work, we first created the training dataset by examining the audio signal properties and next compared the results of the trained models. Fig. 13.1 depicts the Mel Spectrograms used on the training dataset as they provide the best representation of audio signals. The summary tables in Fig. 13.2 present the results for the Autoencoder (AE) neural network performing unsupervised learning and the Convolutional neural network (CNN) performing supervised learning. These early results pave the way to a stage where end-of-line reliability tests will be performed in an automatic fashion.

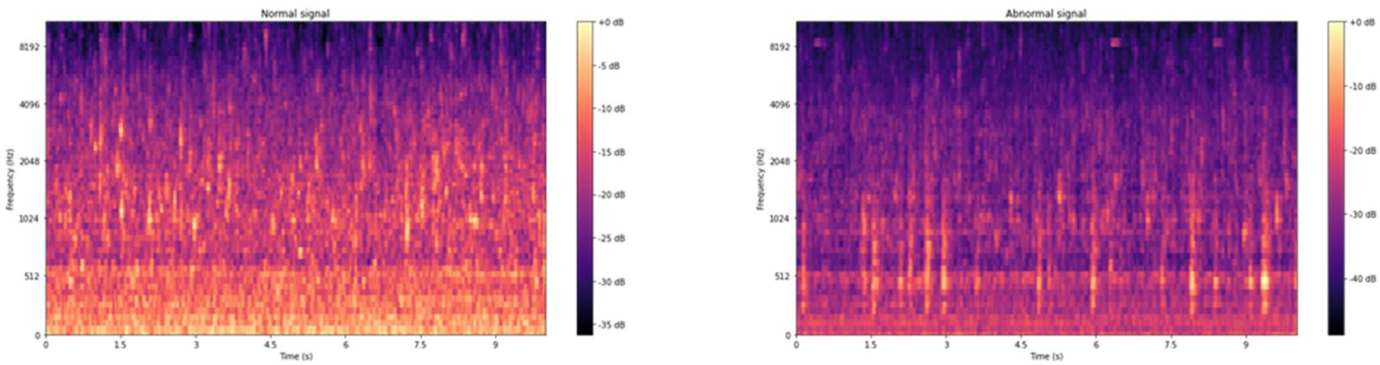
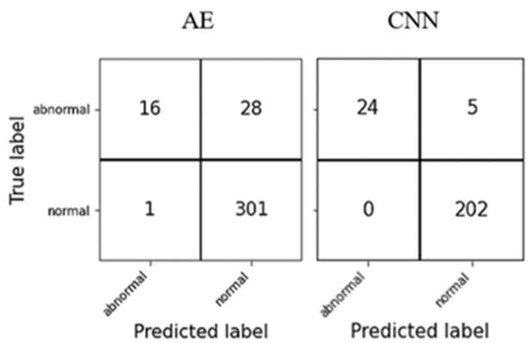


Fig. 13.1: Mel spectrograms.



%	AE	CNN
Accuracy	91.6	97.8
Precision	99.7	100.0
Recall	91.5	82.8
F1 Score	95.4	90.6

Fig. 13.2 Result of deep learning models.

#14. Big data streaming and data analytics infrastructure for efficient AI-based processing on edge and local cloud

MARMARA UNIVERSITY

VeNIT Lab

It is a challenging task to minimize defects on brushless DC electric motors used in household appliances, during the manufacturing phase. To improve the reliability of electric motor production, the data collected from the production plant require caution, which will enable failure detection at the edge and local cloud. For this purpose, a big data streaming and data analytics infrastructure is designed and implemented by Marmara University VeNIT Lab to enable AI-based models detect early failures of electric motors, including multiple components that collect, transfer and store data in a plain yet influential format.

The reduction of human intervention in the test vehicle is established with an automated data collection process. Formerly the test setup consisted of manual acoustic tests conducted by human operators and static calculations on vibration and electromagnetic field (EMF) data collected by the sensors. Latest version of the infrastructure enables the creation and running of automated tests which are enhanced by AI-based fault detection models.

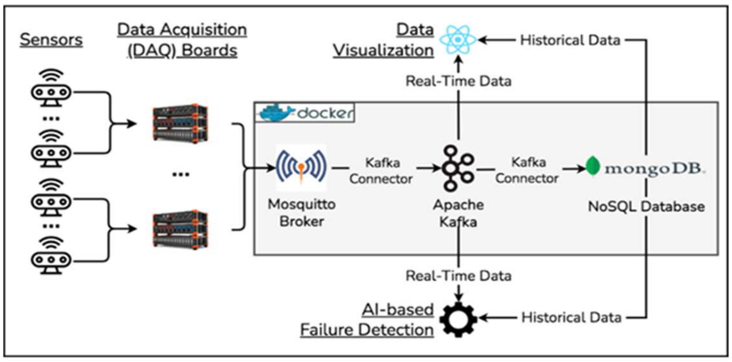


Fig. 14.1: Kafka-centric containerized big data streaming platform.

Another feature of the new infrastructure is the extraction of knowledge by combining the data collected from the test environment. In the initial version of the test setup, the tests carried out on the same electric motors at different time intervals were combined and interpreted at the end of the whole process. Owing to the simultaneous collection and transmission of data to the AI models, the fault detection is ensured that fault detection would be more solid and less time-consuming. MQTT brokers act as an aggregator of multi-sensor data collected from multiple DUTs (Devices Under Test).

To extend the use of the latest infrastructure for multiple test vehicles regardless of the hardware limitations, the scalability of the system plays a crucial role. For that reason, the sensory data streaming infrastructure of VeNIT Lab is designed and implemented with a Kafka-centric approach, which enables the transfer of event streaming data collected from the MQTT broker into different sink components, e.g., NoSQL database and AI-based models, simultaneously. The infrastructure includes multiple Kafka brokers dedicated to the use case to allow the transfer of data into sink components in a fault-tolerant and scalable fashion. The NoSQL-based data storage component, MongoDB, allows the historic data storage which includes a time-series collection feature that will be used as a source for AI-enriched aging tests. The system becomes resource independent, and consistent.

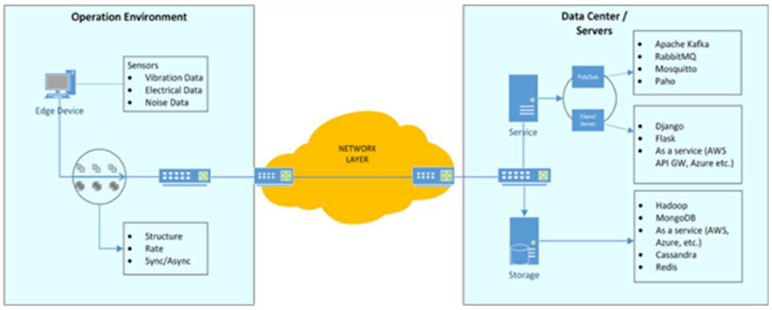


Fig. 14.2: High level architecture of data streaming platform.

Infrastructure built by VeNIT Lab is designed on top of Docker containerization technology to expand the data streaming platform effectively, considering the outlook on future requirements and needs of the test setup. Docker allows to run and adjust multiple isolated spaces which share the same OS. Hence, the data streaming infrastructure can be deployed to various types of solutions, including edge and cloud.

#15. A robust approach for inter-turn fault detection of PMSM used for the in-wheel technology

The usage of permanent magnet synchronous motor (PMSM) in in-wheel technology has several advantages: a simple structure, small size, light weight, and large overload capacity. In other words, the PMSM is compact, efficient, and has a high torque density even at low speed as well as an accurate dynamic performance. The in-wheel motors for electric vehicles are typically supplied with high voltage. According to the defined standards, the main challenge is the protection of person against electric shock. In addition to the high voltage safety considerations, critical motor braking torque may occur if there is a 3-phase winding insulation breakdown. This can seriously affect the reliability and safety of the motor operation.

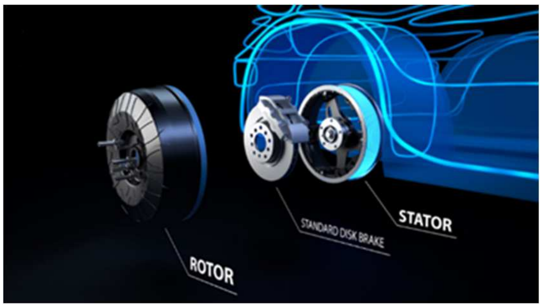


Fig. 15.1: The in-wheel motor.

As it has been reported in the literature, among all types of PMSM faults, the failure of stator winding is the most common one. It can be seen that the inter-turn short circuit (ITSC) fault caused by electrical insulation failure in the stator winding can lead to short to ground resulting in undesired behaviours such as oscillations in torque and localized heating. Furthermore, undetected ITSC fault in a coil can easily evolve to phase-to-phase short circuit and ground short circuit faults. A widely used approach to detect the ITSC fault in the stator winding is based on the state or parameter estimation, which requires the use of mathematical models of the monitored system. Having adopted the extended Kalman filter (EKF), the identification process can be done online using recursive techniques. However, high noise sensitivity is a big deal and this stochastic method requires information about the process and measurement noise statistics. To overcome this limitation, a nonlinear observer, to which a sliding-mode algorithm is adopted, can be applied.

The assumptions of the system definition, which should be satisfied in order to be able to apply this sliding mode algorithm for the estimation of the PMSM parameters, have been considered in our paper that has been accepted to be presented in ICCVE 2022. Unknown parameters, either constant or time-varying, can be identified in a finite time using this algorithm. The stator currents and voltages are only introduced to the estimator and no additional sensors are required. It has been shown in simulation how the introduced sliding mode identification algorithm can detect the fault in different scenarios. The achieved performance has been compared to the results obtained through the EKF. In both of the observers, detection of the ITSC fault is fast enough. However, the sliding mode algorithm has a better performance in the presence of measurement noise as it can be seen in Fig. 15.2. This is due to that in the sliding mode algorithm, the speed sensor information, which has usually more irritating noise, is not incorporated. Furthermore, it is noted that for the sliding mode estimator, the computational effort is low.

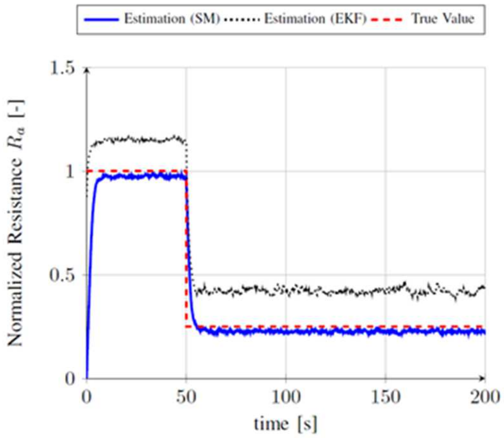


Fig. 15.2: Estimation of stator resistance with abrupt ITSC fault in the presence of measurement .

DISSEMINATION

Scientific results were published in book chapters, journals and presented at international conferences

Books

2 book chapters in "Reliability of Organic Compounds in Microelectronics and Optoelectronics", ed. W. D. van Driel and M. Y. Mehr, Springer, 2022. ISBN 978-3-030-81575-2, DOI: 10.1007/978-3-030-81576-9:

- "Reliability and failures in solid state lighting systems", pp. 211-240
- "Outlook: From physics of failure to physics of degradation", pp 535-538,

Conference Contributions

23 conference contributions and presentations at "31st European Safety and Reliability Conference (ESREL)", "IEEE 8th Workshop on Wide Bandgap Power Devices and Applications (WIPDA)", "2021 IEEE International Electron Device Meeting (IEDM 2021)", "2021 IEEE International Integrated Reliability Workshop (IIRW)", "IEEE International Conference on Connected Vehicles and Expo 2022 (ICCVE2022)", and others. The list of published conference contributions is on a webpage *www.iRel40.eu*.

Published journal articles

1. Olschewski, T. Fast Accurate Defect Detection in Wafer Fabrication. arXiv preprint, arXiv:2108.11757 (2021), DOI: 10.48550/arXiv.2108.11757
2. Millesimo, M., Fiegna, C., Posthuma, N., Borga, M., Bakeroot, B., Decoutere, S., and Tallarico, A. N. High-Temperature Time-Dependent Gate Breakdown of p-GaN HEMTs. IEEE Trans. on Electron Devices 68, no. 11 (2021): 5701-5706, DOI: 10.1109/TED.2021.3111144
3. Tallarico, A. N., Millesimo, M., Bakeroot, B., Borga, M., Posthuma, N., Decoutere, S., Sangiorgi, E., and Fiegnav C. TCAD Modeling of the Dynamic V TH Hysteresis Under Fast Sweeping Characterization in p-GaN Gate HEMTs. IEEE Trans. on Electron Devices 69, no. 2 (2021): 507-513, DOI: 10.1109/TED.2021.3134928
4. Olschewski, T. Defect Detection on Semiconductor Wafers by Distribution Analysis." arXiv pre print, arXiv:2111.03727 (2021), DOI: 10.48550/arXiv.2111.03727
5. Safari, L., Barile, G., Stornelli, V., Minaei, S., and Ferri, G. Towards Realization of a Low-Voltage Class-AB VCII with High Current Drive Capability. Electronics 10, no. 18 (2021): 2303, DOI: 10.3390/electronics10182303.
6. Van Driel, W. D., Jacobs, B., Watte, P., and Zhao, X. Reliability of LED-based systems. Microelectronics Reliability 129 (2022): 114477. DOI: 10.1016/j.microrel.2022.114477
7. Meneghini, M., Santi, C. D., Abid, I., Buffolo, M., et al. GaN-based power devices: Physics, reliability, and perspectives. J. Appl. Phys. 130, no. 18 (2021): 181101, DOI: 10.1063/5.0061354
8. Bonet, F., Aviñó -Salvadó, O., Vellvehi, M., Jordà, X. Godignon, P. and Perpiñà, X. Carrier Concentration Analysis in 1.2 kV SiC Schottky Diodes under Current Crowding. IEEE Electron. Dev. Letters 43, no. 6 (2022): 938 – 941, DOI: 10.1109/LED.2022.3171112.

BOOK CONTRIBUTION

Hot of the press: Reliability of organic compounds in microelectronics and optoelectronics

Editors: Willem van Driel and Maryam Yazdan Mehr

Co-editors: Kouchi Zhang and Xuejun Fan

https://doi.org/10.1007/978-3-030-81576-9

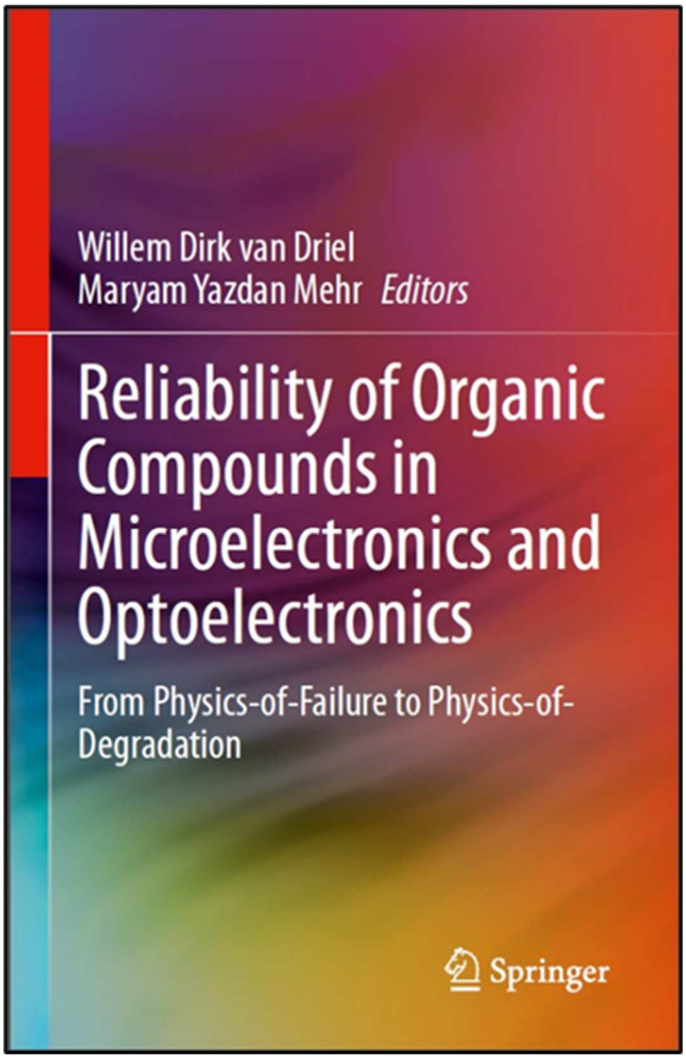


Fig. 16.1: Book cover.

As part of our dissemination activities, several iRel40 partners have contributed to this book, which relates to the physics of degradation, a topic well addressed in iRel40. The book contains chapters related to (i) organic materials (silicones and polycarbonate), (ii) degradation mechanisms in microelectronics materials like moulding compounds, (iii) degradation mechanisms in optoelectronics components like OLED and LEDs and (iv) state-of-the art modelling and lifetime assessment techniques. Parts of the contents in this book are first-hand results from industrial research and development projects. Reading this book, students in different engineering disciplines get an insight and develop an in-depth understanding of different failure and/or degradation mechanisms in organic materials. Also, this book will certainly be useful when it comes to training methodologies of assessing failures, degradations, and reliability of different engineering materials for students. Health monitoring and/or digital twin technologies may support the engineers to understand, master and forecast the physics of degradation. The concept of the digital twin is relatively new. It was conceptualized during the early years of the twenty-first century and has gained traction mainly during the last decade. The primary reason behind it is the further digitalization of the electronic industry, which has been accelerated by the newly emerging IT technologies. Digital twin enables system optimization, monitoring, diagnostics and prognostics using integration of artificial intelligence, machine learning and big data analytics. It can be used for predicting failures and estimating lifetime of electronic components, which then allows for scheduling preventive maintenance. Launching a preventive maintenance program like this allows companies to save time and costs and avoid customer dissatisfaction as well as unwanted lawsuits. This will be embraced in the fourth wave of reliability, physics of degradation, which will also reduce the amount (and cost) of product release testing. This book is a starting point for a next one, that will be fully dedicated to the iRel40 results with the provisional title: *Recent advances in the reliability assessment of electronic devices*.

GENERAL ASSEMBLY MEETING

Istanbul, May 16-20, 2022

intelligent Reliability 4.0

The first face-to-face General Assembly meeting of the ECSEL JU project iRel40 took place from Monday, May 16th to Thursday, May 19th 2022 in Istanbul. Altogether, 95 onsite and more than 40 online participants from 75 organizations out of 13 countries attended the meetings hosted by Marmara University and its VeNIT laboratory.

Fig. 17.1: iRel40 team during the General Assembly meeting.

During the four days event, all technical work packages organized workshops, which were also available online for project partners who could not attend the meeting in person. Workpackage WP2 organized a workshop on Artificial Intelligence. WP3 focused on sharing experimental results on new material characterization and interfaces. In WP4 a lively iRel40 speed dating workshop was organized where the partners introduced themselves for 1.5 minutes and for another 1.5 minutes they introduced their work in iRel40. Workpackage WP5 was organized in addition to presentations also poster presentations to catalyze scientific exchange. Workpackage WP6 includes research and development on the 34 use cases improving reliability. This includes 16 application-driven use cases from the three domains Digital Industry, Energy, and Transport. In addition, the consortium works on 18 so-called industrial pilots which focus on improvement of reliability in production and testing. The status of the use cases was introduced by short highlight presentations. This session was followed by a poster session including all the 34 use cases together with eight special technical posters.

iRel40 is a project that considers the value chain from wafer to chip to package to board/system and application. This includes building bridges between these different domains. This was also a focus topic during a social event, which included a laser show with the iRel40 logo on the Bosporus bridge connecting Europe and Asia.

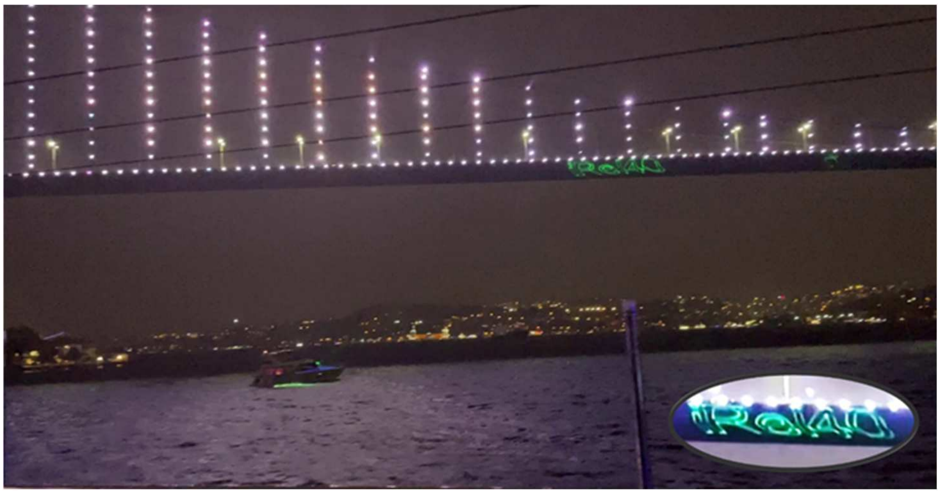


Fig. 17.2: Photo of the iRel40 laser image on the Bosporus bridge.

The Istanbul meetings strengthened the cooperation and collaboration between the participants and their organizations and made a great contribution to improving the reliability of electronic systems and devices. More information can be found at our website www.iRel40.eu/news.

FUNDING

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THIS PROJECT HAS RECEIVED FUNDING FROM THE ECSEL JOINT UNDERTAKING (JU) UNDER GRANT AGREEMENT NO 876659. THE JU RECEIVES SUPPORT FROM THE EUROPEAN UNION'S HORIZON 2020 RESEARCH AND INNOVATION PROGRAMME AND GERMANY, AUSTRIA, SLOVAKIA, SWEDEN, FINLAND, BELGIUM, ITALY, SPAIN, NETHERLANDS, SLOVENIA, GREECE, FRANCE, AND TURKEY. IN ADDITION, GERMANY INCLUDING THE FREE STATES OF SAXONY AND THURINGIA, AUSTRIA, BELGIUM, FINLAND, FRANCE, ITALY, THE NETHERLANDS, SLOVAKIA, SPAIN, SWEDEN, AND TURKEY PROVIDE NATIONAL FUNDING.

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