Ph.D. in Information Technology
Thesis Defenses

October 10th, 2025
At 09:00 a.m.
Room Alpha – Building 24

Matteo GREATTI– XXXVII Cycle

CHALLENGES IN THE DEVELOPMENT OF MODERN GALVANIC ISOLATORS BASED ON POLYMERIC DIELECTRICS: A DEVICE RELIABILITY PERSPECTIVE ANALYSIS
Supervisor: Prof. Gerardo Malavena

Abstract:

The long-term electrical reliability of insulation materials remains a central concern in modern electronic systems, especially in light of the increasing prevalence of highly integrated and miniaturized devices. In this context, galvanic isolation has emerged as a critical area of investigation, characterized by the use of relatively thick dielectric layers, standing in contrast to the extensively studied reliability of thin oxides. Galvanic isolation ensures the safe electrical separation of functional blocks within a system, while still allowing energy or data transmission across the isolation barrier. Among the different materials used to implement isolation barriers, polymeric dielectrics have gained significant attention due to their compatibility with low-cost and high-volume manufacturing processes. However, the use of polymer-based materials presents specific challenges. Their intrinsic characteristics expose them to specific degradation mechanisms when subjected to electrical, thermal or more in general environmental stress over long periods of time. In particular, variations in humidity and temperature, when coupled with prolonged electrical stress, can result in early-stage failure through complex mechanisms that remain an active area of research. Understanding these interactions under realistic operating conditions is thus essential to ensure the development of safe and robust isolation systems. This doctoral research addresses the reliability concerns associated with polymeric dielectrics used for state of the art galvanic isolation devices: the study aims to investigate the failure mechanisms triggered by environmental and electrical stress and to develop models that link material properties, device architecture and stress conditions to long-term insulation performance. The methodology adopted in this work combines characterization techniques, experimental testing under controlled environments and the formulation of physical and compact models to describe the observed degradation phenomena. The initial part of the thesis introduces the functional role of galvanic isolation in electronics, emphasizing its relevance across a wide range of applications, including power conversion, industrial control, renewable energy systems, and medical instrumentation. A comparative analysis of the main isolation technologies including optical, magnetic, and capacitive is provided, outlining their operating principles, performance characteristics and application-specific trade-offs. The thesis then provides a comprehensive analysis of polymeric materials from the perspective of their use as dielectrics. Their chemical configuration, electronic structure and charge transport mechanisms are examined, including a discussion on the influence of structural disorder, molecular mobility and water uptake on dielectric behavior. A focus is placed on how moisture

interacts with the polymer matrix, affects charge dynamics and acts as a precursor to premature dielectric breakdown. The core of the research is organized into three major investigative threads. First, partial discharges are studied as early indicators of insulation degradation. Dedicated test structures and commercial components are used to analyze inception thresholds, repetition rates and causes. Second, the dynamics of moisture absorption and diffusion are examined in relation to the lifetime of galvanic isolation devices. The impact of temperature-dependent moisture behavior on Time-Dependent Dielectric Breakdown (TDDB) is quantified and a physical picture is developed to explain the non-monotonic lifetime trends observed in TDDB tests. Third, the influence of termination geometry on electric field distribution is investigated. The conducted study demonstrates that adopting not specifically studied terminations leads to field enhancement and localized stress, significantly increasing the likelihood of early breakdown. Numerical simulations and experimental validation show that optimized edge profiles can mitigate these effects, offering substantial gains in device reliability without the need to alter the base dielectric material. In conclusion, this work provides a comprehensive reliability framework for polymer-based galvanic isolation, bridging material science, device engineering and degradation modeling. The insights gained can be employed for the design of next-generation isolation systems, combining safety, durability, and manufacturability to meet the demands of future high-performance electronic applications.

Lorenzo Jurij MAZZOLA – XXXVII Cycle

MODELING THE IMPACT OF TEMPERATURE AND MOISTURE ON THE TIME DEPENDENT DIELECTRIC BREAKDOWN IN POLYMERIC DIELECTRICS FOR GALVANIC ISOLATION

Supervisor: Prof. Gerardo Malavena

The reliability of galvanic isolation devices is of critical importance in power electronics, industrial automation, and automotive applications. Polymeric dielectrics have emerged as a key material for galvanic isolation due to their advantageous electrical insulation properties, mechanical flexibility, and cost-effectiveness. However, their long-term performance is significantly affected by environmental conditions, particularly temperature and moisture. This thesis presents a comprehensive study on the impact of these factors on the Time-Dependent Dielectric Breakdown (TDDB) of polymeric insulation layers, combining experimental investigations with advanced modeling approaches to enhance predictive reliability assessments.

The study begins with a review of the fundamental principles of electrical insulation and the role of galvanic isolation in high-voltage applications. A particular emphasis is dedicated to polymeric dielectrics, exploring their physico-chemical properties, charge transport mechanisms, and the degradation processes that lead to electrical failure. After that, the attention is shifted towards the experimental investigations conducted on various galvanic isolation samples to evaluate moisture absorption dynamics, temperature-induced degradation, and TDDB characteristics under different environmental conditions. The results reveal complex interactions between moisture diffusion and polymer degradation, necessitating a refined theoretical framework to describe these phenomena.

To address these challenges, two modeling approaches are developed. First, a temperature-dependent degradation model is proposed, capturing the temperature activation of TDDB lifetimes. This model successfully reproduces experimental trends and offers predictive insights into the reliability of galvanic isolation materials under thermally stressed conditions. Second, a moisture-dependent TDDB model is formulated improving and extending the first one, incorporating polymer-moisture interactions. This model was able to accurately reproduce not only dielectric aging, but also moisture absorption and desorption within the polymeric matrix.

The combination of experimental results and numerical modeling activities presented in this work provides a systematic methodology for assessing the reliability of polymeric dielectrics in galvanic isolation applications. In fact, the findings contribute to the optimization of insulation materials, aiding in the design of more robust and durable galvanic isolators. Furthermore, the developed models offer a foundation for future studies on the interplay between environmental factors and electrical degradation, facilitating improved lifetime predictions for next-generation insulation technologies. More specifically, the thesis is organized as follows.

Chapter 1 introduces the problem of insulation failure in electrical systems, emphasizing its implications in power electronics and semiconductor devices. The role of galvanic isolation in ensuring electrical safety and reliability is discussed, along with an overview of polymeric dielectrics as insulating materials. A discussion on the statistical methodologies employed for analyzing dielectric failure data is also included. The chapter concludes by outlining the objectives and motivations of the research.

Chapter 2 presents a comprehensive review of polymeric dielectrics, covering their chemical and physical structure, charge transport mechanisms, and degradation processes. The effects of environmental stresses, including temperature and moisture, on polymeric insulation performance are discussed in detail. Key reliability concerns, such as electrical treeing, partial discharge activity and microscopic degradation are examined.

Chapter 3 describes the galvanic isolation samples used in the study and details the preconditioning processes required to ensure consistent testing conditions and reproducible experimental results. The experimental setup for TDDB measurements is also described.

Chapter 4 reports the experimental results on the moisture absorption dynamics found in polymeric dielectrics, along with its impact on electrical properties of those materials. Then, the effects of temperature on TDDB behavior are analyzed, highlighting the activation mechanism leading to accelerated degradation. The dependence of TDDB on moisture levels is investigated, revealing correlations between dielectric failure and humidity-induced material dielectric properties variations.

Chapter 5 details an original numerical compact model describing the influence of temperature on TDDB of the investigated devices. The model integrates thermally activated degradation mechanisms and percolative breakdown theories to explain observed experimental trends.

Chapter 6 introduces an evolution of the modeling approach presented in Chapter 5, focusing on the role of moisture in dielectric degradation. The diffusion of water molecules within the polymer matrix and their interaction with polymeric chains are mathematically described. The model captures the progressive weakening of insulation reliability due to internal humidity and successfully replicates experimental TDDB trends under varying moisture conditions.

Finally, the conclusions of the work are detailed in the final chapter, summarizing the key findings of the research, emphasizing the contributions of both experimental investigations and modeling efforts. The implications of the results for the design of more reliable galvanic isolation devices are discussed, along with suggestions for future work to further refine dielectric reliability assessments of polymer-based galvanic isolators.

PhD Committee

Prof. Daniele Ielmini, **Politecnico di Milano**

Prof. Francesco Maria Puglisi, **Università degli Studi di Modena e Reggio Emilia**

Prof. Susanna Reggiani, **Università degli Studi di Bologna**